DESIGN OF A RECREATIONAL FACILITY

TEL R009

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Executive Summary

Worcester Polytechnic Institute (WPI) is in need of a new, modern athletic facility that will meet the requirements of a growing student population and their interests in athletics. The current athletic facilities at WPI do not meet code for effective fire escapes, handicapped access, public bathrooms, and earthquake resistance. Recently, admission rates for incoming students have been growing significantly. This project designs an environmentally friendly building to meet the athletic demands of the increasing student and faculty population at WPI while meeting the current Massachusetts state building code requirements.

The new recreational facility will be located in between the west side of the Quad and the outdoor track. The third floor of the new facility will connect to Harrington Auditorium and provide easy access between the buildings. Included in the new design will be many improved features, such as an Olympic sized swimming and diving pool, an elevated track, six basketball courts, fitness rooms, and various multipurpose rooms. It will also be home to the athletic department offices.

Such an extensive athletic center will result in considerably high levels of energy consumption, making it important to incorporate numerous environmentally friendly features into the building to ensure sustainability and efficiency. This design includes a green roof, solar panels, geothermal heating, and use of natural light, which allows for a lower impact on the surrounding environment as well as minimal running costs. It was important to know the sustainable features early on in order to incorporate the additional loads into the dead weight of the building. The solar panels and the green roof are both located on the roof, requiring a considerably larger truss to support the roof. The additional loading on the roof has an effect on virtually every member of the structural network, flowing from the trusses, to the girders, through the columns, and into the foundation.

The main component of this project is the structural design of the building. A steel frame was chosen to support the structure. Sample beams, columns, girders, connections, stairs and trusses were designed for the building. Beam sizes vary depending on their location in the building, and include W14x48, W14x61, and W16x57. Girder sizes also vary depending on their location in the building and include W24x250, W18x97, W21x122, and W18x192. Columns vary by floors, since the columns on the lower floors will be supporting substantially more weight than the columns of the higher floors and include, from highest to lowest, W14x53, W14x109, W14x176, and W14x193. Sample connections are bolted connections between a girder and a column.

There are two sets of trusses in the new athletic center, each with similar dimensions, spanning a length of 120 feet, a height of 8 feet, with all members using identical lengths and angles. However, the trusses carry different loads and are designed accordingly by using variable member widths. The truss holding up the roof is composed of WT8x50 members, while the truss supporting the basketball courts consists of WT8x55 members. The truss carrying the basketball courts was designed to resist deflection more so than the roof truss in order to keep the courts as flat as reasonably possible and within code requirements. As a result, the deflection sums between the two trusses were 1.417” for the basketball truss, and 2.041” for the roof truss, both within the maximum 6 inch allowable deflection.

This project focuses on designing a modern athletic facility that is efficient in its structural design while meeting the growing athletic demands of the WPI community. Steel was the preferred building material for the new athletic center due to its high strength-to-weight ratio, high ductility, efficiency to be structurally implemented during construction, reduced mass of material required to build the same structure in comparison to other materials, and its relatively low carbon emissions throughout its life cycle. The addition of a green roof, solar panels, geothermal heating, and natural lighting provide energy savings that make the facility more environmentally sustainable and energy independent in an economy where energy costs are directly related to the rapidly increasing global demand for energy.

AUTHORSHIP PAGE

EXECUTIVE SUMMARY	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
AUTHORSHIP PAGE	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
TABLE OF CONTENTS	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
TABLE OF FIGURES	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
INTRODUCTION	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
BACKGROUND	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
Competing Facilities	Nicholas Holovnia
PROCEDURE	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
SUSTAINABILITY	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
Natural Lighting	Nicholas Holovnia & Christine Nilsen
Carbon Offset	Nicholas Holovnia
Solar Energy	Christine Nilsen
Photovoltaic Systems	Christine Nilsen
Solar Heating	Christine Nilsen
Pool Heating	Christine Nilsen
Geothermal Energy	Nicholas Holovnia
Dry Reservoir	Nicholas Holovnia
Hot Water Reservoir	Nicholas Holovnia
Binary Reservoir	Nicholas Holovnia
Geothermal Heating	Nicholas Holovnia
Horizontal Ground Closed Loops	Nicholas Holovnia
Vertical Ground Closed Loops	Nicholas Holovnia
Pond Closed Loops	Nicholas Holovnia
Open Loop System	Nicholas Holovnia
Standing Column Well System	Nicholas Holovnia
Proposed Geothermal Design	Nicholas Holovnia
Green Roofs	Nicholas Holovnia
Greenscope	Nicholas Holovnia
Indoor Air Quality	Nicholas Holovnia
PERMITTING	CHRISTINE NILSEN
STRUCTURAL DESIGN	NICHOLAS HOLOVNIA & CHRISTINE NILSEN
Construction Materials	Christine Nilsen
Steel vs. Reinforced Concrete Construction	Christine Nilsen
Truss Design	Nicholas Holovnia & Christine Nilsen
Truss Design for Roof	Nicholas Holovnia & Christine Nilsen
Truss Design for Natatorium	Nicholas Holovnia & Christine Nilsen

TABLE OF CONTENTS

TABLE OF FIGURES

INTRODUCTION

Worcester Polytechnic Institute (WPI) is in need of a new, modern athletic facility that will meet the requirements of a growing student population and their interests in athletics. WPI currently owns two athletic buildings, Alumni Gymnasium and Harrington Auditorium, which were built in 1916 and 1968, respectively (WPI, 2009). Alumni Gymnasium currently does not meet code for effective fire escapes, handicapped access, public bathrooms, and earthquake resistance (NIRSA, n.d.). As a result, the building will soon become restricted to purely academic use. Harrington Auditorium will maintain athletic purposes as many of its features are still acceptable (NIRSA, n.d.). Joining Harrington Auditorium through a large addition to the building will be the state-of-the-art athletic center which will provide modern day athletic opportunities and safety for the undergraduate and graduate students attending WPI (WPI "Fact Book," 2008).

Between 2001 and 2007, the incoming WPI freshman class of 697 students grew by 16% to 807 students (WPI "Fact Book," 2008). In order for the new athletic facility to be sustainable, it must be designed to handle current and future student populations that will come about throughout the lifespan of the building. Size is a critical aspect of the new athletic center, but the quality of its offerings is equally crucial. Over 75% of WPI students would like to see a larger indoor track, improved weight room and locker rooms, and a modern natatorium (WPI, 2009).

The new athletic center will be located within the space between the "Quad" and the football field. The overall exterior and interior dimensions must provide enough room for a growing student population over the span of many decades. Structural analysis will be performed on the design of the athletic center, and suitable materials will be used in the design. Materials used to build the center should be environmentally friendly, affordable, and efficient in design.

This Major Qualifying Project (MQP) has been designed for the viewings of any and all persons interested in the development and improvement of WPI athletics and its related facilities. We hope that the WPI community can use our results for reference and perhaps also for inspiration on future design methods. The integration of student work and campus architecture is a great way to express the educational value of attending WPI. The structural analysis portion of our project can be used as an example of “real-life” analysis.

During A-term we researched typical layouts for recreation and athletic facilities. We contacted the architects that were in the process of designing the actual building. We studied the layouts provided to us by the architects and thought about designing something a little more innovative. In the end, we chose to go with their general layout of the building, but made some small layout modifications including the width of the track and location of the staircase. The exact dimensions of the building were not given in the floor plans. As a result, the dimensions of the design in this MQP are estimations of what the actual building might be, integrated with applied reasoning of what dimensions would be necessary to accommodate for the features shown in the floor plans.

We planned for A-term to be our research period in which we learned more about typical layouts for recreational facilities and determine what the optimal layout for our new facility should be. Also during A-term we finalized the floor plan of the building. The majority of B-term was dedicated to working on the structural analysis for the new facility using the appropriate method for the construction materials that we choose. The structural analysis includes elements such as trusses, beams, girders, columns, and connections. C-term was mostly spent finishing the structural analysis of the superstructure and designing the foundation and necessary retaining walls. D-term was mostly spent finishing the foundation designs and assembling the report. The results of this MQP were presented to Professor Tahar El-Korchi, head of the Civil and Environmental Engineering Department at WPI, during

D-term 2010 in the form of this written report. In addition, we presented our project to the WPI community on project presentation day during D-Term.

BACKGROUND

There have been a few MQPs done in previous years regarding the design of this particular recreational facility. These past MQPs covered different aspects of the project, whereas ours focuses on the structural design of the building and sustainable building techniques.

This MQP covered how to design a recreational facility. Necessary components of the building includes: locker rooms, lobbies, offices, etc. The Olympic-sized swimming pool is located on the bottom floor and the basketball courts are located on the entry level (the 4th floor).

In order to perform structural analysis on the building, a type of building frame needed to be chosen. A rigid frame will require more welding and bolting, but will allow for more open spaces. A braced frame will allow for less welding in the field to be done, but will also obstruct doorways and windows. For this project, we have designed the building as if it were a rigid frame. We have chosen steel as the structural material because steel has a high strength in both tension and compression. It is also extremely lightweight compared to its strength. This makes it a popular material for the frames of commercial buildings. Another great property of steel is its ductility. Steel is able to deform before fracturing, it will usually fail by yielding rather than fracturing. Steel frames are also able to be assembled quickly, allowing for shorter construction periods. The foundation was designed to be reinforced concrete due to its high strength in compression, resistance to fire, and low cost.

It is important today that buildings are designed in a sustainable manner. The planet's natural resources are being used at an alarming rate – much faster than they can be produced. In order to reduce the consumption of non-renewable resources, many designers are choosing to build "green." This means that the impact of the building is significantly less than that of normal buildings. There are several ways in which this can be achieved. There are alternatives sources of energy, including solar and geothermal, that can produce electricity or heat.

Solar energy is particularly useful for heating water, as explained further in the Pool Heating section. Since there will be a pool in the recreational facility, it would be an excellent idea to use solar heating to heat the pool to the appropriate temperature. Using conventional methods would use a significantly larger amount of resources.

Geothermal energy is commonly used to heat and cool a building. It consists of pumping water or air through a tube into the ground. Since the interior of Earth's crust is at a relatively stable temperature, this can be used to heat during the winter and cool during the summer. Geothermal energy and heating is considered to be one of the most efficient forms of energy and heat production.

Another sustainable element of design is a green roof. While not energy-generating, a green roof will help reduce runoff caused by the building and will help reduce the impact of the building on the local water quality. This water could also be collected for other uses, such as watering the fields on campus. Green roofs also maintain ecosystems even in the middle of a city. They reduce the "heat island effect" caused by the buildings and pavements.

This MQP builds upon previous MQPs completed on the design and project management aspects of the WPI recreational center. It incorporates best practices from previous MQPs and new concepts to recommend a sustainable, green, and energy efficient design.

COMPETING FACILITIES

Every year, Worcester Polytechnic Institute, Rensselaer Polytechnic Institute (RPI), and Massachusetts Institute of Technology (MIT) compete against each other in a track and field meet that has been a tradition for decades. While the athletic connections between these schools span beyond track and field, the meet represents the strong similarities of the schools in regards to their athletics as well as educational interests. All three schools are part of NCAA Division III athletics and are striving to obtain modern day recreational facilities for their growing student populations.

Rensselaer Polytechnic Institute currently has the largest undergraduate student body out of the three schools with 5,367 students, and also has 1,200 graduate students (“Quick Facts,” 2009). Like WPI, RPI is currently working on a new athletic housing project called “Athletic Village” which is the most extensive athletic construction project in the history of the university (RPI, 2009). The project consists of two phases, the first of which is currently under development. This initial phase includes two gymnasia, a basketball arena with 1,200 seats for spectators and 2,000 seats for special events. The second phase will feature a natatorium with a 50-meter Olympic pool, as well as an indoor track with tennis courts in the center (RPI, 2009).

Massachusetts Institute of Technology has 4,153 undergraduates and 6,146 graduate students. It recently opened the Al and Barrie Zesiger Athletic Center in 2002, which served to expand upon the current lineup of athletic offerings. It was declared one of 10 national Facility of Merit winners at the annual Athletic Business Conference in 2003 ("Al '51 and Barrie Zesiger Sports and Fitness Center," n.d.). The award recognizes facilities that set the design and functionality standard for athletic, recreation and fitness projects (“Zesiger Center wins National Award,” 2003). The Zesiger center consists of 124,000 square feet and is best known for its natatorium which houses a 50-meter Olympic class pool as well as a 25-yard instructional pool. The top floor holds a full use, 200-meter, six-lane track that holds numerous meets annually. The weight and cardiovascular rooms in the Zesiger Center comprise 13,000 square feet, which is four times the size of the previously existed facilities (RPI, 2009).

Worcester Polytechnic Institute is the smallest of the three schools with over 4,000 students (“Facts and Figures,” 2009). Like MIT, WPI is looking to expand its current recreational buildings by attaching a second facility to Harrington Auditorium while transferring Alumni Gymnasium into an academic building. The proposed site for the new facility will be located in a confined space between the already existing track, the “Quad”, and Morgan Hall which will make maximizing its space efficiency a top priority. However, the new WPI athletic facility will still offer the same features as MIT and RPI with a natatorium, basketball arena, and an elevated track. A full list of features can be seen in Figure 1 below (“How a Geothermal Power Plant Works,” 2008).

Program Area	Quantity	Program Area	Quantity
Public Spaces		**Support Spaces**	
Lobby	1	Men's General/Pool Locker	1
Hall of Fame/Trophy Display	1	Women's General/Pool Locker	1
Reception Desk	1	Storage/Collection	1
Vending	1	Loading	1
Lounge	1	**Training/Rehabilitation**	
Public Restrooms	2	Office	2
Activity Spaces		Exam Room	1
4-Cout Gymnasium	1	Secure Storage	1
Elevated Jogging Track	1	Bulk Storage	1
Gym Storage	4	Taping/Treatment/Rehabilitation	1
Fitness Center	1	Hydrotherapy	1
Fitness Center Storage	1	Ice Machine	1
Free Weights	1	Restroom	1
Free Weights Storage	1	**Administration/Coaches**	
Group Exercise/Multipurpose	3	Reception/Secretarial	1

Group Exercise Storage	1	A.D.	1
Classroom	2	A.D. Assistants	3
Classroom Storage	2	Offices	18
Racquetball/Squash Courts	3	Workroom	1
Climbing Wall	1	Video Editing Room	1
Natatorium	1	Storage/Collection	1
Natatorium Storage	1	Secure Storage	1
Pump Room	1	Restroom	1
Natatorium Spectator Seating	1		
Meet Management/Lifeguard	1		
Indoor Rowing Tank	1		

Figure 1: Use of Building Space in the Proposed WPI Recreational Center

PROCEDURE

The floor plan was designed based on the floor plan from the actual building and made some slight alterations. Alterations include a central staircase that descends from the entry level on the fourth floor to the bottom of the building and a wider elevated track on the 5th floor. The structural layout was designed as if it were a rigid frame. This open space in between columns leaves plenty of room for doors and windows. Many sustainable components were incorporated into the building design, including a green roof with solar panels.

Microsoft Word was used while writing the report. Microsoft Excel was utilized while performing the structural analysis of the building for the analysis of the columns and retaining wall. The spreadsheets can be found in Figure 30 and Figure 36. We used Revit Architecture 2010 in order to create a visual representation of the building. We also used MDSolids, Matlab, and Mastan2 to assist in the design of the trusses and the track.

Static analysis was performed on the structure to determine the required member sizes. This method was learned during steel design courses. The floor plan of the building was designed first in order to determine the structural layout. This included the locations of the columns, girders, and beams. Before determining the sizes and lengths of steel needed, we needed to determine the loads that the beams must carry. These were based on the weight of the typical live loads associated with each type of room as well as the require dead loads. For example, a weight room will have a higher live load in pounds per square foot than an office or an entryway will. The weight of the steel also factors into the dead loads of the frame. Therefore, a strong but light member is preferable. We selected appropriate members to carry the loads of the building.

After designing superstructure, we determined what types of foundations the building requires. Since the building has a pool on the bottom floor, it will be necessary to have a concrete base to the building. This is called a mat foundation. We also designed a retaining wall for the floors that are partially underground.

During A-Term, the proposal was completed, steel was chosen as the structural material, and the proposed location of the building was surveyed. A substantial amount of research on sustainability and LEED certification was required. For B-Term, the structural layout of the building frame was determined and analysis was performed on the beams, girders, columns, and connections applying the appropriate loads. After determining a sufficient superstructure, analysis was performed on the foundation of the building, including a mat foundation and retaining walls during C-Term.

The floor plans provided by the actual hired architects for the proposed building can be found in Appendix L. The only components that were altered in this MQP are the track on the fifth floor and the main staircase, as stated before.

SUSTAINABILITY

NATURAL LIGHTING

The first step to becoming more sustainable is to reduce the amount of energy consumed. A building with many windows reduces the need for artificial lighting during the daylight hours. This saves resources and reduces utility costs. It is therefore beneficial for the new WPI recreational center to have an abundant offering of windows as a source of natural lighting.

CARBON OFFSET

Buildings produce a carbon output during construction of the facility as well as regular use of the building after construction is complete, whether it is from harvesting the materials used for construction or from using electricity that is produced by coal. The construction sites of facilities replace areas from ecosystems that previously could have assisted in reducing the effects of carbon in the atmosphere. Using different construction materials can help minimize the carbon output of construction. A software program, NZ Wood online carbon calculator, was used to compare the offsets contributed by wood, steel, and concrete. Variables contributed to the calculations include the size of facility in square meters, and the type of building being constructed, school gymnasium. With an area of 12,470 square feet, the WPI athletic center comes out to be 4675 square meters. The following results take into consideration Life Cycle Assessment (LCA) principles as well as the manufacturing and production process of the materials. It does not include transportation to the construction site.

Figure 2: Carbon Offsets

The results from this simple analysis show that timber version of the WPI athletic center would emit roughly 93.5 tons of CO_2 from the required harvesting of the trees. Steel and concrete both lead to significantly greater carbon offset values, resulting in a 350% and 500% increase, respectably, when compared to the timber value. It appears that timber is a good option when looking into the design of environmentally friendly buildings. However, the structural layout of the building must also be taken into consideration. In the case of the new WPI athletic center, there is an open space of 120' by 250' without any vertical supports. When taking this into consideration, it makes sense to go with the second 'greenest' material, steel, since it can be applied to particularly long-spanned trusses.

SOLAR ENERGY

It is essential that design and construction teams begin to think "green." The use of natural resources has grown significantly over the past few decades to the point where it is unrealistic to think that the non-renewable resources will be available for much longer. Since buildings use a significant amount of energy, estimated at 30 Quadrillion BTUs for the United States alone in 2009, it is especially important for designers to begin incorporating sustainability into their buildings (U.S. Department of

Energy, 2009). Solar energy is a renewable resource with no emissions. There are also many government incentives, such as tax credits, for using solar energy.

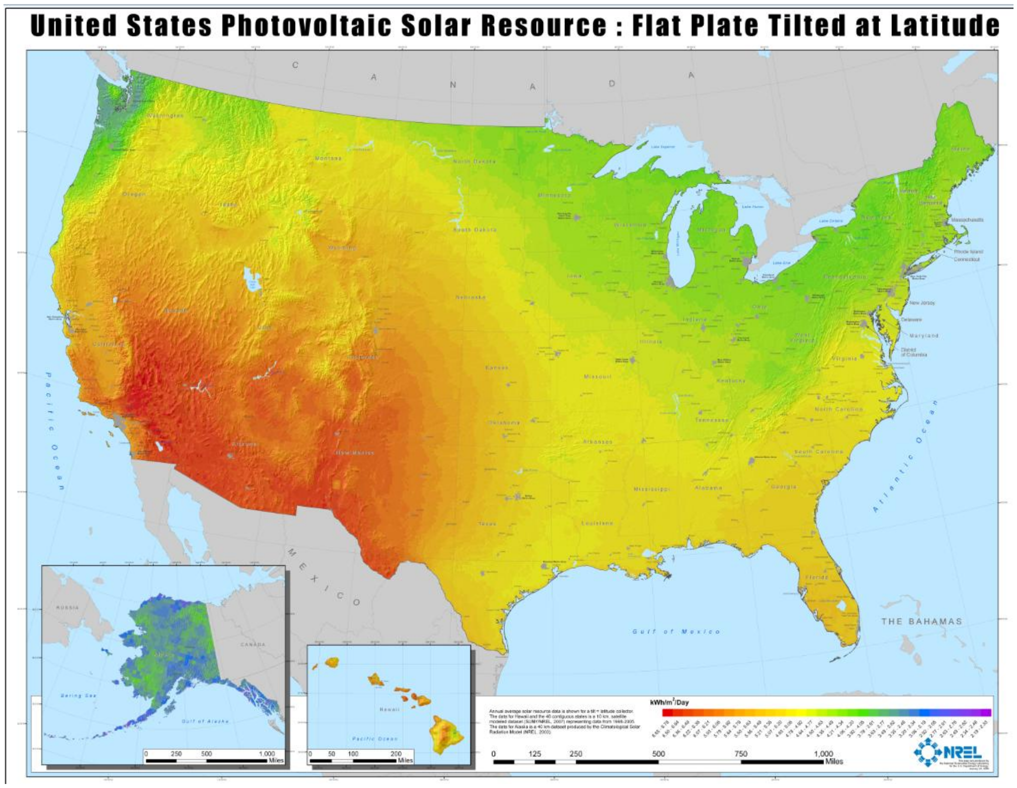


Figure 3: Map of United States Photovoltaic Solar Resource

Photovoltaic Systems

Photovoltaic systems use the sun's energy in order to make electricity. Solar cells are made of semiconductor materials and are often grouped together into modules, which are then grouped into arrays ("Solar Technologies Program," 2008). They are used today to provide power to satellites, lights, and even hand-held calculators ("Solar Technologies Program," 2008). Photovoltaic systems can even be made to look like normal shingles, but they generate electricity ("Solar Technologies Program," 2008).

Solar Heating

Solar heating is a much more energy efficient use of solar power. Instead of converting solar energy to electricity, the solar energy is used to heat air or a liquid. The heat is then transferred directly to what is going to be heated; usually water (“Solar Technologies Program,” 2008). Commercial buildings need to use a lot of hot water, so solar energy would be an efficient, sustainable, “green” source of energy to heat water. Using solar heating to heat water would also be very cost-effective in the long run.

Pool Heating

Heating enough water to fill a commercial-sized pool requires enormous amounts of energy. This energy is typically a significant portion of the operating budget of the pool, since most commercial pools require the water to be approximately 80 degrees Fahrenheit (27 degrees Celsius). Using solar heating to heat a commercial pool can significantly reduce the heating costs. Pool water is heated by pumping the water through “solar collectors” after the water is filtered and then returning it to the pool (U.S. Department of Energy, 2009).

$$\left(143686\ \text{ft}^3\right)\left(\frac{28.31\text{L}}{1\text{ft}^3}\right)\left(\frac{4184\ \text{J}}{(1\text{L})(1°\text{C})}\right)\left(\frac{0.000278\ \text{watt-hour}}{1\ \text{J}}\right)\left(\frac{1\ \text{kilowatt}}{1000\ \text{watts}}\right)=4{,}728\ \frac{\text{kilowatt-hours}}{°\text{C}}$$

It would use close to 5,000 kilowatts-hours to heat the pool designed for this project for every degree Celsius in temperature change. This method of using solar power is extremely reliable and has the fastest “return on investment” of the three types of solar energy systems The return on investment can even be as little as 1.5 years (“Solar Technologies Program,” 2008). It typically costs around $3,000 to $4,000 to buy and install a solar pool heating system (U.S. Department of Energy, 2009).

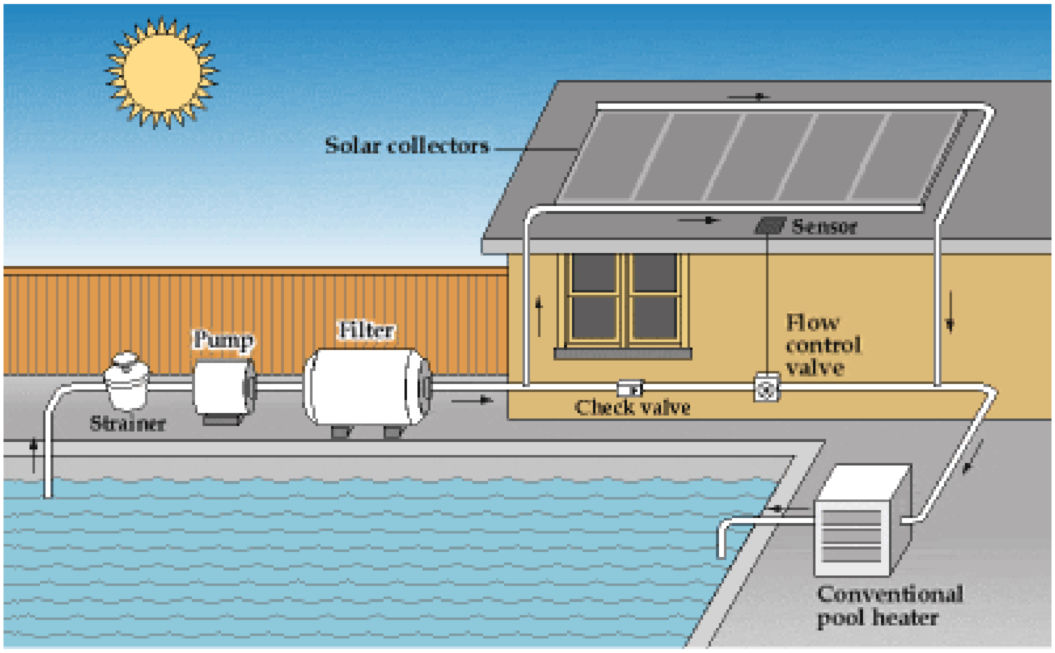


Figure 4: Example of a Solar Pool Heating System (U.S. Department of Energy, 2009)

Since WPI is trying to build sustainably it would be very realistic to use solar energy as a clean energy resource. Solar energy is very cost-effective in the long run and also pays for itself over time. Many types of solar collection panels are able to last for 20-30 years with little maintenance (U.S. Department of Energy, 2009). WPI may also be able to utilize government incentives for using green energy.

GEOTHERMAL ENERGY

The new WPI recreational facility will not solely focus on providing athletic services to students. It will be representative of WPI and global interests toward creating a blend of modern day design fused with environmental sustainability. Around the world an estimated 50% of all green house gases are from today's existing buildings ("The Economies of Being Environmentally Conscious, 2006). The athletic center can do its part in reducing the amount of building-emitted emissions in the world by extracting power from renewable, sustainable energy sources. One example of how this can be achieved is by generating power through the use of geothermal energy.

Geothermal Energy can be defined as energy that is generated by converting hot water or steam from deep beneath the Earth's surface into electricity (Safe Electricity, 2009). The interior of the Earth's crust maintains a relatively steady temperature that is directly related to the annual average air temperature of a particular area. This results in a reliable source of heat and energy that emits little to no air pollution. The Earth's crust consists of a geothermal gradient of 2.5-3.0 degrees Celsius per 100m depth on average (Dickson and Fanelli, 2005). However, it is important to note that some locations may have far higher or lower gradients. Using geothermal energy may also result in LEED credits of up to 17 points under the category of energy and atmosphere.

Dry Reservoir

A geothermal system is divided into three constituents, including a heat source, reservoir, and fluid. The reservoirs can be subdivided into three options, depending on the location, which are labeled as being either "dry", "hot water", or "binary" reservoirs. Dry reservoirs are basic in concept and produce a majority of steam which is transferred through tubing to rotate a turbine generator ("What is Geothermal Energy," 2000).

Hot Water Reservoir

A hot water reservoir (typically ranging from 300-700 degrees Fahrenheit) acts oppositely of a dry reservoir and contains mostly heated water which is transferred to a “flash” power plant (“What is Geothermal Energy,” 2000). While traveling upward to ground level, the heated water is released of pressure from the reservoir and turns into steam through a separating which ultimately moves the turbine.

Binary Reservoir

If a reservoir is located where geothermal temperatures do not reach exceedingly high temperatures, a binary reservoir may be suggested. The binary reservoir transfers heat from the “warm” water (typically ranging from 250-360 degrees Fahrenheit) to an alternate liquid that may boil at a lower temperature (“What is Geothermal Energy,” 2000). Isopentane is often used as the second liquid and ultimately powers the turbine in its steam form before condensing back to liquid phase to repeat the process indefinitely (“What is Geothermal Energy,” 2000).

A binary reservoir geothermal energy system would be recommended over the other options due to its ability to create energy at lower temperatures. A lower working temperature will minimize the depth at which the heating system needs to be located in order to receive heat. This will ease the process of building the heating system which will lower the cost of construction as a result. Shown below is a diagram for each of the geothermal energy reservoirs (“How a Geothermal Power Plant Works”, 2009).

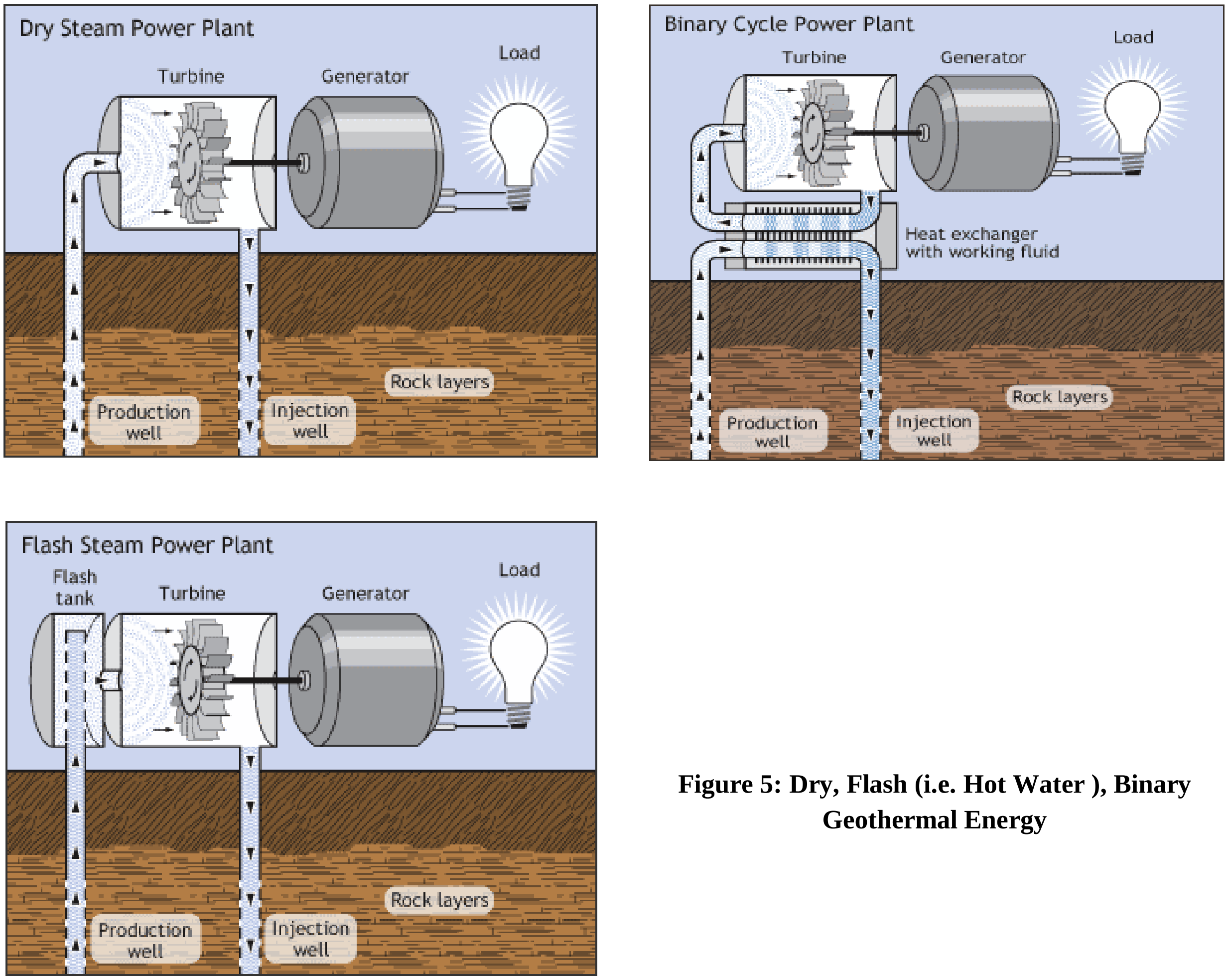


Figure 5: Dry, Flash (i.e. Hot Water), Binary Geothermal Energy

GEOTHERMAL HEATING

Geothermal heat pump (GHP) systems are also known as geothermal, earth-coupled, water-coupled, groundwater, ground-coupled, closed-loop, coiled, slinky, open, and water-source heat pump systems. All names refer to the same general principle which is the process of using energy stored in ground soil or ground water to heat or cool houses and buildings ("Manual on Environmental Issues Related to Geothermal Heat Pump Systems," 1997). GHP systems are largely considered to be the most efficient and environmentally friendly way of heating buildings, as stated in such documents including

The United States General Accounting Office report: *Outlook Limited for Some Uses but Promising for Geothermal Heat Pumps*, and the Environmental Protection Agency report: *Space Conditioning* ("Manual on Environmental Issues Related to Geothermal Heat Pump Systems," 1997). According to the United States Department of Energy, GHP systems use 25-50% less electricity than conventional heating and cooling systems. The heat pumps typically last 20 years while warranties for the piping often last up to 50 years ("Benefits of Geothermal Heat Pump Systems", 2010).

Starting at a certain depth (depending on the soil type), the ground temperature remains at a relatively constant temperature throughout the course of a year, regardless of the season. During the winter, the soil decreases in temperature at a slower rate than surrounding air which allows GHP systems to deliver heat from the ground into buildings. Oppositely, in the summer the ground remains cool and delivers relatively chill temperatures into buildings compared to exterior air temperatures (“Geothermal Heat Pumps”, 2010). As a result, GHP systems reliably heat and cool buildings using 40-70% less energy than other conventional systems (“Geothermal Heat Pumps”, 2010). A 2000-sq-ft home can be heated and cooled through geothermal heating for about $1 a day, making the annual heating and cooling bill only $365 (Henkenius, n.d.). The figure below shows examples of various GHP systems.

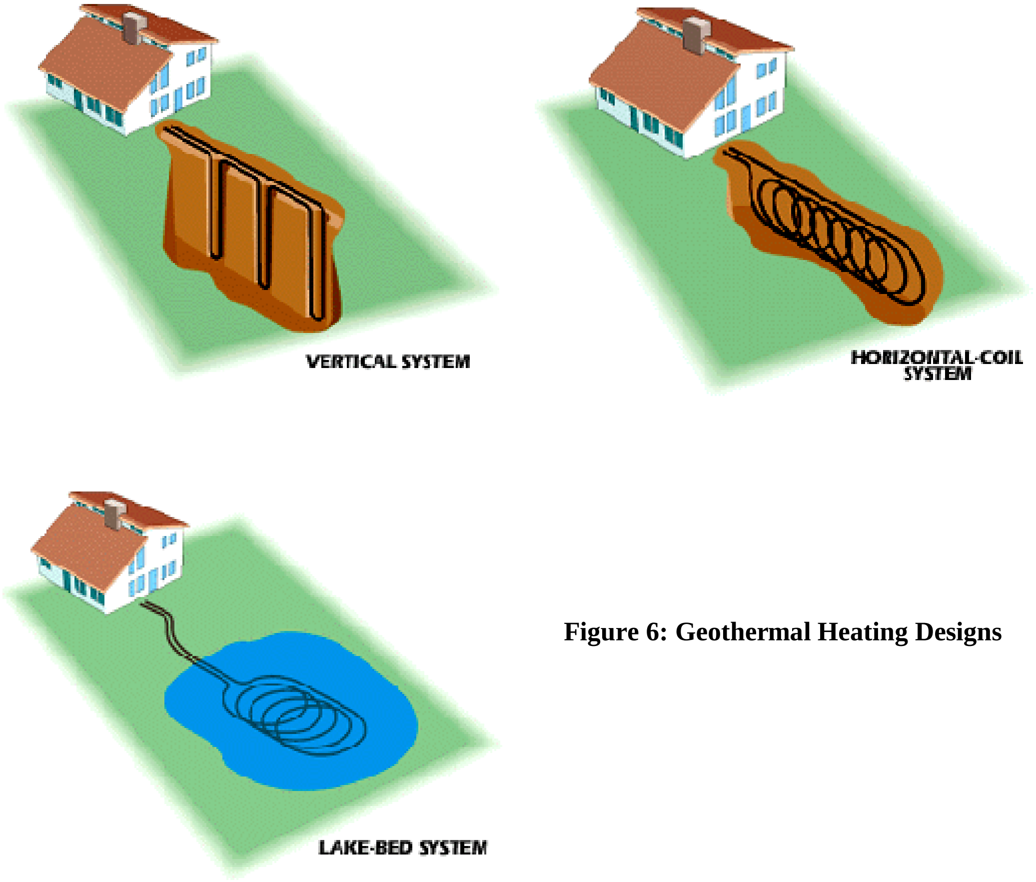


Figure 6: Geothermal Heating Designs

Horizontal Ground Closed Loops

A circulatory system transfers the heat and coolness from the soil into buildings through a variety of potential circulatory arrangements. Such loop systems consist of Horizontal Ground Closed Loops, Vertical Ground Closed Loops, Pond Closed Loops, Open Loop System, and Standing Column Well System. Horizontal Ground Closed Loops are considered to be the most cost effective configuration with a series of parallel plastic pipes ranging from three to six feet underground. The typical length of piping ranges from 400-600 feet and can be shortened by coiling the piping for areas with less usable space (“Geothermal Heat Pumps”, 2010). The amount of piping required for the WPI athletic center would likely require additional piping, and could be dispersed underneath the football field, baseball field, or the Quad. It should be noted that the baseball field will be elevated within the next few years as a new parking garage underneath it is constructed. This would likely require the horizontally closed geothermal heating system to be built underneath the parking garage.

Vertical Ground Closed Loops

When usable yard space is very constricted, a vertical ground closed loop may be the best option to implement. Holes are bored vertically into the ground, ranging from 150-450 feet deep, and each contains one loop (“Geothermal Heat Pumps”, 2010). Each vertical loop is connected by a horizontal member at the top (but still below ground level) and is filled with a liquid medium. The cost of construction is typically higher in this case due to the deeper construction. However, the material costs are lower because the deeper pipes reach more extreme temperature differences (in comparison to ground level), which makes the heating process more efficient per foot of piping in comparison to horizontal ground closed loops. A vertical ground closed loop would be beneficial for the WPI athletic center if a horizontal loop cannot be applied underneath the Quad or various adjacent fields.

Pond Closed Loops

If a home or building is located next to a body of water, a pond closed loop may be the most appropriate system to use. The body of water should be at least 6-8 feet deep at all times to ensure sufficient heat-transfer. Polyethylene piping transfers a liquid-medium into the water, where it is then coiled and loops back to the building (“Geothermal Heat Pumps”, 2010). Pond closed loops should have no impact on the aquatic life as long as construction is done correctly. Parts of the WPI campus are located next to Salisbury pond (with Salisbury Street in between). However, the athletic center would not be close enough on campus to take advantage of a pond closed loop.

Open Loop System

Open loops systems are considered to be the simplest systems to install out of all geothermal heating options. Open loop systems are more integrated into the surrounding soil than closed loops would be, and are applied to areas where ground water is abundant. Two wells are located inside a single aquifer, one of which transfers water into the building, while the other discharges the water (discharge well) out of the building and back into the aquifer. An aquifer can be defined as an underground bed or layer yielding ground water for wells and springs etc ("WordNet Search", 2010). The two wells are separated far enough within the aquifer to allow the water to adjust back to the original ground temperature before potentially travelling back into the building.

Standing Column Well System

Standing Column Well Systems are considered to be "true" open loops and are heavily popular in the Northeastern United States in comparison to other regions. Standing wells typically have a diameter of 6 inches and reach depths of up to 1500 feet. Water is collected at the bottom of the well, then applied to the pump's heat exchanger and released at the top of the water column, in the same well. Ground water used in standing columns is typically new to the system which is why it's considered to be a true open loop. If water in the well reaches a temperature extreme that is too high or low to be useful, the well can flush the water from the system until acceptable temperatures appear ("Geothermal Heat Pumps", 2010).

Proposed Geothermal Design

The horizontal closed loop GHP has a simple design that is shallow and easy to construct. However, the future of WPI's landscape will be changing as future developments are continually being proposed, which may interfere with the location of a horizontal heating system. Meanwhile, a vertical closed loop system requires very little land (horizontally) and generates more heat per foot of piping than a horizontal loop due to its deeper depths. The drawback to vertical closed loops is that the deeper depths are more difficult to construct and the piping is still often at shallow depths since it is constantly travelling between high and low depths. The best way to integrate a geothermal heating system into the new athletic center may be to apply the deeper depths of a vertical system into a steady horizontal system.

The new athletic center will be uniquely built into the side of a hill, where the base of the building is at the base of the hill. A horizontal closed loop GHP could be built at the base of the building, going into the side of the hill. The resulting “deep horizontal” closed loop GHP system would have piping travelling at a constant depth of 36 feet, making it significantly deeper than the 3-6 foot depth of a typical horizontal system. The 36 feet is taken from the height of the first three floors of the building (equivalent to the height of the hill), which is shown in the column design later in the report. Assuming the increase of soil temperature is linearly proportionate to the increase in depth, the deep horizontal GHP system would be 6-12 times more effective in collecting heat than a traditional shallow horizontal GHP system.

The construction process for this proposed system would be roughly the same as that of a vertical system and would be equivalent to tilting a vertical system by 90 degrees. However, contrary to a vertical system, the piping for this would always be at its deepest point, making it more effective. A vertical system would also have to travel at least double the depth of the proposed deep horizontal system to be equally efficient in heat collection, which would then double the cost of piping materials. As a result, a stronger pump would be needed to circulate the additional liquid medium which would then increase running costs of the system, making a vertical system even less efficient than the proposed system. The deep horizontal GHP design would not work for every building, but a close look at the site for the new WPI athletic center shows that this system could be an ideal provider of heat that is sustainable, affordable, and independently sourced.

GREEN ROOFS

As expectations increase for buildings to become more sustainable and environmentally friendly, new facilities like the upcoming WPI athletic center should provide numerous innovative techniques to become more "green". A green roof (also known as a rooftop garden) can be defined as a roof of a building that is partially or completely covered with vegetation and soil, or a growing medium, planted over a waterproofing membrane ("Green Roof," 2009). A vast number of benefits can be found through the use of green roofs and it is highly suggested that WPI incorporate one into the new athletic center.

Figure 7 shows the typical setup for a green roof (Banjo, 2009).

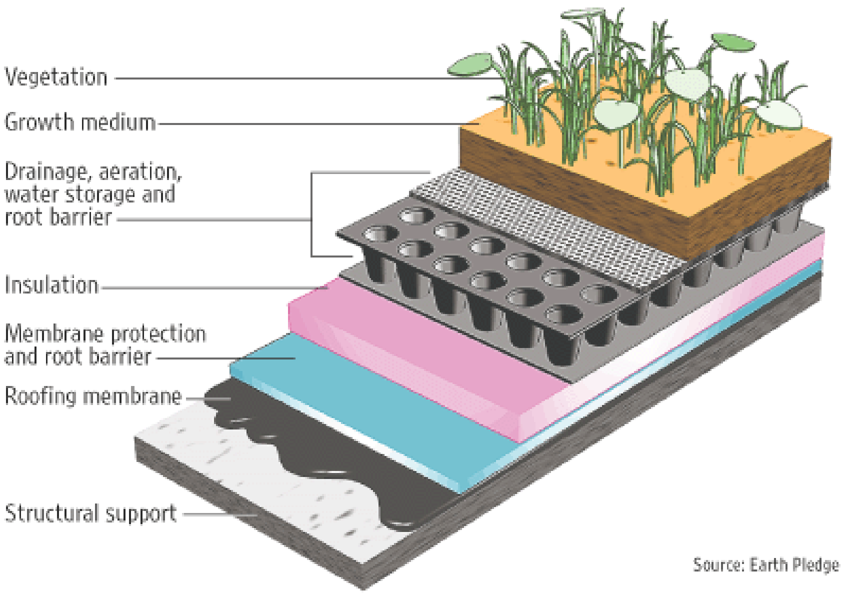


Figure 7: Green Roof Layout

One environmental concern that originated from building rooftops is the "heat island effect" which results in excessive heat. Green roofs are used to reduce the "heat island effect" in urban areas. According to the EPA, urban and suburban areas can reach 2-10 degrees Fahrenheit higher in temperature than rural areas due to the heat island effect caused by local buildings ("Glossary," 2009). According to the National Research Council Canada, green roofs are a way to counteract excessive heat caused from rooftops and allow buildings to remain significantly cooler during spring and summer seasons (Liu and Baskaran, 2005). This can result in up to a 50% decrease in energy demand for building cooling ("Glossary," 2009). Figure 8 shows the distinct difference in heat flows between a building top with a green roof and one without (Liu and Baskaran, 2005).

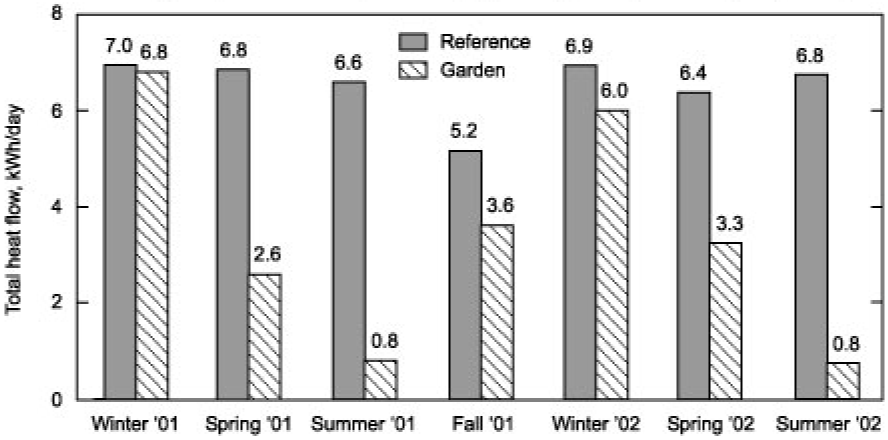
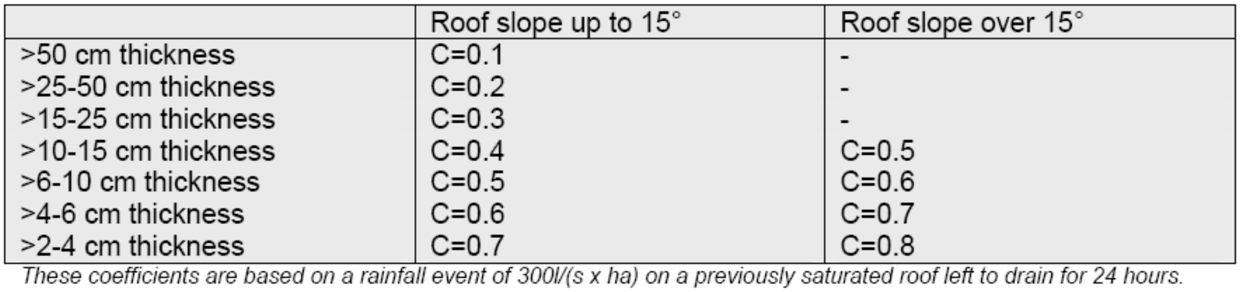


Figure 8: Average daily heat flow through roofing systems

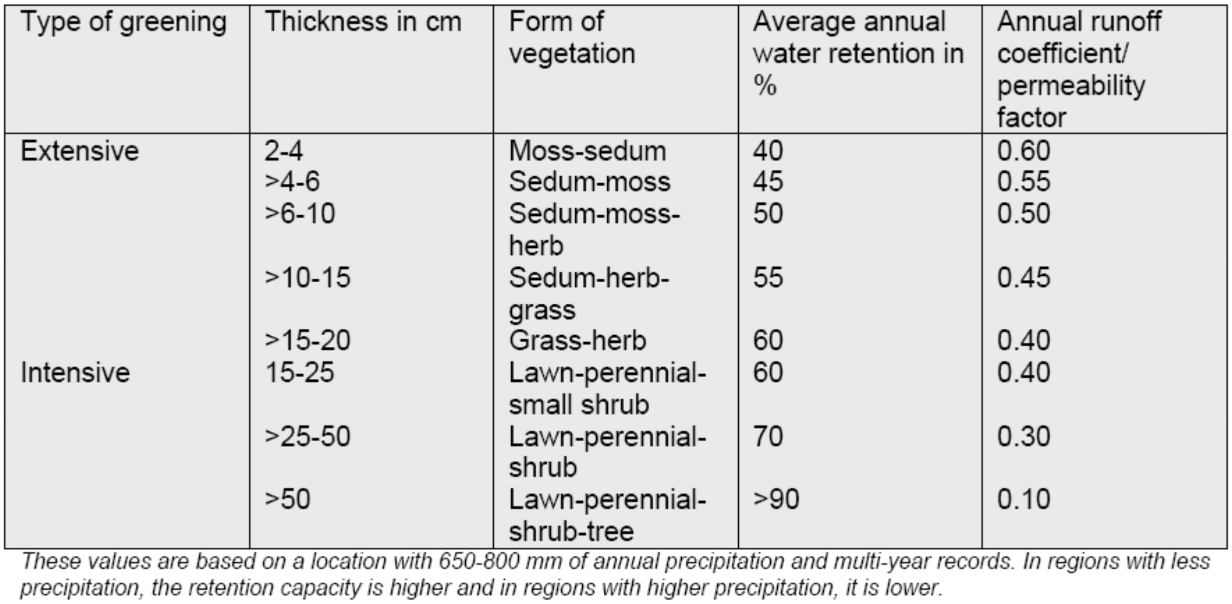
Aside from preventing excessive heat temperatures and energy usage, green roofs are also an effective way to control storm water runoff. Water that runs off of a green roof is considered to be very clean because the vegetation on the roof acts as a medium that filters the water (Ngan, 2004). As a result, the runoff water can be stored and recycled for the use other purposes (such as watering athletic fields) without requiring the use of energy-dependent water treatment. Depending on the runoff coefficient of a green roof, a building can save a 30-90% reduction in wastewater fees (Ngan, 2004). The following figures show the water runoff coefficients based on the thickness, plant types, and angles used for a green roof (Ngan, 2004).



	Roof slope up to 15°	Roof slope over 15°
>50 cm thickness	C=0.1	-
>25-50 cm thickness	C=0.2	-
>15-25 cm thickness	C=0.3	-
>10-15 cm thickness	C=0.4	C=0.5
>6-10 cm thickness	C=0.5	C=0.6
>4-6 cm thickness	C=0.6	C=0.7
>2-4 cm thickness	C=0.7	C=0.8

These coefficients are based on a rainfall event of 300l/(s x ha) on a previously saturated roof left to drain for 24 hours.

Figure 9: Runoff Coefficients According to Green Roof Thickness and Slope



Type of greening	Thickness in cm	Form of vegetation	Average annual water retention in %	Annual runoff coefficient/ permeability factor
Extensive	2-4	Moss-sedum	40	0.60
	>4-6	Sedum-moss	45	0.55
	>6-10	Sedum-moss-herb	50	0.50
	>10-15	Sedum-herb-grass	55	0.45
	>15-20	Grass-herb	60	0.40
Intensive	15-25	Lawn-perennial-small shrub	60	0.40
	>25-50	Lawn-perennial-shrub	70	0.30
	>50	Lawn-perennial-shrub-tree	>90	0.10

These values are based on a location with 650-800 mm of annual precipitation and multi-year records. In regions with less precipitation, the retention capacity is higher and in regions with higher precipitation, it is lower.

Figure 10: Annual Water Retention Percentages of Green Roofs According to Thickness

A green roof will offer numerous advantages to the new WPI athletic center in the form of environmental protection and cost savings. Not only would the center become more energy efficient, but it will save money through LEED credits. With a green roof implemented into the building, the athletic facility could potentially achieve up to 20 LEED credits. Figure 11 shows the various LEED categories and their credit values (“Glossary,” 2009).

Category	Potential LEED Value
Storm Water Design	1
Heat Island Effect	1
Water Efficient Landscaping	1-2
Optimize Energy Performance	1-8
Recycled Content	1-2
Regional Materials	1-2
Innovation and Design Process	1-2

Figure 11 - LEED Credits

GREENSCOPE

As mentioned previously, the future WPI athletic center will be designed to meet LEED certification, continuing the trend of environmentally friendly construction projects at WPI. The East Hall dormitory opened in 2008 and has a Gold LEED rating by using such features as a green roof, efficient use of water, and sustainable materials. While the green roof is a major constituent of the buildings green aspects, the only way to see it is by standing on the roof of the WPI Library (which students don't have access to). In order to better flaunt the planned green roof for the athletic center, it may be beneficial to implement a "greenscope" into the building. For this MQP, a greenscope will be defined as a mirror system that acts similarly to a periscope in which viewers can see the green roof while standing on a different vertical level, such as a lower floor. Mirrors on the roof reflect the vision of the green roof onto mirrors located on the selected floor which are framed and give the appearance of a typical window used to look outside. If the lower half of the greenscope was located on the lobby floor of the athletic center, anyone walking into the building would be able to see the green roof. While not a necessity, a greenscope would act as a creative marketing tool for the environmentally-friendly aspects of the WPI athletic center and allow curious bystanders to learn more about sustainable development, which is becoming increasingly important in modern development.

INDOOR AIR QUALITY

Indoor Air Quality is a term used to describe how polluted the air inside a confined space is (Rabbit Air, 2008). Typical factors that affect the quality of air include temperature, odor, and high or low levels of gases (“Carbon Dioxide Comfort Levels,” 2005). The quality of air inside the future WPI athletic center will need to be clean and safe at all times for the sake of the student and employee health. The building should use modern techniques to optimize the process of maintaining an acceptable indoor air quality rating. If the quality of air isn’t taken into consideration, it may lead to unsafe levels of Carbon Dioxide (CO_2), Carbon Monoxide (CO), or Radon. Causes of poor air quality may be caused by mold, moisture, poor ventilation, gases from the ground soil, or unsafe chemicals that derived from construction, such as Asbestos (“Indoor Air Quality,” 2009).

Demand-controlled Ventilation, as defined by the Federal Energy Management Program (FEMP), is a combination of two technologies, which includes CO_2 sensors that monitor CO_2 levels in the air inside a building, and an air-handling system that uses data from the sensors to regulate the amount of ventilation air admitted (Demand - Controlled Ventilation using CO2 Sensors, 2004). Most ventilation systems run at a constant air replacement rate, but a DCV will monitor the CO_2 emissions of the building occupants and dynamically control the air replacement rate in accordance.

This saves energy when there are fewer (or no) occupants in the building while assuring that the amount of carbon dioxide indoors is always at a safe, healthy level when the building is in full use. The actual savings of a DCV system can range anywhere from $0.05-$1.00+ per square foot annually

(Chivetta, 2004). At a size of 145,000 square feet, the WPI athletic center could potentially save $7,250 - $145,000 per year using DCV technology. Considering the cost savings and extreme levels of CO_2 that an athletic center would experience during full use, it would make sense to implement a DVC system.

One of the facilities featured in the new athletic center will be a modern natatorium. NCAA regulations require that the pool range in temperature from 79-81 degrees Fahrenheit, while the air temperature remains 2-5 degrees warmer (81-86 degrees). It is expected that some of the water will evaporate, and an effort should be made to contain its resultant condensation within the natatorium. To keep chlorinated moisture in the natatorium, the room should have a lower pressure than the rest of the building. This will create an air current flowing into the natatorium rather than out. If chlorinated air were to reach metal objects (e.g. lockers), it could condense leaving hydrochloric acid on the lockers. This would eventually cause lockers or door frames to rust away and not reach their full life expectancy for use (Chivetta, 2004).

EPA defines Radon as a naturally occurring radioactive gas found in soil and rock ("Builders and Contractors," 2009). If a building is constructed where Radon exists in the ground, there is a significant risk of Radon leaking into the building through its foundation. Any lengthened exposure to Radon can lead to dangerous health problems such as lung cancer ("Builders and Contractors," 2009). It is recommended that the construction team check Radon levels at the construction site to determine whether or not Radon would pose a threat to the site. If Radon does exist at threatening levels, several actions can be taken to assure a safe building site once finished. According to the National Association of Home Builders (NAHB), over 1.5 million homes have been built with Radon resistant features since 1990, such as Figure 12 (Rabbit Air, 2008):

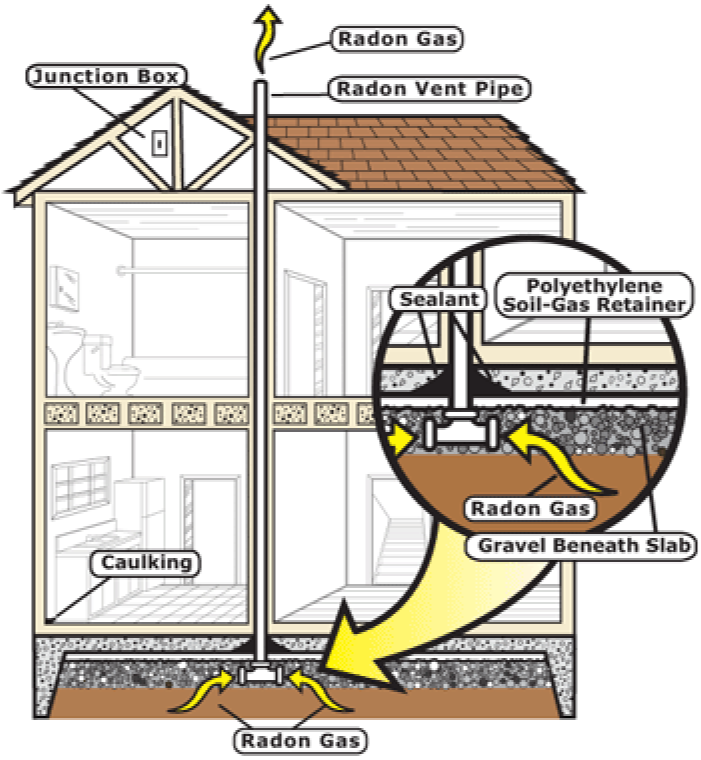


Figure 12: Radon Ventilation System in a Home

Figure 12 shows what can be done to prevent a dangerous build up of Radon gas from entering a building ("Builders and Contractors," 2009). Radon prevention can be achieved by playing thick plastic sheeting over a 4"-thick section of gravel, all of which spans the length of the building foundation. Radon and other gases in the soil travel freely through the gravel and are ventilated through simple PVC piping that releases the gas at the top of the building ("Builders and Contractors," 2009). It would also be beneficial to have a device to monitor the level of Radon, and possibly incorporate it into the Demand Control Ventilation system.

PERMITTING

There are several regulations that need to be followed in order to obtain a construction permit in the city of Worcester. It is important that a construction company abides by the building codes in order for their permits and inspections to be obtained without difficulty. The required permits can all be found in electronic format on the city's website (Building and Zoning, 2009). Since the new recreational facility on campus will have at least one pool, there are several permit applications that will need to be filled out, as seen in Appendix M (Building and Zoning, 2009).

ZONING

One of the important components of obtaining a permit is making sure that the construction project is going to be in the proper zone. Typically, zoning information can be obtained from an inspector who will find the information for a particular location (Building and Zoning, 2009). There is also a map of the city available on the city's website showing which parts of the city are under which zones. It is important that the zoning regulations be followed, because an improper zoning can lead to fines (Building and Zoning, 2009). The campus of Worcester Polytechnic Institute is listed under the zone of "Educational" due to its status as a professional university (Building and Zoning, 2009).

INSPECTION

Construction sites are inspected for compliance with all rules and regulations. An appointment with an inspector is necessary in order to have the construction site inspected (Building and Zoning, 2009).

STRUCTURAL DESIGN

Construction Materials

Since there are many construction materials available today it is necessary to choose which ones to use. As mentioned above, we have chosen to use steel for our main construction material. As seen in Figure 17, there are many types of steel available to be used. They range in price from $0.288 to $0.402 per pound. We show the costs and properties of Portland Cement Concrete just for comparison. Using CES EduPack 2009, we were able to make visual representations in the form of graphs for these values.

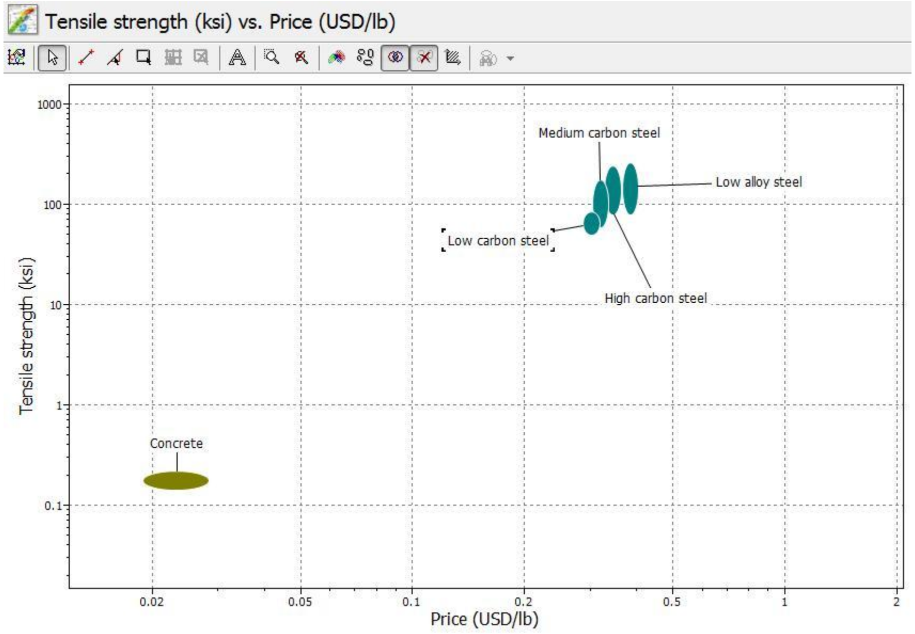


Figure 13: Tensile Strength Comparison

As can be seen in Figure **13**, steel has a considerably higher tensile strength than concrete. Concrete only has tensile strength up to 0.16 - 0.19 ksi (160 to 190 psi), whereas steel can withstand up to 50 – 150 ksi.

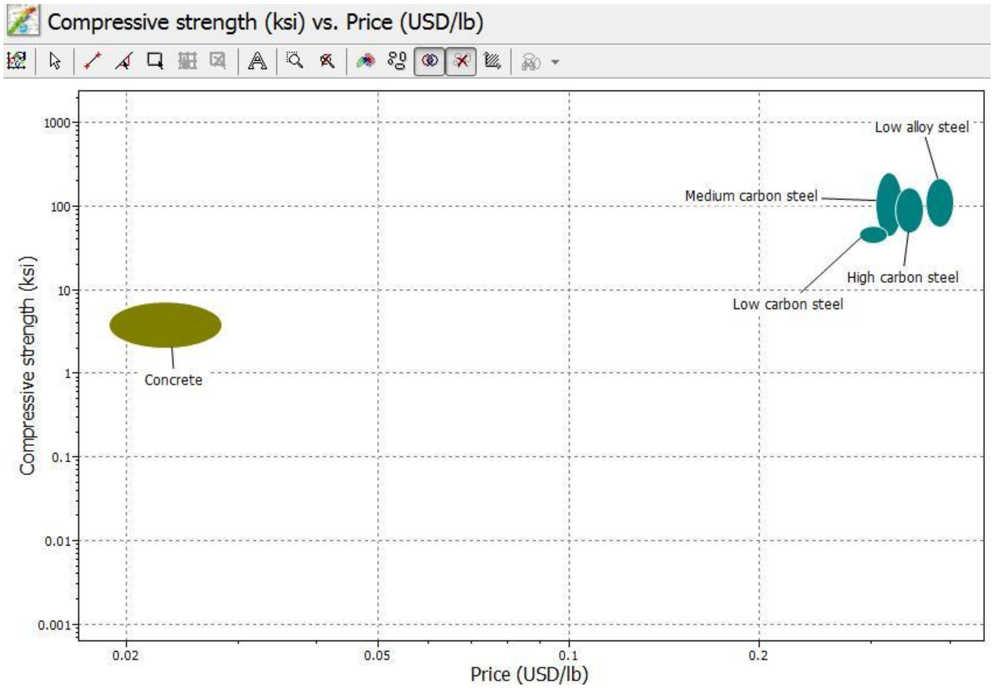


Figure 14: Compressive Strength Comparison

Although concrete is able to withstand almost 10ksi in compression, as seen above, it is significantly less than the 100ksi that steel is able to withstand. The argument in this case would be the enormous price difference; steel costs ten times more per pound than concrete would.

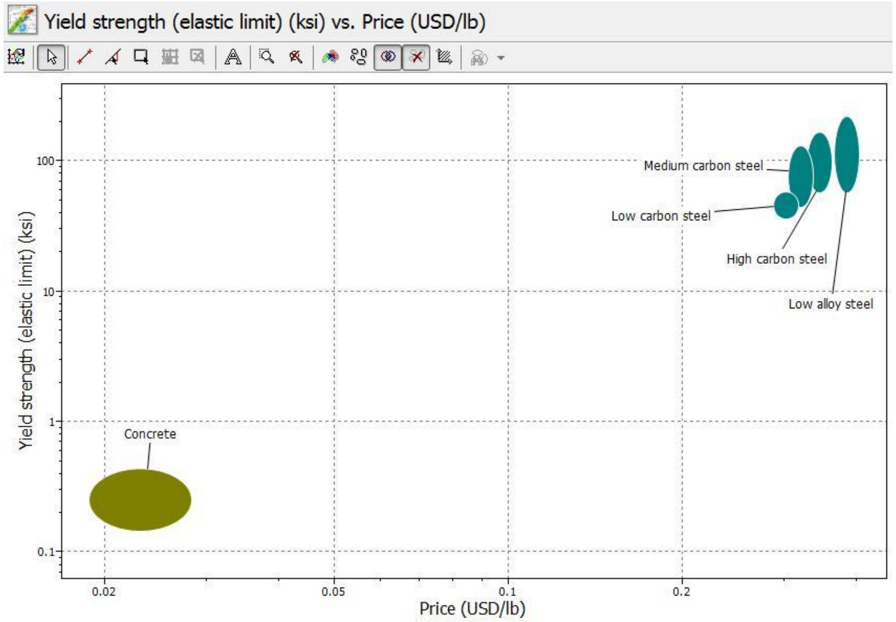


Figure 15: Yield Strength Comparison

The yield strength comparison is similar to the tensile strength comparison, with concrete being significantly weaker than steel.

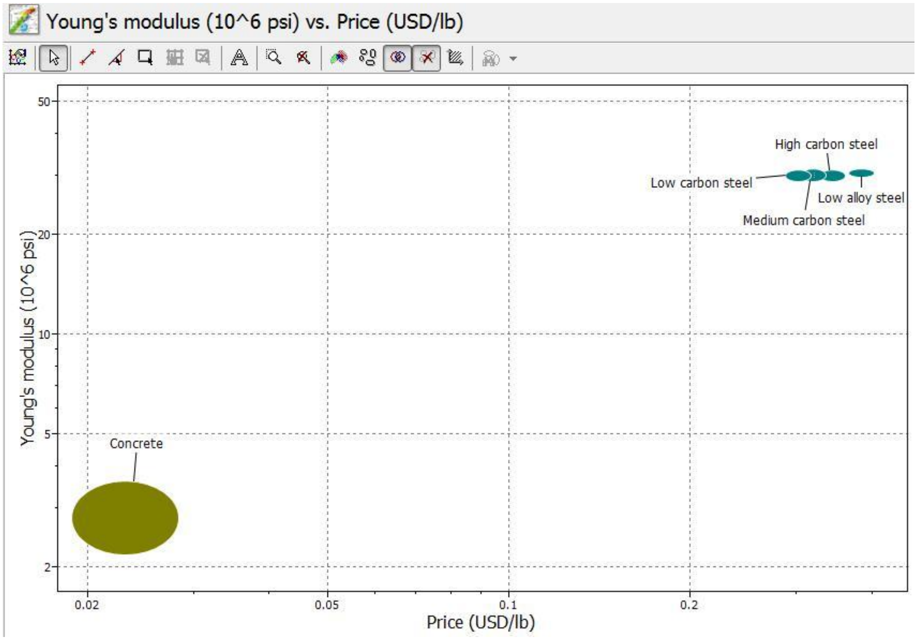


Figure 16: Modulus of Elasticity Comparison

Similar to the Tensile strength and the yield strength graphs, the modulus of elasticity shows that steel has a much higher load capacity than concrete. Since we have chosen steel as our construction material, the decision that now has to be made is what kind of steel to use.

Material	Density (lb/ft^3)	Price(USD/lb)	Young's modulus (*10^6) psi	Yield strength	Tensile Strength	Compressive Strength	Max Service Temp (F)
High Carbon steel	487-493	.328-0.361	29-31.2	58-168 ksi	79.8-238 ksi	48.6-168 ksi	662-752
Low Alloy Steel	487-493	0.366-0.402	29.7-31.5	58-218 ksi	79.8-255ksi	58-218 ksi	932-1020
Low Carbon Steel	487-493	.288-.316	29-31.2	36.3-57.3	50-84.1	36.3-57.3 ksi	662-752
Medium Carbon steel	487-493	.304-.335	29-31.3	44.2-131	59.5-174	44.2-255 ksi	698-788
Portland Cement Concrete	137-162	0.0188-.0282	2.18-3.36	.145-.174	0.16-0.189	1.93-4.35 ksi	896-950

Figure 17: Material Properties

Steel vs. Reinforced Concrete Construction

There are several common building materials today. Wood, steel, reinforced concrete, and masonry are some of the most popular materials today. In commercial construction, it is uncommon to see wood and masonry structures that are as large as this recreational facility being designed today. The two most common structural building materials are steel and reinforced concrete. Each has their own advantages and disadvantages.

For example, steel has a high strength in both tension and compression. It is also extremely lightweight compared to its strength. This makes it a popular material for the frames of commercial buildings. Steel frames that are properly maintained will last for a very long time (McCormac, 2008). Another great property of steel is its ductility. Steel is able to deform before fracturing, it will usually fail by yielding rather than fracturing, allowing warning to building occupants before failure.

Steel also has its disadvantages. Steel will begin to corrode if not properly taken care of. Also, steel needs to be fireproofed to allow the structure to withstand high temperatures for a certain amount of time without yielding. Steel is also susceptible to buckling, which is when beams with perpendicular loads or moment applied to them “swing” out to the side (McCormac, 2008). Although it is less common in buildings, steel can also fracture after withstanding fatigue and low temperatures.

Advantages to using concrete include its availability and low cost. Concrete is available pretty much anywhere, since it requires aggregate, Portland cement, and water. Concrete can also be poured into any shape desired, and can even be cast on site. It is relatively inexpensive, and doesn’t corrode. It also has a high compressive strength. Reinforced concrete can also withstand some tension due to the steel rebar. Concrete also tends to withstand fire better than steel.

Concrete also has some key disadvantages in this situation. Since water is a major component of concrete, it is susceptible to freeze/thaw cycles that are experienced in the Northeastern part of the United States. Concrete is weak in tension, as seen in Figure 13, and will have a brittle failure. To fix this, steel reinforcement is added to the concrete to increase its tensile strength. However, reinforced concrete is still weaker in tension than it is in compression. It would require significantly more concrete by weight than a steel structure would. The heavier the structure is, the more weight the structure needs to support, and the more difficult the design will become. Also, concrete takes approximately 3-4 weeks to cure to a sufficient strength, extending the length of the construction period.

Truss Design

The natatorium will require three stories of open space and feature a truss spanning across the 120 foot width of the room. In order to select a proper truss for the span, four common designs were tested using MDSolids to compare the maximum load forced upon a single member as well as the number of members in tension, compression, and with zero loads. Each truss was loaded with a 1.0 Kip force at the center of the span with simple supports at each end reacting to the force.

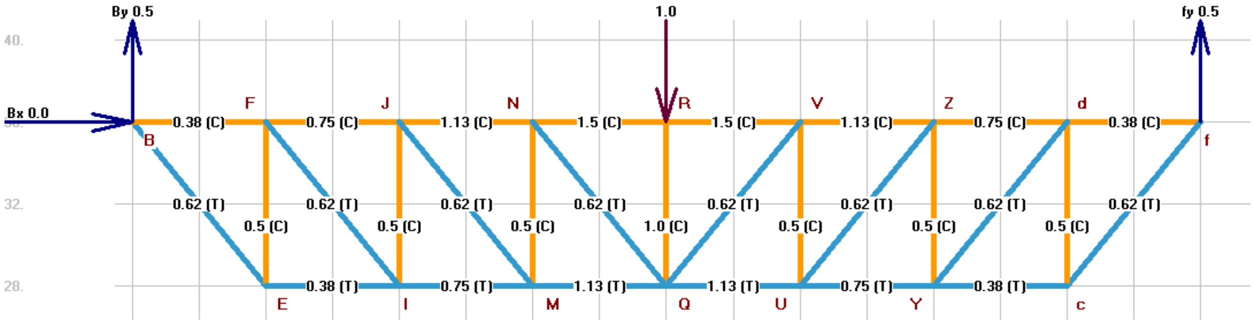


Figure 18: Truss A

Maximum Load on a Member	**1.5 Kips (Compression)**
Number of Members in Tension	**14**
Number of Members in Compression	**15**
Number of Members with Zero Load	**0**

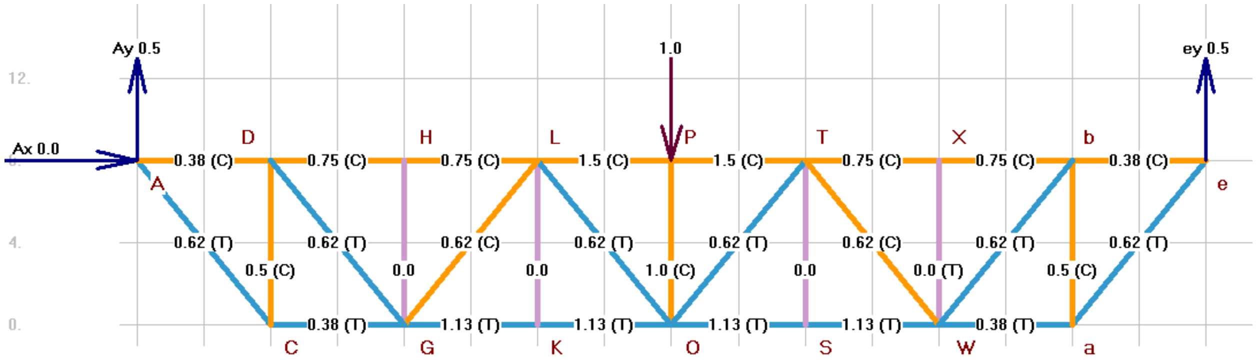


Figure 19: Truss B

Maximum Load on a Member	**1.5 Kips (Compression)**
Number of Members in Tension	**12**
Number of Members in Compression	**13**
Number of Members with Zero Load	**4**

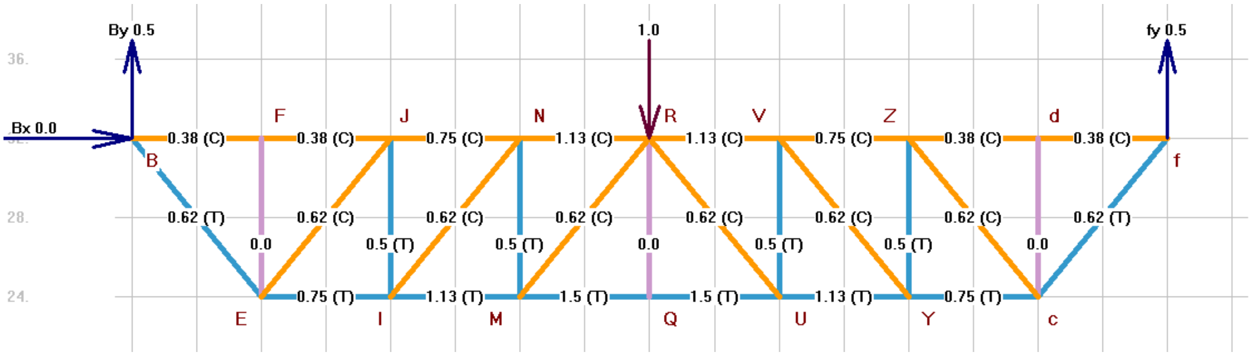


Figure 20: Truss C

Maximum Load on a Member	**1.5 Kips** (Tension)
Number of Members in Tension	**12**
Number of Members in Compression	**14**
Number of Members with Zero Load	**3**

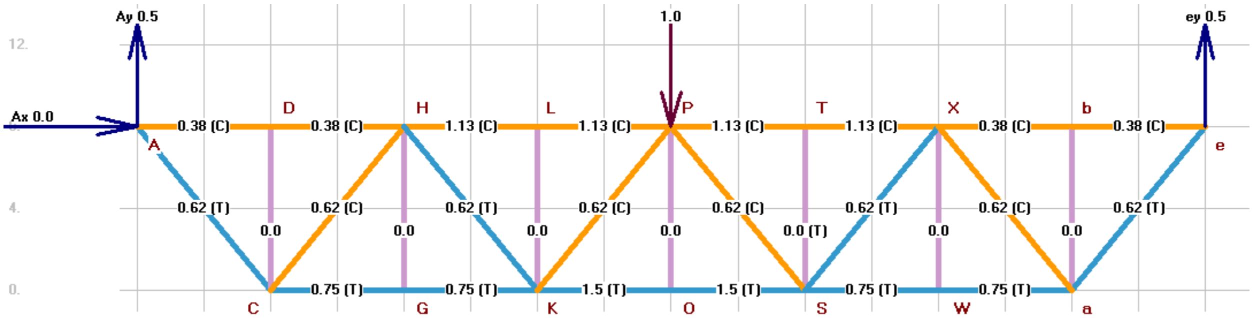


Figure 21: Truss D

Maximum Load on a Member	**1.5 Kips** (Tension)
Number of Members in Tension	**10**
Number of Members in Compression	**12**
Number of Members with Zero Load	**7**

The results of the comparison show that Trusses A & B experience the greatest stress upon a single member while in compression. The opposite lies true for Trusses C & D where the highest stress level for a single member is in Tension. Research through the program, CES EduPack 2009, shows that the tensile strength of each noted steel type is stronger than the compressive strength. This makes Trusses C & D better candidates since their highest stress is in tension rather than compression. Truss D has an equal number of members in tension and compression, however, the truss also has five members with no loading at all. Members of the truss that are not impacted by the loading can be decreased in size, resulting in a more efficient design with lower material costs. These reasons make Truss D the better choice for a span across the natatorium.

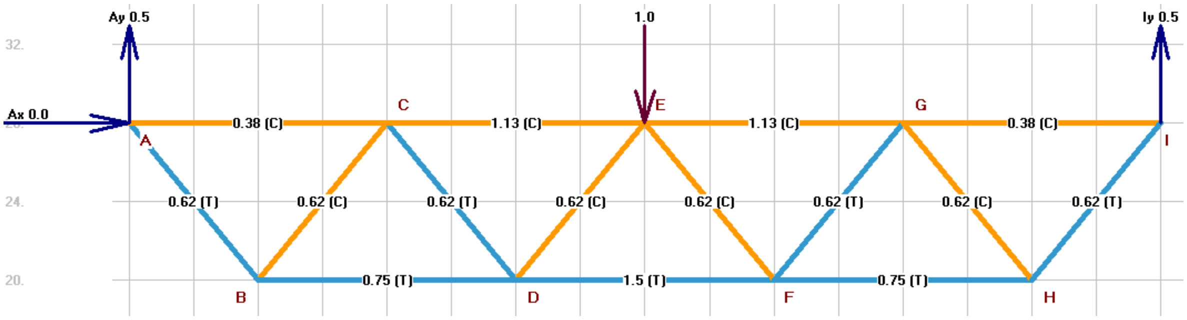


Figure 22: Modified Truss D

To further enhance the design of Truss D, the vertical members of the truss were subtracted from the structure since they were not needed, which creates a “Warren” style truss. Horizontal members that were originally connected to the vertical members were merged to keep the truss structurally stable. Angled members (such as member AB) are set at a 3-4, horizontal-vertical, ratio which will reduce stress levels when compared to a 1-1 ratio. By removing the vertical members of the truss, the structure will require less steel and therefore have a lighter dead load.

Truss Design for Roof

The Warren truss implemented into the final design of the roof spanned a total distance of 120’ while using low carbon steel. The angled members vertically spanned 8’ while horizontally spanning 6’ and all members of the truss were WT8x50 members with F_y = 50 ksi. A calculated distributed load of 828.39 pounds per linear foot (plf) was applied as nine point loads, equaling 9.9408 kips, in order to conduct a simple axial truss analysis. The end points carried half that value with 4.9704 kips on each side. The program, Mastan2, was used to analyze the truss and the results can be seen in Figure 24 and Figure 26. The method for solving the allowable deflection for a 120’ span is (L/240) which results in a value of 6 inches. The actual deflection value for the roof truss is 2.041” at the center of the span. The trusses are spaced three feet on center.

Designated Loads	Load Values
Steel	50 plf per member * (3 2/3) = 183.3 plf
Concrete	148 pcf * 3 ft * (4”/12”) = 148 plf
Green Roof	35 psf * (3 ft) = 105 plf
Metal Decking	3 psf * (3 ft) = 9 plf
Live	20 psf * (3 ft) = 60 plf
Snow	55 psf * (3 ft) = 165 plf

Figure 23: Table of Roof Truss Design Loads

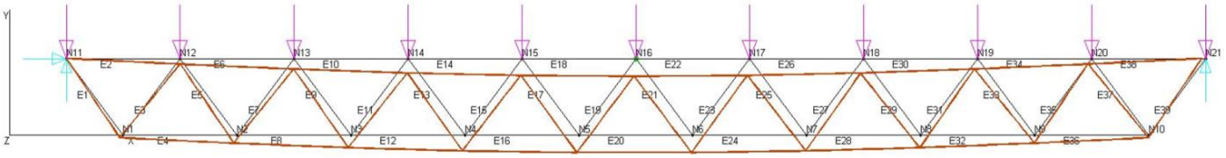


Figure 24: Roof Truss Design and Deflection

Truss Design for Natatorium

For the floor of the basketball court (above the natatorium), the same length dimensions (6’ horizontally by 8’ vertically for angled members) were used on a Warren truss again. However, new calculated dead load and live load values resulted in the used of WT8x55 steel members throughout the truss. The distributed load is 575.15 plf which is translated into nine point loads equaling 6.9018 kips each, and two additional point loads at the ends, equaling 3.4509 kips each. Through Mastan2, the calculated deflection is 1.417” at the center of the span. The deflection in this case is lower than the deflection of the roof in order to minimize any potential curvature of the basketball court floor. The truss and its resultant deflection can be seen in Figure 24. These trusses will be spaced 3 feet on center. The deflections shown in Figure 24 and Figure 26 are exaggerated to show detail.

Designated Loads	Load Values
Steel	50 plf per member * (3 2/3) = 183.3 plf
Concrete	148 pcf * (3 ft) * (4”/12”) = 148 plf
Maple	45 pcf * (.5”/12”) * (3 ft) = 5.625 plf
Metal Decking	3 psf * (3 ft) = 9 plf
Live	100 psf * (3 ft) = 300 plf

Figure 25: Table of Natatorium Truss Design Loads

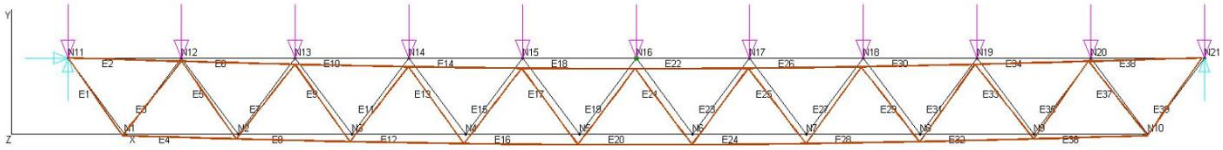


Figure 26: Natatorium Truss Design and Deflection

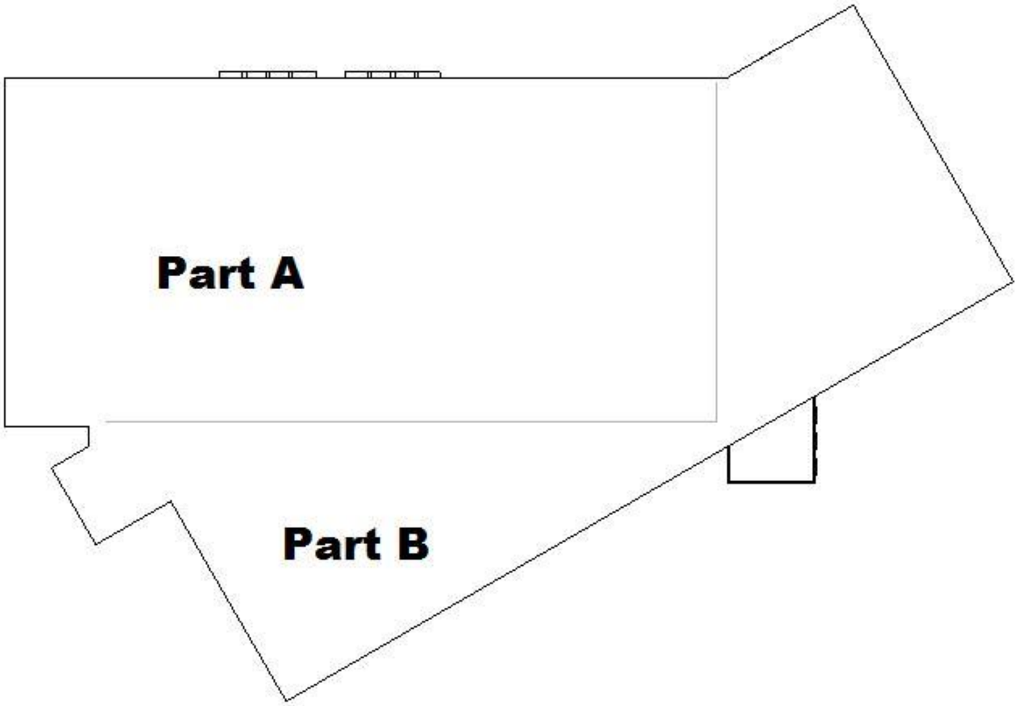


Figure 27: Sections of the Building

Beam Design

Beams are structural members that undergo bending stresses while they carry the loads from the floors and distribute them to the supporting girders. The most commonly used shape steel beam for carrying floor loads is the Wide-Flange beam. In this project, beams exist in the B section, as seen in Figure 27, of the building, and in the A section of the building at the track level. The beams are supported by girders.

B Beam Design

Beams in the B section, as seen in Figure 27, are supported by the B Girders. The B beams are perpendicular to the B Girders. There are 6 B beams on each B Girder. A beam is 30 feet in length and has a tributary width of 5 feet. The Live Load supported by the beams is 100 pounds per square foot based on the Massachusetts State Building Code. The dead load on the beam includes the weight of the beam as well as the concrete flooring and the steel decking. B beams at the roof level are W14x48s. At the other levels, they are W14x61s because the live load on the floors of the building is much higher than the live load supported at the roof.

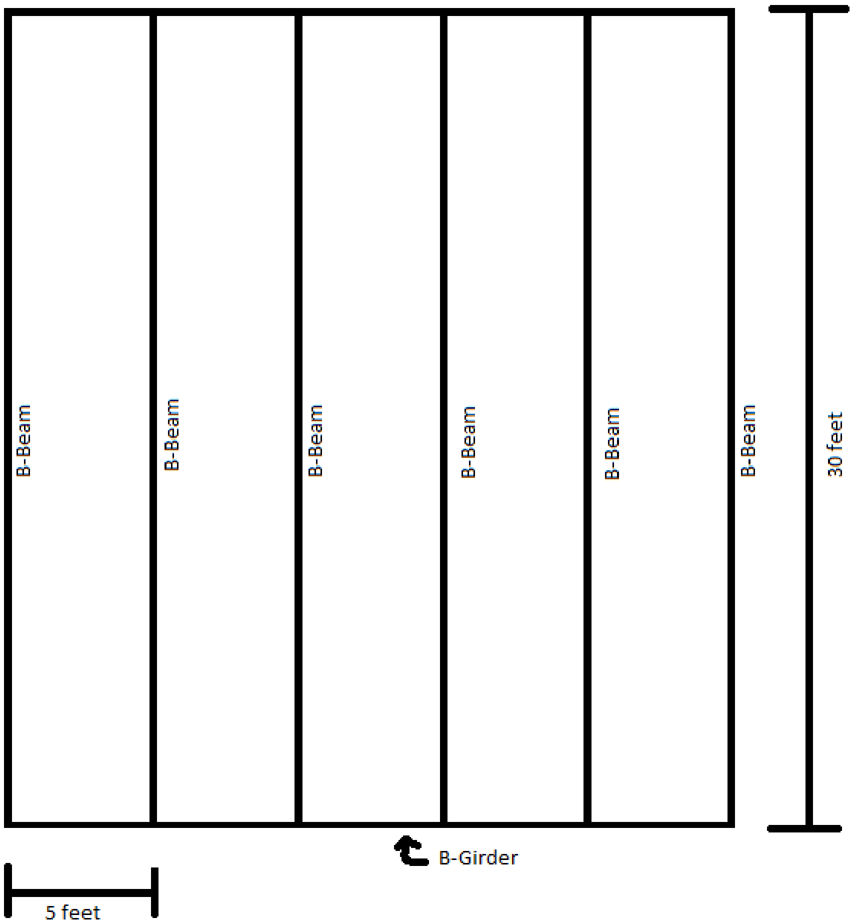


Figure 28: Layout of B-Beams and B-Girders

A Beam Design

The Beams in the A section (as seen in Figure 27) support the track. These A Beams are supported by the A girders at the track level. The A beams are sixteen feet in length and are cantilevered. This means that they are not supported at the end of the beam that is not connected to the A girders. A moment supporting connection with the A girders will be required to support the track loads. Track beams are W16x57.

Girder Design

There are two types of girders, A Girders and B Girders depending on which section of the building the girder is in. Figure 27 shows the different sections of the building and how they are labeled.

A Girder Design

The A Girders run along the outer edges of the A section of the building. They support the trusses at the roof and basketball levels. Each A Girder is attached at either end to a column and supports ten trusses at both the roof and basketball levels, and 6 Track Beams at the track level. All A girders are 30 feet in length. The A Girders are W24x250's at the roof and basketball court levels. At the track level, they are W18x97's.

B Girder Design

The B girders exist in the B-section of the building. This section has a floor at levels 3-5, and the roof. This space consists of smaller rooms than the large open spaces of the pool and basketball courts. They are typically used for offices, multipurpose rooms, locker rooms, and weight rooms. The B girders are much smaller than the A girders. The B girders are also 30 feet in length and are supported at both ends by columns. The B girders support the load of 6 B beams, which are spaced 5 feet on center. The B girders at the roof level are W21x122's while the B girders of the lower levels are W18x192's.

Column Design

We designed the columns by adding up the loads acting upon the column, from the girders, the beams, and the columns above. Each column is 1 floor in length, except for the bottom column which supports the first and “second” floor, since the second floor is not an actual floor.

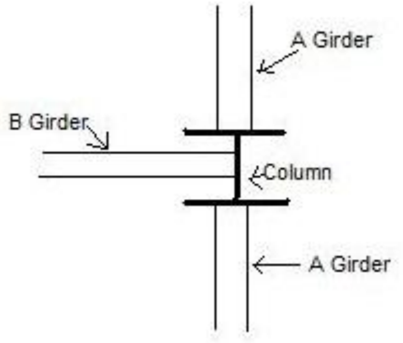


Figure 29 - Sample Column

We created a spreadsheet to help with the repetitive calculations of the columns. The load is measured in Kips, the Area (A) is measured in square inches, I is in inches to the fourth. Size refers to the size of the smallest suitable column.

Floor	Size	Load	K	L	I	A	r	KL/r	ΦcFrc	A-req	ΦcPn
5th	W14x53	604.505	1	18	541	15.6	5.889	36.68	40.347	14.983	629.41
4th	W14x109	1008.12	1	16	1240	32	6.225	30.84	41.689	24.182	1334
3rd	W14x176	2010.31	1	13	1900	46.7	6.378	24.46	43.921	45.771	2051.1
1st & 2nd	W14x193	2227.35	0.7	23	2400	56.8	6.5	29.72	43.353	51.377	2462.4

Figure 30 - Column Design Spreadsheet

Connection Design

Connections are very important in structural design. The connections are what hold the beams, girders and columns together. There are two main types of connections: moment connections and pinned connections. Moment connections can consist of welds, rivets, and/or bolts as long as they are able to support a moment. Pinned connections are usually designed so that they cannot resist moments. Pinned connections are typically designed using bolts. Bolted connections tend to be weaker than welded connections, but are easier to assemble in the field.

Figure 31: Photo of a Sample Bolted Connection in Fuller Labs at WPI

We designed the connection between an A girder and the column, as seen in Figure 29 using a bolted connection. The design is a sample design only. Many of the other connections will need to be welded in order to provide adequate support for the members they are holding up. Figure 31 shows an example of a bolted connection that is used to connect the girders and beams to the column in Fuller Labs, the computer science building on the WPI Campus. The bolted connection design can be seen in Figure 49 and Figure 50 in Appendix D.

Stair Design

The functionality of any building largely depends on the layout of the interior. In the case of the athletic center, there will be a main stair case close to the front entrance of the building that connects the fourth floor to the third floor. General guidelines for the rise-to-run ratio of steps are shown in the table below (“Stair Angle Calculator,” 2010).

Rise (inches)	Run (tread length less nosing in inches)							
	9"	**9-1/4"**	**9-1/2"**	**9-3/4"**	**10"**	**10-1/4"**	**10-1/2"**	**10-3/4"**
6-3/4"	36.9	36.1	35.4					
7"	37.9	37.1	36.4	35.7				
7-1/4"	38.9	38.1	37.3	36.6	35.9			
7-1/2"	39.8	39.0	38.3	37.6	36.9	36.2	35.5	
7-3/4"	40.7	40.0	39.2	38.5	37.8	37.1	36.4	35.8
8"	41.6	40.9	40.1	39.4	38.7	38.0	37.3	36.7
8-1/4"	42.5	41.7	41.0	40.2	39.5	38.8	38.2	37.5
8-1/2"		42.6	41.8	41.1	40.4	39.7	39.0	38.3

Figure 32: Stair Design

The height differential between the floors is 13 feet which causes the length of the staircase to span 17’ ¾”. This includes steps that are 7.428” high and 9.75” long with a resultant slope of 37.3 degrees, which is within the acceptable range. It should be noted that if the height and length of the steps were both “simple” numbers the staircase would have an extra step that would have a different height than the rest of the steps. Out of safety concerns, the 7.428" height of the steps allows all steps to be even and prevent any lack of coordination for visitors in the center.

Our design uses steel pans filled with concrete to make the treads of the stairs. The steel pans are held up by two C-Shaped beams on each side that connect to the third and fourth floors. The design can be seen in Figure 51 and Figure 52 in Appendix E.

Figure 33: Stairs with Concrete-Filled Steel Pans

Foundation

Foundations come in many types, but are generally separated into deep foundations and shallow foundations. Shallow foundations are typically used when the supporting soil is relatively strong. They usually consist of spread footings, continuous footings, or a mat foundation. Deep foundations are necessary when the soil cannot sufficiently support the structure. Deep foundations usually consist of piles or drilled shafts that go very deep into the soil and use the friction caused by the soil on the sides of the piles to hold up the building.

The site that the new recreational center is going to be placed on has Glacial Till as its soil. This consists mostly of coarse sand, gravel, silt and a small bit of clay. The water table is typically between 8 feet and 30 feet below ground level. Sand and gravel tend to be much better to build on than silt or clay. This is due to the water-retaining properties and shear capacity of silt and clay. Our sample foundation design is of the open area part of the building only. This area includes the natatorium and basketball courts. It will be necessary in practice to design the foundation of the rest of the building as well.

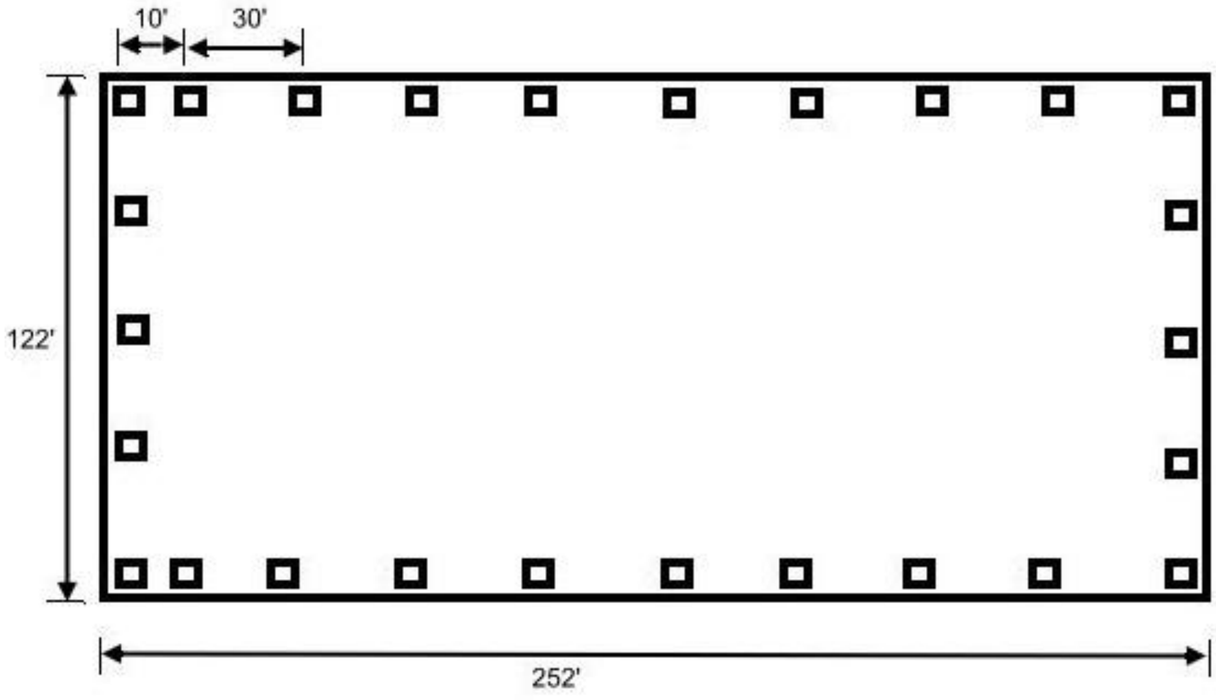


Figure 34: Foundation Layout

The area of the sample foundation is 252 feet by 122 feet, which is the area of this section of the building plus a 1 foot perimeter. The foundation carries 26 columns around its perimeter that support a load of 2227.353 kips each. The foundation has a slight imbalance in weight distribution because the columns at one end are spaced 10 feet from the other columns instead of the normal 30 feet on center, as seen in Figure 34 above. We calculated the necessary depth to be 120 inches, or 10 feet. In reality, the foundation will require steel rebar reinforcements since the loads from the columns are so high. The rebar will need to be placed in locations where there are high tensile forces acting on the concrete in order to help the concrete resist brittle failure.

Retaining Wall

The foundation of the athletic center is located at an especially unique location, standing at the center of a hill, where two considerably different ground heights meet together. As a result, the ground level by the main entrance of the building is on the fourth floor of the building, whereas the ground level on the track side of the building is located on the first floor. On the front side of the building, where parts of the building go beneath the ground level, a retaining wall is required to resist the force of the soil pressure. A wall protecting the third floor is located just beneath ground level, and follows the general design characteristics of a cantilever retaining wall, as shown below.

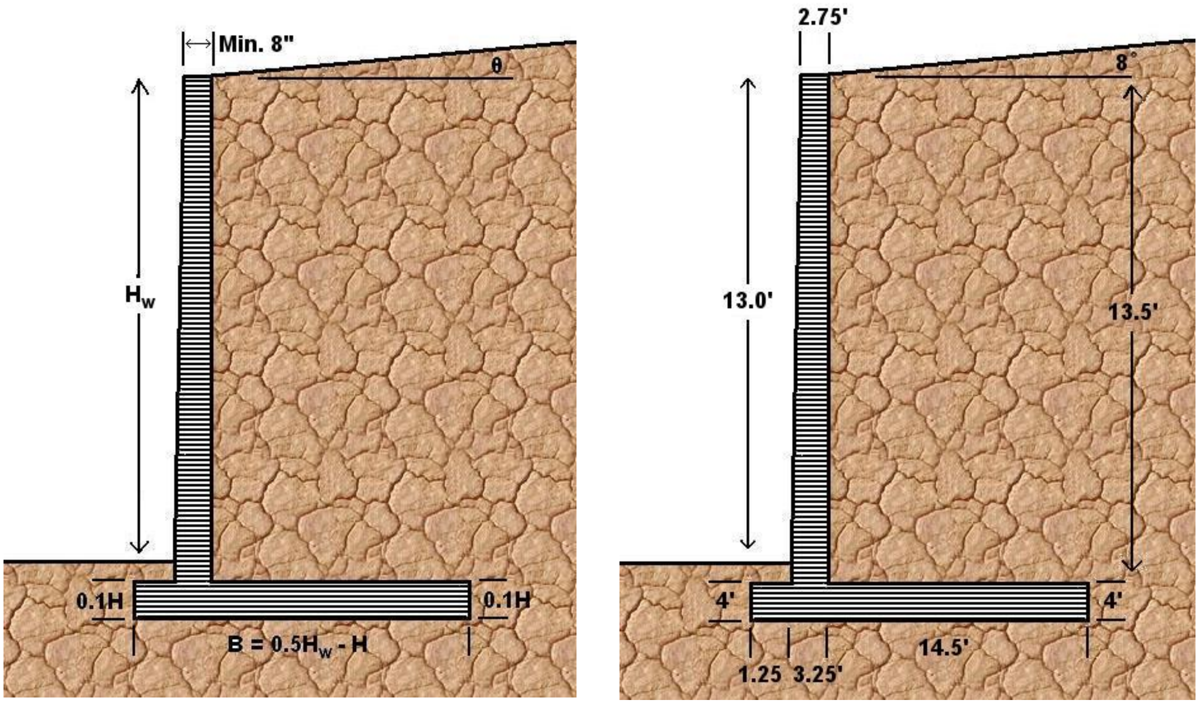


Figure 35: Retaining Wall

In order to match the required factor of safety of 1.5 that was integrated into the design, the dimensions of the wall had to be considerably larger than expected. The height of the wall (H_w) is 13’ and has a width of 3.25 feet at the base and 2.75 feet at the top, where the soil side of the wall is vertical and the opposite side is sloped. The length of the footing (B) is 19’ with a height of 4’, and the wall connects to the footing with 1.25’ left on the building side of the wall, and 14.5’ remaining on the opposite side, underneath the soil.

During the calculations for the wall, Coulomb’s method was used, which determines the active earth pressure coefficient (K_a) and applies it to a series of equations that determine the safety of the design (Coduto, 2001). Possible causes of the particularly high dimensions required could be caused by a relatively low effective friction angle (Ø') in the soil, and the 8 degree (0.13 radian) slope above the wall. If land fill with a high coefficient of friction (μ) was placed around the retaining wall during construction, the dimensions could also be reduced. The table below shows the variables used to perform analysis using an excel spreadsheet on the retaining wall as well as the final loads and factor of safety.

Variables	Values	Variables	Values
Θ	0.13962634 rad	**Footing**	5494.5 plf
ɣ	100 pcf	**Soil**	19616.82231 plf
μ	0.5	**Sum**	32673.94644 plf
α	0	**Vf/b**	11478.31442 plf
Ø'	0.523598775 rad	**45 Degrees**	0.785398163 rad
Øw	0.350811179 rad	**Stem Top**	2.75 ft
ka	0.658836741	**Stem Bottom**	3.25 ft
Gh	61.87097969 pcf	**Base Length**	19 ft
Gv	22.64156331 pcf	**Base Height**	4 ft
λa	111.147728 pcf	**Base Right Side**	14.5 ft
μa	0.333333333	**Total Height**	17.5 ft
F	1.5	**Concrete**	148 pcf
H	15.5932 ft	**Soil Height Left**	0.5 ft
Pa/b	7521.898966 plf	**Total Height Left**	4.5 ft
Va/b	2752.624129 plf	**F_A**	**1.512077046**
Stem	4810 plf	**F_A > 1.5**	YES

Figure 36: Retaining Wall Variables

Pool Design

The natatorium will consist of an Olympic-class, long-course swimming pool. The length will span 164’ 1 ½” and have a width of 75’. A diving section will be integrated into the pool, providing takeoff platforms at 1, 3, and 5 meters. The depth of the pool will be 7’ at the shallow end and 14’ in the diving end. The total volume of the pool will be 143,686 cubic feet with a resultant weight of 8,970 kips. The pool will be divided into 8 lanes, with the six center lanes having widths of 9’ and the two outside lanes having widths of 10.5’. The outer lanes have wider widths due to resistance that is caused by water bouncing off the walls and creating drag for the swimmer. By creating wider lanes next to the walls, any advantages or disadvantages between lanes will be minimized. The additional depth of 14’ located at the diving end of the pool will also help to minimize the resistance of water for the swimmers.

Revit Design

The design of the recreational facility created through this MQP was based on the floor plans of the actual building that will be constructed on the WPI campus. The exact dimensions of the building were not given in the floor plans. As a result, the dimensions of the design in this MQP are estimations of what the actual building might be, integrated with applied reasoning of what dimensions would be necessary to accommodate for the features shown in the floor plans. While the images do not show the green roof and solar panels on the roof, the building has been designed to withstand the dead loads from those features throughout the entire area of the roof. The images of the design, as shown below, were created using Revit Architecture 2010.

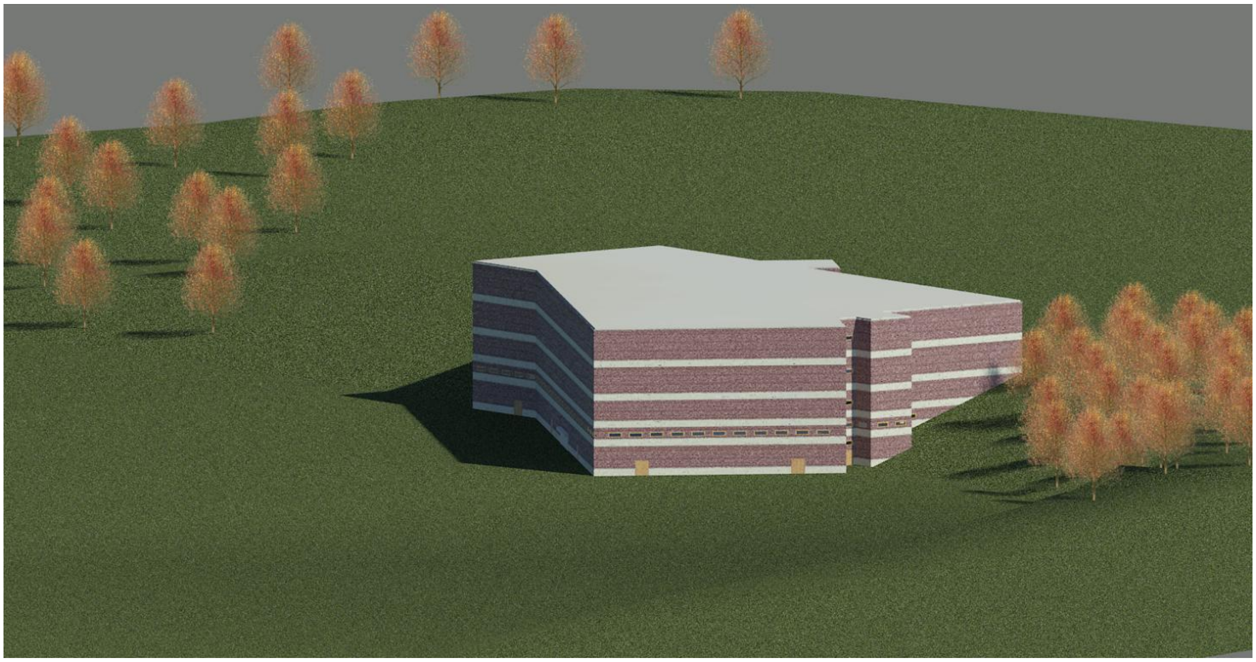


Figure 37: Design View from the South West

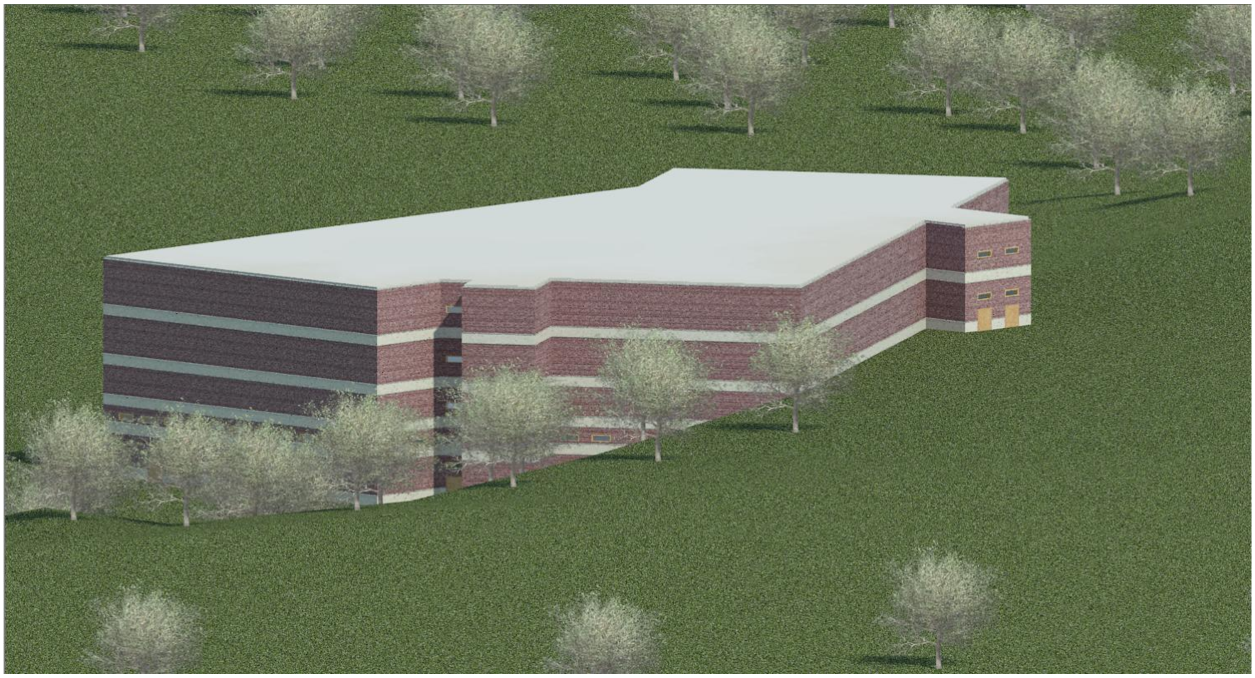


Figure 38: Design View from the South East

CONCLUSION

Worcester Polytechnic Institute has a growing student population with an ever increasing physical demand on the campus. With Harrington Auditorium and Alumni Gym lacking the required capabilities to keep up with the ever growing inflow of students, a new facility will be needed to keep WPI among the most well rounded schools that offer both rigorous educational opportunities and state of the art facilities for extracurricular activities. Our Major Qualifying Project gives way for a new WPI recreational facility that meets all of the athletic needs of the college and then some. Located in the open hill between the Quad and the track, the new recreational facility will host a plethora of benefits including six basketball courts, a natatorium containing an Olympic-size pool with spectator seating, an elevated indoor track, racquetball and squash courts, climbing wall, classrooms, offices, and more.

The new WPI athletic facility will also be a leading example of how modern construction can be environmentally responsible and lead to sustainable development. The facility will take advantage of various “green” developments such as a green roof, solar panels, geothermal heating, and energy efficient lights. Designing the building with an abundance of windows will also allow for minimal dependence on lights, which saves electrical costs and demands less from the environment. The solar panels will further reduce the amount of energy consumed through the grid, while geothermal heating will help keep the building warmer in the winters and cooler in the summers. The green roof removes the need for the water to go through a water treatment plant by acting as a free water filter for all rain water that falls onto the roof. This makes the runoff water immediately available for use elsewhere, such as watering fields and plants on campus.

Our design of the future WPI athletic center consisted of developing an overall layout of the building that would be large enough to house all physical needs, while also fitting into the landscape of the WPI campus and having a realistically affordable cost. After the shape of the building was created, a detailed structural plan was designed to meet Massachusetts building code standards. The facility was designed using steel members, of which included: the natatorium truss, roof truss, track cantilever beams, A-girders, B-beams, B-girders, columns, stairs, and connections. Other features of the building designed in our project include the pool, retaining walls, and foundation design. The designs derived from this project were challenging yet beneficial. While the designs of this project do not represent every factor of the building, they represent key sample designs of the major structural components of the building.

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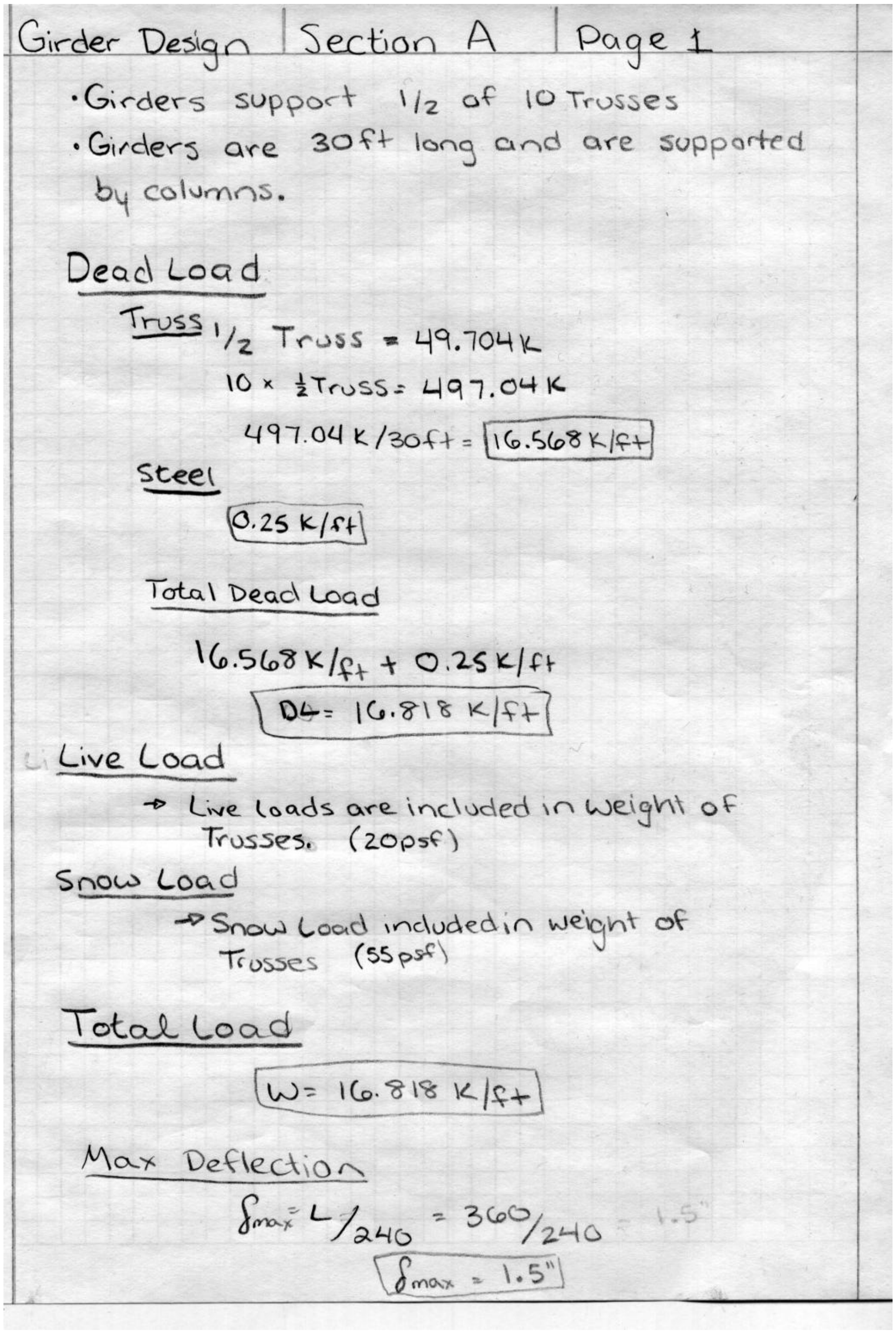
APPENDIX A: GIRDER DESIGN

Section A Girder Design



Girder Design | Section A | Page 1

- Girders support 1/2 of 10 Trusses
- Girders are 30ft long and are supported by columns.

Dead Load

Truss $1/2$ Truss = 49.704K

$10 \times \frac{1}{2}$Truss = 497.04K

$497.04\,K / 30ft = \boxed{16.568\,K/ft}$

Steel

$\boxed{0.25\,K/ft}$

Total Dead Load

$16.568\,K/ft + 0.25\,K/ft$

$\boxed{DL = 16.818\,K/ft}$

Live Load

→ Live loads are included in weight of Trusses. (20psf)

Snow Load

→ Snow Load included in weight of Trusses (55psf)

Total Load

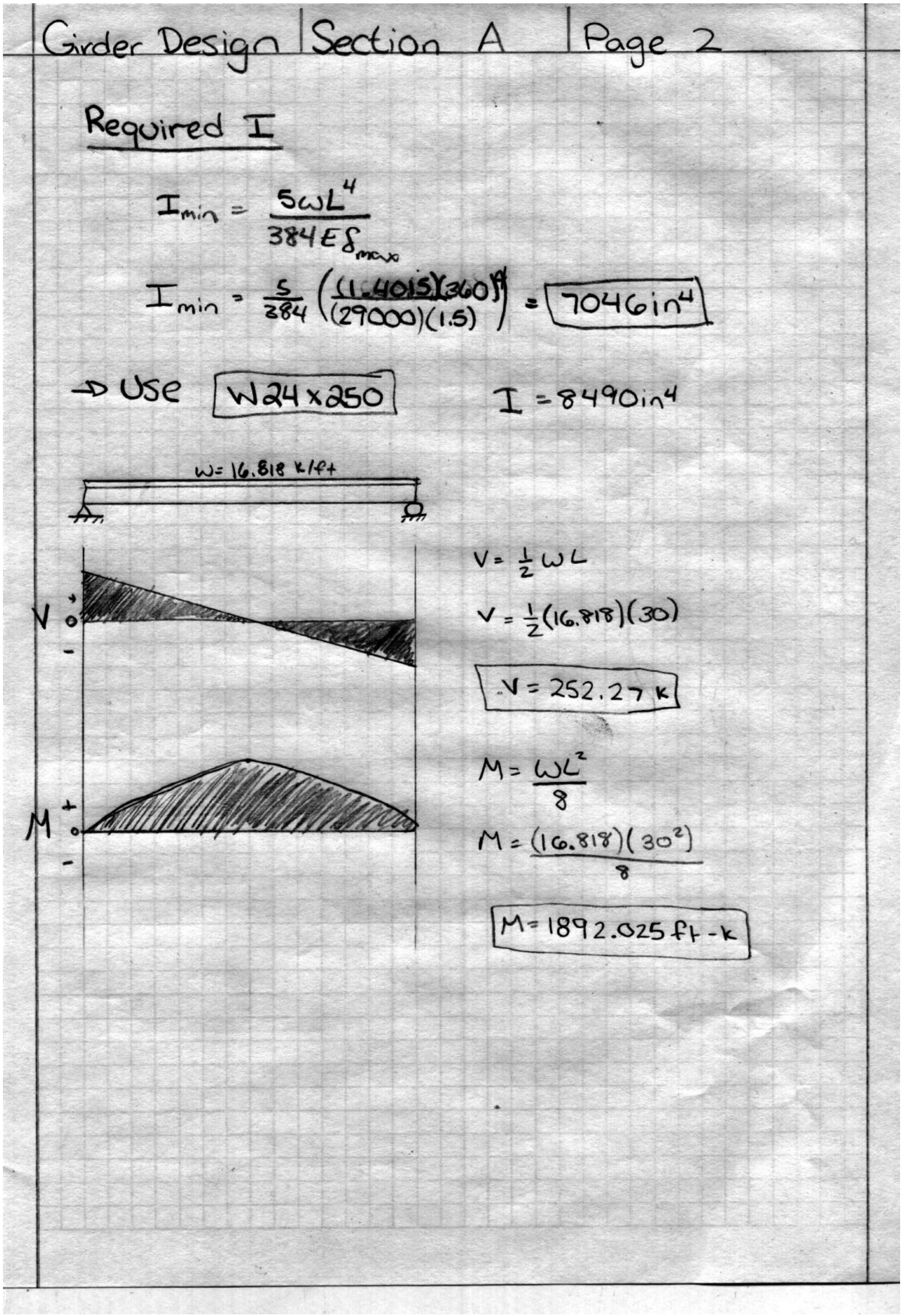
$\boxed{W = 16.818\,K/ft}$

Max Deflection

$\delta_{max} = L/240 = 360/240$ 1.5"

$\boxed{\delta_{max} = 1.5"}$

Figure 39: Section A Girder Design Page 1



Girder Design | Section A | Page 2

Required I

$$I_{min} = \frac{5wL^4}{384 E \delta_{max}}$$

$$I_{min} = \frac{5}{384}\left(\frac{(1.4015)(360)^4}{(29000)(1.5)}\right) = \boxed{7046 in^4}$$

→ Use $\boxed{W24 \times 250}$ $I = 8490 in^4$

$V = \frac{1}{2} wL$

$V = \frac{1}{2}(16.818)(30)$

$\boxed{V = 252.27 k}$

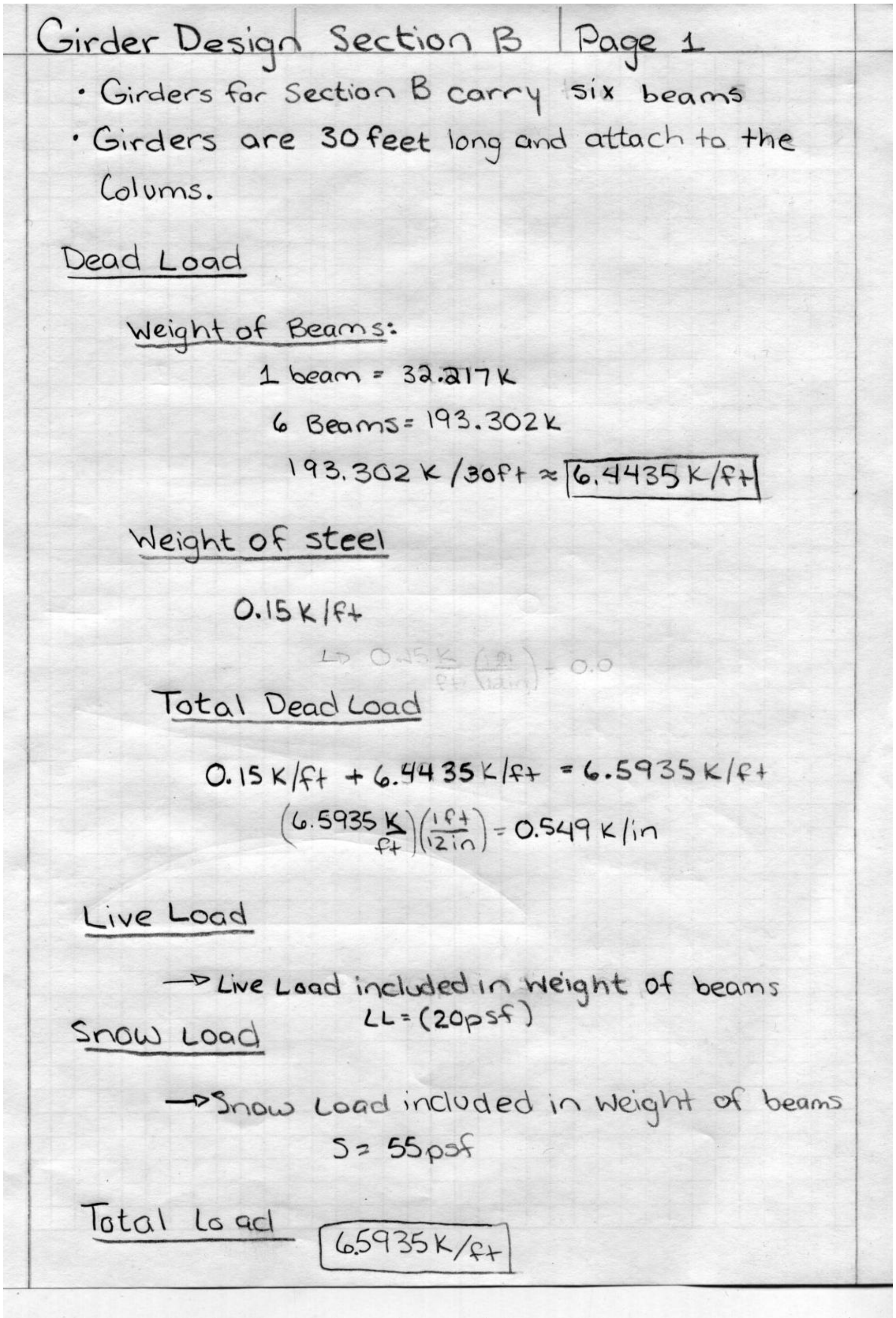
$$M = \frac{wL^2}{8}$$

$$M = \frac{(16.818)(30^2)}{8}$$

$\boxed{M = 1892.025 ft\text{-}k}$

Figure 40: Section A Girder Design Page 2

Section B Girder Design



Girder Design | Section B | Page 1

- Girders for Section B carry six beams
- Girders are 30 feet long and attach to the Colums.

Dead Load

Weight of Beams:

1 beam = 32.217 K

6 Beams = 193.302 K

$193.302\text{ K}/30\text{ft} \approx \boxed{6.4435\text{ K/ft}}$

Weight of steel

0.15 K/ft

Total Dead Load

$0.15\text{ K/ft} + 6.4435\text{ K/ft} = 6.5935\text{ K/ft}$

$\left(6.5935\frac{\text{K}}{\text{ft}}\right)\left(\frac{1\text{ft}}{12\text{in}}\right) = 0.549\text{ K/in}$

Live Load

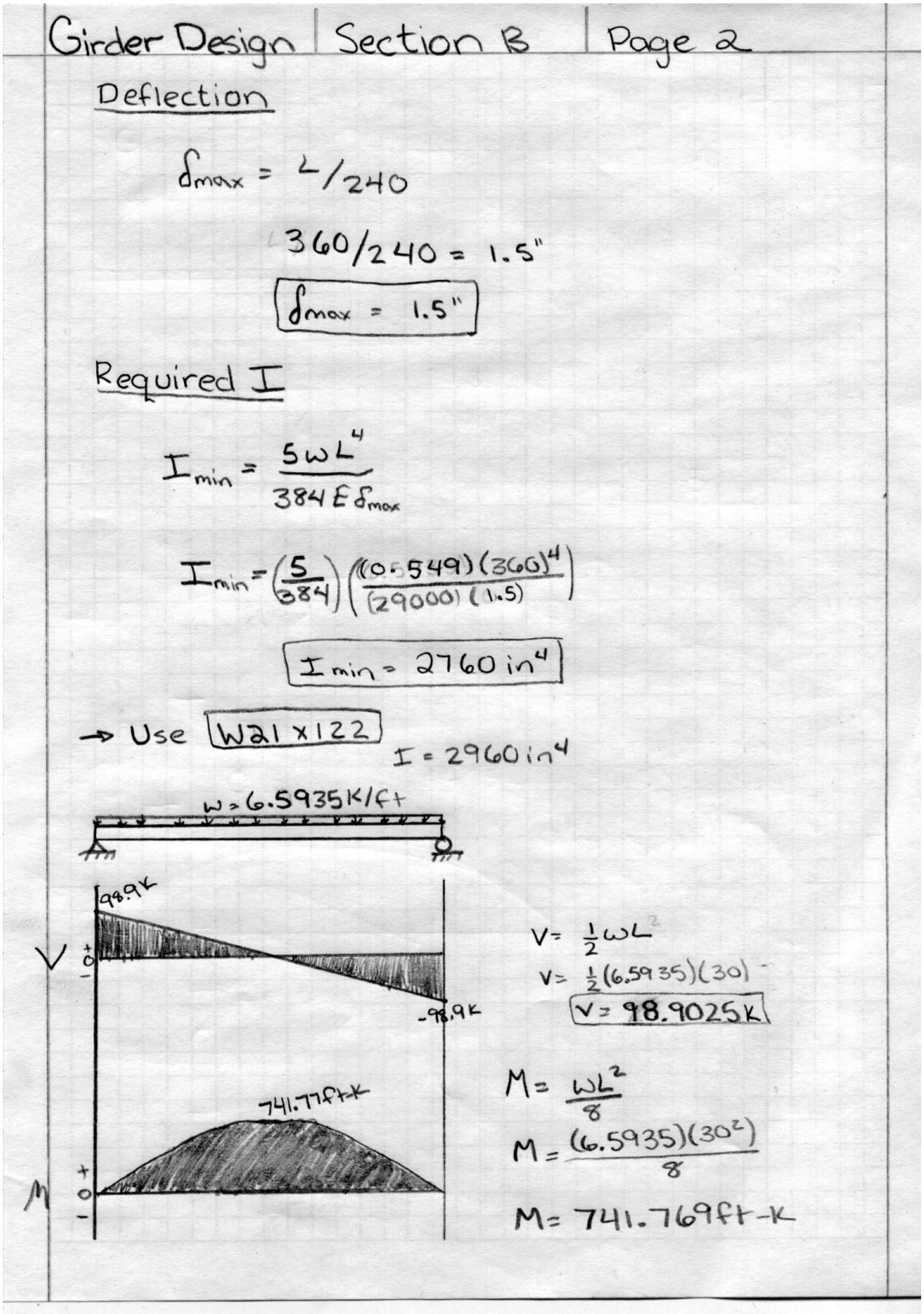
→ Live Load included in weight of beams
LL = (20psf)

Snow Load

→ Snow Load included in weight of beams
S = 55psf

Total Load $\boxed{6.5935\text{ K/ft}}$

Figure 41: Section B Girder Design Page 1



Girder Design | Section B | Page 2

Deflection

$\delta_{max} = L/240$

$360/240 = 1.5''$

$\boxed{\delta_{max} = 1.5''}$

Required I

$$I_{min} = \frac{5wL^4}{384E\delta_{max}}$$

$$I_{min} = \left(\frac{5}{384}\right)\left(\frac{(0.549)(360)^4}{(29000)(1.5)}\right)$$

$\boxed{I_{min} = 2760 \text{ in}^4}$

→ Use $\boxed{W21 \times 122}$

$I = 2960 \text{ in}^4$

$V = \frac{1}{2}wL$

$V = \frac{1}{2}(6.5935)(30)$

$\boxed{V = 98.9025 K}$

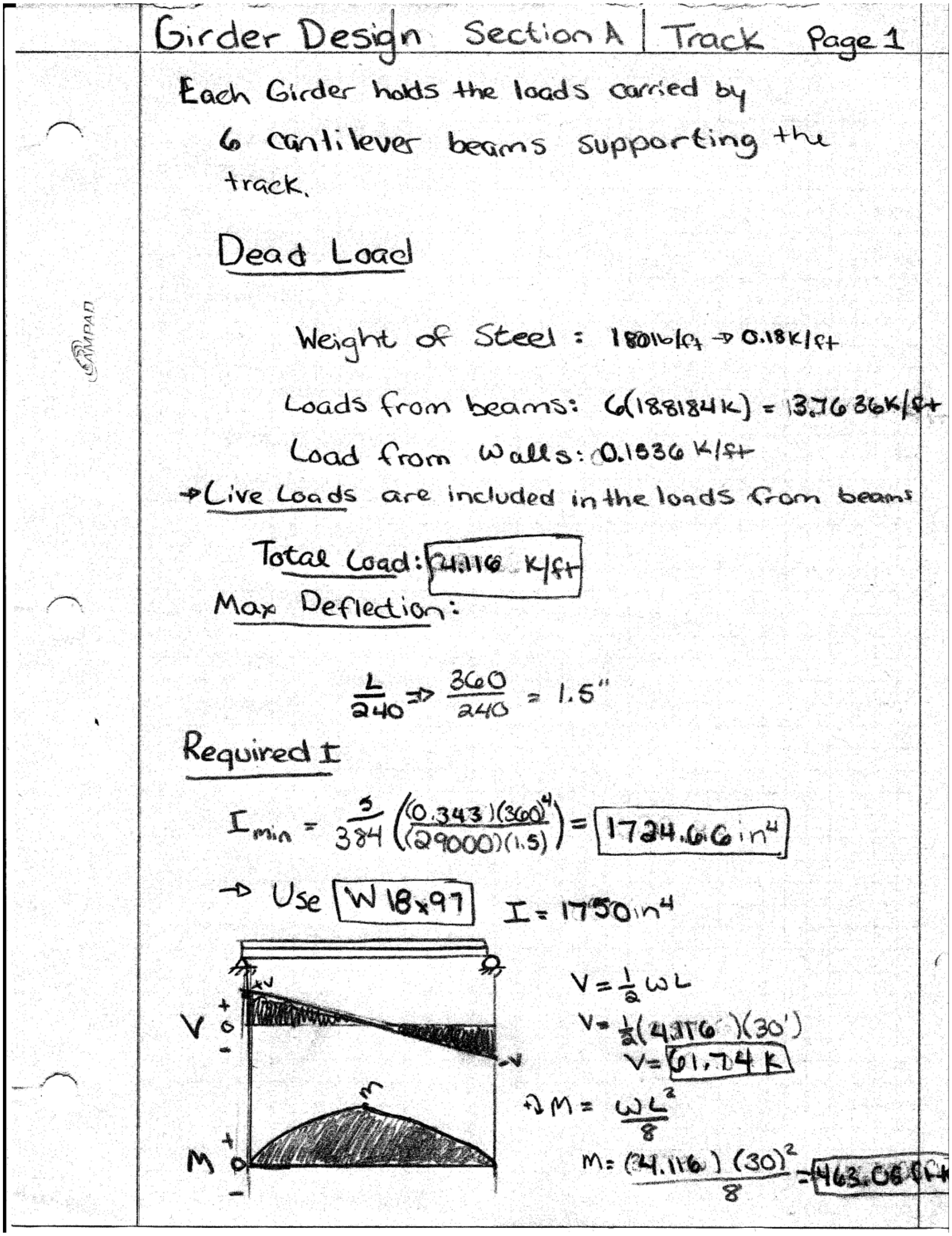
$$M = \frac{wL^2}{8}$$

$$M = \frac{(6.5935)(30^2)}{8}$$

$M = 741.769 \text{ ft-K}$

Figure 42: Section B Girder Design Page 2

Track Girder Design



Girder Design Section A | Track Page 1

Each Girder holds the loads carried by 6 cantilever beams supporting the track.

Dead Load

Weight of Steel : 180 lb/ft → 0.18 K/ft

Loads from beams: 6(18.8184 K) = 3.7636 K/ft

Load from walls: 0.1836 K/ft

→ Live Loads are included in the loads from beams

Total Load: $\boxed{4.116\ \text{K/ft}}$

Max Deflection:

$$\frac{L}{240} \Rightarrow \frac{360}{240} = 1.5''$$

Required I

$$I_{min} = \frac{5}{384}\left(\frac{(0.343)(360)^4}{(29000)(1.5)}\right) = \boxed{1724.66\ \text{in}^4}$$

→ Use $\boxed{\text{W }18\times97}$ $I = 1750\ \text{in}^4$

$V = \frac{1}{2}wL$

$V = \frac{1}{2}(4.116)(30')$

$V = \boxed{61.74\ \text{K}}$

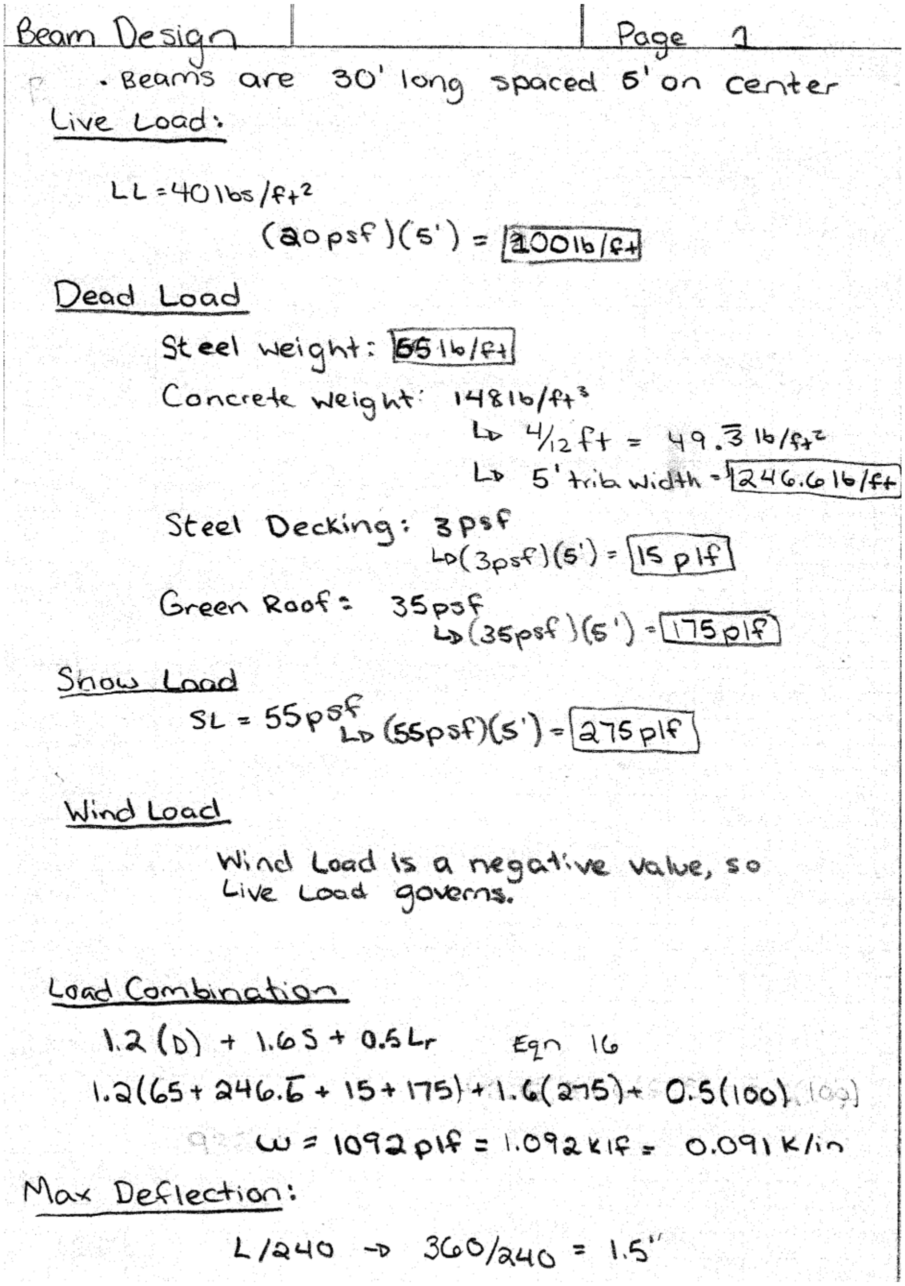
$\curvearrowright M = \frac{wL^2}{8}$

$M = \frac{(4.116)(30)^2}{8} = \boxed{463.05\ \text{ft}}$

Figure 43: Section A Girder Design - Track

APPENDIX B: BEAM DESIGN

Section B Beams



Beam Design | Page 1

- Beams are 30' long spaced 5' on center

Live Load:

$LL = 40\,lbs/ft^2$

$(20psf)(5') = \boxed{100\,lb/ft}$

Dead Load

Steel weight: $\boxed{65\,lb/ft}$

Concrete weight: $148\,lb/ft^3$

↳ $4/12\,ft = 49.\overline{3}\,lb/ft^2$

↳ $5'$ trib width $= \boxed{246.6\,lb/ft}$

Steel Decking: 3 psf

↳ $(3psf)(5') = \boxed{15\,plf}$

Green Roof: 35 psf

↳ $(35psf)(5') = \boxed{175\,plf}$

Snow Load

$SL = 55\,psf$ ↳ $(55psf)(5') = \boxed{275\,plf}$

Wind Load

Wind Load is a negative value, so Live Load governs.

Load Combination

$1.2(D) + 1.6S + 0.5L_r$ Eqn 16

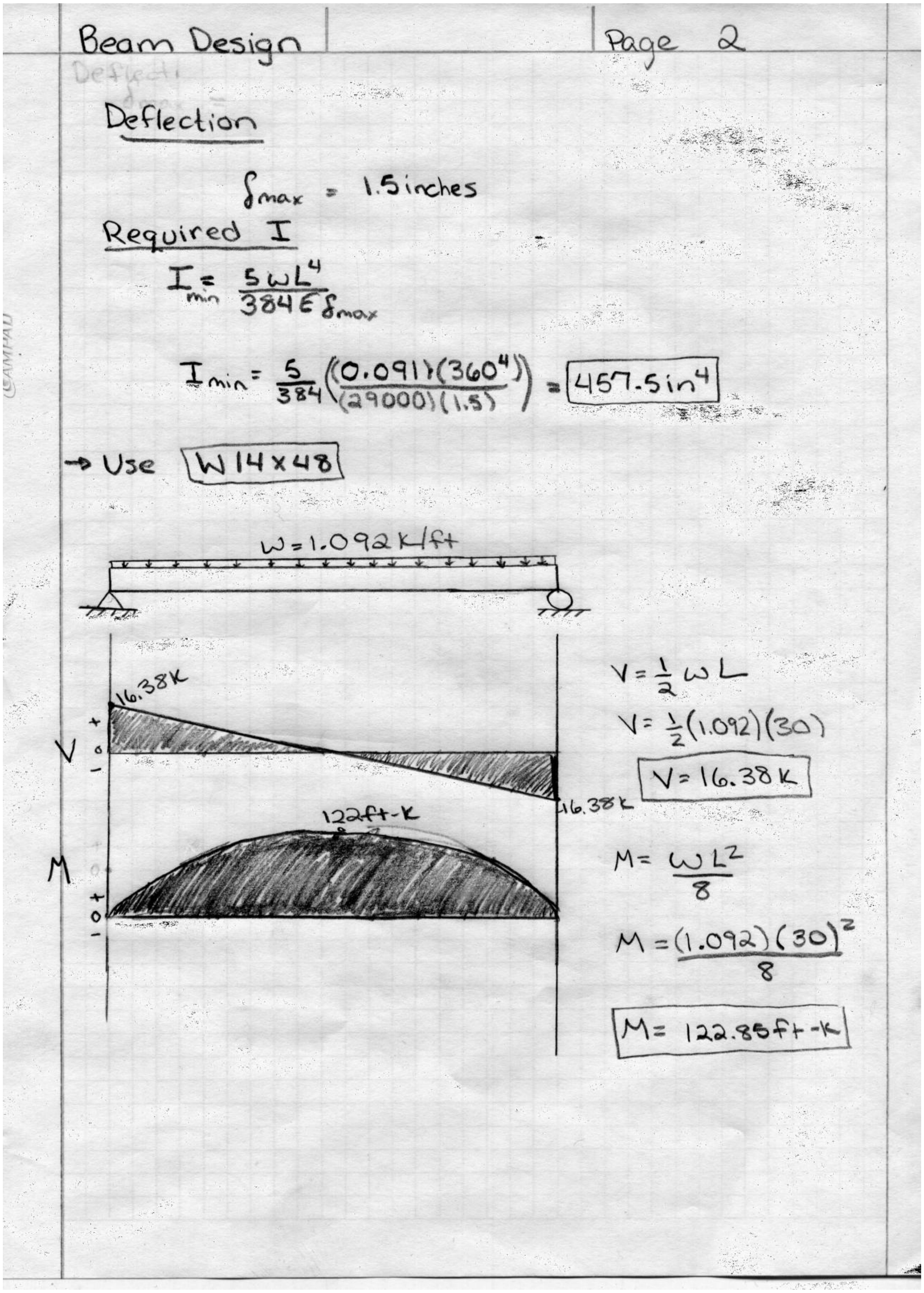
$1.2(65 + 246.\overline{6} + 15 + 175) + 1.6(275) + 0.5(100)$

$w = 1092\,plf = 1.092\,klf = 0.091\,k/in$

Max Deflection:

$L/240 \rightarrow 360/240 = 1.5''$

Figure 44: Section B Beam Design Page 1



Beam Design | Page 2

Deflection

$\delta_{max} = 1.5$ inches

Required I

$$I_{min} = \frac{5wL^4}{384E\delta_{max}}$$

$$I_{min} = \frac{5}{384}\left(\frac{(0.091)(360^4)}{(29000)(1.5)}\right) = \boxed{457.5 in^4}$$

→ Use $\boxed{W14\times48}$

$V = \frac{1}{2}wL$

$V = \frac{1}{2}(1.092)(30)$

$\boxed{V = 16.38K}$

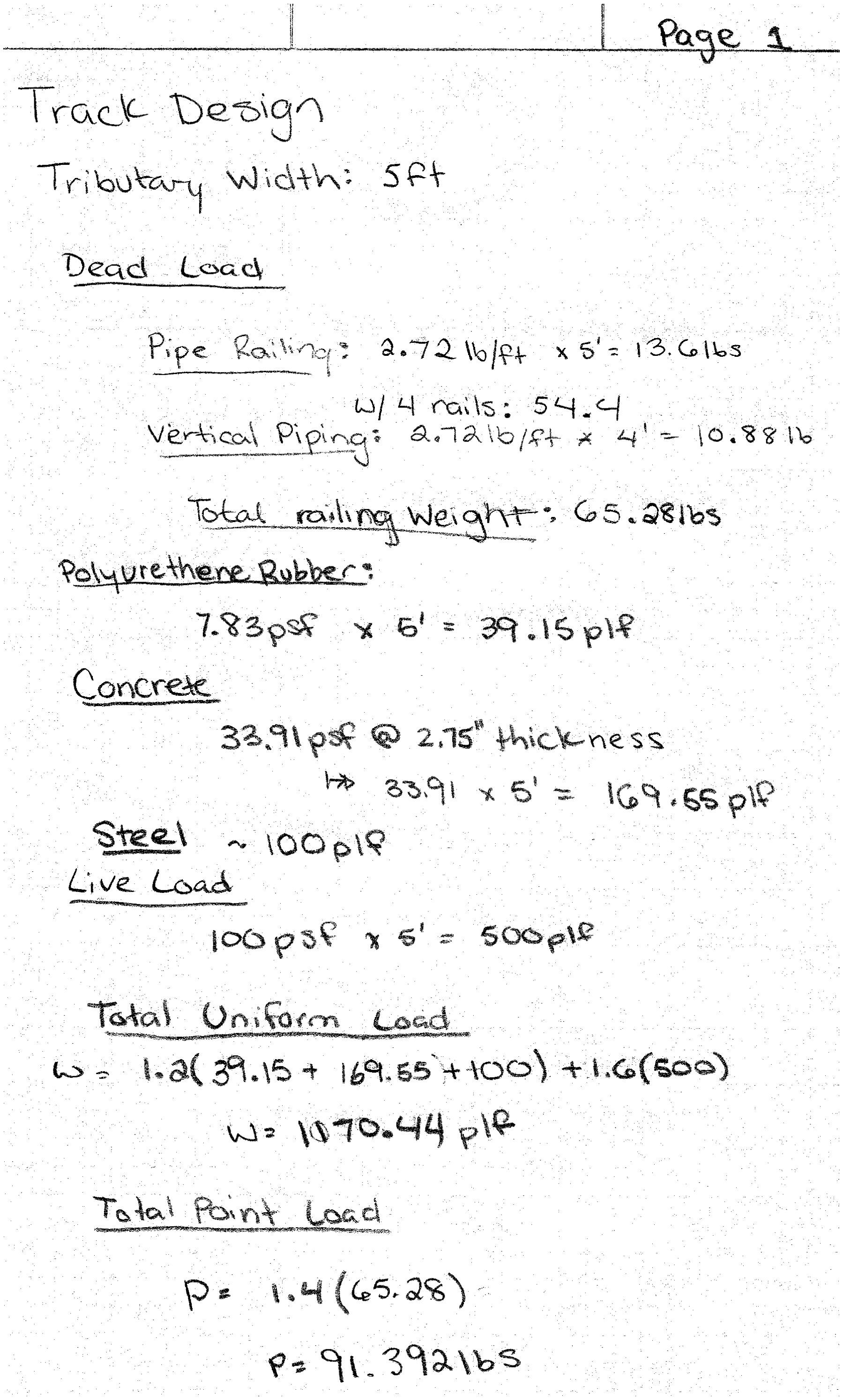
$M = \frac{wL^2}{8}$

$M = \frac{(1.092)(30)^2}{8}$

$\boxed{M = 122.85 ft\text{-}K}$

Figure 45: Section B Beam Design Page 2

Track Beam Design



Page 1

Track Design

Tributary Width: 5ft

Dead Load

Pipe Railing: 2.72 lb/ft x 5' = 13.6 lbs

w/ 4 rails: 54.4

Vertical Piping: 2.72 lb/ft x 4' = 10.88 lb

Total railing weight: 65.28 lbs

Polyurethene Rubber:

7.83 psf x 5' = 39.15 plf

Concrete

33.91 psf @ 2.75" thickness

↦ 33.91 x 5' = 169.55 plf

Steel ~ 100 plf

Live Load

100 psf x 5' = 500 plf

Total Uniform Load

$w = 1.2(39.15 + 169.55 + 100) + 1.6(500)$

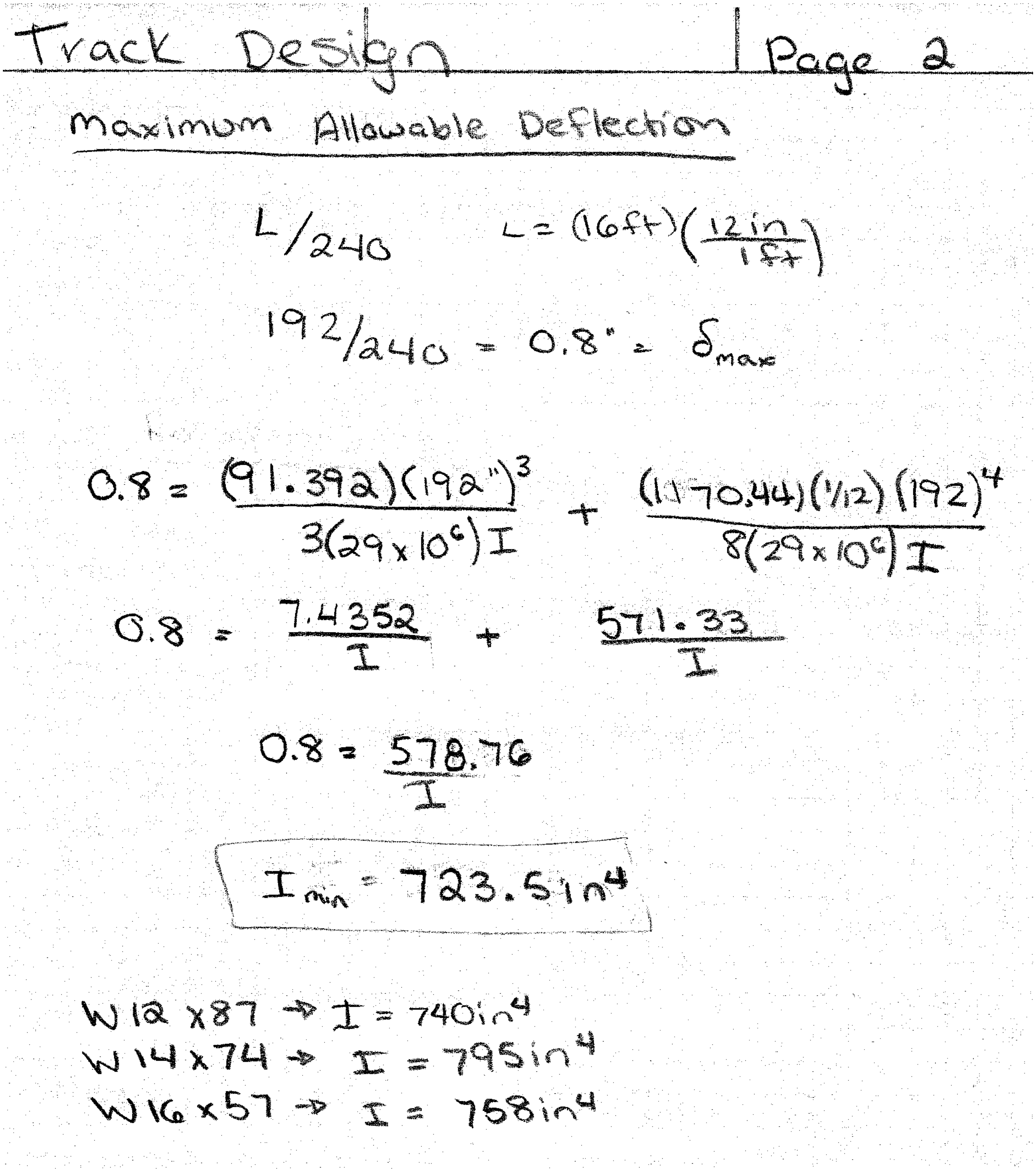
$w = 1070.44$ plf

Total Point Load

$P = 1.4(65.28)$

$P = 91.392$ lbs

Figure 46: Track Design Page 1



Track Design | Page 2

Maximum Allowable Deflection

$L/240 \qquad L = (16ft)\left(\frac{12in}{1ft}\right)$

$192/240 = 0.8" = \delta_{max}$

$$0.8 = \frac{(91.392)(192")^3}{3(29\times10^6)I} + \frac{(1170.44)(1/12)(192)^4}{8(29\times10^6)I}$$

$$0.8 = \frac{7.4352}{I} + \frac{571.33}{I}$$

$$0.8 = \frac{578.76}{I}$$

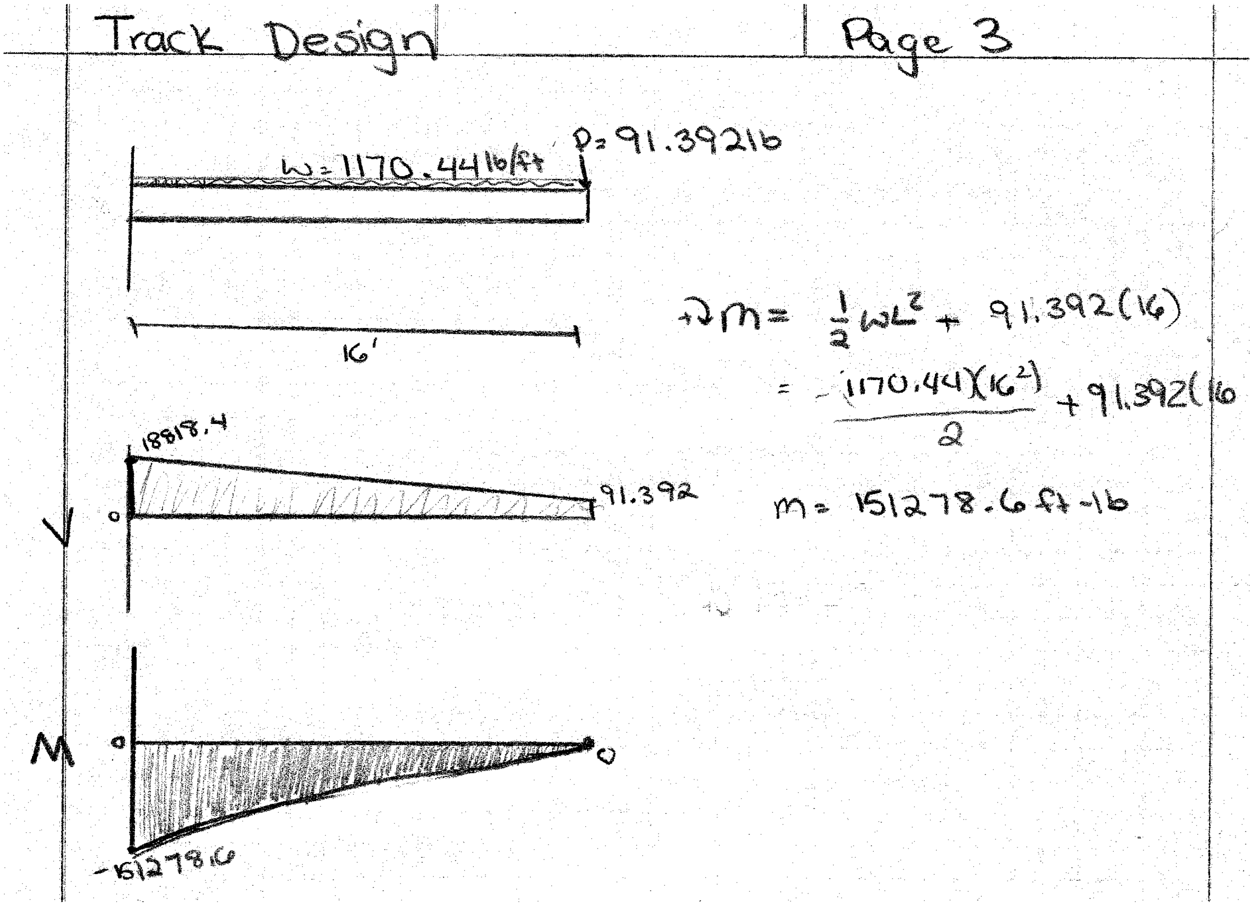
$$\boxed{I_{min} = 723.5 in^4}$$

W12x87 → $I = 740 in^4$

W14x74 → $I = 795 in^4$

W16x57 → $I = 758 in^4$

Figure 47: Track Design Page 2



Track Design | Page 3

$$+\circlearrowleft m = \frac{1}{2}wL^2 + 91.392(16)$$

$$= \frac{1170.44(16^2)}{2} + 91.392(16$$

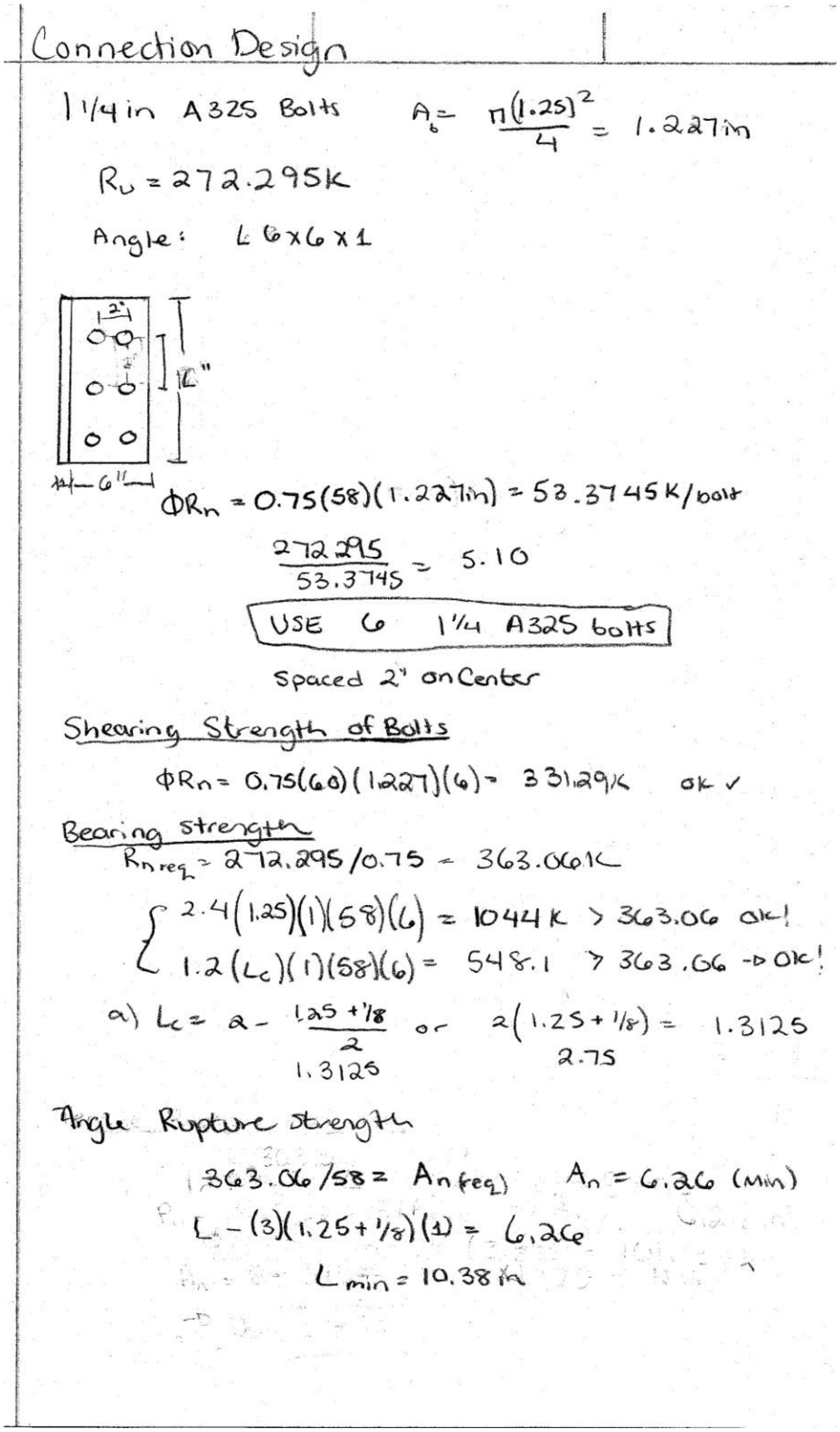
$$m = 151278.6 \text{ ft-lb}$$

Figure 48: Track Design Page 3

Appendix C: Column Design

Unlike many of the other designs, the columns were designed using a spreadsheet to aid with the repetitive calculations. There is no hand-written design page for the columns. The spreadsheet can be found in Figure 30.

APPENDIX D: CONNECTION DESIGN



Connection Design

1 1/4 in A325 Bolts $A_b = \frac{\pi(1.25)^2}{4} = 1.227 \text{in}$

$R_u = 272.295K$

Angle: $\angle 6 \times 6 \times 1$

$\phi R_n = 0.75(58)(1.227\text{in}) = 53.3745 K/\text{bolt}$

$\frac{272.295}{53.3745} = 5.10$

$\boxed{\text{USE } 6 \quad 1\tfrac{1}{4} \text{ A325 bolts}}$

Spaced 2" on Center

Shearing Strength of Bolts

$\phi R_n = 0.75(60)(1.227)(6) = 331.29K$ ok ✓

Bearing strength

$R_{n\,req} = 272.295/0.75 = 363.061K$

$$\begin{cases} 2.4(1.25)(1)(58)(6) = 1044K > 363.06 \text{ ok!} \\ 1.2(L_c)(1)(58)(6) = 548.1 > 363.06 \rightarrow \text{OK!} \end{cases}$$

a) $L_c = 2 - \frac{1.25 + 1/8}{2}$ or $2(1.25 + 1/8) = 1.3125$

$1.3125 \qquad 2.75$

Angle Rupture strength

$363.06/58 = A_{n\,(req)} \qquad A_n = 6.26 \text{ (Min)}$

$L - (3)(1.25 + 1/8)(1) = 6.26$

$L_{min} = 10.38 \text{ in}$

Figure 49: Connection Design Page 1

Connection Design

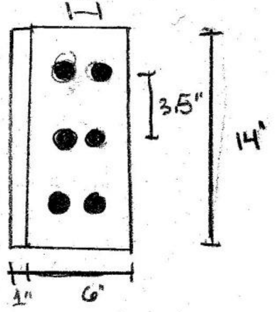
Angle Shear Yield

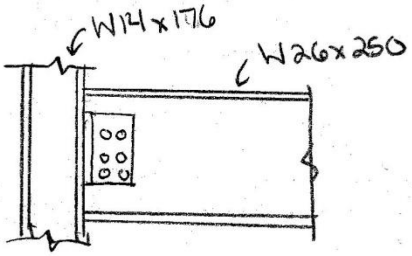
$\phi R_n = 1(0.6)(36)(12)(1) = 259.2K$ N.G.!

$(272.295) = 0.6(36)(4(1)$

$\boxed{L_{min} = 12.6 in}$

→ Use L = 14"





Bolt Bearing on Girder Web

$\phi R_n = 6(0.75)(2.4)(1.25)(1.04)(50ksi) = 702K$

702k > 272.295k ✓ok

Figure 50: Connection Design Page 2

APPENDIX E: STAIR DESIGN

Main Staircase

Difference in height between floors 3-4:
13 feet

Acceptable angles for stair cases:
35.5° to 42.5°

Chosen length per step: 10.0"

9.75"(21 steps) = 204.75" = 17' 3/4" length

13'(12") = 156", 156"/21 steps = 7.428" height

$\tan \theta = 7.428 / 9.75 \Rightarrow \theta = 37.3018°$ OK

Live Load: 100 psf (10"/12") = $83.\bar{3}$ plf

Dead Load:

Steel Pan: 3psf (10"/12) + 3(2)(1.5"/12) = 3.25 plf

Concrete: 148 pcf (1.5"/12)(10"/12) = 15.42 plf

Combination Equation

$1.2(15.42 + 3.25) + 1.6(83.\bar{3}) = 155.7$ plf

155.7 (6'/step) = 934.2 pounds per step

7.428" + 1.5" = 8.928"

$\cos 37.3018 = x / 8.928 \Rightarrow x = 7.1"$

7.1" + 4" (extra space) = 11.1" ⇒ 12"

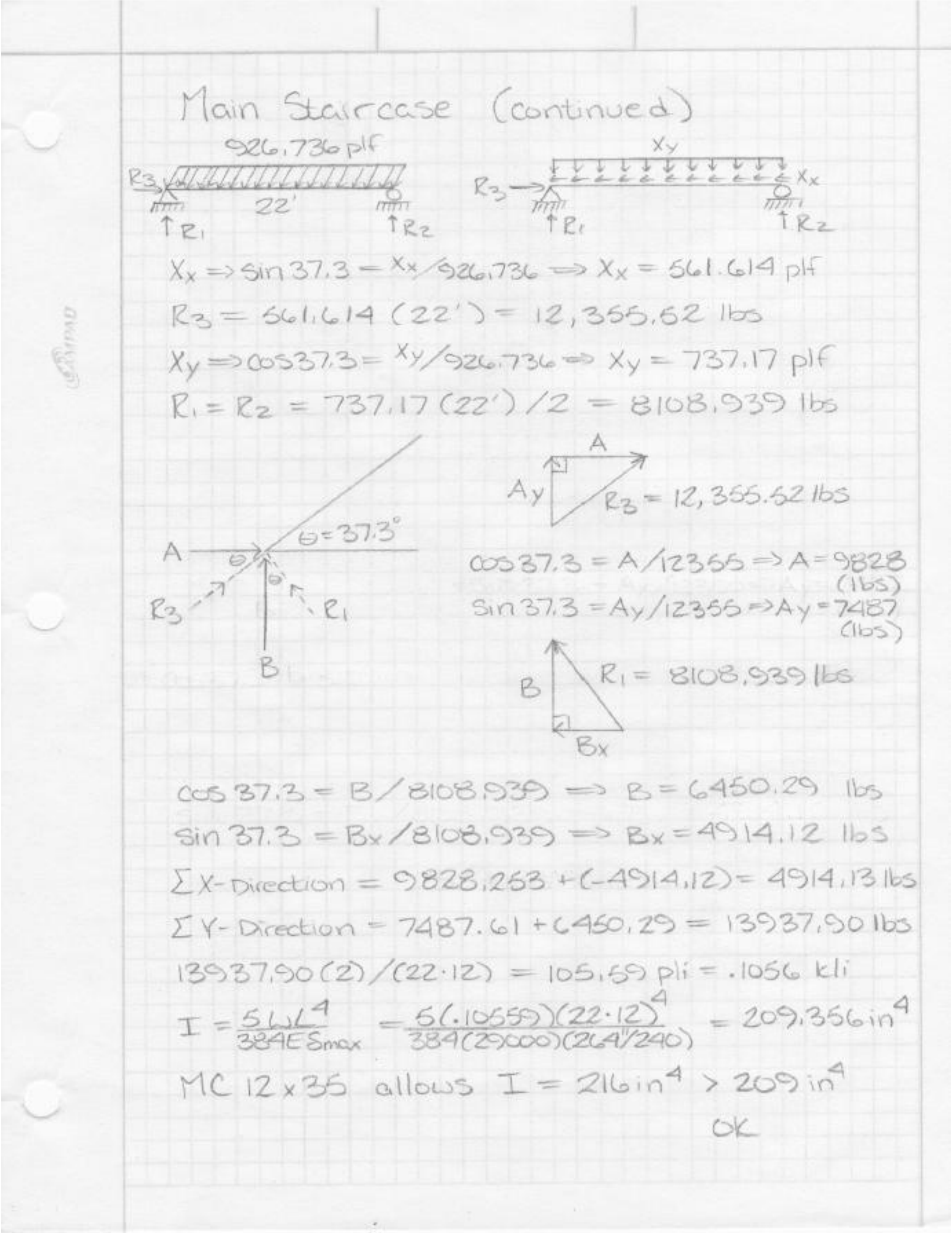
Choose MC 12 x 35 beams

Length $= \sqrt{13^2 + 17.75^2} = 22.001'$

934.2(21)/22 = 891.736 plf

891.736 + 35 = 926.736 plf

Figure 51: Stair Design Page 1



Main Staircase (continued)

$X_x \Rightarrow \sin 37.3 = X_x / 926.736 \Rightarrow X_x = 561.614$ plf

$R_3 = 561.614 (22') = 12,355.62$ lbs

$X_y \Rightarrow \cos 37.3 = X_y / 926.736 \Rightarrow X_y = 737.17$ plf

$R_1 = R_2 = 737.17 (22') / 2 = 8108.939$ lbs

$\cos 37.3 = A / 12355 \Rightarrow A = 9828$ (lbs)

$\sin 37.3 = A_y / 12355 \Rightarrow A_y = 7487$ (lbs)

$\cos 37.3 = B / 8108.939 \Rightarrow B = 6450.29$ lbs

$\sin 37.3 = B_x / 8108.939 \Rightarrow B_x = 4914.12$ lbs

$\sum$ X-Direction = 9828.253 + (-4914.12) = 4914.13 lbs

$\sum$ Y-Direction = 7487.61 + 6450.29 = 13937.90 lbs

13937.90 (2) / (22·12) = 105.59 pli = .1056 kli

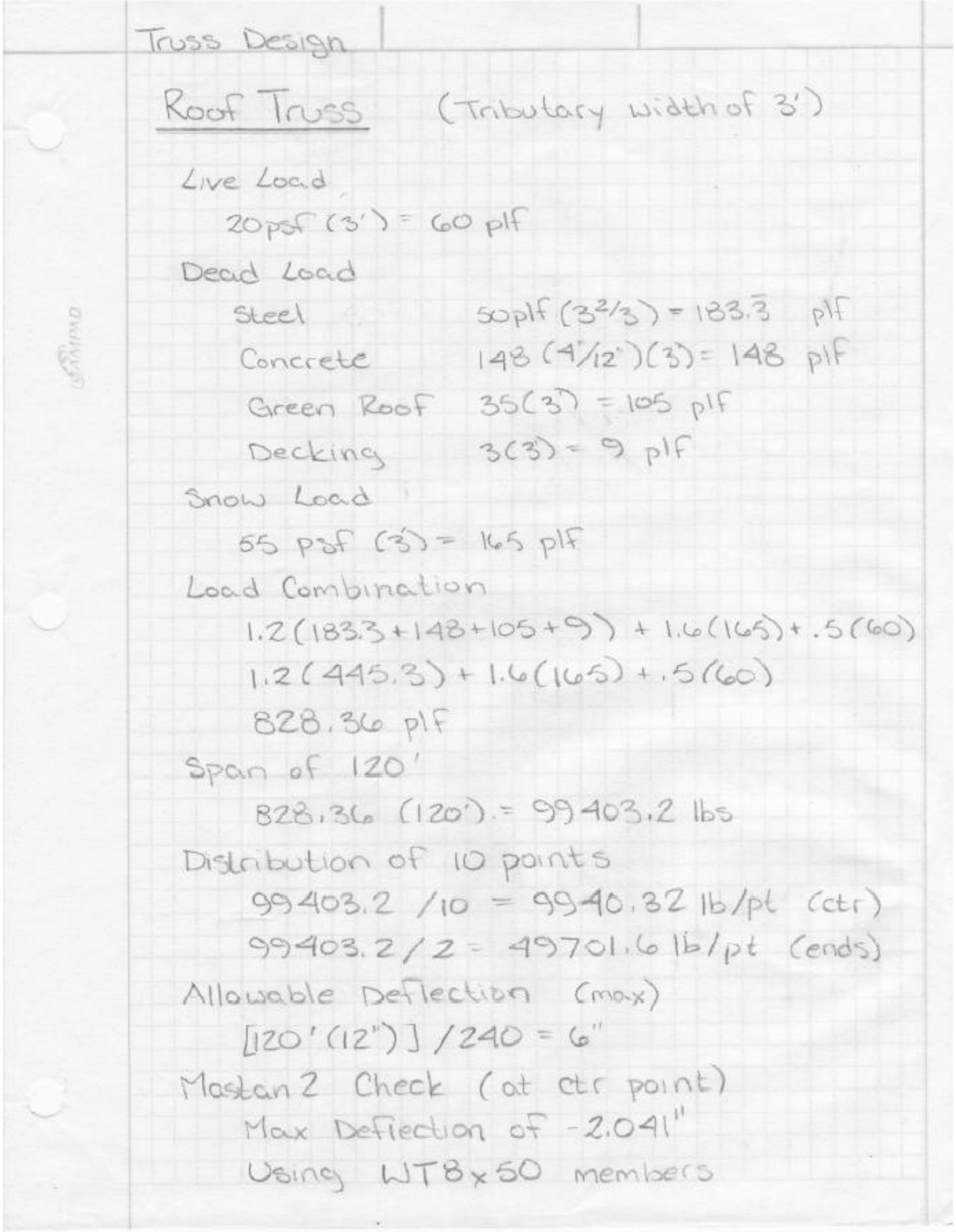
$$I = \frac{5wL^4}{384 E \delta_{max}} = \frac{5(.10559)(22 \cdot 12)^4}{384(29000)(264''/240)} = 209.356 \text{ in}^4$$

MC 12 x 35 allows $I = 216 \text{ in}^4 > 209 \text{ in}^4$

OK

Figure 52: Stair Design Page 2

APPENDIX F: ROOF TRUSS DESIGN



Truss Design

Roof Truss (Tributary width of 3')

Live Load

20psf (3') = 60 plf

Dead Load

Steel	50plf ($3^{2}/_{3}$) = $183.\overline{3}$ plf
Concrete	148 (4"/12")(3') = 148 plf
Green Roof	35(3') = 105 plf
Decking	3(3) = 9 plf

Snow Load

55 psf (3') = 165 plf

Load Combination

1.2(183.3+148+105+9) + 1.6(165) + .5(60)

1.2(445.3) + 1.6(165) + .5(60)

828.36 plf

Span of 120'

828.36 (120') = 99403.2 lbs

Distribution of 10 points

99403.2 /10 = 9940.32 lb/pt (ctr)

99403.2/2 = 49701.6 lb/pt (ends)

Allowable Deflection (max)

[120'(12")] /240 = 6"

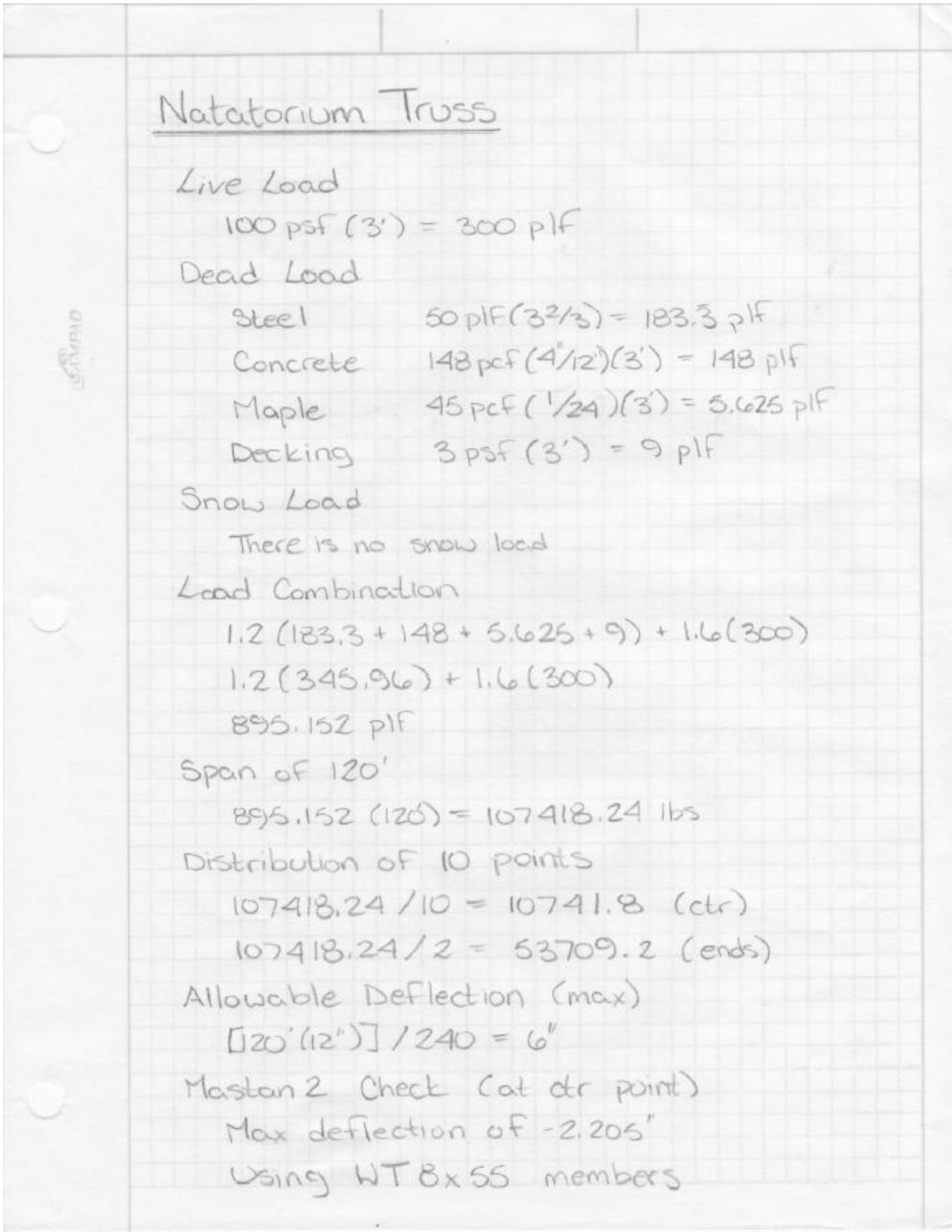
Mastan 2 Check (at ctr point)

Max Deflection of -2.041"

Using WT8x50 members

Figure 53: Roof Truss Design

APPENDIX G: NATATORIUM TRUSS DESIGN



Natatorium Truss

Live Load

100 psf (3') = 300 plf

Dead Load

Steel 50 plf$(3\frac{2}{3})$ = 183.3 plf

Concrete 148 pcf (4"/12")(3') = 148 plf

Maple 45 pcf (1/24)(3') = 5.625 plf

Decking 3 psf (3') = 9 plf

Snow Load

There is no snow load

Load Combination

1.2 (183.3 + 148 + 5.625 + 9) + 1.6(300)

1.2 (345.96) + 1.6 (300)

895.152 plf

Span of 120'

895.152 (120) = 107418.24 lbs

Distribution of 10 points

107418.24 / 10 = 10741.8 (ctr)

107418.24 / 2 = 53709.2 (ends)

Allowable Deflection (max)

[120'(12")] / 240 = 6"

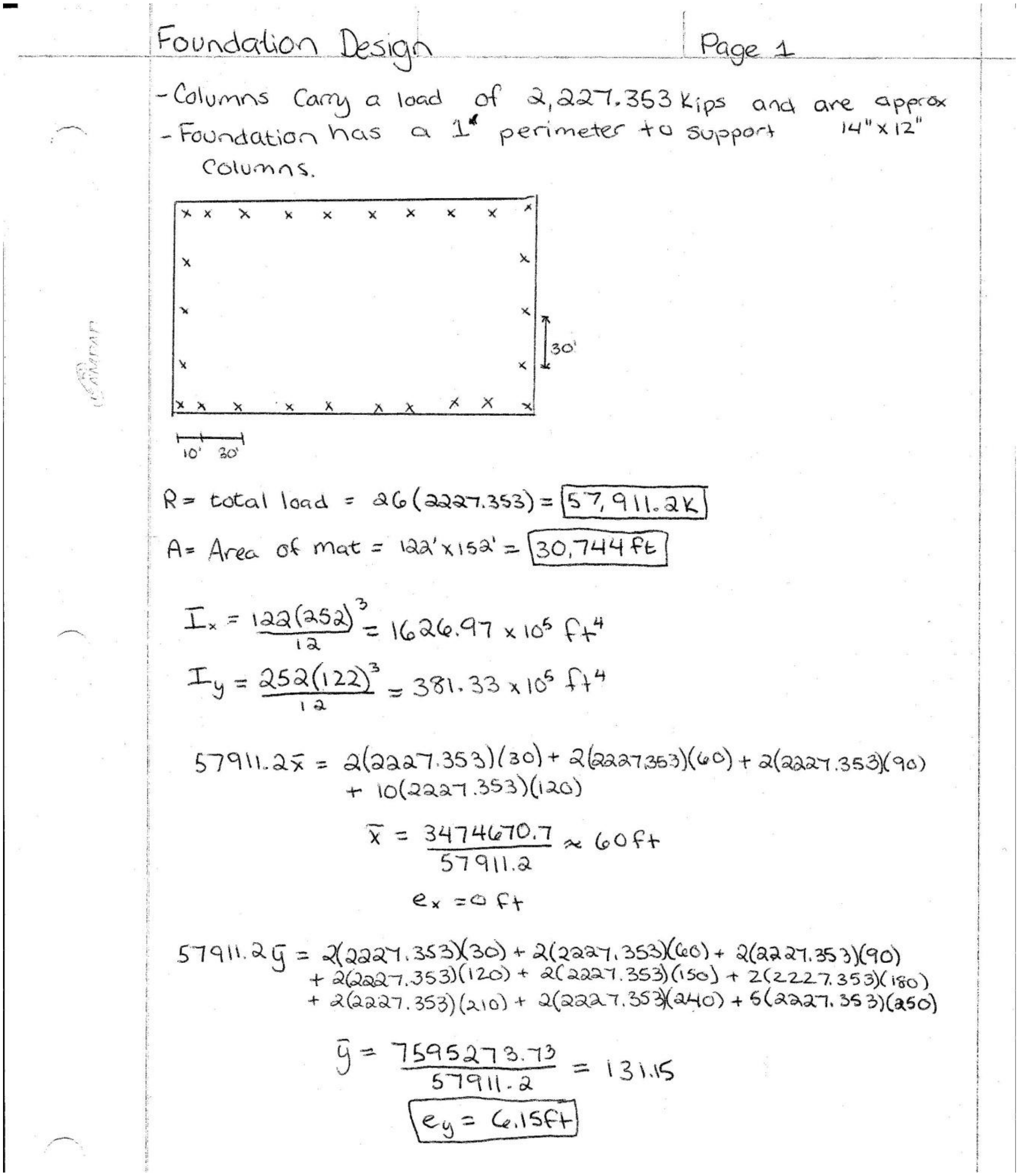
Mastan 2 Check (at ctr point)

Max deflection of -2.205"

Using WT 8x55 members

Figure 54: Natatorium Truss Design

Appendix H – Foundation Design



Foundation Design | Page 1

- Columns Carry a load of 2,227.353 Kips and are approx
- Foundation has a 1" perimeter to support 14"x12" Columns.

R= total load = 26(2227.353) = $\boxed{57,911.2K}$

A= Area of mat = 122'x152' = $\boxed{30,744\text{ ft}}$

$$I_x = \frac{122(252)^3}{12} = 1626.97 \times 10^5 \text{ ft}^4$$

$$I_y = \frac{252(122)^3}{12} = 381.33 \times 10^5 \text{ ft}^4$$

$$57911.2\bar{x} = 2(2227.353)(30) + 2(2227.353)(60) + 2(2227.353)(90) + 10(2227.353)(120)$$

$$\bar{x} = \frac{3474670.7}{57911.2} \approx 60 \text{ ft}$$

$$e_x = 0 \text{ ft}$$

$$57911.2\bar{y} = 2(2227.353)(30) + 2(2227.353)(60) + 2(2227.353)(90) + 2(2227.353)(120) + 2(2227.353)(150) + 2(2227.353)(180) + 2(2227.353)(210) + 2(2227.353)(240) + 5(2227.353)(250)$$

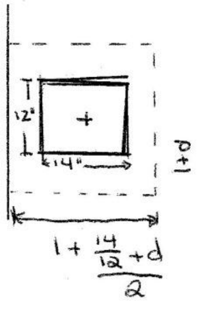
$$\bar{y} = \frac{7595273.73}{57911.2} = 131.15$$

$$\boxed{e_y = 6.15\text{ft}}$$

Figure 55: Foundation Design Page 1

Foundation Design — Page 2

Depth to Satisfy Shear



Perimeter

$$P = 2\left(1.0 + \left(\frac{\frac{14}{12} + d}{2}\right)\right) + 1 + d$$

$$= 2 + \frac{14}{12} + d + 1 + d$$

$$= 4.1\bar{6} + 2d$$

$$dP_{v_c} = LF * Load$$

$V_c = 26.81$ for $f'_c = 3$ksi

$$d(4.1\bar{6} + 2d)(26.81) = 1.6(2227.353)$$

$$d(4.1\bar{6} + 2d) = 132.93$$

$$2d^2 + 4.1\bar{6}\,d = 132.93$$

$$d = 7.117 \text{ ft}$$

USE $D = 8$ ft

Factor of Safety

$$1.2(8\text{ft}) = 9.6\text{ft}$$

→ Use 10ft concrete depth for mat Foundation

Figure 56: Foundation Design Page 2

Appendix I – Retaining Wall Design

Like the columns, the retaining wall was designed using a spreadsheet to aid with the repetitive calculations. There is no hand-written design page for the columns. The spreadsheet can be found in Figure 30.

Appendix J – Original Revit Design

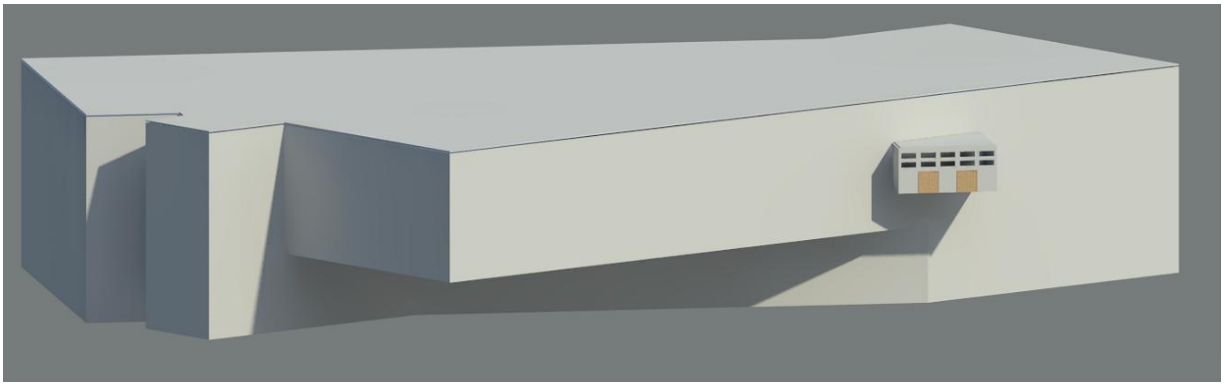


Figure 57: Our Original Revit Design, Front View

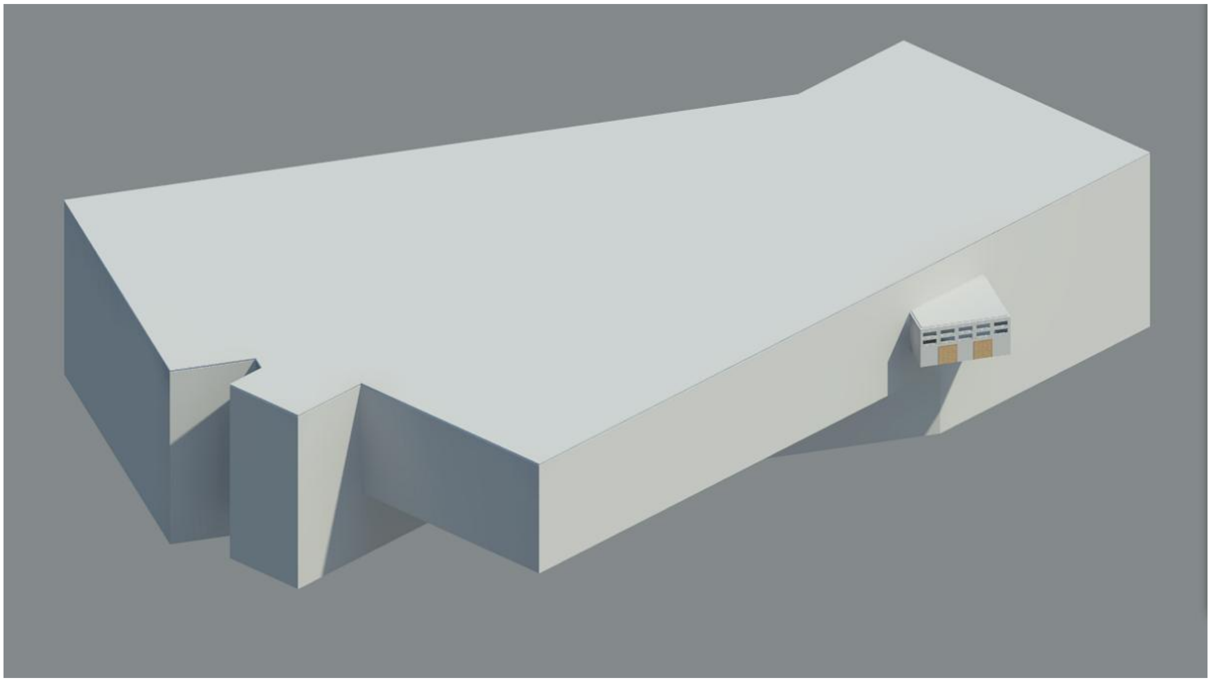


Figure 58: West View

Appendix K: Improved Revit Design

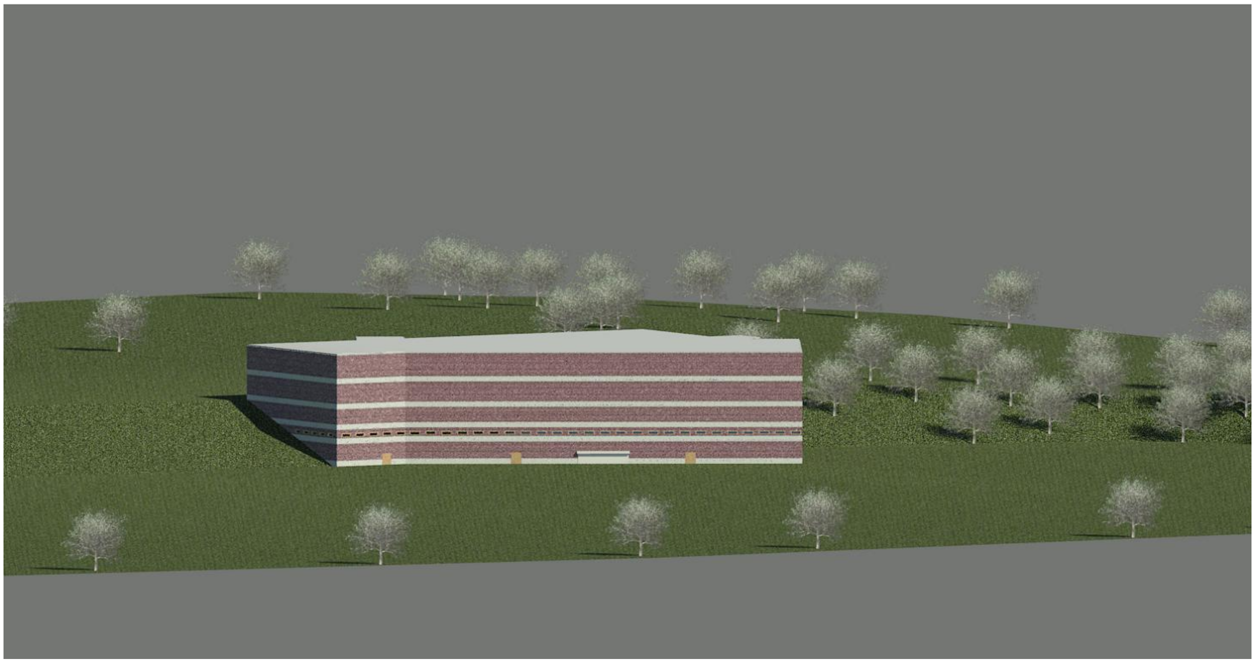


Figure 59: Design View from the West

Figure 60: Design View from the East

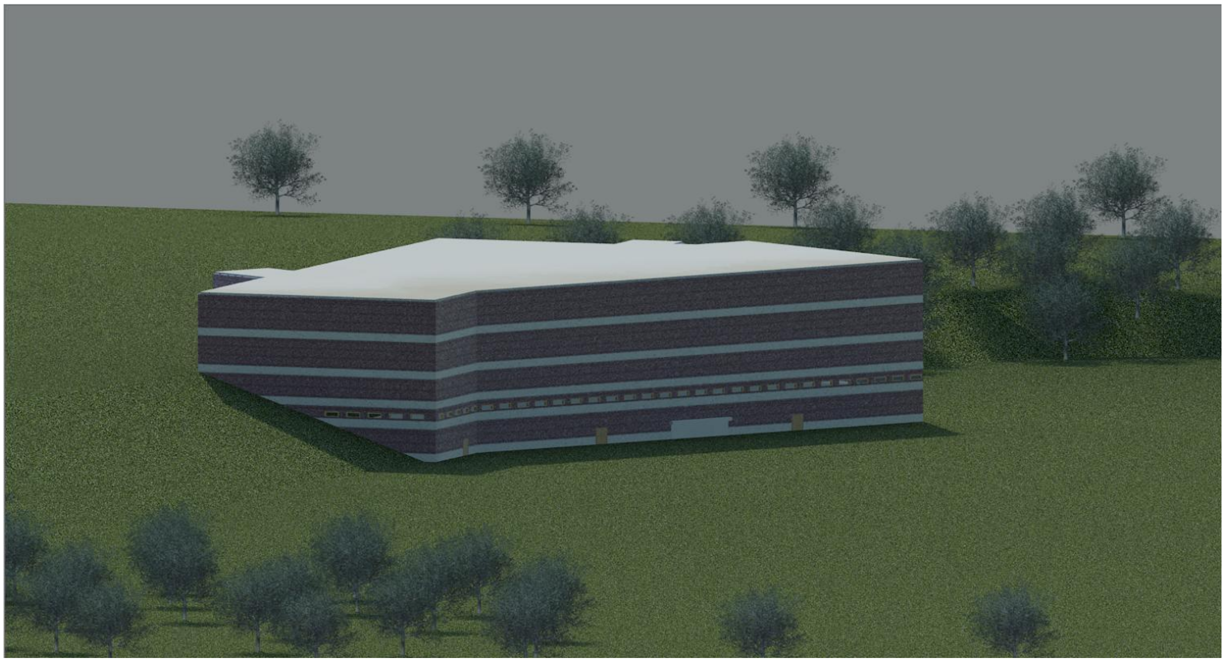


Figure 61: Design View from the North West

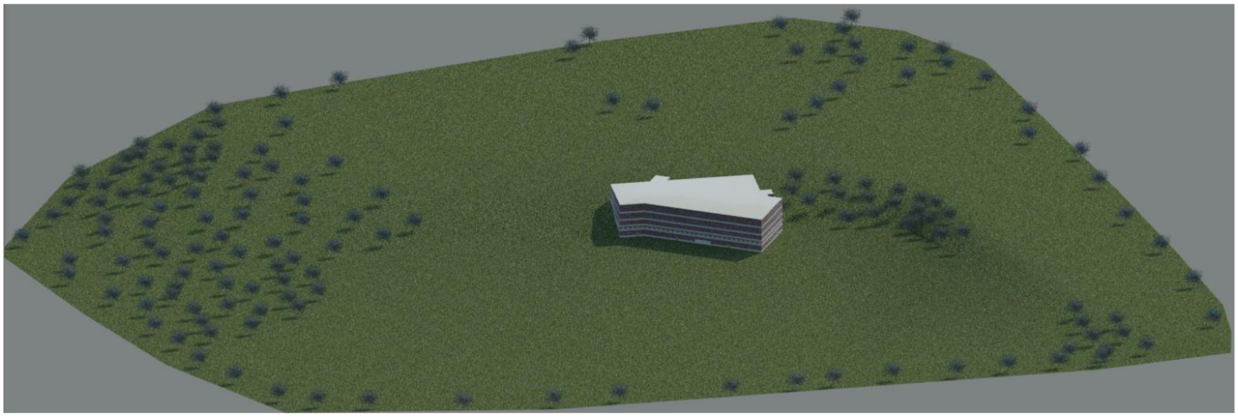


Figure 62: Aerial View

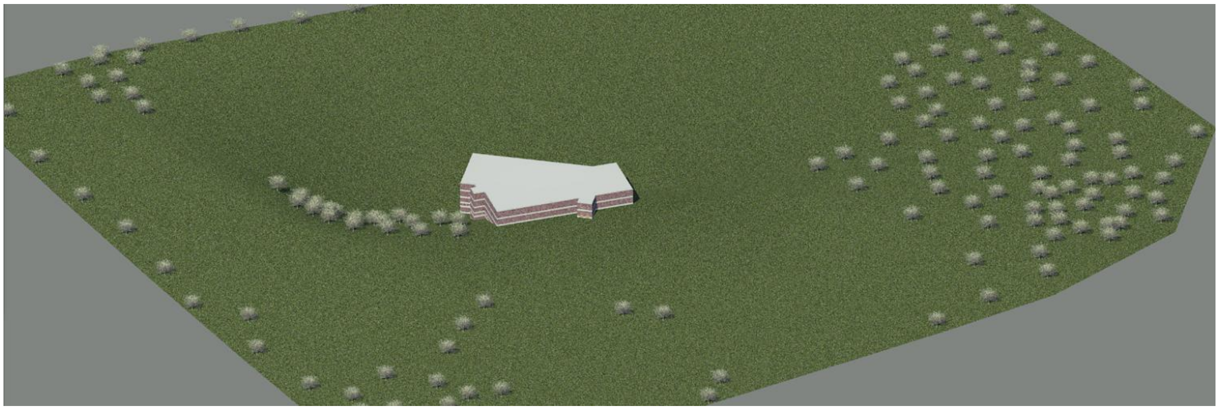


Figure 63: Aerial View from the East

Figure 64: Design View from the South West

APPENDIX L – DESIGNS OF ACTUAL FACILITY

Program and Area Summary	
Baseline Program NSF	99,615
Basement Addition	8,354
Total Net	107,969
Total Gross at 75% (GSF)	143,600
Program Additions NSF	
Locker Rooms, Toilet Rooms, Stadium Toilets, Pool	4,440
Total Gross at 75% (GSF)	5,905
Total Adjusted NSF	112,409
Total Adjusted GSF at 75%	149,519
SD Design Submission	
Total Area GSF at 75%	147,537
Delta (GSF)	
1% below program adjusted GSF (1,982)	(1,982)

Figure 65: Building Space Usage

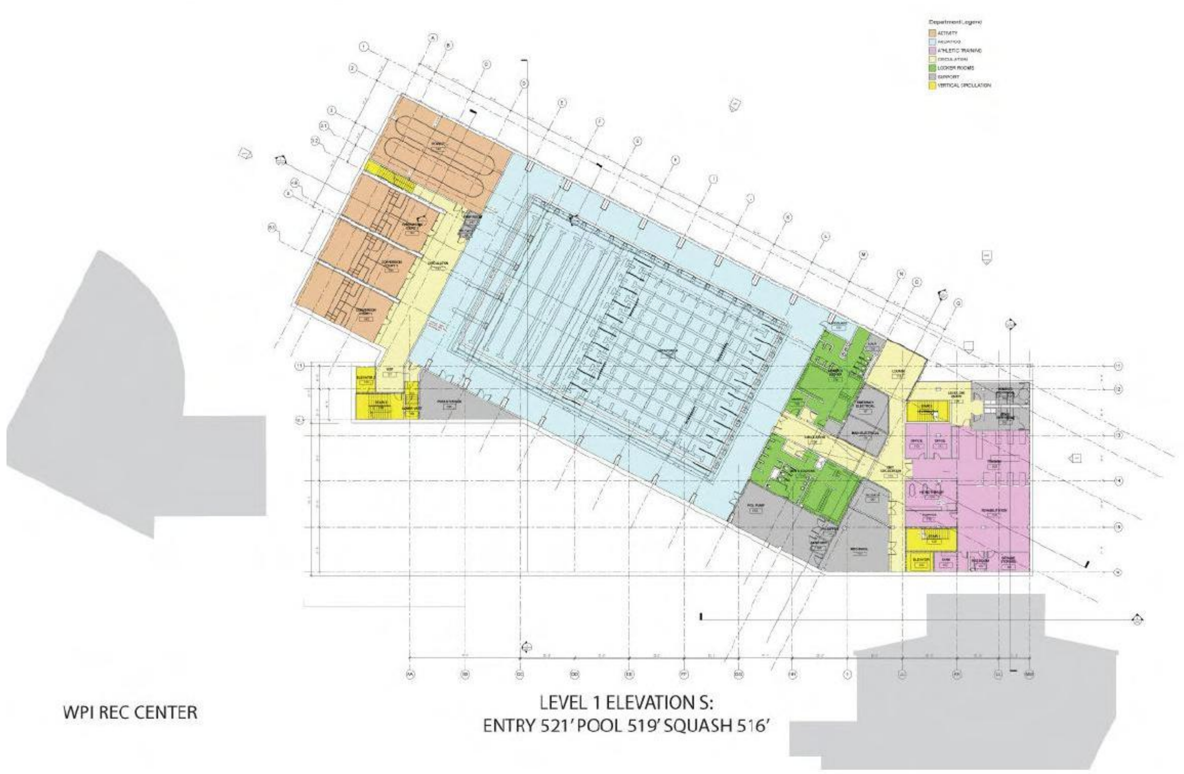


Figure 66: Building Planning Development - Level 1

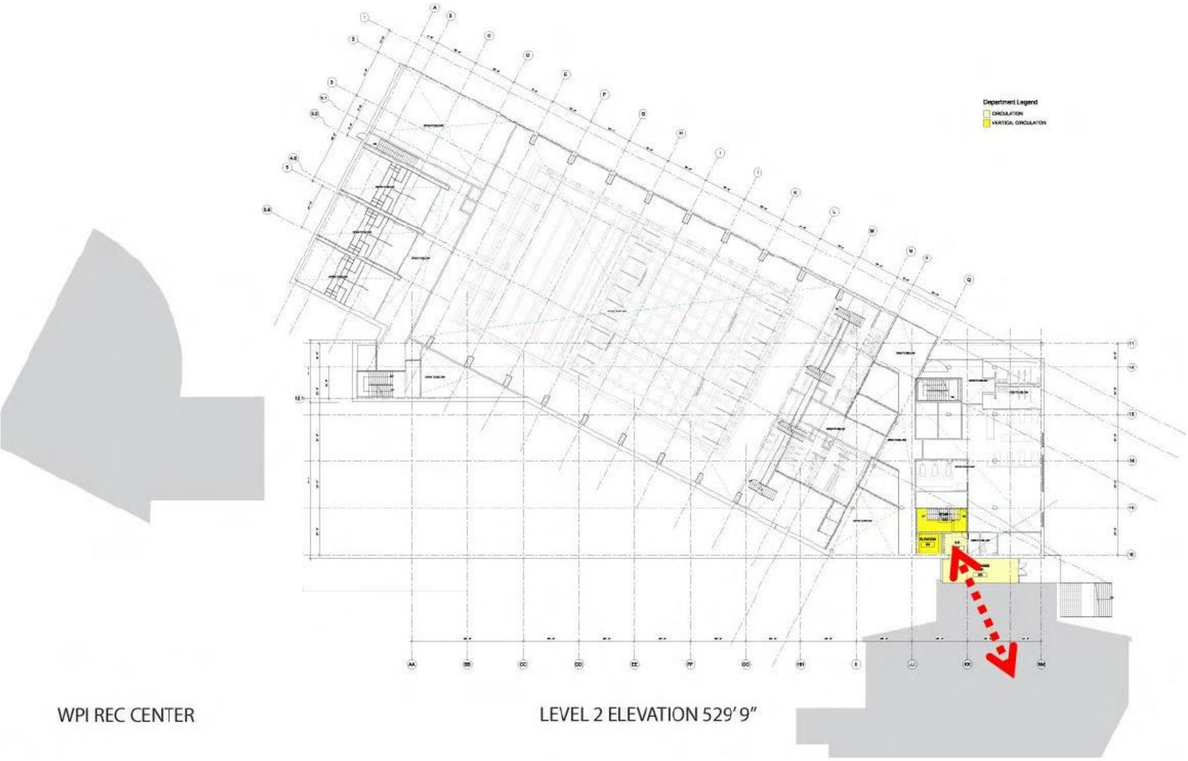


Figure 67: Building Planning Development - Level 2

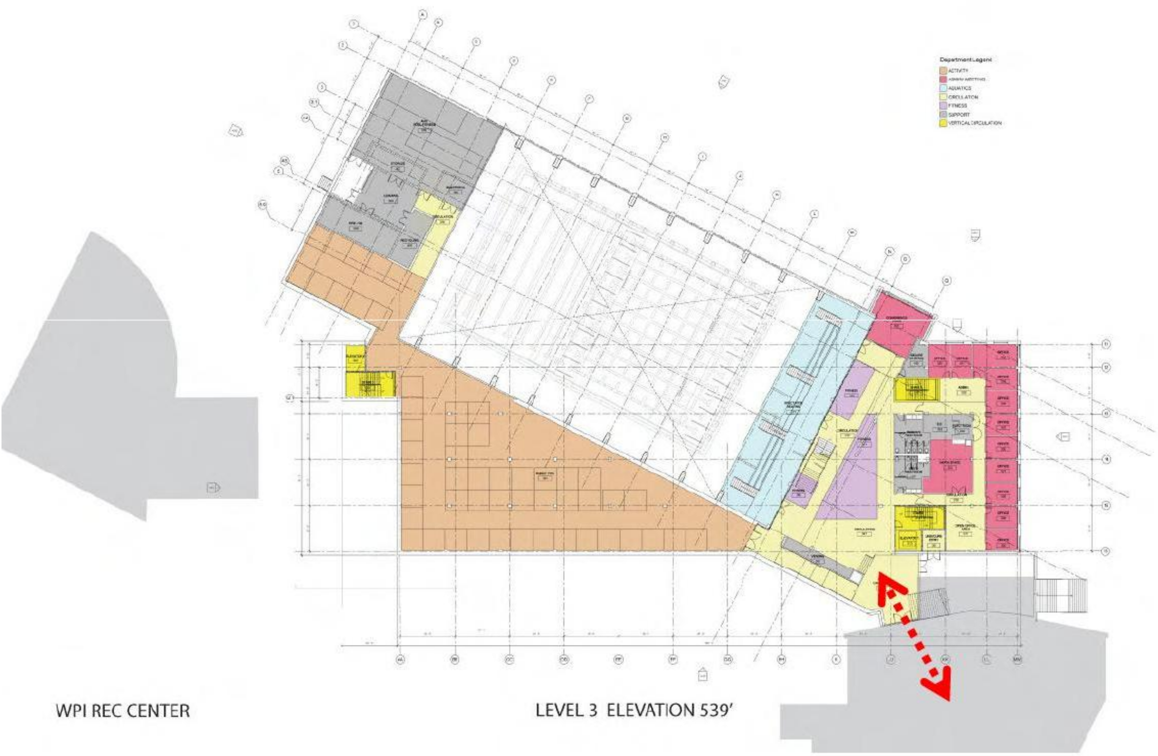


Figure 68: Building Planning Development - Level 3

Figure 69: Building Planning Development - Level 4

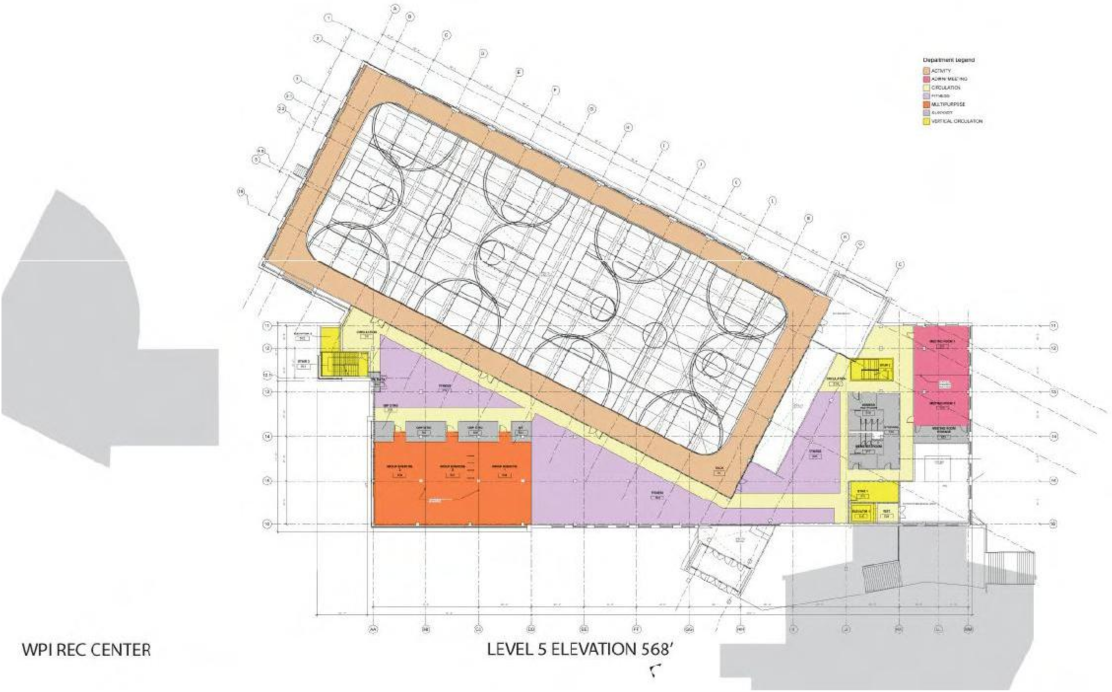
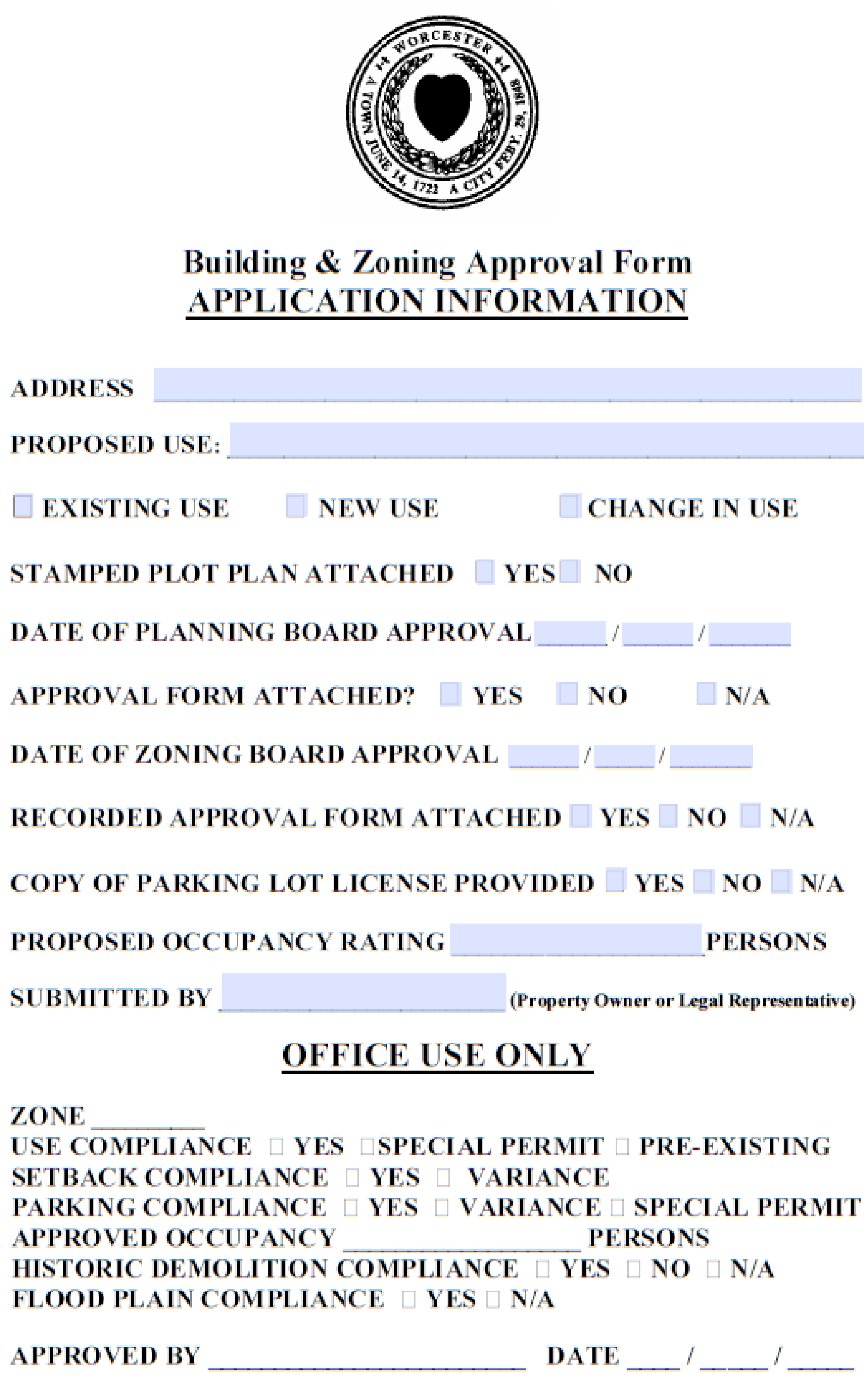


Figure 70: Building Planning Development - Level 5

APPENDIX M: PERMIT APPLICATION



WORCESTER A TOWN JUNE 14, 1722 A CITY FEBY. 29, 1848

Building & Zoning Approval Form

APPLICATION INFORMATION

ADDRESS ____________________

PROPOSED USE: ____________________

☐ EXISTING USE ☐ NEW USE ☐ CHANGE IN USE

STAMPED PLOT PLAN ATTACHED ☐ YES ☐ NO

DATE OF PLANNING BOARD APPROVAL _____ / _____ / _____

APPROVAL FORM ATTACHED? ☐ YES ☐ NO ☐ N/A

DATE OF ZONING BOARD APPROVAL _____ / _____ / _____

RECORDED APPROVAL FORM ATTACHED ☐ YES ☐ NO ☐ N/A

COPY OF PARKING LOT LICENSE PROVIDED ☐ YES ☐ NO ☐ N/A

PROPOSED OCCUPANCY RATING ____________ PERSONS

SUBMITTED BY ____________ (Property Owner or Legal Representative)

OFFICE USE ONLY

ZONE _________
USE COMPLIANCE ☐ YES ☐ SPECIAL PERMIT ☐ PRE-EXISTING
SETBACK COMPLIANCE ☐ YES ☐ VARIANCE
PARKING COMPLIANCE ☐ YES ☐ VARIANCE ☐ SPECIAL PERMIT
APPROVED OCCUPANCY _________________ PERSONS
HISTORIC DEMOLITION COMPLIANCE ☐ YES ☐ NO ☐ N/A
FLOOD PLAIN COMPLIANCE ☐ YES ☐ N/A

APPROVED BY __________________________ DATE ____ / _____ / _____

The Commonwealth of Massachusetts

State Board of Building Regulations and Standards
Massachusetts State Building Code
780 CMR

City of Worcester

Application for a Building Permit

Address

Application Entered By: ______________________

Application Date: ______________________

Plan Reviewed By: ______________________

Date: ______________________

Signature: ______________________

Date Issued: ______________________

Zone: ______ **Proposed Use:** ______ **Census Tract:** ______

Lot Area: ______ square feet

Front yard set back: ______ feet

Rear yard set back: ______ feet

Side yard set back: ______ feet

Side yard set back: ______ feet

Frontage: ______

Site Plan Approval: ______

Parking Approval: ______

ZBA Approval: ______

Zoning Review: ______________________
Zoning Officer

Public Water: ______ **Flood Zone:** ______ **Sewer:** ______

Owner of Record: ______________________

Address: ______________________

Phone Number: ______________________

Cell Number: ______________________

Signature: ______________________

Engineer: ______________________

Architect: ______________________

Address: ______________________

Phone #: ______ **Cell #:** ______

License Number: ______________________

Signature: ______________________

Licensed Construction Supervisor: ______________________

Address: ______________________

Phone #: ______ **Cell#:** ______

License Number: ______________________

Signature: ______________________

Home Improvement Contractor: ______________________

Address: ______________________

Phone #: ______ **Cell#:** ______

License Number: ______________________

Signature: ______________________

City of Worcester

Page Two **Building Permit Application**

Worker's Compensation Insurance Affidavit Submitted: ____________

Description of PROPOSED Work: ______________________________

____

____

Construction Type: ____________ **Floor Area:** ____________ square feet

Number of Stories: ____________ **Use Group:** ____________

Office Use ONLY:

New Construction: ________ **Existing Building:** ________ **Alteration:** ________ **Addition:** ________

Repairs: ________ **Accessory Bldg:** ________ **Demolition:** ________ **Other:** ________

Building Permit Fee: By Office **Permanent Record Retention Fee: By Office** **Sprinkler Fee: By Office**

Other Fee: By Office

Estimated Construction Cost: $ ________.00 Total Fee: $ ________ **Fee Received:** ___/___/___

Received By: ________

Owner Authorization:

I, ______________________, **as owner of the subject property hereby authorize** ______________________, **to act on my behalf in all matters relative to work authorized by this building permit.**

______________________________ ___/___/___

Signature of Owner **Date**

Owner/Authorized Agent Declaration:

I, ______________________ as Owner / Authorized Agent hereby declare that the statements and information on the foregoing application are true and accurate, to the best of my knowledge and belief.

Signed under the pains and penalties of perjury.

____

Print Name

______________________________ ___/___/___

Signature of Owner / Authorized Agent ***Date***

Building Permit Number ______________

Street Address: ____

Do you intend to do interior work only? **Yes:** ________ **No:** ________

If Yes, you do not need to answer any of the questions below.
If No, please answer questions below.
****

If work includes exterior building activity and/or site work, please answer all the following questions.

1. Will any activity take place within 100 feet of a pond, lake, brook, stream, marsh or swamp?
   YES: ______ NO: ______
2. Does this property fill up with water after a rainstorm and hold it for a while?
   YES: ______ NO: ______
3. Will any activity take place within 100 feet of a storm drain component (catch basin, etc)?
   YES: ______ NO: ______
4. Is the property within a flood plain designated under the National Flood Insurance Program?
   YES: ______ NO: ______
5. Is this property steeply sloped? YES: ______ NO: ______
   (over 15% slope - pre or post construction)
   a. If no, will activity alter at least 10,000 square feet of land?
      YES: ______ NO: ______
   b. If yes, will activity alter at least 5,000 square feet of land?
      YES: ______ NO: ______

____
Signature

______________________________ ______________________
Print Name Telephone Number

IF YOU ANSWERED YES TO ANY OF THE ABOVE QUESTIONS, YOU MAY NEED APPROVAL FROM THE WORCESTER PLANNING BOARD OR CONSERVATION COMMISSION BEFORE YOU START WORK.
This is not a legal determination. If you have any doubts or questions, it is your responsibility to notify the office of Division of Land Use.

For additional information regarding Local Wetlands Protection Ordinance and the Massachusetts Wetlands Protection act contact:

Department of Public Works
Engineering Division
20 East Worcester Street
Worcester, MA 01604
(508) 799-1454

Department of Inspectional Services
Worcester, Massachusetts

Building Unit

John R. Kelly
Acting Building Commissioner

Amanda M. Wilson, Director
Housing/Health Inspections

Joseph R. Mikielian
Commissioner

Building Permit # ________20___ will be issued subject to compliance with the requirements of the Commonwealth of Massachusetts State Building Code and the City of Worcester Zoning Ordinance.

Section 114.9 Posting of Permits:

A copy of the building permit provided by the Code Enforcement Division shall be kept in view and protected from the weather on the site of operations, open to public inspection during the entire time of prosecution of the work and until the certificate of occupancy shall have been issued. The building permit shall serve as an inspection record card to allow the building official conveniently to make entries thereon regarding inspection of the work.

Section 114.10 Notice of Start:

At lease twenty-four (24) hours notice of start of work under a building permit shall be given to the building official.

READ BEFORE SIGNING

Signature: ____________________

Print Name: ____________________

Address & Zip Code: ____________________

Telephone: ____________________

Department of Inspectional Services
Worcester, Massachusetts

Building Unit

Joseph R. Mikielian
Commissioner

John R. Kelly
Acting Building Commissioner

Amanda M. Wilson, Director
Housing/Health Inspections

AFFIDAVIT

In accordance with Article 1 Section 111.5 of the Massachusetts State Building Code, I certify that all debris resulting from work associated with Building Permit # ______________
at property ______________________________
Will be properly disposed of at:

____,
A licensed solid waste disposal facility as defined by MGL C 111 & 150 A.

Date	Signature of Permit Applicant
	Print Name of Applicant
	Firm Name (if any)
	Address

The Code Enforcement Division acting under Chapter 8, Article 7 of the 1996 Worcester Revised Ordinances requires proof of disposal of debris generated as a result of this permit. The proof shall be a dated and signed receipt from the licensed disposal facility containing the following information:

A description of the debris, the weight and volume of the debris and the location of the disposal facility. The receipt must also have a signature of the owner/operator of the disposal facility.

Failure to comply with requirements of this ordinance will result in enforcement action by the City of Worcester.

CONSTRUCTION CONTROL

PROJECT NUMBER: ____

PROJECT TITLE: ____

PROJECT LOCATION: ____

NAME OF BUILDING: ____

NATURE OF PROJECT: ____

In accordance with section 116.0 of the Massachusetts State Building Code, I,
______________________________ Registration No. ______________________

Being a Registered Professional Engineer/Architect hereby certify that I have prepared or directly supervised the preparation of all design plans, computations and specification concerning:

___ENTIRE PROJECT ___ARCHITECTURAL ___STRUCTURAL

___MECHANICAL ____FIRE PROTECTION ___ELECTRICAL

___OTHER (SPECIFY)

For the above named project and that to the best of my knowledge, such plans, computations and specifications meet the provisions of the Massachusetts State Building Code, all acceptable engineering practices and all applicable laws and ordinances for the proposed use and occupancy. I further certify that I shall perform the necessary professional services and be present on the construction site on a regular periodic basis to determine that the work is proceeding in accordance with the documents approved for the building permit and shall be responsible for the following specified in Section 780 CMR 116.0, 6th edition of the Massachusetts State Building Code.

SEAL

____
SIGNATURE

Subscribed and sworn to before me this _____ day of ________________2___

Notary public ________________________________

My Commission expires________________

Print Form