May 2015

Designing a Bioshelter in Worcester

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This project sought to create a year-round self-sustainable urban food production system. Such a system may be achieved through a bioshelter. Green energy, compost, and rainwater were considered as alternatives to fossil fuels. This project worked closely with Worcester Common Ground and other community organizations to revitalize an abandoned lot in Worcester's Piedmont neighborhood. Detailed designs, blueprints, and cost analyses were produced to aid Worcester Common Ground with the eventual construction of the bioshelter.

By John Breen, Thomas Fay, Peerapat Luxsuwong, Mark Overdevest, and Yunjae Sohn

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DATE:
MAY 5, 2015

REPORT SUBMITTED TO:

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Abstract

This project sought to create a year-round self-sustainable urban food production system. Such a system may be achieved through a bioshelter. Green energy, compost, and rainwater were considered as alternatives to fossil fuels. This project worked closely with Worcester Common Ground and other community organizations to revitalize an abandoned lot in Worcester's Piedmont neighborhood. Detailed designs, blueprints, and cost analyses were produced to aid Worcester Common Ground with the eventual construction of the bioshelter.

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Acknowledgements

We would like to thank our advisors, **Professor Robert Hersh**, **Professor Derren Rosbach**, and **Professor Elisabeth Stoddard** for guiding this project. Their ideas, support, and genuine interest helped maintain the momentum of this project throughout the academic year.

We would also like to express our gratitude to our project sponsor, **Worcester Common Ground**, and **Yvette Dyson**, for providing information, advice, and inspiration to the group. Without her, this project would not have been possible.

Finally, we would like to extend our sincere thanks to several more individuals and organizations, without whom this project would not have accomplished as much as it did:

- **Ashley Carter, Ascentria Care Alliance**: for meeting with us multiple times and coordinating meetings between us and the refugee farmers
- **Brian Breveleri and his crew:** for providing us with woodchips for the trial Jean Pain Mound and delivering them to the lot
- **Charise Canales, Worcester Common Ground**: for helping us organize community events
- **Engineers Without Borders:** for their assistance with the rainwater catchment system
- **Gaelan Brown**: for his invaluable knowledge on the Jean Pain Mound
- **Jonathan Bates and Eric Toensmeier**: for sharing their bioshelter and expertise with us in Holyoke
- **Laura Hanlan, the librarian:** for teaching us about Gordon Library's Resources
- **Nancee Bershof:** for allowing us to visit her bioshelter in Greenfield multiple times and staying in contact with us throughout the project
- **Rob Johnson, the structural consultant**: for helping with structural plans and designs
- **The Architectural Engineering Department at WPI:** for their moral support and technical advice
- **The City of Worcester:** for meeting with us and guiding us through the approval process
- Waldo: for ubiquitous presence throughout the paper

Executive Summary

The practice of growing and distributing food in cities is called urban agriculture. Over the past decade, urban agriculture has been seen as an effective way to tackle community-oriented problems through improved food security, reuse of vacant property, increased community cohesion, and job creation (Nsar & Smit, 1992; Nugent, 2015). To promote urban agriculture, an increasing number of cities have passed ordinances to stimulate the development of commercial farms in cities.

Urban farmers encounter a number of challenges: poor soil quality, contamination from previous use, limited growing space, and short growing seasons. These limit the volume of urban food production possible (Smit, Ratta, & Nasr, 1996).

One way to address some of these challenges is through a bioshelter. A bioshelter is a self-sustained ecosystem which is achieved by integrating many layers of ecological and mechanical systems (James, 2013). Through these systems, it can provide a year-long growing season, as well as improved plant health in a way that is not reliant on fossil fuels or the power grid. Working together with Worcester Common Ground (WCG), this project designed a bioshelter to promote the benefits of urban agriculture on a vacant lot in the Piedmont neighborhood of Worcester.

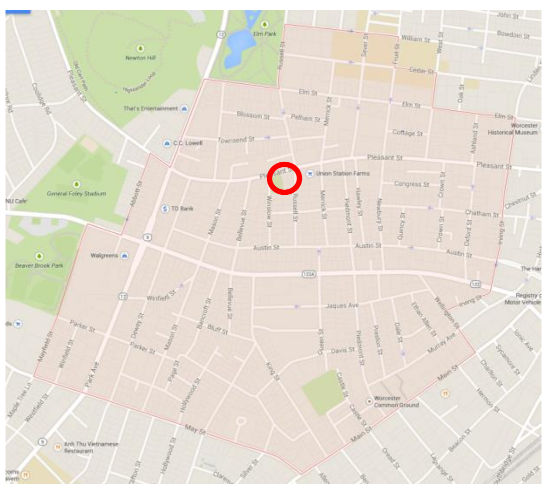


Figure 1: Map of the Piedmont area.

Five major steps were taken to design a bioshelter for the site: existing bioshelters were documented, the purpose and use of the bioshelter were identified, soil and climate conditions of the location were analyzed, critical bioshelter systems and technologies were researched, and a prototype bioshelter was designed. By evaluating other bioshelters through field visits and research, systems for heating, water use, and ventilation were identified.

Figure 2: A picture of a New England bioshelter

Identifying the goals of the sponsors and opinions of local stakeholders provided a general idea of what form the bioshelter should take. Gathering opinions about the bioshelter was an iterative process. As the bioshelter's design changed, the overall purpose and use of the bioshelter also changed along with it. This made continually gathering feedback from not only the sponsors and stakeholders, but also the local residents vital to the project.

A bioshelter is meant to be self-sustaining. To produce an energy efficient design that optimizes the usage of available natural resources of solar, wind, and water, a detailed analysis of the site was conducted. An insolation analysis was performed through Ecotect Analysis software, wind data of Worcester was gathered from Ecotect weather tool, and average rainfall data was obtained from an local weather station's online database.

The bioshelter is comprised of many complex systems, which work together to provide a stable environment. It was designed to maximize available solar energy for plant growth as well as solar heat gain during the winter. In addition, the water requirements of the bioshelter were compared against the available precipitation to determine the effectiveness of a rainwater catchment system. Airflow through the bioshelter was calculated to determine adequate window dimensions for optimal plant health. The effects of various types of heat conservation methods used in the bioshelter were calculated to estimate the net energy consumption, which was attained through software. Finally, additional software was used to model the prototype of the bioshelter to visualize the layout and interaction of the systems.

Figure 3: Photoshop image of the bioshelter placed into the site

The final design of the bioshelter is composed of three main systems: a rainwater catchment system, a heating system, and the structure itself. The goal of these three systems is to work in concert to reduce or eliminate the need for external input to maintain the bioshelter.

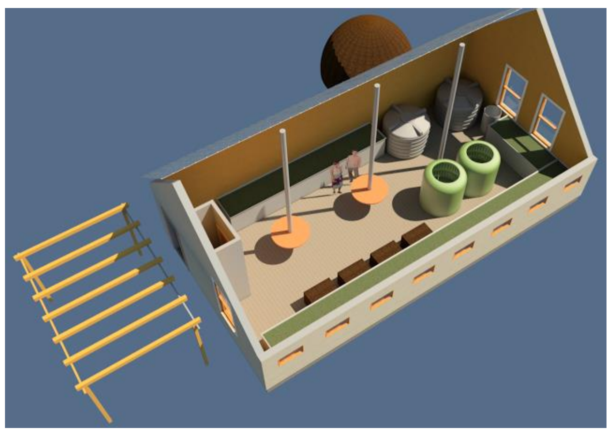


Figure 4: Rending of the bioshelter systems

One of the bioshelter's subsystems is the rainwater catchment system. It is comprised of three different parts: the catching, the conveyance, and the storage. The rainwater catchment system's goal is to capture water and store it for future use. In this design, the water is first caught on the roof of the bioshelter and then conveyed through a series of pipes to the storage tanks.

Figure 5: Rending of the rainwater catchment system

Heating is another important part of the overall bioshelter. New England's climate is not only known for its cold winters, but also for its hot and humid summers. In these cases, the bioshelter must be able to both efficiently retain heat throughout the winter as well as disperse heat during the summer. The heating system of the bioshelter was designed with these two goals in mind.

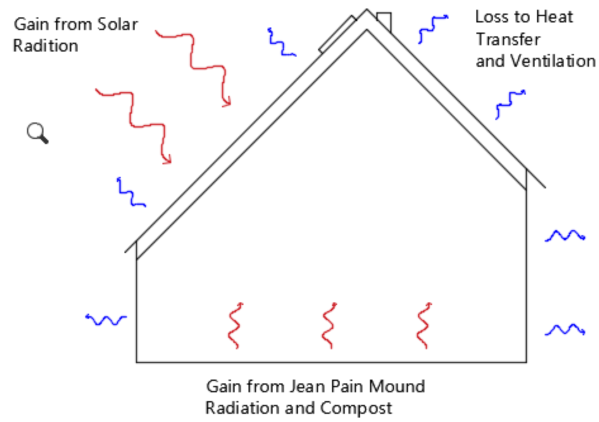


Figure 6: Components of bioshelter heating system

In the proposed design, there are three main methods to retain and disperse heat: the climate battery, compost, and thermal mass. During the summer, the goal of the system is to lower the temperature and humidity in the bioshelter to provide the ideal growing condition for the crops. This may be achieved through the help of the climate battery and thermal mass. The climate battery and thermal mass absorb and store excess heat during hot periods and release it during cooler periods.

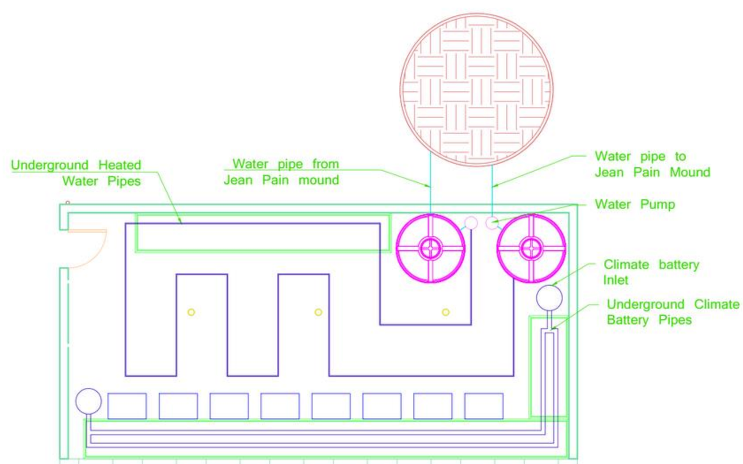


Figure 7: The underground layout of the heat conservation system

Additionally, the heating system was designed to heat the bioshelter to maintain a minimum internal temperature of 40 °F during the winter. During these months, the difference in the outside temperature causes heat loss. The heating system uniformly disperses energy throughout the bioshelter to maintain a consistent internal environment. This design follows a similar approach as the method utilized during the summer except in reverse, where the heat stored by the thermal mass and the climate battery during the day is slowly released to account for energy losses in the system during the night. Additionally, composting makes up the remainder of the leftover energy deficit by constantly producing heat from the breakdown of particles.

The final piece of the bioshelter is the structure itself. When designing the structure, the main design goal was heat retention, ventilation, and circulation during the winter. During the summer, the bioshelter needs to be ventilated. This may be accomplished through passive cross ventilation, and horizontal airflow generated by solar powered fans along the top roof framing of the bioshelter. Although this is also a concern during the winter, the necessity of retaining heat will limit the amount of ventilation that may be achieved. The majority of ventilation during the winter will be through leakage, while an adequate amount of circulation may still be achieved by the solar powered fans.

A budget is one of the most important aspects of any building process. Specifically, in the case of this project, Worcester Common Ground set a limit of $70,000 for the building materials and labor costs of the bioshelter. In order to ensure the bioshelter would not exceed this price, a detailed materials list and cost breakdown was created. The materials entailed in the budget were all new, which led to a higher total price than if used materials were to have been considered. Even though new materials were selected, the budget created was still under $70,000 ($61,000, inclusive of the $15,000 labor cost).

Adequate water, heating, and heat storage were obtained by integrating multiple systems into the bioshelter. This allowed redundancy between the systems to address the possibility of one or more of the systems failing. This was a risk factored into the bioshelter design process as many of the proposed systems incorporated into the bioshelter had not undergone rigorous testing. As such, these systems were considered to be experimental at the time of the writing of this report.

This project initially started out as a movement to promote community development within the Piedmont area. By transforming the unused space of 7, 9 Jaques Avenue into a community asset for food production, a community gathering space was created where people will be able to live, learn, and grow. By building on such pre-existing movements and ideals, the bioshelter will strengthen the community and deliver a positive impact of its own.

Authorship

John Breen is responsible for researching and writing about precipitation analysis, water usage of the bioshelter, rainwater catchment design, and interviewing stakeholders. He also contributed to the Executive Summary and the Conclusion sections.

Tom Fay is responsible for researching and writing about building codes, compost, and the Jean Pain Mound system. He organized the IRT Meeting with the City of Worcester and was the primary contact with sponsors. He was the primary author of the Recommendations section.

Peerapat Luxsuwong is responsible for researching and writing about ventilation, circulation, row covers, power systems, lally columns, and alternative sources of obtaining energy. He was the primary author of the Abstract and Introduction sections. He also was the main editor for this report.

Mark Overdevest is responsible for researching and writing about documenting existing bioshelters, interviewing bioshelter owners, the climate battery system, and different types of thermal mass. He performed solar heat calculations, developed AutoCAD system floor plans, and finalized the budget. He organized the entire report and the references.

Yunjae Sohn is responsible for researching and writing about existing bioshelters, architectural systems of bioshelters, building materials, and solar site analysis. She also evaluated effects of thermal mass and window performance in Ecotect software. Finally, she modeled the bioshelter design in Revit, produced the structural layout in Revit, and created blueprints in AutoCAD. She contributed to the Executive Summary section of the report.

1.0 Introduction

Over the past decade, the practice of growing and distributing food in cities has been seen as an effective way to tackle community-oriented problems, such as food security, reuse of vacant property, building community cohesion and job creation (Nsar & Smit, 1992; Nugent, 2015). To stimulate the development of urban agriculture, an increasing number of cities have passed ordinances.

Despite renewed interest in urban food production, urban growers face many problems. These problems range from poor soil conditions to land contamination and availability. In addition, the above problems combined with short growing seasons make urban farming an unattractive prospect. Before farming can even begin, the farmers must satisfy or solve the requirements presented by the urban environment.

An integrated ecosystem that will fulfill these requirements is a bioshelter. A bioshelter can be used to grow food year round by integrating ecosystems and mechanical systems, which eliminates or reduces reliance on fossil fuels for heating and cooling. As opposed to a greenhouse, a bioshelter uses mechanical systems to capture and store natural sources of energy, such as solar and compost and does not rely on the use of fossil fuels (James, 2013). Such mechanical systems include, but are not limited to, heating, ventilation and circulation, and irrigation.

The project sought to design a bioshelter as part of an ongoing initiative in the city of Worcester. Worcester Common Ground, a community development corporation and the sponsor of the project, along with two local nonprofits, the Regional Environmental Council (REC) and Ascentria Care Alliance (ACA), bought a 8,000 square foot vacant lot in a low income, minority neighborhood in Worcester. The idea was to transform the space into a community asset that would include food production, a community gathering space, an educational component for local children, and integrating refugee farmers into the management of the bioshelter.

To ensure that the design was successful, existing bioshelters were researched. Looking at case studies helped to assess the performance of the bioshelter, as well as to understand the motives for building it. By gaining an understanding of the motives behind the bioshelter, the purpose and use of the bioshelter was identified. REC, ACA, and WCG sponsored the project in order to develop a design that is affordable and that promotes permaculture in the community. Next, the site conditions were evaluated. This involved surveying the lot's soil and the surrounding environment. Finally, various bioshelter systems, including heating, ventilation, and structure, were evaluated to design a prototype bioshelter that is cost efficient. This approach and the previously mentioned steps led to a thorough design that allows for urban farming, which will extend the growing season and foster community bonds.

2.0 Background

In this chapter, background information was provided on urban farming and how the challenges of urban agriculture can be addressed with a bioshelter. This chapter begins with a discussion of the community context of our project. The role that local food production can play in developing community cohesion was then considered. Next, the challenges and difficulties of farming in an urban environment are addressed. Finally, the concept of a bioshelter was reviewed as both a technical and social innovation.

2.1 The Community Setting

The project site is on the corner of Jaques Avenue and Ethan Allen Street in the Piedmont area of Worcester. This is an area with many multi-family houses and apartment complexes. Many of the younger children in the area attend Chandler Street Elementary School, which is across Jaques Avenue (50 feet from the lot). The adjacent house on Jaques Avenue is owned by Worcester Common Ground (Worcester Common Ground, 2014).

Figure 2.1 a: 7 and 9 Jaques Avenue Lot (Worcester Common Ground, 2014)

The multi-stakeholder setting of the project contains a range of interests and a history of cooperation. Key sponsors of this project include Worcester Common Ground (WCG), Ascentria Care Alliance (ACA), Regional Environmental Council (REC), Worcester Tree Initiative (WTI), and Chandler Street Elementary School. Each of these groups hope to utilize the bioshelter lot in different ways and all have a unique following in the community that will help make the bioshelter project a success.

Worcester Common Ground (WCG) is the primary sponsor of this project. This organization, like many community development corporations (CDCs), is a non-profit group that aims to improve local communities. CDCs build and improve local infrastructure, encompassing everything from public parks to sustainable community development projects. They impact the community by building relationships, improving places, and transforming lives. One way CDCs accomplish this is by hosting community events that help people develop support networks and organize community efforts. When a CDC hosts an event it creates an opportunity to improve skills, network professionally, and have a positive influence on the upcoming generation (MACDC, 2014) Worcester Common Ground hopes that building a bioshelter will bring the community closer. Their main goal of the project is to foster community bonds and allow people to come together in a safe, welcoming environment. The bioshelter will act as a community meeting place where residents of Worcester can learn about urban agriculture and experience growing crops in a hands-on way.

Ascentria Care Alliance (ACA), formerly the Lutheran Social Services of New England, is providing farmers to maintain the bioshelter. These farmers are Nepalese refugees who live and work in Worcester. They are looking to supplement their income by selling crops grown on the lot and in the bioshelter. "As one of the largest community service organizations in New England, Ascentria Care Alliance empowers people of all backgrounds to rise together and reach beyond life's challenges" (Ascentria, 2014). Large amounts of refugees flow to Worcester, making projects that help them adjust to their new home important to the health of the community (GoLocalWorcester, 2012). Ascentria Care Alliance wants to use the space to sell a variety of crops that would otherwise be unavailable without the help of a bioshelter. Unlike WCG whose main focus is community integration, ACA's main priority is the farmers and helping them gain some extra money. This creates an interesting challenge that forces both parties to compromise.

The Regional Environmental Council (REC) is made up of two sub-sections. The Environmental Health and Justice group focuses on environmental hazards in low income houses. The Food Justice group focuses on increasing accessibility of fresh, healthy produce to low income families with poor food security. The Food Justice program is working with the bioshelter project through their Urban Garden Resources of Worcester (UGROW) program. UGROW is a network of city-wide gardens, aiming to promote urban agriculture (Recworcester, 2014), and will help manage the community gardening areas on the site. The goals of the REC are not fully known as of now, but once the bioshelter is closer to being built, they will be more involved in the project.

The Worcester Tree Initiative (WTI) has provided and planted fruit-bearing trees for the project site. The Worcester Tree Initiative describes themselves as "a private, non-profit organization based in Worcester, Massachusetts whose mission is to promote urban forestry and stewardship in the City of Worcester and surrounding communities" (Worcester Tree Initiative, 2014). In May of 2014, Worcester Common Ground held an event at the project site where the Worcester Tree Initiative, along with many volunteers, planted 19 fruit-bearing trees on the lot. WTI's main goal in regards to the project is to bring trees to an urban area. They will maintain the trees and harvest some of the fruits from the trees when they are fully grown.

Chandler Street Elementary School will be utilizing the site to enhance their students' education. The school is hoping to use the bioshelter as an educational exercise in biology and life sciences. They are contributing volunteers to help build the bioshelter, when the time comes, and also will provide some waste for compost.

2.2 Urban Agriculture as a Means to Develop Community Cohesion

Urban agriculture is a critical component in addressing the hunger and health problems associated with city life. Food security is a national concern and is defined as "the underlying social, economic, and institutional factors within a community that affect the quantity and quality of available food and its affordability…" (Cohen, Andrews & Kantor, 2002). Food insecurity can have devastating and widespread consequences (Allen, Filice, Patel & Warner, 2012). These consequences range from increased chances of suicide, depression (Alaimo, Olson & Frongillo, 2002), rates of obesity, malnutrition, and crime (Kleinman et al., 1998). A recent study by the Worcester Food and Active Living Policy Council (WFALPC) found that out of the 14 low-income neighborhoods in Worcester, one child in three lives in a family that cannot meet its basic nutritional requirements.

Urban agriculture not only can address food insecurity, but it also can be utilized as a community development tool. Beyond just the direct impacts of local farming, urban agriculture sites can serve as focal points for the community. They provide gathering places for people who share common interests to meet up and start to form communal bonds (Saldivar-Tanaka & Krasny, 2004). This helps build a more united community that is able to face challenges and obstacles together. The community development opportunities that urban agriculture provides can often times provide far more than the actual physical goods produced by the site. Through urban agriculture, previously inactive spaces can serve as development tools for local communities to socially grow and bond.

2.3 Barriers to Urban Agriculture

Despite the possible benefits that may be derived from the introduction of urban agriculture, certain challenges have been identified that can potentially hinder attempts to utilize urban agriculture in community development. Soil quality, access to land, and local land use regulations, as well as climate can affect the viability of urban farming.

Soil Quality

The main functions of soil are to supply nutrients, stabilize the plant, supply water and oxygen and maintain stable temperatures (Maine, 2015). Urban soils are often poor. There are 16 chemical elements that help plants grow well. Three are found in the atmosphere: hydrogen, oxygen and carbon. These take the form of water and carbon dioxide. The other 15 Nutrients are found in the soil. Three of the most important elements are nitrogen, phosphorus and potassium. Most urban soils are lacking these chemicals (Prince, 2015). Not only are important nutrients for plant growth low in urban soils, there are commonly a large number of contaminants such as solvents and heavy metals from past uses. The most common pollutant in soils is lead, which stems from decades of use of leaded fuels and by lead-based paints. Exposure to lead poses health risks, particularly to children. Blood lead levels above 5 parts per million can affect children's intelligence and behavior (EPA, 2015). Every system in the body can be affected by lead exposure, such as the brain, liver, kidney and reproductive organs (Pinchin, 2014).

The average of the three soil tests performed on the lot planned for the bioshelter, 7, 9 Jaques Avenue, show low concentrations of phosphorus and potassium, adequate levels of calcium and excessive magnesium. The lot contains, on average 90 ppm, over four times the amount of lead recommended for growing, which is below 22 ppm (see appendix A). Growing in these high lead contamination levels will cause contamination to the crops grown in this soil. To avoid crop contamination, WCG has decided to use raised beds to grow crops in as well as researching techniques that could be used to remove lead from the soil. The soil results can be seen in Appendix A.

Access to Land

Competition for land raises the value of lots in urban areas, which can make it more difficult for local residents to own land to grow food. Not owning the land for an extended period of time is another problem that makes developing urban farms difficult. When ownership of the land is not guaranteed, few people are willing to make the effort to improve the soil. WCG addressed this previous issue by leasing the land on 7, 9 Jaques Avenue from the city for extended periods of time.

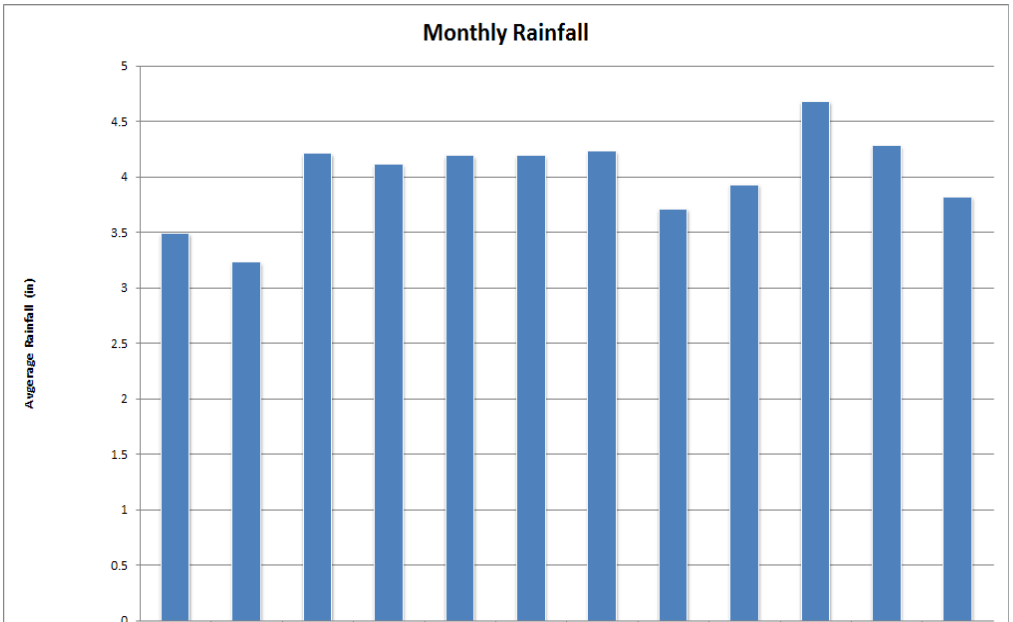
Even if the land can be guaranteed, there still exists a large issue with the limited amount of space that is available for crop growth. To gain the largest economic gain or production from the lot, it is tempting to overpopulation the growing space with crops. Plants not only need space expand their rooting system and foliage. Once plants are competing for important nutrients and sunlight, the growth rates will decrease (Phipps, 2015). Not only will the plants lose the chance to grow to their full potential, the overpopulation of plants will cause the soil to be deprived of nutrients. This will make it very difficult to grow crop for next season. Also, a large amount of money and energy will need to be spent, on compost, to maintain healthy soil.

Limited Growing Season

The local weather and climate can also be a severely limiting factor to agricultural production. There are five major parts to a climate: temperature, humidity, atmospheric pressure, wind, and precipitation.

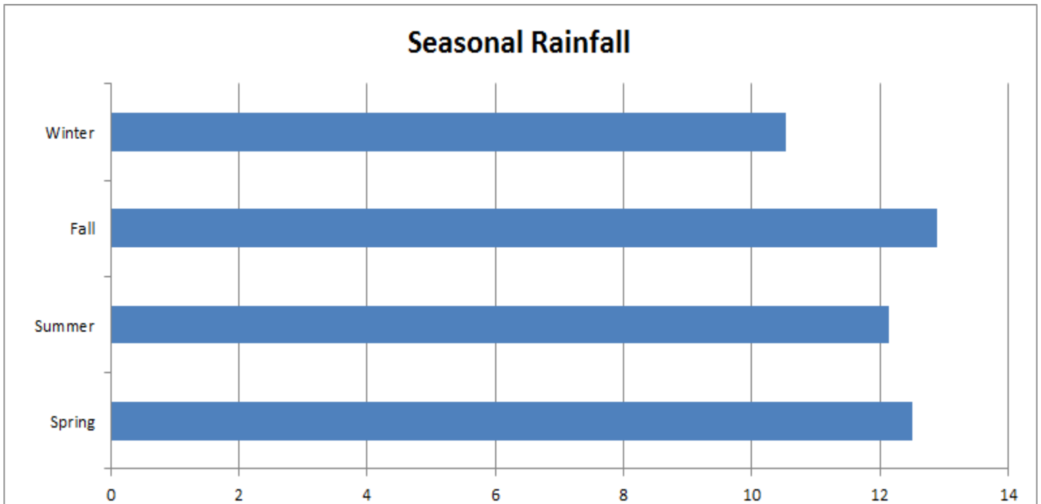
Precipitation is one of the most important aspects that determine a region's climate and what plants are suitable to grow in those conditions. Plants require water for growth as well as maintain cell rigidity and form. Although they can gather resources over a small area through the use of their root system, the resources available to them are largely what are offered by the local area and climate. This means that the local climate’s precipitation can be a severely limiting factor to plants. If there is not enough water to support the plant’s needs, then the plant’s growth can be stunted.

Precipitation can be broken down into two relative categories: quantity and quality. Water quantity is the amount of precipitation available or the average precipitation of an area. This is perhaps the more important measure of the two, because the quantity of water greatly determines what can and cannot grow. Rainfall in Worcester is a relatively constant throughout the year with a slight decrease during the winter months (see Figure 2.2(a) and 2.2(b)). The average yearly rainfall of Worcester is around 48 inches. This is almost twice the amount of the average rainfall for the United States, which sits at a yearly rainfall of only 28 inches (World Databank, 2014). The quality of precipitation is also a factor that needs to be brought into consideration. In highly industrialized environments, pollutants and contaminants can enter the rainwater. This has the potential to harm plant growth by the plants indirectly absorbing the toxins or the toxins changing the pH of the soil.



	January:	February:	March:	April:	May:	June:	July:	August:	September:	October:	November:	December:
Average Rainfall (in)	3.49	3.23	4.21	4.11	4.19	4.19	4.23	3.71	3.93	4.68	4.28	3.82

Figure 2.3(a) Monthly rainfall chart for Worcester area.



	Spring	Summer	Fall	Winter
Rainfall (in)	12.51	12.13	12.89	10.54

Rainfall (in)

Figure 2.3(b) Seasonal rainfall chart for Worcester area

Temperature is another major component of an area's climate. It is also important in dictating what plants can and cannot grow in a region. Some plants have the ability to resist great changes in temperatures and are able to survive in the extremely environments. Other plants are unable to cope with temperature changes and require a stable warm environment. Because of these criteria, temperature can be split into the amount of temperature change in a local area over the season and the highs and lows for the season. Worcester is located in a temperate climate zone. This means that Worcester's climate has four distinct seasons: spring, summer, fall, and winter. These seasons are characterized by great changes of temperature, which result in hot summers and cold winters ("U.S. Climate Data," 2015).

The humidity of a climate zone can also cause issues in plant growth. High humidity can, for instance, interfere with a plant's ability to intake CO_2. Additionally, high humidity can increase the heat load placed on a plant ("Agrometeorology: Relative Humidity and Plant Growth," 2013). Worcester's humidity is relatively constant, although the average daily humidity usually increases slightly during the summer months when the temperature rises. The humidity requirements vary from plant to plant, but on average most plants thrive in between humidity levels of 60% and 75% (Hodgson, 2015).

The effect of wind on plant growth should also be taken into account. Strong winds, for instance, will increase the rate at which plants photosynthesize. During the summer, when most plants will still have leaves, this will affect the water intake of plants substantially, as plants will require more water to continue photosynthesizing (Sciences, 2015). This may be undesirable in circumstances where water is limited. However, an important aspect of plant growth that is heavily dependent on wind is plant pollination. For the pollen produced by a flower to reach and successfully fertilize another plant, there has to be a means of doing so. Wind is an effective means of achieving this goal. Wind also prevents mold and mildew from growing by circulating moisture in the air to prevent pockets of moisture from forming.

Building/Zoning Codes

Most urban agriculture structures, such as greenhouses and rooftop gardens, must satisfy zoning and building regulations. Massachusetts has taken the initiative on exempting agricultural structures from certain zoning restrictions. They have created what is known as the Dover Amendment. It allows agricultural, religious, and educational corporations to build structures to provide necessary services. The City of Worcester, specifically, is in the process of writing an ordinance that will allow agricultural structures to be built in residential zones and also permit the running of community gardens (The Commonwealth of Massachusetts, 2015).

2.4 Bioshelters

Bioshelters are integrated ecosystems that can be used to maximize farming potential in urban sites by overcoming the limitations of urban agriculture and reduced growing seasons in a sustainable manner. Bioshelters are designed to provide a stable environment for plants to grow and protect the plants from harsh weather conditions with little to no energy input (James, 2013). A bioshelter creates a closed ecosystem, in which the plants are less affected by the conditions of their surrounding environment. The plants are protected from contaminated soil, diseases, and temperature extremities, providing, in theory, the optimal growing conditions for plants.

2.4.1 Bioshelter types

The ideas of urban agriculture and permaculture in conjunction with a bioshelter are a relatively new concept and there is very little detailed documentation on methods of construction. This is further complicated by intricacies of the systems within a bioshelter, which are built in order to sustain a climate under a variety of weather conditions and circumstances. Since even the idea of bioshelters is still relatively new, the most detailed information can be found by looking at existing bioshelters. Designing a bioshelter, with no prior knowledge and a vague understanding of the necessary tasks, would have been a time-consuming and inefficient way to approach this project. By drawing useful conclusions from readily accessible examples, a concrete understanding was able to be achieved of not just the goals of this project, but also the process of doing so.

Table 2.4.1(a) Bioshelter research spreadsheet

Name	Location and size	Materials	Systems	Garden
Cape Cod Ark	Cape Cod, MA	Steel Frame Triple-layer polycarbonate and thermopane glass	Active Bioshelter PV solar panels Vents opened in summer/closed in winter Radiant floor heat Passive light during day, fluorescent at night Rock box used for solar hot water storage	Vegetable crops, lemon trees, ornamental plants Diverse insects and frogs Solar aquaponics ponds
Pillow Dome	Cape Cod, MA 30 ft diameter	Aluminum tubing Inflated plastic pillows	Passive Bioshelter Manual operation of pillows for convection venting	Fit tree and raised soil bed crops Solar fish ponds
Composting Greenhouse	Cape Cod, MA 400 sqft	Double polyethylene Inflated glazing	Blowers transfer warm moist air through ducts into the soil beds Manure gives off heat, water vapor, nitrogen gases and carbon dioxide-all essential for plant growth	Seedlings Manure fertilizer
Holyoke Paradise lot Bioshelter	Holyoke, MA	Polyethylene plastic film 2x6 wooden frame 16ft long arches Cheap plastic filled with fiber glass. Ridded foam board (4in thick) 3 layers of plastic sheet.	Active Solar Panel	Hardy vegetables, subtropical fruits, aquatic greens Compost earthworms, soldier fly maggots Fish, fresh water clams, crayfish
Three Sisters Permaculture	Mercer County, PA	Wood Wooden frame with glass windows	Active Firewood, CO2 recovered from compost, chickens, Solar panels Natural Lighting	Year round organic garden Chickens Compost
Greenfield Bioshelter	Greenfield, MA 25ft x 30 ft.	Timber frame Concrete pillar foundation Aluminum roof Heat Vent	Active Connected to the grid Climate battery	Basic hardy crop so far Goldfish planning for eatable fish later
Garfield Community farm	Pittsburgh, PA 26x20 ft.	4x4 wooden post frame 8" concrete block wall 10mm polycarbonate roof Glazing with UV inhibitor	Active Bioshelter Solar Panels Natural Lighting Aluminum gutters used to harvest water	Vegetables, Fruits and Saplings Rabbits

To compare the usefulness of systems from different bioshelters, Table 2.4.1(a) was put together with many different existing bioshelters and their designs (a complete table can be found in Appendix B). For each bioshelter, information was split up into four categories: General Information, Materials, Systems and Garden. Within each section, detailed descriptions were added for each subheading. The most important similarities between all the researched bioshelters are the four main systems that they use: ventilation and circulation, heating and heat storage, rain water collection and aquaponics, and composting.

2.4.2 Passive Architectural Design and Integration of Renewable Energy

A sustainable architectural design for a bioshelter should maximize the natural benefits from the surrounding environment. There are two kinds of building systems: passive and active. Passive systems are self-sufficient and rely solely upon natural sources of energy, as opposed to active systems, which depend on external energy and equipment to create energy and comfort (Hibshman, 2014). It is relatively easy to control an indoor environment with mechanical systems. However, they require energy input as well as system maintenance. Although optimizing the environment for plant growth without any mechanical aspects is a challenge, an architectural design that is geared towards maximizing the natural benefit would reduce the required amount of external resources to maintain the bioshelter. In following sections, various systems that compose a bioshelter will be covered to help understand how to produce a passive design.

Architectural Design for passive

Some basic energy-saving design principles that apply to conventional buildings can also be applied to a bioshelter design. In cold climate, there are two strategies to reduce heating demand: maximize solar heat gain, and minimize heat loss. Building geometry, materials, and orientation are three major deciding factors of the two strategies.

Carefully designed building geometry minimizes heat loss. The width to length ratio of a structure in the northern United States should be around 1.0 to minimize skin surface area compared to its volume (Kibert, 2012). Minimizing the skin surface area would in turn reduce heat transfer through surface area. Another approach to reduce heat transfer is by using materials that have high thermal resistance for building the envelope, the physical materials that separate the conditioned environment from the unconditioned environment. Adequate amount of insulation, as it minimizes heat exchange, reduces heating load (Straube, 2014). The type of insulation should be carefully chosen after considering aspects like R-value--thermal resistance, embodied energy--sum of energy required to produce a material, moisture and insect problems as well as cost. While having a highly insulated wall is important, its' performance should be cost effective.

High thermal resistance in a conventional wall structure is not as challenging to attain as it is in a glazing system. A high thermal resistance attained through quality insulation and glazing materials will help to reduce the heat loss through the building facade. Glazing also directly affects natural solar heat gain. Solar heat gain coefficient (SGHC), determines the performance of a glazing system (Mehta, 2008). This coefficient is the fraction of incident solar radiation admitted through a window. SGHC values range between 0 and 1, with higher numbers indicating more solar heat transmitted. Glazing in a cold climate needs to have a high SHGC value to allow solar heat gain from the sun to reduce the heating load in winter (Gromicko & Ward, 2012). In the northern hemisphere, placing windows with a high SGHC in the south-facing wall of a building increases amount of passive solar heat gain.

Similarly, having a North-South oriented building maximizes the solar heat gain. Having the lengthy section of the wall facing towards the South helps the building to absorb more solar radiation (Frosdick, 2012). Having the long axis of the building running East-West allows for a significant amount of the building's surface to be oriented towards the South. Also placing windows on the southern side, which will receive the most sunlight, ensures maximum heat gain. It should also be noted that the slope of the roof also affects the heat gain. There are also other methods that take advantage of solar energy, as well as other natural resources, which will be covered in the following section.

Natural energy sources

Harnessing natural resources readily available on the site will reduce the dependence of the bioshelter on mechanical systems. The ultimate goal of entertaining a passive design is to maximize the utilization of available resources on-site, thereby reducing maintenance costs. The most prominent resources that are easily integrated into an architectural design are solar energy, compost, wind energy, and rainwater. The following sections will cover how these natural resources relate to the bioshelter's design.

Solar energy

In the previous section, using the bioshelter's orientation to maximize the heat gain was considered. However, passive heat gain through solar energy is not the only benefit of optimizing the bioshelter's orientation. A bioshelter design that is oriented to receive the maximum amount of sunlight not only reduces the heating load, but also provides sunlight for plants. The photoperiod, the interval in a day during which a plant receives sunlight, plays a significant role in plant growth (Jackson, 2009). A bioshelter design should ensure that the plants receive enough sunlight even in the winter. However, a design that captures the maximum amount of sunlight could cause an overheating problem in the summer. To prevent the structure from overheating, an adequate shading system is necessary to protect the bioshelter from the intense summer sun (Charlie's Greenhouse, 2015).

There are also active methods that may be used to harness solar energy. Two well-known and widely-used pieces of solar harnessing equipment are photovoltaic panels and flat-plate collectors. Photovoltaic cells convert sunlight directly into electricity to provide a clean, renewable source of energy (Kibert, 2012). The electricity produced can be used to run supplementary mechanical systems that will be covered in later sections. This electricity can also be used to power mechanical HVAC (heating, ventilation, and air conditioning) systems, or growing lights to lengthen the photoperiod in the winter. Flat-plate collectors may be used to provide hot water. They consist of a transparent cover over small tubes filled with flowing liquid, which are then heated up and stored for later use (Solar Energy, 2015). This heated water can be used for not just irrigation, but also thermal mass to moderate air temperature. Either type of solar energy harvesting will massively benefit the bioshelter.

Passive Heating Strategy

Maintaining an ideal growing temperature for plants in the winter is a prominent issue that needs to be addressed by bioshelters in cold climates. Other than the passive heating obtained through solar energy, other strategies to reduce energy loss and consumption are needed.

Compost

Before more mechanical systems are introduced, it should be noted that there are non-mechanical ways to heat a bioshelter. Compost is an organic heating method that can be integrated into the system. Compost releases heat during its breakdown process (Killoy, 2012). This means that it has the potential to be an invaluable asset in raising the temperature inside the bioshelter to aid the crops' growth (EPA, 2014). For a standard compost pile, it also needs to be able to cultivate growing of plants. In order for compost to be of use to plant life, it requires a Carbon to Nitrogen ratio (C: N) of 25:1 to 30:1 and a moisture level of 40 % to 60 % (Planet Natural, 2014). Using known mathematical formulas, such as $q = m*cp*\Delta T$, and a compost heat calculator developed by Cornell, the heat capabilities of a compost pile and the suitable materials necessary for construction can be analyzed (Richard, 2014). However, a compost pile by itself would not provide sufficient amount of energy to heat a bioshelter and it would require human labor to bring in compost regularly. Therefore, other heating options were looked into.

One option is a Jean Pain Mound, which incorporates woodchips, mulch, and hay bales into a 12 foot diameter by 8 foot high mound (shown in Figure 2.4.2(b)). The woodchips are the primary feedstock of the mound and are thoroughly soaked before construction. The moist woodchips decompose over time and generate enormous amounts of heat. This enables the Jean Pain Mound to reach internal temperatures of up to 130 °F. This heat is captured by running concentric tubes filled with water through the mound and into the bioshelter (Brown, 2014).

Figure 2.4.2(b) Example of a Completed Jean Pain Mound (Brown, 2014)

Thermal mass

Thermal mass is a materials ability to store heat energy. It is generally used in designs where keeping temperature at a constant temperature is important (Centre, 2015). After researching thermal mass, it was found that two systems could be useful for a bioshelter. These are heat sinks and a climate battery system. Both systems function are used to keep the inside of the bioshelter at a constant temperature, during both summer and winter months.

A heat sink is a thermal mass system that is general used in bioshelters to absorb the maximum amount of the solar energy, store it and release it during the colder nights. The most common materials a heat sink is constructed from are Clay, Stone, Concrete, Wood and Water (Webkey, 2015). Generally, the material with the highest heat capacity, amount of energy it takes for one kilogram of material to rise 1 °C and is the most accessible will be the best heat sink material (“Specific Heat,” 2015). These materials were researched and compared to each other. Table 2.4.2(a) shows the heat capacities of the most common materials and the positives and negatives of each.

Table 2.4.2(a) Heat sink materials

Types of Materials	Heat Capacity (KJ/KG C)	Density (Kg/m3)	Heat Capacity (KJ/m3 C)	Cost per Area	Pros	Cons	Website found
Concrete	0.880	2400	2112	$59 per cubic meter	Absorbs and releases heat slowly Durable (will last)	Will be difficult to move if needed Relatively expensive	http://construction.about.com/od/Cost-Control/tp/Estimating-Concrete-Pricing.htm
Wood	1.700	740	1258	$50 to 120 per meter cubed	Easy to obtain	Will rot if not treated Low heat capacity Expensive	http://www.risiinfo.com/Marketing/Commentaries/world_timber.pdf
Water	4.182	1000	4182	$1.148 per cubic meter	Easy to obtain High heat capacity Can be used to water plants	May run low/out of water	http://www.telegram.com/article/20110415/NEWS/104159733/0
Clay (dry/unbaked)	1.381	1600	2209.6	$2.47 per cubic meter	Very cheap	Need to be fired or it will change shape/mold (firing drops heat capacity by half).	http://www.turface.com/howto/why-purchase-amendments-volume-not-weight

The amount of solar energy the bioshelter and heat sink can collect is important to maintain a minimum temperature at night for plant growth and survival. Three properties of solar energy radiation are reflection, absorption and transmission, which influences the amount of energy absorbed in our bioshelter and heat sinks (see Figure 2.4.2(c)). Reflection accounts for the energy that does not enter the system (sunlight reflecting off the windows of the bioshelter and the surface of the heat sinks), absorption is the amount of energy which the system gathers (solar energy contained within the window itself or the water tank), and transmission is the energy that enters the system (solar energy entering the bioshelter or heat sink). Figure 2.4.2(c) is a diagram of how reflection, absorption and transmission effect the heat sinks and bioshelters energy collection. ("Light Absorption, Reflection, and Transmission," 2015).

Two forms of heat transfer that will affect the bioshelter are conduction and convection. Conduction is the transfer of energy from the more energetic to the less energetic particles. In terms of temperature, it means that heat energy from the inside of the bioshelter will transfer to the colder outside energy. Conduction usually occurs between a solid medium that has two different temperatures on each surface (Incropera et al., 2007). Convection is the transfer of energy from a fluid, with more energy, to a solid surface, with less energy, or vice versa (Incropera et al., 2007). In terms of the bioshelter, convection would occur when the warmer inside air is transferring energy on to the surface of the south facing window. Convection and conduction and transmission, absorption and reflection are closely related as they all influence the bioshelter and heat sinks temperature.

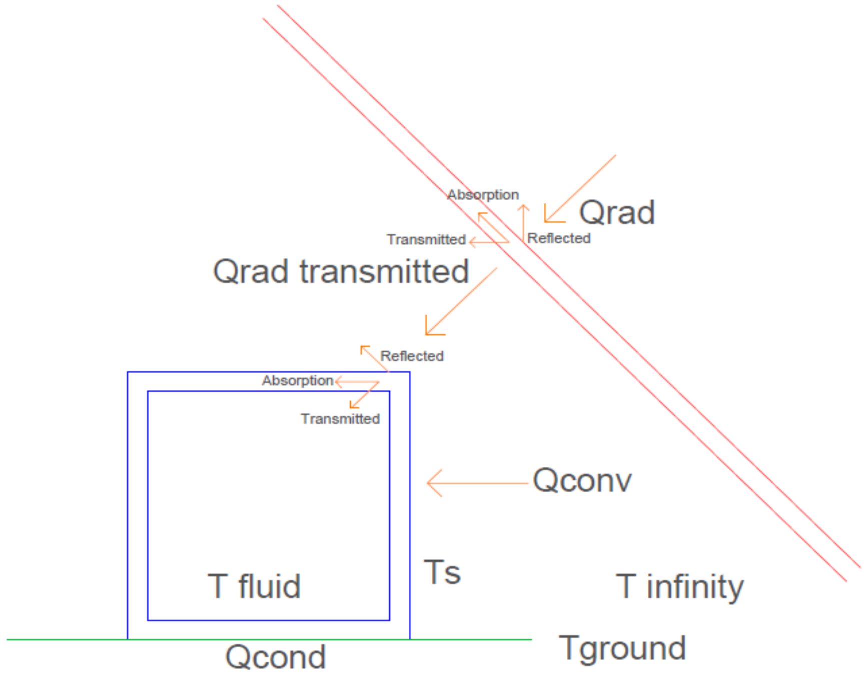


Figure 2.4.2(c) Heat transfer properties

A climate battery is a thermal mass system that utilizes the earth's stable temperature to maintain the temperature of the bioshelter. A series of pipes that lay underground are connected to an entrance and exit pipe. It works by simply moving heat from one place to another. During periods when the bioshelters interior is above a certain temperature, a pump will turn on, sucking the hot air out of the bioshelter and storing in underground. From here one of two things can happen. Either the heat can be left to slowly radiate up through the soil, keeping the soils temperature at a higher temperature or when the bioshelters air temperature drops below a certain point, the climate battery's pump will turn back on, pumping out the stored heat back into the bioshelter ("Eco Systems Design," 2015).

Passive Ventilation and Circulation

Adequate ventilation contributes to plant health by supplying fresh air and controlling humidity. Ventilation controls humidity as well as concentration levels of various gases, including CO_2. A high concentration of CO_2 forms the ideal growing environment for plants by facilitating plants' storage ability of water and nutrients. High level of CO_2 also decreases the environmental stresses an urban bioshelter could face, such as air pollution, high or low air temperatures and air and soil borne pathogens (Plants Need CO_2).

Three types of ventilation systems were proposed: cross ventilation, stack ventilation, and night-flush cooling (Autodesk, 2011). Implementing cross ventilation involves replacing old, oxygen rich air inside the bioshelter with new, carbon-dioxide rich air from outside. This is usually achieved via a horizontal cross-draft blowing through an opening in one side the bioshelter, and out the opposite side.

Implementing stack ventilation would instead utilize the difference in internal temperature and external temperature. As warmer air inside the bioshelter would rise through vents along the roof of the bioshelter, cooler air from outside would be drawn in through vents located along the bottom of the bioshelter. Night-flush cooling works similarly to stack ventilation, with the difference being that night-flush cooling integrates a heat sink into the system. This heat sink introduces a damping attribute to the system that reduces the effect of extreme fluctuations in external temperature on internal temperature. The heat sink also serves to increase the amount of energy that the system would be able to store.

The most effective way to achieve circulation within the bioshelter would be to stimulate horizontal air flow in the bioshelter (Bartok, 2005). To a certain extent, this can be implemented through cross ventilation. However, during the winter when ventilation won't play as active a role, fans will have to be used to maintain HAF.

Rainwater

Rainwater is another important resource that is available to a bioshelter. In addition to providing the necessary water for the plants and internal organisms, rainwater can serve a multitude of other purposes through its use in composting and its ability to act as a heat sink. An eco-friendly way of achieving the necessary water requirements is to make use a rainwater catchment system.

The rainwater catchment system is a subsystem of a bioshelter, which has the job of collecting water for the usage of other systems. It can either be built directly into the bioshelter system acting as a subsystem of the bioshelter or be built external from the bioshelter becoming its own independent system. The rainwater catchment system can be broken down into three sub categories: catching, transportation, and storage.

Catching the rainwater is the first step in creating a rainwater catchment system. The amount of water a rainwater catchment system produces is dependent on the catchment area. Depending on the design and integration of the overall rainwater system, the catchment area can be built into the structure like a roof or exist on its own. Catchment area is measure by the amount of horizontal space provided by the structure. The amount of water collected is then determined by multiplying the catchment area by the rainfall. It can be modeled by the following formula:

Equation 2.4.2(i): HW = CA x RD x CF

where

HW = Harvested water (Gal)

CA = Catchment area (ft^2)

RD = Rainfall depth (in.)

CF = Conversion Factor (0.623)

In addition to the catchment area the slope and material type of the catchment system can greatly affect how efficiently water is collected ("Rainwater Harvesting," 2014). Roofing material is important due to the possibility of rainwater contamination. Some roofing types may leak trace amounts of lead or other harmful chemicals into the collected rainwater. These harmful chemicals may be a detriment to future use of the collected water. Table 2.4.2(b) provides a general overview of the different types of roofing materials as well as a cost analysis.

Table 2.4.2(b) Comparison of various roofing material types and cost analysis

Product	Weight/Square	Lifespan	Cost/Square	Cost/Year
Asphalt (3-tab)	190-250 lb.	15-20 yr.	\$75-\$125	\$4-\$8
Asphalt (laminated)	240-340 lb.	20-30 yr.	\$125-\$200	\$4-\$10
Metal (coated steel)	80-150 lb.	30-50 yr.	\$250-\$450	\$5-\$15
Plastic Polymer	70-300 lb.	50+ yr.	\$400-\$650	\$7-\$13
Clay Tile	600-1,800 lb.	50+ yr.	\$800-\$1,000	\$13-\$20
Concrete Tile	550-1,000 lb.	50+ yr.	\$300-\$500	\$5-\$10
Slate	800-1,000 lb.	75+ yr.	\$1,100-\$2,000	\$10-\$20
Wood (cedar)	200-350 lb.	15-25 yr.	\$350-\$450	\$14-\$30

The next important part of the rainwater catchment system is the transportation to the storage site. This is generally done through a gutter and pipe system. Gutters are typically 5 inches wide across and aggregate the water from the catchment area and funnel it into a piping system. It is widely recommended to have 1 sq. ft. of opening area per 100 ft. of catchment area. The piping system then brings the water the remaining distance to the storage location. In addition during the conveyance the slope must be kept to no less than 1/16 inch per foot ("Rainwater Harvesting," 2014). This ensures that the water will flow in the desire direction and there is no flow back. An optional component that is part of the conveyance is the first flush filter. The first flush filter removes large particles and contaminants that are generally present in the initial rainfall. This has the benefit of making the quality of the collected rainwater much cleaner, but sacrifices the amount of rainfall collected.

2.4.3 Structural Integrity

While mechanical systems of the bioshelter are highly important for passive structure, structural integrity of a building is crucial for building performance. Suitable frame and foundation of the structure would ensure that the structure can resist various loads such as wind, snow, etc.

There are many construction types available that could be used for a bioshelter. Three most common types of construction are wood, steel and concrete frames. Wood frame is considered as sustainable, as it is a regenerative resource. It is also user-friendly due to simple construction techniques; it is cheap, relatively quick and easy to construct (Mehta, 2008). However, it is prone to deterioration and is highly combustible. Steel frame construction are durable, lightweight, and easy to erect, but is more expensive than wood and conducts heat readily, which is problematic in cold weather. Lastly, concrete construction is durable, fire and insect resistant, and is resistant to temperature change. However, it takes longer time to construct and has unattractive aesthetics (Mehta, 2008). More detailed comparison of three types of construction can be found in the Table 2.4.3(a).

Table 2.4.3(a) Pros and Cons of wood, steel and concrete frames

	Wood	Steel	Concrete
Pros	High strength-to-weight ratio of lumber reduces the dead load Sustainable Simpler construction techniques Cheap to build: doesn't need heavy equipment for lifting building components Quick to build: a timber frame structure can be erected and weather tight within a matter of days	Steel Joists are lightweight. As two metal studs weigh a little less than one wood stud; therefore, the energy required to transport metal framing material is less overall. Easy passage of electrical, HVAC ducts. Huge dead space between floors. Strong in tensile and compressive force. High strength to weight ratio. The strength allows for large internal open plan space. Not flammable Durable—not biodegradable Easier to recycle than wood. Easy and fast to erect. Lightweight steel frame is faster to erect than timber frame.	Can take any form—can be poured in, CMU, etc. Can be combined with many other materials for specific uses—reinforced concrete, insulate concrete etc. Air insulation Acoustic insulation Durable Strong against compressive force Concrete blocks are highly resistant to extreme temperatures Repels insects Inherently fire resistant
Cons	Biodeterioration by fungi and insects such as termites, marine-borers and carpenter ants. Vulnerable to humidity Combustible	When made as a light-gauge, galvanized steel metal framing is not as strong as wood. Corrodes over time—needs to be galvanized. Becomes ductile under heat and is expensive to fire proof. Poor acoustics—need extra acoustic insulation. Conducts cold and heat and promotes condensation—requires extra insulation. More expensive than wood Economical only for regular layout	Weak against tensile force—post-tensioned concrete slabs are available but very expensive. Another solution is reinforced steel. Water seepage Unattractive aesthetics Slower to build: takes roughly 28 days to strengthen to its full potential
Sources	Mehta, 2008 Fewins, 2014	Mehta, 2008 Fewins, 2014 Howe, 2014	Mehta , 2014

To ensure the structure will last freezing and thawing of the soil in cold climate, foundation should be properly laid out. There are various types of foundation that are commonly used. The strip foundation, also referred as concrete footing, consists of concrete footing that extends below frost grade. This type of foundation is very versatile, and is suitable for deep frost zones like New England. For a structure that does not require flooring like a bioshelter, Pad or Raft foundations consists of a concrete slab (Chu, 2015). The bioshelter construction does not require such intensive type of foundation as the floor area are often used for farming. Not having concrete slab also reduces material cost.

Another aspect of the structure that has to be accounted for is the load bearing components that will be used. A standard means of providing the necessary structural support is the lally column (Wallender, 2014). A lally column consists of a pipe filled with cement, which helps to distribute the load on the column. Depending on the pipe, and the type and consistency of cement used, a variety of cost-benefit analyses may be drawn. There is no empirical data in regards to how lally columns may be implemented; as such decisions must be made by a professional building advisor.

2.4.4 Food Production

One of the possible end uses of a bioshelter is food production. Similar to greenhouses, bioshelters attempt to stabilize climate changes in the environments around them. This enables year round growing conditions. The types of plants that can be grown are dependent on the type of environment the bioshelter can artificially maintain. The crops within the bioshelter can be thought of as their own subsystem of the bioshelter. They require a certain amount of resource and conditions to maintain.

One of the major requirements for the food production system is water. Plants require enormous amounts water. The amount of water a plant needs it called its evapotranspiration (ET). This is an extremely difficult value to calculate, because it depends on many of the conditions of the environment that the plant is placed in, which are always constantly changing. There are complex sensor rigs built, which can measure the plant's exact water usage (Brown, 2014). One example of these complex systems is a lysimeter, which collects the unused water and subtracts it from the total water to measure water usage. These systems are expensive and do not scale. Instead plant water usage can be calculated using a ratio. This ratio is called the Kc ratio and measures a plant water usage based off a common plant (Perlman, 2014). The common plant is usually grass or alfalfa and acts as a baseline measurement for water usage under certain conditions. In order to find the water usage of a different plant, only the Kc ratio is needed. Table 2.4.4(a) contains some common plants and their various Kc ratios.

Table 2.4.4(a) Various Plant Information

Plant Name	Initial Kc	Mid Kc	Final Kc	Average Growing Temperature (celsius)	Growing Period (days)	pH Levels
Tomato	0.6	1.15	0.8	18-25	90-150	7 to 9
Cabbage	0.7	1.05	0.95	17	120-140	
Peppers	0.6	1.05	0.9	18-27		5.5 to 7
Onions	0.7	1.05	0.75	15-20	130-175	6 to 7
Watermelon	0.4	1	0.75	22-30	80-110	5.8 to 7.2
Potato	0.5	1.15	0.5	18-20	90-180	5 to 6
Pea	0.5	1.15	0.3	17		5.5 to 6.5
Bean	0.4	1.15	0.35	15-20	60-120	5.5 to 6.0
Maize	0.3	1.2	0.5	20	80-110	
Wheat	0.3	1.15	0.3	15-20	100-250	6 to 8

3.0 Design Process

This project seeks to promote both the ideas of urban agriculture and sustainable living by designing a bioshelter. Designing for sustainable living attempts to create a process that causes the least amount of environmental damage (Regenerative LI, 2012). The bioshelter demonstrates a solution that can be applied to overcome many of the challenges of urban farming and sustainable living. In order to overcome these challenges, several primary goals must be achieved to design a bioshelter on 7 and 9 Jaques Avenue in Worcester. The primary goals of this project were:

- **Documenting existing bioshelters** by assessing the strength and performance of techniques they employed to create suitable growing conditions in a New England climate, as well as identifying the systems critical to the functionality of the bioshelter.
- **Identifying the purpose and use of the bioshelter.**
- **Analyzing conditions of the build location** in order to determine the best placement for the bioshelter.
- **Researching and designing critical bioshelter systems and technologies.**
- **Designing a prototype bioshelter** that suits the needs of the various stakeholders involved.

3.1 Documenting Existing Bioshelters

The idea of a bioshelter is a relatively new concept and there is very little detailed documentation on construction and design methods. This is further complicated by intricacies of the systems within a bioshelter that are built to sustain a growing climate under opposing conditions. Designing a bioshelter with no prior knowledge and a vague understanding of the necessary tasks is a time-consuming and inefficient way to approach this project. To streamline the research process, information was found by looking at existing bioshelters. Useful conclusions from readily accessible examples provided a concrete understanding of not just the goals of this project, but also how they could be achieved.

The purpose of documenting existing bioshelters was to compile information on four systems identified by visiting existing bioshelters: ventilation and circulation, heating and heat storage, rain water collection, and composting.

Visiting Bioshelters

Two bioshelters in Massachusetts were visited due to their proximity. In addition, these sites were visited because of the similar climate and weather conditions, which would have to be later addressed in this project. The two bioshelters have different designs. One uses more technically advanced systems at a higher cost, while the other used simple techniques and was cheaper to construct. The bioshelters were used to formulate an initial design, which was iteratively expanded on and improved to obtain a final design.

Visits to both bioshelters examined the agriculture grown both outside and inside. By touring the outside gardens, a variety of crops were observed being grown such as: seed kale, asparagus, raspberries, blueberries, garlic, squash, persimmon trees, red currents, and hardy kiwi, amongst other fruit trees. Identifying crops grown in bioshelters in similar climate regions provided a baseline of potential crops that would also be able to grow in the proposed bioshelter.

The first bioshelter that was visited was in Greenfield, MA and belonged to Nancee Bershof. Data on the performance of her bioshelter was gathered periodically, and eventually compiled as a reference for this project. The bioshelter's dimensions were 25 ft. by 30 ft., with a height of 12.5 ft. The frame was made of timber, while the foundation consisted of concrete pillars, and the walls were made of hardy wood. The roof was made of aluminum on the insulated side, with grooves to allow for rainwater collection, should that be an option in the future. To allow for solar input into the system, the southern side and roof of the bioshelter was not insulated, but covered with polycarbonate to allow sunlight through.

Another key observation obtained from the visit was the setup of the ventilation system. A noteworthy contraption called a solar heat vent opener was used to promote ventilation during the summer months. It was, however, removed in the winter to maximize the heat retained within the bioshelter. Also used in the ventilation design, were two side windows on the east and west walls, which served as a source of ventilation through the bioshelter. In addition to the ventilation, a mechanism called a climate battery assisted in the storage of heat, management of moisture, and promotion of circulation. However, the bulk of the bioshelter's heat retaining capacity was in the 800 gallons of water that was stored in the aquaponics system and water storage barrels. This water was obtained via plumbing from Nancee's house. The heat retention methods were not enough to sustain the bioshelter during the winter months. Heat was added to the bioshelter through compost and two small space heaters powered by solar panels. Compost was also used to maintain a worm trench of red wrigglers, which was covered up with slabs to double up as a walkway.

The second bioshelter that was visited belonged to Eric Toensmeier and Jonathan Bates. Their book, Paradise Lot, documented how they built a bioshelter in their own backyard. It was noted that the primary means of achieving ventilation was via cross ventilation through a side window and door, located on opposite sides in the bioshelter. Similar to Nancee's bioshelter, the bulk of heat storage was achieved through water in storage barrels. The water storage was maintained by an ad hoc rainwater catchment system. Eric and Jonathan also used the storage drums to cultivate an aquaponics system.

Interviewing Bioshelter Owners

Conducting interviews with people that operate existing bioshelters supplied information from the owners' experience of constructing and managing a bioshelter. Bioshelter owners have come across or dealt with flaws that are not found through research, such as critical systems that the owners regret not using or materials that did not meet their expectations. Gaining insight on obstacles the owners came across and how they overcame those problems provides information that can be used during the researching and designing phase of a bioshelter. Also, other design factors and recommendations can be gained by interviews. Semi-structured interviews were conducted to obtain necessary information from experts. Interview questions focused on structure, systems, and economics as well as other aspects of a bioshelter.

First, a selected group of existing bioshelters was chosen by online research that had similar aspects to the project, such as location, weather conditions, size, etc. Interview questions were created using knowledge from research and the visits to bioshelters. The interviews were distributed to the bioshelter owners using Google Survey. The answers were compiled and processed to find relevant components that are important to the design of the bioshelter.

Researching Literature/Websites

While looking into a few bioshelters in detail provides valuable insight on the functions and performance of various systems in a bioshelter, focusing too much on a select few could limit the scope of the design. To avoid this issue, overarching characteristics of numerous bioshelters were compared to construct patterns and similarities among the bioshelters. Major similar components were then further studied in detail to examine how they affected the bioshelters that used them. A database of bioshelters (included in Appendix C) was created by assessing their general information, materials, system, livestock and plants used in the bioshelter

3.2 Identifying the purpose and use of the proposed bioshelter

The next step is to identify the purpose and use of the proposed bioshelter. This means gathering opinions as well as factual data about how and who will use the bioshelter. Most of the data came from two main groups: sponsors and stakeholders. Identifying the goals of the sponsors and opinions of local stakeholders gives a general idea of what form the end result of the bioshelter should take. Gathering opinions about the bioshelter was an iterative process. As the bioshelter's design changed, the overall purpose and use of the bioshelter changed along with it. This makes it vital to continually gather feedback from not only the sponsors and stakeholders, but also the local residents. Gathering feedback is a continual ongoing process that can be continued far after this project to look for further ways to improve the design and functionality.

Interviewing Sponsors and Stakeholder

Interviewing the sponsors and project stakeholders, Worcester Common Ground and Ascentria Care Alliance, was the first step of identifying the purpose for the bioshelter. Both of these groups are vital because they are directly affected by the project. As such, a vision has to be extracted from this group that will shape the goals of the project. This is even more important with a multi-stakeholder project, where each stakeholder has their own visions and suggestions. If possible, interviews and meetings should be attended by all stakeholders. Even though this could not be upheld for every meaning, making a best effort to schedule them in allowed stakeholders to discuss their ideas and compromise with the advice from the team.

The meetings were structured to provide a productive environment for encouraging input. Each meeting was split up into three distinct parts: presentation, question and answer, and discussion. The presentation consisted of a visual update to the current progress of the work accomplished. It would set the stage for what has been done and what still needed to be accomplished. Next, the meeting was moved to a question and answer format, where important decisions on features or design issues were brought up. The last part of the meetings involved transitioning to a discussion based forum in order to provide a chance for new ideas and opinions on the direction of the bioshelter.

After the meetings, records and notes of the meetings were reviewed and then transformed into user stories. The user stories captured the who, what, and why of a requirement in a simple and concise way. Once all the requirements were transformed into user stories, each user story was ranked according to the amount of work it would take to accomplish. These rankings would provide the basis of what could be accomplished between the meetings with the stakeholders.

By identifying and incorporating the constraints captured from the user stories, the overall domain of the problem became much smaller. This process continued until all the important constraints and requirements were fulfilled.

3.3 Analyzing conditions of the build location

Solar Analysis of the Site

In winter, solar heat gain contributes to ensure that the bioshelter maximizes solar gain, there needs to be an understanding of how the site interacts with the sun. Estimating the seasonal variation of the sun's path enabled us to plan the shape and orientation of the bioshelter accordingly. Solar insolation to analyze the heat gain and photoperiod was also utilized.

Both sun path and solar insolation analysis were executed in Autodesk Ecotect Analysis, a 3D interactive environmental analysis tool developed by Autodesk. While the incident angle of solar rays at a given time can be found in any weather database, varying location of the sun relative to the site throughout the day is hard to envision. Ecotect Analysis was performed using U.S. DOE data to create sun path diagrams of the location. The interactive sun path diagrams are provided in 2D and 3D so that it is users can understand how the site interacts with the sun and how the shadows would be casted. The study focused on observing the shadow movement throughout solstices and equinoxes.

Another powerful tool Ecotect Analysis provides is the insolation analysis. Various types of information, such as incident solar radiation to sunlight hours, can be calculated for specific locations with this tool. While this tool can also be used for how much sunlight the interior of the building would receive, it can also be used to analyze how the site interacts with the surrounding environment such as neighboring buildings and trees.

Only the objects on the southern side and the western side of the bioshelter were modeled in the software; the buildings that are located to the north of the lot would not cast any shadows on the site since the solar rays in the northern hemisphere arrive from the south. As Ethan Allen Street separates the lot from the structures to the east, the shadows casted by them would be insignificant. The buildings to the west and south of the site are all three stories tall. However, the nearby trees are about five stories tall. Due to the height of the trees, they cast significant amounts of shadows in the south west corner of the lot. Figure 3.3(a) illustrates the insolation analysis of the site in the summer. Due to the trees in the neighboring lot, the south-western corner of the lot receives about 6.4 hours of sunlight, while the rest receives over 12 hours of sunlight on an average summer day.

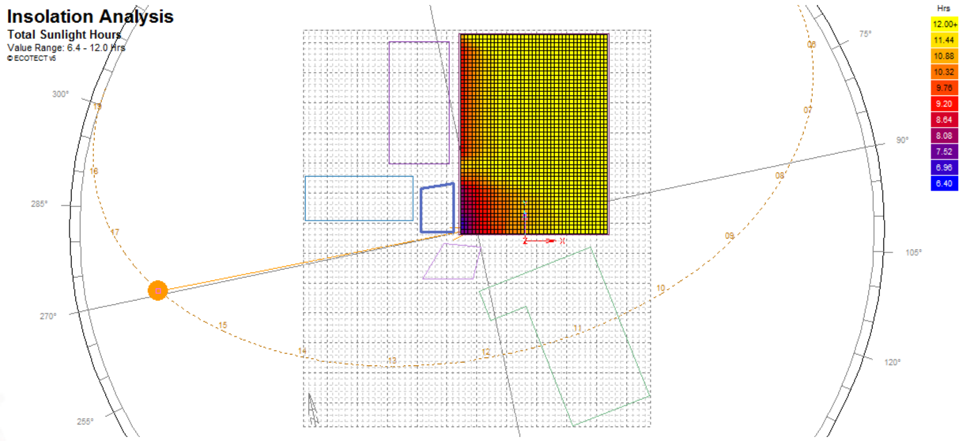


Figure 3.3(a) Summer insolation analysis. The figures that have regular geometry are the buildings and the figures with irregular geometries are trees (two smallest figures). For convenience, the trees were modeled as quadrilaterals.

Since the neighboring tree is a deciduous Maple tree, the corner of the lot is no longer shaded by the tree in the winter. However, because the winter days are shorter, the lot receives only around 6 to 7 hours of sunlight on an average winter day (Figure 3.3(b)). Also, due to the smaller incident angle of solar rays, the neighboring buildings cast longer shadows than in summer, as shown in Figure 3.3(c).

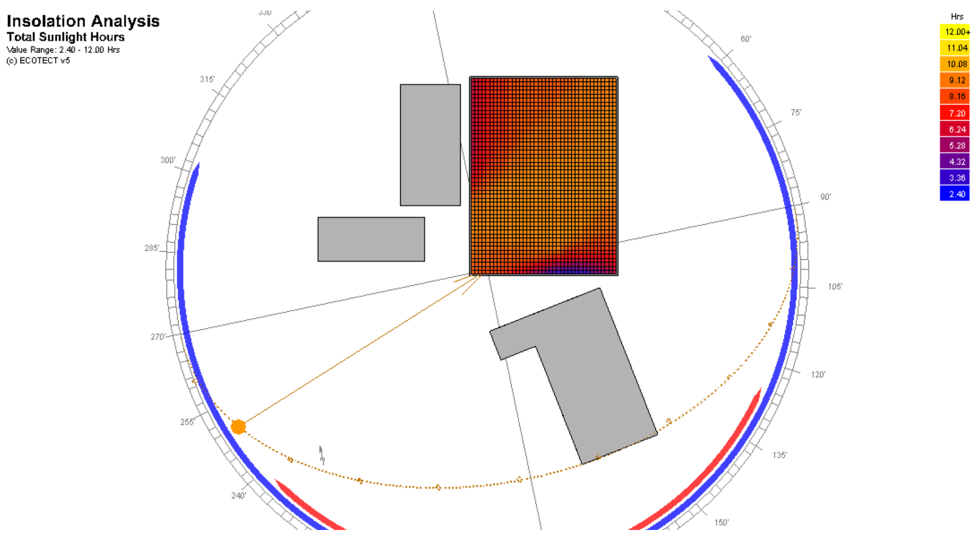


Figure 3.3(b) Winter insolation analysis. The trees were removed from the analysis for convenience.

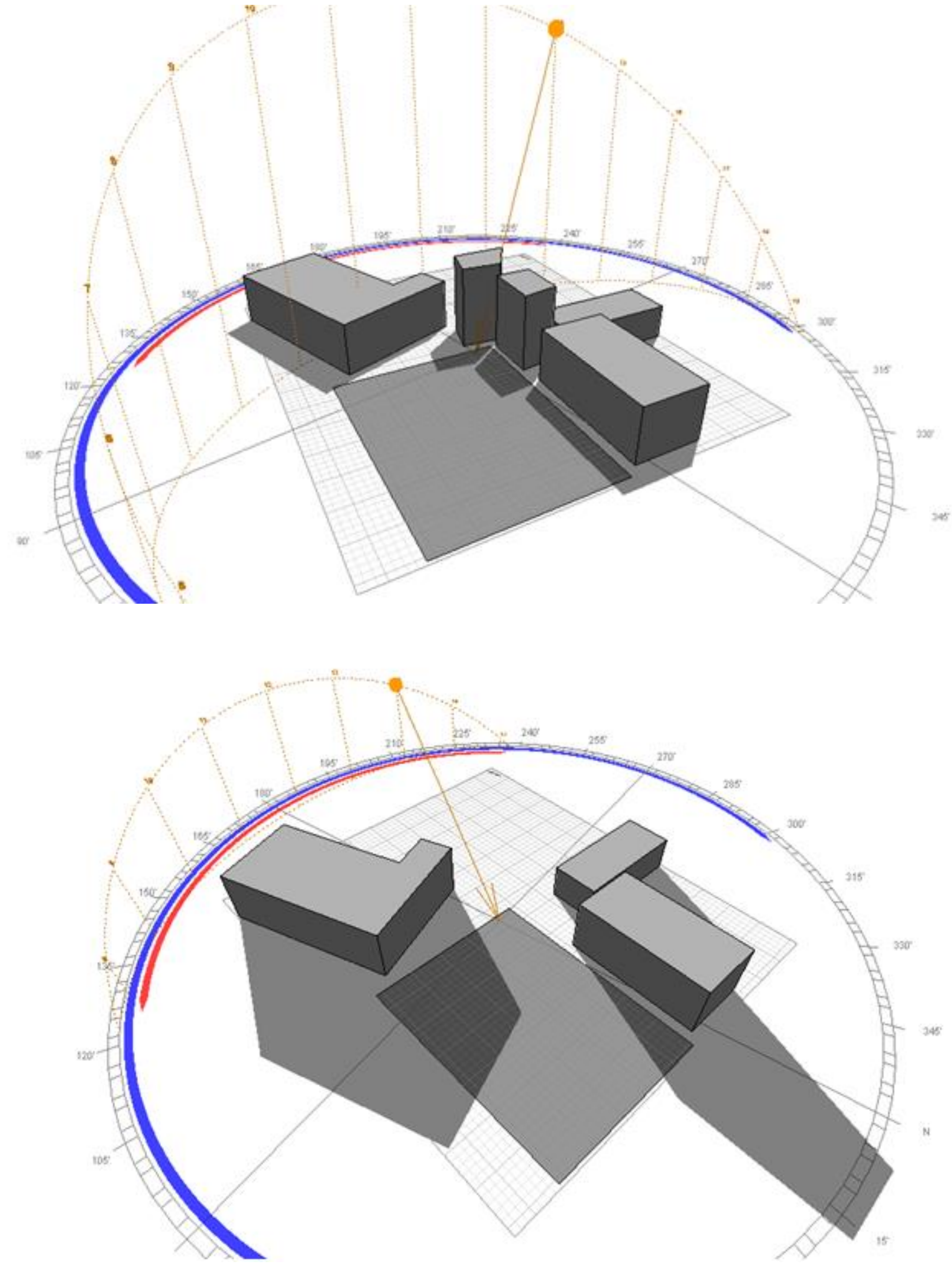


Figure 3.3(c) Examples of shadow studies. Shadow study of the site at 2 p.m. on summer solstice (top). Shadow study of the site at 2 p.m. on winter solstice (bottom). It is easy to see the low angles of the solar rays of winter. The orange dot is the sun's location and the arrow is an incident solar ray.

The future location and orientation of the bioshelter within Jacques Avenue lot was also determined with Ecotect. According to the Ecotect analysis, the optimal orientation for the site is 175°

from the North (Figure 3.3(d)). In other words, the building energy performance would be optimal if the building is facing South. However, because site north does not align with true north, having the design align with site north decreases efficiency. On the other hand, a disoriented design could appear less aesthetically pleasing. Therefore, the building design considered these two factors to ensure the bioshelter receives as much sunlight, while not affecting the street view.

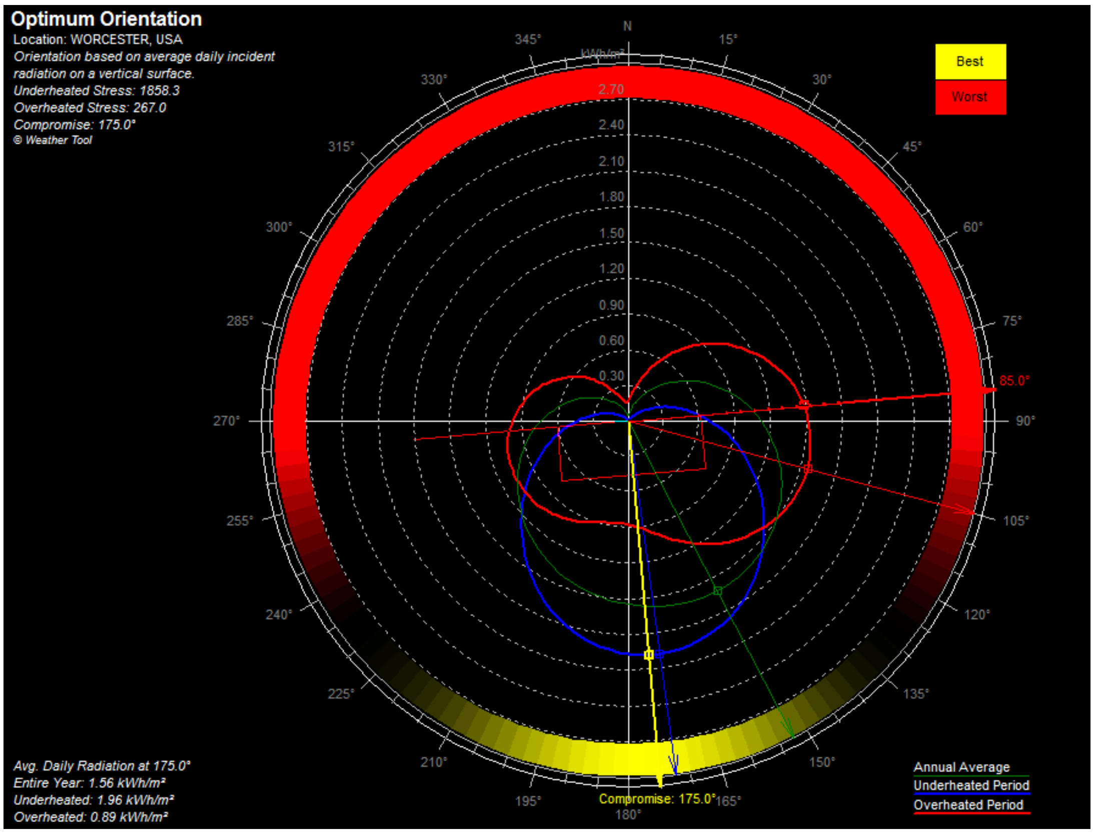


Figure 3.3(d) Optimum Orientation of the building, analyzed by Ecotect.

Wind Analysis of the Site

The Ecotect Weather Tool was used to obtain relevant data on wind velocities in the City of Worcester throughout the year. As indicated in Figure 3.3(e), a large amount of wind flowing through the City of Worcester is towards the West, at 20 km/h. To fully take advantage of wind as a resource, windows will be installed in the East and West sides of the bioshelter to maximize ventilation during the summer. The wind velocity obtained is also assumed to represent the amount of wind flowing through the bioshelter site, and so is used when necessary in later calculations.

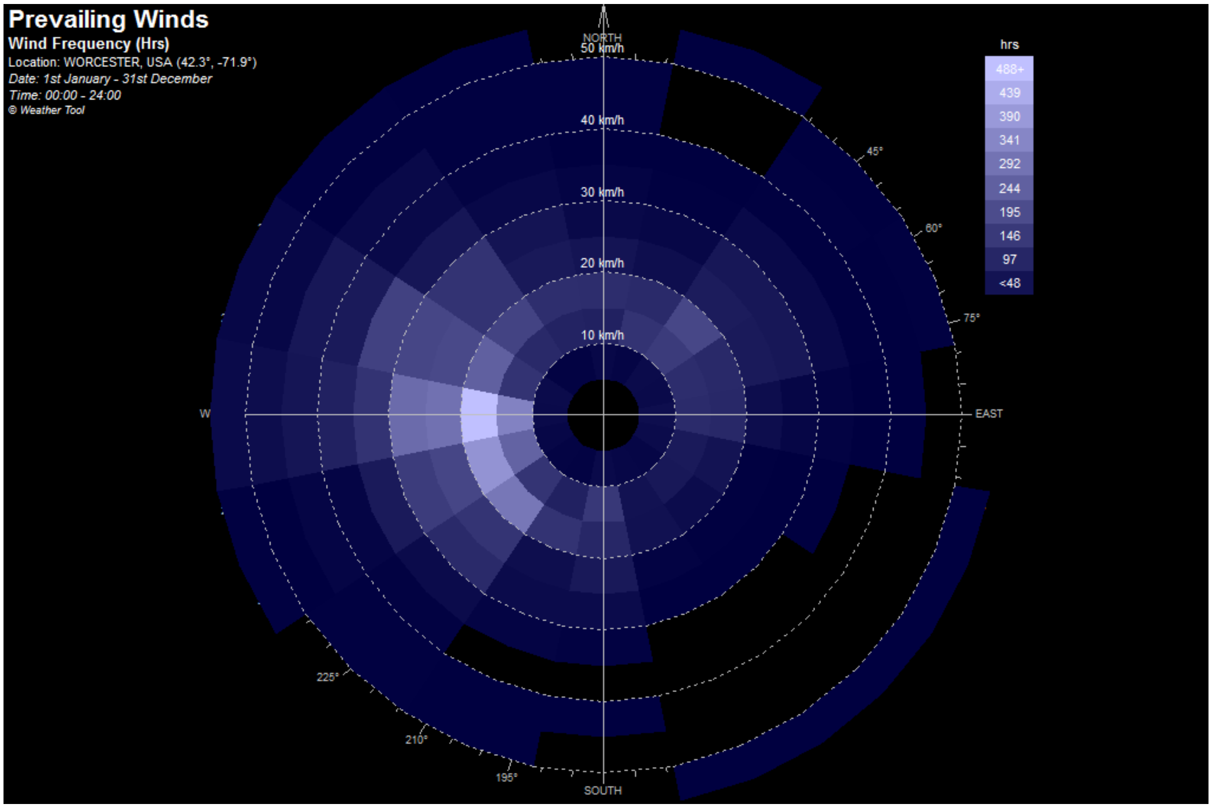


Figure 3.3(e) Wind Analysis of the City of Worcester, analyzed by the Ecotect Weather Tool.

3.4 Initial bioshelter render

An initial design was created based on the information gathered from the initial documentation of existing bioshelters and initial research. The proposed model was based on existing bioshelters, cannibalising a lot of the layout and critical components. It was modeled and rendered in AUTOCAD Revit, which provided a basis for future additions and changes. By creating an initial design, the critical components of the bioshelter could be designed based on the initial model and iteratively improved as a clearer vision of the model was created. It is important to note that no calculations were done to measure the effectiveness of the initial model. Instead, it was simply based on existing functioning bioshelters.

Figure 3.4(a) - Initial bioshelter rendering

3.5 Critical bioshelter systems

A bioshelter relies on heat and energy conservation systems to maintain a stable internal temperature (Frey, 2011). It is comprised of many complex systems, which are all connected together to provide a stable environment. The next part of the design process involved identifying core resources of the bioshelter and measuring the effective estimated consumption of the resources. By identifying the consumption of the resources, a proposed design of each of the components could be iteratively changed to fit the necessary needs of the structure.

3.5.1 Water

Water Usage

The total water usage of the bioshelter was calculated by compiling estimates of the water usage of the bioshelter's subsystems. This was done in an iterative process, starting out with a rough estimate and refining the estimate over time to produce an accurate guess to the actual average water usage. The initial rough water usage estimate was made by looking at similar bioshelter designs and calculating their total water usage estimates based on the proposed dimensions of the planned bioshelter.

Based on this initial calculation, a more refined estimate was made by aggregating the sum of the water usage of the important water-dependent subsystems in the bioshelter. This calculation depended mainly on the plant water usage, compost water usage, and storage water usage.

Plant Water Usage:

Plant water usage was calculated using equation 3.5.1 (i) for a given plant based on its average Kc ratio. This was done by inputting the Kc ratios of crops grown in New England's climate and comparing the output monthly water usages. Due to the complex nature of the bioshelter's systems, an accurate internal climate could not be easily calculated to measure the ET0. Instead, the ET0 used was based on Worcester's average ET0. In addition, the plant growing area used was based on average growing space estimates taken from the initial mockup of the floorplan.

Equation 3.5.1(i) $ET = ET0 * Kc$

where

ET = water usage (inches)

ET0 = average water usage of grass or alfalfa (inches)

Kc = the ratio between ET0 and ET

Table 3.5.1(a): The water usage of different types of plants based on the average ET0 of Worcester.

Plant Name	Average Kc	Average ET0 Worcester (inches / month)	Plant Water Usage (inches / month)	Plant Growing Area (ft^2)	Bioshelter Plant Water Usage (gallons / month)
Tomato	0.85	5.83	4.96	270	833.56
Cabbage	0.9	5.83	5.25	270	882.60
Peppers	0.85	5.83	4.96	270	833.56
Onions	0.83	5.83	4.86	270	817.22
Watermelon	0.72	5.83	4.18	270	702.81
Potato	0.72	5.83	4.18	270	702.81
Pea	0.65	5.83	3.79	270	637.43
Bean	0.63	5.83	3.69	270	621.08
Maize	0.67	5.83	3.89	270	653.78
Wheat	0.58	5.83	3.41	270	572.05

The calculation results for the water usage of plants show a monthly water usage that varies greatly depending on the type of crop being used. The least water dependent crop is wheat, which requires only around 575 gallons of water per month for a 270 square foot growing area. In the above cases, the bioshelter is only assumed to carry one type of plant. This assumption does not hold true in reality, but provides a good baseline measurement, which can be used to determine the total water needs of the bioshelter. For basic calculation purposes, the monthly water usage of cabbages at 885 gallons per month was used with the assumption that it is better to overestimate the water usage.

Compost Water Usage:

Compost water usage was calculated using the average water usage of one bin of compost multiplied by the number of desired bins. The calculations were based on the water usage for a model 3 ft. by 3 ft. by 3 ft compost bin.

Table 3.5.1(b): The amount of water required based on the average monthly water usage of a 3 ft. x 3 ft. x 3 ft. compost bin.

Number of Compost Bins	Water Per Compost Bin (Gallons / Month)	Total Water Usage (Gallons / Month)
1	60	60
2	60	120
3	60	180
4	60	240
5	60	300
6	60	360
7	60	420
8	60	480
9	60	540

In these calculations, it is assumed that the compost bins have a static amount of water usage per month. This was estimated to be around 60 gallons per month. The planned 9 compost bin bioshelter would consume 540 gallons per month on compost.

Storage Water Usage:

The average storage water usage of the bioshelter measures the amount of water lost due to the evaporation of water in the storage tanks. Several calculations (equation 3.5.1 (ii)) were made based on multiple container sizes and based on an estimate of the average water evaporation per month of the New England region.

Equation 3.5.1 (ii) Storage Evap. (gal.) = Area Open (sq. in.) x Avg. Evap. (mm) x 0.00017 Conv. Factor

Table 3.5.1(c): The average amount of water lost due to evaporation in storage based off an average water evaporation rate for the New England climate and various container diameters.

Diameter Container (inches)	Area Open Water (square inches)	Average Water Evaporation (mm/month)	Storage Water Evaporation (gallons/month)
40	1256.64	45	9.63
45	1590.43	45	12.19
50	1963.50	45	15.05
55	2375.83	45	18.21
60	2827.43	45	21.67
65	3318.31	45	25.43
70	3848.45	45	29.50
75	4417.86	45	33.86
80	5026.55	45	38.53
85	5674.50	45	43.49
90	6361.73	45	48.76
95	7088.22	45	54.33
100	7853.98	45	60.20

The average amount of evaporation for the water storage was based on the amount of the surface area of the water exposed to open air. These calculations show that the water loss due to evaporation is dwarfed by the water use by the compost and the plants. For the bioshelter there are two 900 gallon containers of diameter 75 inches and two 400 gallon containers of diameter 60 inches. This combines for a total water usage quantity of 112 gallons per month.

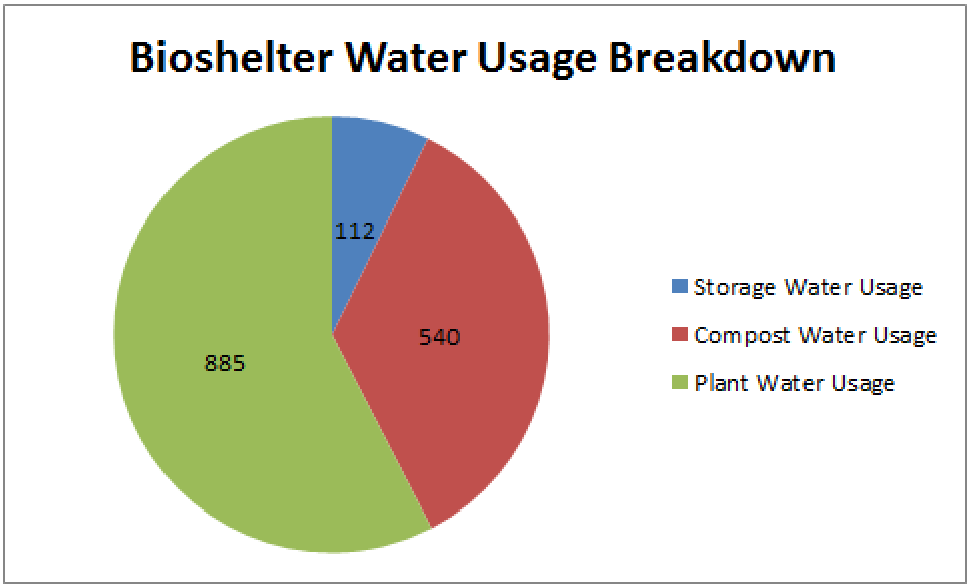


Figure 3.5.1(a): The water usage breakdown in gallons for storage, compost, and plants.

The above chart shows a breakdown of the total water usage. The total estimated water usage by the bioshelter was calculated to be 1537 gallons per month.

Rainwater Collection

The proposed rainwater catchment system serves as a means to obtain water in a sustainable way, without having to rely on sources other than rainfall. This adheres to the bioshelter's principle of relying only on sustainable means to gather the necessary resources. Rainwater that is gathered through this system can be used to water the plants and as thermal mass, which aides with retaining heat inside the bioshelter. In addition, the rainwater catchment system must achieve an equilibrium between the water being used and water being collected. An excess of water input may lead to flooding and such a scenario should be prevented from occurring. Although dependent on the bioshelter, the rainwater catchment system can be viewed as its own separate subsystem. Using the information obtained from the precipitation weather data, an approximation for the total amount of water that may be collected by the catchment system can be calculated. This number can then be compared to the water usage estimates, from the previous section, to determine how much of the required water the catchment system can supply.

Equation 3.5.1 (iii) Harvested Water (gal) = Catch Area (sq. ft.) x Rainfall Depth (in.) x 0.623 Conversion Factor

Table 3.5.1(d): The average amount of water available per month based on the catchment area.

Month	Average Rainfall (inches)	Catchment Area (sq ft.)	Water Available For Catchment (gallons)	Catchment Rate	Water Caught (gallons)
January	3.49	880	1913.3576	0.9	1722.02
February	3.23	880	1770.8152	0.9	1593.73
March	4.21	880	2308.0904	0.9	2077.28
April	4.11	880	2253.2664	0.9	2027.94
May	4.19	880	2297.1256	0.9	2067.41
June	4.19	880	2297.1256	0.9	2067.41
July	4.23	880	2319.0552	0.9	2087.15
August	3.71	880	2033.9704	0.9	1830.57
September	3.93	880	2154.5832	0.9	1939.12
October	4.68	880	2565.7632	0.9	2309.19
November	4.28	880	2346.4672	0.9	2111.82
December	3.82	880	2094.2768	0.9	1884.85

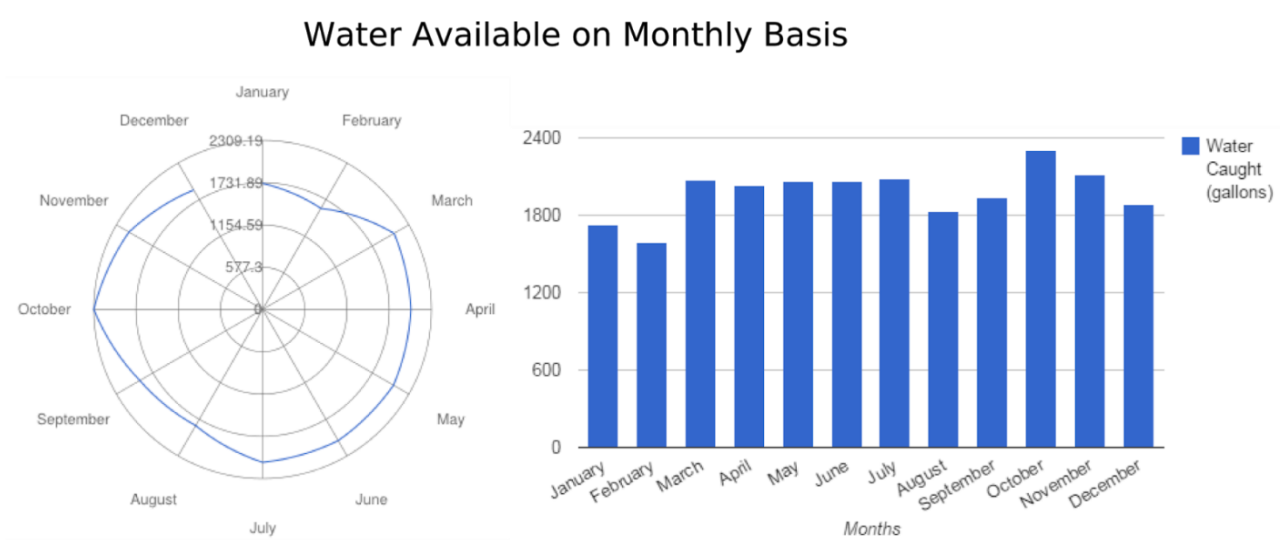


Figure 3.5.1(b): Water Available to Rainwater Catchment System on Monthly Basis.

Table 3.5.1(e): The average amount of water available per season based on the catchment area.

Season	Average Rainfall (inches)	Catchment Area (sq ft.)	Water Available For Catchment (gallons)	Catchment Rate	Water Caught (gallons)
Spring	12.51	880	6858.48	0.9	6172.63
Summer	12.13	880	6650.15	0.9	5985.14
Fall	12.89	880	7066.81	0.9	6360.13
Winter	10.54	880	5778.45	0.9	5200.60

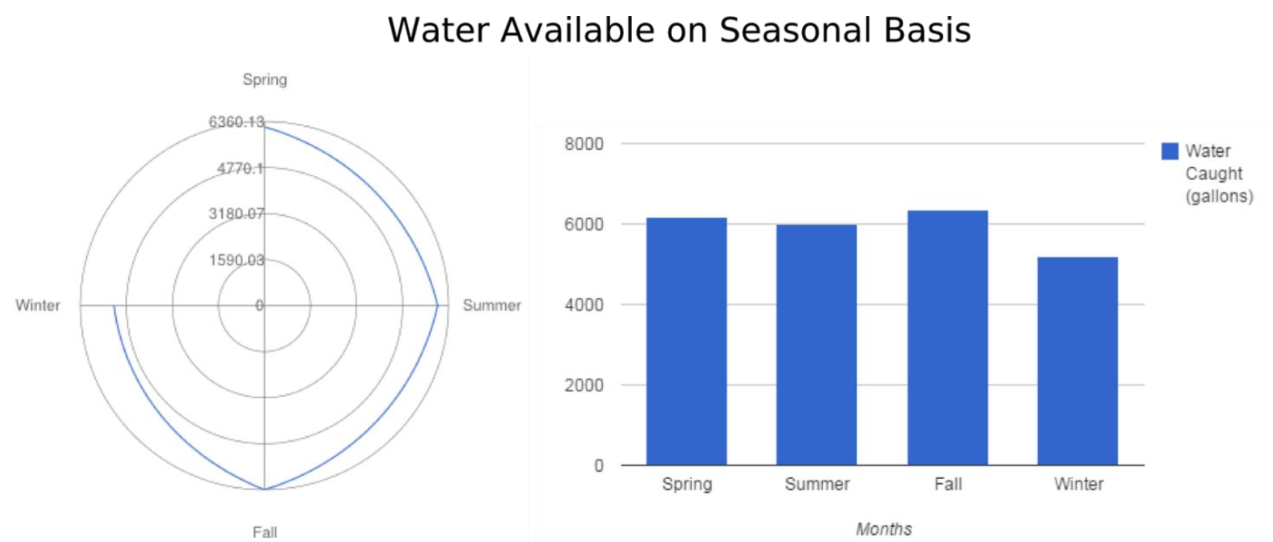


Figure 3.5.1(c): Water Available to Rainwater Catchment System on Seasonal Basis.

The amount of water available to the rainwater catchment system was calculated based on monthly average rainfall collected from local Worcester weather stations. The calculation is also based on the catchment area of the bioshelter, which was taken from an initial rough design. In this case the area of the roof of the bioshelter was used, which was approximated to be 20 ft. by 40 ft. plus an additional 1 ft. by 40 ft. on both sides for the overhang. This resulted in a total area of 880 ft^2. This roof size provides enough space to fulfill the bioshelter's water requirements, even with a 90% catchment rate. Because of New England's winter climate and solid precipitation, water will not be collected during winter months. Due to this, in addition to calculating the amount of water available on a monthly basis, it was also calculated on a seasonal basis (see Table 3.5.1(d)).

Rainwater Catchment System Design

The overall design of the rainwater catchment system is very simple. Building on existing designs, the catchment system becomes a constraint satisfaction problem. Based off of the dimensions of the bioshelter, the catchment system's design may to be modified to fit the new parameters. The main constraints to the catchment system are catching, conveyance, and storage. Each of these can be considered to be their own subsystem.

Catching:

The first step of creating a catchment area for the rainwater catchment system is deciding on the roofing type. The type of roofing utilized must be suitable for the local climate as well as fit within the budget of the project. A simple cost-benefit analysis was done on suggested catchment roofing types to find a type that fit all the needs of the project. If there were several types of roofing that fit the needs of the project, the cheapest was chosen based on cost and expected lifetime.

Another important factor taken into consideration was the roof slope. The slope of the roof must fit the lower bound constraint of 45 degrees due to the New England weather. In addition, various other constraining factors were also taken into account based on the dimensions of the bioshelter.

Conveyance:

Similarly to the catching system, the conveyance subsystem can be looked at as its own constraint satisfaction problem. There are three major constraints placed on the conveyance system: gutter width, downspout area, and conveyance slope.

The gutter width depends on the slope of the roof as well as the volume of expected precipitation. As a general rule, gutters are 5 inches wide. This means that a 5 inch overhang is necessary for the conveyance system on either side of the roof.

The downspout area can be calculated by equation 3.5.1 (iv). This equation requires an estimated roofing area covered by the downspout, which can simply be derived by the total roofing area divided by the number of downspouts.

Equation 3.5.1 (iv): downspout area (sq. in) = roofing area (sq. ft.) / 100 (sq. ft.)

Finally the conveyance slope must fit the constraint of at least 1/16 inch per foot. The total vertical drop can be calculated as the minimum constraint of 1/16 inch per foot * length of conveyance in feet. The system must be able to convey the water to the storage system at a height greater than the tanks height.

Storage:

The storage space of the catchment system was calculated by creating a lower bound of one month's water usage. In addition the placement and orientation of the storage system, was decided based off the locations of the other systems within and outside the bioshelter. The type of storage tank being used was decided again with a simple benefit analysis on common storage tanks with the tie breaking factor being tank price.

Rainwater Catchment Design

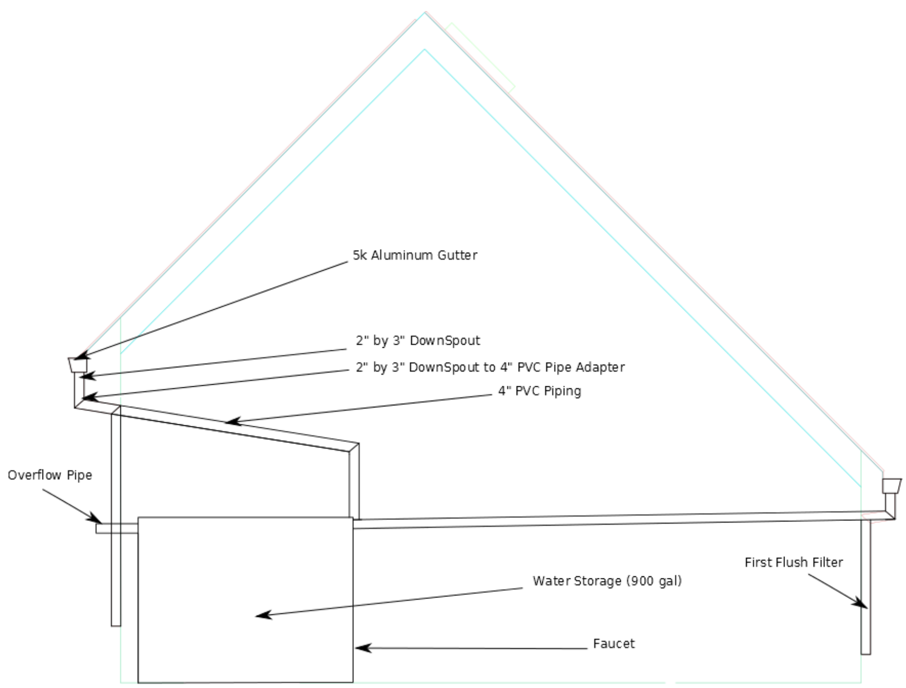


Figure 3.5.1(d): Detailed cross section of conveyance system to rainwater storage.

The rainwater catchment system was designed to be a subsystem of the bioshelter. It is built off the roof by attaching 5 inch gutters along both the 40 ft. length sides. These gutters then funnel the water to the downspout, which is located on the far side of the bioshelter away from the entrance. The downspout's cross-section is 2 feet by 3 feet. This allows the water from both sides of the roof to aggregate to one corner from either side. The water is then funneled into a storage tank inside the bioshelter. As the water is being funneled into the storage tanks, the initial runoff is filtered through a first flush filter, which removes the unwanted initial bit of water. The water storage tanks are located inside the bioshelter in the corner nearest to the Jean Pain mound. The piping leading to the storage tanks are sloped at 1/16 inches per foot. During the winter there is a valve to cut off the piping to the outside, and the first flush filter can be removed to implement a normal gutter system.

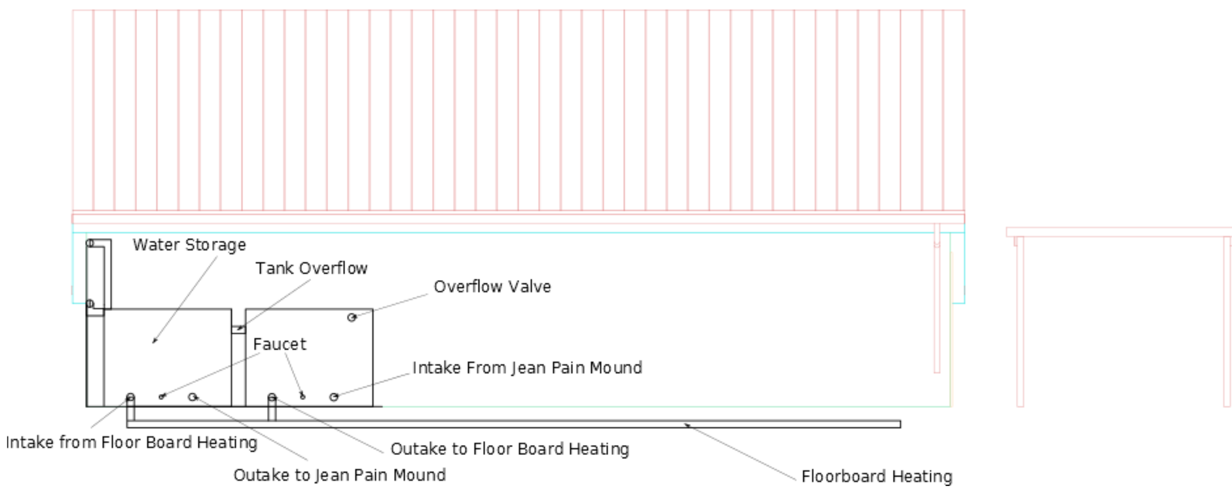


Figure 3.5.1(e): Detailed cross section of rainwater catchment system and floor board heating.

The water storage system consists of two 900 gallon tanks. This brings the total water storage capacity to 1800 gallons, which exceed the monthly gallon water usage rate of the bioshelter of 1600 gallons. This means that almost an entire month's worth of water may be stored. Due to the energy passive nature of the rainwater catchment system, both the tanks must be lower than 5 feet. This is due to the glazed lower wall of the bioshelter being 5 feet high. In order to convey the water into the tanks without power, the tanks intake valve must be placed lower than an inch and half the distance the water enters the bioshelter at. The two tanks are connected at the 800 gallon mark by an overflow tube, which will transfer water between tanks if the water in both the tanks is not above 800 gallons. In addition at the 850 gallon mark there is another overflow pipe, which will direct excess water outside of the bioshelter to the surrounding plants. This is to prevent too much water from being captured and flooding the bioshelter. Like the rainwater collection inlet to the bioshelter, this pipe can also be removed and sealed during the winter months with insulation to prevent cold air from permeating into the bioshelter. Retrieving water from the storage tanks can be done in two ways. The first way is off the top of the tank through a tank cap, which will remain open and will let the user scoop water out directly, or from a hose installed at the bottom of the tank, which will let the person funnel water into a bucket or to a raised bed.

During the winter months, the rainwater collection system will no longer work. The solid precipitation and cold air prevent the rainwater collection system from operating without jeopardizing the functionality of the bioshelter system. Instead during these months, both the outside overflow pipe and downspout inlet can be temporarily “uninstalled” to prevent cold air from permeating the bioshelter. However, this leaves the bioshelter without a supply of water. There were several proposed methods for gathering water during the winter. The first possible method was to bring snow inside the bioshelter. Under optimal conditions, the bioshelter would have enough excess heat to melt the snow, which would be placed in the storage tanks. However, this requires extra manual labor and doesn’t strictly adhere to the self-sufficiency requirement of the bioshelter. The other possible method discussed was to obtain water from an external source, like a neighbor, and bring water into the bioshelter. This also does not adhere to the self-sufficiency requirement of the bioshelter, but both these models are ideal alternatives to having no water in the winter. It is also important to note that during the winter, plants require less water due to their reduced growth rate. Other steps can also be taken to reduce the water consumption of the bioshelter. This is, however, outside the scope of this project and is something that may be further meted out in the future.

3.5.2 Air Movement

A comprehensive understanding of the level of airflow and air exchange necessary to operate the bioshelter needed to be achieved. A literature review on ventilation systems of other bioshelters and greenhouses provided internal systems through which the amount of airflow required could be obtained.

Without proper ventilation and circulatory systems, the air in the bioshelter will stagnate, reducing the quality of plants being grown. Several different types of ventilation may be implemented to achieve an adequate level of airflow in the bioshelter.

Ventilation

Research on relevant types of ventilation was done, primarily through online resources. The different types of ventilation were compiled into a table, and the advantages and disadvantages of each type of ventilation were compared against each other. Certain specifications in regards to how satisfactory ventilation may be achieved in the bioshelter were intentionally left undetermined. Examples of this are the dimensions and types of windows to be used, and location and types of vents to be installed. Proper evaluation by a building advisor is necessary to obtain proper results in this regard, as several variables, such as building codes, may be involved in the ventilation of the bioshelter.

Analyzing how the necessary ventilation could be achieved was done by approximating the wind flowing through the site based on empirical data, and determining the minimum window area required to allow for an adequate amount of airflow into and out of the bioshelter. Ventilating the bioshelter should be done through a combination of individual strategies. Windows should be built into the west and east sides of the bioshelter to stimulate cross ventilation, as the west side is most exposed to wind. Incorporating stack ventilation into the system will not be economical, as the cooling factor due to stack ventilation, at 0.75, is weak. Also, an adequate amount of ventilation may be garnered from cross ventilation alone. However, night flush cooling, a variant of stack ventilation, will be partially incorporated into the bioshelter. By utilizing thermal masses, the bioshelter will be able to draw in cool air during the night, while also cooling the bioshelter via convection currents in the air (Autodesk, 2011).

Passive Ventilation Strategies:	Pros	Cons	Dependencies	Details	Notes
Cross Ventilation	- Precipitation unlikely to enter bioshelter	- Wind is unreliable	- Wind has to flow through the bioshelter	The strategy of cross ventilation relies on wind to pass through the bioshelter for the purpose of cooling the occupants.	- Strategy
Stack Ventilation	- Doesn't depend on wind	- Effective inlet placement may be tough - Precipitation may enter bioshelter	- Temperature of air	Stack ventilation is an alternative design strategy that relies on the buoyancy of warm air to rise and exit through openings located at ceiling height. Cooler outside area replaces the rising warm air through carefully designed inlets placed near the floor.	- Strategy
Night Flush Cooling	- Easily able to maintain relataively stable internal bioshelter temperature - Doesn't depend on wind	- Thermal mass takes up space - Less useful where temperatures are stable - Precipitation may enter bioshelter	- Large diurnal swing needed for strategy to be effective (maximum indoor temperature is below the outdoor maximum temperature) - Thermal mass is needed	The bioshelter acts as a sink through the day and absorbs internal heat gains and solar radiation. Heat can be dissipated from the bioshelter by convective heat loss by allowing cooler air to pass through the bioshelter at night. The next day, the bioshelter will perform as a heat sink, maintaining indoor temperatures below the outdoor temperature.	- Strategy
Solar Vent Openers	- Adapts to temperature	- May require maintenance - Provides opening for precipitation to enter bioshelter - Will require a human to fully close	- Heat of sun	Solar vent controls convert heat energy from the sun into mechanical energy to open the vents. The hotter it gets, the wider the vents are opened.	- Mechanism

Figure 3.5.2(a) Compilation of considered Ventilation Strategies.

Cross Ventilation

Equation 3.5.2(i) $F_{house} = F_{elev}*F_{light}*F_{temp}$

where

F_{house} = house adjustment factor

F_{elev} = elevation factor

F_{light} = light intensity factor

F_{temp} = temperature increase factor

Equation 3.5.2(ii) $CFM_{ventilation} = L*W*8.0*F_{house}$

where

$CFM_{ventilation}$ = Required ventilation (CFM)

L = Length of bioshelter (feet)

W = Width of bioshelter (feet)

F_{house} = house adjustment factor

Based on the table found in Appendix Section D (Vent & Cooling, 2015), appropriate results were calculated.

The cross ventilation necessary for the system was calculated as follows: Worcester wind velocity was calculated through the Ecotect Weather Tool to be an average of 20 km/h westward, which is equivalent to 1094 ft./min. F_{elev} was estimated to be 1.0, F_{light} was estimated to be 1.0, and F_{temp} was estimated to be 0.88. Using Equation 3.5.2(i) the resulting F_{house} was calculated to be 0.88. Substituting this into Equation 3.5.2(ii), $CFM_{ventilation}$ was calculated to be 5632 ft^3/min. This means that a window area of 5.15 ft^2 is required. An appropriate square window would be at least of dimensions 2.27 ft. x 2.27 ft.

Stack Ventilation

The following steps were used to calculate the stack ventilation attainable by the bioshelter.

Step 1: The height between the center of the lowest and the highest opening was determined.

Step 2: Assuming the inlet and exit areas were the same, a target temperature increment was established.

Step 3: The flow rate was obtained for the trial values, and a value for the ventilation for the floor area was obtained. (Refer to Figures 3.5.2(b) and 3.5.2(c))

Step 4: The total internal gains were assumed to be 0 W/m^2.

Step 5: The solar gains were assumed to be 350 W/m^2.

The stack ventilation necessary for the system was calculated as follows: The stack height was calculated to be 11 ft., or 3.3528 m. The temperature tolerance goal was set to be 11°F, or 6°C. Volume flow was calculated to be ~0.54 to determine a height*temp value. A value of 20.1168 was calculated to obtain a value that will be used to determine the cooling power of 0.75, assuming all gains amount to 350 W/m^2 (RIBA, 2015).

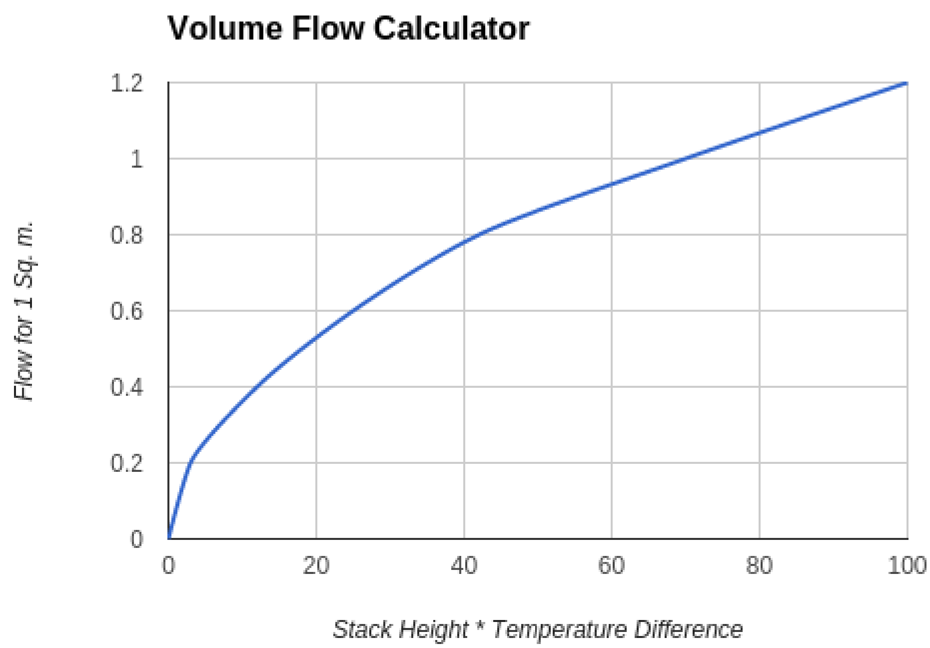


Figure 3.5.2(b) Chart to be used to determine volume flow

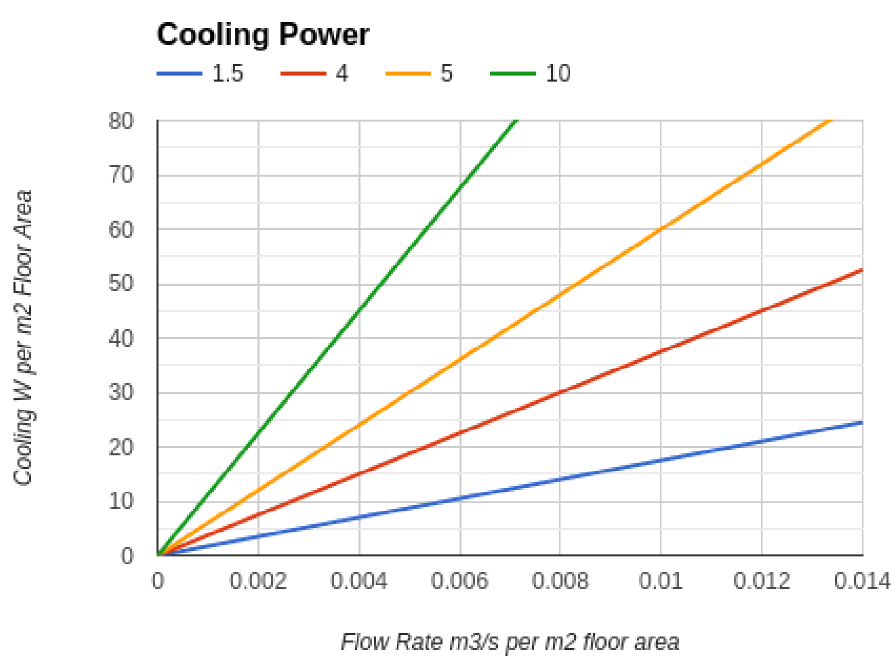


Figure 3.5.2(c) Chart to be used to determine cooling power

Circulation

Solar Vent Openers	- Adapts to temperature	- May require maintenance - Provides opening for precipitation to enter bioshelter - Will require a human to fully close	- Heat of sun	Solar vent controls convert heat energy from the sun into mechanical energy to open the vents. The hotter it gets, the wider the vents are opened.	- Mechanism
Air Circulation Strategies:	Pros	Cons	Dependencies	Details	Notes
Horizontal Air Flow	- Allows for uniform temperatures inside the bioshelter - Replaces air near plants with fresh air with higher carbon-dioxide content - Reduces humidity in air, which reduces incidence of foliar diseases	- Requires fans	- Placement of fan - Fan size	Through the use of fans placed near the ceiling, air is pushed along the length of the bioshelter. Warmer air which tends to gather near the top of the bioshelter will mix with the colder air at the bottom of the bioshelter to generate a more uniform temperature.	- Strategy
Fans	- Can be used not only for air circulation, but air ventilation as well	- Requires electricity	- Power source	Though there are fans designed specifically for air circulation, without a relatively stable power source, running fans will be a challenge. If fans are implemented, they can be turned off during the summer, as Cross Ventilation via open windows will serve as more than ample a means of circulating and ventilating air. During the winter, when most orifices are sealed off, a fan or something similar will be the only means of circulating air within the bioshelter.	- Mechanism

Figure 3.5.2(d) Compilation of considered Circulation Strategies.

Research on means to achieve internal circulation was done, primarily through online resources. Both the type of relevant circulation and possible means through which to achieve the circulation were looked into. Also taken into consideration was the fact that ventilation should be discouraged during the winter season to reduce heat loss.

Calculations for the necessary horizontal airflow inside the bioshelter were calculated as thus: (Fact Sheets, 2015)

Equation 3.5.2(iii) $CFM_{circulation} = 2*A_{floor}$

where

$CFM_{circulation}$ = Required Circulation (CFM)

A_{floor} = Floor Area of Structure ($feet^2$)

Horizontal air flow (HAF) in the bioshelter is not a concern during the summer when cross ventilation will be largely active. During the winter, however, fans will have to be used to maintain HAF. Maintaining HAF is important, as pockets of moisture may form otherwise (Rodriguez, 2010). HAF will also circulate air inside the bioshelter, such that the internal temperature distribution is more uniform (Bartok, 2015). The fans will be powered via solar energy harnessed from external PV panels, or in some cases, stored energy from a battery.

Calculations done to determine the necessary HAF were done as follows: Using Equation 3.5.2(iii), the floor area of the bioshelter was calculated to be 800 ft^2, which resulted in a required CFM of 1600 ft^2.

3.5.3 Heating

Solar Heat

To find out the amount of heat gain from the sun during the winter and summer periods, the two equations below were used. Equation 3.5.3 (i) is a heat absorption equation and Equation 3.5.3 (ii) determines how much solar energy is transmitted through the glazing.

Equation 3.5.3(i) Q = Qflux * A * t * C)

where

Q = Heat Energy (BTU)

Qflux = Flux Heat transfer (kW/hr.*m^2)

A = Area (m^2)

t = Time (hr./day)

C = Conversion factor (kW/BTU)

Equation 3.5.3(ii) Q * SHGC = $Q_{bioshelter}$ (BTU)

where

Q = Heat Energy (BTU)

SHGC = Solar heat gain coefficient

$Q_{bioshelter}$ = Heat Energy (BTU)

Based on Equation 3.5.3 (i), the amount of solar energy hitting the the exterior of bioshelter was calculated to average 0.3kW/m^2h (UOregon, 2015). Assuming that winter has six hours of sunlight and an 800 square foot bioshelter, the BTU gain per day is 456,399 BTU. During the summer, the average solar energy gain was calculated to be 0.6 kW/m^2h. Assuming that Summer has six hours of sunlight per day, the BTU gain per day is 1,216,906 BTU (UOregon, 2015).

Table 3.5.3(a) Shows hand calculations of solar energy

By hand calculations					
	energy/day	energy per 1m^2 (KW)	Bioshelter area (m^2)	Hours per day	KW to BTU
winter	456,339.87	0.3	74.3	6	3412.142
summer	1,216,906.32	0.6	74.3	8	3412.142

The amount of energy calculated, ignores the thermal resistance from the window material. Table 3.5.3(b) shows the amount of energy that enters the bioshelter using different glazing materials based on calculations performed above. The amount of BTU gained per day was calculated using equation 3.5.3 (ii), which utilizes the solar heat gain coefficient (SHGC) of different materials as well as the amount of solar energy hitting the bioshelter's windows.

Table 3.5.3(b) Amount of solar energy per day using varying materials

Glazing type	SHGC value	Solar heat Summer with glazing (BTU/day)	Solar Heat Winter with glazing (BTU/day)
Unobstructed	1	1216906	456340
Poly flim	0.85	1034370	387889
Heat efficient wrap	0.83	1010032	378762
Corrugated Polycarbonate	0.9	1095216	410706
Polycarbonate double wall panel	0.75	912680	342255
Polycarbonate with aerogel application	0.61	742313	278367
Plexiglass double wall panel	0.91	1107385	415269

Table 3.5.3(b) illustrates that plexiglass and corrugated polycarbonate allow the most solar energy to enter the bioshelter. However, these might not be the best materials to use, because their insulation value could be relatively low compared to the other glazing materials. A low insulation value

leads to a high amount of energy loss, especially during the winter months. For example, if there is not a lot of sunlight during the winter, but temperature are below freezing point, it may be better to have material with a higher insulation value over a high SHGC value.

Compost

Using a calculator developed by Cornell University, suitable composting materials that fit within the requirements could be evaluated for use in the bioshelter. It can be seen below in Figure 3.5.3(a).

Moisture and Carbon/Nitrogen Ratio Calculation Spreadsheet (updated March 2014)

Developed by Tom Richard, Department of Agricultural and Biological Engineering, Cornell University

Shamelessly modified by Jake Kruger, The Homestead Laboratory

To use this spreadsheet, select your ingredients in cells A16 to A18 (up to four ingredients).

The spreadsheet then calculates the mixture moisture content and C/N ratio.

Alternatively, the spreadsheet will calculate the proper proportions for moisture and/or C/N goals (see below).

For further explanations of the formulas embedded in this worksheet, see the Science and Engineering section of the

Cornell Composting web site: http://www.cals.cornell.edu/dept/compost/

NOTE - do not copy and paste the existing data out of the table, as the formulas may remain tied to the old data.

Input areas are shaded blue or purple. Formula results are in red cells.

Ingredient	% Moisture	% Carbon	% Nitrogen	Mass (lbs.)		Volume (gal)	gal/yd³ 201.98			
Urine	94.5	0.7	0.9	175.68		20.60				
Leaves, Loose and dry	15.0	48.6	0.9	162.22	) Note:	163.83		**Optimizer Error**	0.00	<---------Use Excel's Solver function to
Garbage (food waste)	69.0	36.0	2.4	137.70	) these masses are solved for in	17.55				minimize this cell by changing cells
Water	100.0	0.0	0.0	0.00	) some of the equations below.	0.00				E16:E19. Check multiple starting
										points to avoid local minima.

Calculated mixture moisture content:	**60.0**	(masses as specified)
Calculated mixture C/N ratio:	**35.0**	(masses as specified)
Calculated mixture volume:	**202.0**	(gallons)

The required mass of the third material can be determined given characteristics, the masses of the first two, and goals:

moisture goal:	60.0	(set these goals to match your requirements)
C/N ratio goal:	35.0	
volume goal (gal):	202.0	

Figure 3.5.3(a) Cornell Carbon to Nitrogen Ratio Calculator (Richard, 2014)

Once proper plant-generating compost estimates were established, the heating capabilities needed to be analyzed. Using Equation 3.5.3(iii); it was determined that a compost pile of 110 lbs. could produce around 1850 BTUs at any one time (as shown below in Figure 3.5.3(b)).

Equation 3.5.3(iii) $q = m*cp*\Delta T$

where

q = thermal energy/Heat

m = mass

cp = specific heat capacity

ΔT = change in Temperature

This was then compared to the necessary heat required to keep the bioshelter at 50 °F, which was found to be around 92,000 BTUs (United Fireplace and Stove, 2012). Therefore, in order to completely heat the bioshelter strictly using standard composting means, around 5470 pounds of compost would be needed. This is an enormous amount of compost and could never be arranged into a 20 x 40 foot bioshelter.

However, to efficiently utilize the heat-generating capabilities of the compost, it was proposed to place four 2 feet wide by 3 feet long by 2 feet deep bins in the bioshelter. These raised compost bins will house red wiggler worms in them. Red wiggler worms eat the raw materials and help create nutrient-rich compost for the raised beds. Therefore, the compost will help moderate temperatures in the bioshelter and will also be placed in a convenient location where it could easily be moved into raised beds when needed (Montana Wildlife Gardener, 2009).

As mentioned above, the heat from compost storage would not be enough to keep plants alive in the winter. Many different heating sources were investigated, and a Jean Pain Mound was determined as the most appropriate choice for the bioshelter. The heat from the Jean Pain Mound, which is generated through the process of decomposition of the woodchips, is transported to the bioshelter via water flowing through pipes, which is then used to provide radiant floor heating to the bioshelter.

q = m*cp*ΔT	This equation assumes a process at constant pressure			
	with a constant specific heat capacity. This assumption			
	is valid for the relatively small changes in pressure and			
	temperature associated with composting			
q	Heat Produced by Compost Pile	kg		
m	Mass	kJ		
cp	Specific Heat at a constant pressure	kJ/(kg*K)		
ΔT	Change in Temperature	K		
m	50 kg (110 lbs)			
Ti(T inside Compost Pile)	311 K (100 degree F)			
To (T in Bioshelter)	294 K (70 degree F)			
Material	**% Present**	**cp**	**% Present * cp**	**Overall cp**
Water	30%	4.184	1.2552	
Newspaper	10%	1.336	0.1336	
Fruit Waste	10%	1.5324	0.15324	2.30204
Hay	50%	1.52	0.76	
q = m*cp*ΔT	q = (50 kg)(2.30204 kJ/(kg*K))(17 K)	**q = 1956.734 kJ**	Heat Produced by the compost pile	
		(1855 BTU)	at any one time	
Mixture Moisture Content	43.10%			

Figure 3.5.3(b) Heating Calculations

Process and Heating Output of the Jean Pain Mound

The Jean Pain Mound was designed to produce an output of 10,000 BTU/hr via hot-water production with a temperature range of 110 to 130 °F, continuously from late October to the end of April (Compost Power, 2011). This would successfully keep the bioshelter adequately warm in the winter. The plan is to supply a storage tank with enough water to provide the radiant floor heating system with sufficient heated water the heat the raised beds. The radiant floor heating system consists of a loop of piping connecting both storage tanks and a simple circulation pump (Taco 1/4-horsepower) which will be used to move hot water from one of the tanks. The pipes will be laid under the bioshelter in a way to allow for the maximum amount of radiant heat to be obtained (Brown, 2014). This process may be seen in the AutoCAD drawings in Appendix F.

It was deemed necessary that a trial Jean Pain Mound be built. The trial mound will test the concept and serve to make sure temperatures obtained from the mound are satisfactory. A detailed plan to build the trial mound was made and will be carried out in the fall by Worcester Common Ground (Appendix E). Woodchips (the feedstock for the mound) were obtained from the City of Worcester, free of charge. The woodchips were delivered to the site in early April and the footprint of the outer diameter of the mound was measured and marked by a 12 foot diameter circle. The lot was also staked out to provide WCG with a realistic idea of the layout of the bioshelter and its surrounding elements. A picture of the delivered woodchips on the lot is shown in Figure 3.5.3(c). The mound will be 12 feet in diameter, 8 feet high, and utilize 40 cubic yards of material. The plan in the fall is to thoroughly soak the compost mixture (around 1000 gallons of water needs to be used) and compile it in the marked out portion of the lot. The outer 12 inches of material will then be packed down manually by the team. After the building process is complete, temperatures and moisture content need to be measured daily over two weeks by a compost thermometer (Brown, 2014). After the two week period is over, the woodchips will then be spread out over the lot as mulch. The best case scenario is that, temperatures inside the mound will allow for the actual building of the Jean Pain Mound to be built when the bioshelter is fully constructed.

Figure 3.5.3(c) 7,9 Jaques Avenue (Fuller, 2015)

The materials used in the construction of the actual Jean Pain Mound will be the same as those used in the trial one. The only exception is that mulch and sawdust will be incorporated into the feedstock to obtain a greater temperature profile. The size will also be kept consistent. The steps for laying the pipes inside the mound and the overall process of building the mound may be seen in the Appendix G. An example of the construction of a Jean Pain Mound is shown in Figure 3.5.3(d).

Figure 3.5.3(d) Jean Pain Mound Details (Compost Power, 2011)

The design of the system includes 100 feet of 4-inch corrugated drainage pipe for aeration. This will be placed in a concentric 10-foot diameter circle with one ending terminating in the center and the other end beyond the footprint of the mound so air can enter. 900 feet of 1-inch polyethylene tubing, purchased in 300 foot sections for compost heat exchange loops and supply/return lines, will then be laid out over 7 layers in a 10-foot diameter circle. 50 hay bales on the vertical side walls will allow for large amounts of heat exchange and enhanced passive aeration. An additional 1/8 hp circulation pump is needed to move water from the storage tank through the compost heat-exchanger loop (Brown, 2014).

The cost of building such a system is expected to be approximately $2500 in the first year. This cost covers all materials and labor. Due to the fact that the mound will be used only in the winter, it will need to be taken down and rebuilt every year. However, the cost of rebuilding the mound will only be around $300 per year because all of the expensive components will have already been purchased. The Jean Pain Mound is an effective solution to supplying the necessary heating needed by the bioshelter in the winter.

City Hall Meeting

In order to obtain proper approval for the building of the bioshelter and the Jean Pain Mound, a meeting with the City of Worcester was set up for the first week of February, 2015. An Interdepartmental Review Team Meeting was held with representatives from the Building, Zoning, Land Use, and Planning Departments. The Chief of the Worcester Fire Department was also in attendance for the meeting. The team prepared a presentation outlining the details of the Bioshelter IQP. The building process of the bioshelter and Jean Pain Mound were explained, along with any possible safety concerns. After the presentation, the IRT Board offered their comments on the project. Their main concerns were in regards to the Jean Pain Mound, and the possibility of undesirable odors and potential fire hazards. Nuisance ordinances dictate that there must be no complaints about odor and that the Jean Pain Mound must remain below temperatures of 150 °F. The Board was assured that these would be non-issues and that the Mound would be built correctly.

The IRT Board also mentioned that because the site was in a residential zone, the bioshelter would have to qualify as an educational site. If approval for this is not granted, a different location will have to be used. However, they told the team that a zoning ordinance is currently being written to allow for agricultural structures to be built in residential zones, and that it may be implemented as early as the fall of 2015.

The sponsor of this project, Worcester Common Ground, contacted the Building Commissioner for the City of Worcester approximately a week after the IRT Meeting. He explained that if WPI, Ascentria Care Alliance, Chandler Elementary School, and the local YMCA can provide a letter that the site qualifies as a teaching facility, then the project may move forward. The Dover Amendment, a Massachusetts law exempting certain agricultural structures from zoning laws (The Commonwealth of Massachusetts, 2015), could help with gaining approval. The building of the trial Jean Pain was also approved. However, the city needs to do further research to give full approval of a Jean Pain Mound system with piping running through it.

3.5.4 Heat retention

Thermal Mass

Along with generating and capturing energy from solar and compost, storing energy is important to maintain the bioshelter at a stable temperature. Thermal mass, or a heat sink, is vital to maintaining the bioshelters temperature that is done by capturing heat energy during the day or warmer periods and releasing it at night or during colder periods. Using the best materials possible is important as it will allow the maximum amount of energy to be captured and stored. There are two main systems for heat storage; heat sinks and a climate battery. Both have been implemented into the bioshelter design.

Water/Stone Heat Sinks

In order for Heat Sinks to be effective, they should have a high heat capacity, be cost effective and be accessible. From table 2.4.2(a) in the background section, is seen that water and concrete are the most effective heat sinks. Water is very easy to obtain, has a high heat capacity and is cheap (or free with a rainwater catchment system). The only negative aspect of water is that it will release heat quickly, compared to other heat sink materials. Stone absorbs and releases heat slower, which will allow the bioshelter to stay warm for a longer period of time. Due to the many roles that water will fulfil in the bioshelter, water was designated to be the main heat sink material, with stone being secondary. Water will be stored in two 800 gallons water collection tanks as well as two 400 gallon tanks that will contain aquaponics. Stone will be used a flooring through the bioshelter.

Determining Water Heat Sink Temperature

Placement of the heat sinks is important in regards to the amount of energy that can be captured. The quantity of solar energy captured by the heat sinks will depend on the bioshelter's heat transfer properties. A MS Excel heat transfer calculator was used to determine the temperature of the heat sinks from solar energy alone, depending on the condition of the day. The heat transfer calculator was designed from basic heat transfer equations for conduction and radiation, ignoring convection; as well as assumptions, such as an ideal world, for simplicity. It is split up into 4 main groups: bioshelter energy gained from the sun, the temperature of the bioshelter from conduction alone, the tank energy gained from the sun, and the tank's energy gained from conduction alone. Ignoring convection does make the calculator a lot less accurate, but producing a calculator that contains every aspect of heat transfer is very difficult, as every phenomenon interacts and depends on each other continuously. During the winter, it was assumed that the inside of the bioshelter will always be warmer than the outside.

To calculate the amount of energy the thermal mass will absorb throughout the year, a MS Excel heat transfer calculator was built using basic heat transfer equations and simplifying assumptions. To use the calculator, a specific day and time is needed. In order to test the calculator, a day was created with certain conditions, which is explained throughout the paper. The calculator was broken into four parts.

The first part of the calculator determines the amount of radiation, depending on the day's conditions, that hit the bioshelter. The sun's radiation is 1360 W/m^2 on a clear day (Stewart, 2015). During a day with scattered clouds, broken clouds or an overcast day, the percent of transmission entering the atmosphere is 89,73 and 32 %, respectively (Schoonmaker, 2015). Table 3.5.4 (a) shows the amount of sun energy clouds allow through. To calculate the amount of radiation that hits the bioshelter, Equation 3.5.4 (i) was used.

Equation 3.5.4 (i) $SR * \%T = Qrad_{clouds}$

where

SR = Suns radiation on a clear day (1360 W/m^2)

%T = Percentage of transmission

$Qrad_{clouds}$ = Radiation Energy transmitted from sun (BTU)

The angle of the sun's radiation on the window affects the amount of energy transmitted into the bioshelter, which will change throughout the day. Table 3.5.4 (b) shows the percentage which is transmitted into the bioshelter depending on the angle (Mazria, 1979). This is calculated with Equation 3.5.4 (ii).

Equation 3.5.4 (ii) $Qrad_{cloud} * \%R = Qrad_{window}$

where

$Qrad_{clouds}$ = Radiation Energy transmitted through clouds

%R = Percentage of Radiation

$Qrad_{window}$ = Radiation Energy transmitted through windows

Using the transmission, reflection and absorption values of the glass, the amount of radiation transmitted and absorbed by the bioshelter can be calculated. The sum of the transmission, reflection and absorption values must be equal to one, resulting in the three equations (shown below) for transmission, reflection and absorption, respectively.

Equation 3.5.4 (iii) $Qrad_{window} * gt = QW_{transmission}$

Equation 3.5.4 (vi) $Qrad_{window} * gr = QW_{reflection}$

Equation 3.5.4 (v) $Qrad_{window} * ga = QW_{absorption}$

where

$Qrad_{window}$ = Radiation Energy transmitted through windows

gt = glass transmission

gr = glass reflection

ga= glass absorption

$QW_{transmission}$ = Energy transmitted through window

$QW_{reflection}$ = Energy reflection from window

$QW_{absorption}$ = Energy absorbed into window

Table 3.5.4 (a) Amount of energy clouds allow through

Q radiation atmosphere (w/m2)	Percentage of Transmittion	1360
No Clouds N Assume 100%	1	1360
Scattered Clouds S	0.89	1210.4
Broken Clouds B	0.73	883.592
Overcast O	0.32	282.74944

Table 3.5.4 (b) Percentage of energy dependent on the angle of the sun

Angle of Sun	Percentage of energy	Angle of Sun	Percentage of energy
0	100	50	64.3
5	99.6	55	57.4
10	98.5	60	50
15	96.5	65	42.3
20	94	70	34.2
25	90.6	75	25.8
30	86.6	80	17.4
35	81.9	85	8.7
40	76.6	90	0
45	70.7		

Using Equation 3.5.4 (iii) and the given data for the example day, glass transmission value of 0.6, No cloud cover, the sun is perpendicular to the bioshelters window (%T = 1), the amount of solar energy transmitted into the bioshelter is 816 W/m^2. These values are shown in table 3.5.4 (c).

Table 3.5.4(c) Part one of the calculator for a sample hour of the day

	Day 1
Time of day (9am-3pm)	9am
Q in from sun	
Cloud Level	N
Q radition-sun (after cloud level)	1360
Percentage of energy from sun angle	1
Q radition-sun (after Sun angle)	1360
Value of Glass transmittion	0.6
Q radition transmitted from sun	816
Value of Glass reflection	0.2
Q radition reflected from sun	272
Value of Glass absorption	0.2
Q raditionabsorped from sun	272

The second part of the calculator uses the amount of energy from the sun via transmission into the bioshelter and calculates the temperature inside the bioshelter. Using the conduction phenomenon equation, shown below, the inside temperature is found.

Equation 3.5.4 (vi) $QW_{transmission} = K_{window}*A_{window}*(Tin-Tout)/L$

where

$QW_{transmission}$ = Energy transmitted through window

K_{window} = Windows thermal conductivity

A_{window} = Window Area

T_{in} = Temperature inside the bioshelter

T_{out} = Temperature outside the bioshelter

L = Thickness of Window

Part two determines amount of energy from the sun via transmission and calculates the temperature inside the bioshelter. On the given day, the outside temperature is 10°C, the windows thermal conductivity (k) value, thickness and window area are 5, 0.05m and 679ft^2 respectively. Using Equation 3.5.4 (vi), the data found from part 1 and the information given above, the temperature inside the bioshelter was found to be 10.46 °C. This data can be seen in table 3.5.4 (d).

Table 3.5.4 (d) Part two of the calculator for a sample hour of the day

Temperature inside Bioshelter	
Energy Transmitted into the bioshelter (Q)	816
Energy Transmitted into bioshelter (KJ/hour)	2937.6
K value of window	5
Window thickness (m)	0.05
Toutside C	10
Tinside C	10.465701
Area of window (ft2)	679
ft^2 to meter^2	0.0929
Area of window (m2)	63.0791

The third part uses the transmission energy of the window and calculates the amount of energy that is absorbed, reflected and transmitted into the water tank. Similar to the equations above, the values for transmission, reflection and absorption of the water container were calculated from the following equations.

Equation 3.5.4 (vii) $QW_{transmission} * ct = QC_{transmission}$

Equation 3.5.4 (viii) - $QW_{transmission} * cr = QC_{reflection}$

Equation 3.5.4 (ix) - $QW_{transmission} * ca = QC_{absorption}$

where

$QW_{transmission}$ = Energy transmitted through window

ct = container transmission

cr = container reflection

ca= container absorption

$QC_{transmission}$ = Energy transmitted through container

$QC_{reflection}$ = Energy reflection from container

$QC_{absorption}$ = Energy absorbed into container

Given that the container's transmission value is 0.2, using the solar radiation transmitted into the bioshelter and equation 3.5.4 (vii), the solar radiation transmitted into the container is 588kJ/hour. These calculations are shown on table 3.5.4 (e).

Table 3.5.4 (e) Part three of the calculator for a sample hour of the day

Tank Info	
Q in from sun (KJ/hour)	2937.6
Value of Container transmittion	0.2
Q radition transmitted from sun	587.52
Value of Container reflection	0.5
Q radition reflected from sun	1468.8
Value of Container absorption	0.3
Q raditionabsorped from sun	881.28

The final part calculates the temperature of the water. Using Equation 3.5.4 (vi) over the container, the temperature of the water inside the container can be found for every hour of the day, shown in equation 3.5.4(x).

Equation 3.5.4(x) $QC_{transmission} = K_{container} * A_{container} * (Tin-Tout)/L_{container}$

$QC_{transmission}$ = Energy transmitted through container

$K_{container}$ = Container thermal conductivity

$A_{container}$ = Container Area

T_{in} = Temperature In

T_{out} = Temperature Out

$L_{container}$ = Thickness of Container

The calculated temperature of water, in theory, should be a lot higher than this value because of the missing convection properties.

Using the calculated outside temperature of 10.465 °C, given container thickness, area and thermal conductivity (k) which are 0.05m, 240ft^2 and 5 respectively and using equation 3.5.4(x), the temperature of the water can be found. During this hour of the day, the water's temperature will increase from 10°C to 10.49 °C. These calculations are shown in table 3.5.4(f) and shows that heat energy will be stored during the day and will stabilize the temperature of the bioshelter. When the air temperature inside the bioshelter drops during the night, reverse conduction occurs, transferring heat energy back into the bioshelter. This will keep the bioshelter warmer during the winter. Although the actual temperature increase inside the bioshelter is unknown (because of the dependence on outside temperature, amount of sunlight etc.), thermal mass will increases the bioshelters inside temperature during the winter.

Table 3.5.4(f) Part four of the calculator for a sample hour of the day

Temperature inside tank	
Energy Transmitted into bioshelter (KJ/hour)	587.52
K value of tank	5
tank thickness (m)	0.05
Toutside C	10.465701
Tinside C	10.490181
Area of tank 1 side (ft2)	40
Area of tank 6 sides (ft2)	240
Area of tank (m2)	22.296

Climate battery

A climate battery is a system that operates by utilizing the earth's constant temperature and helps maintain the temperature inside the bioshelter (Savage, 2014). A climate battery will be implemented by using soil and stone as the heat sink. A local bioshelter in Greenfield MA that utilizes a climate battery system was visited in order to evaluate its capacity to improve temperature stability. Instead of using the climate battery to store energy during day and release it at night, this bioshelter used it to keep the soil in the raised bed at a higher temperature. The stored energy, from the climate battery, is kept below the raised bed and slowly radiates up through the soil. To test if this climate battery is working correctly, two temperature probes were placed throughout the system, one at the inlet of the system and the other at the outlet. Data was taken on several different days during the winter months, in which the inside temperature of the bioshelter had to be above 70° F. From the inlet and outlet air temperatures, the amount of energy stored underneath the raised bed was calculated from Equation 3.5.4(xi).

3.5.4(xi) $q = m*cp*\Delta T$

where

q = thermal energy/Heat

m = mass

cp = specific heat capacity

ΔT = change in Temperature

The amount of energy stored underground, by using the climate battery, can be calculated by using Equation 3.5.4(xi). Table 3.5.4(g) was created, which shows the inlet and outlet temperature and how much energy is stored underneath the raised bed per hour of running the climate battery. The table shows that when the temperature inside the bioshelter is over 70° F, energy is stored underneath the raised beds. It also shows that if the inlet temperature of the bioshelter is below 70° F, heat is not stored, and in some cases, energy is pumped back into the bioshelter. In order to make sure the climate battery is working to its maximum potential in our bioshelter design, temperature sensors will be installed. This will allow the air pump to turn on the automatically once the temperature reaches 70° F and turns off when it is below 70° F. Instead of running the climate battery when the bioshelter drops below a certain temperature, the heat, stored under the raised beds, will be left to radiate up through the soil. This was decided upon the reasoning that during the coldest days, it may not be possible to keep the entire bioshelter above 32° F. If the heat is left to radiate up through the soil, row covers can be used to keep the heat energy trapped in the plants confined area, maximizing the use of the climate battery.

Table 3.5.4(g) Table of data taken from Greenfield bioshelter and amount of energy stored under (Engineering ToolBox, 2015)

Date	Time of day	Notes	Water temperature degrees F	Days Temperature (Outside oF)	Air Temperature inside degrees F	Air Temperature Outside degrees F	Energy Stored flow rate 1 (BTU/h)	Energy Stored flow rate 2 (BTU/h)
12/25/2014	1pm	Overcast	48	47.8	57.2	60.1	-3.19	-5.41
12/26/2014	1.30pm	Sunny warm day	51	45.5	76.5	57.8	20.59	34.87
12/27/2014	2.30pm	Sunny warm day	51		77.7	55.3	24.67	41.77
12/31/2014	7am		47	8	34.9	33.1	1.98	3.36
1/2/2015				53	57.2	57.9	-0.77	-1.31
1/7/2015			38	2	38.8	38.1	0.77	1.31
1/8/2015	10am	minus 8 overnight (2 heaters on)	40		52	56.7	-5.18	-8.76

Mass of Air per hour 1 (lb/h)	Mass of Air per hour 2 (lb/h)	Flow rate 1 of climate battery (ft3/h)	Flow rate 2 of climate battery (ft3/h)	Heat Capacity of Air (BTU/lbm degree F)	Density of air (slugs/ft3)	Density of air (lbm/ft3)
4.59	7.77	62	105	0.24	0.0023	0.0740002

Row Covers

A conventional way of trapping heat to maintain plant growth throughout the winter season is through the use of row covers.

The Johnnyseeds website was recommended by the advisors to be an online resource specializing in row covers, so all the row covers available at the Johnnyseeds website were compiled to compare the effectiveness of each. Depending on the type of plants being grown, different row covers may be more appropriate. Table 3.5.4(h) details the different costs, and benefits, of each category of row cover (Johnny's Selected Seeds, 2015).

Table 3.5.4(h) Cost-Benefit Analysis of Johnny Seeds Row Covers

Growing Season Extending Tools							
Category	Dimensions	Price Per Unit	Sq. Yd. Per Unit	Price per Sq. Yd.	Temp. Range	Transparency	Weight
AG-19	30' x 100'	$92.55	333.33	$0.28	28 deg. F	85%	0.55 oz. / sq. yd.
	10' x 1000'	$259.00	1111.11	$0.23			
	10' x 500'	$155.00	555.56	$0.28			
	10' x 250'	$79.95	277.78	$0.29			
	10' x 50'	$31.15	55.56	$0.56			
	83" x 2000'	$342.00	1537.00	$0.22			
	83" x 1500'	$265.00	1152.78	$0.23			
	83" x 1000'	$186.00	768.56	$0.24			
	83" x 500'	$98.25	384.22	$0.26			
	83" x 250'	$49.95	192.11	$0.26			
	83" x 50'	$25.95	38.44	$0.68			
AG-30	14' x 800'	$498.00	1244.44	$0.40	26 deg. F	70%	0.90 oz. / yd.^2
	83" x 800'	$274.00	614.78	$0.45			
	83" x 250'	$114.00	192.11	$0.59			
AG-50	10' x 1500'	$1,100.00	1666.67	$0.66	24 deg. F	50%	1.50 oz. / sq. yd.
	10' x 500'	$379.00	555.56	$0.68			
	83" x 500'	$269.00	384.22	$0.70			
AG-70	26' x 100'	$252.00	288.89	$0.87	< 24 deg. F	30%	2.00 oz. / sq. yd.
	13' x 100'	$129.00	144.44	$0.89			

It is recommended that row covers of type AG-19 are used, at the very least, as these row covers will serve as another effective means of trapping heat during the winter season. The most reasonable dimension for the bioshelter is the 10'x50' selection. Being effective until temperatures of about 28 ^{o}F, only 15% of the sunlight will be lost. However, since using row covers will add a load to the plants they are covering, so wire framing should be used, and the covers should be distributed carefully.

3.5.5 Energy Use Simulation

Energy use simulation can help gaining a general understanding of the amount of energy necessary to heat the bioshelter in winter months. Ecotect Analysis was used in this project to evaluate energy use of the initial design. The results of the simulation helped assessing the effects of thermal mass and evaluate optimal glazing material and area. Glazing serves as a major heat loss factor through conduction in winter and a major heat gain factor through transmission in summer. Therefore, the properties such as SHGC and U-value and coverage area should be carefully chosen.

As a first step, simplified building geometry was created in Ecotect analysis. Previously entered weather files from the solar site analysis were used in order to evaluate the heating load of the bioshelter. While this study's main goal was to evaluate passive solar heat gain, it was also to study the effects of thermal mass in heating load, to study the performance of glazing materials, as well as to study the building geometry. A total of six cases were evaluated:

Bioshelter with R-4 glazing, without significant amount of fenestration in east and west, without thermal mass,

Bioshelter with R-4 glazing, without significant amount of fenestration in east and west, with thermal mass,

Bioshelter with R-2 glazing, without significant amount of fenestration in east and west, without thermal mass,

Bioshelter with R-2 glazing, without significant amount of fenestration in east and west, with thermal mass,

Bioshelter with R-2 glazing, with significant amount of fenestration in east and west, without thermal mass, and

Bioshelter with R-2 glazing, with significant amount of fenestration in east and west, with thermal mass.

Considering case 3 and 4 as the standard scenario, the effects of increased R value of windows and existence of fenestration in east and west sides of the structure were evaluated. In these studies, some information had to be assumed and held as constants: interior temperature is kept at 40F, there's no heat transfer through the floor, and neither amount of thermal mass nor the location of thermal mass were kept constant but not specific to design. The first assumption had to be made because Ecotect analysis calculated heating load assuming that the temperature in winter months must be at least 40F. The second assumption was made as the floor of the bioshelter would be bare soil. Assuming the foundations are well insulated, the soil would serve as a thermal storage and the structure's heat loss through the floor should be insignificant compared to the loss through the walls and roof. Last decision was made as it is difficult to model complicated system such as climate battery in Ecotect. Other conditions that were kept consistent were the date and month of the conducted test (January 1st and the month of January accordingly), orientation of the building (direct south facing), wall and roof materials, etc.

The test results yielded hourly gains graphs shown below (Figure 3.5.5 (a)). Various lines represent various energy sources (above x-axis) and losses (below x-axis). Overall, use of thermal mass increased direct solar energy gain and use of higher-performance window reduced loss through conduction. Table 3.5.5 (a) is the data of the bioshelter energy need for various cases. Based on these calculations, R-4 glazing (U-.25) for the roof glazing without any east and west windows, with thermal mass in the building yields lowest energy use (Figure 3.5.5(b)).

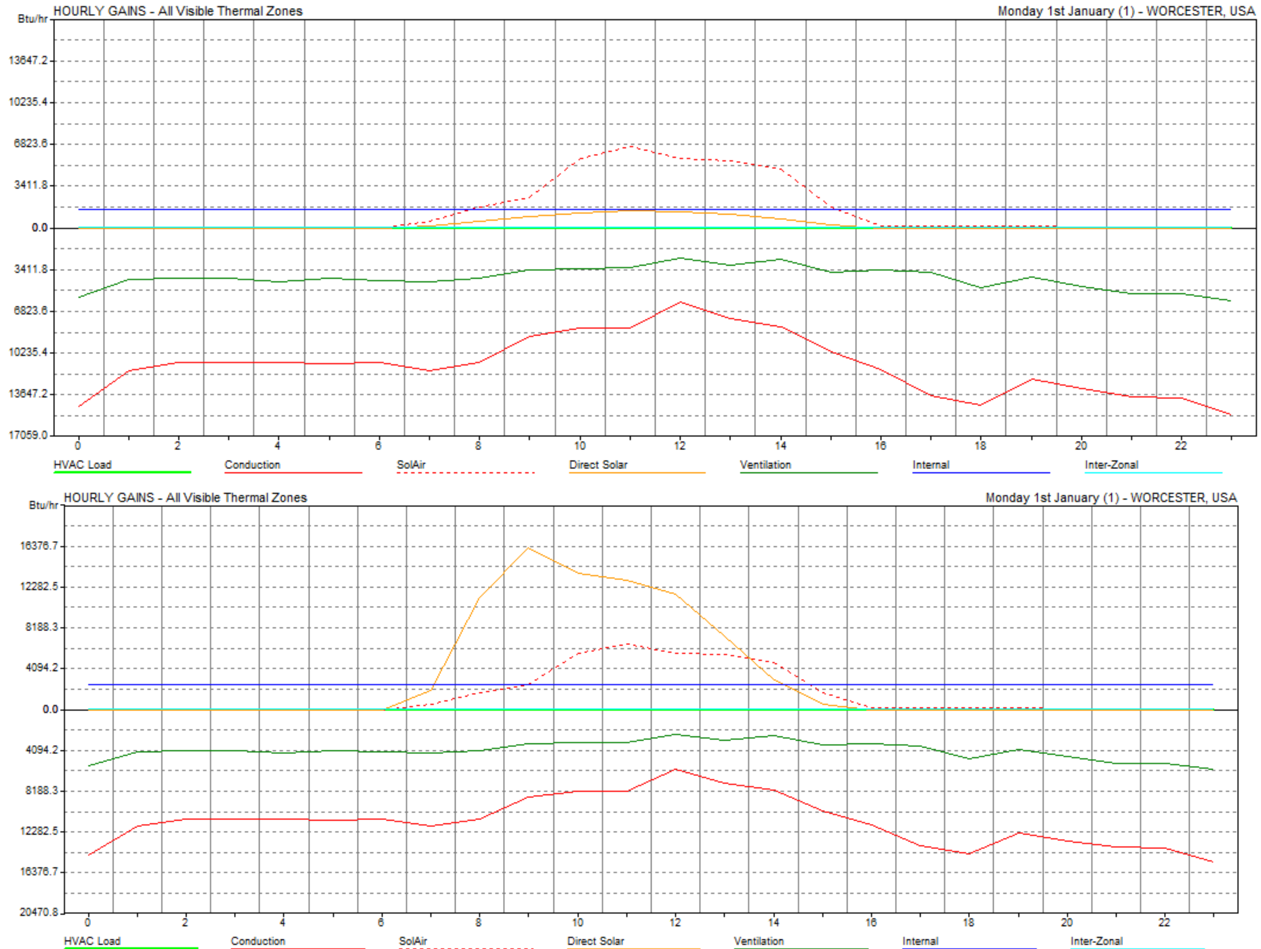


Figure 3.5.5(a) Hourly energy gains and loss graph of Case 1 (top) Case 2 (bottom)

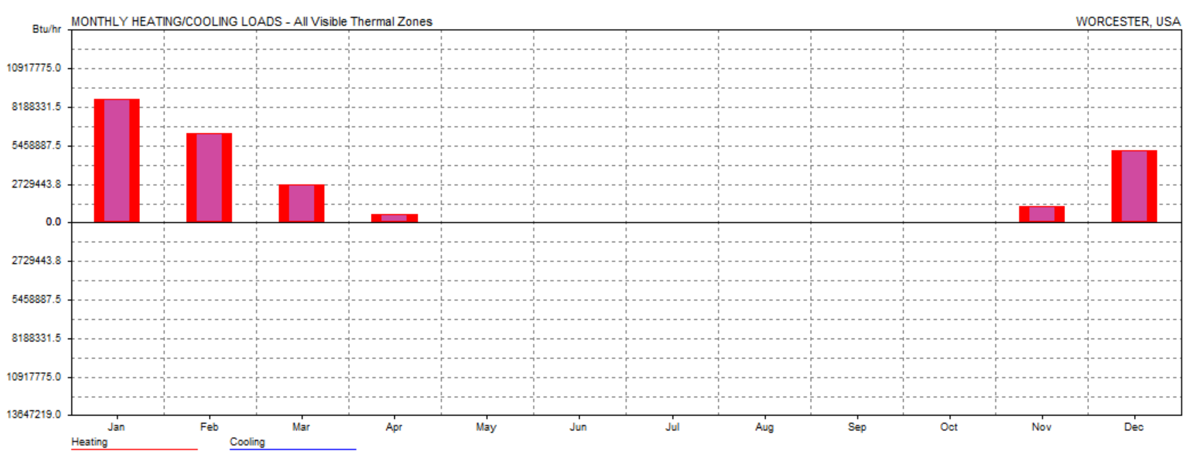


Figure 3.5.5(b) Monthly heating loads of case 2

Table 3.5.5 (a) Energy use in terms of BTUH per month and daily BTUH of the bioshelter for each test case

Thermal mass		Yes	No
R-4 glazing, without E,W windows	BTUH per month	8734219	10462867
	BTUH	11700	14100
R-2 glazing, without E,W windows	BTUH per month	9553053	11372682
	BTUH	12800	15300
R-2 glazing, with E,W windows	BTUH per month	10235414	11941316
	BTUH	13800	16100

The total energy requirement to keep the bioshelter at 40 °F during the winter is 11,700 BTUH. The sizes of the heating systems in the design were selected based off this requirement. It is necessary to make sure that the implemented systems can produce heat to satisfy the needs. From the research performed, a 40 cubic yard Jean Pain Mound produces a heating output of approximately 10,000 BTUH (Brown, 2014). To obtain an accurate heating output of the raised compost bins (48 cubic feet of material, 1.78 cubic yards), a simple calculation had to be performed:

Equation 3.5.5(i) $q(com) = q(JPM)*(d(com)/d(JPM))*(V(com)/V(JPM))$

where

q(com)= Heat produced by Compost Bins

q(JPM)= Heat produced by Jean Pain Mound

d(com)= Density of Materials in Compost Bins

d(JPM)= Density of Materials in Jean Pain Mound

V(com)= Volume of Materials in Compost Bins in cubic yards

V(JPM)= Volume of Materials in Jean Pain Mound in cubic yards

The two numbers that had to be looked up were the densities of the materials for both the compost bins and Jean Pain Mound. The Jean Pain Mound is mostly made up of moist woodchips, which has a density of around 450 pounds/cubic yard (Richard, 2014). Compost has a very high density due to the multitude of materials that make it up and the high levels of moisture content. An approximation for the density was obtained from multiple resources and it is around 1500 pounds/cubic yards.

Plugging in all known values gave an answer of 1700 BTUH produced by the compost bins. Adding this together with the 10,000 BTUH produced by the Jean Pain Mound, gives a total heating output of 11,700 BTUH, which completely satisfies the energy requirement to maintain the bioshelter's temperature at 40 °F.

3.5.6 Power Consumption

Several of the bioshelter's mechanical systems need energy input to function. These include the Jean Pain Mound, the Climate Battery, and the HAF Circulation Fans. Providing the energy to these systems in a sustainable way is another critical goal of the bioshelter.

Solar Panels

The lone source of electricity for the bioshelter will be generated by two photovoltaic cells. A positive net gain was incorporated into the design to account for the possibility of other electronic devices, such as lighting being installed.

Table 3.5.6(a) Power consumption of the bioshelter

	Appliance	Wattage Per Unit	#Units	Total Wattage
Circulation	MegaBreeze 12" HAF Fan	75	2	150
Climate Battery	4 inch in-line fan 165 CFM	113	1	113
	Growbright 4 inch Inline Duct Fan	36	1	36
Jean-Pain Mound	Taco ¼ HP Pump	186	1	186
	Taco ⅛ HP Pump	93	1	93
Consumption				**(-)578**
PV Panels	345W PV module ST Solar STM345-130 monocrystalline	345	2	690

Production	**(+)690**
Net	**(+)112**

As indicated in Table 3.5.6(a), the solar panels are expected to produce enough power to sufficiently power the fans and pumps that are required. The charge controller will prevent overcharging of the batteries, and the inverter will convert the 12V DC output of the controller to 115V AC to power the fans and pumps. If DC is required, the appliance may be directly connected to the charge controller, as 12V is the standard voltage that most appliances using DC should be able to handle. Though the minimum requirement necessary is to have a net power usage of 0 W, the fact that there is a net power gain accounts for the possibility of lights and other miscellaneous appliances being included in the design in the future.

3.6 Designing a prototype bioshelter

To visualize the design of the bioshelter systems, two software systems were used: Autodesk Revit and Autodesk AutoCAD. These software systems are conventionally used in the field of construction. The widespread use of these software systems makes them suitable for creating a blueprint of the project.

Autodesk Revit is a building information modeling software that allows model-based design and construction. Due to its user-friendly interface, exploring a wide variety of systems can be done with relative ease. First, the primary design was created and submitted for review to WCG and Ascentria Care Alliance. After receiving their feedback and studying individual systems that comprise the bioshelter, the design underwent further development. When the final design proposal was approved by the sponsors, the interior layout and the systems were developed.

The building envelope and structure was modeled with the internal layouts in Revit. The aesthetics of the building shell was first determined, and then the building was partitioned off into sections for various uses. The systematic components that were modeled in Revit include: the Jean Pain mound, which sits to the outside of the northern wall, the pergola, located to the west, the three lally columns with two round tables, the rainwater gutter along the roof ledge, the pipework from the gutter to the rainwater barrels, which is located inside the building against the north wall, the aquaponics tanks, the compost bins, and finally the raised beds. By modeling the components into a floorplan, the separate systems can be allocated accordingly, so that they do not overlap. Some of the final renderings of the model are available below (Figure 3.6 (a)). These renderings not only helped us envision the bioshelter, but also contributed in the communication of the design to the sponsors. With the renders of the bioshelter, the sponsors could visualize how the building would appear to the community.

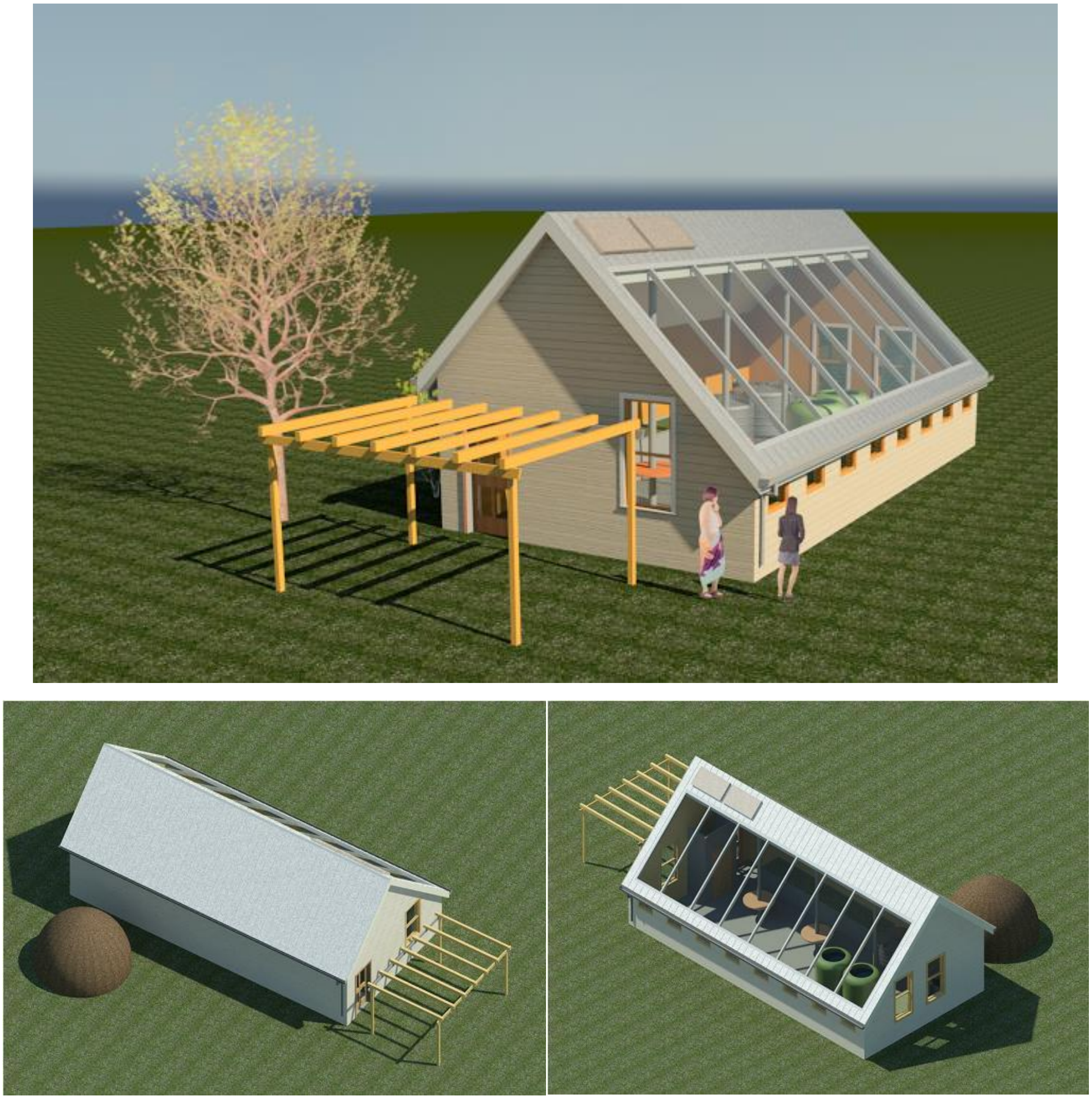


Figure 3.6(a) Renderings of the final design done in Autodesk Revit

After architectural design was finalized with Revit, AutoCAD was used to produce detailed drawings and blueprints. AutoCAD was chosen as it is easier to use than other software, sufficient at modeling in two dimensions, and produces an appealing image. AutoCAD is complicated when it comes to three-dimensional modeling so other software was used instead.

The floor plan (Figure 3.6(b)) shows all the components listed earlier in the Revit model. The climate battery location was added in CAD design to avoid clashing with other components. After floor plan was finalized, the elevations were produced. The elevations (Figure 3.6(c)) detail how the building would appear on the four sides of the building, providing an idea of how the external elements proportionally interact and relate with each other. After the elevations were finalized, the details of the building envelope were determined. The specifics of construction and materials that will be used for the roof, wall, glazing, as well as foundation were determined and recorded using AutoCAD. The following building section (Figure 3.6(d)) detail captures the essence of various features, which will be explained in detail in following paragraphs.

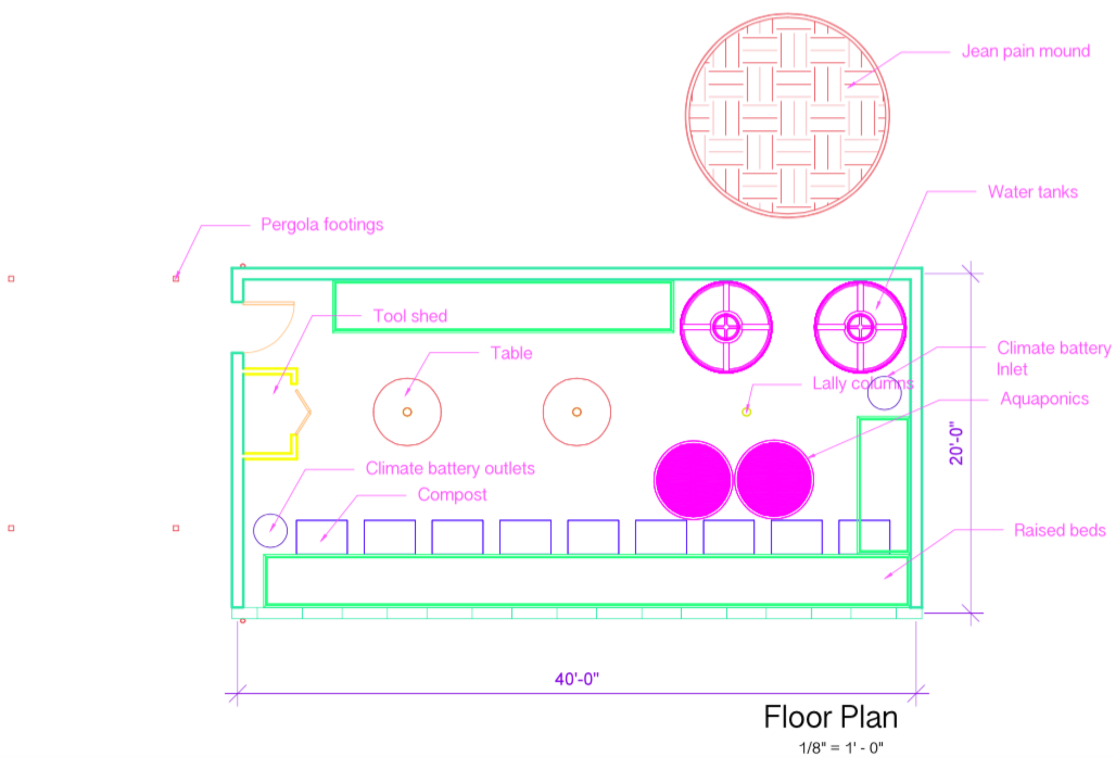


Figure 3.6(b) The floor plan of the bioshelter

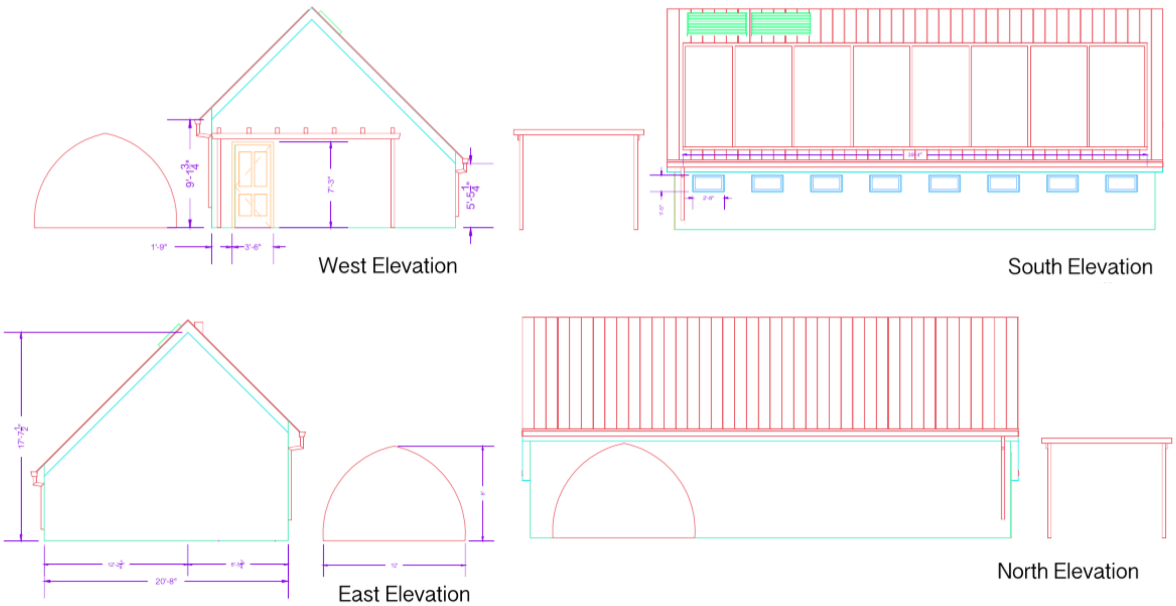


Figure 3.6(c) The elevations of the bioshelter

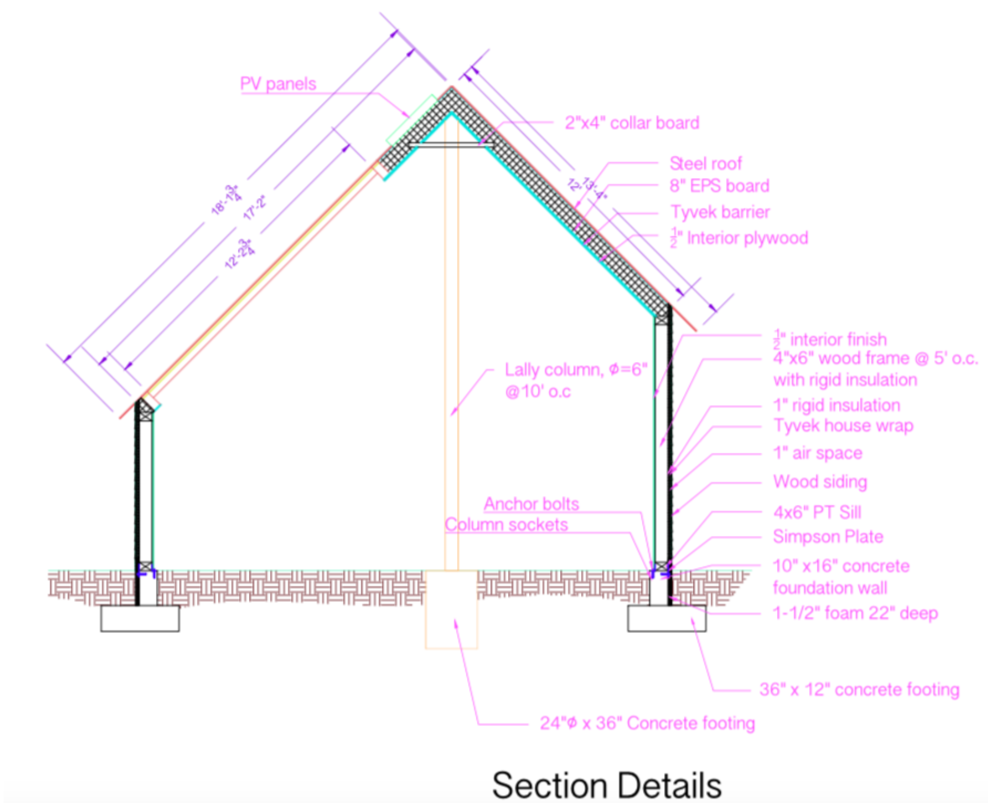


Figure 3.6(d) The section details of the bioshelter

3.6.1 Architectural Drawings

Frame

After comparing materials and consulting the sponsors as well as professionals, wood frame was selected. Though detailed analysis could not be performed such as load calculations, schematic layout of the structural system has been developed (Figure 3.6.1(a) and Figure 3.6.1(b)). Along with the wooden frame, lally columns were placed along the central axis to help support the bioshelter. A key structural component of the bioshelter are the lally columns. A lally column is a support beam, consisting of a steel pipe filled with concrete, and usually serves to provide support between an overhead beam and its footing. Due to the crucial role that lally columns will play in supporting the bioshelter's structure and lack of available resources in regards to obtaining the proper materials, dimensions, and footings of the lally columns, the task of doing so will be delegated to a professional at the appropriate time.

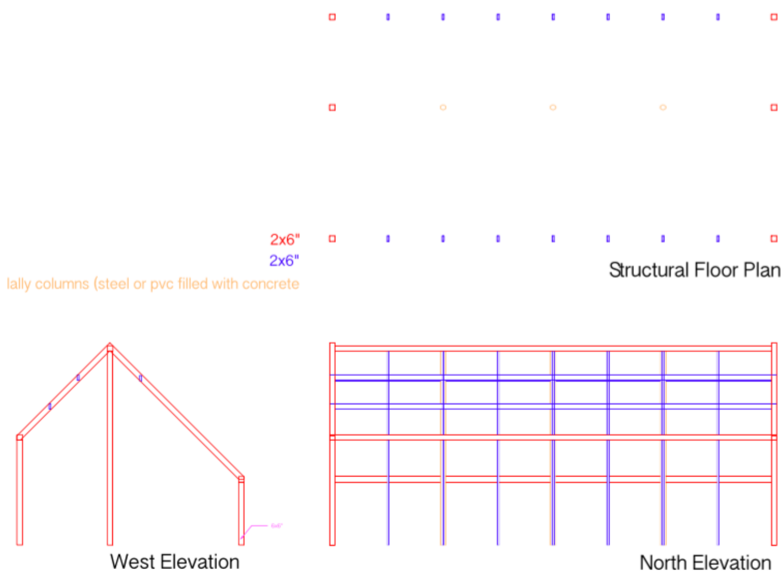


Figure 3.6.1(a) Structural layout of the bioshelter frame

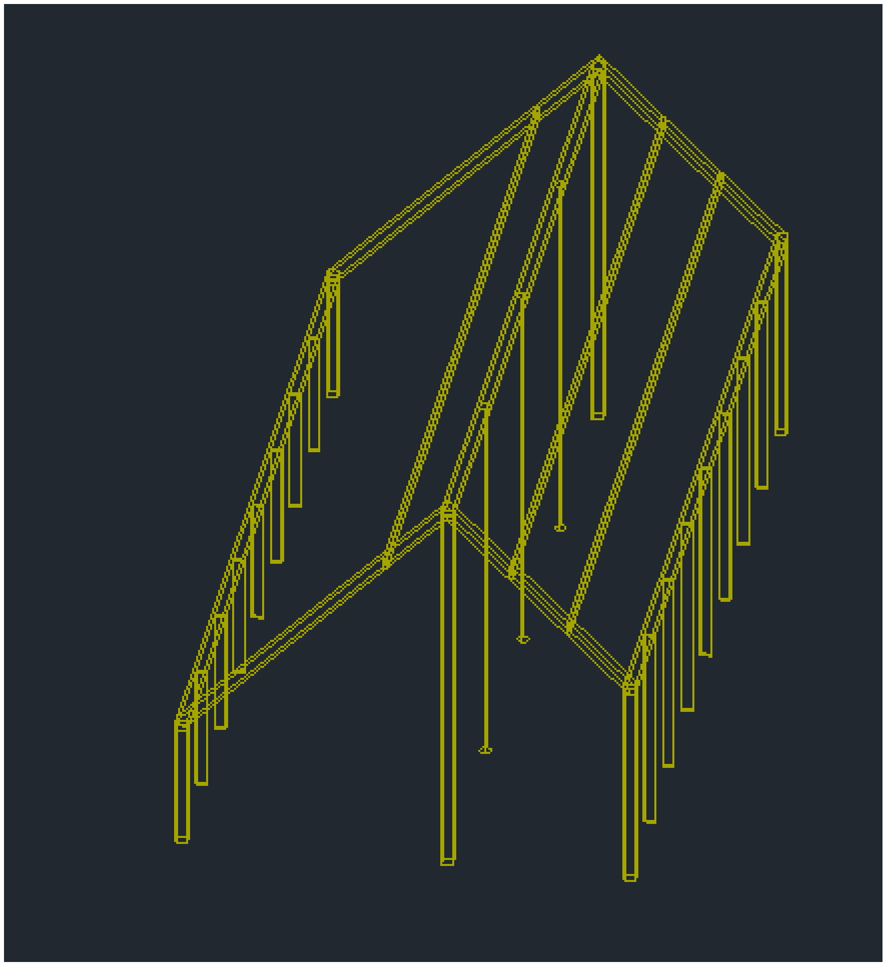


Figure 3.6.1(b) 3D view of the structural layout of the bioshelter

Window

The glazing system directly affects the amount of sunlight transmitted through the bioshelter, which is one of the most precious resources. A comparison chart was created to determine a suitable glazing material for the bioshelter (included in Appendix H). Non-permanent installation of wraps was considered as well as permanent installation of polycarbonates and glass panels. Their R-value, SHGC, pros, and cons were considered to ensure the maximum solar heat gain with minimal heat loss in the winter.

There are total of three types of windows used in the bioshelter. Small operable windows and curtain wall on South facade as well as larger operable windows located in East and West side. The location of the 17”x32” windows in southern facade (Figure 3.6.1(c)), shown in south elevation (Figure 3.6(c)), were chosen to provide lights to the plants as well as direct access to fresh air in summer.

Furthermore, having the tilted roof glazing start 2 feet from the level of the raised beds (3 feet tall), provides the plants some room to grow before they reach the roof. The windows on the east and western facade were placed for ventilation, which will be illustrated in detail later in this report. These windows are made with glass. As long as the U-value is above average, since the total area of the windows are not significant, the heat loss through them should not be problematic. Lastly, the roof glazing punctured towards southern sky was determined to be made with a layer of polycarbonate with a layer of greenhouse wrap underneath it. This should ensure low U-value (R-4.2, which is U-0.23) that would minimize the heat loss through the surface, while the fenestration maximizes the solar heat gain in winter.

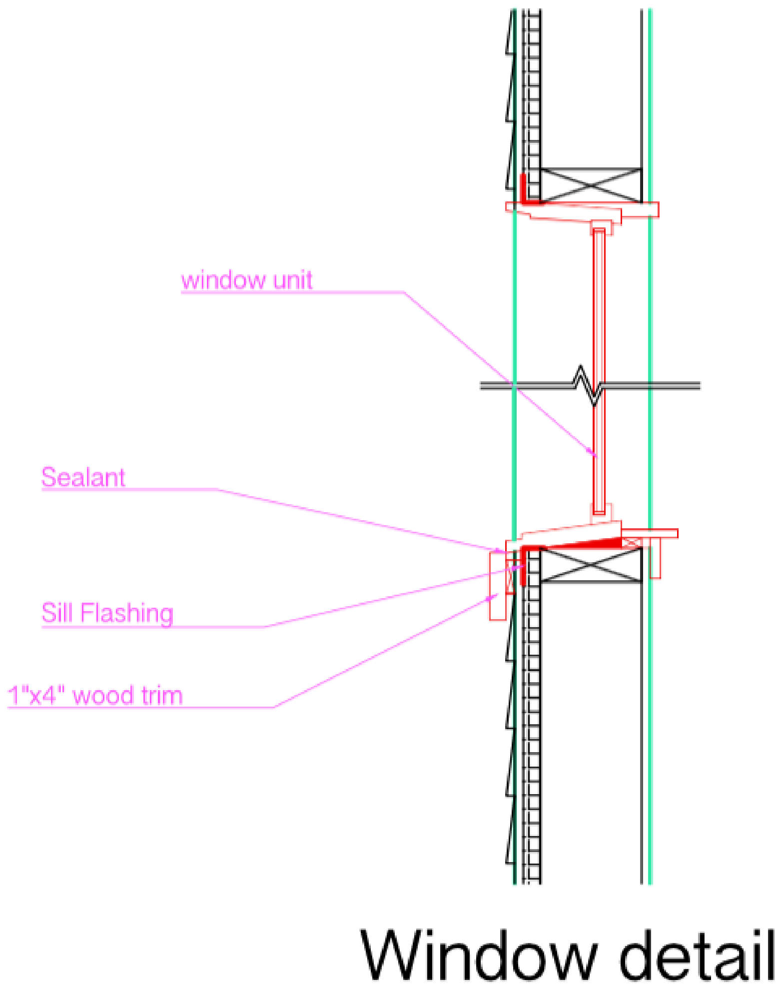


Figure 3.6.1(c) The window detail of the bioshelter

Roof

The roof is composed of the corrugated metal finish, two layers of water resistive 4” rigid insulation board, vapor barrier, and ½” interior plywood finish. To prevent contamination of rainwater, the roof has a corrugated metal finish (Figure 3.6.1(d) and Figure 3.6.1(e)). Due to high R-value (total of R-28) and water resistivity, rigid foam boards were selected. The location of the vapor barrier (to the inside or outside of the insulation board) was contemplated. As the effectivity of the vapor barrier depends on keeping water away from the insulation, whether it should be on top of insulation to keep away rain, or under to prevent condensation was a major issue. A design decision was made that the layer should be under the insulation, since the metal roof is water resistive due to the nature of metal. If installed correctly with sealants, water leak should not be as problematic as condensation; condensation would cause severe damage to the insulation layer, as well as to the wood interior finish.

A few things to consider when selecting insulation are thermal performance, moisture and condensation, lifetime performance, and environmental impacts (Hotel Energy Solutions, 2014). Various types of insulation were considered for the project in order to find an eco-friendly and economic solution that would reduce thermal loss in winter. Conventional insulation materials were studied and charted for the ease of comparison (included in Appendix I). Each material was categorized based on the material (fibrous, granular, foamed insulation) and on the manufacturing process. Characteristics such as R-value, uses, pros, cons, and water resistivity were also recorded.

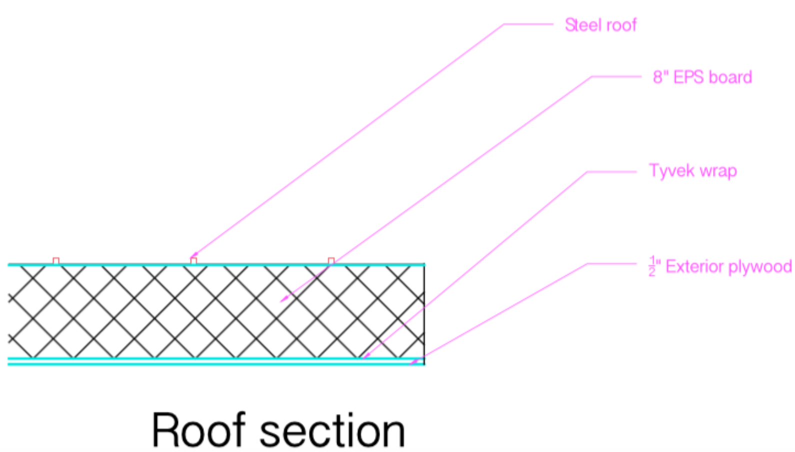


Figure 3.6.1(d) The roof section of the bioshelter

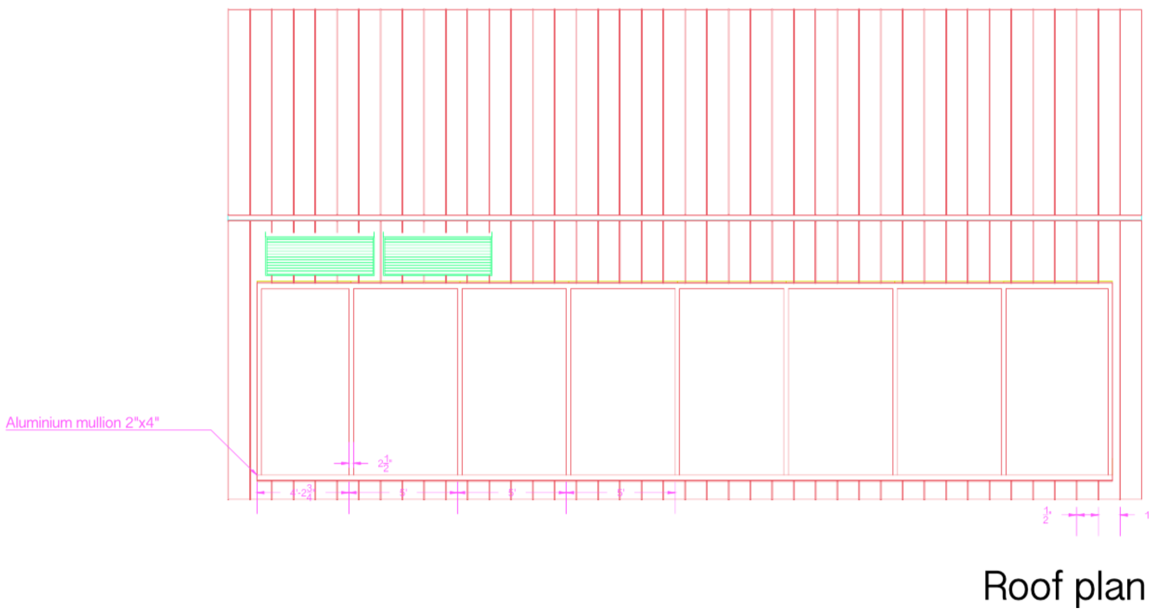


Figure 3.6.1(e) Roof plan of the bioshelter

Wall

The wall is composed with wood frame structure with 4"x6" wood posts. In between the post will be filled with 6" thick rigid insulation (R-22). To the outside of the frame are an additional insulation layer, some air space and wood siding. To the inside of the frame is the vapor barrier, and ½" interior plywood finish. Similar reasoning was used to determine the location of the vapor barrier in the roof was used to determine its location in the wall.

Foundation

The concrete footing is going to be used for foundation around the perimeter of the wall (Figure 3.6.1(f)), as well as under the lally column (Figure 3.6.1(g)), to provide the building structural support. As the climate battery will be located beneath soil, concrete slab is not suitable as an option. Furthermore, having concrete footing foundation would also reduce the construction cost, as it uses fewer materials. The wall should join the concrete footing on pressure treated sill, fastened to the concrete wall through anchor bolts. The concrete slab should be insulated until it joins the exterior foam board insulation on the wall, to reduce heat loss through the conduction through concrete.

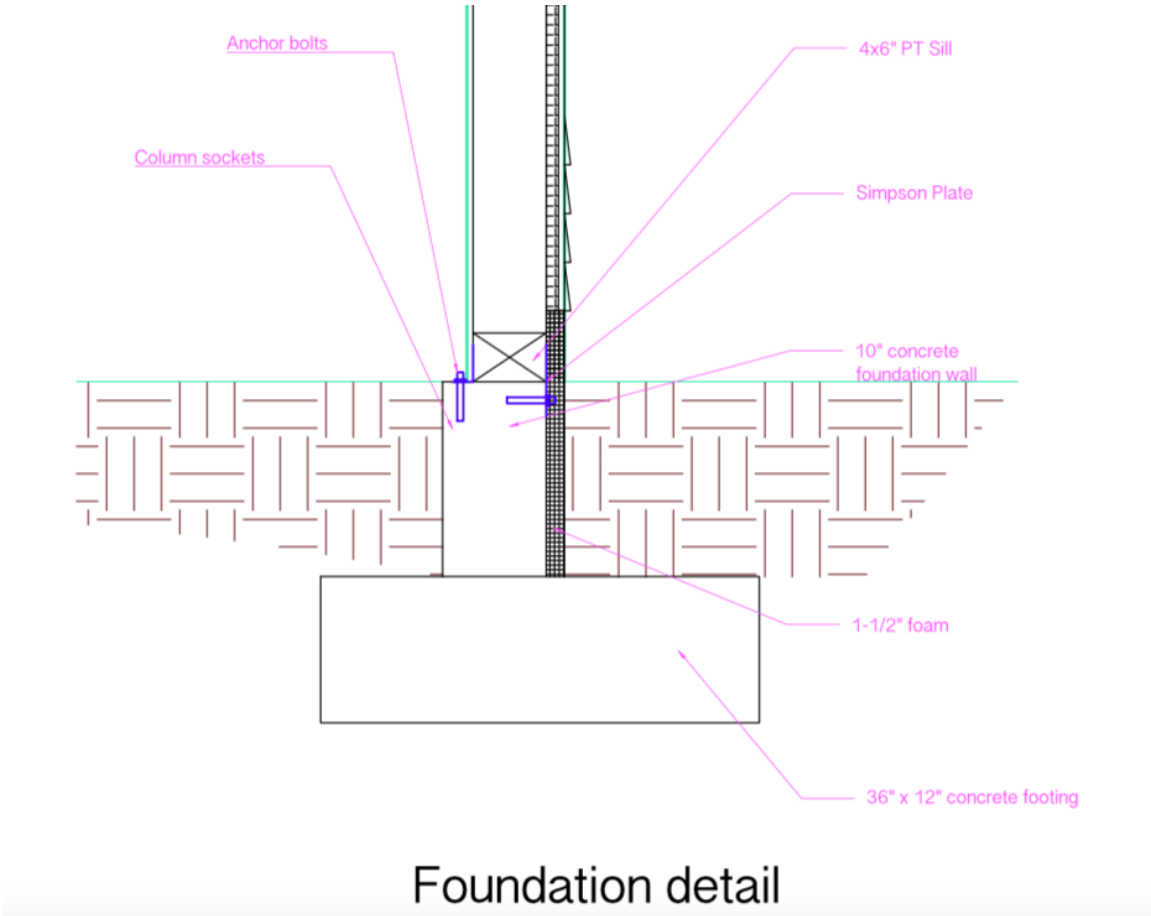


Figure 3.6.1(f) The foundation detail of the bioshelter

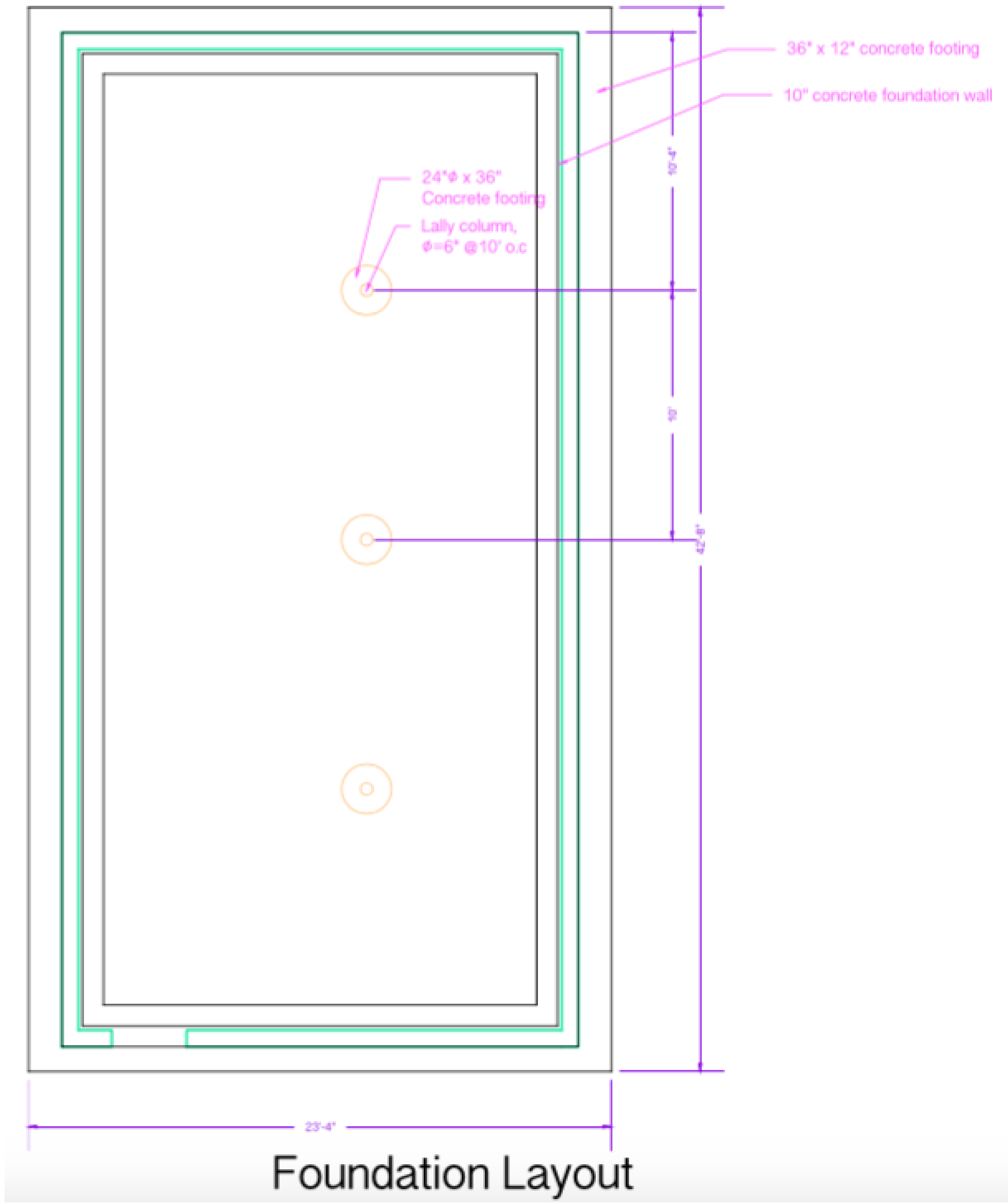


Figure 3.6.1(g) The foundation layout of the bioshelter. The lally columns and its foundation is indicated with orange.

3.6.2 Budget

A budget is one of the most important aspects of the building process. Specifically, in the case of this project, Worcester Common Ground set a target of $70,000 for the building materials of the bioshelter and labor. In order to ensure the bioshelter would not exceed this price, a detailed materials list and cost breakdown was created. The budget can be found in Appendix J. The materials entailed in this budget are new, however some of the materials can be found used at much cheaper prices. Therefore, the actual cost to build the bioshelter will be much less. In total, the cost of materials and labor was calculated to be $60,658.21. This is over $9,000 less than the maximum cost provided by Worcester Common Ground.

4.0 Conclusions

This project worked to create a model for a yearlong sustainable food system, which could exist in both a New England climate and urban environment. In order to realize both of these goals, a basic design and scheme was drawn up for a bioshelter. Although this bioshelter was designed to be built in Worcester on 7 and 9 Jaques Avenue, it can also be used as a general model for future bioshelters in similar environments.

The final design of the bioshelter is composed of three main systems: a rainwater catchment system, a heating system, and the structure itself. The goal of these three systems is to work in concert to reduce or eliminate the need for outside input to maintain the bioshelter.

The first sub system of the bioshelter is the rainwater catchment system. Although the bioshelter tries to eliminate the need for outside resources, a living ecological system cannot exist without a constant supply of water. The rainwater catchment system's goal is balance the input and output of water as well as store excess water for future use.

Heating is another important part of the overall bioshelter. New England's climate is not only known for its cold winter months, but also for its hot and humid summers. In these cases, the bioshelter must be able to both efficiently retain heat throughout the winter months as well as disperse heat during the summer. The heating system of the bioshelter was designed with those two goals in mind.

In the proposed design, there are three main methods to retain and disperse heat: the climate battery, compost, and thermal mass. During the summer months, the goal of the heating system is to cool down the bioshelter to provide the ideal growing conditions for the crops. This is achieved through the help of both the climate battery and thermal mass. Through some calculations that has been done on the exact effects of the climate battery and thermal mass in the bioshelter, reasonable conclusions can be drawn from similar structures, which exist. In these models, the climate battery and thermal mass absorb excess heat and store it to be released during cooler periods.

In addition, the heating system was designed to heat the bioshelter to maintain an internal temperature of 40 °F during the winter months. During these months, the difference in the outside temperature causes heat loss. The heating system equalizes the differences in the flow of energy to maintain an internal constant environment. The design follows a similar approach as the summer months except in reverse, where the heat stored by thermal mass and climate battery during the day is slowly released to account for energy losses in the system during the nighttime. Additionally, composting makes up the remainder of the leftover energy deficit by constantly producing heat from the breakdown of particles.

The final piece of the bioshelter is the structure itself. When designing the structure, the main design goal was heat retention, ventilation, and circulation during the winter months. During the summer months the bioshelter primarily needs to be kept ventilated. This will be accomplished mainly through passive cross ventilation and horizontal airflow, generated by solar powered fans along the top roof framing of the bioshelter. Although this is also a concern during the winter months, the necessity of retaining heat will limit the amount of ventilation that may be achieved during the winter months. The majority of ventilation during the winter months will be through leakage, while an adequate amount of circulation may still be achieved by the solar powered fans.

By integrating multiple systems into the bioshelter, a certain degree of redundancy was built into the bioshelter. This redundancy was based on the assumption of failure. The bioshelter design process and many of the proposed systems within the bioshelter have little actual real life data behind them. Instead, these systems were considered very experimental during the writing of this report. By providing redundancy and backups, even if one system fails the remaining systems can make up for it.

Another important aspects of the project to consider are the social implications. This project worked to create a community gathering space, which would serve as a means for people in the Piedmont area to gather and share cultural traditions and educational knowledge. Worcester Common Ground has undertaken many projects with similar goals, and the bioshelter is just a single example of this. Due to the scope and time constraints of this project, the full effect and potential of this project have yet to be realized. However, it is hoped that through the combined efforts and actions of community development organizations, the City of Worcester, and local Piedmont residents, the bioshelter will be able to strengthen the community, and deliver a lasting positive impact of its own.

5.0 Recommendations

This project will be a good starting point for the eventual building of the bioshelter. This project is the beginning of developing a community asset in a poor neighborhood in Worcester, where land access is limited for farming, soil is contaminated, food insecurity is rising and developing community and social capacity is difficult. We hope that subsequent IQP teams will use and refine our work. Some of these refinements include: researching and designing the ecological system of the bioshelter, building and testing the Jean Pain Mound to determine its effectiveness as a supplementary source of heat, interviewing residents and hosting multiple events to learn more about community perspectives, working with farmers to monitor and assess the functioning of the bioshelter and working with Chandler Elementary School to use the bioshelter as part of their curriculum. Although some research has been done on the types of crops that can potentially be grown in the bioshelter, very little has been done on how the bioshelters systems interact together to form an independent ecosystem. For instance, research can be developed into the aquaponics system and its possible role in the bioshelter.

The Jean Pain Mound was not able to be tested. The best approach to testing the mound's effectiveness is to test it during the winter seasons, in December or January. The Jean Pain Mound should be built and maintained from October to April though it should be noted that colder outdoor temperatures may compromise the ability of the mound to heat up.

Interviews and community events should be held to provide an understanding of how the residents would like to use the space inside the bioshelter. Hosting events that appeal to the Piedmont residents will increase community involvement.

Maintaining the bioshelter assumes that the caretakers have prerequisite knowledge about the system, which they may not have. Creating a user manual for the farmers, who will be the active caretakers, will ensure that the farmers will know the steps necessary to take care of the bioshelter. Different aspects of the bioshelter the user manual should discuss entail: construction and deconstruction of the Jean Pain Mound, maintenance of the rainwater catchment system, maintenance of the radiant floor heating system, an overview of the electrical system, taking care of any new systems introduced, and steps to troubleshooting any of the aforementioned systems.

As the farmers are not native to the community, more thought needs to be put in order for the bioshelter to function smoothly. Having a bioshelter manager that would be able to bridge the gap between the local community and the farmers would facilitate this process. Furthermore, a manager could be used to balance the bioshelter's usage between educational, food production, and social commitments. Since the bioshelter will be used for three different purposes, it is important to plan how the bioshelter can be developed into a community asset. Identifying the social implications of the project will make the bioshelter's importance clearer to the local community. Understanding how the community will want to use the bioshelter is important, as it will be the first step to the community adopting it as their own. Ensuring that the bioshelter becomes a facet of the community that they take pride in, and cherish will not only provide the bioshelter with the community's against vandalism, but will also bring the community together to work towards a common goal.

These suggestions will advance the project into the final stage and allow for the building process to take place starting in the summer of 2016.

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Appendices

Appendix A: Soil test results

UMass Extension

CENTER FOR AGRICULTURE

Soil and Plant Tissue Testing Laboratory
West Experiment Station
682 North Pleasant Street
University of Massachusetts
Amherst, MA 01003
Phone: (413) 545-2311
e-mail: soiltest@umass.edu
website: soiltest.umass.edu

Soil Test Report

Prepared For:
Haley Berube
Worcester Roots Project
5 Pleasant St., Suite #3
Worcester, MA 01603

info@worcesterroots.org
508-343-0035

Sample Information:
Sample ID: WR 38000

Order Number: 3581
Lab Number: S131226-116
Area Sampled:
Received: 12/26/2013
Reported: 1/6/2014

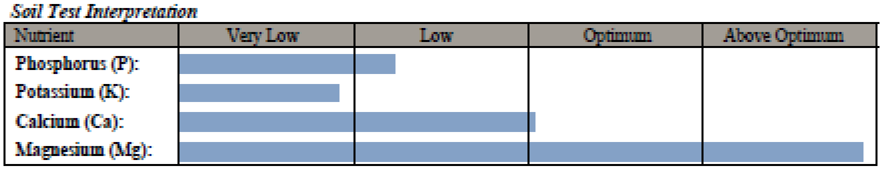
Results

Analysis	*Value Found*	*Optimum Range*
Soil pH (1:1, H2O)	6.4	
Modified Morgan extractable, ppm		
Macronutrients		
Phosphorus (P)	2.4	4-14
Potassium (K)	46	100-160
Calcium (Ca)	1029	1000-1500
Magnesium (Mg)	193	50-120
Sulfur (S)	16.7	>10
Micronutrients *		
Boron	0.2	0.1-0.5
Manganese (Mn)	1.4	1.1-6.3
Zinc (Zn)	33.4	1.0-7.6
Copper (Cu)	1.5	0.3-0.6
Iron (Fe)	4.9	2.7-9.4
Aluminum (Al)	70	<75
Lead (Pb)	61.6	<22

Analysis	*Value Found*	*Optimum Range*
Cation Exch. Capacity, meq/100g	11.3	
Exch. Acidity, meq/100g	4.4	
Base Saturation, %		
Calcium Base Saturation	46	50-80
Magnesium Base Saturation	14	10-30
Potassium Base Saturation	1	2.0-7.0
Scoop Density, g/cc	1.15	

* *Micronutrient deficiencies rarely occur in New England soils; therefore, an Optimum Range has never been defined. Values provided represent the normal range found in soils and are for reference only.*

Soil Test Interpretation



1 of 2 *Sample ID: WR 38000* *Lab Number S131226-116*

UMass Extension

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Sample Information:
Sample ID: WR 38001

Order Number: 3581
Lab Number: S131226-117
Area Sampled:
Received: 12/26/2013
Reported: 1/6/2014

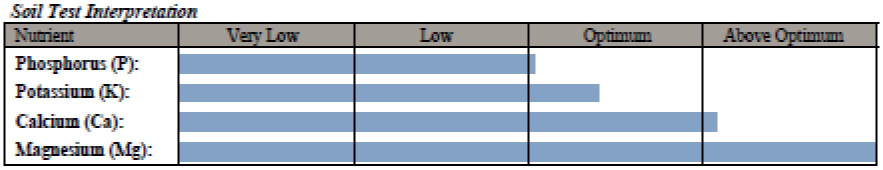
Results

Analysis	*Value Found*	*Optimum Range*
Soil pH (1:1, H2O)	6.4	
Modified Morgan extractable, ppm		
Macronutrients		
Phosphorus (P)	4.5	4-14
Potassium (K)	119	100-160
Calcium (Ca)	1539	1000-1500
Magnesium (Mg)	290	50-120
Sulfur (S)	27.4	>10
Micronutrients *		
Boron	0.4	0.1-0.5
Manganese (Mn)	2.8	1.1-6.3
Zinc (Zn)	11.3	1.0-7.6
Copper (Cu)	1.3	0.3-0.6
Iron (Fe)	5.4	2.7-9.4
Aluminum (Al)	58	<75
Lead (Pb)	53.1	<22

Analysis	*Value Found*	*Optimum Range*
Cation Exch. Capacity, meq/100g	15.7	
Exch. Acidity, meq/100g	5.3	
Base Saturation, %		
Calcium Base Saturation	49	50-80
Magnesium Base Saturation	15	10-30
Potassium Base Saturation	2	2.0-7.0
Scoop Density, g/cc	1.06	

* Micronutrient deficiencies rarely occur in New England soils; therefore, an Optimum Range has never been defined. Values provided represent the normal range found in soils and are for reference only.

Soil Test Interpretation



1 of 2 *Sample ID: WR 38001* *Lab Number S131226-117*

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Sample Information:
Sample ID: WR 38002

Order Number: 3581
Lab Number: S131226-118
Area Sampled:
Received: 12/26/2013
Reported: 1/6/2014

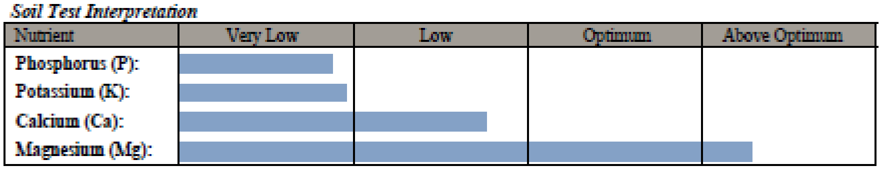
Results

Analysis	*Value Found*	*Optimum Range*
Soil pH (1:1, H2O)	6.7	
Modified Morgan extractable, ppm		
Macronutrients		
Phosphorus (P)	1.7	4-14
Potassium (K)	48	100-160
Calcium (Ca)	880	1000-1500
Magnesium (Mg)	141	50-120
Sulfur (S)	14.8	>10
Micronutrients *		
Boron	0.1	0.1-0.5
Manganese (Mn)	1.0	1.1-6.3
Zinc (Zn)	12.9	1.0-7.6
Copper (Cu)	0.5	0.3-0.6
Iron (Fe)	3.2	2.7-9.4
Aluminum (Al)	56	<75
Lead (Pb)	98.1	<22

Analysis	*Value Found*	*Optimum Range*
Cation Exch. Capacity, meq/100g	9.6	
Exch. Acidity, meq/100g	3.9	
Base Saturation, %		
Calcium Base Saturation	46	50-80
Magnesium Base Saturation	12	10-30
Potassium Base Saturation	1	2.0-7.0
Scoop Density, g/cc	1.21	

* *Micronutrient deficiencies rarely occur in New England soils; therefore, an Optimum Range has never been defined. Values provided represent the normal range found in soils and are for reference only.*

Soil Test Interpretation



1 of 2 *Sample ID: WR 38002* *Lab Number S131226-118*

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e-mail: soiltest@umass.edu
website: soiltest.umass.edu

Recommendations for Crop Code Unknown - Please Specify

Comments:

The lead level in this soil is MEDIUM. See Soil Lead Fact Sheet for more information.
No crop code was received with your submission form, so no lime and fertilizer recommendtions could be made. If you need recommendations, please contact the lab with your lab number, which is located on the upper right corner for your report, and a crop code, found on the second page of the submission form (See References).

References:

Soil Lead: Testing, Interpretation & Recommendations	http://soiltest.umass.edu/fact-sheets/soil-lead-testing-interpretation-recommendations
UMass Soil Lab Submission Forms	http://soiltest.umass.edu/ordering-information

General References:

Interpreting Your Soil Test Results	http://soiltest.umass.edu/fact-sheets/interpreting-your-soil-test-results

2 of 2 ***Sample ID: WR 38002*** ***Lab Number S131226-118***

Appendix B: Existing bioshelter information

					General Information		
Name	Purpose	Organization	Year Built	Designers	Location/Climate	Surrounding Environment	Cost of Constructio
						urban or rural?neighboorhood?	
Cape Cod Ark		New Alchemy Institute	2007	BGHJ PEI, Canada	Hatchville, MA Zone 5		
The Ark		New Alchemy Institute	1976	BGHJ PEI, Canada	Prince Edward Island, Canada		
Pillow Dome		New Alchemy Institute	1982	J. Baldwin	Cape Cod, MA Zone 5		Cheap
Composting Greenhouse		New Alchemy Institute	1984	Bruce Fulford	Cape Cod, MA Zone 5		Cheap
Holyoke Ediable Forest Garden Bioshelter		New Alchemy Institue	2012		Holyoke, MA Zone 5		Cheap
South Burlington Municipal Eco-Machine		Ocean Arks International	1995	Living Technologies Inc. and Dr. John Todd	South Burlington, Vt		
Audubon Society Corkscrew Swamp Sanctuary Eco-Machine		Ocean Arks International	1954	Dr. John Todd and National Audubon Society	Naples, Fla.		less than conventiona technology
The Omega Center for Sustainable Living		Ocean Arks International	2003	*Omega and JTED*	Rinebeck, NY		
Three Sisters Permaculture Design		Three Sisters	1988	The Pennsylvania Energy Office	Mercer County, PA		
Living inside a Bioshelter?					New Hampshire		20000
Paradise Lot		Independant	2013		Holyoke, MA		
Garfield Community Farm		The Open Door Presbyterian Church	2008		Pittsburgh, PA		20000

					Materials							
on	Cost ($/ft^2)	Dimension	Mangagement	Other	Frame	Wall	Roof	Foundation	Glazing	Recycled	Other	Pa
					Steel Frame				triple-layer polycarbonate and thermopane glass			
		5636 sqft		- combines greenhouse, residential house, storage/barn space with solar aquaculture - designed for extreme cold winters and low winter sun angles		standard with 4 in. fiberglass and foam outside	galvanized steel metal over plywood with 0.5- 1ft fiberglass insulation				Shutters under translucent roof	
		30ft diameter			Aluminium tubing	Inflated plastic pillows (3 layers of Tefzel)					Computer modeling showed that insulated reflective structure in north facing wall would help keeping the structure warm	
		400 sqft				double polyethylene			inflated glazing			
						polyethylene plastic film						
				Site served as an educational center for local schools								
nal		70 x 70ft										
					Wood	Wooden frame with glass windows	glass or plastic					
		30' Dome				Wood, Masonry	Glass					
						Plastic	Looks like some kind of plastic					
		26x20 ft			4 by 4 wooden post	8" Concrete Block	10mm Verolite (Polycarbonate)		Glazing with U.V. Inhibtor			

Passive/Active	Energy Source	HVAC (if active)	Lighting	Systems Rainwater	Water	Fire Protection	Running Cost	Other	
Active	Solar energy PV solar panels, solar hot water panels	vents are open in summer, closed in winter, and manually adjusted in spring and fall radiant floor heat in all floors with tubing in cement and bamboo flooring finish. Thermal mass helps keeping the bioshelter warm but at cold nights, it has to be heated.	Passive solar during daylight hours and compact fluorescent light bulbs at night		Rock box chamber used for solar hot water storage				v
Active	Solar storage (30-40 million Btu in winter months) HYDROWIND windplant (25kilowatt) produce about 24 million Btu	active hot air transfer to a rock matrix with back-up wood stove			active solar hot water panels/hot water tanks				:
Passive		Manual operation of pillows for convection venting							r
		Blowers transfer warm moist air through ducts into the soil beds						Manure givves off heat, water vapor, nitrogen gases and carbon dioxide--all essential for plant growth	:
Active	Solar panel								
	Sewage								
	sewage								
Active	Solar panel				domestic wastewater				
Active	Firewood, CO2 recoverd from compost, chickens, Solar pannels		Natural						
Active	Geothermal,	Geothermal, Masonry Heater			Gray water				:
Passive			Natural Lighting						I f
Active	Solar Panels		Natural Lighting	Aluminum Gutters used to harvest water	Harvests it only water				

Vegetation	Fauna	Garden Compost/Fertilizer	Hydroponic?	Aquaponic?	Other	Links
vegetable crops, lemon trees, ornamental plants	Pollinating insects, earthworms, dragonflies ,frogs, diverse insects and toads	Waterless toilet system connected with composting system		solar aquaculture ponds (capture sunlight in daytime and release heat at night)		
Commercial plant-growing area = 1000sqft Resident's interior garden area = 240 sqft Aquaculture facility 40-4ft diameter, 5ft high				Passive solar fish ponds		
Fig tree and raised soil beds for crops				solar fish ponds		
Seedlings (bottom heat and rich air is excellent for sapling growth)		Manure				
Hardy vegetables, subtropical fruits, aquatic greens		Compost earthworms, soldier fly maggots (which are fish food)		fish, fresh water clams, crayfish		
	organisms that metabolized the waste out of water		over 350 species			
typical wetland species			wetlands constructed of 30'x30' plastic lined, artificial marshes fill with crushed limestone			
			aerated aquatic cells		Main use of this buildig is to purify water as a water treatment plant	
Year round organic garden	Chickens	Compost				
Sub tropical, annual veggies, medicinal and tea						
Forty species of fruit and seventy perennials	Poultry		Edible water garden	Under development		
Vegetables, Fruits and Sapplings	Rabbits					

Appendix C: Bioshelter information survey

Gathering Background Information on Other Garden Lots

1) What prompted your organization to get involved in urban food production?
   a) What was the reason for building a bioshelter? (community or commercial)
2) What are your long-term goals for the bioshelter?
3) How close are you to achieving these goals?
4) What is involved in running the bioshelter?
   a) How many staff workers are involved in its maintenance?
   b) Do the seasons affect how often it needs to undergo maintenance?
   c) Do you use fertilizer or produce your own compost?
5) Is your bioshelter active or passive?
   a) What kinds of energy sources are used?
      i) If possible, please describe in detail. (eg what kind of solar panels etc?)
   b) How is your bioshelter ventilated?
   c) How is water (and electricity? Other services? Waste/sewer? Trash collection? Etc.) attained?
   d) How much is the bioshelter's annual upkeep?
6) Construction
7) What were the biggest problems that you overcame during construction?
   a) How did you overcome these problems?
8) What material is your bioshelter made out of?
   a) Frame
   b) Wall
   c) Roof
   d) Foundation
   e) Use of Glazing
9) What are the bioshelter's dimensions?
10) What things would you have wanted to know before starting your bioshelter?
11) Do you regret using the materials you used?
    a) If so, what materials would you have preferred to use?
12) How much did the bioshelter cost to build?

13) What safety measures have been taken with the bioshelter?

   a) How do you discourage vandalism?

   b) Fire safety?

   c) Who to contact in an emergency?

14) Does your bioshelter produce crops all year round?

   a) If not, what period of the year can you produce crops?

   b) What kind of crops do you produce?

15) Does your bioshelter use hydroponics or aquaponics?

16) Does your bioshelter contain animals? What kind of animals?

   a) Do they benefit the bioshelter in any way?

17) Climate

18) What is the weather like?

   a) How hot and cold does it get outside and inside the bioshelter?

   b) Do you collect rainwater for later use? How? (how large is the container)

   c) Do you use snow? How?

Appendix D: Ventilation constants table

Elevation, feet above sea level
TABLE 1

Feet	>1000	1000	2000	3000	4000	5000	6000	7000	8000
F_{Elev}	1.00	1.04	1.08	1.12	1.16	1.20	1.25	1.30	1.36

Maximum interior light intensity, foot-candles
TABLE 2

FC	4000	4500	5000	5500	6000	6500	7000	7500	8000
F_{Light}	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	1.60

Pad-to-fan temperature variation, ΔT °F
TABLE 3

°F	10	9	8	7	6	5	4
F_{Temp}	0.70	0.78	0.88	1.00	1.17	1.40	1.75

Pad-to-fan distance, feet
TABLE 4

F_{VEL}	20	25	30	35	40	45	50	55	60
Feet	2.24	2.00	1.83	1.69	1.58	1.49	1.14	1.35	1.29
F_{VEL}	65	70	75	80	85	90	95	100	
Feet	1.24	1.20	1.15	1.12	1.08	1.05	1.03	1.00	

House temperature above outdoor temperature °F
TABLE 5

°F	18	17	16	15	14	13	12	11	10	9
F_{Winter}	0.83	0.88	0.94	1.00	1.07	1.15	1.25	1.37	1.50	1.67

Appendix E: Trial Jean Pain Mound plan

Project Plan for a Trial Jean Pain Mound

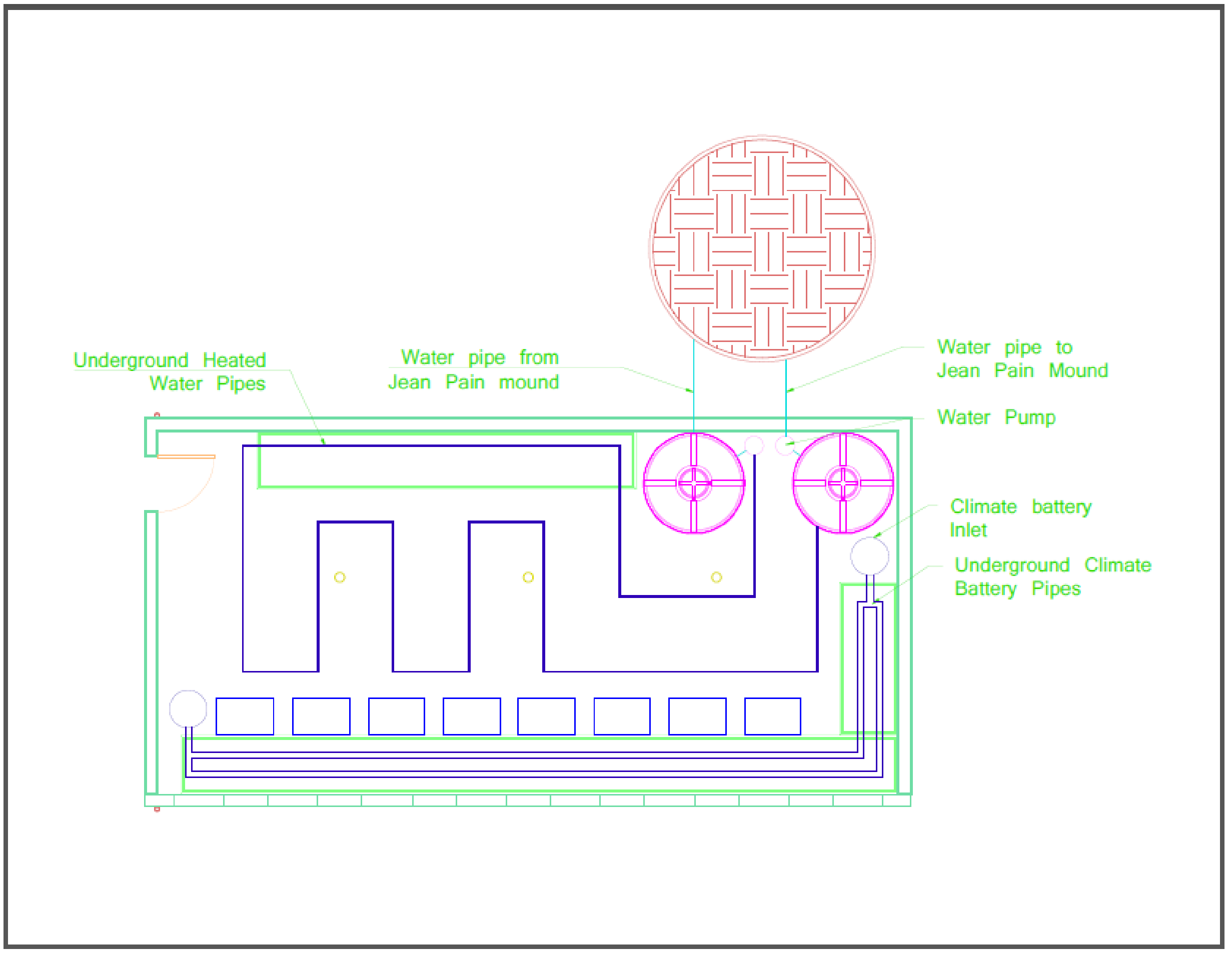
Materials Necessary:

- Woodchips from City of Worcester (Oak, large diameter, need to decompose)
- DIY 4 foot compost thermometer - $15
- PVC piping 1 inch- 4 feet long
- PVC piping ¾ inch – 4 feet long
- Thermometer with a hole in it to attach to PVC with screw
- Insert 1 inch PVC into Mound and leave there, to measure temperature – insert other PVC into 1 inch PVC
- 1000 gallons of water for thorough soaking of material
- 25 feet of chicken wire to wrap around mound - $15
- 5 shovels to get woodchips into mound form
- 5 pairs of gloves
- A truck to deliver woodchips onto lot
- Tape Measure
- Spray Paint - Orange

Steps for a Mock Mound of 40 cubic yards (12 feet in diameter x 8 feet high):

1) Measure and mark the footprint of the outer diameter of the mound in a 12 foot diameter circle
2) Spread out compost mixture (Mixed) that has been thoroughly soaked
3) Pack down outer 12 inches of material with feet/hands
4) Let sit for 2 weeks. Temperature readouts of the compost material should be 130 °F and measure it daily or so.
5) After the two week period is over, spread woodchips out in neighboring lots as mulch

Appendix F: Radiant heating system



Appendix G: Actual Jean Pain Mound plan

Project Plan for an Actual Jean Pain Mound

(Taken from The Compost-Powered Water Heater, by Gaelan Brown)

System Parameters and Goals:

1) Produce a heating output of 10,000 Btu/hr via hot-water production in the temperature range of 110 to 130 °F, continuously from late October to the end of April.
2) Supply an in-bioshelter storage tank with enough 110 to 130 °F water to supply the radiant floor heating system.
3) Locate the compost-powered heating system directly next to the bioshelter to minimize the length of supply/return pipes

Recommended System Design and System Parameters:

1) 40 cubic yards of material is needed to build the Mound. Double-ground brushwood is the ideal feedstock. Fresh sawdust will increase temperature profile by 10 to 20°F. The feedstock must be from a dry storage facility. Around 1000 gallons of water added to soak feedstock as the system is built
2) 900 feet of 1-inch PEX tubing purchased in 300 foot sections for compost heat exchange loops and supply/return lines
   a) Couplings, connectors, and ring clamps for the tubing
   b) 2, 15-foot sections of conduit and 30 feet of pipe insulation
3) Compost heat exchanger – 900 foot loop in compost over 7 layers, laid out in 10-foot diameter circle, 130 to 150 feet per layer
4) Stacked ring of hay bales to provide wall insulation/moisture retention
   a) 15 bales of hay per layer for 12 foot mound (around 50 hay bales)
   b) Vertical side walls enables larger amounts of heat exchange and enhances passive aeration
   c) Could use chicken wire for insulation

5) A 1/8 hp circulator pump needed to move water from storage tank through compost heat-exchanger loop
    a) Rate of circulation should be kept between 1 gallon/minute (if 45° water is being circulated into compost) to 3 gallon/minute (if "cold" water return is above 95°)
    b) Mount circulator pump(s) to cold water supply to the compost on lower end of tank
6) Use a temperature sensor/thermometer on each of the supply/return pipes between the compost system and the water tank to track temperature and heat exchange as long as circulation flow rate is known. The soil above the radiant heating loops in the seedbeds must be monitored as well.
7) Recommended design specifications and elements:
    a) One 40 cubic yard round system approximately 12 feet in diameter at the base and 8 to 12 feet in diameter at the top, and 7 to 8 feet tall
    b) Aeration tubing: 100 feet of 4-inch corrugated/perforated drainage pipe should be laid out in concentric circles on the ground in a 10 foot diameter circle with one end terminating in the center, the other beyond the footprint of the mound so outside air can enter.
    c) Heat Exchange Zones in a Compost Powered Mound
8) A single 900 foot long compost heat-exchange loop of 1 inch diameter polyethylene tubing spread across 7 layers. Lay the first layer of pipe after you spread 18 to 20 inches of feedstock on top of the aeration tubing; spread 10 inches of feedstock in between each subsequent layer of heat-exchange pipe.
9) Each heat-exchange loop will consist of this approximate configuration:
    a) Starting with the first layer of pipe along the outside edge of the compost, unroll the pipe and hold it down in place (using cinder blocks temporarily) while you unroll the pipe and coil it in toward the center; the inner ring of coil should be laid in about a 20 inch diameter circle, taking care not to kink the pipe.
    b) Set the roll of pipe aside and cover the layer of heat-exchange loop with 10 inches of thoroughly soaked feedstock
    c) Repeat step 1 and 2 until you have seven layers until you have 7 layers of heat-exchange tubing in place.
    d) Connect the end of the final-section of heat-exchange pipe to the hot-water return pipe that goes down into the center of the mound and into the insulated pipe/trench

e) Then cover the top layer of feedstock with a 20 to 24 inch layer of feedstock

Step-by-Step Construction Directions

1) Dig a 3 foot deep and 10 to 16 inch wide trench from the location of the water storage tank in the bioshelter to the center of where the compost mound will be located
2) Install pipe insulation on a 15 foot length of poly tubing, and insert that into a 15 foot section of nonpermeable flexible 4 inch corrugated plastic conduit pipe. This will be the hot-water return pipe.
3) Lay that conduit/pipe in the trench with 10 feet of poly tubing extending from the end of the conduit up out of the compost end of the trench. Use duct tape to seal the end of the conduit around the poly tubing to prevent any water from draining down into the conduit.
4) Install pipe insulation on the first 15 feet of one of the 300 foot rolls of tubing. Then insert this into the other 15 foot section of conduit. This is the cold-water supply pipe.
5) Lay the end of the insulated cold-water supply pipe into the trench extending to where the center of the compost mound will be. Set the remainder of the 300 foot roll of tubing aside. Mark this pipe with a *Cold-Water Supply* marker. Use duct tape to seal the end of the conduit in the trench around the extending poly tubing to prevent any groundwater from entering the conduit.
6) Measure and mark the footprint of the outer perimeter of the mound in a 12 foot diameter circle, ensuring that the supply/return pipes to the bioshelter terminate near the center of the perimeter where you'll build the mound.
7) Run any wires for in-mound sensors next to the pipe conduits and into the center of the mound site.
8) Cover the insulated conduit/pipe/wires with dirt, filling the trench.
9) Insert a 10-foot stake into the center of the mound site, where both pipes come out of the trench. Use tape to affix the 10 feet of remaining pipes of the hot-water return and cold-water supply, so that this pipe will extend up into what will be the top/center of the finished compost mound.
10) Lay out perforated aeration tubing in well-spaced concentric circles on the ground, with one end terminating in the center, the other slightly outside the mound perimeter.

11) Lay out the first course of hay bale insulating walls around the perimeter, leaving a 12 foot diameter circle on the inside edges of the bales.
12) Cover the perforated tubing with an 18 to 20 inch layer of compost feedstock that has been thoroughly soaked; spread evenly.
13) Lay out the first heat exchange layer of poly tubing in place (using the remainder of the cold-water supply line that comes from the insulated trench) on top of the first layer of feedstock.
    a) Starting with the outside ring (keeping the pipe 10 to 18 inches from the edge of the compost feedstock), lay out concentric rings spaced 6 inches apart until the inner ring is in place.
    b) As you unroll the pipe and lay it on the feedstock, coiling it in toward the center, hold it in place temporarily using cinder blocks. Lay the inner ring of coil in approximately a 20 inch diameter circle, taking care not to kink the pipe.
    c) Set the remainder of the roll of pipe aside.
    d) Cover that layer of heat-exchange tubing with 10 inches of feedstock that is thoroughly soaked with water; pack down the outer 12 inches and make sure you have a consistently level layer. Use the cinder blocks as a gauge to measure depth.
    e) Remove the blocks. Use feedstock to fill the gaps this leaves.
    f) Repeat steps a through e until you have 7 layers of heat-exchange tubing in place and have used up all 900 feet of the heat-exchange tubing.
    g) Connect the end of the final section of heat-exchange pipe to the hot-water return pipe that goes down into the center of the mound and into the insulated pipe/trench.
    h) Cover the top layer of heat-exchange pipe with a 20 to 24 inch layer of feedstock then a layer of loosely packed wet hay to retain moisture.
14) The compost mound is now complete. What remains is to install the water storage tank, the circulation pump, and the radiant heating system that will pull hot water away from the tank to the radiant heating zones.

Plumbing and Operational Overview

1) Mount a circulator pump to the coldwater supply to the compost on the lower end of the tank.
2) Attach the cold-water supply to a bunghole in the low side of the tank.

3) Insert a fill/bleed valve on the hot-water supply pipe that will later be attached to the high side of the tank.
4) Fill the system with water, ensuring that the fill/bleed valve allows all air to be pushed out of the system as the hot-water supply is connected to the top of the tank.
5) During the first two weeks after the system is built, monitor the temperature readouts. Compost material temperature should be between 130 and 150°F within that time. Once you've achieved temperature in that range, activate the circulation pump from the compost heating loop into the tank, at a flow rate of approximately 1 gallon/minute.
6) Monitor the temperature of thermometers daily during the first two weeks of active circulation. Once the compost temperatures are above 130°F, you should be able to maintain a circulation rate between 1 and 2 gallons/minute if the cold-water line into the compost is above 70°F. If the mound temperature drops at any time, reduce the circulation of the radiant heating side of the system until temperatures stabilizes in the 110 to 140°F range.

Operational Advice

You'll need to monitor and perhaps adjust the flow rate through both sides of the system. You'll also have to monitor the temperatures of the water, the seedbeds, and the compost mound.

If the temperature of the hot-water output water line is within 5°F of the peak temperature readout from probes inside the compost, which means you can pull more heat out of the compost, it is recommended to increase circulation through the mound by 10 percent. If the temperature of the compost mound or the hot-water supply to the radiant system at any time shows a downward trend, reduce the flow rate on both sides of the system by 20 percent/day until the temperature stabilizes.

If at any time there are severe temperature drops in the compost or the hot-water output, stop circulation for 48 hours and then restarting it at a lower flow rate, gradually increasing this flow until the output temperature stabilizes.

If the compost mound dries out, place a sprinkler at the top of the mound, and let a slow trickle of hot water saturate the mound for 4 to 6 hours.

Appendix H: Bioshelter Glazing Materials

Conventional Greenhouse/Bioshelter Glazing Materials (used for any walls designed to transmit sunlight)							
Categories	Types	R-value	SHGC	Pros	Cons	Water-vapor	Source
Wrap	Poly film	0.83	.8-.9	Relatively cheap, lightest, earily removable, easy to install.	Relatively flimsy, less air tight than other materials.		Greenhouse Covering Insulation Chart http://yukongreenhouse.weebly.com/glazing.html
	High efficient wrap	1.7	0.83	Strong (high performance against snow load and wind load), high performance, easily removable, more cost efficient than poly carbonate	Costs more than conventional poly films		http://www.globalplasticsheeting.com/Portals/32796/docs/Comparison%20of%20different%20Greenhouse%20roofing%20materials%20GPS%2010-1-2013_llmp.pdf
Polycarbonate	Corrugated Polycarbonate	0.88	0.9	Offers varying SGHC values (upto 90% light transmission), impact resistant, light weight, weather resistant	Possible to yellow in color, which would reduce in light transmission	High resistance to water and water vapor penetration.	http://www.palramamericas.com/Products/Corrugated-Sheets/SUNTUF/
	Polycarbonate double wall panel (8mm)	1.6	0.75	Light weight, allows abundant natural light into interior spaces.	Expensive compared to poly film but cheaper than polycarbonate sheets with aerogel application. Time consuming to install		Polycarbonate Fill Solutions, Israeli
	Polycarbonate with aerogel application	9.09	0.61	Light weight, highly efficient	Very Expensive		Polycarbonate Fill Solutions
Glass	Plexiglass double wall panel	2.3	0.91	Minimal condensation, sturdy	Expensive and Time consuming to install		http://www.globalplasticsheeting.com/Portals/32796/docs/Comparison%20of%20different%20Greenhouse%20roofing%20materials%20GPS%2010-1-2013_llmp.pdf

Appendix I: Residential Insulation Materials

Conventional Residential Insulation materials (used for Northern Walls of Bioshelter)

Categories	Types	R-value	Uses	Pros	Cons	Water-vapor	Source
Fibrous Insulation							
Batts/blankets	Fiberglass	.2-4.0	Foundation- new construction and retrofit Floor- new construction and retrofit Wall- new construction Ceiling- new construction and retrofit	Easy to install Relatively Inexpensive Can withstand high temperature Fiberglass resistance to microbiological attack and chemicals Sheep's wool dries off moisture by generating heat when moist Cotton is recycled and nontoxic	If not isolated from interior correctly, fibers could cause breathing problems Could leave holes and gaps where air can circulate Needs to be flame resistant if were to left exposed	Needs to be treated with building paper as a vapor retarder	Mehta, "Insulation: Materials and Techniques." "Building shell." , http://home.howstuffworks.com/home-improvement/construction/green/5-green-insulation-
	Sheep's wool	3.0-4.0					
	Rock wool	2.8-3.7					
	Cotton	3.2					
Loose-fill	Fiberglass	2.2-3.6	Wall- new construction and retrofit Ceiling- new construction and retrofit	Easy to retrofit Seals gaps	Takes much energy to produce	Possible condensation	Mehta, "Building shell."
	Cellulosic fiber	3.0-3.7		Easy to retrofit Recycled Material. When blown in wet, the mixture fills in gaps and seals them, which reduces air leakage and infiltration. When installed dry, can be used to insulate walls as long as it is packed tightly. Flame-retardant	May absorb moisture		"Building shell." "Insulation: Materials and Techniques."
	Rock wool	2.8-3.7		Easy to retrofit Seals gaps Great acoustic insulator as well	Requires waterproofing		"Building shell." "Insulation: Materials and Techniques."
Granular Insulation							
Rigid boards	Perlite	.5-3.7	Exterior insulation and finish systems wall systems EPS boards has to be modified to be fire-safe according to ASTM E 84.	Insulating efficient Perlite- Noncombustible High resistance to substrate corrosion EPS – lighter in weight	Inability to withstand high temperatures Only effective when it is dry Break down when exposed to sunlight EPS combustible	Permeable to water since it's beaded Impurities can absorb water Dries slowly- Needs asphalt water repellent treatment Also can be treated with silicone when processing *moistures cause the granules to settle down	Mehta
	Expanded polystyrene (EPS)	5					
Insulating Concrete	Perlite	.7-3.13	Insulating concrete wall, flat roof	Bonds well to most roof substrates High-wind-uplift resistance Fire resistance Easy sloping to drains	Lower-R value compared to others Health risk due to asbestos Heat travels through solid part of the block.		
	Vermiculite	2.08-2.44					
Foamed Insulation							
Rigid boards	Extruded polystyrene	5	Foundation- new construction and retrofit Wall- new construction and retrofit Ceiling- new construction and retrofit	Resistant to fungal growth and chemical decomposition Highest available R-values per inch.	Expensive, Carpenter ants and thermites creates cavities.	High resistance to water and water vapor penetration	Mehta, "Building shell."
	polyisocyanurate	5.6-7.7					"Building shell." "Insulation: Materials and Techniques."
Spray-in	Polyurethane	5.6-6.8	Wall- new construction and retrofit Ceiling- new construction and retrofit Roof- new construction and retrofit	Seals gaps and control leakage. Prevents moisture transmission the best Highest available R-values per inch.	Carpenter ants and thermite.		"Building shell." "Insulation: Materials and Techniques."
Concrete	Portland cement with water and liquid foaming concentrate	3.9	Roof insulation, walls	Higher resistivity than Insulating concrete. Nontoxic and Nonflammable.	Vulnerable to insects. Needs waterproof treatment.	Should be treated with a vapor retarder. Especially in winter, freezing and thawing could damage concrete	Mehta
Non-conventional Eco-friendly Insulation options							
Rigid bales	Strawbale	.94-2.38	Wall- new construction	Cheap and eco-friendly (low embodied energy and biodegradable)	Vulnerable to insects, and other pests. Requires to have thick walls.	Very weak against precipitation. Should be protected from water	http://www.sunfrost.com/straw_bale_R_values.html

Conventional Greenhouse/Bioshelter Glazing Materials (used for any walls designed to transmit sunlight)

Categories	Types	R-value	SHGC	Pros	Cons	Water-vapor	Source
Wrap	Poly film	0.83	.8-.9	Relatively cheap, lightest, earily removable, easy to install.	Relatively flimsy, less air tight than other materials.	High resistance to water and water vapor penetration.	Greenhouse Covering Insulation Chart http://yukongreenhouse.weebly.com/glazing.html
	High efficient wrap	1.7	0.83	Strong (high performance against snow load and wind load), high performance, easily removable, more cost efficient than poly carbonate	Costs more than conventional poly films		http://www.globalplasticsheeting.com/Portals/32796/docs/Comparison%20of%20different%20Greenhouse%20roofing%20materials%20GPS%2010-1-2013_!lmp.pdf
Polycarbonate	Corrugated Polycarbonate	0.88	0.9	Offers varying SGHC values (upto 90% light transmission), impact resistant, light weight, weather resistant	Possible to yellow in color, which would reduce in light transmission		http://www.palramamericas.com/Products/Corrugated-Sheets/SUNTUF/
	Polycarbonate double wall panel (8mm)	1.6	0.75	Light weight, allows abundant natural light into interior spaces.	Expensive compared to poly film but cheaper than polycarbonate sheets with aerogel application. Time consuming to install		Polycarbonate Fill Solutions, Israeli
	Polycarbonate with aerogel application	9.09	0.61	Light weight, highly efficient	Very Expensive		Polycarbonate Fill Solutions
Glass	Plexiglass double wall panel	2.3	0.91	Minimal condensation, sturdy	Expensive and Time consuming to install		http://www.globalplasticsheeting.com/Portals/32796/docs/Comparison%20of%20different%20Greenhouse%20roofing%20materials%20GPS%2010-1-2013_!lmp.pdf

Appendix J: Bioshelter Budget

Bioshelter Building Costs

Material	Unit Length	Size	Cost per unit	Number of Units	Total Cost	Catorgory Cost	Site
Jean Pain Mound Cost (Heat Source)							
Taco 1/4 HP Pump			$670	1	$670		www.supplyhouse.com
Taco 1/8 HP Pump			$270	1	$270		www.supplyhouse.com
Woodchips (20 cubic yards)			Free		$0		
Manure (4 cubic yards)			$100	1	$100		
Sawdust (16 cubic yards)			$160	1	$160		
Hay bales			$6	45	$250		http://www.uwex.edu/ces/forage/pubs/hay_market_report.htm
100 feet of 4 inch corrugated piping for aeration purposes			$75	1	$75		http://www.homedepot.com/p/Advanced-Drainage-Systems-4-in-x-100-ft-Corex-Drain-Pipe-Solid-04510100/100537518?N=5yc1vZbv13
300 feet rolls, 1 inch diameter 100 PSI polyethylene tubing for in-compost heat exchange loop			$75	3	$224		http://www.homedepot.com/p/Advanced-Drainage-Systems-1-in-x-300-ft-IPS-100-PSI-UTY-Poly-Pipe-1100300/203294398?N=5yc1vZbuu4
240 feet of 3/4 inch diameter PEX tubing for radiant floor heating system and to connect to storage tank (purchased in 300 feet section)			$119	1	$119		http://www.supplyhouse.com/Bulldog-T075-300-B-3-4-Blue-PEX-Tubing-300-ft-Coil
Clamps and Couplings for the tubing			$300	1	$300		
3/4 in. Brass PEX Barb 90-Degree Elbow (5-Pack)			$11	4	$43		http://www.homedepot.com/p/SharkBite-3-4-in-Brass-PEX-Barb-90-Degree-Elbow-5-Pack-UC256LFA5/202270596
4, 15 foot sections of conduit and 60 feet of insulation to go over the tubing runs			$120	1	$120		
10 foot Wood Landscape Stake to place in the Mound			$6	1	$6		http://www.lowes.com/pd_189665-199-85345_0__?productId=3386598
Thermometers/Sensors/Probes to efficiently monitor the Mound			$200	1	$200		http://www.agriculturesolutions.com/products/crop-soil-and-water-testing/composting-temperature-probes/reotemp-fast-response-composting-thermometer-48in-probe-detail
Water for soaking of Mound - 1000 gallons			$5	1	$5		
Miscellaneous Materials (Tape, Cinder Blocks)			$20	1	$20		
Total						**$2,562**	

Rainwater Catchment System							
5K Aluminum Gutter	20 ft	5"	$59.00	4	$236.00		http://www.egutter.com/RAIN-GUTTER-COMMERCIAL-GUTTERS-GUTTER-SUPPLY-GUTTER-GUARDS/5-K-
2"x 3" Aluminum Downspout	10ft	2" x 3"	$10.00	2	$20.00		http://www.homedepot.com/p/Amerimax-Home-Products-2-in-x-3-in-White-Aluminum-Downspout-
5k Aluminum Gutter Endcap		5"	$3	4	$12		http://www.lowes.com/pd_48998-205-25105020_0__?productId=3364692
4 in. PVC 90-Degree Hub x Hub Elbow		4"	$3	2	$7		http://www.homedepot.com/p/NDS-4-in-PVC-90-Degree-Hub-x-Hub-Elbow-4P02/100137163?MERCH=REC-_-NavPLPHorizontal1_rr-_-NA-_-100137163-_-N
2 in. x 3 in. x 4 in. Styrene Offset Down Spout Adapter		2" x 3" x 4"	$3	2	$6		http://www.homedepot.com/p/NDS-2-in-x-3-in-x-4-in-Styrene-Offset-Down-Spout-Adapter-904/100377412
Downspout First Flush Diverter Kit, 4" (optional?)		4"	$35.22	2	$70.44		http://www.amazon.com/Downspout-First-Flush-Diverter-Kit/dp/B002RS0V4C/ref=sr_1_1?s=hi&ie=UTF8&qid=1427499835&sr=1-1&keywords=downspout+first+flush+diverter+kit+4
4 in. x 10 ft. PVC Sch. 40 DWV Plain End Pipe	10 ft	4"	$22.00	3	$66.00		http://www.homedepot.com/p/Unbranded-4-in-x-10-ft-PVC-Sch-40-DWV-Plain-End-Pipe-531103/100156409
Total						**$417.18**	

Water Storage							
900 gallon tank		72" d x 55" h	$649.95	2	$1,299.90		http://www.rainharvest.com/info/Dura-Cast/Duracast-900-Gallon-Vertical-Tank-910900.pdf
400 gallon tank		60" d x 35" h	$293.95	2	$587.90		http://www.plastic-mart.com/product/5968/400-gallon-open-top-flat-bottom-cylindrical-tank-crmi-400otf
Total						**$1,887.80**	
Climate Battery							
4 in. Corex Drain Pipe Solid	50 ft		$35	3	$105		http://www.homedepot.com/p/Advanced-Drainage-Systems-4-in-x-50-ft-Corex-Drain-Pipe-Solid-04510050/203246774
55 Gallon Drum plastic			$69	2	$138		http://www.uline.com/Product/Detail/S-10757BLU/Drums/Plastic-Drum-55-Gallon-Closed-Top-Blue?pricode=WY582&gadtype=pla&id=S-10757BLU&gclid=Cj0KEQiw_9OoBRCh9vMo5CHrdUBEiQAJ6YRPY1iTrrD1JhVAPUafWLD180SHO_w3vjXKYAs_O1PYTMaAho-8P8HAQ&gclsrc=aw.ds
4 in. x 10 ft. PVC Sch. 40 DWV Plain End Pipe	10 ft	4"	$22	1	$22		http://www.homedepot.com/p/Unbranded-4-in-x-10-ft-PVC-Sch-40-DWV-Plain-End-Pipe-531103/100156409
4 inch in-line fan 165 CFM			$104.95	1	$104.95		https://www.hydrofarm.com/p/ACDF4
Growbright 4 inch Inline Duct Fan			$24.95	1	$24.95		http://www.htgsupply.com/Product-4in-Inline-Duct-Fan
Thermometers			$41.88	1	$41.88		http://www.amazon.com/Ambient-Weather-WS-21-8-Channel-Thermometer/dp/B00EYM34VM
Total						**$437**	
Circulation							
MegaBreeze 12" HAF Fan	1 ft	15" x 15" x 11"	$110	2	$220		http://www.greenhousemegastore.com/product/megabreeze-haf-fan/circulation-fans
Total						**$220**	
1 Raised Beds (4' x 12' (2' high))							http://blueberryhillcrafting.com/2013/04/24/how-to-galvanized-garden-beds/
8' 2 x 4 boards	8 ft	2" x 4"	$2.67	6	$16.02		http://www.homedepot.com/p/Unbranded-2-in-x-4-in-x-96-in-Premium-Kiln-Dried-Whitewood-Stud-161640/202091220?N=5yc1vZ1z0wwuZ1z11605
8' x 2' galvanized metal		8' x 2'	$9.98	3	$29.94		http://www.homedepot.com/p/Unbranded-2-1-2-in-x-8-ft-Corrugated-UT-Gauge-Galvanized-Steel-Roof-Panel-13513/202092961
12 ' 4" x 4" post	12 ft	4" x 4"	$16.17	1	$16.17		http://www.homedepot.com/p/Unbranded-4-in-x-4-in-x-12-ft-2-Pressure-Treated-Timber-4230254/100073070
12' 2" x 4" board	12 ft	2" x 4"	$5.97	1	$5.97		12-ft-1-Pine-Pressure-Treated-Lumber-185032/204862948
4' x 8' sheet of wire mesh		4' x 8'	$52.23	1	$52.23		http://www.mcnichols.com/ecommerce/eos/additems?execution=e2s1&page=cart
Roofing Screws (100pc)			$9.88	1	$9.88		http://www.lowes.com/Hardware/Fasteners/Screws/Roofing-Screws/_/N-1z0yk3g/pl#
Metal Screws(75pc)			$5.58	2	$11.16		http://www.lowes.com/Hardware/Fasteners/Screws/Sheet-Metal-Screws/Standard-SAE-Sheet-Metal-Screws/_/N-1z0yrdu/pl#
Soil							
Total for one					**$141.37**		
Total for 5 beds(inside Bioshelter)						**$706.85**	
Building Envelope							
Roof							
Tyvek house wrap	773 sqft		$234.97	1	$234.97		https://www.google.com/shopping/product/15819791772418204943?client=safari&rls=en&biw=1439&bih=745&q=permeable+air+wrap&spell=1&bav=on.2,or.r_cp.&bvm=bv.89381419,d.eXY&tch=1&ech=1&psi=UgMYVZccJcWyogSq8YPgBA.1427637075143.11&prds=paur:ClkAsKraX9CKgP1meehXgORmuwLo2wfYBZzCEMxK78ZhH5Clp_lMZvwQtFIP5ZSOumW_J2sROf7qFlCsrpcn-fr48v6AkFPD5hs046U-OSnYWxLkcdTe0E5BtZ4FPvH73s-WvpUxu864kpg6Ze1cl8QU1Gqg&ei=sAMYVZbhLuCBMuJqbAN&ved=0CKMBEKYrMAM
Tyvek tape				1	46.95		https://www.diyhomecenter.com/dupont/tyvek/flashing-tape-4-inches-d13789316.aspx
Steel Roof	773 sqft		$46	17	$782		http://www.homedepot.com/p/Metal-Sales-16-ft-Classic-Rib-Steel-Roof-Panel-in-Burnished-Slate-2313649/204255223?cm_mmc=Shopping%7CBase&gclid=Cj0KEQjwd6oBRCRoMrWmLOCv4BEiQAYyZdkc2NSQne3pmbCJLTaV96pvMUm2xC1E4WGwfuXzaq10aAoI38P8HAQ&gclsrc=aw.ds
8" EPS board	773 sqft		$110	49	$5,390		R14-Type-1-Insulated-Wall-Panel-AMWP142496/204399265?cm_mmc=Shopping%7CBase&gclid=Cj0KEQjwd6oBRCRoMrWmLOCv4BEiQAYyZdkS-V-S7b8Wg7kEgWuHu9t_kpfO2iv0HGT2rfz6q8kUlaAuYM8P8HAQ&gclsrc=aw.ds
0.5" interior plywood	773 sqft		$21.99	100	$2,199.00		http://www.acehardware.com/product/index.jsp?productId=12972558&KPID=991377&kpid=991377&pla=pla_991377
Total						**$8,652.92**	

Window							
17" x 32 " windows			$73	8	$584		http://www.lowes.com/pd_131085-1257-748171594088_0__?productId=3039570
E, W wall windows							
Sealant			$170	1	$170		https://www.google.com/shopping/product/13021613014530194500?q=house+wood+sealant&client=safari&rls=en&biw=1439&bih=748&dpr=1&prds=paur:ClkAsKraX4kE5a8aK6XlZiNNQ9H2ex8-wQKwgAai7ORe2MMgEVLRcDqx30xq_xrtBPntfrCX4ZiZs5rM7wsJvwT4Fi0P5mAsRvKeBWWBKwKHAEdbil_7NZ4FPVH72v9KDWTdKDS5c7IVyTuv98lPXXTw&ei=lAYYVdP1CYgkgwT2hgM&ved=0CLoBEKYrMAI
Sill Flashing	Sum of total window width						http://www.homedepot.com/p/SureSill-Sloped-Sill-Pan-1-1-8-in-Extension-Connector-10-Piece-per-Box-SS-1-18C-EC/203837837?cm_mmc=Shopping%7CBase&gclid=Cj0KEQiwxd6oBRCRoMrWimLOCvI4BEiQAYvZdkVRt5XohWUuH0aQiaEFdnJrrTLSLvhYGcc4PULpWhQaAqq-8P8HAQ&gclsrc=aw.ds
1" x 4" wood trim	Sum of total window width						https://www.google.com/shopping/product/2401271330186249940?q=1%22x+3%22+wood+trim&client=safari&rls=en&biw=1439&bih=748&bav=on.2,or.r_cp.&bvm=bv.89381419,d.eXY&tch=1&ech=1&psi=wqYYVf2UKYGwggSpsYNY.1427637955451.3&prds=paur:ClkAsKraX5avGbD83Wese QL1dquCKqT2zVBeqnVg8Lis1bGFa8HPiht295T8qzNn37lR-5n3dM8UtgkpzLicPMXYR8BP60uegJkSA/S9qWUX2P1x1eVGPlqRIZAFPVH71YiMItY5KeyKcbvS2llgXIhUQg&ei=xQYYVd-sCsLBggTx-lHIDg&ved=0CLcDEKYrMBM
Total						**$754**	
Glazing							
Aluminium mullion 2" x 4"	190 ft		$425	1	$425		
Solar wrap	487 sqft		$2,800	1	$2,800		http://store.globalplasticsheeting.com/solawrap-greenhouse-plastic-free-shipping/
Polycarbonate glazing	487 sqft		$138	1	$138		http://www.homedepot.com/p/LEXAN-Thermoclear-48-in-x-96-in-x-5-8-in-Bronze-Multiwall-Polycarbonate-Sheet-PCTW4896-16MMBZ/205202520?cm_mmc=Shopping%7CBase&gclid=Cj0KEQiwxd6oBRCRoMrWimLOCvI4BEiQAYvZdkb6_di_eSbFFU4-_NhW699iZsXGF027Bs_I_bMLpVIa4ino8P8HAQ&gclsrc=aw.ds
Total						**$3,363**	
Foundation							
36" x 12" concrete footing	100 ft	378 ft^3	$3.25 to $5.25 per ft^3		$1,984.50		http://www.concretenetwork.com/concrete-prices.html
10" x 16" concrete foundation wall	100 ft	134 ft^3	$3.25 to $5.25 per ft^3		$703.50		
1-1/2" foam board	183.33 sqft		$15.32	12	$183.84		
Total						**$2,871.84**	
Framing							
4" x 6" wood frame @ 5' o.c.					$5,000.00		
6" x 6" wood post for corners	28 ft		$112.00	1	$112.00		http://www.chelsealumber.com/subs_materials/pricing.php?deptID=01
anchor bolts			$13.10	24	$314.40		http://www.allcostdata.info/browse.html/051080010/Anchor-bolts
Column sockets				12			
Lally column							
24"O x 36" Concrete Footing	10 cubic feet		$3.25 to $5.25 per ft^3		$52.50		
Lally column d=6" @ 10'o.c			$469.99	3	$1,409.97		http://www.metalsdepot.com/catalog_cart_view.php?msg=
Framing Labor					$15,000.00		
2" x 4" collar board			$2.62	1	$2.62		http://www.homedepot.com/p/Unbranded-2-in-x-4-in-x-92-5-8-in-Premium-Kiln-Dried-Whitewood-Stud-569062/205533769
Total						**$21,891.49**	
Wall							
1/2" interior finish	1038 sqft		$21.99	130	$2,858.70		http://www.acehardware.com/product/index.jsp?productId=1297255&KPID=991377&kpid=991377&pla=pla_991377
Rigid insulation 6" thick	1038 sqft		$99.97	65	$6,498.05		http://www.homedepot.com/p/Amdry-5-9-in-x-24-in-x-96-in-R22-Type-1-Insulated-Wall-Panel-AMWP222496/204399266?N=5yc1vZbaxxZ1z0ua2m
1" polyisocyanurate insulation	1038 sqft		$29.36	129.75	$3,809.46		http://www.drillspot.com/products/2659945/tw_571038_insulation_Polyisocyanurate?CAWELAID=520008640000588295&CAGPSPN=pla&catargetid=520008640000425803&cadevice=c&gclid=Cj0KEQiwxd6oBRCRoMrWimLOCvI4BEiQAYvZdkY9kNw3pFMh8VLEffTNsFUH6L1xY781M95SvKaaD8aAlwG8P8HAQ
Tyvek House wrap	1038 sqft		$234.97	1	$234.97		Panel-T1-11-8-IN-OC-Common-19-32-in-x-4-ft-x-8-ft-Actual-0-563-in-x-48-in-x-96-in-113699/100000016?N=5yc1vZc8aj
Wood siding	1038 sqft		$35.72	33	$1,178.76		Panel-T1-11-8-IN-OC-Common-19-32-in-x-4-ft-x-8-ft-Actual-0-563-in-x-48-in-x-96-in-113699/100000016?N=5yc1vZc8aj
Total						**$14,579.94**	
Foot of the wall							
4x6" PT Sill	100 ft						
Simpson Plate	100 ft						
Row Covers							
Agribon+ AG-19 Row Cover - 10' x 50'			$31.15	1	$31.15		
Wire (will vary depending on height of plants grown)					$40.00		
Total						**$71.15**	

PV Panels							
345W PV module ST Solar STM345-130 monocrystalline			$518	2	$1,036.00		http://www.freecleansolar.com/345W-PV-module-ST-Solar-STM345-130-mono-p/stm345-130.htm?gclid=CjwKEAjw-o6hBRDOmsPSjqakuzYSJADR2V3SoK8u7NF3mS3zJWXM77lKMQyC-Ep3CRjzXbQZk6ClhoCKmDw_wcB
MorningStar TriStar TS-60 Amp Solar Battery Charge Controller			$271	1	$271.00		http://www.amazon.com/MorningStar-TriStar-TS-60-Battery-Controller/dp/B004N3U74Y
Pyle PNV4000 Plug In Car 4000 Watts 12v DC to 115V AC Power Inverter with Modified Sine Wave			$414	1	$414.00		Modified/dp/B003OER25U/ref=sr_1_3?s=automotive&ie=UTF8&qid=1428271281&sr=1-3&keywords=inverter+12+115
Wire (gauges will vary)					$40.00		)
Vmaxtanks Vmaxslr125 AGM Deep Cycle 12v 125ah SLA rechargeable Battery			$284.99	1	$284.99		http://www.amazon.com/Vmaxtanks-Vmaxslr125-rechargeable-Solar-Inverters/dp/B00ACNO2AO/ref=sr_1_1?ie=UTF8&qid=1427852762&sr=8-1&keywords=solar+panel+battery
Total						$2,045.99	
Grand Total for Materials and Labor						**60658.212**	

Total: $60,658.21

Appendix K: Miscellaneous Sections

Windbelt

With solar energy being converted into electricity via solar panels, converting wind energy into electricity was the next logical step. Though wind turbines were considered, the consensus was that they weren't effective options, as large wind turbines would pose a safety hazard to the urban environment of the Piedmont area. Smaller wind turbines were also considered, but more research indicated that smaller wind turbines were magnitudes less efficient than their larger counterparts, and so wind turbines were disregarded as viable options. However, an interesting, albeit underdeveloped technology, that seemed to have potential, especially for use in the bioshelter, was the windbelt generator.

The windbelt has the potential to fulfill more than one key niche in the bioshelter. Not only can the windbelt generate electricity from wind power, but it can also serve as an opportunity for the children from the nearby Chandler Elementary School to learn more about eco-friendly technologies. Not only that, but due to the DIY nature of the windbelt, local adult residents too, can get involved in not only constructing and maintaining windbelt generators, but also possibly developing windbelt technology.

The following equation models the output of a windbelt:

$$W \sim 0.001742 * (\text{Area}) * (\text{Pressure} / \text{Temperature}) * (\text{Velocity})^3$$

Details worth noting about the performance of the windbelt are that the windbelt generator performs better at locations with a high barometric pressure and low temperatures. The wind velocity in particular, heavily affects the output of the windbelt, though it should be noted that the output of the windbelt is expected to plateau above 14 mph. Minimum requirements for the windbelt generator to function effectively are a wind velocity above 4 mph, and an angle of attack less than 60 degrees. Another aspect of the windbelt which makes it more viable than its alternatives is its efficient modular design. Multiple units of windbelts can be joined together with little modification. Other variables found through tests carried out on a prototype are the weight and positioning of the magnet on the belt of the windbelt. Magnets with more mass have been tested to produce a greater current, but the belt will have to be replaced more often, as using heavier magnets will place more strain on the belt.

Cost 	$8 - $30 per unit
Size	Typically 1 x 0.15 m
Power	10 - 100 mW
Maintenance	Variable

Build Order for 7 and 9 Jaques Avenue

Prepare the Site:

1) Petition the town of Worcester for permission to build the bioshelter.
2) Clean up any trash or debris located on the site.
3) Remove the pre existing foundation, which interferes with construction.
4) Check the width of the gate to ensure that the necessary equipment can fit through the gate. If the necessary equipment cannot fit through the gate, part of the gate might have to be temporarily removed to make room.
5) Stake out the lot with detailed measurements for build locations and dimensions.
6) Verify any dig locations with the town of Worcester to avoid sewage and electrical wires.

Pour the Foundation:

1) Level the surrounding area where the foundation is to be placed.
2) Place wooden forms to serve as a template for the foundation.
3) Dig required holes and trenches.
4) Place footings and any other necessary foundation work.
5) Schedule a city inspector to visit the site and ensure the foundation is installed properly and is up to code for the type of construction.

Place Rough Framing:

1) Construct a rough skeleton of the frame of the bioshelter.
2) Install Lally Columns and other structural support
    a) Fit steel tubing over the concrete footing to create a mold for lally columns
    b) Pour concrete into steel tubing
3) Cover the skeleton to avoid moisture infiltration and structure mold or rot.

Construct Roof Framing and Exterior Siding:

1) Place initial roof framing.
2) Add any additional beams needed for support. *Note: At this point it might be advisable to move any large objects inside the bioshelter such as water tanks.

Install Plumbing, Electrical Wiring, and HVAC:

1) Install the plumbing required for the climate battery and Jean Pain mound systems.
2) The Jean Pain Mound system requires radiant floor board heating. (*Note): The radiant floor board heating can be skipped if the Jean Pain Mound is not being used in the final design.
3) Place any HVAC vent piping.
    a) Install each HAF fan on the highest beam possible, 13’ away from their respective ends of the bioshelter. Make sure they are facing in the same direction, towards the west.
4) Lay down any necessary wiring that will supply power from the solar panels to the fans and pumps.
5) Schedule any additional required inspections for the framing, plumbing, and mechanical and electrical systems.

Install Insulation:

1) Install insulation in the framing of the house and in the roof to produce R30 along the non glazed surfaces.
2) Install windows and other glazed surfaces as well as doors.
3) Seal any air gaps in the frame of the construction.
4) Cover the exposed insulation with interior finishing.

Construct Internal Bioshelter Floor Plan:

1) Build the raised beds inside the bioshelter.
    a) Cut materials to appropriate dimensions.
        i) Cut 2 of the 8’ 2x4 boards in half, so that there are 4 of 8’ 2x4 boards, and 4 of 4’ 2x4 boards.
        ii) Cut 1 of the 8’x2’ sheets of galvanized metal in half, so that there are 2 of 8’x2’ sheets, and 1 of 4’x2’ sheets.
        iii) Cut 1 of the 12’ 4x4 post into 6 equal sections, so that there are 6 of 2’ 4x4 posts.

iv) Cut 1 of the 12’ 2x4 board into 8 equal sections, so that there are 8 of 16.5” 2x4 boards.

b) Create lengthwise sides.

i) Lay down 3 of the 4×4 posts 45” apart from each other. Then place 2 of the 8’ 2x4 boards over the top and bottom of the posts, ensuring the corners are square.

ii) Screw in 2 wood screws per corner, and 2 each at the top and bottom of the middle 4x4.

iii) Repeat Steps 1.b.i and 1.b.ii to create a second lengthwise frame.

iv) Lay 1 of the 8’x2’ metal sheets on top of a completed lengthwise frame, ensuring that the sharper cut edge is at the bottom of the frame and that the top of the sheet lines up 1” below the top of the frame.

v) Screw in 4 metal screws at the top and 4 metal screws at the bottom, all evenly spaced out.

vi) Repeat Steps 1.b.iv and 1.b.v to fasten the second 8’x2’ sheet to the second lengthwise frame.

c) Stand the two lengthwise sides up, so that both sides are 4’ apart and their bottom lengths are on the ground. Then attach 2 of the 4’ 2x4 boards to the top and the bottom on each end of the sides, using 2 screws per corner. Make sure the metal sheets are on the inside of the box.

d) Slide 4 of the 16.5” 2x4 boards into the gaps between the metal sheet and the end of the lengthwise frame for all four corners. Attach each board to the metal sheet with metal screws.

e) Line up each of the remaining 16.5” 2x4 boards on the inside of the 4×4 posts on each end of the frame so that the boards from Step 1.d are covered. Use wood screws to attach each board from Step 1.e to the boards from Step 1.d.

f) Slide in the 4’x2’ metal sheets so that the insides of the ends of the box are covered. Use 2 metal screws on each side per sheet to secure the sheets in place. Make sure the top of the metal sheets are lined up 1” below the top of the frame.

g) Relocate the raised beds to the appropriate location, and place the 4’x8’ wire mesh at the bottom of the box.

h) Fill the raised bed with soil.

2) Install compost bins along the raised beds.

a) Drill an appropriate number of holes in the container to be used.

b) Along the edges of the raised beds, dig a hole about the size of the container.
c) Put the container in the hole.
d) Put compost-soil mixture in the container.
e) Cover the container with wooden planks of an appropriate size.

3) Place water storage tanks and aquaponics tanks in specified location.
4) Design and construct the tables surrounding the lally columns.
5) Place the tool shed in the designated area.

Finish Interior Systems:

1) Finish any interior trims or decorations.
   a) This includes: interior growing lights and fans
2) Finish connecting internal systems.
3) Apply finish trims to interior walling.

Install Rainwater Catchment:

1) Install 40 ft of 5 inch aluminum gutter along each of the sides of the roof. Place the gutters with the front ½ inch lower than the back to prevent water from splashing back against the building.
2) Insert the 2” by 3” downspout piping along the non entrance edge of the bioshelter.
3) Convert downspout piping to 4” PVC piping using a 2” by 3” to 4” PVC adapter.
4) Install water diverter and first flush filter. Water being diverted towards the ground will go towards the first flush filter. Water moving towards the bioshelter will go into the rainwater catchment system.
5) Run the PVC piping to the water storage tanks. This will require the gutter installation on the 5’ wall side to travel across the bioshelter along the wall 20ft. The PVC piping will be sloped at 1/16” per foot, so that the water will flow freely.
6) Connect the PVC piping to the 900 gallon storage tanks. There should be enough room to run the water directly into the tank (72” d x 55” h). However, if there is not enough room, a custom connection can be made lower down.
7) Install overflow piping at 50” height mark on the 900 gallon tanks and direct the water outside of the bioshelter away from the foundation.

Construct Jean Pain Mound:

1) Dig a 3 foot deep and 10 to 16 inch wide trench from the location of the water storage tank in the bioshelter to the center of where the compost mound will be located.
2) Install pipe insulation on a 15 foot length of poly tubing, and insert that into a 15 foot section of nonpermeable flexible 4 inch corrugated plastic conduit pipe. This will be the hot-water return pipe.
3) Lay that conduit/pipe in the trench with 10 feet of poly tubing extending from the end of the conduit up out of the compost end of the trench. Use duct tape to seal the end of the conduit around the poly tubing to prevent any water from draining down into the conduit.
4) Install pipe insulation on the first 15 feet of one of the 300 foot rolls of tubing. Then insert this into the other 15 foot section of conduit. This is the cold-water supply pipe.
5) Lay the end of the insulated cold-water supply pipe into the trench extending to where the center of the compost mound will be. Set the remainder of the 300 foot roll of tubing aside. Mark this pipe with a *Cold-Water Supply* marker. Use duct tape to seal the end of the conduit in the trench around the extending poly tubing to prevent any groundwater from entering the conduit.
6) Measure and mark the footprint of the outer perimeter of the mound in a 12 foot diameter circle, ensuring that the supply/return pipes to the bioshelter terminate near the center of the perimeter where you'll build the mound.
7) Run any wires for in-mound sensors next to the pipe conduits and into the center of the mound site.
8) Cover the insulated conduit/pipe/wires with dirt, filling the trench.
9) Insert a 10-foot stake into the center of the mound site, where both pipes come out of the trench. Use tape to affix the 10 feet of remaining pipes of the hot-water return and cold-water supply, so that this pipe will extend up into what will be the top/center of the finished compost mound.
10) Lay out perforated aeration tubing in well-spaced concentric circles on the ground, with one end terminating in the center, the other slightly outside the mound perimeter.
11) Lay out the first course of hay bale insulating walls around the perimeter, leaving a 12 foot diameter circle on the inside edges of the bales.

12) Cover the perforated tubing with an 18 to 20 inch layer of compost feedstock that has been thoroughly soaked; spread evenly.
13) Lay out the first heat exchange layer of poly tubing in place (using the remainder of the cold-water supply line that comes from the insulated trench) on top of the first layer of feedstock.
    a) Starting with the outside ring (keeping the pipe 10 to 18 inches from the edge of the compost feedstock), lay out concentric rings spaced 6 inches apart until the inner ring is in place.
    b) As you unroll the pipe and lay it on the feedstock, coiling it in toward the center, hold it in place temporarily using cinder blocks. Lay the inner ring of coil in approximately a 20 inch diameter circle, taking care not to kink the pipe.
    c) Set the remainder of the roll of pipe aside.
    d) Cover that layer of heat-exchange tubing with 10 inches of feedstock that is thoroughly soaked with water; pack down the outer 12 inches and make sure you have a consistently level layer. Use the cinder blocks as a gauge to measure depth.
    e) Remove the blocks. Use feedstock to fill the gaps this leaves.
    f) Repeat steps a through e until you have 7 layers of heat-exchange tubing in place and have used up all 900 feet of the heat-exchange tubing.
    g) Connect the end of the final section of heat-exchange pipe to the hot-water return pipe that goes down into the center of the mound and into the insulated pipe/trench.
    h) Cover the top layer of heat-exchange pipe with a 20 to 24 inch layer of feedstock then a layer of loosely packed wet hay to retain moisture.
14) The compost mound is now complete. What remains is to install the water storage tank, the circulation pump, and the radiant heating system that will pull hot water away from the tank to the radiant heating zones.

Site work:

1) Build Pergola:
    a) Purchase a Prefabricated Pergola.
    b) Place Pergola in desired location and secure to ground.
2) Plant Bushes and other Plants around the Bioshelter:

a) Choose desired plants that are aesthetically pleasing.

b) Organize a community event to help plant and potentially set up community garden.

3) Pizza Oven:

a) Purchase outdoor oven that is suitable for the site.

b) Hire a mason to complete stonework for the oven.

c) Enjoy pizza!

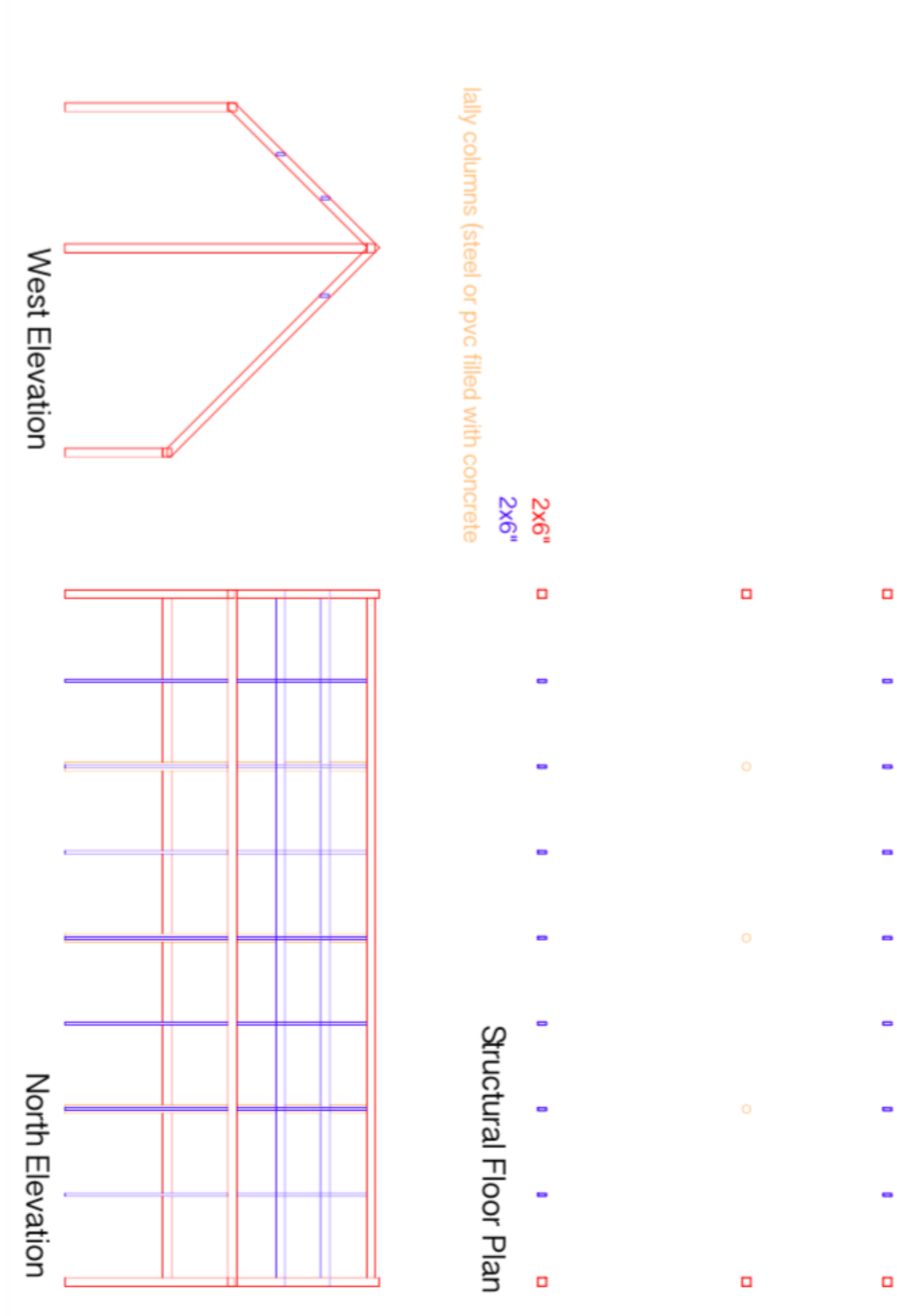
4) Walkway from Entrance to Bioshelter:

a) Create a plan for residents to sponsor a brick for the walkway.

b) Engrave the brick with their names or have the children from Chandler Elementary play a role in this process by contributing artwork.

c) Sponsor a community event at the lot to create a buzz about the bioshelter.

Structural Layout



Solar Site Analysis

Solar **Site** Analysis

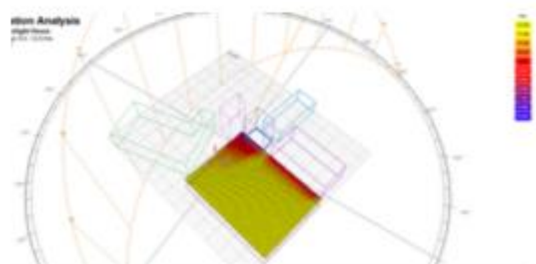
Insolation analysis and shadow studies of 7, 9 Jaques

INSOLATION ANALYSIS

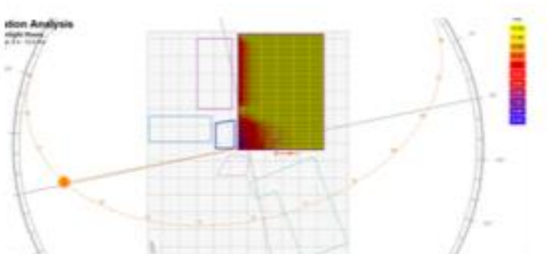
June 21st – September 22nd
Daily average hours

Summer with trees from the neighboring lot

Birdseye view



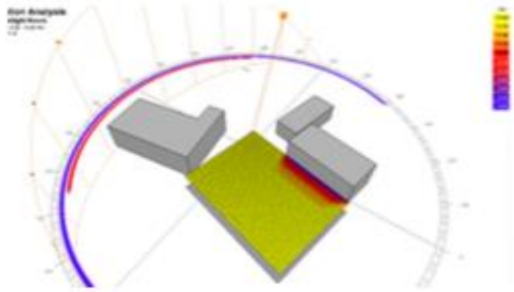
Top view



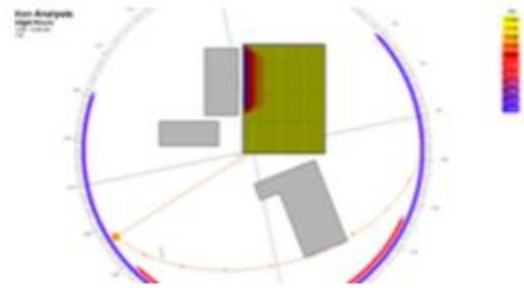
June 21st – September 22nd
Daily average hours

Summer without trees

Birdseye view



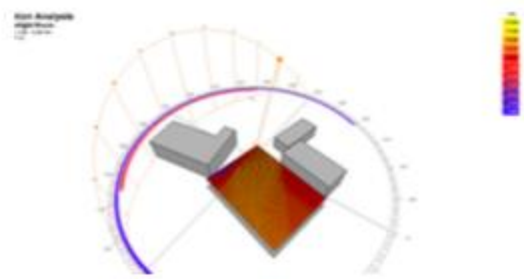
Top view



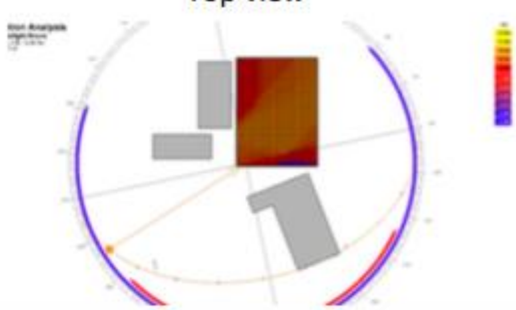
December 21st – March 22nd
Daily average hours

Winter

Birdseye view



Top view



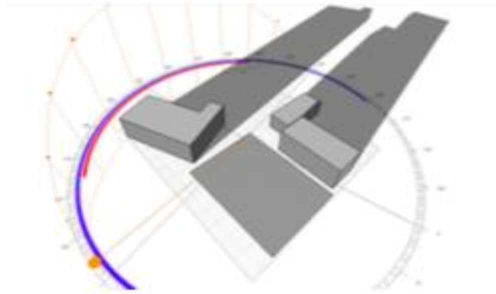
Shadow studies of the lot throughout an year

SHADOW STUDIES

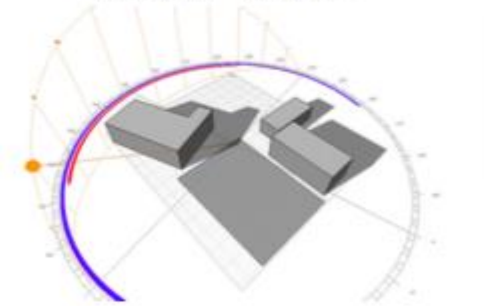
March 20th shadow studies
Sunrise 6:15 am
Sunset 5:45 pm

Vernal Equinox

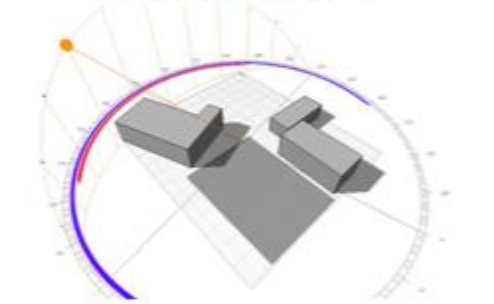
March 20th 6:15 am



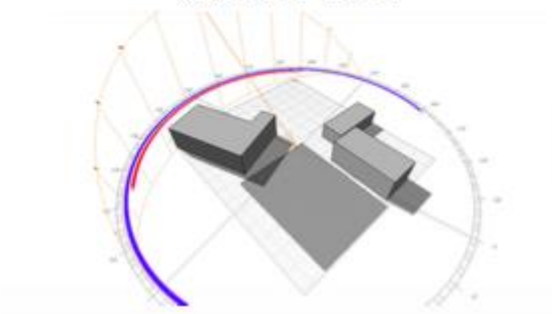
March 20th 8:00 am



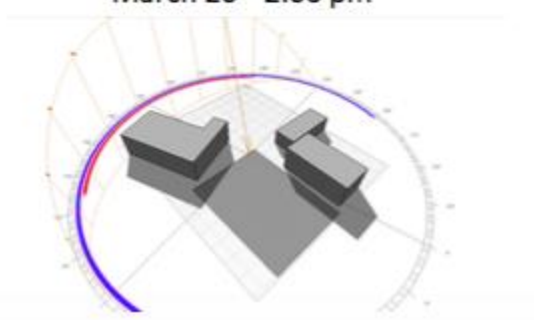
March 20th 10:00 am



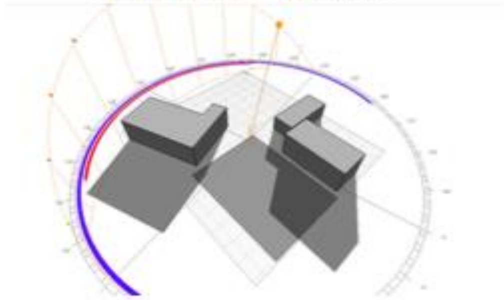
March 20th noon



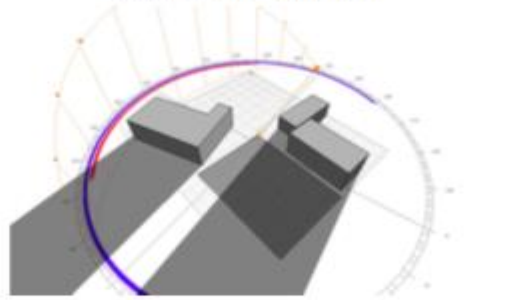
March 20th 2:00 pm



March 20th 4:00 pm



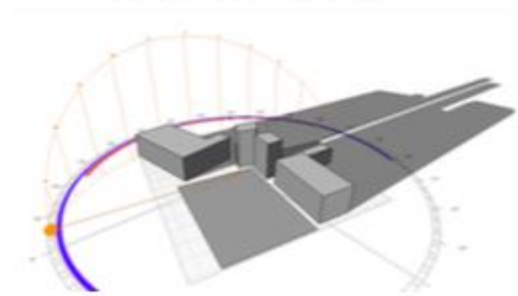
March 20th 5:45 pm



March 20th shadow studies
Sunrise 6:15 am
Sunset 5:45 pm

Vernal Equinox modeled with trees

March 20th 6:15 am



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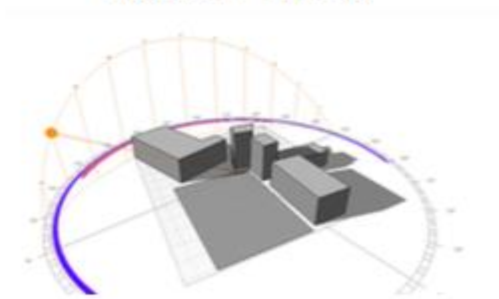
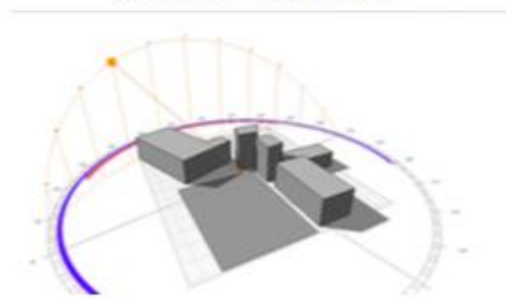
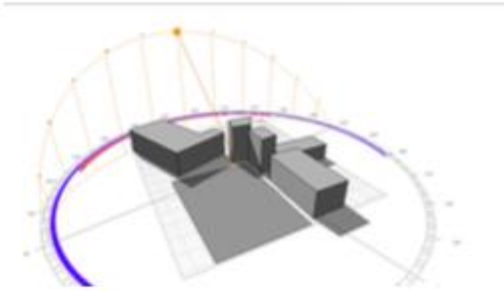


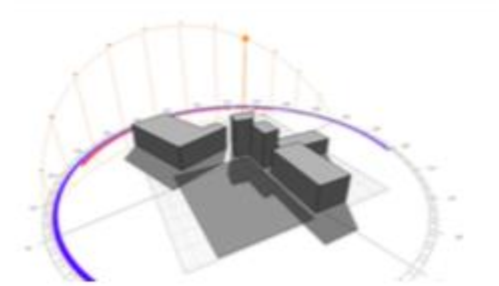
March 20th 10:00 am



March 20th noon



March 20th 2:00 pm



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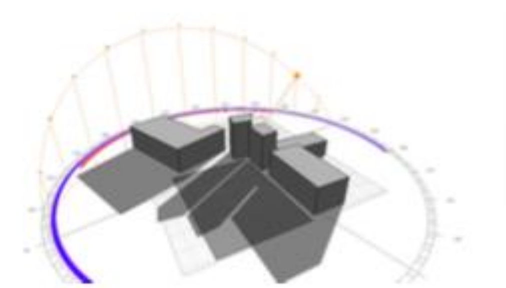
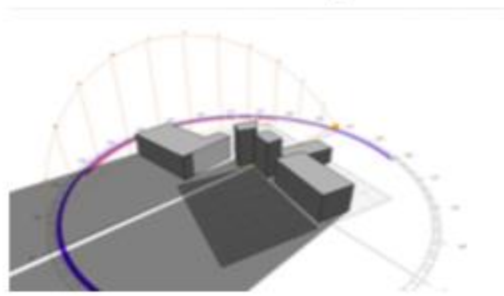


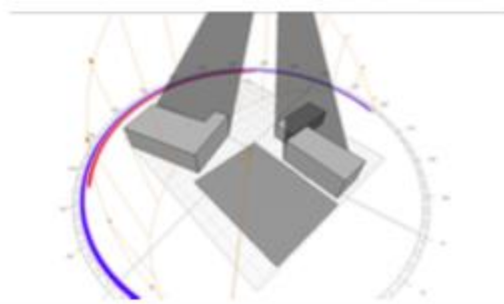
March 20th 5:45 pm



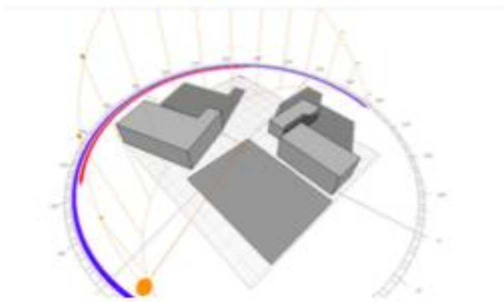
June 21st shadow studies
Sunrise 4:30 am
Sunset 7:15 pm

Summer Solstice

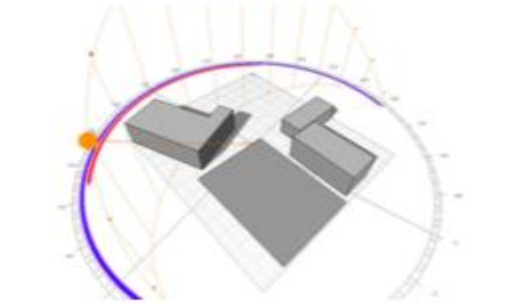
June 21st 4:30 am



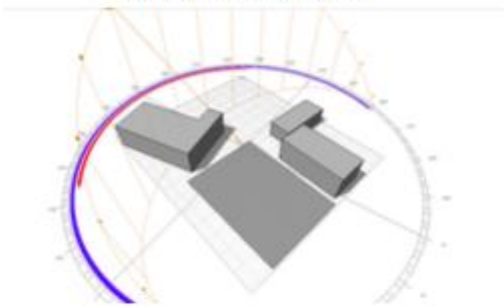
June 21st 6:00 am



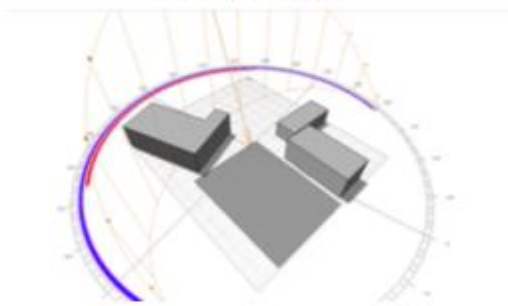
June 21st 8:00 am



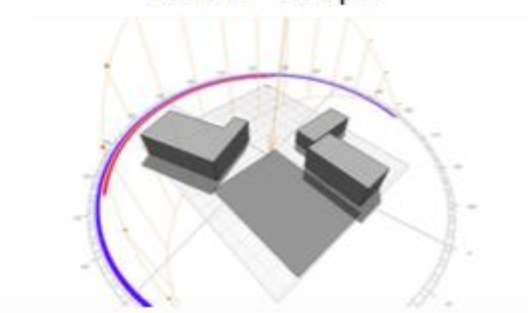
June 21st10:00 am



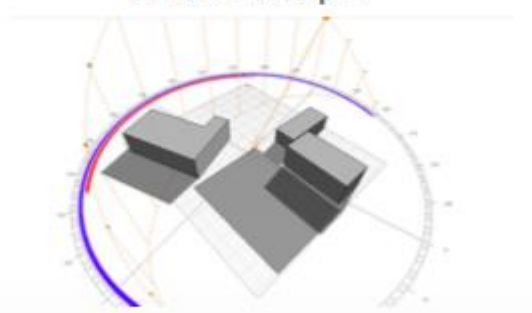
June 21stnoon



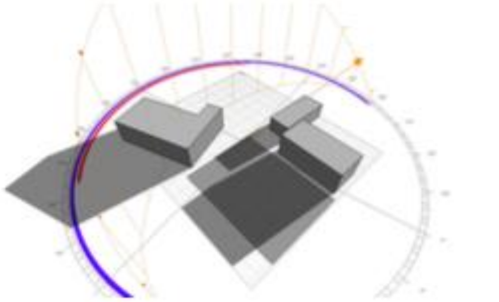
June 21st2:00 pm



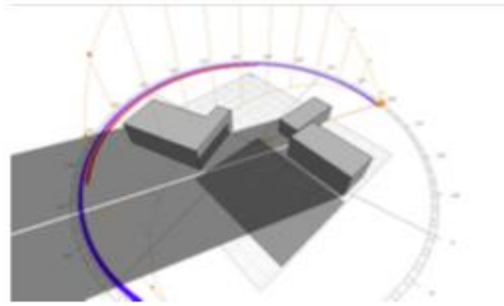
June 21st4:00 pm



June 21st 6:00 pm



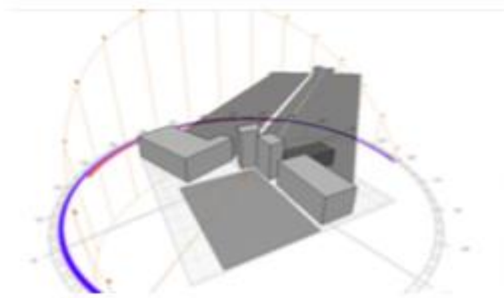
June 21st 7:15 pm



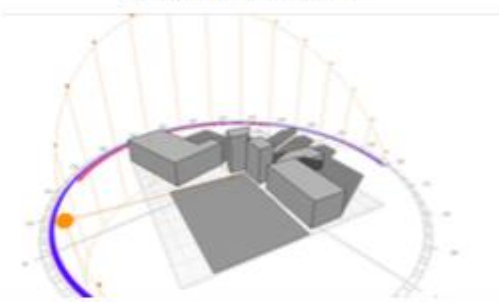
June 21st shadow studies
Sunrise 4:30 am
Sunset 7:15 pm

Summer Solstice modeled with trees

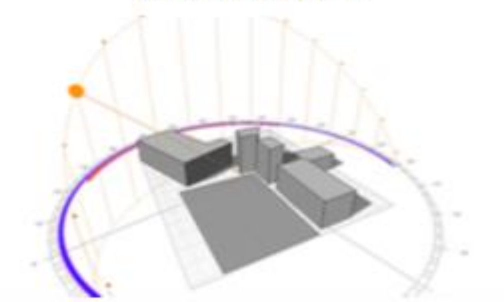
June 21st 4:30 am



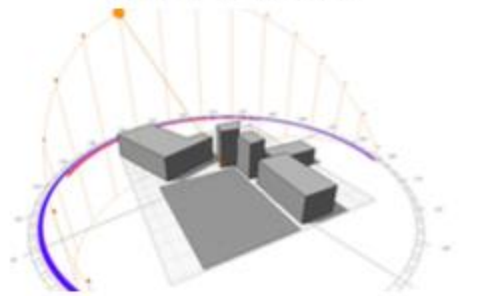
June 21st 6:00 am



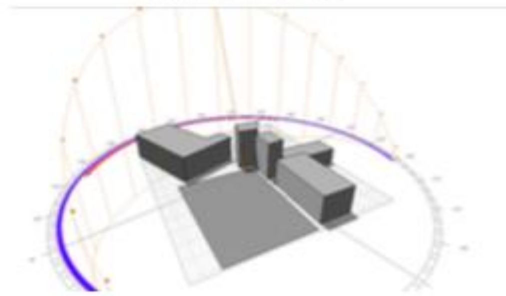
June 21st 8:00 am



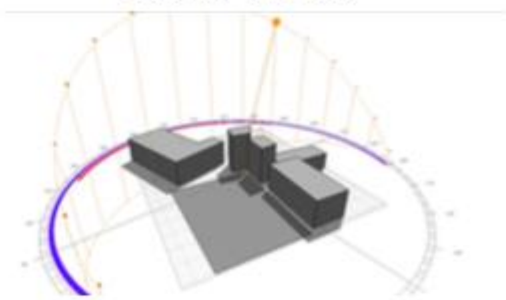
June 21st 10:00 am



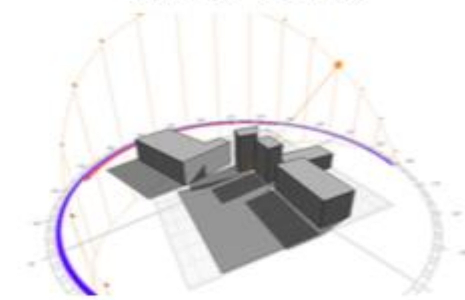
June 21st noon



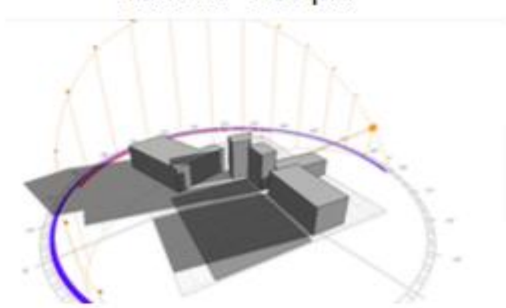
June 21st 2:00 pm



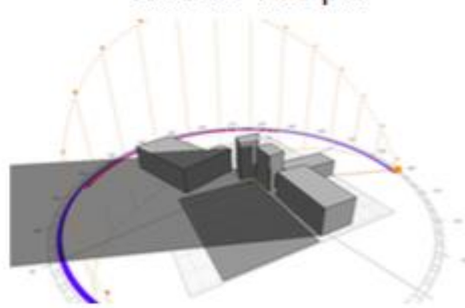
June 21st 4:00 pm



June 21st 6:00 pm



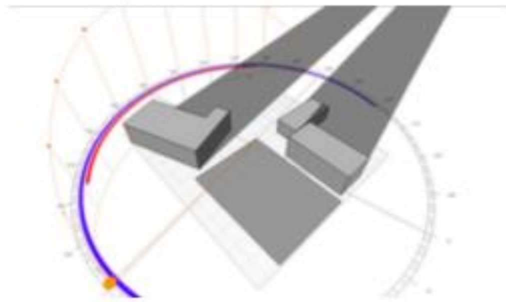
June 21st 7:15 pm



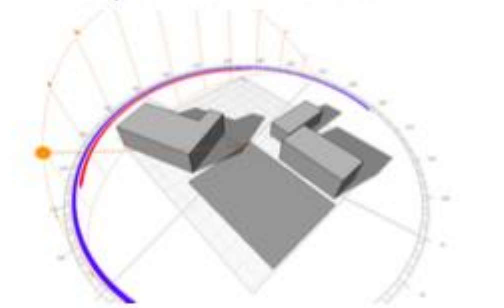
September 22nd shadow studies
Sunrise 5:45 am
Sunset 5:30 pm

Autumnal Equinox

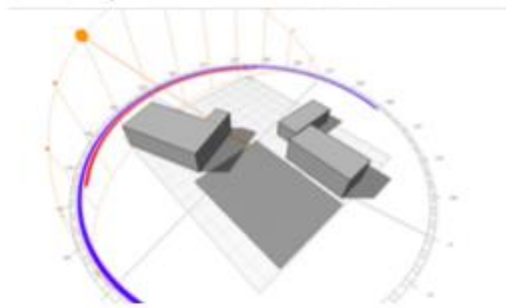
September 22nd 5:45 am



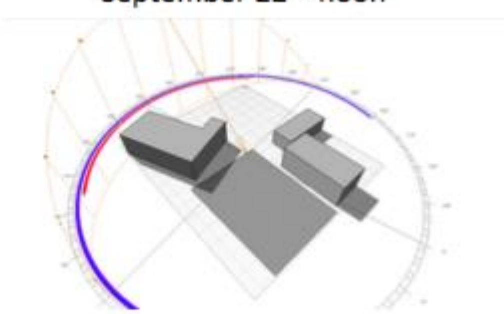
September 22nd 8:00 am



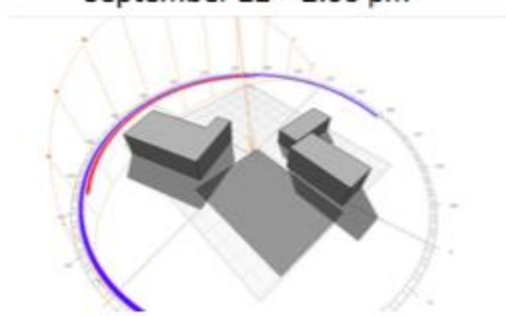
September 22nd 10:00 am



September 22nd noon



September 22nd 2:00 pm



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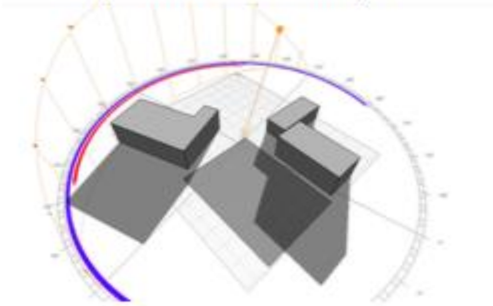
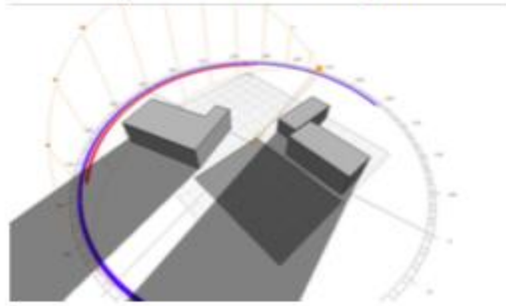


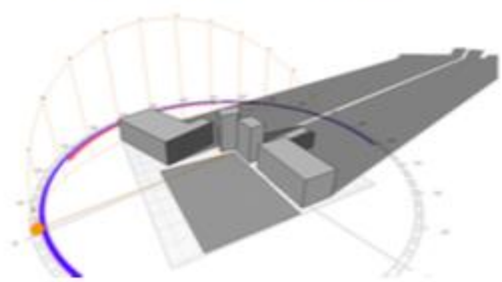
September 22nd 5:30 pm



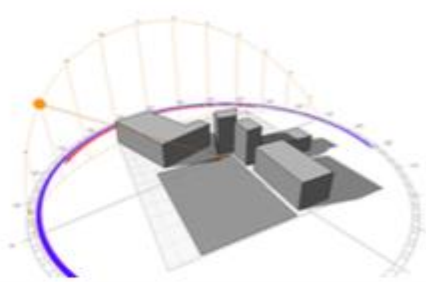
September 22nd shadow studies
Sunrise 5:45 am
Sunset 5:30 pm

Autumnal Equinox modeled with trees

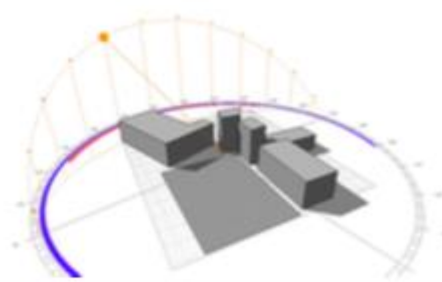
September 22nd 5:45 am



September 22nd 8:00 am



September 22nd 10:00 am



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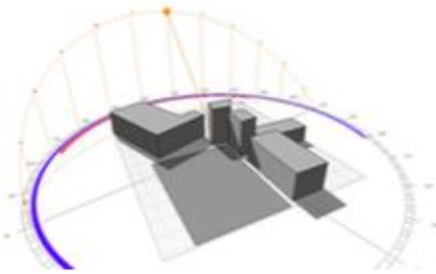

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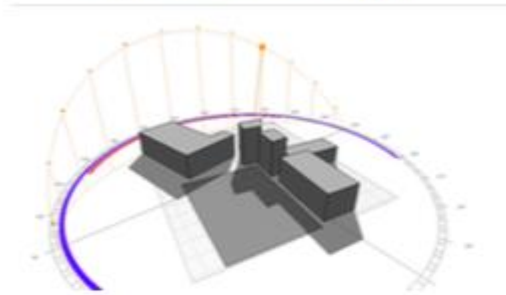
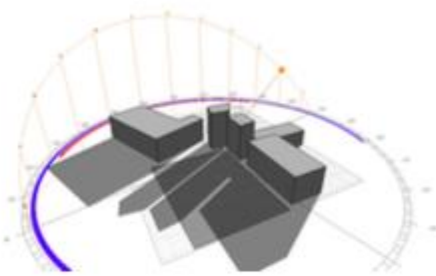
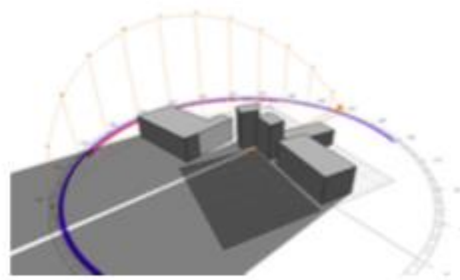


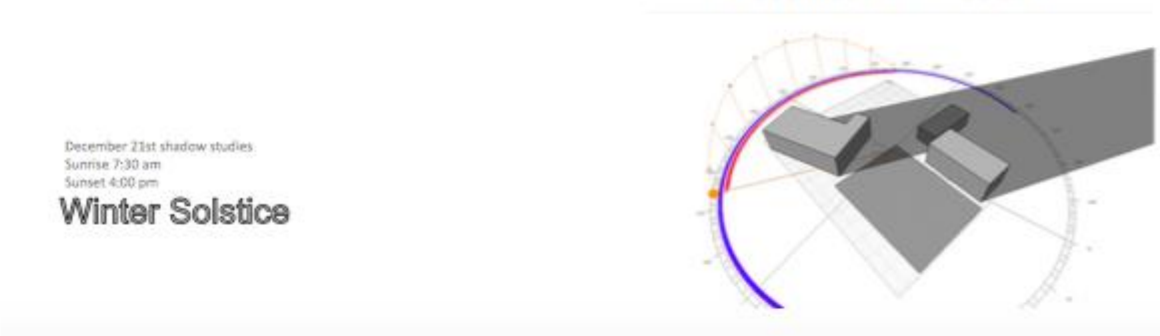
September 22nd 4:00 pm



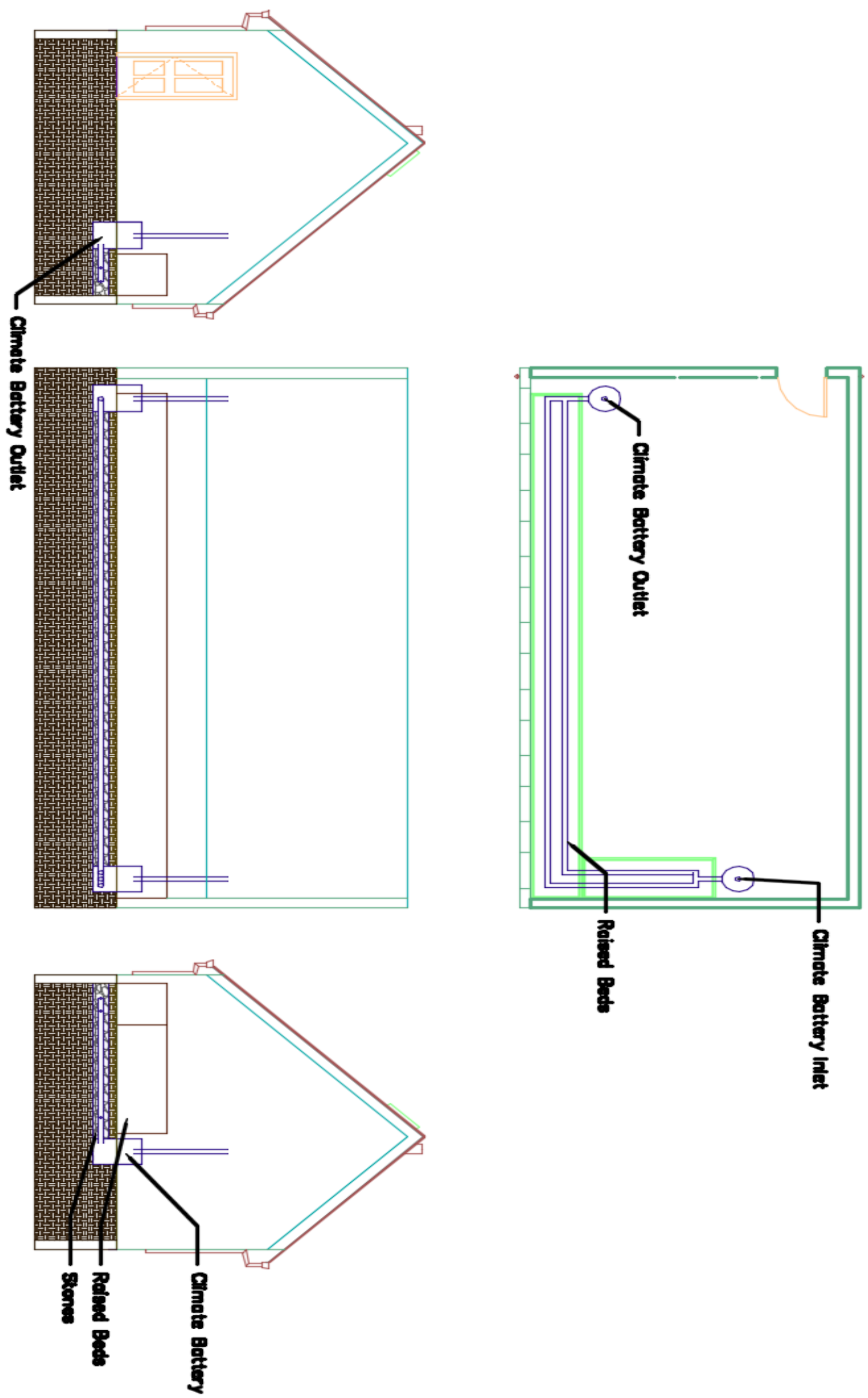
September 22nd 5:30 pm



December 21st 7:30 am



Climate Battery System Cross Section



Bioshelter Electrical System