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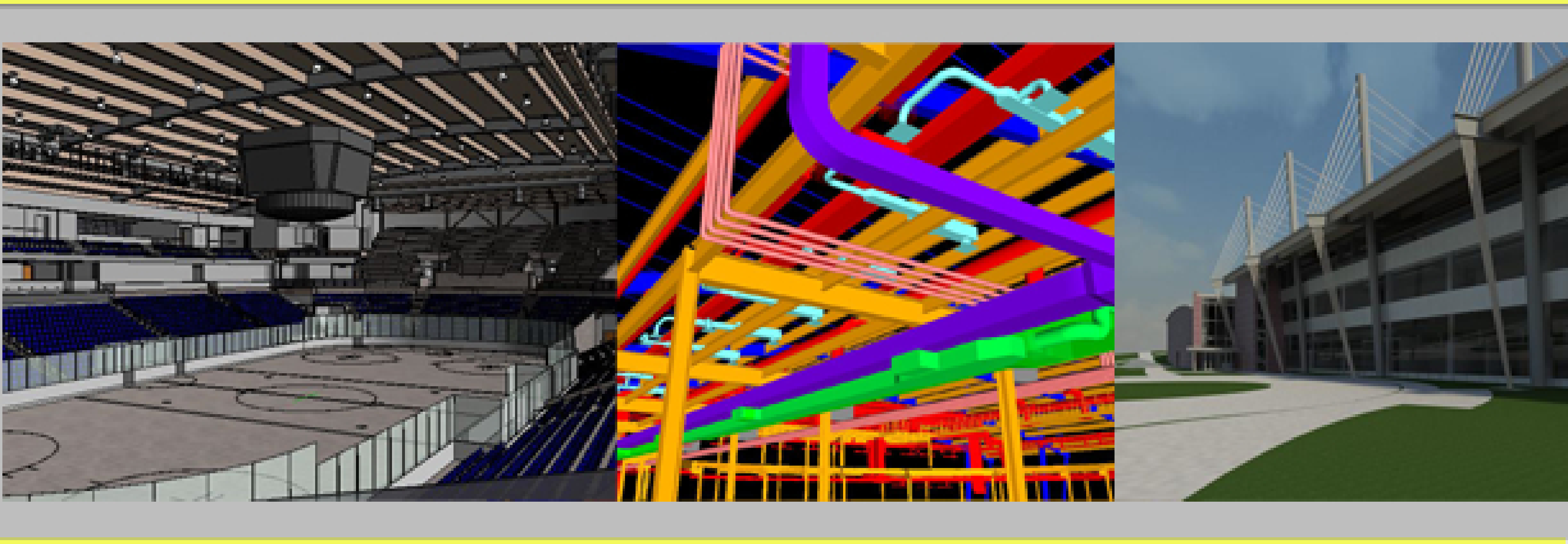

Penn State University
Ice Hockey Arena

lightsout DESIGN

BIM/IPD Thesis FINAL REPORT

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Executive Summary

Lights-Out Design is pleased to present the team's year-long senior capstone thesis project for AE482. Over the course of the year, the team has collaboratively assessed the current Penn State Ice Hockey Arena design and targeted areas where the team could explore design enhancements through integrated project deliver and building information modeling platforms. The Lights-Out Design team consists of a student from each discipline within Architectural Engineering at Penn State. Each discipline came into the IPD/BIM thesis with sufficient background in building information modeling programs. Together, Lights-Out Design has analyzed engineering systems of the Penn State Ice Hockey Arena using BIM software in an IPD environment. Specifically, the team made efforts to analyze and redesign the long span roof, the exterior facade, and to analyze and redesign the existing mechanical system to improve energy efficiency.

The existing arena roof consists of long span steel trusses that span 192 feet over the arena bowl with 30 foot steel joists above the north and south concourses. From an early design stage, Lights-Out Design wanted to investigate the possibility of spanning the arena roof the entire 252 feet from exterior wall to exterior wall. In order to accomplish this, a unique system would be necessary. A cable-stayed solution was selected after careful investigation into other cable structures. Throughout the semester, a cable-stayed roof was designed and compared to the existing design. The new roof proved to be very expensive and significant changes would be necessary to improve the feasibility of the cable-stayed roof.

After deciding to design a cable structure, it became necessary to redesign the existing façade. The existing façade consisted of mainly a brick veneer with slotted windows along the north and south concourse. With the teams new design goal, the façade was redesigned to be lighter through the use of glass and metal panels. A thermal analysis was conducted on the new façade to ensure that the arena would remain energy efficient. After conducting the analysis, it was discovered that the move to glass and metal panels would not impact the energy efficiency of the arena and would only cost $85,701 over the life-cycle of the arena, a mere $3,000 extra per year for 30 years. A new lighter façade is clearly feasible for the arena.

The final major redesign revolved around the community rink roof and the energy efficiency of the mechanical system. With the community rink being used extensively throughout the year, Lights-Out Design wanted to provide a greater aesthetic to the rink through an arched roof and infusing daylighting. In turn, after a preliminary analysis of the mechanical system, the team concluded that mechanical units had to be relocated. Through moving mechanical units to a mechanical loft, the team was able to save close to a million dollars in duct expenses and create flexibility in the design of the community rink roof. This redesign posed major coordination challenges to Lights-Out Design and provided a great opportunity to implement numerous BIM programs to ensure coordination between the engineering systems.

Through each phase of analysis and design, communications between team members and model sharing software needed continuous input. Lights-Out Design chose to continue use of Revit analytical models provided by the design team and share information across a spectrum of BIM software.

Project Background

The Penn State Ice Arena is an approximately 216, 240 square foot arena that will house two ice sheets, a 6,000 seat main arena, a 300 seat community rink, food and retail facilities, offices for the NCAA Division 1 men's and women's hockey teams, and other team facilities. The project is owned by The Pennsylvania State University and is located on the University Park campus just south of the intersection of Curtin Road and University Drive. The arena neighbors the Shields Buildings to its north, the Tennis Facility to the southwest, and Holuba Hall to the south. The main goal of the arena is to provide a championship quality facility for the new hockey teams.

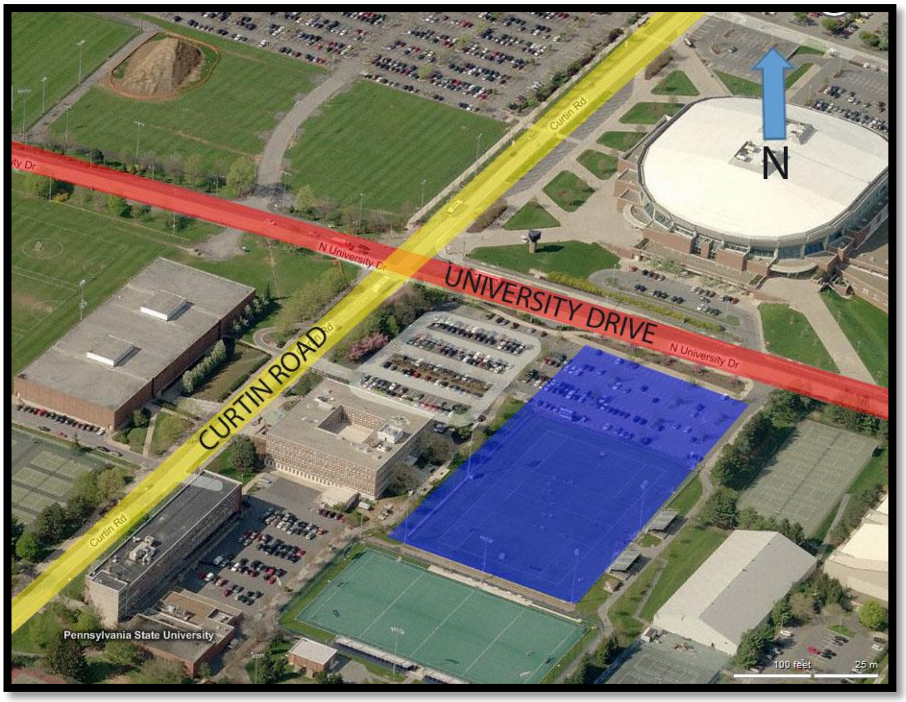


Figure 1. Site Plan of the Penn State Ice Arena (Image from Bing.com)

There are three occupiable floors of the arena. The base level is the Event Level at an elevation of 1156'-1" above sea level. The second level is the Main Concourse Level at 1176'-10" above sea level and the third level is the Club Level, which sits 1206'-1" above sea level. Because the site slopes approximately 21' from the north side of the arena to the south side of the arena, the two main entrances to the main arena occurs at the Main Concourse Level, where entry to community rink on the south of the arena occurs at the Event Level (See Appendix F for selected architectural drawings).

The Event Level houses the community rink which requires locker rooms, skate rentals, and concessions. Both the ice making system and ice supplies are located in the northwest corner of the Event Level providing direct access to both ice sheets. On the north side of the entry level are the division 1 home locker rooms and team lounges, as well as physical therapy rooms. Along the east side of the Event Level, there are rooms for strength training and skill development. The loading dock for the arena is located in the southeast corner of the Event

Level and provides direct access to the main ice sheet. The administrative facilities for the Division 1 hockey teams are located along the south side of the Event Level.

The Main Concourse level serves as the main entry to seating bowl of the main ice sheet. The two entrances are located in the northwest and northeast corners of the arena. In addition to providing direct access to the main seating bowl for patrons, the Main Concourse contains the concession stands, restrooms, and press box. A special banquet facility is located in the southeast corner and provides spectacular views of Mount Nittany.

The Club Level is accessed by a large open stairway in the lobby along the east side of the arena. The Club Level provides 12 suites along the north side of the arena with the potential of adding 12 future suites along the south side of the arena. The suites allow for a more relaxed area to watch games and events with direct access to food and drinks provided by a support staff. Again, there is a special gathering area in the southeast corner of the arena to provide views of Mount Nittany.

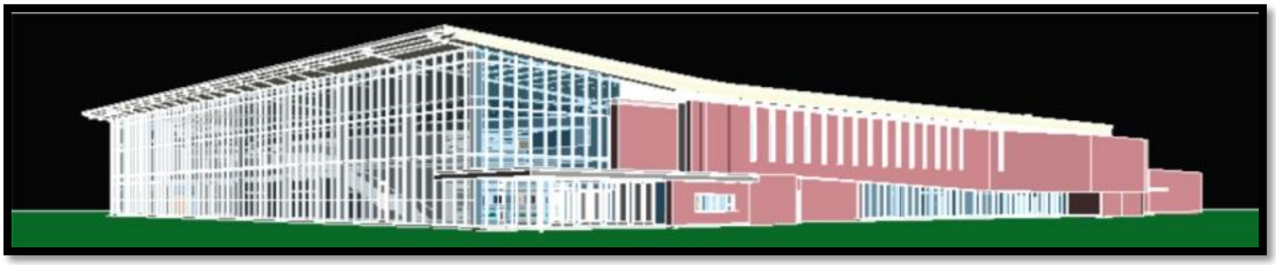


Figure 2. A 3D rendering of the Ice Arena's Main Entrance
(Image adapted from Crawford Architects)

The façade of the Ice Arena reflects on the architectural style of Penn State University with a mix of traditional brick and glass. There is a large class curtain wall that spans the entire façade along University Drive providing a welcoming look into the Arena from the exterior. While the front east façade presents a large open feel, the north and south facades of the arena present a more closed anchored feeling of brick mixed with small glass accents. At the entry level of both the north and south façade, there is a 9' glass curtain wall. Above the entry level, there is a large brick façade with long 2' x 27' slot windows that light the outer concourses. The facades of the community rink are simple brick facades.

Construction Management

The Penn State Ice Arena has a hard completion date of August 2013 in order to be ready for the Penn State Hockey team's inaugural season in the Big Ten Conference. Funding for the project was attained by a donation of $88 million from an alumnus. Roughly $77 million has been set aside for the initial cost of the arena. Mortenson Construction has been named the Construction Manager for the project, and the rest of the project is still in the process of accepting bids for work.

The project site itself is located to the immediate west of University Drive and directly to the south of Shields Building, in the northeast corner of campus. The University's athletic facilities are in the surrounding vicinity, with the field hockey fields to the arena’s west, the football practice facilities to its south, and the Bryce Jordan Center and Multi Sport Facility to its east. Because of its location on campus, the project will encounter challenges in site logistics as it must not obstruct and must protect pedestrian traffic on the surrounding sidewalks and vehicular traffic on adjacent University Drive. For the size of the arena’s footprint, the job site is limited and therefore, logistics will be a concern as there will not be enough room on site for equipment and material storage if not managed carefully. Another constraint of the site is the major utilities duct bank that runs west to east across the north edge of the job site. Work must not damage the duct bank in any way as it is the source of electricity, heat, and plumbing for a huge portion of the University’s campus. An additional restriction for the job site is the soil and rock content of the site, which the geological survey reports contains pinnacle rock very close to the surface, which will likely require blasting for deep excavation.

Existing Structural

Foundation

The foundation of the Penn State Ice Arena is a combination of spread footings, strip footings, and micropiles. To combat the slope of the site, foundation walls exist on the North, East, and West sides of the building. Supporting the foundation walls are strip footings ranging from 1’-6” deep to 2’ deep. On the South side of the arena, grade beams connect the spread footings underneath the exterior columns. In a designated area, micropiles are used instead of spread footings due to the pinnacled nature of the rock on the site of the arena (See Figure 3). Where pile caps were necessary, steel pipe piles ranging in diameter from 5 ½” to 9 ¾” extend through the soil allowing friction to carry the load of the building. The geotechnical report suggested spread footers for columns that carry a load of less than 150 kips, micropiles w/ 5 ½” steel pipes for columns that carry less than 350 kips, and micropiles w/ 7” or 9 ¾” steel pipes where the load was greater than 350 kips.

The slab on grade has some special considerations due to the ice surface needed for both the community and main ice rink. Underneath the two ice surfaces, there is a 6” slab on grade with a 4” thermal barrier and a 10” sand base. It is imperative that the slab under the ice rinks be thermally isolated to prevent frost heave and thaw weakening. This ensures that the ice surface remains flat and uncompromised. The rest of the building has a 6” slab on grade with less strict thermal isolations. The 28 day compressive strength required for formed concrete slabs and beams is 5,000 psi. All other concrete elements require a 28 day compressive strength of 4,000 psi.

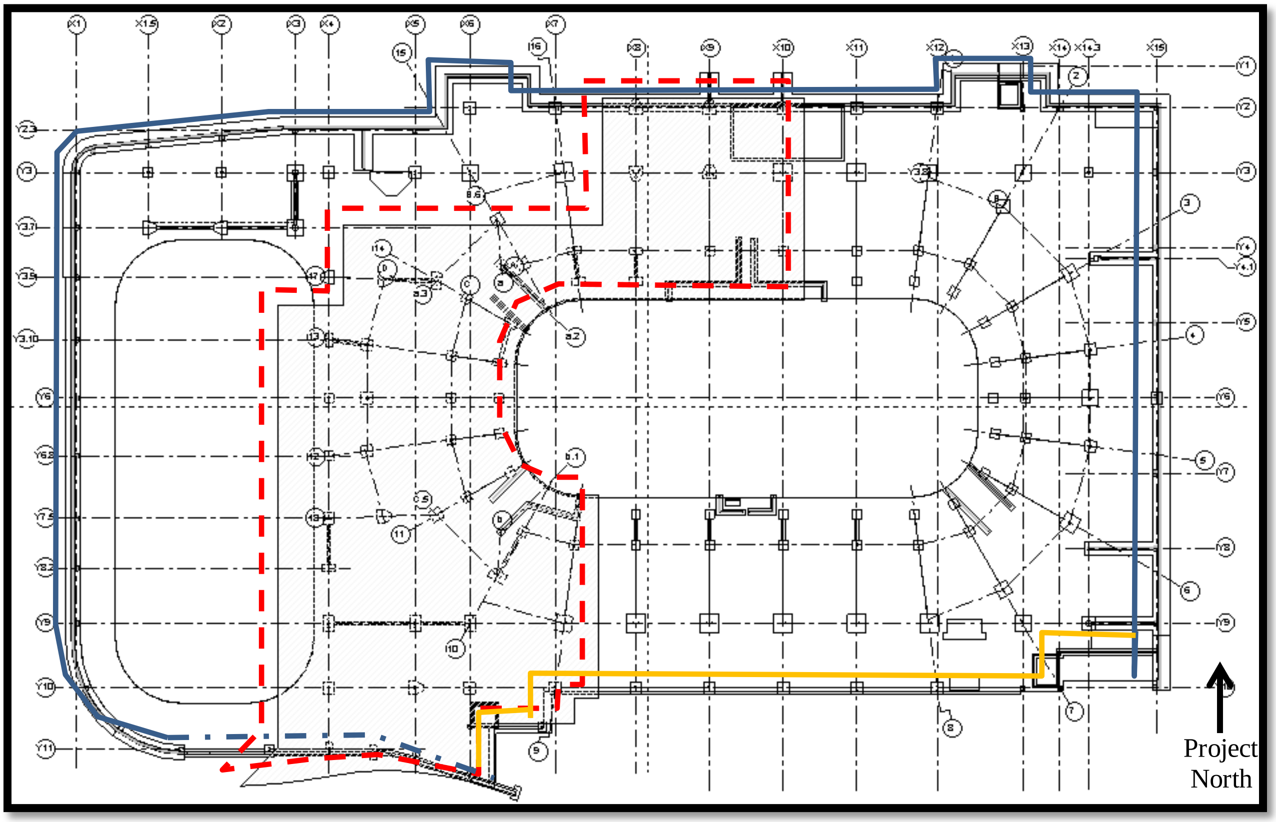


Figure 3. Layout of Foundation System
(Plans Courtesy of Thornton Tomasetti)

Legend:
— Foundation Walls (Dashed= 2' Wall)
- - Area of Micropiles
— Grade Beams

Floor System

The Main Concourse Level and the Club Level are supported by a one way composite steel beam system with varying bay sizes due to the oval seating of the main bowl. The most typical bay size is 32' x 28' along the long sides of the main bowl. The floor deck consists of 3" 18 gauge metal deck with 4 ½" normal weight concrete topping. The floor deck of the typical bay is supported by W24 girders and W18 beams that frame into exterior W14 and interior W24 columns. The main seating bowl consists of precast concrete seating supported by W30 rakers which frame into the W24 columns at the Main Concourse Level.

Roof System

The most difficult part of a long span structure is how to span the long distance required between supports. A 196' steel truss spans the roof over the main seating bowl and main ice rink. The truss consists of W14s for both the top and bottom chord with double angles for web members. There are also vertical W14 members at certain panel points. The top chord of the truss is sloped slightly as the truss is 10' thick at the ends and 12'-6" thick at its center. The truss system supports a center scoreboard, rigging loads, and catwalk, in addition to the roof deck. The roof deck consists of 3" 18 gauge metal deck type N with a built-up membrane roofing material. The bottom chord of the truss sits 50’-0” above the floor of the arena. The overall max height of the high roof is 65’-0” from the top of the roofing material to the Entry Level slab.

The roofs of the surrounding parts of the buildings are supported by steel joists or conventional steel framing. The roof over the Club Level concourse sits approximately 6’ below the high roof supported by the roof trusses. The Club Level roof is supported by 24K8 steel joists. The roof over the lobby area along University Drive slopes slightly up and is supported by taper W30x90s and custom 36LH long span joists. The roof over the student section on the west side of the main bowl is supported by W14s and sits approximately 8’-6” below the high roof. Both the lobby roof and the roof above the student section frame into their respective end steel truss. The roof over the community rink consists of 68DLH16 long span steel joists leaving a clear height of approximately 32’-6” between the bottom chord and the ice slab.

Lateral System

To resist the governing lateral loads caused by wind, the arena relies on a combination of concrete shear walls, braced frames, and moment frames. Shear walls are located on the entry level and extend from the slab on grade to the Main Concourse Level (See Figure 4 for location of shear walls). Because it is necessary to have large open concourse areas, moment frames are used along the concourse corridors. Braced frames are used in the walls behind the student section and extend from the Main Concourse Level to the roof (See Figure 5 for location of frames). There are also braced frames located on the edge of the upper roof that is spanned by the large roof trusses. The steel trusses also aide in the lateral resistance.

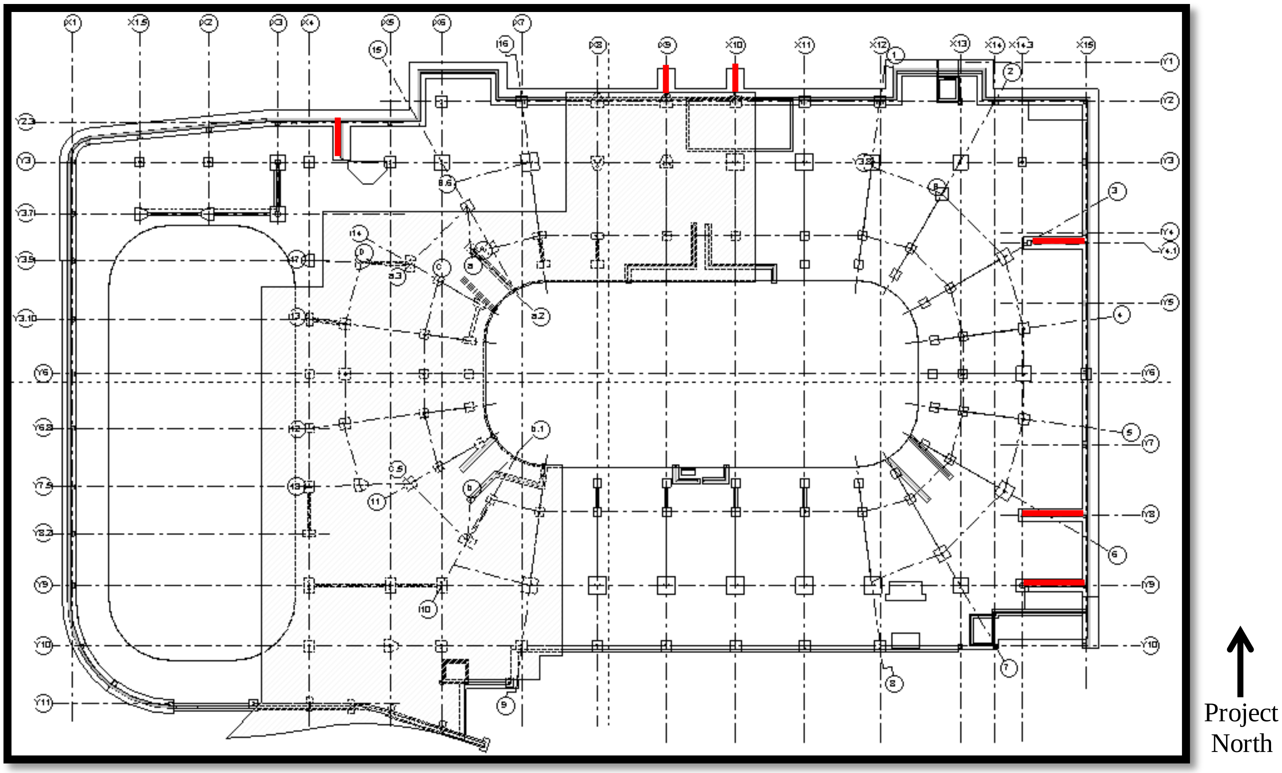


Figure 4. The red lines designate the location of shear walls at the Event Level (Plans Courtesy of Thornton Tomasetti)

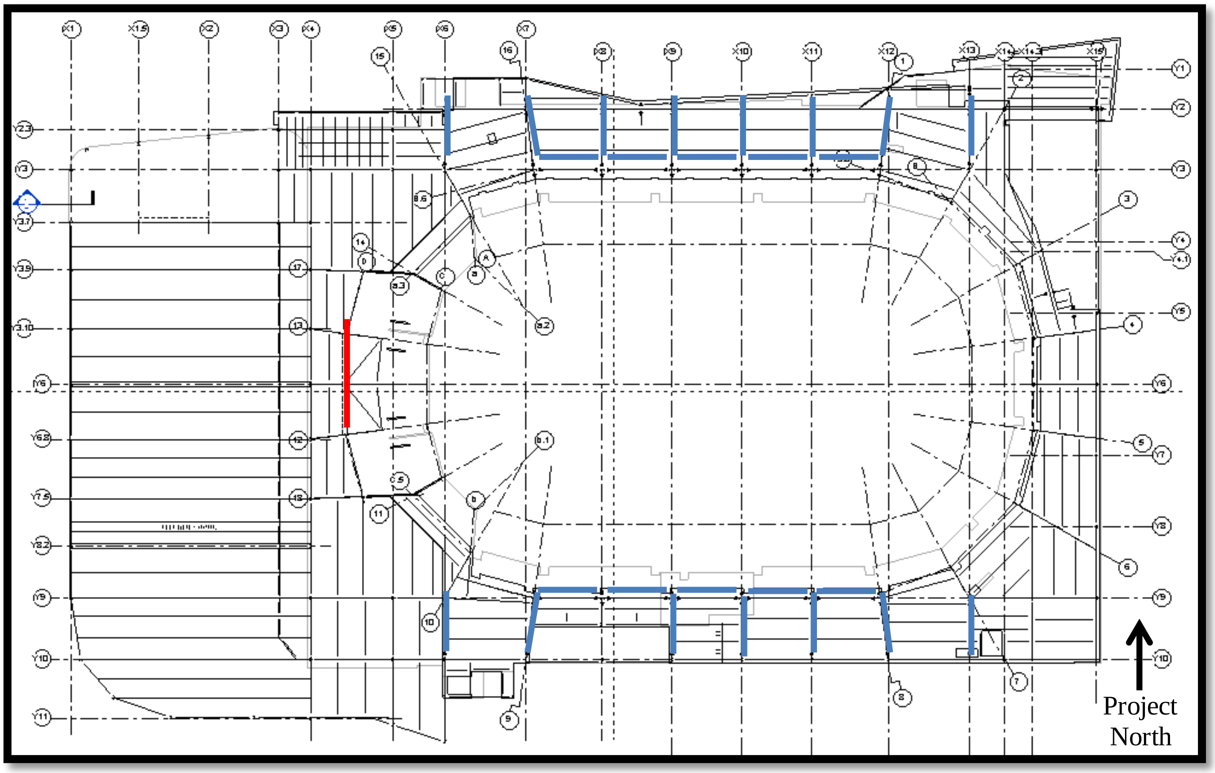


Figure 5. Schematic location of the moment frames and braced frames at the Club Level (Plans Courtesy of Thornton Tomasetti)

Legend:
🟥 Braced Frame
🟦 Moment Frame

Existing Mechanical

The Pegula Ice Arena brings in chilled water and steam from the main campus plant through the mechanical room adjacent to the community rink. Chilled water is distributed by two 770 gpm chilled water pumps. The 150 psi high pressure steam is converted to low pressure steam at a pressure reducing station. Two heat exchangers transfer heat from the low pressure steam to the domestic hot water supply system. Two 230 gpm hot water pumps distribute hot water to the building loads.

The arena heating and cooling loads are met by 5 VAV air handling units, 5 dehumidification units, and 4 energy recovery units. All AHUs are located on the roof between the main arena and community ice rink (See figures 6-8 for AHU/Zones). Suite boxes, mechanical rooms, electrical rooms, concessions, and tel/data rooms are serviced by fan coil units. Electric radiant heaters are located above the stands in the community rink.

On site ammonia chillers are utilized for ice making. There are three screw compressors and one reciprocating compressor. There are also two evaporative condenser towers and three plate and frame evaporators to transfer heat from the glycol to the ammonia refrigerant. Glycol is distributed through concrete slabs under the ice.

The main arena is serviced by two 45,000 CFM VAV AHUs. Outdoor air is sent through an enthalpy wheel and then mixed with return air. The mixed airstream is then sent through a pre-cooling coil to remove humidity and then through a gas fired desiccant wheel for further humidity control. Both units are located on the roof between the main arena and community rink. A single duct from each unit runs the entire length of the arena over the stands on each side.

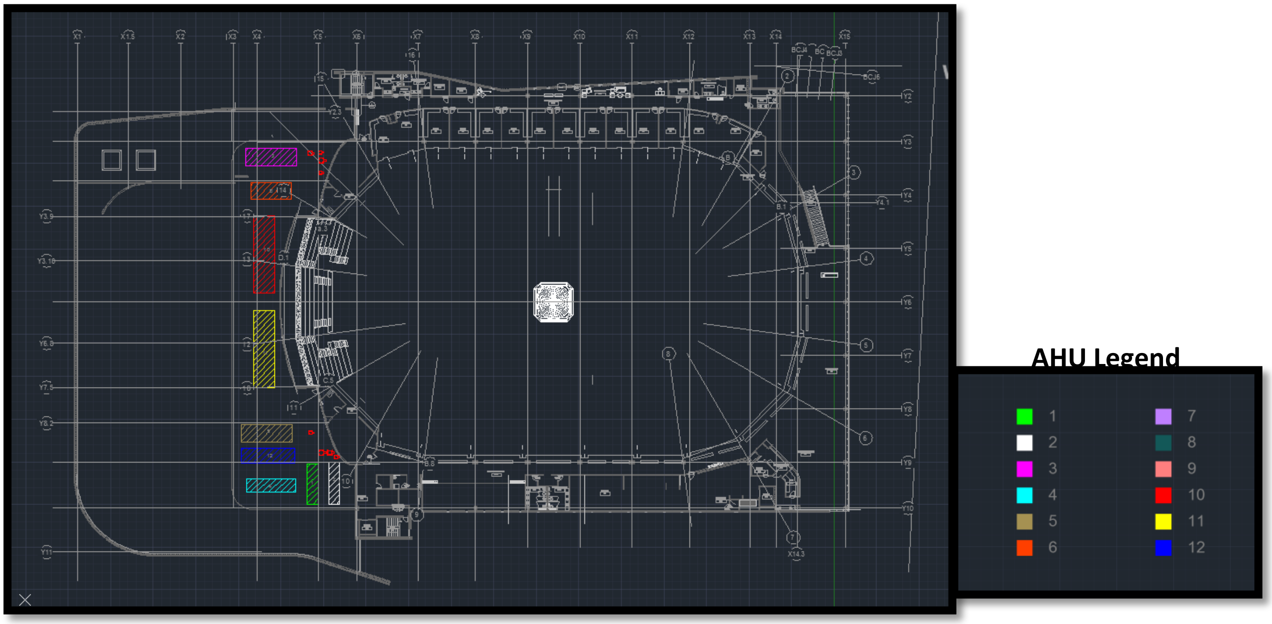


Figure 6. Existing Location of AHUs

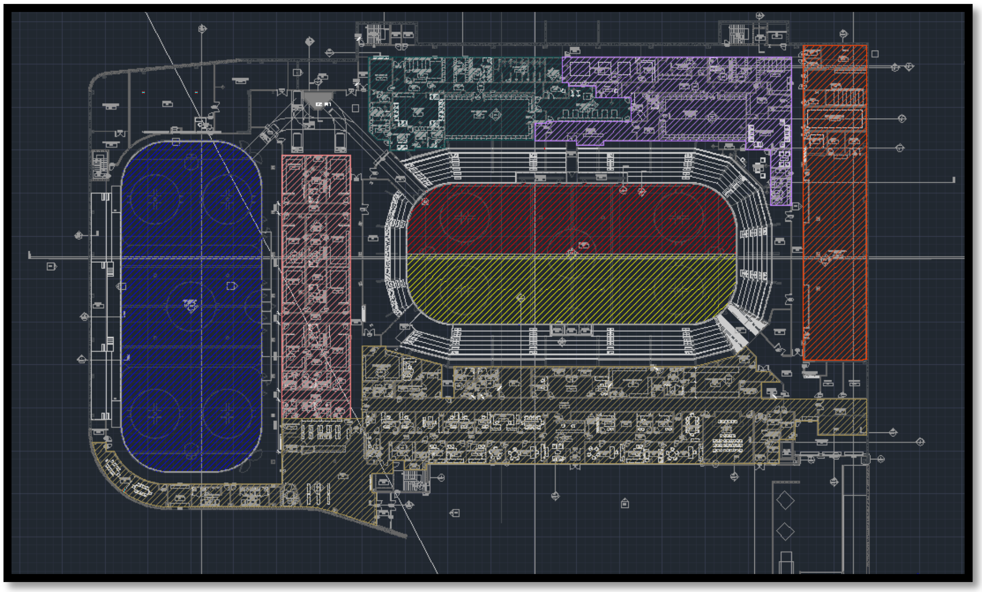


Figure 7. Event Level AHU Zone Diagram

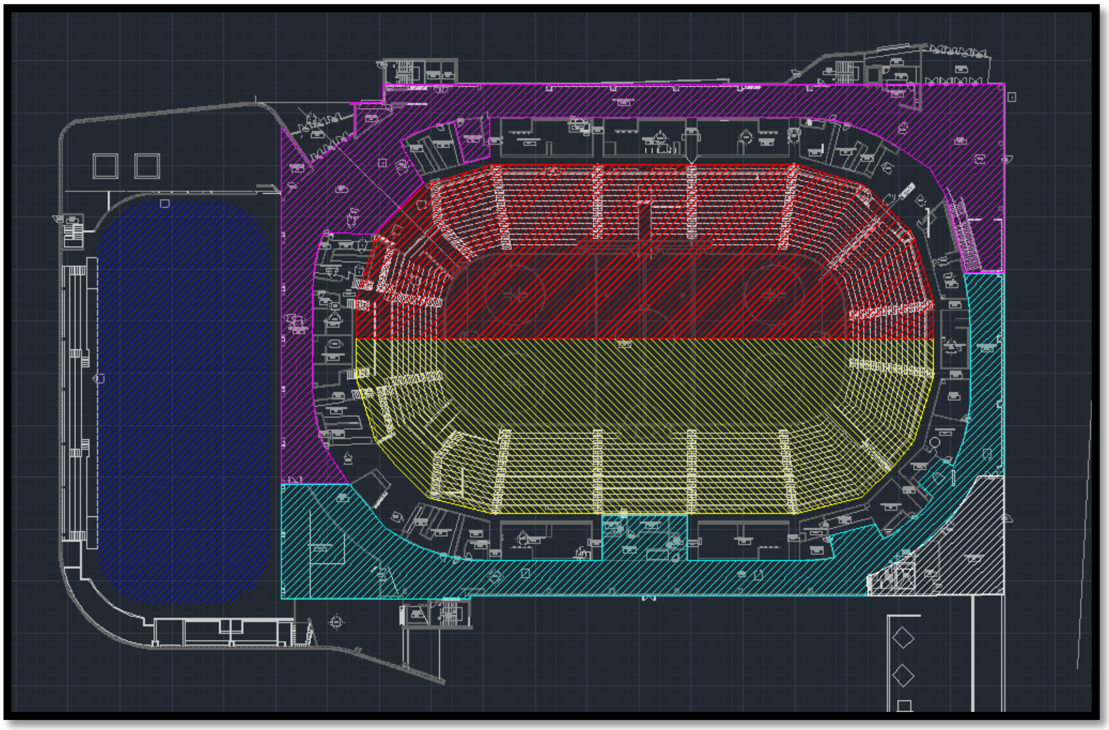


Figure 8. Concourse Level AHU Zone Diagram

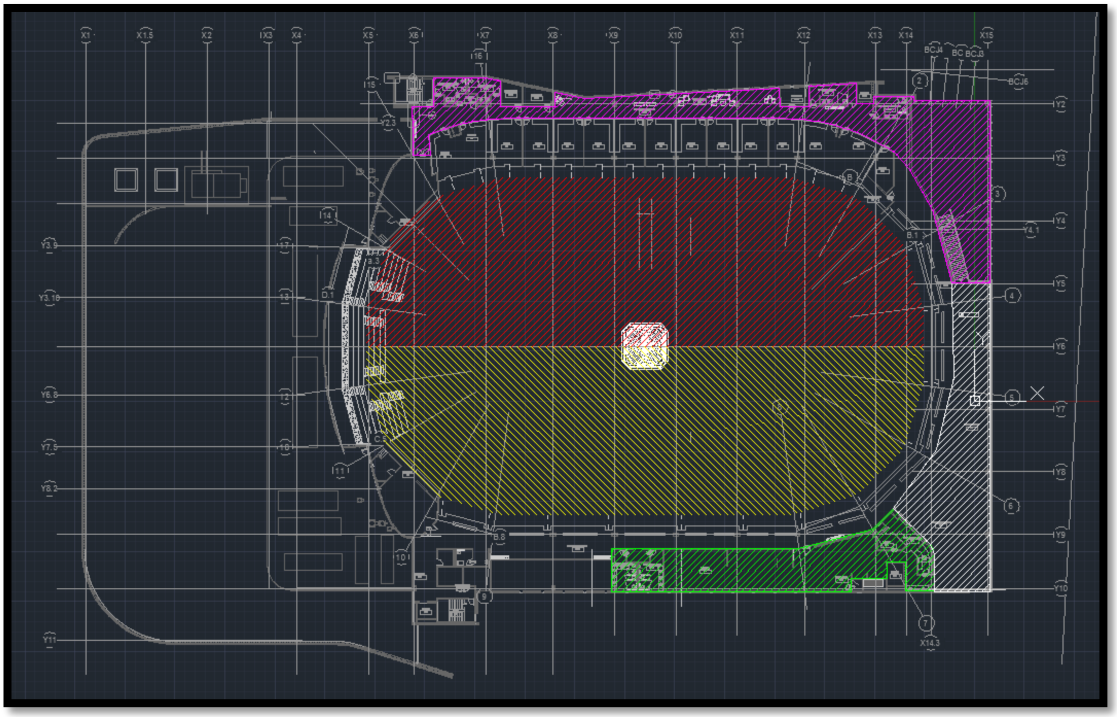


Figure 9. Club Level AHU Zone Diagram

Existing Lighting

The only spaces where existing lighting was provided (as of July 8, 2011) were the exterior site lighting, main arena and community rink. The exterior lighting utilizes “Penn State standard" 250W high pressure sodium path lighting fixtures. These fixtures are mounted on 12' poles with the exception of the fixtures located in the south western parking lot, which are mounted at 25' above the ground. The lighting for the main arena is provided by eighty-four metal halide fixtures with wattages unspecified. These fixtures provide the necessary illuminance levels for NCAA Division 1 hockey and also the broadcasting requirements. The community rink is lit with 2x4 fluorescent fixtures most likely coupled with T8 or T5 lamps. Using fluorescent fixtures greatly decreases the lighting power consumption within the community rink and the building as a whole while still achieving necessary illuminance requirements.

Existing Electrical

The electrical system currently feeding the Ice Hockey Arena is a 12.47kV service through two oil filled 2500kVA service transformers feeding two 3000A main-tie-main switchgears. Distribution begins with the 12.47kV service being stepped down to 480Y/277V to supply equipment and motor loads, then stepped down further at various locations to 208Y/120V service to supply receptacle, lighting and other loads such as sound systems for the two sheets of ice. Emergency power is supplied by a 4160kV service fed through an oil filled 150kVA service transformer 4160kV service is stepped down to 480Y/277V when then feeds an automatic transfer switch with both normal and emergency power. Standby power is fed from one of the two 3000A switchgears, which then feeds an automatic transfer switch with both normal and emergency power.

Main Roof Redesign

In any large arena, a large focus is placed on how to support the roof and provide clear open spaces for spectators. The design team's solution was to span 192 feet of the Main Arena with a steel truss and use steel joists to span the 30 feet above both the North and South Concourse. This creates an efficient steel design that minimizes impact on architectural views and keeps construction costs to a minimum. However, the roof design does not create an exciting exterior view that represents the thrilling hockey action that the arena contains within. This pushed the group Lights-Out Design to consider a new roof design with new goals.

As a group, Lights-Out Design took a "go big or go home" attitude. From a very early design stage, the decision to span the entire 252 foot span of the main arena. In addition, the bulky and deep steel trusses had to be removed and replaced with a design that would provide a sleeker and clean interior system. The last goal was to provide a much more exciting iconic roof design that would be forever synonymous with Penn State Hockey. To summarize, Lights-Out Design wanted to design a roof that spanned the entire arena, while reducing the structural depth and providing a more exciting outward appearance. This presented clear challenges in structural design and construction processes to both the Structural and Construction Management team members. Throughout the design, the Mechanical team member had to ensure that the roof design retained thermal properties necessary to maintain championship conditions inside the Main Arena.

Long Span Roof Research

In order to accomplish the team's goal, a significant amount of research was required to determine if the idea of a thinner roof spanning a large area would be possible. The most obvious structural solution revolved around cable roof structures because of their high strength to size ratio. A cable roof structure would provide both the thin roof and the long span, but the question was whether or not a cable roof structure would be appropriate for an ice arena. Several different design solutions were investigated and the following case studies illustrate how Lights-Out Design determined the roof solution for the Penn State Ice Arena.

Simple Suspended Cables

The simplest cable roof structure is the simple suspended cable. In this application, cable simply suspend in a catenary position across a long span and support the roof cladding above. One of the attractive features of the simple suspended cable roof is that the cables do not need to be pretensioned saving time and money. However, without pretensioning, the cables lack stiffness and considerable movement can occur under wind loading, known as flutter. To reduce flutter, heavy concrete is often chosen as the roofing material to be placed above the cables.

Typically, there are two ways to suspended cables in this manner. One is in a rectangular pattern, which can be seen at Dulles International Airport outside of Washington, D.C., and the other pattern is circular or elliptical with a tension ring in the center and a compression ring at the perimeter, like Oakland-Alameda Coliseum in Oakland, CA. Due to the rectangularity of the given architectural floor plan, Dulles Airport was investigated further to determine if this solution could be applied to the Penn State Ice Hockey Arena.

Figure 10. Nighttime View of the Terminal at Dulles International Airport

The terminal at Dulles International Airport was designed by Eero Saarinen in the early 1960s to provide a monumental building for growing jet airplane industry. Above, you can see the soaring buttresses spaced 40 feet apart with the simple cable system hanging in between. An important feature of the simply suspended cables is the span to sag ratio. The greater the sag in the cables the less horizontal thrust the cables place on the supports and more efficient the cables become. At Dulles, the front entry is 65 feet high at the front entry and 40 feet at the field side allowing for a sag of over 25 feet over the 164 span. This span to sag ratio helps minimize the thrust in the buttresses. The buttresses widen at the base to handle the large thrust and anchor under the terminal.

The single curvature cable design for the Penn State Ice Hockey Arena provided challenges mainly due to the significant sag that would be necessary to allow for a thrust that buttresses would be able to handle. Also, the scoreboard that would hang over the ice would result in extremely high exterior walls in order to produce the necessary sag. There was also concern that flutter caused by wind would be challenging with the single curvature design. Ultimately, a single curvature design was not utilized based on architectural and structural concerns.

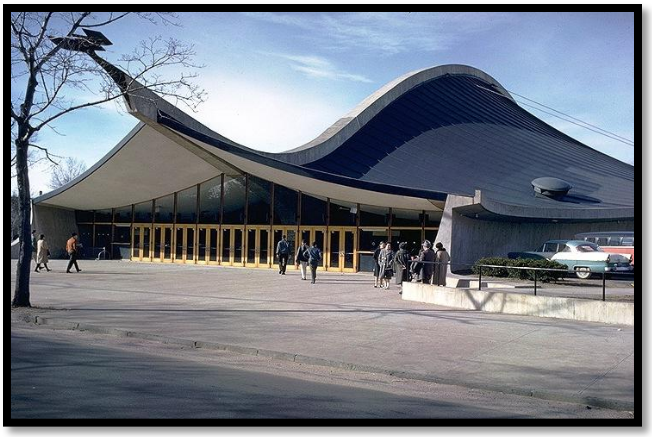


Figure 11. Ingalls Rink at Yale University was another Cable Structure by Saarinen

Double Curvature Design

To overcome flutter concerns, the design turned to a double curvature cable design. The double curvature design acts as a cable truss and provides a much stiffer system than a single curvature design. Also, by adding an additional cable, the natural frequencies of the double cable system are much higher than a single curvature system resulting in reduced flutter. There are three possible shapes that are typical of the double curvature design: convex, concave, and convex-concave. Due to depth concerns at the center of the arena, the convex-concave option was investigated further to determine its feasibility. As a design team, the double curvature system was also intriguing do to its efficiency, ease of construction, and ability to fit multiple different roof shapes.

Figures 12 and 13. Exterior and Interior Views of the Jawerth Cable Truss at Hovet

Hovet, an ice arena, in Stockholm, Sweden was investigated for its use of a double curvature design. The roof supported by a Jawerth cable truss was added in 1962 to enclose the 8,000 seat arena. The arena's ability to deal with similar snow and wind conditions attracted the team to this case study. However, the exterior appearance of the arena and the necessity for awkward backstays led the team to a different design solution. The double curvature truss is most definitely a cheap efficient cable solution, but the arena looks shed-like and not like an iconic image that Penn State Hockey wants.

Cable-Stayed Roof

The last structural cable system that was investigated was the cable-stayed roof. A cable-stayed system is typically made up of multiple parts. First, there is a girder on which secondary roof beams connect and the roof cladding sit on. A mast extends upward on the exterior of the span and cables extend from the mast to the girders to support the roof below. To resist the tension in the cables, a backstay system is typically provided to keep the cable-stay system from falling inwards. The cable-stayed system provided several advantages including: a regular system, concentrated foundations, and a strong visual identity. However, immediate concerns developed around how to build such a system and the thermal breaks that would occur at cable-to-girder connections.

Several arenas and cable-stayed roofs were investigated, but, ultimately, the Ratner Center by Caesar Pelli and Associates at the University of Chicago was selected as our precedent case study. The Ratner Center was built to house a competition sized gymnasium as well as an Olympic-sized natatorium which relates well to the ice hockey arena at Penn State. The cable-stayed system allows free spaces of 160 x 125 feet in the gymnasium and 130 x 200 feet in the natatorium. Primary masts are spaced at 75 feet on center on one side of each space with secondary masts spaced at 25 feet on center on the opposite side. The primary masts support 3 girders while the secondary masts each support one. The masts were composed of composite steel tubes to resist the extensive loads. Large counter weights were used to resist the large uplift forces at the foundation.

Figure 14. Exterior Image of the Ratner Center at the University of Chicago

Once the team saw the Ratner Center, it was determined to attempt a cable-stayed design for the Penn State Ice Hockey Arena. The cable-stayed system would allow for an extremely unique structure that Penn State Ice Hockey would become synonymous for. It would allow for a thin roof section and allow for an open span from exterior wall to exterior wall totaling 252 feet. The system provided a great BIM/IPD study in relation to construction and design of the system while maintaining championship conditions inside the arena. Through integration with the construction manager, the structural system could be designed as efficiently as possible with constructability always in mind.

ASCE 19-10: Structural Applications of Steel Cables for Buildings

Having selected a structural system involving cables, an extensive search ensued to determine how to design a cable structure. The first major guide is provided by the American Society of Civil Engineers. In 1996, a guide on the Structural Applications of Steel Cables for Buildings was developed by a committee compromised of individuals involved in consulting engineering, research, construction industry, education, government, design, and private practice. In 2010, the guide was updated with more detail. The guide provides guidelines for drawings and specifications, design considerations, fittings, fabrication, and erection procedures.

For this project, the section on design consideration was used the most. Inside the design considerations section, the structural engineer can find load combinations, design strength values, reduction factors, and what to consider in the structural analysis. According to ASCE 19-10 the cable tensions shall be calculated for the following load combinations:
T_1 = Cable Tension due to $D + P$
T_2 = Cable Tension due to $D + P + L + (L_r \text{ or } S \text{ or } R)$
T_3 = Cable Tension due to $D + P + (W \text{ or } E)$
T_4 = Cable Tension due to $D + P + (L_r \text{ or } S \text{ or } R) + (W \text{ or } E)$
T_5 = Cable Tension due to C + erection components of D, L, P, and W.

Once the load combinations are applied to the cables, the cables must have a design strength equal or greater than:

a) $2.2T_1$
b) $2.2T_2$
c) $2.2T_3$
d) $2.2T_4$
e) $2.2T_5$

These load combinations and design strengths were used in coordination with manufacturer supplied design values to design the cables.

Cable Manufacturer

Lights-Out Design worked in coordination with WireRope Works, the manufacturer of Bethlehem Wire Rope, in order to get manufactured strengths of cables at various sizes. For roof applications, WireRope Works manufactures three different products: a spiral strand, SS-265, and structural wire rope. The design values for spiral strand and SS-265 were used in the design of the cables for the cable-stayed system. Other than providing the values necessary for the structural design of cables, WireRope Works is also a local manufacturer located in Williamsport, PA, only 62 miles from Penn State.

Figure 15. Location of Wirerope Works in Williamsport, PA

Shape Selection

With cable design technical data in hand, the group focused on what the building would look like and how the cable-stayed system would work. The shape of the roof was the first major item to be determined. Would the roof be flat, angled, or arched? The group moved towards an arched roof for a greater aesthetic and to allow for greater heights at the center of the arena. The curve, also, reflects the curves of skate lines on the ice. An arched roof was selected as the final shape. The overall rise of the arch was determined by working to maintain at least the minimum height needed for the mechanical loft. The final roof rises almost 17 feet at its center from where it springs at the exterior connection to the mast.

Once the shape was determined, the next basic decision was where the masts would be located. If the group maintained the masts at the existing truss gridlines, there would be an extensive number of masts (9 on either side) at a semi-regular spacing. In coordination with the architectural plans the group was given, multiple possible spacings were investigated to determine which spacing would work for the structure and not have a negative impact on the architectural plan. After investigating several spacing alternatives, it was determined that the masts could be spaced at 60 feet on center with little interruption in the existing floor plans. On the interior, the columns would then be spaced at 30 feet on center to increase the regularity of the system on both the exterior and interior.

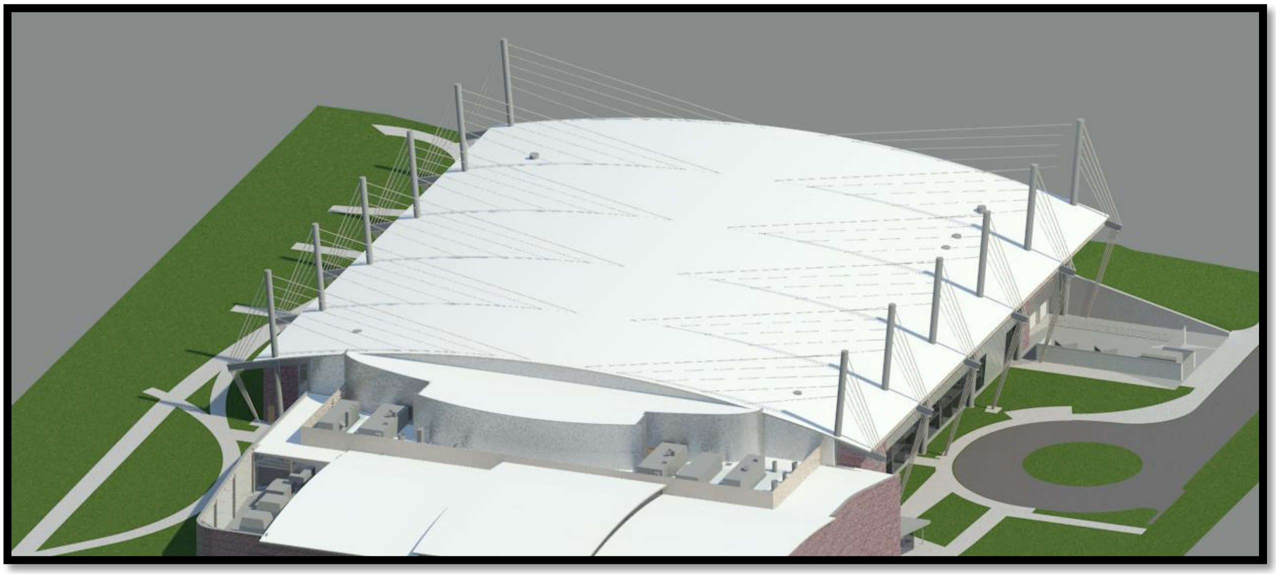


Figure 16. Exterior Image of the New Cable-Stayed Roof

The resulting cable-stayed system had 6 masts on each side spaced at 60 feet. Because the system was symmetric, the masts reach the same overall height above ice level. On the north side of the arena, the masts would be 20 feet less in length than the masts on the south side due to the sloping of the site. This slightly affected the length of the backstay cables. Overall, an extremely regular structure had been created.

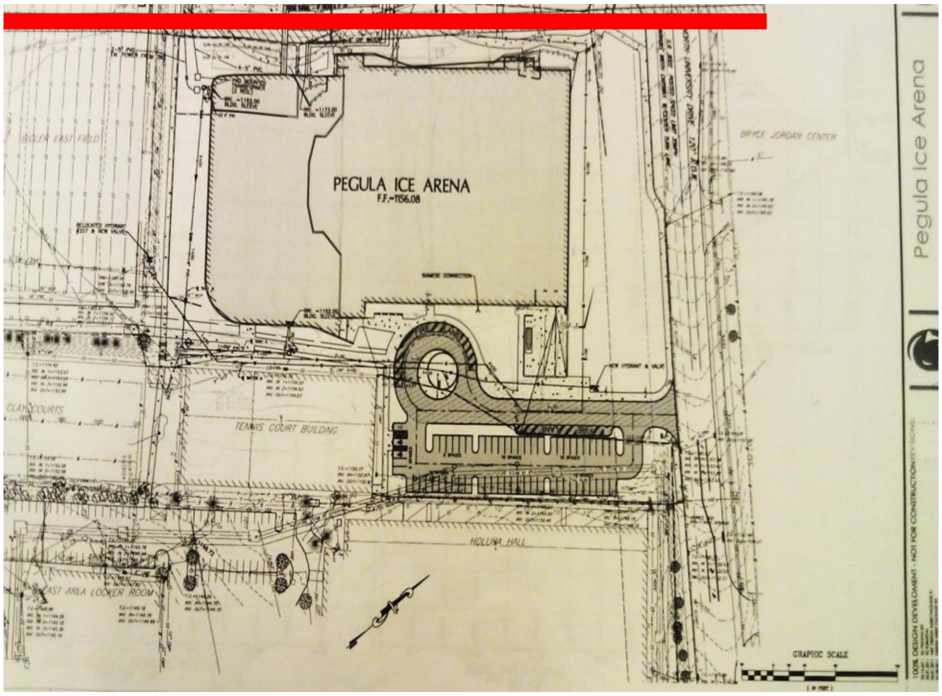


Figure 17. Site Constraints of the Ice Arena (Bus Duct Highlighted in Red)

The last unique feature in our cable-stayed design is a result of massive site restrictions. Typically, the mast backstays reach far out and extend rather intrusively into the site. For the Penn State Ice Hockey Arena, this was not an option. To the north of the site, a large bus duct that services a majority of the university runs just 30 feet from the north façade. On the south of the site, a parking lot and driveway to the loading dock, community rink, and hockey offices cannot be impacted. In order to achieve the necessary backstay and not impact the site, the girder of the cable-stayed system must extend out from the mast like an arm over the ground below. Cables would then extend from the mast to the edge of the girder and then cables would extend from the girder to a foundation near the base of the mast.

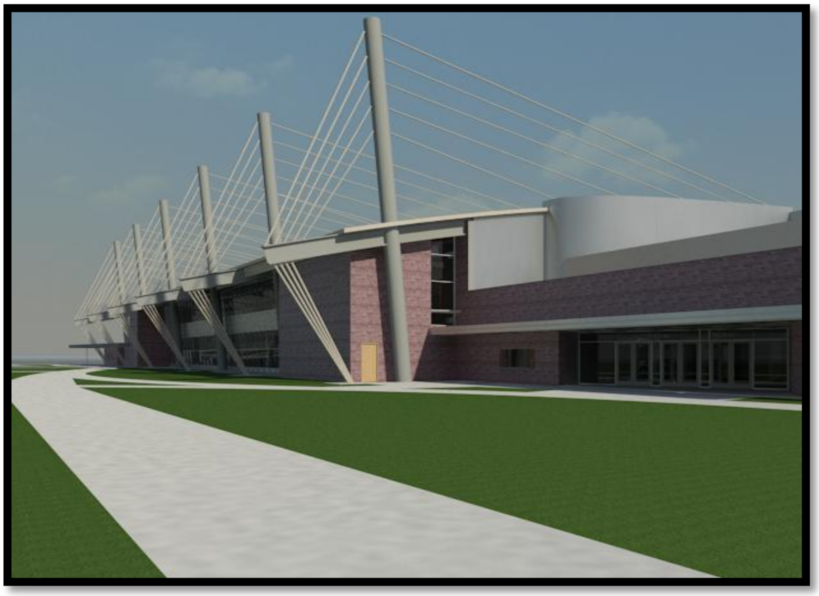


Figure 18. Student Entrance to the Arena

Structural Design of the Roof

With the basic geometry of the roof chosen, the structural design of the roof could commence. The roof system was modeled in SAP2000 as a 2-D model. In the first analysis models, a flat angled roof was analyzed to get a better understanding of how the roof worked in SAP2000 before moving to the final design. The span was approximated at 130 feet for each mast and the girder was divided into three four equal parts so that three cables could anchor to the roof girder. The backstay and mast foundation were modeled as pin connections. After a few struggles, it was determined that nonlinear analysis had to be conducted due to the use of cable elements. Another discovery from early analysis models was the large deflection caused by the last section of the girder from gridline D to E. It was clear that the longest cable had to connect closer to the peak of the roof. Another remedy was to account for the connection to the opposite mast and girder with a roller restricting motion in the x-direction. The last major discovery dealt with the angle of the cable connected to the girder. The more inclined the angle the greater the tension in the cables became. This increased tension caused large jumps in the bending moment at cable-to-girder connections. An attempt to make the cable running from the mast to the girders more horizontal would be made to help decrease irregular bending in the girder.

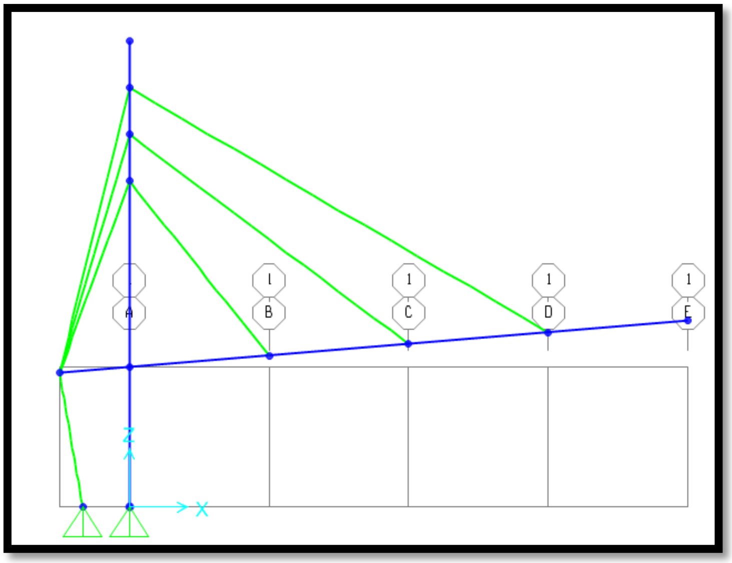
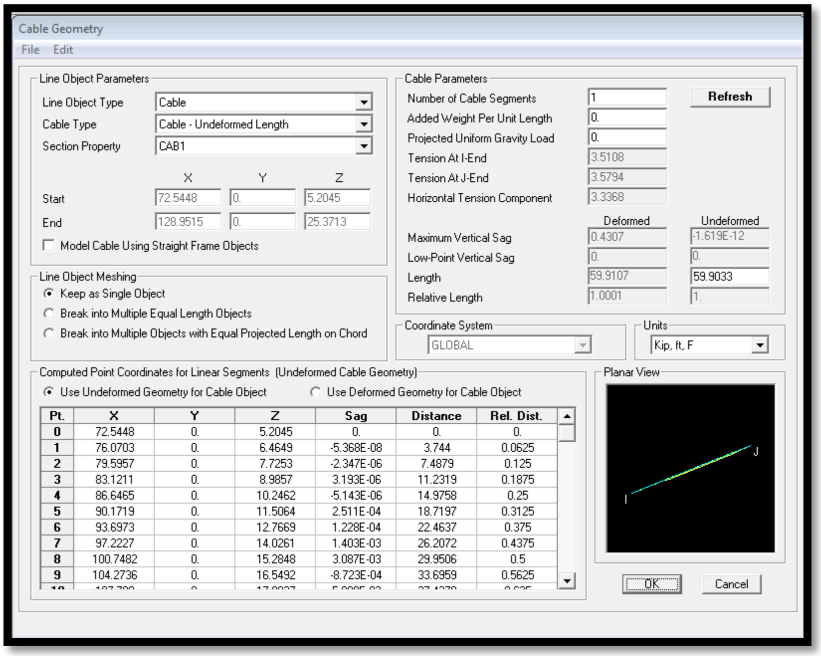


Figure 19. Preliminary SAP2000 Model of the Cable-Stayed Roof System

The early analysis model proved extremely valuable as the design moved forward. With a basic understanding of how the cable analysis worked in SAP2000, the actual design could be modeled and analyzed. First, the mast was modeled as a general frame element in two pieces with one piece running from the foundation to the girder connection and the next piece running from the girder to the maximum height of the mast. The mast was angled at 5 degrees to satisfy architectural ideas. Once the mast was modeled, the curved frame element for the girder was added. This was done by specifying a starting and ending point and then specifying a third point (the connection between the mast and girder) to finalize the curved shape. With those elements modeled, the cable elements could now be modeled. Nodes were placed along the mast and the girder. The nodes on the mast were spaced at 5 foot intervals starting from the top of the mast and nodes were spaced along the girder with connections spaced closer towards the roof peak. The cable elements were then added by specifying starting points and ending points and using the undeformed length option in defining the cable geometry. One of the new features in SAP2000 allows the user to define cable geometry in multiple ways depending on what amount of sag the user wants in the cable. For the cable-stayed roof, the cables are designed to always be in tension so having the cables in their undeformed length was preferred.



Line Object Parameters

Line Object Type: Cable
Cable Type: Cable - Undeformed Length
Section Property: CAB1

	X	Y	Z
Start	72.5448	0.	5.2045
End	128.9515	0.	25.3713

☐ Model Cable Using Straight Frame Objects

Line Object Meshing

● Keep as Single Object
○ Break into Multiple Equal Length Objects
○ Break into Multiple Objects with Equal Projected Length on Chord

Cable Parameters

Number of Cable Segments: 1
Added Weight Per Unit Length: 0.
Projected Uniform Gravity Load: 0.
Tension At I-End: 3.5108
Tension At J-End: 3.5794
Horizontal Tension Component: 3.3368

	Deformed	Undeformed
Maximum Vertical Sag	0.4307	-1.619E-12
Low-Point Vertical Sag	0.	0.
Length	59.9107	59.9033
Relative Length	1.0001	1.

Coordinate System: GLOBAL

Units: Kip, ft, F

Computed Point Coordinates for Linear Segments (Undeformed Cable Geometry)

● Use Undeformed Geometry for Cable Object ○ Use Deformed Geometry for Cable Object

Pt.	X	Y	Z	Sag	Distance	Rel. Dist.
0	72.5448	0.	5.2045	0.	0.	0.
1	76.0703	0.	6.4649	-5.368E-08	3.744	0.0625
2	79.5957	0.	7.7253	-2.347E-06	7.4879	0.125
3	83.1211	0.	8.9857	3.193E-06	11.2319	0.1875
4	86.6465	0.	10.2462	-5.143E-06	14.9758	0.25
5	90.1719	0.	11.5064	2.511E-04	18.7197	0.3125
6	93.6973	0.	12.7669	1.228E-04	22.4637	0.375
7	97.2227	0.	14.0261	1.403E-03	26.2072	0.4375
8	100.7482	0.	15.2848	3.087E-03	29.9506	0.5
9	104.2736	0.	16.5492	-8.723E-04	33.6959	0.5625

Figure 20. Screenshot of the Cable Geometry Input

In order to design the cable-stayed system, load combinations from ASCE 7-10 were used to determine a suitable design. The various loads applied to the structure included snow load, superimposed dead load, wind loads, and pretension. Because the cable load combinations described earlier have no adjustments, ASD load combinations from ASCE 7 were applied to the SAP2000 model. The load combinations used are as follows:

ASCE 7-10 ASD Load Combinations:

1. D
2. $D + L$
3. $D + (Lr \text{ or } S \text{ or } R)$
4. $D + 0.75L + 0.75(Lr \text{ or } S \text{ or } R)$
5. $D + (0.6W \text{ or } 0.7E)$

6a. $D + 0.75L + 0.75(0.6W) + 0.75(Lr \text{ or } S \text{ or } R)$
6b. $D + 0.75L + 0.75(0.7E) + 0.75S$

7. $0.6D + 0.6W$
8. $0.6D + 0.7E$

Due to the arch of the roof, unbalanced snow loads had to be considered according to ASCE 7-10 Section 7.6.2. Being located in State College, PA, earthquake loads were not a major concern, but wind uplift on the roof was indeed a concern and analyzed extensively. The uplift ranged from about 34 psf on the windward quarter to 30 psf on the center half of the roof. Once loads were applied to the structure, the load combinations were applied and the results analyzed.

To determine the pretensioning necessary for the cables, a spreadsheet was created to determine initial strain values that could be applied for the structure. The cables were pretensioned to resist full dead load and half of the snow load. This allowed the cables to always remain in tension. The cable forces were calculated from applied dead and snow loads and then the strain was determined using engineering mechanics. In addition, the cables were conservatively presized based on the cable load combinations presented earlier. Once the sizes were approximately set, the design could be sized down based on iterative analysis.

Once the geometry of the cable-stayed roof was modeled into SAP2000, loads could be applied and designs determined. First, the secondary beams and metal deck was designed so that those loads could be accounted for on the girder. In the team's first design attempt, the same deck that was being used in the actual design was applied to the cable-stayed design. 3N16 metal roof deck spaced at 14 feet on center was selected based on snow loads of 34 psf and a superimposed dead load of 35 psf. With the deck selected, the secondary roof beams were designed to resist the applied dead, snow, and live loads while maintaining serviceability criteria. The roof beams were designed as W30x90 members. Now, these loads could be transferred to the cable-stayed system modeled in SAP2000.

Moving through the first design idea using the existing roof, one concern became readily apparent. Uplift on the roof was going to be a major issue. Due to the weight of the trusses, a light roof cladding could be used without wind concerns, but, by removing the trusses and replacing them with a lighter system, the new design could no longer resist the strong uplift forces. The cable-stayed system was experiencing deflections of over 18 inches upward with the existing roof system. It was clear a heavier roof system would be needed.

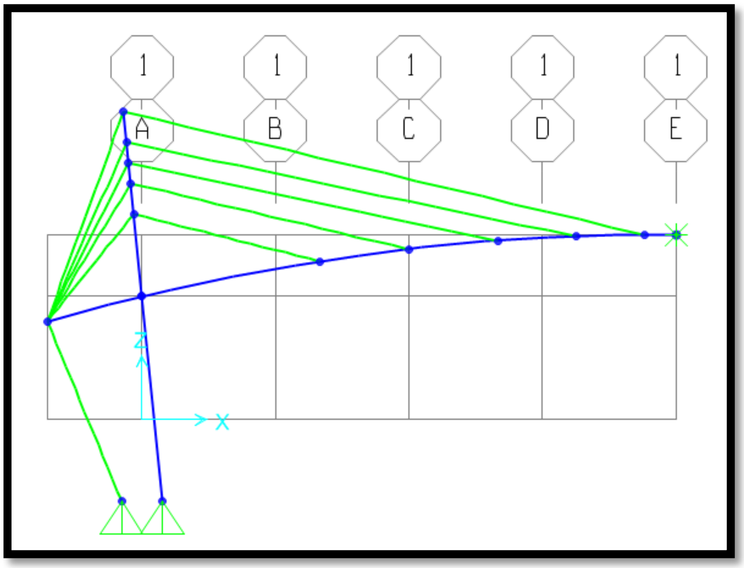


Figure 21. Final SAP2000 Analysis Model of the Cable-Stayed Roof

The team moved to a noncomposite concrete deck system in order to resolve the uplift issue. A new concrete deck provided the weight necessary to resist the uplift forces and also provided for better thermal properties, which would maintain the quality of the ice rink inside. The superimposed dead load increased to a 117 psf and a total load of 151 psf was used to design the new deck system. A 3C18 noncomposite concrete deck with 5" of NWC topping was selected. With the deck selected, the new roof beam could be designed and the resulting roof beam was a W33x130. The overall added weight significantly impacted the movement caused by uplift.

The new dead loads were then applied to the SAP2000 model so that the cables could be redesigned. Originally the cables were upwards of 4 to 5 inches in diameter, but through several iterations the cables sizes decreased slightly. The sizing of the cables became largely affected by serviceability requirements of the girder. If the cables were sized for strength alone, they would have been around 2 inches in diameter. The final cable design ranged in size from 3.375 inches diameter to 5.25 inches diameter. In order to resist the large deflections and forces, (4) 5.25 inch diameter cables were used to anchor the backstay.

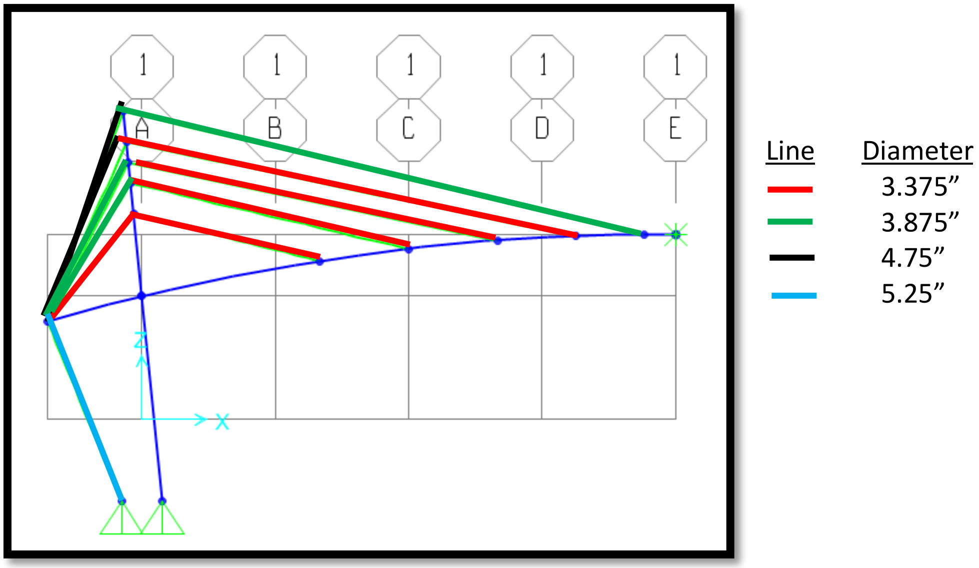


Figure 22. Cable Sizes at Each Location

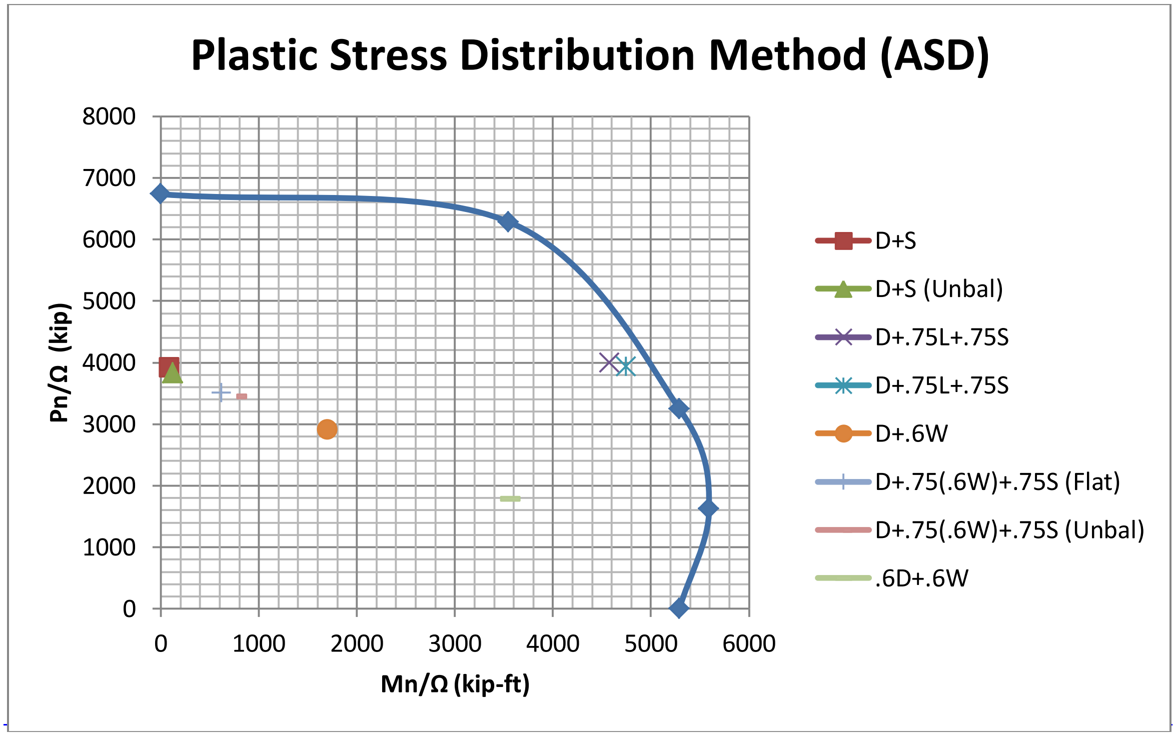
In coordination with the design of the cables, the girder was designed to resist both axial compressive loads caused by the arched design and the bending caused by the large loads. In accordance with AISC Steel Construction Manual part 6 and Chapter H, the girder was designed as a doubly and singly symmetric member in flexure and compression. Once the forces were attained, the combined loading equation H1-1a was applied because the required axial load was over 20% of the axial capacity. Using the table seen below with information from Table 6-1 Combined Axial and Bending in the AISC Steel Construction Manual, the girder was designed as a W40x593. The girder satisfied all necessary strength requirements with serviceability criteria being handled by the cables.

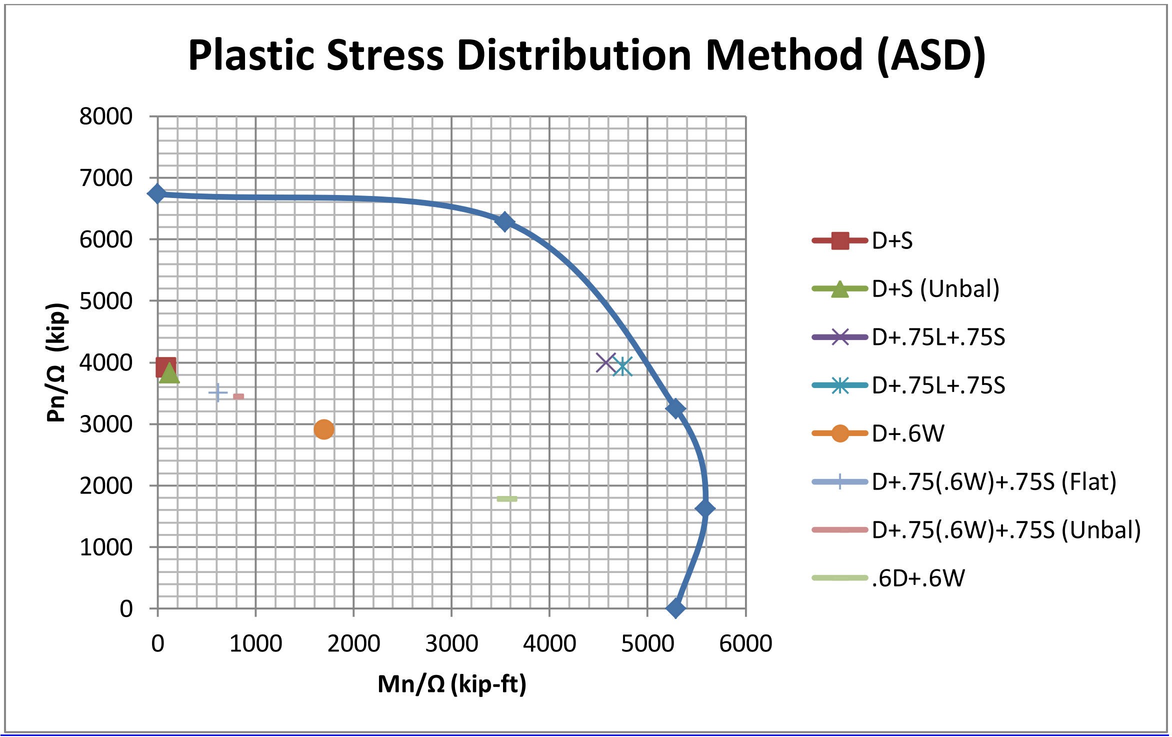
Load Case	P (k)	M (k-ft)	$pP_r \geq 200$	p	b	$pP_r + b_xM_{rx} < 1000?$
D+S (Flat)	2839	3112	596.19	0.21	0.129	997.638
D+S (Unbal)	2653	3421	557.13	0.21	0.129	998.439
D+.75L+.75S (Flat)	2938	1778	616.98	0.21	0.129	846.342
D+.75L+.75S (Unbal)	2889	2031	606.69	0.21	0.129	868.689
D+.6W	2107	2081	442.47	0.21	0.129	710.919

D+.75(.6W)+.75S (Flat)	2546	3019	534.66	0.21	0.129	924.111
D+.75(.6W)+.75S (Unbal)	2889.5	2031	606.795	0.21	0.129	868.794
.6D+.6W	1325	1101	278.25	0.21	0.129	420.279

Table 1. Combined Loading Analysis of the W40x593 Girder

The last major portion of this design dealt with the mast. The mast is takes the loads from the roof transferred through the cables down to the foundation below. With the masts each supporting a tributary width of 60 feet, the axial loads under full load exceeds 4000 kips. In addition to this compression load, the girder induces a large bending moment caused by the wind uplift. In order to resist these large forces, composite columns were investigated. A composite column would provide additional axial capacity as well as greater lateral stiffness and greater redundancy. According to the AISC Steel Construction Manual Chapter I, the nominal strength of composite members subjected to axial force and flexure must be determined using either the plastic stress distribution method or the strain compatibility method. Through discussions with and equations provided by Dr. Geschwindner, the plastic stress distribution method was used to design the composite mast. Using the graph shown below, the mast was designed as a 1.5 inch thick 36 inch diameter steel tube filled with 8 ksi concrete.





Load Case	P (k)	M (k-ft)	Load Case	P (k)	M (k-ft)
D+S (Flat)	3908	94	**D+.6W**	2905	1704
D+S (Unbal)	3831	124	**D+.75(.6W)+.75S (Flat)**	3507	618
D+.75L+.75S (Flat)	3997	4580	**D+.75(.6W)+.75S (Unbal)**	3448	784
D+.75L+.75S (Unbal)	3934	4751	**.6D+.6W**	1783	3575

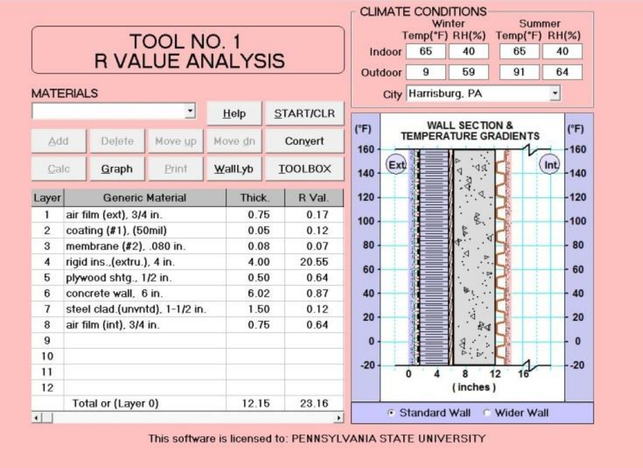
Chart 1 and Table 2. Plastic Stress Distribution Method Analysis of Composite Column

Unfortunately, a greater investigation into possible foundation designs was not possible due to time constraints. However a schematic analysis was performed to get an idea of what the deep foundation system might be. The greatest forces at the foundation were caused by the load case *D + S*. The cable anchors impose an uplift of 2743 kips and the masts applies a compressive force of 4559 kips. To resist the uplift, micropiles were schematically analyzed to determine potential size and shape. Due to the pinnacle rock nature of the site and the large loads on the columns of the arena, the existing design given to the team used micropiles in certain locations. Using the data provided in the geotechnical report, a 7 foot x 7 foot pile cap with (16) 7.5 inch diameter piles would provide the necessary strength to resist the uplift imposed by the cables. Due to size restrictions and the large compressive forces, caissons are probably the best option to transfer the large loads from the mast to the earth. To accomplish an accurate design, further geotechnical investigation should be completed at the specific location of the mast and cable anchors.

Ultimately, deflections impacted the cable-stayed roof system the most. The composite mast added significant stiffness and kept the roof from displacing horizontally. However, much iteration was needed to determine the best design of cable sizes and pretensioning needed in the cables. The final structural design was able to keep deflections limited to slightly less than l/180 which is approximately 7.66 inches. Because the roof is not supporting a ceiling structure, this seems like a plausible limit, but again, more investigation into how that deflection would affect the roof cladding and roof structure would be necessary to ensure no part of the structure would be negatively impacted.

Thermal Analysis of the Roof

The final materials for the roof were coordinated and then modeled in H.A.M. Toolbox. An R-Value Analysis was calculated to find the total R-Value of the wall system. That R-Value was then inputted into the Trane Trace energy model. H.A.M. Toolbox was also used to do a condensation analysis. In order to create championship ice for the arena a roof structure was designed to eliminate condensation from forming in the arena. The indoor temperature settings for the main arena were 65 degrees F and 40 percent relative humidity.



TOOL NO. 1
R VALUE ANALYSIS

CLIMATE CONDITIONS

	Winter		Summer	
	Temp(°F)	RH(%)	Temp(°F)	RH(%)
Indoor	65	40	65	40
Outdoor	9	59	91	64

City Harrisburg, PA

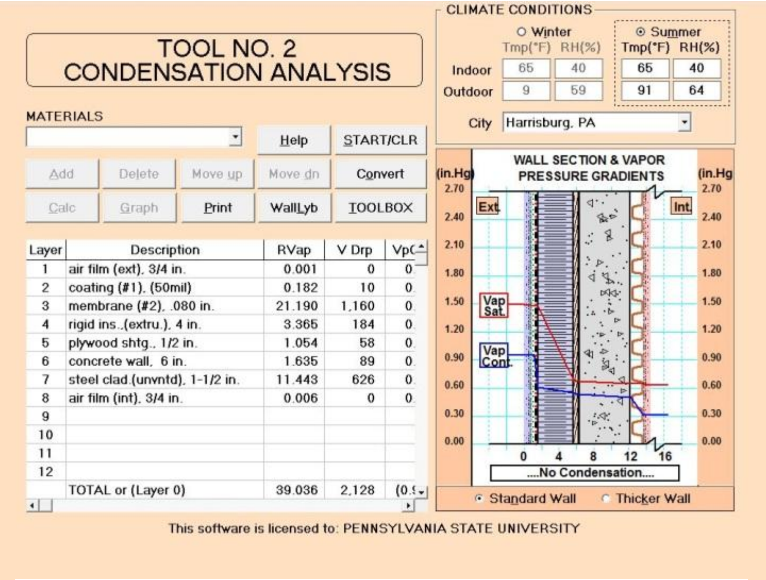
MATERIALS

Layer	Generic Material	Thick.	R Val.
1	air film (ext), 3/4 in.	0.75	0.17
2	coating (#1), (50mil)	0.05	0.12
3	membrane (#2), .080 in.	0.08	0.07
4	rigid ins.,(extru.), 4 in.	4.00	20.55
5	plywood shtg., 1/2 in.	0.50	0.64
6	concrete wall, 6 in.	6.02	0.87
7	steel clad.(unvntd), 1-1/2 in.	1.50	0.12
8	air film (int), 3/4 in.	0.75	0.64
9			
10			
11			
12			
	Total or (Layer 0)	12.15	23.16

● Standard Wall ○ Wider Wall

This software is licensed to: PENNSYLVANIA STATE UNIVERSITY

Figure 23. H.A.M. Toolbox R-Value Analysis



CLIMATE CONDITIONS

	○ Winter		● Summer	
	Tmp(°F)	RH(%)	Tmp(°F)	RH(%)
Indoor	65	40	65	40
Outdoor	9	59	91	64

City: Harrisburg, PA

Layer	Description	RVap	V Drp	VpC
1	air film (ext), 3/4 in.	0.001	0	0
2	coating (#1), (50mil)	0.182	10	0
3	membrane (#2), .080 in.	21.190	1,160	0
4	rigid ins.,(extru.), 4 in.	3.365	184	0
5	plywood shtg., 1/2 in.	1.054	58	0
6	concrete wall, 6 in.	1.635	89	0
7	steel clad.(unvntd), 1-1/2 in.	11.443	626	0
8	air film (int), 3/4 in.	0.006	0	0
9				
10				
11				
12				
	TOTAL or (Layer 0)	39.036	2,128	(0.

● Standard Wall ○ Thicker Wall

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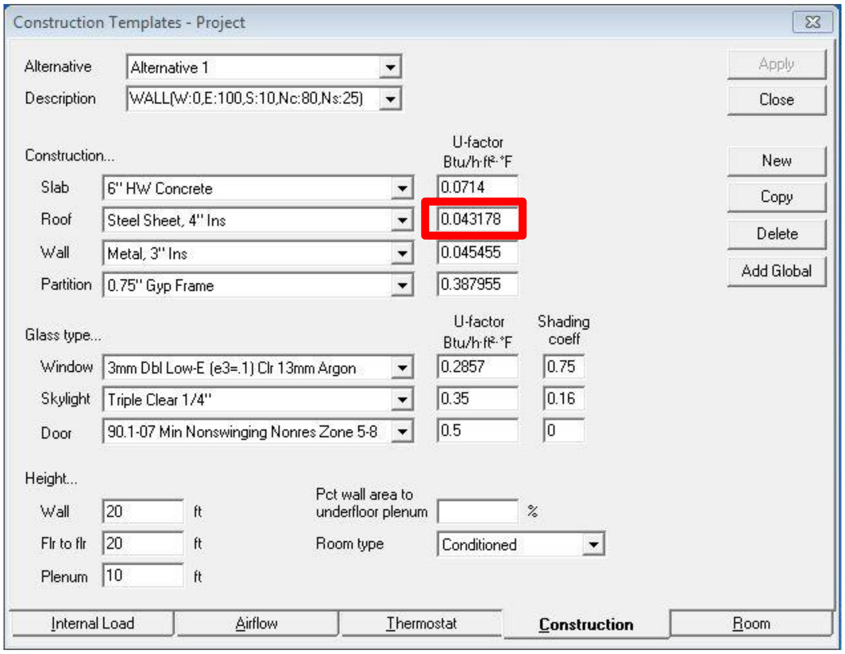
Figure 24. H.A.M. Toolbox Condensation Analysis



Alternative: Alternative 1

Description: WALL(W:0,E:100,S:10,Nc:80,Ns:25)

Construction...

		U-factor Btu/h·ft²·°F
Slab	6" HW Concrete	0.0714
Roof	Steel Sheet, 4" Ins	0.043178
Wall	Metal, 3" Ins	0.045455
Partition	0.75" Gyp Frame	0.387955

Glass type...

		U-factor Btu/h·ft²·°F	Shading coeff
Window	3mm Dbl Low-E (e3=.1) Clr 13mm Argon	0.2857	0.75
Skylight	Triple Clear 1/4"	0.35	0.16
Door	90.1-07 Min Nonswinging Nonres Zone 5-8	0.5	0

Height...

Wall 20 ft

Flr to flr 20 ft

Plenum 10 ft

Pct wall area to underfloor plenum: %

Room type: Conditioned

Figure 25. Trane Trace Construction Template

BIM Modeling of Cable-Stayed System

With the structural design of the roof completed, the question became how you model such a unique system in Revit Structure. There is no cable element in Revit and no columns at the size of the team's mast design. A separate Revit family was created to model the cable-stayed system. Reference lines were drawn at the center of all the elements (cables, masts, and girders). Once all of the reference lines were drawn, profiles of each element were added and the profiles were swept along the path of the reference line to create the overall design. This was done for the W shape of the girder, the cylinder of the mast, and the smaller cylinders of the cables. Steel materials were applied to each shape and the design was then imported into the Revit Structure model and the system was put into its proper place. With the cable-stayed system in place, schematic foundations could be attached to the base of the cable backstays and masts, the secondary roof beams could be added in between the girders, and the roof deck could be added to sit above the girder and beams.

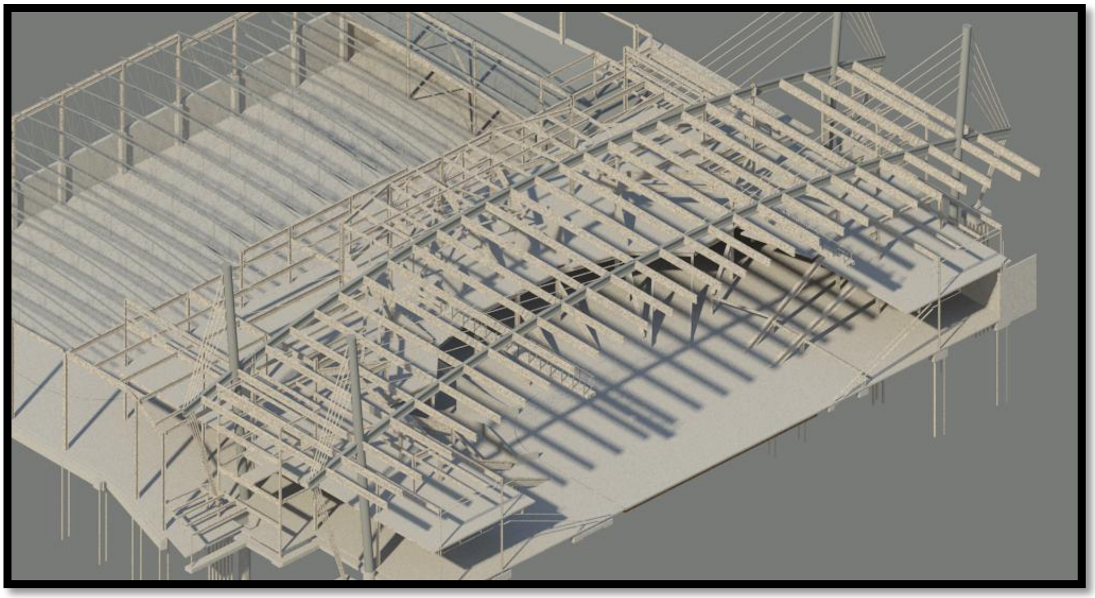


Figure 26. 3D Perspective of the Cable-Stayed Roof System in Revit Structure

Gravity Model of Structural System

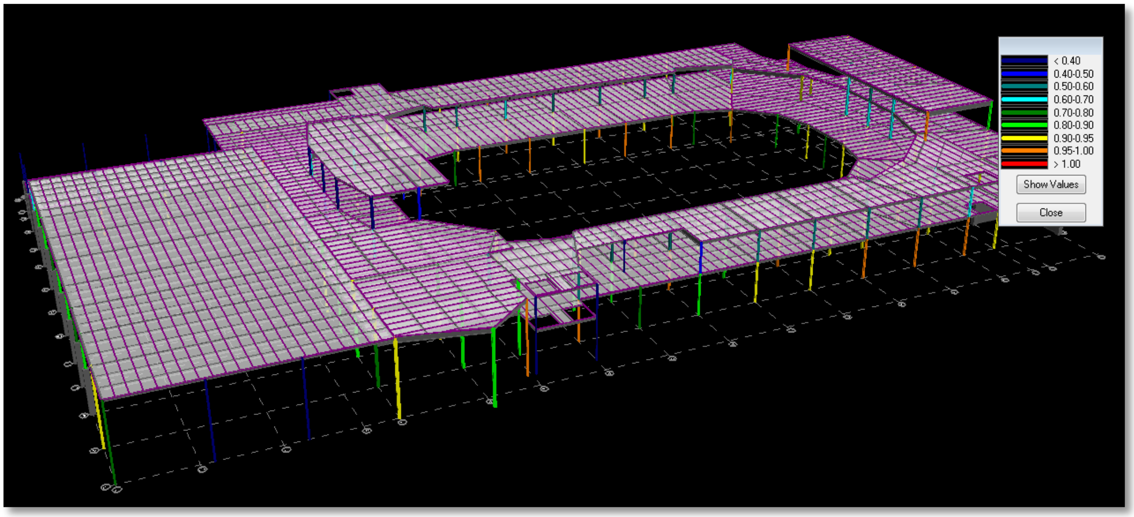


Figure 27. Model of the Gravity Structural System in RAM

Having decided to change the column lines to match the regular spacing and to add a mechanical loft above the lobby, the gravity structure was redesigned using RAM Structural System. After inserting the gridlines into RAM, beams and columns were placed in their appropriate locations. The roof was not modeled in RAM because RAM cannot design long span structures and is built for more regular structures. To account for added weight from the precast seating bowl, "rakers" were modeled as flat beams and the floor deck was extended to cover the precast seating bowl. Appropriate dead and live loads were applied based on the usage of the area. The predominant live load was 100 psf at most locations with 150 psf used for mechanical areas. On the areas exposed to the outside, snow drifts were checked and applied as necessary.

The planned composite decking (3VLI18) was checked for adequacy and used in the RAM model. The new typical bays were 30 x 28 feet compared to 32 x 28 feet, a typical framing plan can be seen below. Once the framing was complete, beams and columns were designed in accordance with the AISC Steel Construction Manual and ASCE 7. Typical column sizes under gravity loads were W10x54 along exterior of the typical concourse bays and W14x90 along the interior of the typical concourse bays.

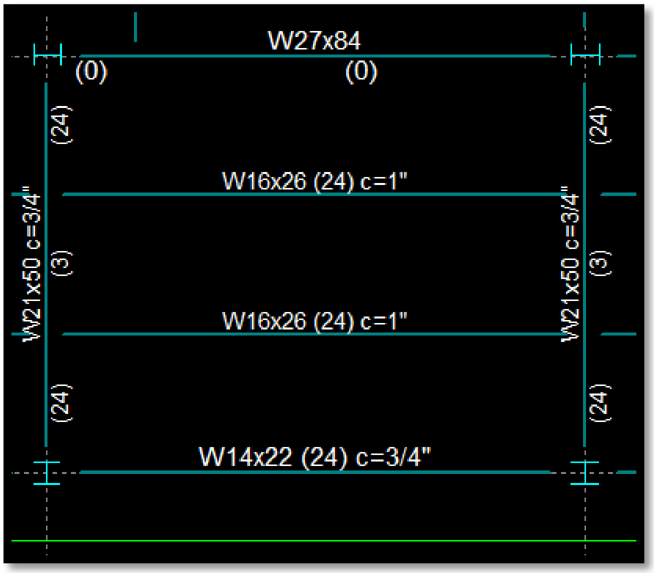


Figure 28. Typical Bay in the Concourse Levels

Once the gravity system was designed in RAM, the Revit Structure model was updated to match new column location and new framing based on coordination with the MEP system. New sizes were loaded into the Revit model as necessary to show actual sizes in the model. Updating the model after this process was extremely important in order to begin coordinating with the MEP system and allowed the team to begin determine areas of clashes. With the gravity model complete, the lateral system could be designed, analyzed, and modeled in Revit to again coordinate with the MEP system.

Lateral Analysis of Structural System

Due to the many structural changes in the roof and realigning several of the column lines, a brief lateral analysis was conducted to determine appropriate sizes of the lateral force resisting system. The existing lateral force resisting system consisted of moment frames along the concourses and shear walls below the Main Concourse Level. This was not changed. An additional moment frame was added due to the smaller bay sizes. The controlling lateral force of the Ice Arena was caused by wind loading. Seismic forces were not a major factor due to the relatively low mass of the structure and the site being designated seismic design category A.

Through the progression of the lateral analysis, several models were attempted in several different structural analysis and design programs. Because the gravity model was analyzed and designed in RAM Structural System, a first attempt was made to model the lateral model in RAM. However, when the program went to run its frame analysis, it had several issues dealing with the large hole in the diaphragm caused by the arena bowl. For some reason, it could not recognize all of the curves in the diaphragm and refused to run an accurate analysis. A second attempt was conducted in ETABS, but again errors resulted. In an attempt to model the diaphragm, the entire floor was modeled and then a hole should have been cut in the floor to represent the bowl. However, ETABS would not recognize the hole. So, in a third and final attempt, the lateral system was modeled and SAP2000. SAP2000, being the most powerful structural analysis program of the three, provided satisfactory results.

The lateral system was modeled in SAP2000 using frame and area elements for the moment frames and shear walls respectively. The wind loads were applied using the automatic lateral loads built in to SAP2000 and checked by loads calculated by hand. Rather than modeling the diaphragm using an area element, a joint was placed at the center of mass and a mass was applied to represent the mass of the floor. Each level was then constrained to create a rigid diaphragm. A displacement limit of h/400 (1 inch) was targeted as the max allowable lateral displacement due to wind forces. With this target set, the moment frames were analyzed and designed using SAP2000. The final moment frame consisted of typical W14x99 columns and W24x104 beams. The shear walls were analyzed as originally designed at 12 inches thick and accepted at their original thickness.

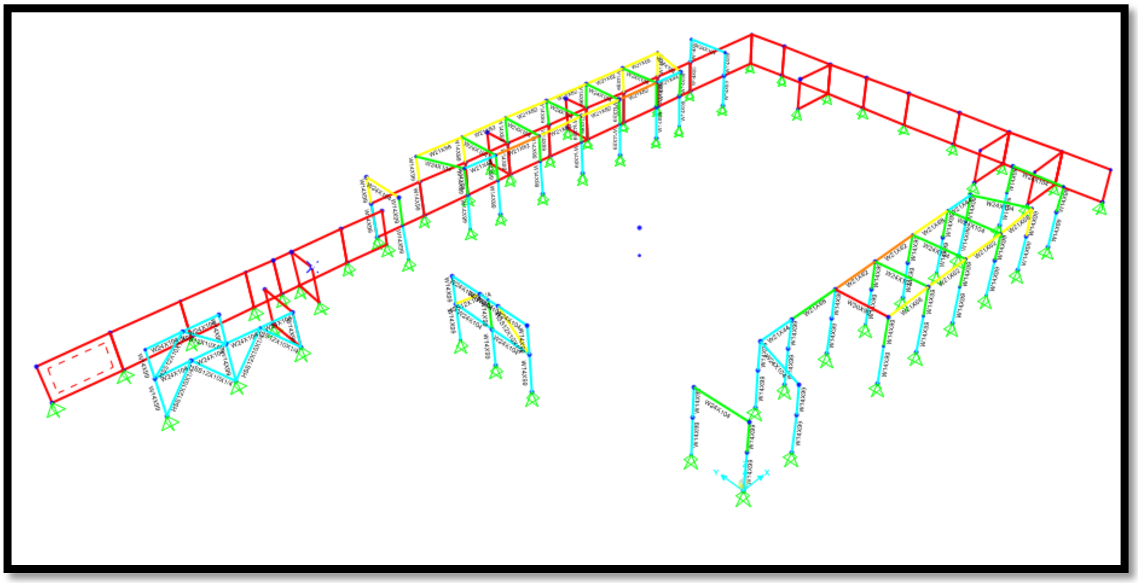
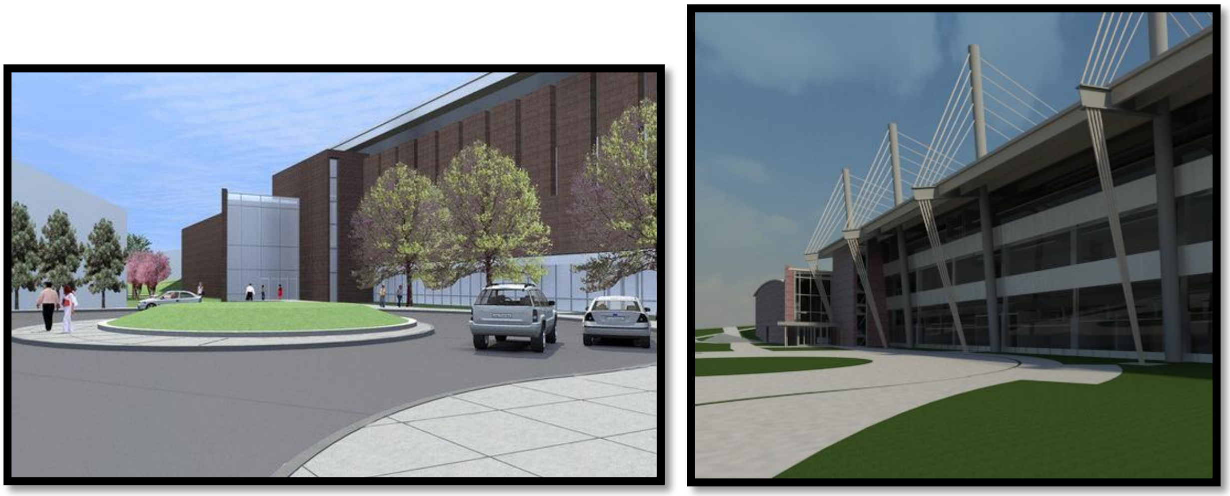


Figure 29. SAP2000 Analysis and Design Model of the Lateral Structural System

Architectural Impacts of New Structural System

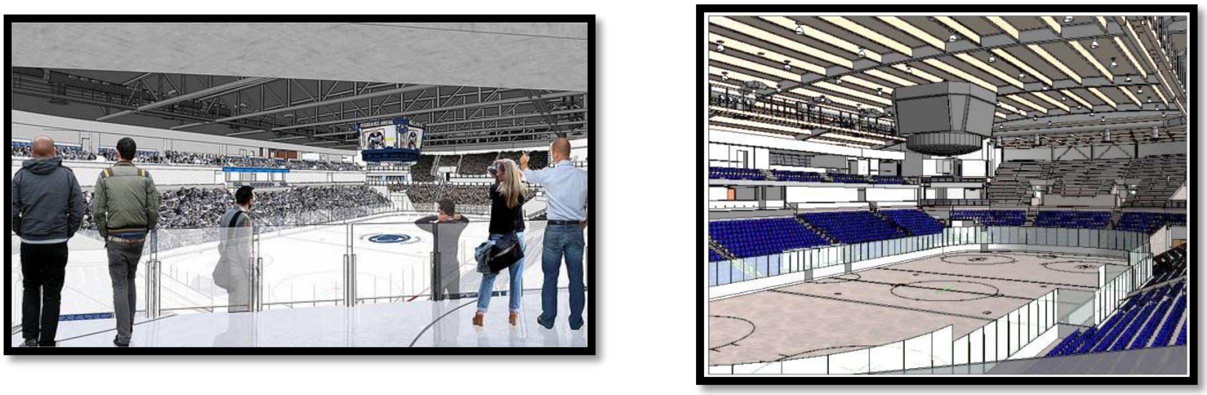
The addition of a cable-stayed roof system and the movement of interior bays had a significant impact on the architectural design. First, the cable-stayed system caused the team to reconsider the façade and that design will be discussed later. In the old design, the building seems rather stagnant and flat, where as the new design is exciting and can be seen from afar as the masts tower 70 feet above the main concourse level where most of the patrons to the arena enter. The three main entrances to the arena now look vastly different due to the cable-stayed system. The main entry is now flanked by two masts on either side. The corners were kept in brick because they locate the vertical cores of the building and help anchor the arena. Below you can see the vast differences of the new design from the old design:

Figures 30 and 31. The figures above shows the original main entrance on the left with the new design on the right

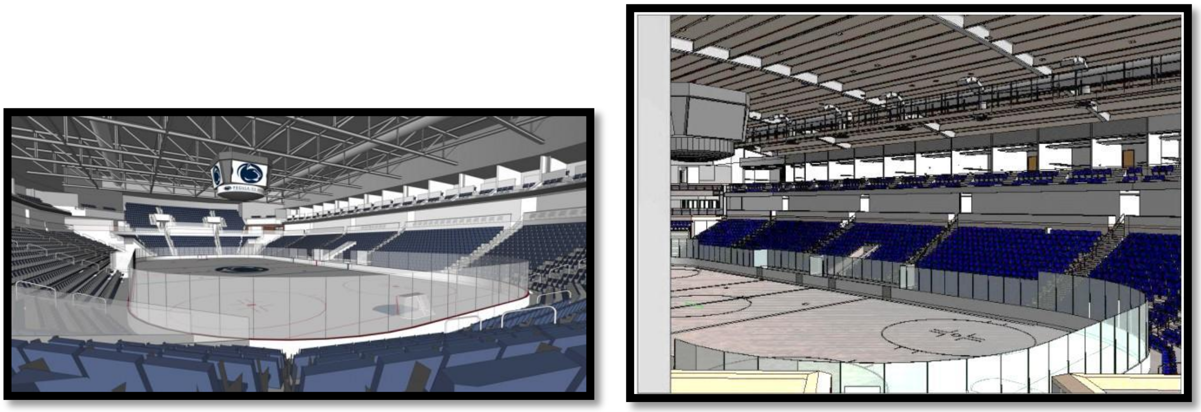


Figures 32 and 33. The figures above shows the original community rink entrance on the left with the new design on the right

The depth of the structural system was reduced from 12 feet to less than 4 feet. This accomplished the sleeker appearance that the team wanted especially on the interior of the arena. The bulky steel trusses have been removed and replaced by a smooth curving steel girder with infill beams. The results can be seen below:



Figures 34 and 35. The figures above shows the original arena interior on the left with the new design on the right



Figures 36 and 37. The figures above shows the original arena interior on the left with the new design on the right

In addition to the obvious changes in exterior and interior appearance, the coordination of architectural plan and column lines was altered to create regular 30 x 28 foot bays. Due to this change, some rooms had to be rearranged and altered slightly to ensure there were no conflicts between the use of the space and the column locations. The most obvious area of change is at the club level. Where large W24x176 columns were once necessary inside the arena to support the large steel trusses, now all of the support for the roof is on the exterior of the arena. This results in a mainly column free interior club level, which allows for greater flexibility in the design of the suites.

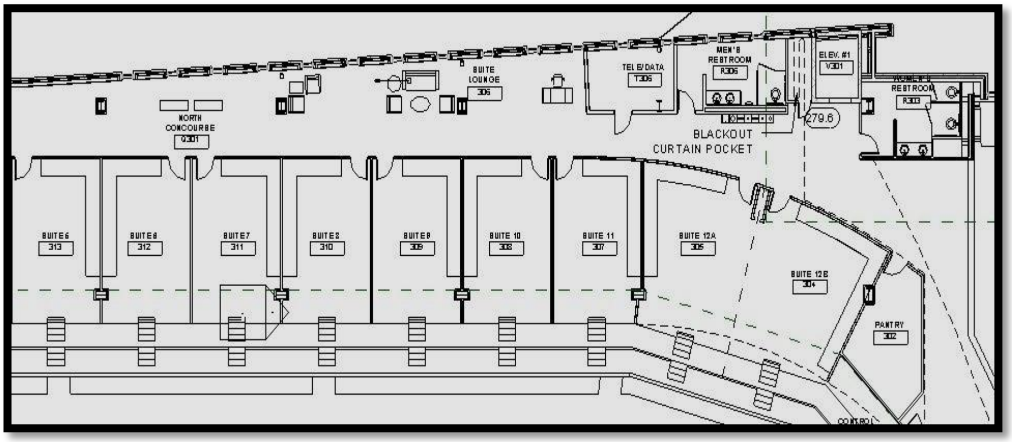


Figure 38. NE Corner of Existing Club Concourse Level Floor Plan

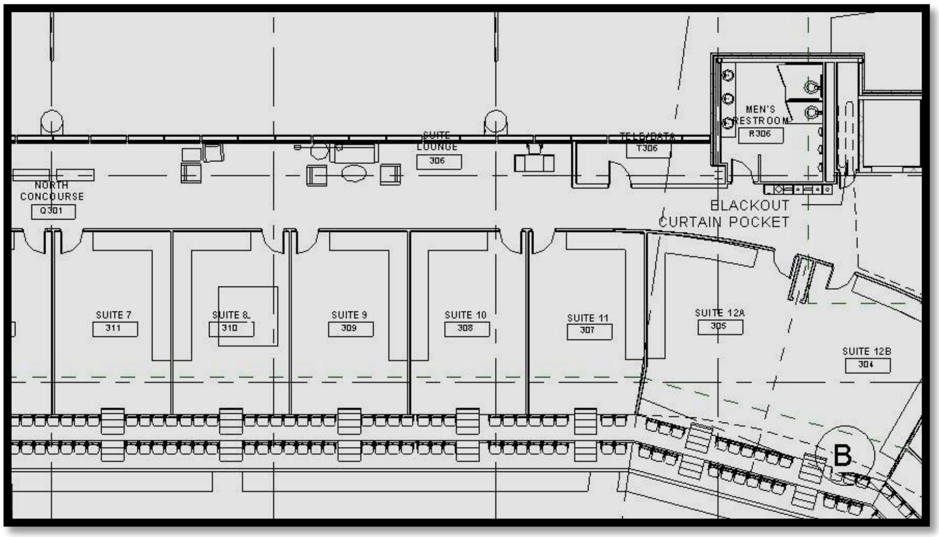


Figure 39. NE Corner of New Club Concourse Level Floor Plan

The exterior columns are still along the exterior façade of the Main Concourse Level, but the movement of column lines had some minor effects on the interior floor plan. In the existing design, columns impact large portions of the restrooms on the Main Concourse and inconvenience the coach's booths. While the new proposed design places more columns in the restrooms, they do not impact the space too much because they are much smaller than the previous interior columns. Thin architectural walls can be placed around the columns and still allow for the room to walk around and use the restroom freely. Columns in restrooms are pretty common in sports facilities and the new design does not negatively impact the restrooms any more than the existing design. However, the interior column relocation benefited the spatial use of the press box area. Columns that closed off the coach's booths in the existing design were moved and now only one column is in the press box area leaving much more usable space.

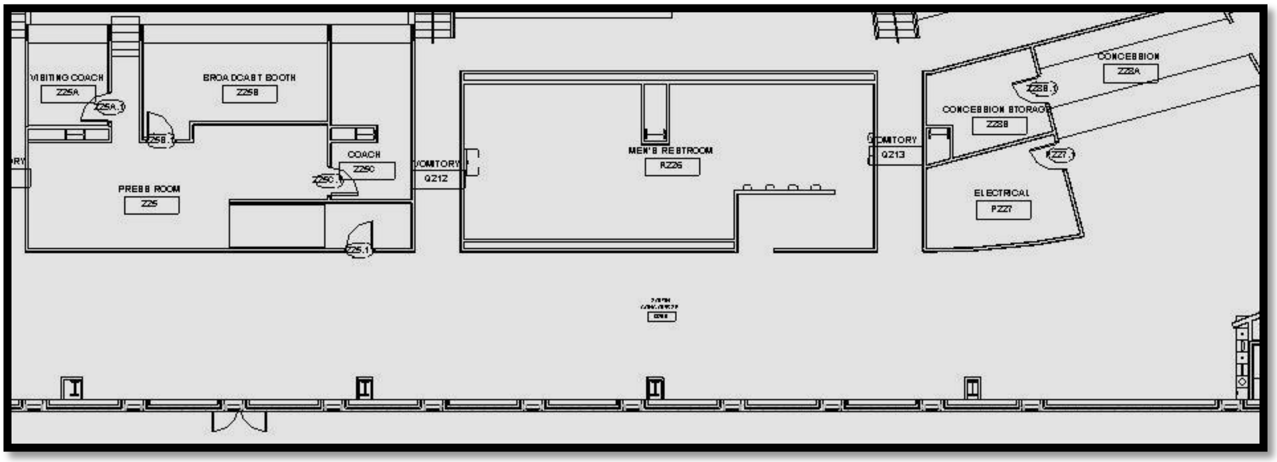


Figure 38. South Portion of the Existing Main Concourse Level Floor Plan

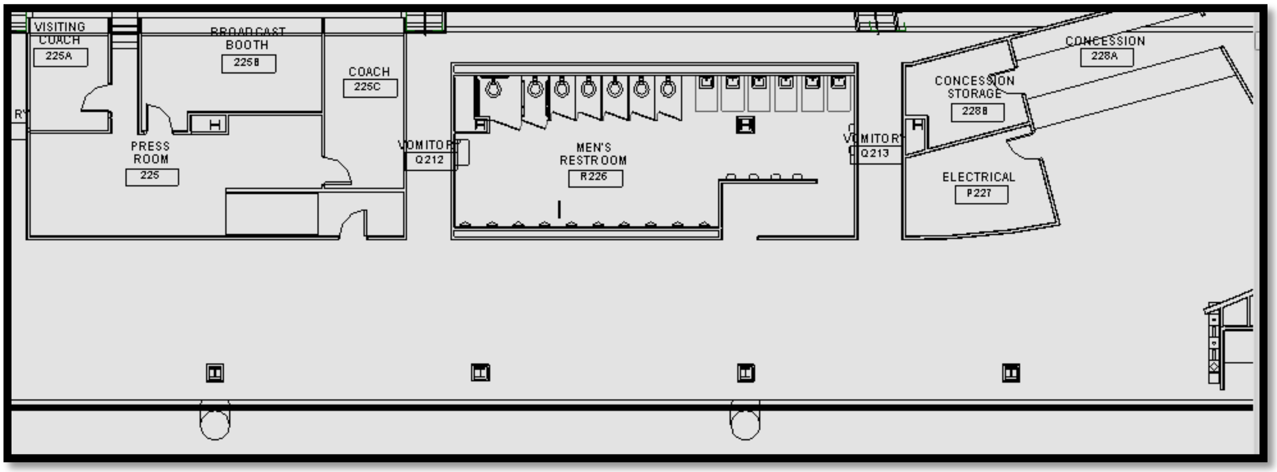


Figure 39. South Portion of the New Main Concourse Level Floor Plan

The relocation of columns affected the Event Level Floor plan the most. On the north portion of the Event Level, the interior columns aligned with the edge of a hallway, so moving them had little impact on the floor plan. However, the offices for the hockey operations are located in the south portion of the Event Level. With so many different smaller rooms located in the hockey operations area of the arena, any movement of columns caused conflict with rooms as they were designed originally. Fortunately, due to the small size of the rooms, they could easily be moved around so that columns impacted the corners of the spaces similar to the original design. The most notable changes occurred by flipping a few rooms around. To accommodate the new locations of columns, the Women's Head Coach's Office was switched with the Women's Recruit Lounge and the entrance to the Hockey Operations was switched with Waiting Area. Overall, the new column lines had minimal impacts on the architectural plans as a whole.

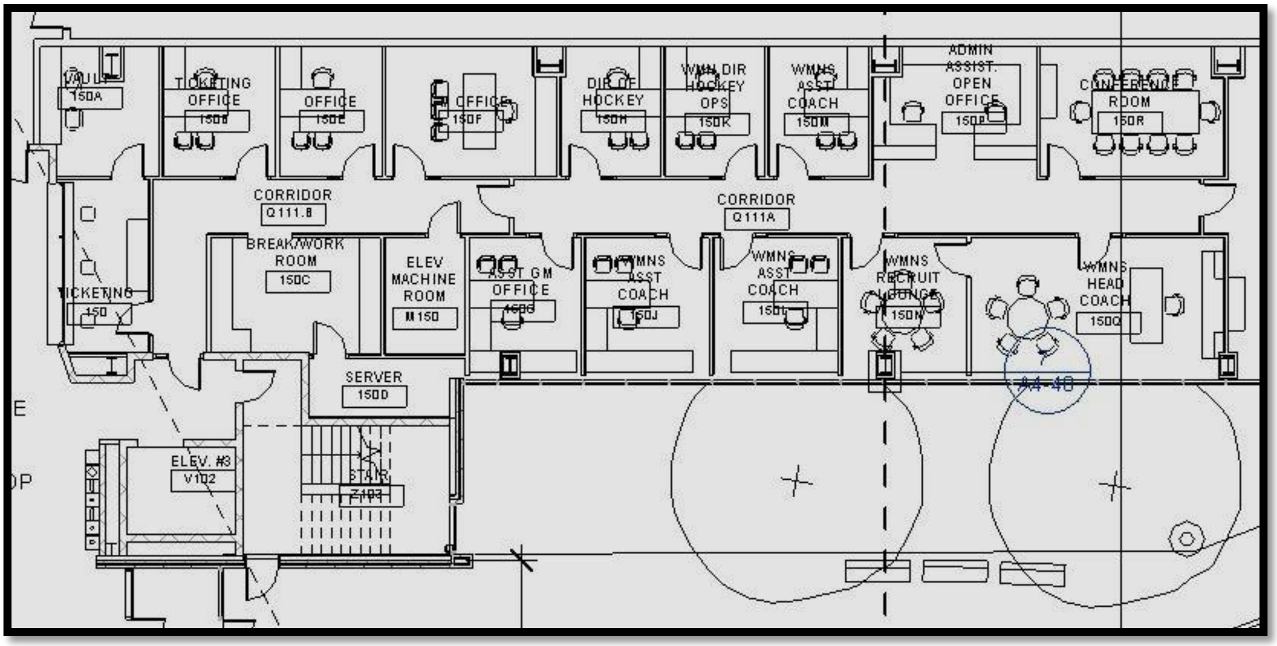


Figure 40. South Portion of the Event Level Floor Plan

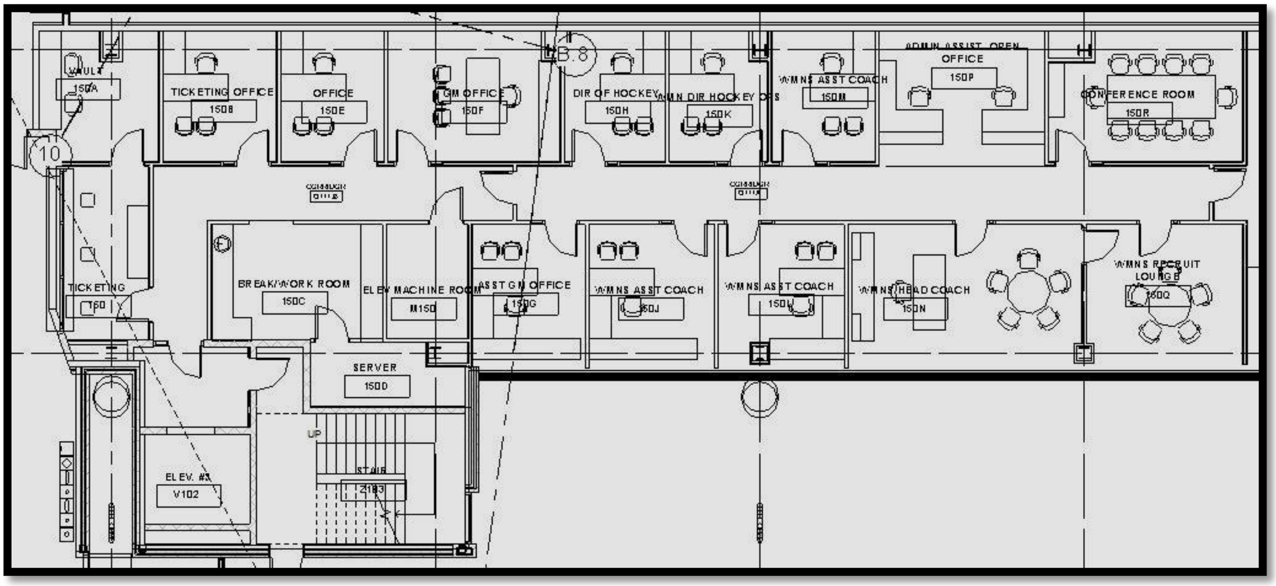


Figure 41. South Portion of the New Event Level Floor Plan

Mast Erection Process

The team elected to use a cable-stayed system to support the main arena's roof. Such a system requires the use of masts to extend upward beyond the roof line and support the weight of the roof through a system of cables. Furthermore, the utilized mast design required a backstay system for further support, which was combined into a singular mast element. Each mast would have to be erected and attached to the roof girders in stages in order to overcome the extreme size of the elements involved.

After coordination with each group member, the team finalized the design for the mast element itself. Taking cues from the Ratner Center in Chicago, the team decided to use a solid, singular, tubular steel mast, as opposed to a system of frames and latticework. The tubular design would be more aesthetic than the alternative and its streamlined look would complement the overall design goals for the arena. Using a singular, tubular mast would, however, create construction issues in terms of its erection. The team's design required 6 masts on both the North and the South faces of main arena. In order to address the difference in elevation between the North and South faces of the building, the masts on the South face had to be a total of 95' tall, as opposed to the masts on the North face which only had to be 75' tall. Transporting a solid steel member of 75' or 95' in length would be extremely impractical in terms of getting it to the site and maneuvering it into position once at the site. Therefore, the team decided to have the mast members cut into two pieces each. For simplicity purposes, it was decided that the masts would arrive on site in lengths of 30', 45', and 50', and would be combined on site to meet the height requirements for each mast, yielding a requirement of 12 mast members of 45', and 6 mast members of 30' and 50' each. These lengths are common enough to be easily transported to the site, and once at the site location, could be offloaded utilizing Mortenson's proposed vehicle/equipment access plan (entering the site at the location of the proposed parking lot to the immediate south of the building).

Once on site, each 45’ length of mast will be offloaded in the vicinity of its intended location. The mast will be hoisted into position by the Grove RT 760 and connected to the foundation. While the mast is being erected, it will be supported by the crane until it is in position, and afterwards will be held upright by temporary supports anchored to the superstructure steel to ensure that the mast section does not collapse or fall over in any way before the roof steel is connected. Once the 45’ length of mast is in place, it will be filled with 8ksi concrete in order to increase the stiffness and axial capacity of the mast. When the concrete has been allowed to cure enough to reach its acceptable strength, the top section of the mast will be hoisted into place and fastened to the bottom section. Again, once in place, the top mast length will be filled with 8ksi concrete. To reiterate, it will be extremely important to erect temporary supports for the masts until the roof girders are connected, as the masts alone will be angled and extremely heavy.

After the mast member is completely erect, work will begin on the backstay support system. Backstay cables will have been previously connected to the foundation system and poured over in place, and will be exposed enough at the top of the foundation to allow for connection to the top backstay cables. The backstay girder will be hoisted into position, again by the Grove RT 760, and connected to the mast by steel workers. It is important to note that the top half of the backstay cables should be attached to the backstay girder section before being hoisted into position in order to reduce the amount of time and work that connecting cables to the girder would require if done after the girder is in position. At this point, the Grove RT 760 will move on to the next mast location to restart this process.

On the erected mast, the foundation backstay cables will have to be connected to the cables hanging from the backstay girder. The bottom and top cables will not initially be able to touch; on the contrary there will be about a six inch gap between them. This gap will be closed during the tensioning process, which will provide more structural strength to the backstay configuration. A crew will set up a foundation cable tensioning device, (Figure 42), around each foundation cable. The device will grasp the exposed length of foundation cable in its bracket and will pull and tension this length up out of the concrete foundation by positioning a set of pressers between the foundation and the crossbeam of the device (see Figure 43). When the device has pulled enough so that the foundation cable can meet the hanging cable, the crew will pin the two cables together through each cable’s connector and the cable will be tensioned. The backstay

Figure 42: Foundation Cable Tensioning Device, *Tensile Surface Structures, p. 103*

cables should be connected in order from the inside of the configuration to the outside. The upper portion of backstay system should connect the mast to the backstay girder in a similar fashion, replacing the foundation cable tensioning device with a standard hydraulic cable tensioning device (Figure 44).

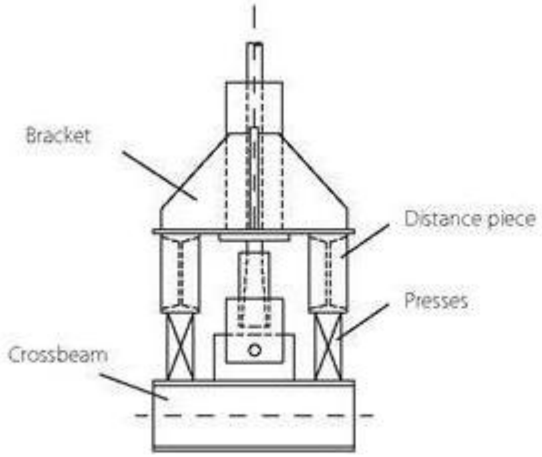


Figure 43: Foundation Cable Tensioning Device Diagram, *Tensile Surface Structures, p. 103*

When the superstructure steel is erected and connected, erection of the roof steel will commence. W40 X 593 girders will span the roof, mast to mast, 252' total. In order to facilitate this construction, the girder will be cut into 42' sections, meaning that there will be six girder sections per span, which will facilitate transportation of the girders onto the site and will allow for easier lifts. The girders will be hoisted into place from the inside of the bowl by the Grove TMS 900E. Girders will be attached to the mast and each other by steel workers as the process progresses. When a girder section is installed, it will first be connected to the mast if it is the first section out or to the previously connected girder. Once the girders are connected, a crew will go up on a man lift and tension the associated cables from the mast to the girder section. After a girder section is installed from one mast and is in the process of being tensioned, the crane will relocate to other side of the bowl and lift the opposite mast's girder into place. The girder sections will meet in the middle of the span and be connected.

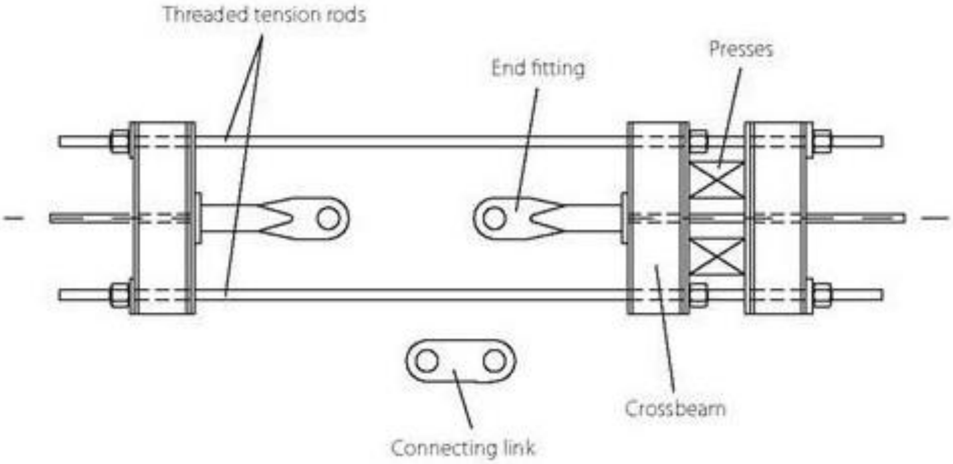


Figure 44: Hydraulic Tensioning Equipment for a free rope length, *Tensile Surface Structures, p. 103*

The spans will be completed from the east side of the building (starting along column line X16) and proceed west to column line X6. After two adjacent girders are completed, the connecting roof beams (W33 X 130s) will be installed between the two girders. For instance, after the girder along X16 is completed, the crane will proceed to erect the girder along X14. Once that girder is completed, the crane will lift the joining roof beams into position, followed by lifting the metal roof deck up onto the roof steel. When the roof deck is attached to the roof beams, a low-slump concrete will be poured over the roof deck. The concrete must be poured almost immediately after the roof deck is installed in order to weigh down the roof deck and prevent it from lifting off of the roof steel should a strong wind arise. It is important to note that the section between column lines X8 and X10 will not have roof steel installed until after the section between X6 and X8 is finished in order allow enough room to lift the roof beams and roof deck up to the span between X6 and X8. Once the section between X6 and X8 is finished, the section between X8 and X10 will be finished, from the north side to the south, and allow the crane to “finish out” through the gap between X8 and X10 in the superstructure steel. When the roof concrete is cured and finished, the roofing crews can continuously install the rest of the built up roof system over the entire roof.

Crane Selection

In order to facilitate the roof’s construction, including the masts, it was determined that the project would need two cranes on site. One crane would operate around the perimeter of the building footprint, specifically used to erect each mast. Another crane would be located in the seating bowl of the arena and would be used to install the superstructure steel and the roof girders, beams, and roof deck. Furthermore, a man lift would have to be used to lift a steel crew into position for connecting the roof girders and tensioning the attached cables. The criteria for selecting each crane would include the boom length, the maximum lifting radius for the heaviest pick, and cost. Research was conducted to find local crane and equipment rental companies in order to obtain a realistic sense of what types of cranes would be available for this project, and their associated rates. Fiore Brothers Leasing Co. and Allison Crane and Rigging were consulted for hourly and daily rates of several cranes, as well as rates for transporting the cranes and associated counterweights to the site, which is reflected in Figure 45.

Crane Selection

Model	Tonnage	Crane Type	Max. Radius For >25,000 lbs Lift (ft)	Rental Rate ($/Hr)	Rental Rate ($/day)	Transportation Fee
Grove TMS 475	50	Truck	25	$ 150.00	$ 1,200.00	$ 1,200.00
Grove RT 760	**60**	**Rough Terrain**	**25**	**$ 180.00**	**$ 1,440.00**	**$ 1,350.00**
P & H T750	75	Truck	40	$ 200.00	$ 1,600.00	$ 1,500.00
Krupp GMT - AT70	80	Truck	45	$ 205.00	$ 1,640.00	$ 1,500.00
Grove TMS 900E	**90**	**Truck**	**65**	**$ 325.00**	**$ 2,600.00**	**$ 1,500.00**
Link-Belt HTC 3140	140	Truck	60	$ 350.00	$ 2,800.00	$ 2,400.00
Liebherr 1150	170	Crawler	120	$ 425.00	$ 3,400.00	$ 3,200.00

Figure 45: Table showing crane selection data

The Grove RT 760, rough terrain crane was chosen as the crane to erect the masts. It was one of the smallest cranes examined, but it could still lift the required 25,000 pounds (the weight of a 50' section of mast) at a radius of 25 feet, which is more than an enough room for the crane to maneuver the mast into place. More savings were realized by selecting a smaller crane in terms of both rental rates and the transportation rate, as the smaller crane requires fewer counterweights.

The Grove TMS 900E was selected as the crane intended to erect the superstructure steel and the roof steel. It was selected because of its mobility as well as its efficiency. Compared to heavier, more expensive cranes, it has a better lift radius for lifting the required 25,000 pounds (weight of each girder section). Through careful planning, it can easily pick every piece of superstructure steel, as well as every girder and roof beam, as shown in Figure 46.

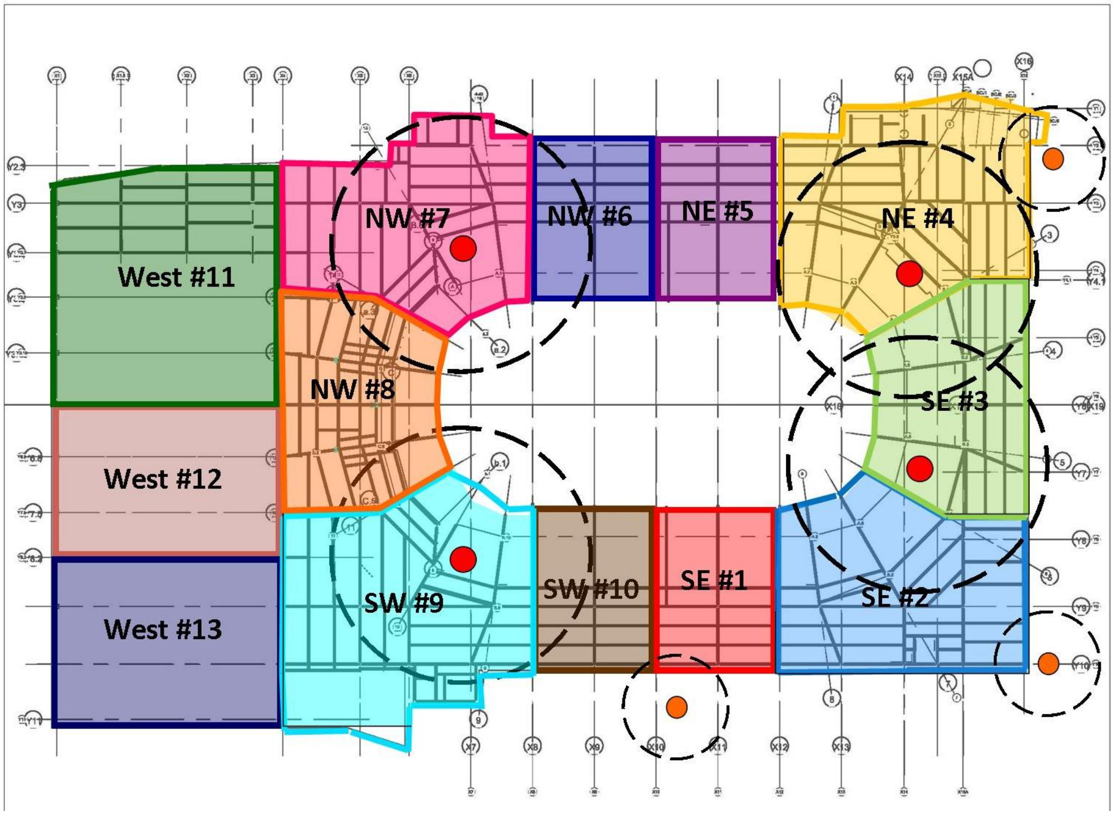
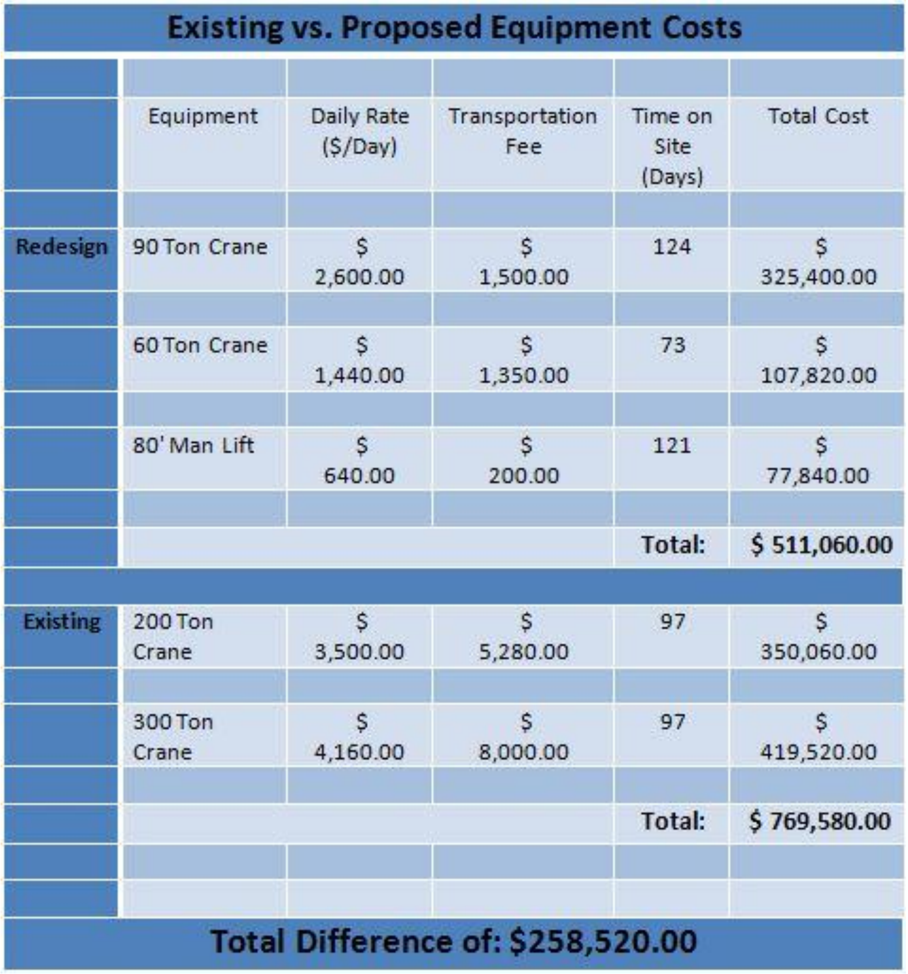


Figure 46: Steel lift configuration map. Orange circles with smaller radii represent locations for the Grove RT 760 and red circles with larger radii represent locations for the Grove TMS 900E.

Crane/Equipment Comparison

In order to fully evaluate whether or not the team's proposed roof design was better than the existing design, the erection process for each and therefore the equipment required for erecting each design had to be compared. It was revealed in a meeting with Gene Hodge, Senior Project Manager for Mortenson Construction, that the existing design would be erecting using two crawler cranes: a 200 ton crane and a 300 ton crane. The 300 ton crane would hoist two-thirds of each roof truss into position while the 200 ton crane would simultaneously hoist the remaining third of each roof truss into position. While still being supported by the cranes, steel crews would climb onto the trusses and bolt them into place. Because Mortenson was still unsure exactly which model of cranes they would use at the time of the interview, rental rates were determined by contacting local crane rental companies that had 200 and 300 ton cranes for rent.

The closest rental company to have these sizes of cranes was Greiner Crane, which has a rental location in Pittsburgh. After talking with a rental representative, it was determined that the 300 ton crane would cost approximately $4,160 per day and $3,500 per day for the 200 ton crane. Additionally, there would be a fee for transportation each crane and its associated counterweights to and from the site: $5,280 (each way) for the 300 ton crane and $8,000 (each way) for the 200 ton crane. The costs for the proposed equipment (two cranes and a man lift) versus the costs associated with the required cranes for the existing roof (300 and 200 ton cranes) are reflected in the Figure 47. The durations required for the proposed equipment were determined after a creating a revised schedule analysis. Durations for the existing system's required equipment reflects a rough estimate ascertained by contacting Mortenson. As shown, adopting the team's proposed cable-stayed roof system will yield a savings of $258,520 in terms of equipment required. Although estimated to be on site for a longer period of time, the proposed equipment's smaller size and lesser rental and transportation rates explain these savings.



Existing vs. Proposed Equipment Costs

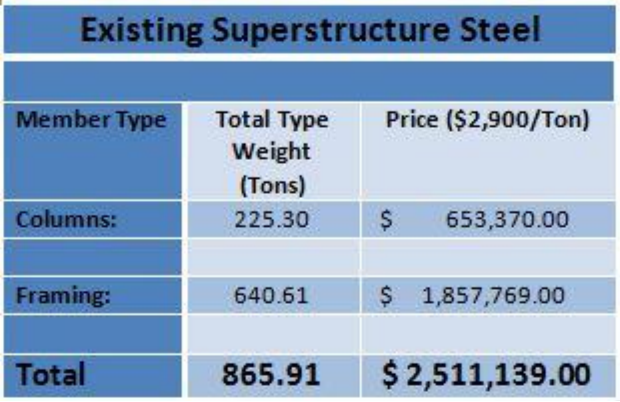
	Equipment	Daily Rate ($/Day)	Transportation Fee	Time on Site (Days)	Total Cost
Redesign	90 Ton Crane	$ 2,600.00	$ 1,500.00	124	$ 325,400.00
	60 Ton Crane	$ 1,440.00	$ 1,350.00	73	$ 107,820.00
	80' Man Lift	$ 640.00	$ 200.00	121	$ 77,840.00
				Total:	**$ 511,060.00**
Existing	200 Ton Crane	$ 3,500.00	$ 5,280.00	97	$ 350,060.00
	300 Ton Crane	$ 4,160.00	$ 8,000.00	97	$ 419,520.00
				Total:	**$ 769,580.00**

Total Difference of: $258,520.00

Figure 47: Table comparing equipment costs for the existing roof design and the redesigned cable stay roof system.

Steel Takeoffs and Cost

To determine whether or not the team's cable-stay roof design should be implemented, the existing and proposed systems were both analyzed from a cost perspective. These cost analyses were executed by using Revit Structure's Quantity Takeoff tool and applying cost data to the required structural members. Cost data was gathered from a meeting with Gene Hodge, Senior Project Manager for Mortenson, who estimated that steel for the roof trusses cost approximately $4,800 per ton of steel and the superstructure steel cost approximately $2,900 per ton of steel. The quantity takeoffs performed in Revit for both the existing system and the proposed system were exported into Microsoft Excel in order to organize the steel's tonnage and cost per ton. First, the existing and proposed systems' superstructure steel requirements were analyzed, as reflected in Figures 48 and 49. Because the team's proposed cable-stay system creates a lighter roof system, the team's structural engineer was able to size down and eliminate many members of the arena's superstructure as it no longer had to support such a heavy roof. This reduction in superstructure steel yielded a savings of 280.48 tons of steel and a cost savings of $813,392.



Existing Superstructure Steel

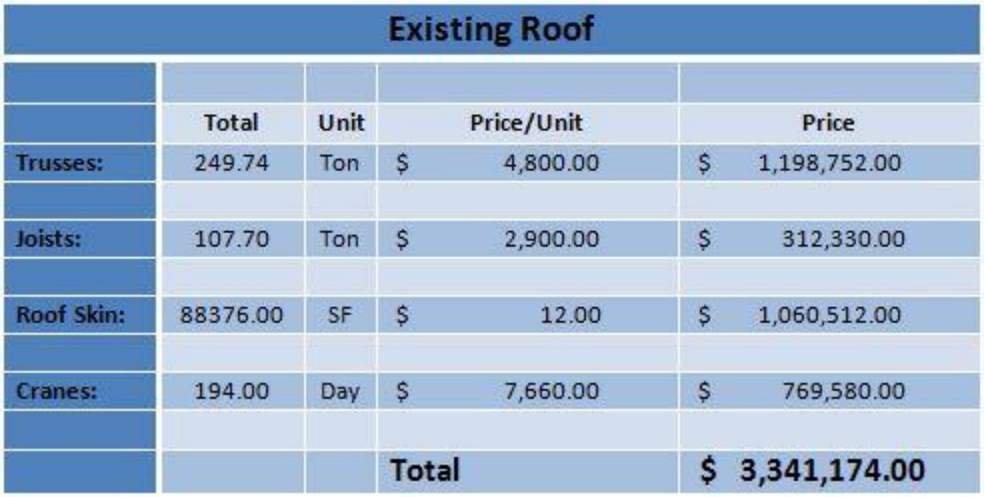
Member Type	Total Type Weight (Tons)	Price ($2,900/Ton)
Columns:	225.30	$ 653,370.00
Framing:	640.61	$ 1,857,769.00
Total	**865.91**	**$ 2,511,139.00**

Figure 48: Table showing the existing superstructure steel tonnage and cost.

Redesigned Superstructure Steel

Member Type	Total Type Weight (Tons)	Price ($2,900/Ton)
Columns:	101.36	$ 293,944.00
Framing:	484.07	$ 1,403,803.00
Total	**585.43**	**$ 1,697,747.00**

Figure 49: Table showing the redesigned cable stay system's required superstructure steel tonnage and cost.



Existing Roof

	Total	Unit	Price/Unit	Price
Trusses:	249.74	Ton	$ 4,800.00	$ 1,198,752.00
Joists:	107.70	Ton	$ 2,900.00	$ 312,330.00
Roof Skin:	88376.00	SF	$ 12.00	$ 1,060,512.00
Cranes:	194.00	Day	$ 7,660.00	$ 769,580.00
			Total	**$ 3,341,174.00**

Figure 50: Table featuring the cost of the existing roof system.

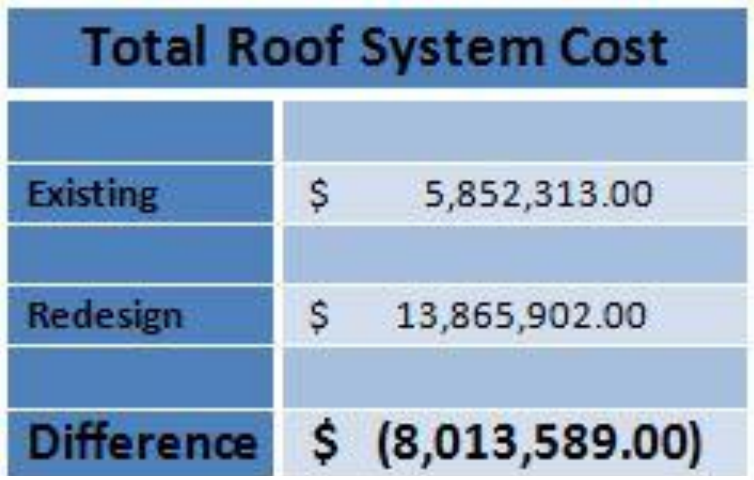
Next, the existing roof system and proposed cable-stay system were analyzed. Again, quantity take offs were performed on each Revit model and exported to Microsoft Excel for organization. The existing roof cost analysis factored the system's required trusses, joists, roof

Redesigned Roof

	Total	Unit	Price/Unit	Price
Beams:	559.25	Ton	$ 2,900.00	$ 1,621,825.00
Girders:	755.48	Ton	$ 4,800.00	$ 3,626,304.00
Masts:	282.54	Ton	$ 2,900.00	$ 819,366.00
Cables:	-	Feet	-	$ 4,500,000.00
Roof Skin:	90800	SF	$ 12.00	$ 1,089,600.00
Cranes:				
60 Ton Crane	73	Day	$ 1,440.00	$ 107,820.00
90 Ton Crane	124	Day	$ 2,600.00	$ 325,400.00
Man Lift:	121	Day	$ 80.00	$ 77,840.00
			Total	**$ 12,168,155.00**

Figure 51: Table reflecting the total cost of the redesigned cable stay roof system.

skin (the cost of which was also provided by Mortenson's Gene Hodge) into the total cost, which can be seen in Figure 51. The proposed, redesign roof cost analysis factored the system's cables, masts, roof girders, roof steel, and crane/equipment costs into the total cost in order to accurately



Total Roof System Cost	
Existing	$ 5,852,313.00
Redesign	$ 13,865,902.00
Difference	**$ (8,013,589.00)**

Figure 52: Table comparing the total costs for the existing roof design and the redesigned cable stay roof system.

compare to the existing roof total cost, and can be seen in Figure 52. The superstructure steel costs of each system are combined with these total roof system costs and summarized in Figure X. As noted, the team's proposed cable-stay system would cost $8,013,589 more than the existing system. Such a massive cost overrun on the part of the redesigned roof system can be attributed to the extensive use of custom made materials in the form of great lengths of extremely large-diameter cables, as well as the cable masts which are extremely irregular. After consulting with Tom Secules, Project Manager for Structural Products for Wirerope Works (our proposed cable manufacturer), who provided the cost estimate for the group's cables, it would seem that the design could realize greater cost savings if the team had more time to coordinate with Wirerope Works on the cable design and keep perfecting the system. He believed such efforts would result in smaller-diameter cables used throughout the project which would significantly reduce the costs of the cables.

Steel Erection Sequence

As previously stated, the steel erection will require two cranes on site: the Grove RT 760 and the Grove TMS 900E. The Grove RT 760 will assist in the erection of the masts and will also lift the community rink's structural steel and the East Mechanical Loft's mechanical equipment into place. The Grove TMS 900E will be positioned in the arena bowl and erect all of the main arena's superstructure steel as well as the roof steel.

Similar to Mortenson's proposed steel erection sequence, the team broke up the superstructure steel sequence into sections (Figure 53). Each section's steel will be erected in its entirety so that all levels' steel will be erected. The steel will be erected in a counter-clockwise direction, starting with SE #1 and initially ending at SW #9. SW #10 will be left open in order to facilitate steel delivery into the arena bowl and allow the TMS 900E to exit the bowl once the roof is erected. SW #10's superstructure steel will be completed as the crane moves out of the main bowl, after the roof steel is erected. The TMS 900E will not erect the community rink's structural steel; after the masts have been erected, the RT 760 will relocate to the west of the building and lift the community rink's structural columns, roof joists, and roof deck into place.

Following the progress of the superstructure steel, the RT 760 will erect the masts associated with each section (ie masts at X10 and X12 for section SE #1, and so on). The team estimated that the erection time for each mast will be approximately 4 days. After analyzing the redesigned construction schedule, it was noted that there will be 12 days between when the RT 760 finishes erecting the north mast at column line X6 and when it can begin work on the southern mast at column line X6, due to the time required for the TMS 900E to finish erection sections NW #7, NW #8, and SW #9. Furthermore, the concrete slab for the East Mechanical Loft will have been cured and finished by this time. Therefore, the RT 760 will relocate to the east side of the building to lift the air handling units that will be relocated to the East Mechanical

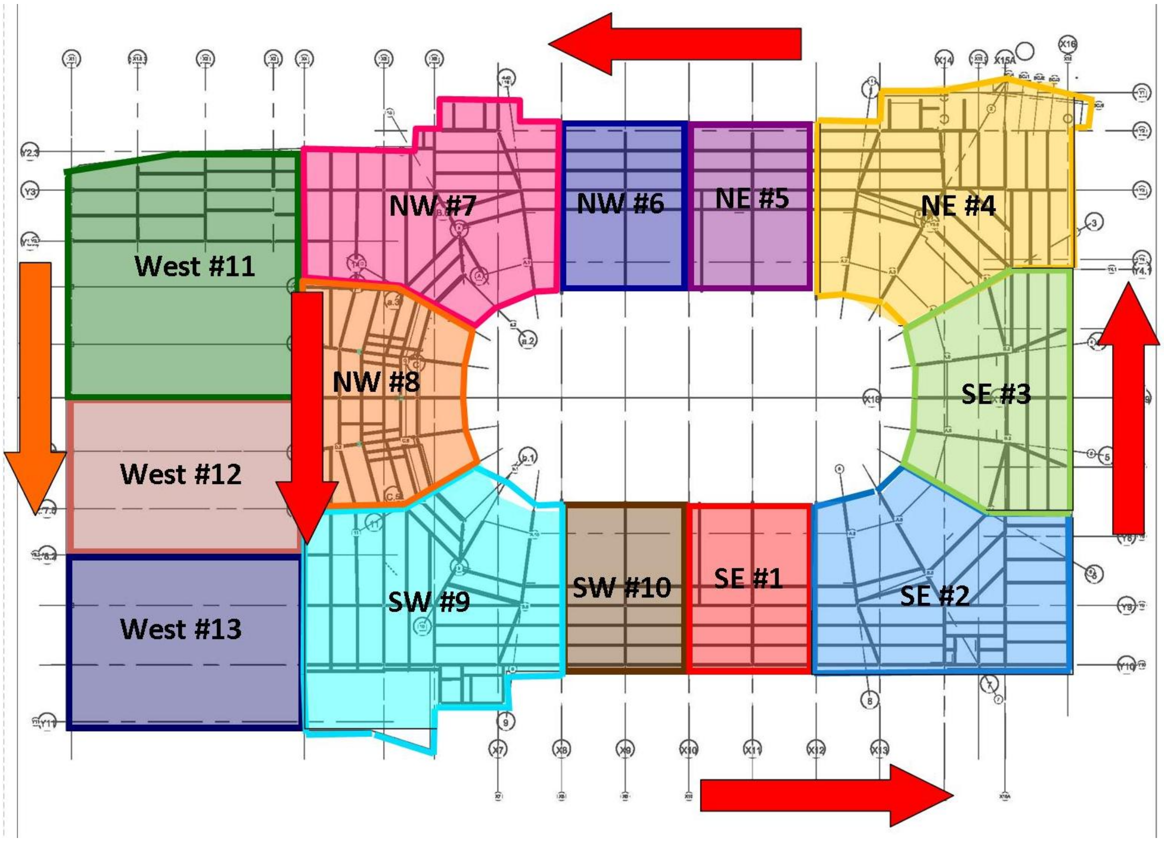


Figure 53: Structural steel erection sequence map. The red arrows indicate the direction of the superstructure steel erection sequence by the TMS 900 Ewhile the orange arrow indicates the structure steel erected and its direction by the RT 760.

Loft. Moving these units during this period of time ensures that they will be able to be lifted in and positioned well before work will begin on the roof immediately overhead. Furthermore, because of the limited clearance between these mechanical units and the roof, installing them at this time will allow plenty time for the crews to install and connect all units before the roof is erected overhead. After the units have been lifted into place and the TMS 900E has completed enough of SW #9's superstructure to continue, the RT 760 will relocate back to SW #9 and install the southern masts at column lines X6 and X8. As previously mentioned, the crane will then move on to erect the community rink's structural steel after the masts have been erected.

Like Mortenson's existing concrete pouring plan, the team split up work into sections (see Figure 54) by combining the previously utilized steel erection sections into groups of three. Concrete will be poured by level over each of these pouring sections. Pouring will begin on the Main Concourse level of SE #1 immediately after the steel floor decking has been installed on the above Club Level. As seen in the redesigned schedule, the work is staggered so that the floor decking of SE #2 and SE #3 will be completed in a fashion that will allow concrete to be poured

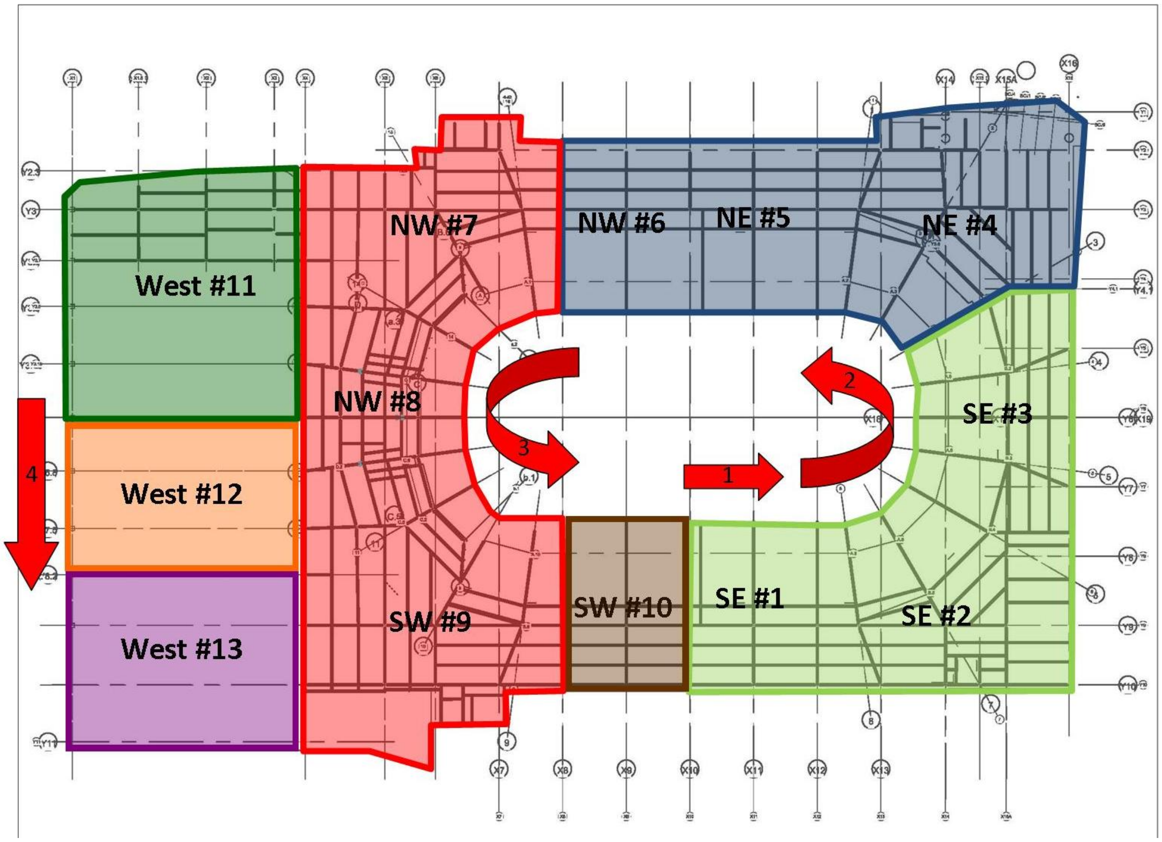


Figure 54: Concrete Pour sequence map. Note that the superstructure erection sections are combined into larger concrete pour sections. Concrete for the community rink will not be poured until after the red section is poured and finished.

virtually continuously over the entire Main Concourse level. Once the Main Concourse level has been poured for a section, crews will repeat the process on the next level, the Club Level. Work will continue in this fashion until all levels of a concrete pour section have been poured over twice. The crew will then move on in a counter-clockwise fashion to the next concrete pour section until SW #9 has been poured, upon which the concrete crew will move on to pour the community rink's slab on grade and roof concrete. It is important to note that the concrete pour section including NW #7, NW #8, and SW #9 will be accessed from the west because work was coordinated so that the community rink (sections West #11-13) will not begin steel erection until after all concrete work in NW #7, NW #8, and SW #9 is complete. This will allow concrete placing equipment such as pump trucks to position themselves closer to where they are required.

SW #10 will be completed after all roof steel has been installed. This omission of superstructure steel and concrete facilitates the unloading of materials in the arena's bowl itself for easy access for the TMS 900E. Furthermore, section SW #10 could not be completed until after the roof steel is erected in order to allow the crane to be removed from the bowl.

Main Roof Redesign Conclusion

After completion of the main roof redesign, several conclusions were apparent. First, several iterations would be necessary to make the cable-stayed roof design feasible. In discussions with WireRope Works, they believed that it was very possible to cut the amount and sizes of cables down if Lights-Out Design were able to continue the design. Also, other shapes and materials could be considered for the backstays of the mast to reduce cost. Overall, the design showed the team how important it is to get involved with the construction manager and cable manufacturer early in the design process. With earlier input and suggestions from the manufacturer, the cost of the roof could have been significantly reduced.

It is now evident why the actual design only spans the main bowl. Without thinking outside the box, a steel truss that spanned out-to-out would have been extremely expensive. In order to span such great lengths, extreme coordination is necessary between every member of the design team. With today's technology, it is now easier than ever to design and fabricate custom shapes and sizes. Without the use of BIM and IPD, the cable-stayed roof design would have been extremely difficult for a team of rather inexperienced engineers. Through the use of Revit and Sketch-Up, the team was successfully able to design a potential roof that would span the entire arena with reduced depth and to develop a potential erection procedure. While the team realizes that our exact design is probably not feasible at this stage, the team feels that through continued shape finding and even greater use of BIM programs a cable-stayed roof design for the Penn State Ice Hockey Arena could become a reality.

Façade Redesign

Continuing with the team's vision of an iconic design the overall building façade is the next system that merited extensive investigation. In keeping with the main concept of a visually light-weight structure and facade, the design-development façade we were given, which utilized a heavy brick façade, was redesigned to produce a building that, architecturally, is more cohesive with our proposed roof design and contextually appropriate. The goal, through this redesign, was to create a visually appealing roof and façade integration where the roof appears to be floating and hovering above the structure itself.

To achieve this goal, thin lightweight materials such as glass and metal panels were investigated for use on the exterior. A secondary consideration in the selection of materials was their context and use around campus. Although the end goal is for an iconic building, our team feels that, by effectively utilizing similar building materials found around campus our proposed design can better fit into the context of the university while still maintaining visual prominence. A large part of inspiration for the selection of materials came from the HUB-Robeson Center located on campus and also from the Ratner Center located at the University of Chicago.

Figure 55. Design Development North Brick Facade

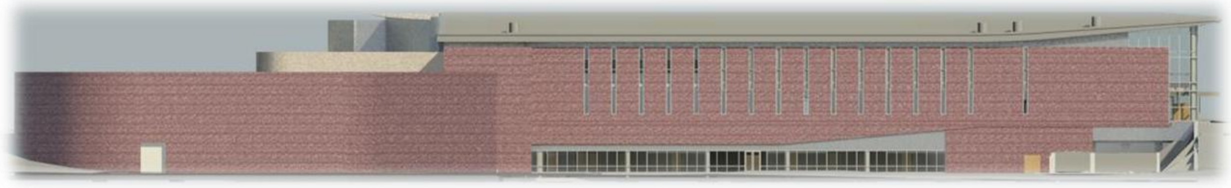


Figure 56. Design Development South Facade

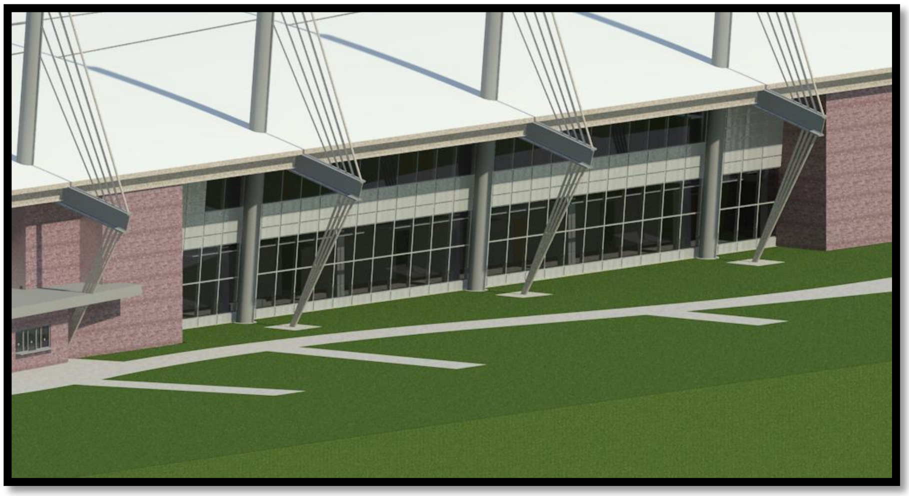
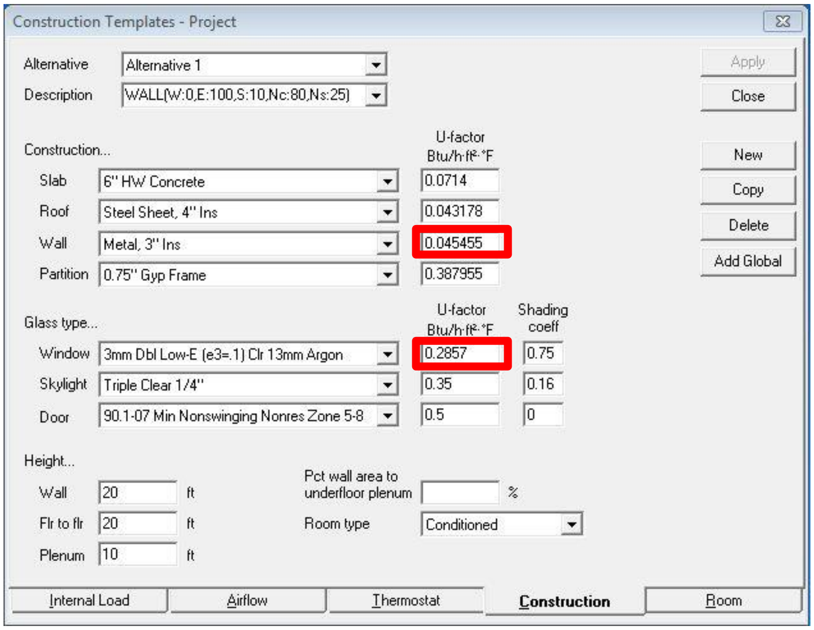


Figure 57. North Concourse Façade

Thermal Analysis of the Façade

The façade was redesigned in order to complement the cable stay roof. The cable stay roof allows for a much lighter façade. With a lighter façade the roof will look as if it floating instead of just sitting on a brick box. Metal panels and glazing substitutes the brick façade only for the concourses in the redesign. Centria Smart-R Wall Solution was chosen for the metal panel façade. Centria is an all-encompassing façade that includes the vapor barriers, insulation, and metal panel in one system. This façade was also chosen for the high R-Values, R22 for the metal panel and R3.5 for the glazing. These R- Values were inserted into the Trane Trace analysis model.

Figure 58. Centria Smart-R Wall Solution



Alternative: Alternative 1
Description: WALL(W:0,E:100,S:10,Nc:80,Ns:25)

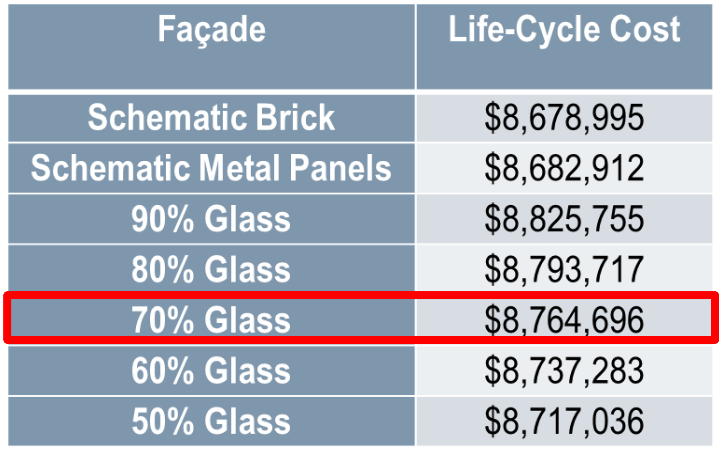
Construction...		U-factor Btu/h·ft²·°F
Slab	6" HW Concrete	0.0714
Roof	Steel Sheet, 4" Ins	0.043178
Wall	Metal, 3" Ins	0.045455
Partition	0.75" Gyp Frame	0.387955

Glass type...		U-factor Btu/h·ft²·°F	Shading coeff
Window	3mm Dbl Low-E (e3=.1) Clr 13mm Argon	0.2857	0.75
Skylight	Triple Clear 1/4"	0.35	0.16
Door	90.1-07 Min Nonswinging Nonres Zone 5-8	0.5	0

Height...
Wall: 20 ft
Flr to flr: 20 ft
Plenum: 10 ft
Pct wall area to underfloor plenum: %
Room type: Conditioned

Figure 59. Trane Trace Construction Template

A life-cycle analysis was performed in order to analyze the energy costs of the façade redesign. The façade for the concourses and event level offices was changed from brick to the metal panel design in the Trane Trace model and the life-cycle cost was calculated. A wall to glass ratio analysis was then performed. The glass percentage of the concourse facades was first evaluated at 90% wall area and then analyzed in 10% increments down to 50%. A breakdown of the analysis is shown in Figure X.



Façade	Life-Cycle Cost
Schematic Brick	$8,678,995
Schematic Metal Panels	$8,682,912
90% Glass	$8,825,755
80% Glass	$8,793,717
70% Glass	$8,764,696
60% Glass	$8,737,283
50% Glass	$8,717,036

Figure 60. Façade Redesign Life-Cycle Cost

The final façade redesign consists of 70 percent wall area glazing. This façade has increased daylighting, a thin feel, and is only $85,701 more in energy costs over 30 years. This equates to less than $3000 a year in additional energy costs. The actual difference is most likely less because the life-cycle analysis did not include a thorough daylighting analysis and the occupation schedules were conservative. The concourse spaces will have low occupancy throughout the life of the arena.

Figure 61. Façade Redesign South Elevation

Figure 62. Façade Redesign North Elevation

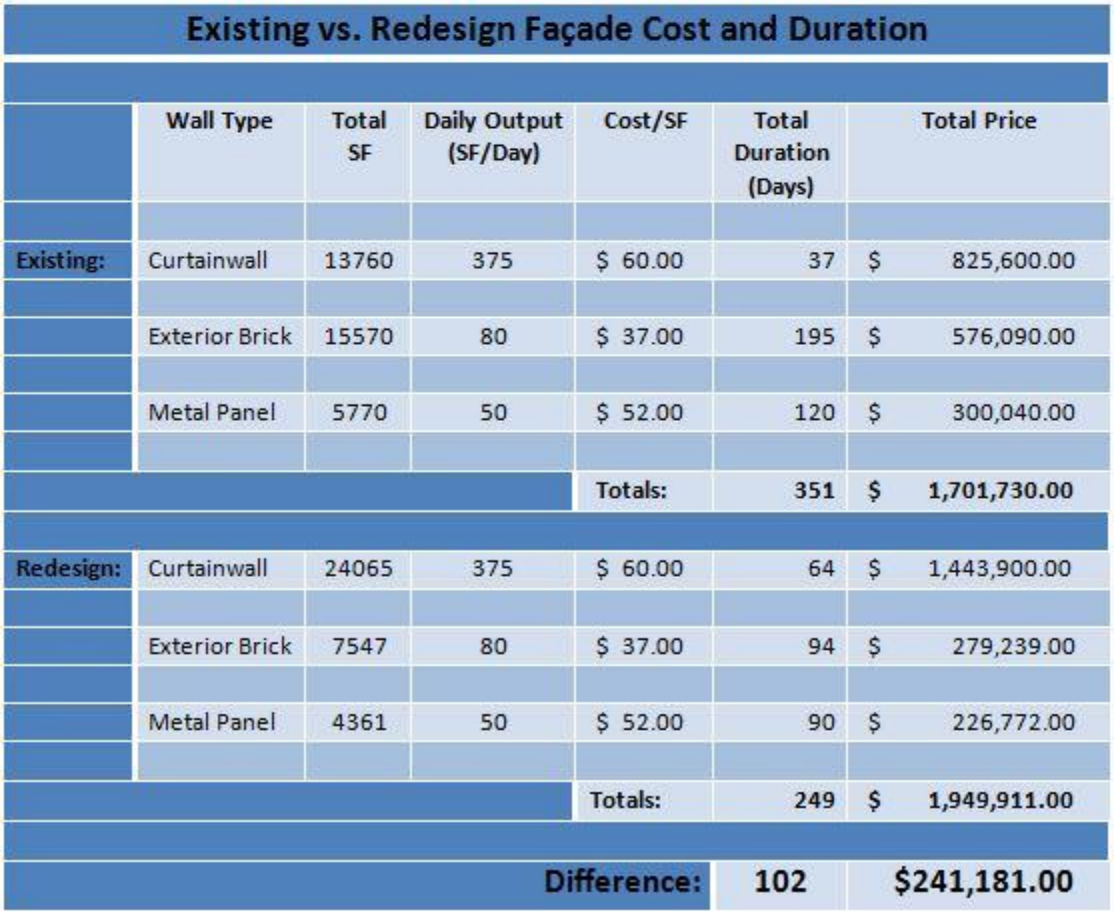
Façade Takeoff and Cost Estimates

After having redesigned the main arena's roof system, the team was afforded the opportunity to redesign the arena's façade. From an architectural standpoint, the team had to create an exterior that would complement the unique, newly designed cable stay roof. The new roof's design appears very streamlined, sleek, and light, as opposed to the existing roof design which seemed very bland and box-like. Furthermore, the existing façade's appearance is very monolithic and imposing, which would not balance well with the lighter, more graceful cable stayed roof. Therefore, the team decided to change the façade's shape and materials to mirror the roof's lightness, and make the roof look almost as if it was floating, like a tent or a canopy.

Through coordination the team began to analyze what affects using new materials would have on the building's performance, appearance, and bottom line. After the MEP engineer came to a conclusion about the ratio of glass to brick to metal panels that would optimize thermal efficiency and still increase daylighting into the arena's concourses, the group as a whole began to incorporate those elements into the façade design. In order to create the appearance that the roof is suspended above the arena, and to reflect the prominent main lobby curtainwall, the team essentially eliminated the exterior brick walls on the building's north and south elevations and replaced them with huge curtainwall sections, which use a combination of glass and metal panels. The brick was kept around the stairwells to create the appearance that they were holding up the roof at each corner, again in keeping with our tent-like theme.

Once the design was finalized, the materials required were tallied up and multiplied by their respective cost and duration values and compared with the original façade design. This take off estimate was performed using Revit Architecture. First, wall sections in the existing design were highlighted to determine the square footage of each section. Once the entire north and south facades had been highlighted and the square footage had been input into Microsoft Excel, each wall section was then labeled by the material it was comprised of; either glass (curtainwall), metal panel, or brick. The same process was done to the redesigned façade. Cost data, given to the team by Gene Hodge, Senior Project Manager for Mortenson Construction, was then applied to each material in a price per square foot format. All of the wall sections were summed up and the total price for each façade design was determined. It should be noted that all prices included the cost of labor. Furthermore, the cost of a brick wall included $20/SF for the brick itself, $12/SF for backup framing and sheathing, $3/SF for rigid insulation, and $2/SF for the waterproofing/moisture barrier. The analyses are summarized in Figure X.

Durations for installing the façade materials were determined based on the anticipated rate for the existing façade design. First, a wall section of a particular material was highlighted in Revit to determine the square footage. Next, that wall section was located in Mortenson's existing construction schedule to determine the amount of days required to complete construction of that particular wall section. Then, the square footage of the wall section was divided by the total amount of days anticipated to complete the wall to yield a duration in the format of square footage completed per day (SF/day). Last, the daily output was multiplied to the total square footage required for that particular façade material. For instance, if a brick wall section was determined to have a square footage of 1,036.85, and it was anticipated to take 13 days to complete the wall including framing, installing lintels, sheathing, air/vapor barrier, brick ties, rigid insulation and brick laying, then the daily output of installing a brick wall all told is 80 SF/day, or 1,036.85 SF / 13 days. The same procedure was used to determine the average daily output and duration for each material type. The daily outputs and derived durations for each wall material are also exhibited in Figure 63.



Existing vs. Redesign Façade Cost and Duration

	Wall Type	Total SF	Daily Output (SF/Day)	Cost/SF	Total Duration (Days)	Total Price
Existing:	Curtainwall	13760	375	$ 60.00	37	$ 825,600.00
	Exterior Brick	15570	80	$ 37.00	195	$ 576,090.00
	Metal Panel	5770	50	$ 52.00	120	$ 300,040.00
				Totals:	**351**	**$ 1,701,730.00**
Redesign:	Curtainwall	24065	375	$ 60.00	64	$ 1,443,900.00
	Exterior Brick	7547	80	$ 37.00	94	$ 279,239.00
	Metal Panel	4361	50	$ 52.00	90	$ 226,772.00
				Totals:	**249**	**$ 1,949,911.00**
				Difference:	**102**	**$241,181.00**

Figure 63: Table comparing the cost and durations of the wall materials associated with both the existing façade system and the redesigned façade system.

The redesigned façade yielded several changes in cost and duration as compared to the existing design. First, the redesigned system is estimated to cost $241,181 more than the existing system. This difference is likely due to the fact that the redesigned façade requires almost 10,000 square feet more of glass curtainwall, which is far more expensive than brick, than the existing design. However, this increase in materials' cost was mitigated by the elimination of about 10,000 square feet of brick used in the façade.

The redesigned façade also saved 102, what we will call, "crew days". Crew days are different from "days" in that implementing the redesigned façade does not mean that the façade will be completely done 102 days sooner than the existing façade would be. On the contrary, according to the redesigned construction schedule, constructing the redesigned façade would actually take longer to complete than the existing. However, these "crew days" are total days that any one crew will have to be on site. Saving 102 crew days means that Mortenson will not have to pay the equivalent of having a combination of crews on site for 102 days. These savings in "crew days" come from the reduction of brick walls used in the façade redesign, because brick walls require a number of crews to be involved in the construction of a single wall (ie. framers, insulation installers, brick layers, etc.). By eliminating the square footage of brick required, the team has eliminated the time required on site for a number of contractors. These savings in "crew days" can be reallocated in the construction schedule in order to realize further savings, say, be hiring multiple brick laying crews simultaneously in order to speed up façade construction.

Lastly, the redesigned system does not take into account savings from energy usage that would be impacted by increasing the amount of daylight into the concourses. Because of this, it can be assumed that there will be a significant decrease in energy usage to light the concourses which will translate into further savings. Despite the increase in cost, there are many advantages to utilizing the team's redesigned façade, including further savings in energy and crew allocation, as well as the advantage of having a more aesthetically appealing arena.

Construction of the redesigned façade will begin at the northwest corner of steel erection section NW #7. Once the concrete is poured and finished at the club level of NW #7, work will commence on the façade and will continue up the entire exterior face and in a clockwise direction around the building. The northwest corner of the main arena was chosen to be the starting point for façade construction because of its distance from the loading dock located at steel erection sequence SE #2. The team wanted to use the loading dock to unload materials that were to be used on the building's interior, such as mechanical ductwork, metal studs, electrical conduit, etc and distribute these materials along the previously poured and finished concourse levels. However, unloading and transporting materials from the loading dock carries with it an inherent risk of damaging previously finished work, such as drywall, mechanical duct installation, etc. Therefore, the northwest corner of the arena was scheduled to begin façade construction first so that it would also be the first section of the building to begin sealing up and start finishing work. That way, materials could be transported from the loading dock, through the unfinished portion of the concourses en route to the northwest corner where finishing work was actually taking place, thus, reducing the risk of going through previously finished sections and damaging that work. Then, the interior work could finish out through the loading dock, or through SW #9 if that would work better.

Façade Redesign Conclusion

The façade redesign was an architectural necessity. The cable stay roof would not have been architectural effective with a thick brick façade. The glass and metal panels succeeded in creating a lightweight feel of the structure. The significant increase in glass improved the daylighting substantially in the concourses surrounding the main bowl. The façade redesign increased energy costs by $85,701 over the life-cycle of the building but this equates to only $3000 more a year in energy costs. The concourse spaces will be occupied at full load only during main events in the arena which only occur a few hours a day. Lights in the lobby and concourse spaces should not have to be turned on during the day which will result in significant energy savings. The cable roof with the façade redesign creates an iconic model for Penn State Ice Hockey. Assuming that the cable roof structure will be constructed, this façade redesign is feasible.

Community Rink Roof Redesign and Mechanical Loft Design

The final topic for redesign that Lights-Out Design chose centered on the design of the community rink roof and the efficiency of the mechanical system. Because the community ice rink will be used more than the main arena and almost 24 hours per day 7 days per week, the group felt that it was important to address daylighting in the community rink. In order to accomplish increased daylighting, the group chose to alter the roof design. The new roof design would allow for more daylighting opportunities in the rink and a more aesthetically pleasing design.

In order to alter the community rink roof, several mechanical units had to be moved. After inspecting the existing mechanical system design, the group felt that the mechanical system's efficiency could be greatly improved by relocating units to another location rather than just grouping them in between the main arena and community rink. So in a sense, the design became driven by two different ideas: one, improve the quality and feel of the community ice rink, and two, improve the efficiency of the overall mechanical system.

In order to increase the efficiency of the mechanical system, the group decided to move several units to a loft above the front lobby. After designing the loft to fit architecturally and structurally, several iterations of clash detection were necessary to coordinate the new structural and mechanical systems. Through the use of BIM/IPD processes, Lights-Out Design was able to efficiently redesign the mechanical and structural systems to coordinate new mechanical shafts and new duct runs. Without the early introduction of BIM, the team would not have been able to realize the design challenges that resulted from the drawings the team was given to work from.

Community Rink Roof Design

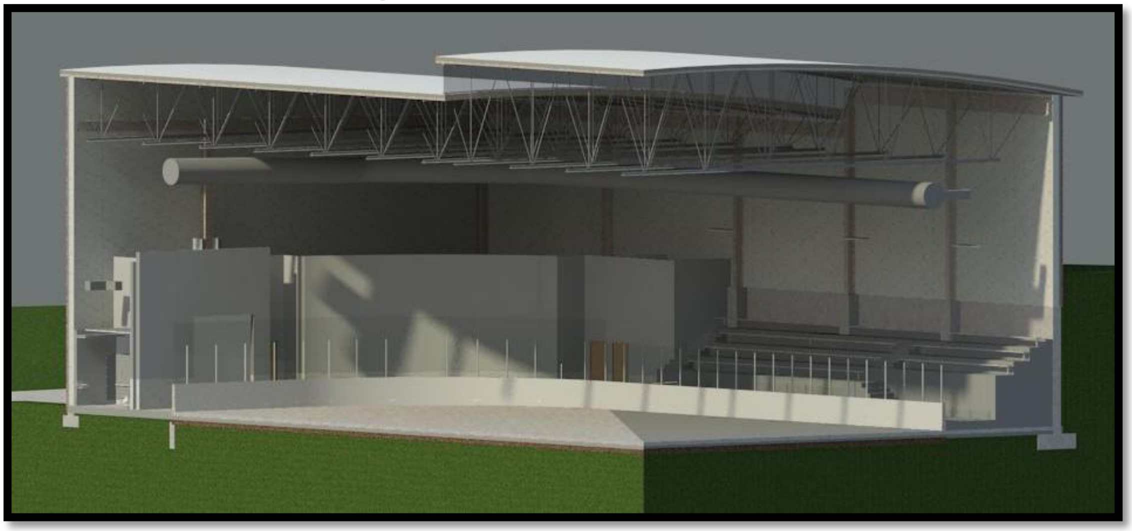


Figure 64. 3D Section of the Community Rink Roof

The community rink roof design was driven by the daylight design. In coordination with the lighting/electrical team member, the structural engineer worked to design a roof that could accomplish the daylighting goals and create an aesthetically pleasing complement to the cable-stayed roof of the Main Arena. In order to create a design different from the flat roof of the existing design, mechanical units had to move to the east of gridline X4. With the creation of the mechanical loft, a flexible roof design could be accomplished.

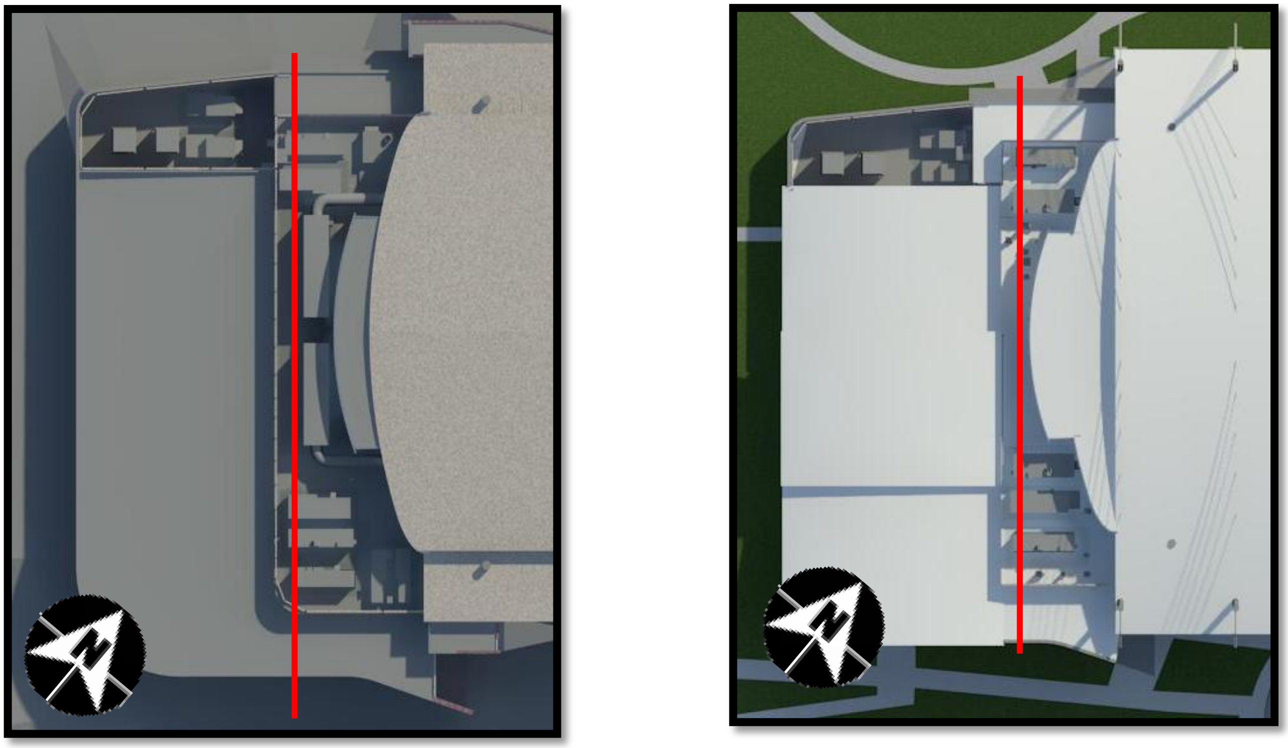


Figure 65 and Figure 66. The Movement of Mechanical Units to the East of Gridline X4

Through discussions with the lighting/electrical team member, the team chose to create an arched roof similar to the main arena roof. To infuse daylighting into the arena, the roof would be divided into three equal parts with the center part raised higher above the two flanking sides. This would create an area where a ribbon of windows could be placed between the lower section of the roof and the raised section of the roof. To help minimize cost and increase regularity, a bowstring joist from New Millennium Building Systems, a special steel joist manufacturer.

To use the special steel joist catalog provided by New Millennium, the structural team member used the design method provided by New Millennium. A roof dead load of 31 psf, snow load of 34 psf, and uplift of 20 psf was applied to the community rink roof. To keep the joists somewhat regular and similar to the original flat long span joists, a spacing of 11.5 feet was used for the joists. The bowstring joists are specified based on span, end depth, center depth, and top chord radius. A radius of 332 feet was selected based on aesthetics for the bowstring joists. To create the ribbon of windows between the lower section of roof and the upper section, the center depth of the joists was varied using 104 inches for the lower roof sections and 164 inches for the upper roof sections. Unbalanced snow loads and drift was checked to ensure the joists would not fail under such conditions. At first, sloping the joists was considered to help minimize the effect of unbalanced snow loads and drift, but it was discovered that the minimal slope that we could achieve failed to have an effect on the design. Ultimately, the smaller joists were designed to be New Millennium 104 SPBW 738/391/230 (TL/LL/UL in plf) with a span of 110 feet and a top chord radius of 332 feet with a 7.5 inch seat depth and 5 rows of bridging. The larger joists are a New Millennium 164 SPBW 738/391/230 with a span of 110 feet and a top chord radius of 332 feet with a 7.5 inch seat depth and 5 rows of bridging.

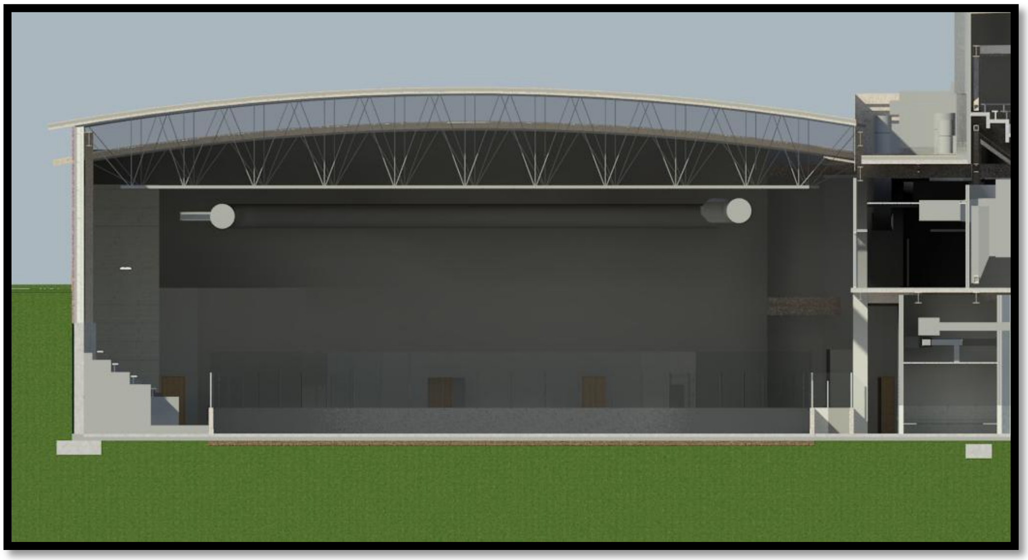


Figure 67. Transverse Section of the Community Rink Roof

Mechanical Loft Structural Design

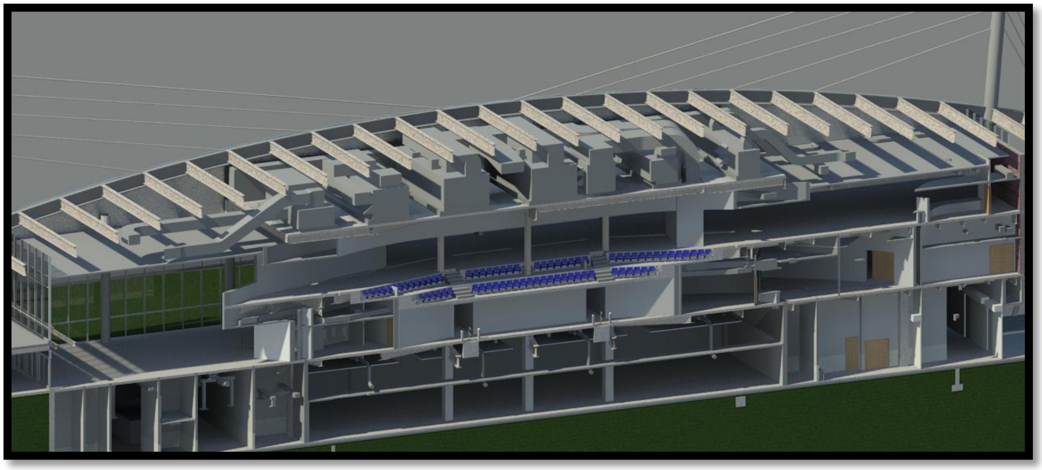


Figure 68. 3D Transverse Section of the Mechanical Loft

Having decided to move mechanical units to a loft underneath the roof and above the front lobby, the first question was how to support the large units. The exterior columns from the front lobby could be extended to support the loft on the exterior, but what was to be done on the interior. Five columns were extended from the Club Level floor up to the new Mechanical Loft, which was set at 16 feet above the Club Level to allow for adequate ceiling heights at the Club Level. The columns were added to support the loft and the best attempt possible to limit their impact on patron views was made.

Three steel framing ideas were designed and analyzed and the framing that produced the least steel weight was selected. The same loads that were applied to the Mechanical Area (DL=130 psf and LL=150 psf) were used to design the Mechanical Loft. Due to the arena bowl, a large 10 foot cantilever was necessary. This accounted for larger sizes in the girders as compared to the infill beams. Once the loft structure was designed, extensive coordination between the structural and mechanical team member was required to ensure that the systems could work together.

Figure 69. Structural Design of the Loft Level from RAM

Mechanical System Redesign

At the beginning of the project, Lights Out Design was given a set of Design Development drawings from the design team. The mechanical drawings in the set show all 14 air handling units to the west end of the main bowl on the mechanical deck above the concourse level. The main duct runs from these units funnel into two shafts, one on the north end and one on the south. The ductwork drawings include single line drawn ducts with only the main duct runs sized. Figure X shows the event level single line ductwork drawing.

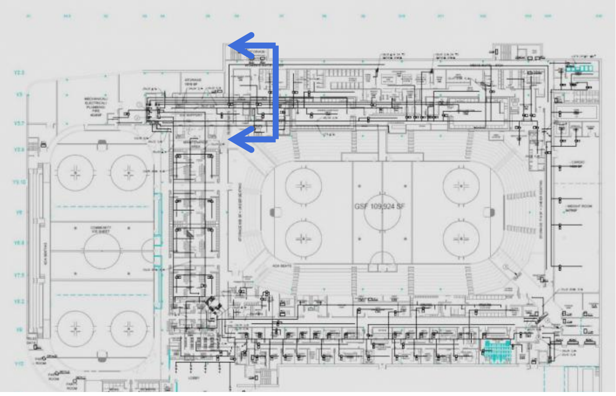


Figure 70. Event Level Single Line Ductwork

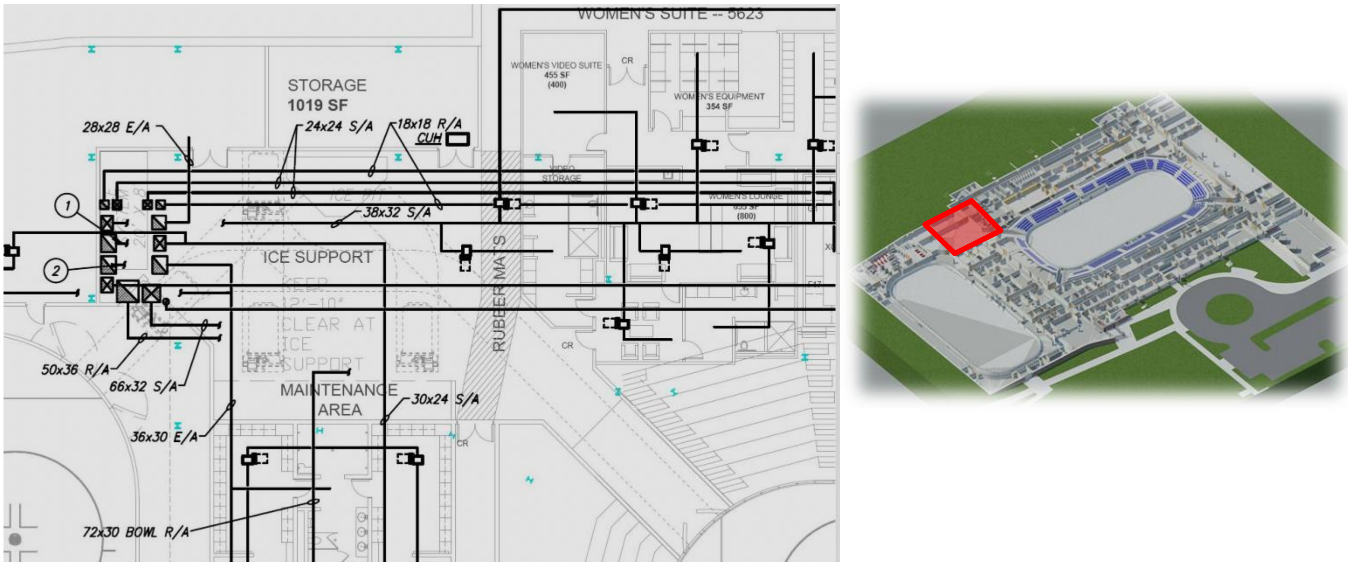


Figure 71. Single Line Ductwork Drawing Blow Up

Figure 72 shows the section shown in blue of the event level plenum space. All the ductwork is shown in the single line drawing in drawn into the Revit Architecture model.

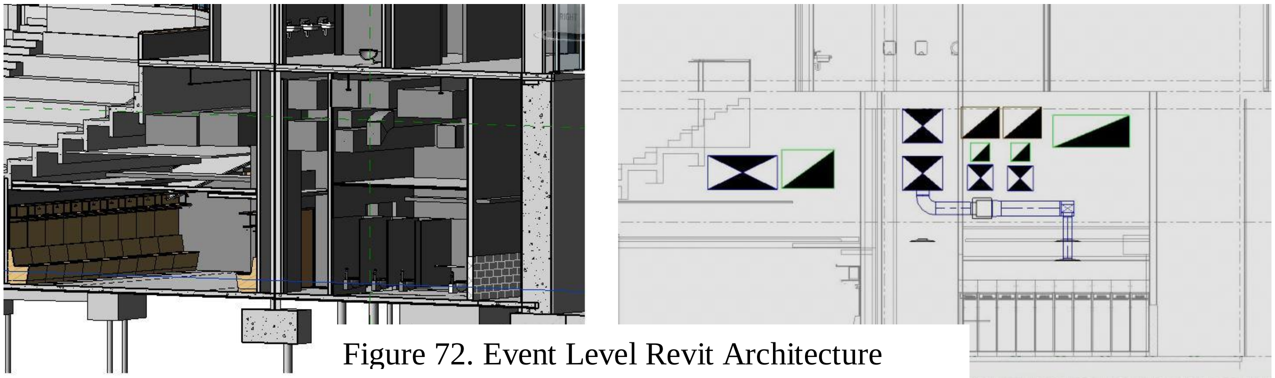


Figure 72. Event Level Revit Architecture

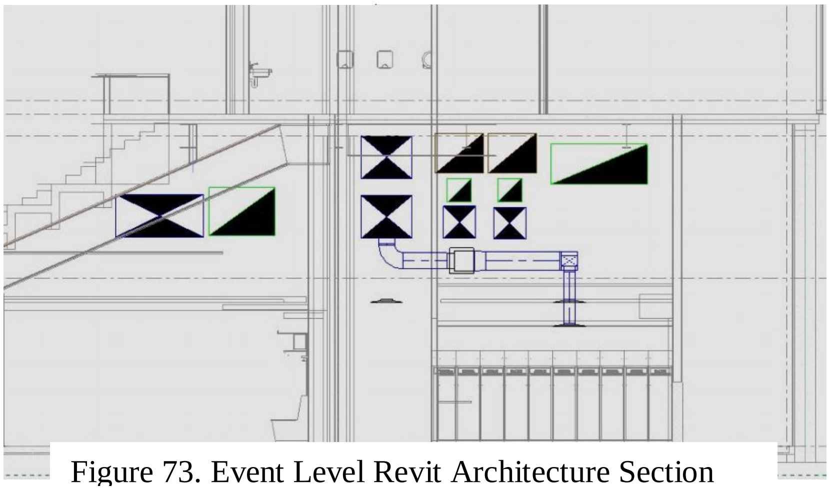


Figure 73. Event Level Revit Architecture Section

After drawing the ductwork into the event level Revit Architecture model the Revit Structure model was linked into the model. This ductwork configuration is clearly impossible as there is no room for piping or conduit; there is not even enough room for ductwork. Ductwork from this section will have to be removed in order for this plenum space to be coordinated. The section of the south event level plenum is cluttered but can be coordinated. There is definitely though not enough room for more ductwork.

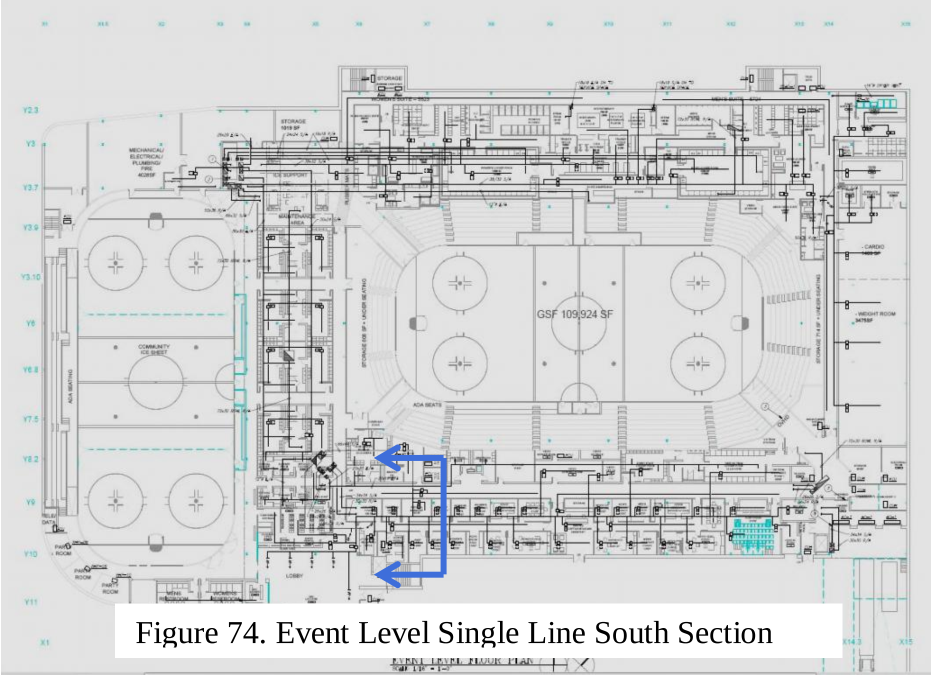


Figure 74. Event Level Single Line South Section

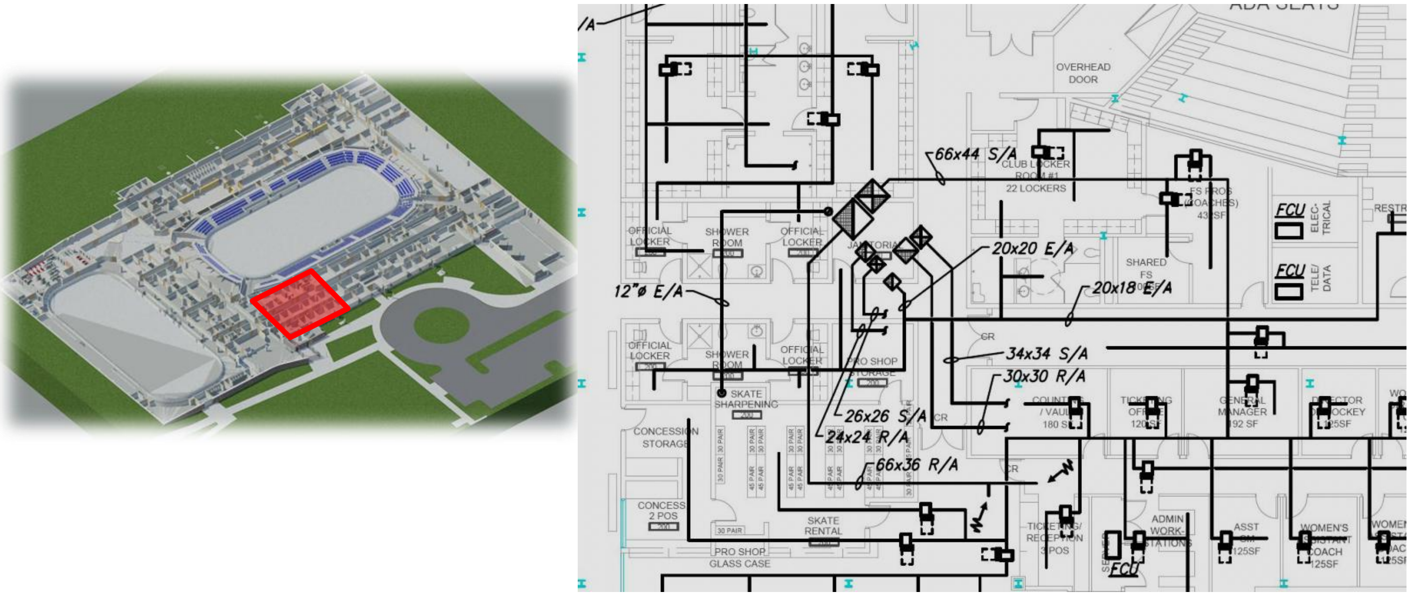


Figure 75. Event Level Single Line South Shaft

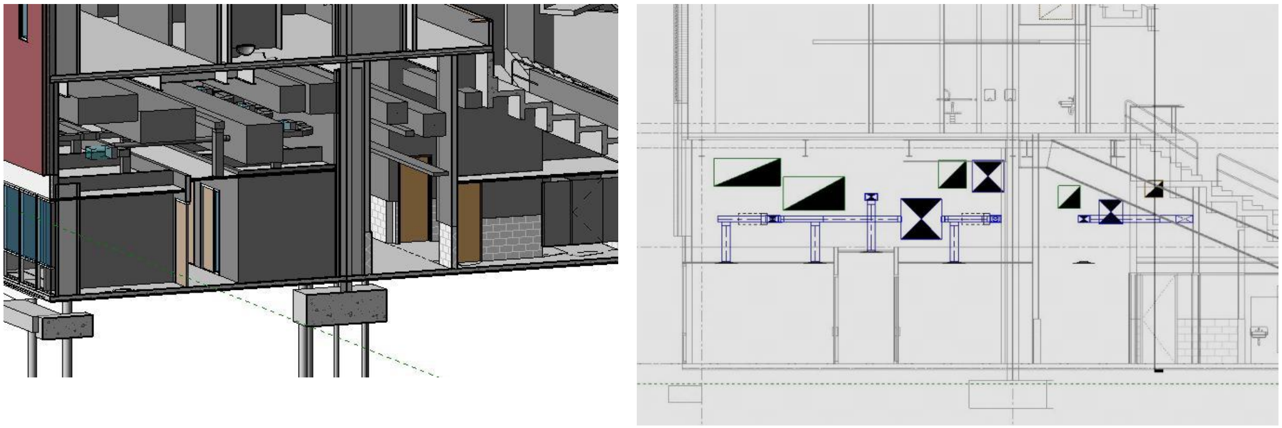


Figure 76. Event Level South Plenum Section

Lights Out Design concluded that at least two air handling units had to be removed from the mechanical deck in order for the coordination to work. If AHU-6 and AHU-7 are removed from the mechanical deck then the north plenum can be coordinated and the whole mechanical system can be coordinated. AHU-6 in the design development drawings sits on the mechanical deck and the supply ductwork runs the entire length of the arena before it starts to supply air to the workout rooms. The supply and return also clash with the structural rakers supporting the stands.

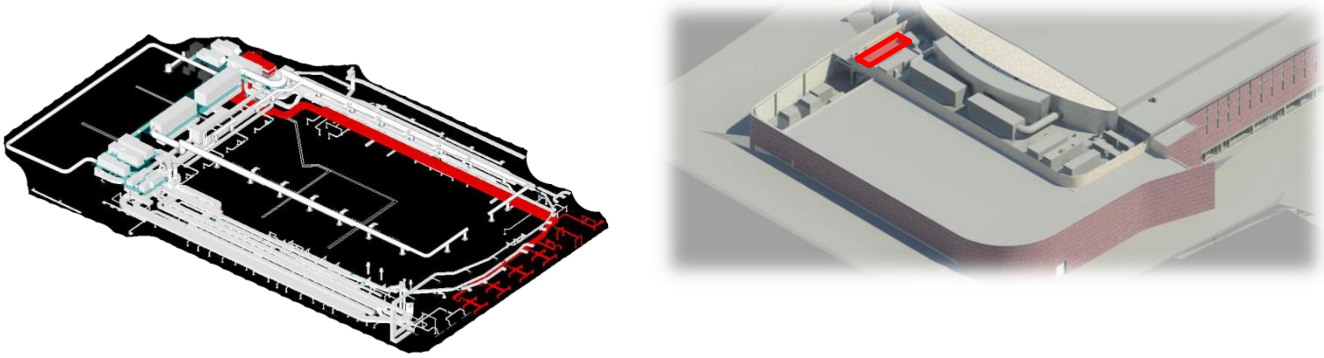


Figure 77. Design Development AHU-6 Layout

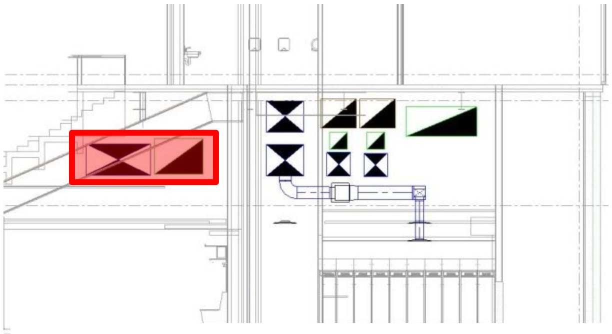


Figure 78. AHU-6 Clashing with Structural Rakers

Lights Out Design got to see the final construction documents of the mechanical system two weeks before the final presentation. The team believes that the design team came to the same conclusion about AHU-6. Along with the design development drawings LOD was given a schematic Revit MEP model. The model is very basic showing maybe 10 percent of the total MEP system. In the model AHU-6 is floating in space and is not shown on the mechanical deck. The design team knew from the earliest design stage that AHU-6 needed to be moved to the east side of the arena. The final construction documents show AHU-6 on the event level by the loading dock.

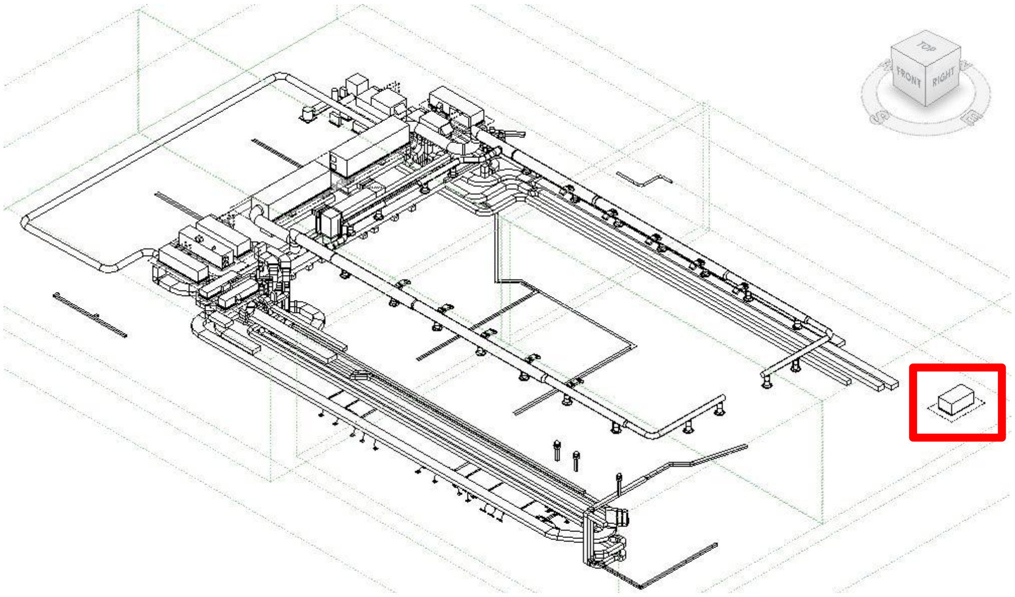


Figure 79. Schematic Revit MEP Model

In the schematic drawings AHU-7 and AHU-8 are not actually shown on the mechanical deck but on the concourse level directly above the northwest mechanical room. The supply duct run for AHU-7 runs halfway across the arena before it starts supplying are to the locker rooms, AHU-8 covers the first half.

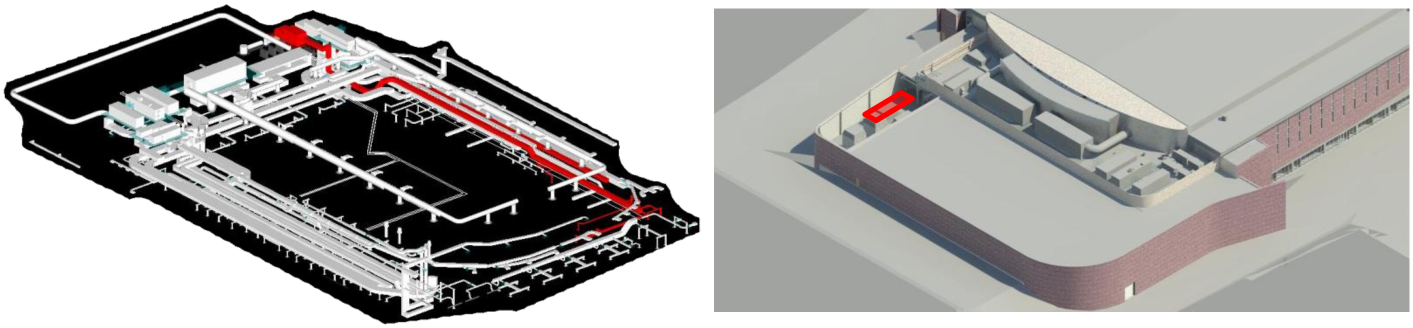


Figure 80. Schematic AHU-7 Ductwork Layout

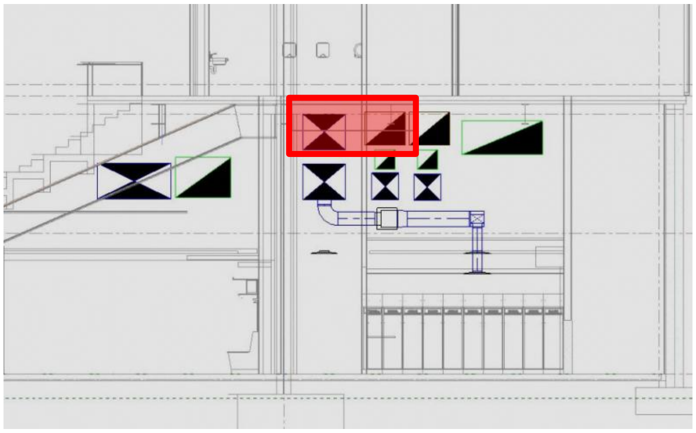


Figure 81. Schematic AHU-7 North Event Level

The design team combined AHU-7 and AHU-8 into one larger unit above the northwest mechanical room. This eliminated another two ducts from the north event level plenum. The team then moved the supply and return ductwork for AHU-13 and AHU-14, that supply the main locker rooms, to underneath the steel rakers. These changes removed four main duct runs from the plenum and allow for coordination.

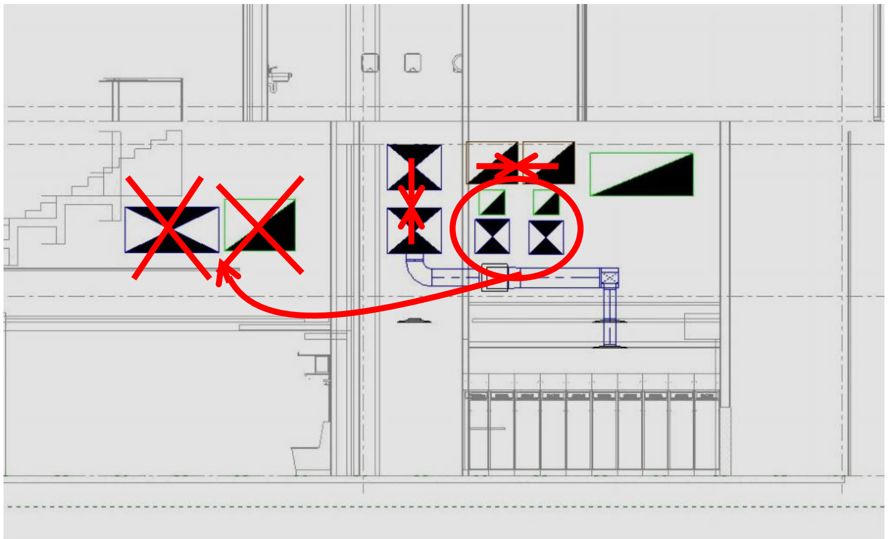


Figure 82. Design Team Construction Documents

In the LOD redesign AHU-6 and AHU-7 were moved to the mechanical loft to the east of the main bowl. The duct runs from the unit to the zone are now 30 feet instead of 300 feet. AHU-9 was moved from its location on the mechanical deck and moved in place of AHU-7 in order to free up space on the mechanical deck.

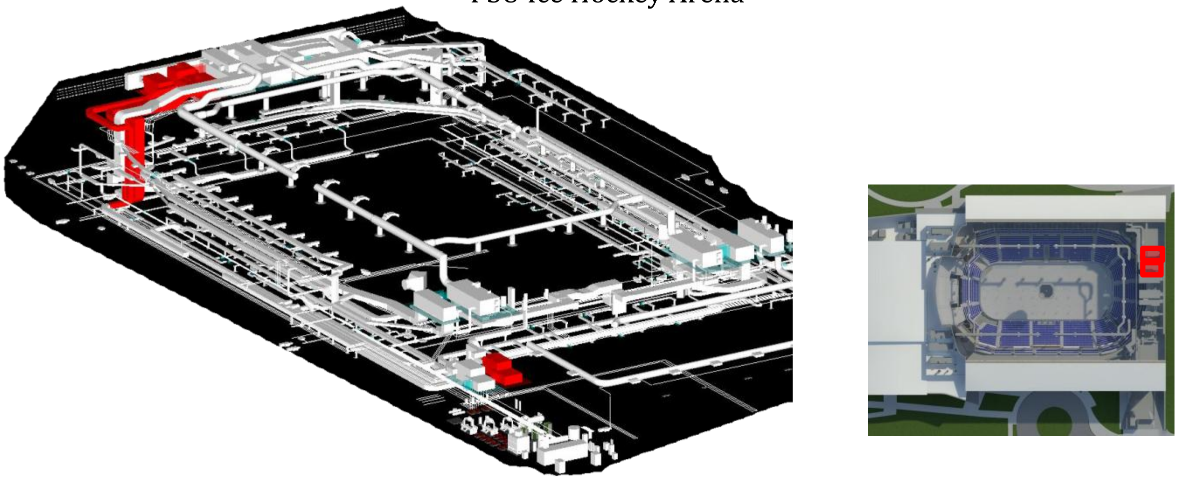


Figure 83. AHU-6 and AHU-7 Mechanical Loft

The mechanical loft was created in order to remove AHU-6 and AHU-7 from the mechanical deck and the event level north plenum. Once the mechanical loft was created it opened up an opportunity to move multiple units from the mechanical deck. Moving units allowed for shorter main duct runs and greater energy efficiency for the mechanical system. The first units that were redesigned were the main bowl air dehumidification units 10 and 11. In the schematic drawings two dehumidification air handling units located on the mechanical deck supply air to the main arena. The main supply ducts span the length of the arena over the stands from the mechanical deck. The return consists of three large return louvers, one below the mechanical deck and two located on the other side of the arena. The return louvers are located in the concourses outside of the main arena. Air is drawn from the main arena creating an air lock that keeps outside air from entering the arena. The air in the concourse is conditioned very differently than the air in the main arena.

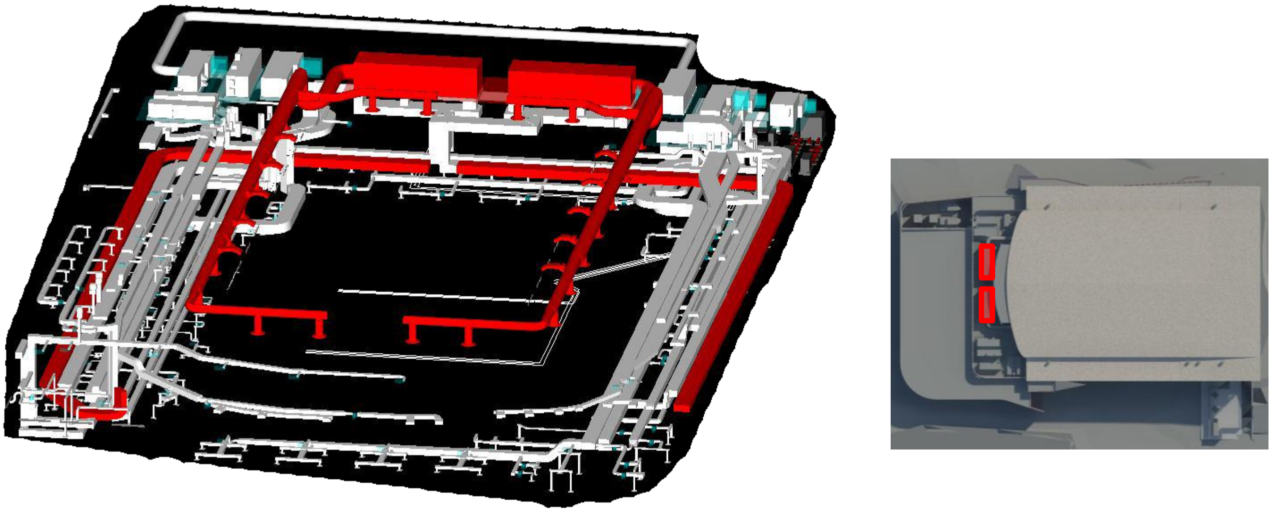


Figure 84. Schematic Main Bowl Ductwork Layout

The redesign consists of moving AHU-11 to the mechanical loft. The main bowl units on either side are then split into two. The units are split into smaller units to fit in the smaller mechanical spaces. The units on either side are connected so at low loads one can be shut off in order to save energy and run the system more efficiently. Since the air in the redesign travels a much shorter distance the main supply ducts were reduced in size. The two return louvers on the side of the arena opposite the mechanical deck are now much closer to AHU-11. The 786 feet of 72x30 return duct is reduced to only 217 feet. The 72x30 duct is now no longer in the plenum space of the north and south event levels.

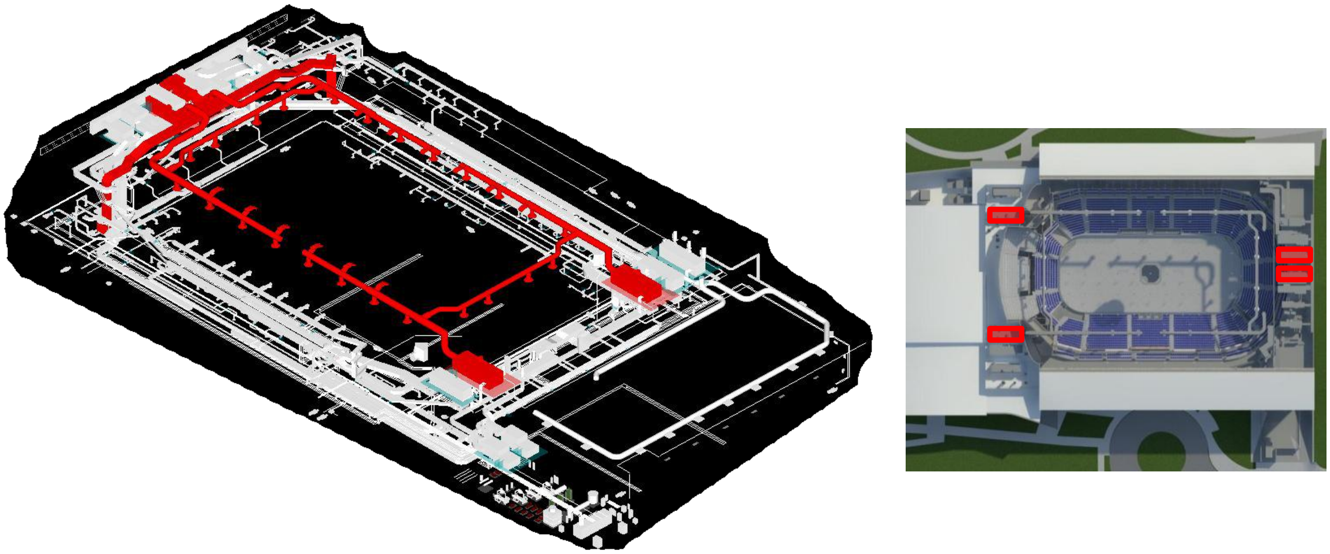


Figure 85. Main Bowl Ductwork Layout Redesign

The next unit that was moved to the mechanical loft was AHU-4. AHU-4 supplies air to the south main concourse. The idea behind moving AHU-4 is to reduce clutter in the concourse level plenum under the mechanical deck. Since the main duct is now on the other side of the arena the main duct in the concourse plenum space is now much smaller. This allows for easier coordination.

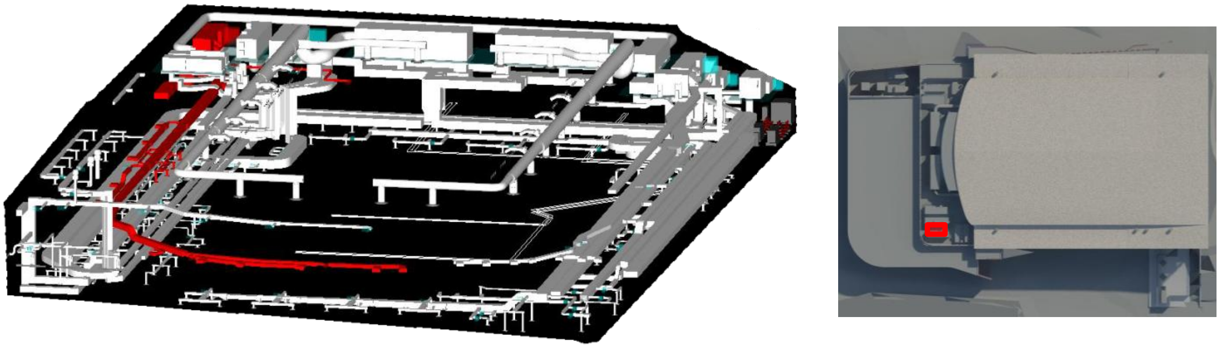


Figure 86. Schematic AHU-4 Ductwork Layout

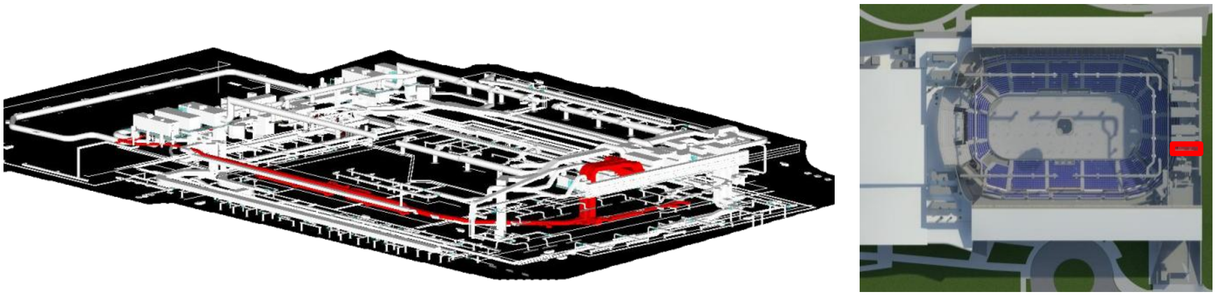


Figure 87: AHU-4 Ductwork Layout Redesign

Finally AHU-1 and AHU-2 were moved from the mechanical deck to the mechanical loft. AHU-1 and AHU-2 supply air to the kitchen and Mount Nittany room at the east end of the arena. Over 1200 feet of ductwork was removed from the design by moving these units to the other side of the arena.

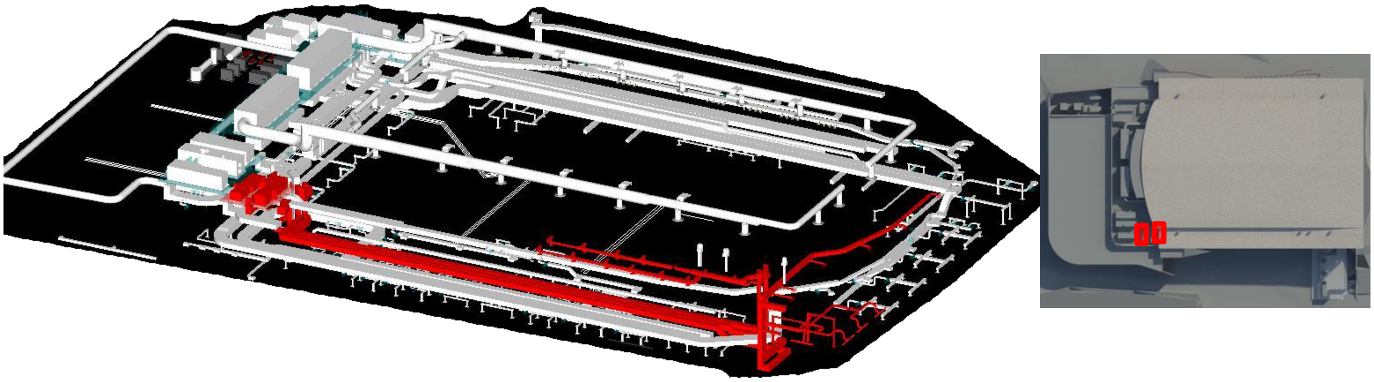


Figure 88. Schematic AHU-1 and AHU-2 Ductwork

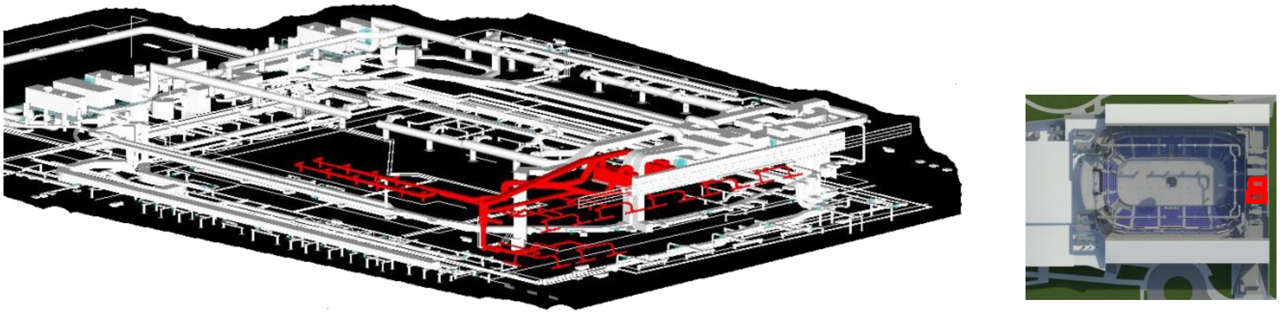
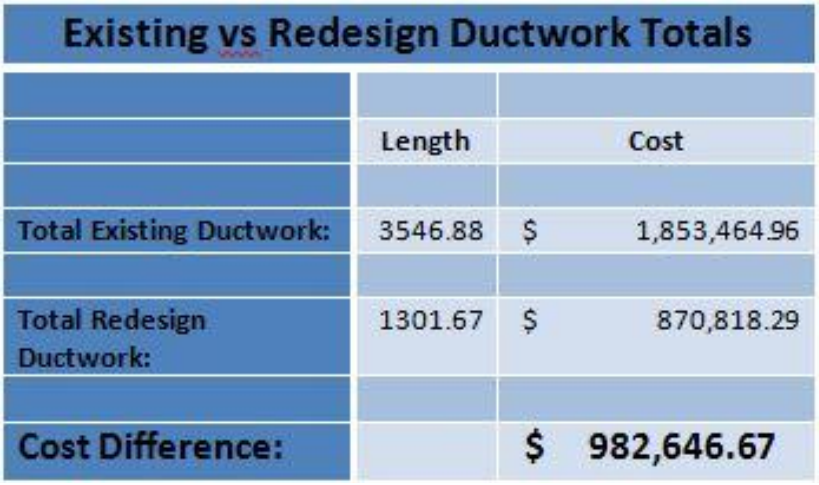


Figure 89. AHU-1 and AHU-2 Ductwork Layout

Mechanical Redesign Cost Estimate

The team's MEP engineer proposed that a mechanical loft be constructed above the arena's main lobby so that 7 air handling units could be relocated in an attempt to increase the units' efficiency as well as reduce the amount of ductwork required for the systems. In order to justify building an entirely new mechanical loft, a takeoff estimate was conducted to determine the amount of ductwork that would be eliminated or sized down and the cost savings associated with those changes. The cost data applied to the ductwork take off estimates come from the 2012 National Plumbing & HVAC Estimator, and include material and labor costs. Ductwork takeoffs were performed using Revit Mechanical, for both the existing mechanical layout as well as the team's proposed relocation layout. It is important to note that the takeoffs only included ductwork that was associated with the affected 7 air handling units; ductwork associated with units not planning to be relocated was not counted. The takeoffs including total the total length of the ductwork required and the associated cost of that ductwork is summarized in Figure 90.



Existing vs Redesign Ductwork Totals

	Length	Cost
Total Existing Ductwork:	3546.88	$ 1,853,464.96
Total Redesign Ductwork:	1301.67	$ 870,818.29
Cost Difference:		**$ 982,646.67**

Figure 90: Table comparing the total costs for the existing roof design and the redesigned cable stay roof system.

Because the MEP engineer for the team was able to reduce the total amount of ductwork by two-thirds and size down much of the remaining lengths of ductwork, relocating the air handling units can save the project $982,646.67 in ductwork costs alone. Because the structure of the East Mechanical Loft (where these units would be relocated to) was already factored into the redesigned superstructure takeoff estimate (which yielded positive savings), there would be no real costs associated with construction of the mechanical loft itself. Therefore, implementing this proposed mechanical loft would save almost a million dollars by itself, without incurring any other costs, making this a fully worthwhile alternative to pursue.

Shaft Coordination

After the creation of the mechanical loft, the mechanical shafts from the mechanical deck can now be reevaluated. The single line ductwork drawing shows how cluttered the north and south shafts are in the schematic design. The single lines stemming from the shaft in the schematic drawings do not even fit. The lines from AHU-6 are cut in the drawing and reappear on the opposite end of the arena. The other lines that are cut in the single line drawing are the two 38x32 exhaust ducts for AHU-7 and AHU-8. The north shaft is impossible to coordinate with AHU-6 and AHU-7 on the mechanical deck. The south shaft is possible to coordinate but two structural beams are passing through it. The redesign removes ductwork from AHU-1 and AHU-2 from the south shaft. The beams are avoided in the redesign.

Figure 91. North and South Mechanical Deck Shafts

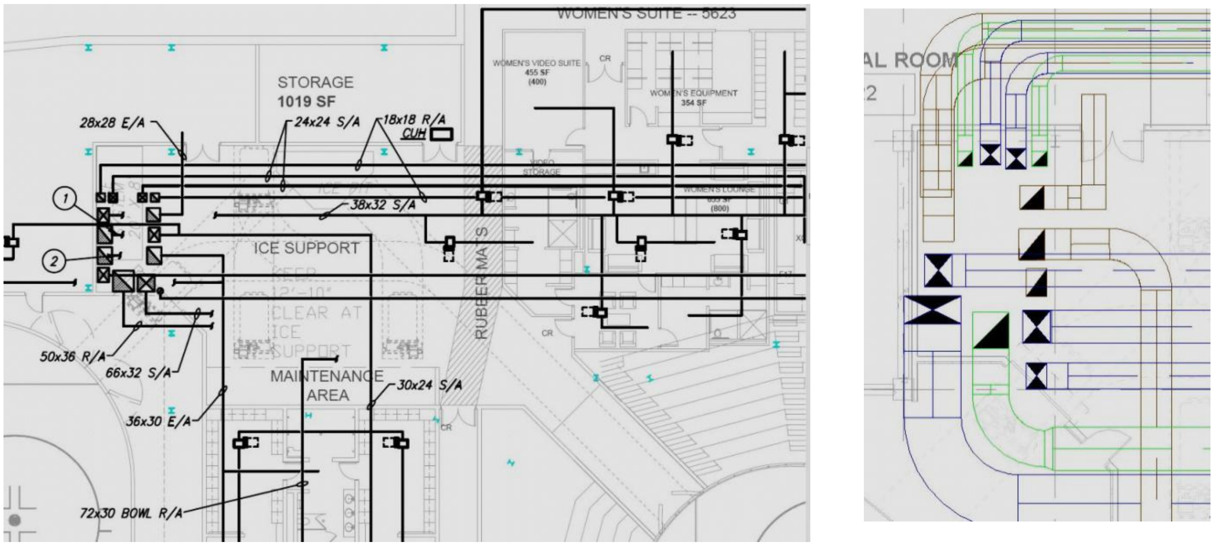


Figure 92. Design Development North Shaft

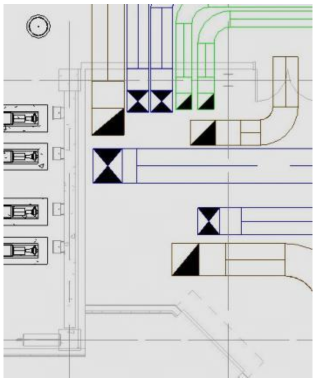


Figure 93. Redesign North Shaft Coordination

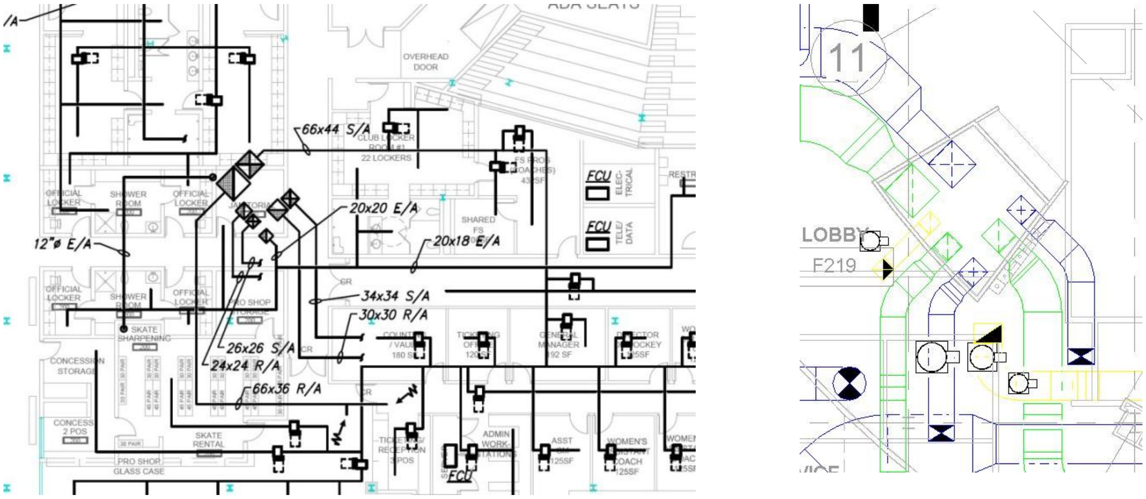


Figure 94. Design Development South Shaft Coordination

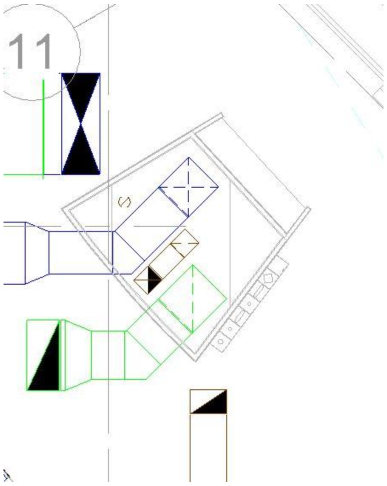


Figure 95. Redesign South Shaft Coordination

Piping Model

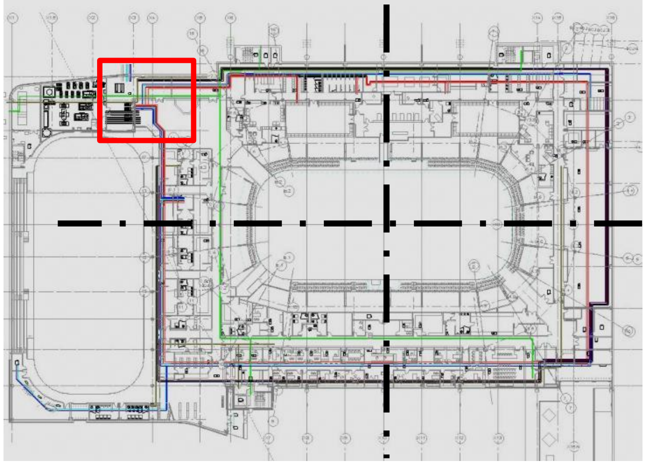


Figure 96. Event Level Piping Plan

The piping for the ice sheet originates from the ice plant in the northwest of the arena. Steam and chilled water from the campus plant enters the arena in the mechanical room next to the ice plant. The steam to hot water heat exchangers are located in the same mechanical room. The hot and chilled water pumps are also located in the northwest mechanical room. The main plumbing lines are modeled around the perimeter of the arena. The sanitary lines drop underground into the campus sanitary system. Domestic hot and cold water originates from the plumbing mechanical room next to the northwest mechanical room. The fire protection lines run through the central corridors of the arena. The fire protection standpipes are located in each of the main stairwells. The arena can be broken into four quadrants by drawing lines through the center of the main arena horizontally and vertically. Risers for the mechanical piping are located in each of the four quadrants up from the event level through to the club level.

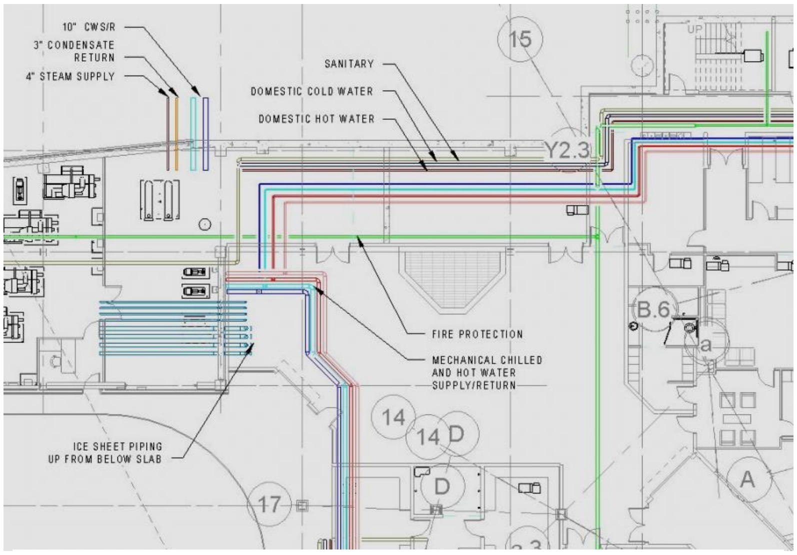


Figure 97. Event Level Piping Mechanical Room Plan

The hot and chilled water supply and return for the redesign mechanical deck air handling units rise up to the mechanical deck from the concourse plenum. The gas for the desiccant wheel main bowl AHUs also rise from the concourse level up to the mechanical deck.

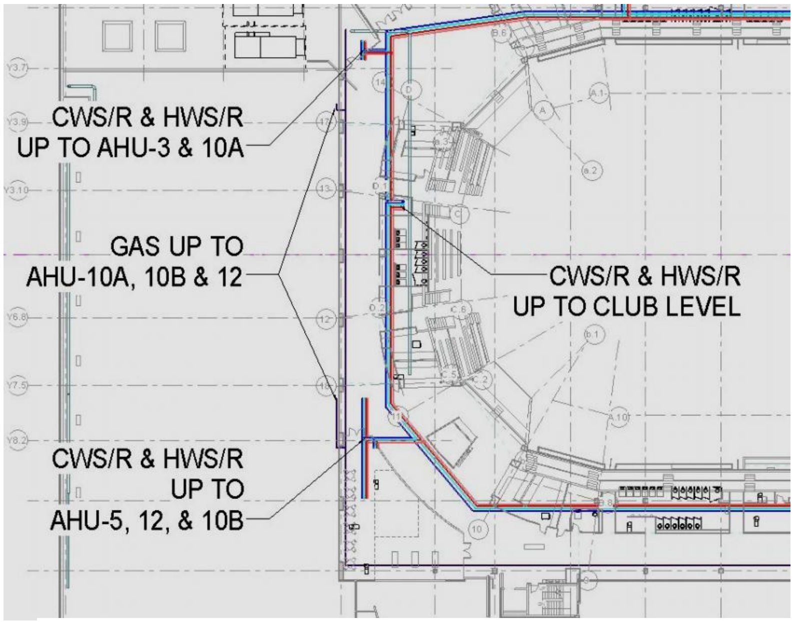


Figure 98. Concourse Level Piping Plan

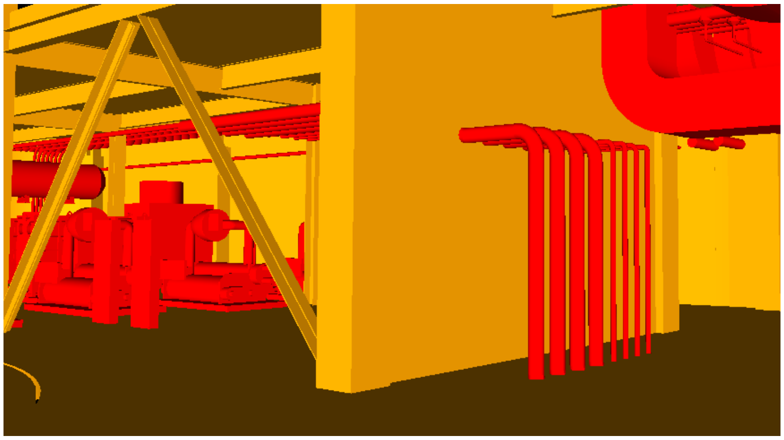


Figure 99. Ice Plant Piping From Mechanical Room To Ice Slab

Electrical Design

The electric power stems from two transformers outside the electrical room located just to the west of the ice plant. Conduit from the switchgear in the electrical room spreads to four electrical rooms on the event level located one in each quadrant. The conduit is run down the central corridors of the event level. The four electrical rooms of the concourse and club levels sit right above the event level electrical rooms. Next to the four electrical rooms are the tel/data rooms. Tel/data cable is run on cable trays running low through the central corridors. The tel/data rooms also run straight up through the arena.

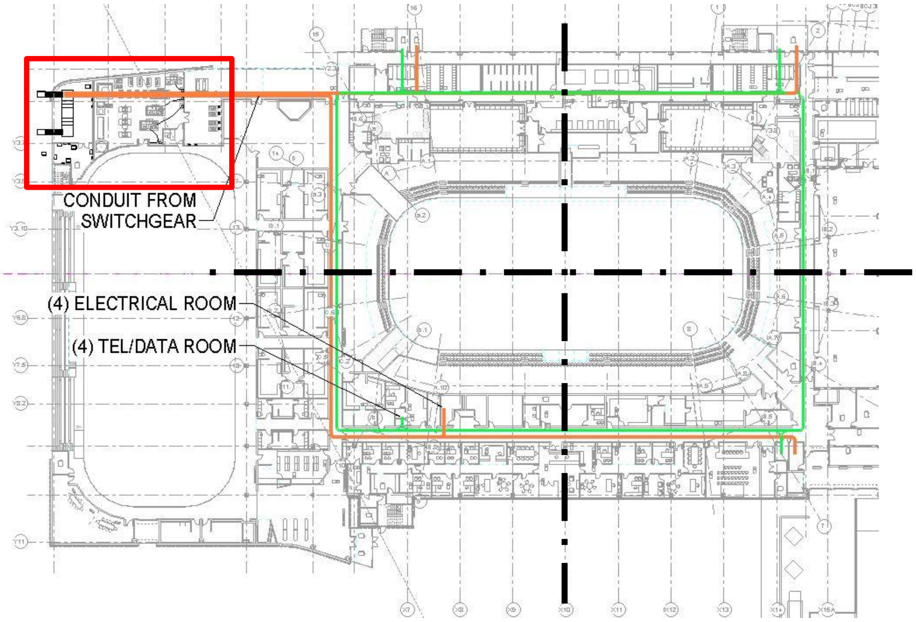


Figure 100. Conduit and Cable Tray Event Level Plan

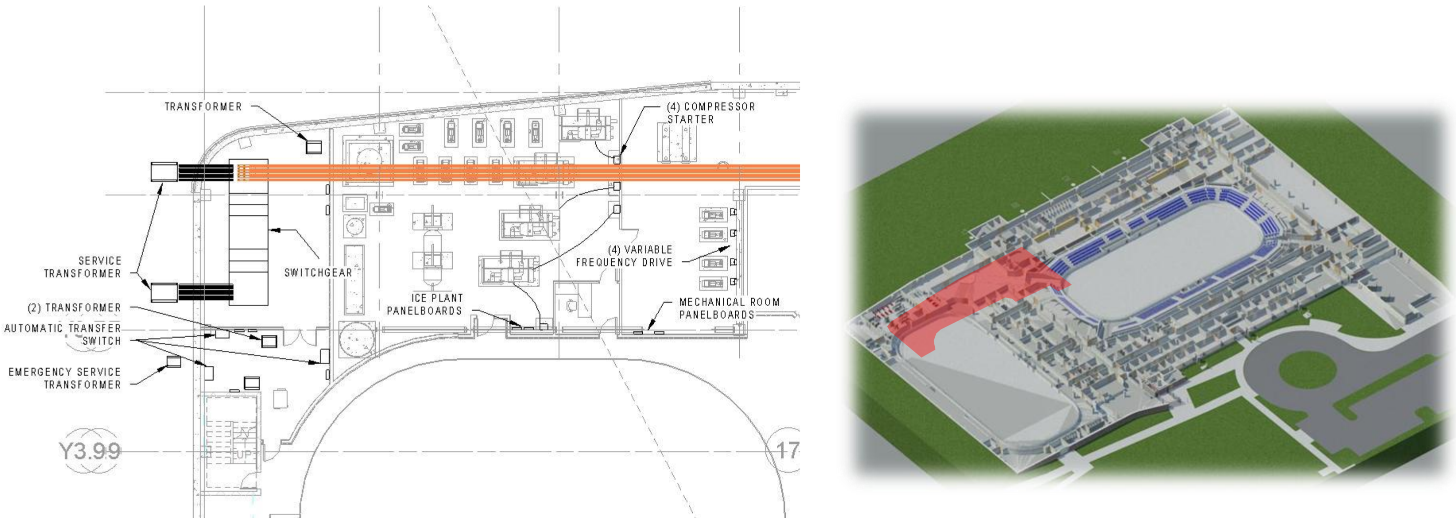


Figure 101. Electrical Room Detail

Figure 102 shows the wire layout for a typical suite. This layout could also apply to an office. The conduit for each room in the arena runs from the room to the nearest electrical room in the respective quadrants. Figure 102 also includes a section showing how the fan coil unit in each suite supplies air.

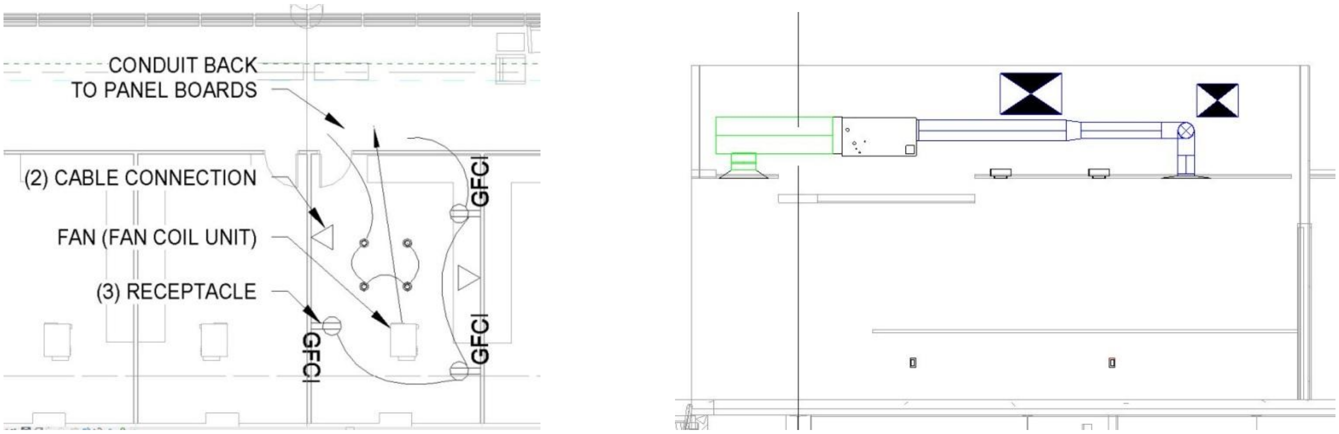


Figure 102. Wiring and Section Detail for Box

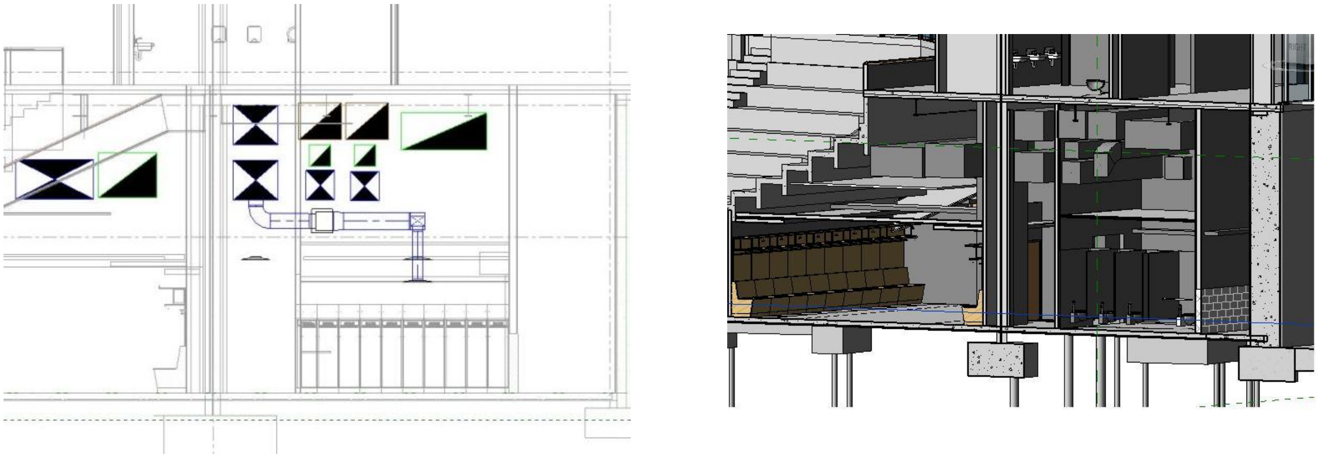


Figure 103. Design Development Event Level Ductwork

The design development drawings did not allow for complete coordination of the event level plenum on the north side of the arena. Lights Out Design was able to coordinate this plenum after moving the previously mentioned AHUs from the mechanical deck to the mechanical loft. Figure 104 revisits the plenum s shown in the single line ductwork drawings. Figure 104 illustrates the LOD coordination of this plenum. The conduit is run high just under the steel. Below is a space dedicated to mechanical piping and plumbing main lines and branches. The main ductwork runs fit underneath the piping. AHU-8 is now able to branch and supply air to both sides of the event level. The cable trays for tel/data cable run lowest for easy access and maintenance.

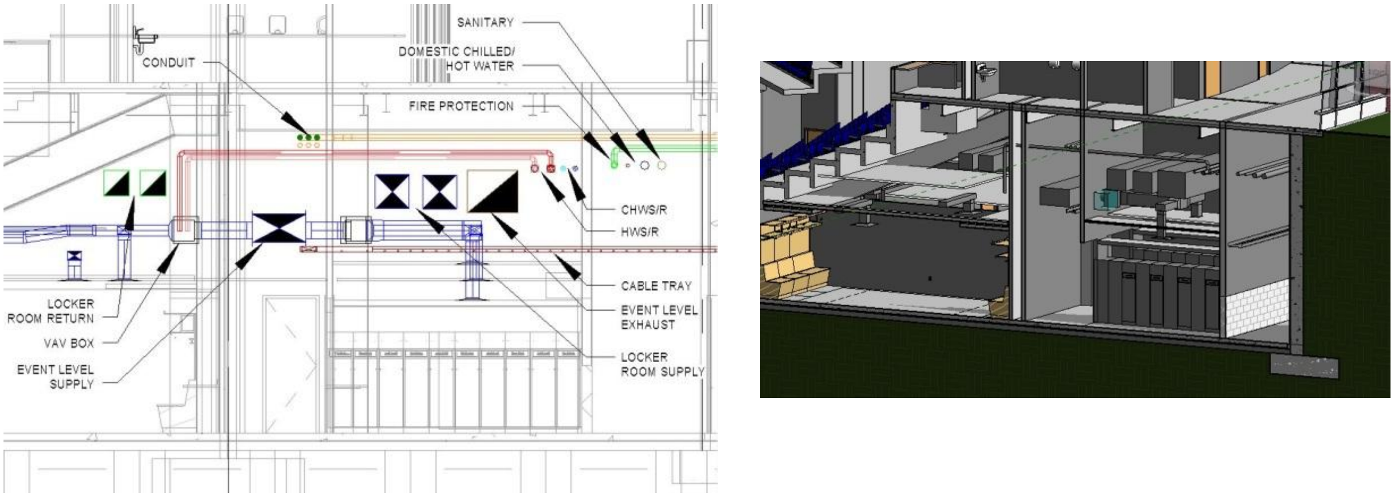


Figure 104. Event Level North Plenum Coordination

Mechanical Loft Shaft Coordination

Mechanical shafts had to be created in order for ductwork and piping to reach the mechanical loft. A pipe shaft is drawn in the design development drawings in the northeast quadrant. Piping to the mechanical loft taps into the pipes coming up through this shaft from the concourse level. The piping runs underneath the mechanical loft while the ductwork runs above the AHUs on the mechanical loft.

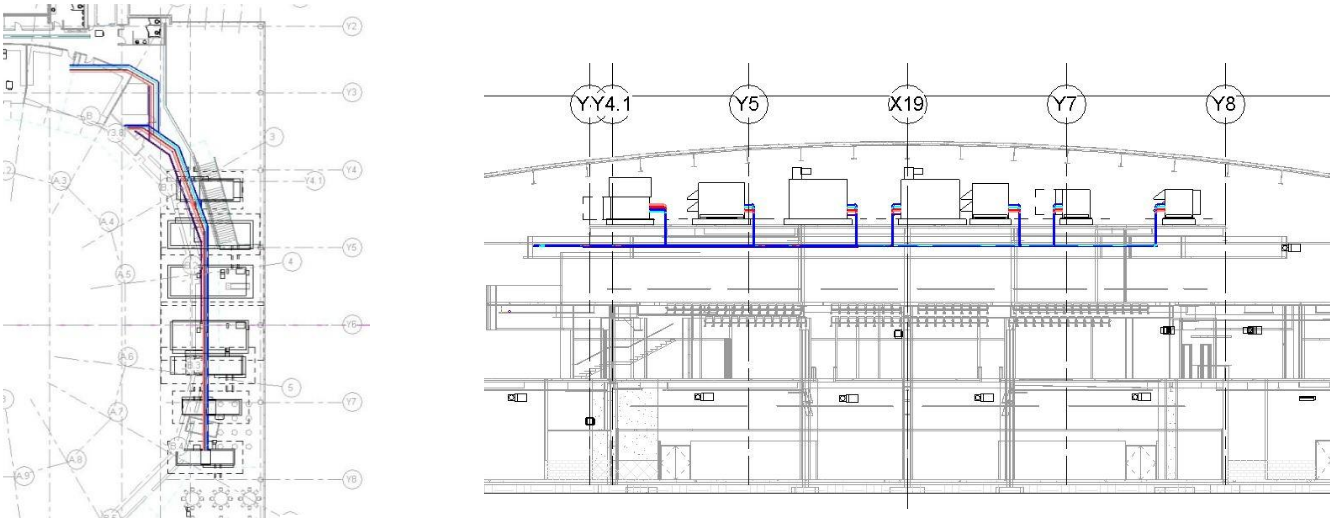


Figure 105. Mechanical Loft Piping Plan and Section

The piping shaft was expanded in the redesign to allow for ductwork to reach the event level from the mechanical loft.

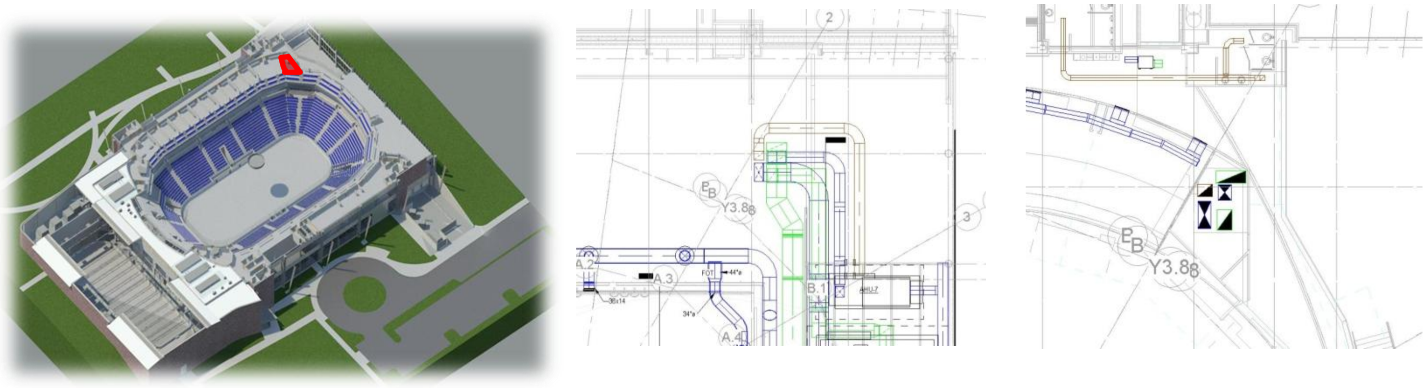


Figure 106. Mechanical Loft Ductwork Shaft Coordination

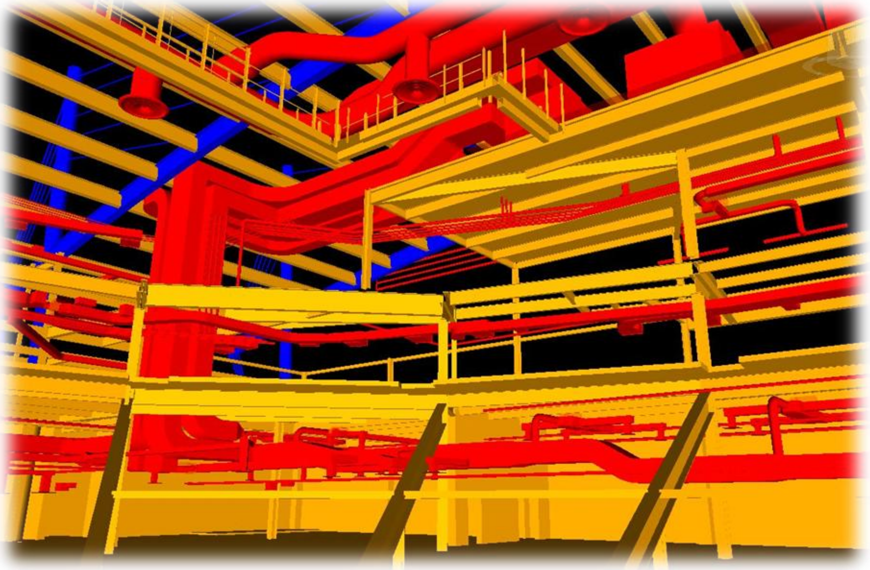


Figure 107. Mechanical Loft Navisworks Shaft Coordination

Main Concourse Plenum Coordination

The MEP model given to LOD at the beginning of the year shows only a small percentage of the total MEP system. The model does not include any exhaust ductwork or branch supply ductwork. In order to coordinate the arena the exhaust and branch ductwork was modeled into Revit MEP based on the single line ductwork design development drawings. The mechanical loft made coordination possible in the event level plenum. The next task was to coordinate the main concourse ductwork. Figure 108 shows the single line ductwork drawing. The 30x30 exhaust duct is drawn below the column line. The duct will not fit here because there are stub cantilevers holding up the stands in the way. Figure 109 illustrates the clash detected in

Navisworks. The exhaust duct had to be moved inside the column line but it still clashed with the supply branch. The duct had to be flattened as it did not fit as a 30x30 square.

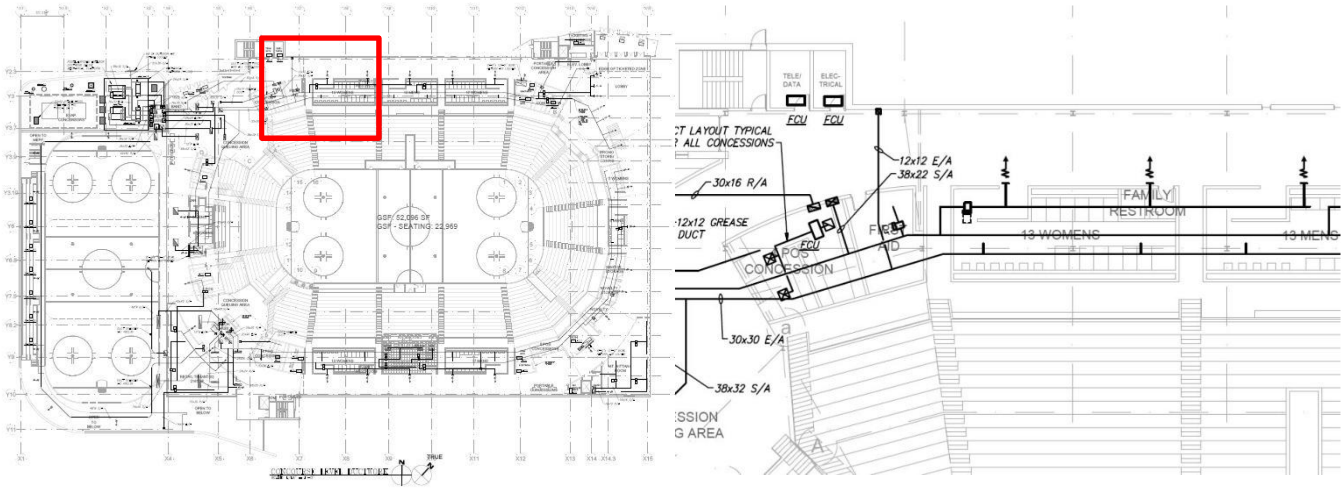


Figure 108. Mechanical Loft Navisworks Shaft Coordination

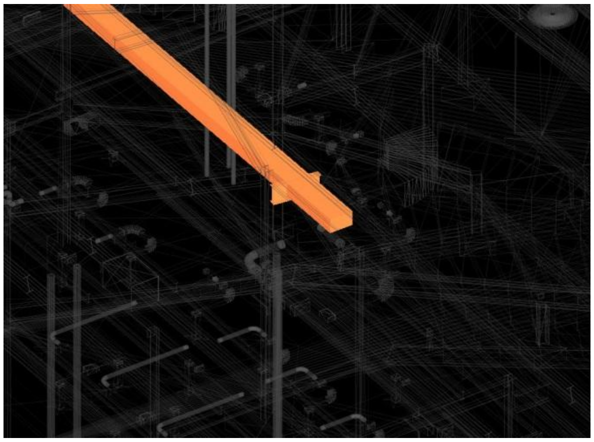


Figure 109. Exhaust Duct and Stub Cantilever Clash

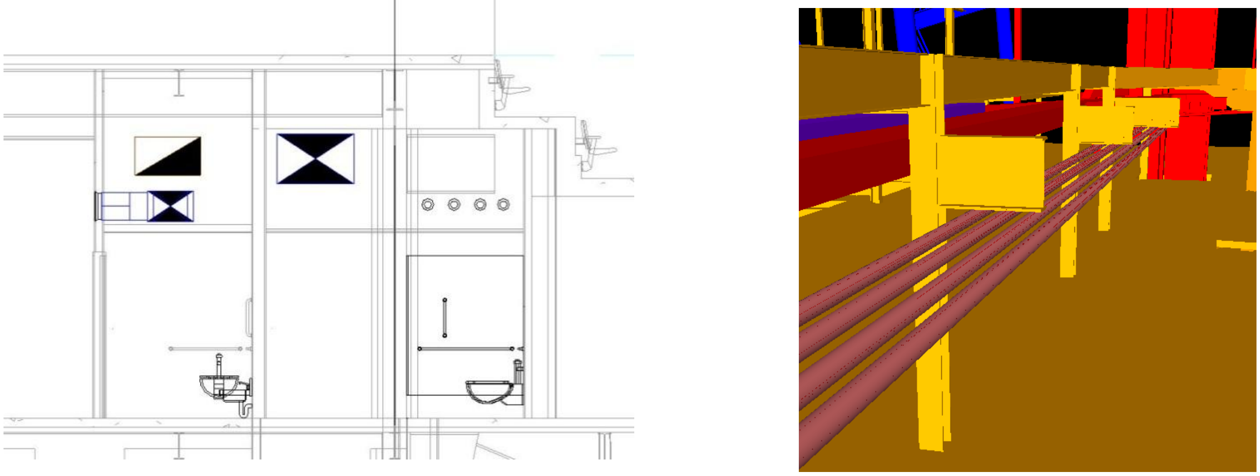


Figure 110. Lights Out Design Main Concourse Plenum

The rest of the MEP system was coordinated with the structure using Navisworks Manage. The first clash detection run between the MEP and structure resulted in 595 clashes. In order to reduce this number going through the clashes one by one would be tedious and inefficient. The construction manager of LOD looked for areas with a large number of clashes and then informed the structural and MEP engineers. These areas would be evaluated and then clash detection would be run again. Each of these runs resulted in fewer and fewer clashes. A significant number of clashes were reduced when the structural engineer created openings in the slab and shear walls for ductwork to pass through shafts and walls. At this same instance the MEP engineer reviewed all ductwork clashes with the structural diagonal rakers supporting the stands. The goal of LOD was to get the number of clashes below 100. When the team got down to 133 it was necessary to view the clashes one by one as they were localized instances. Once the team reached 95, the clashes were viewed one by one to make sure there were no major issues. The final 95 were concluded to be easy fixes during construction. Figure X shows one of these instances where a sidewall diffuser on the concourse level is encroaching a column by only a few inches.

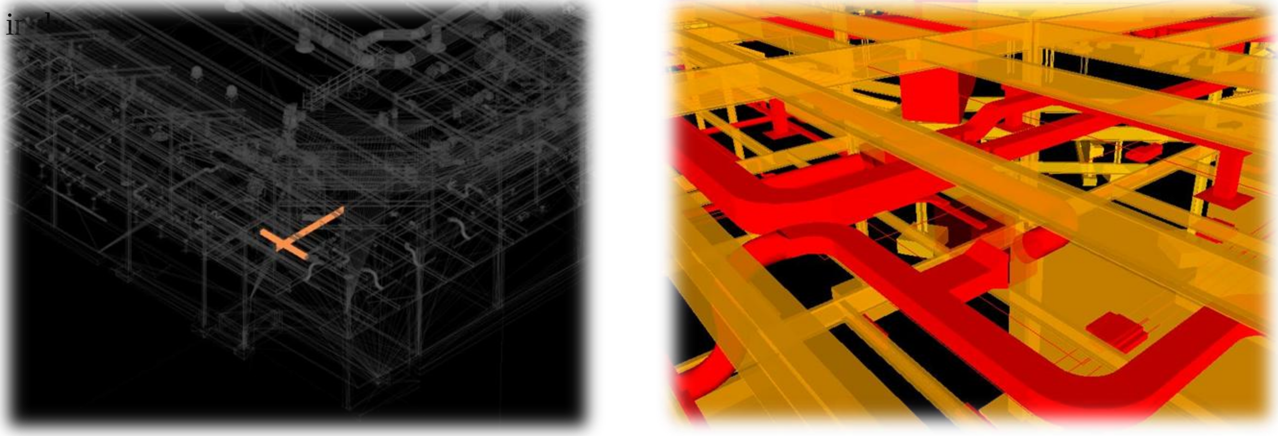


Figure 111. Clash Highlighting Major Area of Clashes

Clash Runs	# of Clashes
1	595
2	540
3	494
4	457
5	215
6	177
7	131
8	100
9	95

Figure 112. Clash Detection History

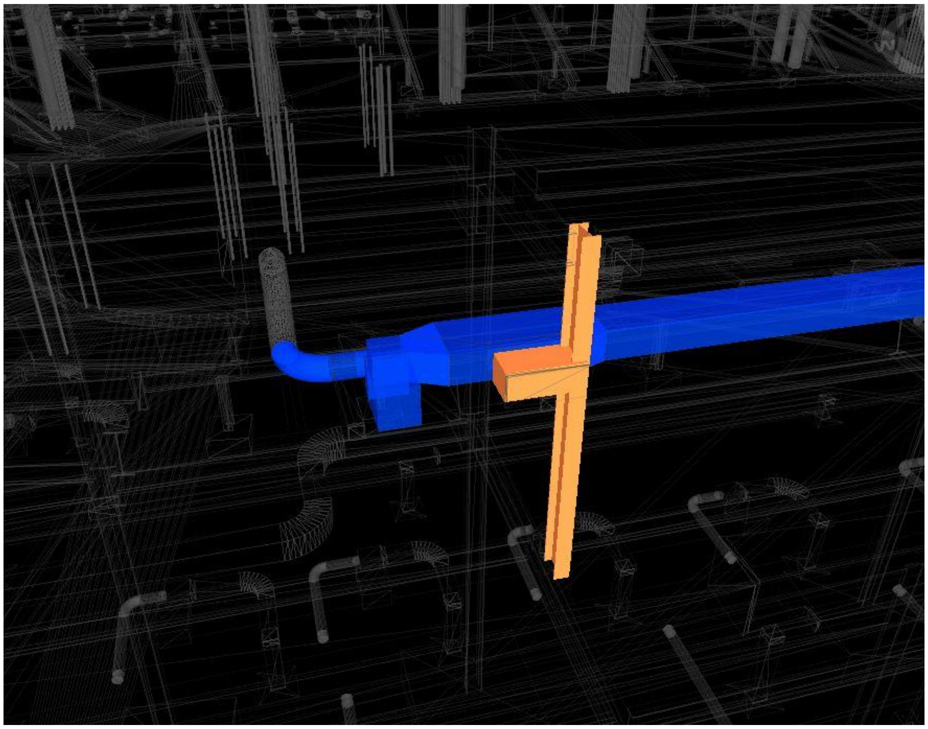


Figure 113. Minor Clash between Diffuser and Column

Navisworks Coordination

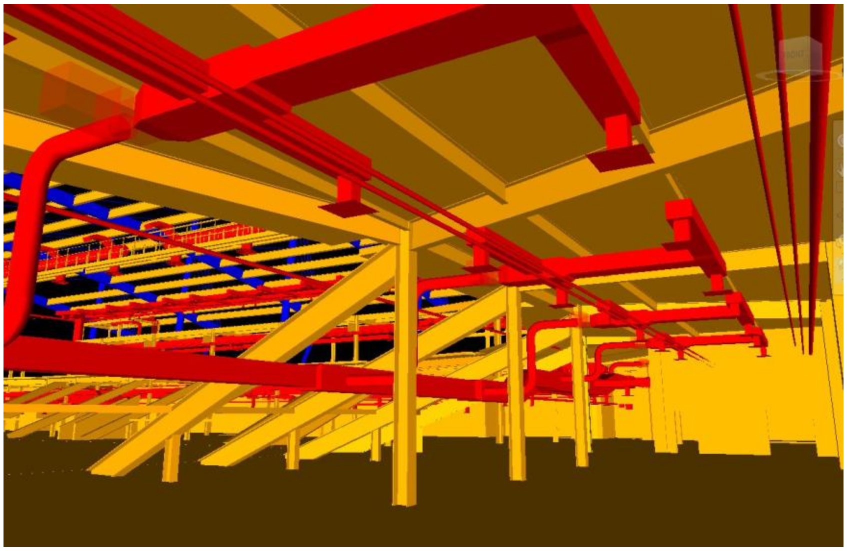


Figure 114. AHU-6 Weight Room Plenum Coordination

Figure 114 shows the ductwork and piping coordination in the weight rooms. The main supply run from AHU-6 had to be kept low to avoid clashing with the diagonal rakers. The branch ductwork had to be kept high in order to accommodate the high ceiling heights of the weight room. Main piping lines run the perimeter of the arena.

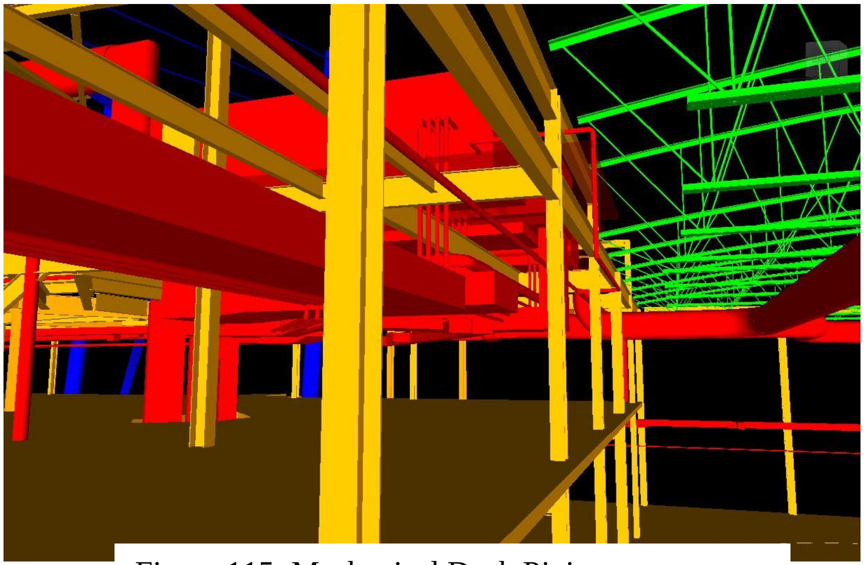


Figure 115. Mechanical Deck Piping

Figure 115 illustrates the mechanical piping rising from the concourse level up to the AHUs on the mechanical deck. The objects in green are the pan joists supporting the roof of the community rink.

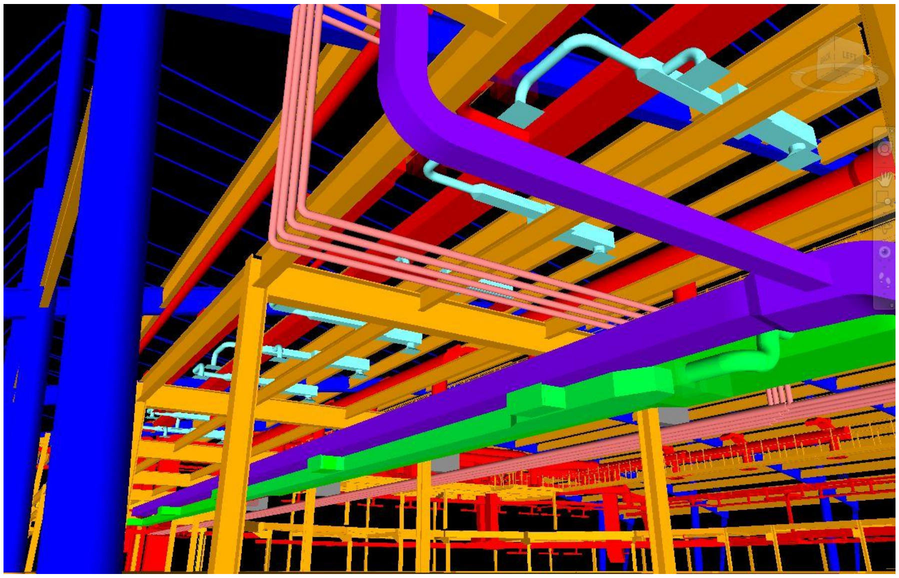


Figure 116. Main Concourse Plenum

Figure116 is a screen shot of the main concourse coordination and its relationship to the club level. The blue is the masts and cables supporting the roof. The light blue is the fan coil units and ductwork supplying air to the suites. Purple is the exhaust ductwork for the main concourse and the branch up to the club level. Green is the supply branch supplying air to the north concourse on the concourse level. Pink is the mechanical piping branching up from under the stub cantilevers and then up to the club level.

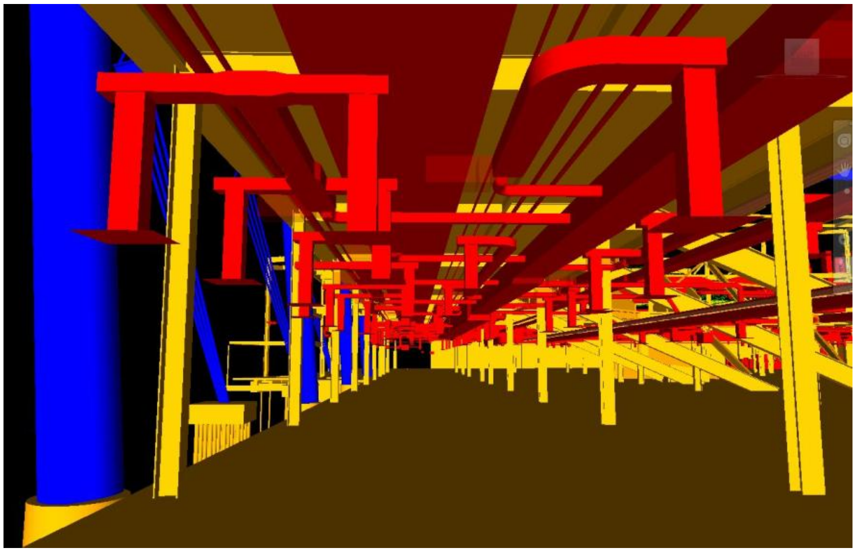


Figure 117. Event Level South Concourse Coordination

Figure 117 illustrates the south event level redesign coordination. The conduit runs high as well as piping. Ductwork is free to run above the plenum and branch in any direction. The cable tray runs low for easy maintenance.

Mechanical Loft Architectural Impact

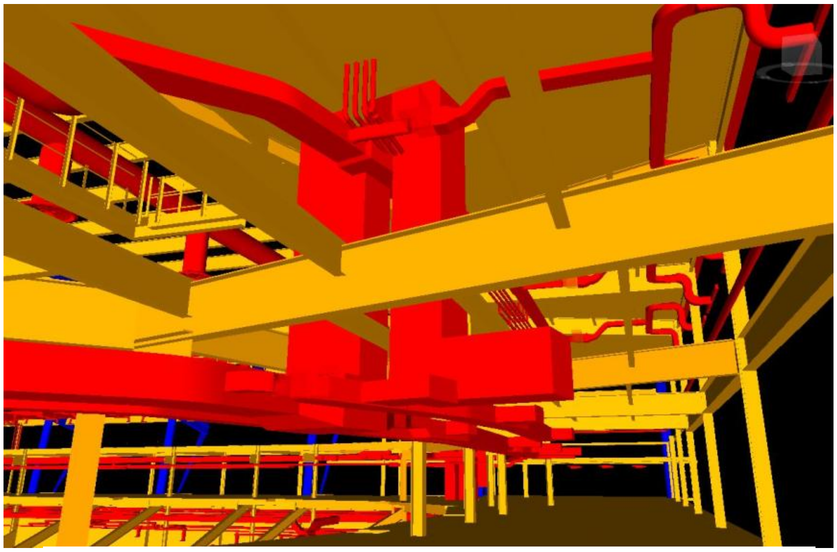


Figure 118. South Mechanical Loft Shaft Coordination

The coordination of getting AHU-4 down to the concourse level from the mechanical loft proved to be difficult. It does not clash with the structure but there are multiple MEP clashes. Moving AHU-4 to the mechanical loft would require some architectural modifications.

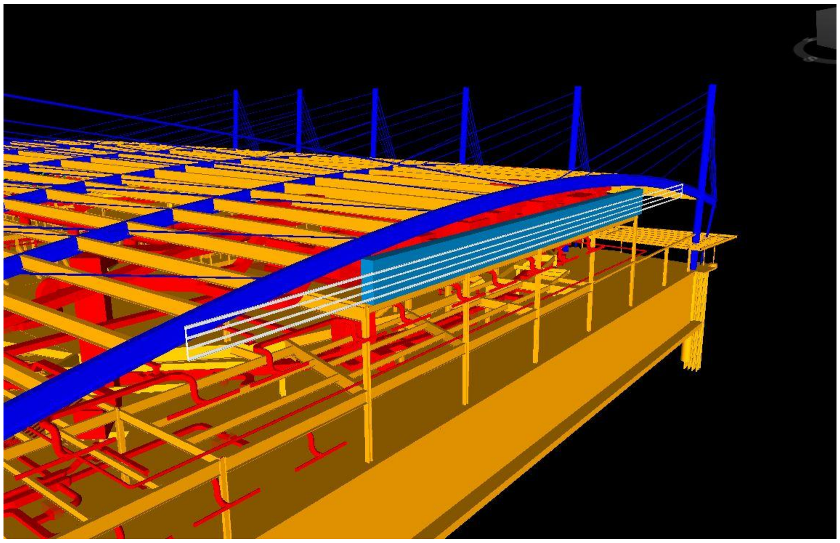


Figure 119. South Mechanical Loft Shaft

In order for the mechanical loft to work a plenum space would have to be created behind the front façade for the AHUs to tap into. For air to get into the plenum a louver would be placed across the front of the façade. With the metal panels and glass the grill could be implemented into the front façade. Convincing the architect of this significant change could prove to be difficult.

Community Rink Roof Redesign and Mechanical Loft Design Conclusion

The redesign of the community rink roof and the mechanical loft design was an extremely successful example of how BIM/IPD can benefit a project. By taking the single line mechanical drawings that the team was given and modeling the ductwork in Revit, the team was able to realize that there were major coordination issues in the event level plenum space. In coordination with the desire for a flexible community rink roof, the team was successfully able to create a mechanical loft that housed many air handling units that were relocated. The relocation of units saved close to a million dollars of duct expenses and allowed for daylighting to be infused into the community rink through an arched bowstring joist design.

Once the mechanical loft was created, the team was able to work through Navisworks to determine areas of clashing systems. Without this advantage, the arena could be constructed without realizing that there were multiple issues between the mechanical ductwork and the steel structure. Lights-Out Design was able to recognize these conflicts before they ever reached the construction phases. This would ultimately save time and money during the construction phase of the project. Overall, through the help of BIM programs and the IPD process, this redesign was extremely successful and feasible.

Conclusion

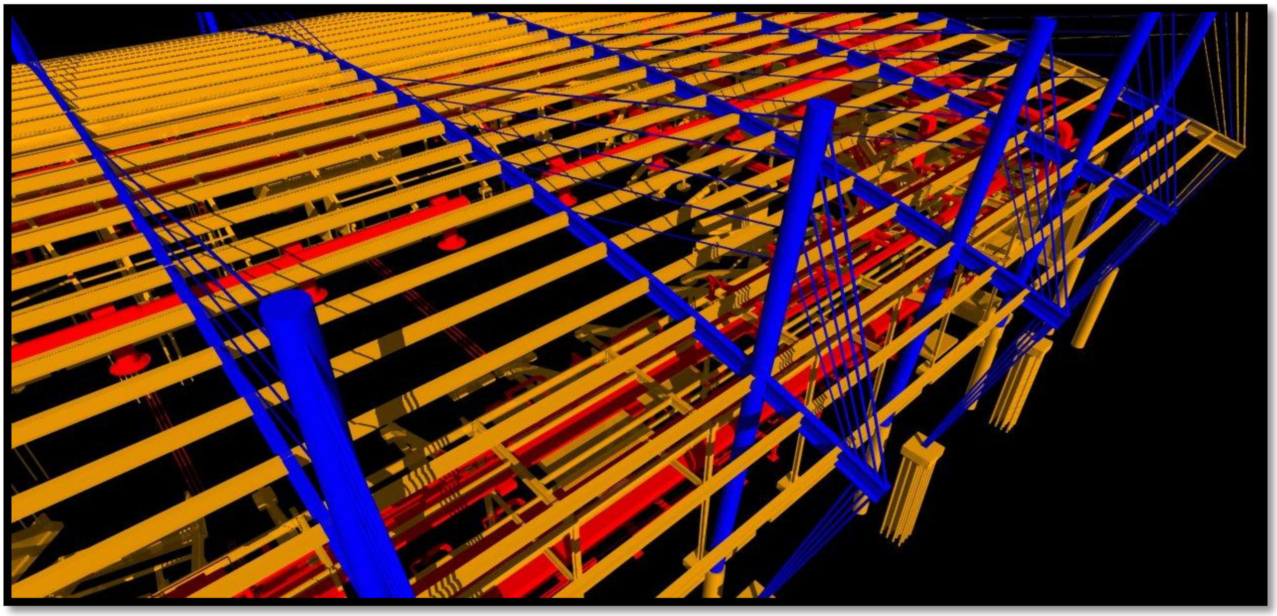
Lights-Out Design has worked hard throughout the 2011-2012 academic year to achieve goals set in the fall semester. Through integrated project delivery and building information modeling platforms, we can say with confidence that a majority of our goals for this capstone project have been achieved.

The first major redesign centered on the long span roof. Throughout the semester, the team, especially the structural engineer and construction manager, worked closely to produce a cable-stayed roof that would span the entire arena. The team successfully designed a cable-stayed roof that reduced the structural depth of the roof, spanned the entire arena, and created an iconic structure that would become synonymous with Penn State hockey. However, this design came at a significant cost. In comparison to the existing design, the structure was over 8 million dollars more than the original design. After analyzing the team's results, we believe that a cable-stayed roof could be possible with further iterations and more detailed investigations.

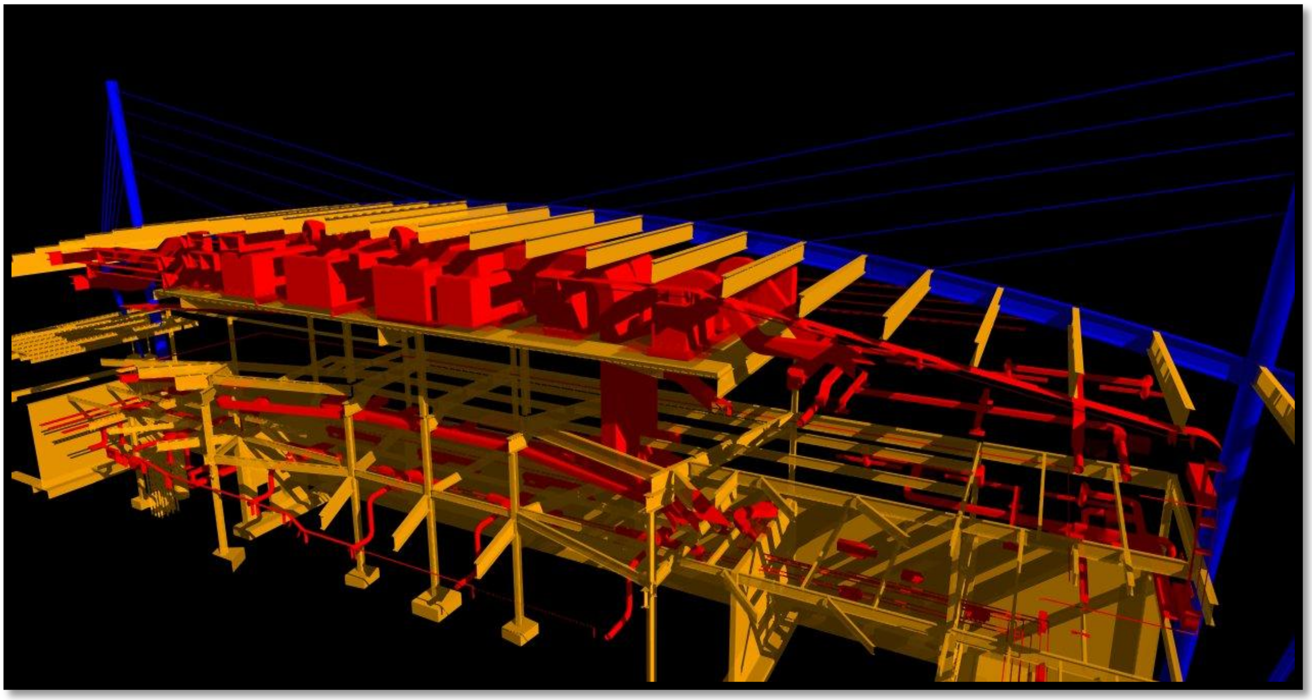
The second major focus dealt with the arena's exterior façade. With the decision to design a cable-stayed roof, a newly designed lighter appearing façade was a necessity. A thermal analysis was conducted on the new façade to ensure that the arena would remain energy efficient. After conducting the analysis, it was discovered that the move to glass and metal panels would not impact the energy efficiency of the arena and would only cost $85,701 over the life-cycle of the arena, a mere $3,000 extra per year for 30 years. A new lighter façade is clearly feasible for the arena.

The final major redesign revolved around the community rink roof and the energy efficiency of the mechanical system. With the community rink being used extensively throughout the year, Lights-Out Design wanted to provide a greater aesthetic to the rink through an arched roof and infusing daylighting. In turn, after a preliminary analysis of the mechanical system, the team concluded that mechanical units had to be relocated. Through moving mechanical units to a mechanical loft, the team was able to save close to a million dollars in duct expenses and create flexibility in the design of the community rink roof. Navisworks analyses allowed the team to locate areas of clashes between engineering systems and resolve them prior to construction. Overall, this redesign was extremely successful specifically as a result of coordination using BIM and the integrated project deliver process.

After concluding this semester, the design team looked back and reflected on the work we had done. This project clearly showed how important it was to collaborate between disciplines. Without collaboration, we would never have recognized potential issues with the mechanical system and had the ability to design a unique structure. Throughout the process, it was very clear that one major person was missing: an architect. Without involvement from an architect, it was difficult to choose a design idea and some liberties were taken in redesigning the engineering systems. Overall, BIM and IPD can be extremely successful for complicated projects like a hockey arena. BIM and IPD allowed us to recognize conflicts early in the design process which would ultimately save a lot of time and headache through the construction phase.



Structural Appendix



Appendix A. Structural MAE Requirements

To complete this thesis, coursework from multiple graduate level classes was necessary. Computer modeling knowledge gained from AE 597A was used to model both the cable-stayed roof system and lateral system model in SAP2000. In addition, computer modeling ideas from AE 597A were applied to the gravity structural system that was designed in RAM Structural System. In order to accurately model the lateral structural system, knowledge gained from AE 538 was used to determine appropriate sizes of the moment frames. In addition, knowledge gained from AE 537 was used to consider loading conditions that often cause structural failures. Unbalanced loads and drifting snow was checked throughout the structure to ensure the structural members were of adequate strength. This was especially important for the community rink roof which was supported by relatively unstable steel joists.

Appendix B. Structural Loads

Live Loads	
Fixed Arena Seating	60 psf
Arena Aisles	100 psf
Mechanical Rooms	150 psf
Light Storage	125 psf
Event Floor & Truck Access (SOG)	350 psf
Catwalks	40 psf
All Others	100 psf
Others	
Superimposed Dead Load	15 psf

Snow Load Check

SNOW LOAD CALCS ASCE 7-10 | January 11, 2012 | BIM Thesis

7.3 Flat Roof Snow Load, p_f

$p_f = 0.7 C_e C_t I_s p_g$

$C_e = 1.0$ (Exposure C, Partially Exposed)
$C_t = 1.1$ (Structure kept just above freezing due to ice rink)
$I_s = 1.1$ (Risk category III)
$p_g = 40$ psf (Centre County Code specified)

$p_f = (0.7)(1.0)(1.1)(1.1)(40) = \underline{34 \text{psf} + \text{drifts}}$

7.3.4 Min Snow Load for Low-slope Roof, p_m

- curved roof where vert angle from eaves to crown is less than 10° ⇒ 7°

$p_g > 20$ psf $\quad p_m = 20(I_s) = 20(1.1) = \underline{22 \text{psf}}$

7.4 Sloped Roof Snow Loads, p_s

$p_s = C_s p_f$

7.4.2 Cold Roof Slope Factor, C_s

$C_t = 1.1$, unobstructed slippery surface = use dashed line Fig 7-2b

slope = 7°
slope @ eaves = 13°

$C_s = 1.0$ @ 7° slope
$C_s^* = .95$ @ 13° slope @ eaves

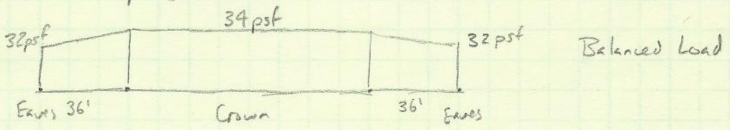
$p_s = (1)(34) = \underline{34 \text{psf}}$ $\quad p_s = .95(34) = 32$ psf

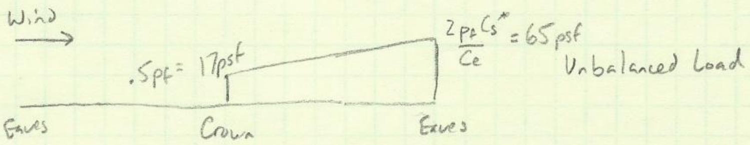
7.4.5 Ice Dams + Icicles Along Eaves

- if $R < 30$ ft²hr°F/BTU unventilated or $R < 20$ ft²hr°F/BTU ventilated
- load on overhang = $2p_f = 2(34) = 68$ psf only applied on overhang w/ dead loads on rest

7.6.2. Unbalanced Snow Loads for Curved Roof

Fig 7-3 Case 1: Slopes @ eaves < 30°





Snow Load Calcs | BIM Thesis

7.7 Drifts on Lower Roofs

7.7.1 Lower Roof of a Structure

$\frac{h_c}{h_b} > .2$ drifts req. by observation

$\gamma = .13 p_g + 14 < 30$ pcf $\gamma = .13(40)+14 = 19.$ pcf < 30 pcf ok✓

$h_b = \frac{p_g}{\gamma} = \frac{40}{19} = 2.1'$ $h_c = 10' - 2.1' = 8'$

leeward

if curved roof doesn't extend over entire arena, $l_u = 250'$ => drifts on both mechanical areas

if curved roof extends over entire arena, $l_u = 310'$ => drifts on mechanical area between rinks

$h_d = 0.43 \sqrt[3]{l_u} \sqrt[4]{p_g+10} - 1.5$

$l_u = 250'$

$h_d = .43 \sqrt[3]{250} \sqrt[4]{40+10} - 1.5 = 5.7'$

$p_d = h_d \gamma = 5.7(19) = 108$ psf

$h_d < h_c$ $w = 4h_d$

$w = 4(5.7) = 23'$

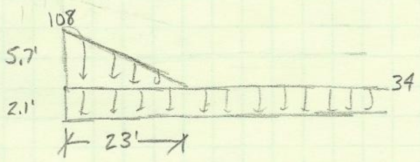
$w < 8h_c = 64'$ ok

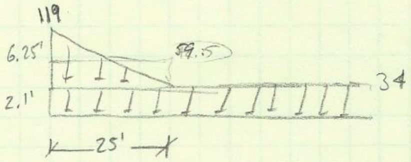
$l_u = 310'$

$h_d = .43 \sqrt[3]{310} \sqrt[4]{50} - 1.5 = 6.25'$

$p_d = 6.25(19) = 119$ psf

$w = 4(6.25') = 25' < 64'$ ok





7.9 Sliding Snow

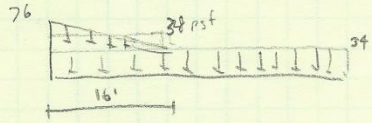
-No sliding snow on lower roofs, but should consider snow falling onto/near walks

Drift for Community Roof

$h_b = 2.1'$ $l_u = 110'$

$h_d = .43 \sqrt[3]{110} \sqrt[4]{40+10} - 1.5 = 4' < 8' = h_c$ $p_d = 4(19) = 76$ psf

$w = 4h_d = 4(4) = 16'$

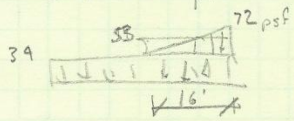


Drift on Student Sec. Roof

$h_{bot} = 4'$ $h_d = 5.7' > h_c = 2'$

$w = \frac{4h_d^2}{h_c} = 65' =$ whole roof $> \boxed{16'}$

$2'(19) = 38$ psf



Wind Loads

Wind Load Calcs BIM Thesis

Risk Category: III (Table 1.5-1)
Exposure Category: C (26.7.3)
Basic Wind Speed: V = 120 mph (Fig 26.5-1B)
Gust Effect Factor: G = .85
Internal Pressure Coefficient: GC_{pi} +/-.18, Enclosed Bldg = Enclosure Classification
Velocity Pressure $q_z = .00256 K_z K_{zt} K_d V^2$

259-297

K_z = From Table 27.3.1
K_{zt} = 1 Table 26.8
K_d = .85 Table 26.6-1, Arched Roof
V = 120 mph

Table 27.3-1
$K_h + K_z$

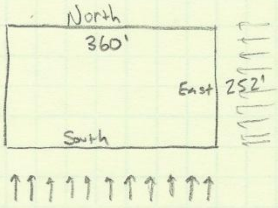
Ht above ground level, z, (ft)	Exposure C	q_z (psf)
0-15	.85	26.63
20	.90	28.2
25	.94	29.45
30	.98	30.7
40	1.04	32.59
50	1.09	34.15
60	1.13	35.41
70	1.17	36.66
80	1.21	37.91
90	1.24	38.85
100	1.26	39.48
120	1.31	41.05

$p = q G C_p - q_i (GC_{pi})$

$q = q_z$ for windward walls @ ht z
$q = q_h$ for leeward walls, side walls, + roofs @ ht h
$q_i = q_h$ for windward, side, + leeward walls + roofs of enclosed bldgs + for neg internal pressure eval in partially enclosed bldgs
G = .85
(GC_{pi}) = +/-.18
C_p = External pressure coefficient from Fig 27.4-1,2,3

Figure 27.4-1
Wall Pressure Coefficients, C_p

Surface	L/B	Cp	Use w/
Windward Wall	All	.8	q_z
Leeward Wall	0-1	-.5	q_h
	2	-.3	
	≥4	-.2	
Side Wall	All	-.7	q_h



North: B = 360' L = 252' L/B = 0.7
South: B = 360' L = 252' L/B = 0.7
East: B = 252' L = 360' L/B = 1.43

Windward: $C_p = .8$ w/ q_z
Side Wall: $C_p = -.7$ w/ q_h
Leeward Wall:
North + South: $C_p = -.5$ w/ q_h
East: $C_p = -.414$ w/ q_h

$C_{P_{east}} = -.5 + (1.43-1)\left(\frac{-.3 + .5}{1}\right) = -.414$

Wind Load Calcs BIM Thesis

Fig 27.4-3, Arched Roofs w/ q_h

Conditions	Rise-to-span ratio, r	C_p		
		Windward quarter	Center half	Leeward quarter
Roof on elevated Structure	$0 < r < .2$	$-.9$	$-.7 - r$	$-.5$
	$0.2 \le r < .3$	$1.5r - .3$	$-.7 - r$	$-.5$
	$0.3 \le r \le .6$	$2.75r - .7$	$-.7 - r$	$-.5$

- 13' rise over 252' span $r = \frac{13}{252} = .05$

	C_p
Windward quarter	$-.9$
Center Half	$-.75$
Leeward Quarter	$-.5$

For Parallel to Ridge ie East Wall w/ q_h

$h = 45'$ $L = 360'$ $h/L = .125 \le .5$

Horiz Dist from Windward Edge	C_p
0-22.5 ft	-.9, -.18
22.5 - 45 ft	-.9, -.18
45-90 ft	-.5, -.18
>90 ft	-.3, -.18

Wall Pressures

North Wall $h = 45'$ $q_h = 32.59 + (45-40)\left(\frac{34.15-32.59}{10}\right) = 33.37$ psf

Windward Wall

Ht above Ground, z	$p = q_z GC_p - q_h(GC_{pi})$	$p = q_z GC_p + q_h(GC_{pi})$
0-15	12.1	24.12
20	13.17	25.18
25	14.02	26.04
30	14.87	26.89
40	16.15	28.17
50	17.22	29.23
60	18.07	30.08
70	18.92	30.94
80	19.78	31.79
90	20.41	32.43
100	20.84	32.85
120	21.91	33.93

Leeward Wall $p = q_h(GC_p \pm GC_{pi})$ $p = -8.18$ psf
$p = -20.19$ psf

Side Wall $p = q_h(GC_p \pm GC_{pi})$ $p = -13.85$ psf
$p = -25.86$ psf

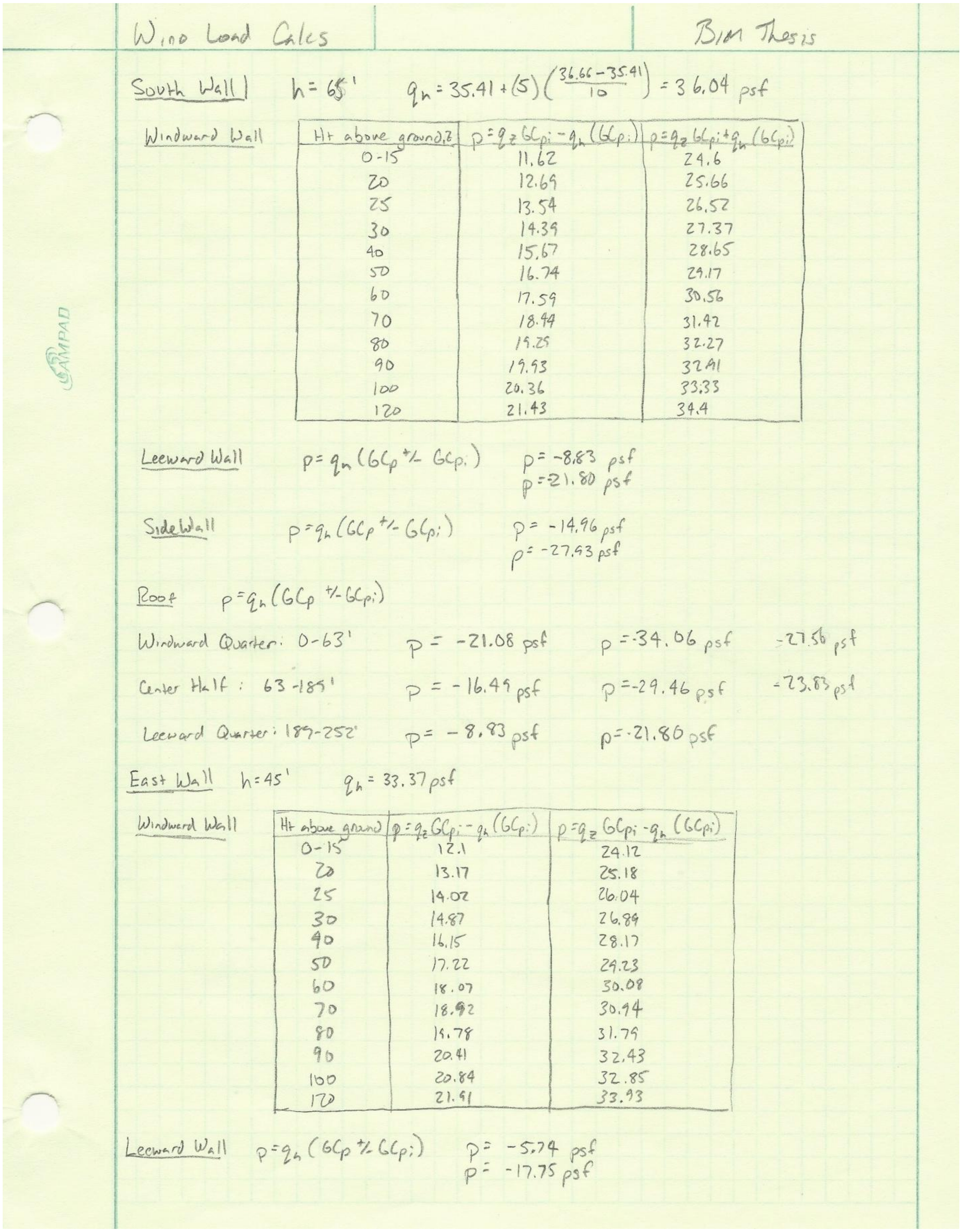
$G = .85$ $GC_{pi} = \pm .18$

Roof $p = q_h(GC_p \pm GC_{pi})$

Windward Quarter: 0-63' $p = -19.52$ psf $p = -31.53$ psf

Center Half: 63'-189' $p = -15.27$ psf $p = -27.28$ psf

Leeward Quarter: 189'-252' $p = -8.17$ $p = -20.19$



Wind Load Calcs BIM Thesis

South Wall $h = 65'$ $q_h = 35.41 + (5)\left(\frac{36.66-35.41}{10}\right) = 36.04$ psf

Windward Wall

Ht above ground, z	$p = q_z GC_{pi} - q_h(GC_{pi})$	$p = q_z GC_{pi} + q_h(GC_{pi})$
0-15	11.62	24.6
20	12.69	25.66
25	13.54	26.52
30	14.39	27.37
40	15.67	28.65
50	16.74	29.17
60	17.59	30.56
70	18.44	31.42
80	19.25	32.27
90	19.93	32.91
100	20.36	33.33
120	21.43	34.4

Leeward Wall $p = q_h(GC_p +/- GC_{pi})$ $p = -8.83$ psf
$p = -21.80$ psf

SideWall $p = q_h(GC_p +/- GC_{pi})$ $p = -14.96$ psf
$p = -27.93$ psf

Roof $p = q_h(GC_p +/- GC_{pi})$

Windward Quarter: 0-63' $p = -21.08$ psf $p = -34.06$ psf -27.56 psf

Center Half: 63-189' $p = -16.49$ psf $p = -29.46$ psf -23.83 psf

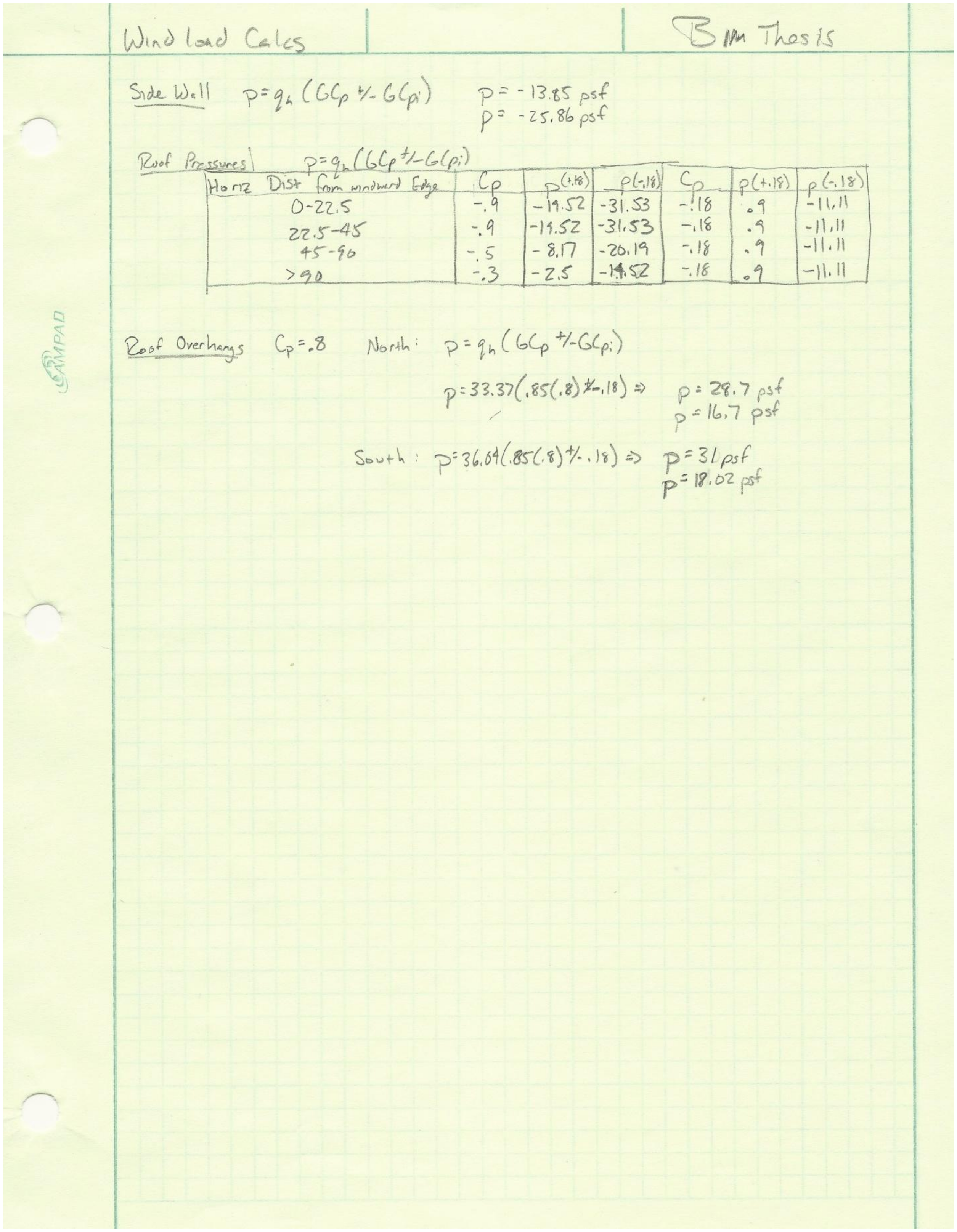
Leeward Quarter: 189-252' $p = -8.83$ psf $p = -21.80$ psf

East Wall $h = 45'$ $q_h = 33.37$ psf

Windward Wall

Ht above ground	$p = q_z GC_{pi} - q_h(GC_{pi})$	$p = q_z GC_{pi} - q_h(GC_{pi})$
0-15	12.1	24.12
20	13.17	25.18
25	14.02	26.04
30	14.87	26.89
40	16.15	28.17
50	17.22	29.23
60	18.07	30.08
70	18.92	30.94
80	19.78	31.79
90	20.41	32.43
100	20.84	32.85
120	21.91	33.93

Leeward Wall $p = q_h(GC_p +/- GC_{pi})$ $p = -5.74$ psf
$p = -17.75$ psf



Wind load Calcs

BIM Thesis

Side Wall $p = q_h(GC_p +/- GC_{pi})$ $p = -13.85$ psf
$p = -25.86$ psf

Roof Pressures $p = q_h(GC_p +/- GC_{pi})$

Horiz Dist from windward Edge	C_p	$p(+.18)$	$p(-.18)$	C_p	$p(+.18)$	$p(-.18)$
0-22.5	-.9	-19.52	-31.53	-.18	.9	-11.11
22.5-45	-.9	-19.52	-31.53	-.18	.9	-11.11
45-90	-.5	-8.17	-20.19	-.18	.9	-11.11
>90	-.3	-2.5	-14.52	-.18	.9	-11.11

Roof Overhangs $C_p = .8$ North: $p = q_h(GC_p +/- GC_{pi})$

$p = 33.37(.85(.8) +/- .18) \Rightarrow$ $p = 28.7$ psf
$p = 16.7$ psf

South: $p = 36.04(.85(.8) +/- .18) \Rightarrow$ $p = 31$ psf
$p = 18.02$ psf

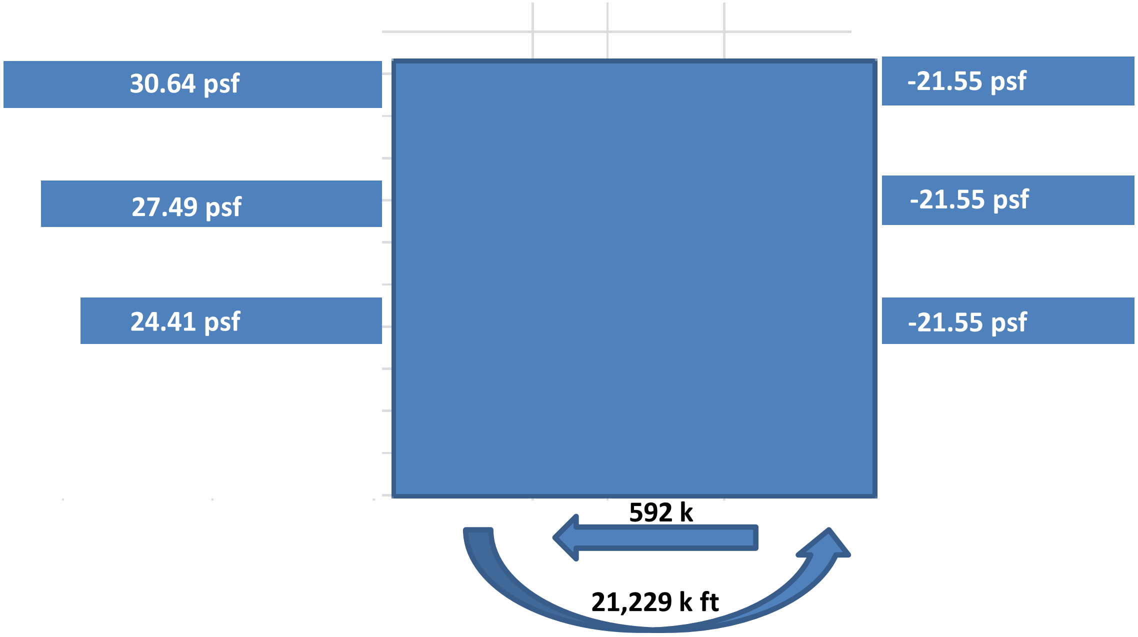
South Wall Wind Forces

Criteria		**N-S Direction**					
Arena		**Floor**	**Height (ft)**	**K_z**	**q_z (psf)**	**p (windward) (psf)**	**p(leeward) (psf)**
G_f	0.85	Roof	61.75	1.14	35.627	30.64	-21.55
C_p (Windward)	0.8	Club Level	36.42	1.02	31.961	27.49	-21.55
C_p (Leeward)	-0.5	Main Conc.	20.75	0.91	28.389	24.41	-21.55
GC_{pi}	0.18	Entry	0	0	0.000	0.00	0.00

N-S Direction

Floor	**Height (ft)**	**Height Below (ft)**	**Height Above (ft)**	**Trib Area (ft2)**	**Story Force (K)**
Roof	61.75	25.33	0	3799.5	116.41
Club Level	36.42	15.67	25.33	9676	265.96
Main Conc.	20.75	20.75	15.67	8595.12	209.85
Entry	0	0	0	0	0.00

Base Shear (K)	**592**
Overturning moment (k ft)	**21229**



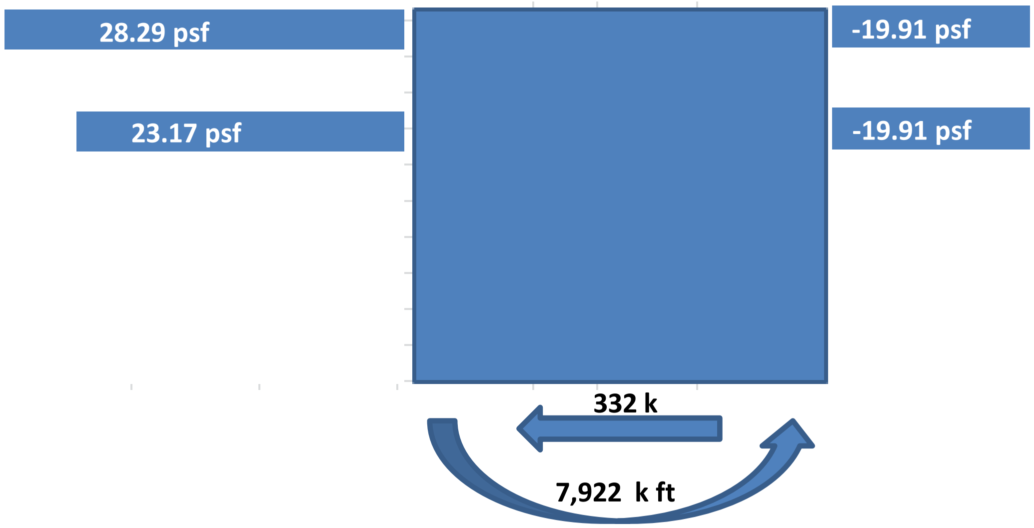
North Wall Wind Forces

Criteria		N-S Direction					
Arena		**Floor**	**Height (ft)**	**K_z**	**q_z (psf)**	**p (windward) (psf)**	**p(leeward) (psf)**
G_f	0.85	Roof	41	1.05	32.901	28.29	-19.91
C_p (Windward)	0.8	Club Level	15.67	0.86	26.948	23.17	-19.91
C_p (Leeward)	-0.5	Main Conc.	0	0	0.000	0.00	0.00
GC_{pi}	0.18	Entry	0	0	0.000	0.00	0.00

N-S Direction

Floor	Height (ft)	Height Below (ft)	Height Above (ft)	Trib Area (ft2)	Story Force (K)
Roof	41	25.33	0	3799.5	107.51
Club Level	15.67	15.67	25.33	9676	224.24
Main Conc.	0	0	15.67	3698.12	0.00
Entry	0	0	0	0	0.00

Base Shear (K)	**332**
Overturning moment (k ft)	**7922**



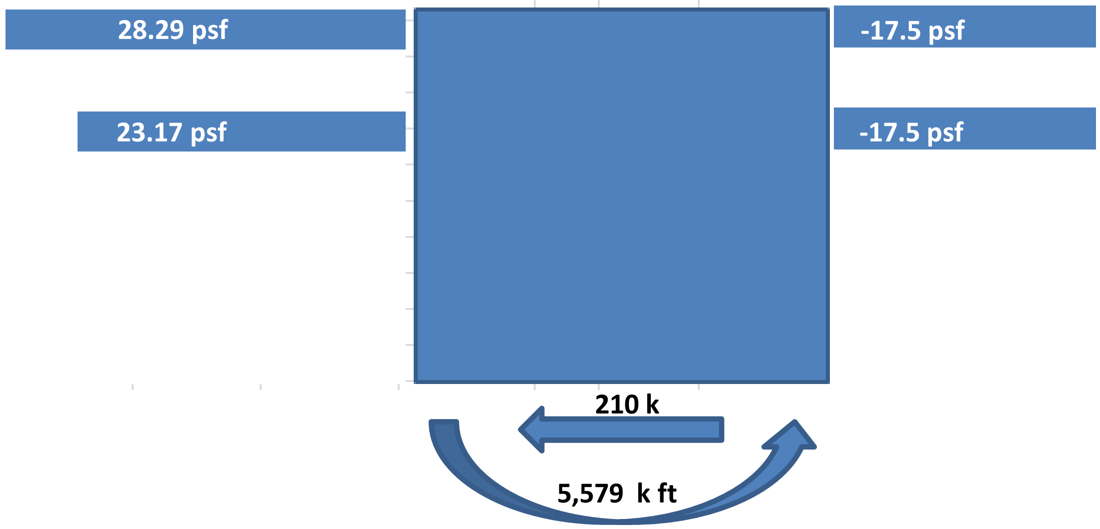
East/West Wall Wind Forces

Criteria		N-S Direction					
Arena		**Floor**	**Height (ft)**	**K_z**	**q_z (psf)**	**p (windward) (psf)**	**p(leeward) (psf)**
G_f	0.85	Roof	41	1.05	32.901	28.29	-17.50
C_p (Windward)	0.8	Club Level	15.67	0.86	26.948	23.17	-17.50
C_p (Leeward)	-0.414	Main Conc.	0	0	0.000	0.00	0.00
GC_{pi}	0.18	Entry	0	0	0.000	0.00	0.00

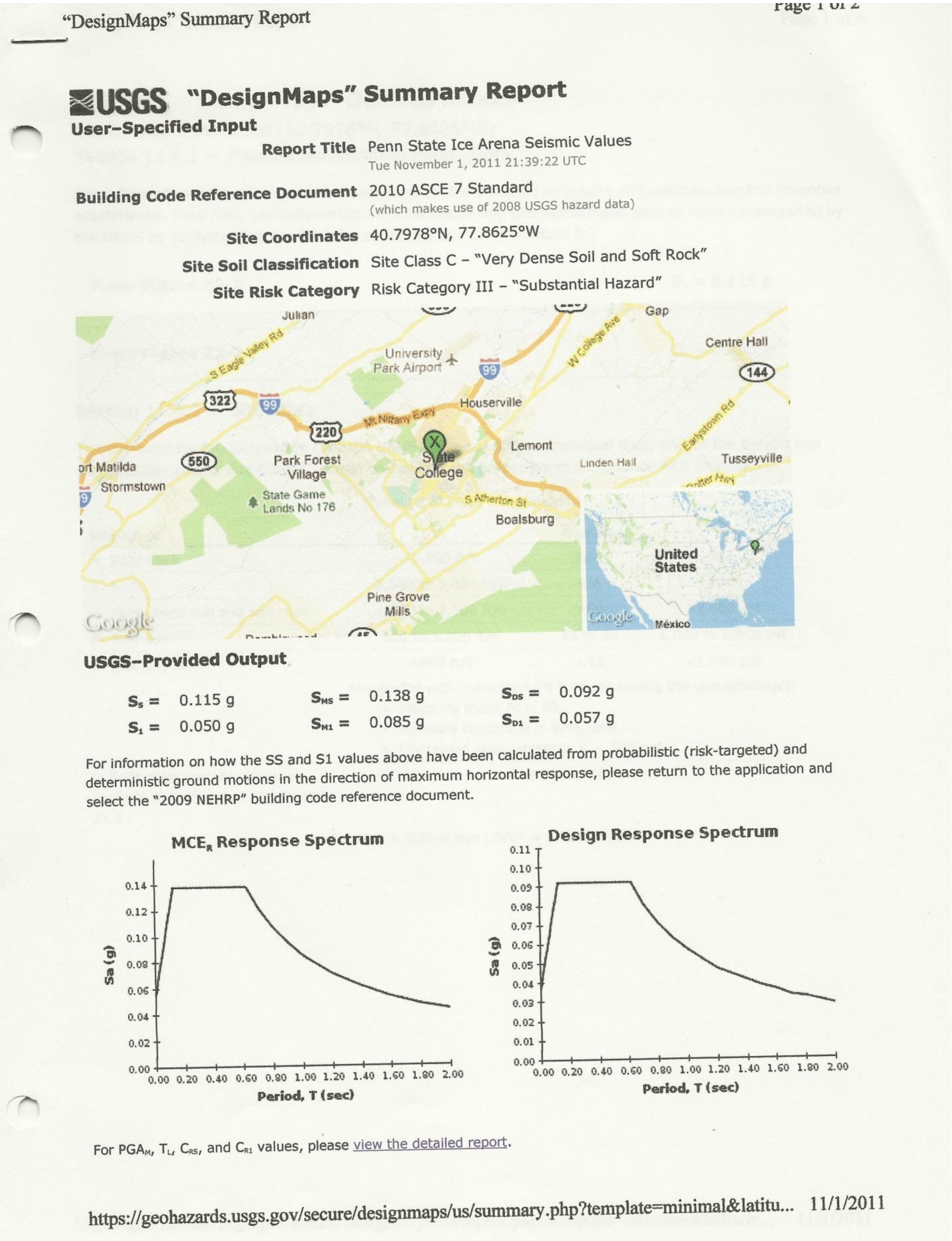
N-S Direction

Floor	Height (ft)	Height Below (ft)	Height Above (ft)	Trib Area (ft2)	Story Force (K)
Roof	41	25.33	0	3191.58	90.31
Club Level	15.67	15.67	25.33	5166	119.72
Main Conc.	0	0	15.67	1974.42	0.00
Entry	0	0	0	0	0.00

Base Shear (K)	**210**
Overturning moment (k ft)	**5579**



Seismic Calcs



“DesignMaps” Summary Report Page 1 of 2

USGS “DesignMaps” Summary Report

User–Specified Input

Report Title	Penn State Ice Arena Seismic Values Tue November 1, 2011 21:39:22 UTC
Building Code Reference Document	2010 ASCE 7 Standard (which makes use of 2008 USGS hazard data)
Site Coordinates	40.7978°N, 77.8625°W
Site Soil Classification	Site Class C – “Very Dense Soil and Soft Rock”
Site Risk Category	Risk Category III – “Substantial Hazard”

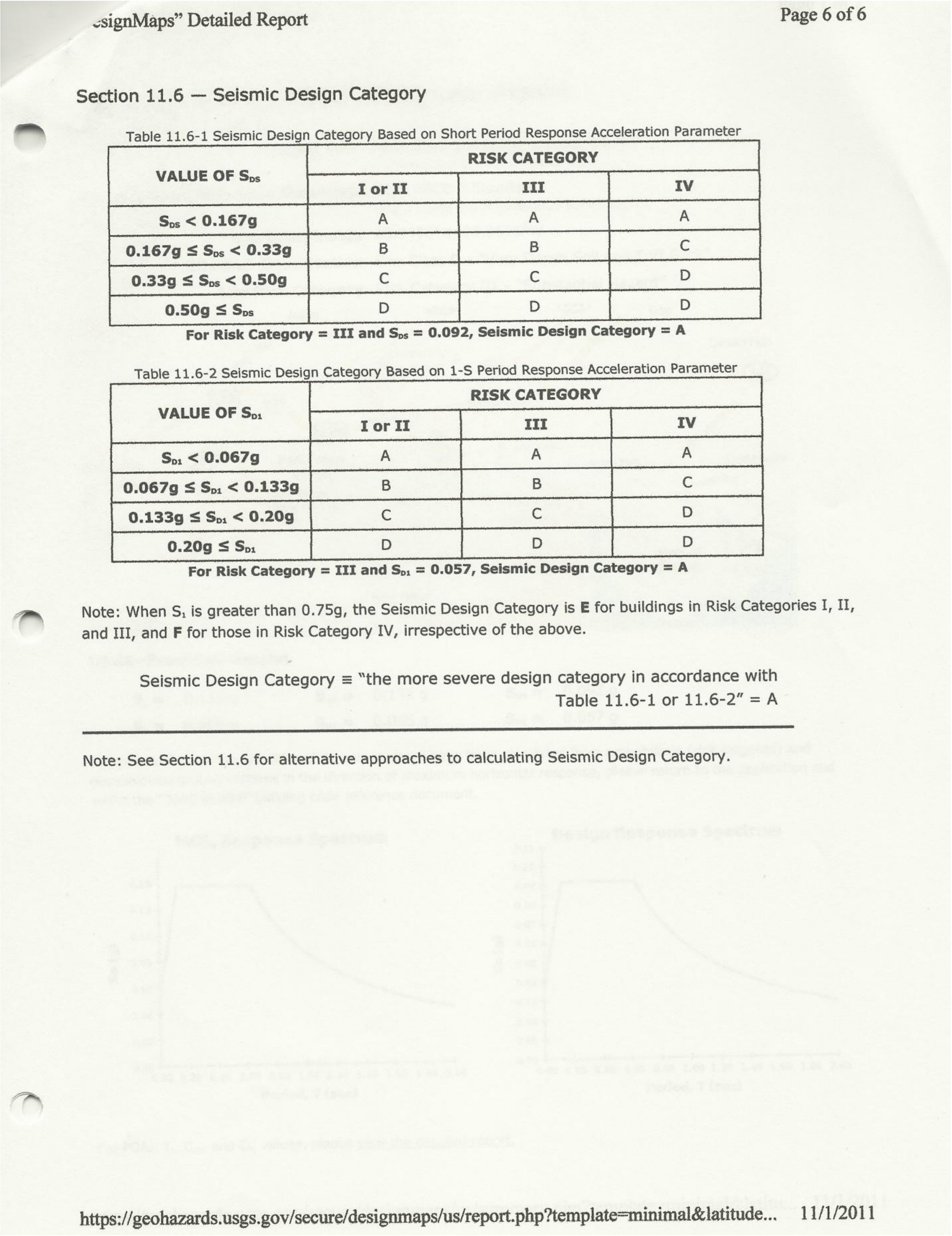
USGS–Provided Output

S_S =	0.115 g	S_{MS} =	0.138 g	S_{DS} =	0.092 g
S_1 =	0.050 g	S_{M1} =	0.085 g	S_{D1} =	0.057 g

For information on how the SS and S1 values above have been calculated from probabilistic (risk-targeted) and deterministic ground motions in the direction of maximum horizontal response, please return to the application and select the “2009 NEHRP” building code reference document.

For PGA_M, T_L, C_{RS}, and C_{R1} values, please view the detailed report.

https://geohazards.usgs.gov/secure/designmaps/us/summary.php?template=minimal&latitu... 11/1/2011



ɛsignMaps" Detailed Report

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Section 11.6 — Seismic Design Category

Table 11.6-1 Seismic Design Category Based on Short Period Response Acceleration Parameter

VALUE OF S_{DS}	RISK CATEGORY		
	I or II	III	IV
$S_{DS} < 0.167g$	A	A	A
$0.167g \leq S_{DS} < 0.33g$	B	B	C
$0.33g \leq S_{DS} < 0.50g$	C	C	D
$0.50g \leq S_{DS}$	D	D	D

For Risk Category = III and S_{DS} = 0.092, Seismic Design Category = A

Table 11.6-2 Seismic Design Category Based on 1-S Period Response Acceleration Parameter

VALUE OF S_{D1}	RISK CATEGORY		
	I or II	III	IV
$S_{D1} < 0.067g$	A	A	A
$0.067g \leq S_{D1} < 0.133g$	B	B	C
$0.133g \leq S_{D1} < 0.20g$	C	C	D
$0.20g \leq S_{D1}$	D	D	D

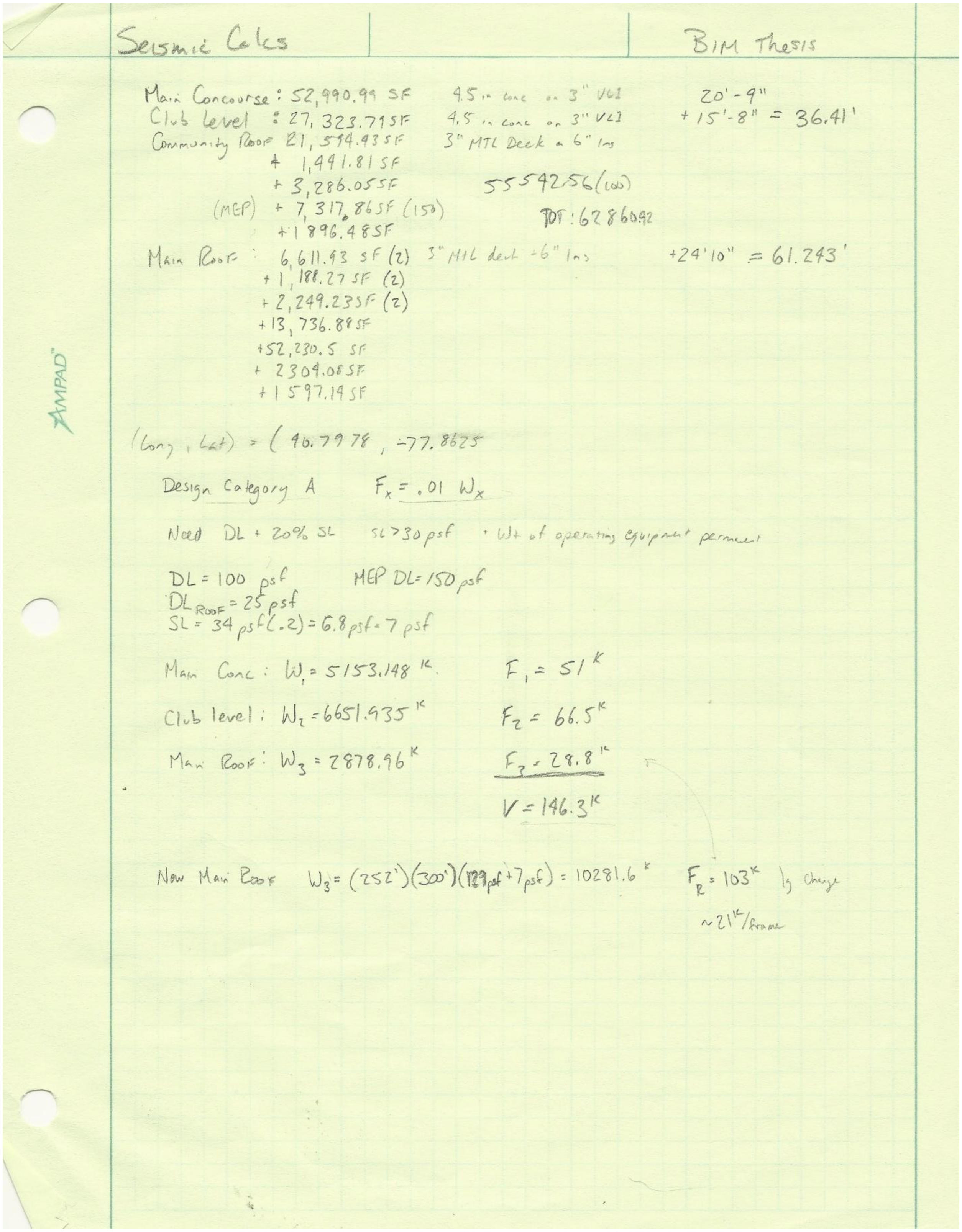
For Risk Category = III and S_{D1} = 0.057, Seismic Design Category = A

Note: When S_1 is greater than 0.75g, the Seismic Design Category is **E** for buildings in Risk Categories I, II, and III, and **F** for those in Risk Category IV, irrespective of the above.

Seismic Design Category ≡ "the more severe design category in accordance with Table 11.6-1 or 11.6-2" = A

Note: See Section 11.6 for alternative approaches to calculating Seismic Design Category.

https://geohazards.usgs.gov/secure/designmaps/us/report.php?template=minimal&latitude... 11/1/2011



Seismic Calcs

BIM Thesis

Main Concourse : 52,990.99 SF 4.5 in conc on 3" VLI 20'-9"
Club Level : 27,323.79 SF 4.5 in conc on 3" VLI + 15'-8" = 36.41'
Community Roof 21,594.93 SF 3" MTL Deck + 6" Ins
+ 1,441.81 SF
+ 3,286.05 SF 5554256 (100)
(MEP) + 7,317.86 SF (150) TOT : 6286092
+ 1896.48 SF
Main Roof : 6,611.93 SF (2) 3" MtL deck + 6" Ins +24'10" = 61.243'
+ 1,188.27 SF (2)
+ 2,249.23 SF (2)
+ 13,736.88 SF
+ 52,230.5 SF
+ 2309.08 SF
+ 1597.14 SF

(Long, Lat) = (40.7978 , -77.8625

Design Category A $F_x = .01\ W_x$

Need DL + 20% SL SL > 30 psf + Wt of operating equipment permanent

DL = 100 psf MEP DL = 150 psf
DL_{ROOF} = 25 psf
SL = 34 psf (.2) = 6.8 psf ≈ 7 psf

Main Conc : W_1 = 5153.148 ^{K} $F_1 = 51^K$

Club level : W_2 = 6651.935 ^{K} $F_2 = 66.5^K$

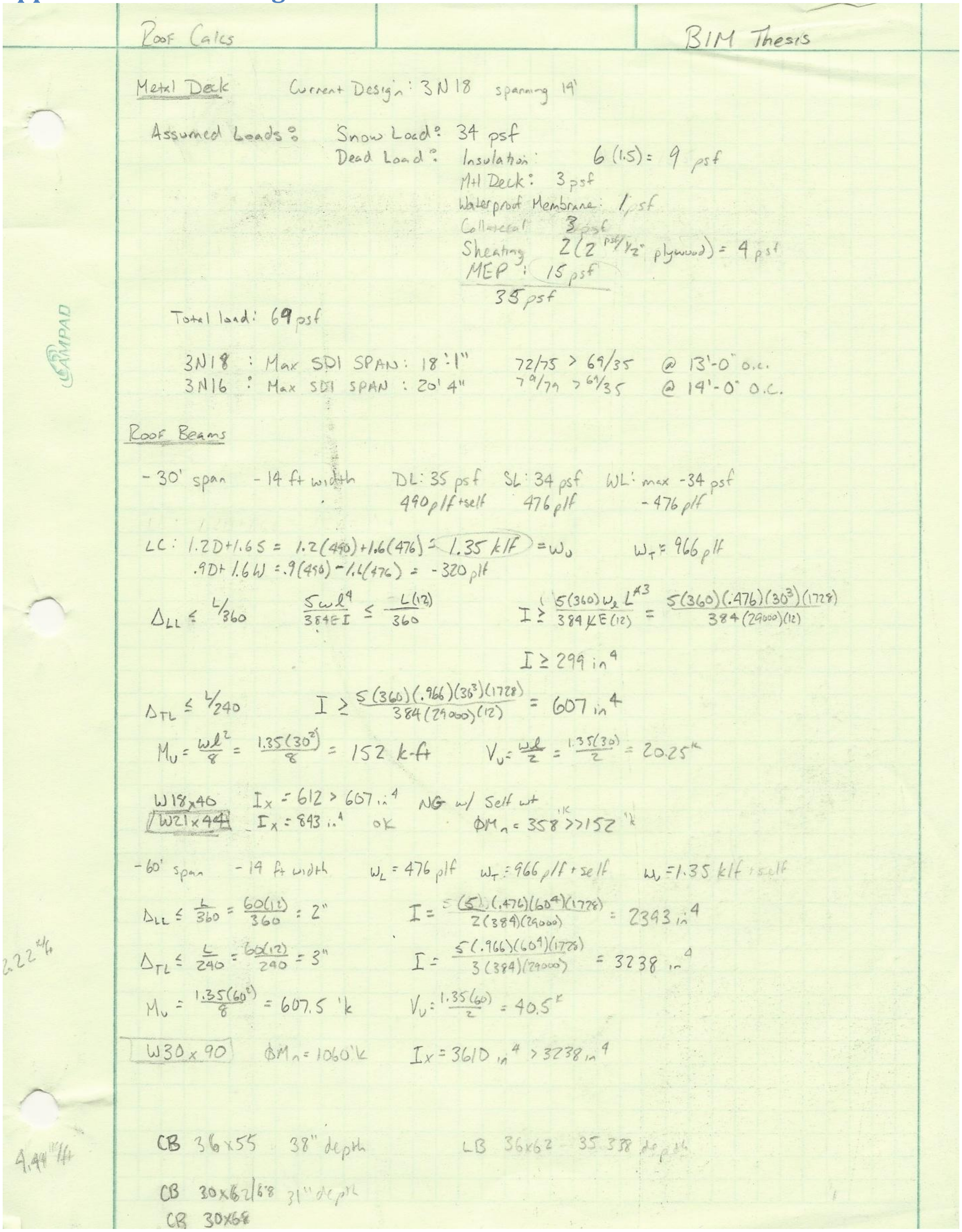
Main Roof : W_3 = 2878.96 ^{K} $F_3 = 28.8^K$

$V = 146.3^K$

New Main Roof $W_3 = (252')(300')(129\text{psf} + 7\text{psf}) = 10281.6^K$ $F_R = 103^K$ ly Change

~21^K/frame

Appendix C. Roof Design



Roof Calcs BIM Thesis

Metal Deck Current Design: 3N18 spanning 14'

Assumed Loads: Snow Load: 34 psf
Dead Load: Insulation: 6 (1.5) = 9 psf
Mtl Deck: 3 psf
Waterproof Membrane: 1 psf
Collateral 3 psf
Sheating 2(2 psf/½" plywood) = 4 psf
MEP: 15 psf
35 psf

Total load: 69 psf

3N18 : Max SDI SPAN: 18'-1" 72/75 > 69/35 @ 13'-0" o.c.
3N16 : Max SDI SPAN: 20' 4" 79/79 > 69/35 @ 14'-0" o.c.

Roof Beams

- 30' span - 14 ft width DL: 35 psf SL: 34 psf WL: max -34 psf
490 plf +self 476 plf -476 plf

LC: $1.2D+1.6S = 1.2(490)+1.6(476) = \boxed{1.35\ klf} = w_u$ $w_T = 966$ plf
$.9D+1.6W = .9(490) - 1.6(476) = -320$ plf

$\Delta_{LL} \le L/360$ $\frac{5wl^4}{384EI} \le \frac{L(12)}{360}$ $I \ge \frac{5(360)w_L L^{43}}{384 \cancel{K} E(12)} = \frac{5(360)(.476)(30^3)(1728)}{384(29000)(12)}$

$I \ge 299\ in^4$

$\Delta_{TL} \le L/240$ $I \ge \frac{5(360)(.966)(30^3)(1728)}{384(29000)(12)} = 607\ in^4$

$M_u = \frac{wl^2}{8} = \frac{1.35(30^2)}{8} = 152$ k-ft $V_u = \frac{wl}{2} = \frac{1.35(30)}{2} = 20.25^k$

W18x40 $I_x = 612 > 607\ in^4$ NG w/ Self wt
$\boxed{W21x44}$ $I_x = 843\ in^4$ ok $\phi M_n = 358'^k >> 152'^k$

- 60' span - 14 ft width $w_L = 476$ plf $w_T = 966$ plf + self $w_u = 1.35$ klf + self

$\Delta_{LL} \le \frac{L}{360} = \frac{60(12)}{360} = 2"$ $I = \frac{5(.476)(60^4)(1728)}{2(384)(29000)} = 2393\ in^4$

$\Delta_{TL} \le \frac{L}{240} = \frac{60(12)}{240} = 3"$ $I = \frac{5(.966)(60^4)(1728)}{3(384)(29000)} = 3238\ in^4$

$M_u = \frac{1.35(60^2)}{8} = 607.5\ 'k$ $V_u = \frac{1.35(60)}{2} = 40.5^k$

$\boxed{W30 \times 90}$ $\phi M_n = 1060'k$ $I_x = 3610\ in^4 > 3238\ in^4$

2.22 #/ft

4.44 #/ft

CB 36x55 38" depth LB 36x62 35.338 depth

CB 30x62/68 31" depth
CB 30x68

Roof Calcs | BIM Thesis

Heavier Roof SL = 34 psf
DL = 82 psf Noncomposite deck
+ 30 MEP
+ 5 roofing finishing
117 psf

Total = 151 psf

Composite 34 + 35 = 69 psf
3VLI 19 @ 12' 147 >> 69 psf

8" total
3C16 Max Span 11' 0"
3C18 Max Span 11' 0"

Roof Beam Design $w_D = 117 psf(11) = 1.287 ^{k}/_{f}$ $w_L = 34(11) = .374 ^{k}/_{ft}$

Castellated
CB 40 x 84 Depth = 40.275"
CB 36 x 94 Depth = 35.975"
↳ 9.5 psf

if Composite: CB30x44/68 Depth: 30.675
78 studs

Regular $1.2(1.287) + 1.6(.374) = 2.14 ^{k}/_{ft}$ $1.4D = 1.80 ^{k}/_{ft}$

$\Delta_{LL} \leq \frac{L}{360} = \frac{60(12)}{360} = 2''$

$I = \frac{5(.374)(60^4)(1728)}{2(384)(29000)} = 1880 in^4$

$\Delta_{TL} \leq \frac{L}{240} = \frac{60(12)}{240} = 3''$

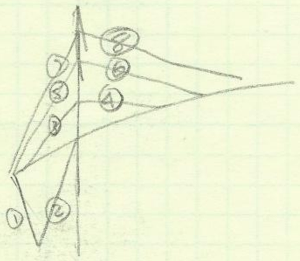
$I = \frac{5(1.661)(60^4)(1728)}{3(384)(29000)} = 5567 in^4$

W33x118 5900 > 5567
NG w/ self wt

$M_u = \frac{2.14(60^2)}{8} = 963'k$ 1750'k > 963'k

$\boxed{W33 x 130}$ 6710 > 5567
↳ 12 psf

Loads on Girder D: 117 + 12 = 129 psf = 7.74 k/ft
L: 34 psf ⇒ 2.04 k/ft



4 - 4
4.75 - 3, 8
5.25 - 1, 2, 7
5.5 - 5, 6

42" 2" thick 10 ksi conc
W40x593 girder

- Too much defl ↓

Roof Calcs | Thoughts | BIM Thesis

Roof Loads Girder

S: 34 psf ⇒ 2.04 ↙Bn Allowance
D: 35 psf +10 psf + 15 psf ↙extra L/E = 60 psf = $3.6^{k/ft}$
W: N windward -31.53 psf for half -27.28 psf for half
S windward - 34.06 psf for half - 29.46 psf for half

Unbalanced drift: 17 psf 65 psf

Roof Bms:
Catwalk Load: 1/4" Checkered plate 10 psf HSS 14x10x1/2 .75 $^{k/ft}$ 50 psf 36" wide ∠4x4x3/4 = 9.8 $^{lb/ft}$ = 49^{lbs} x 2 = 98^{lb} @5'

Prestress will be calculated for D+.5(L or S)

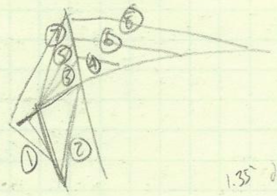
ASD Load Combo: D+L
Pre D+S/L D+S
~~D+.75S~~
Pre+D+W D+W
Pre+D+.75W+.75S D+.75W+.75S
Pre+.6D+W .6D+W
x3 = 1
x2 = 2,3,5,7

Cable Load Combos: $T_1 = D+P$
$T_2 = D+\cancel{L}+S+P$
$T_3 = D+P+W$
$T_4 = D+P+L_r/S+W$
$T_5 =$ C + erection components

Design Strength: $S_d \geq$ $2.2T_1$
$2.2T_2$
$2.0T_3$
$2.0T_4$
$2.0T_5$

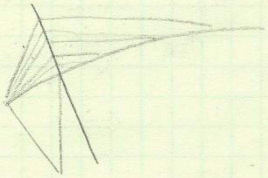
7 1/2" deep, long span deck w/ 2 1/2" topping

4.25"
5.25"
4.5"
5.5"



13.18^k No Mod.
13.15 ^{k}

1.35" depth?



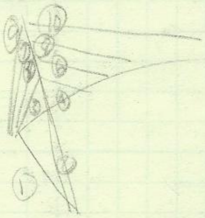
- Adjust Cable Sizes, Prop Modifiers

$\ell/240$ = 6.5"

-

First Idea
Mast Section: 36" pipe 1.5" thick filled w/ 8 ksi concrete
Girder 40x372

.75 case
- 4" deformation under full snow → possible up tension
- 13" def ⇒ more prestress under Pre+D+S/L
- 3" def under just dead



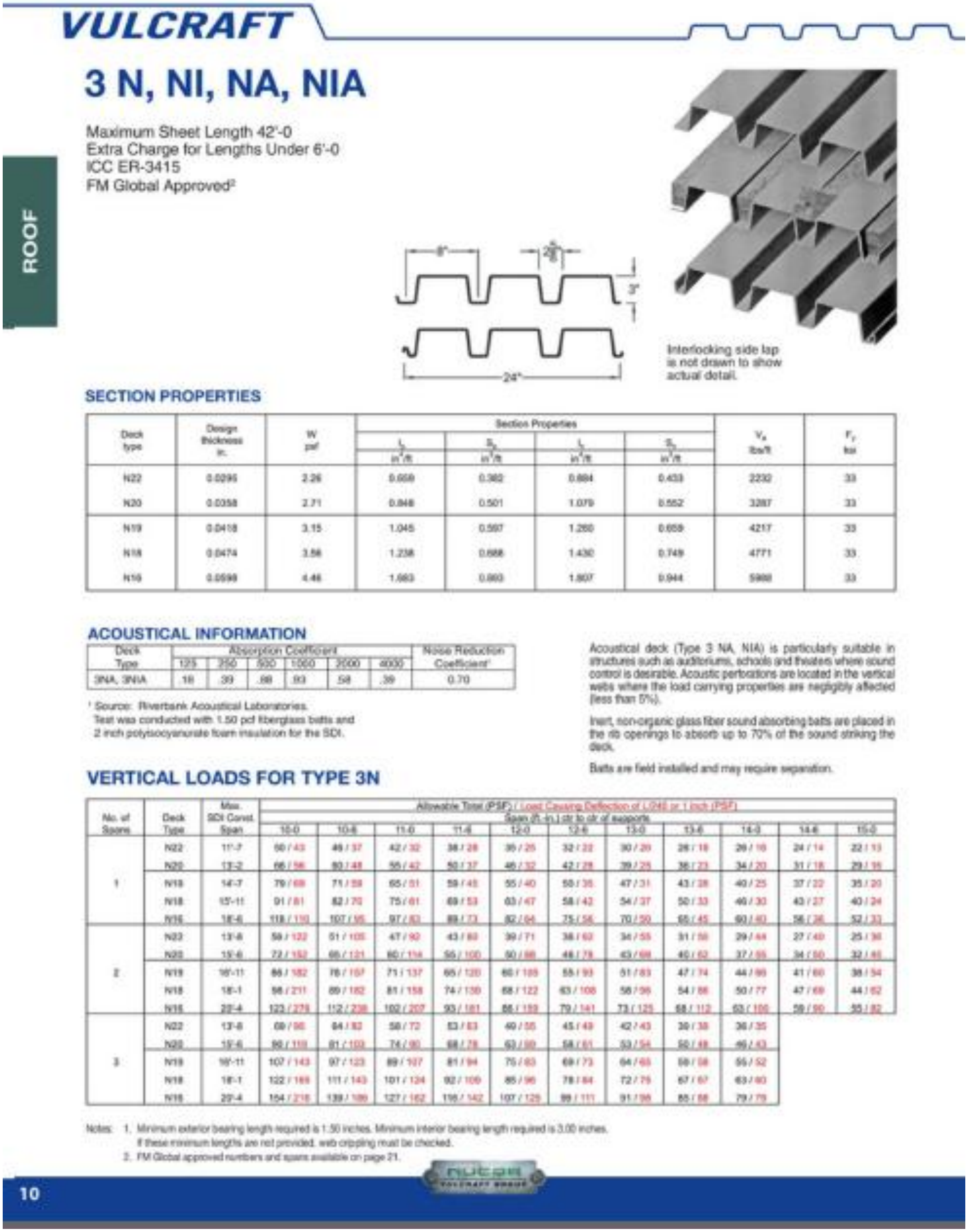
Need heavier roof

r = .11

Main - 20.75'
Club 15.667
Loft 16

130, 45
0, 30

40x431 .289 | .182



VULCRAFT

ROOF

3 N, NI, NA, NIA

Maximum Sheet Length 42'-0
Extra Charge for Lengths Under 6'-0
ICC ER-3415
FM Global Approved[2]

Interlocking side lap is not drawn to show actual detail.

SECTION PROPERTIES

Deck type	Design thickness in.	W psf	Section Properties				V_a lbs/ft	F_y ksi
			I_p in^4/ft	S_p in^3/ft	I_n in^4/ft	S_n in^3/ft		
N22	0.0295	2.26	0.659	0.382	0.884	0.433	2232	33
N20	0.0358	2.71	0.848	0.501	1.079	0.552	3287	33
N19	0.0418	3.15	1.045	0.597	1.260	0.659	4217	33
N18	0.0474	3.58	1.238	0.688	1.430	0.749	4771	33
N16	0.0598	4.46	1.583	0.883	1.807	0.944	5988	33

ACOUSTICAL INFORMATION

Deck Type	Absorption Coefficient						Noise Reduction Coefficient[1]
	125	250	500	1000	2000	4000	
3NA, 3NIA	.18	.39	.88	.93	.58	.39	0.70

[1] Source: Riverbank Acoustical Laboratories.
Test was conducted with 1.50 pcf fiberglass batts and 2 inch polyisocyanurate foam insulation for the SDI.

Acoustical deck (Type 3 NA, NIA) is particularly suitable in structures such as auditoriums, schools and theaters where sound control is desirable. Acoustic perforations are located in the vertical webs where the load carrying properties are negligibly affected (less than 5%).

Inert, non-organic glass fiber sound absorbing batts are placed in the rib openings to absorb up to 70% of the sound striking the deck.

Batts are field installed and may require separation.

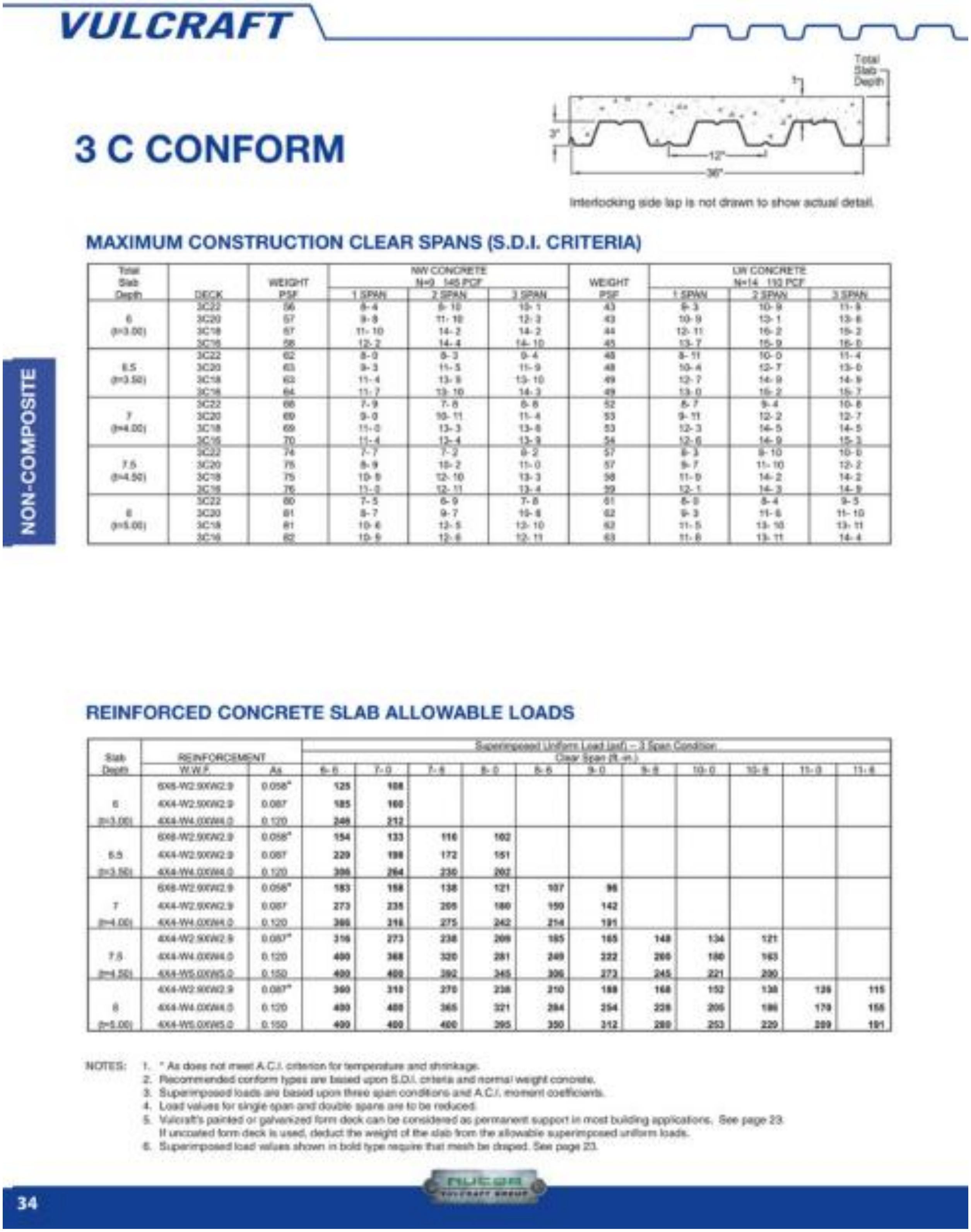
VERTICAL LOADS FOR TYPE 3N

No. of Spans	Deck Type	Max. SDI Const. Span	Allowable Total (PSF) / Load Causing Deflection of L/240 or 1 inch (PSF)										
			Span (ft.-in.) ctr to ctr of supports										
			10-0	10-6	11-0	11-6	12-0	12-6	13-0	13-6	14-0	14-6	15-0
1	N22	11'-7	50 / 43	46 / 37	42 / 32	38 / 28	35 / 25	32 / 22	30 / 20	28 / 18	26 / 16	24 / 14	22 / 13
	N20	13'-2	66 / 56	60 / 48	55 / 42	50 / 37	46 / 32	42 / 28	39 / 25	36 / 23	34 / 20	31 / 18	29 / 16
	N19	14'-7	79 / 68	71 / 59	65 / 51	59 / 45	55 / 40	50 / 35	47 / 31	43 / 28	40 / 25	37 / 22	35 / 20
	N18	15'-11	91 / 81	82 / 70	75 / 61	69 / 53	63 / 47	58 / 42	54 / 37	50 / 33	46 / 30	43 / 27	40 / 24
	N16	18'-6	118 / 110	107 / 95	97 / 83	89 / 73	82 / 64	75 / 56	70 / 50	65 / 45	60 / 40	56 / 36	52 / 33
2	N22	13'-8	59 / 122	51 / 105	47 / 92	43 / 80	39 / 71	36 / 62	34 / 55	31 / 50	29 / 44	27 / 40	25 / 36
	N20	15'-6	72 / 152	66 / 131	60 / 114	55 / 100	50 / 88	46 / 78	43 / 69	40 / 62	37 / 55	34 / 50	32 / 45
	N19	16'-11	86 / 182	78 / 157	71 / 137	65 / 120	60 / 105	55 / 93	51 / 83	47 / 74	44 / 66	41 / 60	38 / 54
	N18	18'-1	98 / 211	89 / 182	81 / 158	74 / 139	68 / 122	63 / 108	58 / 96	54 / 86	50 / 77	47 / 69	44 / 62
	N16	20'-4	123 / 279	112 / 238	102 / 207	93 / 181	86 / 159	79 / 141	73 / 125	68 / 112	63 / 100	59 / 90	55 / 82
3	N22	13'-8	69 / 96	64 / 82	58 / 72	53 / 63	49 / 55	45 / 49	42 / 43	39 / 38	36 / 35		
	N20	15'-6	90 / 119	81 / 103	74 / 90	68 / 78	63 / 69	58 / 61	53 / 54	50 / 48	46 / 43		
	N19	16'-11	107 / 143	97 / 123	89 / 107	81 / 94	75 / 83	69 / 73	64 / 65	59 / 58	55 / 52		
	N18	18'-1	122 / 169	111 / 143	101 / 124	92 / 109	85 / 96	78 / 84	72 / 75	67 / 67	63 / 60		
	N16	20'-4	154 / 218	139 / 186	127 / 162	116 / 142	107 / 125	99 / 111	91 / 98	85 / 88	79 / 79		

Notes: 1. Minimum exterior bearing length required is 1.50 inches. Minimum interior bearing length required is 3.00 inches. If these minimum lengths are not provided, web crippling must be checked.
2. FM Global approved numbers and spans available on page 21.

NUCOR VULCRAFT GROUP

10



3 C CONFORM

Interlocking side lap is not drawn to show actual detail.

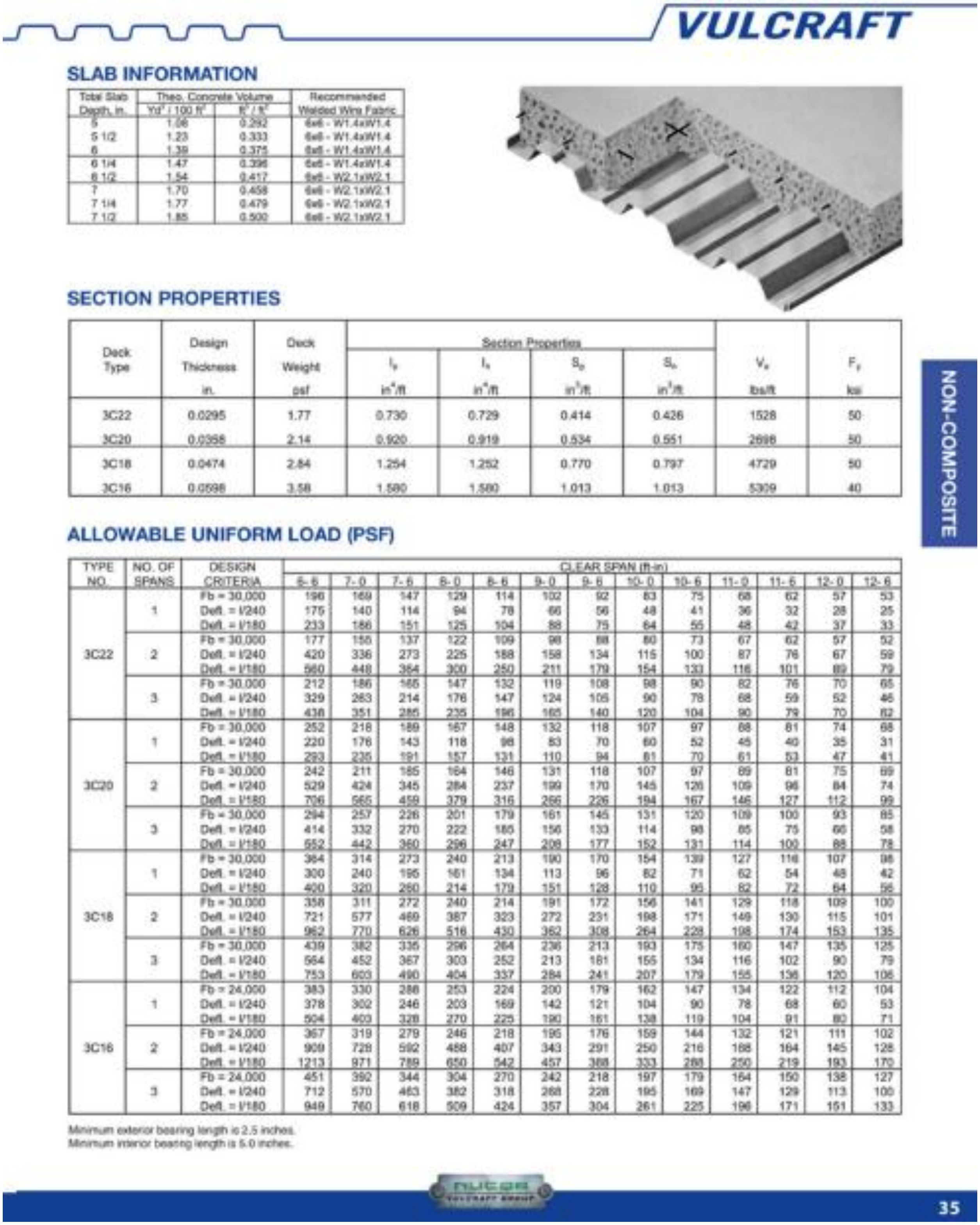
MAXIMUM CONSTRUCTION CLEAR SPANS (S.D.I. CRITERIA)

Total Slab Depth	DECK	WEIGHT PSF	NW CONCRETE N=9 145 PCF			WEIGHT PSF	LW CONCRETE N=14 110 PCF		
			1 SPAN	2 SPAN	3 SPAN		1 SPAN	2 SPAN	3 SPAN
6 (t=3.00)	3C22	56	8-4	8-10	10-1	43	9-3	10-9	11-9
	3C20	57	9-8	11-10	12-3	43	10-9	13-1	13-6
	3C18	57	11-10	14-2	14-2	44	12-11	16-2	15-2
	3C16	58	12-2	14-4	14-10	45	13-7	15-9	16-0
6.5 (t=3.50)	3C22	62	8-0	8-3	9-4	48	8-11	10-0	11-4
	3C20	63	9-3	11-5	11-9	48	10-4	12-7	13-0
	3C18	63	11-4	13-9	13-10	49	12-7	14-9	14-9
	3C16	64	11-7	13-10	14-3	49	13-0	16-2	15-7
7 (t=4.00)	3C22	68	7-9	7-8	8-8	52	8-7	9-4	10-8
	3C20	69	9-0	10-11	11-4	53	9-11	12-2	12-7
	3C18	69	11-0	13-3	13-6	53	12-3	14-5	14-5
	3C16	70	11-4	13-4	13-9	54	12-6	14-9	15-3
7.5 (t=4.50)	3C22	74	7-7	7-2	8-2	57	8-3	8-10	10-0
	3C20	75	8-9	10-2	11-0	57	9-7	11-10	12-2
	3C18	75	10-9	12-10	13-3	58	11-9	14-2	14-2
	3C16	76	11-0	12-11	13-4	59	12-1	14-3	14-9
8 (t=5.00)	3C22	80	7-5	6-9	7-8	61	8-0	8-4	9-5
	3C20	81	8-7	9-7	10-8	62	9-3	11-6	11-10
	3C18	81	10-6	12-5	12-10	62	11-5	13-10	13-11
	3C16	82	10-9	12-6	12-11	63	11-6	13-11	14-4

REINFORCED CONCRETE SLAB ALLOWABLE LOADS

Slab Depth	REINFORCEMENT		Superimposed Uniform Load (psf) – 3 Span Condition Clear Span (ft.-in.)										
	W.W.F.	As	6-6	7-0	7-6	8-0	8-6	9-0	9-6	10-0	10-6	11-0	11-6
6 (t=3.00)	6X6-W2.9XW2.9	0.058*	125	108									
	4X4-W2.9XW2.9	0.087	185	160									
	4X4-W4.0XW4.0	0.120	246	212									
6.5 (t=3.50)	6X6-W2.9XW2.9	0.058*	154	133	116	102							
	4X4-W2.9XW2.9	0.087	220	198	172	151							
	4X4-W4.0XW4.0	0.120	306	264	230	202							
7 (t=4.00)	6X6-W2.9XW2.9	0.058*	183	158	138	121	107	96					
	4X4-W2.9XW2.9	0.087	273	235	205	180	150	142					
	4X4-W4.0XW4.0	0.120	386	316	275	242	214	191					
7.5 (t=4.50)	4X4-W2.9XW2.9	0.087*	316	273	238	209	185	165	148	134	121		
	4X4-W4.0XW4.0	0.120	400	368	320	281	249	222	200	180	163		
	4X4-W5.0XW5.0	0.150	400	400	392	345	306	273	245	221	200		
8 (t=5.00)	4X4-W2.9XW2.9	0.087*	360	318	270	238	210	188	168	152	138	126	115
	4X4-W4.0XW4.0	0.120	400	400	365	321	284	254	228	205	186	170	155
	4X4-W5.0XW5.0	0.150	400	400	400	395	350	312	280	253	220	209	191

NOTES:
1. * As does not meet A.C.I. criterion for temperature and shrinkage.
2. Recommended conform types are based upon S.D.I. criteria and normal weight concrete.
3. Superimposed loads are based upon three span conditions and A.C.I. moment coefficients.
4. Load values for single span and double spans are to be reduced.
5. Vulcraft's painted or galvanized form deck can be considered as permanent support in most building applications. See page 23. If uncoated form deck is used, deduct the weight of the slab from the allowable superimposed uniform loads.
6. Superimposed load values shown in bold type require that mesh be draped. See page 23.



VULCRAFT

NON-COMPOSITE

SLAB INFORMATION

Total Slab Depth, in.	Theo. Concrete Volume		Recommended Welded Wire Fabric
	Yd³ / 100 ft²	ft³ / ft²	
5	1.08	0.292	6x6 - W1.4xW1.4
5 1/2	1.23	0.333	6x6 - W1.4xW1.4
6	1.39	0.375	6x6 - W1.4xW1.4
6 1/4	1.47	0.396	6x6 - W1.4xW1.4
6 1/2	1.54	0.417	6x6 - W2.1xW2.1
7	1.70	0.458	6x6 - W2.1xW2.1
7 1/4	1.77	0.479	6x6 - W2.1xW2.1
7 1/2	1.85	0.500	6x6 - W2.1xW2.1

SECTION PROPERTIES

Deck Type	Design Thickness in.	Deck Weight psf	Section Properties				V_n lbs/ft	F_y ksi
			I_p in⁴/ft	I_n in⁴/ft	S_p in³/ft	S_n in³/ft		
3C22	0.0295	1.77	0.730	0.729	0.414	0.426	1528	50
3C20	0.0358	2.14	0.920	0.919	0.534	0.551	2698	50
3C18	0.0474	2.84	1.254	1.252	0.770	0.797	4729	50
3C16	0.0598	3.58	1.580	1.580	1.013	1.013	5309	40

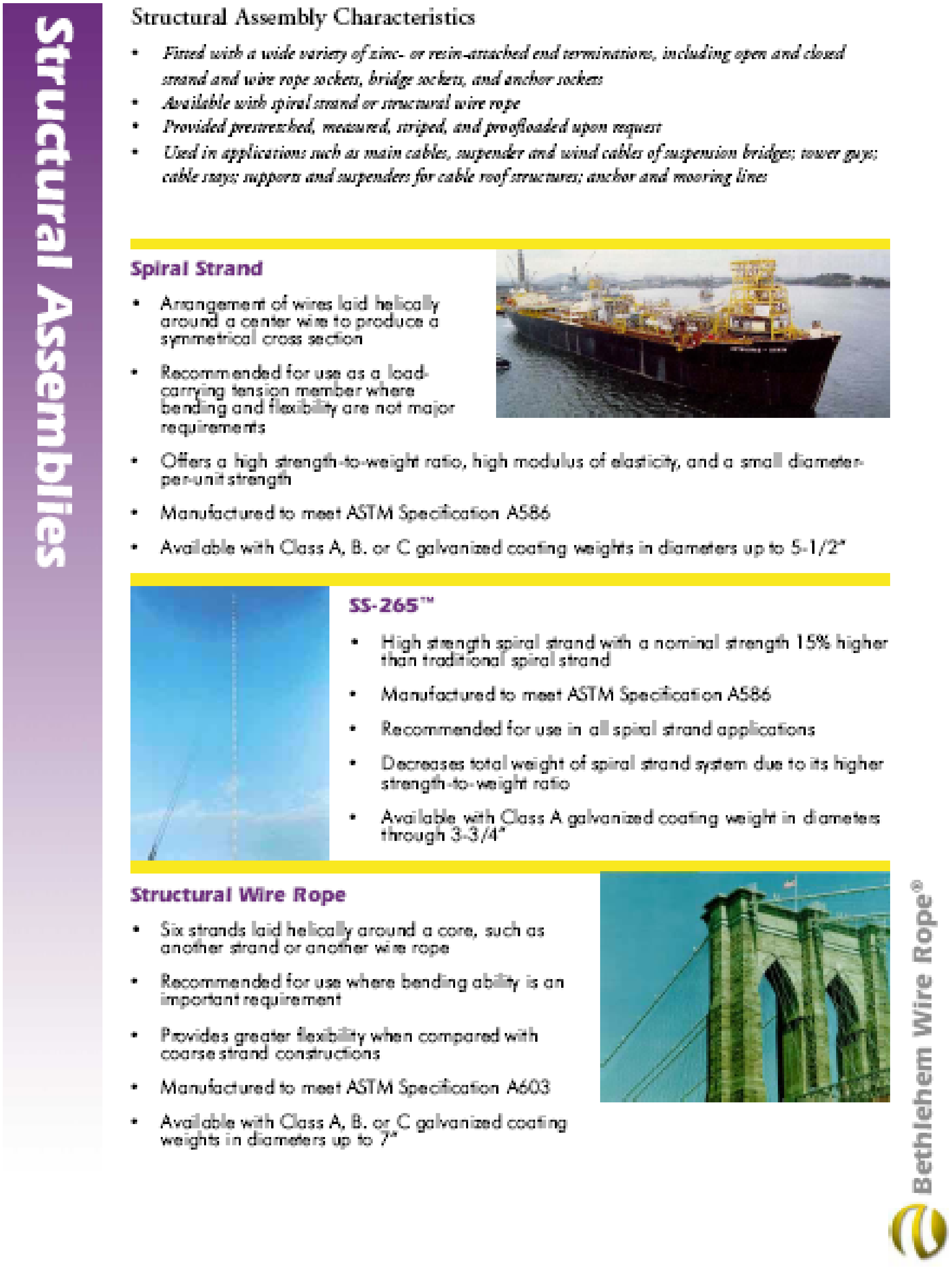
ALLOWABLE UNIFORM LOAD (PSF)

TYPE NO.	NO. OF SPANS	DESIGN CRITERIA	CLEAR SPAN (ft-in)												
			6-6	7-0	7-6	8-0	8-6	9-0	9-6	10-0	10-6	11-0	11-6	12-0	12-6
3C22	1	Fb = 30,000	196	169	147	129	114	102	92	83	75	68	62	57	53
		Defl. = l/240	175	140	114	94	78	66	56	48	41	36	32	28	25
		Defl. = l/180	233	186	151	125	104	88	75	64	55	48	42	37	33
	2	Fb = 30,000	177	155	137	122	109	98	88	80	73	67	62	57	52
		Defl. = l/240	420	336	273	225	188	158	134	115	100	87	76	67	59
		Defl. = l/180	560	448	364	300	250	211	179	154	133	116	101	89	79
	3	Fb = 30,000	212	186	165	147	132	119	108	98	90	82	76	70	65
		Defl. = l/240	329	263	214	176	147	124	105	90	78	68	59	52	46
		Defl. = l/180	438	351	285	235	196	165	140	120	104	90	79	70	62
3C20	1	Fb = 30,000	252	218	189	167	148	132	118	107	97	88	81	74	68
		Defl. = l/240	220	176	143	118	98	83	70	60	52	45	40	35	31
		Defl. = l/180	293	235	191	157	131	110	94	81	70	61	53	47	41
	2	Fb = 30,000	242	211	185	164	146	131	118	107	97	89	81	75	69
		Defl. = l/240	529	424	345	284	237	199	170	145	126	109	96	84	74
		Defl. = l/180	706	565	459	379	316	266	226	194	167	146	127	112	99
	3	Fb = 30,000	294	257	226	201	179	161	145	131	120	109	100	93	85
		Defl. = l/240	414	332	270	222	185	156	133	114	98	85	75	66	58
		Defl. = l/180	552	442	360	296	247	208	177	152	131	114	100	88	78
3C18	1	Fb = 30,000	364	314	273	240	213	190	170	154	139	127	116	107	98
		Defl. = l/240	300	240	195	161	134	113	96	82	71	62	54	48	42
		Defl. = l/180	400	320	260	214	179	151	128	110	95	82	72	64	56
	2	Fb = 30,000	358	311	272	240	214	191	172	156	141	129	118	109	100
		Defl. = l/240	721	577	469	387	323	272	231	198	171	149	130	115	101
		Defl. = l/180	962	770	626	516	430	362	308	264	228	198	174	153	135
	3	Fb = 30,000	439	382	335	296	264	236	213	193	175	160	147	135	125
		Defl. = l/240	564	452	367	303	252	213	181	155	134	116	102	90	79
		Defl. = l/180	753	603	490	404	337	284	241	207	179	155	136	120	106
3C16	1	Fb = 24,000	383	330	288	253	224	200	179	162	147	134	122	112	104
		Defl. = l/240	378	302	246	203	169	142	121	104	90	78	68	60	53
		Defl. = l/180	504	403	328	270	225	190	161	138	119	104	91	80	71
	2	Fb = 24,000	367	319	279	246	218	196	176	159	144	132	121	111	102
		Defl. = l/240	909	728	592	488	407	343	291	250	216	188	164	145	128
		Defl. = l/180	1213	971	789	650	542	457	388	333	288	250	219	193	170
	3	Fb = 24,000	451	392	344	304	270	242	218	197	179	164	150	138	127
		Defl. = l/240	712	570	463	382	318	268	228	195	169	147	129	113	100
		Defl. = l/180	949	760	618	509	424	357	304	261	225	196	171	151	133

Minimum exterior bearing length is 2.5 inches.
Minimum interior bearing length is 5.0 inches.

35

Cable Design



Structural Assemblies

Structural Assembly Characteristics

- *Fitted with a wide variety of zinc- or resin-attached end terminations, including open and closed strand and wire rope sockets, bridge sockets, and anchor sockets*
- *Available with spiral strand or structural wire rope*
- *Provided prestretched, measured, striped, and proofloaded upon request*
- *Used in applications such as main cables, suspender and wind cables of suspension bridges; tower guys; cable stays; supports and suspenders for cable roof structures; anchor and mooring lines*

Spiral Strand

- Arrangement of wires laid helically around a center wire to produce a symmetrical cross section
- Recommended for use as a load-carrying tension member where bending and flexibility are not major requirements
- Offers a high strength-to-weight ratio, high modulus of elasticity, and a small diameter-per-unit strength
- Manufactured to meet ASTM Specification A586
- Available with Class A, B, or C galvanized coating weights in diameters up to 5-1/2"

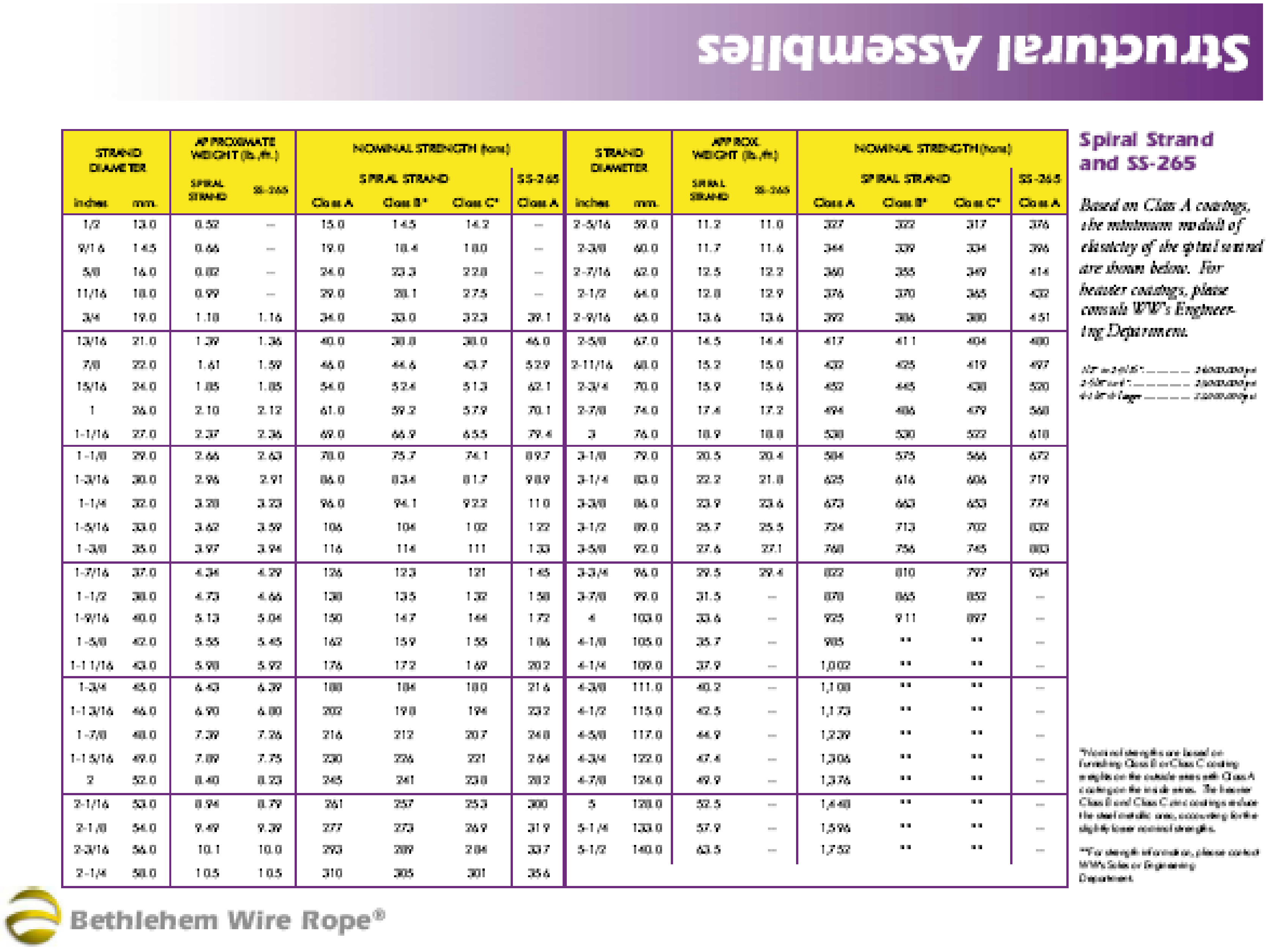
SS-265™

- High strength spiral strand with a nominal strength 15% higher than traditional spiral strand
- Manufactured to meet ASTM Specification A586
- Recommended for use in all spiral strand applications
- Decreases total weight of spiral strand system due to its higher strength-to-weight ratio
- Available with Class A galvanized coating weight in diameters through 3-3/4"

Structural Wire Rope

- Six strands laid helically around a core, such as another strand or another wire rope
- Recommended for use where bending ability is an important requirement
- Provides greater flexibility when compared with coarse strand constructions
- Manufactured to meet ASTM Specification A603
- Available with Class A, B, or C galvanized coating weights in diameters up to 7"

Bethlehem Wire Rope®



Structural Assemblies

Spiral Strand and SS-265

Based on Class A coatings, the minimum moduli of elasticity of the spiral strand are shown below. For heavier coatings, please consult WW's Engineering Department.

1/2" to 2-9/16" ------ 24,000,000 psi
2-5/8" [illegible] ------ 23,000,000 psi
[illegible] & larger ------ 22,000,000 psi

STRAND DIAMETER		APPROXIMATE WEIGHT (lb./ft.)		NOMINAL STRENGTH (tons)			
				SPIRAL STRAND			SS-265
inches	mm.	SPIRAL STRAND	SS-265	Class A	Class B*	Class C*	Class A
1/2	13.0	0.52	—	15.0	14.5	14.2	—
9/16	14.5	0.66	—	19.0	18.4	18.0	—
5/8	16.0	0.82	—	24.0	23.3	22.8	—
11/16	18.0	0.99	—	29.0	28.1	27.5	—
3/4	19.0	1.18	1.16	34.0	33.0	32.3	39.1
13/16	21.0	1.39	1.36	40.0	38.8	38.0	46.0
7/8	22.0	1.61	1.59	46.0	44.6	43.7	52.9
15/16	24.0	1.85	1.85	54.0	52.4	51.3	62.1
1	26.0	2.10	2.12	61.0	59.2	57.9	70.1
1-1/16	27.0	2.37	2.36	69.0	66.9	65.5	79.4
1-1/8	29.0	2.66	2.63	78.0	75.7	74.1	89.7
1-3/16	30.0	2.96	2.91	86.0	83.4	81.7	98.9
1-1/4	32.0	3.28	3.23	96.0	94.1	92.2	110
1-5/16	33.0	3.62	3.59	106	104	102	122
1-3/8	35.0	3.97	3.94	116	114	111	133
1-7/16	37.0	4.34	4.29	126	123	121	145
1-1/2	38.0	4.73	4.66	138	135	132	158
1-9/16	40.0	5.13	5.04	150	147	144	172
1-5/8	42.0	5.55	5.45	162	159	155	186
1-11/16	43.0	5.98	5.92	176	172	169	202
1-3/4	45.0	6.43	6.39	188	184	180	216
1-13/16	46.0	6.90	6.80	202	198	194	232
1-7/8	48.0	7.39	7.26	216	212	207	248
1-15/16	49.0	7.89	7.75	230	226	221	264
2	52.0	8.40	8.23	245	241	238	282
2-1/16	53.0	8.94	8.79	261	257	253	300
2-1/8	54.0	9.49	9.39	277	273	269	319
2-3/16	56.0	10.1	10.0	293	289	284	337
2-1/4	58.0	10.5	10.5	310	305	301	356
2-5/16	59.0	11.2	11.0	327	322	317	376
2-3/8	60.0	11.7	11.6	344	339	334	396
2-7/16	62.0	12.5	12.2	360	355	349	414
2-1/2	64.0	12.8	12.9	376	370	365	432
2-9/16	65.0	13.6	13.6	392	386	380	451
2-5/8	67.0	14.5	14.4	417	411	404	480
2-11/16	68.0	15.2	15.0	432	425	419	497
2-3/4	70.0	15.9	15.6	452	445	438	520
2-7/8	74.0	17.4	17.2	494	486	479	568
3	76.0	18.9	18.8	538	530	522	618
3-1/8	79.0	20.5	20.4	584	575	566	672
3-1/4	83.0	22.2	21.8	625	616	606	719
3-3/8	86.0	23.9	23.6	673	663	653	774
3-1/2	89.0	25.7	25.5	724	713	702	832
3-5/8	92.0	27.6	27.1	768	756	745	883
3-3/4	96.0	29.5	29.4	822	810	797	934
3-7/8	99.0	31.5	—	878	865	852	—
4	103.0	33.6	—	925	911	897	—
4-1/8	105.0	35.7	—	985	**	**	—
4-1/4	109.0	37.9	—	1,002	**	**	—
4-3/8	111.0	40.2	—	1,108	**	**	—
4-1/2	115.0	42.5	—	1,173	**	**	—
4-5/8	117.0	44.9	—	1,239	**	**	—
4-3/4	122.0	47.4	—	1,306	**	**	—
4-7/8	124.0	49.9	—	1,376	**	**	—
5	128.0	52.5	—	1,448	**	**	—
5-1/4	133.0	57.9	—	1,596	**	**	—
5-1/2	140.0	63.5	—	1,752	**	**	—

*Nominal strengths are based on furnishing Class B or Class C coating weights on the outside wires with Class A coatings on the inside wires. The heavier Class B and Class C zinc coatings reduce the steel metallic area, accounting for the slightly lower nominal strengths.

**For strength information, please contact WW's Sales or Engineering Department.

Bethlehem Wire Rope®

Preliminary Cable Sizing Example

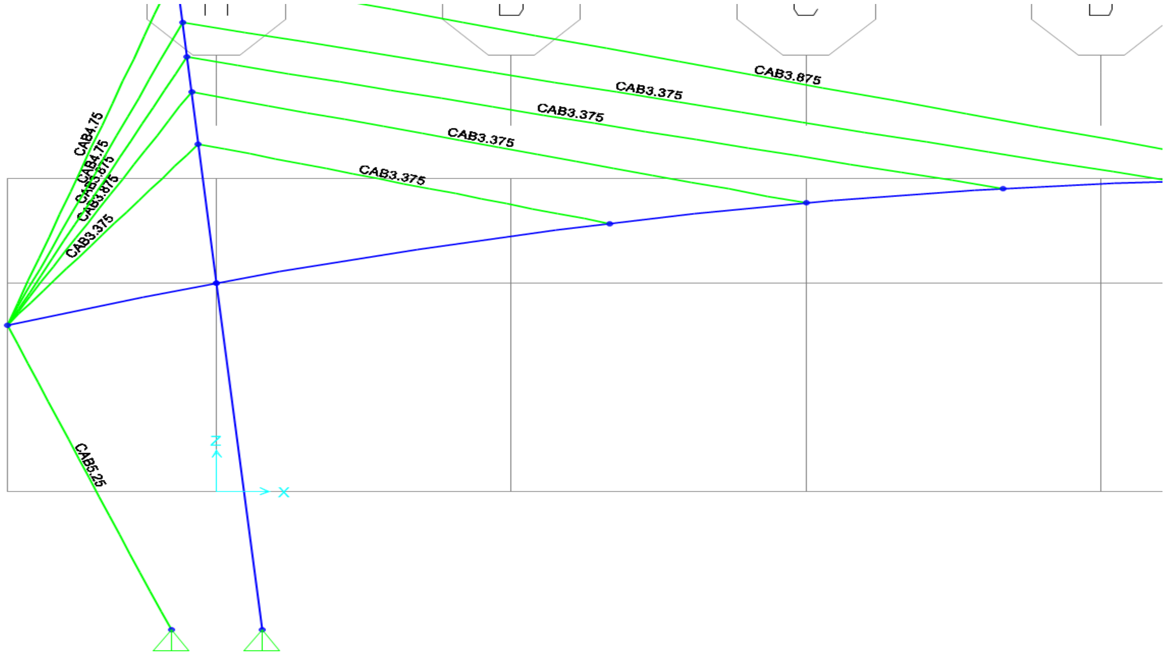
	T_1 = D+P	T_2 = D+S+P	T_3 = D+P+W	T_4 = D+P+S+W	$2.2T_1$	$2.2T_2$	$2.0T_3$	$2.0T_4$	S_d>? (kips)	S_d>? (tons)	2 Cables
1	2342	2871	1951	2486	5152.4	6316.2	3902	4972	6316.2	3158.1	1579.05
3	193	226	167	201	424.6	497.2	334	402	497.2	248.6	
4	135	167	109	141	297	367.4	218	282	367.4	183.7	
5	245	307	198	261	539	675.4	396	522	675.4	337.7	
6	146	183	117	154	321.2	402.6	234	308	402.6	201.3	
7	271	336	222	288	596.2	739.2	444	576	739.2	369.6	
8	152	192	122	162	334.4	422.4	244	324	422.4	211.2	
9	294	362	243	312	646.8	796.4	486	624	796.4	398.2	
10	162	204	131	174	356.4	448.8	262	348	448.8	224.4	
11	315	386	263	334	693	849.2	526	668	849.2	424.6	
12	176	220	144	188	387.2	484	288	376	484	242	
13	331	403	277	350	728.2	886.6	554	700	886.6	443.3	
14	190	236	157	202.5	418	519.2	314	405	519.2	259.6	
15	471	582	389	502	1036.2	1280.4	778	1004	1280.4	640.2	
16	201	249	167	215	443	547.8	334	430	547.8	273.9	
17	488	600	406	519	1073.6	1320	812	1038	1320	660	
18	214	264	179	229	470.8	580.8	358	458	580.8	290.4	
19	561	674	479	593	1234.2	1482.8	958	1186	1482.8	741.4	
20	343	424	285	367	754.6	932.8	570	734	932.8	466.4	

🟥	5.25
🟧	3.75
🟩	2.25
🟦	3

Preliminary Cable Pretensioning

# of cables	Cable	E (ksi)	Diameter (in)	Area (in^2)	P_D (kips)	P_L (kips)	P_{PRE} (kips)	$\sigma = P_{PRE}/A$	$\varepsilon = \sigma/E$
2	1	22000	5	43	2140	571	3500	80.84	-0.00367
1	3	22000	2	4	189	59	219	54.95	-0.00250
1	4	22000	2	4	123	58	152	38.23	-0.00174
1	5	22000	4	11	241	66	274	24.81	-0.00113
1	6	22000	2	4	139	56	167	41.95	-0.00191
1	7	22000	4	11	261	69	296	26.76	-0.00122
1	8	22000	2	4	152	49	176	44.32	-0.00201
1	9	22000	4	11	278	74	315	28.52	-0.00130
1	10	22000	2	4	165	45	187	46.99	-0.00214
1	11	22000	4	11	292	77	331	29.92	-0.00136
1	12	22000	2	4	177	46	200	50.30	-0.00229
1	13	22000	4	11	303	80	343	31.06	-0.00141
1	14	22000	2	4	188	49	212	53.39	-0.00243
1	15	22000	3	7	424	112	480	67.93	-0.00309
1	16	22000	2	4	197	51	223	55.96	-0.00254
1	17	22000	3	7	433	114	490	69.38	-0.00315
1	18	22000	2	4	206	53	233	58.61	-0.00266
1	19	22000	3	7	488	128	552	78.11	-0.00355
1	20	22000	4	11	332	86	375	33.99	-0.00155
20									

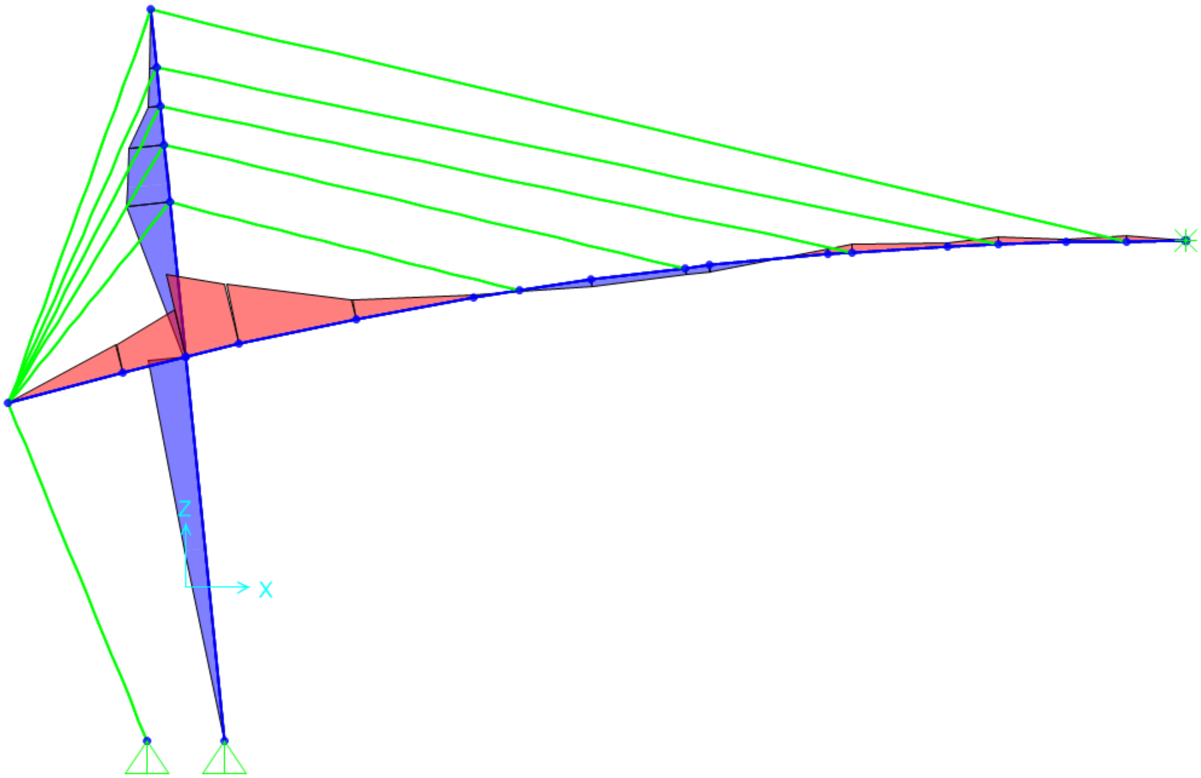
Final Cable Sizes in SAP2000



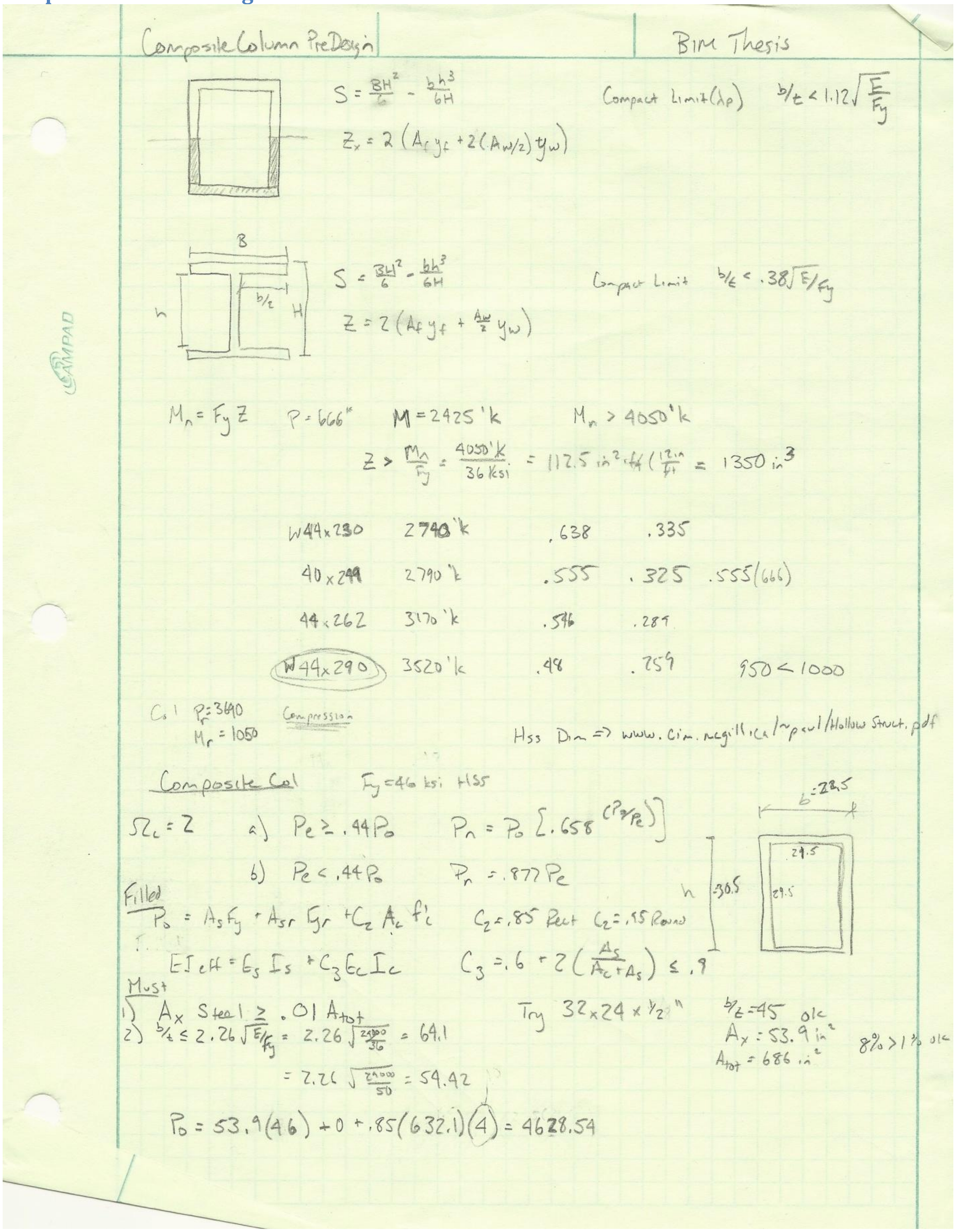
Final Maximum Deflection of Roof Under All Load Cases

Load Case	U3 (in)	R2 (rad)
D+S (Flat)	-7.31	.0055
D+S (Unbal)	-6.88	.0035
D+.75L+.75S (Flat)	-6.15	-.012
D+.75L+.75S (Unbal)	-5.96	-.014
D+.6W	-.69	-.0003
D+.75(.6W)+.75S (Flat)	-5.3	.003
D+.75(.6W)+.75S (Unbal)	-4.21	.0017
.6D+.6W	7.53	-.0067

Sample Moment Diagram Under D+S Loading



Composite Column Design



Composite Column PreDesign | BIM Thesis

$S = \frac{BH^2}{6} - \frac{bh^3}{6H}$

$Z_x = 2\left(A_f y_f + 2(A_w/2) y_w\right)$

Compact Limit (λ_p) $b/t < 1.12\sqrt{\frac{E}{F_y}}$

$S = \frac{BH^2}{6} - \frac{bh^3}{6H}$

$Z = 2\left(A_f y_f + \frac{A_w}{2} y_w\right)$

Compact Limit $b/t < .38\sqrt{E/F_y}$

$M_n = F_y Z$ $P = 666^k$ $M = 2425'k$ $M_n > 4050'k$

$Z > \frac{M_n}{F_y} = \frac{4050'k}{36\,ksi} = 112.5\,in^2 \cdot ft\,(\frac{12\,in}{ft} = 1350\,in^3$

W44x230	2740'k	.638	.335	
40x249	2790'k	.555	.325	.555(666)
44x262	3170'k	.546	.289	
W44x290	3520'k	.48	.259	950 < 1000

Col $P_r = 3640$
$M_r = 1050$
Compression

Hss Dim => www.cim.mcgill.ca/~paul/HollowStruct.pdf

Composite Col $F_y = 46$ ksi HSS

$\Omega_c = 2$ a) $P_e \geq .44 P_o$ $P_n = P_o\left[.658^{(P_o/P_e)}\right]$

b) $P_e < .44 P_o$ $P_n = .877 P_e$

Filled

$P_o = A_s F_y + A_{sr} F_{yr} + C_2 A_c f'_c$ $C_2 = .85$ Rect $C_2 = .95$ Round

$EI_{eff} = E_s I_s + C_3 E_c I_c$ $C_3 = .6 + 2\left(\frac{A_s}{A_c + A_s}\right) \leq .9$

Must
1) A_x Steel $\geq .01 A_{tot}$
2) $b/t \leq 2.26\sqrt{E/F_y} = 2.26\sqrt{\frac{29000}{36}} = 64.1$

$= 2.26\sqrt{\frac{29000}{50}} = 54.42$

Try 32x24x½"

$b/t = 45$ ok
$A_x = 53.9\,in^2$
$A_{tot} = 686\,in^2$
8% > 1% ok

$P_o = 53.9(46) + 0 + .85(632.1)(4) = 4628.54$

Composite Column Pre Design | $w_c^{1.5}\sqrt{f'_c} = 3.54 \times 10^8$ | BIM Thesis

$$EI_{eff} = 29000(9880) + \overset{\text{conservative}}{.757}(5700\sqrt{4})\left(\frac{29.5(21.5^3)}{12}\right) = 2.39 \times 10^8$$

$$C_3 = .6 + 2\left(\frac{53.9}{686}\right) = .757$$

$$P_e = \frac{\pi^2(EI_{eff})}{(KL)^2} = \frac{\pi^2(3.54\times10^8)}{(360^2)} = 26959$$

$P_e \geq .44P_o$ $\quad P_n = 4628\left[.658^{\frac{4628}{26959}}\right] = 4307^k \quad \Omega = 2.0$

$P_{all} = 2153^k$

if $f'_c = 10^{ksi}$

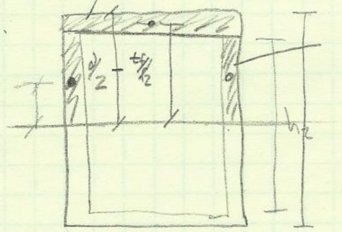
$P_o = 7852.25$ if $f'_c = 10^{ksi}$ $\quad EI_{eff} = \overset{21.5}{4.888} \times 10^8$

$P_e = 37224 \quad P_n = 7852.25\left[.658^{\frac{7852.25}{37224}}\right) = 7188^k \quad \Omega = 2.0$

$P_{All} = 3594$

$P_{All} = 3795$ if $KL = 20'$

$A = bt_f \cdot \frac{(d-t_f)}{2}$



$A = h_2/2 \cdot t_w\left(\cdot \frac{h_2}{4}\right)$

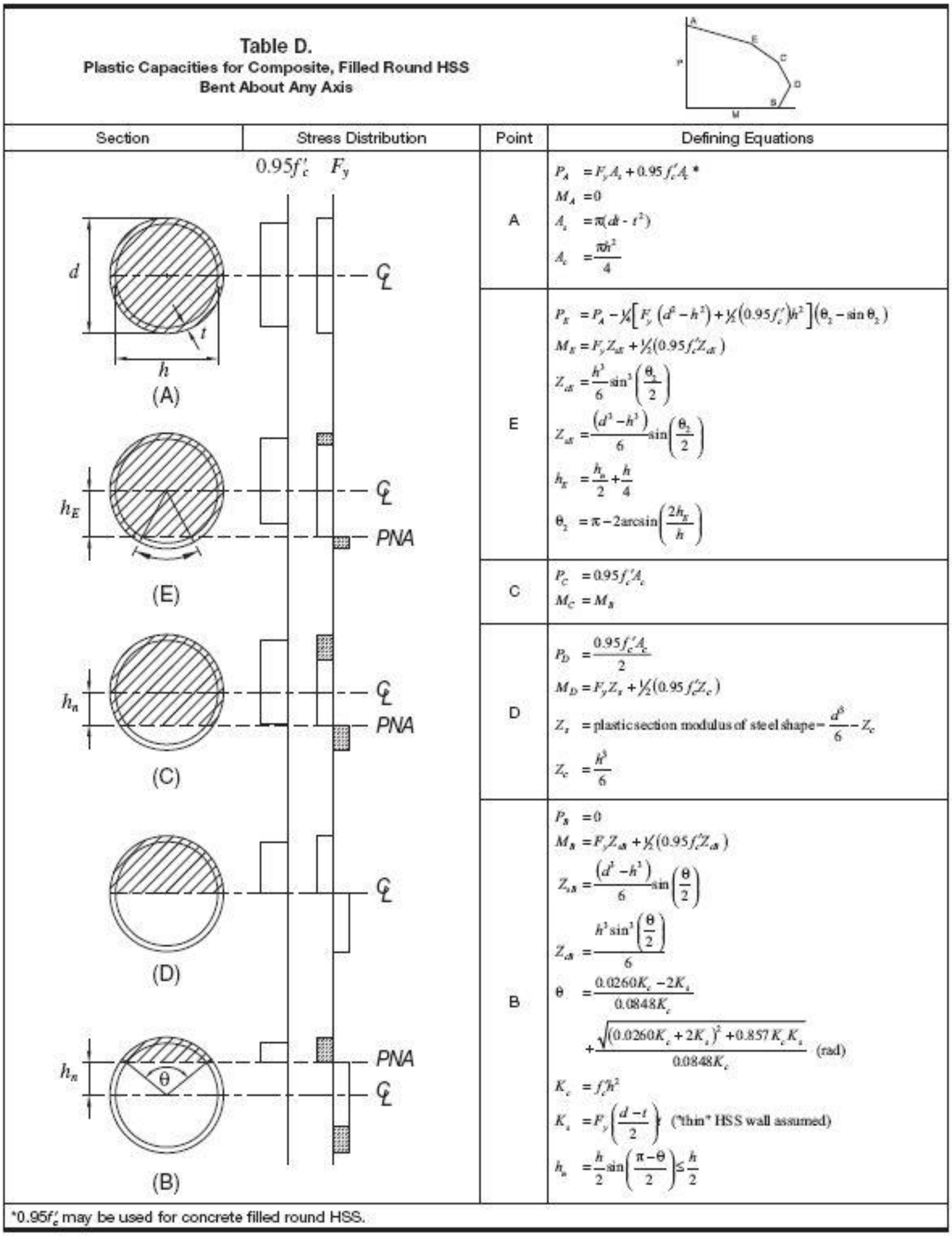


Table D.
Plastic Capacities for Composite, Filled Round HSS Bent About Any Axis

Section	Stress Distribution	Point	Defining Equations
(A)		A	$P_A = F_y A_s + 0.95 f'_c A_c$ * $M_A = 0$ $A_s = \pi(dt - t^2)$ $A_c = \frac{\pi h^2}{4}$
(E)		E	$P_E = P_A - \frac{1}{4}\left[F_y\left(d^2 - h^2\right) + \frac{1}{2}\left(0.95 f'_c\right)h^2\right]\left(\theta_2 - \sin\theta_2\right)$ $M_E = F_y Z_{sE} + \frac{1}{2}(0.95 f'_c Z_{cE})$ $Z_{cE} = \frac{h^3}{6}\sin^3\left(\frac{\theta_2}{2}\right)$ $Z_{sE} = \frac{\left(d^3 - h^3\right)}{6}\sin\left(\frac{\theta_2}{2}\right)$ $h_E = \frac{h_n}{2} + \frac{h}{4}$ $\theta_2 = \pi - 2\arcsin\left(\frac{2h_E}{h}\right)$
(C)		C	$P_C = 0.95 f'_c A_c$ $M_C = M_B$
(D)		D	$P_D = \frac{0.95 f'_c A_c}{2}$ $M_D = F_y Z_s + \frac{1}{2}(0.95 f'_c Z_c)$ Z_s = plastic section modulus of steel shape $= \frac{d^3}{6} - Z_c$ $Z_c = \frac{h^3}{6}$
(B)		B	$P_B = 0$ $M_B = F_y Z_{sB} + \frac{1}{2}(0.95 f'_c Z_{cB})$ $Z_{sB} = \frac{\left(d^3 - h^3\right)}{6}\sin\left(\frac{\theta}{2}\right)$ $Z_{cB} = \frac{h^3\sin^3\left(\frac{\theta}{2}\right)}{6}$ $\theta = \frac{0.0260K_c - 2K_s}{0.0848K_c} + \frac{\sqrt{(0.0260K_c + 2K_s)^2 + 0.857K_cK_s}}{0.0848K_c}$ (rad) $K_c = f'_c h^2$ $K_s = F_y\left(\frac{d-t}{2}\right)t$ ("thin" HSS wall assumed) $h_n = \frac{h}{2}\sin\left(\frac{\pi - \theta}{2}\right) \le \frac{h}{2}$

*$0.95f'_c$ may be used for concrete filled round HSS.

Plastic Capacities for Composite, Filled Round HSS Bent About Any Axis

Properties

A_s=	162.5774198	in^2
d=	36	in
t_w=	1.5	in
$h=d-2t_w$=	33	in
A_c=	855.2985999	in^2
F_y=	50	ksi
f'_c=	8	ksi
E_s=	29000	ksi
I_s=	24234.19664	in^4
I_c=	58213.76096	in^4

Limitations:	
$A_s>.01A_{tot}$	0.15972
$D/t<0.15(E/F_y)$	24

Point	Defining Equations		Units
A	$P_A= P_o= A_sF_y+A_c(.95f'_c)$=	14629.14035	k
	$M_A= 0$ =	0	k-in
E	$P_E= P_A -.25[F_y(d^2-h^2)+.5(.95f'_c)h^2](\Theta_2-\sin\Theta_2)$=	12571.09094	k
	$M_E= F_yZ_{sE}+.5(.95f'_cZ_{cE})$ =	71095.71702	k-in
	$Z_{cE}= h^3/6*\sin^3(\Theta_2/2)$ =	2109.356203	in^3
	$Z_{sE}=(d^3-h^3)/6*\sin(\Theta_2/2)$ =	1261.603269	in^3
	$h_E= h_n/2+d/4$ =	11.68241678	in
	$\Theta_2= \Pi-2\arcsin(2h_E/h)$	1.568196788	rad
C	$P_C= A_c(.95f'_c)$ =	6500.26936	k
	$M_C = M_B$ =	105995.0011	k-in
D	$P_D= .95f'_cA_c/2$ =	3250.13468	k
	$M_D= Z_sF_y + .5Z_c(.95f'_c)$ =	112085.1	k-in
	$Z_s= d^3/6- Z_c$ =	1786.5	in^3
	$Z_c= h^3/6$ =	5989.5	in^3
B	$P_B = 0$ =	0	k
	$M_B= F_yZ_{sB} + .5(.95f'_cZ_{cB})$ =	105995.0011	k-in
	$Z_{sB}= (d^3-h^3)/6*\sin(\Theta/2)$ =	1689.43124	in^3
	$Z_{cB}= h^3/6*\sin(\Theta/2)$ =	5664.062923	in^3

	$\Theta=(.0260K_c-2K_s)/.0848K_c+ [(.0260K_c+2K_s)2+.857K_cK_s]^{.5}/.0848K_c =$	2.479270097	rad
	$K_c = f'_ch^2$	8712	k
	$K_s = F_y[(d-t)/2]t$	1293.75	k
	$h_n = (h/2)\sin[(\Pi-\Theta)/2] \leq h/2 =$	5.364833564	in

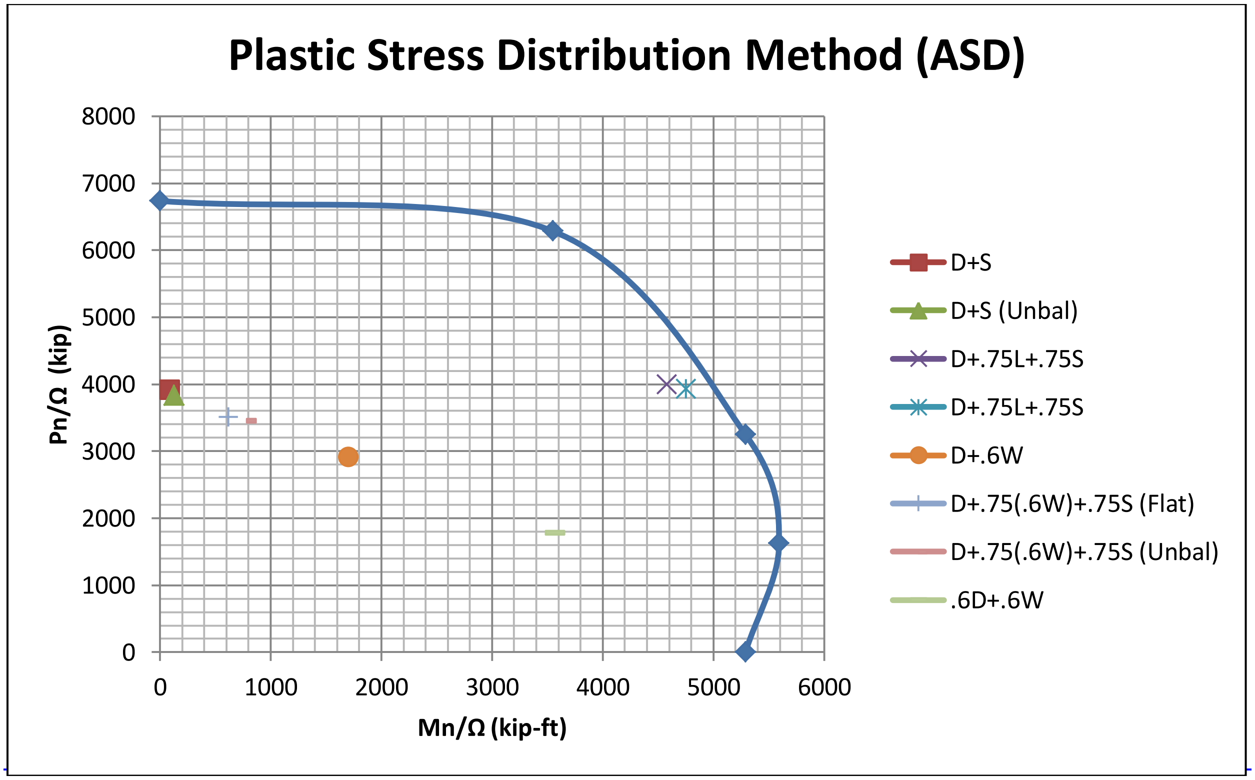
Compressive Strength Check

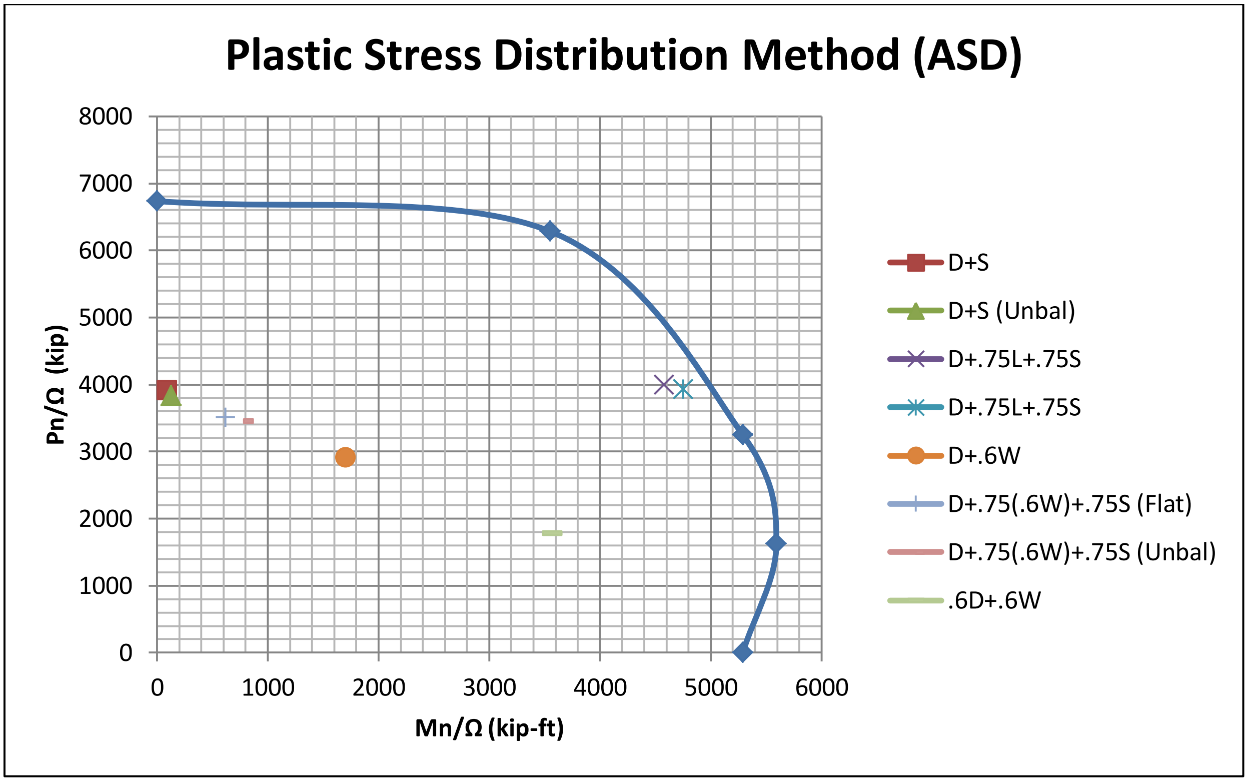
$E_s=$	29000	ksi
$E_c= w_c^{1.5}(f'_c)^{.5})=$	5196.152423	ksi
$w_c=$	150	lb/ft^3
$K=$	1	
$L=$	360	in
$EI_{eff}= E_sI_s + C_3E_cI_c =$	975030520.2	in^4
$C3= .6 + 2(As/Atot) \leq .9 =$	0.9	
$P_e= \Pi^2(EI_{eff})/(KL)^2 =$	74252.82032	
$P_o=$	14629.14035	k
$.44P_o=$	6436.821754	k
(a) When $P_e \geq .44P_o$	74252.82032	k
$P_n = P_o (.658^{(Po/Pe)}) =$	13471.19243	k
(b) When $P_e < 0.44P_o$	74252.82032	k
$P_n= .877P_e$	65119.72342	k

Load Case	P (k)	M (k-ft)
D+S (Flat)	3908	94
D+S (Unbal)	3831	124
D+.75L+.75S (Flat)	3997	4580
D+.75L+.75S (Unbal)	3934	4751
D+.6W	2905	1704
D+.75(.6W)+.75S (Flat)	3507	618
D+.75(.6W)+.75S (Unbal)	3448	784
.6D+.6W	1783	3575

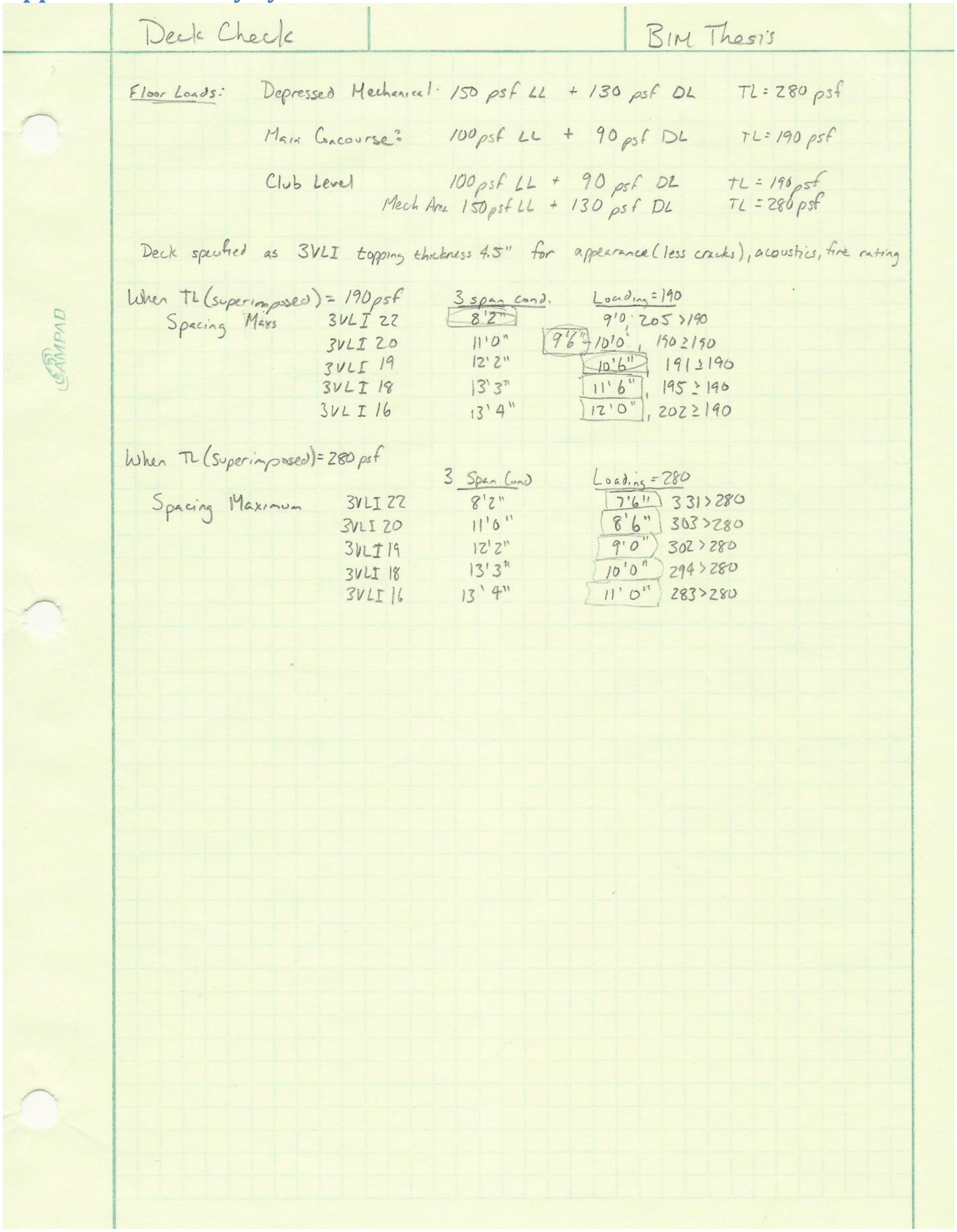
Factors	
Ωc=	2
Ωb=	1.67
Φc=	0.75
Φb=	0.9

Interaction Diagram						
Point	**Mn**	**Pn**	**ΦMn**	**ΦPn**	**Mn/Ω**	**Pn/Ω**
A	0	13471.19	0	10103.39	0	6735.596
E	5924.643	12571.09	5332.179	9428.318	3547.69	6285.545
C	8832.917	6500.269	7949.625	4875.202	5289.172	3250.135
D	9340.425	3250.135	8406.383	2437.601	5593.069	1625.067
B	8832.917	0	7949.625	0	5289.172	0




Plastic Stress Distribution Method (ASD)
Pn/Ω (kip)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
1000
2000
3000
4000
5000
6000
Mn/Ω (kip-ft)
D+S
D+S (Unbal)
D+.75L+.75S
D+.75L+.75S
D+.6W
D+.75(.6W)+.75S (Flat)
D+.75(.6W)+.75S (Unbal)
.6D+.6W

Appendix D. Gravity System



Deck Check

BIM Thesis

Floor Loads: Depressed Mechanical: 150 psf LL + 130 psf DL TL = 280 psf

Main Concourse: 100 psf LL + 90 psf DL TL = 190 psf

Club Level 100 psf LL + 90 psf DL TL = 190 psf

Mech Area 150 psf LL + 130 psf DL TL = 280 psf

Deck specified as 3VLI topping thickness 4.5" for appearance (less cracks), acoustics, fire rating

When TL (superimposed) = 190 psf

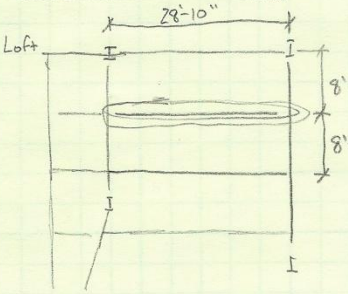
		3 span cond.	Loading = 190
Spacing Maxs	3VLI 22	8'2"	9'0; 205 > 190
	3VLI 20	11'0"	9'6" 10'0", 190 ≥ 190
	3VLI 19	12'2"	10'6", 191 ≥ 190
	3VLI 18	13'3"	11'6", 195 ≥ 190
	3VLI 16	13'4"	12'0", 202 ≥ 190

When TL (superimposed) = 280 psf

		3 Span Cond	Loading = 280
Spacing Maximum	3VLI 22	8'2"	7'6" 331 > 280
	3VLI 20	11'0"	8'6" 303 > 280
	3VLI 19	12'2"	9'0" 302 > 280
	3VLI 18	13'3"	10'0" 294 > 280
	3VLI 16	13'4"	11'0" 283 > 280

Gravity Check BIM Thesis

Composite Beam Design



LL = 150 psf (Mech Area) Constr Loads = 50 psf

DL = 100 psf

Deck: 3VLI 19 w/ 4.5" topping : 75 psf + 15 psf MEP + 10 psf misc

$A_T = (8.1667)(28.8) = 235\text{ sf} < 400\text{ sf}$ No Reduction

$W_L = 150(8.1667) = \underline{1.225}\ ^{k}/_{ft}$ $w_u = 1.2(1.225) + 1.6(.817)$

$W_D = 100(8.1667) = \underline{.817}\ ^{k}/_{ft}$ $w_u = \underline{2.78\ ^{k}/_{ft}}$

$M_u = \frac{w_u L^2}{8} = \frac{2.78(28.8)^2}{8} = 288\ 'k$ $V_u = \frac{w_u l}{2} = \frac{2.78(28.8)}{2} = 40^k$

$\Delta_{LL} = \frac{l}{360} = \frac{28.8(12)}{360} = .96"$ $\Delta_{wc} = \frac{l}{240} = \frac{28.8(12)}{240} = 1.44"$

$b_{eff} \leq 2\left(\frac{28.8(12)}{84}\right) = \boxed{86"}$

$2\left(\frac{8.1667(12)}{2}\right) = 98"$

Composite Design Assume a = 1" Y2 = 7.5 - ½" = 7"

Try 18x35 (From RAM) $\phi M_n = 382$ $\Sigma Q_n = 129$ $a = \frac{\Sigma Q_n}{.85 f'_c b_{eff}} = \frac{129}{.85(4)(86)} = .44" < 1"$ ok

$\frac{\Sigma Q_n}{14.6} = \frac{129}{14.6} = (8.83)(2) = 20\ ^{studs}/_{bm} < 28.8$

$\frac{129}{17.2} = (7.5)(2) = 15 = 16\ ^{studs}/_{bm}$

Unshored Strength: $\phi_b M_p = 249\ 'k$ $w_u = 1.4(75)(8.1667) + 1.4(35) = 907\ ^{lbs}/_{ft}$

$w_u = 1.2[(75)(8.1667) + 35) + 1.6(50)(8.1667) = \underline{1.43\ ^{k}/_{ft}}$

$M_u = \frac{1.43(28.8)^2}{8} = 148'k < 249'k$ ok ✓

Wet Conc. Deflection $W_{wc} = 75(8.2) + 35 = .650^{klf}$ $I_{LB} = 1030\text{ in}^4$

$\Delta_{wc} = \frac{5(.650)(28.8)^4(1728)}{384(29000)(1030)} = .34" < 1.44"$ ok

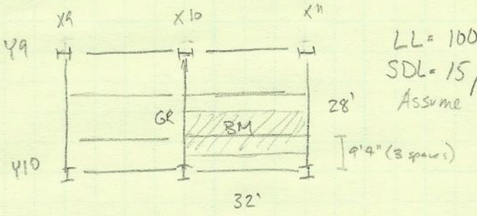
$\boxed{18\text{x}35 \text{ w/ } 16 \text{ studs}}$ ok RAM ⇒ 18x35 w/ 44 studs → More Load Accounted in RAM for Unknown Reason

Gravity Check

BIM Thesis

Beam Spot Check

Concourse level: Between X-9, X-10, X-11 + Y-9, Y-10



LL = 100 psf
SDL = 15 psf
Assume Composite Deck of 2" topping concrete ⇒ 40psf
DL = 55psf

$\Delta_{LL} \leq \frac{\ell}{360} = \frac{32(12)}{360} = 1.07''$

$\Delta_{TL} \leq \frac{\ell}{240} = \frac{32(12)}{240} = 1.6''$

Live: $100(9.33) = 933\ ^{lb}/_{ft} = w_L$

Dead: $55(9.33) = 513.15\ ^{lb}/_{ft} = w_D$

$W_u = 1.2(513.15) + 1.6(933) = 2.109\ ^{K}/_{ft}$

$M_u = \frac{w_u \ell^2}{8} = \frac{(2.109)(32)^2}{8} = 270\ 'k$

$V_u = \frac{w_u \ell}{2} = \frac{2.109(32)}{2} = 34^{K}$

$\Delta_{LL} \leq \frac{L}{360} = \frac{32(12)}{360} = \frac{5 w_L \ell^4}{384 EI} = \frac{5(933)(32^4)(1728)}{384(29000) I_x (1000)}$ $I_x \geq 712\ in^4$

$\Delta_{TL} \leq \frac{L}{240} = \frac{32(12)}{240} = \frac{5(1.446)(32^4)(1728)}{384(29000) I}$ $I_x \geq 735\ in^4 \leftarrow$ controls   use W21x44 non composite

Composite: Assume $f'c = 4^{ksi}$ $a = 1''$ $a = \frac{\Sigma Q_n}{b_{eff}\ .85(f'c)}$

$Y2 = 4 - \frac{1}{2} = 3.5$

$b_{eff} \leq \frac{32(12)}{8} = \boxed{48''}$

$b_{eff} \leq \frac{1}{2}(9.33)(12) = 56''$

W18x35 $\Sigma Q_n = 129$ $\frac{129}{17.2} = 7.5(2) = 16$ stud/bm

$a = \frac{129}{48(.85)(4)} = .79'' < 1''$ ok

Check Unshored strength: $w_u = 1.4(40)(9.33) + 1.4(35) = 571.5$ plf

$w_u = 1.2[(40)(9.33) + 35] + 1.6(20)(9.33) = 788.4$ plf

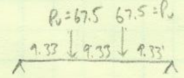
$M_u = \frac{(.788)(32)^2}{8} = 101\ 'k < 249$ ok

Wet Conc. Deflection = $W_{wc} = 40(9.33) = \underbrace{.373}.2$ klf $\Delta_{wc} = \frac{5(.373)(32^4)(1728)}{384(29000)(510)} = .595'' < 1.6''$ ok

Check LL Defl : $W_{LL} = .933\ ^{k}/_{ft}$ $I_{Lb} = 825$ $\Delta_{LL} = \frac{5(.933)(32^4)(1728)}{384(29000)(825)} = .92'' < 1.07''$ ok

- Possibly a bit conservative but ok

Check Girder



$M_u = P_u a = 67.5(9.33) = 630\ 'k$ W24x62

Assume $a = 1''$ $Y2 = 3.5$ $\Sigma Q_n = 228$ $a = \frac{228}{.85(4)(42)} = 1.59$ can't assume a = 1   try $a = 2'$

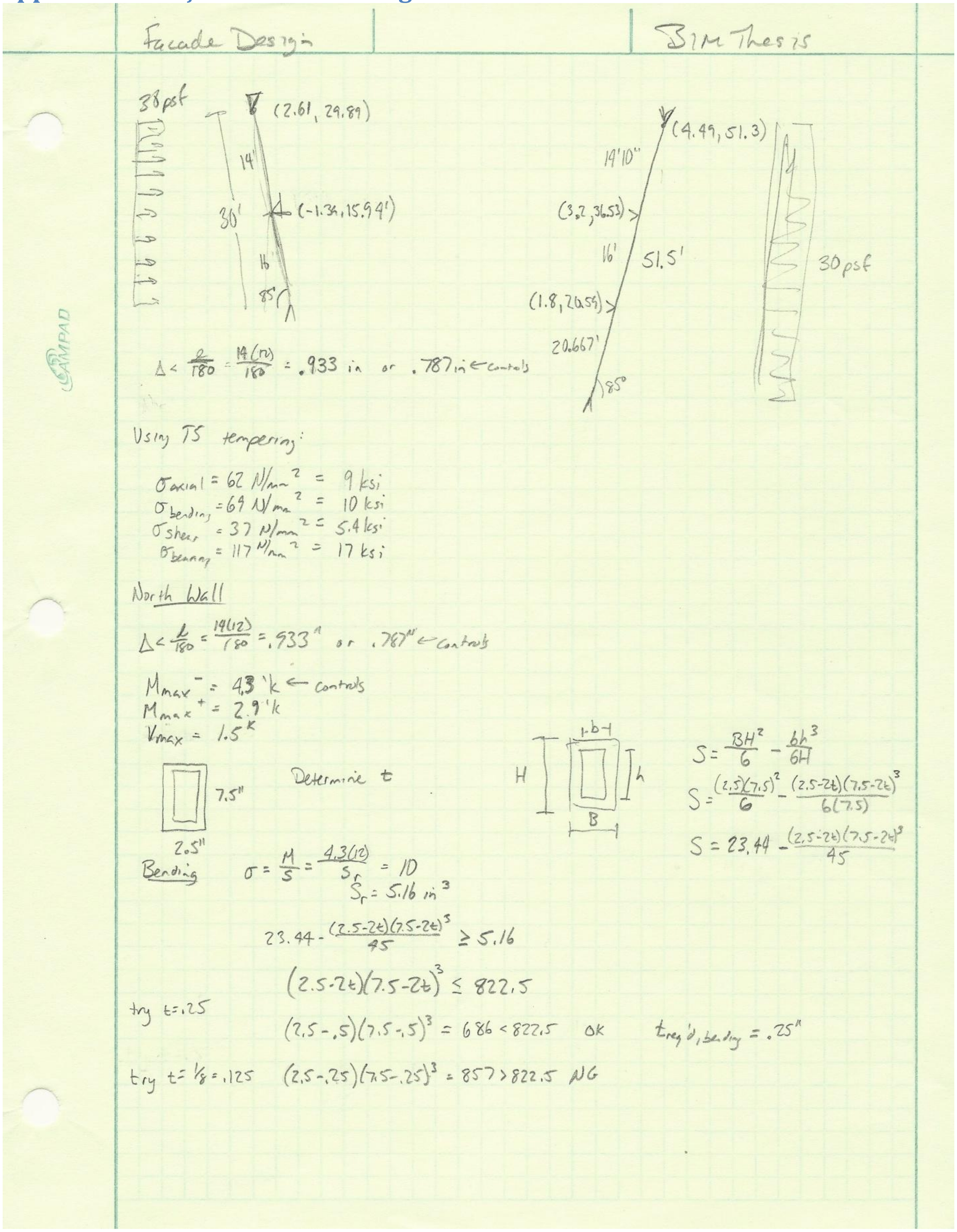
$b_{eff} \leq \frac{28(12)}{8} = 42''$ So $Y2 = 3''$ $M = 784 > 630$ ok

Check Unshored: $P_u = [1.2((40)(9.33) + 62) + 1.6(20)(9.33)]32 = 26.26^{K}$ $M_u = 245 < 574$ ok

Check LL Defl: $\Delta_{LL} = \frac{P_L L^3 (1728)}{28(E)(I_{Lb})} = \frac{(29.86)(28)^3(1728)}{28(29000)(2360)} = .59'' \leq .933''$ OK

$P_L = 29.86^{K}$ $\Delta_{LL} \leq \frac{\ell}{360} = \frac{28(12)}{360} = .93''$

Appendix E. Façade Mullion Design



Facade Design

BIM Thesis

$\Delta < \frac{l}{180} = \frac{14(12)}{180} = .933$ in or $.787$ in ← controls

Using TS tempering:

$\sigma_{axial} = 62\ N/mm^2 = 9$ ksi
$\sigma_{bending} = 69\ N/mm^2 = 10$ ksi
$\sigma_{shear} = 37\ N/mm^2 = 5.4$ ksi
$\sigma_{bearing} = 117\ N/mm^2 = 17$ ksi

North Wall

$\Delta < \frac{l}{180} = \frac{14(12)}{180} = .933"$ or $.787"$ ← controls

$M_{max}^{-} = 4.3\ 'k$ ← controls
$M_{max}^{+} = 2.9\ 'k$
$V_{max} = 1.5^{k}$

Determine t

$$S = \frac{BH^2}{6} - \frac{bh^3}{6H}$$

$$S = \frac{(2.5)(7.5)^2}{6} - \frac{(2.5-2t)(7.5-2t)^3}{6(7.5)}$$

$$S = 23.44 - \frac{(2.5-2t)(7.5-2t)^3}{45}$$

Bending $\sigma = \frac{M}{S} = \frac{4.3(12)}{S_r} = 10$

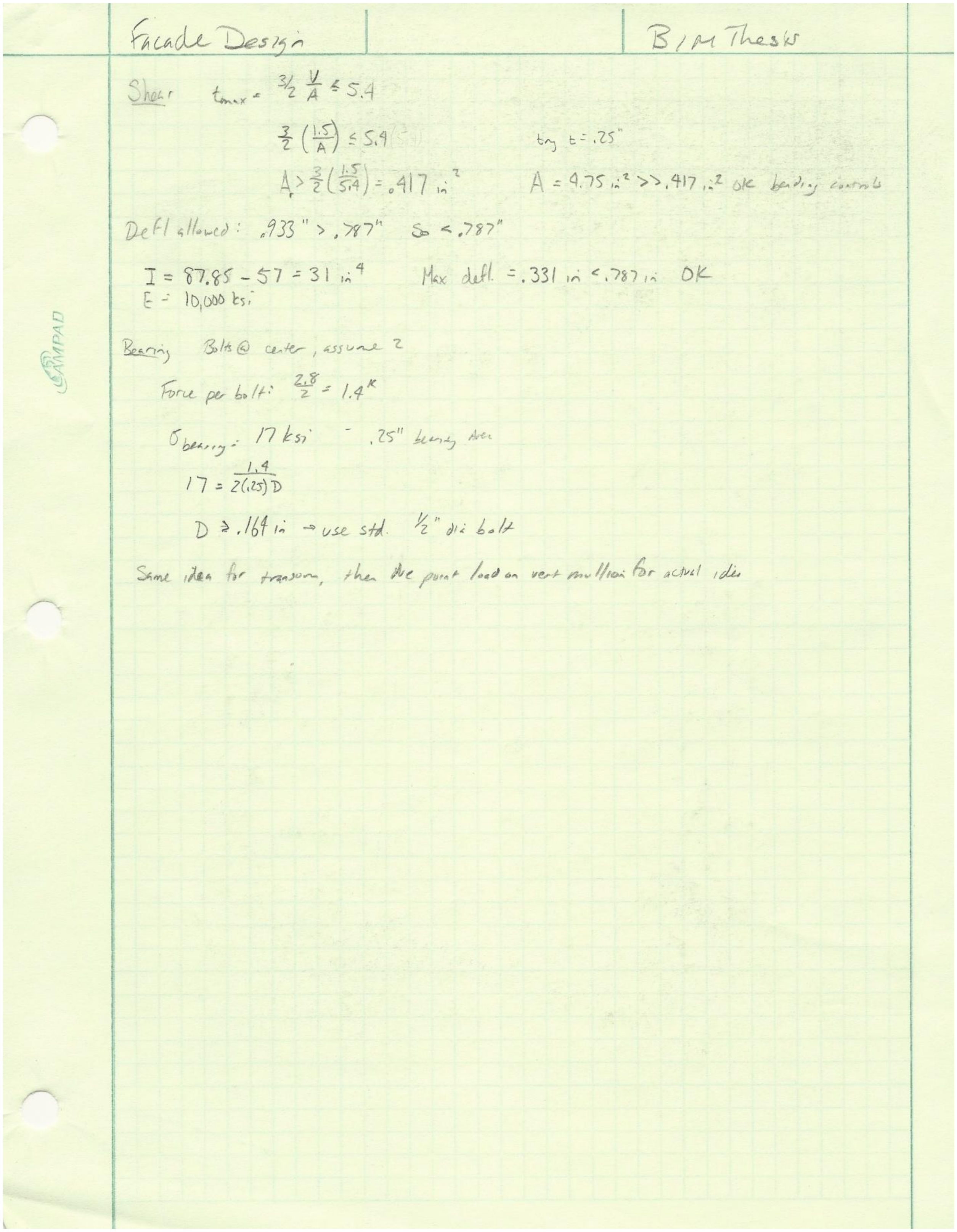
$S_r = 5.16\ in^3$

$$23.44 - \frac{(2.5-2t)(7.5-2t)^3}{45} \geq 5.16$$

$$(2.5-2t)(7.5-2t)^3 \leq 822.5$$

try $t = .25$ $(2.5-.5)(7.5-.5)^3 = 686 < 822.5$ OK $t_{req'd, bending} = .25"$

try $t = 1/8 = .125$ $(2.5-.25)(7.5-.25)^3 = 857 > 822.5$ NG



Facade Design | | BIM Thesis

Shear $t_{max} = \frac{3}{2}\frac{V}{A} \leq 5.4$

$\frac{3}{2}\left(\frac{1.5}{A}\right) \leq 5.4$ try t = .25"

$A_r > \frac{3}{2}\left(\frac{1.5}{5.4}\right) = .417 \text{ in}^2$ $A = 4.75 \text{ in}^2 >> .417 \text{ in}^2$ OK bending controls

Defl allowed: .933" > .787" So < .787"

$I = 87.85 - 57 = 31 \text{ in}^4$ Max defl. = .331 in < .787 in OK
E = 10,000 ksi

Bearing Bolts @ center, assume 2

Force per bolt: $\frac{2.8}{2} = 1.4^K$

$\sigma_{bearing}$: 17 ksi - .25" bearing Area

$17 = \frac{1.4}{2(.25)D}$

D ≥ .164 in → use std. ½" dia bolt

Same idea for transom, then the point load on vert mullion for actual idea

Appendix F. Community Rink Roof Design

BOWSTRING JOIST (SPBW) TABLES

The following weight tables are representative of SP-Series joist designs for Bowstring Joists with parameters shown in the diagram below. The maximum allowable Live Load deflection is L/240 for a Live Load equal to 75 percent of the Total Load listed in the table. The tables also give bridging requirements per Section 904.5(d), the required seat depth for the given profile, as well as the estimated self-weight in pounds per linear foot. This catalog provides two design examples for reference and clarification on design issues. The following tables are not representative of any limits or constraints on design or constructability by NMBS. For further information, please contact your nearest NMBS representative or visit www.newmill.com.

ALL TABLES ARE BASED ON ASD

BOWSTRING JOIST (SPBW)

Bowstring Joist Design

Design Criteria:

Design Code:	IBC 2009, ASCE 7-10	Clear Span:	110	ft
Project Location:	State College, PA	Joist Span:	110	ft
Load Combination:	ASD	Spacing:	11.5	ft
Building Class:	III	Radius:	332	ft
Importance Factor:	1.1	Exposure C		

Loading:

Roof Dead Load (D):	30	psf	inc self wt (5), MEP (15), roofing (10)
Roof Live Load (L_r):	34	psf	
Roof Net Uplift (UL):	20	psf	
	230	plf	

Snow Load:

Ground Snow	p_g=	40.0	psf
	C_e=	1.0	
	C_t=	1.1	
	C_s=	1.0	
Flat Roof Snow Load:	p_f=.7$C_eC_tIp_g$=	33.9	psf
Sloped Snow Load:	p_s=C_sp_f =	33.9	psf

Profile Projection Ratio, R_{pr}

R_{pr} = ((2*radius*pi)/(span*180^o))*sin^{-1}(span/(2*radius))=	R_{pr}=	1.005

Linear Loading:

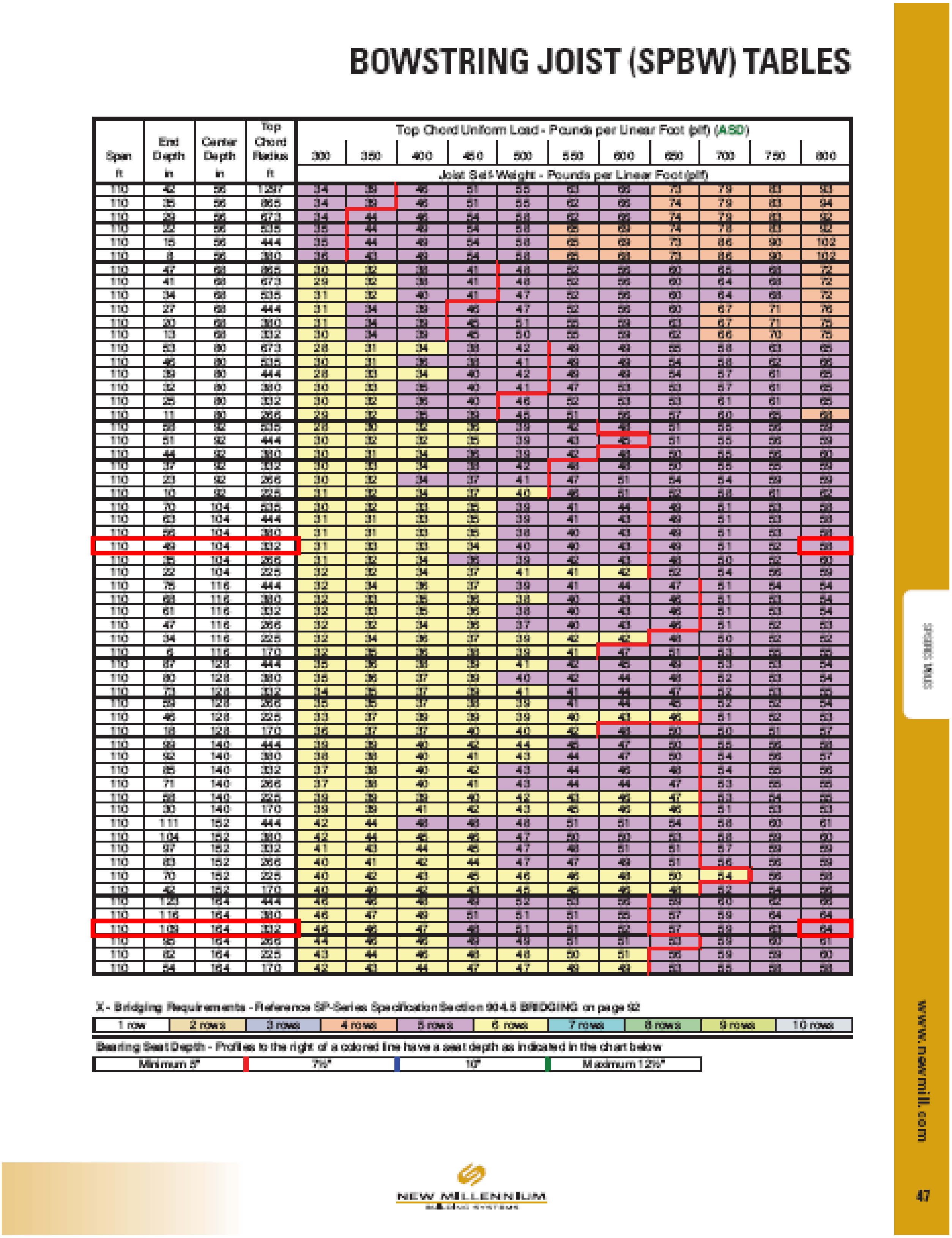
Adjusted Dead Load=	D*R_{pr}*joist spacing=	346.7	plf
Roof Live Load =	L_r*joist spacing=	391.0	plf
Uniform Snow Load=	S*joist spacing=	389.6	plf
Total Uniform Load=	TL= D+(L_r or S)=	737.7	plf

Uniform Snow Load Case	TL=	737.7	plf	
TL Check	W_{eqV-TL} = W_{eqM-TL} =	737.7	plf	
LL Check	W_{eqM-LL} =	391.0	plf	Less than 600 plf (.75*800), LL Deflection OK

Unbalanced Snow Load Case						
Windward Side:						
No Snow Load per Figure 7.3 Case 1 with the slope at the eave < 30 degrees						
Leeward Side:						
Snow Load S=	$2*p_f*C_s/C_e$=	67.8	psf			
	S*Spacing=	779.2	plf	at eave		
Snow Load S=	$.5*p_f$=	16.9	psf			
	S*Spacing=	194.8	plf	at crown		
For simplicity, the equivalent uniform load is calculated using a simple beam with the leeward unbalanced snow at the inside face of the wall and not at the eave or end of extension. This is slightly conservative and has negligible effect on the resulting maximum moment						
	V_{ub}=	22400.0	lbs			
	M_{ub}=	364200.0	lbs-ft			
W_{eqV-TL}=	$2*V_{ub}/L$=	407.3	plf			
W_{eqM-TL}=	$8*M_{ub}/L2$=	240.8	plf			
Sloped Adjustment						
	Rise=	0.0				
	Run=	1.0				
$R_s=(Rise^2+Run^2)^{.5}/Run$=	R_s=	1.00				
Adjusted W_{eq} =	W_{eq}/R_s =	737.7	plf	at sloped span	53.75	feet
Adjusted W_{eqLL} =	W_{eqLL}/R_s =	391.0	plf			

Small Joist: New Millennium 104 SPBW 738/391/230, span=110’, Radius=332’, 7.5 inch seat depth, 5 rows of bridging

Large Joist: New Millennium 164 SPBW 738/391/230, span=110’, Radius=332’, 7.5 inch seat depth, 5 rows of bridging



BOWSTRING JOIST (SPBW) TABLES

Span ft	End Depth in	Center Depth in	Top Chord Radius ft	Top Chord Uniform Load - Pounds per Linear Foot (plf) (ASD) 300	350	400	450	500	550	600	650	700	750	800
				Joist Self-Weight - Pounds per Linear Foot (plf)										
110	42	56	1287	34	39	46	51	55	63	66	73	79	83	93
110	35	56	865	34	39	46	51	55	62	66	74	79	83	94
110	29	56	673	34	44	46	54	58	62	66	74	79	83	92
110	22	56	535	35	44	49	54	58	65	69	74	78	83	92
110	15	56	444	35	44	49	54	58	65	69	73	86	90	102
110	8	56	380	36	43	49	54	58	65	69	73	86	90	102
110	47	68	865	30	32	38	41	48	52	56	60	65	69	72
110	41	68	673	29	32	38	41	48	52	56	60	64	68	72
110	34	68	535	31	32	40	41	47	52	56	60	64	68	72
110	27	68	444	31	34	39	46	47	52	56	60	67	71	76
110	20	68	380	31	34	39	45	51	55	59	63	67	71	75
110	13	68	332	30	34	39	45	50	55	59	62	66	70	75
110	53	80	673	28	31	34	38	42	49	49	55	58	63	65
110	46	80	535	30	31	36	38	41	49	49	54	58	62	66
110	39	80	444	28	33	34	40	42	49	49	54	57	61	65
110	32	80	380	30	33	35	40	41	47	53	53	57	61	65
110	25	80	332	30	32	36	40	46	52	53	53	61	61	65
110	11	80	266	29	32	36	39	45	51	56	57	60	65	68
110	58	92	535	28	30	32	35	39	42	48	51	55	56	59
110	51	92	444	30	32	32	35	39	43	45	51	55	56	59
110	44	92	380	30	31	34	36	39	42	48	50	55	56	60
110	37	92	332	30	33	34	38	42	48	48	50	55	55	59
110	23	92	266	30	32	34	37	41	47	51	54	54	59	59
110	10	92	225	31	32	34	37	40	46	51	52	58	61	62
110	70	104	535	30	32	33	35	39	41	44	49	51	53	58
110	63	104	444	31	31	33	35	39	41	43	49	51	53	58
110	56	104	380	31	31	33	35	38	40	43	49	51	53	58
110	49	104	332	31	33	33	34	40	40	43	49	51	52	58
110	35	104	266	31	32	34	36	39	42	43	48	50	52	60
110	22	104	225	32	32	34	37	41	41	42	52	54	56	59
110	75	116	444	32	34	36	37	39	41	44	47	51	54	54
110	68	116	380	32	33	35	36	38	40	43	46	51	53	54
110	61	116	332	32	33	35	36	38	40	43	46	51	53	54
110	47	116	266	32	32	34	36	37	40	43	46	51	52	53
110	34	116	225	32	34	36	37	39	42	42	48	50	52	52
110	6	116	170	32	35	36	38	39	41	47	51	53	55	55
110	87	128	444	35	36	38	39	41	42	45	48	53	53	54
110	80	128	380	35	36	37	39	40	42	44	48	52	53	54
110	73	128	332	34	35	37	39	41	41	44	47	52	53	55
110	59	128	266	35	35	37	38	39	41	44	45	52	52	54
110	46	128	225	33	37	39	39	39	40	43	46	51	52	53
110	18	128	170	36	37	37	40	40	42	48	50	50	51	57
110	99	140	444	39	39	40	42	44	45	47	50	55	56	58
110	92	140	380	38	38	40	41	43	44	47	50	54	56	57
110	85	140	332	37	38	40	42	43	44	46	48	54	55	56
110	71	140	266	37	38	40	41	43	44	44	47	53	55	55
110	58	140	225	39	39	39	40	42	43	45	47	53	54	55
110	30	140	170	39	39	41	42	43	45	46	46	51	53	53
110	111	152	444	42	44	48	48	48	51	51	54	58	60	61
110	104	152	380	42	44	45	45	47	50	50	53	58	59	60
110	97	152	332	41	43	44	45	47	48	51	51	57	59	59
110	83	152	266	40	41	42	44	47	47	49	51	56	56	59
110	70	152	225	40	42	43	45	46	46	48	50	54	56	58
110	42	152	170	40	40	42	43	45	45	46	48	52	54	56
110	123	164	444	46	46	48	49	52	53	56	59	60	62	66
110	116	164	380	46	47	49	51	51	51	55	57	59	64	64
110	109	164	332	46	46	47	48	51	51	52	57	58	63	64
110	95	164	266	44	46	46	49	49	51	51	53	59	60	61
110	82	164	225	43	44	46	48	48	50	51	56	59	59	60
110	54	164	170	42	43	44	47	47	49	49	53	55	58	58

X - Bridging Requirements - Reference SP-Series Specification Section 904.5 BRIDGING on page 92

1 row	2 rows	3 rows	4 rows	5 rows	6 rows	7 rows	8 rows	9 rows	10 rows

Bearing Seat Depth - Profiles to the right of a colored line have a seat depth as indicated in the chart below

Minimum 5"	7½"	10"	Maximum 12½"

SPBW TABLES

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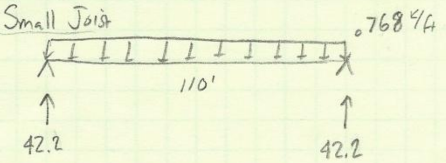
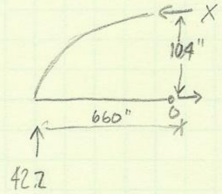
Community Roof Design | BIM Thesis

Bowstring Chord Size

Small Joist





$\Sigma M_o = 0 \quad 42.2(660) = 104X$

$X = 268^k$

Tension (AISC D2)

Angles: $F_y = 36$ ksi $\quad F_u = 58$ ksi

Yielding

$P_n = F_y A_g \qquad \frac{P_n}{\Omega} > P_a \qquad \Omega = 1.67$

$F_y A_g > P_a \Omega$

$A_g > \frac{268(1.67)}{36}$

$A_g > 12.43$ in^2 } OK

Use 2L5x5x 3/4 $\quad A_g = 14$ in^2
for Bot. Chord.

Rupture

$P_n = F_u A_e$

$A_e > \frac{P_a(\Omega)}{F_u}$

$A_e > \frac{268(1.67)}{58}$

$A_e > 7.72$ in^2

Compression (AISC E3) Try 2L5x5x 3/4 for Top Chord $\quad r = 1.5$

Slenderness Check: $\frac{b}{t} = \frac{5}{.75} = 6.67 \qquad .45\sqrt{\frac{E}{F_y}} = .45\sqrt{\frac{29000}{36}} = 12.77$

6.67 < 12.77 ok Not Slendor

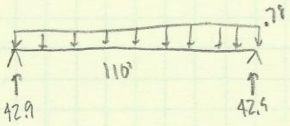
$4.71\sqrt{\frac{E}{F_y}} = 4.71\sqrt{\frac{29000}{36}} = 133.7 \qquad \frac{KL}{r} = \frac{60}{1.5} = 40$

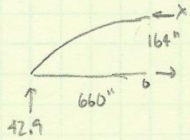
$40 < 133.7 \longrightarrow F_{cr} = [.658^{F_y/F_e}]F_y = [.658^{\frac{36}{179}}]36 = 33$ ksi

$F_e = \frac{\pi^2 E}{(\frac{KL}{r})^2} = \frac{\pi^2(29000)}{(40)^2} = 179$

$P_n = F_{cr} A_g = 33(14) = 462 > 268(1.67) = 448$ OK $\quad$ Use 2L5x5x 3/4 for Top Chord

Big Joist





$\Sigma M_o = 0$

$42.9(660) = X(164)$

$X = 173^k$

Tension

Yielding: $A_g > \frac{P_a \Omega}{F_y} = \frac{173(1.67)}{36} = 8$ in^2 } ok

Use 2L5x5x 1/2 $\quad A_g = 9.58$ in^2

Rupture: $A_e > \frac{173(1.67)}{58} = 5$ in^2

Community Roof Design BIM Thesis

Compression L=5 K=1 Try same as T: $2L5\times5\times\frac{5}{8}$ $r=1.52$

$$4.71\sqrt{\frac{E}{F_y}} = 4.71\sqrt{\frac{29000}{36}} = 133.7$$

$$F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2} = \frac{\pi^2(29000)}{\left(\frac{60}{1.52}\right)^2} = 184$$

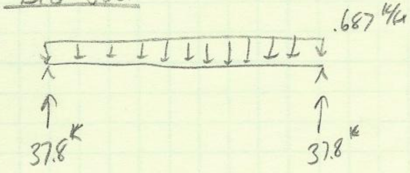
$$\frac{KL}{r} = \frac{60}{1.52} = 39.5 < 133.7 \Rightarrow F_{cr} = \left[.658^{\frac{36}{184}}\right]36 = 33.2 \text{ ksi}$$

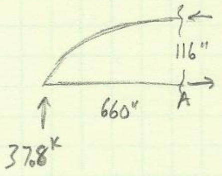
$$P_n = F_{cr} A_g$$

$$P_n = 33.2(11.8) = 392 > 221(1.67) = 369 \quad \text{OK}$$

CAN use $\boxed{2L5\times5\times\frac{5}{8}}$

Big Joist





$\Sigma M_A = 0$

$37.8(660) = 116X$

$X = 215^K$

Tension

$36(11.8) \geq 215(1.67)$

$425 > 359$ OK ✓

Compression

$P_n = 33.2(11.8) = 392 > 359$ OK ✓

Appendix G. Structural References

American Society of Civil Engineers. *ASCE 19-10 Structural Applications of Steel Cables for Buildings*. New York: ASCE, 2010.

Book: This book acts as a standard for cable structure design. It is the only standard provided by the ASCE regarding cable supported structures.

Barnes, Michael, and Michael Dickson. *Widespan Roof Structures*. London: Thomas Telford Publishing, 2000.

Book: Barnes and Dickson compiled multiple case studies on widespan roof structures into this book. It contains many pictures and illustrations of current cable supported structures.

Bethlehem Steel. *Cable Roof Structures*. Bethlehem Steel Corporation, 1968.

Book: This contains many case studies of cable roof structures produced by Bethlehem Steel.

Buchholdt, H.A. *An Introduction to Cable Roof Structures: Second Edition*. London: Thomas Telford Publications Ltd., 1999.

Book: Buchholdt introduces cable design basics and then delves into structural calculations of cable structures. The chapters contain multiple tables and graphs for structural design of several types of cable systems.

Christoforou, C., Treece, R., Monteiro, A., & Scarangello, T. (2007, February). The Newark Arena: Future Home of the New Jersey Devils. *Structure Magazine* .

Article: Case study from the structural design engineers of the Newark Arena.

Harris, James, and Kevin Pui-K Li. *Masted Structures in Architecture*. London: Butterworth Architecture, 1996.

Book: This book compiles hundreds of examples of masted cable structures. Harris and Pui-K Li introduce several case studies and categorize cable mast structures.

Krishna, Prem. *Cable-Suspended Roofs*. United States of America: McGraw-Hill, 1978.

Book: This book introduces the different types of cable structures and details the different parts of cable structures. Krishna also introduces several equations to design cable structure systems.

Monolithic. (n.d.). *Monolithic*. Retrieved August 25, 2011, from http://www.monolithic.com/

Website: Site devoted to monolithic dome structures. Contains information about different uses and benefits of monolithic domes. Also, contains product information about the domes.

Narayanan, Subramanian. *Space Structures: Principles and Practice*. United Kingdom: Multi-Science Publishing Co., 2006.

Book: Narayanan introduces the many ways to design space structures for long span buildings. A few chapters focus on cable structures and go into design examples of real cable structures.

Salvadori, M. (2002). *Why Buildings Stand Up: The Strength of Architecture.* New York: W.W. Norton & Company.

Book: Describes different types of structure from the ancient world up to today. Includes chapters on domed, tent, pneumatic, and hanging structures

Salvadori, M., & Levy, M. (2002). *Why Buildings Fall Down: How Structures Fail.* New York: W.W. Norton & Company.

Book: Details many notorious buildings failures from the ancient world up to today. Includes case studies of many long-span structural failures.

Scalzi, J.B., W. Jr. Podolny, and W. C. Teng. *Design Fundamentals of Cable Roof Structures.* Pittsburgh: United States Steel Corporation, 1969.

Book: This book introduces basic cable structural calculations and contains real life design examples.

Seidel, Michael. *Tensile Surface Structures: A Practical Guide to Cable and Membrane Construction.* Berlin: Deutsche Nationalbibliothek, 2009.

Book: Seidel illustrates and describes the construction of cable and membrane structures. The book contains hundreds of pictures and illustrations to detail the construction of these types of structures.

Solomon, N. (2010, May). Flights of Fancy in Long-Span Design. *Architectural Record* .

Article: Architectural case studies on recent successful long-span structures.

Tow, D., & Schrauben, C. (2004, May). Center Stage. *Modern Steel Construction*.

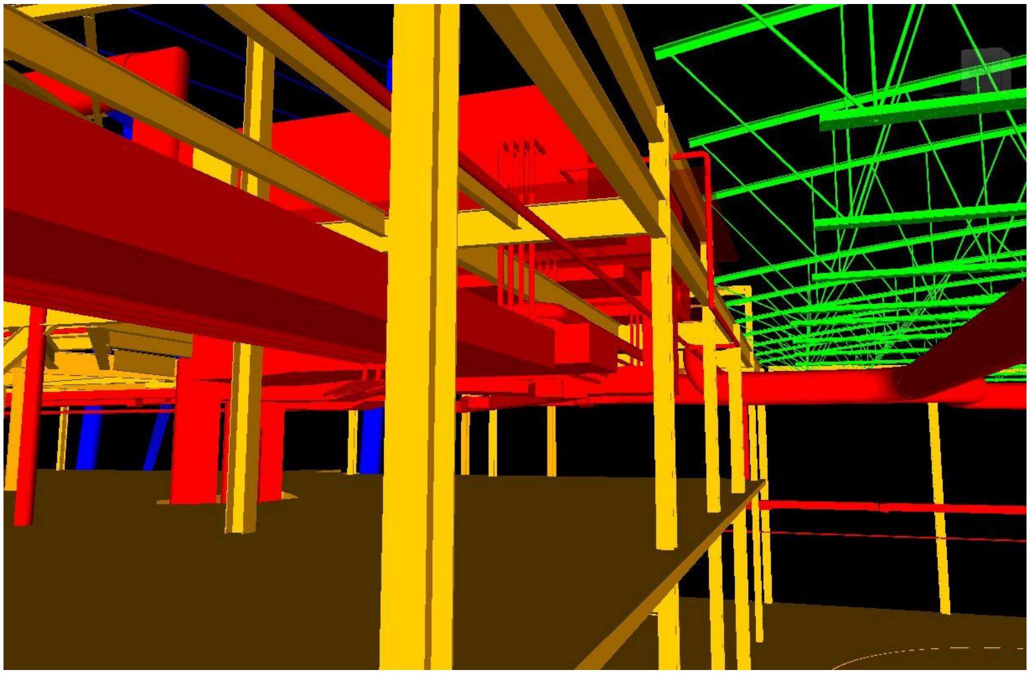
Article: Case study on the cost and construction effectiveness of the new Arena at Gwinnett Center

Tyler, T. (n.d.). *Large Domes*. Retrieved September 5, 2011, from http://largedomes.com/

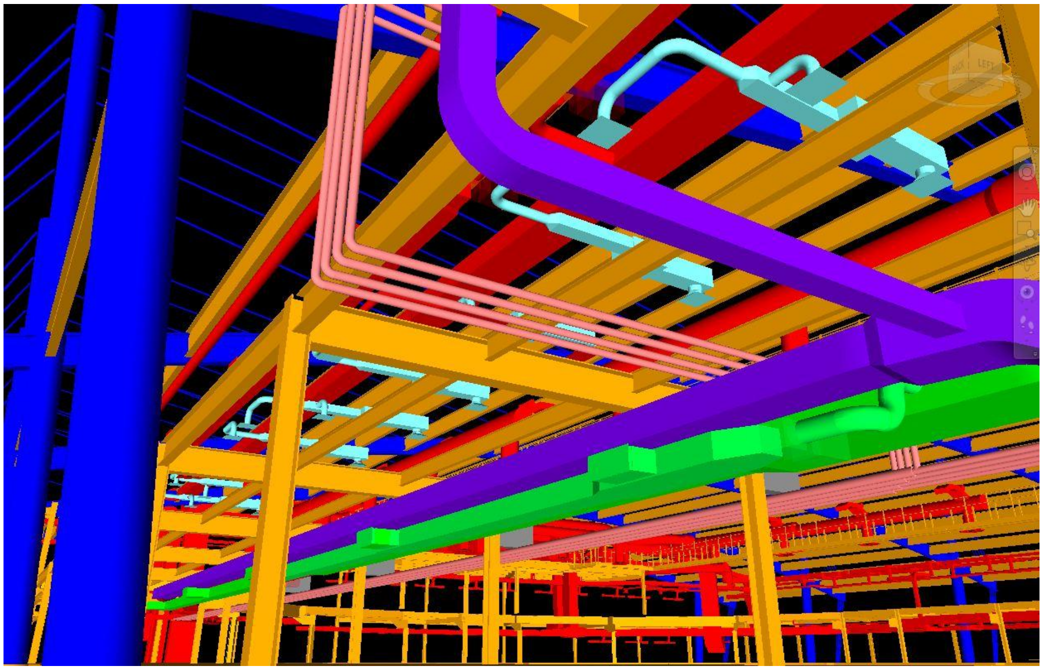
Website: Site includes ranking of world's largest domes with images and statistics. Also provides links to several sites that have more information about different ways to design a long span structure

Wong, R. (2001, February). *Long Span and Complex Structure.* Retrieved September 1, 2011, from personal.cityu.edu.hk/~bswmwong/pl/pdf/longspan.pdf

Presentation: PowerPoint Presentation that describes basic technical aspects to categorize long span structures. It then shows examples of these structures through case studies



Mechanical Appendix

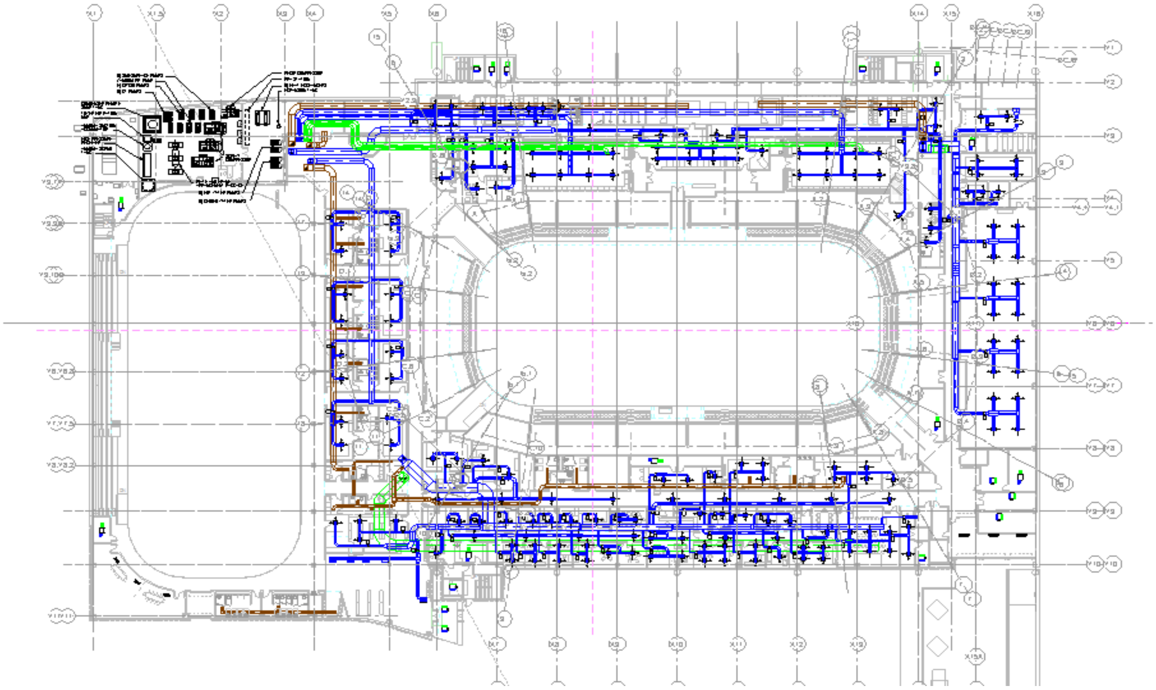


Appendix H. Mechanical MAE Requirements

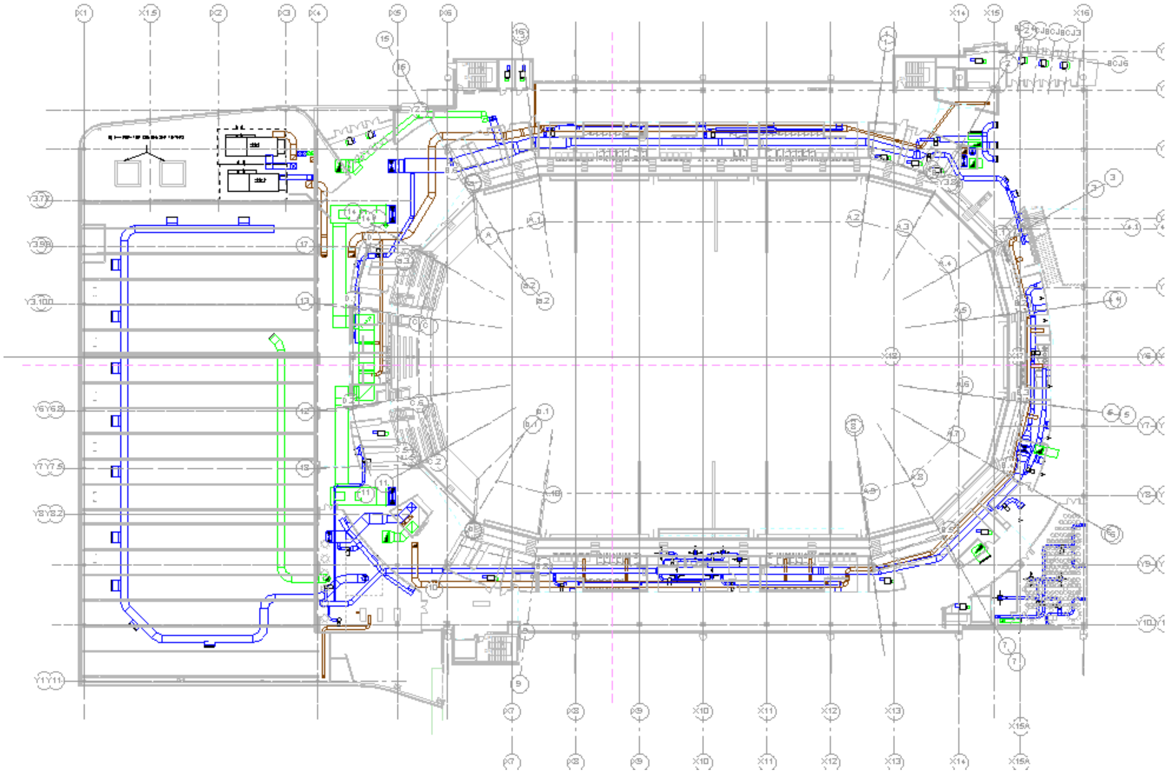
The redesign of the mechanical units supplying the main arena was assisted by information from AE 555-Building Automation and Control. Material from AE 542-Building Enclosure Science and Design was used in the façade design analysis and for the roof design analysis. Principles from AE 558-Centralized Heating Production and Distribution Systems and AE 557-Centralized Cooling Production and Distribution Systems were implemented into the relocation of the mechanical units and the life-cycle cost analysis. The indoor air quality of the main arena was evaluated based on lessons learned in AE 552-Air Quality in Buildings. Knowledge from AE 467 Advanced Building Electrical Design was used to design the electrical system for the arena.

Appendix I. Redesign Floor Plans

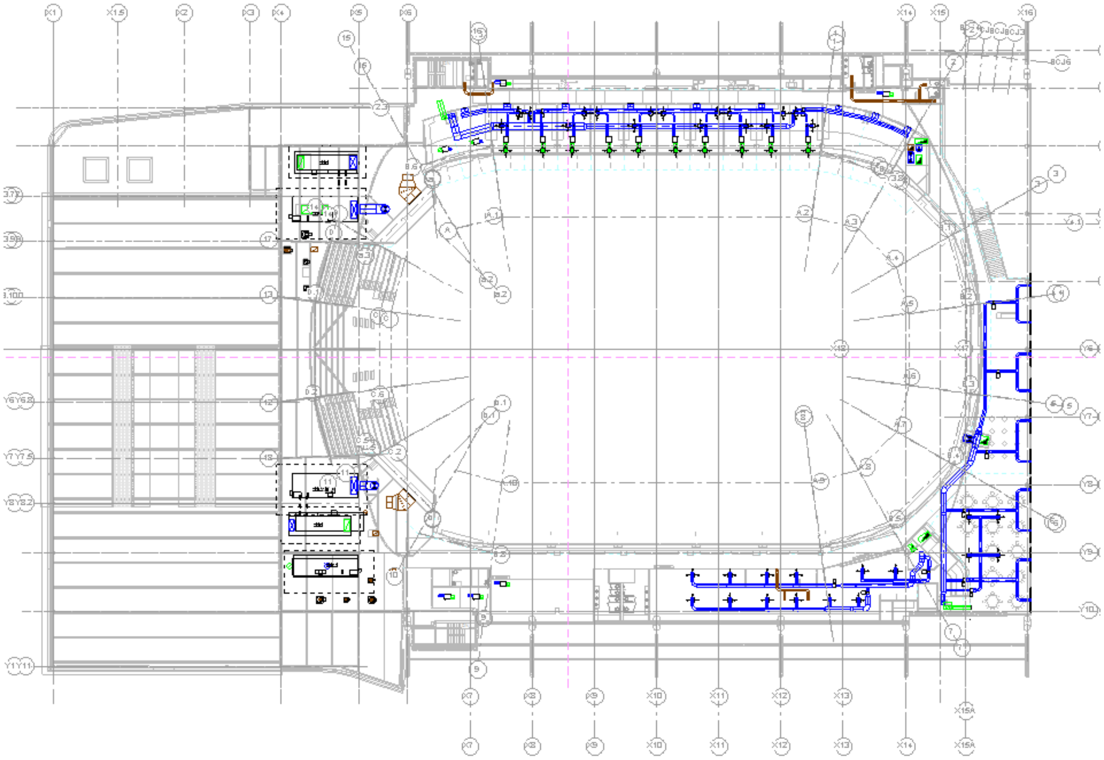
Event Level Ductwork Plan



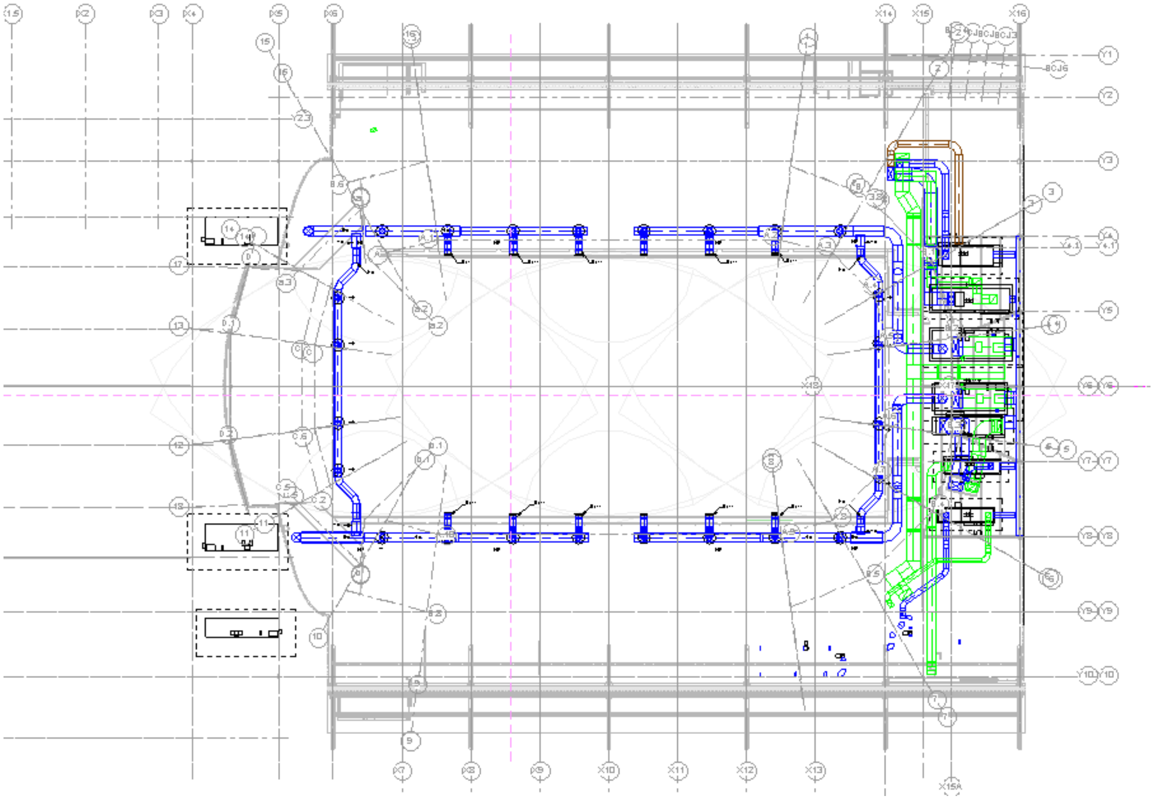
Concourse Level Ductwork Plan



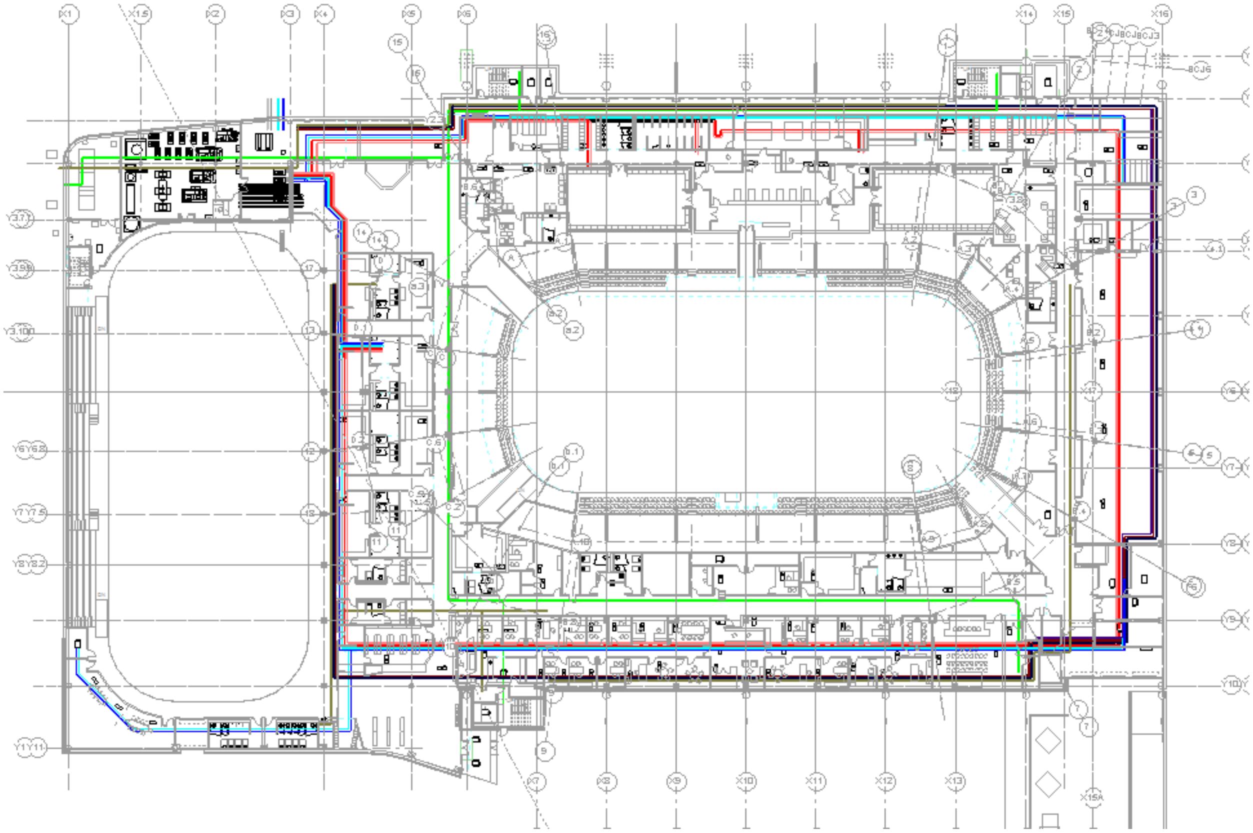
Club Level Ductwork Plan



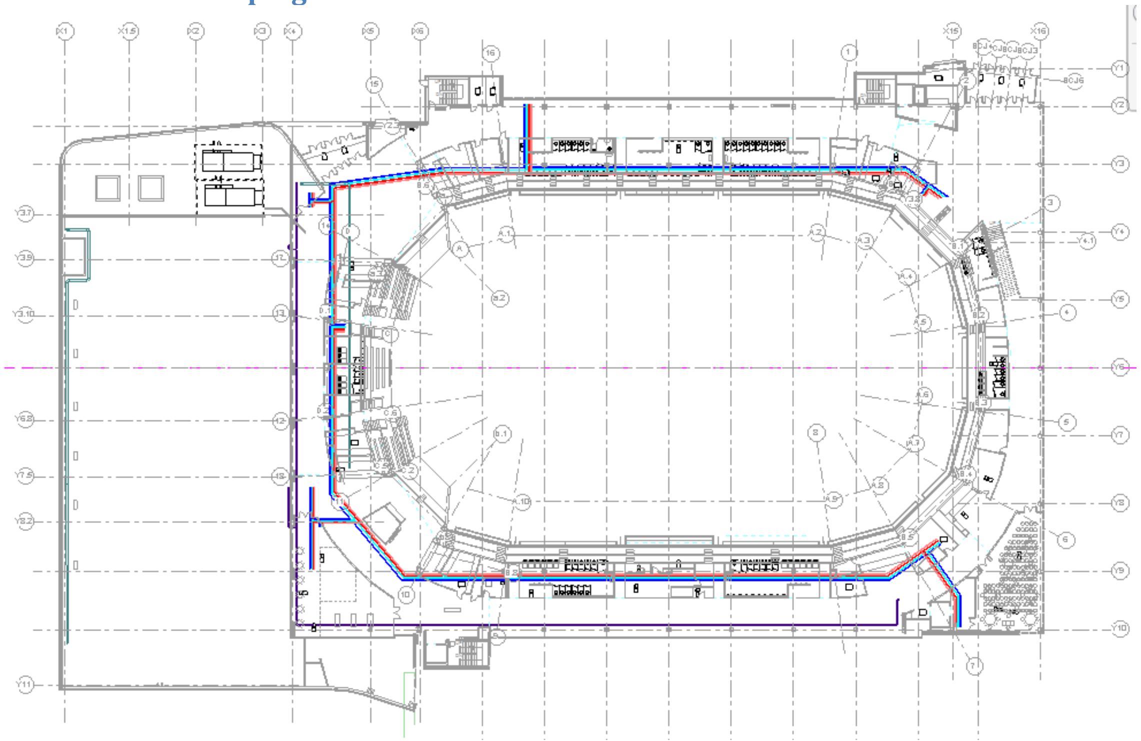
Catwalk Level Ductwork Plan



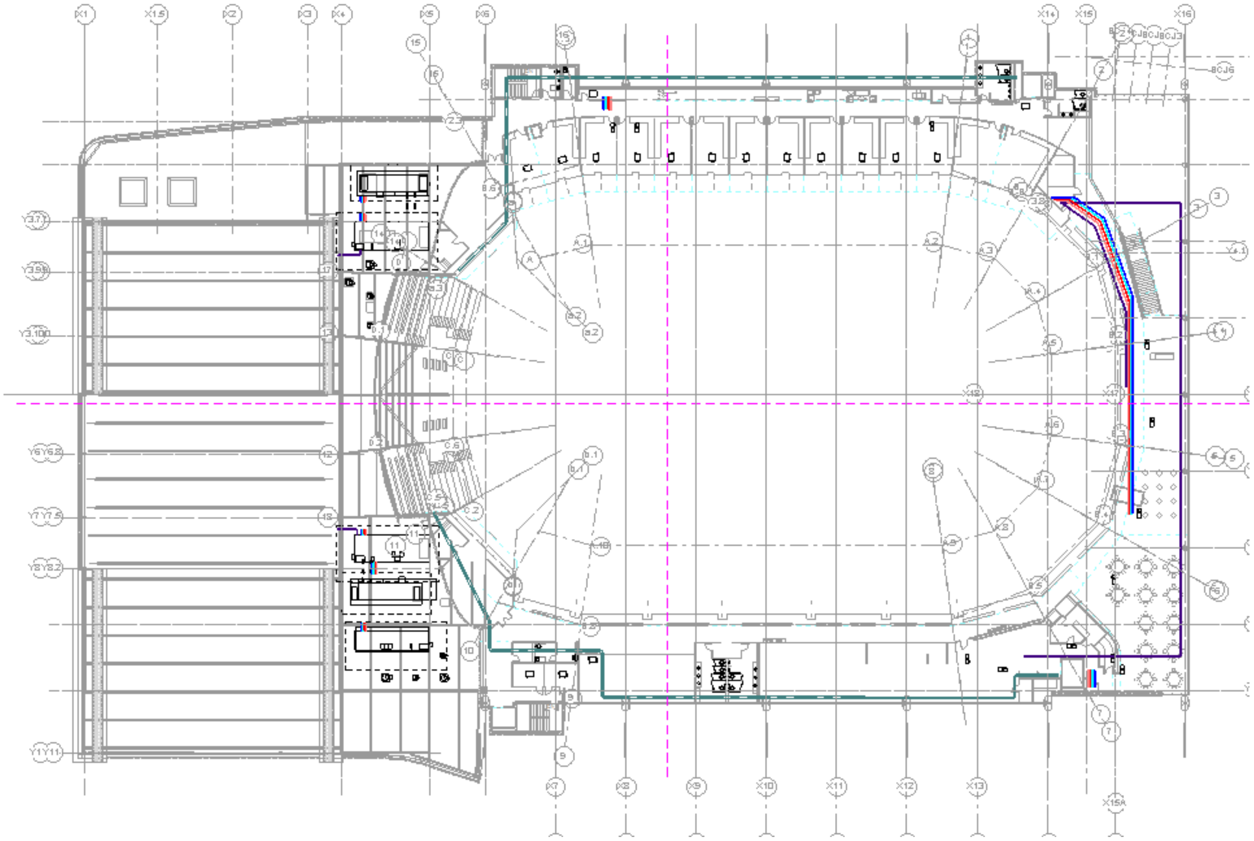
Event Level Piping Plan



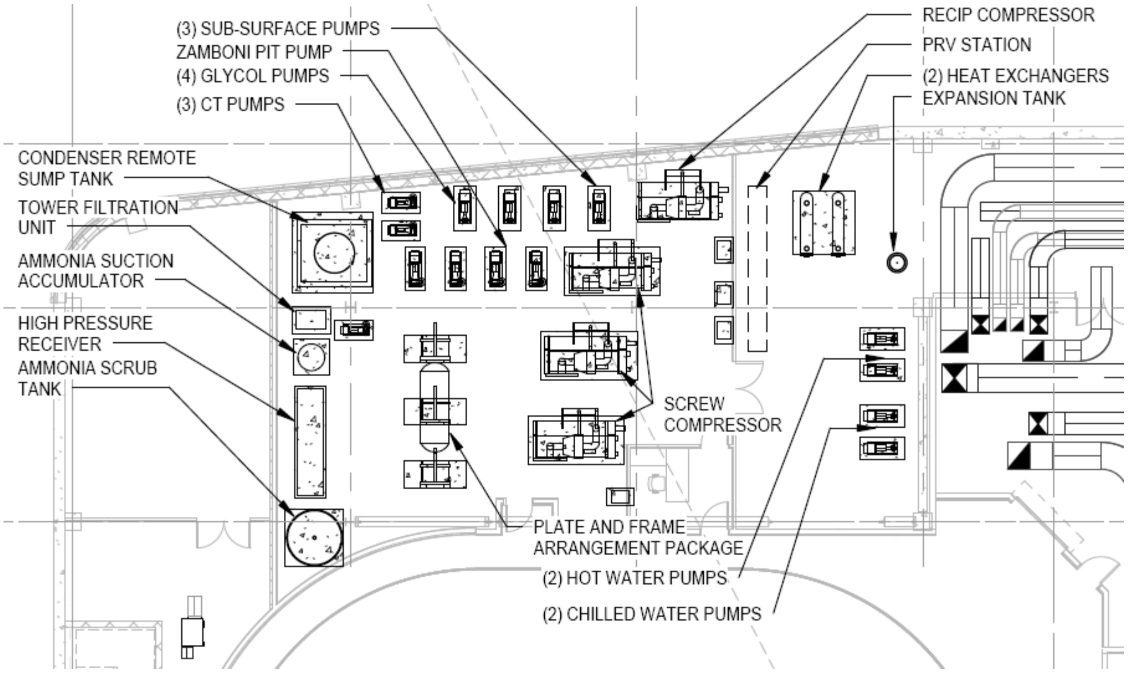
Concourse Level Piping Plan



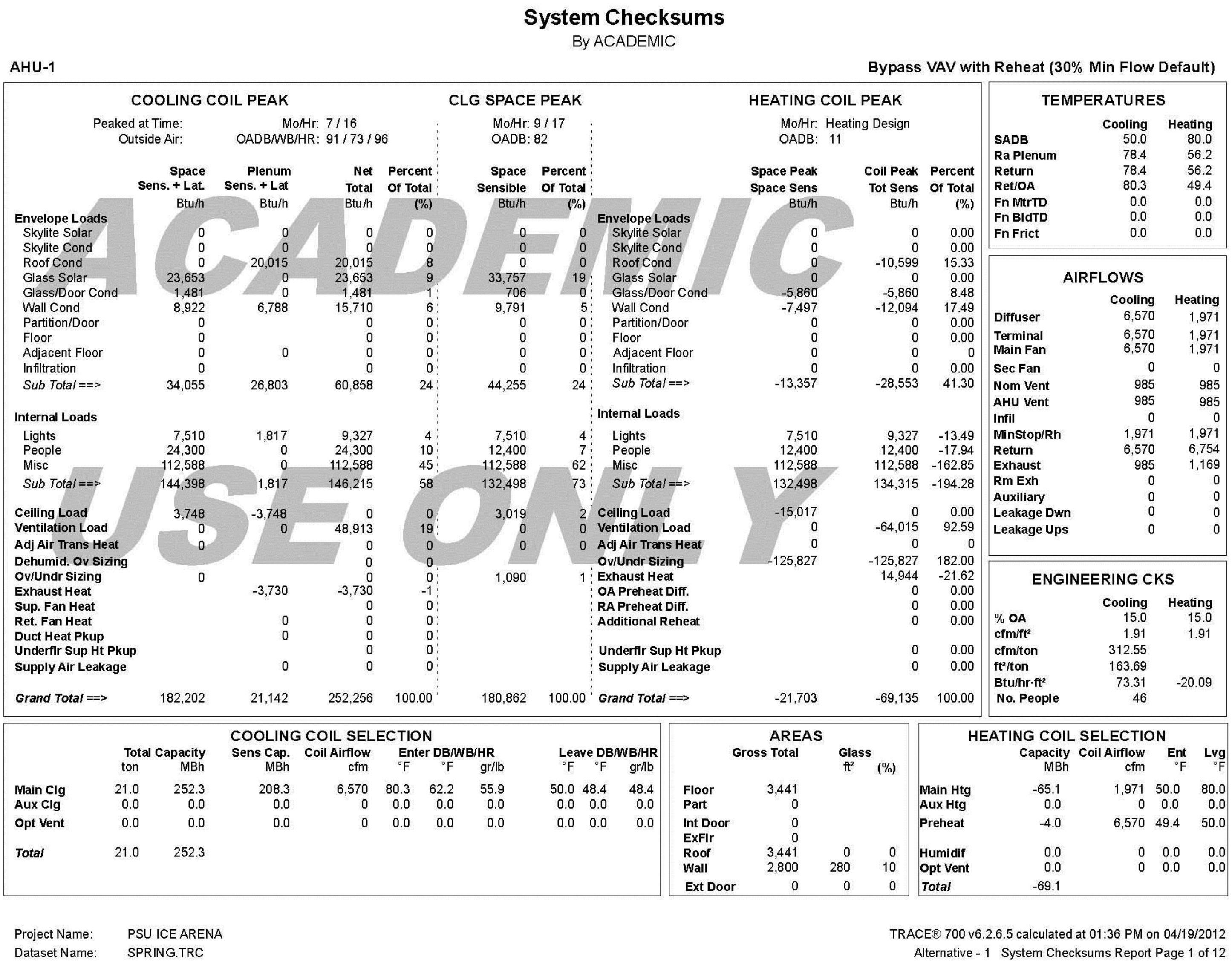
Club Level Piping Plan



Mechanical Room Detail



Appendix J. Trane Trace AHU System Checksums



System Checksums
By ACADEMIC

AHU-1

Bypass VAV with Reheat (30% Min Flow Default)

COOLING COIL PEAK

Peaked at Time: Mo/Hr: 7 / 16
Outside Air: OADB/WB/HR: 91 / 73 / 96

CLG SPACE PEAK

Mo/Hr: 9 / 17
OADB: 82

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	20,015	20,015	8	0	0
Glass Solar	23,653	0	23,653	9	33,757	19
Glass/Door Cond	1,481	0	1,481	1	706	0
Wall Cond	8,922	6,788	15,710	6	9,791	5
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	34,055	26,803	60,858	24	44,255	24
Internal Loads						
Lights	7,510	1,817	9,327	4	7,510	4
People	24,300	0	24,300	10	12,400	7
Misc	112,588	0	112,588	45	112,588	62
Sub Total ==>	144,398	1,817	146,215	58	132,498	73
Ceiling Load	3,748	-3,748	0	0	3,019	2
Ventilation Load	0	0	48,913	19	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	1,090	1
Exhaust Heat		-3,730	-3,730	-1		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	182,202	21,142	252,256	100.00	180,862	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-10,599	15.33
Glass Solar	0	0	0.00
Glass/Door Cond	-5,860	-5,860	8.48
Wall Cond	-7,497	-12,094	17.49
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-13,357	-28,553	41.30
Internal Loads			
Lights	7,510	9,327	-13.49
People	12,400	12,400	-17.94
Misc	112,588	112,588	-162.85
Sub Total ==>	132,498	134,315	-194.28
Ceiling Load	-15,017	0	0.00
Ventilation Load	0	-64,015	92.59
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	-125,827	-125,827	182.00
Exhaust Heat		14,944	-21.62
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-21,703	-69,135	100.00

TEMPERATURES

	Cooling	Heating
SADB	50.0	80.0
Ra Plenum	78.4	56.2
Return	78.4	56.2
Ret/OA	80.3	49.4
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	6,570	1,971
Terminal	6,570	1,971
Main Fan	6,570	1,971
Sec Fan	0	0
Nom Vent	985	985
AHU Vent	985	985
Infil	0	0
MinStop/Rh	1,971	1,971
Return	6,570	6,754
Exhaust	985	1,169
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	15.0	15.0
cfm/ft²	1.91	1.91
cfm/ton	312.55	
ft²/ton	163.69	
Btu/hr·ft²	73.31	-20.09
No. People	46	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	21.0	252.3	208.3	6,570	80.3	62.2	55.9	50.0	48.4	48.4
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	21.0	252.3								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	3,441		
Part	0		
Int Door	0		
ExFlr	0		
Roof	3,441	0	0
Wall	2,800	280	10
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-65.1	1,971	50.0	80.0
Aux Htg	0.0	0	0.0	0.0
Preheat	-4.0	6,570	49.4	50.0
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-69.1			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
Alternative - 1 System Checksums Report Page 1 of 12

System Checksums

By ACADEMIC

AHU-2 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 9 / 12; Outside Air: OADB/WB/HR: 78 / 63 / 64

CLG Space Peak — Mo/Hr: 10 / 12; OADB: 63

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	20,266	20,266	4	0	0
Glass Solar	335,981	0	335,981	69	407,866	86
Glass/Door Cond	-12	0	-12	0	-15,394	-3
Wall Cond	217	1,662	1,879	0	861	0
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	336,186	21,928	358,114	74	393,333	83
Internal Loads						
Lights	25,457	2,911	28,367	6	25,457	5
People	87,600	0	87,600	18	47,715	10
Misc	6,058	0	6,058	1	6,058	1
Sub Total ==>	119,115	2,911	122,025	25	79,230	17
Ceiling Load	1,933	-1,933	0	0	1,121	0
Ventilation Load	0	0	4,870	1	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-1,086	-1,086	0		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	457,233	21,820	483,923	100.00	473,684	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-26,225	23.44
Glass Solar	0	0	0.00
Glass/Door Cond	-76,794	-76,794	68.63
Wall Cond	-643	-5,181	4.63
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-77,436	-108,200	96.70
Internal Loads			
Lights	25,457	28,367	-25.35
People	47,715	47,715	-42.65
Misc	6,058	6,058	-5.41
Sub Total ==>	79,230	82,140	-73.41
Ceiling Load	-18,594	0	0.00
Ventilation Load	0	-96,277	86.05
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		10,448	-9.34
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-16,801	-111,889	100.00

TEMPERATURES

	Cooling	Heating
SADB	61.2	71.6
Ra Plenum	75.7	63.6
Return	75.7	63.6
Ret/OA	75.8	61.1
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	31,258	9,377
Terminal	31,258	9,377
Main Fan	31,258	9,377
Sec Fan	0	0
Nom Vent	1,482	1,482
AHU Vent	1,482	1,482
Infil	0	0
MinStop/Rh	9,377	9,377
Return	31,258	31,264
Exhaust	1,482	1,488
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	4.7	4.7
cfm/ft²	3.41	3.41
cfm/ton	775.12	
ft²/ton	227.27	
Btu/hr·ft²	52.80	-12.21
No. People	183	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	40.3	483.9	444.7	31,258	75.8	62.5	64.3	61.2	57.2	64.3
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	40.3	483.9								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	9,165		
Part	0		
Int Door	0		
ExFlr	0		
Roof	7,321	0	0
Wall	4,740	3,669	77
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-107.3	9,377	61.2	71.6
Aux Htg	0.0	0	0.0	0.0
Preheat	-4.6	31,258	61.1	61.2
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-111.9			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
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System Checksums

By ACADEMIC

AHU-3 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Peaked at Time: Mo/Hr: 7 / 10 — CLG Space Peak Mo/Hr: 6 / 10
Outside Air: OADB/WB/HR: 81 / 70 / 95 — OADB: 76

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	8,718	8,718	1	0	0
Glass Solar	586,846	0	586,846	49	709,212	67
Glass/Door Cond	9,063	0	9,063	1	-11,147	-1
Wall Cond	5,399	10,817	16,216	1	5,308	1
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	601,308	19,535	620,843	52	703,373	67
Internal Loads						
Lights	60,805	12,997	73,802	6	60,805	6
People	198,250	0	198,250	17	120,630	11
Misc	169,101	0	169,101	14	169,101	16
Sub Total ==>	428,156	12,997	441,153	37	350,536	33
Ceiling Load	2,605	-2,605	0	0	2,663	0
Ventilation Load	0	0	138,097	12	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	38	0
Exhaust Heat		-2,462	-2,462	0		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	1,032,069	27,466	1,197,632	100.00	1,056,610	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-14,666	5.47
Glass Solar	0	0	0.00
Glass/Door Cond	-150,122	-150,122	55.98
Wall Cond	-6,827	-18,819	7.02
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-156,949	-183,607	68.46
Internal Loads			
Lights	60,805	73,802	-27.52
People	120,630	120,630	-44.98
Misc	169,101	169,101	-63.05
Sub Total ==>	350,536	363,533	-135.55
Ceiling Load	-40,849	0	0.00
Ventilation Load	0	-333,975	124.53
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		38,604	-14.39
OA Preheat Diff.		0	0.00
RA Preheat Diff.		-152,737	56.95
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	152,737	-268,182	100.00

TEMPERATURES

	Cooling	Heating
SADB	59.7	71.1
Ra Plenum	75.4	63.2
Return	75.4	63.2
Ret/OA	75.9	58.9
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	62,698	18,809
Terminal	62,698	18,809
Main Fan	62,698	18,809
Sec Fan	0	0
Nom Vent	5,141	5,141
AHU Vent	5,141	5,141
Infil	0	0
MinStop/Rh	18,809	18,809
Return	62,698	62,886
Exhaust	5,141	5,329
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	8.2	8.2
cfm/ft²	3.32	3.32
cfm/ton	628.22	
ft²/ton	189.41	
Btu/hr·ft²	63.35	-15.41
No. People	491	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	99.8	1,197.6	1,015.3	62,698	75.9	63.2	67.5	59.7	56.9	65.7
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	99.8	1,197.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	18,904		
Part	0		
Int Door	0		
ExFlr	0		
Roof	4,127	0	0
Wall	10,980	7,173	65
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-236.7	18,809	59.7	71.1
Aux Htg	0.0	0	0.0	0.0
Preheat	-54.8	62,698	58.9	59.7
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-291.4			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

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System Checksums

By ACADEMIC

AHU-4 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 7 / 16; Outside Air: OADB/WB/HR: 91 / 73 / 96

CLG Space Peak — Mo/Hr: 11 / 15; OADB: 62

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	357,306	0	357,306	32	700,970	68
Glass/Door Cond	29,937	0	29,937	3	-1,398	0
Wall Cond	0	2,536	2,536	0	0	0
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	387,242	2,536	389,779	35	699,572	67
Internal Loads						
Lights	76,016	18,367	94,383	8	76,016	7
People	160,850	0	160,850	14	94,325	9
Misc	142,112	0	142,112	13	142,112	14
Sub Total ==>	378,978	18,367	397,345	35	312,453	30
Ceiling Load	2,940	-2,940	0	0	2,941	0
Ventilation Load	0	0	344,019	30	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	21,534	2
Exhaust Heat		-2,497	-2,497	0		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	769,161	15,467	1,128,646	100.00	1,036,501	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-118,460	-118,460	43.67
Wall Cond	0	-1,824	0.67
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-118,460	-120,284	44.34
Internal Loads			
Lights	76,016	94,383	-34.79
People	94,325	94,325	-34.77
Misc	142,112	142,112	-52.39
Sub Total ==>	312,453	330,820	-121.96
Ceiling Load	-74,213	0	0.00
Ventilation Load	0	-425,038	156.69
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		63,022	-23.23
OA Preheat Diff.		0	0.00
RA Preheat Diff.		-119,781	44.16
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	119,781	-271,261	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	70.3
Ra Plenum	75.4	61.3
Return	75.4	61.3
Ret/OA	77.5	54.3
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	47,069	14,121
Terminal	47,069	14,121
Main Fan	47,069	14,121
Sec Fan	0	0
Nom Vent	6,543	6,543
AHU Vent	6,543	6,543
Infil	0	0
MinStop/Rh	14,121	14,121
Return	47,069	49,335
Exhaust	6,543	8,808
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	13.9	13.9
cfm/ft²	1.76	1.76
cfm/ton	500.45	
ft²/ton	284.66	
Btu/hr·ft²	42.16	-10.33
No. People	378	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	94.1	1,128.7	829.8	47,069	77.5	60.3	51.7	55.0	51.5	51.7
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	94.1	1,128.7								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	26,773		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	6,060	5,660	93
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-238.5	14,121	55.0	70.3
Aux Htg	0.0	0	0.0	0.0
Preheat	-38.1	47,069	54.3	55.0
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-276.6			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

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System Checksums

By ACADEMIC

AHU-5 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Peaked at Time: Mo/Hr: 7 / 17 — Mo/Hr: 9 / 17
Outside Air: OADB/WB/HR: 89 / 72 / 92 — OADB: 82

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	296,917	0	296,917	33	429,936	57
Glass/Door Cond	19,327	0	19,327	2	7,097	1
Wall Cond	6,587	10,369	16,957	2	7,351	1
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	322,831	10,369	333,201	37	444,384	59
Internal Loads						
Lights	56,376	4,801	61,177	7	56,376	7
People	182,250	0	182,250	20	106,925	14
Misc	148,878	0	148,878	16	148,878	20
Sub Total ==>	387,504	4,801	392,305	43	312,179	41
Ceiling Load	1,688	-1,688	0	0	1,686	0
Ventilation Load	0	0	188,777	21	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	67	0
Exhaust Heat		-1,610	-1,610	0		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	712,024	11,873	912,674	100.00	758,317	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	-79,029	-79,029	27.80
Wall Cond	-5,676	-13,740	4.83
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-84,705	-92,769	32.63
Internal Loads			
Lights	56,376	61,177	-21.52
People	106,925	106,925	-37.61
Misc	148,878	148,878	-52.37
Sub Total ==>	312,179	316,980	-111.50
Ceiling Load	-39,764	0	0.00
Ventilation Load	0	-358,690	126.17
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		37,906	-13.33
OA Preheat Diff.		0	0.00
RA Preheat Diff.		-187,711	66.03
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	187,711	-284,283	100.00

TEMPERATURES

	Cooling	Heating
SADB	60.1	72.0
Ra Plenum	75.3	63.8
Return	75.3	63.8
Ret/OA	76.9	57.5
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	46,115	13,835
Terminal	46,115	13,835
Main Fan	46,115	13,835
Sec Fan	0	0
Nom Vent	5,521	5,521
AHU Vent	5,521	5,521
Infil	0	0
MinStop/Rh	13,835	13,835
Return	46,115	47,134
Exhaust	5,521	6,540
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	12.0	12.0
cfm/ft²	2.29	2.29
cfm/ton	606.33	
ft²/ton	264.63	
Btu/hr·ft²	45.35	-15.67
No. People	430	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	76.1	912.7	734.8	46,115	76.9	63.7	68.1	60.1	57.2	66.3
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	76.1	912.7								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	20,127		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	6,520	3,776	58
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-182.4	13,835	60.1	72.0
Aux Htg	0.0	0	0.0	0.0
Preheat	-133.0	46,115	57.5	60.1
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-315.3			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

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System Checksums

By ACADEMIC

AHU-6 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 7 / 14; Outside Air: OADB/WB/HR: 91 / 74 / 102

CLG Space Peak — Mo/Hr: 7 / 15; OADB: 91

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	0	0	0	0	0	0
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	0	0	0	0	0	0
Internal Loads						
Lights	18,951	207	19,158	4	18,951	16
People	39,800	0	39,800	8	19,990	16
Misc	81,934	0	81,934	17	81,934	67
Sub Total ==>	140,685	207	140,892	30	120,875	100
Ceiling Load	21	-21	0	0	22	0
Ventilation Load	0	0	330,280	70	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	538	0
Exhaust Heat		-161	-161	0		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	140,707	24	471,012	100.00	121,434	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	0	0	0.00
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	0	0	0.00
Internal Loads			
Lights	18,951	19,158	-2.11
People	19,990	19,990	-2.21
Misc	81,934	81,934	-9.04
Sub Total ==>	120,875	121,082	-13.36
Ceiling Load	-2,230	0	0.00
Ventilation Load	0	-51,500	5.68
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		930	-0.10
OA Preheat Diff.		-848,739	93.63
RA Preheat Diff.		-128,262	14.15
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	118,645	-906,489	100.00

TEMPERATURES

	Cooling	Heating
SADB	68.3	70.0
Ra Plenum	75.0	68.9
Return	75.0	68.9
Ret/OA	88.5	66.1
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	16,425	4,927
Terminal	16,425	4,927
Main Fan	16,425	4,928
Sec Fan	0	0
Nom Vent	14,248	793
AHU Vent	14,248	793
Infil	0	0
MinStop/Rh	4,927	4,927
Return	16,425	16,647
Exhaust	14,248	1,014
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	86.7	4.8
cfm/ft²	2.49	2.49
cfm/ton	418.46	
ft²/ton	168.30	
Btu/hr·ft²	71.30	-137.22
No. People	67	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	39.3	471.0	364.1	16,425	88.5	73.3	101.0	68.3	65.7	92.1
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	39.3	471.0								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	6,606		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	0	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-9.3	4,927	68.3	70.0
Aux Htg	0.0	0	0.0	0.0
Preheat	-897.2	16,425	18.7	68.3
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-906.5			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
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System Checksums

By ACADEMIC

AHU-7 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak – Peaked at Time: Mo/Hr: 7 / 14; Outside Air: OADB/WB/HR: 91 / 74 / 102

Clg Space Peak – Mo/Hr: 7 / 15; OADB: 91

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	0	0	0	0	0	0
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	0	0	0	0	0	0
Internal Loads						
Lights	17,665	1,942	19,607	6	17,665	14
People	76,250	0	76,250	23	44,115	34
Misc	47,369	0	47,369	14	47,369	36
Sub Total ==>	141,284	1,942	143,226	43	109,149	84
Ceiling Load	440	-440	0	0	439	0
Ventilation Load	0	0	190,661	57	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	20,772	16
Exhaust Heat		-1,168	-1,168	0		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	141,723	335	332,719	100.00	130,360	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	0	0	0.00
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	0	0	0.00
Internal Loads			
Lights	17,665	19,607	-6.97
People	44,115	44,115	-15.68
Misc	47,369	47,369	-16.84
Sub Total ==>	109,149	111,091	-39.49
Ceiling Load	-10,512	0	0.00
Ventilation Load	0	-336,934	119.78
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		44,800	-15.93
OA Preheat Diff.		-1,378	0.49
RA Preheat Diff.		-98,869	35.15
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	98,637	-281,289	100.00

TEMPERATURES

	Cooling	Heating
SADB	57.4	70.0
Ra Plenum	75.2	65.1
Return	75.2	65.1
Ret/OA	87.1	23.3
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	6,707	2,012
Terminal	6,707	2,012
Main Fan	6,707	2,012
Sec Fan	0	0
Nom Vent	5,213	5,186
AHU Vent	5,213	5,186
Infil	0	0
MinStop/Rh	2,012	2,012
Return	6,707	9,963
Exhaust	5,213	8,442
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	77.7	77.3
cfm/ft²	0.98	0.98
cfm/ton	241.91	
ft²/ton	245.86	
Btu/hr·ft²	48.81	-41.26
No. People	178	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	27.7	332.7	198.9	6,707	87.1	72.1	95.9	57.4	57.3	71.4
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	27.7	332.7								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	6,817		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	0	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-28.0	2,012	57.4	70.0
Aux Htg	0.0	0	0.0	0.0
Preheat	-253.3	6,707	23.1	57.4
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-281.3			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
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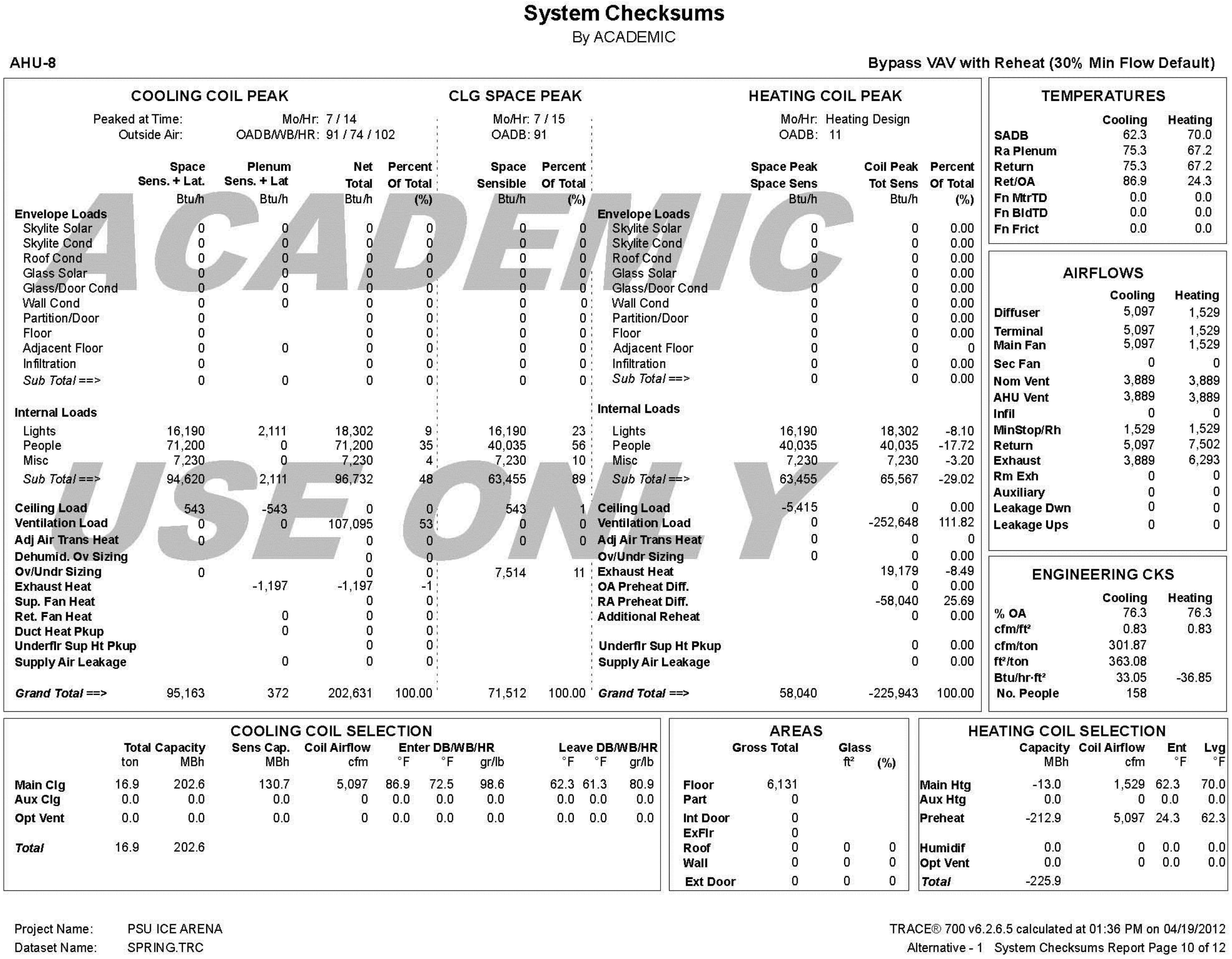

System Checksums

By ACADEMIC

AHU-8 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 7 / 14; Outside Air: OADB/WB/HR: 91 / 74 / 102

Clg Space Peak — Mo/Hr: 7 / 15; OADB: 91

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	0	0	0	0	0	0
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	0	0	0	0	0	0
Internal Loads						
Lights	16,190	2,111	18,302	9	16,190	23
People	71,200	0	71,200	35	40,035	56
Misc	7,230	0	7,230	4	7,230	10
Sub Total ==>	94,620	2,111	96,732	48	63,455	89
Ceiling Load	543	-543	0	0	543	1
Ventilation Load	0	0	107,095	53	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	7,514	11
Exhaust Heat		-1,197	-1,197	-1		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	95,163	372	202,631	100.00	71,512	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	0	0	0.00
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	0	0	0.00
Internal Loads			
Lights	16,190	18,302	-8.10
People	40,035	40,035	-17.72
Misc	7,230	7,230	-3.20
Sub Total ==>	63,455	65,567	-29.02
Ceiling Load	-5,415	0	0.00
Ventilation Load	0	-252,648	111.82
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		19,179	-8.49
OA Preheat Diff.		0	0.00
RA Preheat Diff.		-58,040	25.69
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	58,040	-225,943	100.00

TEMPERATURES

	Cooling	Heating
SADB	62.3	70.0
Ra Plenum	75.3	67.2
Return	75.3	67.2
Ret/OA	86.9	24.3
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	5,097	1,529
Terminal	5,097	1,529
Main Fan	5,097	1,529
Sec Fan	0	0
Nom Vent	3,889	3,889
AHU Vent	3,889	3,889
Infil	0	0
MinStop/Rh	1,529	1,529
Return	5,097	7,502
Exhaust	3,889	6,293
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	76.3	76.3
cfm/ft²	0.83	0.83
cfm/ton	301.87	
ft²/ton	363.08	
Btu/hr·ft²	33.05	-36.85
No. People	158	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	16.9	202.6	130.7	5,097	86.9	72.5	98.6	62.3	61.3	80.9
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	16.9	202.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	6,131		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	0	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-13.0	1,529	62.3	70.0
Aux Htg	0.0	0	0.0	0.0
Preheat	-212.9	5,097	24.3	62.3
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-225.9			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
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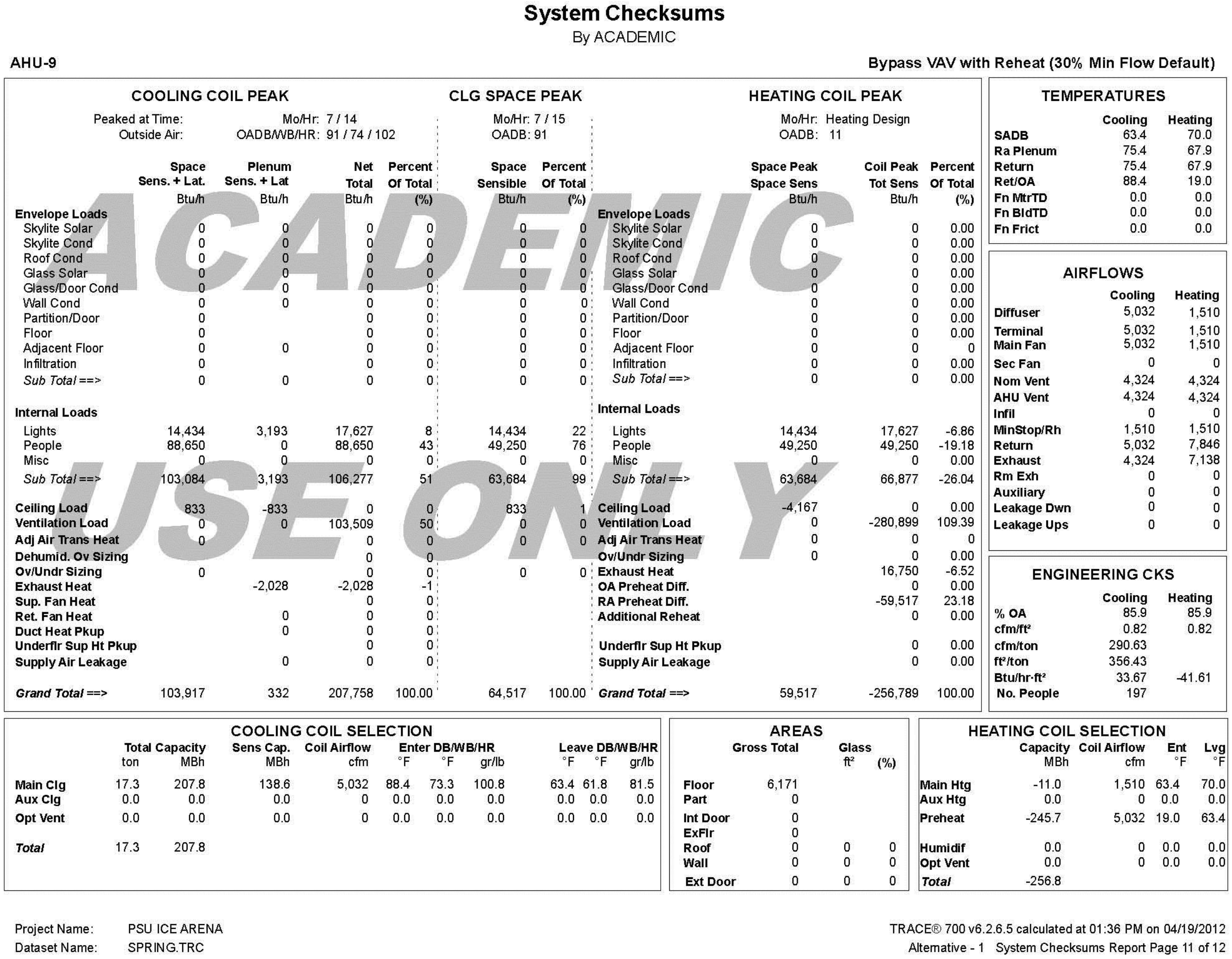

System Checksums

By ACADEMIC

AHU-9 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak: Peaked at Time: Mo/Hr: 7 / 14; Outside Air: OADB/WB/HR: 91 / 74 / 102

Clg Space Peak: Mo/Hr: 7 / 15; OADB: 91

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	0	0	0	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	0	0	0	0	0	0
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	0	0	0	0	0	0
Internal Loads						
Lights	14,434	3,193	17,627	8	14,434	22
People	88,650	0	88,650	43	49,250	76
Misc	0	0	0	0	0	0
Sub Total ==>	103,084	3,193	106,277	51	63,684	99
Ceiling Load	833	-833	0	0	833	1
Ventilation Load	0	0	103,509	50	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-2,028	-2,028	-1		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	103,917	332	207,758	100.00	64,517	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	0	0.00
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	0	0	0.00
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	0	0	0.00
Internal Loads			
Lights	14,434	17,627	-6.86
People	49,250	49,250	-19.18
Misc	0	0	0.00
Sub Total ==>	63,684	66,877	-26.04
Ceiling Load	-4,167	0	0.00
Ventilation Load	0	-280,899	109.39
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		16,750	-6.52
OA Preheat Diff.		0	0.00
RA Preheat Diff.		-59,517	23.18
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	59,517	-256,789	100.00

TEMPERATURES

	Cooling	Heating
SADB	63.4	70.0
Ra Plenum	75.4	67.9
Return	75.4	67.9
Ret/OA	88.4	19.0
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	5,032	1,510
Terminal	5,032	1,510
Main Fan	5,032	1,510
Sec Fan	0	0
Nom Vent	4,324	4,324
AHU Vent	4,324	4,324
Infil	0	0
MinStop/Rh	1,510	1,510
Return	5,032	7,846
Exhaust	4,324	7,138
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	85.9	85.9
cfm/ft²	0.82	0.82
cfm/ton	290.63	
ft²/ton	356.43	
Btu/hr·ft²	33.67	-41.61
No. People	197	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	17.3	207.8	138.6	5,032	88.4	73.3	100.8	63.4	61.8	81.5
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	17.3	207.8								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	6,171		
Part	0		
Int Door	0		
ExFlr	0		
Roof	0	0	0
Wall	0	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-11.0	1,510	63.4	70.0
Aux Htg	0.0	0	0.0	0.0
Preheat	-245.7	5,032	19.0	63.4
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-256.8			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
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System Checksums

By ACADEMIC

AHU-10

Bypass VAV with Reheat (30% Min Flow Default)

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 7 / 15; Outside Air: OADB/WB/HR: 91 / 74 / 101

Clg Space Peak — Mo/Hr: 7 / 16; OADB: 91

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	236,308	236,308	8	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	0	0	0	0	0	0
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	0	236,308	236,308	8	0	0
Internal Loads						
Lights	141,746	0	141,746	5	141,746	10
People	2,400,000	0	2,400,000	80	1,200,000	87
Misc	0	0	0	0	0	0
Sub Total ==>	2,541,746	0	2,541,746	84	1,341,746	97
Ceiling Load	35,891	-35,891	0	0	36,013	3
Ventilation Load	0	0	252,253	8	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-12,888	-12,888	0		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	2,577,637	187,529	3,017,419	100.00	1,377,759	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design; OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-102,415	17.72
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	0	0	0.00
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	0	-102,415	17.72
Internal Loads			
Lights	141,746	141,746	-24.53
People	1,200,000	1,200,000	-207.65
Misc	0	0	0.00
Sub Total ==>	1,341,746	1,341,746	-232.18
Ceiling Load	-113,212	0	0.00
Ventilation Load	0	0	0.00
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	-1,779,651	-1,779,651	307.95
Exhaust Heat		0	0.00
OA Preheat Diff.		0	0.00
RA Preheat Diff.		0	0.00
Additional Reheat		-37,577	6.50
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	-551,116	-577,896	100.00

TEMPERATURES

	Cooling	Heating
SADB	50.0	80.0
Ra Plenum	67.2	53.1
Return	67.2	53.1
Ret/OA	68.7	53.1
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	83,419	25,026
Terminal	83,419	25,026
Main Fan	83,419	25,026
Sec Fan	0	0
Nom Vent	5,364	0
AHU Vent	5,364	0
Infil	0	0
MinStop/Rh	25,026	25,026
Return	83,419	83,419
Exhaust	5,364	0
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	6.4	0.0
cfm/ft²	1.61	1.61
cfm/ton	331.75	
ft²/ton	206.46	
Btu/hr·ft²	58.12	-15.92
No. People	6,000	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	251.5	3,017.4	1,718.7	83,419	68.7	62.5	75.9	50.0	49.8	53.7
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	251.5	3,017.4								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	51,914		
Part	0		
Int Door	0		
ExFlr	0		
Roof	51,914	0	0
Wall	0	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-826.7	25,026	50.0	80.0
Aux Htg	0.0	0	0.0	0.0
Preheat	0.0	0	0.0	0.0
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-826.7			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
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System Checksums

By ACADEMIC

AHU-12 **Bypass VAV with Reheat (30% Min Flow Default)**

COOLING COIL PEAK / CLG SPACE PEAK

Cooling Coil Peak — Peaked at Time: Mo/Hr: 7 / 15; Outside Air: OADB/WB/HR: 91 / 74 / 101

CLG Space Peak — Mo/Hr: 7 / 16; OADB: 91

	Space Sens. + Lat. Btu/h	Plenum Sens. + Lat Btu/h	Net Total Btu/h	Percent Of Total (%)	Space Sensible Btu/h	Percent Of Total (%)
Envelope Loads						
Skylite Solar	0	0	0	0	0	0
Skylite Cond	0	0	0	0	0	0
Roof Cond	0	144,651	144,651	24	0	0
Glass Solar	0	0	0	0	0	0
Glass/Door Cond	0	0	0	0	0	0
Wall Cond	20,983	18,420	39,402	6	25,728	12
Partition/Door	0		0	0	0	0
Floor	0		0	0	0	0
Adjacent Floor	0	0	0	0	0	0
Infiltration	0		0	0	0	0
Sub Total ==>	20,983	163,070	184,053	30	25,728	12
Internal Loads						
Lights	85,487	1,050	86,537	14	85,487	39
People	123,500	0	123,500	20	68,000	31
Misc	6,563	0	6,563	1	6,563	3
Sub Total ==>	215,550	1,050	216,600	36	160,050	73
Ceiling Load	34,363	-34,363	0	0	33,762	15
Ventilation Load	0	0	232,888	38	0	0
Adj Air Trans Heat	0		0	0	0	0
Dehumid. Ov Sizing			0	0		
Ov/Undr Sizing	0		0	0	0	0
Exhaust Heat		-26,920	-26,920	-4		
Sup. Fan Heat			0	0		
Ret. Fan Heat		0	0	0		
Duct Heat Pkup		0	0	0		
Underflr Sup Ht Pkup			0	0		
Supply Air Leakage		0	0	0		
Grand Total ==>	270,896	102,837	606,621	100.00	219,540	100.00

HEATING COIL PEAK

Mo/Hr: Heating Design
OADB: 11

	Space Peak Space Sens Btu/h	Coil Peak Tot Sens Btu/h	Percent Of Total (%)
Envelope Loads			
Skylite Solar	0	0	0.00
Skylite Cond	0	0	0.00
Roof Cond	0	-66,985	28.97
Glass Solar	0	0	0.00
Glass/Door Cond	0	0	0.00
Wall Cond	-15,450	-29,077	12.57
Partition/Door	0	0	0.00
Floor	0	0	0.00
Adjacent Floor	0	0	0
Infiltration	0	0	0.00
Sub Total ==>	-15,450	-96,062	41.54
Internal Loads			
Lights	85,487	86,537	-37.42
People	68,000	68,000	-29.40
Misc	6,563	6,563	-2.84
Sub Total ==>	160,050	161,100	-69.66
Ceiling Load	-42,955	0	0.00
Ventilation Load	0	-130,697	56.52
Adj Air Trans Heat	0	0	0
Ov/Undr Sizing	0	0	0.00
Exhaust Heat		17,268	-7.47
OA Preheat Diff.		-80,214	34.69
RA Preheat Diff.		-102,655	44.39
Additional Reheat		0	0.00
Underflr Sup Ht Pkup		0	0.00
Supply Air Leakage		0	0.00
Grand Total ==>	101,645	-231,261	100.00

TEMPERATURES

	Cooling	Heating
SADB	55.0	60.2
Ra Plenum	69.5	55.6
Return	69.5	55.6
Ret/OA	72.5	51.9
Fn MtrTD	0.0	0.0
Fn BldTD	0.0	0.0
Fn Frict	0.0	0.0

AIRFLOWS

	Cooling	Heating
Diffuser	28,520	8,556
Terminal	28,520	8,556
Main Fan	28,520	8,556
Sec Fan	0	0
Nom Vent	4,007	2,352
AHU Vent	4,007	2,352
Infil	0	0
MinStop/Rh	8,556	8,556
Return	28,520	28,748
Exhaust	4,007	2,579
Rm Exh	0	0
Auxiliary	0	0
Leakage Dwn	0	0
Leakage Ups	0	0

ENGINEERING CKS

	Cooling	Heating
% OA	14.1	8.2
cfm/ft²	1.09	1.09
cfm/ton	564.18	
ft²/ton	517.79	
Btu/hr·ft²	23.18	-8.72
No. People	270	

COOLING COIL SELECTION

	Total Capacity ton	Total Capacity MBh	Sens Cap. MBh	Coil Airflow cfm	Enter DB/WB/HR °F	Enter DB/WB/HR °F	Enter DB/WB/HR gr/lb	Leave DB/WB/HR °F	Leave DB/WB/HR °F	Leave DB/WB/HR gr/lb
Main Clg	50.6	606.6	440.2	28,520	72.5	61.8	66.4	55.0	54.5	63.5
Aux Clg	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Opt Vent	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0
Total	50.6	606.6								

AREAS

	Gross Total	Glass ft²	Glass (%)
Floor	26,175		
Part	0		
Int Door	0		
ExFlr	0		
Roof	22,075	0	0
Wall	6,740	0	0
Ext Door	0	0	0

HEATING COIL SELECTION

	Capacity MBh	Coil Airflow cfm	Ent °F	Lvg °F
Main Htg	-49.2	8,556	55.0	60.2
Aux Htg	0.0	0	0.0	0.0
Preheat	-179.2	28,520	49.3	55.0
Humidif	0.0	0	0.0	0.0
Opt Vent	0.0	0	0.0	0.0
Total	-228.4			

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 01:36 PM on 04/19/2012
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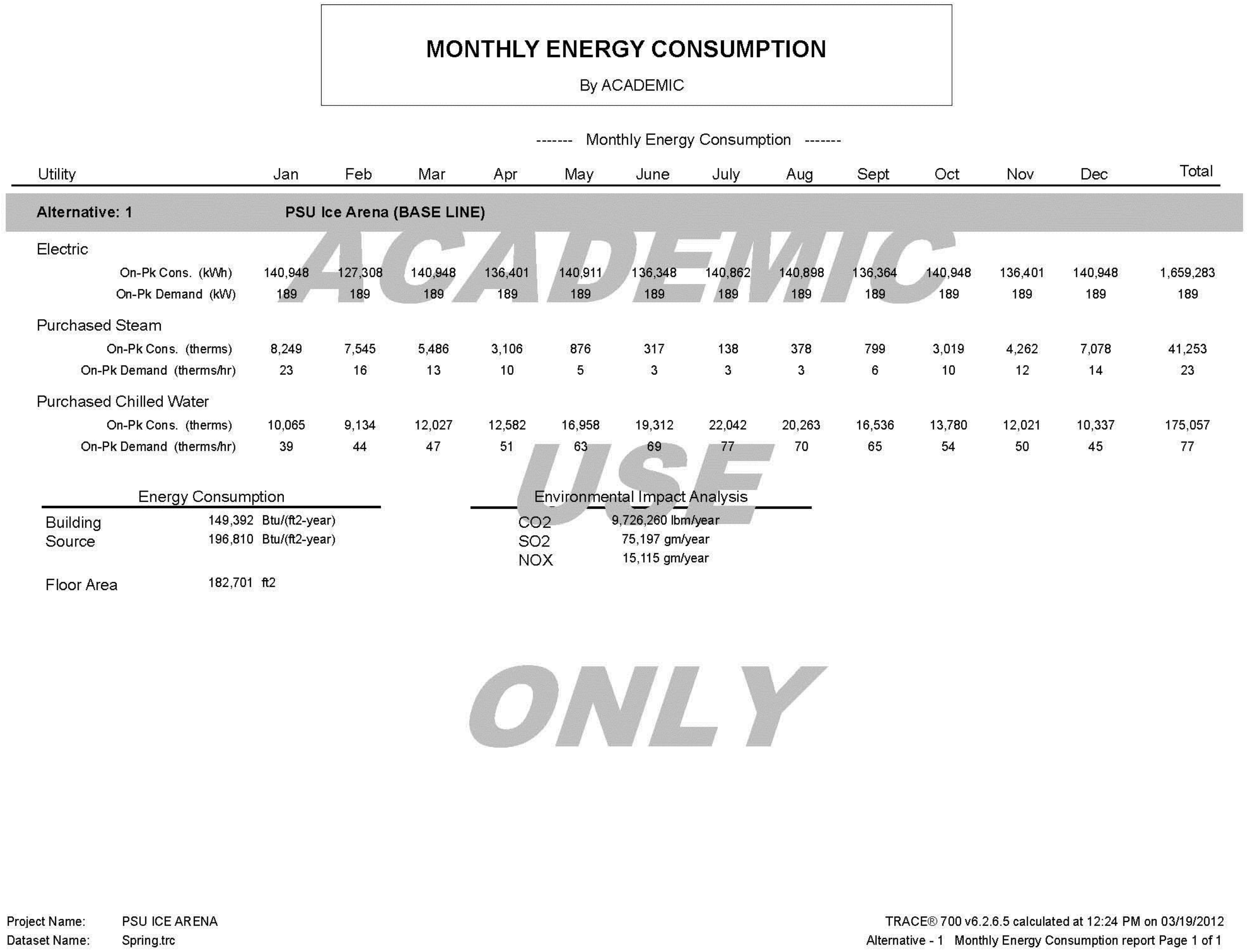
Appendix K. Façade Life-Cycle Cost Analysis Energy Consumption Reports

Baseline Brick



MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**PSU Ice Arena (BASE LINE)**												
Electric													
On-Pk Cons. (kWh)	140,948	127,308	140,948	136,401	140,911	136,348	140,862	140,898	136,364	140,948	136,401	140,948	1,659,283
On-Pk Demand (kW)	189	189	189	189	189	189	189	189	189	189	189	189	189
Purchased Steam													
On-Pk Cons. (therms)	8,249	7,545	5,486	3,106	876	317	138	378	799	3,019	4,262	7,078	41,253
On-Pk Demand (therms/hr)	23	16	13	10	5	3	3	3	6	10	12	14	23
Purchased Chilled Water													
On-Pk Cons. (therms)	10,065	9,134	12,027	12,582	16,958	19,312	22,042	20,263	16,536	13,780	12,021	10,337	175,057
On-Pk Demand (therms/hr)	39	44	47	51	63	69	77	70	65	54	50	45	77

Energy Consumption

Building	149,392	Btu/(ft2-year)
Source	196,810	Btu/(ft2-year)
Floor Area	182,701	ft2

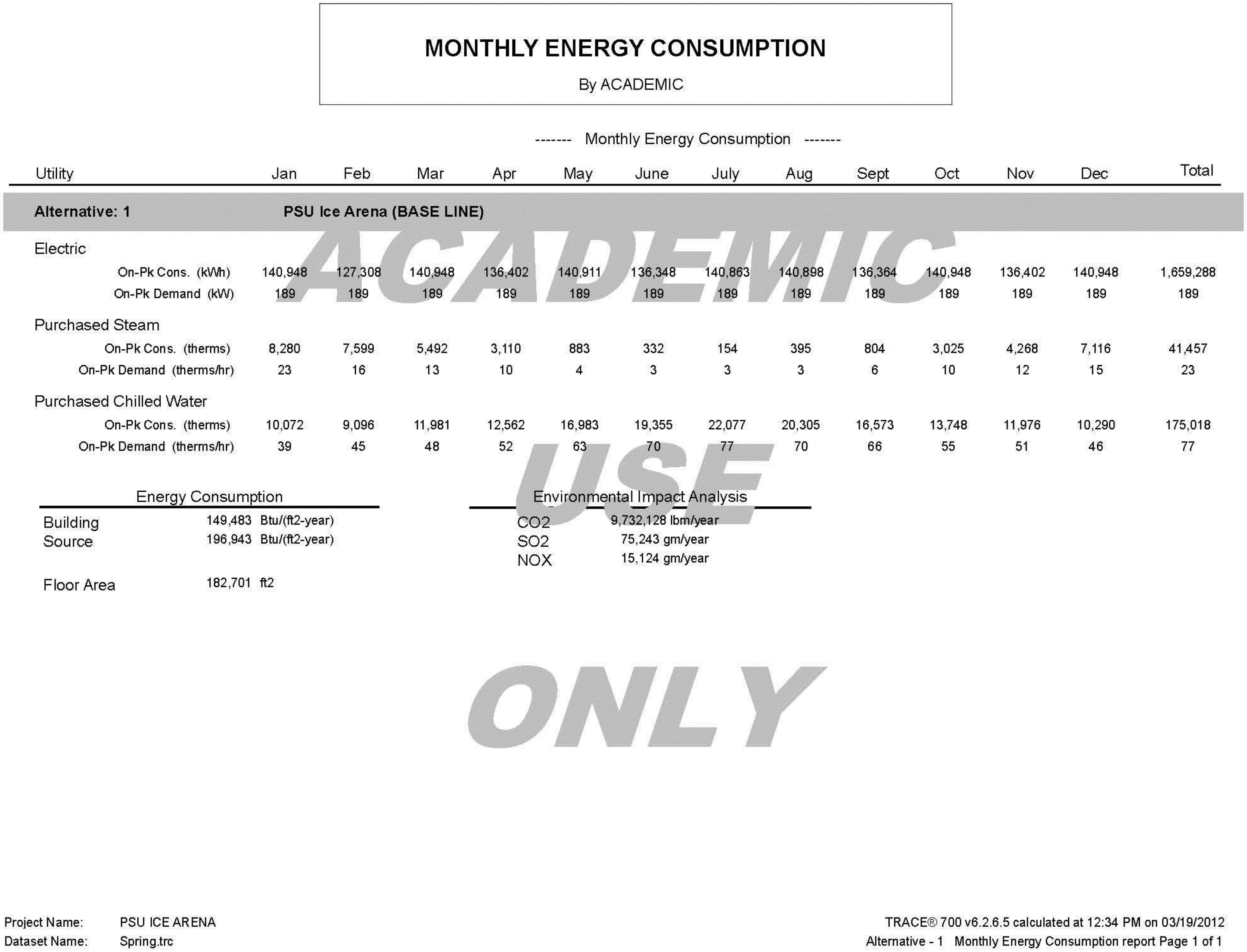
Environmental Impact Analysis

CO2	9,726,260	lbm/year
SO2	75,197	gm/year
NOX	15,115	gm/year

Project Name: PSU ICE ARENA
Dataset Name: Spring.trc

TRACE® 700 v6.2.6.5 calculated at 12:24 PM on 03/19/2012
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

Baseline Metal Panels



MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**PSU Ice Arena (BASE LINE)**												
Electric													
On-Pk Cons. (kWh)	140,948	127,308	140,948	136,402	140,911	136,348	140,863	140,898	136,364	140,948	136,402	140,948	1,659,288
On-Pk Demand (kW)	189	189	189	189	189	189	189	189	189	189	189	189	189
Purchased Steam													
On-Pk Cons. (therms)	8,280	7,599	5,492	3,110	883	332	154	395	804	3,025	4,268	7,116	41,457
On-Pk Demand (therms/hr)	23	16	13	10	4	3	3	3	6	10	12	15	23
Purchased Chilled Water													
On-Pk Cons. (therms)	10,072	9,096	11,981	12,562	16,983	19,355	22,077	20,305	16,573	13,748	11,976	10,290	175,018
On-Pk Demand (therms/hr)	39	45	48	52	63	70	77	70	66	55	51	46	77

Energy Consumption

Building	149,483	Btu/(ft2-year)
Source	196,943	Btu/(ft2-year)
Floor Area	182,701	ft2

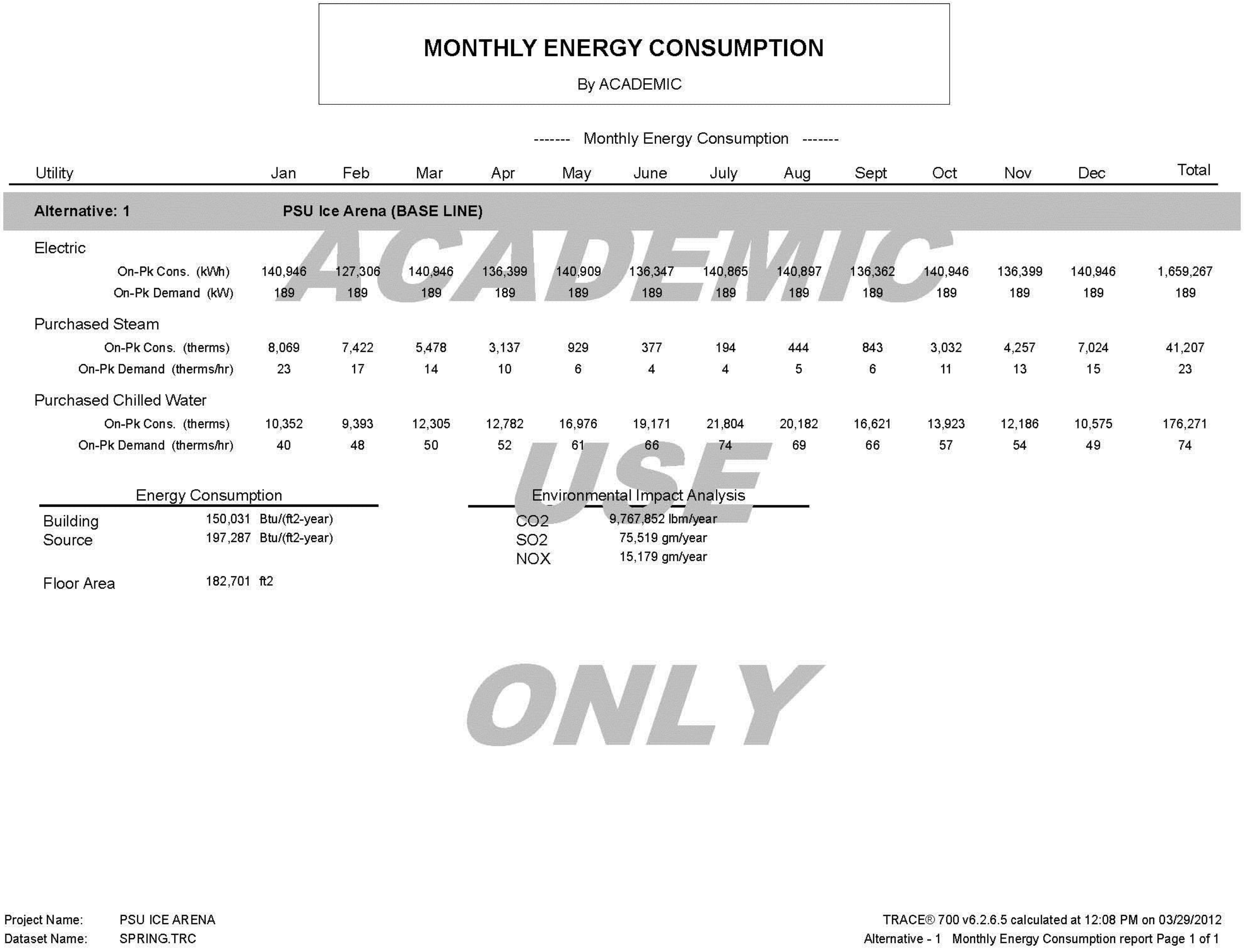
Environmental Impact Analysis

CO2	9,732,128 lbm/year
SO2	75,243 gm/year
NOX	15,124 gm/year

Project Name: PSU ICE ARENA
Dataset Name: Spring.trc

TRACE® 700 v6.2.6.5 calculated at 12:34 PM on 03/19/2012
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

50% Glass



MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**PSU Ice Arena (BASE LINE)**												
Electric													
On-Pk Cons. (kWh)	140,946	127,306	140,946	136,399	140,909	136,347	140,865	140,897	136,362	140,946	136,399	140,946	1,659,267
On-Pk Demand (kW)	189	189	189	189	189	189	189	189	189	189	189	189	189
Purchased Steam													
On-Pk Cons. (therms)	8,069	7,422	5,478	3,137	929	377	194	444	843	3,032	4,257	7,024	41,207
On-Pk Demand (therms/hr)	23	17	14	10	6	4	4	5	6	11	13	15	23
Purchased Chilled Water													
On-Pk Cons. (therms)	10,352	9,393	12,305	12,782	16,976	19,171	21,804	20,182	16,621	13,923	12,186	10,575	176,271
On-Pk Demand (therms/hr)	40	48	50	52	61	66	74	69	66	57	54	49	74

Energy Consumption

Building	150,031	Btu/(ft2-year)
Source	197,287	Btu/(ft2-year)
Floor Area	182,701	ft2

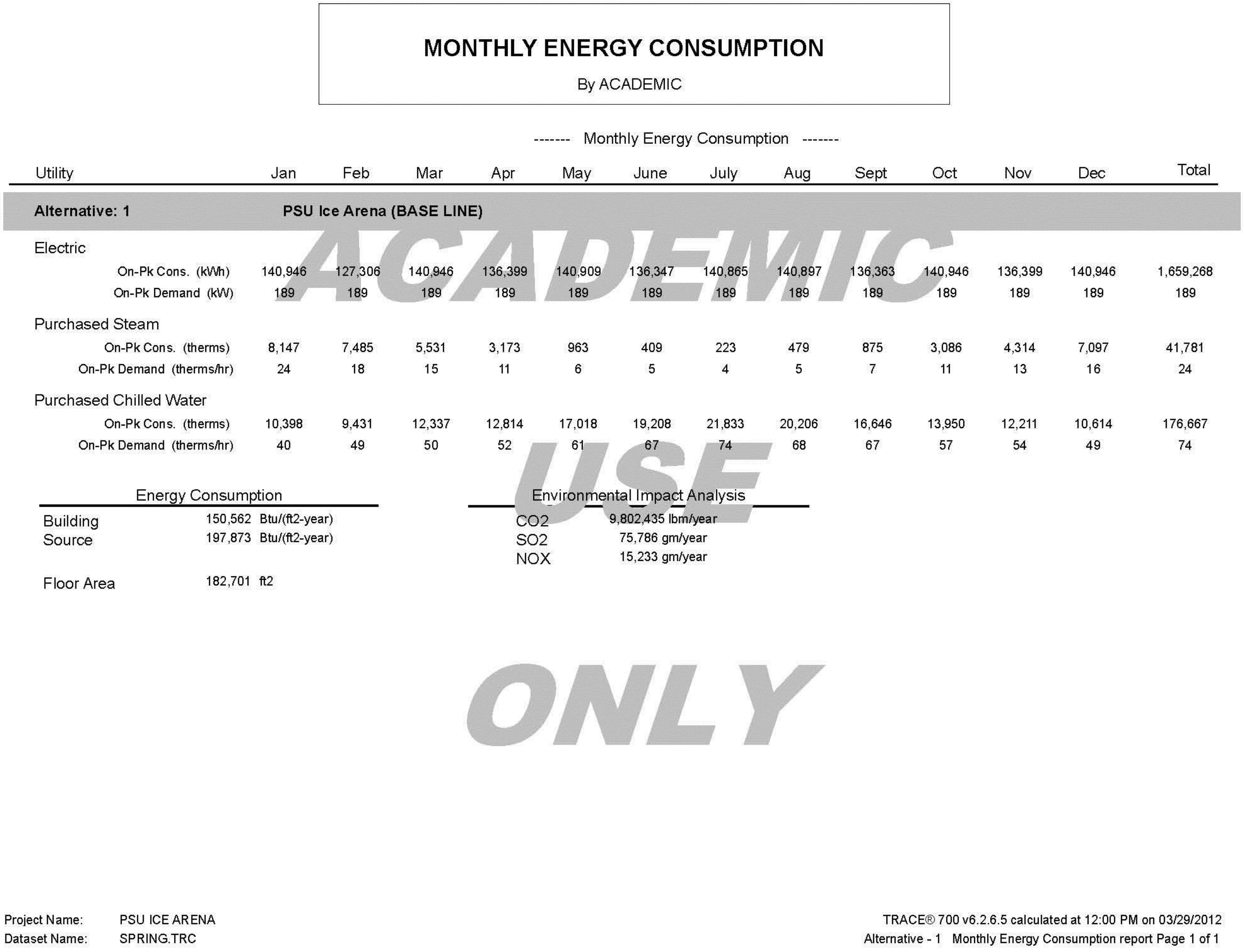
Environmental Impact Analysis

CO2	9,767,852 lbm/year
SO2	75,519 gm/year
NOX	15,179 gm/year

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 12:08 PM on 03/29/2012
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

60% Glass



MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**PSU Ice Arena (BASE LINE)**												
Electric													
On-Pk Cons. (kWh)	140,946	127,306	140,946	136,399	140,909	136,347	140,865	140,897	136,363	140,946	136,399	140,946	1,659,268
On-Pk Demand (kW)	189	189	189	189	189	189	189	189	189	189	189	189	189
Purchased Steam													
On-Pk Cons. (therms)	8,147	7,485	5,531	3,173	963	409	223	479	875	3,086	4,314	7,097	41,781
On-Pk Demand (therms/hr)	24	18	15	11	6	5	4	5	7	11	13	16	24
Purchased Chilled Water													
On-Pk Cons. (therms)	10,398	9,431	12,337	12,814	17,018	19,208	21,833	20,206	16,646	13,950	12,211	10,614	176,667
On-Pk Demand (therms/hr)	40	49	50	52	61	67	74	68	67	57	54	49	74

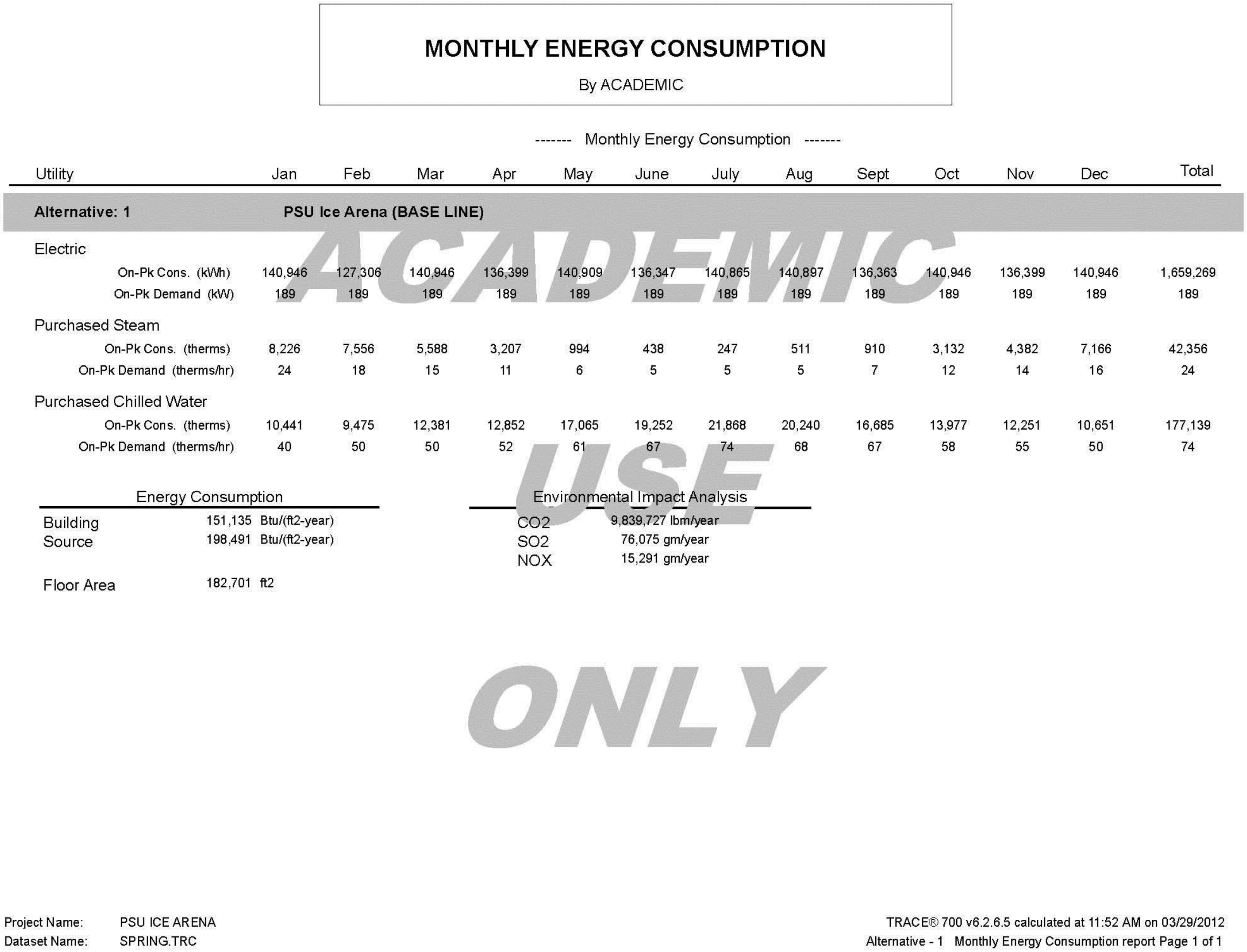
Energy Consumption		
Building	150,562	Btu/(ft2-year)
Source	197,873	Btu/(ft2-year)
Floor Area	182,701	ft2

Environmental Impact Analysis	
CO2	9,802,435 lbm/year
SO2	75,786 gm/year
NOX	15,233 gm/year

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 12:00 PM on 03/29/2012
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

70% Glass



MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**PSU Ice Arena (BASE LINE)**												
Electric													
On-Pk Cons. (kWh)	140,946	127,306	140,946	136,399	140,909	136,347	140,865	140,897	136,363	140,946	136,399	140,946	1,659,269
On-Pk Demand (kW)	189	189	189	189	189	189	189	189	189	189	189	189	189
Purchased Steam													
On-Pk Cons. (therms)	8,226	7,556	5,588	3,207	994	438	247	511	910	3,132	4,382	7,166	42,356
On-Pk Demand (therms/hr)	24	18	15	11	6	5	5	5	7	12	14	16	24
Purchased Chilled Water													
On-Pk Cons. (therms)	10,441	9,475	12,381	12,852	17,065	19,252	21,868	20,240	16,685	13,977	12,251	10,651	177,139
On-Pk Demand (therms/hr)	40	50	50	52	61	67	74	68	67	58	55	50	74

Energy Consumption		
Building	151,135	Btu/(ft2-year)
Source	198,491	Btu/(ft2-year)
Floor Area	182,701	ft2

Environmental Impact Analysis		
CO2	9,839,727	lbm/year
SO2	76,075	gm/year
NOX	15,291	gm/year

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 11:52 AM on 03/29/2012
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

80% Glass

MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**PSU Ice Arena (BASE LINE)**												
Electric													
On-Pk Cons. (kWh)	140,946	127,306	140,946	136,399	140,910	136,347	140,865	140,897	136,363	140,946	136,399	140,946	1,659,271
On-Pk Demand (kW)	189	189	189	189	189	189	189	189	189	189	189	189	189
Purchased Steam													
On-Pk Cons. (therms)	8,292	7,620	5,651	3,249	1,022	465	271	541	947	3,195	4,446	7,224	42,923
On-Pk Demand (therms/hr)	25	18	15	12	6	5	5	6	8	12	14	17	25
Purchased Chilled Water													
On-Pk Cons. (therms)	10,480	9,517	12,430	12,901	17,117	19,301	21,911	20,282	16,734	14,026	12,292	10,685	177,675
On-Pk Demand (therms/hr)	40	50	51	52	61	67	75	68	67	58	56	51	75

Energy Consumption		
Building	151,739	Btu/(ft2-year)
Source	199,130	Btu/(ft2-year)
Floor Area	182,701	ft2

Environmental Impact Analysis		
CO2	9,879,037	lbm/year
SO2	76,379	gm/year
NOX	15,352	gm/year

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 11:44 AM on 03/29/2012
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

90% Glass

MONTHLY ENERGY CONSUMPTION

By ACADEMIC

------- Monthly Energy Consumption -------

Utility	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Alternative: 1	**PSU Ice Arena (BASE LINE)**												
Electric													
On-Pk Cons. (kWh)	140,947	127,307	140,946	136,400	140,910	136,347	140,865	140,897	136,363	140,947	136,400	140,947	1,659,275
On-Pk Demand (kW)	189	189	189	189	189	189	189	189	189	189	189	189	189
Purchased Steam													
On-Pk Cons. (therms)	8,358	7,684	5,718	3,294	1,047	488	293	566	977	3,262	4,508	7,288	43,482
On-Pk Demand (therms/hr)	25	19	16	13	7	6	5	6	9	13	14	17	25
Purchased Chilled Water													
On-Pk Cons. (therms)	10,524	9,563	12,492	12,959	17,178	19,360	21,968	20,338	16,791	14,086	12,340	10,726	178,325
On-Pk Demand (therms/hr)	41	51	51	53	61	68	75	68	68	59	56	52	75

Energy Consumption

Building	152,401	Btu/(ft2-year)
Source	199,812	Btu/(ft2-year)
Floor Area	182,701	ft2

Environmental Impact Analysis

CO2	9,922,133 lbm/year
SO2	76,712 gm/year
NOX	15,419 gm/year

Project Name: PSU ICE ARENA
Dataset Name: SPRING.TRC

TRACE® 700 v6.2.6.5 calculated at 11:29 AM on 03/29/2012
Alternative - 1 Monthly Energy Consumption report Page 1 of 1

Appendix L. Life-Cycle Cost Analysis Spreadsheet Example

70% Glass

Alternative 1: Purchased District Steam and Chilled Water								
	ELECTRIC		**STEAM**		**CHILLED WATER**			
Ann. Use	1,659,269	kWh	42,356	therms	177,139.00	therms		
Unit Cost	$ 0.08	$/kWh	$ 1.14	$/therm	$ 1.40	$/therm		
Ann. Cost	$ 132,742		$ 48,286		$ 247,995			
	Discount Rate	2.30	%	(OMB 30 Year)				
Date	Year	Capital	Other Mat.	Elect. Escalation	Nat. Gas Escalation	Elect. Cost	Steam Cost	Chilled Water Cost
2011	1	$ -	$ 3,000	1.00	1.00	$ 132,742	$ 48,286	$ 247,995
2012	2	$ -	$ 3,000	0.96	0.98	$ 127,432	$ 47,320	$ 238,075
2013	3	$ -	$ 3,000	0.93	0.95	$ 123,450	$ 45,872	$ 230,635
2014	4	$ -	$ 3,000	0.91	0.91	$ 120,795	$ 43,940	$ 225,675
2015	5	$ -	$ 3,000	0.91	0.90	$ 120,795	$ 43,457	$ 225,675
2016	6	$ -	$ 3,000	0.90	0.90	$ 119,467	$ 43,457	$ 223,195
2017	7	$ -	$ 3,000	0.90	0.91	$ 119,467	$ 43,940	$ 223,195
2018	8	$ -	$ 3,000	0.91	0.92	$ 120,795	$ 44,423	$ 225,675
2019	9	$ -	$ 3,000	0.93	0.93	$ 123,450	$ 44,906	$ 230,635
2020	10	$ -	$ 3,000	0.94	0.94	$ 124,777	$ 45,389	$ 233,115
2021	11	$ -	$ 3,000	0.94	0.95	$ 124,777	$ 45,872	$ 233,115
2022	12	$ -	$ 3,000	0.94	0.97	$ 124,777	$ 46,837	$ 233,115
2023	13	$ -	$ 3,000	0.94	0.98	$ 124,777	$ 47,320	$ 233,115
2024	14	$ -	$ 3,000	0.94	0.99	$ 124,777	$ 47,803	$ 233,115
2025	15	$ -	$ 3,000	0.94	1.00	$ 124,777	$ 48,286	$ 233,115
2026	16	$ -	$ 3,000	0.94	1.01	$ 124,777	$ 48,769	$ 233,115
2027	17	$ -	$ 3,000	0.94	1.02	$ 124,777	$ 49,252	$ 233,115
2028	18	$ -	$ 3,000	0.94	1.03	$ 124,777	$ 49,734	$ 233,115
2029	19	$ -	$ 3,000	0.93	1.04	$ 123,450	$ 50,217	$ 230,635
2030	20	$ -	$ 3,000	0.93	1.05	$ 123,450	$ 50,700	$ 230,635
2031	21	$ -	$ 3,000	0.93	1.06	$ 123,450	$ 51,183	$ 230,635
2032	22	$ -	$ 3,000	0.94	1.07	$ 124,777	$ 51,666	$ 233,115
2033	23	$ -	$ 3,000	0.94	1.08	$ 124,777	$ 52,149	$ 233,115
2034	24	$ -	$ 3,000	0.95	1.09	$ 126,104	$ 52,632	$ 235,595
2035	25	$ -	$ 3,000	0.95	1.09	$ 126,104	$ 52,632	$ 235,595
2036	26	$ -	$ 3,000	0.95	1.11	$ 126,104	$ 53,597	$ 235,595
2037	27	$ -	$ 3,000	0.95	1.12	$ 126,104	$ 54,080	$ 235,595
2038	28	$ -	$ 3,000	0.94	1.14	$ 124,777	$ 55,046	$ 233,115
2039	29	$ -	$ 3,000	0.94	1.15	$ 124,777	$ 55,529	$ 233,115
2040	30	$ -	$ 3,000	0.93	1.17	$ 123,450	$ 56,494	$ 230,635
	Column NPV	$ -	$ 64,499			$ 2,670,749	$ 1,039,815	$4,989,633
		Total NPV						**$ 8,764,696**

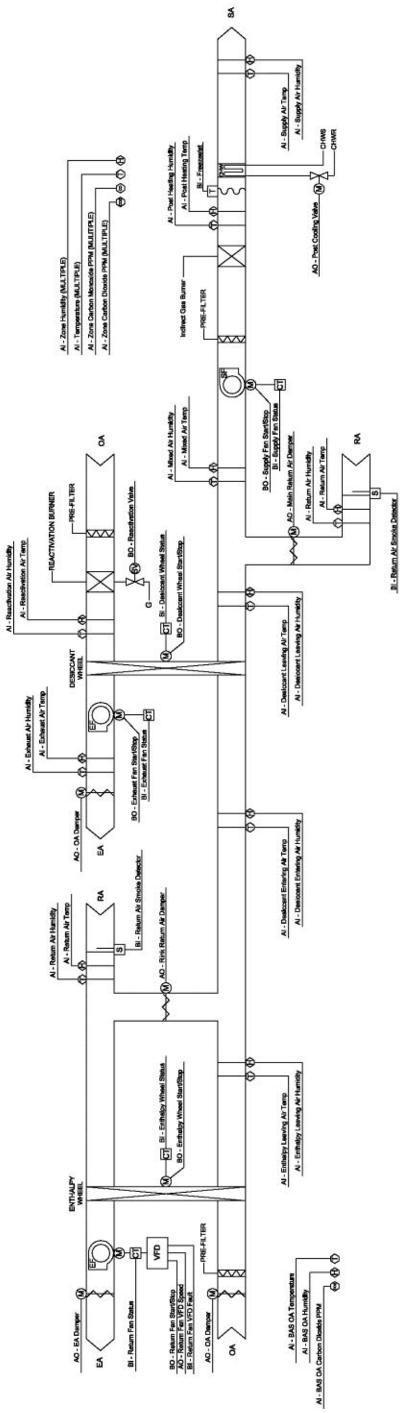
Appendix M. AHU Room CFM Table Example

AHU-9 CFM Calculations

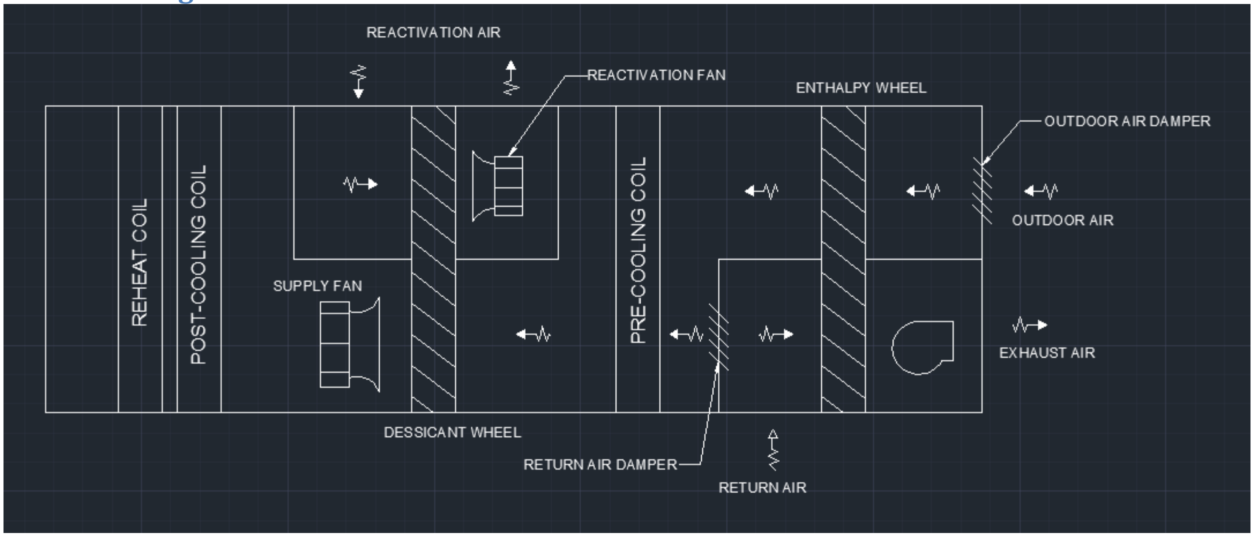
		CFM
136	LOCKER ROOM	1000
134A	RESTROOM	0
134	LOCKER ROOM	1000
135A	RESTROOM	0
Q108	CORRIDOR	100
137	LOCKER ROOM	1000
134B	SHOWER	150
135	LOCKER ROOM	1000
135B	SHOWER	150
140	LOCKER ROOM	1000
138B	SHOWER	200
138A	RESTROOM	0
138	LOCKER ROOM	1000
Q109	CORRIDOR	75
141	LOCKER ROOM	1000
139B	SHOWER	200
139A	RESTROOM	0
139	LOCKER ROOM	800
144	OFFICIAL LOCKER ROOM	200
142A	BATHROOM	0
142	OFFICIAL LOCKER ROOM	200
J142	JAN	75
Q110	CORRIDOR	75
143A	BATHROOM	0
145	OFFICIAL LOCKER ROOM	200
143	OFFICIAL LOCKER ROOM	200
147A	STORAGE	75
		9700

Appendix N. Mechanical System Schematic

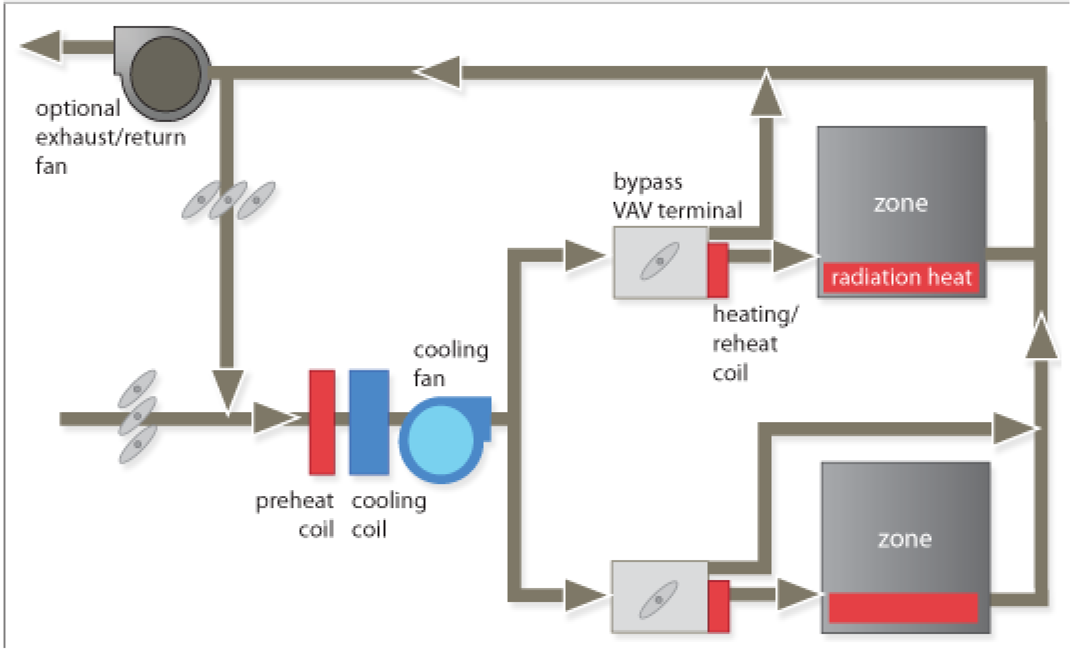
Dehumidification Unit Control Diagram



VAV AHU Diagram



Trane Trace System Schematic



Appendix O. Mechanical References

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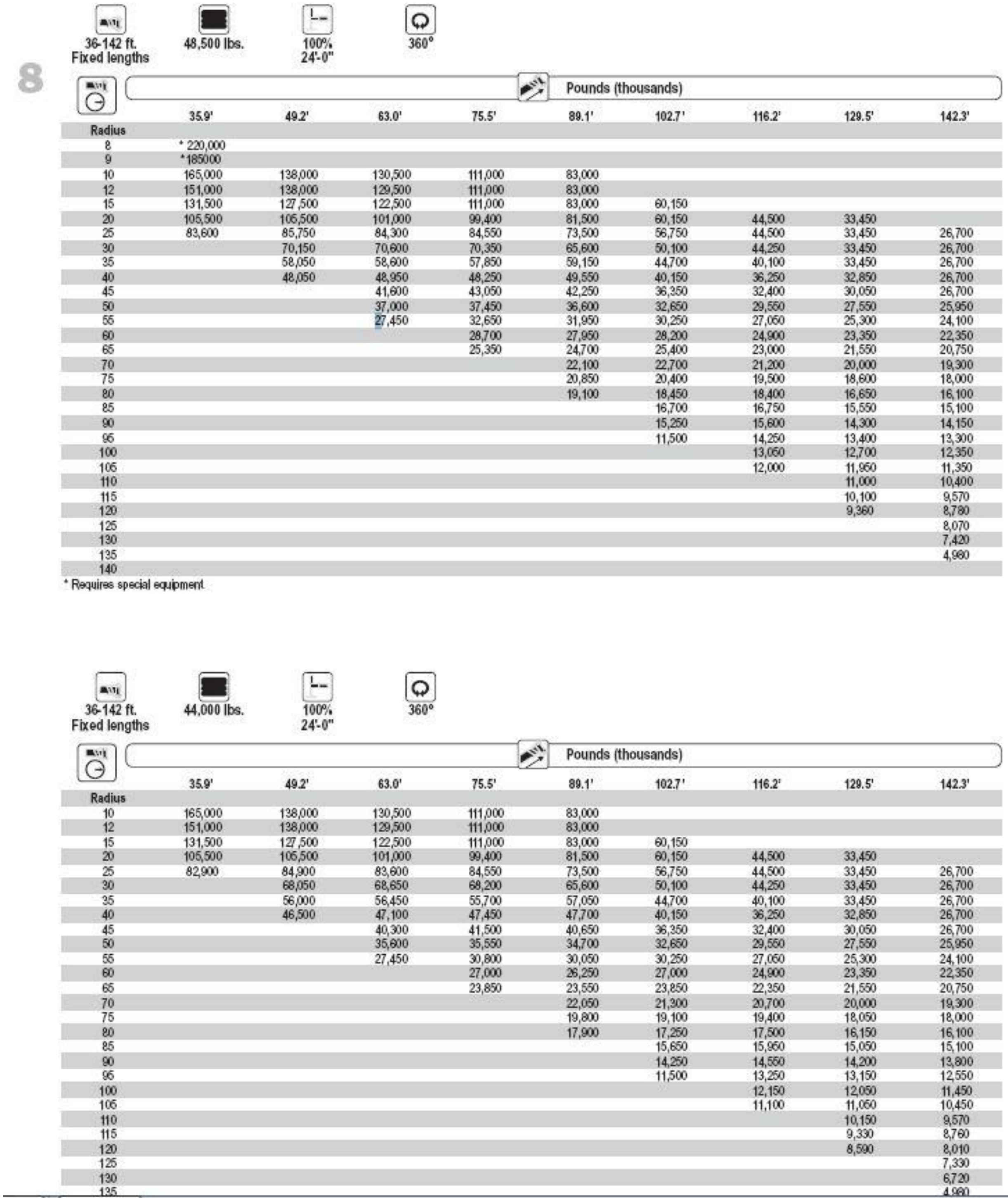
Construction Appendix

Appendix P. Crane Load Charts



8

36-142 ft.
Fixed lengths
48,500 lbs.
100%
24'-0"
360°

Pounds (thousands)

Radius	35.9'	49.2'	63.0'	75.5'	89.1'	102.7'	116.2'	129.5'	142.3'
8	* 220,000								
9	*185000								
10	165,000	138,000	130,500	111,000	83,000				
12	151,000	138,000	129,500	111,000	83,000				
15	131,500	127,500	122,500	111,000	83,000	60,150			
20	105,500	105,500	101,000	99,400	81,500	60,150	44,500	33,450	
25	83,600	85,750	84,300	84,550	73,500	56,750	44,500	33,450	26,700
30		70,150	70,600	70,350	65,600	50,100	44,250	33,450	26,700
35		58,050	58,600	57,850	59,150	44,700	40,100	33,450	26,700
40		48,050	48,950	48,250	49,550	40,150	36,250	32,850	26,700
45			41,600	43,050	42,250	36,350	32,400	30,050	26,700
50			37,000	37,450	36,600	32,650	29,550	27,550	25,950
55			27,450	32,650	31,950	30,250	27,050	25,300	24,100
60				28,700	27,950	28,200	24,900	23,350	22,350
65				25,350	24,700	25,400	23,000	21,550	20,750
70					22,100	22,700	21,200	20,000	19,300
75					20,850	20,400	19,500	18,600	18,000
80					19,100	18,450	18,400	16,650	16,100
85						16,700	16,750	15,550	15,100
90						15,250	15,600	14,300	14,150
95						11,500	14,250	13,400	13,300
100							13,050	12,700	12,350
105							12,000	11,950	11,350
110								11,000	10,400
115								10,100	9,570
120								9,360	8,780
125									8,070
130									7,420
135									4,980
140									

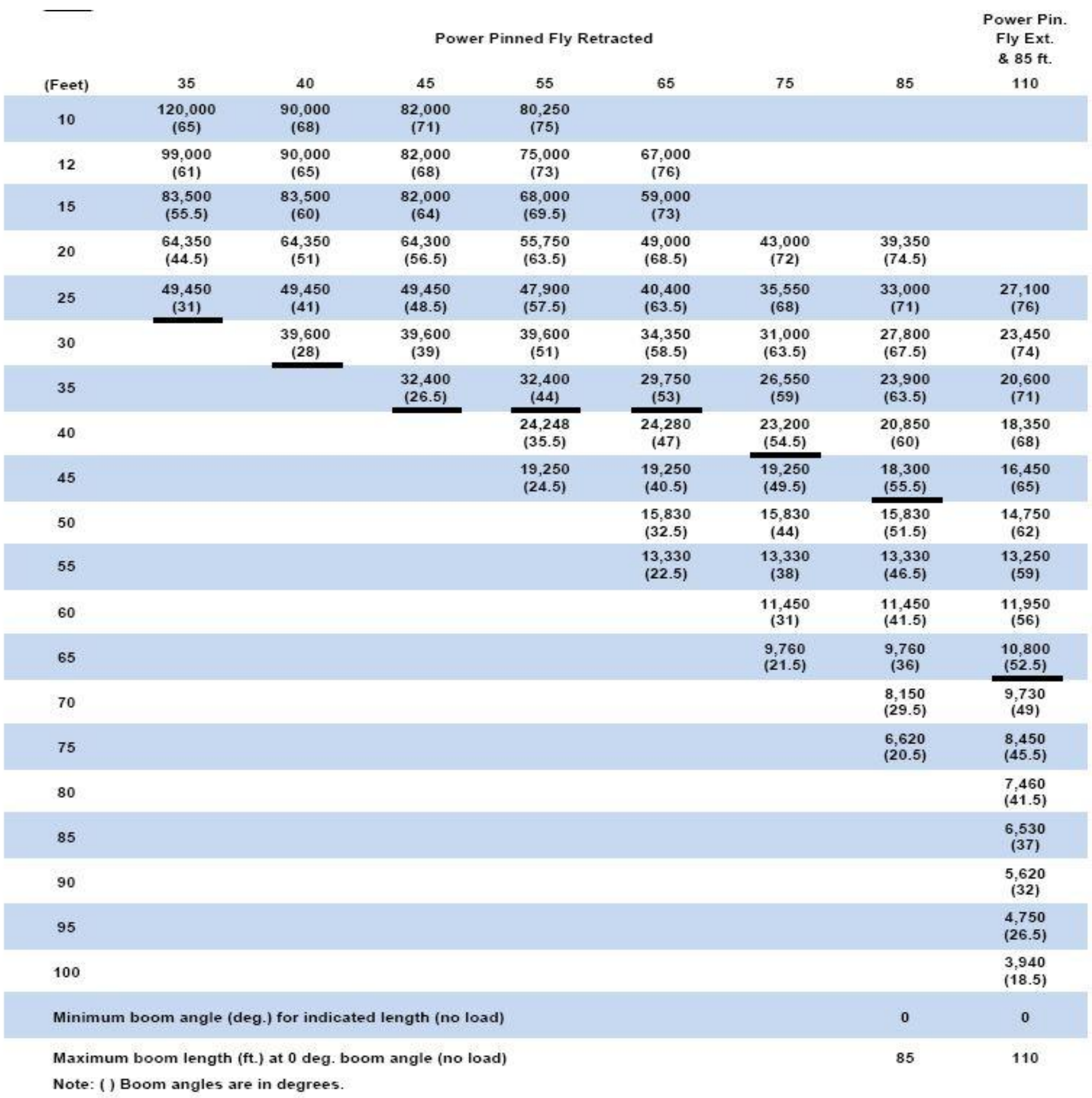
* Requires special equipment

36-142 ft.
Fixed lengths
44,000 lbs.
100%
24'-0"
360°

Pounds (thousands)

Radius	35.9'	49.2'	63.0'	75.5'	89.1'	102.7'	116.2'	129.5'	142.3'
10	165,000	138,000	130,500	111,000	83,000				
12	151,000	138,000	129,500	111,000	83,000				
15	131,500	127,500	122,500	111,000	83,000	60,150			
20	105,500	105,500	101,000	99,400	81,500	60,150	44,500	33,450	
25	82,900	84,900	83,600	84,550	73,500	56,750	44,500	33,450	26,700
30		68,050	68,650	68,200	65,600	50,100	44,250	33,450	26,700
35		56,000	56,450	55,700	57,050	44,700	40,100	33,450	26,700
40		46,500	47,100	47,450	47,700	40,150	36,250	32,850	26,700
45			40,300	41,500	40,650	36,350	32,400	30,050	26,700
50			35,600	35,550	34,700	32,650	29,550	27,550	25,950
55			27,450	30,800	30,050	30,250	27,050	25,300	24,100
60				27,000	26,250	27,000	24,900	23,350	22,350
65				23,850	23,550	23,850	22,350	21,550	20,750
70					22,050	21,300	20,700	20,000	19,300
75					19,800	19,100	19,400	18,050	18,000
80					17,900	17,250	17,500	16,150	16,100
85						15,650	15,950	15,050	15,100
90						14,250	14,550	14,200	13,800
95						11,500	13,250	13,150	12,550
100							12,150	12,050	11,450
105							11,100	11,050	10,450
110								10,150	9,570
115								9,330	8,760
120								8,590	8,010
125									7,330
130									6,720
135									4,980

TMS 900E Load Chart (source: bigge.com)



	Power Pinned Fly Retracted							Power Pin. Fly Ext. & 85 ft.
(Feet)	35	40	45	55	65	75	85	110
10	120,000 (65)	90,000 (68)	82,000 (71)	80,250 (75)				
12	99,000 (61)	90,000 (65)	82,000 (68)	75,000 (73)	67,000 (76)			
15	83,500 (55.5)	83,500 (60)	82,000 (64)	68,000 (69.5)	59,000 (73)			
20	64,350 (44.5)	64,350 (51)	64,300 (56.5)	55,750 (63.5)	49,000 (68.5)	43,000 (72)	39,350 (74.5)	
25	49,450 (31)	49,450 (41)	49,450 (48.5)	47,900 (57.5)	40,400 (63.5)	35,550 (68)	33,000 (71)	27,100 (76)
30		39,600 (28)	39,600 (39)	39,600 (51)	34,350 (58.5)	31,000 (63.5)	27,800 (67.5)	23,450 (74)
35			32,400 (26.5)	32,400 (44)	29,750 (53)	26,550 (59)	23,900 (63.5)	20,600 (71)
40				24,248 (35.5)	24,280 (47)	23,200 (54.5)	20,850 (60)	18,350 (68)
45				19,250 (24.5)	19,250 (40.5)	19,250 (49.5)	18,300 (55.5)	16,450 (65)
50					15,830 (32.5)	15,830 (44)	15,830 (51.5)	14,750 (62)
55					13,330 (22.5)	13,330 (38)	13,330 (46.5)	13,250 (59)
60						11,450 (31)	11,450 (41.5)	11,950 (56)
65						9,760 (21.5)	9,760 (36)	10,800 (52.5)
70							8,150 (29.5)	9,730 (49)
75							6,620 (20.5)	8,450 (45.5)
80								7,460 (41.5)
85								6,530 (37)
90								5,620 (32)
95								4,750 (26.5)
100								3,940 (18.5)
Minimum boom angle (deg.) for indicated length (no load)							0	0
Maximum boom length (ft.) at 0 deg. boom angle (no load)							85	110

Note: ( ) Boom angles are in degrees.

RT 760 Load Chart (source: bigge.com)

Appendix Q. Existing and Redesigned Ductwork Lengths, Pressure Drops, and Costs

Existing Return Ductwork

	Duct Size	Length	# Elbows	P Drop	SF	Diameter	Gauge	Unit Weight (lbs/ft)	Elbow Weight (lbs)	Total Weight (lbs)	Unit Cost ($/lb)	Elbow Cost	Total Cost
AHU-1	32x20	27.467	6	0.024	269.34	27.5	24	11.2	34.5	514.63	$ 7.85	$ 240.00	$ 3,854.90
	26x26	2	2	0.0014	16.44	28.4	24	11.2	28.7	79.80	$ 8.20	$ 218.65	$ 620.98
	24x24	310.7	3	0.3434	2482.62	26.2	24	10.3	24.2	3272.81	$ 7.05	$ 169.50	$ 23,069.98
AHU-2	48x20	12.9	2	0.005	145.57	33.1	22	17	64.7	348.70	$ 7.85	$ 320.00	$ 2,361.51
	30x30	345.86	7	0.319	3464.2	32.8	22	15	37.9	5453.20	$ 6.85	$ 311.07	$ 37,714.61
AHU-6	42x42	6	1	0.0033	70.4	45.9	22	21	80.9	206.90	$ 8.20	$ 593.70	$ 1,626.90
	50x36	306.75	7	0.216	4395.13	46.2	22	21.5	88.4	7213.93	$ 6.85	$ 625.00	$ 49,551.61
BOWL	72x40	786.25	8		13649.08	58.0	20	32.5	175	26953.13	$ 6.85	$ 1,300.00	$ 185,438.91
											Return Total Cost:		**$ 364,736.55**

Existing Supply Ductwork

	Duct Size	Length	# Elbows	P Drop	SF	Diameter	Gauge (no.)	Unit Weight (lbs/ft)	Elbow Weight (lbs)	Total Weight (lbs)	Unit Cost ($/lb)	Elbow Cost	Total Cost
AHU-1	32x20	41.108	4	0.072	395.88	27.5	24	11.2	34.5	598.41	$ 7.85	$ 240.00	$ 4,574.22
	26x26	294.25	2	0.219	2520.54	28.4	24	11.2	28.7	3353.00	$ 7.05	$ 218.65	$ 23,671.28
AHU-2	34x20	12.56	2	0.029	130.96	28.3	24	11.6	38	221.70	$ 8.20	$ 278.00	$ 1,750.71
	34x34	334.55	9	0.1968	3757.84	37.2	22	17.0	60.5	6231.85	$ 6.85	$ 433.62	$ 42,860.93
AHU-6	66x32	355.75	8	0.1617	5771.21	49.4	22	24.5	144	9867.88	$ 6.85	$ 1,000.00	$ 67,703.74
AHU-7	38x32	208.03	9	0.1081	2292.54	38.1	22	17.5	60.8	4187.73	$ 7.05	$ 440.30	$ 29,628.40
BOWL	70	102.8	3	-	1888.9	70	20	34.1	500	5005.48	$ 100.00	$ 1,000.00	$ 353,548.00
	68	117	-	-	2084	68	20	33.1	-	3872.70	$ 95.75	$ 1,000.00	$ 370,811.03
	62	94.3	-	-	3062	62	20	30.2	-	2847.86	$ 93.50	$ 1,000.00	$ 266,274.91
	48	188.6	-	-	1448	48	22	19.9	-	3753.14	$ 72.00	$ 850.00	$ 270,226.08
											Supply Cost:		**$ 1,488,728.41**

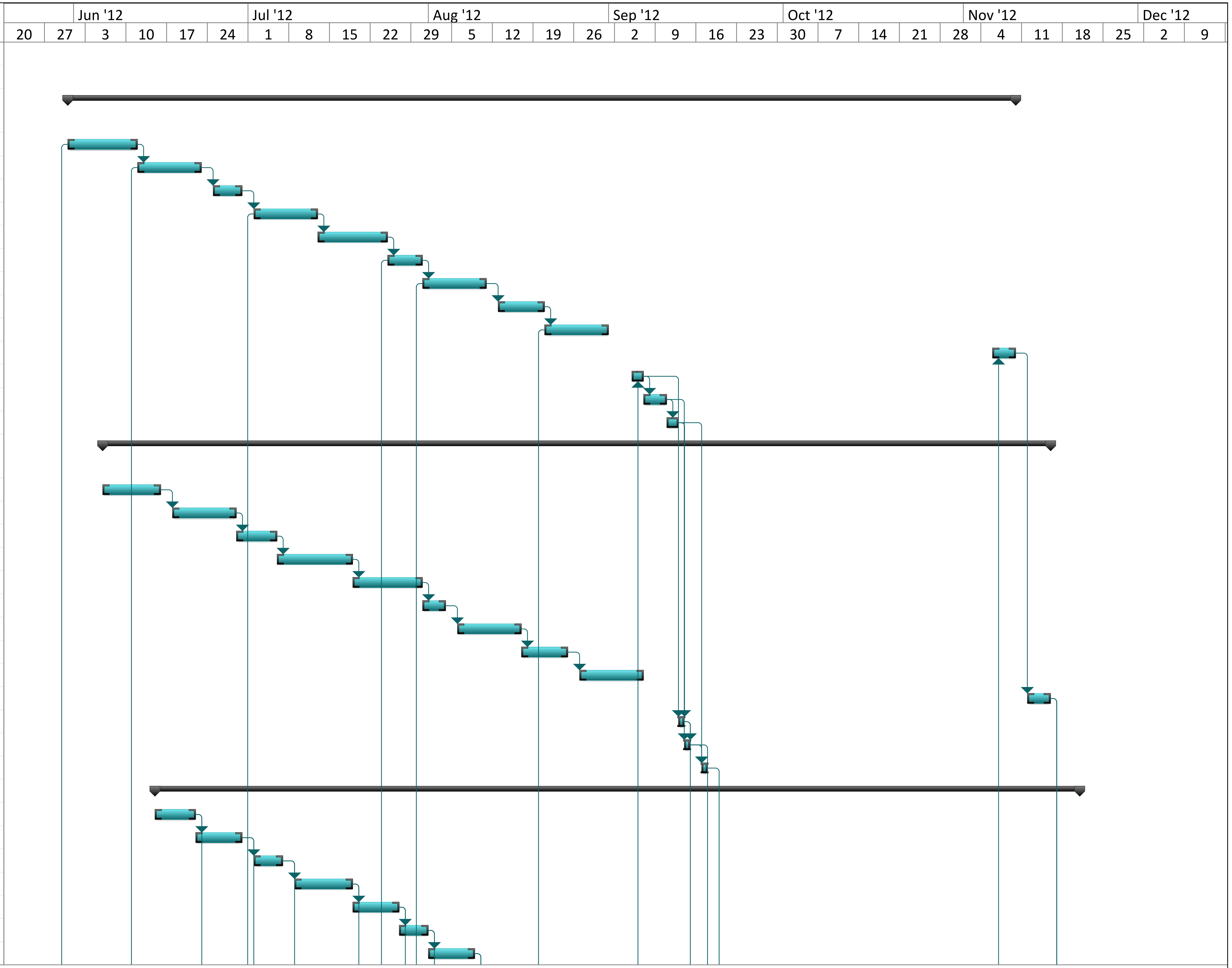
Redesign Return Ductwork

Unit	Duct Size	Length	# Elbows	P Drop	SF	Diameter	Gauge	Unit Weight (lbs/ft)	Elbow Weight (lbs)	Total Weight (lbs)	Unit Cost ($/lb)	Elbow Cost	Total Cost
AHU-1	24x24	54.55	5	0.0606	438.2	26.2	24	10.3	24.2	682.87	$ 7.55	$ 169.50	$ 5,089.58
AHU-2	48x20	81.25	2	0.0741	921.7	33.1	22	17.0	64.7	1510.65	$ 7.30	$ 320.00	$ 10,723.13
AHU-6	50x36	77.85	9	0.0589	1319.79	46.2	22	21.5	88.4	2469.38	$ 7.30	$ 625.00	$ 17,843.56
BOWL	72x30	217.07	6	-	3740.36	49.6	20	29.6	160	7385.27	$ 6.85	$ 1,000.00	$ 50,013.11
											Return Total Cost:		**$ 99,526.90**

Redesign Supply Ductwork

	Duct Size	Length	# Elbows	P Drop	SF	Diameter	Gauge	Unit Weight (lbs/ft)	Elbow Weight (lbs)	Total Weight (lbs)	Unit Cost ($/lb)	Elbow Cost	Total Cost
AHU-1	26x26	37.5	5	0.0281	327.68	28.4	24	11.2	28.7	563.50	$ 7.85	$ 218.65	$ 4,390.25
AHU-2	34x20	15.5	2	0.0116	139.23	28.3	24	11.6	37.2	254.20	$ 7.85	$ 278.00	$ 1,967.43
AHU-6	66x32	63.25	5	0.0289	1034.36	49.4	22	24.5	144	2269.63	$ 11.40	$ 1,000.00	$ 22,665.73
AHU-7	38x32	208.03	9	0.1081	2292.54	38.1	22	17.5	60.8	4187.73	$ 11.40	$ 440.30	$ 45,464.69
BOWL	50	157.7	4	-	2036.06	50	22	20.6	300	4448.62	$ 75.50	$ 875.00	$ 248,770.81
	48	168.95	-	-	2013.97	48	22	19.9	-	3362.11	$ 72.00	$ 850.00	$ 242,071.56
	40	220.02	-	-	2248.66	40	24	13.6	-	2992.27	$ 60.50	$ 800.00	$ 181,032.46
											Supply Total Cost:		**$ 771,291.39**

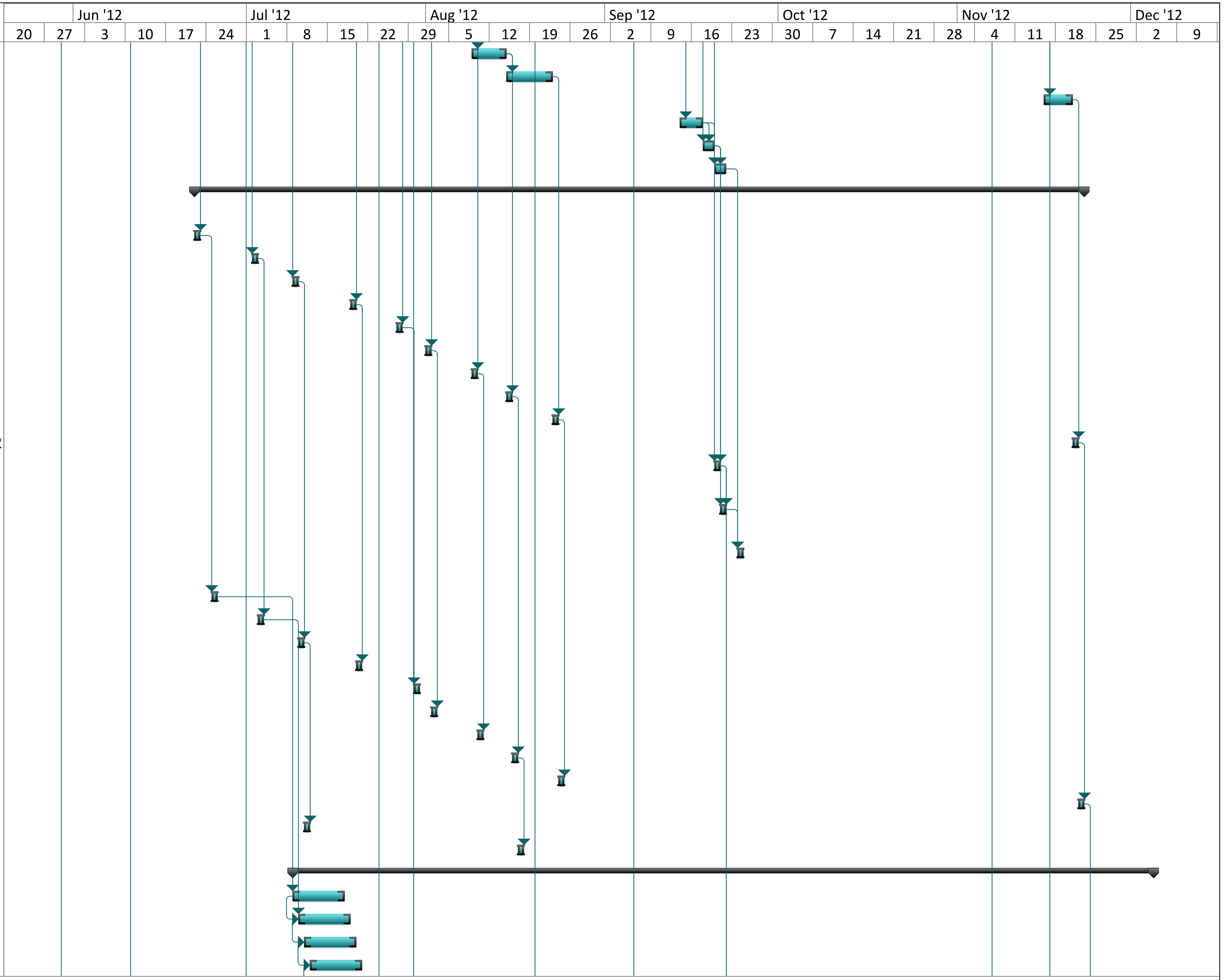
ID	ℹ	Task Name	Duration	Start	Finish
1		Excavation			
2		Foundations			
3		**Erect Structural Steel (and Risers)**	**117 days**	**Thu 5/31/12**	**Fri 11/9/12**
4		SE #1	8 days	Thu 5/31/12	Mon 6/11/12
5		SE #2	9 days	Tue 6/12/12	Fri 6/22/12
6		SE #3	5 days	Mon 6/25/12	Fri 6/29/12
7		NE #4	9 days	Mon 7/2/12	Thu 7/12/12
8		NE #5	8 days	Fri 7/13/12	Tue 7/24/12
9		NW #6	4 days	Wed 7/25/12	Mon 7/30/12
10		NW #7	9 days	Tue 7/31/12	Fri 8/10/12
11		NW #8	6 days	Mon 8/13/12	Mon 8/20/12
12		SW #9	9 days	Tue 8/21/12	Fri 8/31/12
13		SW #10	4 days	Tue 11/6/12	Fri 11/9/12
14		West #11	2 days	Wed 9/5/12	Thu 9/6/12
15		West #12	2 days	Fri 9/7/12	Mon 9/10/12
16		West #13	2 days	Tue 9/11/12	Wed 9/12/12
17		**Plumb/Bolt/Weld Structural Steel**	**117 days**	**Wed 6/6/12**	**Thu 11/15/12**
18		SE #1	8 days	Wed 6/6/12	Fri 6/15/12
19		SE #2	9 days	Mon 6/18/12	Thu 6/28/12
20		SE #3	5 days	Fri 6/29/12	Thu 7/5/12
21		NE #4	9 days	Fri 7/6/12	Wed 7/18/12
22		NE #5	8 days	Thu 7/19/12	Mon 7/30/12
23		NW #6	4 days	Tue 7/31/12	Fri 8/3/12
24		NW#7	9 days	Mon 8/6/12	Thu 8/16/12
25		NW #8	6 days	Fri 8/17/12	Fri 8/24/12
26		SW #9	9 days	Mon 8/27/12	Thu 9/6/12
27		SW #10	4 days	Mon 11/12/12	Thu 11/15/12
28		West #11	1 day	Thu 9/13/12	Thu 9/13/12
29		West #12	1 day	Fri 9/14/12	Fri 9/14/12
30		West #13	1 day	Mon 9/17/12	Mon 9/17/12
31		**Lay Metal Deck**	**113 days**	**Fri 6/15/12**	**Tue 11/20/12**
32		SE #1 All Levels	5 days	Fri 6/15/12	Thu 6/21/12
33		SE #2 All Levels	6 days	Fri 6/22/12	Fri 6/29/12
34		SE #3 All Levels	5 days	Mon 7/2/12	Fri 7/6/12
35		NE #4 All Levels	8 days	Mon 7/9/12	Wed 7/18/12
36		NE #5 All Levels	6 days	Thu 7/19/12	Thu 7/26/12
37		NW #6 All Levels	3 days	Fri 7/27/12	Tue 7/31/12
38		NW #7 All Levels	6 days	Wed 8/1/12	Wed 8/8/12



Project: Penn State Ice Arena
Date: Fri 4/20/12

Task	▬	Project Summary	▬	Inactive Milestone	◇	Manual Summary Rollup	▬	Deadline	⬇
Split	┄	External Tasks	▬	Inactive Summary	▭	Manual Summary	▬	Progress	▬
Milestone	◆	External Milestone	◆	Manual Task	▬	Start-only	[		
Summary	▬	Inactive Task	▭	Duration-only	▬	Finish-only	]		

ID	ℹ	Task Name	Duration	Start	Finish
39		NW #8 All Levels	4 days	Thu 8/9/12	Tue 8/14/12
40		SW #9 All Levels	6 days	Wed 8/15/12	Wed 8/22/12
41		SW #10 All Levels	3 days	Fri 11/16/12	Tue 11/20/12
42		West #11 All Levels	2 days	Fri 9/14/12	Mon 9/17/12
43		West #12 All Levels	2 days	Tue 9/18/12	Wed 9/19/12
44		West #13 All Levels	2 days	Thu 9/20/12	Fri 9/21/12
45		**MEP Sleeve/Penetration**	**110 days**	**Fri 6/22/12**	**Thu 11/22/12**
46		SE #1 Main Conc.	1 day	Fri 6/22/12	Fri 6/22/12
47		SE #2 Main Conc.	1 day	Mon 7/2/12	Mon 7/2/12
48		SE #3 Main Conc.	1 day	Mon 7/9/12	Mon 7/9/12
49		NE #4 Main Conc.	1 day	Thu 7/19/12	Thu 7/19/12
50		NE #5 Main Conc.	1 day	Fri 7/27/12	Fri 7/27/12
51		NW #6 Main Conc.	1 day	Wed 8/1/12	Wed 8/1/12
52		NW #7 Main Conc.	1 day	Thu 8/9/12	Thu 8/9/12
53		NW #8 Main Conc.	1 day	Wed 8/15/12	Wed 8/15/12
54		SW #9 Main Conc.	1 day	Thu 8/23/12	Thu 8/23/12
55		SW #10 Main Conc.	1 day	Wed 11/21/12	Wed 11/21/12
56		West #11 Main Conc. /Roof	1 day	Thu 9/20/12	Thu 9/20/12
57		West #12 Main Conc. /Roof	1 day	Fri 9/21/12	Fri 9/21/12
58		West #13 Main Conc. /Roof	1 day	Mon 9/24/12	Mon 9/24/12
59		SE #1 Club Level	1 day	Mon 6/25/12	Mon 6/25/12
60		SE #2 Club Level	1 day	Tue 7/3/12	Tue 7/3/12
61		SE #3 Club Level	1 day	Tue 7/10/12	Tue 7/10/12
62		NE #4 Club Level	1 day	Fri 7/20/12	Fri 7/20/12
63		NE #5 Club Level	1 day	Mon 7/30/12	Mon 7/30/12
64		NW #6 Club Level	1 day	Thu 8/2/12	Thu 8/2/12
65		NW #7 Club Level	1 day	Fri 8/10/12	Fri 8/10/12
66		NW #8 Club Level	1 day	Thu 8/16/12	Thu 8/16/12
67		SW #9 Club Level	1 day	Fri 8/24/12	Fri 8/24/12
68		SW #10 Club Level	1 day	Thu 11/22/12	Thu 11/22/12
69		SE #3 Mech. Loft	1 day	Wed 7/11/12	Wed 7/11/12
70		West Mech. Loft	1 day	Fri 8/17/12	Fri 8/17/12
71		**Floor Slab Pours**	**107 days**	**Mon 7/9/12**	**Tue 12/4/12**
72		SE #1 Main Conc.	7 days	Mon 7/9/12	Tue 7/17/12
73		SE #2 Main Conc.	7 days	Tue 7/10/12	Wed 7/18/12
74		SE #3 Main Conc.	7 days	Wed 7/11/12	Thu 7/19/12
75		SE #1 Club Level	7 days	Thu 7/12/12	Fri 7/20/12



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Date: Fri 4/20/12

Task	▬	Project Summary	▬	Inactive Milestone	◇	Manual Summary Rollup	▬	Deadline	⇩
Split	┈	External Tasks	▬	Inactive Summary	▭	Manual Summary	▬	Progress	▬
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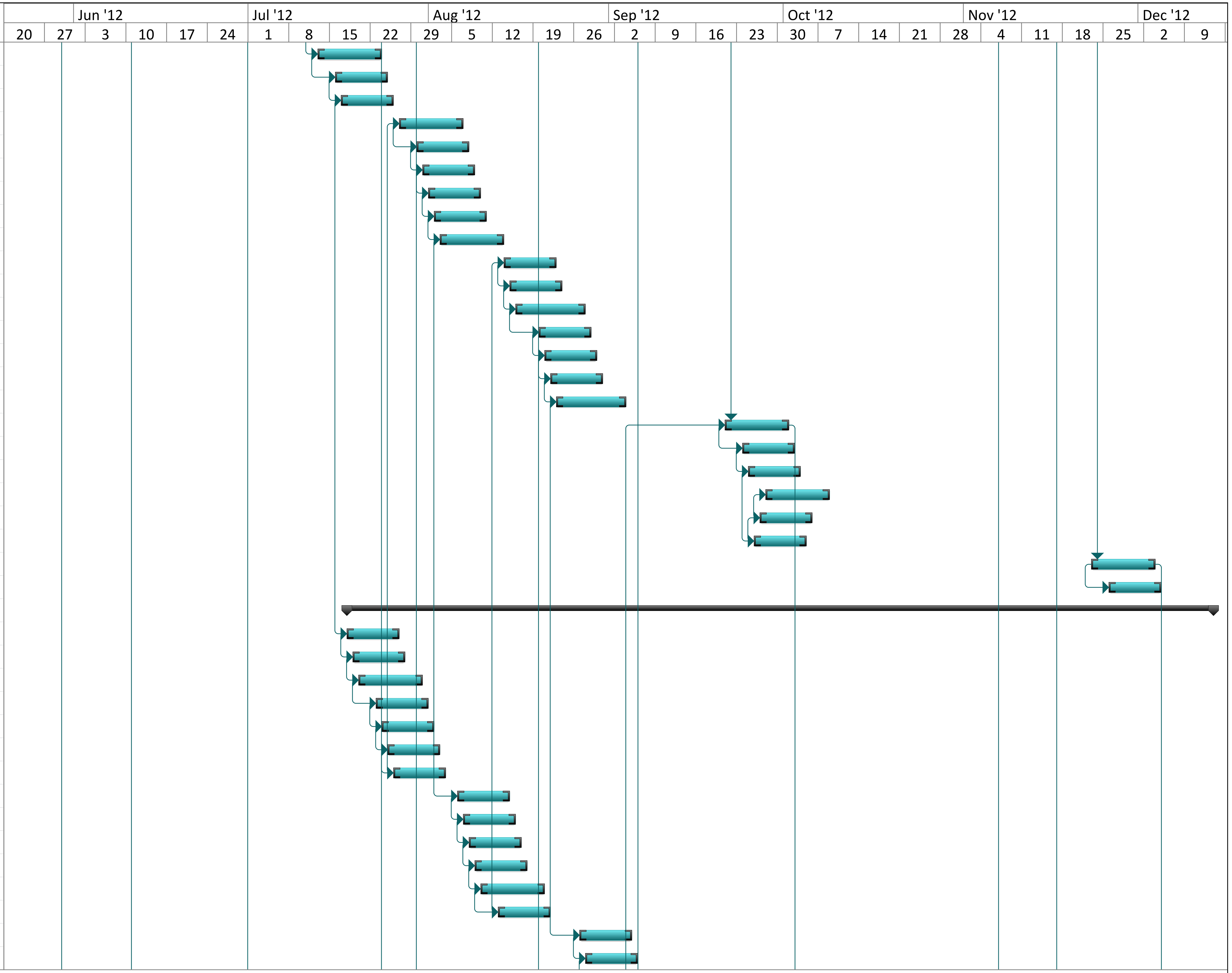
Summary	▬	Inactive Task	▭	Duration-only	▬	Finish-only	]		

ID	ℹ	Task Name	Duration	Start	Finish
76		SE #2 Club Level	7 days	Fri 7/13/12	Mon 7/23/12
77		SE #3 Club Level	7 days	Mon 7/16/12	Tue 7/24/12
78		SE #3 Mech. Loft	7 days	Tue 7/17/12	Wed 7/25/12
79		NE #4 Main Conc.	7 days	Fri 7/27/12	Mon 8/6/12
80		NE #5 Main Conc.	7 days	Mon 7/30/12	Tue 8/7/12
81		NW #6 Main Conc.	7 days	Tue 7/31/12	Wed 8/8/12
82		NE #4 Club Level	7 days	Wed 8/1/12	Thu 8/9/12
83		NE #5 Club Level	7 days	Thu 8/2/12	Fri 8/10/12
84		NW #6 Club Level	7 days	Fri 8/3/12	Mon 8/13/12
85		NW #7 Main Conc.	7 days	Tue 8/14/12	Wed 8/22/12
86		NW #8 Main Conc.	7 days	Wed 8/15/12	Thu 8/23/12
87		SW #9 Main Conc.	8 days	Thu 8/16/12	Mon 8/27/12
88		NW #7 Club Level	7 days	Mon 8/20/12	Tue 8/28/12
89		NW #8 Club Level	7 days	Tue 8/21/12	Wed 8/29/12
90		West Mech. Loft	7 days	Wed 8/22/12	Thu 8/30/12
91		SW #9 Club Level	8 days	Thu 8/23/12	Mon 9/3/12
92		West #11 Main Conc.	7 days	Fri 9/21/12	Mon 10/1/12
93		West #12 Main Conc.	7 days	Mon 9/24/12	Tue 10/2/12
94		West #13 Main Conc.	7 days	Tue 9/25/12	Wed 10/3/12
95		West #11 Roof	7 days	Fri 9/28/12	Mon 10/8/12
96		West #12 Roof	7 days	Thu 9/27/12	Fri 10/5/12
97		West #13 Roof	7 days	Wed 9/26/12	Thu 10/4/12
98		SW #10 Main Conc.	7 days	Fri 11/23/12	Mon 12/3/12
99		SW #10 Club Level	7 days	Mon 11/26/12	Tue 12/4/12
100		**Secondary Pour**	**107 days**	**Wed 7/18/12**	**Thu 12/13/12**
101		SE #1 Main Conc.	7 days	Wed 7/18/12	Thu 7/26/12
102		SE #2 Main Conc.	7 days	Thu 7/19/12	Fri 7/27/12
103		SE #3 Main Conc.	7 days	Fri 7/20/12	Mon 7/30/12
104		SE #1 Club Level	7 days	Mon 7/23/12	Tue 7/31/12
105		SE #2 Club Level	7 days	Tue 7/24/12	Wed 8/1/12
106		SE #3 Club Level	7 days	Wed 7/25/12	Thu 8/2/12
107		SE #3 Mech. Loft	7 days	Thu 7/26/12	Fri 8/3/12
108		NE #4 Main Conc.	7 days	Mon 8/6/12	Tue 8/14/12
109		NE #5 Main Conc.	7 days	Tue 8/7/12	Wed 8/15/12
110		NW #6 Main Conc.	7 days	Wed 8/8/12	Thu 8/16/12
111		NE #4 Club Level	7 days	Thu 8/9/12	Fri 8/17/12
112		NE #5 Club Level	7 days	Fri 8/10/12	Mon 8/20/12
113		NW #6 Club Level	7 days	Mon 8/13/12	Tue 8/21/12
114		NW #7 Main Conc.	7 days	Mon 8/27/12	Tue 9/4/12
115		NW #8 Main Conc.	7 days	Tue 8/28/12	Wed 9/5/12



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Date: Fri 4/20/12

Task	▬	Project Summary	▬	Inactive Milestone	◇	Manual Summary Rollup	▬	Deadline	↓
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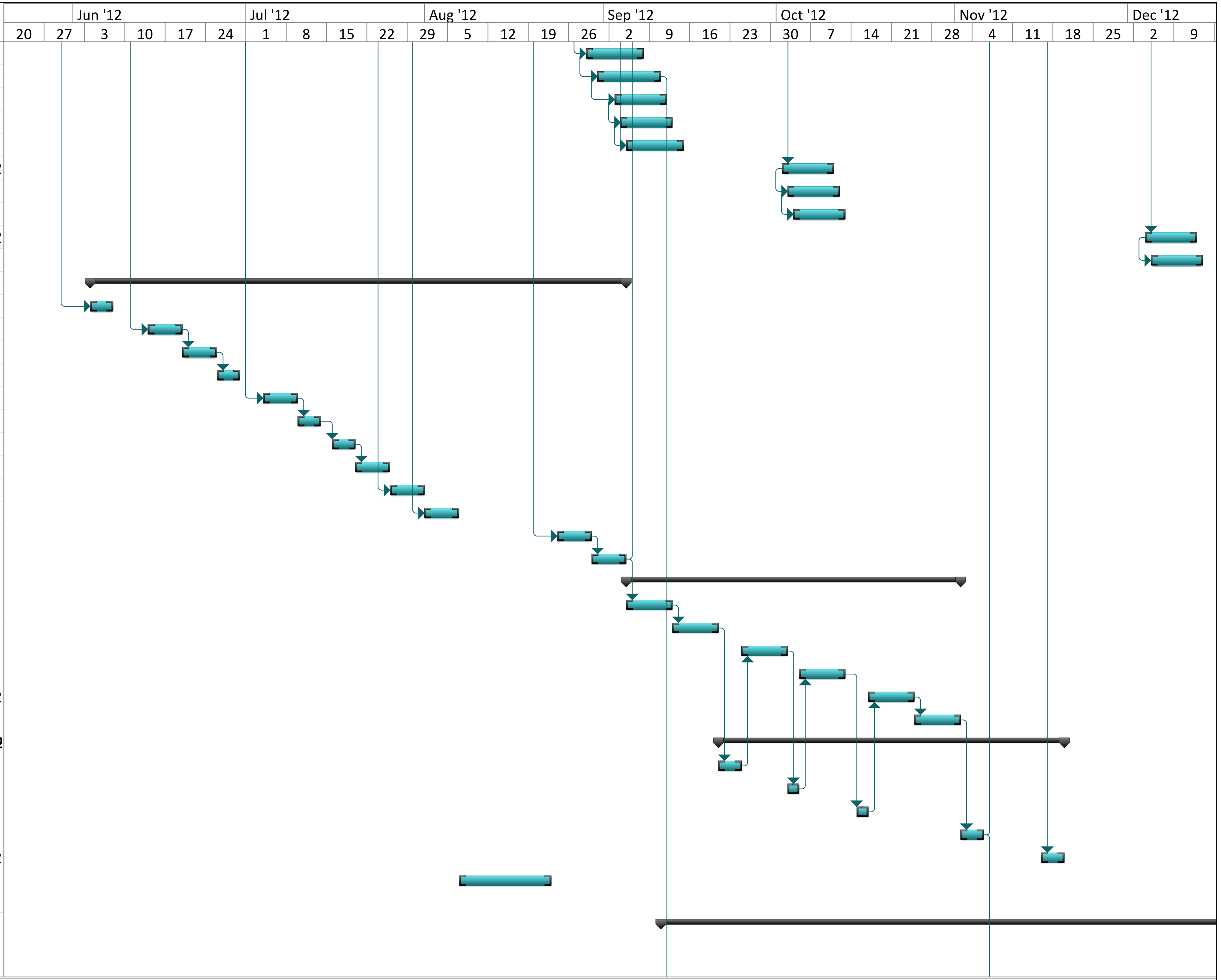
Milestone	◆	External Milestone	◆	Manual Task	▬	Start-only	[		
Summary	▬	Inactive Task	▭	Duration-only	▬	Finish-only	]		

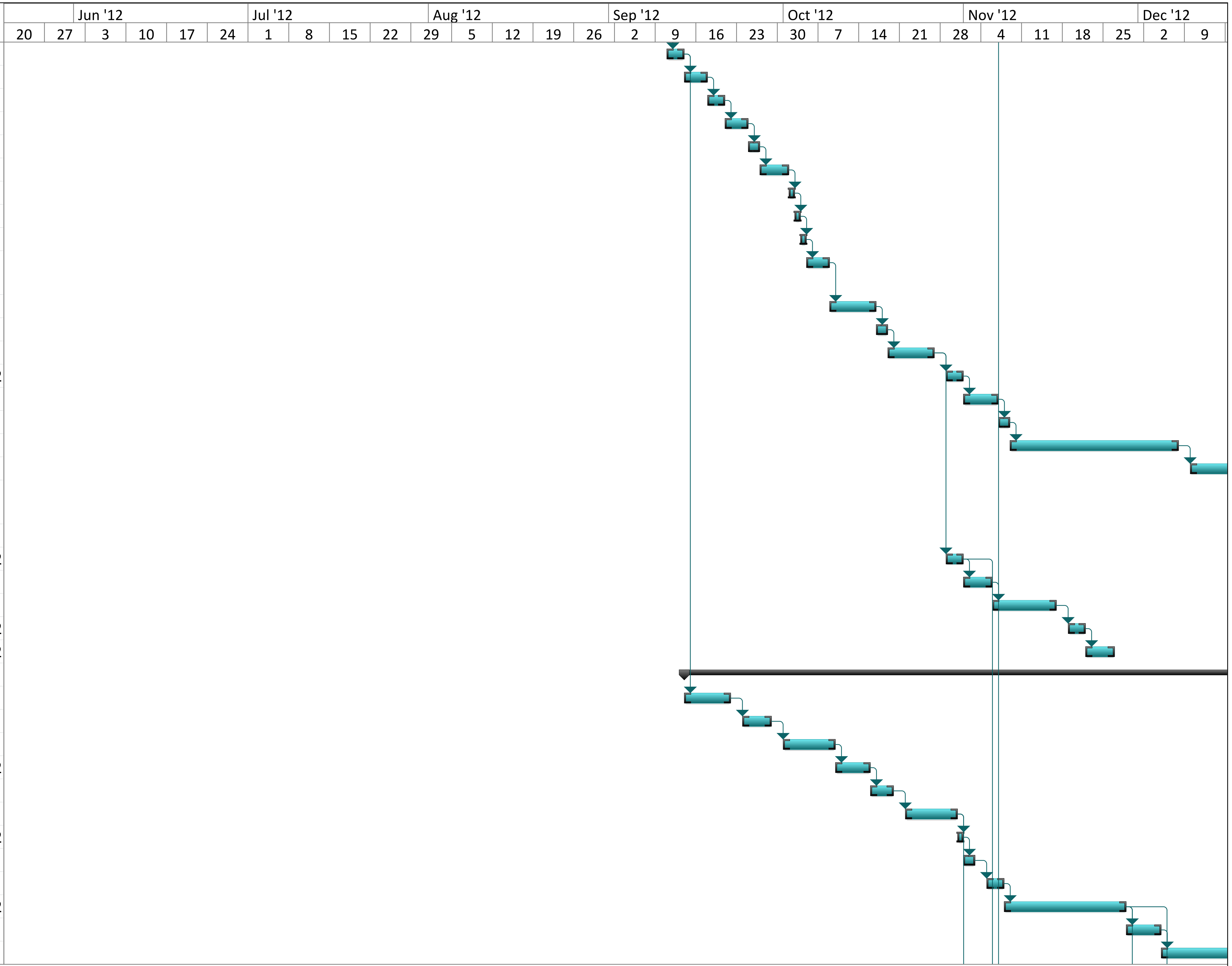
ID	Task Name	Duration	Start	Finish
116	SW #9 Main Conc.	8 days	Wed 8/29/12	Fri 9/7/12
117	NW #7 Club Level	7 days	Fri 8/31/12	Mon 9/10/12
118	NW #8 Club Level	7 days	Mon 9/3/12	Tue 9/11/12
119	West Mech. Loft	7 days	Tue 9/4/12	Wed 9/12/12
120	SW #9 Club Level	8 days	Wed 9/5/12	Fri 9/14/12
121	West #11 Main Conc.	7 days	Tue 10/2/12	Wed 10/10/12
122	West #12 Main Conc.	7 days	Wed 10/3/12	Thu 10/11/12
123	West #13 Main Conc.	7 days	Thu 10/4/12	Fri 10/12/12
124	SW #10 Main Conc.	7 days	Tue 12/4/12	Wed 12/12/12
125	SW #10 Club Level	7 days	Wed 12/5/12	Thu 12/13/12
126	**Mast Erection**	**67 days**	**Mon 6/4/12**	**Tue 9/4/12**
127	South X10	4 days	Mon 6/4/12	Thu 6/7/12
128	South X12	4 days	Thu 6/14/12	Tue 6/19/12
129	South X14	4 days	Wed 6/20/12	Mon 6/25/12
130	South X16	4 days	Tue 6/26/12	Fri 6/29/12
131	North X16	4 days	Wed 7/4/12	Mon 7/9/12
132	North X14	4 days	Tue 7/10/12	Fri 7/13/12
133	North X12	4 days	Mon 7/16/12	Thu 7/19/12
134	North X10	4 days	Fri 7/20/12	Wed 7/25/12
135	North X8	4 days	Thu 7/26/12	Tue 7/31/12
136	North X6	4 days	Wed 8/1/12	Mon 8/6/12
137	South X6	4 days	Fri 8/24/12	Wed 8/29/12
138	South X8	4 days	Thu 8/30/12	Tue 9/4/12
139	**Girder Spans**	**42 days**	**Wed 9/5/12**	**Thu 11/1/12**
140	X16	6 days	Wed 9/5/12	Wed 9/12/12
141	X14	6 days	Thu 9/13/12	Thu 9/20/12
142	X12	6 days	Tue 9/25/12	Tue 10/2/12
143	X10	6 days	Fri 10/5/12	Fri 10/12/12
144	X8	6 days	Wed 10/17/12	Wed 10/24/12
145	X6	6 days	Thu 10/25/12	Thu 11/1/12
146	**Roof Beams**	**42 days**	**Fri 9/21/12**	**Mon 11/19/12**
147	X16-X14	2 days	Fri 9/21/12	Mon 9/24/12
148	X14-X12	2 days	Wed 10/3/12	Thu 10/4/12
149	X12-X10	2 days	Mon 10/15/12	Tue 10/16/12
150	X8-X6	2 days	Fri 11/2/12	Mon 11/5/12
151	X10-X8	2 days	Fri 11/16/12	Mon 11/19/12
152	Mechanical Unit Installation	12 days	Tue 8/7/12	Wed 8/22/12
153	**Wall Framing, Sheathing, Insulation, etc.**	**106 days**	**Tue 9/11/12**	**Tue 2/5/13**



Project: Penn State Ice Arena
Date: Fri 4/20/12

Task		Project Summary		Inactive Milestone	◇	Manual Summary Rollup		Deadline	↓
Split		External Tasks		Inactive Summary		Manual Summary		Progress	
Milestone	◆	External Milestone	◆	Manual Task		Start-only	[		
Summary		Inactive Task		Duration-only		Finish-only	]		

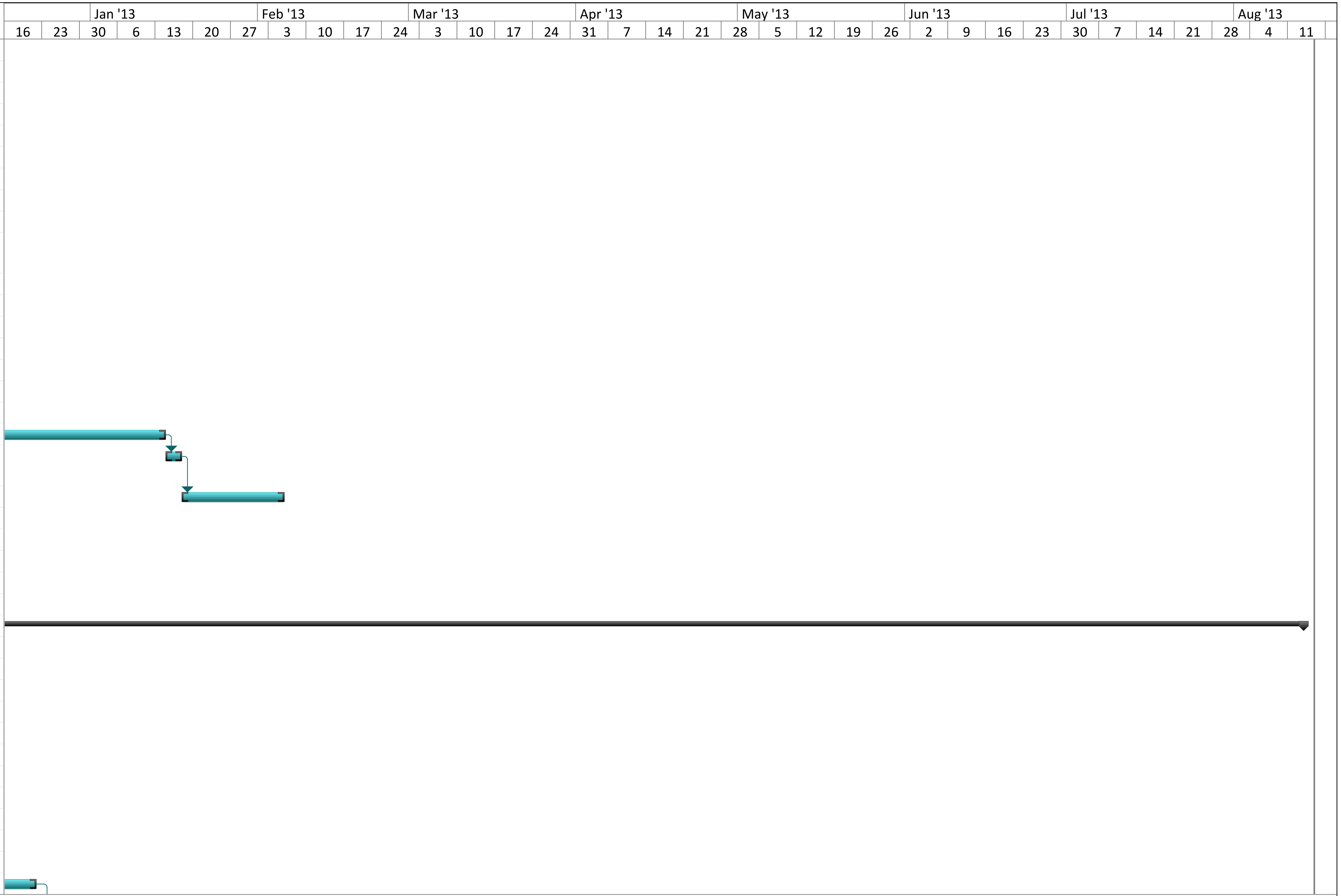
ID	ℹ	Task Name	Duration	Start	Finish
154		Student Ent. Wall	3 days	Tue 9/11/12	Thu 9/13/12
155		NW Stairwell (W)	2 days	Fri 9/14/12	Mon 9/17/12
156		NW Stairwell (N)	3 days	Tue 9/18/12	Thu 9/20/12
157		NW Stairwell (E)	2 days	Fri 9/21/12	Mon 9/24/12
158		NE Stairwell (W)	2 days	Tue 9/25/12	Wed 9/26/12
159		NE Stairwell (N)	3 days	Thu 9/27/12	Mon 10/1/12
160		NE Stairwell (E)	1 day	Tue 10/2/12	Tue 10/2/12
161		Low Box Office	1 day	Wed 10/3/12	Wed 10/3/12
162		High Box Office	1 day	Thu 10/4/12	Thu 10/4/12
163		Loading Dock (Metal Panel)	2 days	Fri 10/5/12	Mon 10/8/12
164		Loading Dock (Brick)	6 days	Tue 10/9/12	Tue 10/16/12
165		SW Stairwell (E)	2 days	Wed 10/17/12	Thu 10/18/12
166		SW Stairwell (S)	6 days	Fri 10/19/12	Fri 10/26/12
167		Comm. Rink Entrance (E)	3 days	Mon 10/29/12	Wed 10/31/12
168		Comm. Rink Entrance (S)	4 days	Thu 11/1/12	Tue 11/6/12
169		Curved Comm. Rink Ent.	2 days	Wed 11/7/12	Thu 11/8/12
170		Comm. Rink (S)	21 days	Fri 11/9/12	Fri 12/7/12
171		Comm. Rink (W)	26 days	Mon 12/10/12	Mon 1/14/13
172		NW Comm. Rink Curved Corner	3 days	Tue 1/15/13	Thu 1/17/13
173		Comm. Rink (N)	13 days	Fri 1/18/13	Tue 2/5/13
174		West Arena Wall 1	3 days	Mon 10/29/12	Wed 10/31/12
175		West Arena Wall 2	3 days	Thu 11/1/12	Mon 11/5/12
176		West Arena Wall 3	9 days	Tue 11/6/12	Fri 11/16/12
177		West Arena Wall 4	3 days	Mon 11/19/12	Wed 11/21/12
178		West Arena Wall 5	3 days	Thu 11/22/12	Mon 11/26/12
179		**Brick Walls**	**238 days**	**Fri 9/14/12**	**Tue 8/13/13**
180		Student Ent. Wall	6 days	Fri 9/14/12	Fri 9/21/12
181		NW Stairwell (W)	5 days	Mon 9/24/12	Fri 9/28/12
182		NW Stairwell (N)	7 days	Mon 10/1/12	Tue 10/9/12
183		NW Stairwell (E)	4 days	Wed 10/10/12	Mon 10/15/12
184		NE Stairwell (W)	4 days	Tue 10/16/12	Fri 10/19/12
185		NE Stairwell (N)	7 days	Mon 10/22/12	Tue 10/30/12
186		NE Stairwell (E)	1 day	Wed 10/31/12	Wed 10/31/12
187		Low Box Office	2 days	Thu 11/1/12	Fri 11/2/12
188		High Box Office	3 days	Mon 11/5/12	Wed 11/7/12
189		Loading Dock	15 days	Thu 11/8/12	Wed 11/28/12
190		SW Stairwell (E)	4 days	Thu 11/29/12	Tue 12/4/12
191		SW Stairwell (S)	13 days	Wed 12/5/12	Fri 12/21/12



Project: Penn State Ice Arena
Date: Fri 4/20/12

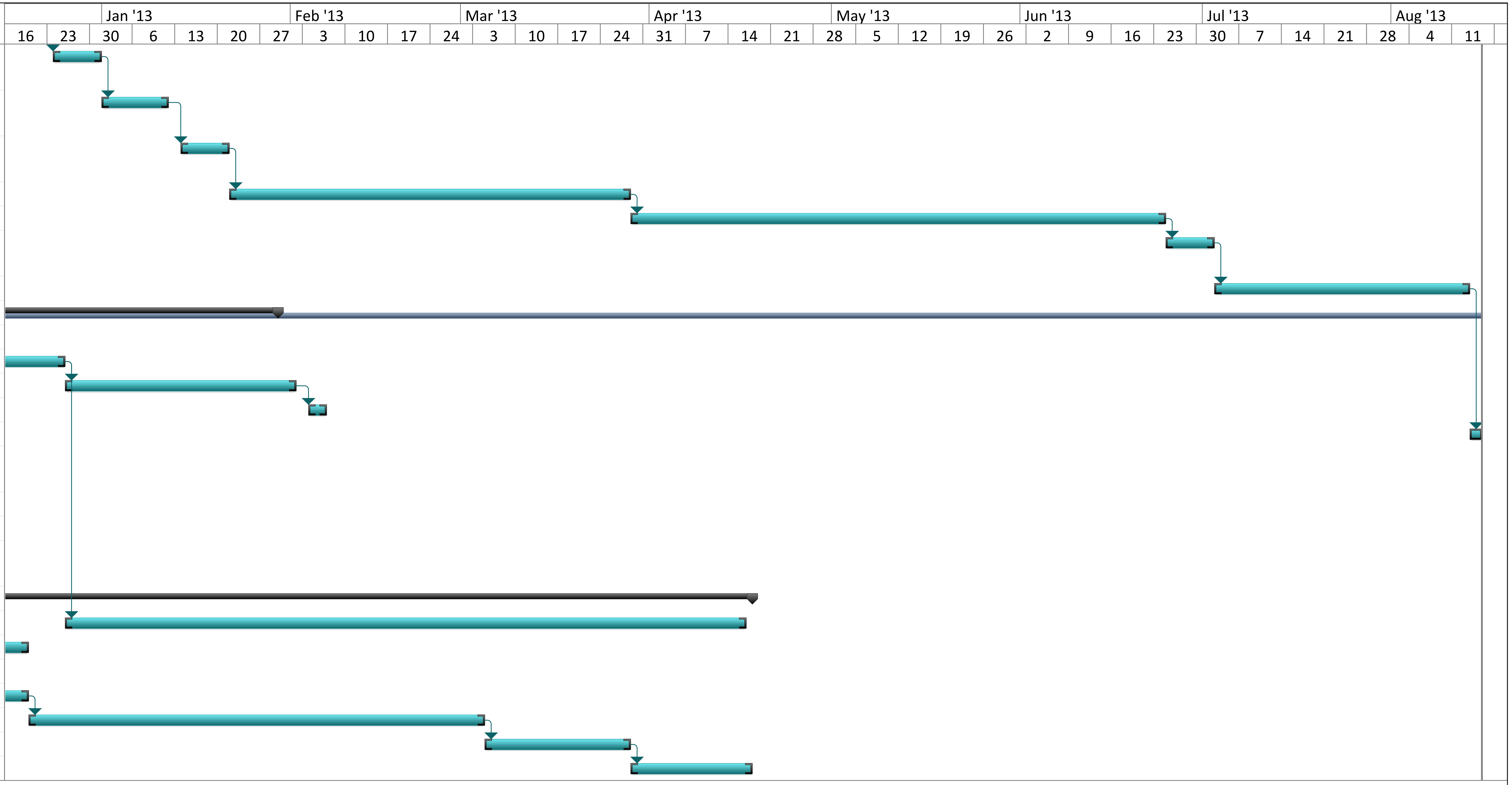
Task	▬	Project Summary	▬	Inactive Milestone	◇	Manual Summary Rollup	▬	Deadline	⇩
Split	┈	External Tasks	▬	Inactive Summary	▭	Manual Summary	▬	Progress	▬
Milestone	◆	External Milestone	◆	Manual Task	▬	Start-only	[		
Summary	▬	Inactive Task	▭	Duration-only	▬	Finish-only	]		

ID	ℹ	Task Name	Duration
154		Student Ent. Wall	3 days
155		NW Stairwell (W)	2 days
156		NW Stairwell (N)	3 days
157		NW Stairwell (E)	2 days
158		NE Stairwell (W)	2 days
159		NE Stairwell (N)	3 days
160		NE Stairwell (E)	1 day
161		Low Box Office	1 day
162		High Box Office	1 day
163		Loading Dock (Metal Panel)	2 days
164		Loading Dock (Brick)	6 days
165		SW Stairwell (E)	2 days
166		SW Stairwell (S)	6 days
167		Comm. Rink Entrance (E)	3 days
168		Comm. Rink Entrance (S)	4 days
169		Curved Comm. Rink Ent.	2 days
170		Comm. Rink (S)	21 days
171		Comm. Rink (W)	26 days
172		NW Comm. Rink Curved Corner	3 days
173		Comm. Rink (N)	13 days
174		West Arena Wall 1	3 days
175		West Arena Wall 2	3 days
176		West Arena Wall 3	9 days
177		West Arena Wall 4	3 days
178		West Arena Wall 5	3 days
179		**Brick Walls**	**238 days**
180		Student Ent. Wall	6 days
181		NW Stairwell (W)	5 days
182		NW Stairwell (N)	7 days
183		NW Stairwell (E)	4 days
184		NE Stairwell (W)	4 days
185		NE Stairwell (N)	7 days
186		NE Stairwell (E)	1 day
187		Low Box Office	2 days
188		High Box Office	3 days
189		Loading Dock	15 days
190		SW Stairwell (E)	4 days
191		SW Stairwell (S)	13 days



Task		Project Summary		Inactive Milestone	◇	Manual Summary Rollup		Deadline	⬇
Split		External Tasks		Inactive Summary		Manual Summary		Progress	
Milestone	◆	External Milestone	◆	Manual Task		Start-only	[		
Summary		Inactive Task		Duration-only		Finish-only	]		

ID	ℹ	Task Name	Duration
192		Comm. Rink Entrance (E)	6 days
193		Comm. Rink Entrance (S)	9 days
194		Curved Comm. Rink Ent.	6 days
195		Comm. Rink (S)	48 days
196		Comm. Rink (W)	62 days
197		NW Comm. Rink Curved Corner	6 days
198		Comm. Rink (N)	30 days
199		**Curtainwall Installation**	**66 days**
200		North Curtainwall	13 days
201		Main Lobby	19 days
202		South Curtainwall	28 days
203		Comm. Rink Entrance	3 days
204		Student Ent.	2 days
205		**Arena Roof Construction**	**40 days**
206		Roof Deck Installation	26 days
207		Concrete Pour	35 days
208		Built Up Membrane System	30 days
209		**Metal Panel Installation**	**117 days**
210		East Mechanical Loft	80 days
211		Loading Dock	10 days
212		West Arena Wall 1	14 days
213		West Arena Wall 2	18 days
214		West Arena Wall 3	53 days
215		West Arena Wall 4	18 days
216		West Arena Wall 5	14 days



Project: Penn State Ice Arena
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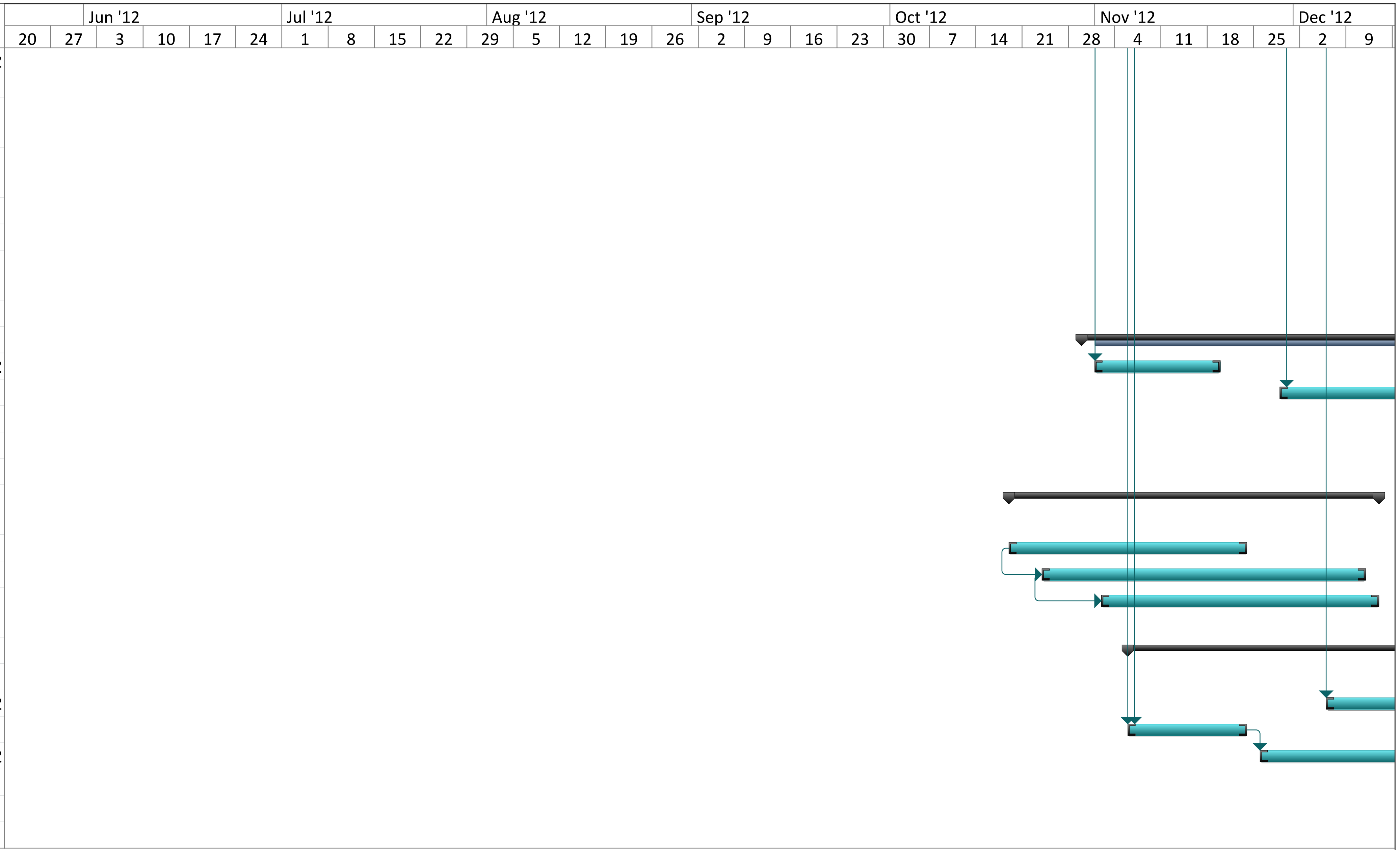
Task	▬	Project Summary	▬	Inactive Milestone	◇	Manual Summary Rollup	▬	Deadline	⬇
Split	┈	External Tasks	▬	Inactive Summary	▭	Manual Summary	▬	Progress	▬
Milestone	◆	External Milestone	◆	Manual Task	▬	Start-only	[		
Summary	▬	Inactive Task	▭	Duration-only	▬	Finish-only	]		

ID	ℹ	Task Name	Duration	Start	Finish
192		Comm. Rink Entrance (E)	6 days	Mon 12/24/12	Mon 12/31/12
193		Comm. Rink Entrance (S)	9 days	Tue 1/1/13	Fri 1/11/13
194		Curved Comm. Rink Ent.	6 days	Mon 1/14/13	Mon 1/21/13
195		Comm. Rink (S)	48 days	Tue 1/22/13	Thu 3/28/13
196		Comm. Rink (W)	62 days	Fri 3/29/13	Mon 6/24/13
197		NW Comm. Rink Curved Corner	6 days	Tue 6/25/13	Tue 7/2/13
198		Comm. Rink (N)	30 days	Wed 7/3/13	Tue 8/13/13
199		**Curtainwall Installation**	**66 days**	**Tue 10/30/12**	**Tue 1/29/13**
200		North Curtainwall	13 days	Thu 11/1/12	Mon 11/19/12
201		Main Lobby	19 days	Thu 11/29/12	Tue 12/25/12
202		South Curtainwall	28 days	Wed 12/26/12	Fri 2/1/13
203		Comm. Rink Entrance	3 days	Mon 2/4/13	Wed 2/6/13
204		Student Ent.	2 days	Wed 8/14/13	Thu 8/15/13
205		**Arena Roof Construction**	**40 days**	**Fri 10/19/12**	**Thu 12/13/12**
206		Roof Deck Installation	26 days	Fri 10/19/12	Fri 11/23/12
207		Concrete Pour	35 days	Wed 10/24/12	Tue 12/11/12
208		Built Up Membrane System	30 days	Fri 11/2/12	Thu 12/13/12
209		**Metal Panel Installation**	**117 days**	**Tue 11/6/12**	**Wed 4/17/13**
210		East Mechanical Loft	80 days	Wed 12/26/12	Tue 4/16/13
211		Loading Dock	10 days	Thu 12/6/12	Wed 12/19/12
212		West Arena Wall 1	14 days	Tue 11/6/12	Fri 11/23/12
213		West Arena Wall 2	18 days	Mon 11/26/12	Wed 12/19/12
214		West Arena Wall 3	53 days	Thu 12/20/12	Mon 3/4/13
215		West Arena Wall 4	18 days	Tue 3/5/13	Thu 3/28/13
216		West Arena Wall 5	14 days	Fri 3/29/13	Wed 4/17/13



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Milestone	◆	External Milestone	◆	Manual Task	▬	Start-only	[		
Summary	▬	Inactive Task	▭	Duration-only	▬	Finish-only	]		

Appendix S. Construction References

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