Worcester Technical High School Greenhouse:
The Repurposing of an Abandoned Structure into a Four-Season Greenhouse
Project Number: SVD-ABGV and SVD-ABEU

A Major Qualifying Project Report submitted to the Faculty of the Worcester Polytechnic Institute in partial fulfilment of the requirements for the Degree of Bachelor of Science in Architectural Engineering by:

Matthew Howard Cody Lattin Leah Morales Derrick Naugler Abigail Sawyer

Submitted on March 22, 2018

Keywords:
- Greenhouse
- Design
- Structural Analysis
- Thermal Analysis
- Structural
- Mechanical

Advised by:
Professor Steven Van Dessel, Major Advisor
Professor Leonard D. Albano, Co-Advisor
Professor Kenneth M. Elovitz, Co-Advisor

Abstract

This project presents the design of a four-season greenhouse that involves the repurposing of an abandoned building on the Worcester Technical High School campus. The team developed a structural design, selected appropriate mechanical systems and developed conceptual drawings, including unique detail drawings that conform to building code and fit the requirements of WPI's Major Qualifying Project. The team focused on architectural engineering principles while balancing the use of the existing structure and integration of newly designed building components.

Acknowledgements

We take this opportunity to thank the people that have supported us over the course of our project. Without their guidance, we would not have been able to complete this project in a timely and successful manner.

First, we would like to thank our advisors Professors Steven Van Dessel, Leonard D. Albano, and Kenneth M. Elovitz for all of their guidance, support and patience during the iterative design development process.

We would also like to thank Siena Mamayek of Simpson Gumpertz & Heger for serving as our mentor over the duration of this project. Her building technology expertise and industry experience proved to be a valuable resource during our analyses and throughout our design process.

Lastly, we would like to thank the following representatives from Worcester Technical High School for providing critical information to guide our research and analyses:

- Kyle Brenner, Principal of Worcester Technical High School
- Dr. Patricia Suomala, Director Career and Technical Education

Capstone Design Statement

The goal of this Major Qualifying Project is to develop a design concept stemming from previous work completed by Worcester Polytechnic Institute students on repurposing an abandoned building on the Worcester Technical High School campus into a four-season greenhouse. This mainly involved developing a suitable structure that works with the existing building, developing a strategy to maintain optimal interior conditions, and creating a comprehensive set of drawings and construction considerations for the high school.

This capstone design experience serves as a stepping stone between school and becoming a professional engineer. The students in this Major Qualifying Project applied a variety of coursework in order to demonstrate that each student achieved design competence in their selected curriculum areas. These students and their selected curriculum areas are:

- Matthew Howard - Building Structural Systems;
- Cody Lattin - Building Structural Systems;
- Leah Morales - Building Mechanical Systems and Electrical & Computer Engineering (See Appendix A: ECE MQP) ;
- Derrick Naugler - Building Structural Systems;
- Abigail Sawyer - Building Structural Systems.

As a capstone design experience, this Major Qualifying Project involved structural calculations to size both wood and steel members to be used in a unique structure that works in conjunction with the existing building. It also involved performing thermal analyses in order to optimize the thermal performance of the building, and sizing an HVAC system in order to maintain the desired interior conditions. The project then culminated with the team making decisions regarding construction materials in pursuance of optimizing the building for the desired use of the owner, and developing design details suited to the custom structure that was designed. Other topics this capstone design experience addressed include interdisciplinary coordination, the application of engineering principles, building performance and sustainability, constructability, ethics, and environmental and societal implications.

Interdisciplinary Coordination

The structural system designed for this greenhouse coordinates with the mechanical system and works within the overall architectural design to define a unique, functional space that is structurally sound, maintained at the desired temperature and humidity levels, as well as aesthetically pleasing.

Collaboration among team members and between disciplines was integral to the completion of this project. Some techniques that were used to maximize coordination include weekly meetings, technical review sessions, online file sharing, and a constant chain of communication within the student group as well as between the students and advisors.

Application of Engineering Principles

The following methods and techniques, including computer-based technologies, were used to perform calculations and prepare design documents:

- Allowable Stress Design was used to perform the structural design and analysis of the members and components that comprise the structural system
- Spreadsheets were used to organize and perform calculations for both the structural and mechanical analyses
- The structural analysis software RISA 2D was used as a check for hand calculations in the structural analysis
- Thermal Peak Load CLF/CLTD Method was used to determine maximum loading in the building
- Simplified Energy Analysis based on ASHRAE TC4.7 was used to perform quasi-steady-state calculations at different outdoor temperatures
- Custom Bin Calculations were used to convert calculated loads to projected energy use
- Dew point calculations were used to analyze the proposed wall construction for moisture transmittance through the selected materials
- AutoCAD was used to prepare the final design drawings
- Google SketchUp was used to create a model for the high school to better visualise the proposed design

Building Performance and Sustainability

In order to ensure satisfactory building performance, the design process applied the following codes and standards: *2015 International Building Code, 2015 International Energy Conservation Code, and ASCE 7-10*.

The design also considered fundamental attributes of building performance including structural efficiency, solar heat gain, heat losses, heat gain, and movement of moisture.Those considerations were incorporated in the design through sizing the structural members appropriately, selecting the proper glazing system, designing a thermally efficient building, and designing systems in the building to handle the high levels of humidity present in a greenhouse.

Constructability

Various systems were studied to develop the final design of this building and to ensure that the Worcester Technical High School students could maximize their role in the construction of the greenhouse. The overall size, height, and layout of the building were considered as well as the size of the systems used and the optimal construction schedule.

Ethics

All professional engineers assume a level of responsibility that requires high standards of honesty and integrity. The Major Qualifying Project team replicated these standards throughout the project. We followed the *NSPE Code of Ethics for Engineers* in that we aimed to hold paramount the safety, health and welfare of the public, act as a faithful agent of the Worcester Technical High School, and conduct ourselves honorably, responsibly and ethically.

Environmental and Societal Implications

In this project, the team acknowledged the environmental and societal implications of the work completed. The project is located on an abandoned site, and a substantial amount of existing construction was reused to minimize environmental impact. This project also aimed to revitalize an area of the Worcester Technical High School campus that is often overlooked by high school students as the pass by on their way to class.

Accordingly, this report demonstrates that the student authors completed a major design project that utilizes knowledge and skills acquired in earlier course and project work and that the project incorporates engineering standards and realistic constraints. By completing this project, the students demonstrated the ability to design a system, component, or process to meet desired needs.

Executive Summary

During the 2015-2016 academic year, Worcester Technical High School (WTHS) challenged WPI students to develop a design to repurpose an abandoned building on the school's site into a greenhouse. The redesigned structure would be a space constructed by students in the WTHS‘ construction and engineering programs and utilized by their culinary arts students.

The building to be repurposed is a 32‘ by 42‘ structure that consists of exterior stone walls, minimal interior wood-stud partitions, and a dilapitaded wood-framed roof. It is bordered by a parking lot on the east side, wooded areas on the north and west sides and a cleared portion of land on the south side.

This project was first taken on by WPI students in a Building Envelope Design class in January of 2016. The culmination of their work was an initial design, selected by representatives of the high school, that the high school wanted to pursue. Our work aims to develop the design concept from these students‘ work into a design for an energy efficient greenhouse. The team split this work into the following objectives: to develop a suitable structure that works with the existing building, to develop a strategy to maintain optimal interior conditions, and to create a comprehensive set of drawings and considerations for the WTHS.

Methodology:

After performing background research on the methods and materials commonly used in modern construction of greenhouses, the team chose to pursue the use of wood and steel for the structural components and the use of glass and polycarbonate for the glazing system.

The team began by extracting the building requirements from the 2015 Edition of the *International Building Code* (IBC) and the *International Energy Conservation Code* (IECC). Per the IBC, this building is classified as a Group U occupancy and permitted to be a Type VB construction type which allows for maximum flexibility in construction materials.

Then we performed a structural analysis using the method of Allowable Stress Design and loads from both the IBC and *ASCE 7-10*. The main structure in this building consists of rafters, five beams that run the length of the building, and four arches that transfer the load to the foundation. A lateral system to resist forces in the longitudinal direction of the building was also developed. Before beginning the analysis, the decision to use simple connections was made to provide an ease of construction for the high school. We performed all of our calculations by hand and used the simple structural analysis software RISA 2D as a check.

A mechanical system also had to be incorporated into the building for the high school to use the space year-round. After performing analyses using the Thermal Peak Load CLF/CLTD Method and a Simplified Energy Analysis based on ASHRAE TC4.7, the loads for the building were determined and an HVAC system was selected.

As part of the project, detail drawings were developed through an iterative process and using details provided by specific manufacturers.

Results and Discussion:

The structural system that came from our structural analysis was a set of 10” x 10” wooden arches, 8” x 10” beams that run the length of the building, 2” x 6” rafters spaced 6’ on center, and a lateral bracing system consisting of 0.375” diameter galvanized steel cable bracing. The arches sit upon footings with dimensions of 4’ x 1.5’ for the footings located in the corners of the building and 7’ x 1.5’ for the footings elsewhere. These members were sized using the dead load of a glass glazing system which means the lighter, more thermally efficient polycarbonate could also be used on this structure.

In order to maintain optimal interior conditions the team selected the Effinity Unit Heater developed by Modine HVAC and a fabric air dispersion product by Ductsox Corporation. Ventilation would also be utilized during the warmer months to provide air flow.

Recommendations and Conclusions:

Aspects of the building that were outside of the scope of this project include electrical work, plumbing and analysis of the structural integrity of the existing wall. The team did leave space in the floor plan for electrical equipment, but specific equipment and equipment sizes were not developed. The team also designed a bathroom adjacent to the existing municipal sewer hook-up, however plumbing for sinks and any hoses was not addressed. Additionally the team did not evaluate the structural integrity of the existing stone wall. Instead, we designed a structure that does not introduce any new lateral loads on the existing masonry as well as a new interior wall that would aid in supporting the existing masonry. All of these areas should be addressed before construction of the greenhouse begins.

In conclusion, the team was able to develop a structure that works in conjunction with the existing building while salvaging the existing exterior masonry wall. The team was also able to develop a strategy to maintain the desired interior conditions for use of the greenhouse year-round as well as develop custom details for the unique structure.

Table of Contents

Abstract i
Acknowledgements ii
Capstone Design Statement iii
Executive Summary vii
Table of Contents ix
Table of Figures xi
Table of Tables xii
1 Introduction 13
2 Background 15
2.1 Components of the Greenhouse 15
2.1.1 Case studies 15
2.1.2 Commonly used glazing systems, structural systems, and insulation 17
2.2 Existing Conditions and Previous Work 19
2.2.1 Preliminary Design from Building Envelope Design Class 24
2.3 Summary 25
3 Methodology 26
3.1 Building Demands 26
3.2 Structural Design and Analysis 27
3.2.1 Rafters, Beams and Main Arch System 27
3.2.2 Application of RISA-2D 31
3.2.3 Lateral System 32
3.2.4 Footing Design 34
3.3 Thermal Analysis 38
3.4 Dew Point Calculation 45

4 Results and Discussion 48
4.1 Final Design 48
4.2 Structural System 48
4.3 HVAC System 49
4.4 Final Drawings and Details Using a Polycarbonate Glazing System 50
4.5 Final Drawings and Details Using a Glass Glazing System 63
5 Recommendations and Conclusions 65
Bibliography 68
Appendix A: ECE MQP – Self Sustainable Greenhouse 71
Appendix B: Notes on Code Review and Relevant Definitions 91
Appendix C: Loads Used in Structural Analysis 97
Appendix D: Wind Load Calculation 99
Appendix E: Member Qualities Used in Calculations 101
Appendix F: Rafter Sizing Calculations 102
Appendix G: Rafter Dead Load Calculations 110
Appendix H: Beam Sizing Calculations 111
Appendix I: Main Arch System Sizing Calculations 115
Appendix J: Lateral Load Calculations 131
Appendix K: Equations Used in Structural Spreadsheets 134
Appendix L: Footing Calculations 140
Appendix M: Mechanical Calculations 143
Appendix N: Dew Point Analysis Calculations 146
Appendix O: Renderings of Proposed Greenhouse 148
Appendix P: Scaled Polycarbonate Drawings 150
Appendix Q: Scaled Glass Drawings 169

Table of Figures

Figure 1.1 (left): The WTHS campus (does not include buildings in bottom right) with the site of the existing building outlined 13

Figure 1.2 (right): An enlarged picture of the site of the existing building 13

Figure 2.1: Entrance to the site with the existing building 19

Figure 2.2: Section of the existing wall construction and a picture of the existing wall at a window opening 20

Figure 2.3: Exterior view of the existing structure (East Wall) 21

Figure 2.4: Interior of the existing building 21

Figure 2.5: Crawl space next to foundation of existing building 23

Figure 2.6: South elevation from design developed in 2016 24

Figure 2.7: East elevation from design developed in 2016 24

Figure 3.1: Main arch system with loads applied 29

Figure 3.2: RISA model of main structure 31

Figure 3.3: Soil survey of the greenhouse site 34

Figure 3.4: Floor plan with labeled footing locations 35

Figure 3.5: Chart categorizing the heat loss by construction 42

Figure 3.6: Initial Wall Dewpoint Analysis 46

Figure 3.7: Wall Dewpoint Analysis 47

Figure 4.1: Google SketchUp model of the final design 48

Table of Tables

Table 2.1: Comparison of Common Glazing Systems (Moore, 2016) 17

Table 3.1: Summary table of loads used in structural design 28

Table 3.2: Concentrically Loaded Footing Calculations 36

Table 3.3: Eccentric Footing Calculations.. 37

Table 3.5: Peak heat gain by month an hour of the existing wall with glass roof............ 41

Table 3.6: Proposed Wall U-Value Calculation 42

Table 3.7: Peak heat gain/loss of the construction options... 43

Table 3.8: Space Cooling/Heating from the Simplified Energy Analysis........................ 44

1 Introduction

During the 2015-2016 academic year, Worcester Technical High School (WTHS) challenged WPI students to develop a design to repurpose an abandoned building on the school's site into a greenhouse. The redesigned structure would be a space for students in the school's culinary arts program to grow their own plants to use in their cooking. Another goal was to design a structure that students in the school's construction and engineering programs could build.

The building to be repurposed was used years ago as a tuberculosis lab for a state hospital located on the same site. Now, the 32' by 42' structure consists of exterior stone walls with large openings for windows and doors and minimal interior wood-stud walls. The roof barely sits atop these walls due to damage and rotting materials. The building sits on property within Green Hill Park that is bordered by a parking lot on the east side and wooded areas on the west and north sides. The south side of the building faces a flat open area intersected by frequently used pathways leading from the main street, around the building and up to the high school. The location of the existing building can be seen in Figures 1.1 and 1.2 below.

Figure 1.1 (left): The WTHS campus (does not include buildings in bottom right) with the site of the existing building outlined

Figure 1.2 (right): An enlarged picture of the site of the existing building

In January 2016, the architectural and civil engineering students at WPI in the Building Envelope Design class first conducted a site visit to survey and gather necessary information about the existing site. The WPI students then compiled a drawing set of existing conditions to use to develop their designs. The main factors considered during the design process were:

- Repurposing the current building;
- Ensuring the proposed design could be easily assembled;
- Designing a greenhouse that could be used throughout all four seasons;
- And providing eco-friendly amenities, if possible.

The purpose of this Major Qualifying Project (MQP) is to develop the design concept from the 2016 class project into a design for an energy efficient greenhouse. The MQP was split into the following objectives: to develop a suitable structure that works with the existing building, to develop a strategy to maintain optimal interior conditions, and to create a comprehensive set of drawings and considerations for the WTHS.

2 Background

2.1 Components of the Greenhouse

Designing a greenhouse requires understanding the methods and materials commonly used in the modern construction of greenhouses, including glazing systems, structural members, and insulation. That understanding comes from review of case studies along with manufacturer literature and performance data.

2.1.1 Case studies

In order to better understand what makes an energy efficient structure, we examined a case study of a net zero building. A net zero building is energy efficient and uses no more energy than the renewable energy it generates on the site. Homeowner Eric Thomas discusses factors that contribute to an affordable, net zero house in his article "A Net-Zero-Energy House for $125 a Square Foot" (Thomas, 2013). This article explains Thomas' thought process when constructing an affordable and energy-efficient house in Seattle, WA. He worked with Ted L. Clifton of Zero Energy Home Plans throughout the whole process.

The foundation was slab-on-grade with R-20 rigid foam insulation underneath. The contractor easily applied an acid stain directly to the slab in order to make it a durable and attractive floor. Within this concrete slab are loops of PEX tubing filled with a glycol solution heated by a Unico Unichiller air to water heat pump. The heat pump extracts heat from the outdoor air, transferring the heat to water which is then used for space heating and preheating domestic water. One main focus of Thomas' project was to make the exterior shell of the building airtight and maintain high R-values in the shell. For this, Thomas chose structural insulated panels (SIPs) made out of expanded polystyrene (EPS) foam and oriented strand board (OSB) to be erected on the concrete slab. These panels have a R-26 rating when the ratings of the siding and drywall are included. The windows have triple pane glass with low e-coatings and argon gas fill between panes. The house also has a balanced ventilation system using a Fantec 240-cfm supply fan, delivering fresh outdoor air to the bedrooms and living room. Exhaust fans were located in the kitchen and bathrooms. These passive and active systems were able to keep the house comfortable year-round while still producing a surplus of energy (Thomas, 2013).

Lindsey Schiller explores the topic of net zero energy greenhouses in her article "Is a Net-Zero Energy Greenhouse Really Possible?" Schiller highlights that the materials used for traditional greenhouses do not make it easy to construct an energy efficient structure, especially in places with extreme climates, however, many aspects of greenhouses can be modified to make the structure more energy efficient.

In most cases, greenhouses collect far too much heat. This excess heat is then vented in order to keep the greenhouse at the desired temperature. Schiller also notes that greenhouses in harsher climates require additional systems to maintain the right temperature for year-round plant growth. For harsher climates, a better option would be to use thermal storage methods to recycle the excess heat for use at night and during colder months.

In her article, Schiller states, "the final step to building a net-zero energy greenhouse, is supplying, or offsetting, the electricity usage" (2017). She does note that not all greenhouses need electricity and in mild climates, eliminating electricity from the greenhouse design is an excellent option. However, when constructing a greenhouse in an area that experiences extreme climates, electricity might be essential in order to maintain the desired interior conditions. Exhaust fans, for example, are useful electrical equipment used to prevent greenhouses from overheating. One way to supply the energy for any necessary electrical equipment is to integrate a solar panel system in the greenhouse. When installing this system, there are three options to consider when deciding how the panels will supply energy to the structure:

- An off-the-grid system would use batteries to store the energy collected by the panels;
- A grid-tied solar array is connected to the utility power grid;
- A grid-tied system with backup batteries uses batteries to store the energy collected but is still connected to the power grid.

Both of these cases demonstrate exemplary techniques used during the design and construction process and are not what is typically done during the design and construction of an ordinary greenhouse. Although designing a net zero greenhouse is not one of the goals of this project, we considered some of the techniques discussed by Thomas and Schiller, such as incorporating insulation, in order to improve the efficiency of our design.

2.1.2 Commonly used glazing systems, structural systems, and insulation

Traditionally, greenhouses are constructed using a glass glazing system with an aluminum structural frame, but that construction is not always the best for every application.

Other than glass, the two most prominent materials used in greenhouse glazing systems are polycarbonate and acrylic. These glazing materials can come in different thicknesses and arrangements. Three common options for glass are single pane, double pane and double pane with a low-emissivity coating. A few options for polycarbonate are single layer, double wall, triple wall, and 5-layer. Lastly, the best option for acrylic is the double wall system. A comparison chart of these different options and their properties can be seen in Table 2.1 below.

Table 2.1: Comparison of Common Glazing Systems (Moore, 2016)

	Lifespan (Years)	Light Transmittance	R-Value	Weight (psf)	Cost	Pros	Cons	Recommended Uses
GLASS								
Single Pane	25+	88-93%	0.9	3.3	Low	Low cost	Low R-Value; Heavy	Vertical applications where R-Value is not of concern
Double Pane	25+	75-80%	1.4	3.3-6.6	$5/sq ft	Balance of light transmittence and insulation; Easily sealed	Heavy	Vertical applications and view windows
Double Pane, Low-e	25+	60-70%	2-4	3.3-6.6	High	Can be used for roof applications	High cost	Roof applications if glass is necessary
POLYCARBONATE								
Single Layer	10-15	90%	0.9	0.184	Low	Low cost	Low efficiency	Few recommended uses
Double Wall (6-10mm)	10-15	80-85%	1.5 - 2	0.276 - 0.46	$3/sq ft	Light-weight and durable	Low R-Value	Wide range of roof or wall applications
Triple Wall (8-16mm)	15-20	70-80%	1.8 - 2.3	0.368 - 0.55	$5/sq ft	Balance of light transmission and insulation	Prone to thermal expansion	Almost any roof or wall application, especially in colder climates
5-Layer (32mm)	15-40	50%	4	1.47	$7/sq ft	High R-Value	Low light transmission	Climates with harsh and sunny winters; areas used for working or sitting
ACRYLIC								
Double Wall (16mm)	20-30	80-90%	2	0.9	$5/sq ft	Balance of light transmission and insulation; Longer lifespan than polycarbonate	Prone to thermal expansion	Almost any wall or roof application

Glass as a glazing system is long-lasting and transmits light well when properly cleaned and maintained. On the other hand, it is very heavy and requires strong supporting members. Single- and double-pane glass also have low R-Values making them poor insulators which may be acceptable for greenhouses that are used seasonally, but are not well-suited for greenhouses in climates where temperatures often drop below freezing.

Polycarbonate panels are engineered to resist loads, resist damage from UV light, and prevent discoloration over time while lasting a minimum of 10 years. Polycarbonate systems allow for a high percentage of light transmittance and diffusion which is beneficial for plant growth. The panels are relatively low in cost, lightweight and easy to install. One drawback of polycarbonate is that its thermal expansion coefficient is roughly seven times that of glass ("Coefficients of Linear Thermal Expansion").

Acrylic glazing, or plexiglass, has very similar properties to those of polycarbonate glazing. Acrylic glazing systems are very durable and well-suited for use in harsh climates because it can withstand heavy rains, snow, wind and even hail. Double Wall Acrylic is long-lasting and also cost-effective given its relatively high R-Value. This material is also prone to thermal expansion with a thermal expansion coefficient approximately eight times that of glass ("Coefficients of Linear Thermal Expansion"). This can lead to difficulties in the design and installation of acrylic systems.

Common materials for the greenhouse frame include wood, aluminum and steel. Wood is popular because it is easy to assemble, low in price, and flexible in its application. When working with wood, one has to consider the humidity of the surrounding space as well as the moisture content of the wood itself. Aluminum is lightweight, strong and corrosion resistant. However, aluminum is expensive compared to alternative materials. Steel is similar to aluminum as certain treatments, such as epoxy coatings, can be applied to make steel resist corrosion, though these treatments can require maintenance. Steel members are stronger than aluminum members of comparable size but are also heavier.

In most cases, greenhouses have little to no insulation in their wall structure because the majority of the envelope consists of glazing. If a greenhouse does contain walls that are not glazing, the material used to construct these walls would have to withstand the raised humidity levels that exist within greenhouses. Mineral wool, closed cell rigid board, and insulated concrete masonry units, are materials that can be applied in greenhouse construction due to their high resistance to moisture.

Based on our research of the materials typically used in greenhouses, the team chose to pursue a select few. For the glazing system, glass and polycarbonate were analyzed. Glass was chosen due to its popularity and widespread use in greenhouses and was also part of the original design presented to the Worcester Technical High School. Polycarbonate was investigated because of its improved performance over glass.

Wood and steel were analyzed as the main structural materials for reasons similar to those of the glazing systems: wood was chosen because it was the original design, and steel was chosen because of its improved performance.

2.2 Existing Conditions and Previous Work

The existing structure belonged to a state hospital and was used as a tuberculosis lab decades ago. The site belongs to the Green Hill Park Coalition. The Green Hill Park Coalition has allowed the school to use the building with the request that the school transform the building into something involving nature. The greenhouse would meet that goal and be a multi-function building that park-goers can admire and students of WTHS can use for their education.

The structure runs lengthwise North to South and is located beside a parking area. The entrance to the site is shown below in Figure 2.1.

Figure 2.1: Entrance to the site with the existing building

The existing structure is dilapidated, but some parts are salvageable. The building is a very simple structure with four thick exterior walls, two interior walls that split the building into three different spaces, and a wood framed roof that rests upon the exterior walls. The exterior wall is made up of large granite blocks as the exterior face, a small air gap and a layer of brick. This brick is then surfaced with a white tile. This assembly is shown below in Figure 2.2.

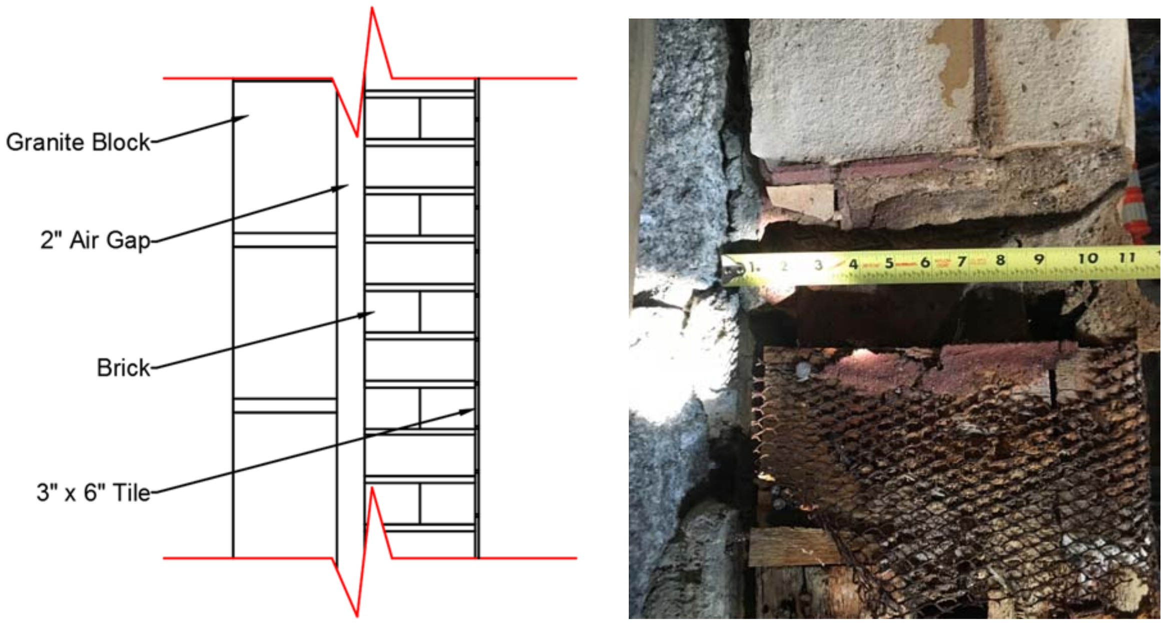


Figure 2.2: Section of the existing wall construction and a picture of the existing wall at a window opening

The walls contain large openings for windows and doors that have long-since been replaced by plywood in attempts to keep trespassers out. The exterior granite block portion of the walls is in relatively good shape as can be seen in Figure 2.3 below.

Figure 2.3: Exterior view of the existing structure (East Wall)

Upon initial assessment, the granite blocks appear to have little to no damage. In contrast, the interior tile and brick portion of the wall is in very poor shape as seen in Figure 2.4 below.

Figure 2.4: Interior of the existing building

Many tiles have broken and fallen off the interior face of the wall. The bricks behind the tile are also deteriorated towards the top of the wall. The lower courses of brick appear to be in decent condition, but the mortar would need repair if the brick portion of the wall were to be salvaged.

The two interior partitions in the building are made up of wood joists, lath, and the same tile that is used on the interior face of the exterior wall. These walls are in worse condition than the interior face of the exterior wall. The wood is rotting, and the tiles have either fallen off or been vandalized. They are also not part of the structural system that supports the roof.

The existing roof is constructed using wooden trusses surfaced with plywood and asphalt shingles. Many sections of the roof are completely caved in while the sections that are still standing are severely warped. A significant portion of the eastern side of the roof is collapsed into the building.

Many unknowns surround the design and condition of the current foundation. A set of drawings depicting the existing structure is unavailable which means that the exact design of the foundation cannot be determined without excavating the area around the building. There is, however, a crawl space that runs around the perimeter of the building that can be used to deduce a few details on the foundation. This narrow crawl space is only under part of the floor and is shown in Figure 2.5 below.

Figure 2.5: Crawl space next to foundation of existing building

Using this crawl space, it was determined that the floor slab is slab-on-grade and the exterior granite wall is supported by a continuous footing. Part of this footing can be seen in Figure 2.5 above. A key assumption we are making in our design is that the floor slab notches into the outer stone wall and is not simply cantilevering over the crawl space depicted in Figure 2.5. The parts of the foundation that can be seen in the crawlspace are in good condition, however there are still many unknowns surrounding the existing foundation that have to be considered in our final design.

Overall, many existing structural components are in conditions beyond repair, but some components can be salvaged and used. The structural integrity of the existing components served as a guide in the design of the greenhouse as it is one of the goals of the WTHS to reuse as much of the existing structure as reasonably possible.

2.2.1 Preliminary Design from Building Envelope Design Class

The preliminary design developed in 2016 drew inspiration from the Tower Hill Botanic Gardens in Boylston, MA - more specifically, the arches used in one of the botanic garden buildings. Drawings of the south and east facades of this design can be seen below in Figures 2.6 & 2.7.

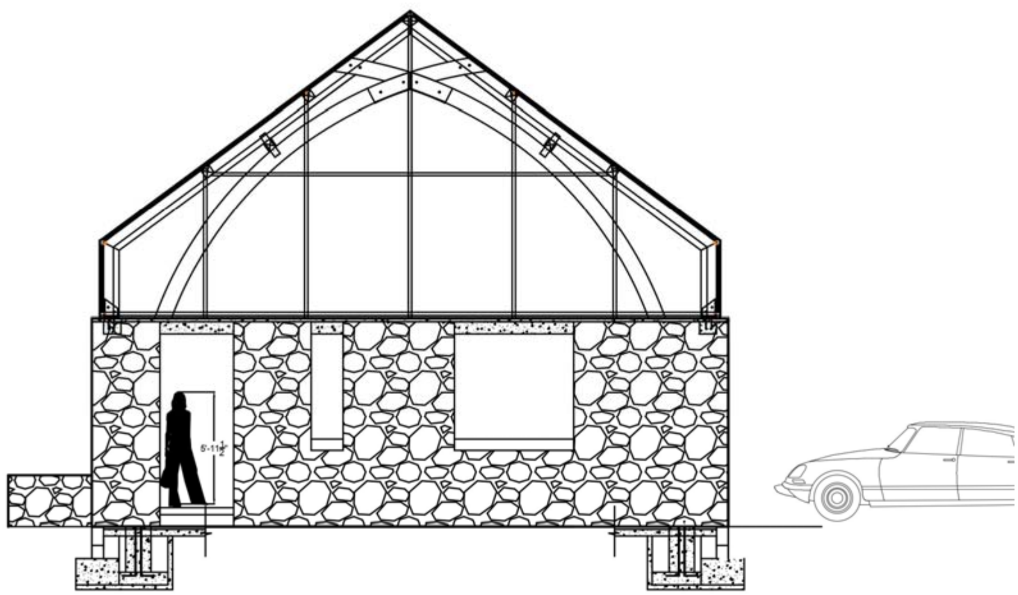


Figure 2.6: South elevation from design developed in 2016

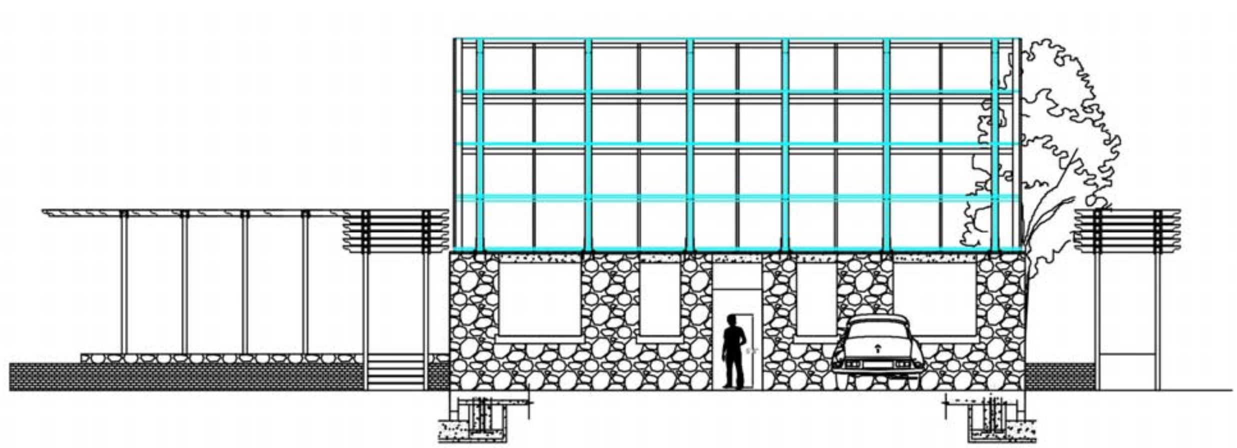


Figure 2.7: East elevation from design developed in 2016

The arches shown in Figures 2.6 and 2.7 are a key feature of the design. Incorporating these large arches requires a strong base. The arches will sit on concrete footings that can be cast into the existing crawl space under the building. The arches and new foundations then carry a majority of the loads from the new roof structure. That way, the existing walls, in their unknown structural state, will not carry any additional load. To help stabilize the wall, the design includes a concrete beam to be cast on top of the existing walls. Large wooden beams span between the arches to support the roof members. Smaller members as well as rafters sit on top of the longitudinal beams to support the proposed double-pane glass roof.

Additional features were added to the design to make the building more versatile. Gutters on the perimeter of the roof collect and direct rain water to a collection tank at the back of the building. This rainwater is available to water the plants. A covered trellis walkway around the building leads to a raised, covered seating area. This seating area was designed to be handicap accessible. Solar panels on top of the trellis area provide power for the greenhouse and shade the seating area.

2.3 Summary

After the completion of preliminary research and a site analysis, the team decided to pursue the use of the insulation systems discussed by Thomas and Schiller in our case studies. In regards to the glazing system, the team decided to pursue the possibilities of using glass and polycarbonate as glass is a standard material and polycarbonate performs better than both glass and acrylic. The structural systems that the team chose to evaluate are a wooden system and steel system. We decided that aluminum would not be advantageous with the large scale of the design. Wood and steel were selected in order to provide a grandiose structure that is the focal point of the building. The team then used the initial design that came from Building Envelope Design class as a starting point for our analyses and design.

3 Methodology

3.1 Building Demands

One of the preliminary steps in this project was to research relevant building codes and how they apply to our design. Massachusetts uses the *Massachusetts State Building Code* (MSBC), currently in its ninth edition, that is published by the Board of Building Regulations and Standards. This code is made up of international model codes and a series of amendments adopted by the Board of Building Regulations and Standards. We based our code review on the 2015 edition of the *International Building Code* which is referenced by the Ninth Edition of the MSBC. It is important to note that the Board of Building Regulations had yet to release any amendments to this edition while we were performing our code review (Commonwealth of Massachusetts, 2010). In addition to the 2015 IBC, we reviewed the 2015 Edition of the *International Energy Conservation Code* (IECC) and *ASCE 7-10: Minimum Design Loads for Buildings and Other Structures*, both of which are referenced by the IBC.

The IBC divides buildings into 10 different groups according to their uses. The code describes a Group U occupancy as accessory and miscellaneous structures that do not fit into any other specific occupancy. Furthermore, greenhouses are listed as an example of a structure that would fit into this occupancy classification. Therefore, the proposed greenhouse qualifies as a Group U occupancy because it is accessory to the school's main buildings.

The IBC also organizes buildings into one of nine different construction types. Buildings are limited to these construction types for a given occupancy classification and desired building size. Our greenhouse is within the height and area limits for all construction types of Group U occupancies. For a Group U, Type VB building, the building height is limited to 40 feet or 1 story above grade plane and the building area is limited to 5,500 square feet. The preliminary design with which we were presented is well within all of these limitations. Therefore, we chose to design the greenhouse based on the requirements for a Type VB construction in order to maximize the flexibility of construction materials. This is the least stringent building type in the code as structural elements, exterior walls and interior walls can be constructed using any materials permitted by code.

In addition to these takeaways, there are no fire resistance requirements for any components of the building, nor is an automatic sprinkler system required (Table 504.3, *International Building Code*, 2015).

The IBC also provides occupant load factors, which, when used in conjunction with the square footage of a space, can be used to define the occupant load of that area. We used the factor of 300 gross square feet per person that is associated with an agricultural building to determine that the building is required to have one exit per Table 1006.2.1 in the IBC. Because the high school might use this space for instructional purposes, we also analyzed the means of egress using the 30 net square feet per person listed in the IBC for shops/vocational room areas. Similar to the prior occupant loading, this new loading requires only one exit. The existing building has two exits, both of which are retained in our design. Therefore, the number of exits in our design is sufficient. An additional requirement for the means of egress in this greenhouse is that any occupiable space cannot be more than 300 feet from an exit (*International Building Code*, 2015). This requirement is also met because the building is only 42 feet long.

Per Section C402.1.1 of the IECC, greenhouses are exempt from any building envelope requirements in the code (*International Energy Conservation Code*, 2016). A table with notes taken during the code review as well as some notable definitions from Chapter 2 of the *International Building Code* is included in Appendix B.

3.2 Structural Design and Analysis

3.2.1 Rafters, Beams and Main Arch System

The structural design for this building utilizes the Allowable Stress Design (ASD) method which, per the 2015 Edition of the IBC, requires that 9 different load combinations be considered. These load combinations are listed below.

$$D + F$$

$$D + H + F + L$$

$$D + H + F + (L_r \text{ or } S \text{ or } R)$$

$$D + H + F + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$$

$$D + H + F + (0.6W \text{ or } 0.7E)$$

$$D + H + F + 0.75(0.6)W + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$$

$$D + H + F + 0.75(0.7)E + 0.75L + 0.75S$$

$$0.6D + 0.6W + H$$

$$0.6(D + F) + 0.7E + H$$

The meanings of the symbols used in the above load combinations as well as their values can be found in Table 3.1 below. The symbol "W" in the load combinations stands for the wind load. This wind load is represented by four different loads in Table 3.1 to account for the location of the load on the building. *ASCE 7-10* and the IBC were used to determine the value of these loads.

Table 3.1: Summary table of loads used in structural design

Loads			Units
L	Live load	0	psf
D	Dead load	11.7	psf
Lr	Roof live load	14.18	psf
H	Lateral earth pressure	NA	
F	Load due to fluids	NA	
S	Snow load	15.4	psf
R	Rain Load	0	psf
WW_r	Windward roof load	4.4	psf
WW_W	Windward wall load	11.2	psf
LW_r	Leeward roof load	-9.8	psf
LW_W	Leeward wall load	-8.1	psf
E	Earthquake load	NA	

A more detailed table, including calculations and sources can be found in Appendix C. Before continuing with our analysis, we made the decision that our structure would use simple connections for a majority of the joints in the frame. We made this decision in order to provide an ease of construction for the high school. This is because simple connections transfer only shear forces and not bending moments. In other words, the connections in our design can be a bolted connection instead of a heavily reinforced connection. The joints that are required to be moment resisting connections are the joints between the rafters and the vertical members that connect to the top of the existing wall. The forces that these connections are required to resist are less than 200 lbs while a simple Simpson Strong-Tie PS Strap can resist over 750 lbs ("Simpson Strong-Tie Wood Construction Connectors", 2017). Because our structure includes a majority of simple connections, i.e. non-moment-resisting connections, racking of the structure is prevented using a lateral bracing system that provides lateral stability.

Next, we applied the loads to the building in order to calculate the required sizes of the structural members. The loads applied to the main arch system can be seen in Figure 3.1 below.

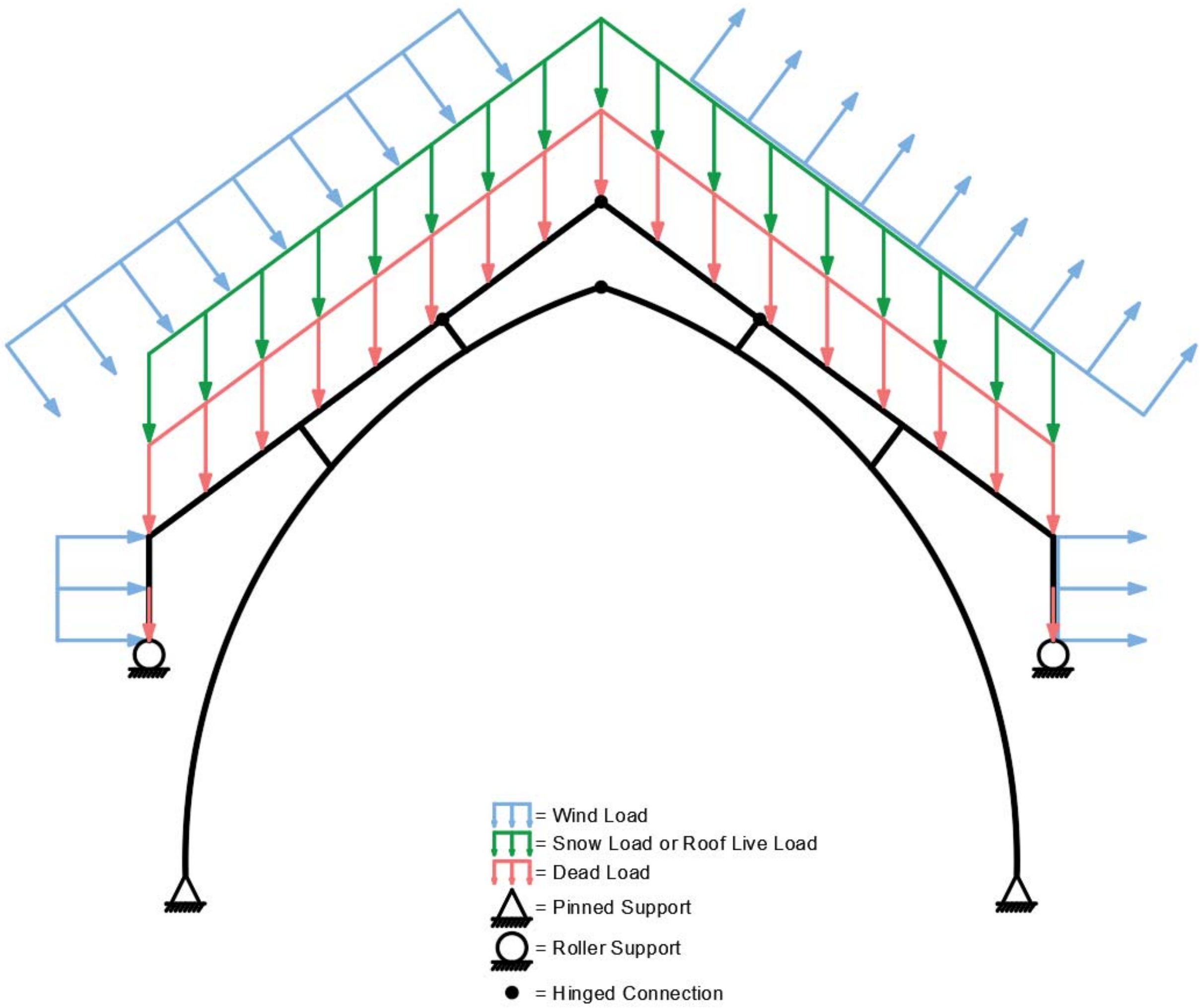


Figure 3.1: Main arch system with loads applied

The snow and wind loads applied to the structure are gathered by the glazing system and they, along with the weight of the glazing system, would be transferred into the rafters, to one of the five beams that run the length of the building, to the arches and finally into the foundation.

Sizes of the structural members, for both steel and wood members, were calculated in the same order as the load path.

The required size of the rafters was found using deflection criteria listed for glass which is equal to length of each pane of glass divided by 175 (Section 2403.3, *International Building Code*, 2015). The team performed calculations for rafters spaced in 1 foot increments from 1 foot to 8 feet. Depending on the spacing, the rafters varied in sizes from 1” x 3” wooden members to 2” x 4” members. A hollow structural section with dimensions of 2” x 1” x 3/16” is the smallest manufactured structural steel available and could be used no matter the spacing of the rafters.

These rafters then rest on five beams that run the length of the building and connect all four of the arches. The beams are located on each of the four connections shown between the arch and rafters in Figure 3.1 and at the peak of the rafters. These beams carry all of the load from the rafters down to the arches and span the 12-14 feet in between the arches. Due to their large span, the team calculated that these members need to be 8” x 10” wooden members or hollow structural section that is 3” x 2.5” x 5/16”.

The load then travels into the four arches which are the focal point of our structure. The arches carry all of the loads down into the foundation. Using the weight of the wooden members, the maximum moment present in the arch was found to be roughly 8.9 kips-ft. A 10” x 10” wooden member proves to be sufficiently sized in order to resist this moment. The maximum moment is slightly larger for the steel members due to the increased weight of the structure, 9.1 kips-ft, yet the steel members can be W4 x 13 members or HSS 3.5 x 2.5 x 5/16 members.

The team found that the members that run vertical from the rafters to the top of the existing wall are required to be 1” x 8” or 2” x 5” wooden members. Steel hollow structural section members with dimensions of 2.25” x 2” x 3/16” or 2” x 2” x ¼” would also be sufficient. A notable detail about these members is that the connection between our newly designed structural system and the existing granite wall was represented by compression-only rollers. This design allows for movement horizontally yet transmits vertical forces into the wall. The lateral forces exerted on these vertical members are transferred to the gable ends of the building and back into the arches. Eliminating the transfer of lateral forces into the wall reduces the risk of the new structure toppling over the existing wall. The vertical, compressive forces transferred into the wall would also act to hold the existing wall together. These compressive forces were calculated to be 134 lbs/ft where granite blocks have a compressive strength of 19,000 psi and the weakest mortar permitted by code has a strength of 900 psi ("Building Stone Institute...", 2015; "Masonry Information…", 2002). This means that, theoretically, the 7.5" granite block wall should be able to handle a load of 81,000 lbs/ft which is well above the load our design transfers through the existing wall.

In-depth spreadsheets with all of the calculations performed throughout the structural analysis can be found in Appendices C through J.

3.2.2 Application of RISA-2D

In our structural analysis, we also used RISA 2D, a simple structural analysis software that served as a check for some of the hand calculations, particularly for the main arch. RISA allows the user to define structural members along with their cross sectional and material properties in order to investigate the performance of the structure under various loading combinations as per the IBC. Our RISA model consists of the structure which includes the main arch, roof structure, cross bracing and the existing stone wall - see Figure 3.2 below.

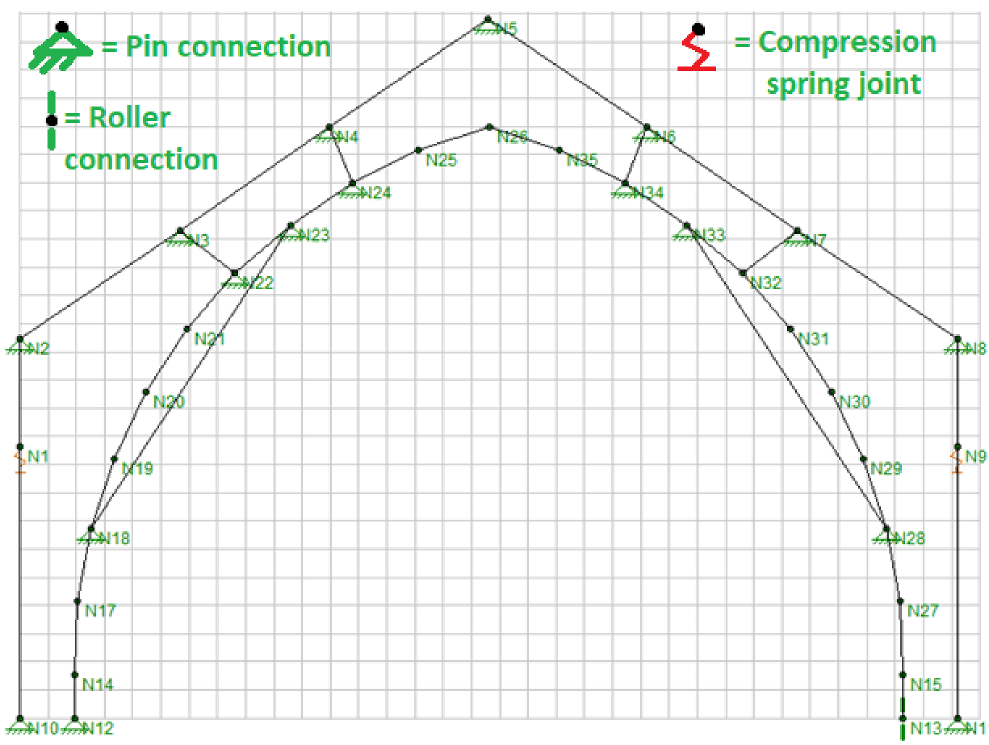


Figure 3.2: RISA model of main structure

This model allowed us to view deflection, axial, shear and moment diagrams based on specified load combinations. With this information, we easily determined the most critical load combination which varied between D + H + F + 0.6W and D + H + F + 0.75(0.6)W + 0.75L + 0.75S for different members in the structure. These load combinations represent the key loads in the design which is a combination of wind and snow loads. In these equations, the lateral earth pressure, H, and fluid load, F, are not applicable to our structure. We also used these diagrams to determine where the critical points in the structure are located for our hand calculations.

As with many software analysis approaches, it is not always possible to mimic the intended design. For example, we modeled the node where the existing stone wall meets the roof structure as a compression spring joint in RISA. In reality we do not want to use the existing wall as the main supporting structure for the roof and arches. As previously stated, this decision was made in order to direct most of the load from the roof structure into the arches instead of the stone wall of unknown structural integrity.

The software differs from our hand calculations in another area. RISA limits the model to straight lines, so the arches were modeled as multiple straight segments; the use of straight segments produced larger internal bending moments than would be present in curved members. However, because we used RISA solely for the purpose of visualizing the effects of the loading and examining the geometry of the structure, this was not a problem.With the structural calculations complete and checked using RISA, the team was able to finalize the sizes of the members to carry into our thermal analysis and final design.

3.2.3 Lateral System

The structural system previously discussed primarily resists vertical loads and horizontal loads acting parallel to the arches. However, the building also needs a system to tie the arches together and resist forces in the longitudinal direction of the building.

The most common method to resist lateral load is typical sidewall bracing that is used in most steel-framed buildings. This technique uses metal rods or cables arranged in an “X” in certain bays of the building in order to transfer the lateral loads to the foundation. Other variations of sidewall bracing considered for this application include single sidewall bracing with a rigid roof and sidewall portal frames. Both of these methods allow for bays to be unobstructed.

However, single sidewall bracing is susceptible to torsion and portal frames require rigid connections which both contradict our decision to use simple framing.

It is also common practice to completely avoid sidewall bracing through the use of fixed base columns or shear walls. Again, these methods stray from simple framing and would complicate the construction of the building.

With all of these options in mind, the team decided to use typical sidewall bracing in order to handle the lateral loads in our design. This would be the easiest option for the high school to construct and the most cost effective for this application.

In order to determine the geometry of the bracing, we examined the aesthetics of different configurations for the heights of the connections between the bracing and the arches. During this process we considered how the bracing would interact with the space, specifically, whether or not it would interfere with usable floor space. From this analysis, the team decided that connections were best positioned at heights of 7 feet and 18 feet above the floor slab. This keeps the bracing from interfering with the occupants of the building.

Once the layout was determined, we applied the loads to the structure, calculated the forces that would be present in each bracing member, and used those forces to size each member. In order to improve accuracy in sizing the bracing members, we used values from the manufacturer TriPyramid Structures Inc. TriPyramid was selected because they specialize in designing and fabricating complex hardware and component systems, like this sidewall bracing system. Using data provided on their website, we selected their Galvanized Steel Wire Rope Cable with a diameter of 0.375 inches, product No. AS25-0375, as well as their compatible Adjustable Jaw Turnbuckle, product No. B310-0375. We selected galvanized steel wire because it resists rusting and the greenhouse will have high levels of humidity. The adjustable turnbuckle that TriPyramid manufactures eliminates the need for larger, midspan turnbuckles and improves the aesthetics of the system.

Once we calculated the forces present in the bracing members, we had to double check that the arches were sized appropriately to handle the forces exerted on them by the bracing. At this point in the analysis, it had already been decided to use timber members which meant the arches should be 10" x 10". We determined that these 10" x 10" members were sufficiently sized to handle the normal forces exerted on them by the bracing. We then designed a custom connection between the lateral system and arches that would distribute the shear forces over an area large enough for the arches to handle. Refer to Drawing 13 in the Results Section. The team determined that the area of this connection would have to be 93.98 square inches which means that a 10 inch tall bracket would have to be at least 9.40 inches wide.

The loading is then transferred from the arches into the footings.

3.2.4 Footing Design

Footings supporting concentric loads were sized using the following equation, found in *Foundation Engineering* by Peck et al:

$$q_{soil} \geq P_u / (B * L)$$

q_{soil} = the load bearing capacity of the soil

P_u= total load (lbs) acting on the footing

B= the width (ft) of the footing

L= the length (ft) of the footing

The existing soil around our greenhouse building was determined by using an online government database (United States Department of Agriculture, 2017). The soil is primarily Paxton fine sandy loam, see Figure 3.3, which can be categorized as "Sand silty clay, clayey sand, silty gravel and clayey gravel (SW, SP, SM, SC, GM, GC)" found in Table 1806.2 *Presumptive Load Bearing Values* in the IBC.

Worcester County, Massachusetts, Northeastern Part (MA613)

Worcester County, Massachusetts, Northeastern Part (MA613)

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
102C	Chatfield-Hollis-Rock outcrop complex, 0 to 15 percent slopes	0.0	1.2%
305B	Paxton fine sandy loam, 3 to 8 percent slopes	0.1	98.8%
Totals for Area of Interest		**0.1**	**100.0%**

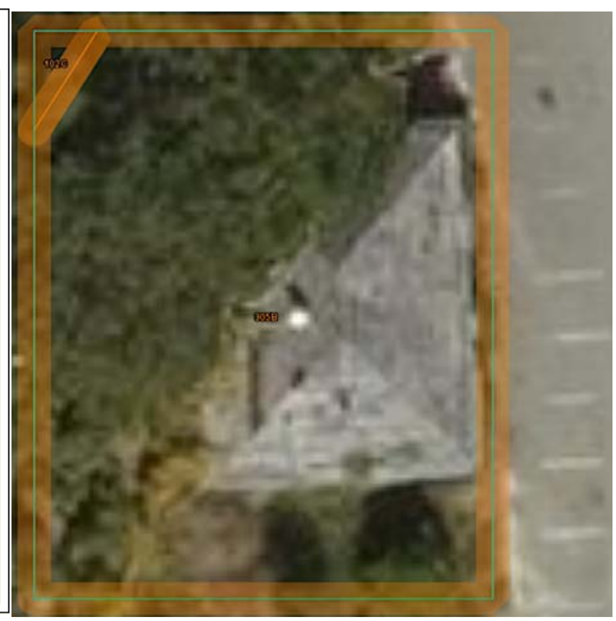


Figure 3.3: Soil survey of the greenhouse site

This soil category shows that 2000 psf should be the value used as the load bearing capacity of the greenhouse soil (qsoil). The total load is the sum of the dead load of the structure, the roof live load, the wind loads on the building and the roof snow load. The next step is to define the tributary area associated with each of the footing locations. This is found by calculating the area halfway to another foundations' location. The footings at each of the corners of the building have a smaller tributary area therefore, they have a smaller required footing area. After finding these areas, we multiplied each footing locations' tributary area by the load to find the specific load acting in that space. From there, we could manipulate the equation to find the total footing dimensions required (B*L) by finding Pu / qsoil. Knowing these required dimensions, footings with the correct length and width were created to fit into the overall design.

Figure 3.4 below shows the floor plan of the building with the footing locations labeled which correspond to the footing labels in Table 3.2.

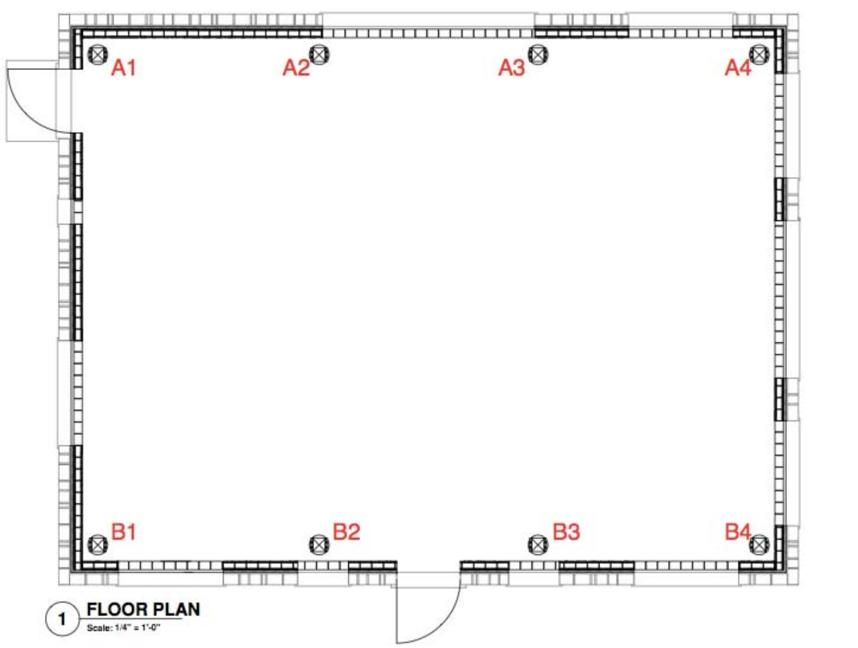


Figure 3.4: Floor plan with labeled footing locations

Table 3.2: Concentrically Loaded Footing Calculations

$q_{soil}=P_u/BL$						Square Footing		Rectangular Footing	
Footing Location	D+L+W		Tributary Area	P_u Total	$P_u/q = BL$	B	L	B	L
A1	41.4	psf	235	10,600	5.3	2.3	2.3	1.5	3.5
A2	41.4	psf	469	20,300	10.1	3.2	3.2	1.5	6.8
A3	41.4	psf	469	20,300	10.1	3.2	3.2	1.5	6.8
A4	41.4	psf	235	10,600	5.3	2.3	2.3	1.5	3.5
B1	41.4	psf	235	10,600	5.3	2.3	2.3	1.5	3.5
B2	41.4	psf	469	20,300	10.1	3.2	3.2	1.5	6.8
B3	41.4	psf	469	20,300	10.1	3.2	3.2	1.5	6.8
B4	41.4	psf	235	10,300	5.3	2.3	2.3	1.5	3.5

Our calculations show that the required area of the four footings in the corners, A1, A4, B1 and B4, should round up to 5.5 square feet while the remainder of the footings should round up to 10.5 square feet.

The existing footing is visible from the crawl space located within the building, but the exact dimensions and depth are unknown. Since we do not have the as-built drawings and are not performing an excavation, we had to develop a footing based on what can be observed from the crawl space. This led the team to explore an eccentric footing - a footing off-center in each location - which wouldn't interfere with the existing foundation. The equation for this type of footing is:

$$q_{soil} \geq [P_u / (B * L)] + [(6P_u * e) / (B * L^2))]$$

q_{soil} = the load bearing capacity of the soil

P_u= total load (lbs) acting on the footing

B= the width (ft) of the footing

L= the length (ft) of the footing

e = eccentricity

(*Foundation Engineering* (2nd Edition) by Ralph B. Peck, Walter E. Hanson, Thomas H. Thornburn, 1974)

We followed the same methods for the eccentric footing design as we did for the concentrically loaded footing design above, but also factored in eccentricity (e) which is the length measured from the symmetrical axis of the footing. The calculations investigating different eccentric footing sizes for both corner and middle footings can be found in Table 3.3 below.

Table 3.3: Eccentric Footing Calculations

$q_{soil}=[P_u/(B*L)]+[(6P_u*e)/(B*L^2)]$										
Footing Location	***D+L+W***		***B***	***L***	***e = L/2 - 0.75***	***B * L^2***	**Result of q**		**q soil**	
Corner	9,960	psf	6	6	2.25	216	899	</=	2,000	Satisfies
Middle	19,700	psf	6	6	2.25	216	1,780	</=	2,000	Satisfies
Corner	9,960	psf	6	5	1.75	150	1,030	</=	2,000	Satisfies
Middle	19,700	psf	6	5	1.75	150	2,030	</=	2,000	Does not
Corner	9,960	psf	6	4	1.25	96	1,190	</=	2,000	Satisfies
Middle	19,700	psf	6	4	1.25	96	2,360	</=	2,000	Does not
Corner	9,960	psf	5	4	1.25	80	1,430	</=	2,000	Satisfies
Middle	19,700	psf	5	4	1.25	80	2,830	</=	2,000	Does not
Corner	9,960	psf	4	4	1.25	64	1,790	</=	2,000	Satisfies
Middle	19,700	psf	4	4	1.25	64	3,530	</=	2,000	Does not
Corner	9,960	psf	4	5	1.75	100	1,540	</=	2,000	Satisfies
Middle	19,700	psf	4	5	1.75	100	3,050	</=	2,000	Does not
Corner	9,960	psf	4	6	2.25	144	1,350	</=	2,000	Satisfies
Middle	19,700	psf	4	6	2.25	144	2,660	</=	2,000	Does not
Corner	9,960	psf	5	4	1.25	80	1,430	</=	2,000	Satisfies
Middle	19,700	psf	5	4	1.25	80	2,830	</=	2,000	Does not

After comparing the two types of footings, we found that the best option would be a concentric rectangular shaped footing. The dimensions for this footing can be found in Table 3.2 under the Rectangular Footing column. The width of the footing stays constant at 1.5 feet while the length of the footing varies based on the required area. This allows the footing to be adjacent to the existing foundation while the depth can vary.

3.3 Thermal Analysis

Worcester Technical High School has a vision for the greenhouse to yield crops for their culinary department. Microgreen crops common to the region were chosen as the primary plants for students to grow within the greenhouse. Growing microgreens requires a room temperature of 60-80 degrees. While this temperature range is similar to the comfort zone for most occupants, the heating and cooling loads are quite different from other building types. This is because over 70 percent of the building envelope is glazing, including a fully glazed roofing system. Additionally, this building will operate primarily during the winter months, so the largest mechanical concern will be overcoming heat loss through the glazing.

To begin the analysis we evaluated the building in its existing condition. The existing walls are made up of exterior granite block and interior brick; originally the walls included a tile-finished surface, but, due to the poor state of the tile, it would need to be removed and was not included in calculating the existing wall U-value. The U-value of the wall was calculated according to Table 3.4 shown below.

Table 3.4: Existing Wall U-Value Calculation

Existing Wall Construction		
Outside Surface (15mph wind)	-	0.17
7.5" Granite Block	-	0.60
2" Air Space	-	0.90
Brick	-	1.60
Inside Surface	-	0.68
	Total Resistance	3.95
	U - Value	**0.25**

The surface films of the inner and outer walls vary based on whether it is winter or summer; in order to find the maximum loading on the building, the winter values were used because they result in a larger U-value and overall larger loading.

A group designation is necessary when choosing the correct cooling load temperature difference (CLTD) for calculating the cooling load from sunlit walls. The existing walls were categorized as group C because they have mass but no insulation.

The building was then divided into six orientations: North, South, East, West, Sloping East, and Sloping West. Each wall was categorized separately because there are seasonal time-of-day variations in the solar load which are different for each orientation. The reason for designating the sloping orientations separately is that the solar heat gain factor (SHGF) varies with the slope of the glazing of the building, but the cooling load factor (CLF) is the same for the slope as the corresponding wall orientation.

Calculating the heat loss in the building is a simple transmission equation that is consistent at each month and hour.

Transmission Heat Loss:

$$Q = U * A * \Delta T$$

U = Heat transfer coefficient of the construction

A= Surface Area

ΔT = Temperature difference

By adding the heat loss through the existing walls and the proposed glazing system it was found that the total loss in the building with the existing walls and a completely glass glazing system would be 143,052 BTUH.

To determine the total cooling load on the building, we needed to calculate how much heat gain there is through the walls and windows. The heat gain for opaque surfaces is a simple transmission calculation, whereas the heat gain through the windows includes transmission as well as solar heat gain. The equations used in our calculations can be seen below.

Transmission through Opaque Surfaces (Walls and Roofs):

$$Q = U * A * CLTD$$

U = Heat transfer coefficient of the construction

A= Surface Area of the walls

CLTD* = Cooling load temperature difference

*This is a table value that is adjusted for the inside/outside temperature difference and the latitude and month

Transmission through Fenestration (Glazing):

$$Q_{Transmission} = U * A * CLTD$$

U = Heat transfer coefficient of the construction

A= Surface Area of the walls

CLTD* = Cooling load temperature difference

*This is a table value that is adjusted for the inside/outside temperature difference but does not include a latitude and month correction

Solar gain through Fenestration (Glazing):

$$Q_{Solar} = A * SC * SHGF * CLF$$

A= Surface Area of the glazing

SC = Shading Coefficient of the Window

SHGF* = Solar Heat Gain Factor

CLF = Cooling Load Factor

*This is a table value that is adjusted for the sloping roof glazing

Total Heat Gain through Fenestration:

$$Q_{Total} = Q_{Transmission} + Q_{Solar}$$

CLTD incorporates indoor-outdoor temperature difference, the effect of the sun, and the time lag due to thermal mass of the structure. As a result it varies by orientation, time of day, and construction. SC is a property of the glass, SHGF is a function of the angle of the sun and fundamentally is a measure of incident solar radiation, and CLF is a function of the time of day. When the month is changed there is an adjustment made for the SHGF and the CLTD correction; the hour of the day impacts the CLTD and the CLF. Through the use of a spreadsheet that is linked to the various tables, it was possible to analyze each month and hour from 8:00AM to 4:00PM.

Table 3.5: Peak heat gain by month an hour of the existing wall with glass roof

Heat gain by month and hour (BTUH)

Month/ Hour	8	9	10	11	12	13	14	15	16
January	41,081	58,223	69,523	76,042	77,790	89,210	99,658	108,326	113,426
February	66,523	85,606	96,606	100,642	99,547	111,234	124,297	136,179	144,544
March	108,135	128,417	138,497	139,627	135,458	147,015	162,444	177,518	189,263
April	137,914	158,089	166,754	165,350	158,773	169,740	186,480	203,728	217,942
May	149,811	169,426	176,959	173,992	166,046	176,445	193,673	211,998	227,530
June	161,107	180,562	187,784	184,458	176,229	186,463	203,737	222,339	238,179
July	157,671	177,018	184,453	181,578	173,785	184,090	201,090	219,197	234,531
August	154,940	174,738	183,278	182,018	175,671	186,511	202,923	219,848	233,765
September	142,799	162,446	172,370	173,848	170,167	181,534	196,352	210,789	221,928
October	93,933	112,618	123,434	127,526	126,581	138,114	150,884	162,510	170,657
November	59,995	76,934	88,118	94,620	96,400	107,732	118,058	126,633	131,666
December	28,414	44,457	55,689	63,167	66,094	77,267	86,479	93,720	97,413

As shown in Table 3.5 above, the peak load of the building will occur in June at 4pm, and using the existing walls and a completely glass glazing system, the heat gain will be 238,179 BTUH.

A new wall design was developed in efforts to increase the structural stability of the building, as well as increase its energy performance. The makeup of this wall and its corresponding U-value can be seen below in Table 3.6. Since the only insulating material in the wall is the polyiso board, it was decided to use a thickness of two inches rather than one. When the new wall design was incorporated into the thermal analysis, we saw a reduction of heat loss from 143,052 BTUH to 128,349 BTUH, a 10% drop. There was also a reduction in heat gain from 238,179 BTUH to 234,425 BTUH, only 2% decrease.

Table 3.6: Proposed Wall U-Value Calculation

Proposed Wall Construction		
Outside Surface (15mph wind)	-	0.17
7.5" Granite Block	-	0.60
1" Air Space	-	0.90
2" Polyiso R6	-	12.00
6" CMU	-	1.00
Inside Surface	-	0.68
	Total Resistance	15.35
	U - Value	**0.07**

The analysis of the new wall showed that the new construction will perform better, but led us to believe it will not have a substantial impact on our building. To confirm these suspicions, the heat loss was broken down by building components. The sloping glass had the largest contribution and made up 54% of the buildings heat loss, the horizontal glass contributed 42%, and the walls in the building only contributed 4% of the heat loss in the building. A graphical representation of this breakdown can be seen in Figure 3.5 below.

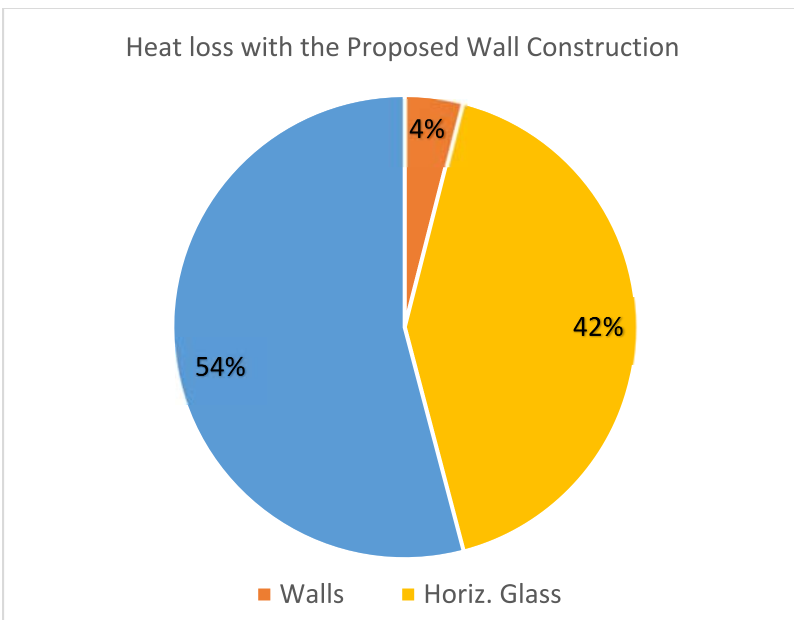


Figure 3.5: Chart categorizing the heat loss by construction

It is beneficial to increase the resistance of the wall, but due to the small impact it has on the overall energy analysis, the focus from a thermal point of view shifted to the material used for the sloped glazing.

In the background section of this paper it was concluded that polycarbonate has the best thermal performance for traditional greenhouses; when polycarbonate was substituted as the material for the sloped glazing in the building there was another decrease in the heat loss and heat gain in the building. The heat gains and losses with the different construction types can be seen below in Table 3.7. From this table it is obvious to see that the best option from a peak load standpoint is combining the new wall construction with a polycarbonate roofing system.

Table 3.7: Peak heat gain/loss of the construction options

	Heat Gain			Heat Loss		
Construction	BTUH	Δ	%	BTUH	Δ	%
Esxisting Wall/Glass Roof	238,179			143,052		
New Wall/Glass Roof	234,425	(3,754)	-2%	128,349	(14,703)	-10%
New Wall/Poly. Roof	217,653	(20,526)	-9%	108,861	(34,191)	-24%

After understanding the loading on the building, it was possible to move forward to a simplified energy analysis. This approach is a modified bin method and is based on the ASHRAE TC4.7, which performs quasi-steady-state calculations at different outdoor temperatures and accounts for a large number of factors affecting the building loads and energy usage. This procedure expresses the building loads as a function of outdoor temperature and adjusts peak load calculations used for design to represent diversified loads for projecting energy use. Spreadsheet techniques that Professor Elovitz developed for this calculation helped implement the Simplified Energy Analysis Technique.

Table 3.8: Space Cooling/Heating from the Simplified Energy Analysis

OS Temp	Space Cooling MBH	Space Heating MBH	Space Net MBH
97	212.5	0.0	212.5
92	212.5	0.0	212.5
87	197.0	0.0	197.0
82	181.5	0.0	181.5
77	166.0	0.0	166.0
72	150.5	0.0	150.5
67	135.0	0.0	135.0
62	119.5	0.0	119.5
57	104.0	0.0	104.0
52	88.5	0.0	88.5
47	73.9	-1.0	72.9
42	60.2	-2.7	57.4
37	46.4	-4.5	41.9
32	32.7	-6.2	26.4
27	19.3	-8.4	10.9
22	9.0	-13.6	-4.6
17	0.0	-20.1	-20.1
12	0.0	-35.6	-35.6
7	0.0	-51.1	-51.1
2	0.0	-66.6	-66.6
-3	0.0	-66.6	-66.6

A custom bin calculation was developed to convert calculated loads to projected energy use. Rather than comparing the occupied to unoccupied hours of the building based on the presence of people, it was more appropriate to compare the hours of sunlight because of the large impact of solar heat gain. Ordinarily, solar heat gain on one side of a building cannot offset the heat loss on the opposite side, but in this case it can because of the open footprint of the greenhouse. The offset of the heat loss and gain allowed us to use the data from our diversified load calculation to find the net BTUH of the building, shown in Table 3.7 above, which would be used as our day time energy in our bin calculation. The important takeaway from this table is that on an average over the course of the year, we have enough solar heat gain during daylight hours to offset losses until the outdoor temperature is below 25.

Our night time BTUH was a combination of the transmission and the infiltration. We began by using the same procedure as before to find the transmission skin gain/loss of the building, then the difference in temperature was adjusted for each bin, and the setback temperature for our night time hours was 62 degrees Fahrenheit. Infiltration was calculated according to the basic model in the ASHRAE fundamentals handbook. The effective air leakage in the building was calculated to be 33 in^2 and the maximum infiltration CFM is 68 meaning that the peak air change/hour (ACH) would be 0.14. This is a lower leakage rate, but this makes sense for this analysis since manufactured components have a low leakage area and infiltration is not a factor during the daytime cooling hours, and at night the building will be closed so there will be less air travel through the doors and windows.

The final result from this bin calculation is that at 80% efficiency, 1,879 therms/year will be used, from this the annual gas use is 1,810 equivalent full load hours.

3.4 Dew Point Calculation

The thermal analysis determined that the insulation in the wall would not play a major role in the efficiency of the building. Therefore, the primary concern is the moisture permeability of the wall construction. To address this, a dew point calculation was performed to identify the location in which a vapor barriers is required. The intent of this barrier is to keep moisture out of the new wall construction and allow any unwanted moisture to drain through weep holes at the bottom of the airspace. The dew point analysis was performed using a spreadsheet, which can be found in Appendix N.

The dew point temperature within a wall can be determined by the comparison of the temperature gradient and moisture gradient for each material located from outdoors to indoors. The moisture gradient across each material is proportional to the vapor diffusion resistance of that element. The temperature gradient is proportional to the the resistance of each element in the wall. The equation to determine the surface temperature value of each element is shown below.

$$\boldsymbol{T_{surface} = T_{inside} - \frac{R_{material}}{R_{wall}} \times \Delta T}$$

This equation is used to find the surface temperature of the first material in the wall assembly. After this value is calculated, it is necessary to substitute this calculated $T_{surface}$ for T_{inside} to find the surface temperature of the next material in the assembly. T_{inside} essentially becomes $T_{surface, previous material}$ and $T_{surface}$ becomes $T_{surface, next material}$.

The temperature and dew point gradients are placed on the same graph to show their relationship. The points of intersection between the two result in the location(s) where it is necessary to install a vapor barrier. The graph for the dew point analysis of the new wall construction is shown in Figure 3.6 below.

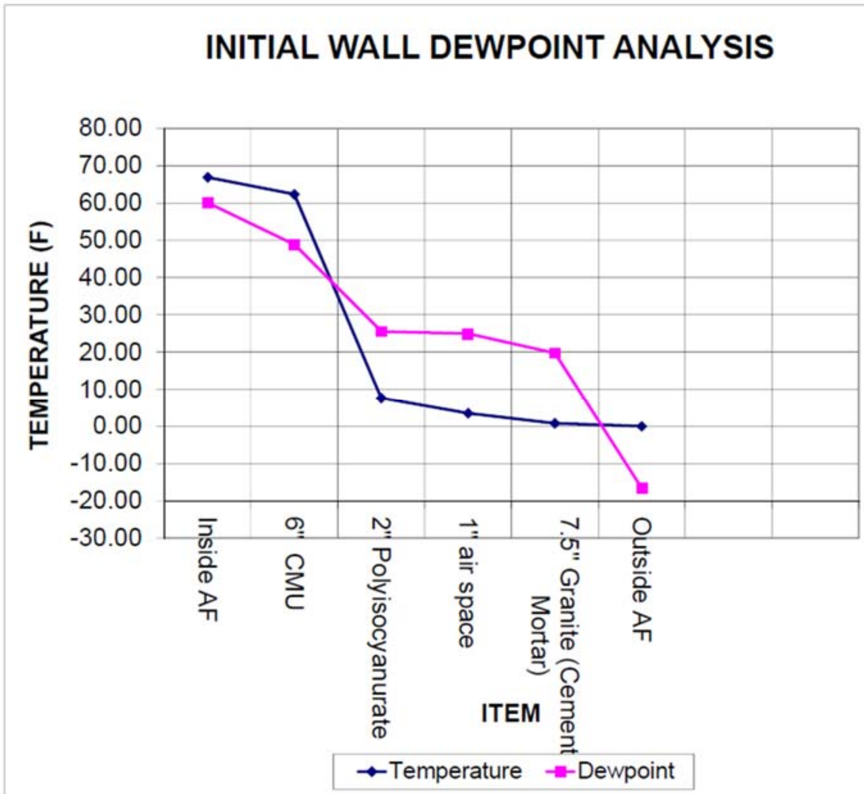


Figure 3.6: Initial Wall Dewpoint Analysis

It was found that the intersections lie at the concrete masonry units and at the exterior granite. Therefore, it became necessary to add some low permeance materials at these locations. This would help to avoid any intersections, therefore eliminating any dew point locations within the wall. A foil liner was added to the outer-side of the polyisocyanurate board and a low-permeance latex paint, Benjamin Moore Super Spec® Latex Vapor Barrier Primer Sealer 260, was applied to the inner-side of the concrete masonry units. The new relationship between temperature and moisture gradients is represented in Figure 3.7.

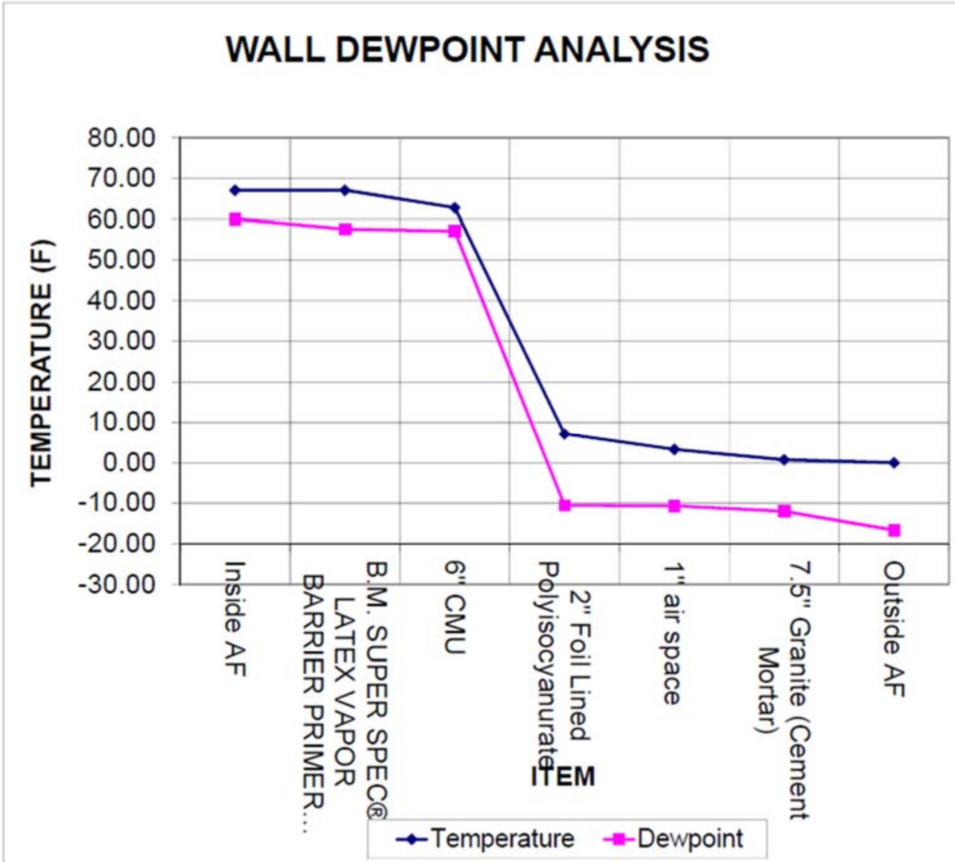


Figure 3.7: Wall Dewpoint Analysis

After our final calculation, we were able to develop the remaining details. The process of developing these details for our design primarily involved researching the methods specific manufacturers use for similar connections and sometimes carrying their details directly into our design. Water infiltration/control, continuity of insulation, constructability, and air infiltration were issues of primary concerns throughout the many iterations of each detail. We also aimed to limit the number of gaps and openings where bugs, dirt and dust could accumulate. Calculations involving the requirements of the structural connections being detailed were the force that drove all of the decisions in regards to those details. The details that were developed stem from the decisions made after our structural and thermal analyses were completed and are presented in the Results and Discussion chapter of this report.

4 Results and Discussion

4.1 Final Design

Figure 4.1 below is a Google SketchUp model of the final design that was created as a visual aid. Additional renderings from the model can be found in Appedix O.

Figure 4.1: Google SketchUp model of the final design

4.2 Structural System

The main structure carried into our final design is a set of four 10” x 10” wooden arches. The team elected to use wood because the high school expressed a preference for wood and these large wooden members would make the structural members a focal point in the building.

Other structural members in the building include 2” x 6” rafters spaced at 6 feet on center, 2” x 6” wall members that run from the base of the rafters to the top of the existing wall, five 8” x 10” beams that run the length of the building. These members are stabilized using a 0.375” diameter galvanized steel cable bracing system and sit on foundations with dimensions of 4’ x 1.5’ for the corners and 7’ x 1.5’ for the middle footings. The steel bracing system is connected to the arches using a custom connection that consists of two 9.5” x 10” steel plates that are bolted together through the arches. The other notable connection in the structure is the connection between our new structural system and the existing wall. This connection consists of two teflon pads that permit the connection to slide laterally yet transfer compressive forces into the existing wall.

All of these members and connections were designed using the dead loads of a glass glazing system because glass is heavier than polycarbonate. Therefore, the high school could choose to replace the glass with polycarbonate and the structural members would still be able to support the loads on the building.

4.3 HVAC System

The final design of the greenhouse HVAC system adhered to a system selection criterion that are as follows:

- Accommodates limited room for mechanical equipment
- Consumes low amounts of energy
- Provides innovative ways of heating and cooling
- Maintains optimal conditions for plant life

The small size of the building played a large role in the selection of the HVAC system. The team did not want to take up working space to include a mechanical room inside of the building. It was also decided that a boiler and any piping containing water should not be exposed to the outside environment, due to corrosion and potential freezing. On the grounds that there is no suitable space for the mechanical room, it was omitted from the design. This prevented the use of a large space for a boiler, and led the team to believe that the most appropriate design would be gas-fired unit heating elements.

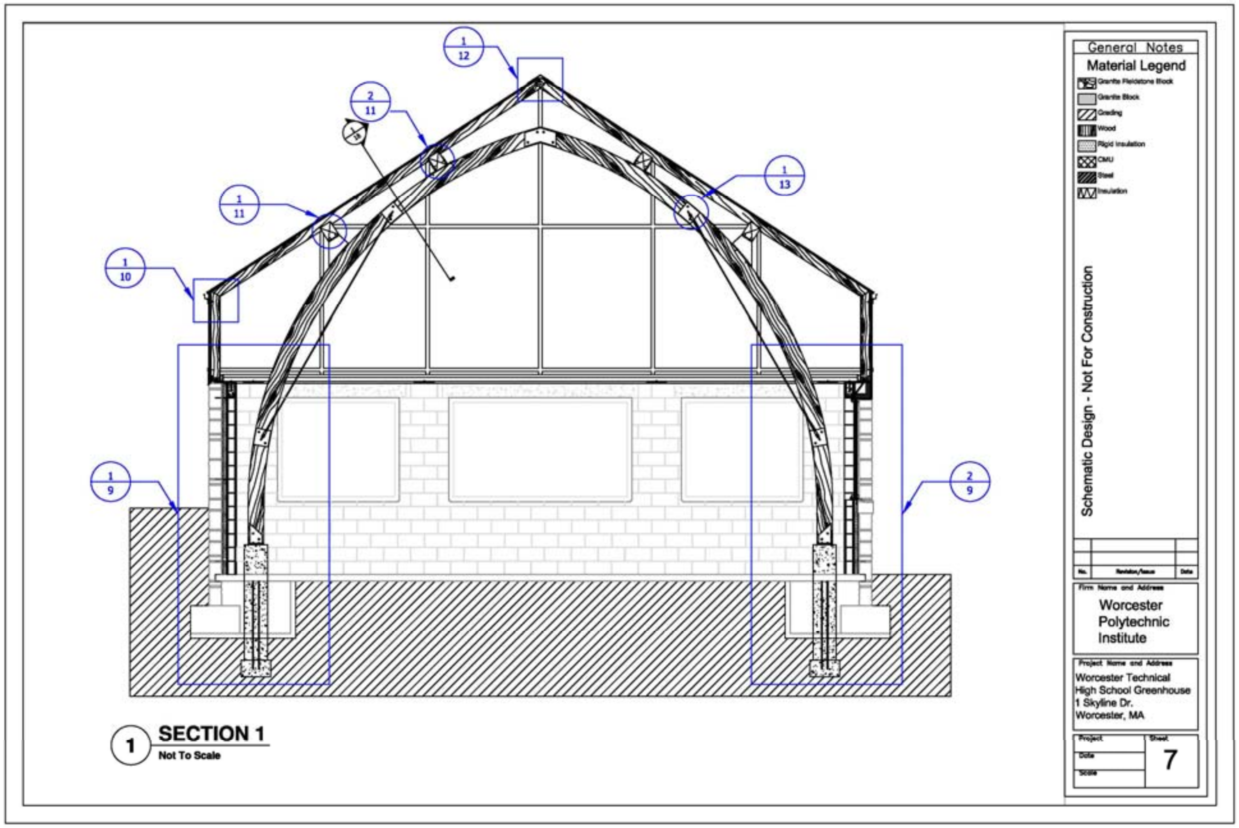
A heating product that meets the criterion of our system is the Effinity Unit Heater developed by Modine HVAC. This is a gas-fired unit that operates at 93% efficiency, which results in substantial energy savings, lower fuel costs and a minimum of a 15% decrease in CO_2 emissions compared to other gas-fired heaters (Effinity™ (PTC/BTC), n.d). Modine also offers ten model sizes so that it can be customized to meet the specifications of the building.

In the warmer months when there is no concern for heating, the focus of the mechanical system shifts to keeping the building cool. It was determined that it would be possible to provide enough ventilation to bring the building to a suitable temperature without having to use extra energy on a cooling system. A ventilation system also provides considerable benefits in the winter months; ventilation during colder weather will allow untampered air to be introduced into the building, as well as provide destratification if warm air collects higher up on sunny winter days. With a building volume of approximately 30,000 ft^3 and designing for 15 air changes per hour, the required output of the ventilation system is 6,900 CFM. This can be accomplished using either a single 30” duct or two 18” ducts.

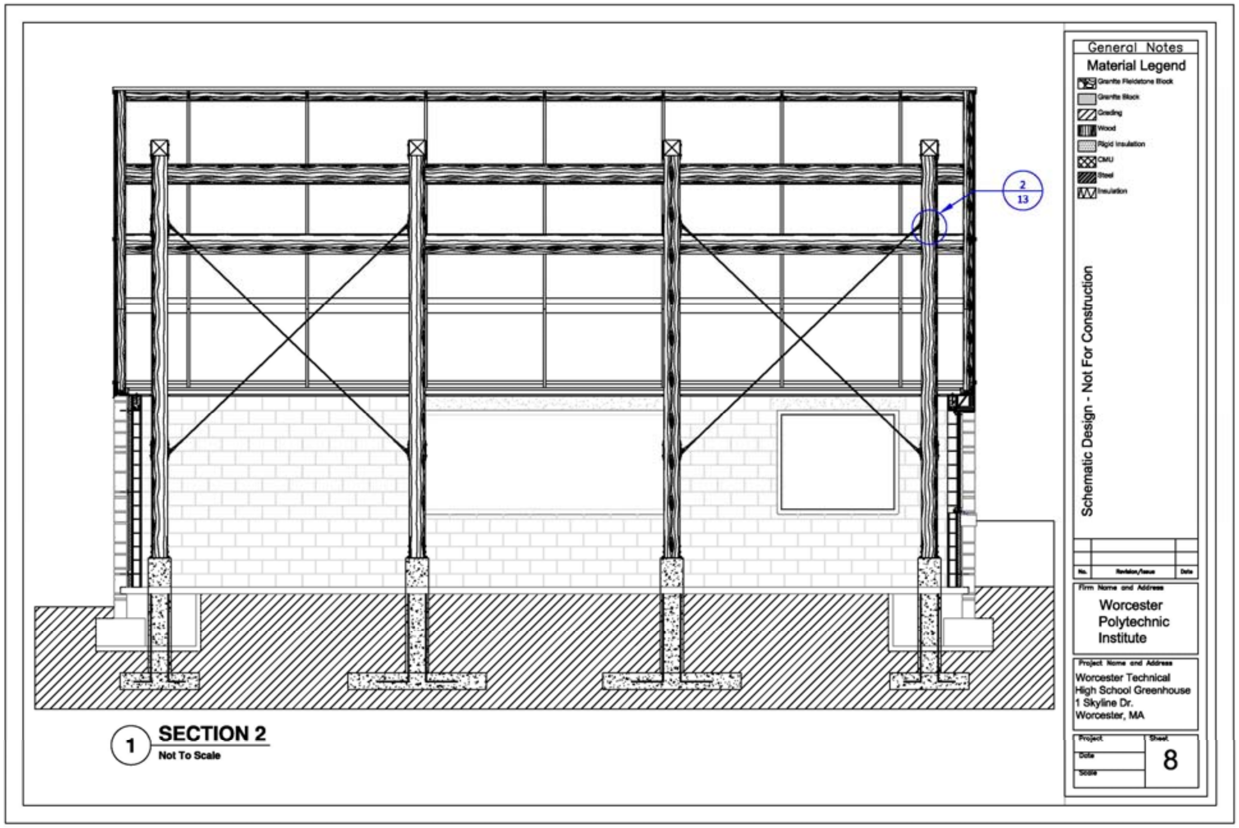
The team elected to use two 18” ducts for aesthetic reasons. The 18” ducts would be less obstructive than one large 30” duct. Ductsox Corporation is a manufacturer of commercial and industrial fabric air dispersion products for open ceiling architecture. Their fabric ducts are quieter than traditional metal ducts, are easy to install, and the entire duct acts as a diffuser so that air can be supplied in a uniform manner.

4.4 Final Drawings and Details Using a Polycarbonate Glazing System

The drawings included in this section depict notable details developed by the team for a polycarbonate glazing system and are accompanied by short discussions on what each drawing represents. The full drawing set for this glazing system, including plans and elevations, can be found in Appendix P. It is important to note that the drawings included in the body of this report are not to scale, while the drawings included in the appendix are properly scaled. Additionally, all of the drawings developed by our team are schematic drawings and not intended for construction.

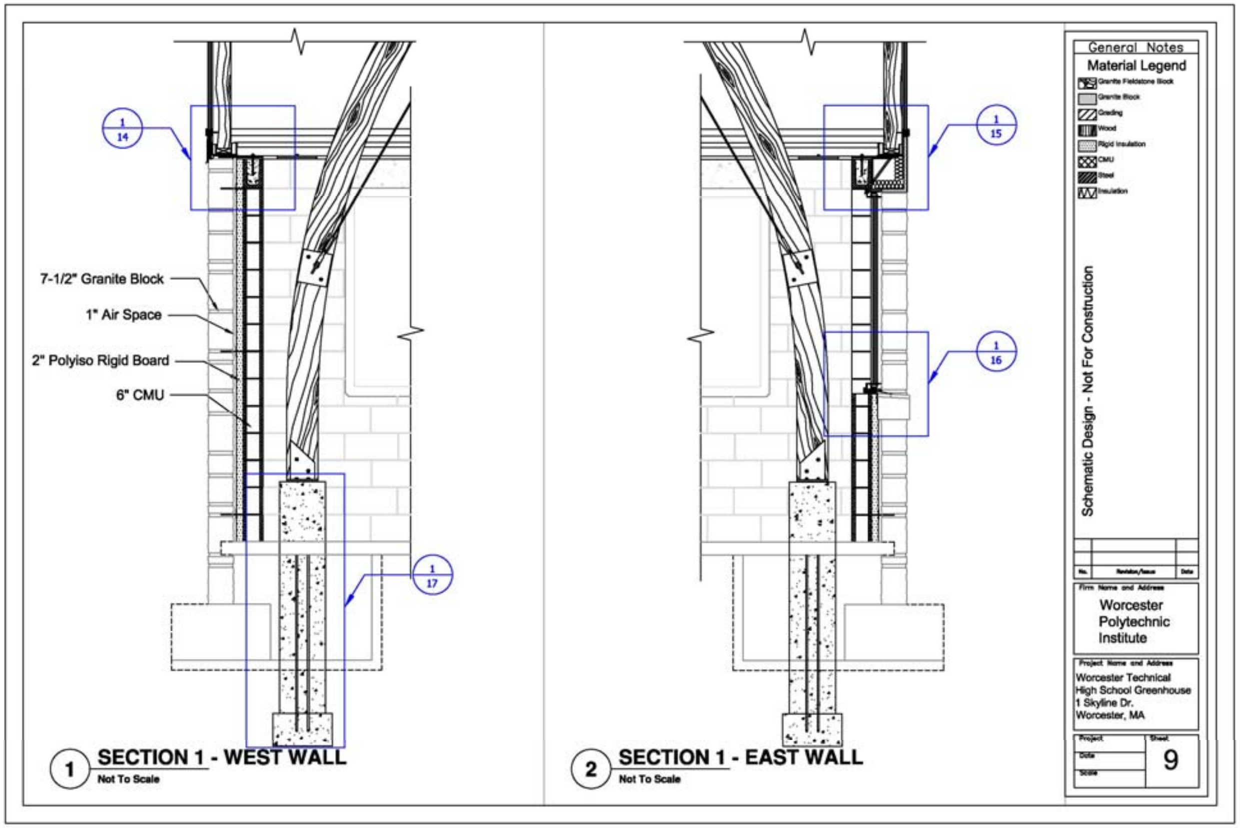


This transverse section of the building depicts the main arch system and includes callouts which show the naming convention for the details that the team developed.

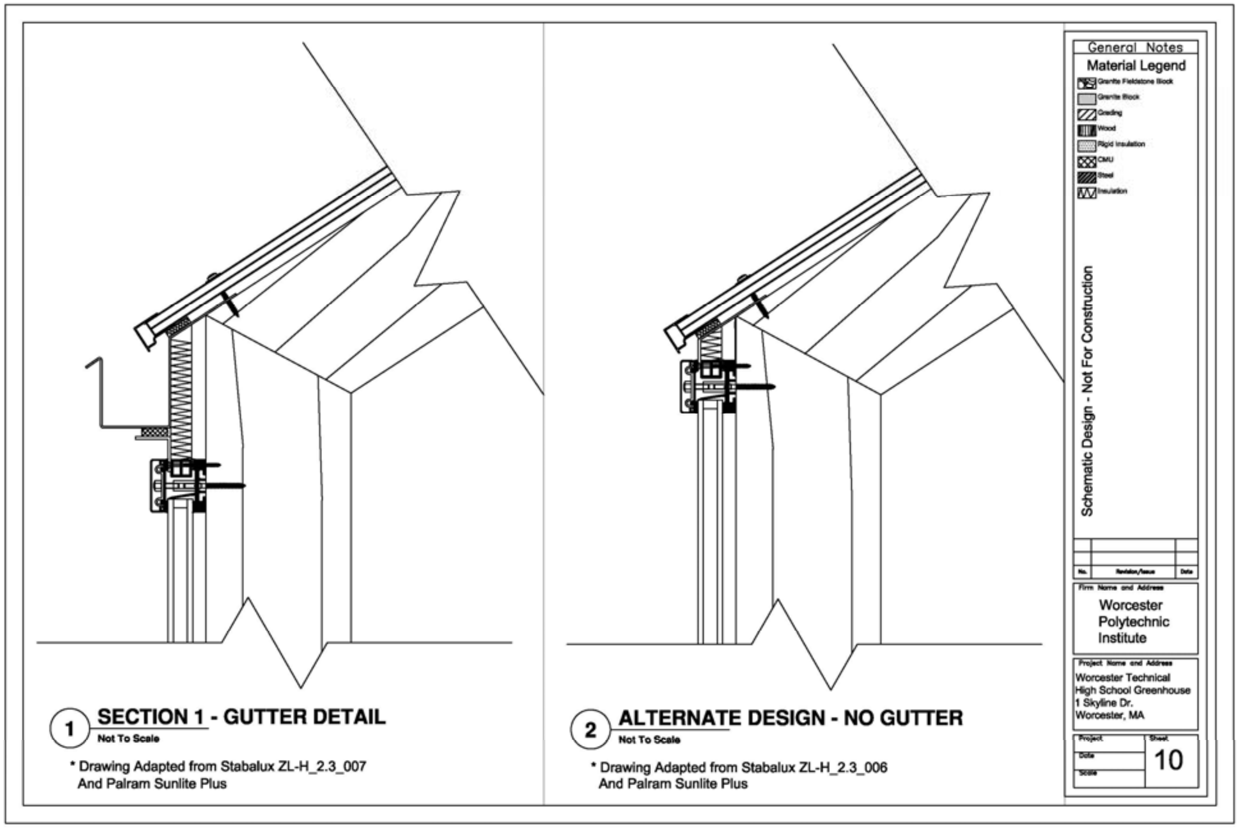


09

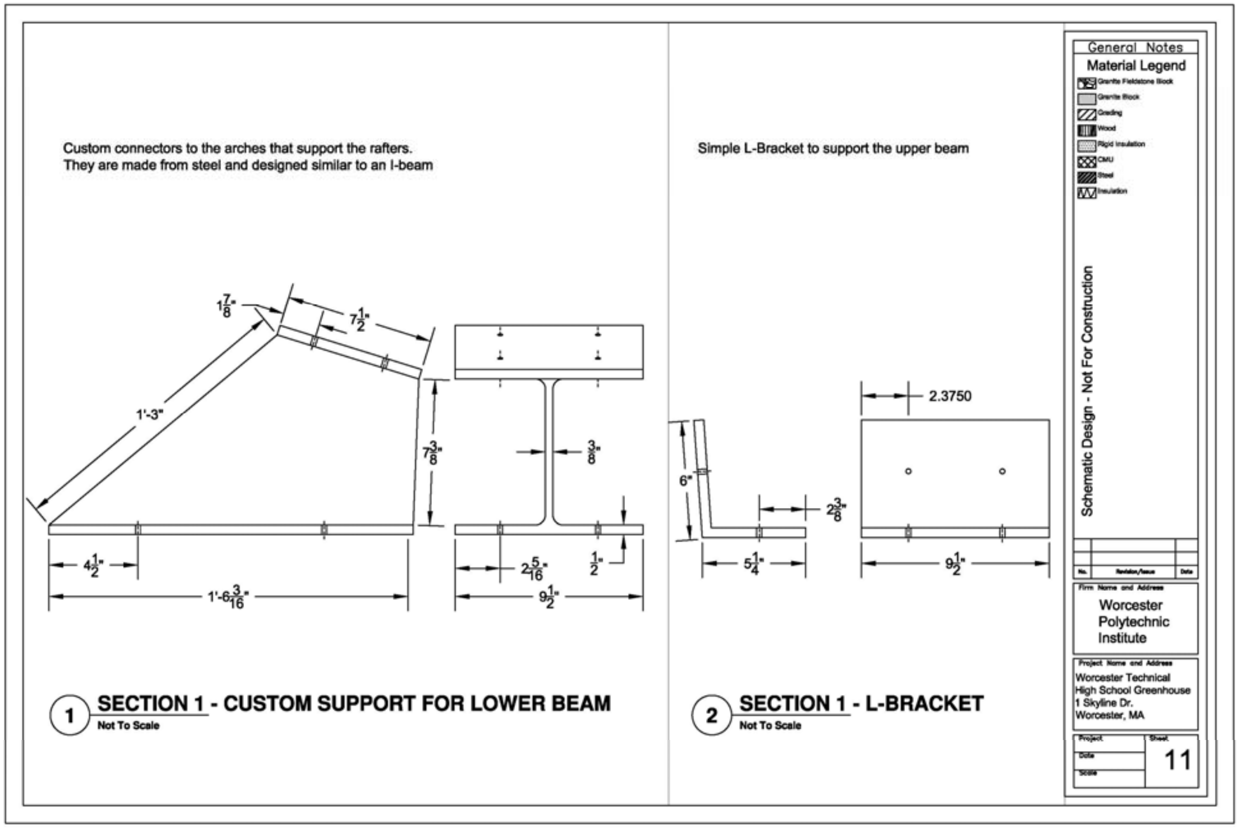
This longitudinal section of the building illustrates the main structural system and also includes callouts for the details not depicted in the prior drawing (SECTION 1).



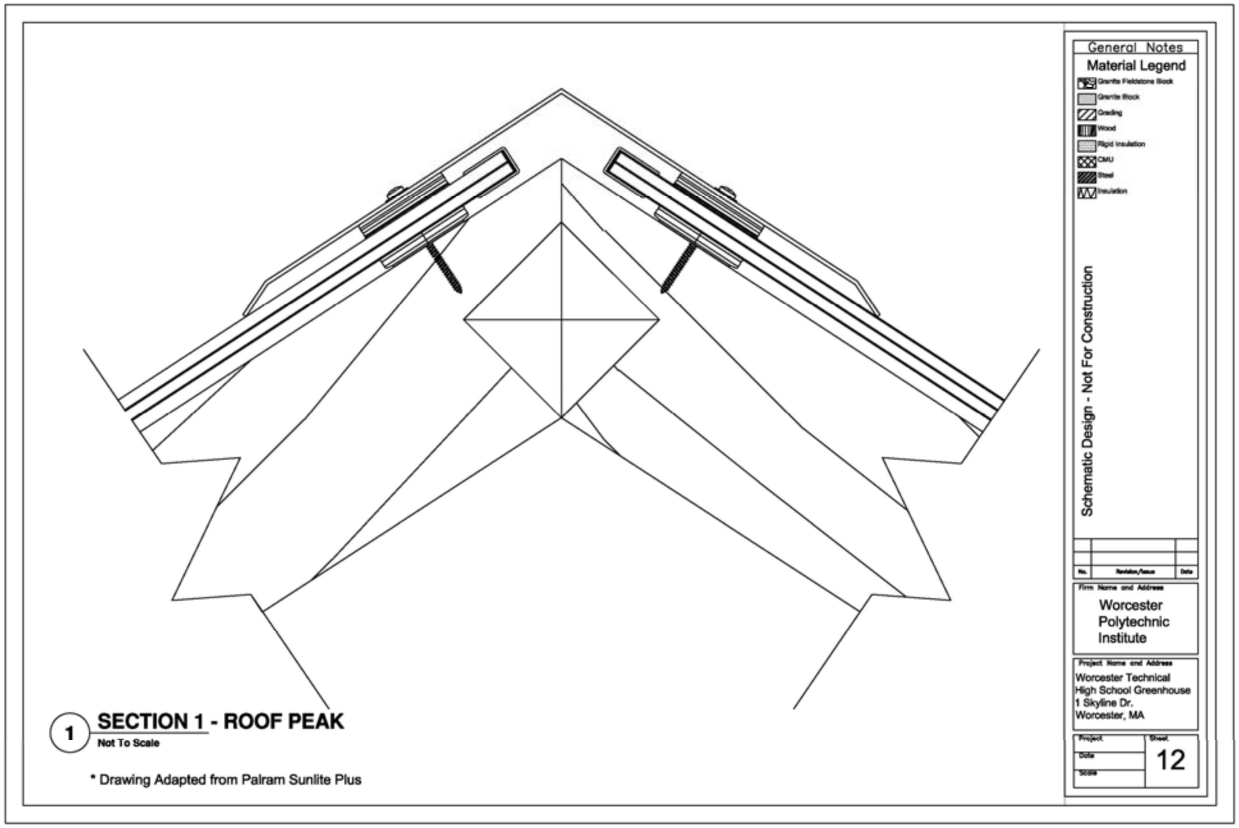
These two section drawings show the wall construction of the building and also outline where the window base and window head details are located.



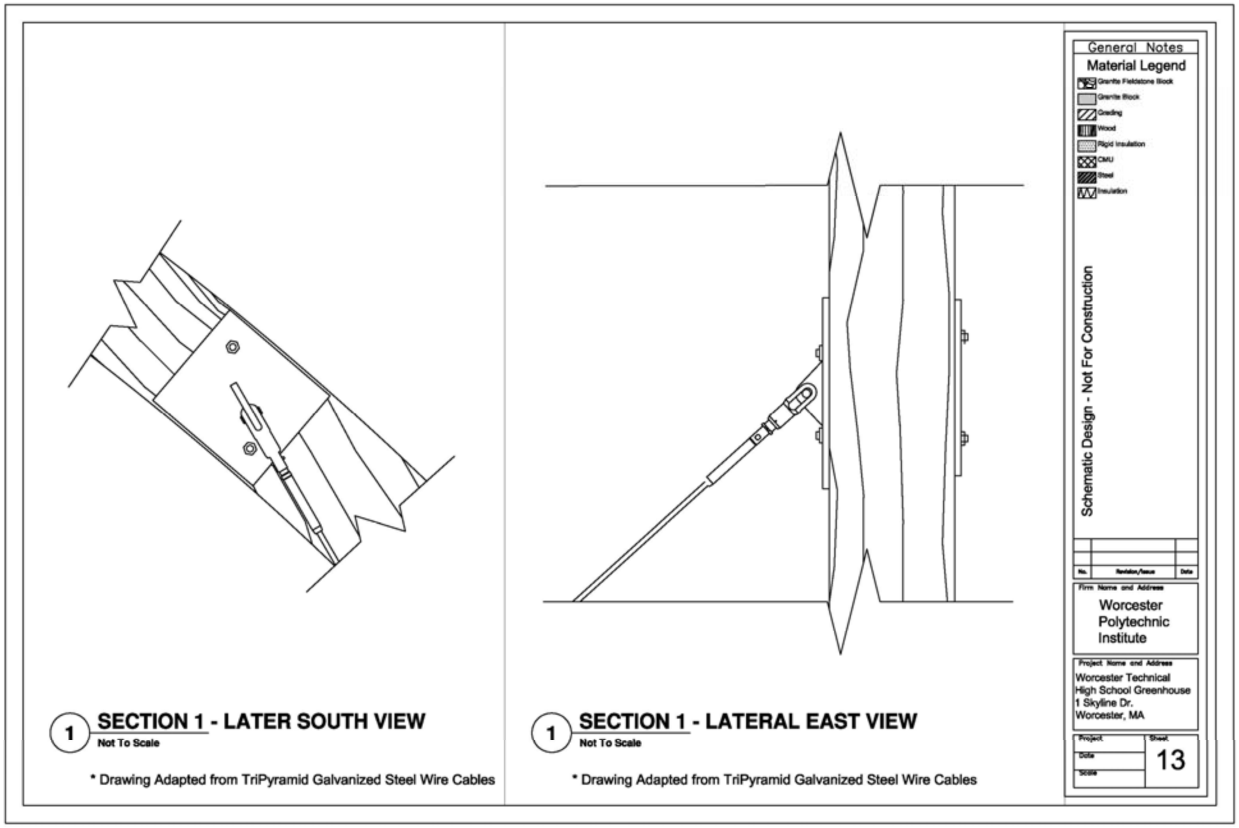
These drawings show two different options for the base of the roof. Option 1 includes a gutter while option 2 does not. The key differences include the length of the flashing as well as the location of the connection between the flashing, polycarbonate glazing and wooden beams of the roof.



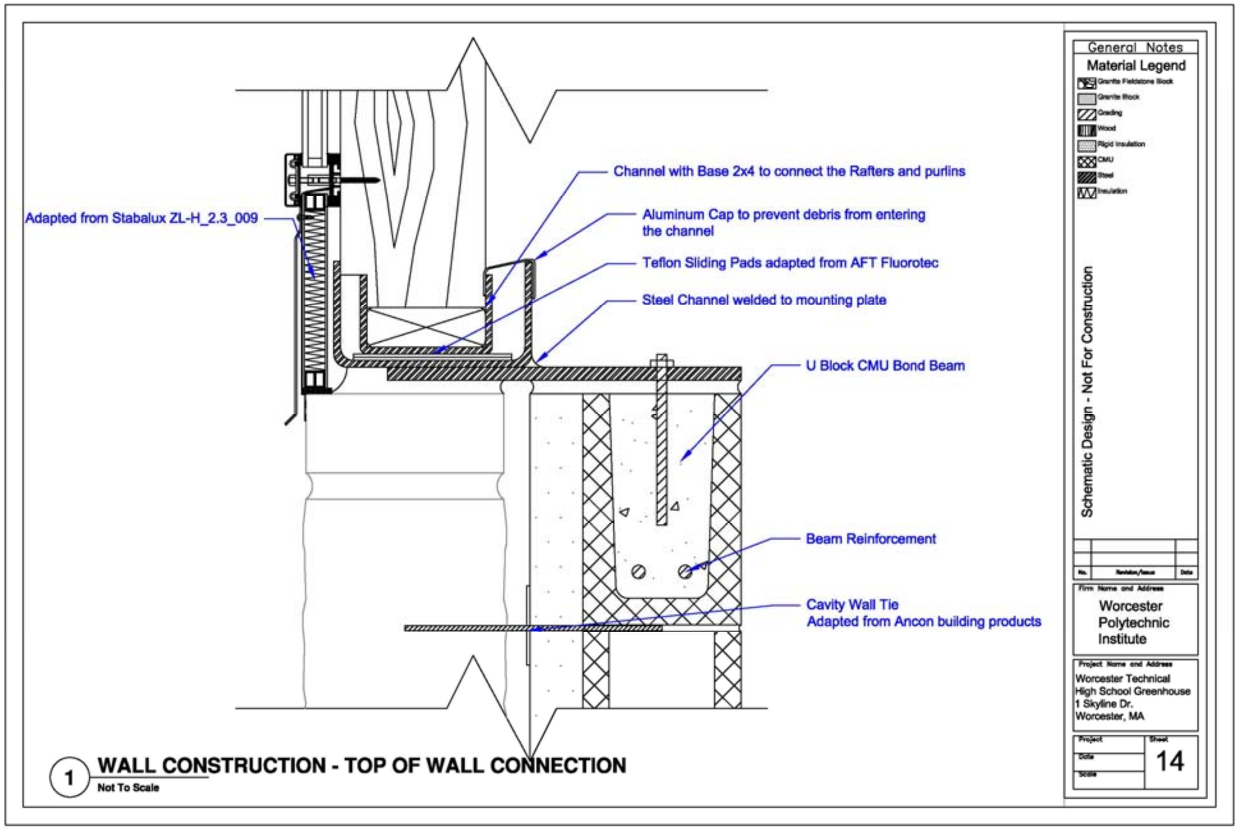
The left section is a custom connector which attaches to the arches while supporting the rafters of the building. These supports are made from steel and are designed similar to I-beams. The right section is an L-Bracket supporting the upper beam.



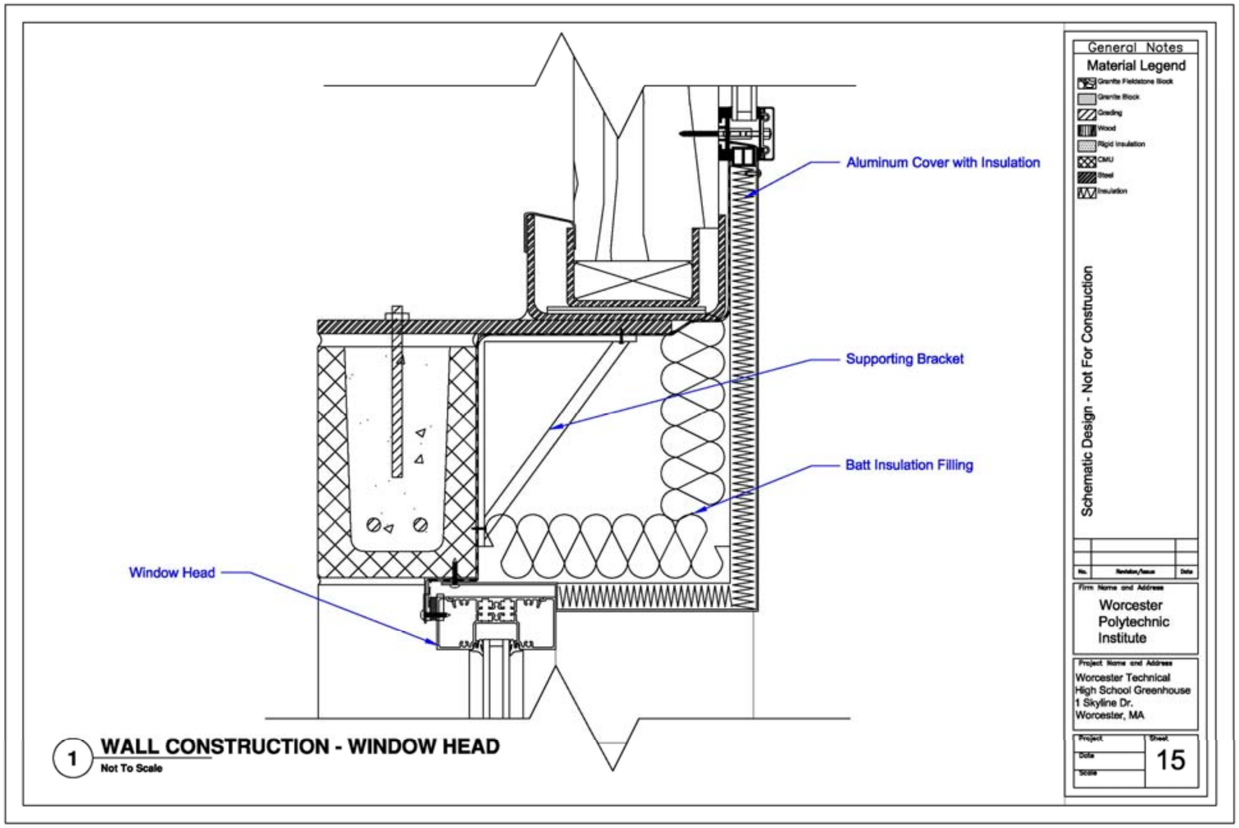
This detail shows the connections at the roof peak. The polycarbonate glazing is screwed into the roof and a cap is placed above the glazing as to seal off the opening of the roof to avoid moisture accumulation. These drawings were adapted from the manufacturer Palram Sunlite Plus.



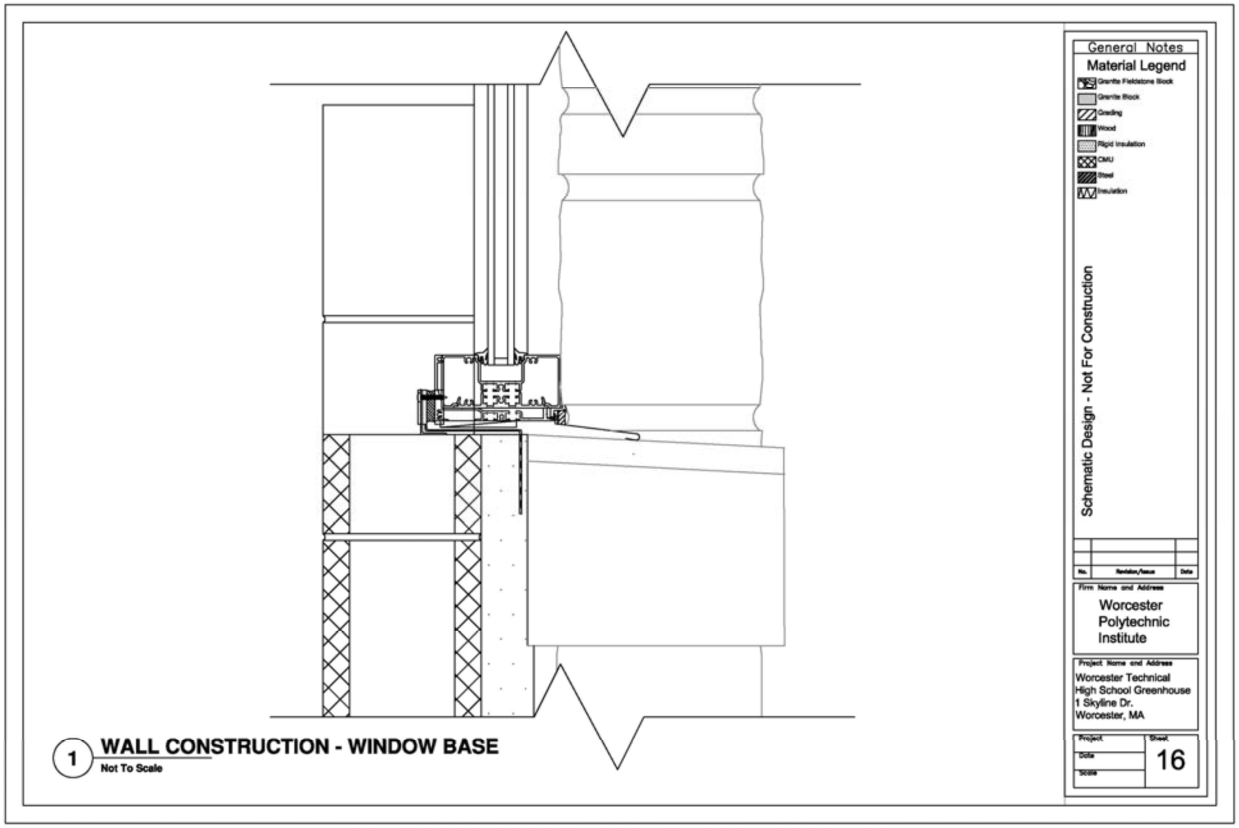
This detail drawing shows the connections between our lateral bracing system and the wooden arches. This system transfers the lateral loading into the foundation through steel cables arranged in an X shape in four bays of the building. This custom connection consists of two 9.5” x 10” steel plates which are bolted together through the arches.



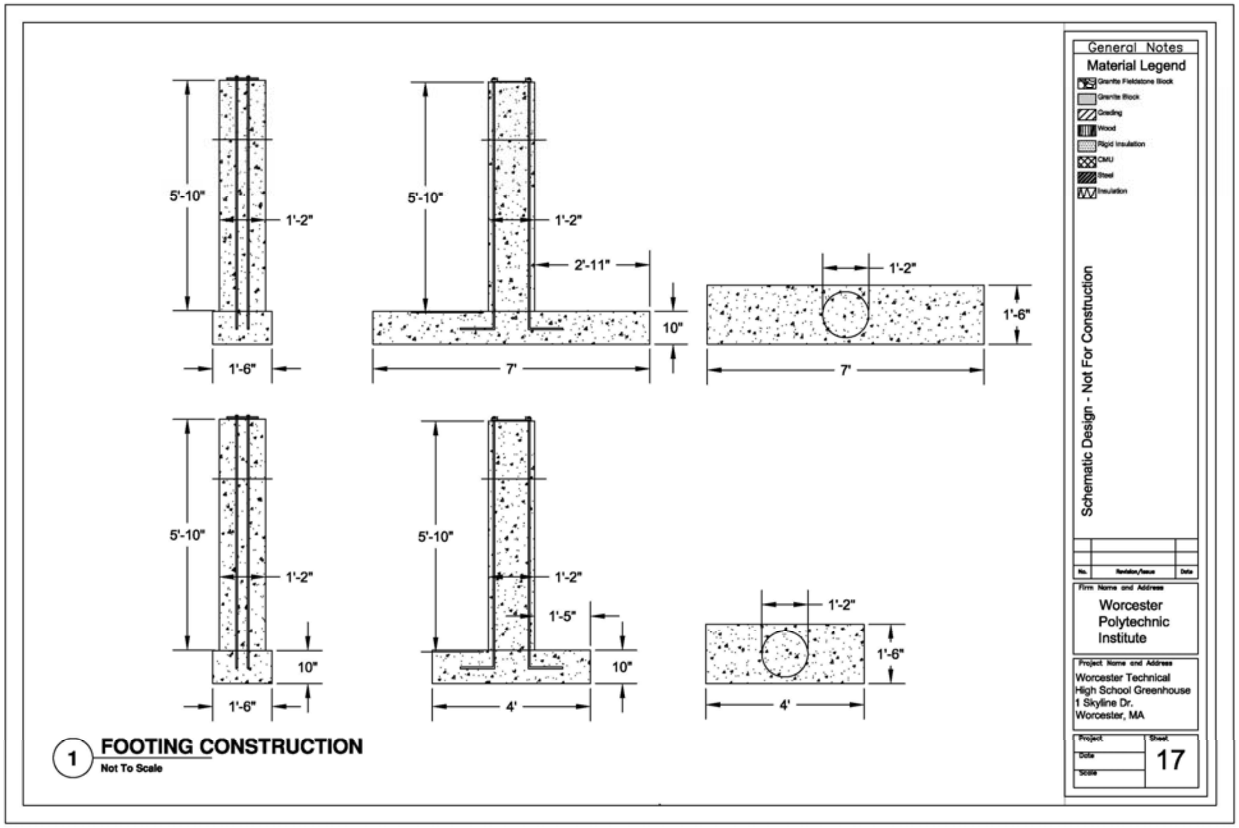
This drawing shows the connection at the top of the wall. The cavity wall tie serves as a connection between the existing exterior stone wall and the newly constructed interior wall. The teflon pads are an important part of this connection as they allow the roof structure to slide within the steel channel. This decision was necessary to mitigate imposed loads onto the existing wall from the roof. The steel channel includes an aluminum cap to prevent unnecessary buildup of debris like dirt, leaves, insects, and other such debris. The top left part of this detail includes a drip edge so that runoff water does not travel down the wall, but is instead directed away from the wall.



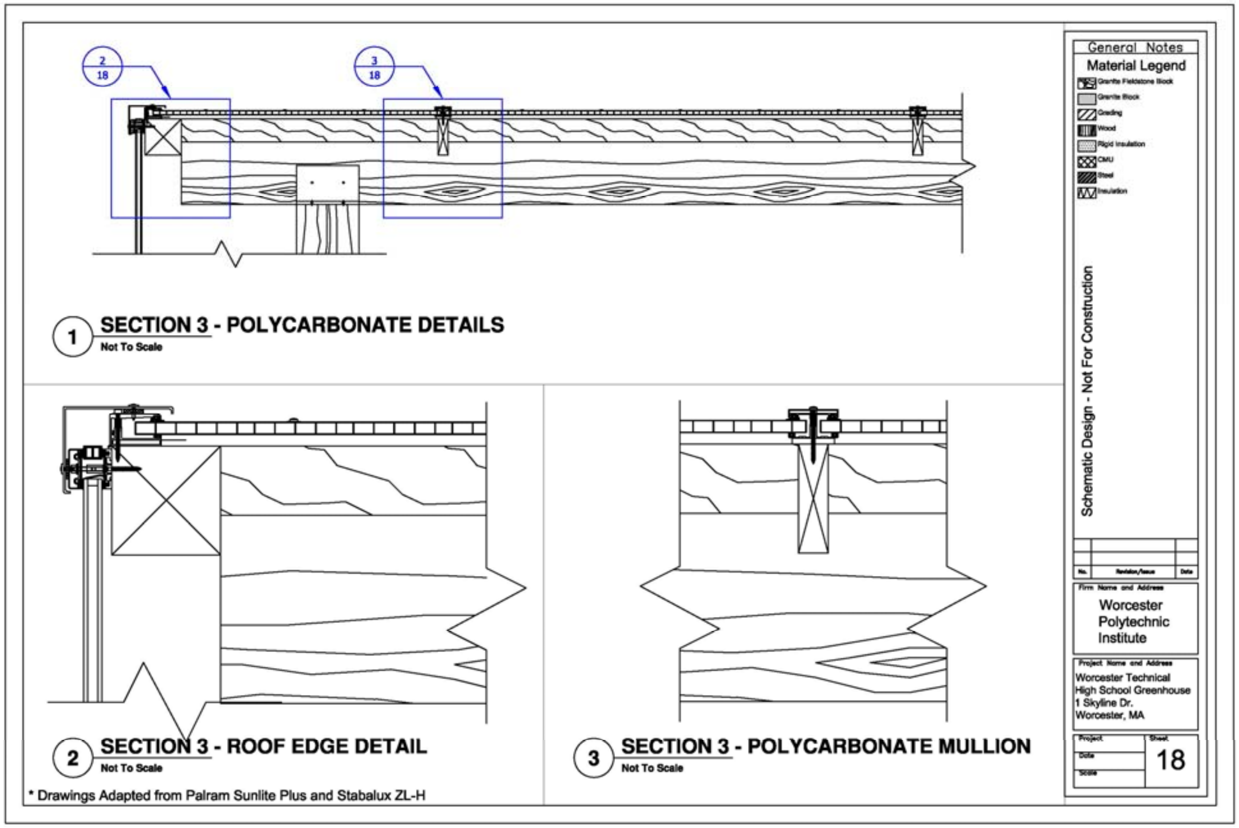
This drawing depicts the same connection as Drawing 14, except this detail is altered for locations where the roof glazing system meets a window instead of the wall. Other than the addition of a window, the major differences include an extension of the insulated aluminum cover and the addition of a supporting bracket. The aluminum cover was extended to fill the space that exists above the window, next to the bond beam. This build-out provides a level plane on the exterior of the building. The supporting bracket was added in order to provide additional structural support for the sliding joint that extends around the perimeter of the greenhouse.



This drawing shows the window base connection between the interior and exterior walls.



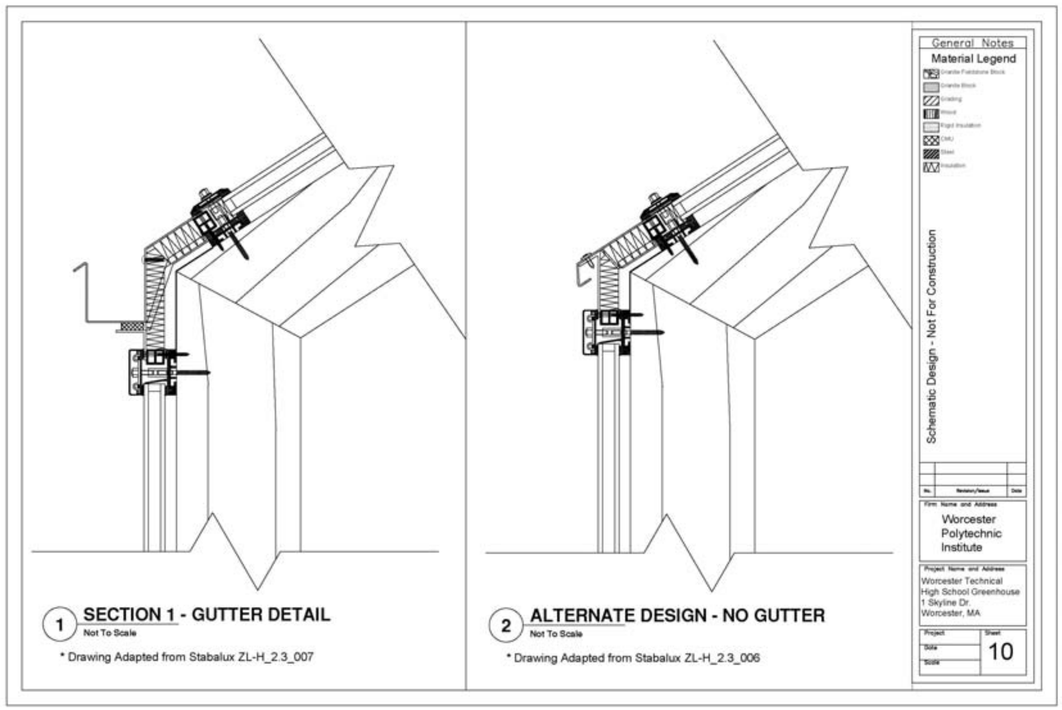
This drawing shows the two different footing sizes which will be used in our design. The top footing will be placed in the four middle foundation locations due to the larger tributary area being transferred. The bottom footing will be placed at the four outside foundation locations.



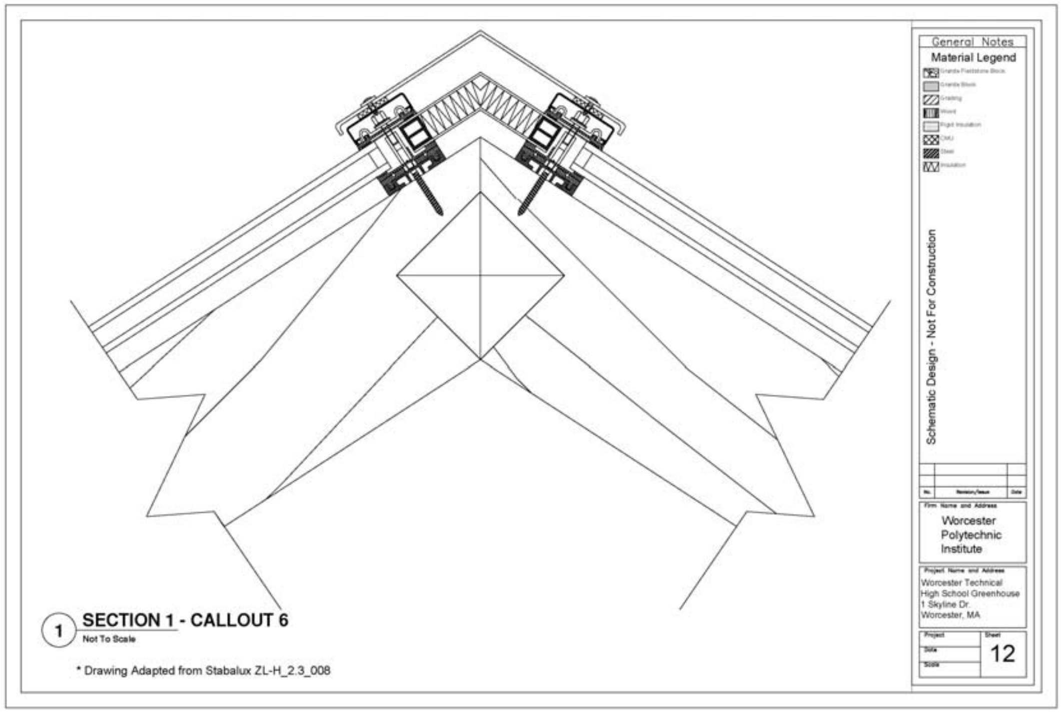
These drawings specify how the polycarbonate details should be connected at the roof edge as well as at the window mullions.

4.5 Final Drawings and Details Using a Glass Glazing System

In addition to the drawing set using a polycarbonate glazing system, the team developed a drawing set using a glass glazing system. The full glass glazing system drawing set can be found in Appendix Q. A majority of the details are the same for both drawing sets, so this section only includes the details that are unique to the glass glazing system. Again, the drawings in the body of this report are not to scale, and all of the drawings developed by the team are schematic drawings not intended for constructio



These two details portray two options for the joint between the vertical glazing and sloped roof. Detail 1 on this page depicts this joint with a rainwater collection gutter while Detail 2 on this drawing illustrates the same joint without a gutter. A notable difference in this joint using a glass glazing system instead of a polycarbonate system is that the glass does not require a large expansion joint at the base of the sloped glazing. These details were developed using drawings from the manufacturer Stabalux.



This drawing details the ridge cap for a glass roofing system. This joint includes an insulated cap in the space between the glass panels as well as flashing in order to prevent water penetration. This detail was developed from drawings provided by the manufacturer Stabalux.

5 Recommendations and Conclusions

Overall, the team was able to design an energy-efficient greenhouse that will meet the needs of the WTHS. The wooden structure that was designed works in accordance with the existing structure while providing the aesthetic appeal of the initial design selected by the WTHS. Additionally, the building envelope that was designed and HVAC systems that were selected provide a favorable environment for plant growth year-round. The team concluded the project by developing design drawings and details that provide information on the intricate details in the greenhouse. Our work provides a solid foundation for the high school to continue the project in the future.

Staff members at the Worcester Technical High School would like their students to be the primary builders of the greenhouse. Since the students are studying various trades, they are capable of building some parts of the greenhouse, but we do not know to what extent they will be involved. Some aspects of this project will definitely require hired professionals, such as professionally licensed engineers, licensed contractors, etc. To facilitate the coordination of the project we have identified the sequence of events as well as some considerations for this project to be successfully completed.

To begin, our architectural, structural and mechanical plans and details need to be reviewed and stamped by licensed professionals. Building projects require stamped drawings to be constructed, which is something the students and ourselves are not qualified to do. Once this phase is completed and there is a full set of stamped drawings, the school may need to obtain a building permit, assuming they do not already have one.

Following these preliminary steps, it is crucial that the existing stone wall is investigated to determine its structural integrity; if any damage is noticed, it needs to be addressed and repaired as deemed necessary. Our design calls for the exterior stone walls to be kept in place, so these four walls would need temporary shoring during demolition and construction to maintain their stability. This temporary bracing is critical during demolition in order to prevent damage to the existing structure that will be reused.

After this, the existing site needs to be cleared and prepared for construction; this step would include clearing trees, weeds and tall grass around the building that would interfere with the construction process. Next would be excavation of the site, which includes lowering the grade on the North and West sides of the building. Excavating in the specified areas will make the grade around the building more uniform, as well as prevent precipitation build up at the window sill. During excavation it is important to address existing utilities and establish the location of new utilities.

The state of the existing foundation and the unknowns surrounding it need to be investigated before the footing design can be finalized. Once a design has been approved, footings need to be laid out, excavated, reinforced, inspected and poured. We also recommend that a new concrete slab should be placed on top of the existing floor slab.

Once the foundation work and floor slab are complete, the new CMU interior wall can be constructed. The steel members that connect the bond beam and channel that houses the teflon pads, need to be put in place before the concrete bond beam is poured.

Fabrication and delivery of structural and mechanical members and components is a process that can take place before, during, and/or after the aforementioned work is completed; this decision is entirely up to WTHS, but it would logically occur during other activities to ensure timely completion of the project. The primary parts that require fabrication include: laminated wood arch members, lateral support system cables and connections, purlins, HVAC system & ductwork, windows and doors.

With the footings in place, the wooden arches can be constructed and placed on the footings. Once the arches are built, the lateral cross-bracing cables can be installed on the arches as specified in the drawings. Wooden beams that span between the arches should then be erected to support the roof structure.

Before the roof structure can be installed, the teflon pads need to be placed in the channel atop the existing stone wall. With all of these structural components in place, the roof structure can be constructed atop the arches and existing stone wall.

Since the roof completes the essential structural members, interior work can begin. This work includes installation of HVAC components, lighting, and plumbing for the bathroom. At the same time, exterior finishes and landscaping (terrace area and sidewalks) can be completed as necessary. Once the interior systems are installed, the interior hardware can be installed accordingly.

The final steps of the construction process typically include a final inspection, use & occupancy certificate, walkthrough, punch list, cleaning and move-in. The final inspection would need to be done by a certified building inspector. The punch list would address any errors in the construction process and amend them as necessary. Cleaning would simply be the removal of tools and equipment and ensuring the space is ready to be used by the students and faculty of WTHS. There are many possible timelines a construction project can follow, but this sequence of events highlights the key activities needed to effectively construct this greenhouse.

In addition to the sequence of construction, there are some considerations that need to be accounted for with the greenhouse. First of all, there will likely be sinks in the open floor space of the greenhouse for use by students while they work with the plants. These sinks will require a plumbing system and floor drains at various locations across the floor. Additionally, we have proposed a location for a bathroom, per the high school's request. The proposed location is next to the existing municipal sewer connection and would need to be included in the plumbing system. This bathroom would have two key components apart from the plumbing fixtures (toilet and sink): a sub ceiling and a small space heater. Another necessary component in the greenhouse is an electrical system, including lighting. Electrical systems are outside the scope of this project but need to be addressed in the construction of the building. We have allocated a space on the floor plan for the electrical systems. The final component of the greenhouse that needs to be designated is a storage area for items such as gardening tools, soil and perhaps storage for the harvested plants.

Bibliography

"ACRYLITE Alltop Technical Information." Evonik Industries. Web. <https://www.acrylite-shop.com/pdfs/16%20mm%20ACRYLITE%20Alltop%20acrylic%20double%20skin%20sheet%20Techinical%20Data%20Sheet%202013.pdf>.

ASCE 7-10: Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers, 2013. Print.

ASTM International. *ASTM A36/36M Standard Specification for Carbon Structural Steel*. 2014. Print.

ASTM A6/A6M-17a: Standard Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes and Sheet Piling. West Conshohocken, PA: ASTM International, 2017. Print.

"Building Stone Institute: Recommended Best Practices." *Building Stone Institute*. 2015. Web.<http://www.buildingstoneinstitute.org/wp-content/uploads/2015/09/bsi-recommended-practices.pdf>.

"Coefficients of Linear Thermal Expansion." Web. <https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html>.

Commonwealth of Massachusetts. "MA State Building Code - 780 CMR." https://www.mass.gov/ma-state-building-code-780-cmr. August 2010. Web.

Effinity™ (PTC/BTC). (n.d.). Retrieved March 20, 2018, from https://www.modinehvac.com/web/products/commercial-gas-fired-unit-heaters/effinitytm-ptcbtc.htm

"Glass Weight Calculator." *Dulles Glass & Mirror*. Web. <https://www.dullesglassandmirror.com/glass-weight-calculator>.

Greg Susman - GS Design, Inc. Web. <http://www.b4ubuild.com/resources/schedule/6kproj.shtml>.

Elovitz, Kenneth M. “Understanding What Humidity Does and Why” *ASHRAE Journal*, April 1999.

Hollow Structural Sections Dimensions and Section Properties: ASTM A1085. Glenview, IL: The Steel Tube Institute of North America, 2013. Print.

International Building Code. 2015 ed. International Code Council, Inc., 2015. Print.

International Energy Conservation Code. 2015 ed. International Code Council, Inc., 2016. Print.

"Masonry Information - Mortar Cement: Product Data Sheet." *Portland Cement Association* (2002) Web.

Moore, Michelle. "You Should Judge a Greenhouse by its Cover -- Your Plants Will." *The Greenhouse Catalog.* 2016. Web. <https://www.greenhousecatalog.com/greenhouse-covering>.

Peck, Ralph B., Walter E. Hanson, and Thomas H. Thornburn. *Foundation Engineering*. 2nd ed. John Wiley & Sons, 1974. Print.

Schiller, Lindsey. "Is a Net-Zero Energy Greenhouse really Possible?" *Maximum Yield* (2017)Web.

"Simpson Strong-Tie Wood Construction Connectors." *Simpson Strong-Tie.* April 17, 2017. Web. <http://embed.widencdn.net/pdf/plus/ssttoolbox/p9s7azvrst/C-C-2017-p303.pdf>.

Steel Construction Manual. 14th Edition. American Institute of Steel Construction, 2011. Print.

“Structural Tension Assemblies.” Web. <http://www.tripyramid.com/tension-elements>.

"SUNLITE Multiwall Polycarbonate Sheet Specifications." *PalramAmericas.* Web. <https://www.palramamericas.com/docs/upload/F1200-Sunlite-Sell-Sheet.pdf>.

Thomas, Eric. "A Net-Zero-Energy House for $125 a Square Foot." *Green Building Advisor* (2013) Web.

United States Department of Agriculture. "Web Soil Survey." *Natural Resources Conservation Services.* August 21, 2017. Web. <https://websoilsurvey.nrcs.usda.gov/app/>.

Appendix A: ECE MQP – Self Sustainable Greenhouse

Self-Sustainable Greenhouse

Leah Morales, ECE MQP 2017/2018

In addition to the large four-season greenhouse that was designed for the Worcester Technical High School, a small self-sustainable greenhouse was developed to aid in plant growth as well as act as an educational device. This apparatus was designed to satisfy the Electrical and Computer Engineering requirements for the Major Qualifying Project; it includes electrical sensors and equipment, as well as a mechanical design and computer science programming.

Idea Development

The purpose of this project is to develop a self-sustainable outdoor greenhouse using small sensors in connection with the Arduino interface, which will be able to maintain the life of a small plant as well as be controllable and aesthetically pleasing to the user.

In order to maintain the life of plant, it was necessary to provide water, a light source, nutrients, and for the plant to remain in optimal temperatures. Many design aspects were considered in order to reach this goal and are shown here:

- Temperature/Humidity Sensor - to record the current temperature and adjust the environment to prevent overheating/freezing
- Soil Moisture Sensor – to water the plant when necessary
- Water Collection Tank – to collect and store water for the plant
- Water Level Sensor – allows the user to check water tank level
- Small Linear Actuator/DC Motor – to open the greenhouse and allow for ventilation
- Fans – to provide air circulation
- Solar Panel – main power source
- Solar Tracker – uses photocells to track the sun and optimize the solar panel

- Heating Pad – to provide heat in colder months
- Thermal mass – to conserve heat

Upon further investigation it was realized that one of the most important factors of this self-sustainable device would be making it as passive as possible – this is to limit power consumption, to ensure reliability of the device, and to create a more obtainable goal with a more professional outcome. In order to do this, some of the original design considerations were omitted.

Instead of being used year-round the greenhouse was limited to three seasons, this is so because heating the device would be near impossible with the limited power supply, and it is assumed that the user would not have as much interest in this product during colder months. That is to say, if someone uses this device to grow herbs for their kitchen, they will be less likely to want use an outdoor standalone device in the winter when they could have an indoor unit.

To keep the device running as far into the colder seasons as possible, thermal masses were added. A larger water tank was placed on the back side of the greenhouse to conserve as much heat as possible. Stones were also added below the dirt to be used as for irrigation as well as to provide a small thermal mass.

The solar tracker was also omitted. Having a solar panel that tracks the sun optimizes the energy gained through the panel, unfortunately the amount of power gained would be approximately equivalent to the power used by the servo motors that would be used to move the panel. In addition to this, small servo motors are not as reliable, especially in outdoor applications.

Fans were not incorporated in the later designs because the focus could be placed on passive ventilation, and there is the potential that the fans dry out the plants and the soil.

Fewer electronic components will be used, but a more intelligent mechanical design and savvy computer coding will create an eco-friendlier, reliable system.

Mechanical Design

The first obstacle in the design of the greenhouse was developing a mechanism so that the greenhouse could easily open and close. Prototypes of the greenhouse included a traditional shape that used small linear actuators to open the roof of the small house; unfortunately, this design was more susceptible to damage and would potentially allow for buildup of water or debris that would be held in by the walls. To avoid these hazards, a new design was developed that used a half-dome to turn around the plant, so that the plant can be completely exposed or completely covered.

The base of this design consists of a 1 – ¼” brass stand that was turned on the lathe to produce a ¾” end with a ¼” threaded hole. On top of the base sits two 12 inch acrylic circles, which are sandwiched between two teflon washers to prevent friction, and two metal washer to prevent the bases from wobbling. By seating all of this on the stand it allows the large circles to rotate, while a 10 inch acrylic circle is screwed down to the top of the stand so that it is stationary. The construction of the base can be seen below in Figures 1 and 2.

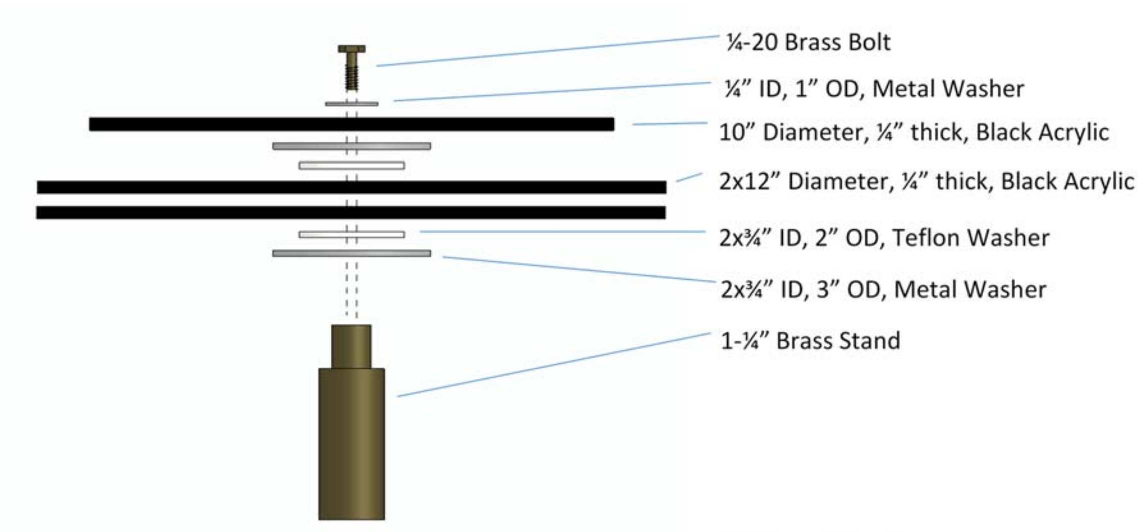


Figure 1: Exploded diagram of the greenhouse base construction

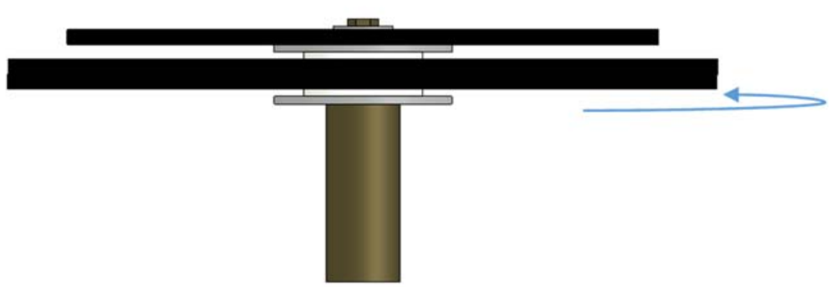


Figure 1: Greenhouse base with revolving 12 inch acrylic

The plant bed and water tank will sit on the stationary 10 inch circle, while the acrylic half-dome is placed on the rotating 12 inch circles. In order to rotate the 12 inch base, a gear pattern was laser cut into the bottom circle, while the top circle has a slot to allow any conduit from the electrical components to pass through so that they will not get caught when the base rotates. The design of these two plates are shown in Figure 3 below.

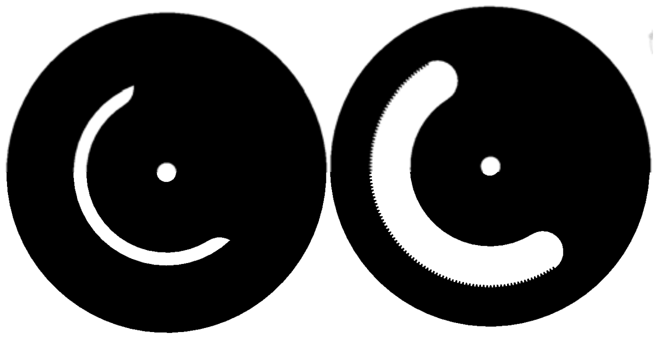


Figure 1: 12 inch rotating base design

Once the base of the greenhouse was designed, the acrylic half-dome was glued in place, as was the half-cylinder which houses the plant bed.

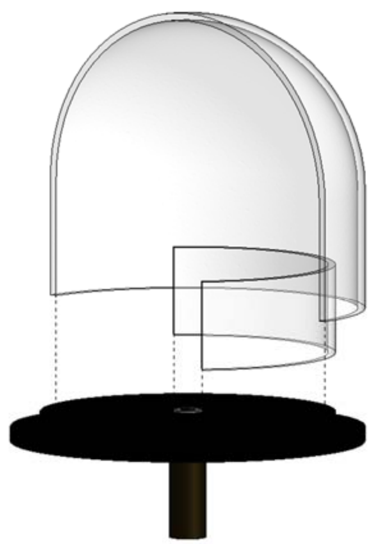


Figure 1: Installment of the acrylic half-dome cover and the half-cylinder plant holder

The water tank is designed to be a part of the plant housing to provide a thermal mass. A funnel is placed at the top of the back of the housing to collect rainwater and direct it into the tank, and a water pump is underneath the tank so that it can deliver the collected water to the plant when needed.

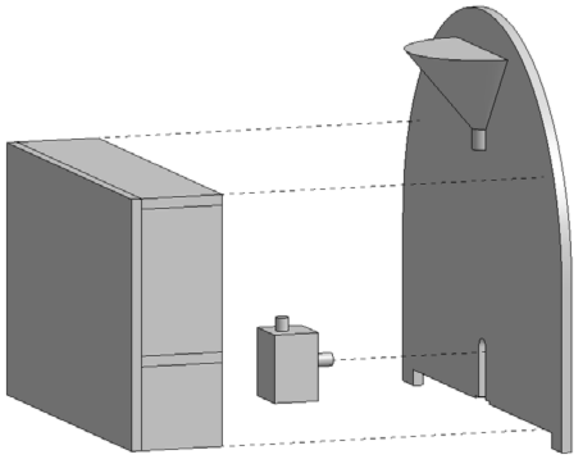


Figure 2: Water tank assembly

To attach the motor to the brass stand it was placed within a clear acrylic block which extends from the edge of the 12 inch base to the brass stand. The block is then attached to an L-bracket which is secured to the brass stand with a U-bolt, as seen in Figure 6.

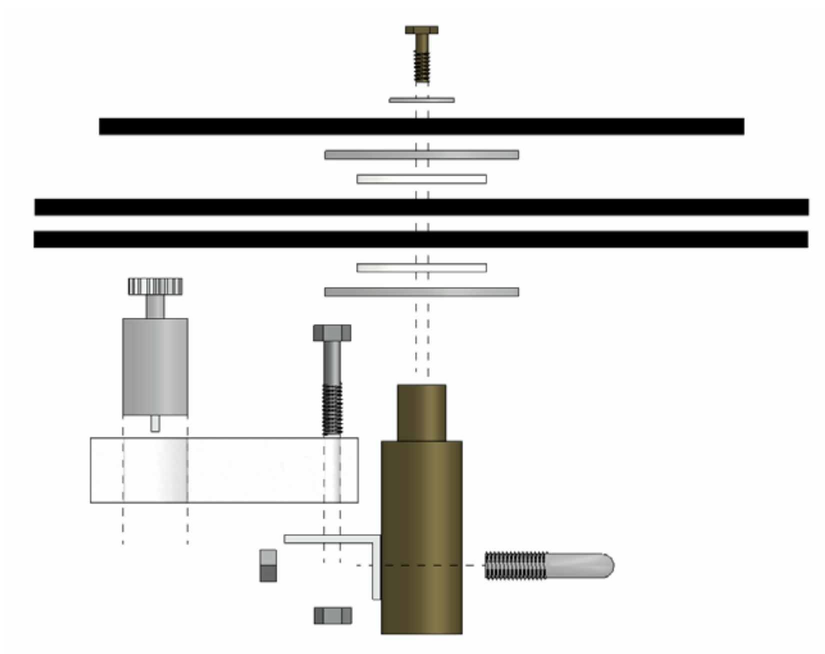


Figure 3: Base construction with motor assembly

The final aspect of this mechanical design is the tubing from the water pump to the plant. Initially the tubing was going to be concealed under the soil, but the small brushless motor does not included a valve, and with gravity the water would flood the plant. A creative alternative, which is shown in Figure 7, is to bend the tubing in a way that it would be higher than the water and work like fountain when water the plant. Not only would this prevent excess water, but it would allow the user to view when the plant is being watered. To achieve the necessary height, a small brass rod is used as the skeleton of the tubing and is attached to a small base which is covered by the soil.

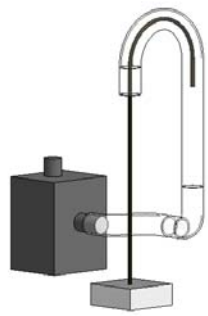


Figure 4: Water pump and tubing assembly

Each of the mechanical components were brought together into one cohesive structure.

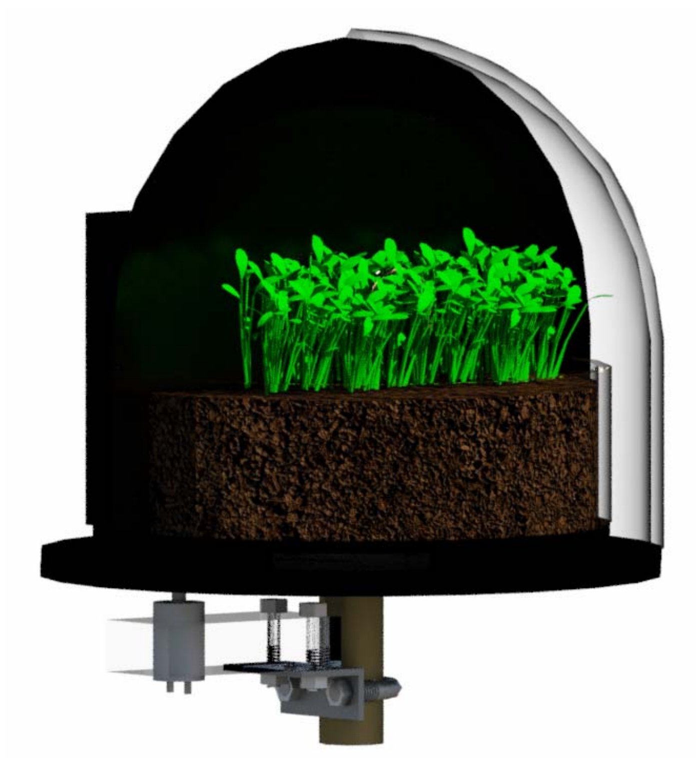


Figure 5: Rendering of Final greenhouse mechanical design

Figure 6: Images of the final Greenhouse Design

Electrical Design

The systems of the greenhouse are controlled by the Arduino mega 2560, this microcontroller was chosen because it is designed for projects that require more I/O than the Arduino Uno. In this section the pin designations will be referring to the pins on the Arduino Mega 2560 board.

To begin, the temperature and humidity levels around the plant are monitored. This is done using the DHT11 – temperature/humidity sensor, which uses a capacitive humidity sensor and thermistor to measure the surrounding air, then returns a digital signal output. The DHT11 is connected to the digital pin 7. The readings from this sensor are used to control the opening and closing of the greenhouse, based on if it is too hot or too cold.

The second sensor used is the soil moisture sensor. This sensor uses two probes which act as a variable resistor, an increase of water in the soil increases the conductivity and lowers the resistance. The sensor outputs analog values, which are read on the analog pin 3. If the readings from this sensor are below the desired moisture level, then our program signals the water pump to feed water to the plant.

The third sensor used to monitor the greenhouse vitals is the water detection sensor, this sensor works similarly to the soil moisture sensor, but it is placed within the water tank to alert the user if the water tank is empty. This sensor also has an analog output and is connected to the analog pin 4.

The output of the three sensors can be viewed on a 16x2 liquid crystal display that is placed on the front of the greenhouse.

To open the greenhouse a small DC motor was used. Similarly, to pump the water from the tank a small DC water pump was used. Both the motor and the pump operate at 12V, while the microcontroller only operates at 5V, so an external power supply was necessary. To connect these components to the Arduino mega, the Rev3 motor shield was used. This motor shield is a dual full-bridge driver designed to drive inductive loads such as DC motors. The shield can drive two DC motors and control their speed and direction independently, and also measures each motors current absorption. The shield pins are shown below in Table 1. The motor was connected to channel A and the water pump was connected to channel B.

Table 1: Arduino Rev3 Motor Shield Pin Out

Function	pins per Ch. A	pins per Ch. B
Direction	D12	D13
PWM	D3	D11
Brake	D9	D8
Current Sensing	A0	A1

For the purposes of this greenhouse, we wanted to open the dome by turning the base 180 degrees counter clockwise, and close it by turning the base back 180 degrees clockwise. In order to accomplish this, there needed to be a way to signal to the motor when to stop. It was obvious that some sort of switch was going to be used on either side of greenhouse, but due to the limited space the best option was a Hall effect switch.

The Hall effect sensor is a transducer that varies its output voltage in response to a magnetic field, meaning that when the sensor comes into contact with a magnet, its voltage will change, and in our case it will go to zero. The sensor was simply attached to the rotating base, and two magnets were placed on the stationary base in the two positions that it was desired for the motor to stop, leaving the dome open or closed.

Virtual Design

In addition to the tangible electrical components, a Bluetooth module was used to allow for a virtual aspect of this project. The HC-05 Bluetooth module connects to the serial 1 TX and RX on digital pins 18 and 19 and allows the module to transmit data to and from an app on a phone. This module is used in conjunction with the Blynk platform, which has iOS and Android apps that can be used to control the Arduino. It uses a digital dashboard where you can build a graphic interface for the project by adding widgets.

Three buttons were added to the app which connect directly to the digital pins on our Arduino mega. A button connected to pin 20 will manually open and close the greenhouse as long as the temperature surrounding the plant does not exceed or fall below the maximum and minimum temperatures. Another button connected to pin 21 will allow the user to manually control the water pump. And the final button will check the level of the water in the tank. A schematic of all of the pin connections to our Arduino Mega 2560 can be seen in Figure 12.

The Blynk platform also allows for virtual pins to be used where a direct pin is not applicable. Virtual pins were used to read and write data from our program to the app. Virtual pins V0 and V1 were connected to two stepper controls. These controls allow the user to change the increase or decrease a value which is written to the program; the controls were used so that the user could specify the maximum and minimum temperatures desired in the greenhouse.

Virtual pins V2 and V3 display labeled values in the app, these pins simply read the temperature and humidity values from our DHT11 sensor and display them at the top of the dashboard. The fourth and fifth pins are connected to gauges that read the data from the water level sensor and the soil moisture sensor and display them on a gauge.

The final virtual pin, V6, is connected to terminal that can read output from the program, similar to a serial monitor that is used in the Arduino interface. The app also incorporates a super chart, which will track the temperature, humidity, and soil moisture over time. The chart allows you to visualize live and historical data of the greenhouse vitals. Each of the virtual components can be seen in the dashboard of the Blynk app, which is displayed in the screenshots in Figure 10.

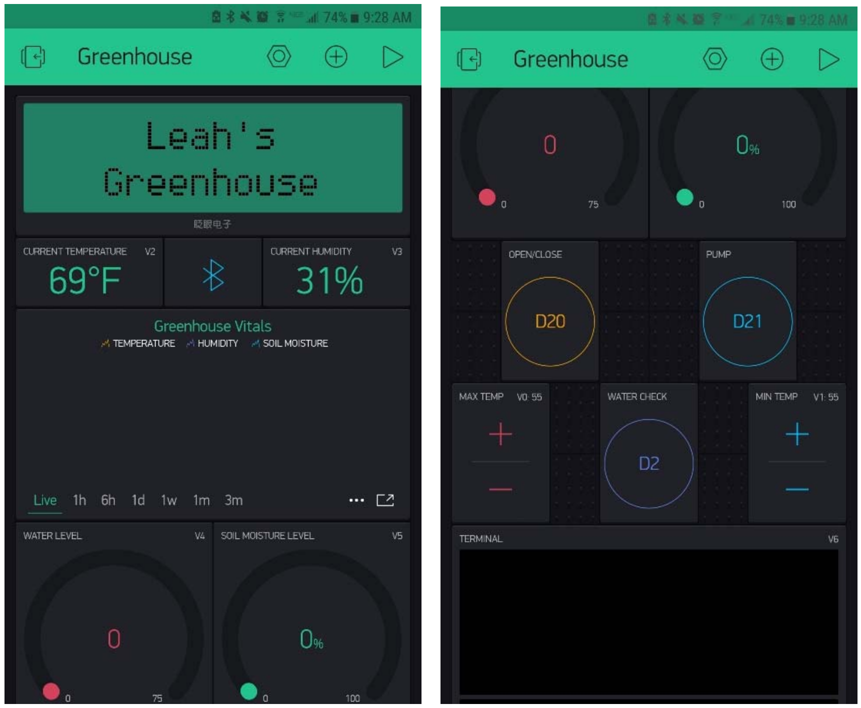


Figure 7: Blynk app greenhouse dashboard

The schematic for the virtual pins are shown here.

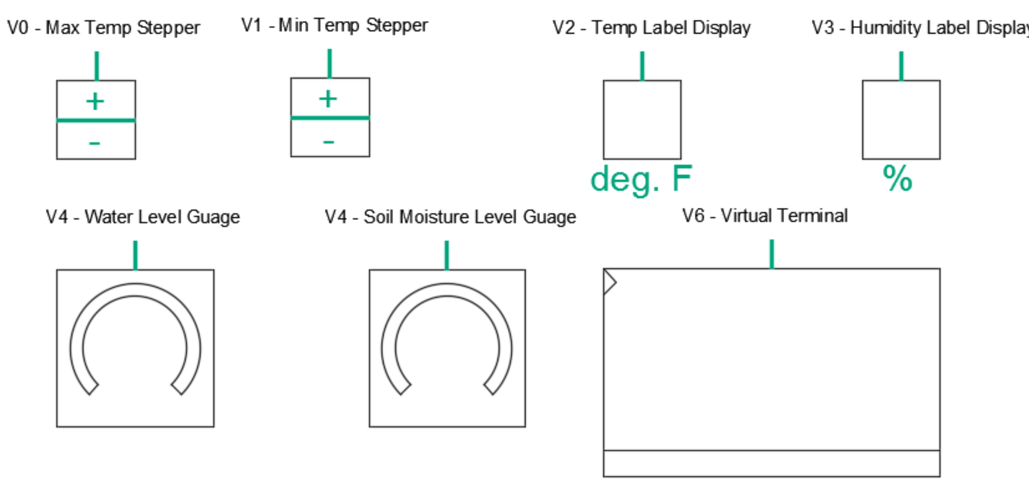
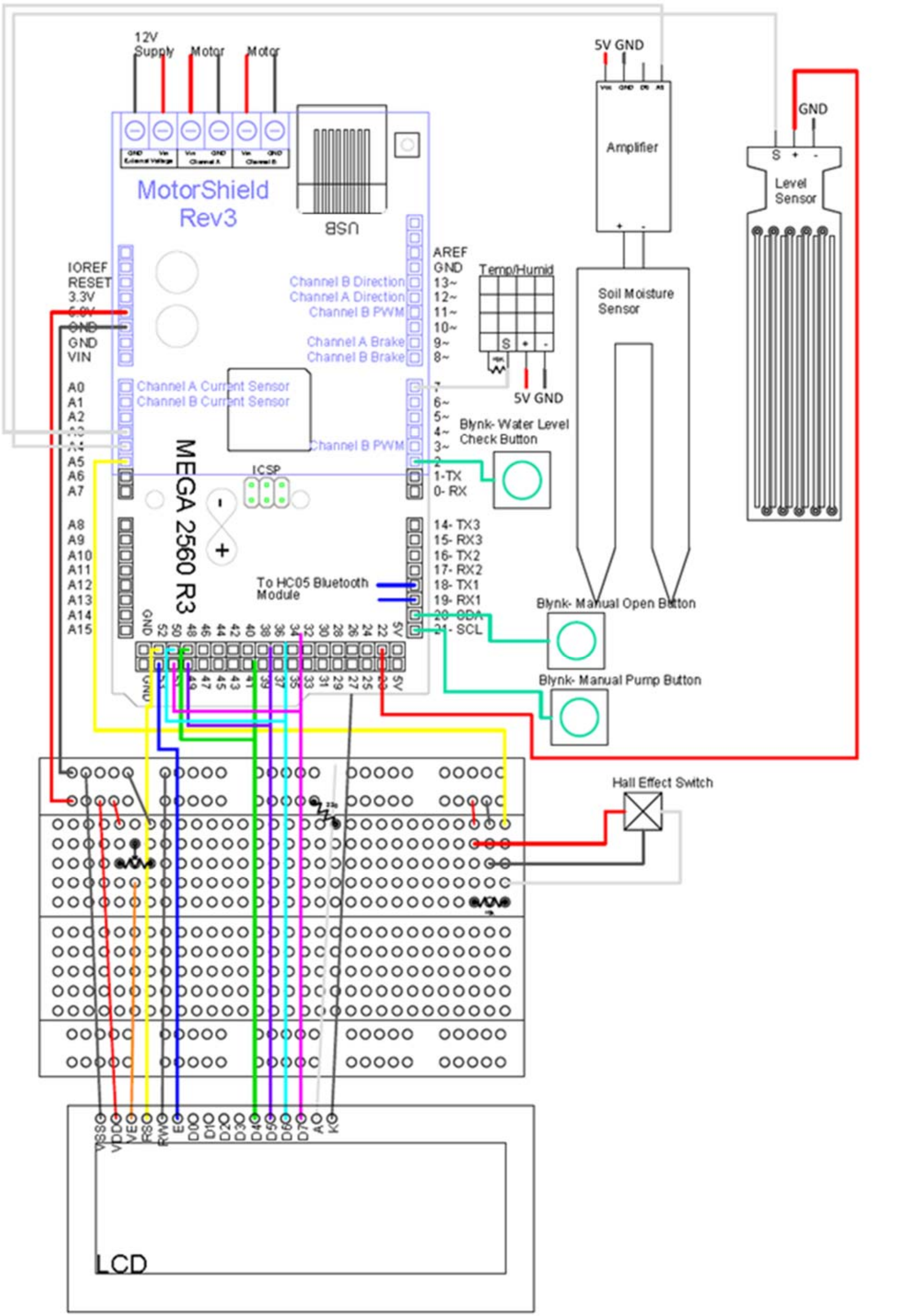


Figure 8: Virtual pin schematic


12V Supply
Motor
Motor
MotorShield Rev3
USB
5V GND
Amplifier
GND
S + -
Level Sensor
IOREF
RESET
3.3V
5.0V
GND
GND
VIN
A0
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
A15
AREF
GND
13~
12~
11~
10~
9~
8~
7
6~
5~
4~
3~
2
1-TX
0- RX
Channel B Direction
Channel A Direction
Channel B PWM
Channel A Brake
Channel B Brake
Channel A Current Sensor
Channel B Current Sensor
Channel B PWM
Temp/Humid
5V GND
Soil Moisture Sensor
Blynk- Water Level Check Button
MEGA 2560 R3
ICSP
14- TX3
15- RX3
16- TX2
17- RX2
18- TX1
19- RX1
20- SDA
21- SCL
To HC05 Bluetooth Module
Blynk- Manual Open Button
Blynk- Manual Pump Button
Hall Effect Switch
VSS
VDD
VE
RS
RW
E
D0
D1
D2
D3
D4
D5
D6
D7
A
K
LCD

Coding

```
/* Leah Morales Greenhouse Project
 *  ECE MQP 2017/2018
 *
 */

#include <math.h>

//Setup for Blynk Bluetooth Control
/* Comment this out to disable prints and save space */
#define BLYNK_PRINT Serial

#include <BlynkSimpleSerialBLE.h>
#include <SoftwareSerial.h>

// You should get Auth Token in the Blynk App.
// Go to the Project Settings (nut icon).
char auth[] = "665b006f745b47298d1ec3705e3845d7";

WidgetTerminal terminal(V6);

//Setup for Motor Control
#define Motor_Direction 12
#define Motor_Brake 9
#define Motor_Moving 3

#define Manual_open 20     //Blynk Button Pin - 20 for Interrupt

#define Hall_effect A5
int Wait_opening;

int closed;

//Setup for Pump Control

#define Pump_Direction 13
#define Pump_Brake 8
#define Pump_Moving 11

#define Manual_pump 21     //Blynk Button Pin - 21 for Interrupt
int Wait_pumping;

//Setup for Temp/Humidity Sensor
#include <DHT.h>
#define DHT11_PIN 7         //DHT connected to Pin 7~
#define DHTTYPE DHT11

DHT dht(DHT11_PIN, DHTTYPE);

int Current_temp;
int Current_humidity;
int Max_temp_setting;
int Min_temp_setting;
```

```
//Setup for LCD
#include <LiquidCrystal.h>
LiquidCrystal lcd(52, 53, 48, 49, 50, 51);

int LCD_clear;

byte thermometer[8] = //icon for thermometer
{
    B00100,
    B01010,
    B01010,
    B01110,
    B01110,
    B11111,
    B11111,
    B01110
};
byte droplet[8] =     //icon for water droplet
{
    B00100,
    B00100,
    B01010,
    B01010,
    B10001,
    B10001,
    B10001,
    B01110,
};
byte level[8] =       //icon for water level
{
    B10001,
    B10001,
    B10001,
    B11001,
    B11111,
    B11111,
    B11111,
    B11111,
};
byte shovel[8] =      //icon for soil moisture level
{
    B01110,
    B01110,
    B00100,
    B00100,
    B01110,
    B01010,
    B01010,
    B00100,
};

//Setup for Water Level Sensor
#define Manual_check 2
#define Water_sensor_on 22
#define Water_level A4
int Liquid_level;
```

```
//Setup for Soil Moisture Sensor
#define Soil_level A3
int Moisture_level;


void setup() {
  // put your setup code here, to run once:

  cli(); //Stop interrupts

  //Set timer1 interrupt at 10HZ

  TCCR1A = 0; //Set enture TCCR1A register to 0
  TCCR1B = 0; //Same for TCCR1B
  TCNT1 = 0;  //Initialize counter value to 0

  //Set compare match register for 10hz increments

  OCR1A = 1560;  // = (16*10^6)/(10*1024) -1
  //Turn on CTC mode
  TCCR1B |= (1 << WGM12);
  //Set CS10 and CS12 bits for 1024 prescaler
  TCCR1B |= (1<<CS12) | (1<<CS10);
  //Enable timer compare interrupt
  TIMSK1 |= (1<<OCIE1A);

  sei(); //Enable interrupts

  //Blynk Pin Designation
  Serial.begin(9600);

  Serial1.begin(9600);
  Blynk.begin(Serial1, auth);

  terminal.println(F("Blynk v" BLYNK_VERSION ": Device started"));
  terminal.println(F("-------------"));
  terminal.flush();

  Serial.println("Waiting for connections...");

  //DHT Initialization
  dht.begin();
  Max_temp_setting = 95;    //Initialize the Max temperature setting to 95
  Min_temp_setting = 45;    //Initialize the Min temperature setting to 45

  //LCD Initialization
  lcd.begin(16, 2);
  lcd.createChar(1,thermometer);
  lcd.createChar(2,droplet);
  lcd.createChar(3,level);
  lcd.createChar(4,shovel);

  //Water Sensor Initialization
  pinMode(Manual_check, INPUT);
  attachInterrupt(digitalPinToInterrupt(Manual_check), Water_level_check,
RISING);
  pinMode(Water_sensor_on, OUTPUT);
```

```
  pinMode(Water_level, INPUT);

  digitalWrite(Water_sensor_on, LOW);

  //Soil Moisture Sensor Initialization
  pinMode(Soil_level, INPUT);

  //Motor Pin Designation
  pinMode(12, OUTPUT);          //Direction Pin for Channel A
  pinMode(9, OUTPUT);           //Brake Pin for Channel A
  pinMode(10, INPUT);           //Speed Pin for Channel A
  pinMode(Manual_open, INPUT);  //Blynk Button Pin Designation
  attachInterrupt(digitalPinToInterrupt(Manual_open), Open, RISING);

  //Greenhouse is Open/Closed
  closed = 1;
  digitalWrite(Motor_Direction, LOW); //Establishes Forward Direction
  digitalWrite(Motor_Brake, HIGH);    //Engages Brake

  //Water Pump Pin Designation
  pinMode(13, OUTPUT);          //Direction Pin for Channel B
  pinMode(8, OUTPUT);           //Brake Pin for Channel B
  pinMode(11, INPUT);           //Speed Pin for Channel B
  pinMode(Manual_pump, INPUT);  //Blynk Button Pin Designation
  attachInterrupt(digitalPinToInterrupt(Manual_pump), Pump, RISING);

  //Pump is off
  digitalWrite(Pump_Direction, HIGH); //Establishes Forward Direction
  digitalWrite(Pump_Brake, HIGH);     //Engages Brake

}

void loop() {
  // put your main code here, to run repeatedly:

  //Blynk Function Call
  Blynk.run();          //Start bluetooth communication

  Temperature_check();  //Check Temperature

  Water_level_write();  //Check Water Level

  Soil_level_check();   //Check Soil Moisture

  Draw();               //Draw to LCD

}

ISR(TIMER1_COMPA_vect){

  Wait_opening++;
  Wait_pumping++;
  LCD_clear++;

  int Hall_state = analogRead(Hall_effect);

  //Motor is stopped if it has been running more than a second
```

```
  // and if the hall effect switch is low

  if((Wait_opening > 5) && (Hall_state < 512)){
    digitalWrite(Motor_Brake, HIGH);
  }

  //Pump is stopped after running for 5 seconds

  if(Wait_pumping > 50){
     digitalWrite(Pump_Brake, HIGH);     //Engage the Brake
  }

  //Clear the LCD once per minute

  if(LCD_clear > 600){
    lcd.clear();
    LCD_clear = 0;
  }
}


void Open(){

  //Designate the direction of the motor based on current state
  if (closed){
    if(Current_temp < Min_temp_setting){
      Serial.println("Temperature is Below Min Setting, Greenhouse Will
Remain Closed");
    }
    else{
      Serial.println("Opening");
      digitalWrite(Motor_Direction, LOW); //Establishes Forward Direction
      digitalWrite(Motor_Brake, LOW); //Disengage the Brake
      analogWrite(Motor_Moving, 125); //Spins Motor at Half Speed

      closed = 0;
    }
  }

   else{
    if(Current_temp > Max_temp_setting){
       Serial.println("Temperature Exceeds Max Setting, Greenhouse Will
Remain Open");
    }
    else{
      Serial.println("Closing");
      digitalWrite(Motor_Direction, HIGH);  //Establishes Backward Direction
      digitalWrite(Motor_Brake, LOW);       //Disengage the Brake
      analogWrite(Motor_Moving, 125);       //Spins Motor at Half Speed

      closed = 1;
    }
  }

  Wait_opening = 0;

}
```

```
void Pump(){

  Serial.print("Pumping");
  digitalWrite(Pump_Direction, HIGH); //Establishes Forward Direction
  digitalWrite(Pump_Brake, LOW);      //Disengage the Brake
  analogWrite(Pump_Moving, 255 );      //Spins Motor at Half Speed

  Wait_pumping = 0;

}


BLYNK_WRITE(V0){

  Max_temp_setting = param.asInt(); // assigning incoming value from pin V0
to a variable
  Serial.print("The Maximum temperature is set to: ");
  Serial.println(Max_temp_setting);

}

BLYNK_WRITE(V1){

  Min_temp_setting = param.asInt(); // assigning incoming value from pin V1
to a variable
  Serial.print("The Minimum temperature is set to: ");
  Serial.println(Min_temp_setting);

}


void Temperature_check(){

  Current_temp = dht.readTemperature(true);
  Current_humidity = round(dht.readHumidity());


  if((Current_temp > Max_temp_setting) && (closed == 1)){

    Serial.println("Temperature Exceeds Max Setting, Greenhouse Will Remain
Open");
    terminal.println("Temperature Exceeds Max Setting, Greenhouse Will Remain
Open");
    terminal.flush();

    Open();
  }

  if((Current_temp < Min_temp_setting) && (closed == 0)){

    Serial.println("Temperature is Below Min Setting, Greenhouse Will Remain
Closed");
    terminal.println("Temperature is Below Min Setting, Greenhouse Will
Remain Closed");
    terminal.flush();

    Open();
```

```
  }

  Blynk.virtualWrite(V2, Current_temp);
  Blynk.virtualWrite(V3, Current_humidity);
}

void Water_level_check(){

  digitalWrite(Water_sensor_on, HIGH);

  Liquid_level = analogRead(Water_level);

  digitalWrite(Water_sensor_on, LOW);

}

void Water_level_write(){

  int Virtual_level = fscale( 100, 300, 0, 100, Liquid_level, 1);

  Blynk.virtualWrite(V4, Virtual_level);

}

void Soil_level_check(){

  Moisture_level = analogRead(Soil_level);

  int Virtual_moisture = fscale(0, 1024, 100, 0, Moisture_level, 0);

  Blynk.virtualWrite(V5, Virtual_moisture);

  if(Virtual_moisture < 20){
    Pump();
  }
}


void Draw(){
  lcd.setCursor(0,0);
  lcd.write(1);
  lcd.print(" ");
  lcd.print(Current_temp);
  lcd.print((char)223);
  lcd.print("F");
  lcd.setCursor(0,1);
  lcd.write(2);
  lcd.print(" ");
  lcd.print(Current_humidity);
  lcd.print("%");
  lcd.setCursor(7,0);
  lcd.write(3);
  lcd.print(" ");
  lcd.print(Liquid_level);//analog reading 0 - 260
  lcd.setCursor(7,1);
  lcd.write(4);
  lcd.print(" ");
```

```
  lcd.print(Moisture_level);//analog reading 0 - ??

}


/*
 *  FScale Function
 *
 */
#include <math.h>

int j;
float scaledResult;

 float fscale( float originalMin, float originalMax, float newBegin, float
newEnd, float inputValue, float curve){

  float OriginalRange = 0;
  float NewRange = 0;
  float zeroRefCurVal = 0;
  float normalizedCurVal = 0;
  float rangedValue = 0;
  boolean invFlag = 0;


  // condition curve parameter
  // limit range

  if (curve > 10) curve = 10;
  if (curve < -10) curve = -10;

  curve = (curve * -.1) ; // - invert and scale - this seems more intuitive -
postive numbers give more weight to high end on output
  curve = pow(10, curve); // convert linear scale into lograthimic exponent
for other pow function

  /*
   Serial.println(curve * 100, DEC);   // multply by 100 to preserve
resolution
   Serial.println();
   */

  // Check for out of range inputValues
  if (inputValue < originalMin) {
    inputValue = originalMin;
  }
  if (inputValue > originalMax) {
    inputValue = originalMax;
  }

  // Zero Refference the values
  OriginalRange = originalMax - originalMin;

  if (newEnd > newBegin){
    NewRange = newEnd - newBegin;
  }
  else
```

```
  {
    NewRange = newBegin - newEnd;
    invFlag = 1;
  }

  zeroRefCurVal = inputValue - originalMin;
  normalizedCurVal  =  zeroRefCurVal / OriginalRange;   // normalize to 0 - 1
float

  /*
  Serial.print(OriginalRange, DEC);
   Serial.print("   ");
   Serial.print(NewRange, DEC);
   Serial.print("   ");
   Serial.println(zeroRefCurVal, DEC);
   Serial.println();
   */

  // Check for originalMin > originalMax  - the math for all other cases i.e.
negative numbers seems to work out fine
  if (originalMin > originalMax ) {
    return 0;
  }

  if (invFlag == 0){
    rangedValue =  (pow(normalizedCurVal, curve) * NewRange) + newBegin;

  }
  else     // invert the ranges
  {
    rangedValue =  newBegin - (pow(normalizedCurVal, curve) * NewRange);
  }

  return rangedValue;
}
```

Appendix B: Notes on Code Review and Relevant Definitions

Topic	Details	Reference
IBC (2015 Edition)		
Use and occupancy	Classified in Utility and Miscellaneous Group U, maybe Group E?	Section 312.1 or 305.1
Construction Type	Classified as Type V construction: the structural elements, exterior walls, and interior walls are of any materials permitted by this code.	Section 602.4.9
Allowable height	Most restrictive height for Group U and E occupancy is 40 ft. above grade plane (Type VB, nonsprinklered construction).	Table 504.3
Allowable height	Most restrictive height in entire code is 40 feet.	Table 504.3
Allowable number of stories	Most restrictive number of stories for Group U occupancy is 1 story above grade plane (Type VB, nonsprinklered construction); most restrictive for Group E is 1 story (Type VB, nonsprinklered).	Table 504.4
Allowable number of stories	Most restrictive number of stories in entire code is 1 story; Type VB nonsprinklered not permitted for H-1 or I-2 occupancy.	Table 504.4
Allowable area	Most restrictive area for Group U occupancy, non-sprinklered, Type VB construction is 5,500 sf (does not include area factor increase due to frontage); Group E is 9,500 sf (Type VB, nonsprinklered, no increase due to factors).	Table 506.2
Allowable area	Most restrictive area in entire code is 4,500 for I-1, nonsprinklered, Type VB; Type VB I-2 not permitted and Type VB H-1 not permitted.	Table 506.2
Accessory occupancies	Accessory occupancies are occupancies that are ancillary (providing necessary support to the primary activities or operation) to the main occupancy.	Section 508.2
Accessory occupancies	The allowable height and number of stories shall be in accordance with Section 504 for the main occupancy.	Section 508.2.2
Accessory occupancies	The allowable area shall be based on Section 506 for the main occupancy and the accessory occupancies shall not occupy more than 10 percent of the floor area of the story in which they are located.	Section 508.2.3
Accessory occupancies	Separation is not required between accessory occupancies and the main occupancy except for Group H-2, H-3, H-4 and H-5; Group I-1, R-1, R-2, and R-3 shall be separated from other dwelling/sleeping units and from accessory occupancies.	Section 508.2.4
Fire resistance	Fire resistance for all building elements in Type VB construction allowed to be 0.	Table 601
Projections	Cornices, eave overhangs, exterior balconies and similar projections extending beyond the exterior wall shall conform to the requirements of this section (705.2) and Section 1406. Projections shall not extend any	Section 705.2

	closer to the line used to determine the fire separation distance than shown in Table 705.2..	
Projections	Projections from walls of Type III, IV or V construction shall be of any approved material.	Section 705.2.2
Projections	Combustible projections extending to within 5 feet of the line used to determine the fire separation distance shall be of not less than 1-hour fire-resistance-rated construction, Type IV construction, fire-retardant-treated wood or as required by Section 1406.3. EXCEPTION: Type VB construction shall be allowed for combustible projections in Group R-3 and U occupancies with a fire separation distance greater than or equal to 5 feet.	Section 705.2.3
Area of exterior wall openings	The area of openings in a building containing only a Group U occupancy, private garage or carport with a fire separation distance of 5 feet or greater shall not be limited.	Table 705.8
Parapet	A parapet is not required because the exterior wall is not required to be fire-resistance rated in accordance with Table 602 because of fire separation distance.	Section 705.11
Fire barriers	The fire-resistance rating requirements for fire barrier assemblies or horizontal assemblies between fire areas for a Group U occupancy is 1 hour.	Table 707.3.10
Vertical penetrations	Penetrations, concealed and unconcealed, shall be permitted where protected in accordance with Section 714.	Section 712.1.4
Ducts and air transfer openings	Penetrations by ducts and air transfer openings shall be protected in accordance with Section 717.	Section 712.1.6
Fire resistance calculations	Section 722 provides equations and values to calculate the fire resistance of specific materials and combinations of materials.	Section 722
Fire Protection Systems	An automatic sprinkler system is required in Group E occupancies throughout all Group E fire areas greater than 12,000 square feet in area and throughout every portion of educational buildings below the lowest level of exit discharge serving that portion of the building.	Section 903.2.3
Fire Protection Systems	In all occupancies other than Group U an automatic sprinkler system shall be installed for building design or hazards in stories without openings, rubbish and linen chutes, buildings 55 feet or more in height, ducts conveying hazardous exhausts, commercial cooking operations, and those areas outlined in Table 902.11.6.	Section 903.2.11
Fire safety and evacuation	Fire safety and evacuation plans shall be provided for all occupancies and buildings where required by the International Fire Code. Such fire safety and evacuation plans shall comply with the applicable provisions of Sections 401.2 and 404 of the IFC.	Section 1001.4
Occupant load	The maximum floor area allowances per occupant are as follows: Accessory storage area, mechanical equipment room and agricultural buildings = 300 gross, classroom area = 20 net, shops and other	Table 1004.1.2

	vocational room areas = 50 net.	
Occupant load	The occupant load permitted in any building, or portion thereof, is permitted to be increased from that number established for the occupancies in Table 1004.1.2, provided that all other requirements of the code are met based on such modified number and the occupant load does not exceed one occupant per 7 square feet of occupiable floor space.	Section 1004.2
Occupant load	Yards, patios, courts and similar outdoor areas accessible to and usable by the building occupants shall be provided with means of egress as required by this chapter. The occupant load of such outdoor areas shall be assigned by the building official in accordance with anticipated use.	Section 1004.5
Egress	The capacity, in inches, of means of egress components other than stairways shall be calculated by multiplying the occupant load served by such component by a means of egress capacity factor of 0.2 inch per occupant.	Section 1005.3.2
Egress	Where more than one exit or access to more than one exit is required, the means of egress shall be configured such that the loss of any one exit or access to one exit shall not reduce the available capacity or width to less than 50 percent of the required capacity or width.	Section 1005.5
Egress	Doors, when fully opened, shall not reduce the required width by more than 7 inches. Doors in any position shall not reduce the required width by more than one half. EXCEPTIONS: surface-mounted latch release hardware shall be exempt from inclusion in the 7 inch-maximum encroachment where the hardware is mounted on the side of the door facing away from the adjacent wall where the door is in the open position and the hardware is mounted between 34 and 48 inches above the finished floor.	Section 1005.7.1
Egress	Handrail projections shall be in accordance with Section 1014.8. Other nonstructural projections such as trim and similar decorative features shall be permitted to project into the required width not more than 1.5 inches on each side.	Section 1005.7.2
Egress	Two exits or exit access doorways from any space shall be provided where the design occupant load or common path of egress travel distance exceeds the values listed in Table 1006.2.1.	Section 1006.2.1
Egress	One exit or exit access doorway is permitted for Group U occupancies with a maximum occupant load of 49, and a maximum common path of egress travel distance of 100 feet for an occupant load of 30 or less and 75 feet for an occupant load greater than 30.	Table 1006.2.1
Egress	One exit or exit access doorway is permitted for Group E occupancies with a maximum occupant load of 49, and a maximum common path of egress travel distance of 75 feet.	Table 1006.2.1

Accessibility	Accessible spaces shall be provided with not less than one accessible means of egress. Where more than one means of egress are required by Section 1006.2 or 1006.3 from any accessible space, each accessible portion of the space shall be served by not less than two accessible means of egress.	Section 1009.1
Egress	The required capacity of each door opening shall be sufficient for the occupant load thereof and shall provide a minimum clear width of 32 inches. Clear openings of doorways with swinging doors shall be measured between the face of the door and the stop, with the door open 90 degrees.	Section 1010.1.1
Exit signs	Exit signs are not required in rooms or areas that require only one exit or exit access, where main exterior exit doors or gates are obviously and clearly identifiable as exits as approved by the building official and in Group U occupancies.	Section 1013.1
Egress	For Group U occupancies without a sprinkler system the exit access travel distance shall not exceed 300 feet; 200 feet for Group E.	Table 1017.2
Egress	Exit access travel distance shall be measured from the most remote point within a story along the natural and unobstructed path of horizontal and vertical egress travel to the entrance to an exit.	Section 1017.3
Egress	Exits shall discharge directly to the exterior of the building. The exit discharge shall be at grade or shall provide a direct path of egress travel to grade. The exit discharge shall not reenter a building.	Section 1028.1
Egress	The minimum width or required capacity of the exit discharge shall be not less than the minimum width or required capacity of the exits being served.	Section 1028.2
Accessibility	See Table 1106.1 for required accessible parking spaces.	Table 1106.1
Natural ventilation	Natural ventilation of an occupied space shall be through windows, doors, louvers, or other openings to the outdoors. The operating mechanism for such openings shall be provided with ready access so that the openings are readily controllable by the building occupants.	Section 1203.5
Temperature control	Interior spaces intended for human occupancy shall be provided with active or passive space heating systems capable of maintaining an indoor temperature of not less than 68 degrees F at a point 3 feet above the floor on the design heating day. EXCEPTION: Space heating systems are not required for interior spaces where the primary purpose of the space is not associated with human comfort and Group F, H, S or U occupancies.	Section 1204.1
Lighting	The minimum net glazed area of a building shall be not less than 8 percent of the floor area of the room served.	Section 1205.2
Lighting	Artificial light shall be provided that is adequate to provide an average illumination of 10 footcandles (107 lux) over the area of the room at a height of 30 inches above the floor level.	Section 1205.3
Weather protection	Flashing shall be installed in such a manner so as to prevent moisture entering the wall and roof through joints in copings, through moisture	Section 1503.2

	permeable materials and at intersections with parapet walls and other penetrations through the roof plane.	
PV panels	Rooftop pv panels and modules shall be installed in accordance with the manufacturer's instructions and shall be listed and labeled in accordance with UL 1703	Section 1510.7.4
Deflection limits	See Table 1604.3 for maximum deflection limits.	Table 1604.3
Risk Category	Classified as risk category I (maybe II if occupancy is other than Group U).	Table 1604.5
IECC (2015 Edition)		
Climate zone	Massachusetts is in Climate Zone 5A (A = moist).	Figure C301.1
Interior design temperatures	The interior design temperatures used for heating and cooling load calculations shall be a maximum of 72 degrees F for heating and a minimum of 75 degrees F for cooling.	Section C302.1
U-Factors	See Tables C303.1.3(1) and (2) for default fenestration and door U-factors.	Table C303.1.3
Building envelope requirements	Greenhouses, buildings that do not contain conditioned space and buildings with with a peak design rate of energy usage less than 3.4 Btu/h * sf or 1.0 watt per square foot of floor area for space conditioning purposes are exempt from the building envelope requirements in IECC.	Section C402.1.1
Minimum efficiency requirements	See Tables C403.2.3 for minimum efficiency requirements for specified equipment.	Table C403.2.3
Additional information	See Chapter 4[CE] Commercial Energy Efficiency for any additional information.	Chapter 4
ASCE 7-10		
Earthquake load	Agricultural storage structures that are intended for incidental human occupancy are exempt from earthquake loads	11.1.2.3
Wind load	One story buildings with h less than or equal to 30 feet are exempt from the torsional wind load cases	D.1.1

Word	Definition
IBC (2015 Edition)	
Grade Plane	A reference plane representing the average of finished ground level adjoining the building at exterior walls. Where the finished ground level slopes away from the exterior walls, the reference plane shall be established by the lowest points within the area between the building and the lot line or, where the lot line is more

	than 6 feet from the building, between the building and a point 6 feet from the building.
Fire Area	The aggregate floor area enclosed and bounded by fire walls, fire barriers, exterior walls or horizontal assemblies of a building. Areas of the building not provided with surrounding walls shall be included in the fire area if such areas are included within the horizontal projection of the roof or floor next above.
Fire Separation Distance	The distance measured from the building face to one of the following: the closest interior lot line, to the centerline of a street, an alley, or a public way, to an imaginary line between two buildings on the lot. The distance shall be measured at right angles from the face of the wall.
Means of Egress	A continuous and unobstructed path of vertical and horizontal egress travel from any occupied portion of a building or structure to a public way. A means of egress consists of three separate and distinct parts: the exit access, the exit and the exit discharge.
Exit Access	That portion of a means of egress system that leads from any occupied portion of a building or structure to an exit.
Common Path of Egress	That portion of the exit access travel distance measured from the most remote point within a story to that point where the occupants have separate and distinct access to two exits or exit access doorways.

Appendix C: Loads Used in Structural Analysis

Loads			Units	Notes
L	Live load	0	psf	One story building - no live load on new structure
D	Dead load	See below		Sum of values for glass + purlins
Lr	Roof live load	14.18	psf	See calculations below
H	Lateral earth pressure	0	psf	Not present for new structure
F	Load due to fluids	0	psf	Not present for new structure
S	Snow load	15.40	psf	See calculations below
R	Rain Load	0	psf	Not present for new structure
W	Wind load	See below		See calculations below
E	Earthquake load	0	psf	Greenhouses exempt from earthquake loads

Dead Loads for Different Glazing Systems				
Glazing System		Load	Units	Source
Dg	Glass	6.6	psf	Dulles Glass & Mirror
Dp	Polycarbonate	0.55	psf	“SUNLITE Multiwall Polycarbonate Sheet Specifications.”
Da	Acrylic	0.9	psf	“ACRYLITE Alltop Technical Information”

Dead Loads of Rafters (Includes 5 psf Allowance for HVAC)				
Structure		Load	Units	Source
Dw	Wood	5.1518	psf	See Appendix F
Ds	Steel	5.5081	psf	See Appendix F

Roof Live Load Calculation			
Variable		Value	Source
Tributary area	At	260	Calculated from geometry
Inches of rise per foot of run	F	8.92	Calculated from geometry
Unreduced roof live load	Lo	20	IBC Table 1607.1
Reduction factor 1	R1	0.94	IBC Equation 16-28
Reduction factor 2	R2	0.754	IBC Equation 16-31
Roof live load	Lr	14.18	IBC Equation 16-26

Snow Load Calculation			
Variable		**Value**	**Source**
Ground snow load	pg	50	*ASCE 7-10* Figure 7-1
Exposure factor	Ce	1	*ASCE 7-10* Table 7-2
Thermal factor	Ct	1	*ASCE 7-10* Table 7-3
Importance factor	Is	0.8	*ASCE 7-10* Section 7.3.3
Snow load on flat roofs	pf	28	*ASCE 7-10* Equation 7.3-1
Slope factor	Cs	0.55	*ASCE 7-10* Figure 7-2
Snow load	S	15.40	*ASCE 7-10* Equation 7.4-1

Wind Loads				
WWr	*Windward roof load	4.4	psf	See Appendix C
WW	**Windward wall load	11.2	psf	See Appendix C
LWr	*Leeward roof load	9.8	(-) psf	See Appendix C
LW	**Leeward wall load	8.1	(-) psf	See Appendix C

*Roof loads are values for 13-25 feet above grade

**Wall loads are values for up to 15 feet above grade

Appendix D: Wind Load Calculation

Basic Parameters			
Risk Category		I	*ASCE 7-10* Table 1.5-1
Basic Wind Speed	V	115	*ASCE 7-10* Figure 26.5-1A
Wind Directionality Factor	Kd	0.85	*ASCE 7-10* Table 26.6-1
Exposure Category		B	*ASCE 7-10* Section 26.7
Topographic Factor	Kzt	1	*ASCE 7-10* Section 26.8
Gust Effect Factor	Gf	0.85	*ASCE 7-10* Section 26.9
Enclosure Classification		Enclosed	*ASCE 7-10* Section 26.10
Internal Pressure Coefficient	GCpi	0.18	*ASCE 7-10* Table 26.11-1
Terrain Exposure Constant	a	7	*ASCE 7-10* Table 26.9-1
Terrain Exposure Constant	zg	1200	*ASCE 7-10* Table 26.9-1

Wall Pressure Coefficients			
Windward Wall Width	B	43.58	From geometry
Side Wall Width	L	33.42	From geometry
L/B Ratio		0.77	Calculated
Windward Wall Coefficient	Cp	0.8	*ASCE 7-10* Figure 27.4-1
Leeward Wall Coefficient	Cp	-0.5	*ASCE 7-10* Figure 27.4-1
Side Wall Coefficient	Cp	-0.7	*ASCE 7-10* Figure 27.4-1

Roof Pressure Coefficients			
Roof Slope	q	37	From geometry
Median Roof Height	h	25	From geometry
Velocity Pressure Exposure Coef.	Kh	0.67	*ASCE 7-10* Table 27.3-1
Velocity Pressure	qh	19.14	*ASCE 7-10* Equation 27.3-1
h/L Ratio		0.75	Calculated
*Windward Roof Area		0	See note
*Roof Area Within 13 ft of WW Edge		0	See note

*0 used for a conservative result

<table>
<tr><th colspan="7">Roof Coefficients</th><th rowspan="9">ASCE 7-10 Figure 27.4-1</th></tr>
<tr><th colspan="2" rowspan="2">Location</th><th rowspan="2">Min/Max</th><th colspan="4">Horiz Distance From Windward Edge</th></tr>
<tr><th>0</th><th>12.5</th><th>25</th><th>50</th></tr>
<tr><td rowspan="2">Windward Roof Coefficient Normal to Ridge</td><td rowspan="2">Cp</td><td>Min</td><td>-0.16</td><td>-0.16</td><td>-0.16</td><td>-0.16</td></tr>
<tr><td>Max</td><td>0.27</td><td>0.27</td><td>0.27</td><td>0.27</td></tr>
<tr><td rowspan="2">Leeward Roof Coefficient Normal to Ridge</td><td rowspan="2">Cp</td><td>Min</td><td>-0.60</td><td>-0.60</td><td>-0.60</td><td>-0.60</td></tr>
<tr><td>Max</td><td>-0.60</td><td>-0.60</td><td>-0.60</td><td>-0.60</td></tr>
<tr><td rowspan="2">Roof Coefficient Parallel to Ridge</td><td rowspan="2">Cp</td><td>Min</td><td>-1.10</td><td>-1.10</td><td>-0.60</td><td>-0.50</td></tr>
<tr><td>Max</td><td>-0.18</td><td>-0.18</td><td>-0.18</td><td>-0.18</td></tr>
</table>

<table>
<tr><th colspan="12">Structure Pressure Summary</th></tr>
<tr><th rowspan="3">Height (ft)</th><th rowspan="3">Kz</th><th rowspan="3">qz</th><th colspan="4">Walls</th><th colspan="3">Roof</th><th colspan="2">Internal</th></tr>
<tr><th rowspan="2">WW</th><th rowspan="2">LW</th><th rowspan="2">WW + LW</th><th rowspan="2">Side</th><th colspan="2">Normal to Ridge</th><th rowspan="2">Parallel to Ridge</th><th rowspan="2">Positive</th><th rowspan="2">Negative</th></tr>
<tr><th>WW</th><th>LW</th></tr>
<tr><td>0</td><td>0.57</td><td>16.54</td><td>11.25</td><td rowspan="11">-8.13</td><td>19.38</td><td rowspan="11">-11.39</td><td>Min:</td><td>Min:</td><td>Min:</td><td>3.44</td><td rowspan="11">-3.44</td></tr>
<tr><td>2.5</td><td>0.57</td><td>16.54</td><td>11.25</td><td>19.38</td><td rowspan="4">-2.60</td><td rowspan="4">-9.76</td><td rowspan="4">-17.87</td><td>3.44</td></tr>
<tr><td>5</td><td>0.57</td><td>16.54</td><td>11.25</td><td>19.38</td><td>3.44</td></tr>
<tr><td>7.5</td><td>0.57</td><td>16.54</td><td>11.25</td><td>19.38</td><td>3.44</td></tr>
<tr><td>10</td><td>0.57</td><td>16.54</td><td>11.25</td><td>19.38</td><td>3.44</td></tr>
<tr><td>12.5</td><td>0.57</td><td>16.54</td><td>11.25</td><td>19.38</td><td>Max:</td><td>Max:</td><td>Max:</td><td>3.44</td></tr>
<tr><td>15</td><td>0.57</td><td>16.54</td><td>11.25</td><td>19.38</td><td rowspan="5">4.40</td><td rowspan="5">-9.76</td><td rowspan="5">-2.93</td><td>3.44</td></tr>
<tr><td>17.5</td><td>0.60</td><td>17.28</td><td>11.75</td><td>19.89</td><td>3.44</td></tr>
<tr><td>20</td><td>0.62</td><td>17.96</td><td>12.21</td><td>20.34</td><td>3.44</td></tr>
<tr><td>22.5</td><td>0.65</td><td>18.57</td><td>12.63</td><td>20.76</td><td>3.44</td></tr>
<tr><td>25</td><td>0.67</td><td>19.14</td><td>13.01</td><td>21.15</td><td>3.44</td></tr>
</table>

Appendix E: Member Qualities Used in Calculations

Wood Qualities for Member Sizing				
Fb	Bending Strength	775	psi	Values for No. 1 Eastern White Pine from Table 4A in 2015 NDS Supplement Design Values for Wood Construction
Fv	Shear Strength	135	psi	
Ft	Ultimate Tensile Strength*	350	psi	
Fc	Compressive Strength*	1,000	psi	

* Values are for forces parallel to the grain of the wood

Steel Qualities for Member Sizing				
Fy	Yield Strength	36,000	psi	ASTM A36/A36M Standard Specification for Carbon Structural Steel Table 2
Fv	Shear Yield Strength	21,600	psi	AISC Steel Construction Manual Part 16.1 Section G2.1
Fu	Ultimate Tensile Strength	58,000	psi	ASTM A36/A36M Standard Specification for Carbon Structural Steel Table 2
Fc	Compressive Strength	16,000	psi	AISC Steel Construction Manual Table C-E3.1

Appendix F: Rafter Sizing Calculations

The maximum allowable deflection of each glass pane is equal 1/175 of the glass edge length or ¾ inches, whichever is less (Section 2403.3, *International Building Code*, 2015). With each pane of glass being 6.5 feet, the maximum allowed deflection ended up being 6.5/175 or 0.0371 ft. Rafter sizes were developed for spacing from 1 foot to 8 feet. These calculations can be seen below.

Distributed Loads							
Spacing		Load Combinations					
		D+F		D+H+F+L		D+H+F+(Lr or S or R) D+H+F+S	
1	ft.	5.56	lbs/ft	5.56	lbs/ft	18.53	lbs/ft
2	ft.	11.12	lbs/ft	11.12	lbs/ft	37.05	lbs/ft
3	ft.	16.67	lbs/ft	16.67	lbs/ft	55.58	lbs/ft
4	ft.	22.23	lbs/ft	22.23	lbs/ft	74.11	lbs/ft
5	ft.	27.79	lbs/ft	27.79	lbs/ft	92.63	lbs/ft
6	ft.	33.35	lbs/ft	33.35	lbs/ft	111.16	lbs/ft
7	ft.	38.91	lbs/ft	38.91	lbs/ft	129.68	lbs/ft
8	ft.	44.46	lbs/ft	44.46	lbs/ft	148.21	lbs/ft

Distributed Loads (cont.)							
Spacing		Load Combinations					
		D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W) +0.75L+0.75(Lr or S or R)	
		D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75L +0.75S**	
1	ft.	15.28	lbs/ft	8.20	lbs/ft	17.26	lbs/ft
2	ft.	30.57	lbs/ft	16.40	lbs/ft	34.53	lbs/ft
3	ft.	45.85	lbs/ft	24.59	lbs/ft	51.79	lbs/ft
4	ft.	61.14	lbs/ft	32.79	lbs/ft	69.06	lbs/ft
5	ft.	76.42	lbs/ft	40.99	lbs/ft	86.32	lbs/ft
6	ft.	91.71	lbs/ft	49.19	lbs/ft	103.59	lbs/ft
7	ft.	106.99	lbs/ft	57.39	lbs/ft	120.85	lbs/ft
8	ft.	122.27	lbs/ft	65.58	lbs/ft	138.11	lbs/ft

Distributed Loads (cont.)							
Spacing		Load Combinations					
		D+H+F+0.75(0.7E) +0.75L+0.75S		**0.6D+0.6W+H**		**0.6(D+F)+0.7E+H**	
1	ft.	15.28	lbs/ft	5.97	lbs/ft	3.33	lbs/ft
2	ft.	30.57	lbs/ft	11.95	lbs/ft	6.67	lbs/ft
3	ft.	45.85	lbs/ft	17.92	lbs/ft	10.00	lbs/ft
4	ft.	61.14	lbs/ft	23.90	lbs/ft	13.34	lbs/ft
5	ft.	76.42	lbs/ft	29.87	lbs/ft	16.67	lbs/ft
6	ft.	91.71	lbs/ft	35.85	lbs/ft	20.01	lbs/ft
7	ft.	106.99	lbs/ft	41.82	lbs/ft	23.34	lbs/ft
8	ft.	122.27	lbs/ft	47.80	lbs/ft	26.68	lbs/ft

Distributed Loads (cont.)							
Spacing		**Load Combinations (Using Leeward W)**					
		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W) +0.75L+0.75(Lr or S or R)			
		D+H+F+0.6W		**D+H+F+0.75(0.6W)+0.75L+ 0.75S**		**0.6D+0.6W+H**	
1	ft.	-0.32	lbs/ft	10.87	lbs/ft	9.21	lbs/ft
2	ft.	1.40	lbs/ft	21.75	lbs/ft	18.43	lbs/ft
3	ft.	16.67	lbs/ft	32.62	lbs/ft	27.64	lbs/ft
4	ft.	22.23	lbs/ft	43.50	lbs/ft	36.86	lbs/ft
5	ft.	27.79	lbs/ft	54.37	lbs/ft	46.07	lbs/ft
6	ft.	33.35	lbs/ft	65.25	lbs/ft	55.29	lbs/ft
7	ft.	38.91	lbs/ft	76.12	lbs/ft	64.50	lbs/ft
8	ft.	44.46	lbs/ft	86.99	lbs/ft	73.72	lbs/ft

Required Wood I							
Spacing		**Load Combinations**					
						D+H+F+(Lr or S or R)	
		D+F		**D+H+F+L**		**D+H+F+S**	
1	ft.	0.4553	in^4	0.0017	in^4	0.0055	in^4
2	ft.	0.9106	in^4	0.0033	in^4	0.0111	in^4
3	ft.	1.3659	in^4	0.0050	in^4	0.0166	in^4
4	ft.	1.8212	in^4	0.0066	in^4	0.0221	in^4
5	ft.	2.2765	in^4	0.0083	in^4	0.0276	in^4
6	ft.	2.7318	in^4	0.0099	in^4	0.0332	in^4
7	ft.	3.1871	in^4	0.0116	in^4	0.0387	in^4
8	ft.	3.6424	in^4	0.0133	in^4	0.0442	in^4

Required Wood I (cont.)							
Spacing		Load Combinations					
		D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W) +0.75L+0.75(Lr or S or R)	
		D+H+F+0.75L+0.75S		D+H+F+0.6W		D+H+F+0.75(0.6W)+0.75L +0.75S	
1	ft.	0.0046	in^4	0.0024	in^4	0.0051	in^4
2	ft.	0.0091	in^4	0.0049	in^4	0.0103	in^4
3	ft.	0.0137	in^4	0.0073	in^4	0.0154	in^4
4	ft.	0.0182	in^4	0.0098	in^4	0.0206	in^4
5	ft.	0.0228	in^4	0.0122	in^4	0.0257	in^4
6	ft.	0.0274	in^4	0.0147	in^4	0.0309	in^4
7	ft.	0.0319	in^4	0.0171	in^4	0.0360	in^4
8	ft.	0.0365	in^4	0.0196	in^4	0.0412	in^4

Required Wood I (cont.)							
Spacing		Load Combinations					
		D+H+F+0.75(0.7E) +0.75L+0.75S		0.6D+0.6W+H		0.6(D+F)+0.7E+H	
1	ft.	0.0046	in^4	0.0018	in^4	0.0010	in^4
2	ft.	0.0091	in^4	0.0036	in^4	0.0020	in^4
3	ft.	0.0137	in^4	0.0053	in^4	0.0030	in^4
4	ft.	0.0182	in^4	0.0071	in^4	0.0040	in^4
5	ft.	0.0228	in^4	0.0089	in^4	0.0050	in^4
6	ft.	0.0274	in^4	0.0107	in^4	0.0060	in^4
7	ft.	0.0319	in^4	0.0125	in^4	0.0070	in^4
8	ft.	0.0365	in^4	0.0143	in^4	0.0080	in^4

Required Wood I (cont.)							
Spacing		Load Combinations (Using Leeward W)					
		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W) +0.75L+0.75(Lr or S or R)			
		D+H+F+0.6W		**D+H+F+0.75(0.6W)+0.75L +0.75S**		**0.6D+0.6W+H**	
1	ft.	-0.0001	in^4	0.0032	in^4	0.0027	in^4
2	ft.	0.0004	in^4	0.0065	in^4	0.0055	in^4
3	ft.	0.0050	in^4	0.0097	in^4	0.0082	in^4
4	ft.	0.0066	in^4	0.0130	in^4	0.0110	in^4
5	ft.	0.0083	in^4	0.0162	in^4	0.0137	in^4
6	ft.	0.0099	in^4	0.0195	in^4	0.0165	in^4
7	ft.	0.0116	in^4	0.0227	in^4	0.0192	in^4
8	ft.	0.0133	in^4	0.0259	in^4	0.0220	in^4

Required Steel I							
Spacing		Load Combinations					
						D+H+F+(Lr or S or R)	
		D+F		**D+H+F+L**		**D+H+F+S**	
1	ft.	0.0001	in^4	0.0001	in^4	0.0002	in^4
2	ft.	0.0001	in^4	0.0001	in^4	0.0004	in^4
3	ft.	0.0002	in^4	0.0002	in^4	0.0006	in^4
4	ft.	0.0003	in^4	0.0003	in^4	0.0008	in^4
5	ft.	0.0003	in^4	0.0003	in^4	0.0010	in^4
6	ft.	0.0004	in^4	0.0004	in^4	0.0013	in^4
7	ft.	0.0004	in^4	0.0004	in^4	0.0015	in^4
8	ft.	0.0005	in^4	0.0005	in^4	0.0017	in^4

Required Steel I (cont.)							
Spacing		Load Combinations					
		D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W) +0.75L+0.75(Lr or S or R)	
		D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75 L+0.75S**	
1	ft.	0.0002	in^4	0.0001	in^4	0.0002	in^4
2	ft.	0.0003	in^4	0.0002	in^4	0.0004	in^4
3	ft.	0.0005	in^4	0.0003	in^4	0.0006	in^4
4	ft.	0.0007	in^4	0.0004	in^4	0.0008	in^4
5	ft.	0.0009	in^4	0.0005	in^4	0.0010	in^4
6	ft.	0.0010	in^4	0.0006	in^4	0.0012	in^4
7	ft.	0.0012	in^4	0.0006	in^4	0.0014	in^4
8	ft.	0.0014	in^4	0.0007	in^4	0.0016	in^4

Required Steel I (cont.)							
Spacing		Load Combinations					
		D+H+F+0.75(0.7E) +0.75L+0.75S		**0.6D+0.6W+H**		**0.6(D+F)+0.7E+H**	
1	ft.	0.0002	in^4	0.0001	in^4	0.0000	in^4
2	ft.	0.0003	in^4	0.0001	in^4	0.0001	in^4
3	ft.	0.0005	in^4	0.0002	in^4	0.0001	in^4
4	ft.	0.0007	in^4	0.0003	in^4	0.0002	in^4
5	ft.	0.0009	in^4	0.0003	in^4	0.0002	in^4
6	ft.	0.0010	in^4	0.0004	in^4	0.0002	in^4
7	ft.	0.0012	in^4	0.0005	in^4	0.0003	in^4
8	ft.	0.0014	in^4	0.0005	in^4	0.0003	in^4

Required Steel I (cont.)							
Spacing		Load Combinations (Using Leeward W)					
		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75 L+0.75(Lr or S or R)			
		D+H+F+0.6W		**D+H+F+0.75(0.6W)+0.75 L+0.75S**		**0.6D+0.6W+H**	
1	ft.	0.0000	in^4	0.0001	in^4	0.0001	in^4
2	ft.	0.0000	in^4	0.0002	in^4	0.0002	in^4
3	ft.	0.0002	in^4	0.0004	in^4	0.0003	in^4
4	ft.	0.0003	in^4	0.0005	in^4	0.0004	in^4
5	ft.	0.0003	in^4	0.0006	in^4	0.0005	in^4
6	ft.	0.0004	in^4	0.0007	in^4	0.0006	in^4
7	ft.	0.0004	in^4	0.0009	in^4	0.0007	in^4
8	ft.	0.0005	in^4	0.0010	in^4	0.0008	in^4

Member Sizing			
Material	**Spacing**	**Max. Required I**	**Required Member Size**
Wood	1 ft.	0.4553 in^4	1 x 3 or 2 x 3
	2 ft.	0.9106 in^4	1 x 3 or 2 x 3
	3 ft.	1.3659 in^4	1 x 4 or 2 x 3
	4 ft.	1.8212 in^4	1 x 6 or 2 x 3
	5 ft.	2.2765 in^4	1 x 6 or 2 x 4
	6 ft.	2.7318 in^4	1 x 6 or 2 x 4
	7 ft.	3.1871 in^4	1 x 6 or 2 x 4
	8 ft.	3.6424 in^4	1 x 6 or 2 x 4
Steel	1 ft.	0.0002 in^4	HSS 2 x 1 x 3/16
	2 ft.	0.0004 in^4	HSS 2 x 1 x 3/16
	3 ft.	0.0006 in^4	HSS 2 x 1 x 3/16
	4 ft.	0.0008 in^4	HSS 2 x 1 x 3/16
	5 ft.	0.0010 in^4	HSS 2 x 1 x 3/16
	6 ft.	0.0013 in^4	HSS 2 x 1 x 3/16
	7 ft.	0.0015 in^4	HSS 2 x 1 x 3/16
	8 ft.	0.0017 in^4	HSS 2 x 1 x 3/16

Appendix G: Rafter Dead Load Calculations

Wood											
Purlin Size	**Specific Gravity of Species***	**Moisture Content**		**Calculated Density**		**Weight/Length of Purlin****		**Spacing**		**Weight of Purlins**	
2 x 4	0.36	3	%	22.92	lbs/cf	0.911	lbs/ft	6	ft	0.1518	psf

*Value for No. 1 Eastern White Pine from Table 4A in 2015 NDS Supplement Design Values for Wood Construction

**Value from Table 1B in 2015 NDS Supplement Design Values for Wood Construction

Steel										
Purlin Size	**Density***		**Area of Member****		**Weight/Length of Purlin**		**Spacing**		**Weight of Purlins**	
HSS2X1X3/16	490	lbs/cf	0.896	in^2	3.049	lbs/ft	6	ft	0.508	psf

*Density taken from ASTM A6

**Value for HSS2x1x3/16 from *Hollow Structural Sections Dimensions and Section Properties: ASTM A1085, 2013*

Appendix H: Beam Sizing Calculations

The following figure shows the structure of the five beams that run the length of the building. The members are split at points B and C. This figure also shows the naming convention used in the following calculations.

The following equations were obtained from the AISC Steel Construction Manual and are used in the following spreadsheets to obtain the moments in the purlins.

$$M_{Span\ of\ AB\ \&\ CD} = \frac{w}{8l^2}(l+a)^2(l-a)^2$$

$$M_{Overhang\ of\ AB\ and\ CD} = \frac{wa^2}{2}$$

l =length between A and B or C and D

a =length of overhang from A or from D

$$M_{BC} = \frac{wL^2}{8}$$

L =length between B and C

Wooden Beam Sizing						
	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Distributed Load	11.75	lbs/ft	11.75	lbs/ft	27.15	lbs/ft
Maximum Moments:						
Span of AB and CD	2803.28	lbs-ft	2803.28	lbs-ft	6476.80	lbs-ft
Overhang of AB and CD	356.96	lbs-ft	356.96	lbs-ft	824.74	lbs-ft
Member BC	2979.09	lbs-ft	2979.09	lbs-ft	6882.99	lbs-ft
Required S	46.13	in^3	46.13	in^3	106.58	in^3

Wooden Beam Sizing (cont.)						
	Load Combinations					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75L +0.75S**	
Distributed Load	23.30	lbs/ft	16.00	lbs/ft	26.48	lbs/ft
Maximum Moments:						
Span of AB and CD	5558.42	lbs-ft	3815.70	lbs-ft	6317.73	lbs-ft
Overhang of AB and CD	707.79	lbs-ft	485.88	lbs-ft	804.48	lbs-ft
Member BC	5907.01	lbs-ft	4055.00	lbs-ft	6713.95	lbs-ft
Required S	91.46	in^3	62.79	in^3	103.96	in^3

Wooden Beam Sizing (cont.)						
	Load Combinations					
	D+H+F+0.75(0.7E) +0.75L+0.75S		**0.6D+0.6W+H**		**0.6(D+F)+0.7E+H**	
Distributed Load	23.30	lbs/ft	11.30	lbs/ft	7.05	lbs/ft
Maximum Moments:						
Span of AB and CD	5558.42	lbs-ft	2694.38	lbs-ft	1681.97	lbs-ft
Overhang of AB and CD	707.79	lbs-ft	343.10	lbs-ft	214.18	lbs-ft
Member BC	5907.01	lbs-ft	2863.36	lbs-ft	1787.45	lbs-ft
Required S	91.46	in^3	44.34	in^3	27.68	in^3

Steel Beam Sizing						
	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Distributed Load	12.11	lbs/ft	12.11	lbs/ft	27.51	lbs/ft
Maximum Moments:						
Span of AB and CD	2888.28	lbs-ft	2888.28	lbs-ft	6561.79	lbs-ft
Overhang of AB and CD	367.79	lbs-ft	367.79	lbs-ft	835.56	lbs-ft
Member BC	3069.42	lbs-ft	3069.42	lbs-ft	6973.32	lbs-ft
Required Z	1.02	in^3	1.02	in^3	2.32	in^3

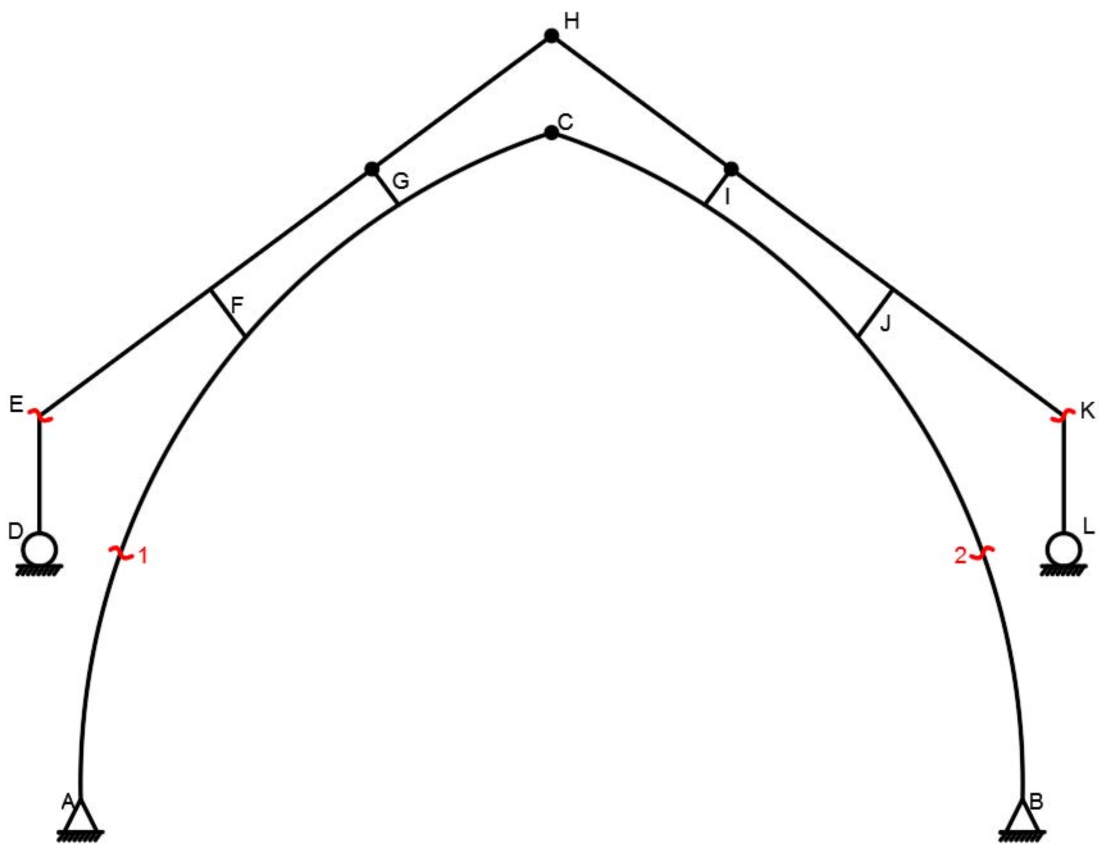
Steel Beam Sizing (cont.)						
	Load Combinations					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75L +0.75S**	
Distributed Load	23.66	lbs/ft	16.35	lbs/ft	26.84	lbs/ft
Maximum Moments:						
Span of AB and CD	5643.41	lbs-ft	3900.69	lbs-ft	6402.72	lbs-ft
Overhang of AB and CD	718.62	lbs-ft	496.70	lbs-ft	815.30	lbs-ft
Member BC	5997.34	lbs-ft	4145.32	lbs-ft	6804.27	lbs-ft
Required Z	2.00	in^3	1.38	in^3	2.27	in^3

Steel Beam Sizing (cont.)						
	Load Combinations					
	D+H+F+0.75(0.7E)+0.75L +0.75S		0.6D+0.6W+H		0.6(D+F)+0.7E+H	
Distributed Load	23.66	lbs/ft	11.51	lbs/ft	7.26	lbs/ft
Maximum Moments:						
Span of AB and CD	5643.41	lbs-ft	2745.38	lbs-ft	1732.97	lbs-ft
Overhang of AB and CD	718.62	lbs-ft	349.59	lbs-ft	220.67	lbs-ft
Member BC	5997.34	lbs-ft	2917.56	lbs-ft	1841.65	lbs-ft
Required Z	2.00	in^3	0.97	in^3	0.61	in^3

Required Wooden Member Size
8 x 10, 10 x 10 or larger
Required Steel Member Size
W4 x 13, HSS 3 x 2.5 x 5/16, or HSS 3 x 3 x 1/4

Appendix I: Main Arch System Sizing Calculations

The image below shows the main arch system labelled. These points will be referred to in the spreadsheets with all of the calculations from the structural analysis. The members from E to H and K to H are the rafters and calculations regarding them are included in Appendix E.



Internal Forces with Wooden Structure						
Resultant Force	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Fdy	437.75	lbs	437.75	lbs	680.30	lbs
Ffy	185.09	lbs	185.09	lbs	427.64	lbs
Ffx	0.00	lbs	0.00	lbs	0.00	lbs
Fgy	537.64	lbs	537.64	lbs	1242.19	lbs
Fgx	0.00	lbs	0.00	lbs	0.00	lbs
Fly	437.75	lbs	437.75	lbs	680.30	lbs
Fjy	185.09	lbs	185.09	lbs	427.64	lbs
Fjx	0.00	lbs	0.00	lbs	0.00	lbs
Fiy	537.64	lbs	537.64	lbs	1242.19	lbs
Fix	0.00	lbs	0.00	lbs	0.00	lbs
Fhy (WW)	925.45	lbs	925.45	lbs	2138.20	lbs
Fhx (WW)	0.00	lbs	0.00	lbs	0.00	lbs
Fhy (LW)	-925.45	lbs	-925.45	lbs	-2138.20	lbs
Fhx (LW)	0.00	lbs	0.00	lbs	0.00	lbs
Fby	1686.38	lbs	1686.38	lbs	3896.28	lbs
Fbx	703.87	lbs	703.87	lbs	1626.26	lbs
Fay	1686.38	lbs	1686.38	lbs	3896.28	lbs
Fax	703.87	lbs	703.87	lbs	1626.26	lbs
Fcx (WW)	703.87	lbs	703.87	lbs	1626.26	lbs
Fcy (WW)	0.00	lbs	0.00	lbs	0.00	lbs
Fcx (LW)	703.87	lbs	703.87	lbs	1626.26	lbs
Fcy (LW)	0.00	lbs	0.00	lbs	0.00	lbs

Internal Forces with Wooden Structure (cont.)						
Resultant Force	**Load Combinations**					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75L+0.75S**	
Fdy	619.66	lbs	665.73	lbs	790.65	lbs
Ffy	367.00	lbs	18.71	lbs	242.22	lbs
Ffx	0.00	lbs	227.20	lbs	170.40	lbs
Fgy	1066.06	lbs	418.65	lbs	976.81	lbs
Fgx	0.00	lbs	290.83	lbs	218.12	lbs
Fly	619.66	lbs	166.25	lbs	416.04	lbs
Fjy	367.00	lbs	319.39	lbs	467.73	lbs
Fjx	0.00	lbs	-288.73	lbs	-216.55	lbs
Fiy	1066.06	lbs	566.40	lbs	1087.63	lbs
Fix	0.00	lbs	-430.45	lbs	-322.84	lbs
Fhy (WW)	1835.02	lbs	893.42	lbs	1810.99	lbs
Fhx (WW)	0.00	lbs	355.59	lbs	266.69	lbs
Fhy (LW)	-1835.02	lbs	-760.53	lbs	-1711.32	lbs
Fhx (LW)	0.00	lbs	-574.69	lbs	-431.02	lbs
Fby	3343.81	lbs	2653.42	lbs	4069.09	lbs
Fbx	1395.66	lbs	1336.32	lbs	1870.00	lbs
Fay	3343.81	lbs	433.94	lbs	2404.48	lbs
Fax	1395.66	lbs	-11.53	lbs	859.11	lbs
Fcx (WW)	1395.66	lbs	667.07	lbs	1368.06	lbs
Fcy (WW)	0.00	lbs	586.56	lbs	439.92	lbs
Fcx (LW)	1395.66	lbs	331.94	lbs	1116.71	lbs
Fcy (LW)	0.00	lbs	586.56	lbs	439.92	lbs

Internal Forces with Wooden Structure (cont.)						
Resultant Force	Load Combinations					
	D+H+F+0.75(0.7E)+0.75L +0.75S		0.6D+0.6W+H		0.6(D+F)+0.7E+H	
Fdy	619.66	lbs	490.63	lbs	262.65	lbs
Ffy	367.00	lbs	-55.33	lbs	111.05	lbs
Ffx	0.00	lbs	227.20	lbs	0.00	lbs
Fgy	1066.06	lbs	203.59	lbs	322.59	lbs
Fgx	0.00	lbs	290.83	lbs	0.00	lbs
Fly	619.66	lbs	-8.85	lbs	262.65	lbs
Fjy	367.00	lbs	245.35	lbs	111.05	lbs
Fjx	0.00	lbs	-288.73	lbs	0.00	lbs
Fiy	1066.06	lbs	351.35	lbs	322.59	lbs
Fix	0.00	lbs	-430.45	lbs	0.00	lbs
Fhy (WW)	1835.02	lbs	523.24	lbs	555.27	lbs
Fhx (WW)	0.00	lbs	355.59	lbs	0.00	lbs
Fhy (LW)	-1835.02	lbs	-390.34	lbs	-555.27	lbs
Fhx (LW)	0.00	lbs	-574.69	lbs	0.00	lbs
Fby	3343.81	lbs	1978.87	lbs	1011.83	lbs
Fbx	1395.66	lbs	1054.77	lbs	422.32	lbs
Fay	3343.81	lbs	-240.61	lbs	1011.83	lbs
Fax	1395.66	lbs	-293.08	lbs	422.32	lbs
Fcx (WW)	1395.66	lbs	385.53	lbs	422.32	lbs
Fcy (WW)	0.00	lbs	586.56	lbs	0.00	lbs
Fcx (LW)	1395.66	lbs	50.39	lbs	422.32	lbs
Fcy (LW)	0.00	lbs	586.56	lbs	0.00	lbs

Internal Forces at Cut Locations with Wooden Structure						
Resultant Force	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Mk	0.00	lbs-ft	0.00	lbs-ft	0.00	lbs-ft
Nk	-185.09	lbs	-185.09	lbs	-427.64	lbs
Vk	0.00	lbs	0.00	lbs	0.00	lbs
Me	0.00	lbs-ft	0.00	lbs-ft	0.00	lbs-ft
Ne	-185.09	lbs	-185.09	lbs	-427.64	lbs
Ve	0.00	lbs	0.00	lbs	0.00	lbs
M1	3171.07	lbs-ft	3171.07	lbs-ft	7326.57	lbs-ft
M2	-3171.07	lbs-ft	-3171.07	lbs-ft	-7326.57	lbs-ft

Internal Forces at Cut Locations with Wooden Structure (cont.)						
Resultant Force	Load Combinations					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		D+H+F+0.6W		D+H+F+0.75(0.6W)+0.75L+0.75S	
Mk	0.00	lbs-ft	187.00	lbs-ft	140.00	lbs-ft
Nk	-367.00	lbs	86.41	lbs	-163.38	lbs
Vk	0.00	lbs	-104.00	lbs	-78.00	lbs
Me	0.00	lbs-ft	259.00	lbs-ft	194.00	lbs-ft
Ne	-367.00	lbs	-413.07	lbs	-537.99	lbs
Ve	0.00	lbs	-144.00	lbs	-108.00	lbs
M1	6287.70	lbs-ft	-628.88	lbs-ft	3437.73	lbs-ft
M2	-6287.70	lbs-ft	-6705.65	lbs-ft	-8938.63	lbs-ft

Internal Forces at Cut Locations with Wooden Structure (cont.)						
Resultant Force	Load Combinations					
	D+H+F+0.75(0.7E)+0.75L +0.75S		0.6D+0.6W+H		0.6(D+F)+0.7E+H	
Mk	0.00	lbs-ft	187.00	lbs-ft	0.00	lbs-ft
Nk	-367.00	lbs	261.51	lbs	-9.99	lbs
Vk	0.00	lbs	-104.00	lbs	0.00	lbs
Me	0.00	lbs-ft	259.00	lbs-ft	0.00	lbs-ft
Ne	-367.00	lbs	-237.97	lbs	-9.99	lbs
Ve	0.00	lbs	-144.00	lbs	0.00	lbs
M1	6287.70	lbs-ft	-1897.31	lbs-ft	1902.64	lbs-ft
M2	-6287.70	lbs-ft	-5437.22	lbs-ft	-1902.64	lbs-ft

Internal Forces with Steel Structure						
Resultant Force	**Load Combinations**					
					D+H+F+(Lr or S or R)	
	D+F		**D+H+F+L**		**D+H+F+S**	
Fdy	451.02	lbs	451.02	lbs	693.57	lbs
Ffy	190.70	lbs	190.70	lbs	433.25	lbs
Ffx	0.00	lbs	0.00	lbs	0.00	lbs
Fgy	553.95	lbs	553.95	lbs	1258.50	lbs
Fgx	0.00	lbs	0.00	lbs	0.00	lbs
Fly	451.02	lbs	451.02	lbs	693.57	lbs
Fjy	190.70	lbs	190.70	lbs	433.25	lbs
Fjx	0.00	lbs	0.00	lbs	0.00	lbs
Fiy	553.95	lbs	553.95	lbs	1258.50	lbs
Fix	0.00	lbs	0.00	lbs	0.00	lbs
Fhy (WW)	953.51	lbs	953.51	lbs	2166.26	lbs
Fhx (WW)	0.00	lbs	0.00	lbs	0.00	lbs
Fhy (LW)	-953.51	lbs	-953.51	lbs	-2166.26	lbs
Fhx (LW)	0.00	lbs	0.00	lbs	0.00	lbs
Fby	1737.51	lbs	1737.51	lbs	3947.41	lbs
Fbx	725.21	lbs	725.21	lbs	1647.60	lbs
Fay	1737.51	lbs	1737.51	lbs	3947.41	lbs
Fax	725.21	lbs	725.21	lbs	1647.60	lbs
Fcx (WW)	725.21	lbs	725.21	lbs	1647.60	lbs
Fcy (WW)	0.00	lbs	0.00	lbs	0.00	lbs
Fcx (LW)	725.21	lbs	725.21	lbs	1647.60	lbs
Fcy (LW)	0.00	lbs	0.00	lbs	0.00	lbs

Internal Forces with Steel Structure (cont.)						
Resultant Force	**Load Combinations**					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75L+0.75S**	
Fdy	632.94	lbs	679.01	lbs	803.92	lbs
Ffy	372.62	lbs	24.32	lbs	247.83	lbs
Ffx	0.00	lbs	227.20	lbs	170.40	lbs
Fgy	1082.36	lbs	434.95	lbs	993.11	lbs
Fgx	0.00	lbs	290.83	lbs	218.12	lbs
Fly	632.94	lbs	179.52	lbs	429.31	lbs
Fjy	372.62	lbs	325.00	lbs	473.34	lbs
Fjx	0.00	lbs	-288.73	lbs	-216.55	lbs
Fiy	1082.36	lbs	582.71	lbs	1103.93	lbs
Fix	0.00	lbs	-430.45	lbs	-322.84	lbs
Fhy (WW)	1863.08	lbs	921.48	lbs	1839.05	lbs
Fhx (WW)	0.00	lbs	355.59	lbs	266.69	lbs
Fhy (LW)	-1863.08	lbs	-788.59	lbs	-1739.38	lbs
Fhx (LW)	0.00	lbs	-574.69	lbs	-431.02	lbs
Fby	3394.94	lbs	2704.55	lbs	4120.21	lbs
Fbx	1417.00	lbs	1357.66	lbs	1891.34	lbs
Fay	3394.94	lbs	485.07	lbs	2455.61	lbs
Fax	1417.00	lbs	9.81	lbs	880.45	lbs
Fcx (WW)	1417.00	lbs	688.42	lbs	1389.40	lbs
Fcy (WW)	0.00	lbs	586.56	lbs	439.92	lbs
Fcx (LW)	1417.00	lbs	353.28	lbs	1138.05	lbs
Fcy (LW)	0.00	lbs	586.56	lbs	439.92	lbs

Internal Forces with Steel Structure (cont.)						
Resultant Force	Load Combinations					
	D+H+F+0.75(0.7E)+0.75L +0.75S		0.6D+0.6W+H		0.6(D+F)+0.7E+H	
Fdy	632.94	lbs	498.60	lbs	270.61	lbs
Ffy	372.62	lbs	-51.96	lbs	114.42	lbs
Ffx	0.00	lbs	227.20	lbs	0.00	lbs
Fgy	1082.36	lbs	213.37	lbs	332.37	lbs
Fgx	0.00	lbs	290.83	lbs	0.00	lbs
Fly	632.94	lbs	-0.89	lbs	270.61	lbs
Fjy	372.62	lbs	248.72	lbs	114.42	lbs
Fjx	0.00	lbs	-288.73	lbs	0.00	lbs
Fiy	1082.36	lbs	361.13	lbs	332.37	lbs
Fix	0.00	lbs	-430.45	lbs	0.00	lbs
Fhy (WW)	1863.08	lbs	540.07	lbs	572.11	lbs
Fhx (WW)	0.00	lbs	355.59	lbs	0.00	lbs
Fhy (LW)	-1863.08	lbs	-407.18	lbs	-572.11	lbs
Fhx (LW)	0.00	lbs	-574.69	lbs	0.00	lbs
Fby	3394.94	lbs	2009.54	lbs	1042.51	lbs
Fbx	1417.00	lbs	1067.58	lbs	435.13	lbs
Fay	3394.94	lbs	-209.93	lbs	1042.51	lbs
Fax	1417.00	lbs	-280.27	lbs	435.13	lbs
Fcx (WW)	1417.00	lbs	398.33	lbs	435.13	lbs
Fcy (WW)	0.00	lbs	586.56	lbs	0.00	lbs
Fcx (LW)	1417.00	lbs	63.19	lbs	435.13	lbs
Fcy (LW)	0.00	lbs	586.56	lbs	0.00	lbs

Internal Forces at Cut Locations with Steel Structure						
Resultant Force	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Mk	0.00	lbs-ft	0.00	lbs-ft	0.00	lbs-ft
Nk	-190.70	lbs	-190.70	lbs	-433.25	lbs
Vk	0.00	lbs	0.00	lbs	0.00	lbs
Me	0.00	lbs-ft	0.00	lbs-ft	0.00	lbs-ft
Ne	-190.70	lbs	-190.70	lbs	-433.25	lbs
Ve	0.00	lbs	0.00	lbs	0.00	lbs
M1	3267.22	lbs-ft	3267.22	lbs-ft	7422.71	lbs-ft
M2	-3267.22	lbs-ft	-3267.22	lbs-ft	-7422.71	lbs-ft

Internal Forces at Cut Locations with Steel Structure (cont.)						
Resultant Force	Load Combinations					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		D+H+F+0.6W		D+H+F+0.75(0.6W)+0.75L+0.75S	
Mk	0.00	lbs-ft	187.00	lbs-ft	140.00	lbs-ft
Nk	-372.62	lbs	80.80	lbs	-168.99	lbs
Vk	0.00	lbs	-104.00	lbs	-78.00	lbs
Me	0.00	lbs-ft	259.00	lbs-ft	194.00	lbs-ft
Ne	-372.62	lbs	-418.68	lbs	-543.60	lbs
Ve	0.00	lbs	-144.00	lbs	-108.00	lbs
M1	6383.84	lbs-ft	-532.74	lbs-ft	3533.87	lbs-ft
M2	-6383.84	lbs-ft	-6801.79	lbs-ft	-9034.77	lbs-ft

Internal Forces at Cut Locations with Steel Structure (cont.)						
Resultant Force	Load Combinations					
	D+H+F+0.75(0.7E)+0.75L +0.75S		0.6D+0.6W+H		0.6(D+F)+0.7E+H	
Mk	0.00	lbs-ft	187.00	lbs-ft	0.00	lbs-ft
Nk	-372.62	lbs	261.21	lbs	-10.29	lbs
Vk	0.00	lbs	-104.00	lbs	0.00	lbs
Me	0.00	lbs-ft	259.00	lbs-ft	0.00	lbs-ft
Ne	-372.62	lbs	-238.27	lbs	-10.29	lbs
Ve	0.00	lbs	-144.00	lbs	0.00	lbs
M1	6383.84	lbs-ft	-1839.62	lbs-ft	1960.33	lbs-ft
M2	-6383.84	lbs-ft	-5494.90	lbs-ft	-1960.33	lbs-ft

Wooden Members ED and KL Sizing						
Resultant Force	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Max Moment	0.00	lbs-in	0.00	lbs-in	0.00	lbs-in
Required S	0.00	in^3	0.00	in^3	0.00	in^3
Max Tensile Stress	-185.09	lbs	-185.09	lbs	-427.64	lbs
Required A	-0.53	in^2	-0.53	in^2	-1.22	in^2
Max Compressive Stress	185.09	lbs	185.09	lbs	427.64	lbs
Required A	0.19	in^2	0.19	in^2	0.43	in^2
Max Shear Stress	0.00	lbs	0.00	lbs	0.00	lbs
Required A (bd)	0.00	in^2	0.00	in^2	0.00	in^2
Min. Member Size	1 x 8, 2 x 5. or 3 x 4					

Wooden Members ED and KL Sizing (cont.)						
Resultant Force	**Load Combinations**					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75L +0.75S**	
Max Moment	0.00	lbs-in	3106.25	lbs-in	2329.69	lbs-in
Required S	0.00	in^3	4.01	in^3	3.01	in^3
Max Tensile Stress	-367.00	lbs	86.41	lbs	-163.38	lbs
Required A	-1.05	in^2	0.25	in^2	-0.47	in^2
Max Compressive Stress	367.00	lbs	413.07	lbs	537.99	lbs
Required A	0.37	in^2	0.41	in^2	0.54	in^2
Max Shear Stress	0.00	lbs	144.48	lbs	108.36	lbs
Required A (bd)	0.00	in^2	1.61	in^2	1.20	in^2
Min. Member Size	1 x 8, 2 x 5. or 3 x 4					

Wooden Members ED and KL Sizing (cont.)						
Resultant Force	**Load Combinations**					
	D+H+F+0.75(0.7E)+0.75L +0.75S		**0.6D+0.6W+H**		**0.6(D+F)+0.7E+H**	
Max Moment	0.00	lbs-in	3106.25	lbs-in	0.00	lbs-in
Required S	0.00	in^3	4.01	in^3	0.00	in^3
Max Tensile Stress	-367.00	lbs	261.51	lbs	-9.99	lbs
Required A	-1.05	in^2	0.75	in^2	-0.03	in^2
Max Compressive Stress	367.00	lbs	237.97	lbs	9.99	lbs
Required A	0.37	in^2	0.24	in^2	0.01	in^2
Max Shear Stress	0.00	lbs	144.48	lbs	0.00	lbs
Required A (bd)	0.00	in^2	1.61	in^2	0.00	in^2
Min. Member Size	1 x 8, 2 x 5. or 3 x 4					

Wooden Arch Member Sizing						
Resultant Forces	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Max Moment	38052.89	lbs-in	38052.89	lbs-in	87918.82	lbs-in
Required S	49.10	in^3	49.10	in^3	113.44	in^3
Min. Member Size	10 x 10 or larger					

Wooden Arch Member Sizing (cont.)						
Resultant Forces	Load Combinations					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		D+H+F+0.6W		D+H+F+0.75(0.6W)+0.75L+0.75S	
Max Moment	75452.34	lbs-in	80467.77	lbs-in	107263.50	lbs-in
Required S	97.36	in^3	103.83	in^3	138.40	in^3
Min. Member Size	10 x 10 or larger					

Wooden Arch Member Sizing (cont.)						
Resultant Forces	Load Combinations					
	D+H+F+0.75(0.7E)+0.75L +0.75S		0.6D+0.6W+H		0.6(D+F)+0.7E+H	
Max Moment	75452.34	lbs-in	65246.61	lbs-in	22831.73	lbs-in
Required S	97.36	in^3	84.19	in^3	29.46	in^3
Min. Member Size	10 x 10 or larger					

Steel Members ED and KL Sizing						
Resultant Force	Load Combinations					
					D+H+F+(Lr or S or R)	
	D+F		D+H+F+L		D+H+F+S	
Max Moment	0.00	lbs-in	0.00	lbs-in	0.00	lbs-in
Required Z	0.00	in^3	0.00	in^3	0.00	in^3
Max Tensile Stress	-190.70	lbs	-190.70	lbs	-433.25	lbs
Required A	0.00	in^2	0.00	in^2	-0.01	in^2
Max Compressive Stress	190.70	lbs	190.70	lbs	433.25	lbs
Required A	0.01	in^2	0.01	in^2	0.02	in^2
Max Shear Stress	0.00	lbs	0.00	lbs	0.00	lbs
Required A	0.00	in^2	0.00	in^2	0.00	in^2
Min. Member Size	HSS2.25 x 2 x 3/16 or HSS2 x 2 x 1/4					

Steel Members ED and KL Sizing (cont.)						
Resultant Force	Load Combinations					
	D+H+F+0.75L+0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		D+H+F+0.6W		D+H+F+0.75(0.6W)+0.75L +0.75S	
Max Moment	0.00	lbs-in	3106.25	lbs-in	2329.69	lbs-in
Required Z	0.00	in^3	0.09	in^3	0.06	in^3
Max Tensile Stress	-372.62	lbs	80.80	lbs	-168.99	lbs
Required A	-0.01	in^2	0.00	in^2	0.00	in^2
Max Compressive Stress	372.62	lbs	418.68	lbs	543.60	lbs
Required A	0.02	in^2	0.02	in^2	0.02	in^2
Max Shear Stress	0.00	lbs	144.48	lbs	108.36	lbs
Required A	0.00	in^2	0.00002	in^2	0.00	in^2
Min. Member Size	HSS2.25 x 2 x 3/16 or HSS2 x 2 x 1/4					

Steel Members ED and KL Sizing (cont.)						
Resultant Force	**Load Combinations**					
	D+H+F+0.75(0.7E)+0.75L +0.75S		**0.6D+0.6W+H**		**0.6(D+F)+0.7E+H**	
Max Moment	0.00	lbs-in	3106.25	lbs-in	0.00	lbs-in
Required Z	0.00	in^3	0.09	in^3	0.00	in^3
Max Tensile Stress	-372.62	lbs	261.21	lbs	-10.29	lbs
Required A	-0.01	in^2	0.00	in^2	0.00	in^2
Max Compressive Stress	372.62	lbs	238.27	lbs	10.29	lbs
Required A	0.02	in^2	0.01	in^2	0.00	in^2
Max Shear Stress	0.00	lbs	144.48	lbs	0.00	lbs
Required A	0.00	in^2	0.00002	in^2	0.00	in^2
Min. Member Size	HSS2.25 x 2 x 3/16 or HSS2 x 2 x 1/4					

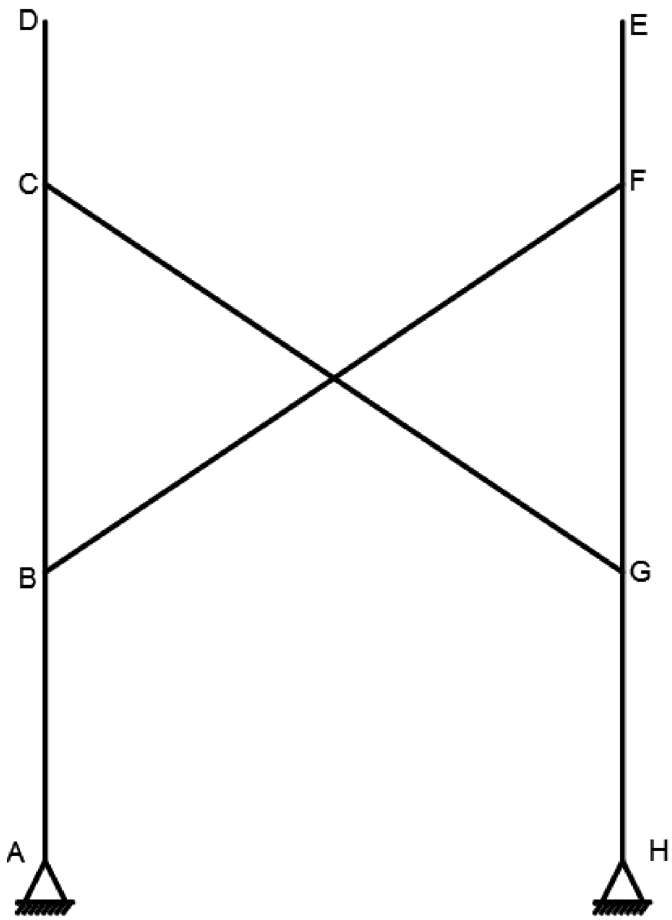
Steel Arch Member Sizing						
Resultant Forces	**Load Combinations**					
					D+H+F+(Lr or S or R)	
	D+F		**D+H+F+L**		**D+H+F+S**	
Max Moment	39206.606	lbs-in	39206.606	lbs-in	89072.5413	lbs-in
Required Z	1.0891	in^3	1.0891	in^3	2.4742	in^3
Min. I-Beam Size	W4 x 13, M5 x 18.9, S4 x 7.7, C5 x 6.7, L4 x 3 x 1/2, WT5 x 9.5					
Min. Rectangle Size	HSS3.5 x 2.5 x 5/16					
Min. Square Size	HSS3 x 3 x 5/16					

Steel Arch Member Sizing (cont.)						
Resultant Forces	**Load Combinations**					
	D+H+F+0.75L +0.75(Lr or S or R)		D+H+F+(0.6W or 0.7E)		D+H+F+0.75(0.6W)+0.75L +0.75(Lr or S or R)	
	D+H+F+0.75L+0.75S		**D+H+F+0.6W**		**D+H+F+0.75(0.6W)+0.75L+0.75S**	
Max Moment	76606.0575	lbs-in	81621.4848	lbs-in	108417.2166	lbs-in
Required Z	2.1279	in^3	2.2673	in^3	3.0116	in^3
Min. I-Beam Size	W4 x 13, M5 x 18.9, S4 x 7.7, C5 x 6.7, L4 x 3 x 1/2, WT5 x 9.5					
Min. Rectangle Size	HSS3.5 x 2.5 x 5/16					
Min. Square Size	HSS3 x 3 x 5/16					

Steel Arch Member Sizing (cont.)						
Resultant Forces	**Load Combinations**					
	D+H+F+0.75(0.7E)+0.75L+ 0.75S		**0.6D+0.6W+H**		**0.6(D+F)+0.7E+H**	
Max Moment	76606.0575	lbs-in	65938.8424	lbs-in	23523.9636	lbs-in
Required Z	2.1279	in^3	1.8316	in^3	0.6534	in^3
Min. I-Beam Size	W4 x 13, M5 x 18.9, S4 x 7.7, C5 x 6.7, L4 x 3 x 1/2, WT5 x 9.5					
Min. Rectangle Size	HSS3.5 x 2.5 x 5/16					
Min. Square Size	HSS3 x 3 x 5/16					

Appendix J: Lateral Load Calculations

Below is an image of two arches connected utilizing our lateral bracing system. The image shows the points to which the spreadsheets included in this section refer.



Windward Reactions			Leeward Reactions		
Fay	-7463.14	lbs	Fay	4797.73	lbs
Fax	-4049.15	lbs	Fax	2603.03	lbs
Fhy	7463.14	lbs	Fhy	-4797.73	lbs
Ft (from x)	0.00	lbs	Ft (from x)	0.00	lbs
Ft (from y)	11277.64	lbs	Ft (from y)	-7249.91	lbs
Ft (total)	11.28	kips	Ft (total)	-7.25	kips

Rod Options from Manufacturer	Cost Index	Diameter (in.)	Yield Strength (kips)	Manufacturer
High Strength Stainless Rod	16.2	0.33	14	Tripyramid Structures Inc.
Medium Strength Stainless Rod	4.00	0.375	12.1	Tripyramid Structures Inc.
*LCW Stainless Steel Rod	7.6	0.625	12.8	Tripyramid Structures Inc.

*Often used where strength isn't primary purpose

Cable Options from Manufacturer	Cost Index	Diameter (in.)	Breaking Strength (kips)	Manufacturer
Galvanized Steel Wire Rope Cable	1.1	0.375	13	Tripyramid Structures Inc.
Stainless Steel Structural Strand Cable	2.3	0.375	14.5	Tripyramid Structures Inc.
Stainless Steel Wire Rope Cable	2.3	0.375	12	Tripyramid Structures Inc.

Knowing the maximum tension force present in the cables, the arch must be able to handle the forces exerted on it by the lateral system and the connections to the arch must be designed in order to distribute the load over a large enough area. At this point in the project, the decision to use wood has already been made. The required cross sectional area of the arch can be seen calculated below.

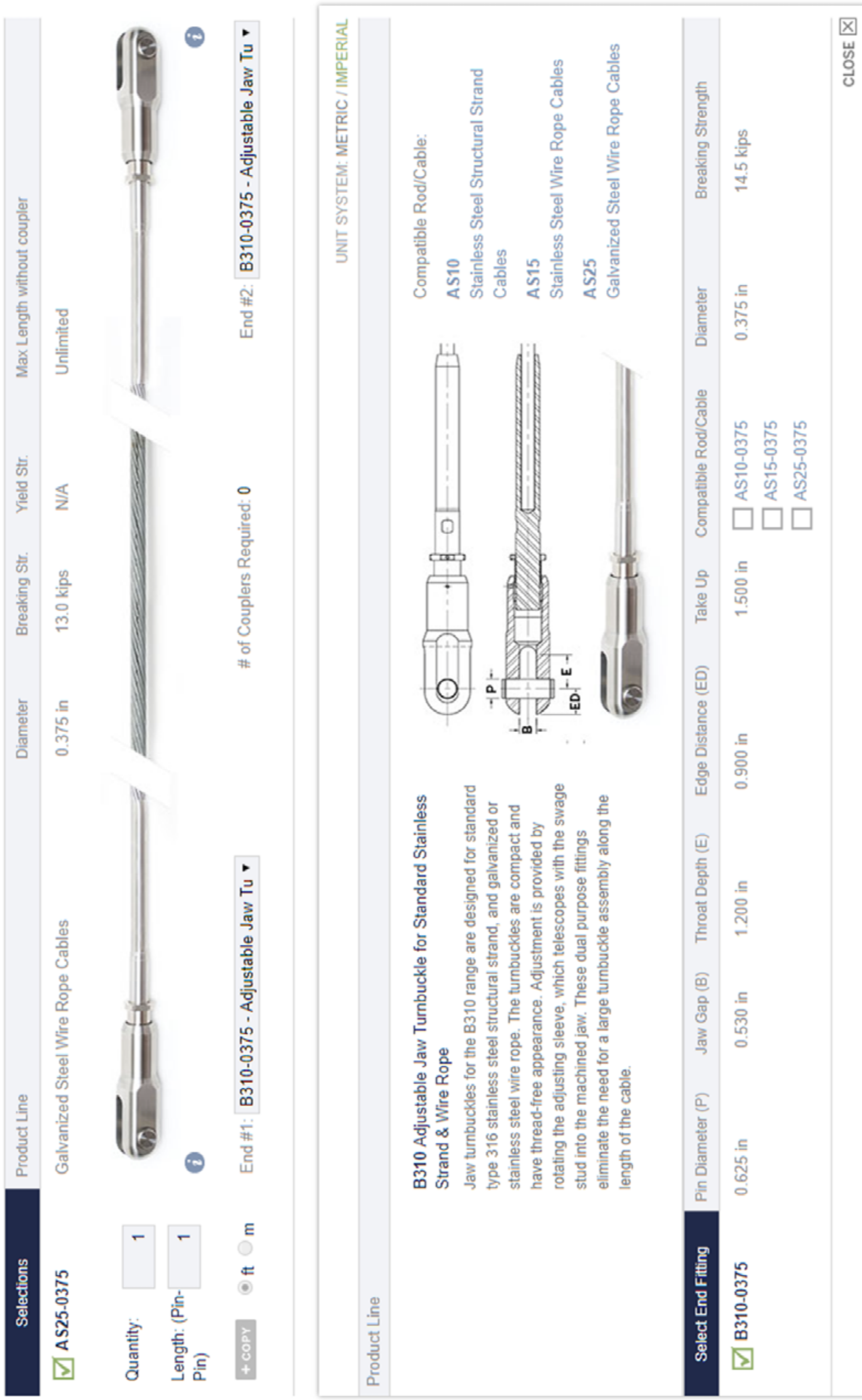
$$A_{\ Cross\ Section} = \frac{Normal\ stress\ from\ tension}{Allowable\ tensile\ stress} = \frac{11278(11.25/17)}{350} = 21.32\ in^2$$

The area of the cross section of the arch must be at least 21.32 square inches. This is met using the selected 10 x 10 arch. The required area of the connection using the shear stress of wood can be seen calculated below.

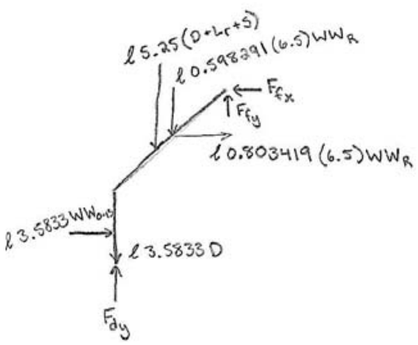
$$\boldsymbol{A_{Connection} = \frac{3V}{2(Allowable\ shear\ stress)} = \frac{3(11278)(12.75/17)}{2(135)} = 93.98\ in^2}$$

The area of the connection must be 93.98 square inches. With the 10 x 10 arch selected, the connection must be 10 inches tall and occupy at least 9.40 inches of the width of the arch.

Manufacturer Data on Selected Systems



Appendix K: Equations Used in Structural Spreadsheets



$$\circlearrowright + \Sigma M_F = 0 = 5.25 F_{Dy} - 5.25 \ell\, 3.5833 D - 2.625 \ell\, 5.25 (D + L_r + S) - 3.02885 \ell\, 6.5 (0.598291) WW_R$$
$$- 2.24359 \ell\, 6.5 (0.803419) WW_R - 5.70833 \ell\, 3.5833\, WW_{0\text{-}15}$$

$$F_{dy} = \ell\, 3.5833 D + \ell\, 2.625 (D + L_r + S) + \ell\, 2.24359\, WW_R + \ell\, 2.23172\, WW_R + \ell\, 3.89613\, WW_{0\text{-}15}$$

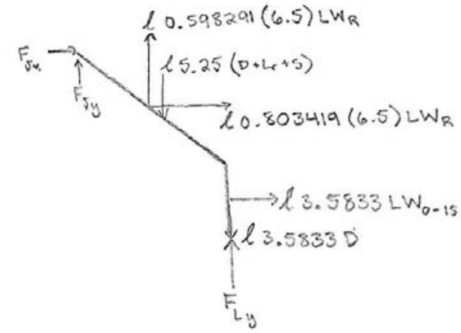
$$\boxed{F_{dy} = \ell\, 6.2083 D + \ell\, 2.625 (L_r + S) + \ell\, 4.47531\, WW_R + \ell\, 3.89613\, WW_{0\text{-}15}}$$

$$\Sigma F_y = 0 = F_{fy} + F_{dy} - \ell\, 5.25 (D + L_r + S) - \ell\, 6.5 (0.598291) WW_R - \ell\, 3.5833 D$$

$$\boxed{F_{fy} = \ell\, 8.8333 D + \ell\, 5.25 (L_r + S) + \ell\, 3.8889\, WW_R - F_{dy}}$$

$$\Sigma F_x = 0 = \ell\, 3.5833\, WW_{0\text{-}15} + \ell\, 0.803419 (6.5) WW_R - F_{fx}$$

$$\boxed{F_{fx} = \ell\, 3.5833\, WW_{0\text{-}15} + \ell\, 5.2222\, WW_R}$$



$$\curvearrowright \Sigma M_J = 0 = -5.25 F_{Ly} + 5.25 \ell\, 3.5833D + 2.625 \ell\, 5.25(D + L_r + S) - 3.02885 \ell\, 6.5(0.598291) LW_R$$
$$- 2.24359 \ell\, 6.5(0.803419) LW_R - 5.70833 \ell\, 3.5833 LW_{0\text{-}15}$$

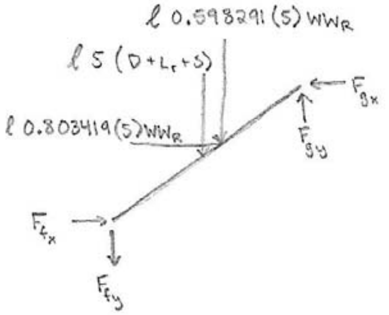
$$\boxed{F_{Ly} = \ell\, 6.2083D + \ell\, 2.625(L_r + S) - \ell\, 4.47531 LW_R - \ell\, 3.89613 LW_{0\text{-}15}}$$

$$\Sigma F_y = 0 = F_{Jy} + F_{Ly} - \ell\, 5.25(D + L_r + S) + \ell\, 6.5(0.598291) LW_R - \ell\, 3.5833 D$$

$$\boxed{F_{Jy} = \ell\, 8.8333D + \ell\, 5.25(L_r + S) - \ell\, 3.8889 LW_R - F_{Ly}}$$

$$\Sigma F_x = 0 = F_{Jx} + \ell\, 0.803419(6.5) LW_R + \ell\, 3.5833 LW_{0\text{-}15}$$

$$\boxed{F_{Jx} = -\ell\, 5.2222 LW_R - \ell\, 3.5833 LW_{0\text{-}15}}$$



$$\Sigma F_x = 0 = -F_{gx} + F_{fx} + \ell\, 0.803419(5)\, WW_R$$

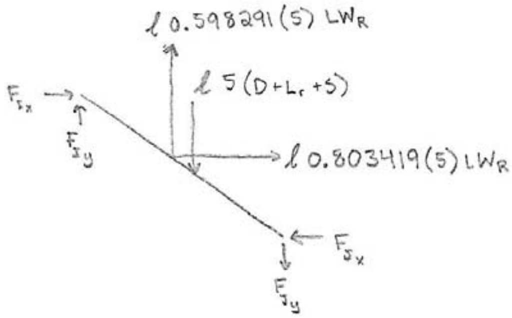
$$F_{gx} = F_{fx} + \ell\, 0.803419(5)\, WW_R$$

$$\boxed{F_{gx} = F_{fx} + \ell\, 4.0171\, WW_R}$$

$$\Sigma F_y = 0 = F_{gy} - F_{fy} - \ell\, 5(D+L_r+S) - \ell\, 0.598291(5)\, WW_R$$

$$F_{gy} = F_{fy} + \ell\, 5(D+L_r+S) + \ell\, 0.598291(5)\, WW_R$$

$$\boxed{F_{gy} = F_{fy} + \ell\, 5(D+L_r+S) + \ell\, 2.9915\, WW_R}$$



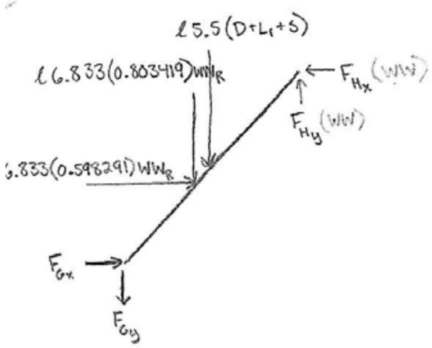
$$\Sigma F_x = 0 = F_{Ix} - F_{Jx} + \ell\, 0.803419(5)\, LW_R$$

$$\boxed{F_{Ix} = F_{Jx} - \ell\, 4.0171\, LW_R}$$

$$\Sigma F_y = 0 = F_{Iy} - F_{Jy} + \ell\, 0.598291(5)\, LW_R - \ell\, 5(D+L_r+S)$$

$$\boxed{F_{Iy} = 0 = F_{Jy} + \ell\, 5(D+L_r+S) - \ell\, 2.9915\, LW_R}$$

(WW)



$$\Sigma F_x = 0 = -F_{H_x} + F_{G_x} + \ell 6.8333(0.598291) WW_R$$

$$F_{H_x} = F_{G_x} + \ell 6.8333(0.598291) WW_R$$

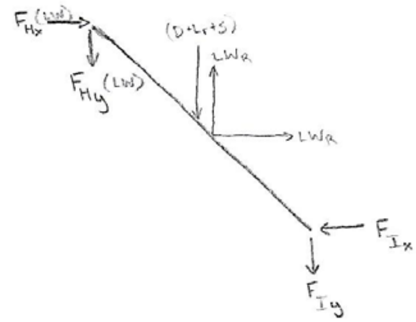
$$F_{H_x} = F_{G_x} + \ell 4.0883 WW_R$$

$$\Sigma F_y = 0 = F_{H_y} - F_{G_y} - \ell 6.8333(0.803419) WW_R - \ell 5.5(D + L_r + S)$$

$$F_{H_y} = F_{G_y} + \ell 6.8333(0.803419) WW_R + \ell 5.5(D + L_r + S)$$

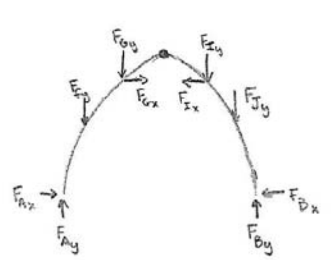
$$F_{H_y} = F_{G_y} + \ell 5.49 WW_R + \ell 5.5(D + L_r + S)$$

(LW)



$$F_{H_x} = F_{I_x} - \ell 4.0883 LW_R$$

$$F_{H_y} = -F_{I_y} + \ell 5.49 LW_R - \ell 5.5(D + L_r + S)$$

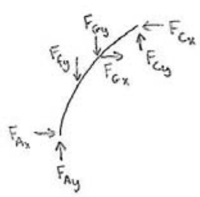


$$\circlearrowright + \Sigma M_A = 0 = 5.0833 F_{Fy} + 9.75 F_{Gy} + 14.1667 F_{Gx} + 19.0833 F_{Iy} - 14.1667 F_{Ix} + 23.75 F_{Jy} - 28.8333 F_{By}$$

$$F_{By} = 0.1763 F_{Fy} + 0.3382 F_{Gy} + 0.4913 F_{Gx} + 0.6618 F_{Iy} - 0.4913 F_{Ix} + 0.8237 F_{Jy}$$

$$\Sigma F_y = 0 = F_{Ay} - F_{Fy} - F_{Gy} - F_{Iy} - F_{Jy} + F_{By}$$

$$F_{Ay} = F_{Fy} + F_{Gy} + F_{Iy} + F_{Jy} - F_{By}$$



$$\circlearrowright + \Sigma M_C = 0 = 14.4167 F_{Ay} - 9.3333 F_{Fy} - 4.6667 F_{Gy} - 2.25 F_{Gx} - 20.5 F_{Ax}$$

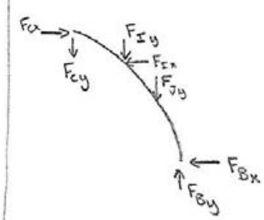
$$F_{Ax} = 0.7033 F_{Ay} - 0.4553 F_{Fy} - 0.2276 F_{Gy} - 0.1098 F_{Gx}$$

$$\Sigma F_y = 0 = F_{Ay} - F_{Fy} - F_{Gy} + F_{Cy}$$

$$F_{Cy} = -F_{Ay} + F_{Fy} + F_{Gy}$$

$$\Sigma F_x = 0 = F_{Ax} + F_{Gx} - F_{Cx}$$

$$F_{Cx} = F_{Ax} + F_{Gx}$$



$$\circlearrowright + \Sigma M_C = 0 = -14.4167 F_{By} + 9.3333 F_{Jy} + 4.6667 F_{Iy} + 2.25 F_{Ix} + 20.5 F_{Bx}$$

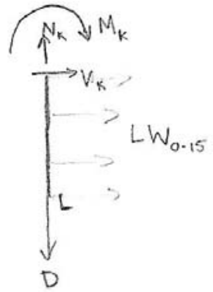
$$F_{Bx} = 0.7033 F_{By} - 0.4553 F_{Jy} - 0.2276 F_{Iy} - 0.1098 F_{Ix}$$

$$\Sigma F_y = 0 = -F_{Cy} - F_{Iy} - F_{Jy} + F_{By}$$

$$F_{Cy} = -F_{Iy} - F_{Jy} + F_{By}$$

$$\Sigma F_x = 0 = F_{Cx} - F_{Ix} - F_{Bx}$$

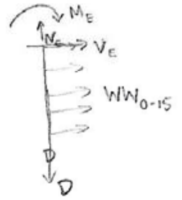
$$F_{Cx} = F_{Ix} + F_{Bx}$$



$$M_K = \ell\, 3.5833\, LW_{0\text{-}15} \left(\frac{3.5833}{2}\right) = \ell\, 6.4200\, LW_{0\text{-}15}$$

$$N_K = \ell\, 3.5833 (D_g + D_p)$$

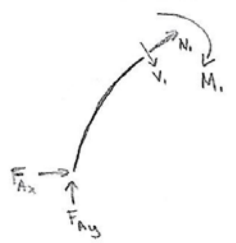
$$V_K = -\ell\, 3.5833\, LW_{0\text{-}15}$$



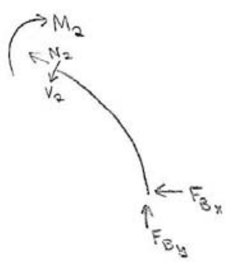
$$M_E = \ell\, 3.5833\, WW_{0\text{-}15} \left(\frac{3.5833}{2}\right) = \ell\, 6.4200\, WW_{0\text{-}15}$$

$$N_E = \ell\, 3.5833 (D_g + D_p)$$

$$V_E = \ell\, 3.5833\, WW_{0\text{-}15}$$



$$M_1 = F_{Ax}(7.5) - F_{Ay}(1.25)$$



$$M_2 = F_{By}(1.25) - F_{Bx}(7.5)$$

Appendix L: Footing Calculations

Load Combinations										
DL				**LL**		**W**		**S**		
purlins	5.2	psf		14.18	psf	0	psf	15.4	psf
glass	6.6	psf							
arch	855.8	lbs							

qsoil=Pu/BL	
qsoil	strength of soil
Pu	DL+LL+ W+ S
B	width of footing
L	length of footing

Arch Dead Load (Volume arch * 50pcf)		
V =	Length * cross sectional area	
V =	27.31ft*(9.5" * 9.5")/144	
V =	17.11616319	ft^3
Arch DL =	**855.8**	**lbs**

$q_{soil}=P_u/BL$						Square Footing		Rectangular Footing	
Footing Location	P_u		**Tributary Area**	P_u **Total**	$P_u/q = BL$	**B**	**L**	**B**	**L**
A1	41.4	psf	234.5	10,565.9	5.3	2.3	2.3	1.5	3.5
A2	41.4	psf	469	20,276.1	10.1	3.2	3.2	1.5	6.8
A3	41.4	psf	469	20,276.1	10.1	3.2	3.2	1.5	6.8
A4	41.4	psf	234.5	10,565.9	5.3	2.3	2.3	1.5	3.5
B1	41.4	psf	234.5	10,565.9	5.3	2.3	2.3	1.5	3.5
B2	41.4	psf	469	20,276.1	10.1	3.2	3.2	1.5	6.8
B3	41.4	psf	469	20,276.1	10.1	3.2	3.2	1.5	6.8
B4	41.4	psf	234.5	10,565.9	5.3	2.3	2.3	1.5	3.5

qsoil=[Pu/(B*L)]+[(6Pu*e)/(B*L^2)]	
qsoil	strength of soil
Pu	DL+LL+ W+ S
B	width of footing
L	length of footing
e	eccentricity measured from center axis of footing

$q_{soil}=[P_u/(B*L)]+[(6P_u*e)/(B*L^2)]$										
Footing Location	***P_u Total***		***B***	***L***	***e = L/2 - 0.75***	***B * L^2***	**Result of q**		**q_{soil}**	
Corner	9,959.0	psf	6	6	2.25	216	899.1	</=	2,000	Satisfies
Middle	19,669.2	psf	6	6	2.25	216	1,775.7	</=	2,000	Satisfies
Corner	9,959.0	psf	6	5	1.75	150	1,029.1	</=	2,000	Satisfies
Middle	19,669.2	psf	6	5	1.75	150	2,032.5	</=	2,000	Does not
Corner	9,959.0	psf	6	4	1.25	96	1,193.0	</=	2,000	Satisfies
Middle	19,669.2	psf	6	4	1.25	96	2,356.2	</=	2,000	Does not
Corner	9,959.0	psf	5	4	1.25	80	1,431.6	</=	2,000	Satisfies
Middle	19,669.2	psf	5	4	1.25	80	2,827.4	</=	2,000	Does not
Corner	9,959.0	psf	4	4	1.25	64	1,789.5	</=	2,000	Satisfies
Middle	19,669.2	psf	4	4	1.25	64	3,534.3	</=	2,000	Does not
Corner	9,959.0	psf	4	5	1.75	100	1,543.7	</=	2,000	Satisfies
Middle	19,669.2	psf	4	5	1.75	100	3,048.7	</=	2,000	Does not
Corner	9,959.0	psf	4	6	2.25	144	1,348.6	</=	2,000	Satisfies
Middle	19,669.2	psf	4	6	2.25	144	2,663.5	</=	2,000	Does not
Corner	9,959.0	psf	5	4	1.25	80	1,431.6	</=	2,000	Satisfies
Middle	19,669.2	psf	5	4	1.25	80	2,827.4	</=	2,000	Does not

Appendix M: Mechanical Calculations

PEAK LOAD

Peak OSA Temp for --	Worcester, MA	Indoor Temp	76 F	HEAT LOSS DATA		
40 Degrees N. Lat		Daily Range	17 F	Inside	70	F
		CLFHEAVY		Outside	0	F

Existing Walls w/ Glass Roof

	Orien-	Wall			Glass			Peak	Peak	Total	Wall		Glass				Heat
Room	tation	Area	Grp	U	Area	U	SC	Mnth	Hour	S&T	CLTD	BTUH	SHGF	CLF	CLTD	BTUH	Loss
	N	222	C	0.25	440	0.57	0.88	6	16	16543	11	601	48	0.70	11.7	15942	21482
	E	301	C	0.25	270	0.57	0.88	6	16	16244	28	2113	216	0.24	11.7	14131	16122
Slope	E				870	0.57	0.88	6	16	54678			266	0.24	11.7	54678	34713
	S	257	C	0.25	367	0.57	0.88	6	16	16723	17	1088	95	0.43	11.7	15635	19197
	W	337	C	0.25	272	0.57	0.88	6	16	28402	15	1254	216	0.49	11.7	27148	16825
Slope	W				870	0.57	0.88	6	16	105590			266	0.49	11.7	105590	34713
									Total	238179						Total	143052

New Walls w/ Glass Roof

	Orien-	Wall			Glass			Peak	Peak	Total	Wall		Glass				Heat
Room	tation	Area	Grp	U	Area	U	SC	Mnth	Hour	S&T	CLTD	BTUH	SHGF	CLF	CLTD	BTUH	Loss
	N	222	C	0.07	440	0.57	0.88	6	16	16097	11	155	48	0.70	11.7	15942	18565
	E	301	C	0.07	270	0.57	0.88	6	16	14675	28	544	216	0.24	11.7	14131	12157
Slope	E				870	0.57	0.88	6	16	54678			266	0.24	11.7	54678	34713
	S	257	C	0.07	367	0.57	0.88	6	16	15915	17	280	95	0.43	11.7	15635	15812
	W	337	C	0.07	272	0.57	0.88	6	16	27471	15	323	216	0.49	11.7	27148	12390
Slope	W				870	0.57	0.88	6	16	105590			266	0.49	11.7	105590	34713
									Total	**234425**						**Total**	**128349**

New Walls w/ Polycarbonate Roof

	Orien-	Wall			Glass			Peak	Peak	Total	Wall		Glass				Heat
Room	tation	Area	Grp	U	Area	U	SC	Mnth	Hour	S&T	CLTD	BTUH	SHGF	CLF	CLTD	BTUH	Loss
	N	222	C	0.07	440	0.57	0.88	6	16	16097	11	155	48	0.70	11.7	15942	18565
	E	301	C	0.07	270	0.57	0.88	6	16	14675	28	544	216	0.24	11.7	14131	12157
Slope	E				870	0.41	0.80	6	16	48606		0	266	0.24	11.7	48606	24969
	S	257	C	0.07	367	0.57	0.88	6	16	15915	17	280	95	0.43	11.7	15635	15812
	W	337	C	0.07	272	0.57	0.88	6	16	27471	15	323	216	0.49	11.7	27148	12390
Slope	W				870	0.41	0.80	6	16	94890		0	266	0.49	11.7	94890	24969
									Total	**217653**						Total	**108861**

ANNUAL HVAC ENERGY USE ESTIMATE

Operating Schedule		Shift	01-08	09-16	17-24		SHR =
			Mid-8a	8a-4p	4p-Mid		0.80
	6a-6p	Hrs/Day	1	8	2		kw/ton =
	M-F	Days/Wk	7	7	7		1.2

OS Temp	Transmission Skin Gain	Infiltration CFM	Infiltration BTUH	Night Time MBTUH	Day Time Net MBTUH	Vent CFM	Fan Runtime	Night MBTU	Day MBTU	Hrs/yr Day	Hrs/yr Night
95/99	54247	54	1459	56	213	6900	100%	0	638	3.0	0.0
90/94	46498	53	1134	48	213	6900	100%	143	5738	27.0	3.0
85/89	38748	51	825	40	197	6900	100%	505	18371	93.3	12.8
80/84	30998	49	533	32	182	6900	100%	1502	37277	205.4	47.6
75/79	23249	48	257	24	166	6900	100%	2830	47247	284.6	120.4
70/74	15499	46	0	15	150	6900	100%	4090	49379	328.1	263.9
65/69	7750	48	-257	7	135	6900	100%	2910	43548	322.6	388.4
60/64	0	49	-533	-1	119	6900	100%	-223	37992	318.0	419.0
55/59	-7750	51	-825	-9	104	6418	93%	-3622	32606	313.6	422.4
50/54	-15499	53	-1134	-17	88	4095	59%	-6579	25431	287.5	395.5
45/49	-23249	54	-1459	-25	73	2702	39%	-9272	19678	269.8	375.3
40/44	-30998	56	-1799	-33	57	1773	26%	-12742	18754	326.5	388.5
35/39	-38748	57	-2154	-41	42	1109	16%	-18242	14131	337.0	446.0
30/34	-46498	58	-2523	-49	26	612	9%	-23444	8502	321.8	478.3
25/29	-54247	60	-2905	-57	11	225	3%	-18882	2419	221.6	330.4
20/24	-61997	61	-3300	-65	-5	0	0%	-15516	-672	146.4	237.6
15/19	-69746	62	-3709	-73	-20	0	0%	-11679	-1970	98.0	159.0
10/14	-77496	64	-4129	-82	-36	0	0%	-9234	-1990	55.9	113.1
05/09	-85246	65	-4562	-90	-51	0	0%	-7117	-1623	31.8	79.3
00/04	-92995	66	-5007	-98	-67	0	0%	-3749	-849	12.8	38.3
<0	-103845	68	-5649	-109	-67	0	0%	-2710	-416	6.3	24.8

Total	Ht Los:	(143,010)	(7,521)
	Ht Gair	11,978	361,711
			1,882 Therms/year at 80% efficier

(1,812) EFLH

Appendix N: Dew Point Analysis Calculations

WALL INSULATION AND DEWPOINT ANALYSIS

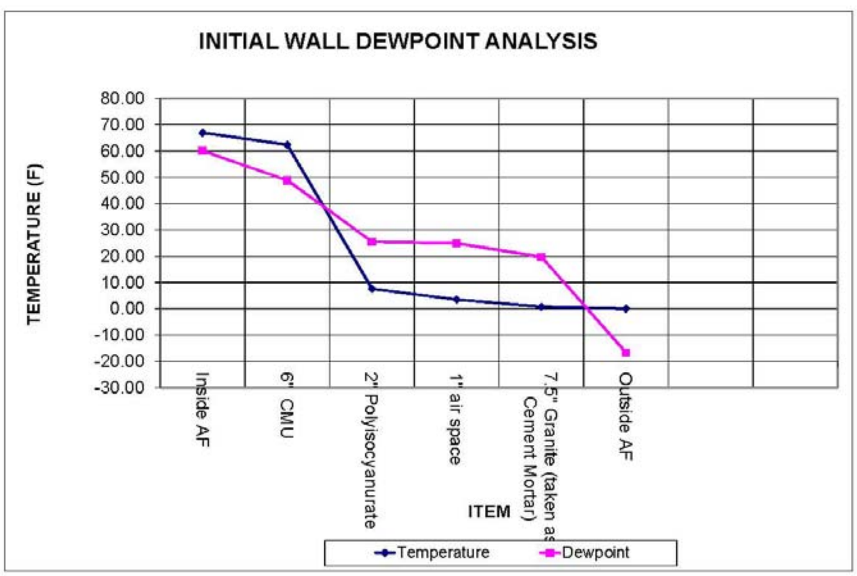
CMU Construction (No Vapor Barrier)

Indoor conditions =	70 F		70% RH
Indoor moisture =	77.3	gr/lb	
Outdoor conditions =	0 F		40% RH
Outdoor moisture =	2.2	gr/lb	

Item	(1) Item R-value	Cumulative R-value	(2) Fraction of Temp. Diff.	(3) Surface Temp F	C	(4) Perms	(5) Reps	Cumulative Reps	(6) Fraction of Moisture Difference	(7) Surface gr/lb	(8) Dewpoint F	C
Inside AF	0.68	0.68	0.044	66.90	19.4	0	0.000	0.000	0.000	77.31	60.1	15.6
6" CMU	1	1.68	0.109	62.34	16.9	2.4	0.417	0.417	0.350	51.05	48.9	9.4
2" Polyisocyanurate	12	13.68	0.891	7.62	-13.5	2	0.500	0.917	0.769	19.53	25.5	-3.6
1" air space	0.9	14.58	0.950	3.51	-15.8	120	0.008	0.925	0.776	19.01	25.0	-3.9
7.5" Granite (taken as Cement Mortar)	0.6	15.18	0.989	0.78	-17.3	15	0.067	0.992	0.832	14.80	19.7	-6.8
Outside AF	0.17	15.35	1.000	0.00	-17.8	5	0.200	1.192	1.000	2.20	-16.6	-27.0

Notes

- (1) Thermal resistance R in °F•ft²•h/Btuh
- (2) Fraction of Temp. Diff = Cum. R-value / Total R-value
- (3) Surface Temp = Inside Temp. — Fraction of Temp. Difference x Temperature Difference
  Temperature on outside face of item
- (4) Perm = Water Vapor Permeance M (lb per sq.ft. per hour per in Hg)
- (5) Reps = Diffusion Resistance Z = 1 / Perm
- (6) Fraction of Moisture Diff = Cum. Reps / Total Reps
- (7) Surface Moisture = Indoor Moisture — Fraction of Moisture Difference x Moisture Difference
- (8) Dew point = Temperature at which moisture will begin to condense on outside face of item



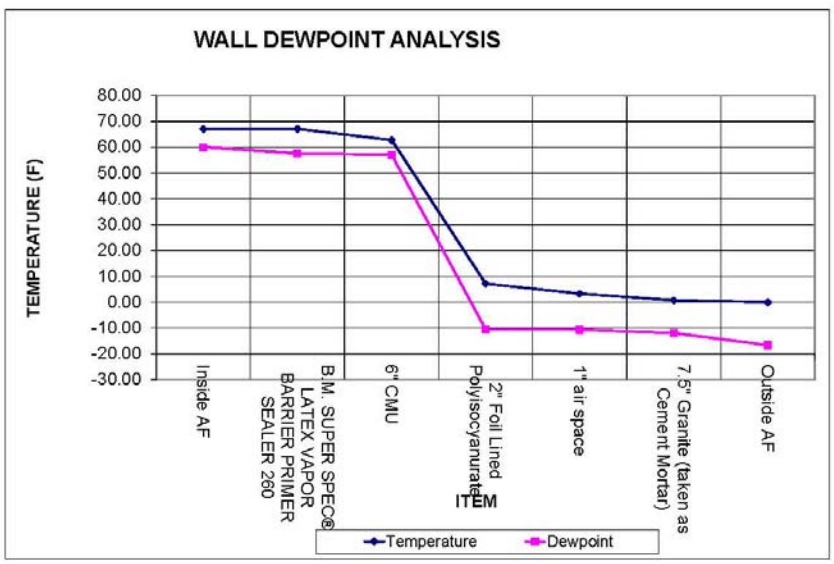
WALL INSULATION AND DEWPOINT ANALYSIS

CMU Construction with Vapor Barrier

Indoor conditions =	70 F		70% RH
Indoor moisture =	77.3	gr/lb	
Outdoor conditions =	0 F		40% RH
Outdoor moisture =	2.2	gr/lb	

Item	(1) Item R-value	Cumulative R-value	(2) Fraction of Temp. Diff.	(3) Surface Temp F	C	(4) Perms	(5) Reps	Cumulative Reps	(6) Fraction of Moisture Difference	(7) Surface gr/lb	(8) Dewpoint F	C
Inside AF	0.68	0.68	0.042	67.09	19.5	0	0.000	0.000	0.000	77.31	60.1	15.6
B.M. SUPER SPEC® LATEX VAPOR BARRIER PRIMER SEALER 260	0	0.68	0.042	67.09	19.5	0.5	2.000	2.000	0.088	70.69	57.6	14.2
6" CMU	1	1.68	0.103	62.81	17.1	2.4	0.417	2.417	0.107	69.31	57.1	13.9
2" Foil Lined Polyisocyanurate	13	14.68	0.898	7.15	-13.8	0.05	20.000	22.417	0.988	3.11	-10.5	-23.6
1" air space	0.9	15.58	0.953	3.30	-15.9	120	0.008	22.425	0.988	3.08	-10.7	-23.7
7.5" Granite (taken as Cement Mortar)	0.6	16.18	0.990	0.73	-17.4	15	0.067	22.492	0.991	2.86	-12.0	-24.4
Outside AF	0.17	16.35	1.000	0.00	-17.8	5	0.200	22.692	1.000	2.20	-16.6	-27.0

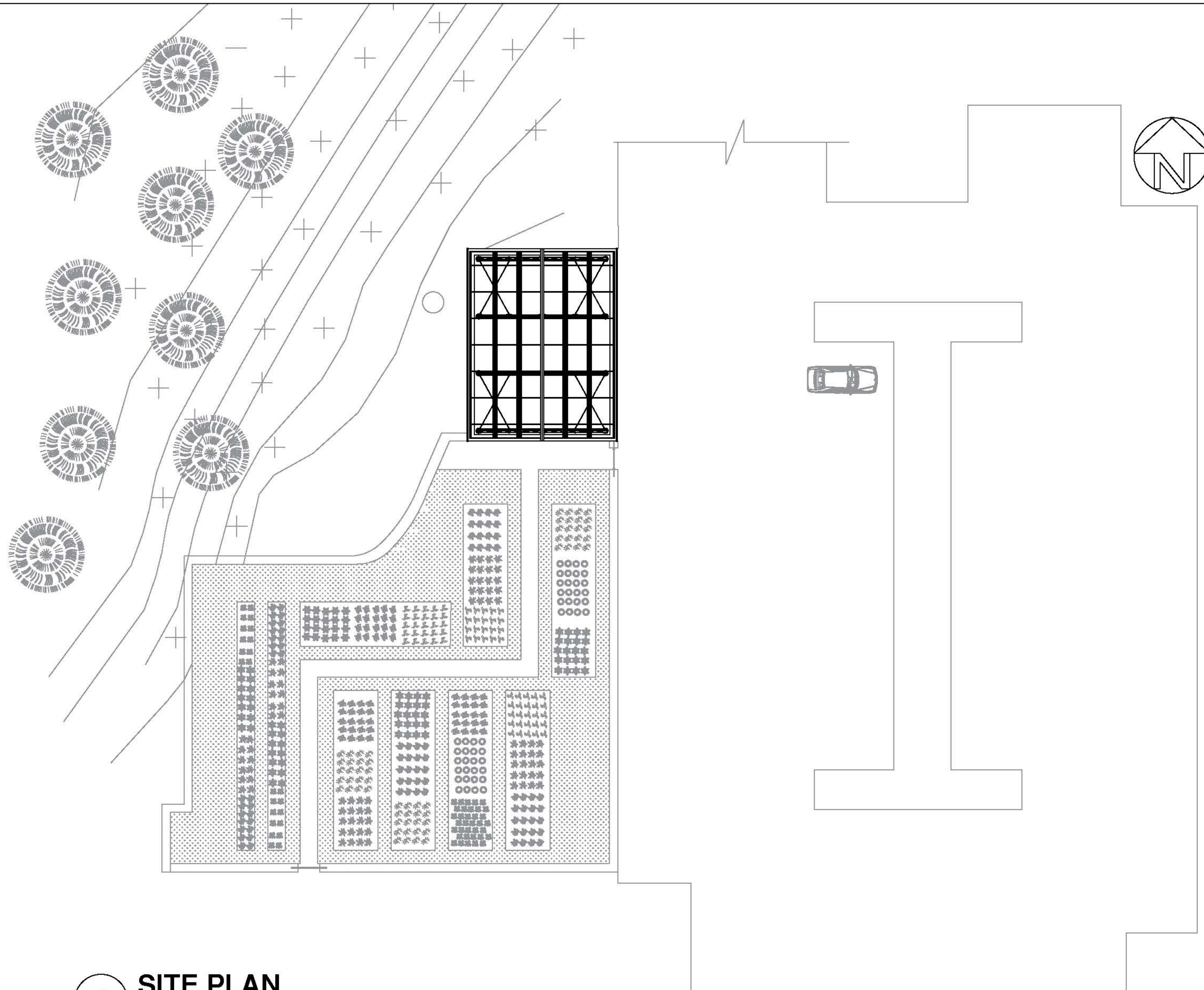
Notes
- (1) Thermal resistance R in °F•ft²•h/Btuh
- (2) Fraction of Temp. Diff = Cum. R-value / Total R-value
- (3) Surface Temp = Inside Temp. — Fraction of Temp. Difference x Temperature Difference
  Temperature on outside face of item
- (4) Perm = Water Vapor Permeance M (lb per sq.ft. per hour per in Hg)
- (5) Reps = Diffusion Resistance Z = 1 / Perm
- (6) Fraction of Moisture Diff = Cum. Reps / Total Reps
- (7) Surface Moisture = Indoor Moisture — Fraction of Moisture Difference x Moisture Difference
- (8) Dew point = Temperature at which moisture will begin to condense on outside face of item



Appendix O: Renderings of Proposed Greenhouse

Appendix P: Scaled Polycarbonate Drawings

The drawings in this appendix were developed using a polycarbonate glazing system. It is important to note that these are schematic design drawings and not intended as construction drawings. These drawings have not been stamped by a professionally licensed engineer.



1 **SITE PLAN**

Scale: 1/24" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

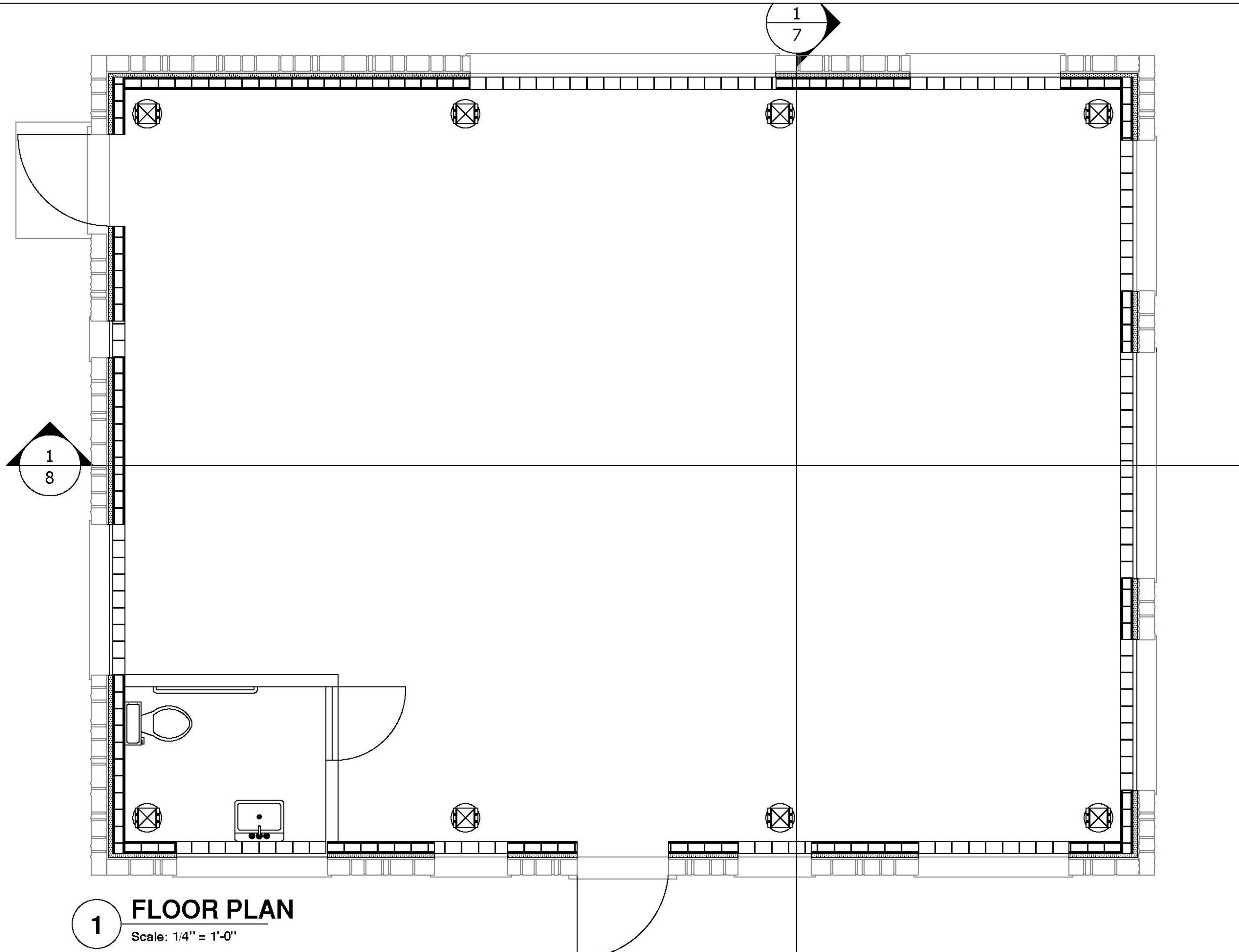
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet 1
Date	
Scale	



1 **FLOOR PLAN**

Scale: 1/4'' = 1'-0''

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

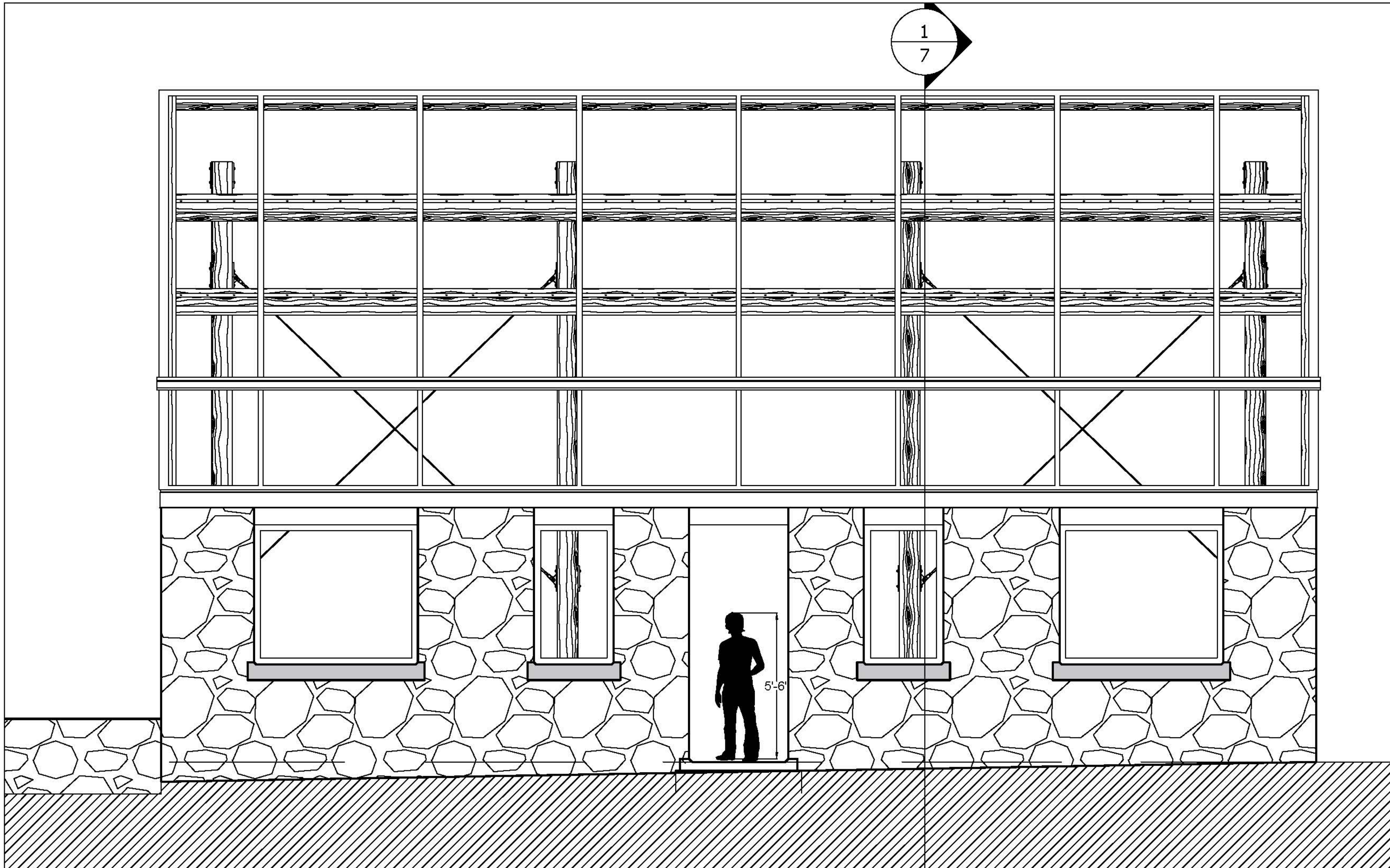
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet 2
Date	
Scale	



1 EAST ELEVATION

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

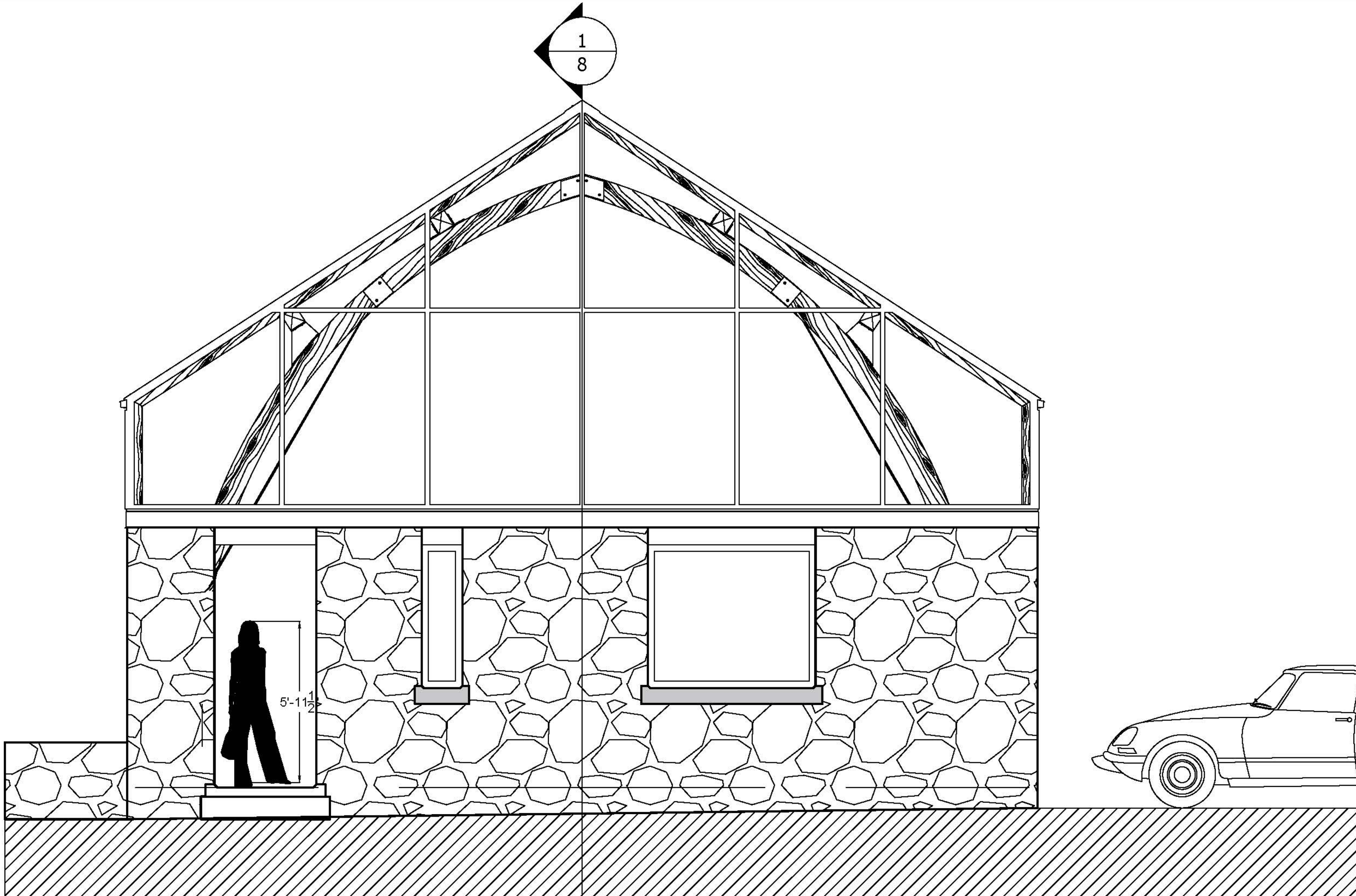
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

Date

Scale

Sheet 3



1 **SOUTH ELEVATION**

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

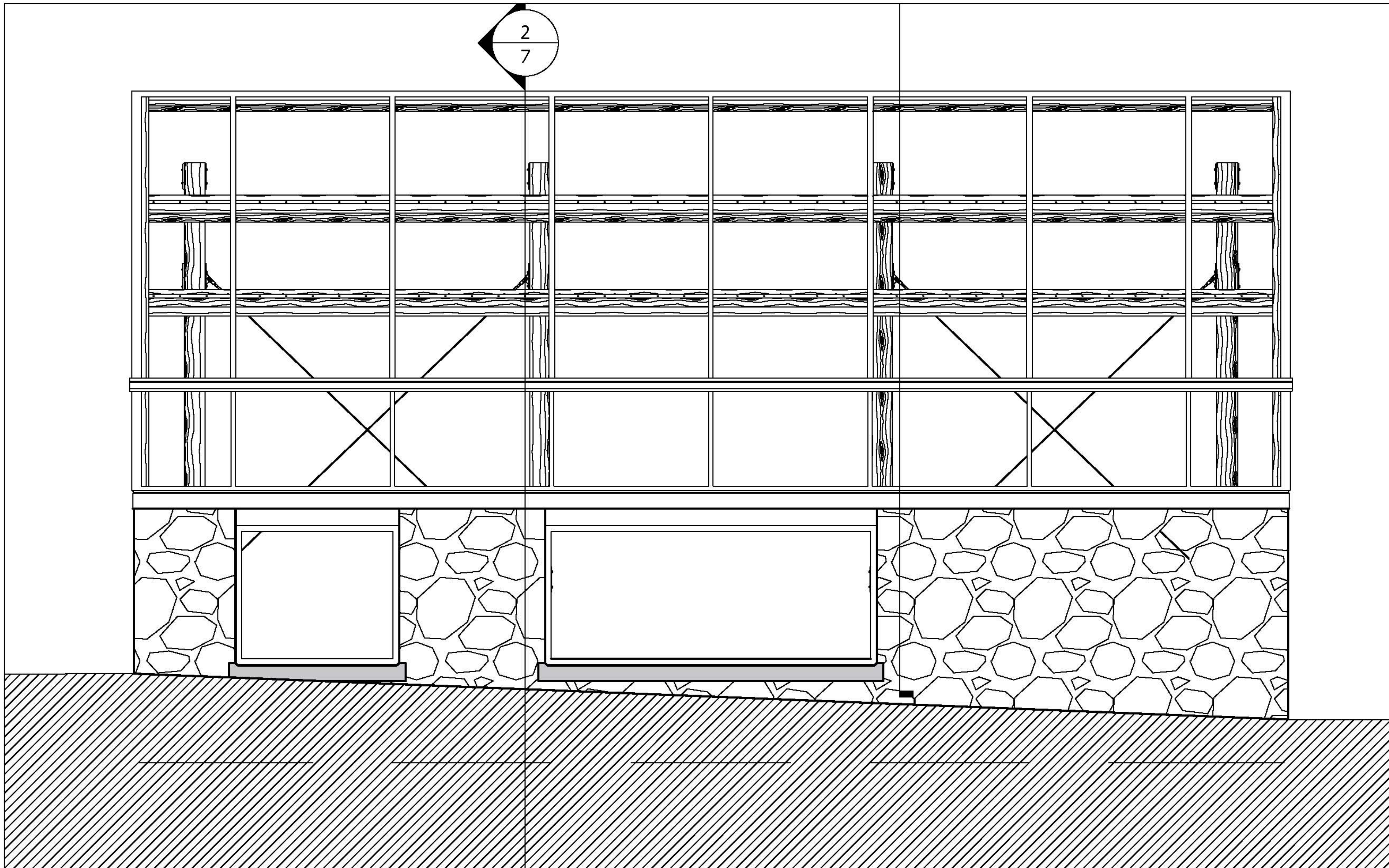
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet 4
Date	
Scale	



1 **WEST ELEVATION**

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

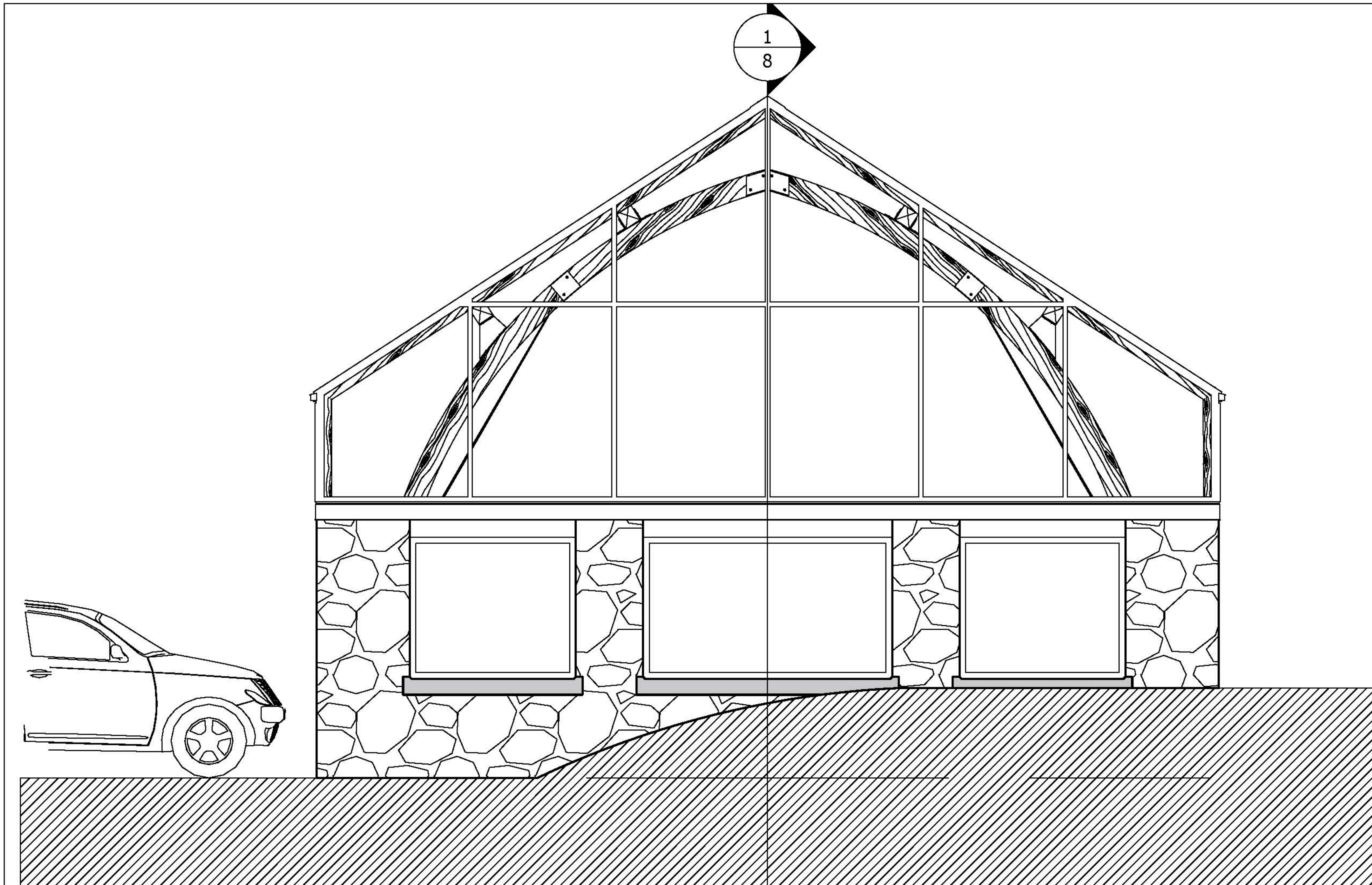
Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project
Date
Scale

Sheet 5



1 NORTH ELEVATION

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

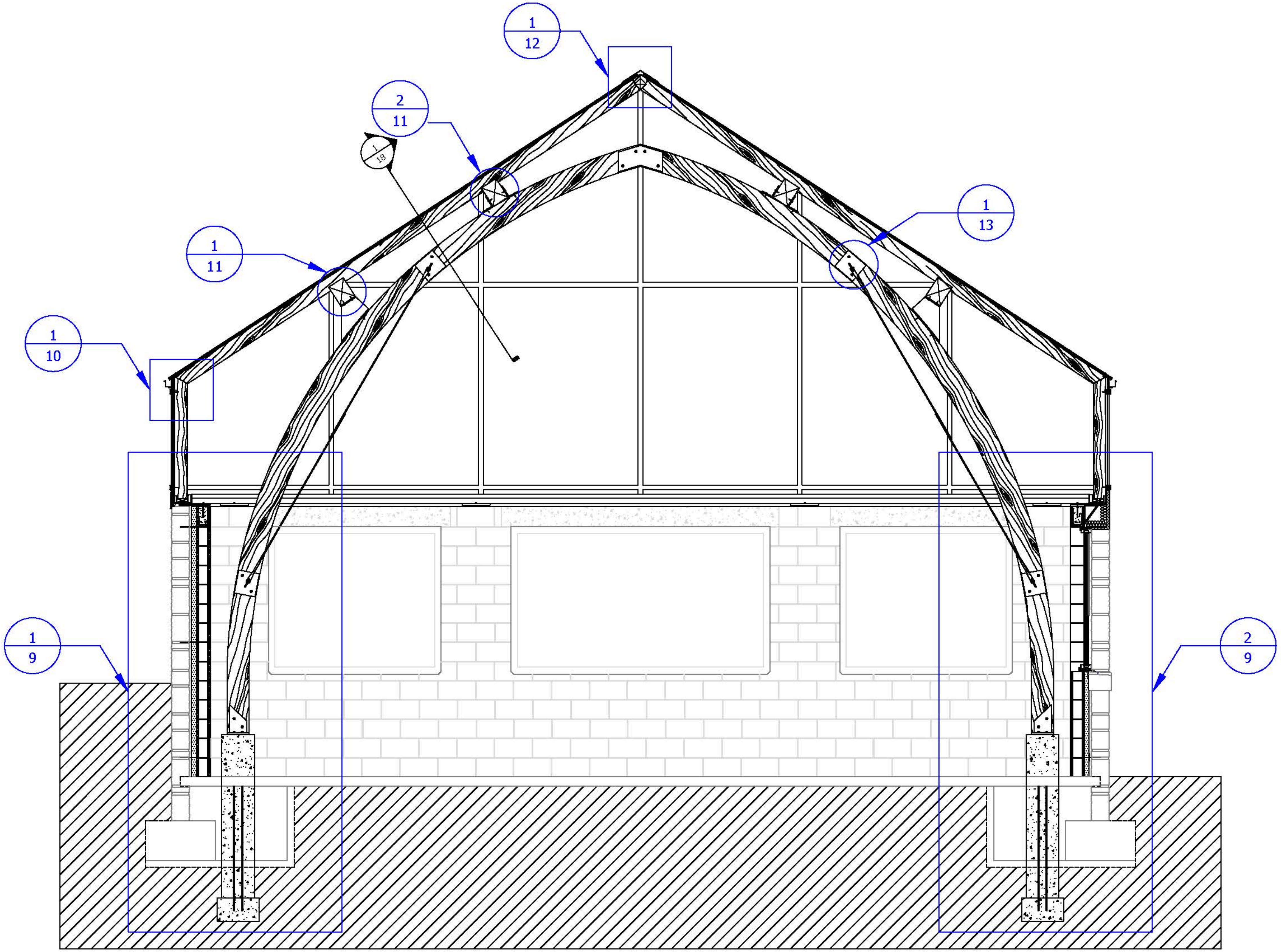
Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project
Date
Scale

Sheet 6



1 **SECTION 1**

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

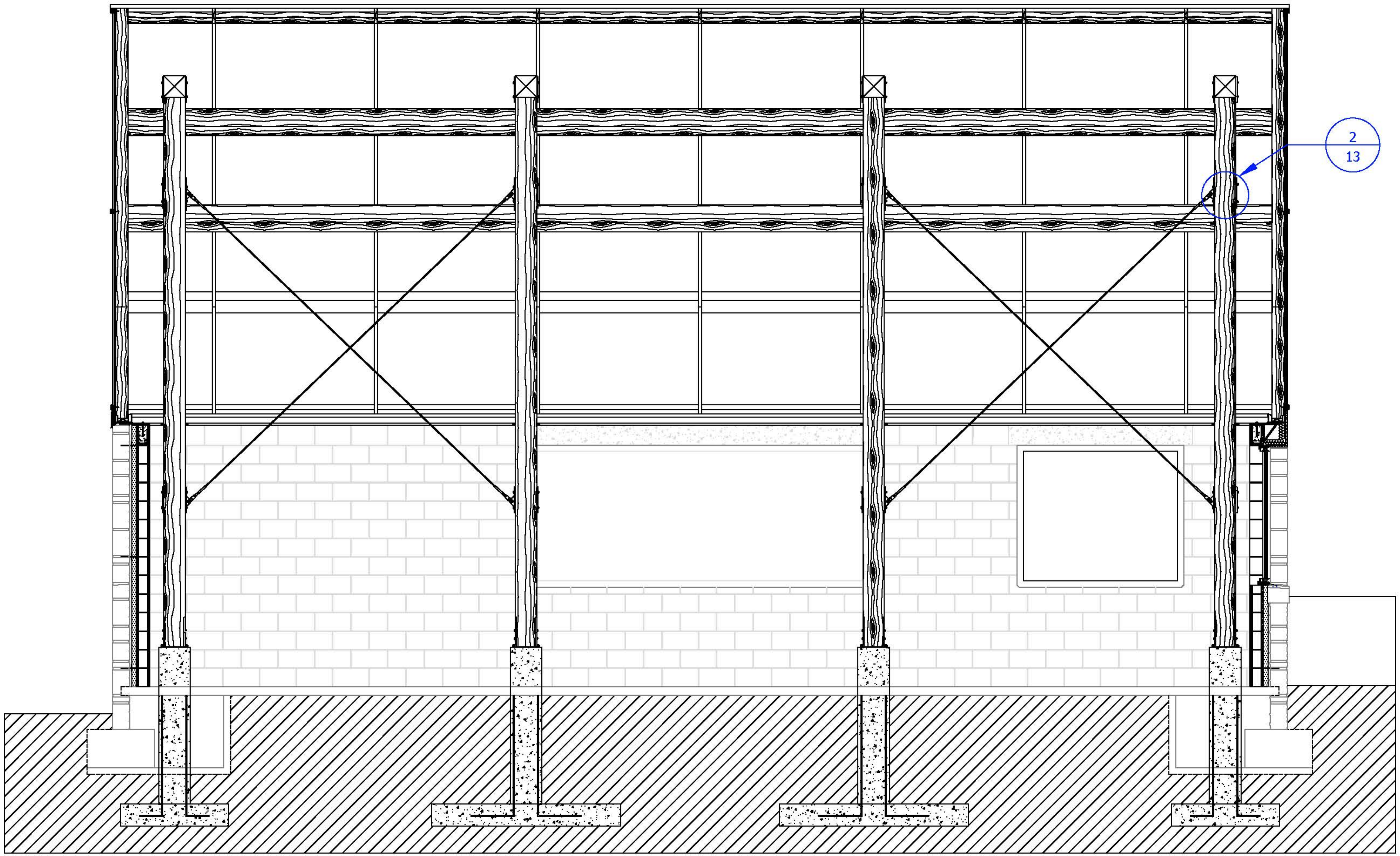
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

Date

Scale

Sheet 7



1 **SECTION 2**

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

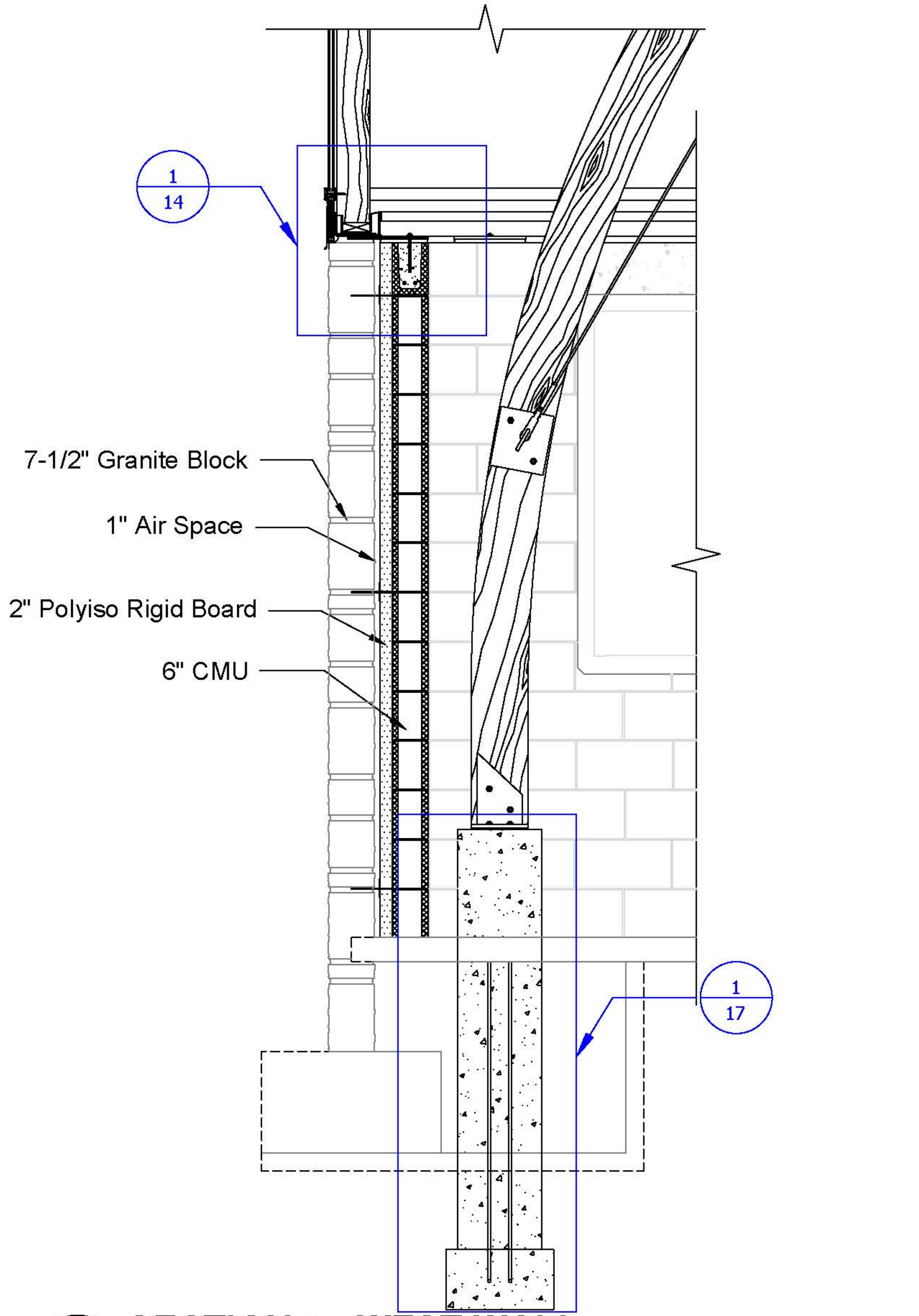
Project

Date

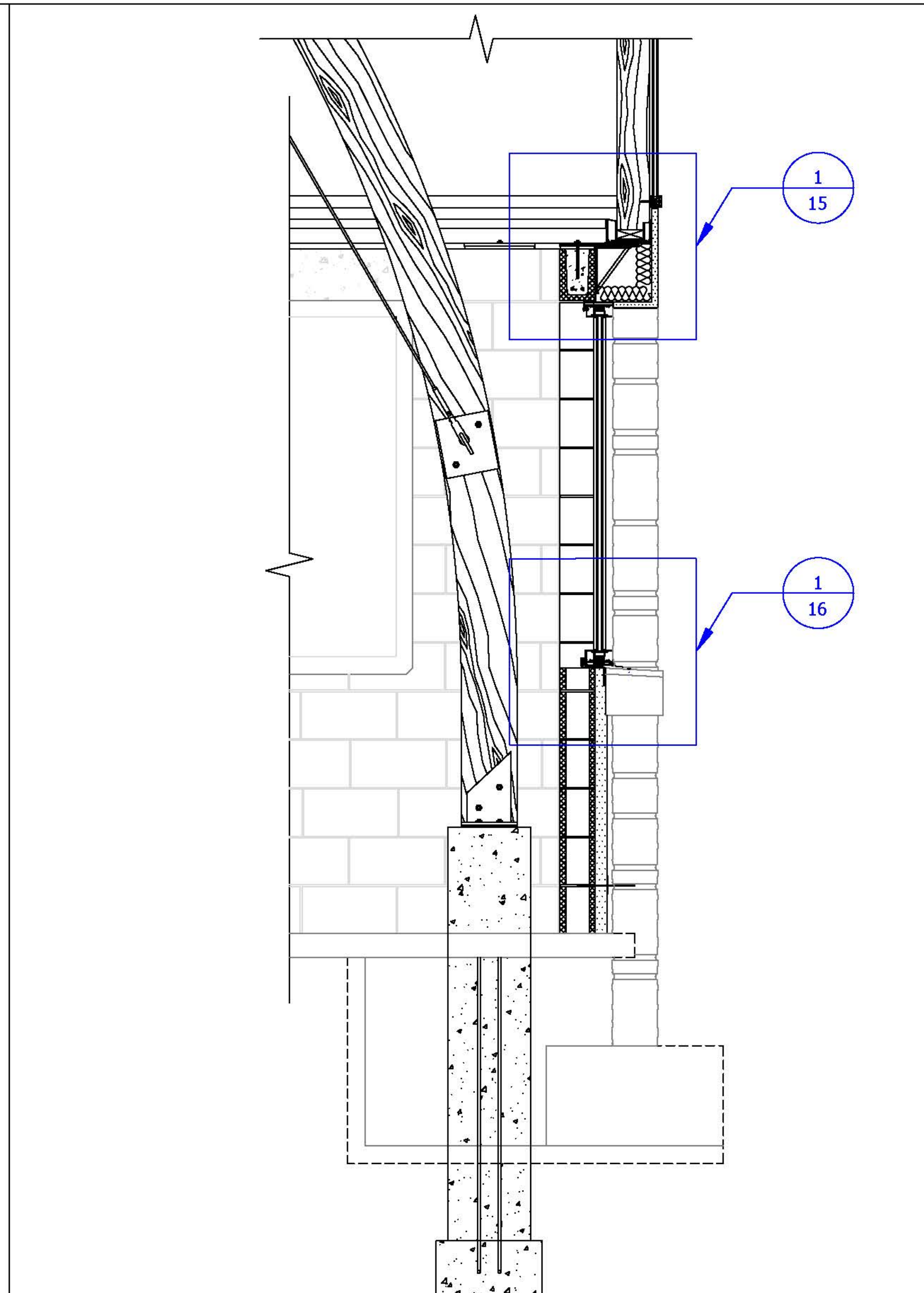
Scale

Sheet

8



1 SECTION 1 - WEST WALL
Scale: 1/2" = 1'-0"



2 SECTION 1 - EAST WALL
Scale: 1/2" = 1'-0"

General Notes

Material Legend
- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

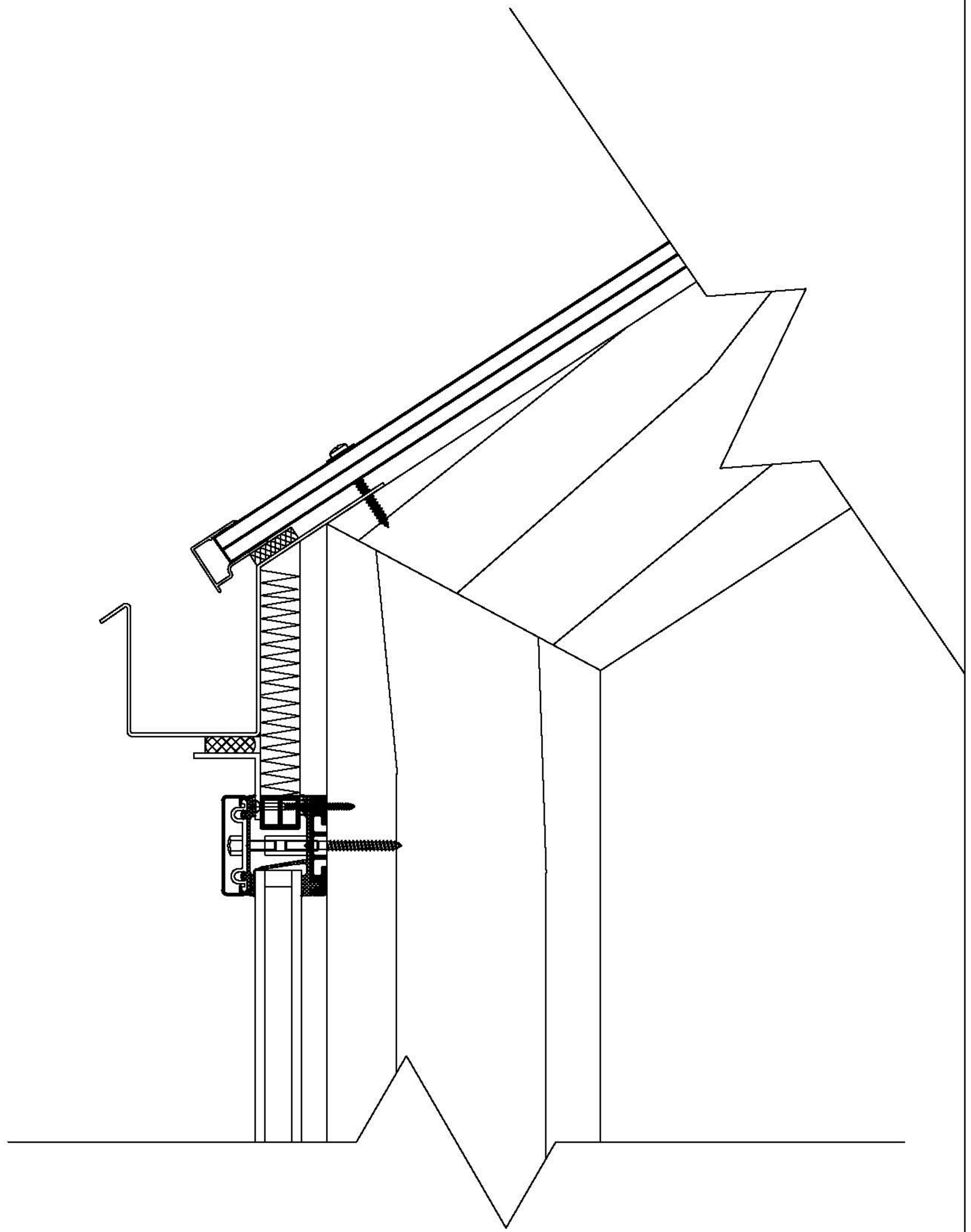
Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address
Worcester Polytechnic Institute

Project Name and Address
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

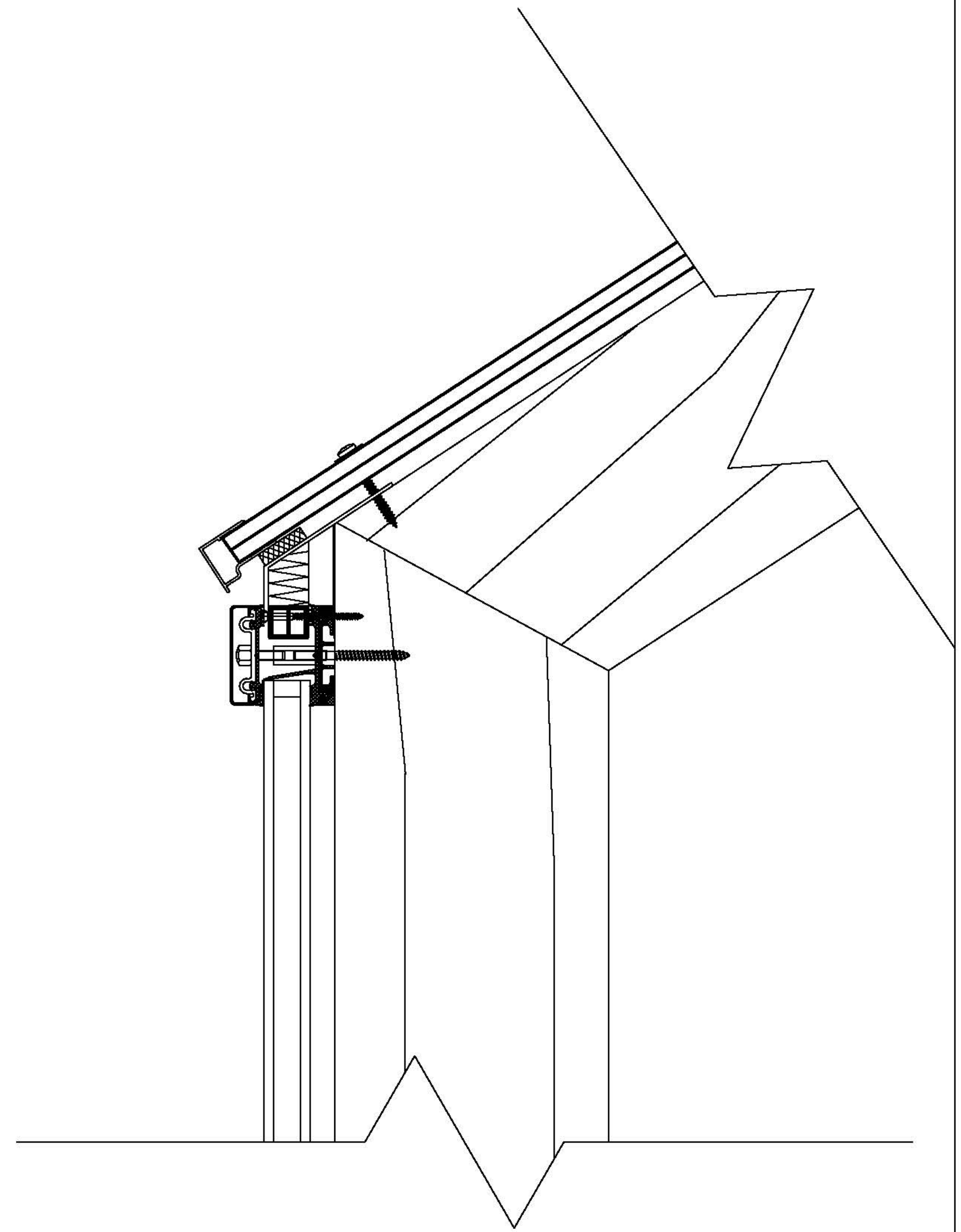
Project
Date
Scale
Sheet 9



1 **SECTION 1 - GUTTER DETAIL**

Scale: 4" = 1'-0"

* Drawing Adapted from Stabalux ZL-H_2.3_007
And Palram Sunlite Plus



2 **ALTERNATE DESIGN - NO GUTTER**

Scale: 4" = 1'-0"

* Drawing Adapted from Stabalux ZL-H_2.3_006
And Palram Sunlite Plus

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

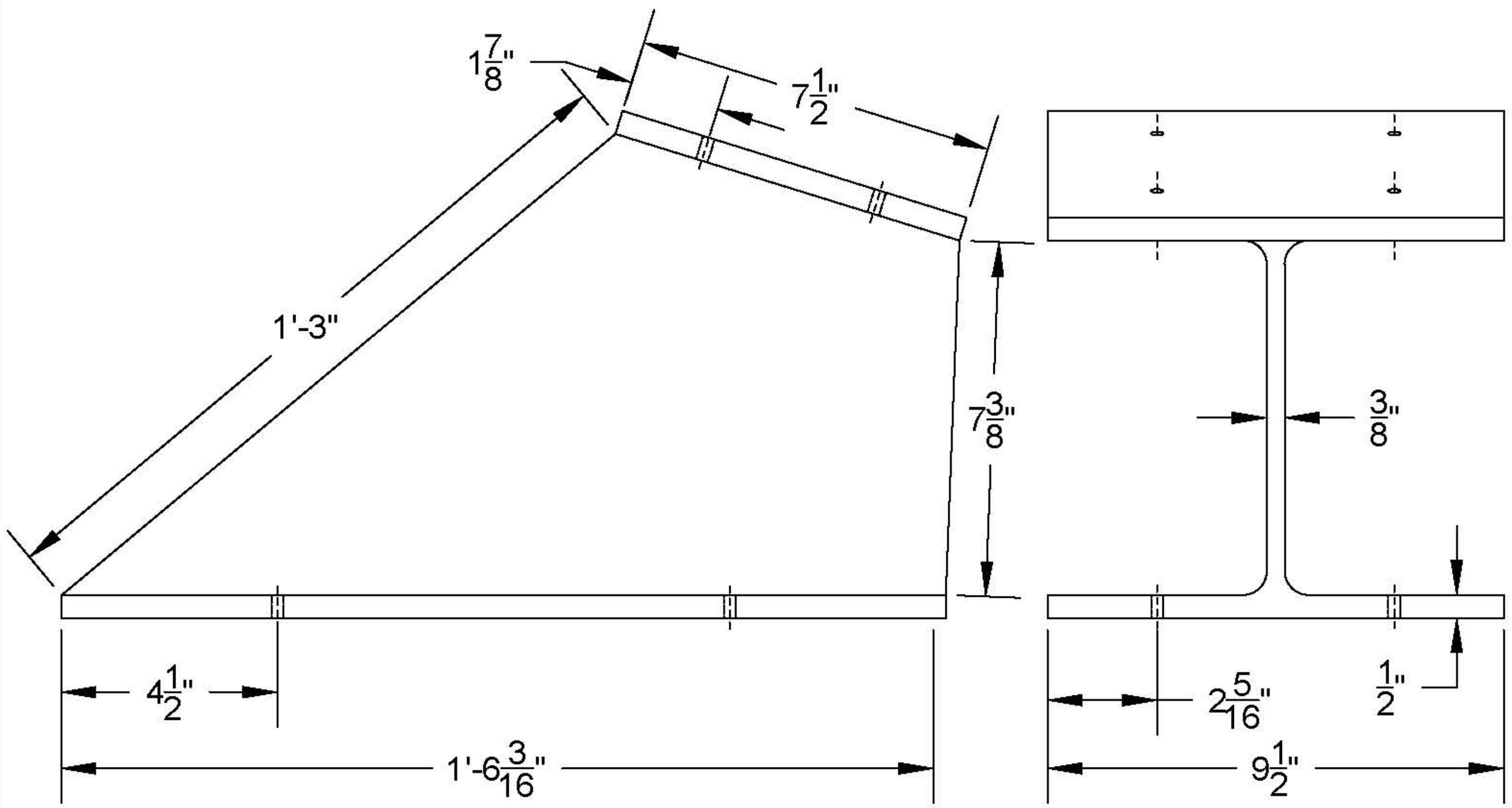
Worcester
Polytechnic
Institute

Project Name and Address

Worcester Technical
High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	10
Scale	

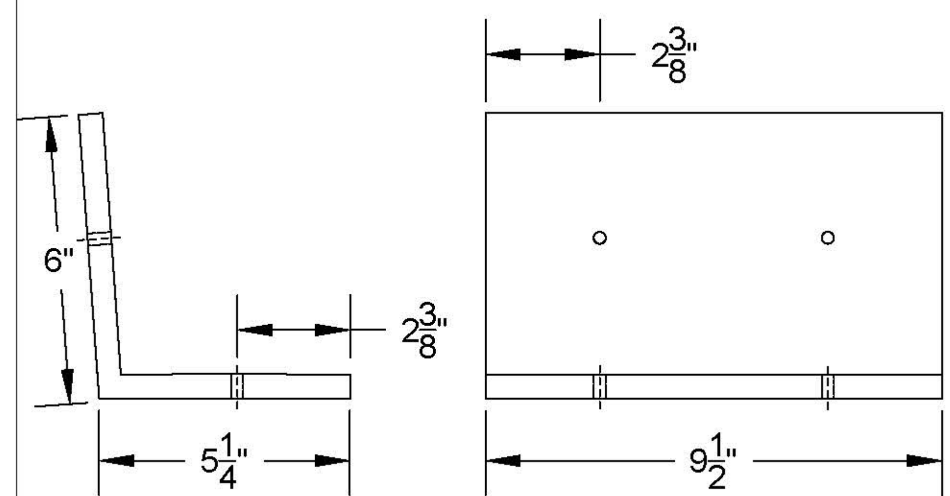
Custom connectors to the arches that support the rafters.
They are made from steel and designed similar to an I-beam



1 **SECTION 1 - CUSTOM SUPPORT FOR LOWER BEAM**

Scale: 3" = 1'-0"

Simple L-Bracket to support the upper beam



2 **SECTION 1 - L-BRACKET**

Scale: 3" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

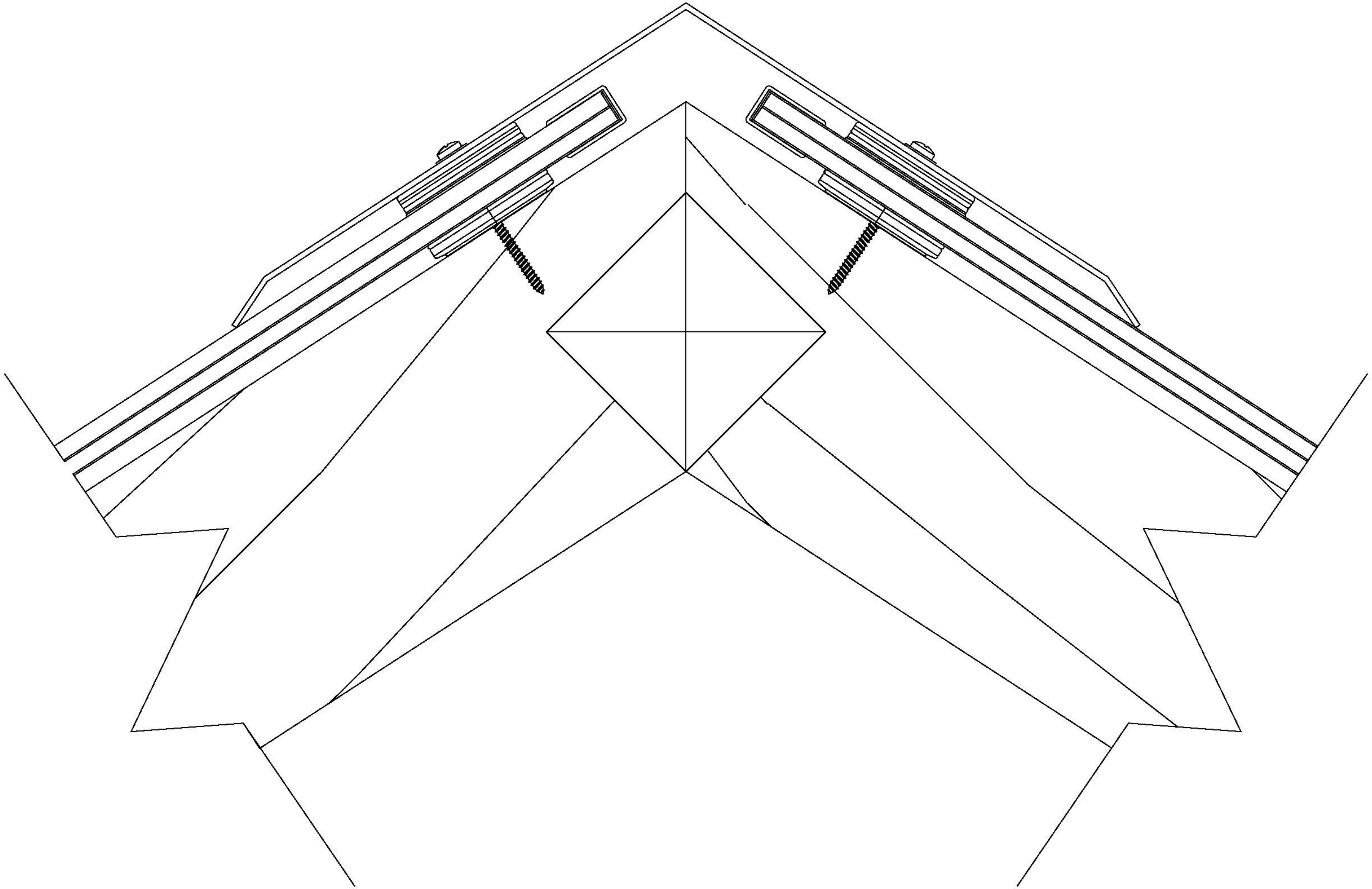
Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project
Date
Scale

Sheet 11



1 SECTION 1 - ROOF PEAK
Scale: 6'' = 1'-0''

* Drawing Adapted from Palram Sunlite Plus

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

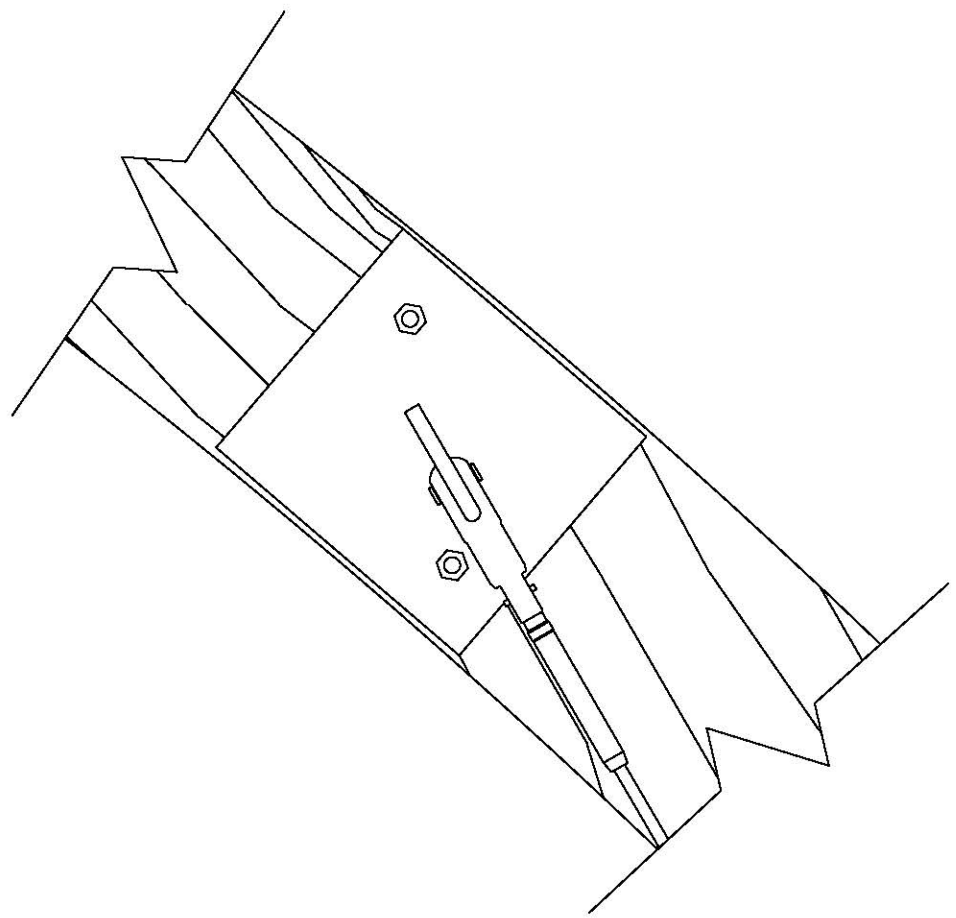
Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address
Worcester Polytechnic Institute

Project Name and Address
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

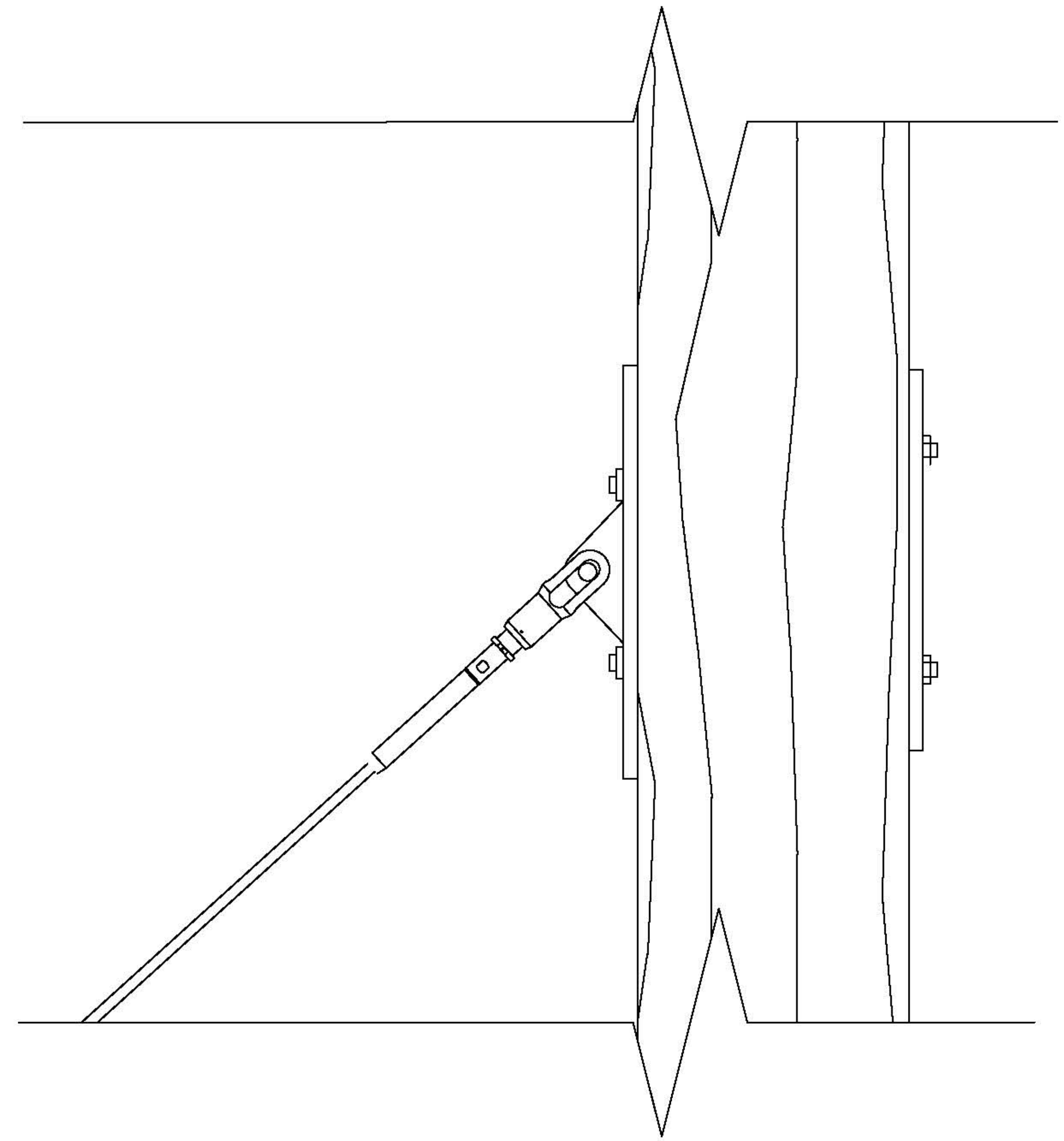
Project
Date
Scale
Sheet 12



1 SECTION 1 - LATER SOUTH VIEW

Scale: 2'' = 1'-0''

* Drawing Adapted from TriPyramid Galvanized Steel Wire Cables



1 SECTION 1 - LATERAL EAST VIEW

Scale: 2'' = 1'-0''

* Drawing Adapted from TriPyramid Galvanized Steel Wire Cables

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

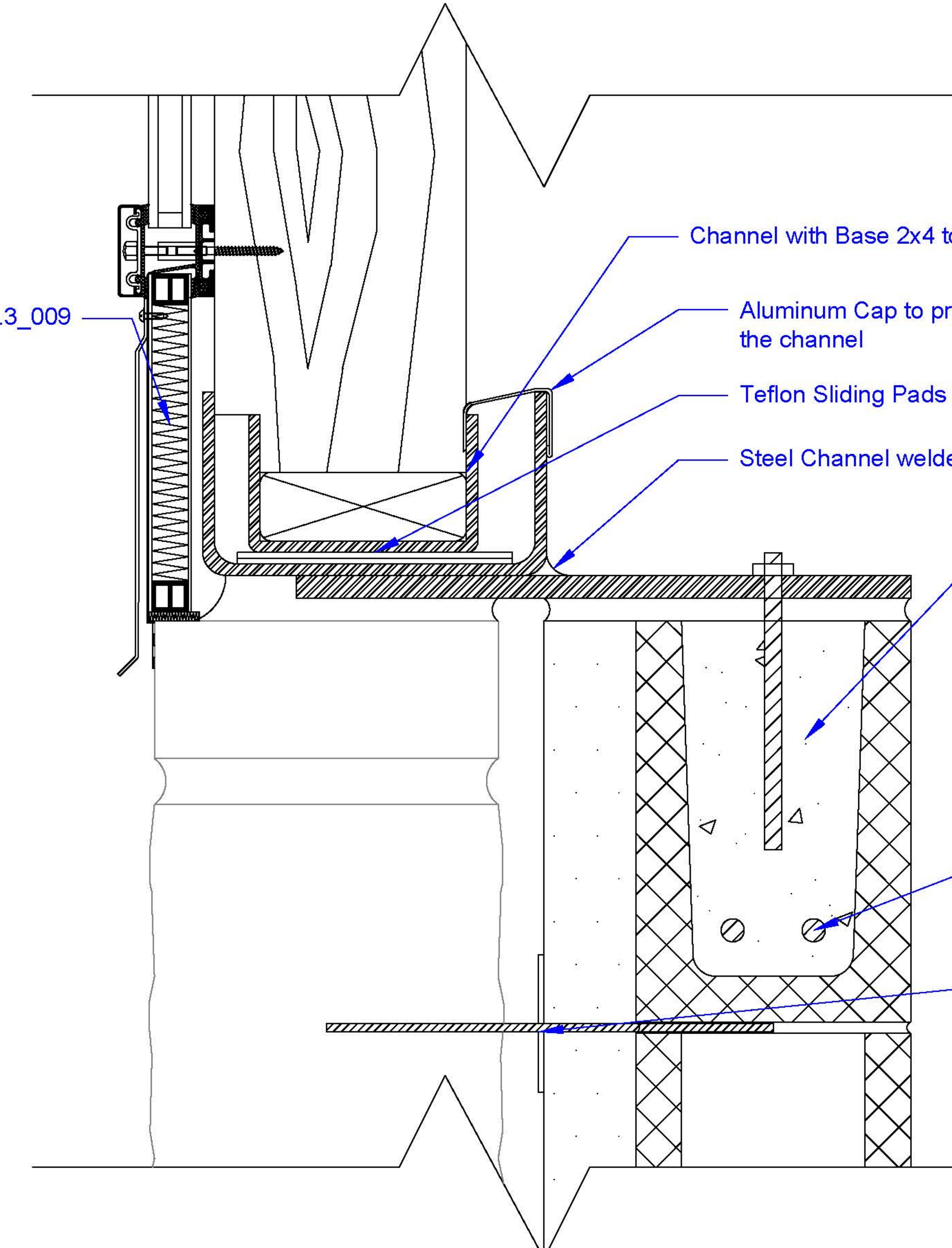
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	13
Scale	



1

WALL CONSTRUCTION - TOP OF WALL CONNECTION

Scale: 4'' = 1'-0''

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

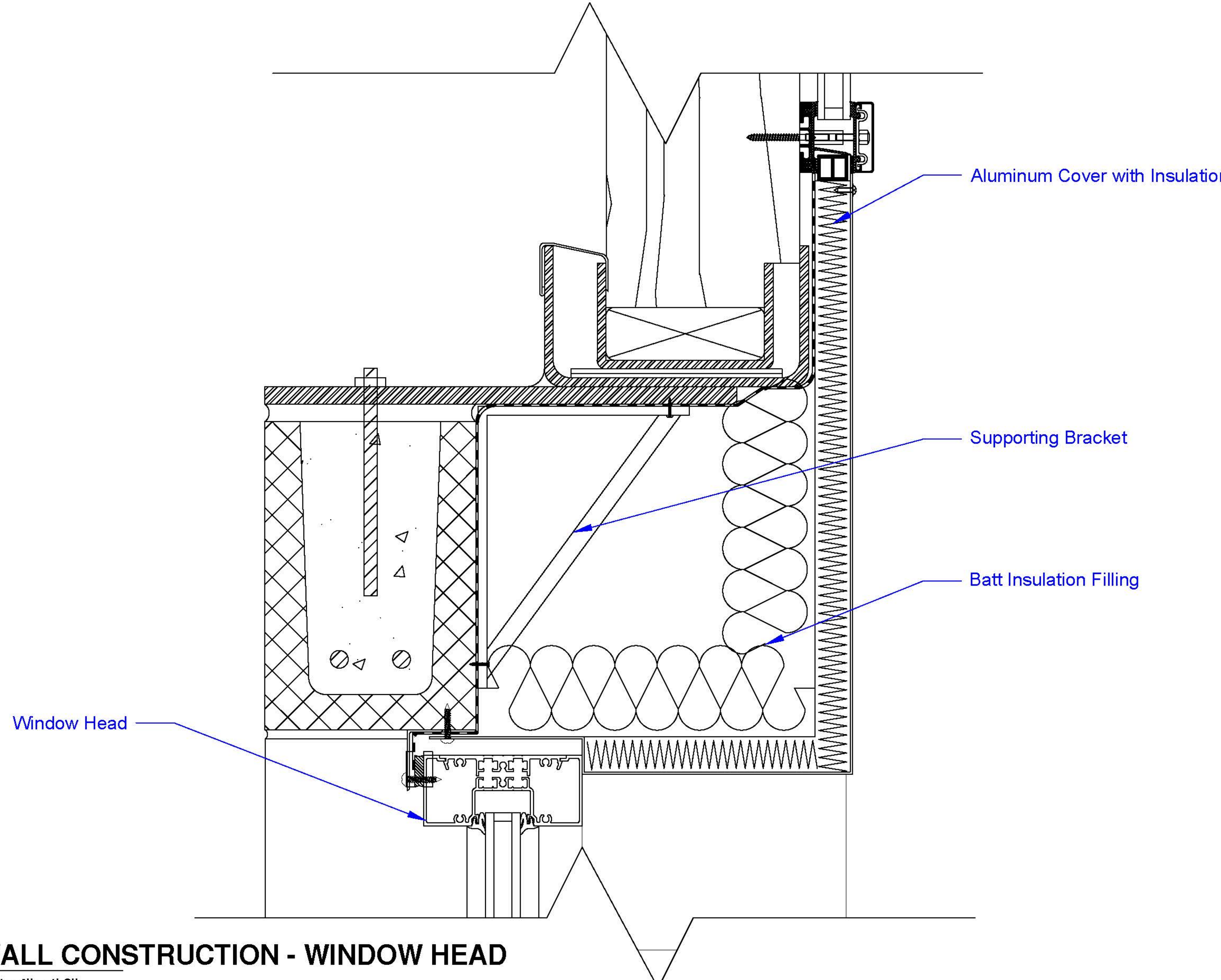
Project

Date

Scale

Sheet

14



1 **WALL CONSTRUCTION - WINDOW HEAD**

Scale: 4'' = 1'-0''

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

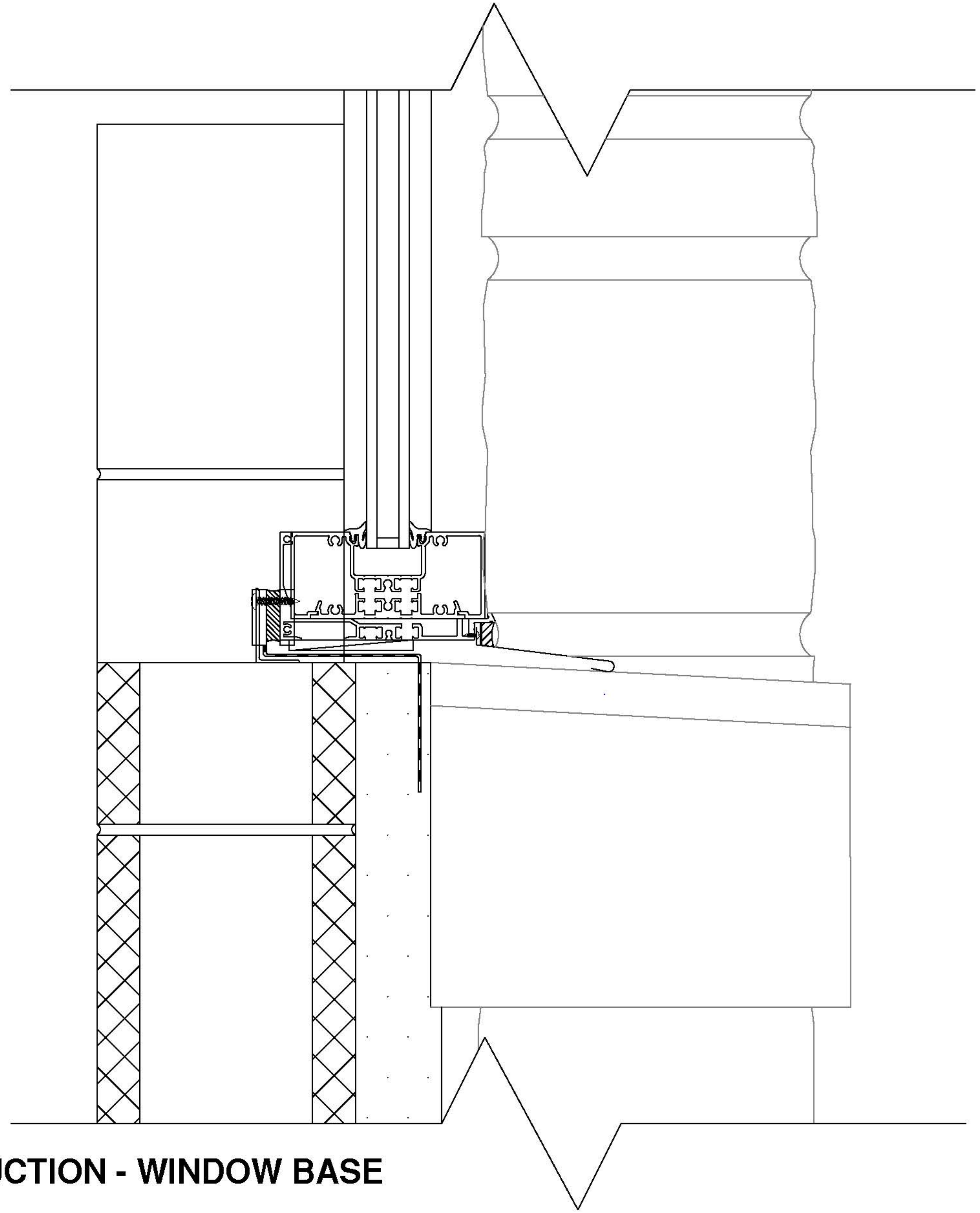
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	15
Scale	



1 WALL CONSTRUCTION - WINDOW BASE

Scale: 4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

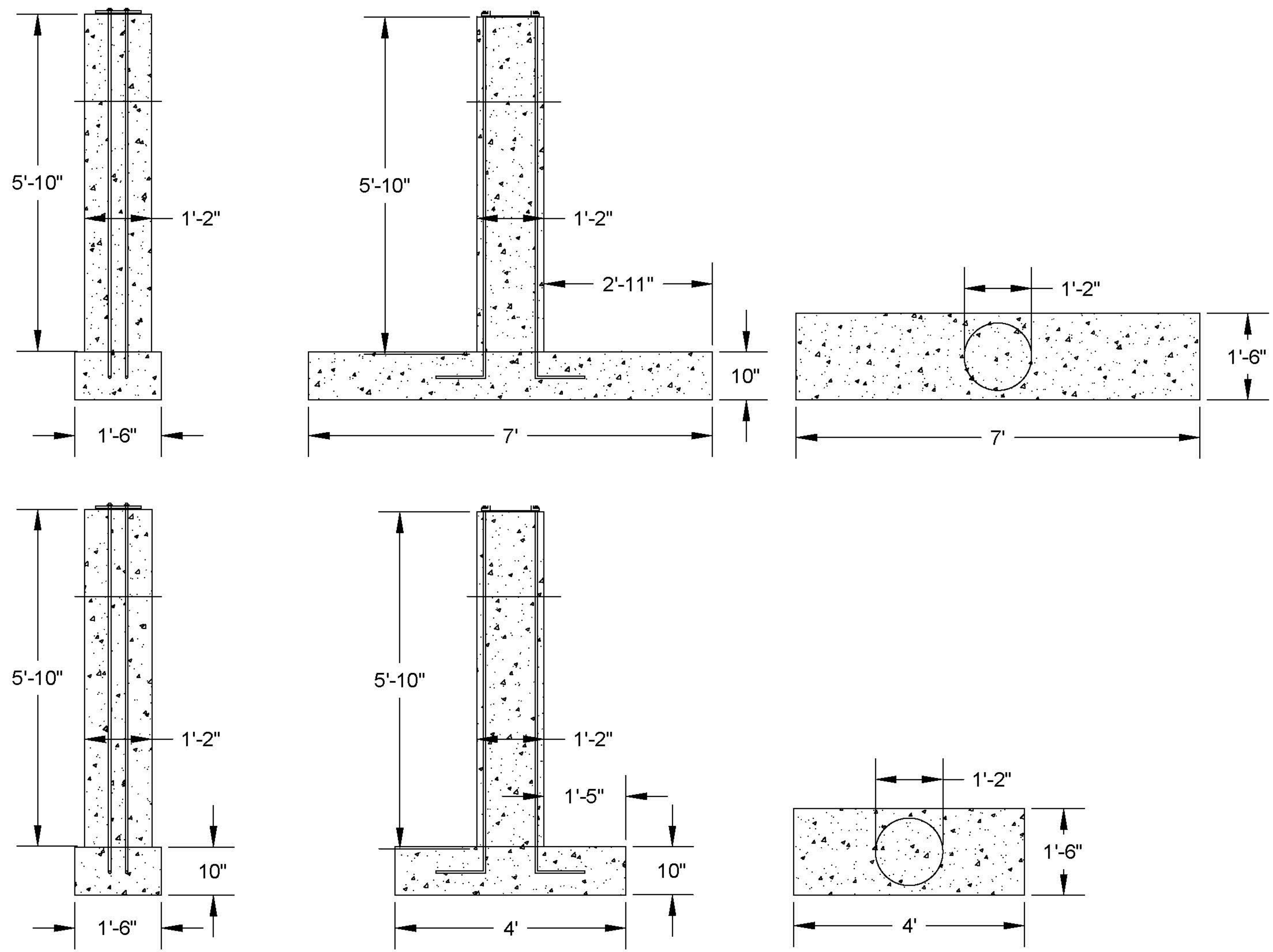
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

Date

Scale

Sheet 16



1 **FOOTING CONSTRUCTION**

Scale: 1/2'' = 1'-0''

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

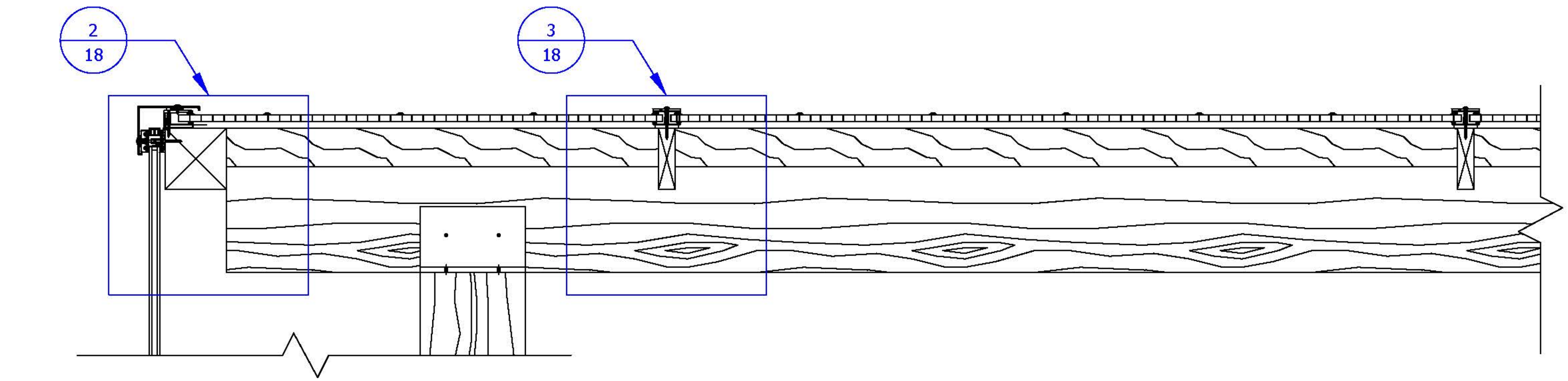
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

Date

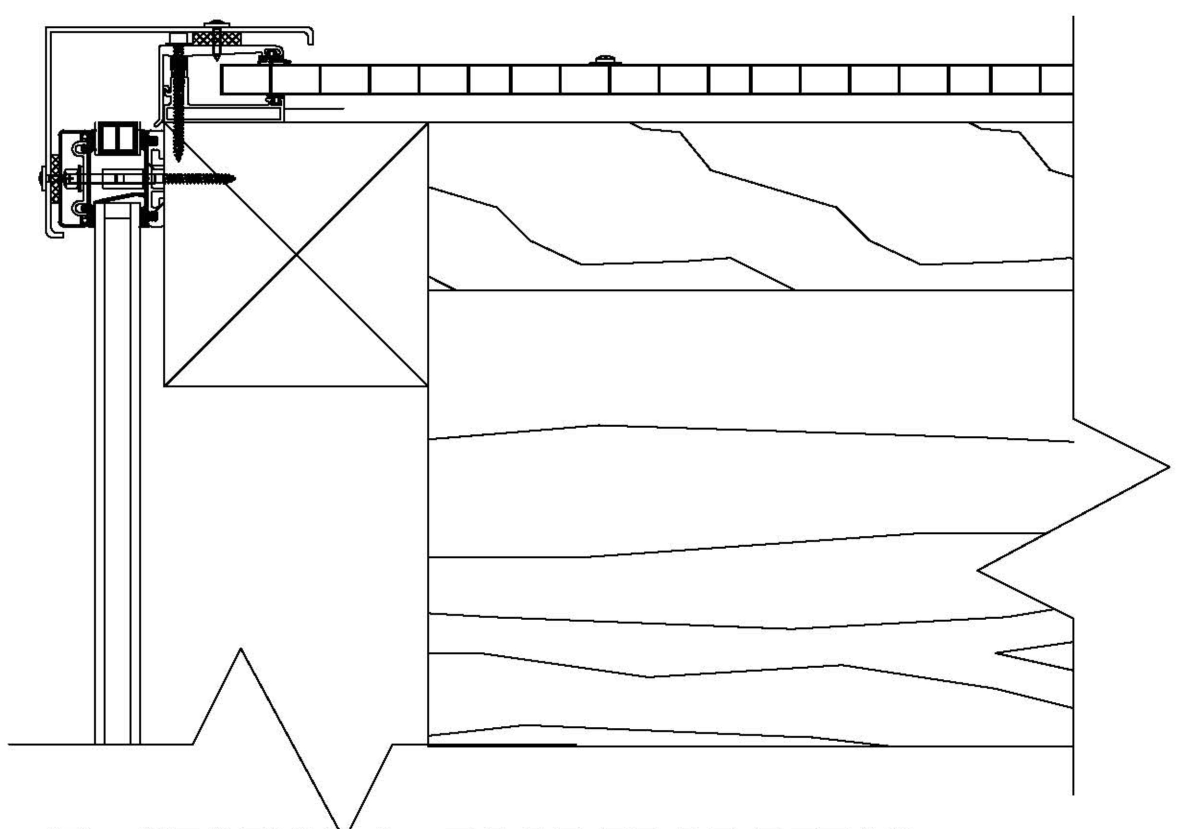
Scale

Sheet 17



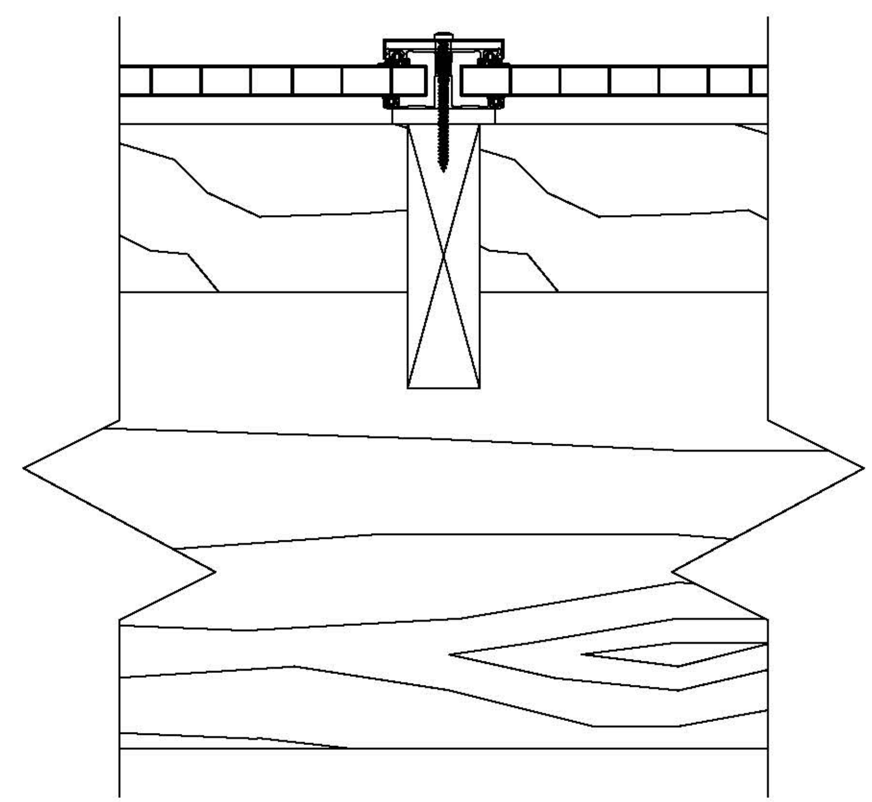
1 SECTION 3 - POLYCARBONATE DETAILS

Scale: 1'' = 1'-0''



2 SECTION 3 - ROOF EDGE DETAIL

Scale: 3'' = 1'-0''



3 SECTION 3 - POLYCARBONATE MULLION

Scale: 3'' = 1'-0''

* Drawings Adapted from Palram Sunlite Plus and Stabalux ZL-H

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

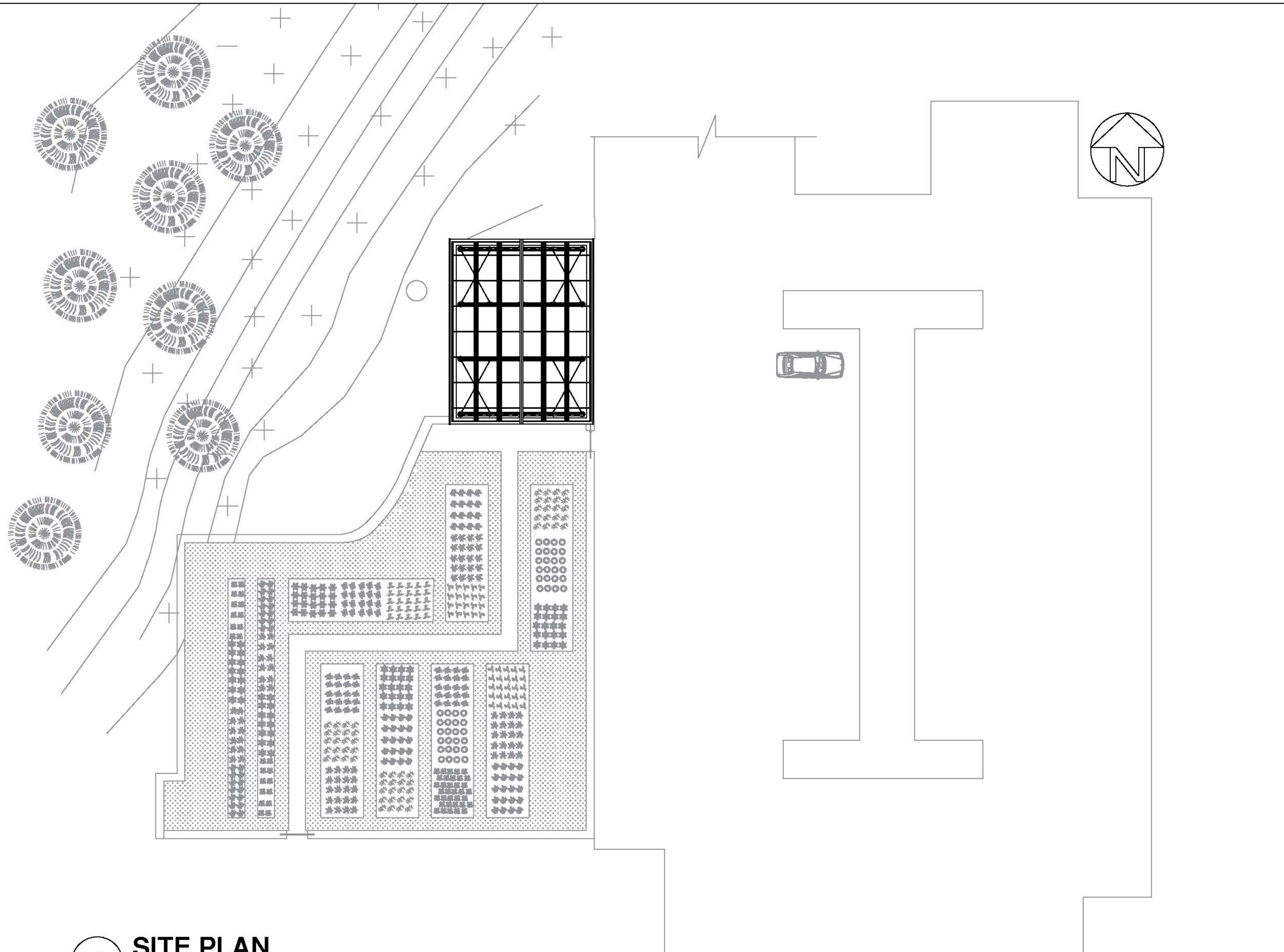
Date

Scale

Sheet 18

Appendix Q: Scaled Glass Drawings

The drawings in this appendix were developed using a glass glazing system. It is important to note that these are schematic design drawings and not intended as construction drawings. These drawings have not been stamped by a professionally licensed engineer.



1 SITE PLAN

Scale: 1/24'' = 1'-0''

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

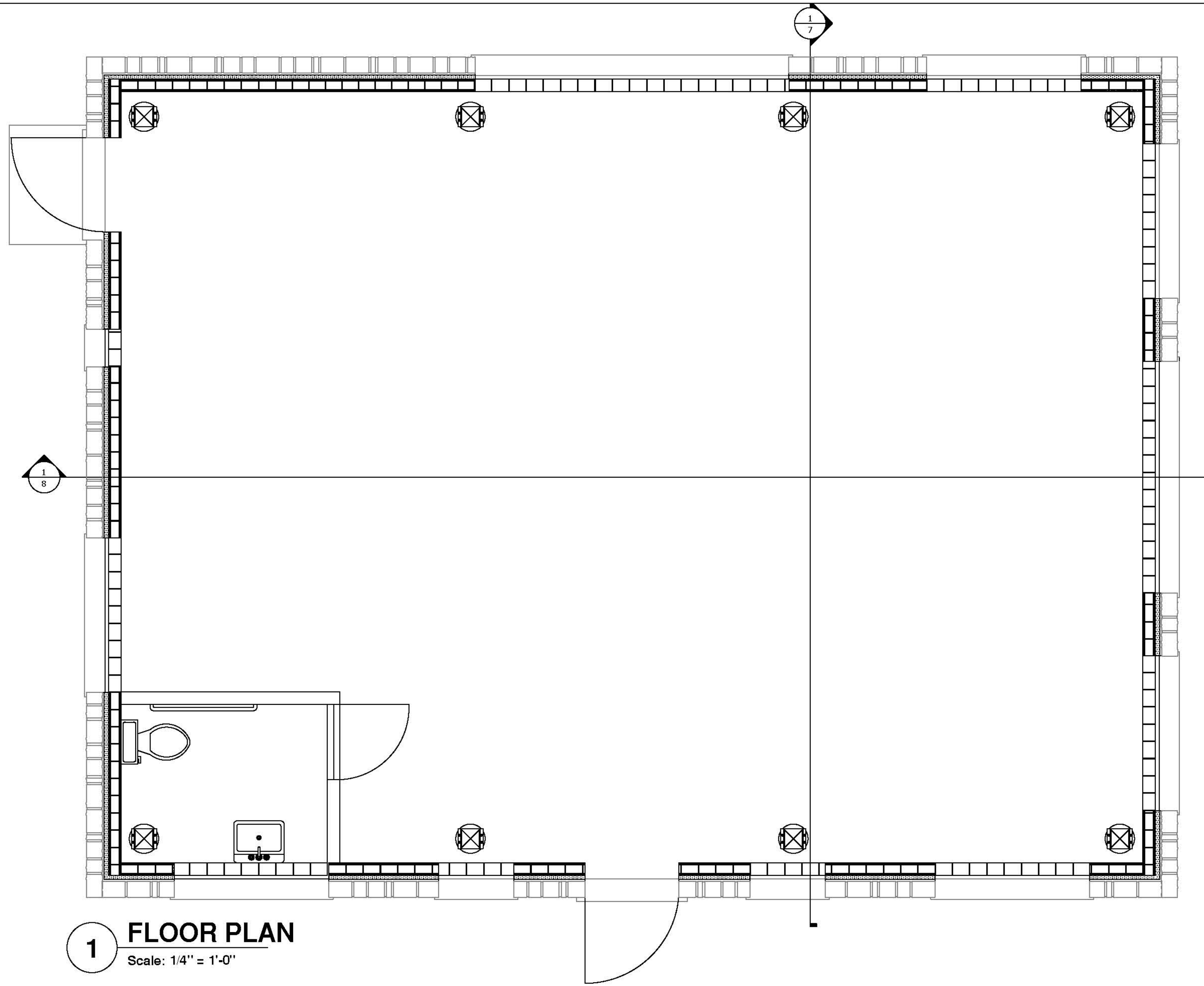
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet 1
Date	
Scale	



1 FLOOR PLAN

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

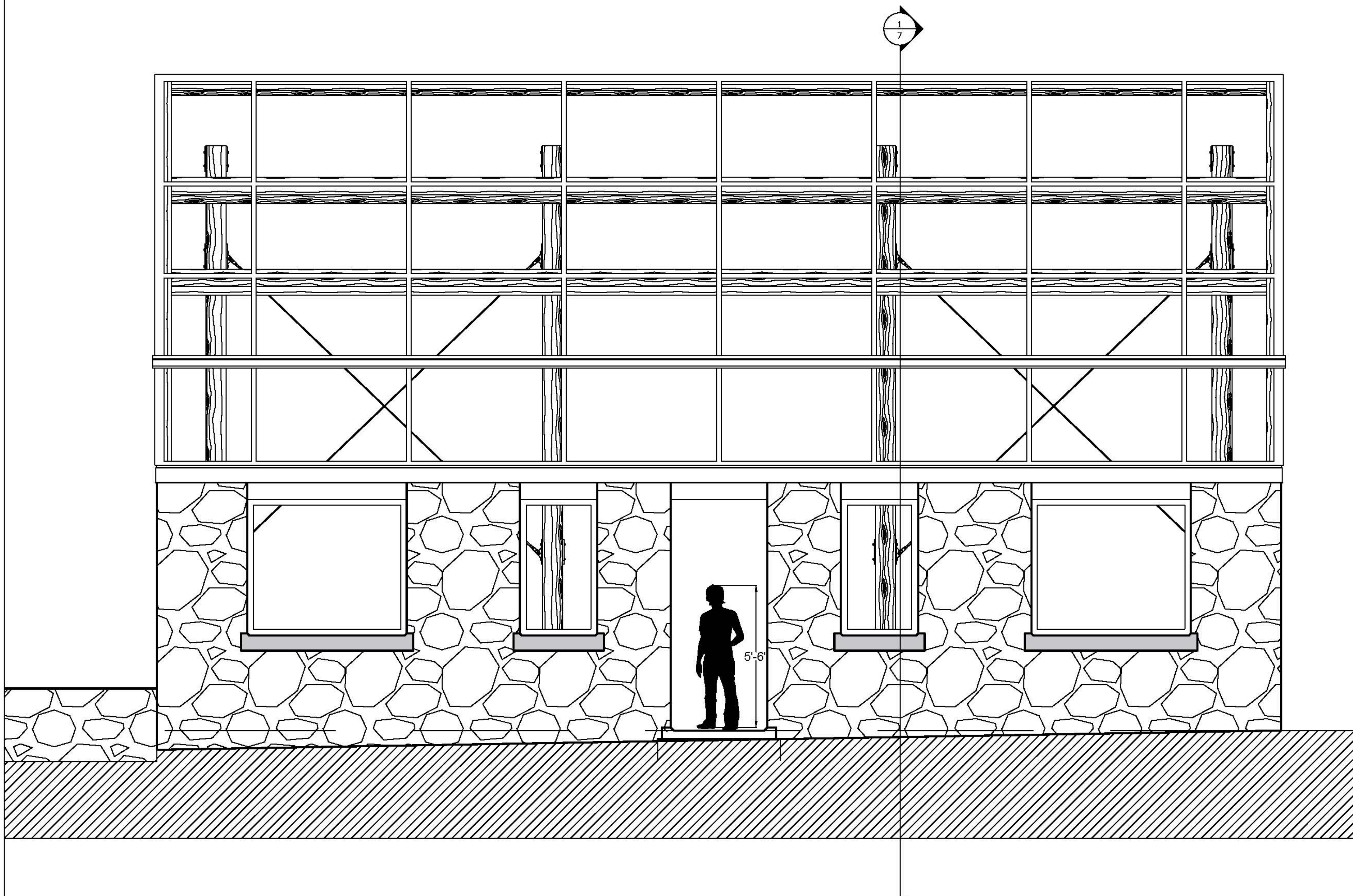
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	2
Scale	



EAST ELEVATION

1 EAST ELEVATION
Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

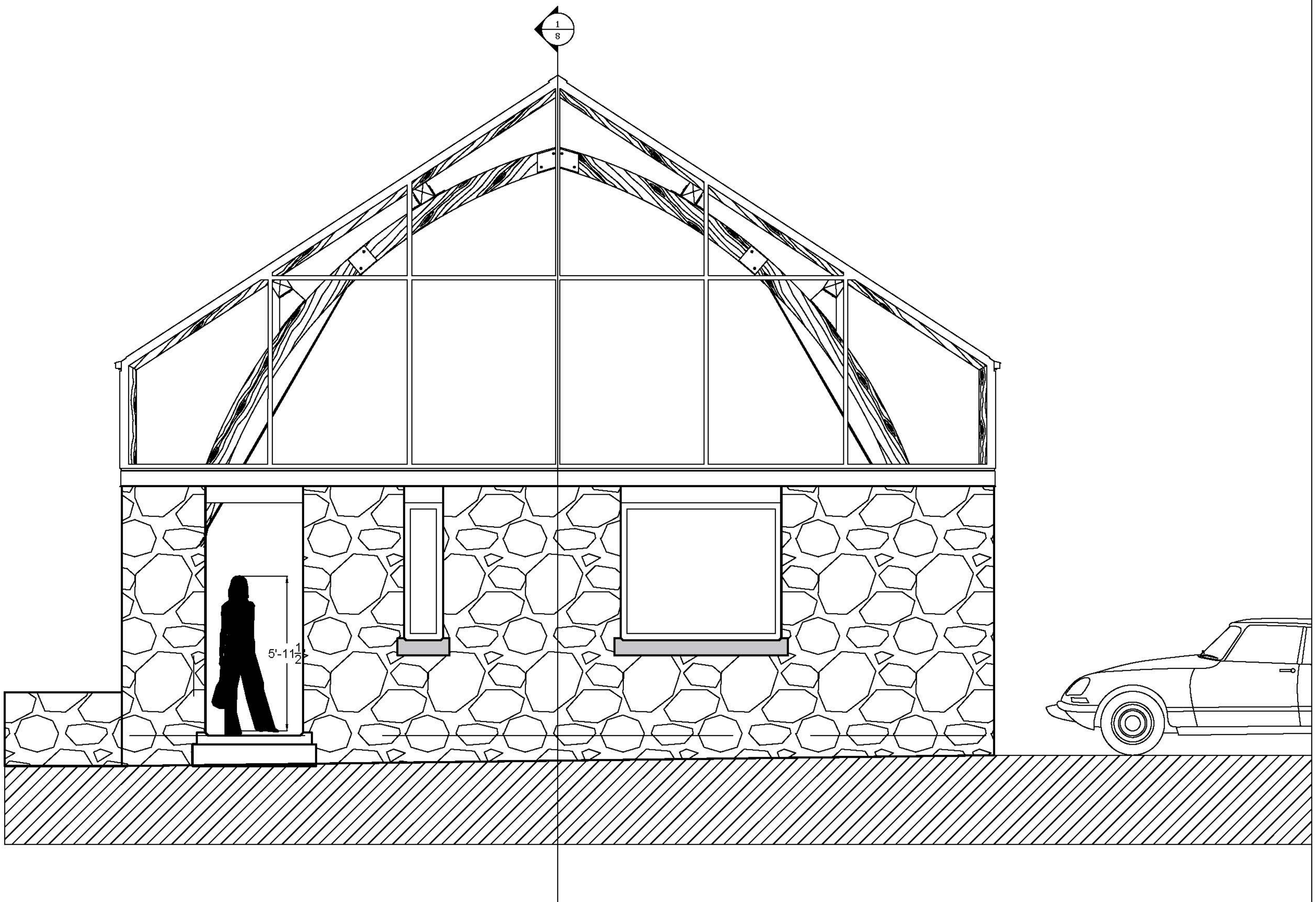
Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address
Worcester Polytechnic Institute

Project Name and Address
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	3
Scale	



1 **SOUTH ELEVATION**

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

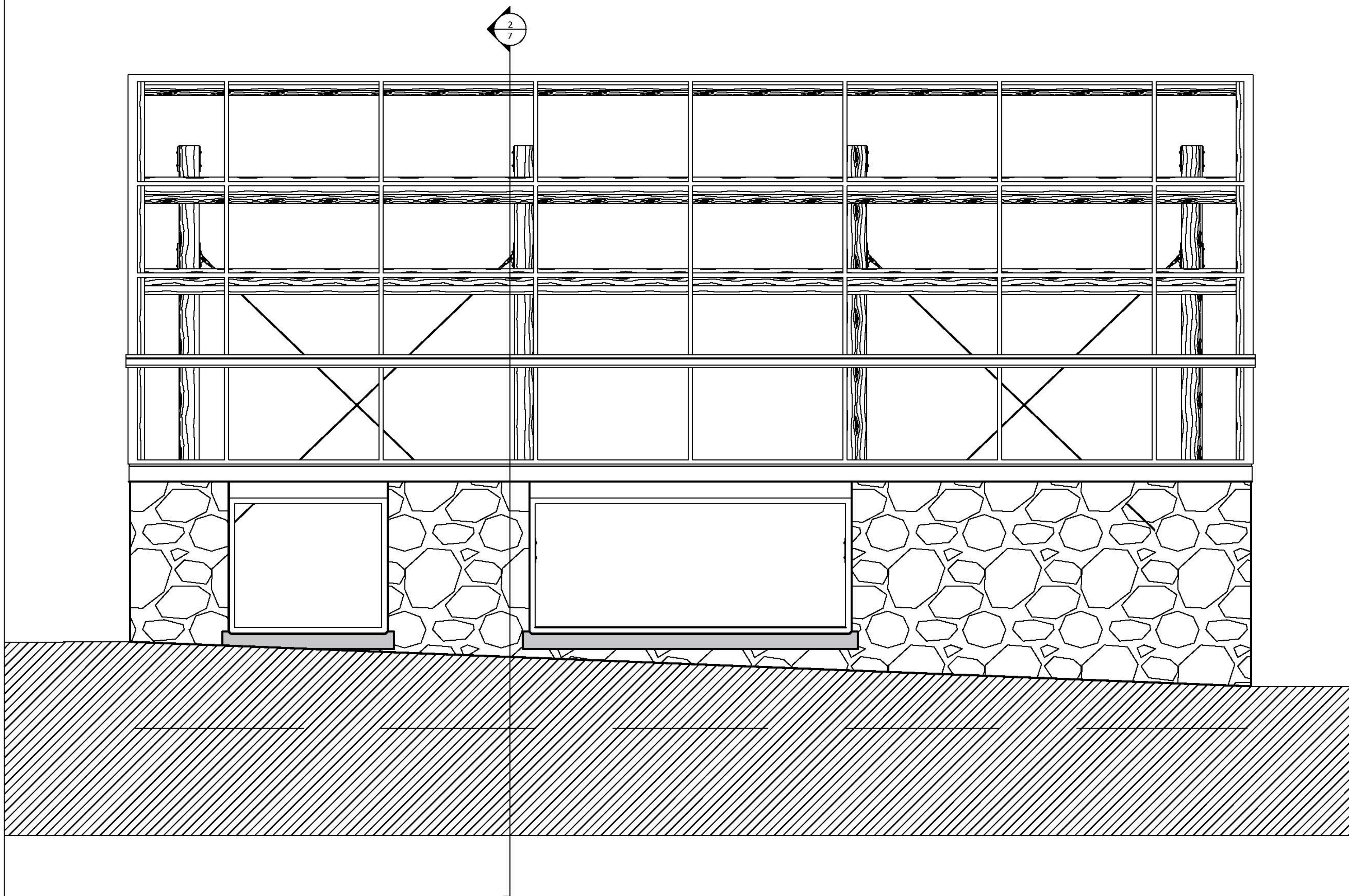
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	4
Scale	



1 WEST ELEVATION

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

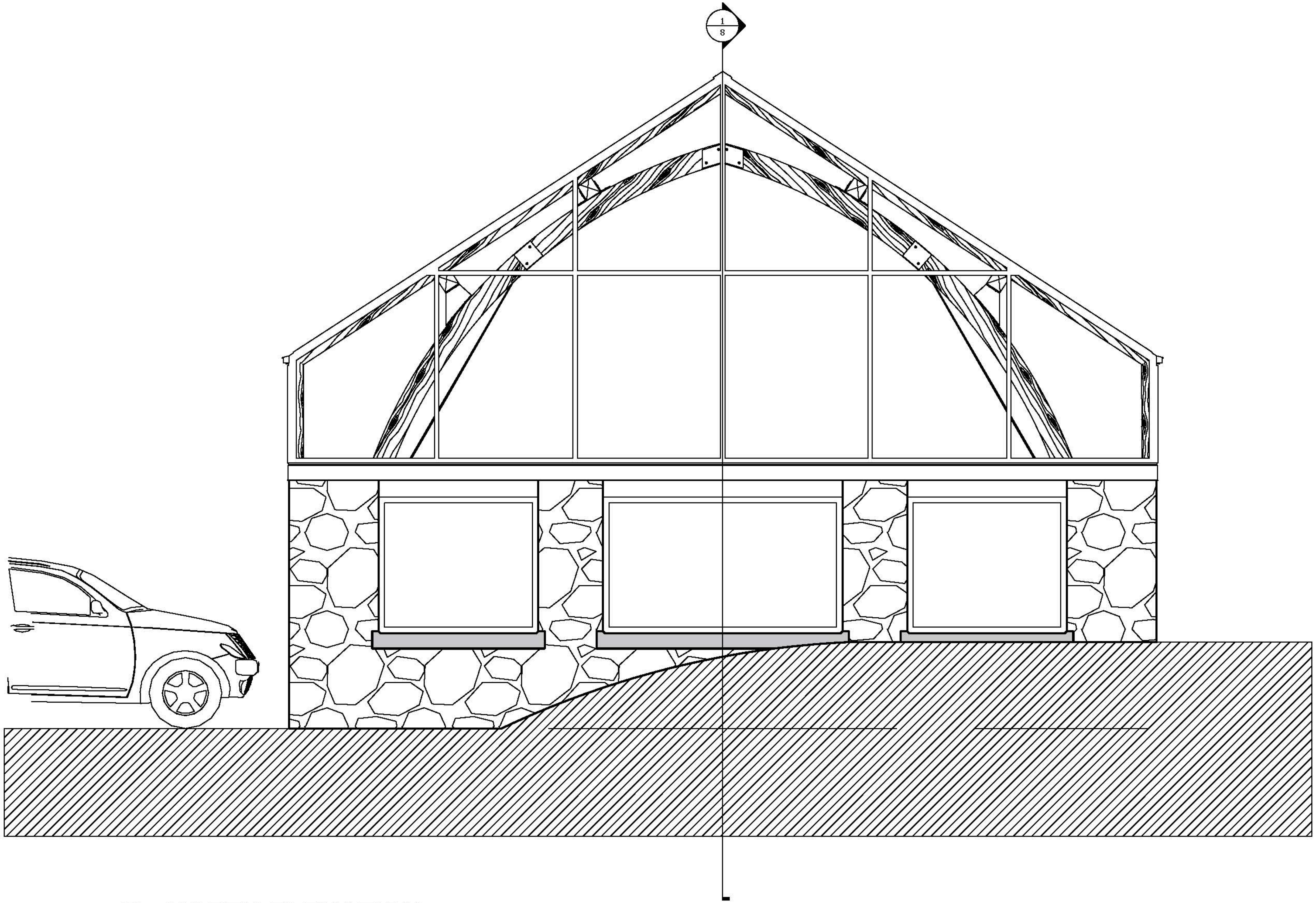
Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	5
Scale	



1 **NORTH ELEVATION**

Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

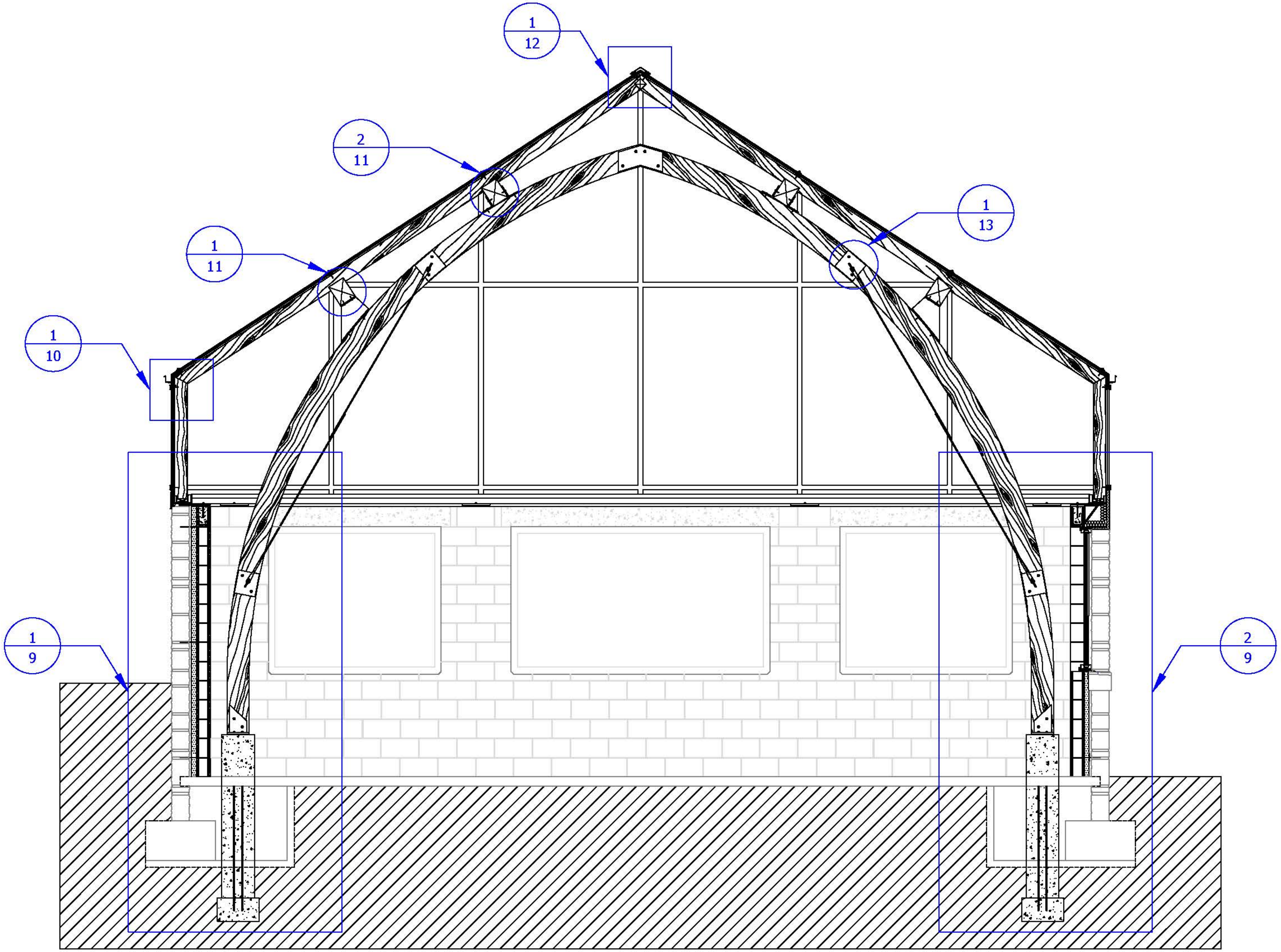
Firm Name and Address

Worcester
Polytechnic
Institute

Project Name and Address

Worcester Technical
High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project	Sheet
Date	6
Scale	



1 **SECTION 1**
Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

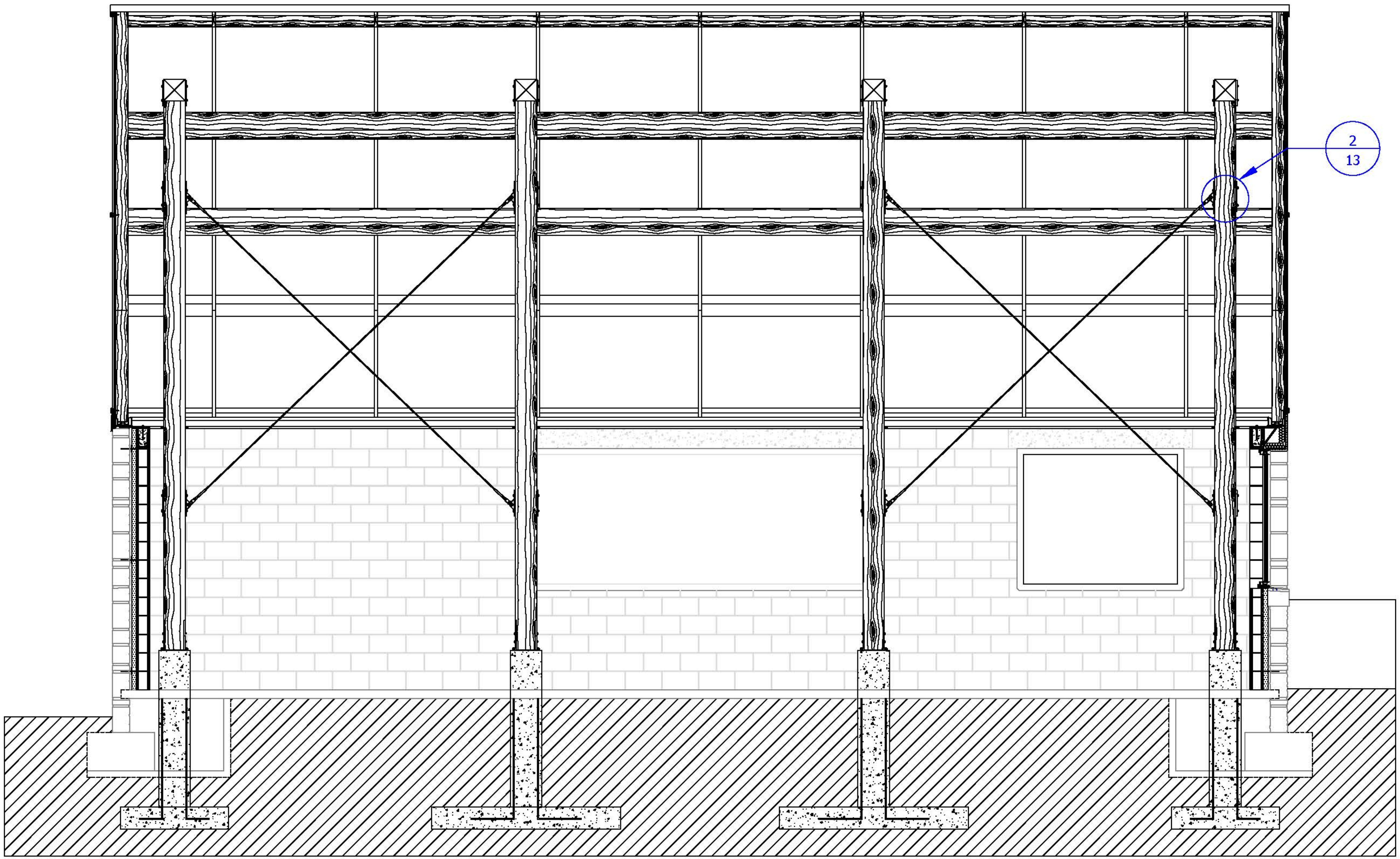
Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address
Worcester Polytechnic Institute

Project Name and Address
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project
Date
Scale
Sheet 7



1 **SECTION 2**
Scale: 1/4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

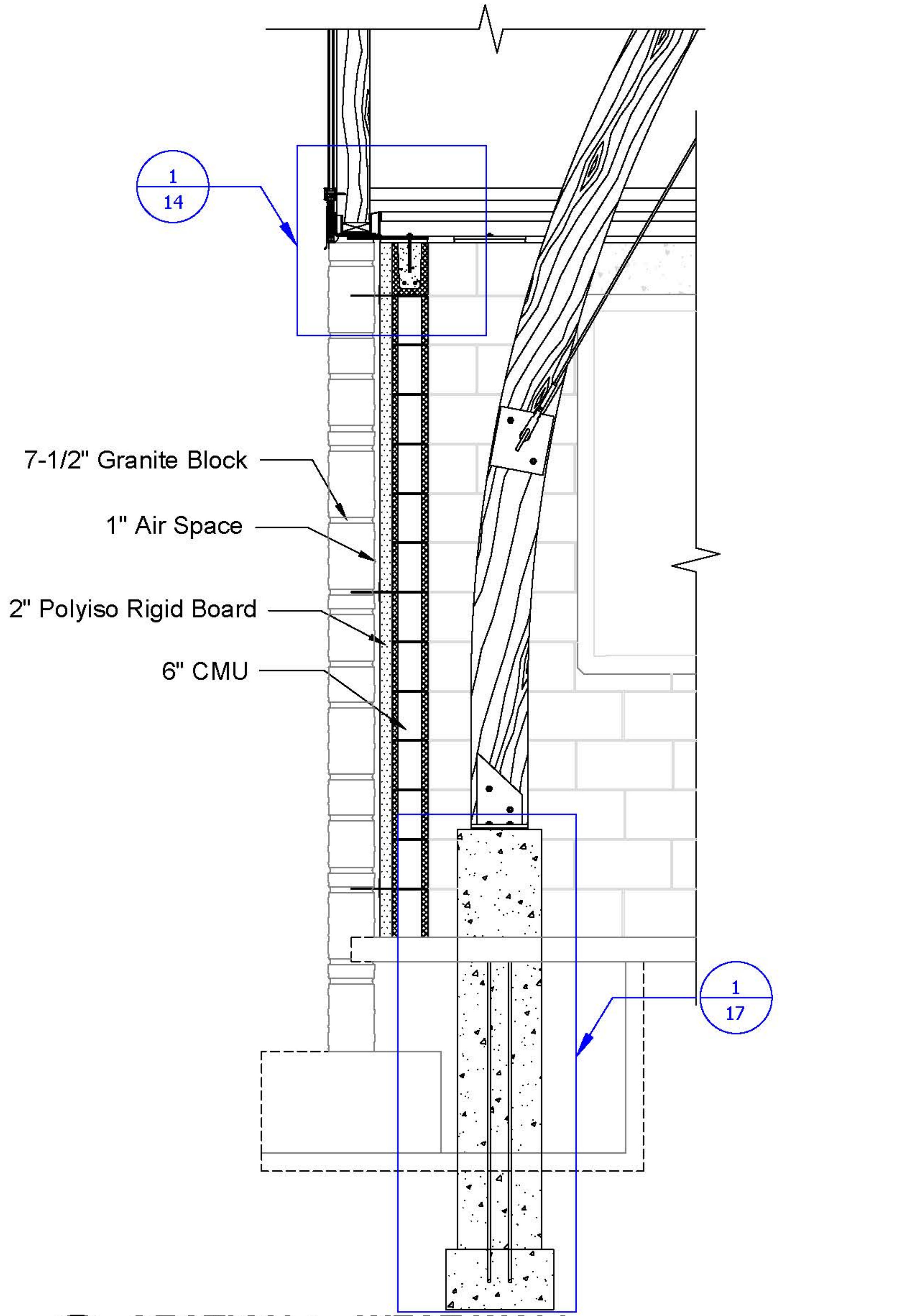
Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address
Worcester Polytechnic Institute

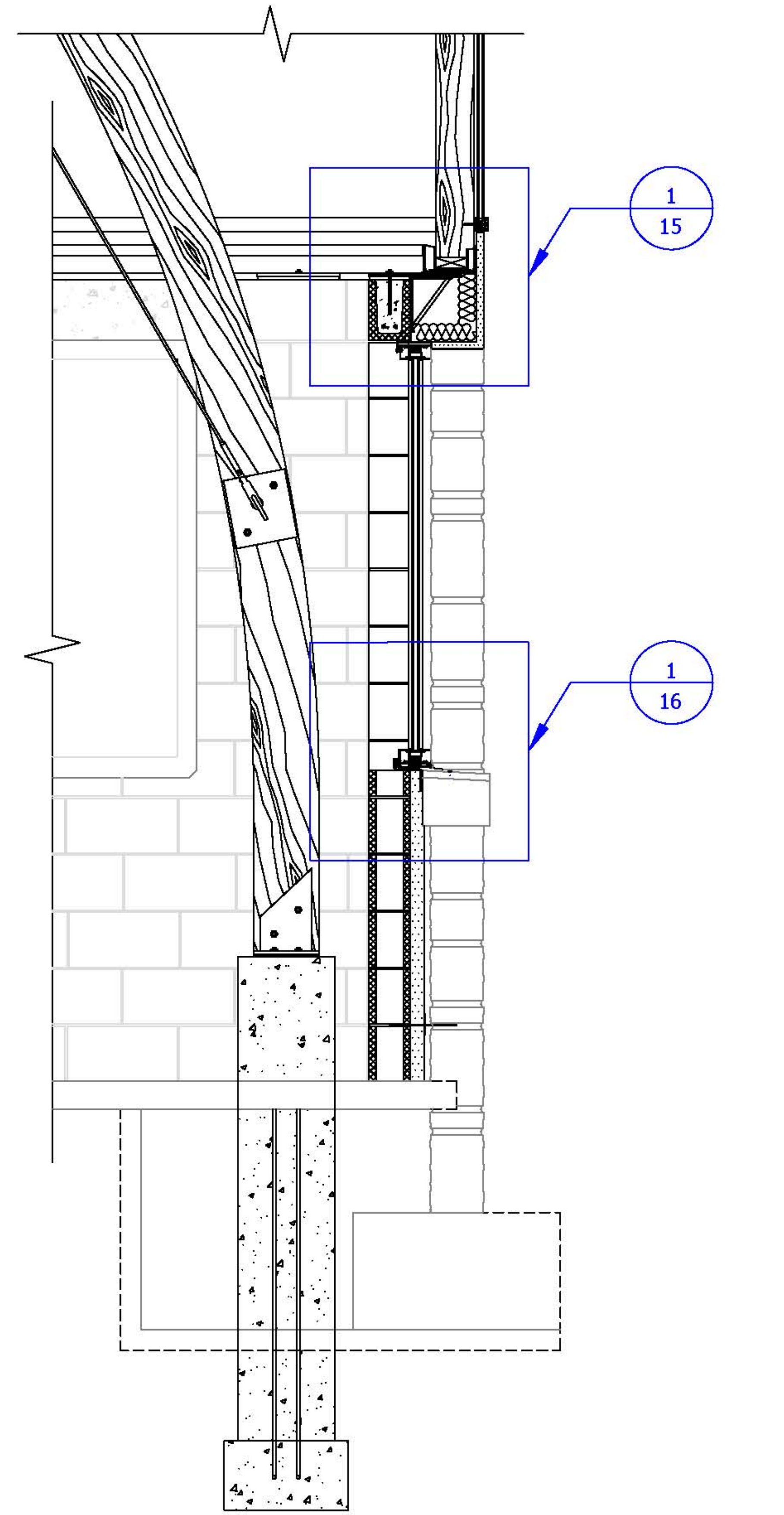
Project Name and Address
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project
Date
Scale
Sheet 8



1 SECTION 1 - WEST WALL

Scale: 1/2" = 1'-0"



2 SECTION 1 - EAST WALL

Scale: 1/2" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

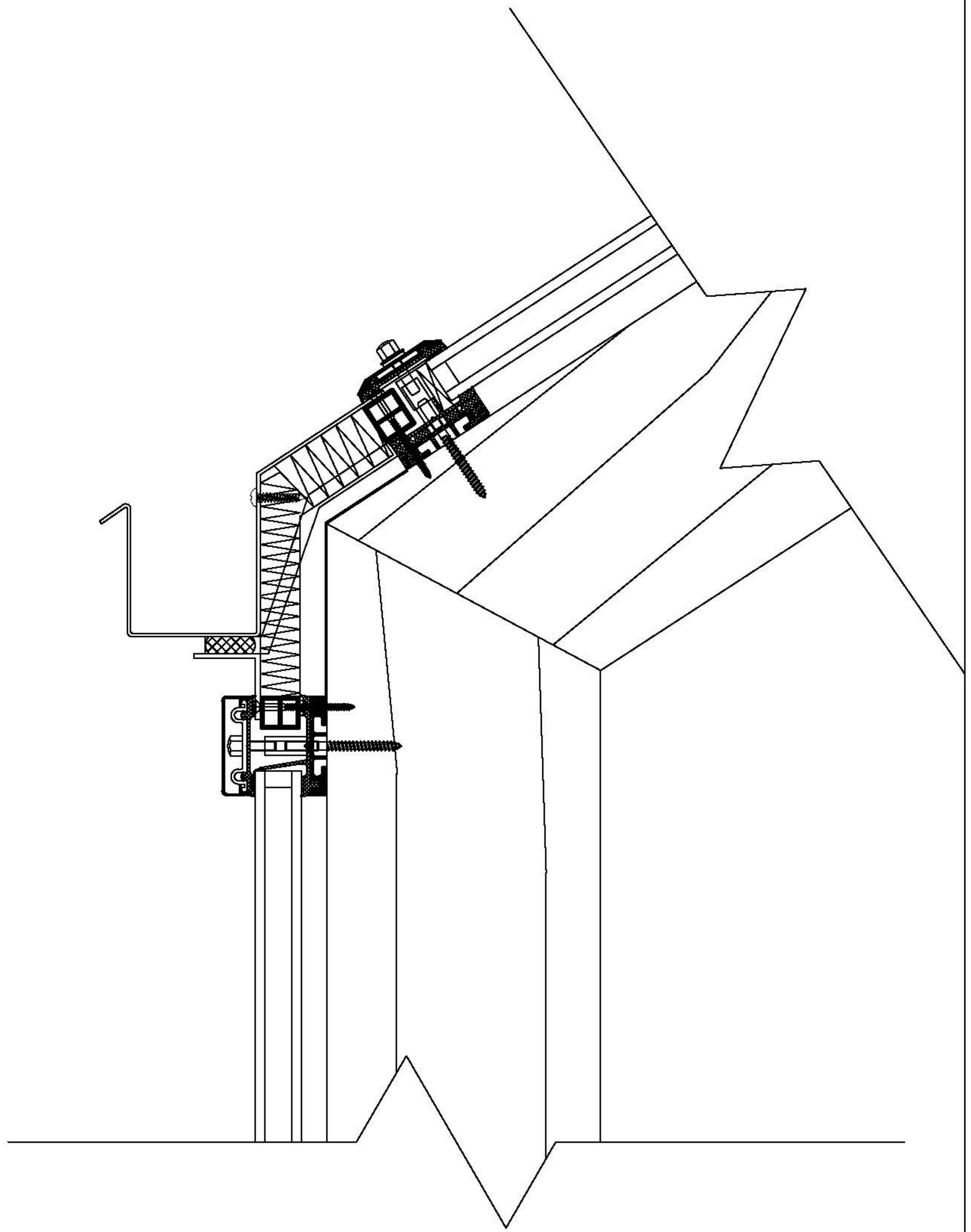
Project

Date

Scale

Sheet

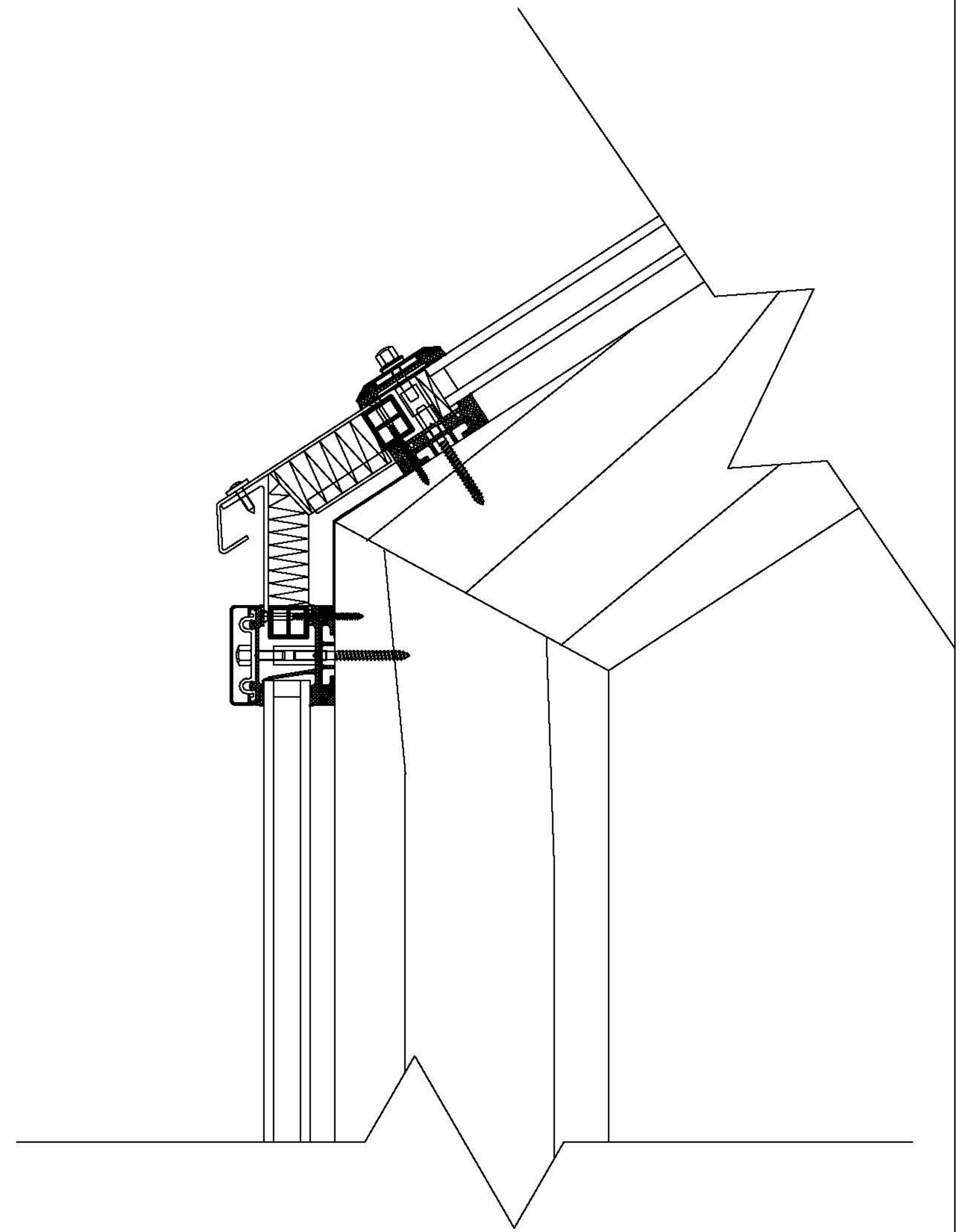
9



1 SECTION 1 - GUTTER DETAIL

Scale: 4" = 1'-0"

* Drawing Adapted from Stabalux ZL-H_2.3_007



2 ALTERNATE DESIGN - NO GUTTER

Scale: 4" = 1'-0"

* Drawing Adapted from Stabalux ZL-H_2.3_006

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

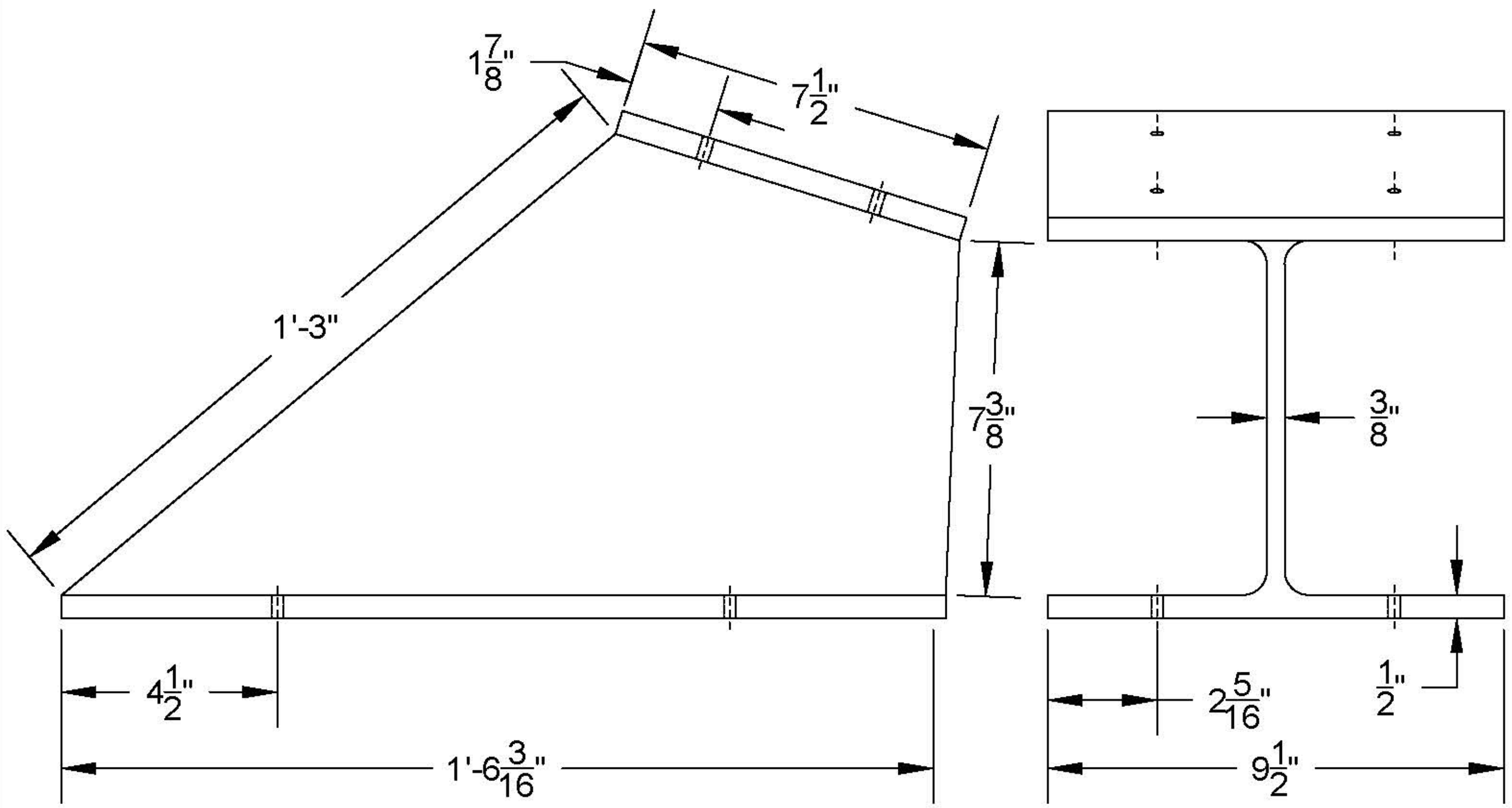
Project

Date

Scale

Sheet 10

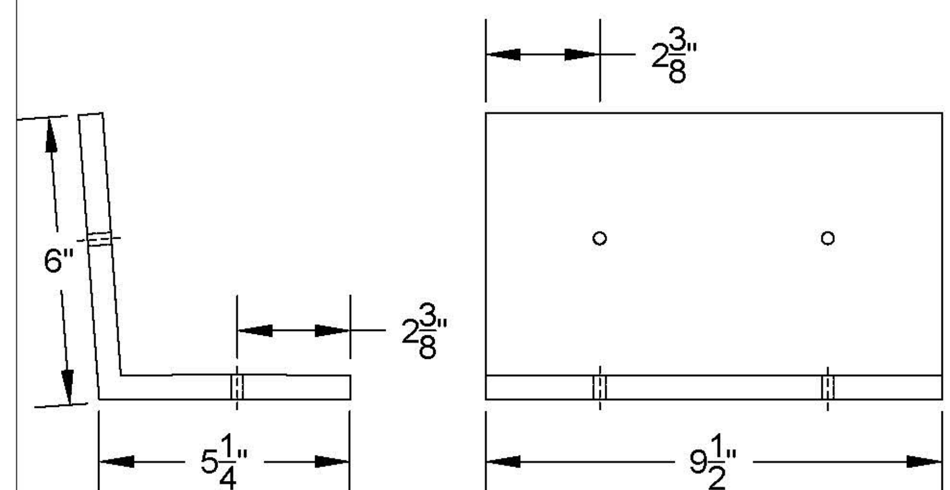
Custom connectors to the arches that support the rafters.
They are made from steel and designed similar to an I-beam



1 **SECTION 1 - CUSTOM SUPPORT FOR LOWER BEAM**

Scale: 3" = 1'-0"

Simple L-Bracket to support the upper beam



2 **SECTION 1 - L-BRACKET**

Scale: 3" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

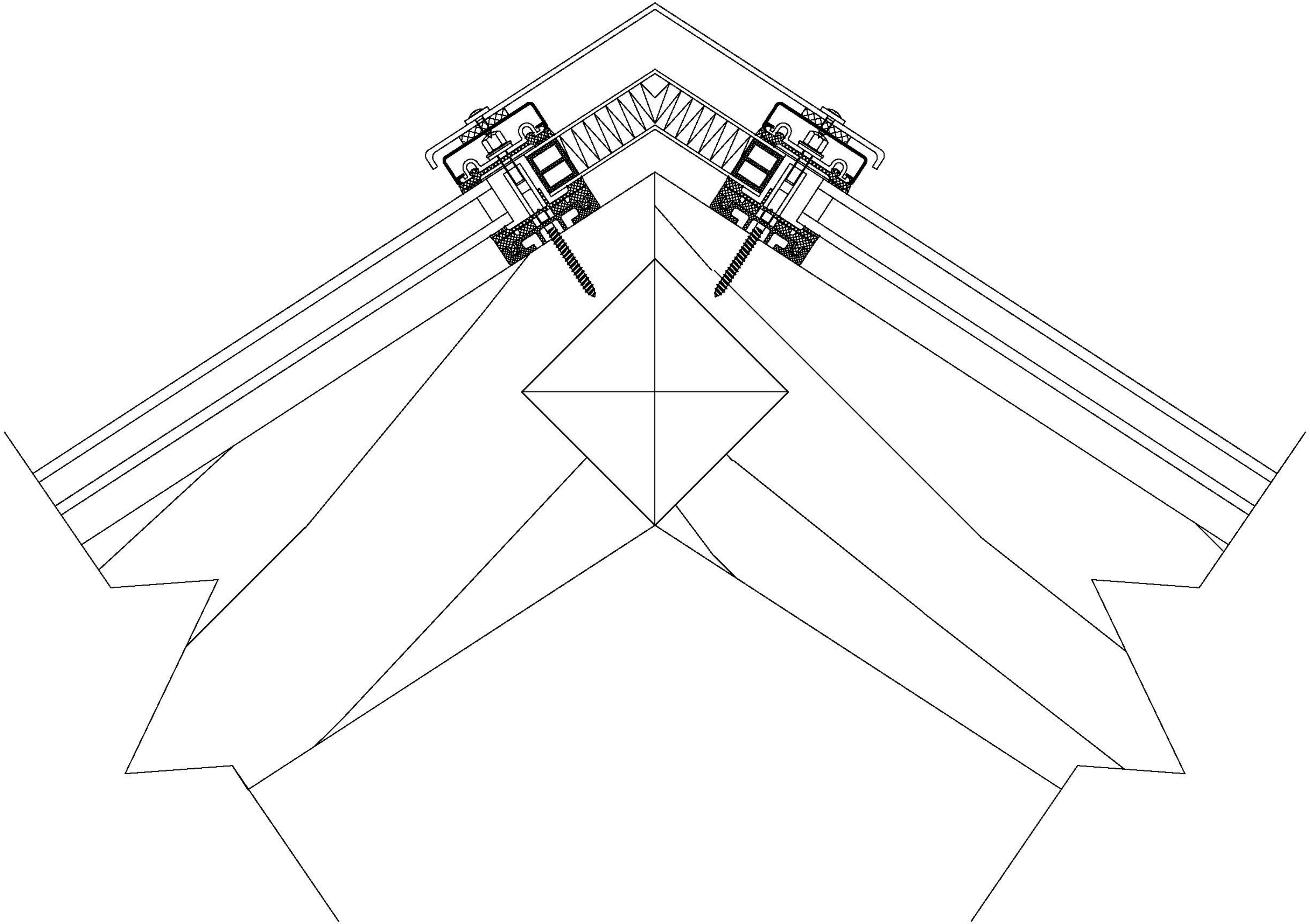
Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project
Date
Scale

Sheet 11



SECTION 1 - CALLOUT 6

1

Scale: 6" = 1'-0"

* Drawing Adapted from Stabalux ZL-H_2.3_008

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

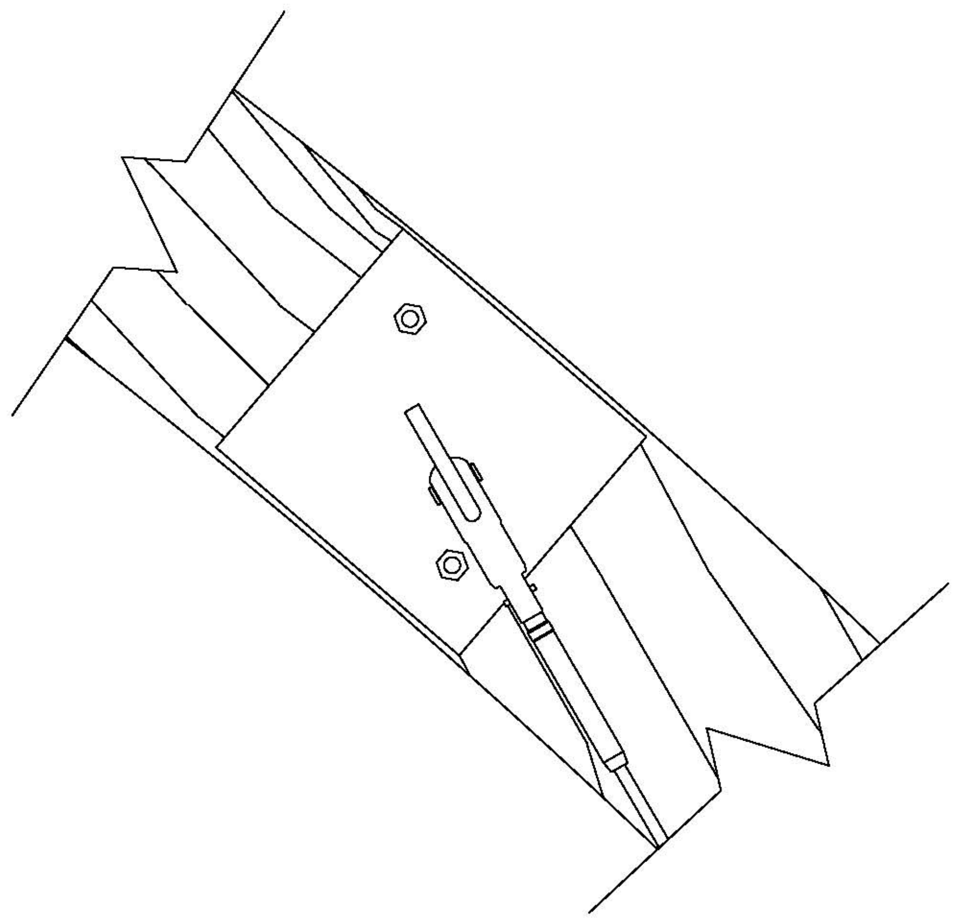
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

Date

Scale

Sheet 12

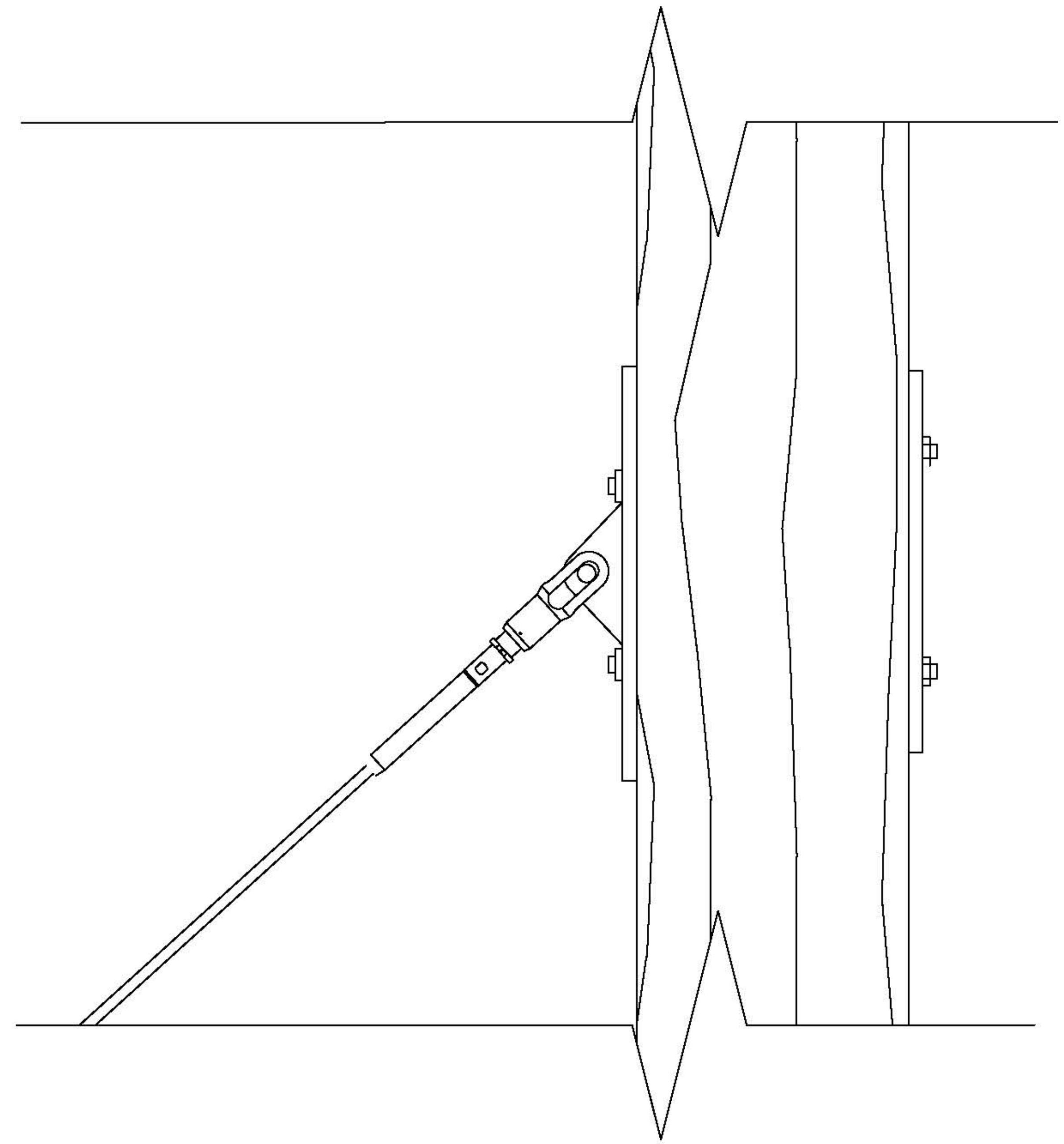


SECTION 1 - LATER SOUTH VIEW

1

Scale: 2'' = 1'-0''

* Drawing Adapted from TriPyramid Galvanized Steel Wire Cables



SECTION 1 - LATERAL EAST VIEW

1

Scale: 2'' = 1'-0''

* Drawing Adapted from TriPyramid Galvanized Steel Wire Cables

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

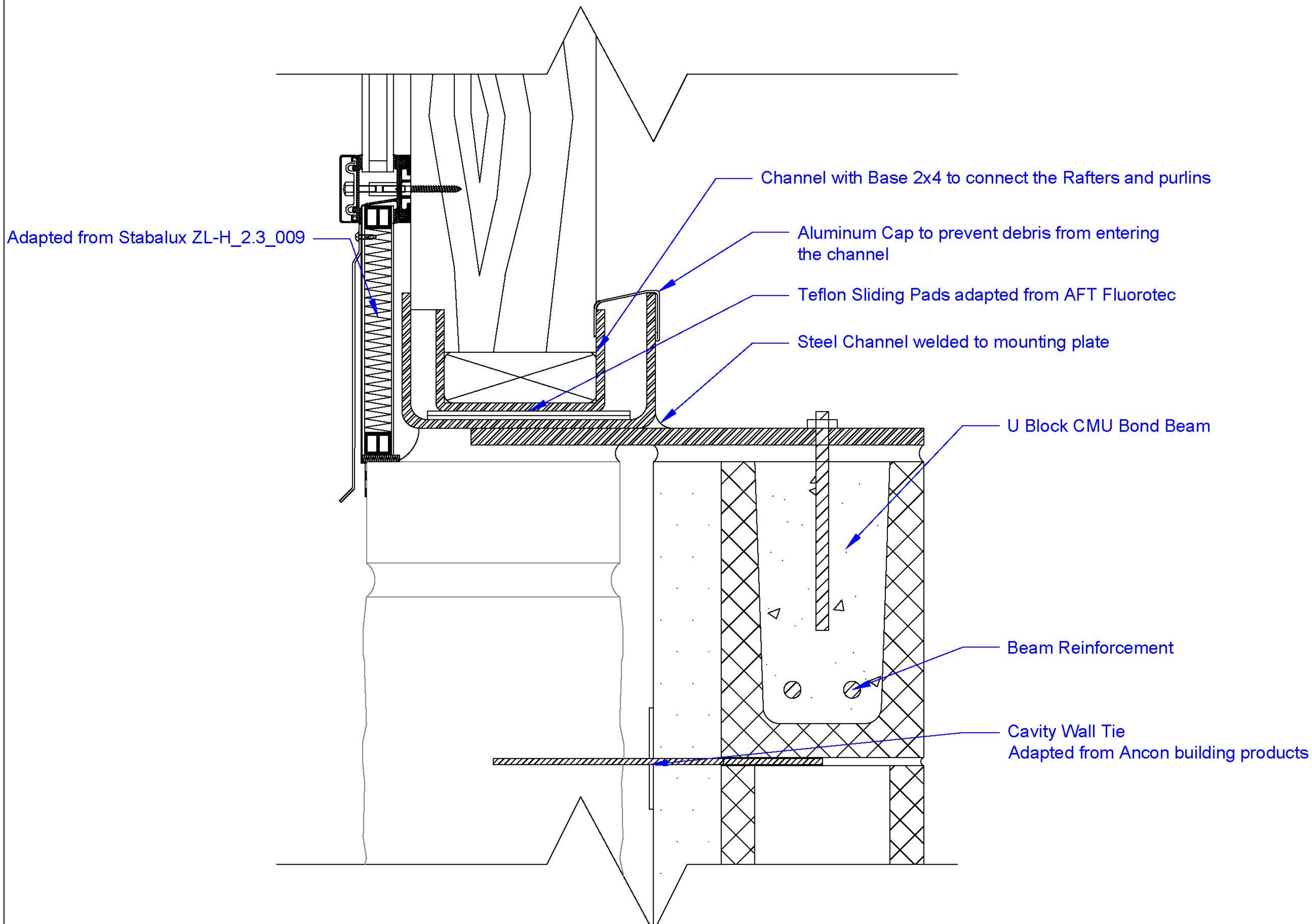
Project

Date

Scale

Sheet

13



1 WALL CONSTRUCTION - TOP OF WALL CONNECTION

Scale: 4'' = 1'-0''

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

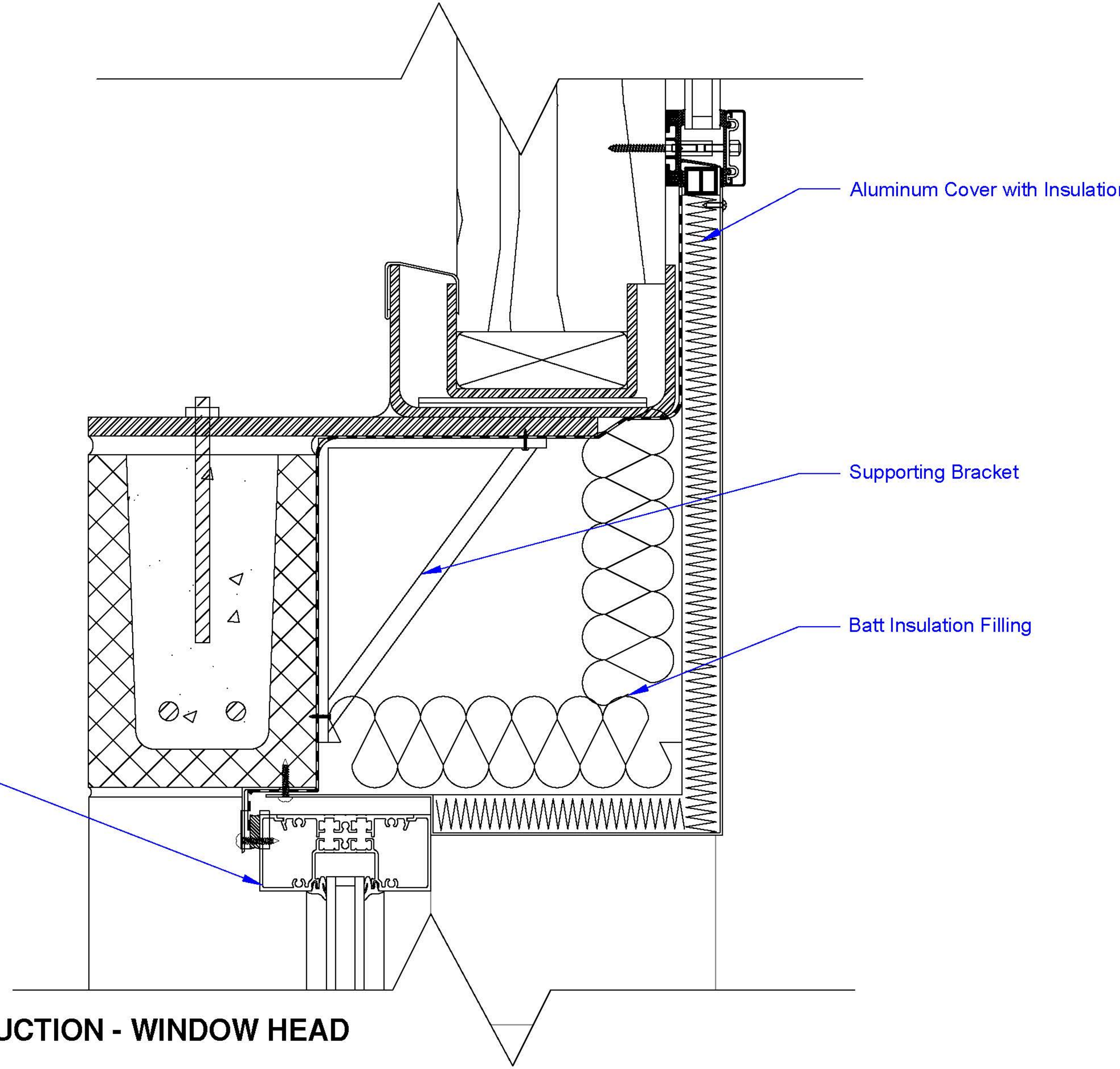
Project

Date

Scale

Sheet

14



1 WALL CONSTRUCTION - WINDOW HEAD

Scale: 4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

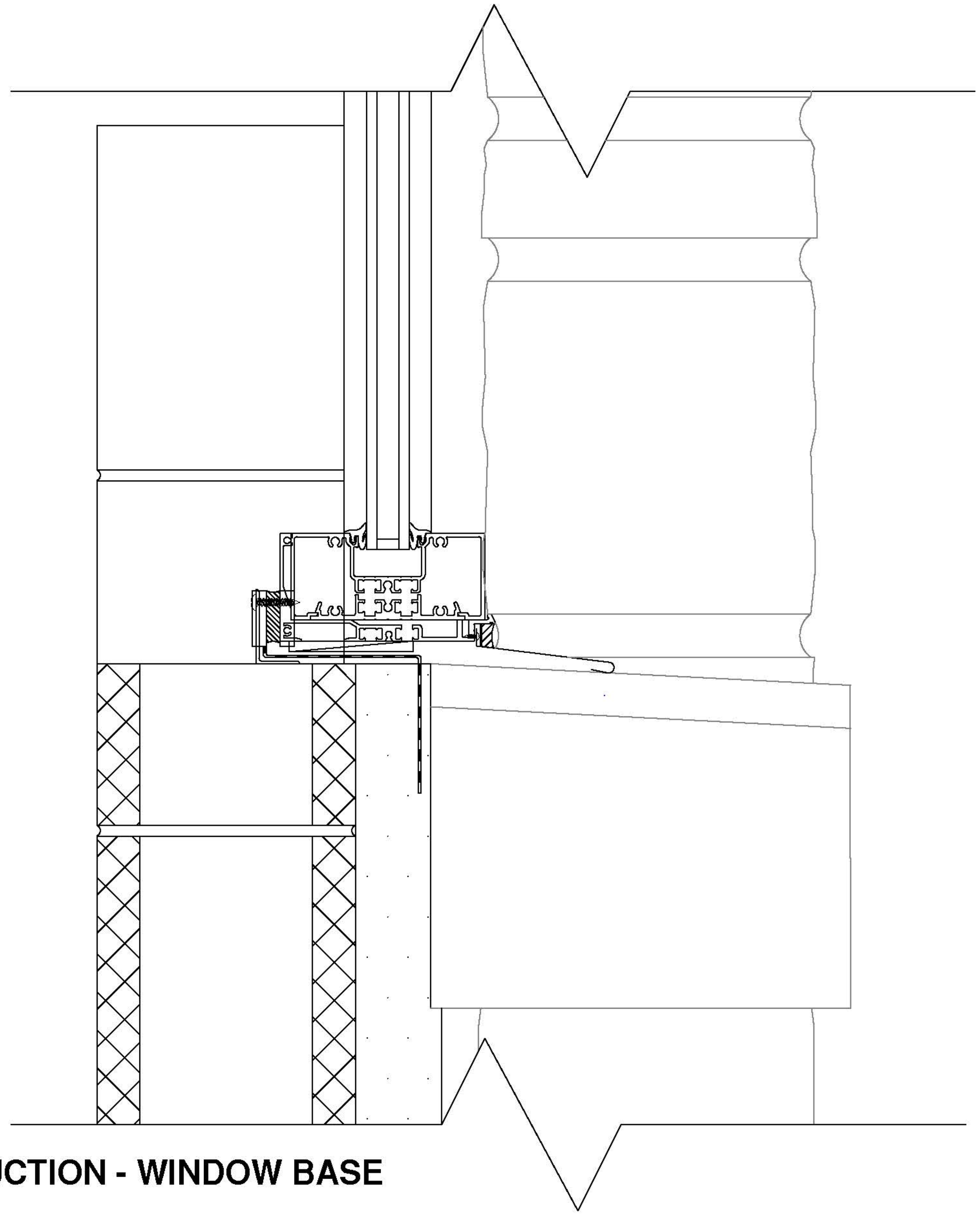
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

Date

Scale

Sheet 15



1 **WALL CONSTRUCTION - WINDOW BASE**
Scale: 4" = 1'-0"

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

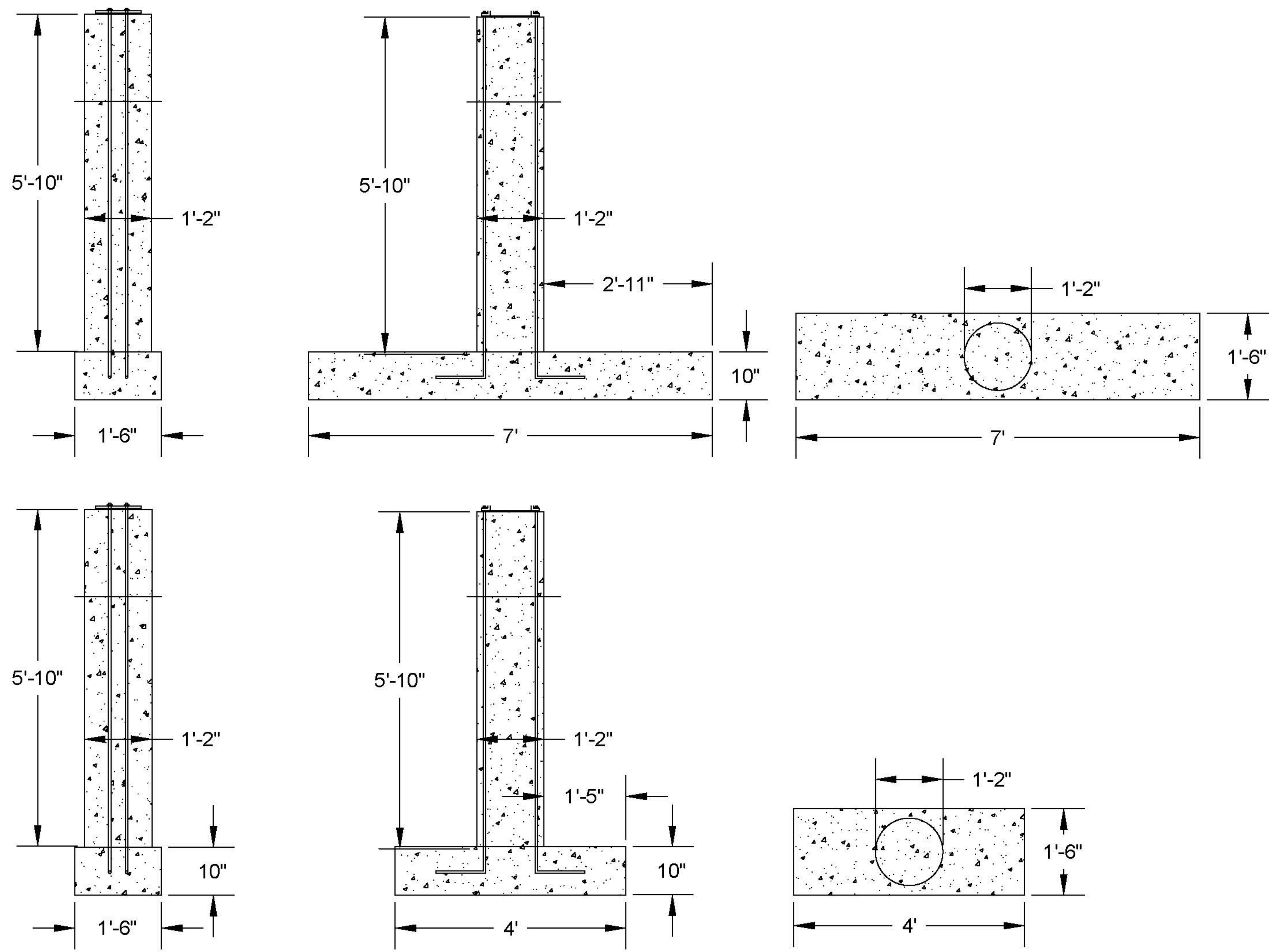
No.	Revision/Issue	Date

Firm Name and Address
Worcester Polytechnic Institute

Project Name and Address
Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project
Date
Scale

Sheet
16



1 **FOOTING CONSTRUCTION**

Scale: 1/2'' = 1'-0''

General Notes

Material Legend

- Granite Fieldstone Block
- Granite Block
- Grading
- Wood
- Rigid Insulation
- CMU
- Steel
- Insulation

Schematic Design - Not For Construction

No.	Revision/Issue	Date

Firm Name and Address

Worcester Polytechnic Institute

Project Name and Address

Worcester Technical High School Greenhouse
1 Skyline Dr.
Worcester, MA

Project

Date

Scale

Sheet 17