Final Report

[Arena Stage]

Washington, DC

Joni Richelle Anderson
Construction Management
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Spring 2009

[Arena Stage]

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BASIC PROJECT INFORMATION

Occupancy Type: Performing Arts Center
Size: 200,000 SF
Number of Stories: (3) Above Grade, (1) Below Grade
Dates of Construction: January 2008 – June 2010
Overall Project Cost: $125 million
Delivery Method: Cost Plus Fee with a GMP

DESIGN AND CONSTRUCTION TEAM

Owner: Washington Drama Society Inc. (Arena Stage)
Owner's Representative: KCM, Inc.
General Contractor: Clark Construction Group, LLC
Architect: Bing Thom Architects Inc.
Structural Engineer: Fast + Epp
Mechanical Engineer: Yoneda & Associates
Electrical Engineer: Stantec Consulting Ltd.

STRUCTURAL SYSTEM & ARCHITECTURAL FEATURES

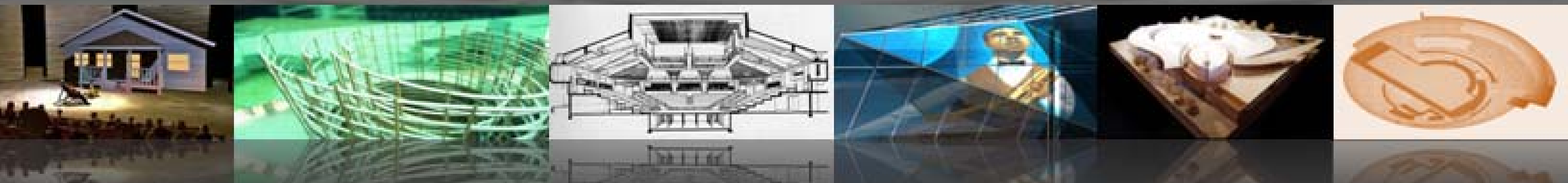
The existing Fichandler and Kreeger Theatres will maintaining their original structures of CIP concrete, CMU, and masonry veneer. The new Cradle Theatre is using a PERI RUNDFLEX formwork system to achieve the sloped ellipse-shaped CIP nestled walls. The three theatres are encased in a 45' glass façade supported by several 30" diameter parallam timber columns that extend to the roof. A series of wide flange trusses support the roof which is composite deck with a waterproof membrane. The roof of the building is then accented by a scalloped EIFS, synthetic stucco, soffit.

MECHANICAL SYSTEM

The HVAC system consists of a four pipe, air-water Fan Coil System, including (31) Fan Coil Units with capacities ranging from 220 to 2,900 cfm. These are served by (18) Air Handling Units with sizes ranging from 3,000 to 43,100 cfm. The (2) Cooling Towers, located on an outdoor terrace, operate in conjunction with (2) Chillers and (4) Boilers. Fire Suppression is combination of a wet and dry system using a Class I standpipe with an open water supply valve.

ELECTRICAL SYSTEM

Arena Stage's power is provided by Pepco Supply. The main feed is brought into the building and is stepped down to a 3Φ, 4 wire, 277/480V, 3000A Bus. The electrical system is adjusted throughout the building with (8) Dry Type Transformers. Emergency power is supplied by (1) 275kW/344kVA separately derived fixed Generator which feeds (3) emergency multi-duct conduit systems. Stage lighting includes a number of 20A high-density, solid-state dimmers above the stages.



e-Portfolio: http://www.engr.psu.edu/ae/thesis/portfolios/2009/jra204/

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Executive Summary

This final thesis report is a culmination of the research that I have performed during this academic year on Arena Stage. The beginning of this document provides general information about the client, project delivery, construction team, project schedule, building location, existing site conditions, and a building systems summary. The remainder of the report is comprised of three analyses in which there are proposed building changes, suggested as methods of enhancement for Arena Stage. The analyses are as follows:

Analysis I: *Redesign of the Curtain Wall System: Elimination of the 4 Degree Slope*
[Constructability Depth & Architectural Breadth]
The current design of the curtain wall is set on an inverted 4 degree slope that runs along a serpentine comprised of multiple radii. There are several sections of glass that are trapezoidal, as opposed to rectangular, because of the gradual increase in unit size due to the slope of the wall. Very few of the 365 total units are the same size and shape, which has caused the glazing to be very expensive. In this analysis, the slope of the glazing was eliminated and the faces were redesigned to create more uniform unit sizes. By making this small architectural adjustment, the number of individual glazing unit sizes was reduced from 148 to only 21. Also, a 32% reduction in the cost of the glazing was achieved and the construction time was cut in half. The redesign was done to prove that the owner has an option to approve a slight modification to the appearance of the building, resulting in significant cost and schedule reductions.

Analysis II: *Application of Photovoltaic Panels*
[Electrical Breadth : Critical Industry Issue]
In October 2008, a technical training topic titled "Energy & Economy" was discussed at the PACE Roundtable. Both PACE and a course titled *Solar Photovoltaic Solutions* influenced the decision to utilize renewable energy at Arena Stage. A 6 kW solar array was designed to match the lighting load of Arena Stage's parking garage using Uni-Solar's building integrated solar laminate modules and a Fronius inverter. The initial cost of the system was determined to be $40,409, which is a marginal price when compared to the overall building cost of $125 million. However, the payback period was a lengthy 51 years, which was reduced to 32 years once the $15,000 of incentives was taken into account. While solar photovoltaic systems provide owners with greater energy independence and reduces the use of fossil fuels, it was decided that this particular array is not a reasonable investment for Arena Stage.

Analysis III: *Redesign of the Fichandler Stage Air Distribution System*
[Mechanical Breadth]
Retrofitting the Fichandler Theater with new mechanical equipment was a challenge due to the minimal space that was available. The supply air to the stage is delivered by high-throw branch ducts located far above the stage within the wood ceiling. This design requires a lot of excess sheet metal duct that needs to be installed in a very tight space. This analysis examined a redesign of the system using exposed fabric duct hung beneath the stage catwalk. It not only eliminated more than half of the sheet metal, but the cost to furnish and install the system was reduced by 54% and the schedule was decreased by an impressive 67%. The proposed mechanical design is fast, affordable, and environmentally friendly making it a logical application at Arena Stage.

Project Overview

CLIENT INFORMATION

Washington Drama Society, Inc. DBA Arena Stage is a not-for-profit organization and is the largest producing theater in North America that focuses on American plays. For the last sixty years, Arena Stage has entertained over 200,000 patrons and is considered a very important community attraction. Despite the fact that it is not old enough to be considered a historic landmark, Arena Stage's cultural significance and positive impact on the public earned it a spot in the District of Columbia Inventory of Historic Sites.

In 1999, Arena Stage decided to build a new facility and, instead of relocating to a new site, the Board of Trustees chose to remain in their waterfront location. The rebirth of Arena Stage, called The Next Stage Campaign, involves a massive renovation of the Fichandler and Kreeger theaters complete with modern amenities, updated décor, enhanced acoustics, and brand new building equipment. A new Back of House (BOH) space will be added for administrative offices and an underground parking garage. Also, an additional theater called the Cradle is being added to promote the writing and production of new American plays. For the public, the complex will not only provide opportunity for a diverse workforce, but plans for community outreach and educational programs are in order.

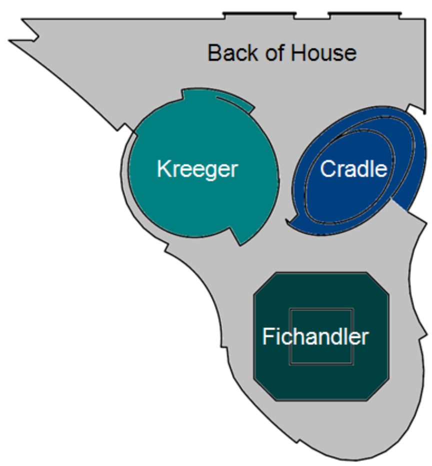


Figure 1: Layout of the new Arena Stage

When the decision was made to construct a new facility, the opportunity to move Arena Stage to a high-end, downtown location was tempting. However, by staying in the original location, The Next Stage Campaign became a part of the city's Anacostia Waterfront Initiative (AWI) (www.AnacostiaWaterfront.net). The goal of the initiative is to make the Southwest DC Waterfront a more alluring section of the city and join the ranks as a leading attraction. It is currently the city's number one economic development priority. The new Arena Stage is a crucial part of the city's revitalization, just like the New Nationals Ballpark which was one of the first major movements. The city hopes that these new public landmarks will have a contagious effect on other markets and encourage them to join the AWI.

Arena Stage did not publicly announce that it was building a new complex for many years due to a lack of funding. However, two Life Trustees, named Gilbert and Jaylee Mead, made the vision possible. As long time supporters of the performing arts in DC, the couple donated over $100 million toward the Campaign. The couple's unyielding support is expressible through their service on the Arena Stage Board of Trustees, sponsorship of productions, community service, and philanthropy toward multiple theaters in the Washington region. Sadly, Gilbert Mead passed away in May of 2007. In recognition of the Mead's commitment and generosity, the new theater complex will be named "The Mead Center for American Theater" in their honor.

In December of 2007, Arena Stage moved to a new location in Crystal City, VA to allow for the 2-year construction process. Since performing arts facilities operate in terms of seasons, the project schedule is very important to the owner. Arena Stage needs the project to be completed on time so that they can move back to the new theater and have the grand opening for the 2010-2011 season.

Since the project's funding is coming from donations, a major fundraising feasibility study was performed to make sure that the architect's design for the building was achievable. As it usually is, cost is a crucial factor for Arena Stage. Multiple design changes were made through value engineering so that the project is delivered within the budget. Although the cost of the project has fluctuated throughout the last 8 years, there has been no compromise of the project's quality. As stated before, the new complex is going to be a very modern, high-end facility that will serve as a role model for other movements of the Anacostia Waterfront Initiative. It has been requested by the owner that the cost information pertaining to the project not be revealed. The total project cost, $125 million, is the only number being released to the public.

PROJECT DELIVERY SYSTEM

Arena Stage is being delivered as a modified bid and project proposal process. Due to the complexity and uniqueness of the project, Arena Stage chose not to use the traditional bid process.

The owner presented the proposed building to 5 different contractors who they hand-picked with the help of the project manager. All of the selected contractors had experience in building either stadiums or theaters and therefore seemed like qualified candidates. When 2 general contractors (GCs) responded with eager interest in the project, Arena Stage requested that each company submit a detailed proposal.

Each group submitting a proposal had to provide a 2 hour presentation detailing how they would construct the project. This consisted of scheduling, construction procedure, staffing, and material procurement. It also consisted of a question and answer sequence concerning the sub-contractor bid and buyout process.

Since the contract is a Guaranteed Maximum Price (GMP) based on an open book buyout with the owner involved, the only competitive comparison was that of the proposed fee and also a quantitative look at the General Conditions between the submitting GCs. It was also important for the candidates to have a firm grasp on the complex requirements of the project. In May 2007, Clark Construction Group, LLC was awarded the construction contract for Arena Stage.

The owner would not disclose the types of contracts held between their consultants, nor would Clark describe their bonding and insurance requirements in detail. However, all of the subcontractors working for Clark were selected through competitive bid and all of the contracts are lump sum. Insurance is generally required for all subcontractors. The size of the contracts determines the bonding requirements. For the larger contracts, like those for the major building systems shown in Figure 2 on the next page, bonds are required.

The delivery system for Arena Stage was tailored to meet the requirements of the project; therefore it is an appropriate approach. There are many complexities that go into the construction of the building and they may not have been recognized by the construction companies had it been a competitive bid. The fact that the contractors got to work closely with the Arena Stage and KCM during the bidding process assured them that all facets of the project were being considered and, therefore, satisfactory results could be produced.

PROJECT TEAM

Owner: Washington Drama Society, Inc. (Arena Stage)

Project Manager: KCM, Inc.

General Contractor: Clark Construction Group, LLC

Architect: Bing Thom Architects Inc.

Structural Engineer: Fast + Epp

Mechanical Engineer: Yoneda & Associates

Electrical Engineer: Stantec Consulting Ltd.

Steel Subcontractor: Banker Steel Company, LLC

Concrete Subcontractor: Clark Concrete

Electrical Subcontractor: Truland Systems Corp.

Mechanical/Plumbing Subcontractor: Southland Industries

ORGANIZATIONAL CHART

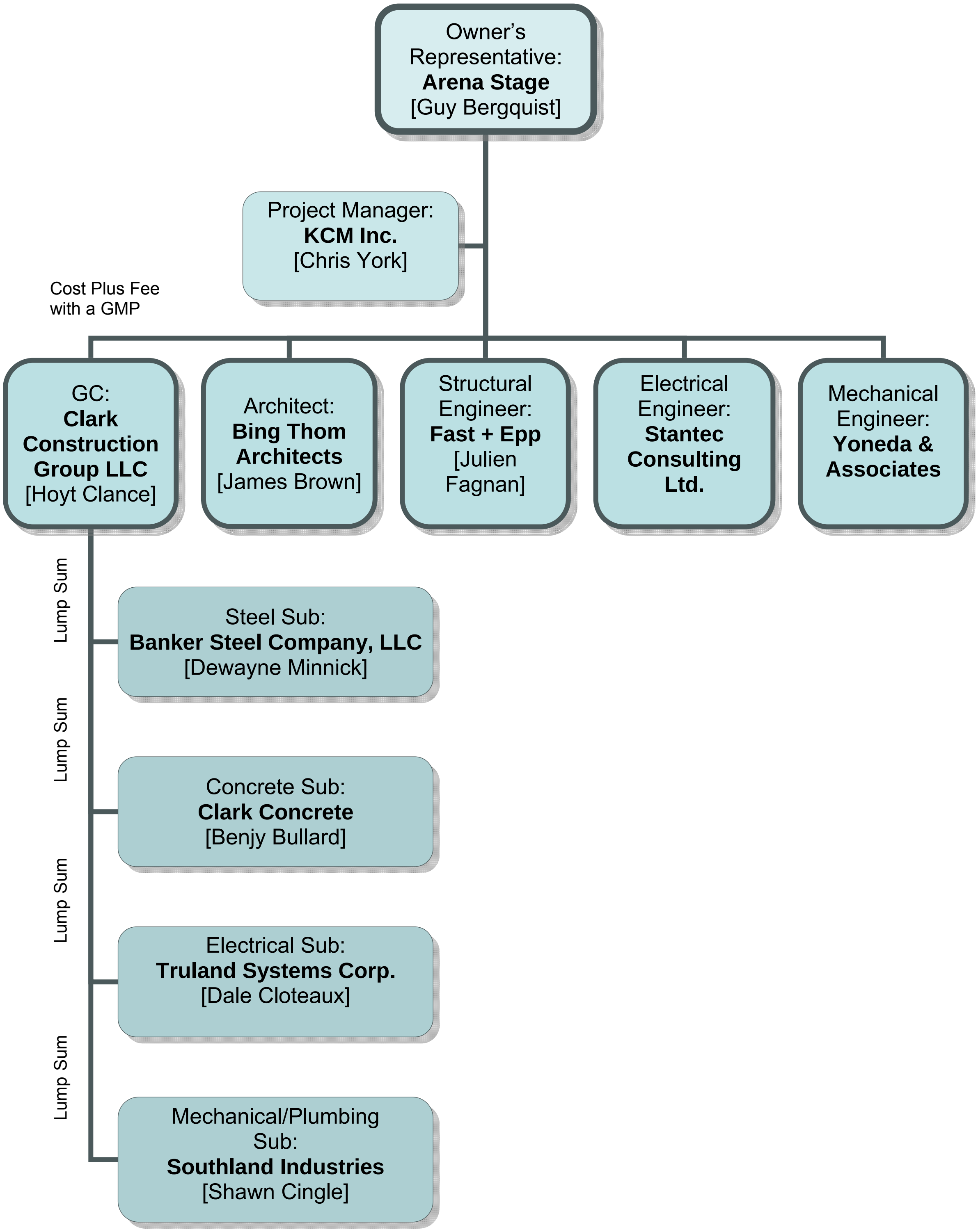


Figure 2: Arena Stage Organizational Chart

PROJECT SCHEDULE SUMMARY

Clark Construction Group, LLC was awarded the construction contract from Arena Stage in May 2007. That gave the company 9 months to prepare for the beginning of construction, including obtaining permits. When construction started with the notice to proceed in January of 2008, the first items on the critical path were utility work, excavation, and demolition. Once permanent power was cut and temporary power was installed, excavation began. Underpinning and sheeting and shoring were installed on the Fichandler and the Kreeger and piles were drilled for the Cradle foundation.

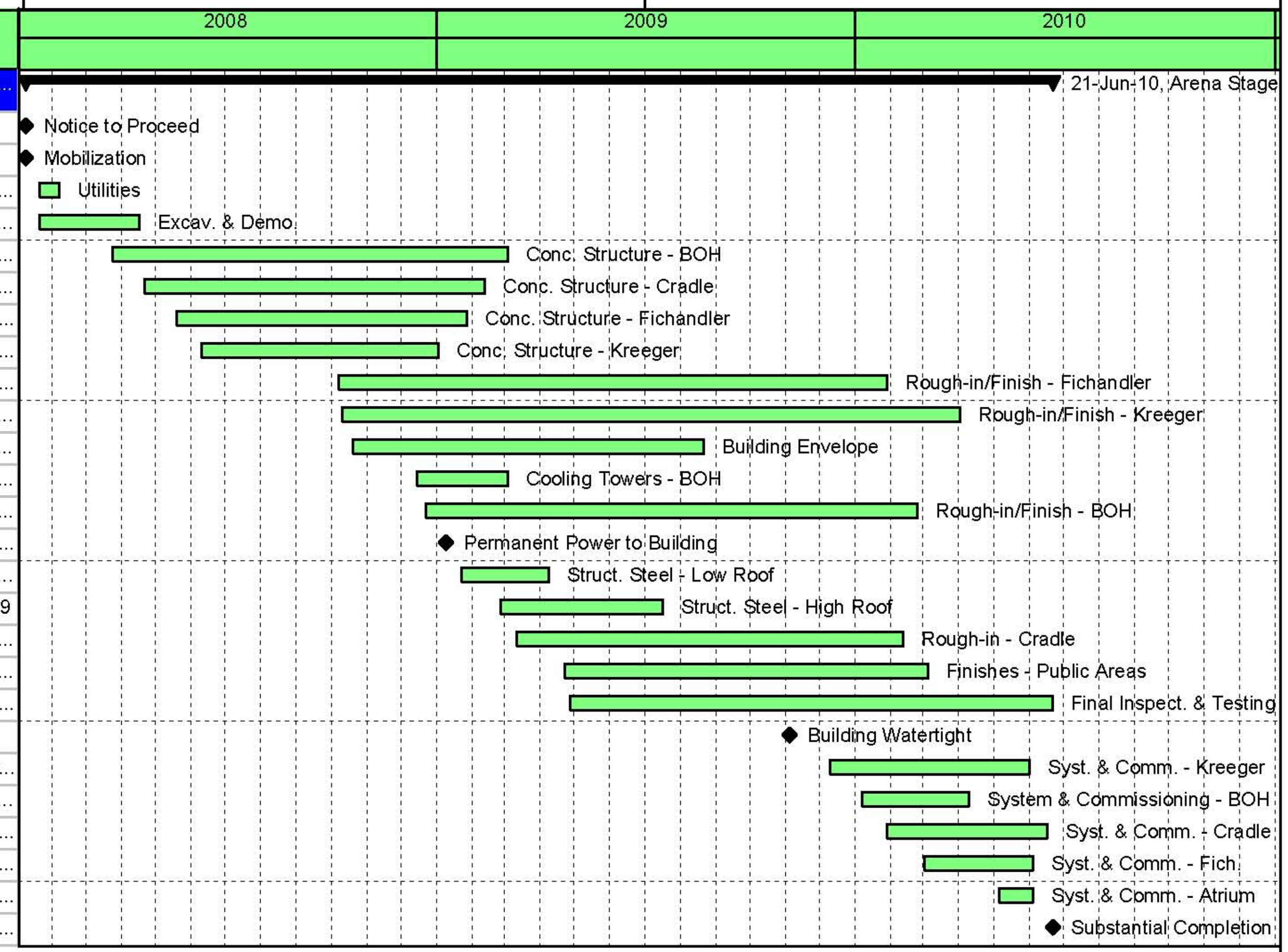
Upon completion of excavation, the concrete work began in the Back of House and was soon followed by the Cradle. Minor concrete work in the Fichandler and the Kreeger is followed by the structural steel of the low mezzanine and high roof. The glass curtain wall around the perimeter of the theaters will be installed in November of 2009 and, upon its completion, the building will achieve watertight status.

Renovation of the Fichandler and the Kreeger is categorized by the MEP rough-in and finishes, which occur somewhat simultaneously. These are the longest durations on the schedule due to the massive amounts of work being done during those processes. Many other activities occur during this time including installation of major mechanical equipment and finish work in public spaces. Permanent power was installed in January of 2009.

The final inspection and testing set the stage for the systems and commissioning which will take approximately 6 months for the entire project. Substantial completion is the final milestone which is scheduled for June 2010.

Arena Stage Schedule Summary | Start Date: January 8, 2008 | Finish Date: June 21, 2010

Activity ID	Activity Name	ginal ation	Start	Finish
	Arena Stage	640	08-Jan-...	21-Jun-...
MS1	Notice to Proceed	0	08-Jan-...	
MS2	Mobilization	0	08-Jan-...	
A1(	Utilities	14	21-Jan-...	07-Feb...
A2(	Excav. & Demo.	64	21-Jan-...	17-Apr-...
A31	Conc. Structure - BOH	248	24-Mar...	04-Mar...
A32	Conc. Structure - Cradle	213	21-Apr-08	11-Feb...
A33	Conc. Structure - Ficha...	181	19-May...	26-Jan-...
A34	Conc. Structure - Kreeger	149	10-Jun-...	02-Jan-...
A63	Rough-in/Finish - Ficha...	341	08-Oct-08	27-Jan-...
A64	Rough-in/Finish - Kree...	386	10-Oct-08	02-Apr-...
A4(	Building Envelope	220	20-Oct-08	21-Aug...
A61	Cooling Towers - BOH	58	15-Dec...	04-Mar...
A61	Rough-in/Finish - BOH	306	23-Dec...	23-Feb...
MS3	Permanent Power to B...	0		08-Jan-...
A51	Struct. Steel - Low Roof	55	22-Jan-...	08-Apr-...
A52	Struct. Steel - High Roof	102	26-Feb...	17-Jul-09
A62	Rough-in - Cradle	240	12-Mar...	10-Feb...
A8(	Finishes - Public Areas	227	23-Apr-09	05-Mar...
A9(	Final Inspect. & Testing	301	27-Apr-09	21-Jun-...
MS4	Building Watertight	0	03-Nov...	
A74	Syst. & Comm. - Kreeger	124	09-Dec...	31-May...
A71	System & Commissioni...	68	06-Jan-...	09-Apr-...
A72	Syst. & Comm. - Cradle	101	28-Jan-...	17-Jun-...
A73	Syst. & Comm. - Fich.	70	01-Mar...	04-Jun-...
A7(	Syst. & Comm. - Atrium	22	06-May...	04-Jun-...
MS5	Substantial Completion	0		21-Jun-...



Actual Work | Critical Remaining Work | Remaining Work ◆ | ◆ Milestone

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Joni Anderson
AE481 W
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Local Conditions

PROJECT LOCATION

Arena Stage is located on the corner of Sixth Street and Main Avenue in Southwest Washington, DC. Main Avenue SW is a busy street that runs the length of the Washington Channel and terminates at the Tidal Basin with the intersection of 17th Street and Independence Ave. The site has an awkward triangular shape and is adjacent to several residential high-rises to the north and east.

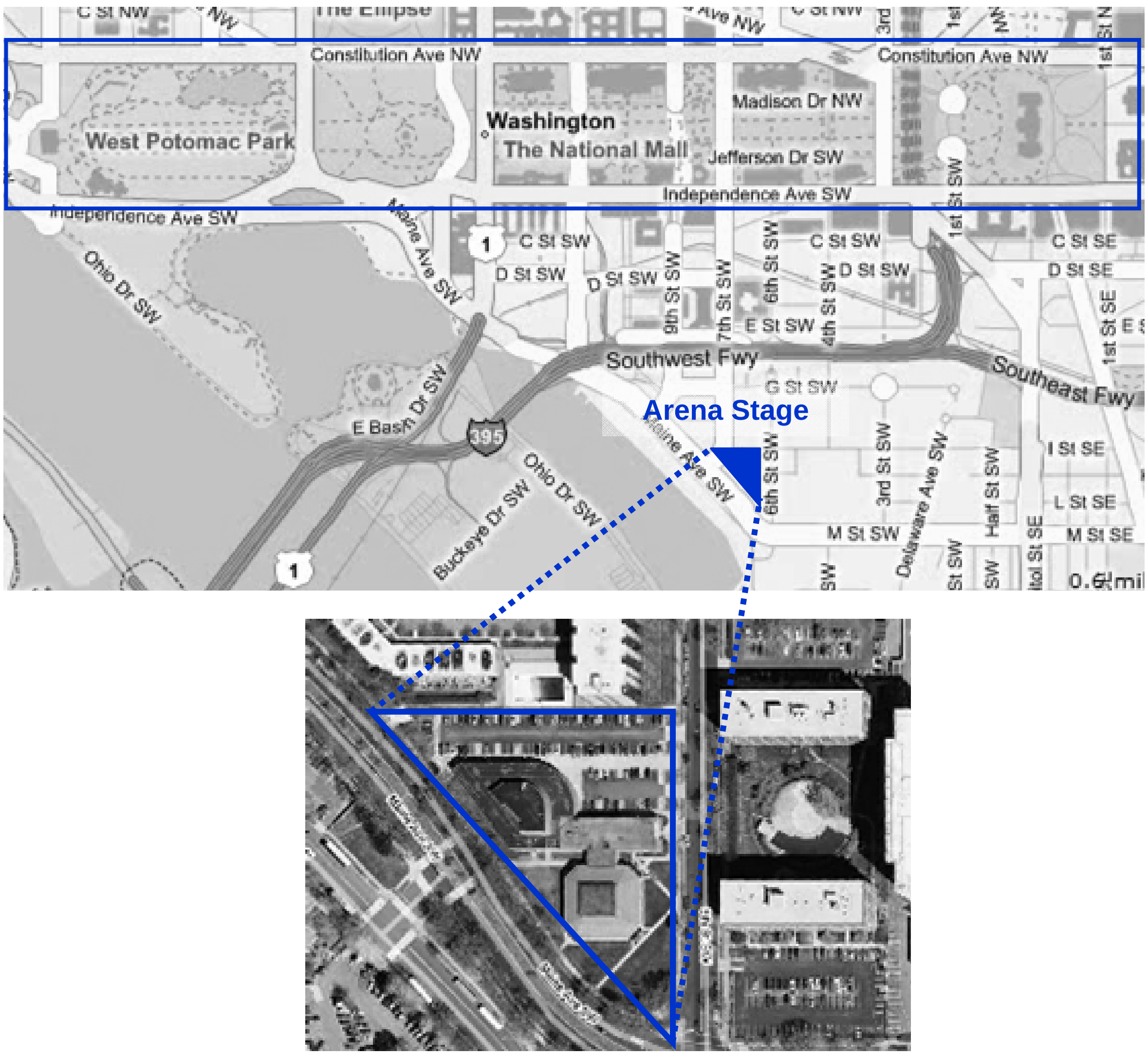


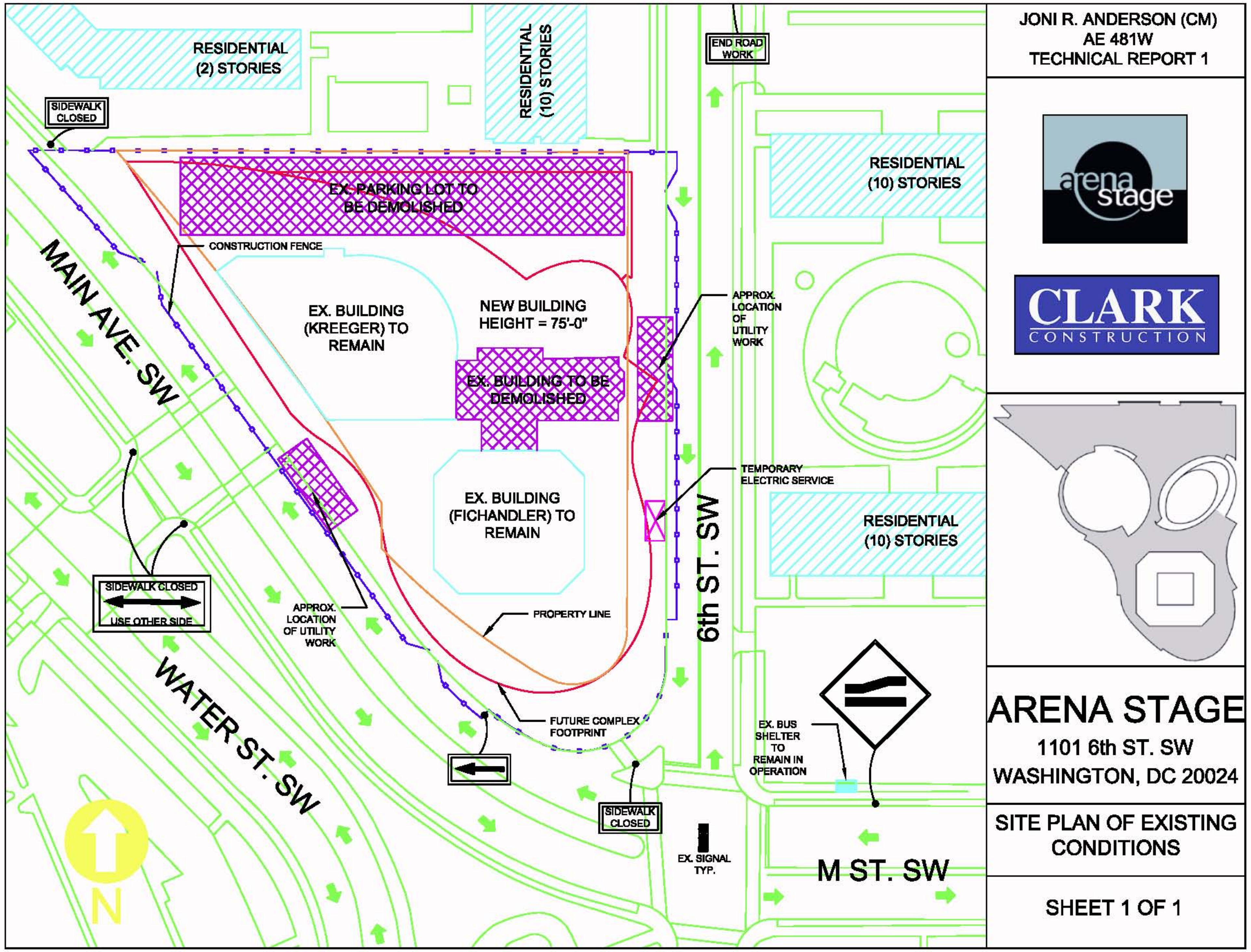
Figure 3: Map of the National Mall and Arena Stage (enlarged aerial view of the old building)

GEOTECHNICAL REPORT

Based on a geotechnical report prepared by ATC Associates, Inc., the natural subsoils on the site are Coastal Plain Lowland Deposits. 12 soil test borings were performed and the subsurface soil conditions of the site have been generalized into 3 strata types. The first, stratum A, is located closest to the existing surface under about 4 to 6 inches of topsoil. It consists of light brown, moist silty to gravely sand to very fine silty clay with possible fill materials. Although most of this material had a relatively dense consistency, 2 borings reflected loose material near finish floor elevations. The second, stratum B, was wet, light grayish-brown, very soft silty clay to loose silty or gravely sand and was located 26 to 48.5 feet from the surface. The last, stratum C, at depths of 36.5 to 55 feet, was very moist and dark. It consists of medium to extremely dense silty sand.

The subsurface water conditions were determined from groundwater readings. Level measurements were taken in each of the borings after drilling. Also, two monitoring wells, extending to 55 feet below the surface, were installed and obtained measurements for approximately 4 weeks. From this, scientist predicted that the long-term static water level for the project is expected to remain at an elevation of -5 feet, mean sea level (msl). Since the finish floor elevation is approximately 9 feet msl, a wellpoint dewatering system was not suggested, but precautions are suggested for perched or trapped water. Sump pumps were added as a result.

SITE PLAN OF EXISTING CONDITIONS



Building Systems Summary

Table 1: Building Systems Summary Checklist

Yes	No	Work Scope
✓		**Demolition Required**
✓		**Structural Steel Frame**
✓		**Cast in Place Concrete**
	✓	**Precast Concrete**
✓		**Mechanical System**
✓		**Electrical System**
✓		**Masonry**
✓		**Curtain Wall**
✓		**Support of Excavation**

DEMOLITION

The existing Arena Stage consists of two theaters: the Fichandler Theater, built in 1960, and the Kreeger Theater, later added in 1971. Both of the structures are concrete block with steel frame and are two stories above grade with a below grade basement. Portions of the Kreeger Theater, administrative offices, and the connecting building were razed prior to the beginning of the new construction. Due to the age of the existing facility, multiple items containing hazardous materials were identified throughout the building. Included were asbestos, lead paint, potential sources of poly-chlorinated biphenyl (PCBs), and a 55 gallon drum of HVAC water treatment chemicals. Asbestos was found in pipe fitting insulation, mastic, duct insulation, ceiling tiles, floor tiles, spray-on insulation, and transite asbestos board. Luckily, most of these items were classified as being in fair to good, non-friable condition. Possible PCB containing sources were the old fluorescent light ballasts, power transformers, and hydraulic fluid from the elevator. During demolition and during renovation, the building had containment areas for asbestos abatement. Preventive measures were taken while removing the contaminated materials from the building and also during their disposal. With the exception of some salvageable masonry, recycling of materials was not a major priority during the demolition of the original Arena Stage.

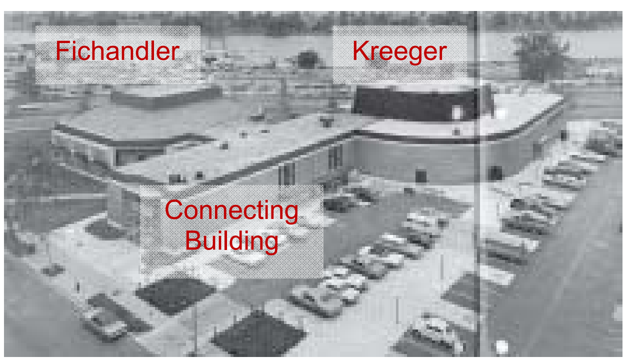


Figure 4: The original Arena Stage built circa 1960/1971

STRUCTURAL STEEL FRAME

The structural steel used on Arena Stage is primarily located in the ceiling and the truss supported roof. A series of wide flange girders and beams make up the ceiling system, which carry the loads of the 45’ glass façade and transfer them to the PSL timber columns (described in the curtain wall section) along the building perimeter. For acoustical reasons, many of the trusses are bearing on isolation pads on steel brackets. This allows for separation of the decks of the composite floor slabs from floor to floor.

Figure 5: Isolation Pad (Cradle)

The roof support is a matrix of diamond oriented bracing trusses and hollow structural section (HSS) beams. The scalloped soffit is made of stucco and the roof parapet will be DensDeck, a highly mold resistant roof panel that consists of a moisture-resistant, noncombustible core of specially treated gypsum with glass mat facings. The high roof is a hot fluid applied material. Due to the intense structural system of the roof, a finalized steel schedule is not yet available.

Two tower cranes are available on Arena Stage’s site. The first has a 245' jib length and a 6,600 pound weight capacity. The second tower crane has a 180' jib length and a 6,280 pound weight capacity. They are located in areas of the site where multiple trades can take advantage of their use. One is on the northwest tip of the site and the other is to the southeast of the Fichandler. The use of both cranes makes is possible to reach around the entire site.

Figure 6: The two tower cranes hovering over the Fichandler

CAST-IN-PLACE CONCRETE

A majority of the new work on Arena Stage utilizes cast-in-place (CIP) concrete. While only a minimal amount was placed in the Fichandler and the Kreeger, the majority was used on the underground parking garage and the Cradle Theater. The horizontal pours, along with some vertical work, were placed using standard formwork with a traditional scaffold frame and stringer/joist assembly.

Due to the nestled, ellipse-shaped walls of the Cradle, the vertical formwork was a much more complex system. To achieve this architectural element that was designed on a 4 degree slope, Clark Concrete used a PERI Formwork System. It consisted of a CB 240 climbing platform and RUNDFLEX circular wall formwork. The CB 240 system uses strongbacks which are connected to brackets via a carriage that has a rack and an adjustable brace. 2.40 meter wide pre-fabricated decking is then set level with the brackets and the carriage.

Figure 7: PERI CB 240 climbing platform system (Cradle)

Figure 8: Movement to next lift via crane

The RUNDFLEX circular wall formwork was a flexible solution to the shape and slope of the Cradle walls. There were over 2,000 templates that circulated the project in order to successfully place the concrete walls. The templates were placed on the back of the RUNDFLEX formwork, which is then adjusted by either tightening or loosening the joints on the back of it. Once the template was matched, the walls were prepared for pouring in 10' lifts. Since the walls sit on a 4 degree slope, gaps began to appear in between the runs of formwork. Although it was only about 1" at the bottom of the wall, it was as large as 17" at the lift's completion. In order to close this gap, custom cut fillers were wedged between the formwork to create a smooth face and consistent horizontal wall joint.

Figure 9: PERI RUNDFLEX formwork prepared for a lift pour

Figure 10: Movement to next lift via crane

This method allows for high bearing capacity, simple moving procedure by crane, ease of retracting large formwork without a crane, and less tripping hazards.

MECHANICAL SYSTEM

The HVAC system consists of central boiler and chiller plants and central outdoor air distribution to multiple constant volume air handling systems for the acoustically sensitive spaces and other large spaces. Fan powered induction systems are used for smaller zone control of the back of house areas.

The mechanical classification is a 4-pipe, air-water fan coil system. 4 gas-fired boilers are located in the boiler room located on level 49.5', served by dedicated constant flow primary heating hot water pumps. 2 electric centrifugal chillers are located in the chiller room on level 0.0' of the Fichandler and served by 3 condenser pumps. 2 single cell counterflow centrifugal fan type cooling towers are located on the terrace of level 43.0'.

There are 2, 100% outside air handling units (OHUs). One is located on the roof of the Cradle and the other is in the Kreeger mechanical room. The Kreeger and the Fichandler are each served by 2 separate constant volume air handling units (AHUs), one for the seating area and one for the stage. Due to the smaller size of the black box theater, the Cradle is only being served by one AHU. 13 other AHUs serve the lobby, mall, switchgear rooms, and other administrative locations. The air handling units, whether constant or variable, range from 3,000 to 43,100 cfm.

Fan powered induction units (FPIUs) provide individual zone temperature control and ventilation to multiple areas in the back of house. Horizontal and vertical fan coil units (FCUs) are provided for unoccupied areas that require cooling/heating. A total of 31 FCUs ranging from 220 to 2,900 cfm are scattered throughout the complex. The primary method for controlling and monitoring the mechanical system is a state of the art control system with stand alone digital controllers.

The fire suppression system implemented in Arena Stage consists of both a wet and dry sprinkler system. It is a combined standpipe and sprinkler system; the sprinkler system is supplied from the standpipe system. Automatic wet-type, Class I standpipe system has an open water supply valve with maintained pressure. It is capable of supplying water demand in a short amount of time.

ELECTRICAL SYSTEM

Arena Stage's electrical service is supplied by Pepco, a regulated electric utility that provides transmission and distribution services to most of Washington, DC. The main feed is brought into the building and stepped down by a Pepco transformer to a 3Φ, 4 wire, 277/480V, 3000A bus. The size is adjusted throughout the building with 8 Dry Type Transformers. Emergency power is supplied by one 275kW/344kVA separately derived fixed generator system. The generator runs on an 1800 rpm-speed diesel engine that powers 3 emergency multi-duct conduit (EMDC) systems. It was sized to carry the loads of the fire pump, mechanical system, snow melting, lighting, and uninterrupted power supply.

MASONRY

Since both the Fichandler and the Kreeger were originally constructed with concrete masonry units (CMUs), cast-in-place concrete, and brick veneer, the same wall type was matched for the renovation. The brick veneer will be used to restore the exterior faces of the 2 existing theaters and the back side of the Cradle Theater where it connects to the BOH and the Fichandler.

Scaffolding will be used in areas where large spans of masonry are being laid to high elevations. Reinforcing steel and grout is used on load bearing walls and brick veneer is connected to the structure using corrugated metal ties, wire ties, adjustable anchors to structural members, and partition top anchors. Any masonry that was salvageable during demolition, and was in adequate condition, will be reused.

CURTAIN WALL

The 45' tall curtain wall is one of the main design features of Arena Stage. The glazing is on an inverted 4 degree slope and the wall is a serpentine comprised of multiple radii. It is sectioned off into 12'×6-8" insulated glass frames which weigh approximately 850 pounds per unit. They are hung from the ceiling by stainless steel cables, supporting the dead load of the glass. Since the glass units are so heavy, the system was designed to be installed from the top down. This was done in order to load the cables that are anticipated to stretch ½" as a result of the weight. The cables are then supported by wide flange beams located in the ceiling above the lobby.

Huge parallel strand lumber (PSL) timber columns, designed by StructureCraft Inc., back up the façade and support the entire system. The ellipse-shaped, solid columns range from 48' to 58' in length and are approximately 30" in diameter. Sitting 3' off of the glass, they are placed 36' on center along the perimeter of the building and run continuous up to the roof. Sprouting off the columns are support arms that connect the horizontal muntins which carry the lateral loads of the façade. These pieces are connected by an aluminum plate which is penetrated by the stainless steel support cables. The base of the columns is an exaggerated pin made of cast ductile-iron that is bolted to the floor.

Figure 11: Parallel Strand Lumber Columns with support arms and muntins

Figure 12: Cast ductile-iron bases

Figure 13: This detail shows the connection of the support arm and muntins to the aluminum plate with (4) tight-fit pins. Also shown is the intersection of the support cable with the aluminum plate.

SUPPORT OF EXCAVATION

Since the original structures of the Fichandler and the Kreeger theaters are remaining for renovation, proper support was required during excavation. A temporary earth retention system was installed using underpinning and sheeting and shoring. Materials include WF and HP steel piles, low carbon steel lagging studs, tieback tendons, 3" thick hardwood for lagging, tieback grout, and pile shaft backfill.

The underpinning was performed through installation of drilled or driven cantilevered, braced, and tieback HP solider bearing piles. Approach pits and underpinning pits were dug and then excavated with interpier (beam/wale) lagging between pits to the tieback elevation. The Fichandler has underpinning on the interior of three perimeter walls and the Kreeger has it in areas where support walls were removed. Although the system is primarily temporary, several underpinning locations are permanent.

Sheeting and shoring was also used. After the piles were laid out, they were driven/drilled. Excavation was done and lagging was installed to one foot below each tie or brace elevation. Once the tiebacks were installed and tested, excavation was continued to the subgrade and if required, braces were installed. Cantilevered sheeting was installed on the Main Avenue side of the Kreeger. Above-ground shoring was installed in necessary locations around the Kreeger as well. Tiedback sheeting is on the interior 6th Street wall of the Fichandler. Additional sheeting surrounds the majority of the site around the new building footprint.

Another necessary utility support was for an existing 8" water line along 6th Street SW. The system is free draining with no allowance for hydrostatic pressures. Based on the groundwater reports, sump pumps were provided on the parking level as the foundation and underslab drainage systems. It was installed prior to excavation to eliminate all hydrostatic pressures against the sheeting system and to lower and maintain the water table below design subgrade.

Figure 14: Fichandler Underpinning (left) and Kreeger above-ground shoring (right)

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Introduction to Analyses

Arena Stage is a very unique project, making the execution of certain analyses difficult due to the complexity of the building's geometry, function, and overall scope of construction. A total of 3 analyses were performed during the completion of this senior thesis project.

The first analysis is titled *Redesign of the Curtain Wall System: Elimination of the 4 Degree Slope.* This analysis contains both a constructability depth and an architectural breadth. The curtain wall not only generated personal interest, but it became apparent throughout my research that it is one of the most challenging facets of the project. It is a detailed design which resulted in both high cost and grueling coordination. The redesign of this architectural element was done to prove that a slight adjustment in the appearance of the building could result in significant cost and schedule reduction. Covered in the analysis is an investigation of the current design, suggestion for a new design, cost and schedule impacts of the new design, a constructability discussion, and an architectural discussion.

Analysis II is named *Application of Photovoltaic Panels*. This analysis came about a result of the PACE Roundtable which took place in October 2008. I attended a technical training topic about "Energy & Economy" facilitated by Dr. Riley. A discussion about building systems resulted in the general consensus that educating the owner and stressing the life-cycle cost of the building is very important. There is currently a high demand for energy retrofits and clients need to be aware of the long term cost savings that can be achieved despite a high upfront cost. This analysis contains an electrical breadth, focusing on the design of a photovoltaic system for Arena Stage and the expected payback period.

The third and final analysis is the *Redesign of the Fichandler Stage Air Distribution System.* Retrofitting the Fichandler Theater with new mechanical equipment was a challenge due to the minimal space that was available. The supply air to the stage is delivered by high-throw branch ducts located far above the stage within the wood ceiling. This design requires excess sheet metal duct that needs to be installed in a very tight space. Analysis III contains a mechanical breadth, examining a redesign of the system using fabric duct hung beneath the catwalk. Fabric duct is often a lower cost solution and, in this case, provides closer air distribution.

Although these analyses are not directly related to one another, all proposed ideas were viewed as ways to enhance the project without compromising the quality. They were completed based on the knowledge that I have gained throughout my collegiate career and through the use of resources that were made available during this semester. Each analysis contains a write up on each of the following topics:

- Background
- Problem Statement
- Objective
- Methodology
- Tools/Resources
- Expectations
- Analysis
- Cost and Schedule Impact
- Conclusion and Recommendation

Analysis I: Redesign of the Curtain Wall System: Elimination of the 4 Degree Slope

[Constructability Depth : Architectural Breadth]

BACKGROUND

The 45' tall curtain wall at Arena Stage is both a structural component and a key architectural feature of the building. While the curtain wall does not enclose the entire building, it runs continuously from the Kreeger café to the exterior wall of the Cradle Theater and is the most prominent exterior enclosure. Primarily, the curtain wall consists of two components: the glazing and the structural system. The glazing follows a serpentine path along the outside of the three theaters and sits on a 4 degree inclined slope. Each face of the façade is approximately 7 frames high, made of 1 1/8"-thick insulated vision glass that are custom cut to achieve the architectural "curve" of the façade.

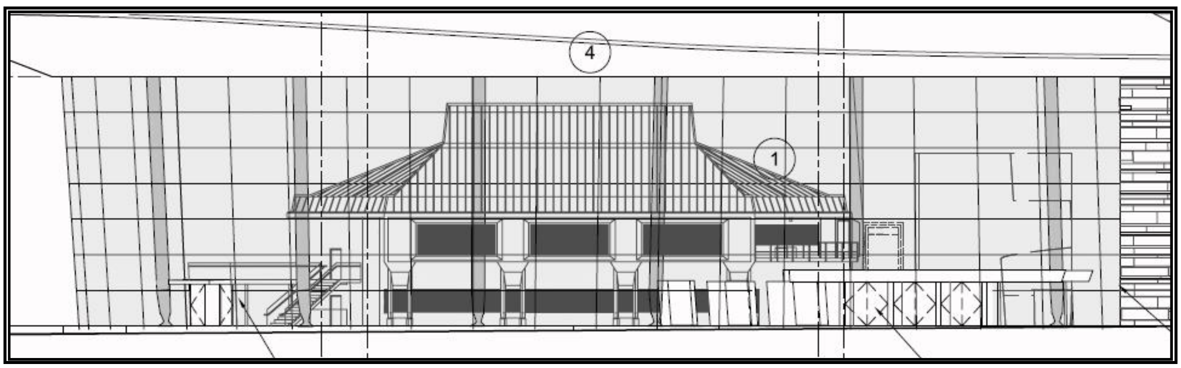


Figure 15: Architectural Elevation showing the faces of the façade with glazing runs at 7 frames high

The glass is hung from the ceiling by stainless steel cables, which are supported by wide flange beams located in the ceiling above the lobby. Finally, the load is passed off to timber columns, supported by cast ductile-iron bases. As one of the main design features of Arena Stage, the curtain wall is a very extravagant and expensive component. The number of custom glazing units greatly increases the cost of the glass portion of the curtain wall.

PROBLEM STATEMENT

Although sloped curtain walls are known to reduce the glare of the sun and increase visibility in and out of the building, they can be very expensive and difficult to construct. The 4 degree slope of the Arena Stage curtain wall causes the glazing units to increase in size as the slope progresses, producing a combination of rectangular and trapezoidal pieces. The size and shape of the glazing units vary slightly from frame to frame, making coordination difficult and construction meticulous.

OBJECTIVE

To slightly adjust the architecture of the curtain wall by eliminating the 4 degree slope so that the façade is vertically plumb along the serpentine path, creating more uniform glazing unit sizes within each face.

METHODOLOGY

1. Determine what parts of the system are going to be straightened
2. Determine the impact that straightening the curtain wall has on the wood support system
3. Perform a quantity take-off of the glazing units of the current curtain wall design
4. Determine the exact number of frames and individual sizes
5. Figure out which end point to project the curtain wall from
6. Design a new layout and standardize the glazing unit sizes
7. Determine the impact that the new design will have on the cost and schedule of the curtain wall
8. Perform a constructability review
9. Discuss the architectural implications of the design change
10. Make a recommendation on whether straightening the curtain wall is an appropriate adjustment for Arena Stage

TOOLS / RESOURCES

- Clark Construction Group, LLC
- Arena Stage Construction Documents/Specifications
- StructureCraft Inc.
- Icon Exterior Building Solutions, LP
- Curtain Wall Shop Drawings
- Glazing Mock-Up Design/Test Procedure narrative
- Structural Wind Load Testing and Tolerance narrative
- Penn State AE Faculty

Figure 16: Curtain wall similar to Arena Stage (image provided by StructureCraft Inc.)

EXPECTATIONS

By eliminating the 4 degree slope of the curtain wall, I expect that more uniform glazing unit sizes can be used to construct the system. There will no longer be trapezoidal units, more standardized sizes can be manufactured, and the cost of the system will go down. This simplification will also decrease installation time since there will be less independent unit sizes to coordinate. While this change is not expected to greatly impact the wood structural system, being able to install the system vertically plumb is going to make construction much easier.

ANALYSIS

In order to honor the request of Arena Stage and not publicize any hard costs, the actual value of the curtain wall system is unknown and therefore cannot be used as a comparison. Very little reference was made to estimating resources or literature because of the uniqueness of the slanted glass and the PSL wood structure. A price of $3.9 million is going to be used as a ballpark estimate and representative figure for the cost of the PSL wood structure system alone. A price of $3.5 million is going to represent the cost of the glazing system alone.

The Structural Support of the Curtain Wall

Parallel strand lumber (PSL) timber columns provide the support for the entire curtain wall system. These solid wood columns, ranging from 48' to 58' tall, are shaped into ellipses on a lathe. To provide enough support for the glazing, 18 columns, sitting 3' off the glass, are placed 36' on center along the perimeter of the building.

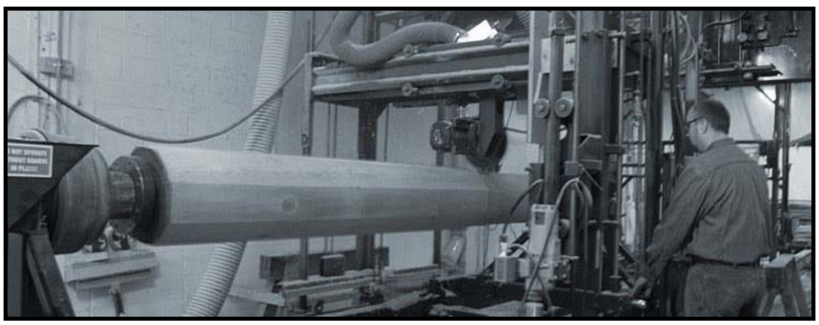


Figure 17: Shaping the PSL timber columns on the lathe (Provided by StructureCraft Inc.)

The columns support the glazing through a series of structural components. Each column has an exaggerated pin base made of cast ductile-iron, 12 wooden support arms, 12 wooden muntins, 12 aluminum plates and 2 stainless steel cables ranging in length.

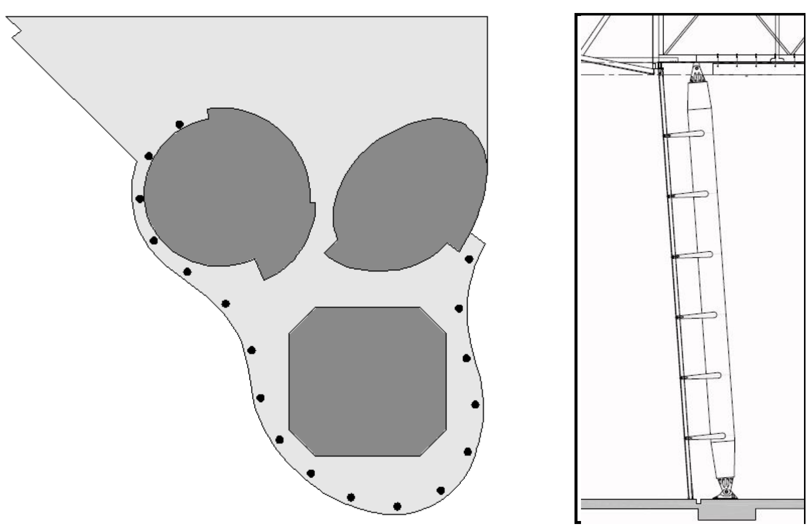


Figure 18: Plan view of the 18 columns (left) and an elevation of a column (right)

When the consideration was made to straighten the curtain wall, two options were presented for the redesign:

1. Straighten the glass and leave the columns sloped to make the system appear as if it were still sloped, or
2. Straighten the entire system.

For the first option, it was realized that this would over-complicate the structural system of the curtain wall. As shown in Figure 18 on page 26, the original design shows that the columns are aligned parallel to the glass of the curtain wall. This allows for all of the support arms to be the same length and for there to be uniformity from column to column. If the glass was to be straightened and the columns were kept sloped, this would no longer be the case. The (6) support arms that run from the top to the bottom would all vary in length, making engineering, fabrication, and installation more complicated. This option would cost more and potentially take longer to coordinate installation.

The second option consists of leaving the curtain wall at it is, but pivoting the entire system to eliminate the 4 degree slope. StructureCraft explained that this will allow for the structural system to remain relatively the same. The support arms and muntins will remain uniform from top to bottom and from column to column. Minimal design changes will have to be made to the wood column support portion of the curtain wall. It will entail slight adjustments to the top and bottom supports and connection points to the structural system of the ceiling.

Figure 19: Model of Arena Stage showing the Curtain Wall and PSL Timber Columns

The Glazing of the Curtain Wall

The layout of the glazing is dependent upon the PSL timber columns. Each column supports a module of glass, made of two faces, and two adjacent infill panels. For example, in Figure 20 below, wood column 14 (WC14) will support Module 2, which is flanked on the left by Infill 15 and on the right by Infill 14.

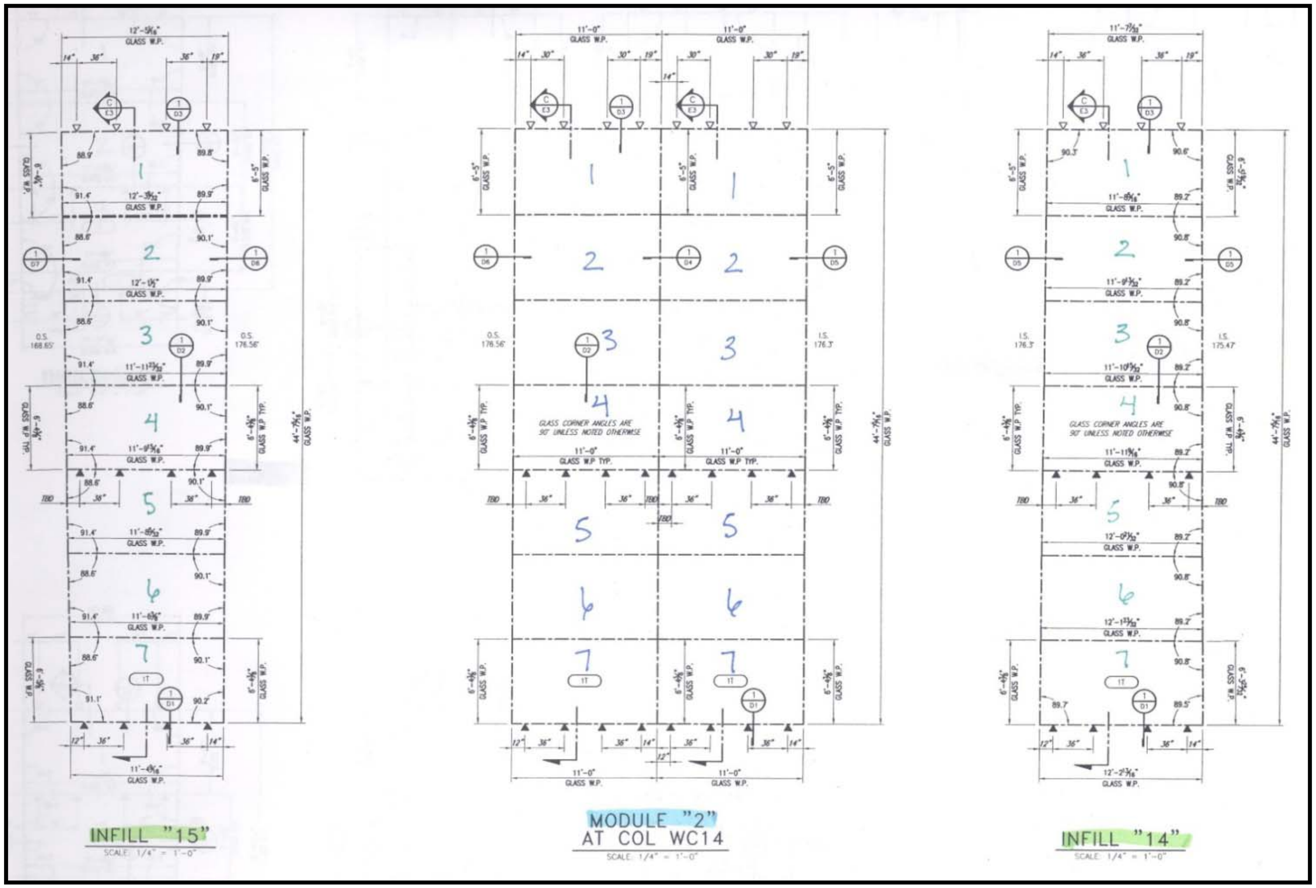


Figure 20: Example of a Glazing Elevation (Provided by Icon Exterior Building Solutions, LP)

A quantity take-off revealed that there are a total of 55 glass faces that make up the curtain wall. Of those 55 faces, 36 are modules (or 18 module pairs) and 19 are infills. The modules contain solely rectangular units, while the infills contain the trapezoidal-shaped units. These diverse trapezoids make up 34.5% of the wall. It was also determined that there are a total of 365 units in the entire curtain wall system, 148 of which are exclusively independent sizes, meaning that 40.5% of the curtain wall is made up of non-repeating units. Not only is this an extreme number of custom units to manufacture, which brings the cost way up, but it is going to be a nightmare to coordinate when it comes time to deliver, layout, and install the panels.

Figure 21: Break Down of the Curtain Wall Glazing Units

On the following pages there are a series of tables showing the modules and infills that make up the Arena Stage curtain wall. Light blue represents the module faces and gray represents the infill faces. Each table shows the number of panels along with the top, bottom, left, and right dimensions of each glazing unit. These take-offs were derived from the shop drawings produced for Arena Stage by Icon Exterior Building Solutions, LP. There are certain modules and infills that were not listed in the shop drawings because they were either duplicate sizes or their sizes are still unknown. This is because they are either undergoing design changes or still need to be field verified. The sizes of some of these faces and their specific units were estimated according to adjacent panels that they are required to match up with and the plan views of the curtain wall. There are also portals, or entrance points, where doors located which cause some of the faces to have less than 7 units of glass.

Module List

Module 1B					&	Module 1B				
(T to B)	**Top**	**Bottom**	**Left**	**Right**		(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-0"	12'-0"	6'-5 19/32"	6'-5"		**Panel 1**	12'-0"	12'-0"	6'-5"	6'-5 19/32"
Panel 2	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 2**	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 3**	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"
Panel 4	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 4**	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"
Panel 5	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 5**	12'-0"	12'-0"	6'-4 3/8"	6'-4 3/8"
Portal						**Panel 6**	12'-0"	12'-0"	2'-8 15/32"	2'-7 7/8"
Panel 6	12'-0"	12'-0"	6'-3 25/32"	6'-4 3/8"		Portal				

Module 2					&	Module 2				
(T to B)	**Top**	**Bottom**	**Left**	**Right**		(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-0"	11'-0"	6'-5"	6'-5"		**Panel 1**	11'-0"	11'-0"	6'-5"	6'-5"
Panel 2	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 2**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 3**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 4**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 5**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 6**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 7**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"

Module 3					&	Module 3				
(T to B)	**Top**	**Bottom**	**Left**	**Right**		(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-0"	11'-0"	6'-4 1/4"	6'-5"		**Panel 1**	11'-0"	11'-0"	6'-5"	6'-4 1/4"
Panel 2	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 2**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 3**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 4**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 5**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"		**Panel 6**	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-0"	11'-0"	6'-5 1/8"	6'-4 3/8"		**Panel 7**	11'-0"	11'-0"	6'-4 3/8"	6'-5 1/8"

Module 3A				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-0"	11'-0"	6'-4 1/4"	6'-5"
Panel 2	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-0"	11'-0"	6'-5 1/8"	6'-4 3/8"

&

Module 3A				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-0"	11'-0"	6'-5"	6'-4 1/4"
Panel 2	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-0"	11'-0"	6'-4 3/8"	6'-5 1/8"

Module 3B				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-0"	11'-0"	6'-4 1/4"	6'-5"
Panel 2	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-0"	11'-0"	1'-5 19/32"	1'-4 27/32"

&

Module 3B				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-0"	11'-0"	6'-5"	6'-4 1/4"
Panel 2	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-0"	11'-0"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-0"	11'-0"	1'-4 27/32"	1'-5 19/32"

Infill List

Infill 2				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	10'-7 1/4"	10'-9 1/4"	6'-5 19/32"	6'-5 19/32"
Panel 2	10'-9 1/4"	10'-11 7/32"	6'-4 3/8"	6'-4 3/8"
Panel 3	10'-11 7/32"	11'-1 3/16"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-1 3/16"	11'-3 1/8"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-3 1/8"	11'-5 3/32"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-5 3/32"	11'-5 29/32"	2'-7 7/8"	2'-7 7/8"
Portal				

Infill 3				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-7 1/4"	11'-8 13/16"	6'-5"	6'-5 19/32"
Panel 2	11'-8 13/16"	11'-10 11/32"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-10 11/32"	11'-11 7/8"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-11 7/8"	12'-1 13/32"	6'-4 3/8"	6'-4 3/8"
Panel 5	12'-1 13/32"	12'-2 15/16"	6'-4 3/8"	6'-4 3/8"
Panel 6	12'-2 15/16"	12'-4 15/32"	6'-4 3/8"	6'-4 3/8"
Panel 7	12'-4 15/32"	12'-6"	6'-4 3/8"	6'-3 25/32"

Infill 5				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-4 27/32"	12'-2 27/32"	6'-4 1/4"	6'-4 1/4"
Panel 2	12'-2 27/32"	12'-0 13/16"	6'-4 3/8"	6'-4 3/8"
Panel 3	12'-0 13/16"	11'-10 13/16"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-10 13/16"	11'-8 13/16"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-8 13/16"	11'-6 25/32"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-6 25/32"	11'-4 25/32"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-4 25/32"	11'-2 3/4"	6'-5 1/8"	6'-5 1/8"

Infill 6				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-5 3/32"	12'-2 7/16"	6'-4 1/4"	6'-4 1/4"
Panel 2	12'-2 7/16"	11'-11 13/16"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-11 13/16"	11'-9 3/16"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-9 3/16"	11'-6 9/16"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-6 9/16"	11'-3 29/32"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-3 29/32"	11'-2 3/32"	4'-5 1/16"	4'-5 1/16"
Portal				

Infill 8				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-5 3/16"	12'-3 3/32"	6'-4 1/4"	6'-4 1/4"
Panel 2	12'-3 3/32"	12'-1 1/32"	6'-4 3/8"	6'-4 3/8"
Panel 3	12'-1 1/32"	11'-10 15/16"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-10 15/16"	11'-8 27/32"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-8 27/32"	11'-6 25/32"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-6 25/32"	11'-4 11/16"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-4 11/16"	11'-2 19/32"	6'-5 1/8"	6'-5 1/8"

Infill 9				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-5 27/32"	12'-4 1/8"	6'-5"	6'-4 1/4"
Panel 2	12'-4 1/8"	12'-2 3/8"	6'-4 3/8"	6'-4 3/8"
Panel 3	12'-2 3/8"	12'-0 21/32"	6'-4 3/8"	6'-4 3/8"
Panel 4	12'-0 21/32"	11'-10 29/32"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-10 29/32"	11'-9 3/16"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-9 3/16"	11'-7 7/16"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-7 7/16"	11'-5 11/16"	6'-4 3/8"	6'-5 1/8"

Infill 11				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-4 15/32"	12'-2 1/4"	6'-4 1/4"	6'-4 1/4"
Panel 2	12'-2 1/4"	12'-0"	6'-4 3/8"	6'-4 3/8"
Panel 3	12'-0"	11'-9 25/32"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-9 25/32"	11'-7 17/32"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-7 17/32"	11'-5 5/16"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-5 5/16"	11'-3 1/16"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-3 1/16"	11'-0 13/16"	6'-5 1/8"	6'-5 1/8"

Infill 12				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-7 1/8	11'-7 13/16"	6'-5 19/32"	6'-4 1/4"
Panel 2	11'-7 13/16"	11'-8 1/2"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-8 1/2"	11'-9 3/16"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-9 3/16"	11'-9 27/32"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-9 27/32"	11'-10 17/32"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-10 17/32"	11'-11 7/32"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-11 7/32"	11'-11 29/32"	6'-3 25/32"	6'-5 1/8"

Infill 14				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-7 7/32"	11'-8 5/16"	6'-5"	6'-5 19/32"
Panel 2	11'-8 5/16"	11'-9 13/32"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-9 13/32"	11'-10 15/32"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-10 15/32"	11'-11 9/16"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-11 9/16"	12'-0 21/32"	6'-4 3/8"	6'-4 3/8"
Panel 6	12'-0 21/32"	12'-1 23/32"	6'-4 3/8"	6'-4 3/8"
Panel 7	12'-1 23/32"	12'-2 13/16"	6'-4 3/8"	6'-3 25/32"

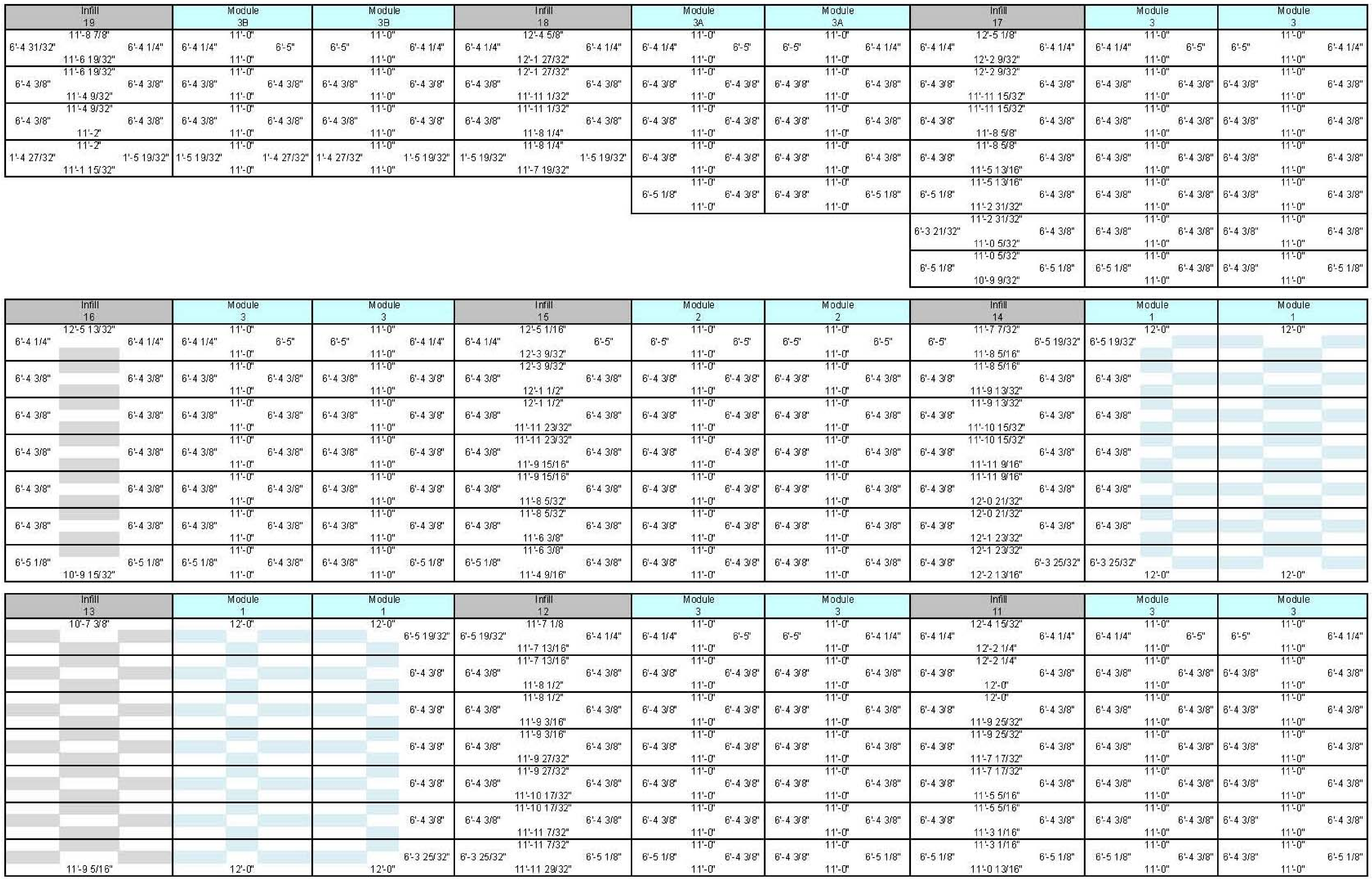
Infill 15				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-5 1/16"	12'-3 9/32"	6'-4 1/4"	6'-5"
Panel 2	12'-3 9/32"	12'-1 1/2"	6'-4 3/8"	6'-4 3/8"
Panel 3	12'-1 1/2"	11'-11 23/32"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-11 23/32"	11'-9 15/16"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-9 15/16"	11'-8 5/32"	6'-4 3/8"	6'-4 3/8"
Panel 6	11'-8 5/32"	11'-6 3/8"	6'-4 3/8"	6'-4 3/8"
Panel 7	11'-6 3/8"	11'-4 9/16"	6'-5 1/8"	6'-4 3/8"

Infill 17				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-5 1/8"	12'-2 9/32"	6'-4 1/4"	6'-4 1/4"
Panel 2	12'-2 9/32"	11'-11 15/32"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-11 15/32"	11'-8 5/8"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-8 5/8"	11'-5 13/16"	6'-4 3/8"	6'-4 3/8"
Panel 5	11'-5 13/16"	11'-2 31/32"	6'-5 1/8"	6'-4 3/8"
Panel 6	11'-2 31/32"	11'-0 5/32"	6'-3 21/32"	6'-4 3/8"
Panel 7	11'-0 5/32"	10'-9 9/32"	6'-5 1/8"	6'-5 1/8"

Infill 18				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	12'-4 5/8"	12'-1 27/32"	6'-4 1/4"	6'-4 1/4"
Panel 2	12'-1 27/32"	11'-11 1/32"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-11 1/32"	11'-8 1/4"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-8 1/4"	11'-7 19/32"	1'-5 19/32"	1'-5 19/32"

Infill 19				
(T to B)	**Top**	**Bottom**	**Left**	**Right**
Panel 1	11'-8 7/8"	11'-6 19/32"	6'-4 31/32"	6'-4 1/4"
Panel 2	11'-6 19/32"	11'-4 9/32"	6'-4 3/8"	6'-4 3/8"
Panel 3	11'-4 9/32"	11'-2"	6'-4 3/8"	6'-4 3/8"
Panel 4	11'-2"	11'-1 15/32"	1'-4 27/32"	1'-5 19/32"

From the module and infill take-offs, a "matrix" was made to show the curtain wall as a continuous elevation from its west terminus to its east terminus. It is shown on the next two pages in increments of (9) and (10) faces.



Infill 10	Module 2	Module 2	Infill 9	Module 3	Module 3	Infill 8	Module 3	Module 3
12'-5 7/8" / 6'-4 1/4" / 6'-5"	11'-0" / 6'-5" / 6'-5" / 11'-0"	11'-0" / 6'-5" / 6'-5" / 11'-0"	12'-5 27/32" / 6'-5" / 6'-4 1/4" / 12'-4 1/8"	11'-0" / 6'-4 1/4" / 6'-5" / 11'-0"	11'-0" / 6'-5" / 6'-4 1/4" / 11'-0"	12'-5 3/16" / 6'-4 1/4" / 6'-4 1/4" / 12'-3 3/32"	11'-0" / 6'-4 1/4" / 6'-5" / 11'-0"	11'-0" / 6'-5" / 6'-4 1/4" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-4 1/8" / 6'-4 3/8" / 6'-4 3/8" / 12'-2 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-3 3/32" / 6'-4 3/8" / 6'-4 3/8" / 12'-1 1/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-2 3/8" / 6'-4 3/8" / 6'-4 3/8" / 12'-0 21/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-1 1/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-10 15/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-0 21/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-10 29/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-10 15/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-8 27/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-10 29/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-9 3/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-8 27/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-6 25/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-9 3/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-7 7/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-6 25/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-4 11/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-5 1/8" / 6'-4 3/8" / 11'-7"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-7 7/16" / 6'-4 3/8" / 6'-5 1/8" / 11'-5 11/16"	11'-0" / 6'-5 1/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-5 1/8" / 11'-0"	11'-4 11/16" / 6'-5 1/8" / 6'-5 1/8" / 11'-2 19/32"	11'-0" / 6'-5 1/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-5 1/8" / 11'-0"

Infill 7	Module 3	Module 3	Infill 6	Module 3	Module 3	Infill 5	Module 3	Module 3
12'-4 7/8" / 6'-4 1/4" / 6'-4 1/4"	11'-0" / 6'-4 1/4" / 6'-5" / 11'-0"	11'-0" / 6'-5" / 6'-4 1/4" / 11'-0"	12'-5 3/32" / 6'-4 1/4" / 6'-4 1/4" / 12'-2 7/16"	11'-0" / 6'-4 1/4" / 6'-5" / 11'-0"	11'-0" / 6'-5" / 6'-4 1/4" / 11'-0"	12'-4 27/32" / 6'-4 1/4" / 6'-4 1/4" / 12'-2 27/32"	11'-0" / 6'-4 1/4" / 6'-5" / 11'-0"	11'-0" / 6'-5" / 6'-4 1/4" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-2 7/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-11 13/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-2 27/32" / 6'-4 3/8" / 6'-4 3/8" / 12'-0 13/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-11 13/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-9 3/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-0 13/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-10 13/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-9 3/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-6 9/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-10 13/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-8 13/16"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-6 9/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-3 29/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-8 13/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-6 25/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-3 29/32" / 4'-5 1/16" / 4'-5 1/16" / 11'-2 3/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-6 25/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-4 25/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"
6'-5 1/8" / 6'-5 1/8" / 10'-6 9/32"	11'-0" / 6'-5 1/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-5 1/8" / 11'-0"	Portal	11'-0" / 6'-5 1/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-5 1/8" / 11'-0"	11'-4 25/32" / 6'-5 1/8" / 6'-5 1/8" / 11'-2 3/4"	11'-0" / 6'-5 1/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-5 1/8" / 11'-0"

Infill 4	Module 2	Module 2	Infill 3	Module 1B	Module 1B	Infill 2	Module 1A	Module 1A	Infill 1
12'-5 7/16" / 6'-4 1/4" / 6'-5"	11'-0" / 6'-5" / 6'-5" / 11'-0"	11'-0" / 6'-5" / 6'-5" / 11'-0"	11'-7 1/4" / 6'-5" / 6'-5 19/32" / 11'-8 13/16"	12'-0" / 6'-5 19/32" / 6'-5" / 12'-0"	12'-0" / 6'-5" / 6'-5 19/32" / 12'-0"	10'-7 1/4" / 6'-5 19/32" / 6'-5 19/32" / 10'-9 1/4"	12'-0" / 6'-5 19/32"	11'-1 27/32"	12'-1 5/16"
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-8 13/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-10 11/32"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	10'-9 1/4" / 6'-4 3/8" / 6'-4 3/8" / 10'-11 7/32"	6'-4 3/8"		
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-10 11/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-11 7/8"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	10'-11 7/32" / 6'-4 3/8" / 6'-4 3/8" / 11'-1 3/16"	6'-4 3/8"		
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-11 7/8" / 6'-4 3/8" / 6'-4 3/8" / 12'-1 13/32"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	11'-1 3/16" / 6'-4 3/8" / 6'-4 3/8" / 11'-3 1/8"	6'-4 3/8"		
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-1 13/32" / 6'-4 3/8" / 6'-4 3/8" / 12'-2 15/16"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	12'-0" / 6'-4 3/8" / 6'-4 3/8" / 12'-0"	11'-3 1/8" / 6'-4 3/8" / 6'-4 3/8" / 11'-5 3/32"	6'-4 3/8"		
6'-4 3/8" / 6'-4 3/8"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-2 15/16" / 6'-4 3/8" / 6'-4 3/8" / 12'-4 15/32"	12'-0" / 6'-4 3/8" / 2'-8 15/32" / 12'-0"	12'-0" / 2'-8 15/32" / 2'-7 7/8" / 12'-0"	11'-5 3/32" / 2'-7 7/8" / 2'-7 7/8" / 11'-5 29/32"	2'-7 7/8"		
6'-5 1/8" / 6'-4 3/8" / 11'-7 13/32"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	11'-0" / 6'-4 3/8" / 6'-4 3/8" / 11'-0"	12'-4 15/32" / 6'-4 3/8" / 6'-3 25/32" / 12'-6"	12'-0" / 6'-3 25/32" / 6'-4 3/8" / 12'-0"	Portal	Portal		11'-11 3/16"	11'-11 7/8"

In order to straighten the curtain wall, it is important to consider which endpoint, top or bottom, will the new curtain wall be projected from. This is an issue for Arena Stage because the property line of the building is very close to the base edge of the curtain wall. Referring to Figure 22, the dotted line represents the property line, the outermost solid line is the roof soffit, and the innermost solid line is the outer perimeter of the building. Since the roof and the top of the curtain wall exceed the property line, a vertically plumb design must be projected vertically from the bottom perimeter of the wall. This will ensure that the curtain wall will remain within the property boundaries.

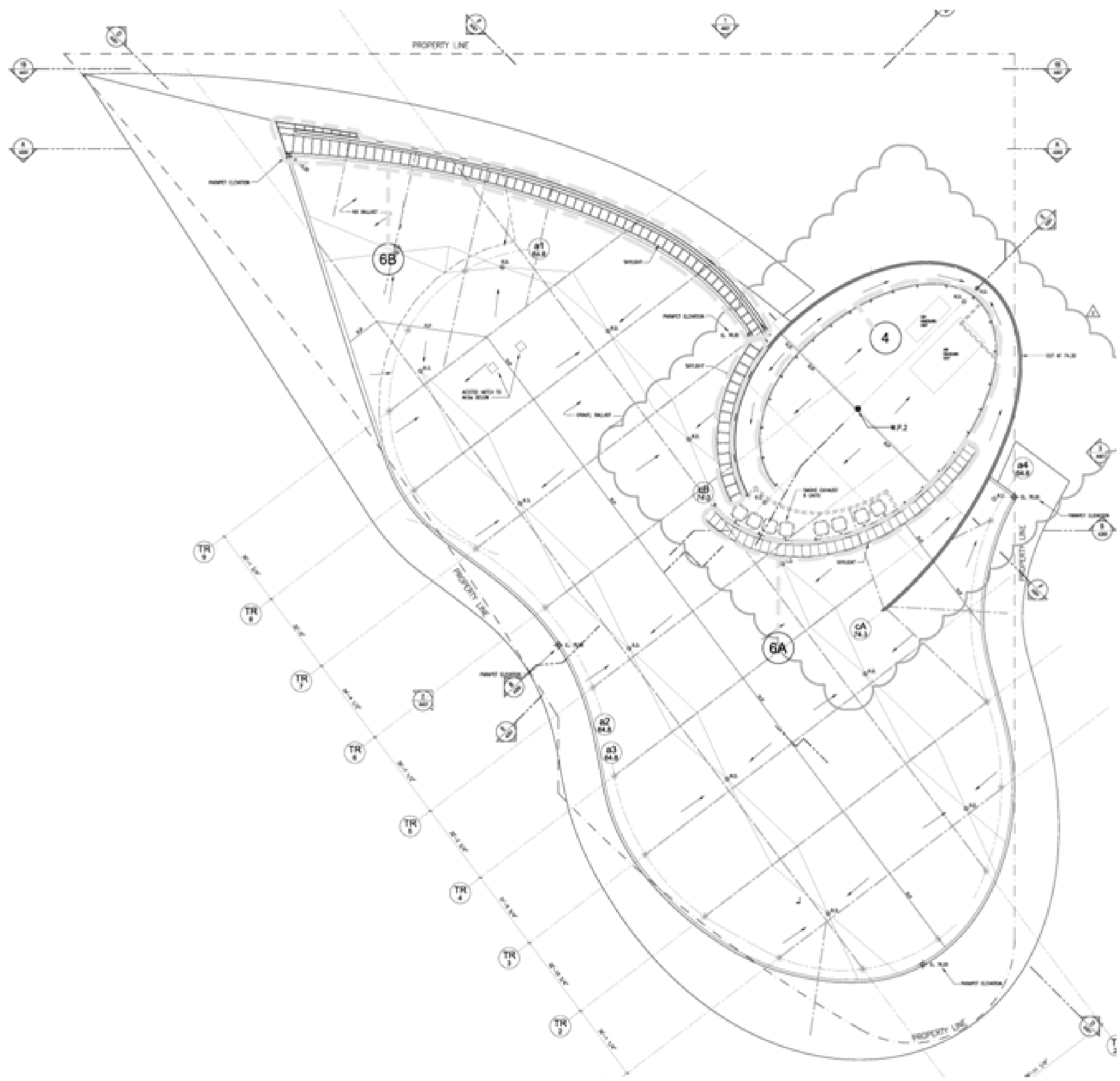


Figure 22: Roof Plan Showing the Proximity of the Property Line to the Boundary Line

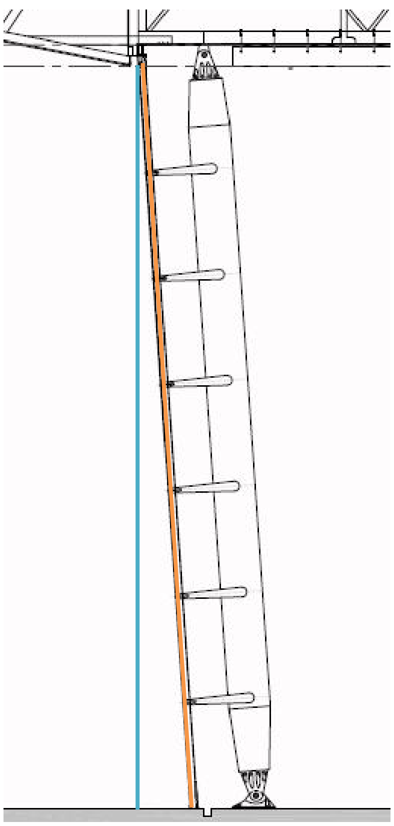
What is interesting about the proposed change is that it will not be eliminating any significant amounts of the building's floor area. The curtain wall is mainly a component of the lobby and does not physically connect with any portion of the building except for the terminal points: at the exterior wall of the Cradle Theater and at the Kreeger Theater café. The ceiling area is the main portion of the building that will be slightly reduced by this change.

In order to redesign the glazing of the curtain wall, there are two major design elements that must be considered:

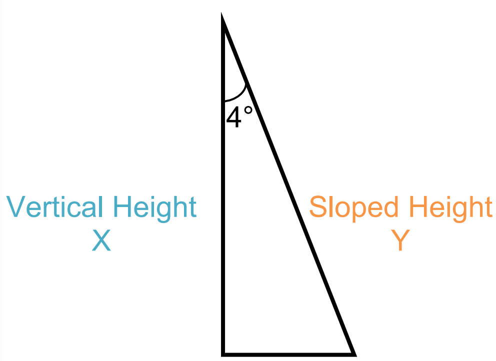
1. Adjusting the height of the glazing units. Since the curtain wall was designed on a 4 degree slope, straightening it is going to make the vertical distance from the ground level to the roof level greater. The height of the glazing units must be decreased in order for this distance to remain the same.
2. Figuring out a path width for each face of units. This path must not only maintain the curved appearance of the original curtain wall, but it must also create more uniform sizes for each face. If each face is made more uniform, then standardizing the unit sizes can be achieved more easily.

The aforementioned design aspects of the curtain wall must be taken into consideration simultaneously. Since the curtain wall is broken up into faces, which it then broken up into units, or panels, it is imperative that each unit match up to its adjoining units on its left and right. Using the individual take-offs, the modules and infills were analyzed independently from one another to figure out the height of each frame without the slope.

The following values are the different elevation heights of the curtain wall sections. They are going to be adjusted from their sloped distance to the vertically plumb distance they will be in the proposed design:



The vertical height was found using simple geometry: taking the sloped height and multiplying it by the cosine of 4 degrees.



$$X = Y(\cos 4°)$$

Table 2: Face Height Conversions

Sloped Height (Y)	Vertical Height (X)
20’-6 19/32”	20’-5 31/32”
31’-10 ½”	31’-9 9/16”
44’-7 ¼”	44’-5 15/16”
36’-2 13/16”	36’-1 24/32”
34’-6 31/32”	34’-5 31/32

The vertical heights of the face elevations translate to the take-off matrix, from the west terminus to the east terminus the 55 faces are in the following order:

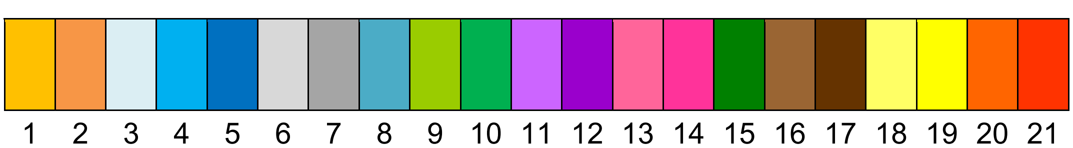
- (4) faces at 20’-5 31/32”
- (2) faces at 31’-9 9/16”
- (33) faces at 44’-5 15/16”
- (1) face at 36’-1 24/32” (due to portals)
- (10) faces at 44’-5 15/16”
- (3) faces at 34’-5 31/32 (due to portals)
- (2) faces at 44’-5 15/16”

The biggest challenge was adjusting the matrix, changing the unit sizes so that they were more standardized in both height and width. First, the unit heights were altered to correspond with the new face vertical heights. This was done by finding the most recurring height value in the original curtain wall design, using it as the height of the majority of the units, and completing the faces by finding the remaining height in the face series. In the case of this curtain wall, 6’-4 3/8” was the most common unit height. With the majority of the faces being 44’-5 15/16” high, 6 of the units were made 6’-4 3/8” high, and the remaining unit was given a height of 6’-3 ¾”. This procedure was followed the entire way across the elevation of the curtain wall. Occasionally, portal entrances occur in the curtain wall faces, in which case customized heights were designed to accommodate for them. In this manner, the size of the portals was not compromised and no adjustments had to be made to their design.

Next, the widths of the units were altered. Since the widths of the rectangular module faces were generally already the same, these dimensions were not adjusted. The widths remained as originally designed and only their heights were changed. The unit widths of the infills, however, were the most inconsistent dimensions of the system because of the trapezoid-shaped units. The widths of many of the faces would vary from top to bottom, causing most units to be independently sized from one another. As stated before, it was decided to project the curtain wall from the bottom perimeter, so the bottom width dimension on the lowest unit of each infill face dictated the new base dimensions. These base dimensions of the infills were added together and averaged to create a string of repeating unit sizes. This averaging method was done between faces that had portals. Units above portals were not adjusted so that the original size of the portals could be maintained without any impact from the redesign of the curtain wall.

Once the entire matrix was adjusted and all units had been made as uniform as possible, the matrix was color-coordinated according to individual glazing unit sizes. Before, 40.5% of the curtain wall was non-repeating units. By eliminating the slope of the curtain wall and redesigning the unit sizes, there are now only 21 independent sizes, or 6%, of the entire wall.

A matrix depicting the elevation of the proposed curtain wall redesign can be found on the subsequent pages. The 21-shade color-codes below represents the 21 different unit sizes of the new system.



Infill 19	Module 3B	Module 3B	Infill 18	Module 3A	Module 3A	Infill 17	Module 3	Module 3
11'-4 1/2" 6'-4 3/8" 6'-4 3/8" 11'-4 1/2"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 1/2" 6'-4 3/8" 6'-4 3/8" 11'-4 1/2"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 1/2" 6'-4 3/8" 6'-4 3/8" 11'-4 1/2"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 1/2" 6'-4 3/8" 6'-4 3/8" 11'-4 1/2"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 1/2" 6'-4 3/8" 6'-4 3/8" 11'-4 1/2"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 1/2" 6'-4 3/8" 6'-4 3/8" 11'-4 1/2"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 1/2" 1'-4 27/32" 1'-4 27/32" 11'-4 1/2"	11'-0" 1'-4 27/32" 1'-4 27/32" 11'-0"	11'-0" 1'-4 27/32" 1'-4 27/32" 11'-0"	11'-4 1/2" 1'-4 27/32" 1'-4 27/32" 11'-4 1/2"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
				11'-0" 6'-4 1/16" 6'-4 1/16" 11'-0"	11'-0" 6'-4 1/16" 6'-4 1/16" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
						11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
						11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"

Infill 16	Module 3	Module 3	Infill 15	Module 2	Module 2	Infill 14	Module 1	Module 1
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"
11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	12'-0" 6'-3 3/4" 6'-3 3/4" 12'-0"	12'-0" 6'-3 3/4" 6'-3 3/4" 12'-0"

Infill 13	Module 1	Module 1	Infill 12	Module 3	Module 3	Infill 11	Module 3	Module 3
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	12'-0" 6'-3 3/4" 6'-3 3/4" 12'-0"	12'-0" 6'-3 3/4" 6'-3 3/4" 12'-0"	11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"

Infill 10	Module 2	Module 2	Infill 9	Module 3	Module 3	Infill 8	Module 3	Module 3
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"

Infill 7	Module 3	Module 3	Infill 6	Module 3	Module 3	Infill 5	Module 3	Module 3
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-2 3/32" 6'-4 3/8" 6'-4 3/8" 11'-2 3/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-2 3/32" 6'-4 3/8" 6'-4 3/8" 11'-2 3/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-2 3/32" 6'-4 3/8" 6'-4 3/8" 11'-2 3/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-2 3/32" 6'-4 3/8" 6'-4 3/8" 11'-2 3/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-2 3/32" 6'-4 3/8" 6'-4 3/8" 11'-2 3/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-4 3/8" 6'-4 3/8" 11'-4 5/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-2 3/32" 4'-3 7/8" 4'-3 7/8" 11'-2 3/32"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"
11'-4 5/32" 6'-3 3/4" 6'-3 3/4" 11'-4 5/32"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	Portal	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-9 3/8" 6'-3 3/4" 6'-3 3/4" 11'-9 3/8"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"

Infill 4	Module 2	Module 2	Infill 3	Module 1B	Module 1B	Infill 2	Module 1A	Module 1A	Infill 1
11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-5 29/32" 6'-4 3/8" 6'-4 3/8" 11'-5 29/32"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 7/8" 6'-4 3/8" 6'-4 3/8" 11'-11 7/8"
11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-5 29/32" 6'-4 3/8" 6'-4 3/8" 11'-5 29/32"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 7/8" 6'-4 3/8" 6'-4 3/8" 11'-11 7/8"
11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-5 29/32" 6'-4 3/8" 6'-4 3/8" 11'-5 29/32"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 7/8" 6'-4 3/8" 6'-4 3/8" 11'-11 7/8"
11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-5 29/32" 6'-4 3/8" 6'-4 3/8" 11'-5 29/32"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 7/8" 6'-4 3/8" 6'-4 3/8" 11'-11 7/8"
11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	11'-5 29/32" 6'-4 3/8" 6'-4 3/8" 11'-5 29/32"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 7/8" 6'-4 3/8" 6'-4 3/8" 11'-11 7/8"
11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-0" 6'-4 3/8" 6'-4 3/8" 11'-0"	11'-9 3/8" 6'-4 3/8" 6'-4 3/8" 11'-9 3/8"	12'-0" 6'-4 3/8" 6'-4 3/8" 12'-0"	12'-0" 2'-8 1/12" 2'-8 1/12" 12'-0"	11'-5 29/32" 2'-8 1/12" 2'-8 1/12" 11'-5 29/32"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 3/16" 6'-4 3/8" 6'-4 3/8" 11'-11 3/16"	11'-11 7/8" 6'-4 3/8" 6'-4 3/8" 11'-11 7/8"
11'-9 3/8" 6'-3 3/4" 6'-3 3/4" 11'-9 3/8"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-0" 6'-3 3/4" 6'-3 3/4" 11'-0"	11'-9 3/8" 6'-3 3/4" 6'-3 3/4" 11'-9 3/8"	12'-0" 6'-3 3/4" 6'-3 3/4" 12'-0"	Portal	Portal	11'-11 3/16" 6'-3 3/4" 6'-3 3/4" 11'-11 3/16"	11'-11 3/16" 6'-3 3/4" 6'-3 3/4" 11'-11 3/16"	11'-11 7/8" 6'-3 3/4" 6'-3 3/4" 11'-11 7/8"

COST AND SCHEDULE IMPACT

The Structural Support of the Curtain Wall

According to a representative from SturctureCraft Inc., the cost of both the structural system and the glazing can be broken down into the 5 categories. The table below only accounts for the $3,900,000 structural wood support broken down into the 5 categories:

Table 3: Cost Breakdown of the Curtain Wall Structural System

Component	Percentage of Overall Cost	Cost
Engineering Design	10%	$390,000
Detailing (Connections)	10%	$390,000
Material	30%	$1,170,000
Shop Fabrication	25%	$975,000
Site	25%	$975,000
Total		**$3,900,000**

As indicated by StructureCraft, the straightening of the curtain wall will cause the follow adjustments to the cost of the structural system:

Table 4: Expected Cost Savings for the Structural System

Component	Percentage of Overall Cost	Expected Decrease	Expected Savings	Adjusted Cost
Engineering Design	10%	5% of 10%	$19,500	$370,500
Detailing (Connections)	10%	3% of 10%	$11,700	$378,300
Material	30%	2% of 30%	$23,400	$1,146,600
Shop Fabrication	25%	0% of 25%	$0	$975,000
Site	25%	0% of 25%	$0	$975,000
Total			**$54,600**	**$3,845,400**

As expected, an extremely small impact was made on the structural system due to the proposed design change. A savings of only $54,600 is anticipated, which is a mere 1.4% of the cost.

Similarly, A StructureCraft representative explained that straightening the curtain wall, and the PSL columns, would in no way impact the installation time. It would still require 10 days to install the base plates and approximately 102 days to erect the columns. The columns would only be slightly shorter, but would require the same amount of effort to install. Also, the same number of support arms and muntins would be required on each column. Therefore, the schedule of the structural system is expected to stay at 112 days as shown below.

Figure 23: Selection from the Arena Stage Façade Schedule

The Glazing of the Curtain Wall

Similar to the structural system, the glazing has been broken down into the same component categories with its total cost of $3.5 million.

Table 5: Cost Breakdown of the Curtain Wall Glazing

Component	Percentage of Overall Cost	Cost
Engineering Design	10%	$350,000
Detailing (Connections)	10%	$350,000
Material	30%	$1,050,000
Shop Fabrication	25%	$875,000
Site	25%	$875,000
Total		**$3,500,000**

The proposed redesign of the curtain wall is expected to have a substantial impact on the cost of the glazing units. Decreasing the number of independent sizes from 148 units to 21 units should cause a significant reduction in each component category. The material category should have a cost change because producing trapezoidal pieces generates a lot of glazing waste. Now that the units are rectangular, it should decrease the amount of waste produced.

During design, Clark Construction Group, LLC value engineered (VE) a series of 90 degree returns for the curtain wall. The cost savings determined by those VE ideas were compared to this proposed design change. As suggested by the Clark VE savings, the straightening of the curtain wall will cause the follow adjustments to the cost of the glazing:

Table 6: Expected Cost Savings for the Glazing

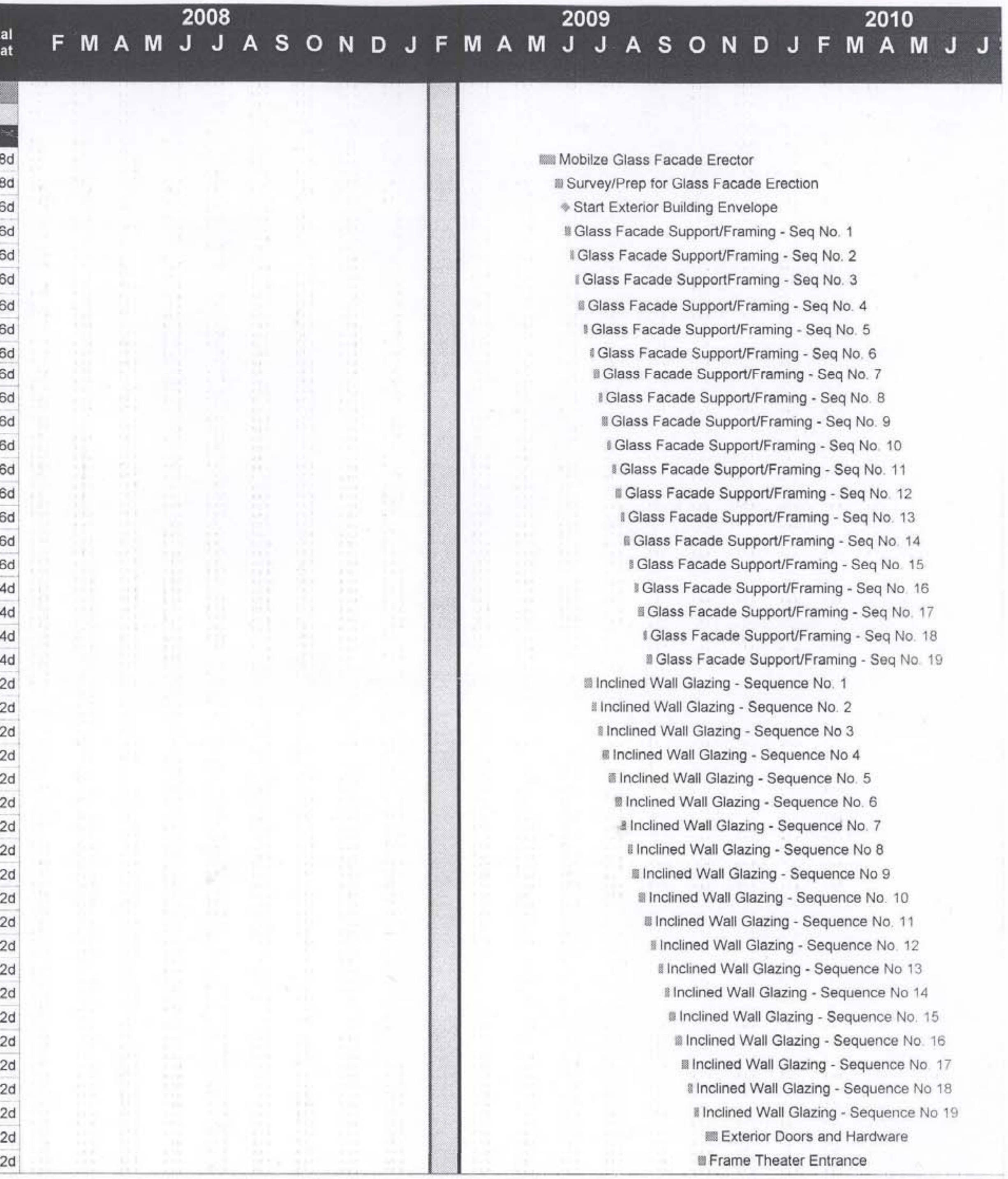
Component	Percentage of Overall Cost	Expected Decrease	Expected Savings	Adjusted Cost
Engineering Design	10%	45% of 10%	$157,500	$192,500
Detailing (Connections)	10%	30% of 10%	$105,000	$245,000
Material	30%	10% of 30%	$105,000	$945,000
Shop Fabrication	25%	57% of 25%	$498,750	$376,250
Site	25%	29% of 25%	$253,750	$621,250
Total			**$1,120,000**	**$2,380,000**

As expected, $1,120,000 is a likely cost saving that could be produced by this change. It is a 32% adjustment to the cost, which is a considerable amount of money when taking the original cost of the glazing into account.

The cost savings the structural and glazing systems combined is $1,174,600, which is 16% of the total cost of the curtain wall.

The Clark schedule for the glazing is shown on the next page. It is broken down into two major activities; first is the construction of the support and framing of the curtain wall and second is the placement for the wall glazing. These activities occur in a series of 19 sequences. According to the schedule, each sequence is allotted 3 days for the support and framing and 4 days for the erection of the glazing.

Act ID	Description	Orig Dur	maini uratic	Early Start	Early Finish	Total Float
BUILDING ENVELOPE						
Glass Facade						
BECW0010	Mobilze Glass Facade Erector	10	10	19MAY09	02JUN09	18d
BECW0020	Survey/Prep for Glass Facade Erection	5	5	03JUN09	09JUN09	18d
BECW0050	Start Exterior Building Envelope	0	0	12JUN09		16d
BECW0100	Glass Facade Support/Framing - Seq No. 1	3	3	12JUN09	16JUN09	16d
BECW0200	Glass Facade Support/Framing - Seq No. 2	3	3	17JUN09	19JUN09	16d
BECW0300	Glass Facade SupportFraming - Seq No. 3	3	3	22JUN09	24JUN09	16d
BECW0400	Glass Facade Support/Framing - Seq No. 4	3	3	25JUN09	29JUN09	16d
BECW0500	Glass Facade Support/Framing - Seq No. 5	3	3	30JUN09	02JUL09	16d
BECW0600	Glass Facade Support/Framing - Seq No. 6	3	3	06JUL09	08JUL09	16d
BECW0700	Glass Facade Support/Framing - Seq No. 7	3	3	09JUL09	13JUL09	16d
BECW0800	Glass Facade Support/Framing - Seq No. 8	3	3	14JUL09	16JUL09	16d
BECW0900	Glass Facade Support/Framing - Seq No. 9	3	3	17JUL09	21JUL09	16d
BECW1000	Glass Facade Support/Framing - Seq No. 10	3	3	22JUL09	24JUL09	16d
BECW1100	Glass Facade Support/Framing - Seq No. 11	3	3	27JUL09	29JUL09	16d
BECW1200	Glass Facade Support/Framing - Seq No. 12	3	3	30JUL09	03AUG09	16d
BECW1300	Glass Facade Support/Framing - Seq No. 13	3	3	04AUG09	06AUG09	16d
BECW1400	Glass Facade Support/Framing - Seq No. 14	3	3	07AUG09	11AUG09	16d
BECW1500	Glass Facade Support/Framing - Seq No. 15	3	3	12AUG09	14AUG09	16d
BECW1600	Glass Facade Support/Framing - Seq No. 16	3	3	17AUG09	19AUG09	34d
BECW1700	Glass Facade Support/Framing - Seq No. 17	3	3	20AUG09	24AUG09	34d
BECW1800	Glass Facade Support/Framing - Seq No. 18	3	3	25AUG09	27AUG09	34d
BECW1900	Glass Facade Support/Framing - Seq No. 19	3	3	28AUG09	01SEP09	34d
BEGL0100	Inclined Wall Glazing - Sequence No. 1	4	4	30JUN09	06JUL09	12d
BEGL0200	Inclined Wall Glazing - Sequence No. 2	4	4	07JUL09	10JUL09	12d
BEGL0300	Inclined Wall Glazing - Sequence No 3	4	4	13JUL09	16JUL09	12d
BEGL0400	Inclined Wall Glazing - Sequence No 4	4	4	17JUL09	22JUL09	12d
BEGL0500	Inclined Wall Glazing - Sequence No. 5	4	4	23JUL09	28JUL09	12d
BEGL0600	Inclined Wall Glazing - Sequence No. 6	4	4	29JUL09	03AUG09	12d
BEGL0700	Inclined Wall Glazing - Sequence No. 7	4	4	04AUG09	07AUG09	12d
BEGL0800	Inclined Wall Glazing - Sequence No 8	4	4	10AUG09	13AUG09	12d
BEGL0900	Inclined Wall Glazing - Sequence No 9	4	4	14AUG09	19AUG09	12d
BEGL1000	Inclined Wall Glazing - Sequence No. 10	4	4	20AUG09	25AUG09	12d
BEGL1100	Inclined Wall Glazing - Sequence No. 11	4	4	26AUG09	31AUG09	12d
BEGL1200	Inclined Wall Glazing - Sequence No. 12	4	4	01SEP09	04SEP09	12d
BEGL1300	Inclined Wall Glazing - Sequence No 13	4	4	08SEP09	11SEP09	12d
BEGL1400	Inclined Wall Glazing - Sequence No 14	4	4	14SEP09	17SEP09	12d
BEGL1500	Inclined Wall Glazing - Sequence No. 15	4	4	18SEP09	23SEP09	12d
BEGL1600	Inclined Wall Glazing - Sequence No. 16	4	4	24SEP09	29SEP09	12d
BEGL1700	Inclined Wall Glazing - Sequence No. 17	4	4	30SEP09	05OCT09	12d
BEGL1800	Inclined Wall Glazing - Sequence No 18	4	4	06OCT09	09OCT09	12d
BEGL1900	Inclined Wall Glazing - Sequence No 19	4	4	12OCT09	15OCT09	12d
BEGL2000	Exterior Doors and Hardware	7	7	23OCT09	02NOV09	12d
BEGL2010	Frame Theater Entrance	5	5	16OCT09	22OCT09	12d



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Run date	05MAR09
Page number	1A
Project name	AST9

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CLARK CONSTRUCTION GROUP
ARENA STAGE - FEBRUARY UPDATE

To understand what a sequence entails, each sequence contains one of the 19 infill faces and the 2 module faces located on either side of it. This means that since there are 3 faces per sequence, approximately 21 frames are completed per sequence. Figure 24 below shows an example sequence. Sequence Number 17 includes infill 17, one frame of module 3 on its right, and one frame of module 3A on its left (elevation view). Sequence No. 17 will be used as a model sequence throughout the rest of this analysis.

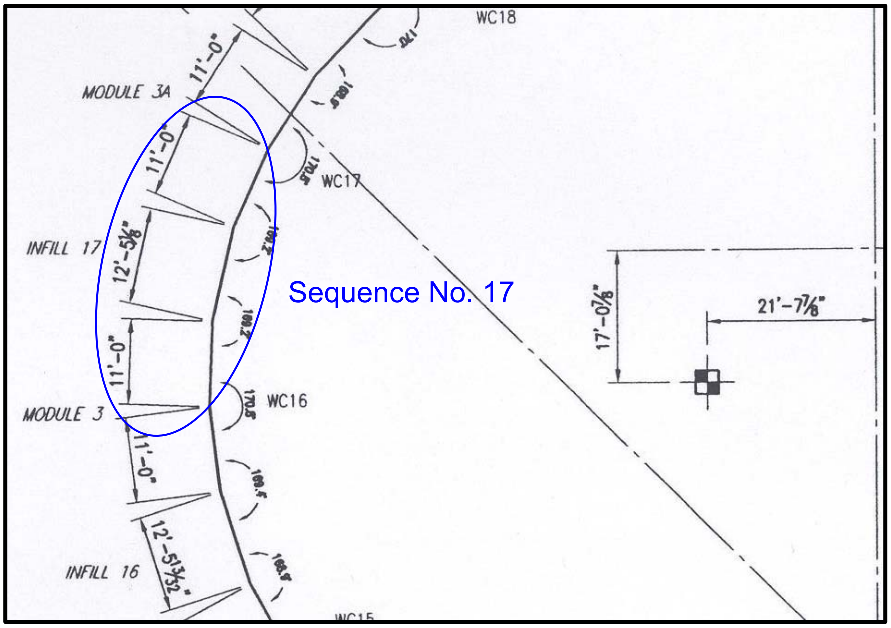


Figure 24: Northwest Section of the Curtain Wall Plan

It is important to consider the fact that the infill frames consist of all trapezoidal units. The modules do not. It was instructed that the installation time for the infills will be longer than those of the modules because they do not line up as easily as the rectangular units do. Consequently, both the framing/support and the erection of the glazing will take longer for the infills as depicted in the pie chart below:

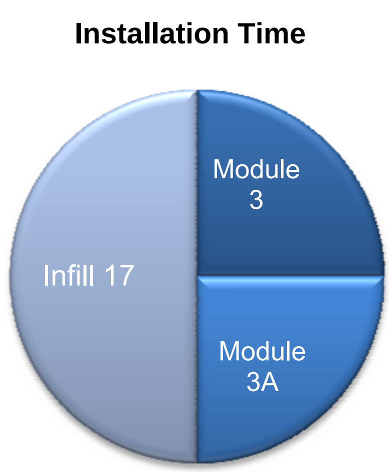


Figure 25: Pie Chart of Glass Installation

Framing/Support:	3 days total
Infill 17	1.5 days
Module 3	0.75 days
Module 3A	0.75 days
Glazing Erection:	4 days total
Infill 17	2 days
Module 3	1 day
Module 3A	1 day

The current schedule shows that it is going to take 133 days to complete the glass portion of the curtain wall; 57 days to put up the framing and support and 76 days to hang the glazing units. By straightening the curtain wall and making all of the units rectangular and more consistent, a large deduction in schedule can be expected. Not only are the trapezoidal units being eliminated, but the 4 degree setting is no longer required. A curtain wall that is vertically plumb is going to be much faster to install and easier to line up across the frames.

According to the original schedule, a 50% reduction in installation time is probable for each activity. This means that the support/framing of each sequence would only take 1.5 days and hanging the glazing would only take 2 days per sequence.

Table 7: Comparison of the Installation Time of the Original and Proposed Designs

	Original Design	Proposed Design
Framing/Support (1 Sequence)	3 days	1.5 days
Glazing Erection (1 Sequence)	4 days	2 days
Total (19 Sequences)	**133 days**	**66.5 days**

This reduces that installation time down to 66.5 days total; 28.5 days to put up the framing and support and 38 days to hang the glazing units. This substantial time savings would be a major benefit to Arena Stage, providing the construction team with more than enough time to complete the project on time.

CONSTRUCTABILITY DISCUSSION

For the construction team on Arena Stage, the construction of the curtain wall is the most anticipated and difficult challenge since the cast-in-place concrete. No one is 100% sure about how the entire system will come together, or what unknown challenges they will run into. As for the known challenges, they are going to be dealt with to the best of the construction team's ability.

First, there is a long lead time for both the structural system and the glazing units. The structural system takes approximately 8 months to manufacture because the massive PSL wood columns are individually spun on a lathe and the pieces of wood that make up the support arms and mullions are intricate. The glazing requires a long time because of the number of pieces that are being specially cut. Each of the 365 openings has to be field verified by Icon Exterior Building Solutions before manufacturing can begin. Not only are there a lot of units, but since so many of them are different sizes, the machines that cut the glass must be reset constantly. Cutting repeated sizes does not occur frequently with this design.

Second, every piece must be installed in its proper location. Installations that require a great deal of coordination have a tendency to run into problems during construction. It is not uncommon for them to be installed incorrectly. With 365 units of glass on site, it is likely that a shipment of glass might end up in the wrong zone on site, and one or two units could end up being installed in the wrong place. This would cause a big headache during the remainder of construction trying to figure out where the mistake was made. Similarly, if a unit of glass was damaged during construction, there would most likely not be another unit to take its place while another one was being manufactured. Also, having frames remanufactured and delivered back to the site can be expensive and always slows down the construction schedule.

Third, the curtain wall is being constructed on an angle. Not only does this complicate the system on its own, but the wall also follows a serpentine of multiple radii. This creates a series of workpoints that influence everything from design to construction. Numerous workpoints can be confusing in construction, making it easy to make a simple mistake. Coordination between the glazing and structural subcontractors is going to have to be immaculate in order for the curtain wall to be completed on schedule. Setting glass on a perfect 4 degree angle is challenging because if it is not done correctly, the system will not come together as the design intended. Precision and accuracy are vital.

The proposed elimination of the 4 degree slope would aid in the manufacturing of the glazing, allow for more standardized unit sizes that could be interchangeable, and ease construction since the wall would not have to be set on an angle. Coordination would be simpler and it would increase crew productivity since the pieces could be installed vertically plumb instead of sloped.

ARCHITECTURAL DISCUSSION

Architecturally, the curtain wall is one of Arena Stage's most prominent features. Since the inception of its design, the curtain wall has been the one facet of the project that the owner is most reluctant to change. This is out of fear that any alterations would compromise the quality of the curtain wall. One of the goals of the building was to make it transparent "exposing the outside to the inside and the inside to the outside." The curtain wall was the solution to facilitate that goal. The 4 degree slope was incorporated into the design because it is supposed to reduce the glare off of the glass, making it easier to see into the building. This same slope was applied to the Cradle Theater, allowing the two structures to complement one another.

The slope is the one characteristic of the curtain wall that greatly increased the cost of the system and is going to make the construction much more complicated. Eliminating the slope is going to alleviate both cost and constructability, but it will interrupt the architectural consistency between the curtain wall and the Cradle Theater. The Cradle is significantly taller and more compact than the curtain wall, making the slope of the ellipse much more noticeable to the naked eye. By just glancing at the building, one might not notice that curtain wall slanted at all. The sketches below were drawn based off of the architectural model created by Bing Thom Architects in Rhinoceros®. The orange sketch is the curtain wall with the 4 degree slope, while the blue sketch is the proposed curtain wall without the slope. As shown by the sketches, the visual difference between the two designs is minimal from an isometric standpoint.

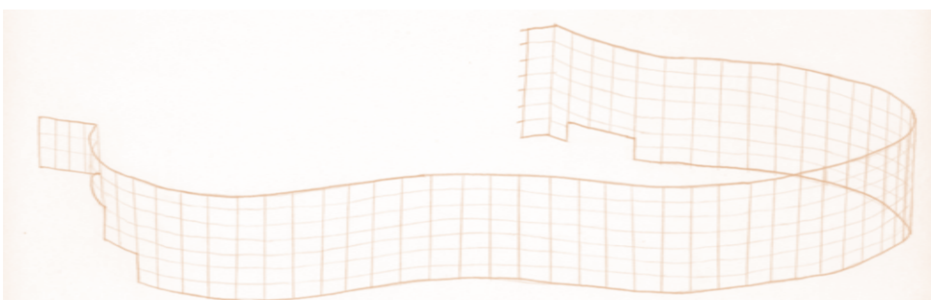


Figure 26: Sketch of the Sloped Curtain Wall

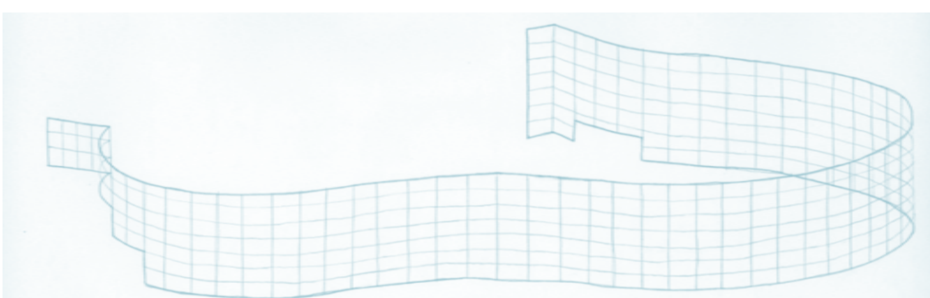


Figure 27: Sketch of the Vertically Plumb Curtain Wall

The proposed adjustment to the curtain wall is in no way reducing the quality of the overall design. The same materials are being used and the extravagant PSL wood columns are being maintained. Only the architecture is being adjusted. Ultimately, it would be up to the owner to decide if the $1.17 million cost savings was worth compromising the architectural parallel between the curtain wall and the Cradle Theater.

CONCLUSION AND RECOMMENDATION

Eliminating the 4 degree slope of the curtain wall is a logical option for Arena Stage. By making the curtain wall vertically plumb and redesigning it with more uniform glazing units, the objectives of this analysis were accomplished. The cost of the entire curtain wall system was estimated at $7,400,000 and by making this small architectural adjustment, a total savings of 16% or, $1,174,600, was made. More impressively, the 32% reduction in the cost of the glazing was where the majority of the savings occurred.

The curtain wall is one of many complicated elements of the construction of Arena Stage. It is not to say that the proposed curtain wall would be simple to erect because it is still on a serpentine that depends on multiple workpoints. However, it would be much more manageable than the current sloped design. From engineering design, to manufacturing, to erection, all stages of the project would be less complicated. This analysis also demonstrated that the installation time of the glazing system would be cut in half with the recommended design. Being able to install all 365 glazing units in 66.5 days instead of 133 would give Arena Stage much more leeway when trying to meet the schedule for the project's completion in June 2010.

From a construction standpoint, the proposed curtain wall is unquestionably more favorable. As discussed above, setting structural elements on a slope is a very difficult task due to the checking and rechecking of the angles and the probable alignment issues. Coordinating the location of the 365 glazing units would be incredibly difficult if there were no standard sizes. In order to get the curtain wall erected on time, management would have to be on a steadfast watch of the entire process, making sure that everything was being constructed as it was designed. A simple mistake could set the entire schedule behind, which is extremely unfavorable since the curtain wall determines the achievement of watertight status.

From an architectural standpoint, the proposed curtain wall is a compromise to the reoccurrence of the 4 degree slope within the building. However, it is not a compromise to the quality of the project. The curtain wall would still be just as grand since it is specially designed and custom manufactured. Also, the serpentine path is being preserved, allowing the impressive shape of the building to stay the same. As stated above, the decision to adopt the suggested design could only be made by the owner who would have to choose between cost, schedule, and architectural congruence.

Analysis II: Application of Photovoltaic Panels

[Electrical Breadth : Critical Industry Issue]

BACKGROUND

Theaters, including Arena Stage, are commonly known for expending a lot of energy due to their high, open ceilings and excess mechanical and lighting loads.

PROBLEM STATEMENT

The energy consumption of Arena Stage was not a major consideration when designing the new building. Since the expansion of the complex was designed approximately 8 years ago, no sustainable elements were a part of its original conception nor was any thought given to making the project LEED certified. Although an energy model was not created for Arena Stage, it is projected that the building will consume large amounts of energy. Despite this prediction, no major precautions were taken to make the theater more energy conscious.

OBJECTIVE

To design a grid-tied photovoltaic (PV) array for Arena Stage that will counter a specific energy load within the building without having much physical impact on the unique architecture of the building. Specifically, a small load such as the lighting loads of the underground parking garage will be matched as an example of how renewable energy can provide energy independence on any scale.

METHODOLOGY

1. Collect sun exposure data for Washington, DC
2. Create a Google Sketch Up model and perform a shadow analysis
3. Determine the lighting loads for the parking garage
4. Choose a PV panel
5. Choose an inverter
6. Size an array based on the chosen PV panel and inverter
7. Determine an unobstructed location on the roof to place the array
8. Find a product-specific PV/inverter provider and installer near Washington, DC
9. Calculate the cost of the system and the payback period
10. Make a recommendation on whether implementing a photovoltaic array is a beneficial investment for Arena Stage

TOOLS / RESOURCES

- Clark Construction Group, LLC
- Arena Stage Construction Documents/Specifications
- Uni-Solar website
- Fronius website
- Google Earth
- Google Sketch Up
- EDSGN 498A: Solar Photovoltaic Solutions
- Penn State AE Faculty

EXPECTATIONS

By adding small photovoltaic array to Arena Stage, I expect that it will match the lighting loads of the parking garage at a relatively low cost and with little detriment to the architecture of the building. Although cost is a concern at Arena Stage, implementing an environmentally conscious component has the ability to attract donors since it is favorable to the Anacostia Waterfront Initiative.

RECAPITULATION OF THE CRITICAL INDUSTRY ISSUE

The technical training topic that I attended at the PACE Roundtable, in October 2008, was the “Energy & Economy” session facilitated by Dr. Riley. Industry members generated the majority of the discussion seeing as they are currently experiencing the impacts that the economy is having on the construction industry. The volatility of materials and their dependence on oil was the first topic. With oil prices as high and they are, it is wise to consider using local materials in order to cut down on transportation costs. Also, using alternative materials, which may or may not be known to the market, is a cost-saving measure that is often overlooked due to lack of education. It was suggested to explore both of these possibilities and to observe escalation factors, including buyout tactics and historic trends.

While discussing building systems, the general consensus was the importance of educating the owner and stressing the life-cycle cost of the building. There is a high demand for energy retrofits and clients need to be aware of the long term cost savings despite a high upfront cost. When an early focus is placed on the design of controls and criteria changes, high energy savings can be expected. Many buildings have power inefficiencies and steps need to be taken to avoid them. Understanding the importance of commissioning and making sure that the systems are running properly will prevent certain sources of power inefficiency. Using TP-1 transformers, sizing conductors with more copper, and changing lighting systems from high pressure sodium to high pressure fluorescent were all measures suggested by the industry members.

ANALYSIS

Analyzing the Site and the Sun

In order to get a general idea of when sun exposure would be best on site, sun path charts were created using The University of Oregon Solar Radiation Monitoring Laboratory's Sun Path Chart Program (http://solardat.uoregon.edu/SunChartProgram.php). They were generated based on the following information:

Hemisphere:	Northern
Time:	EST
Address:	1101 6th Street SW Washington, DC 20024
Latitude:	38° 52' N
Longitude:	77° 01' W
Average Elevation:	~14 feet

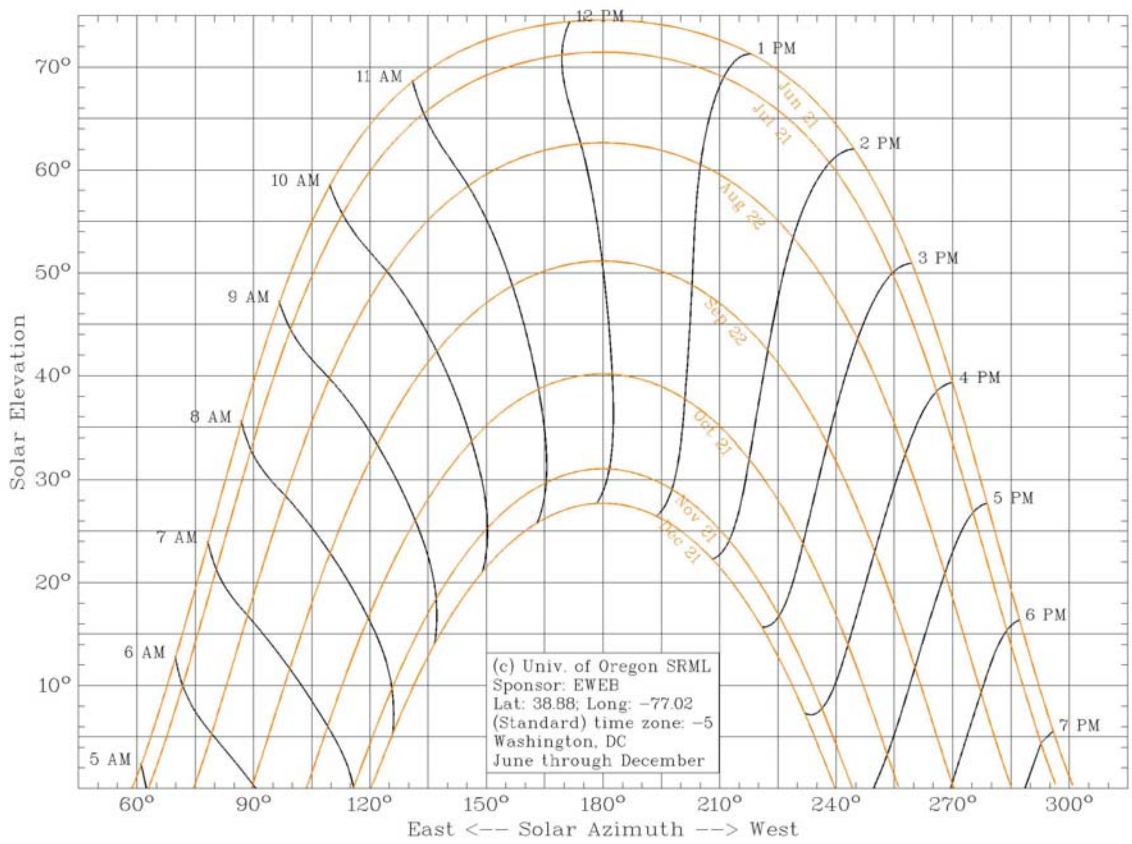


Figure 28: Washington, DC Sun Path Chart, June through December

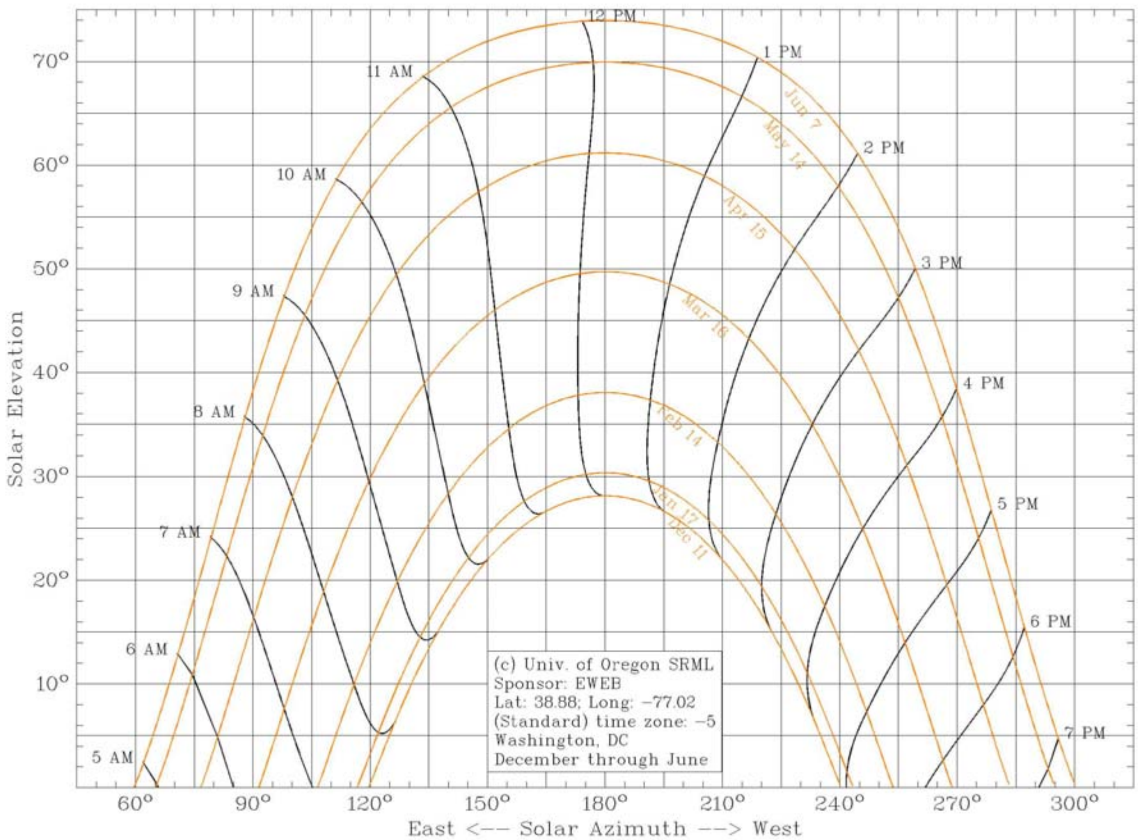


Figure 29: Washington, DC Sun Path Chart, December through June

The sun path charts help to determine what time of day the sun will be highest in the sky for maximum sun exposure. At a minimum, arrays should have access to an unobstructed solar window from at least 09:00 am to 03:00 pm (*Photovoltaic Systems*, ATP pg. 67).

Time Frame: from 09:00 am to 03:00 pm (highest priority)

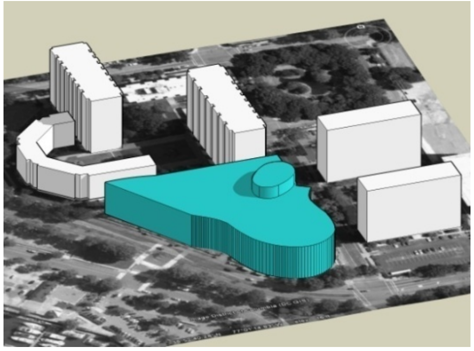
Next, a Google Sketch Up model was created and placed into a map from Google Earth in order to perform a shadow analysis. Since the construction of Arena Stage is scheduled to complete in June of 2010, the model was run through a shadow simulation from Fall 2010 through Spring 2011, the first year that Arena Stage would be open for production.

Dates: It is important to evaluate the performance of the sun during four times of the year (obtained from www.timeanddate.com Seasonal Calculator):

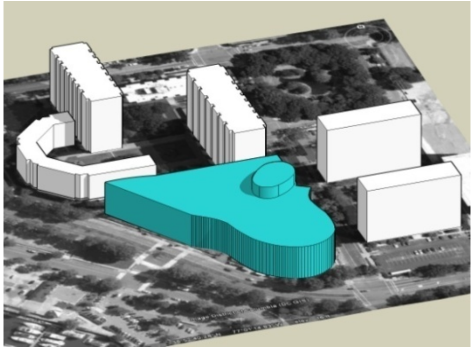
Autumnal Equinox	September 23, 2010	(03:09 am)
Winter Solstice	December 21, 2010	(11:39 am)
Vernal Equinox	March 20, 2011	(11:21 pm)
Summer Solstice	June 21, 2011	(05:16 pm)

On the subsequent pages, there are snapshots from Google Sketch Up which show how the sun will strike Arena Stage during these dates and the shadows that result.

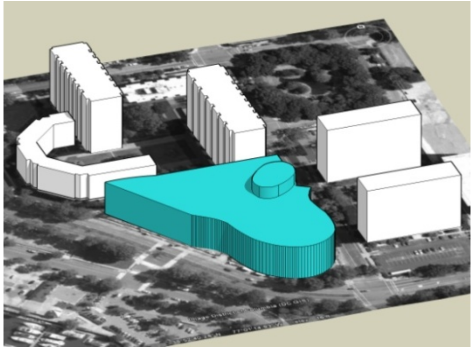
Autumnal Equinox: September 23, 2010 (3:09am)



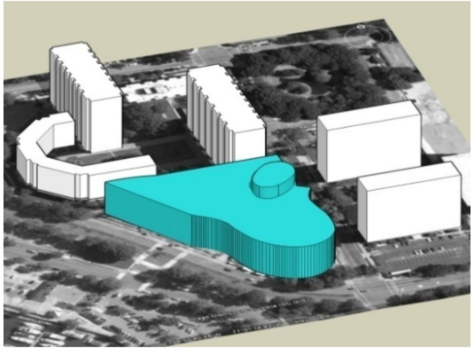
09:00 am



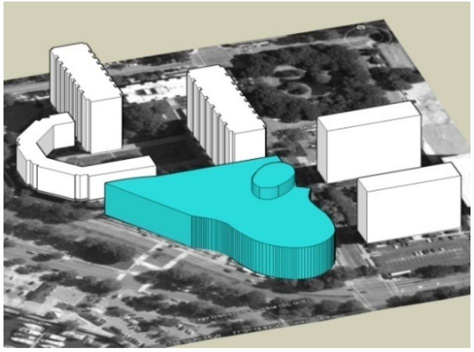
10:00 am



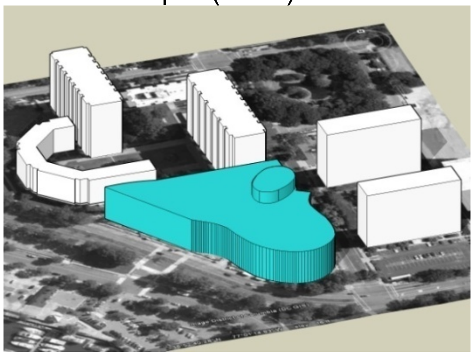
11:00 am



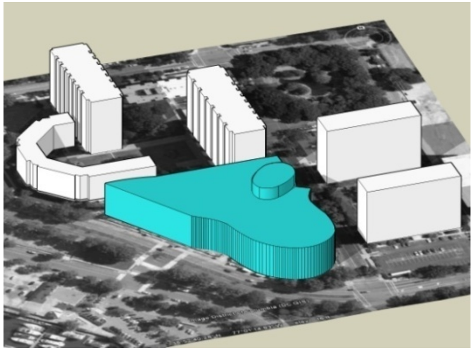
12:00 pm (noon)



01:00 pm

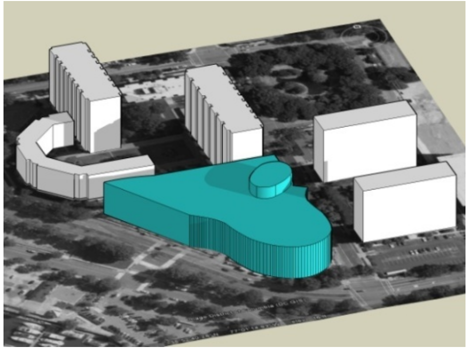


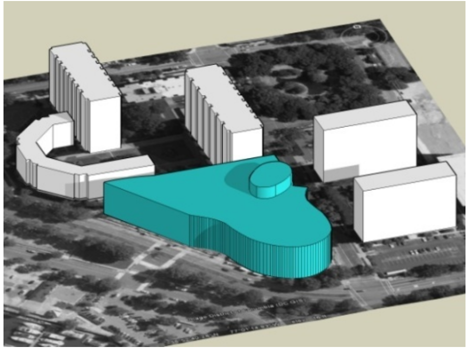
02:00 pm

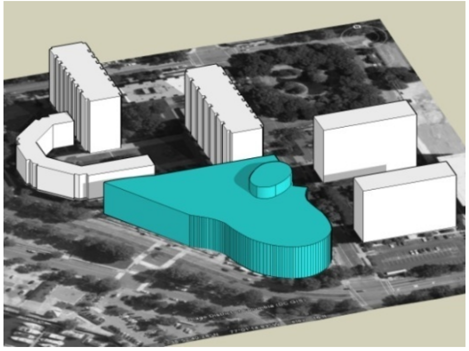


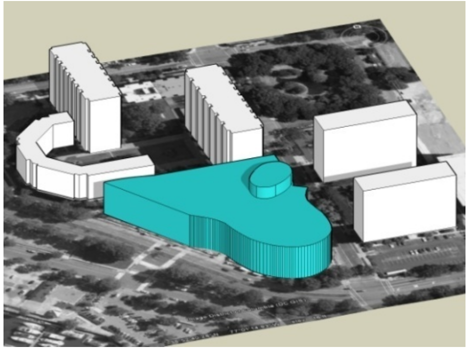
03:00 pm

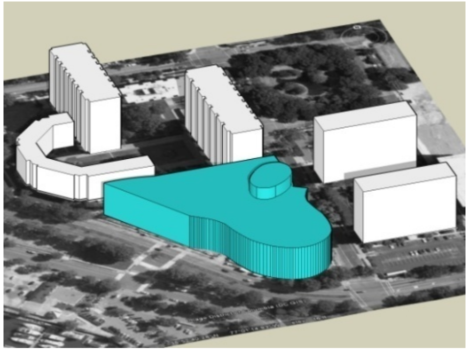
Winter Solstice: December 21, 2010 (11:39 am)


09:00am


10:00 am


11:00 am


12:00 pm (noon)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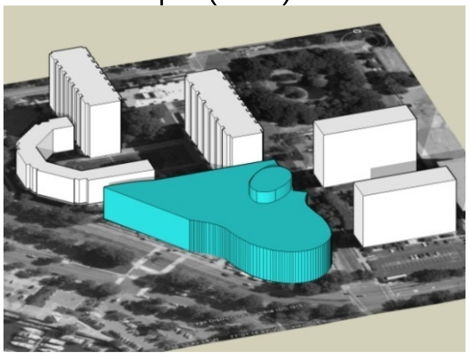
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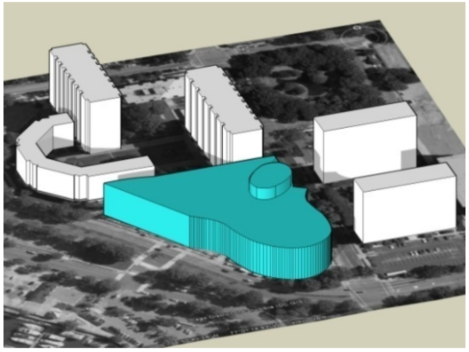
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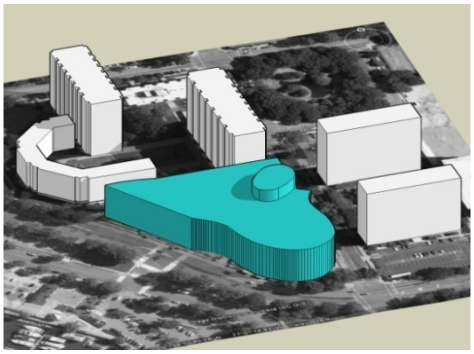
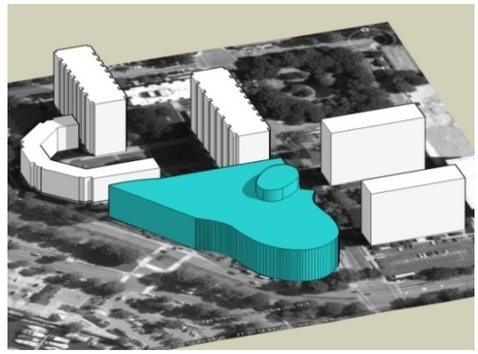
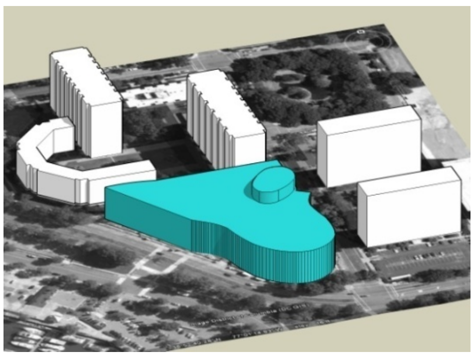
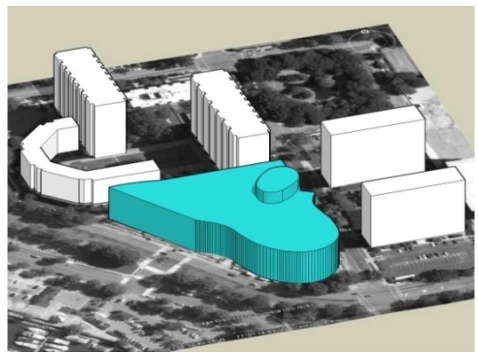
Vernal Equinox: March 20, 2011 (11:21 pm)


09:00am


10:00 am


11:00 am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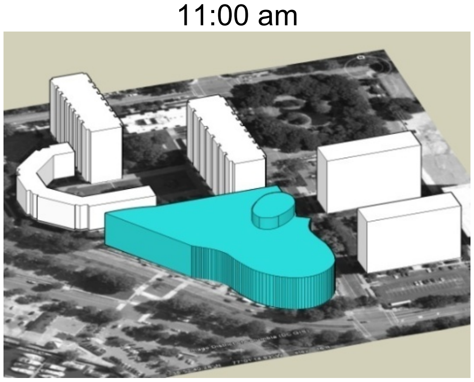
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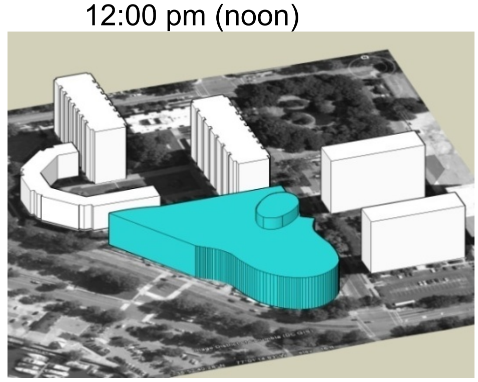
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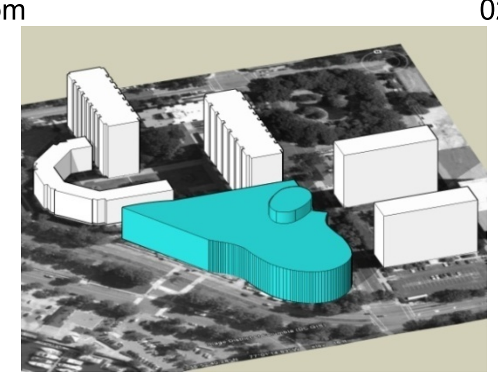
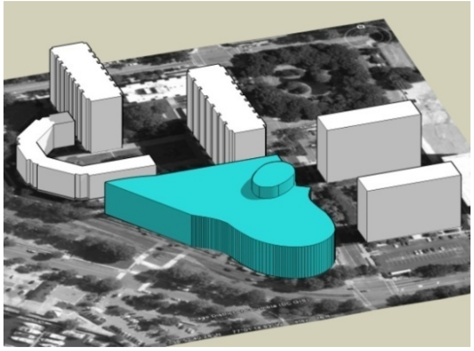
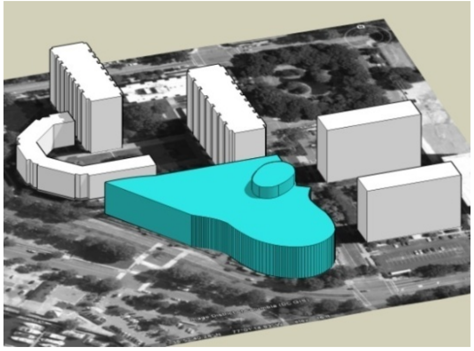

03:00 pm

Summer Solstice: June 21, 2011 (5:16 pm)



09:00am



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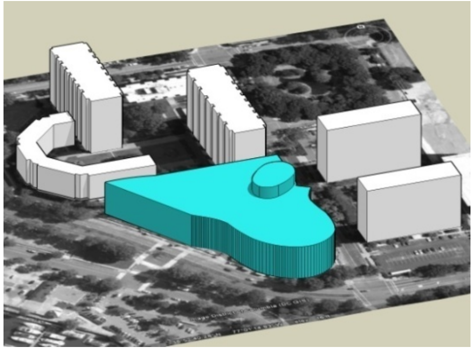
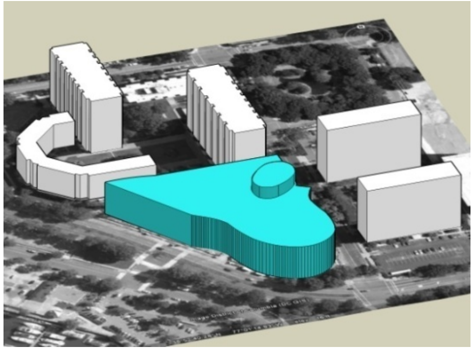
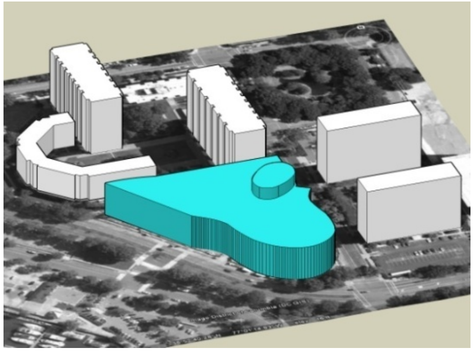


11:00 am



12:00 (noon)



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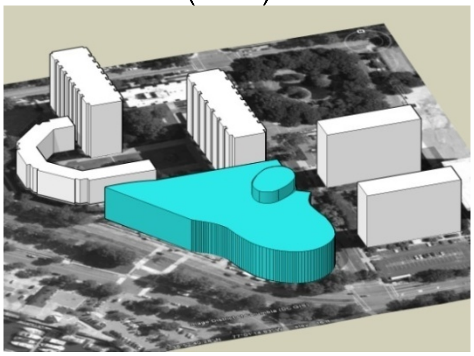

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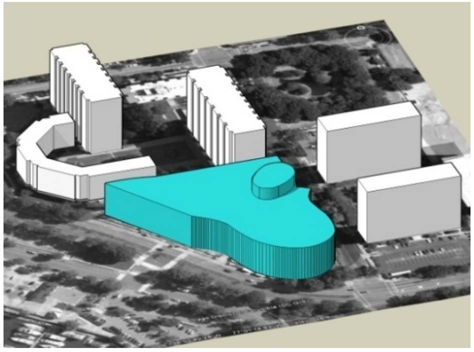


03:00 pm

This map in Figure 30 shows the amount of solar energy, in hours, received each day on an optimally tilted surface during the worst month of the year (based on accumulated worldwide solar insolation data). According to this image, Washington, DC receives 2.0-2.9 hours of solar energy each day based on the parameters listed above. This means that, worst case scenario, Arena Stage would not meet the ideal requirement of the 6 hour unobstructed solar window from 09:00 am to 03:00 pm all year around.

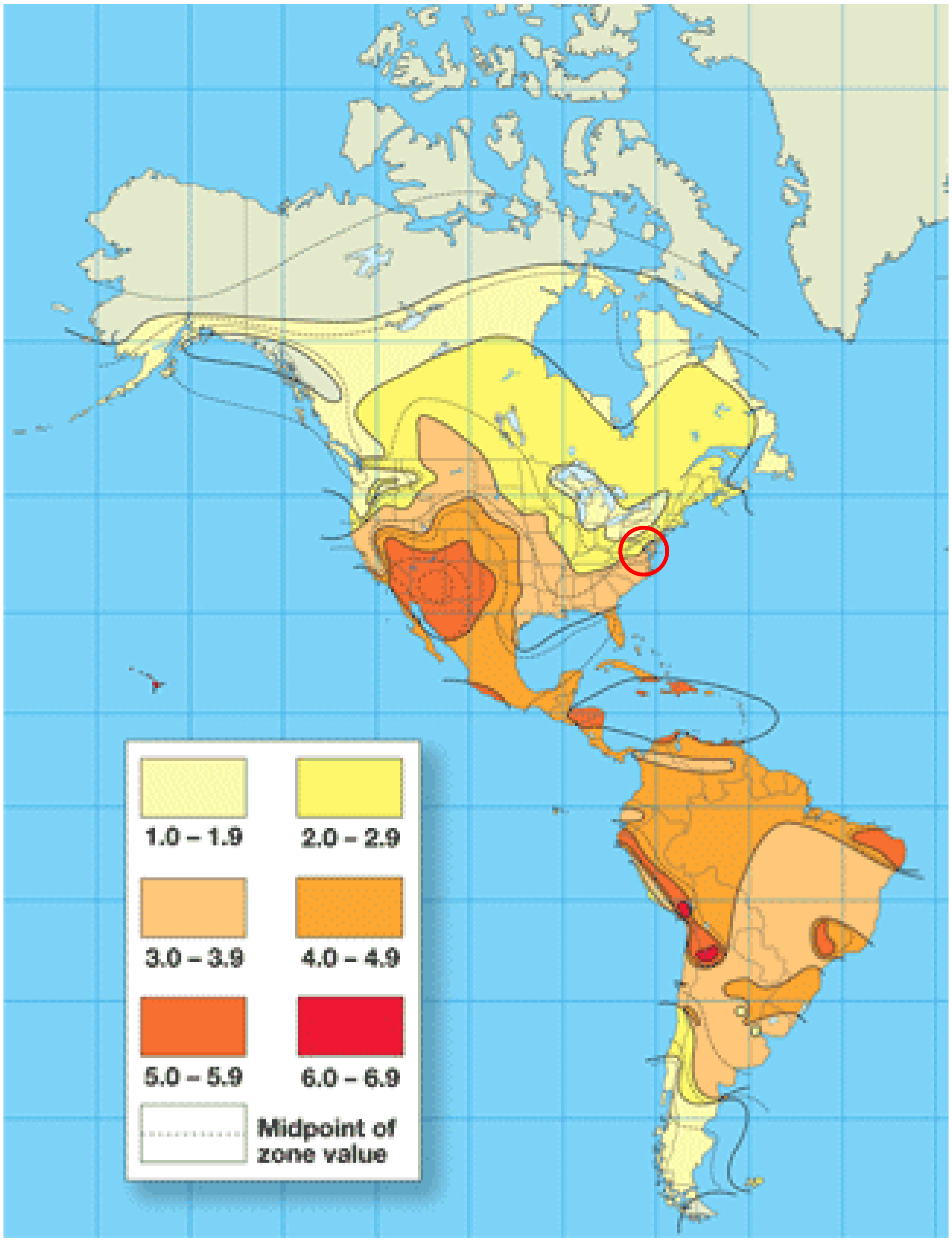


Figure 30: World Insolation Map provided by SunWize (http://www.sunwize.com/)

Determining the Lighting Load of the Parking Garage

The Arena Stage parking garage is relatively small when compared to the rest of the building. It is only one level and has a total of 62 parking stalls. It is illuminated by a series of 32W T8 fluorescent strips, occasional 13W TTT compact fluorescent downlights, and a few 35.50W metal halide surface lens step lights. All of the lighting is on one of two panel boards; either Panel HPA(1) or Panel EMA(1) as shown below.

PANEL HPA (1)

DESCRIPTION	W/kW	BKR	CIRCUIT NO.	CIRCUIT NO.	BKR	W/kW	DESCRIPTION
SPARE		15A	1	2	15A	2Φ	GEN RM
SPARE		15A	3	4	15A	3Φ	VEST.
SPARE		15A	5	6	15A	3Φ	PARKING
SPARE		15A	7	8	15A	3Φ	PARKING
LTG	220	15A	9	10	15A	2Φ	TEL. RM.
SECURITY EQUIPMENT	200	15A	11	12	20A	0.5	DOOR OPERATOR
PARKING LTG	1080	15A	13	14	15A	150	ELEV. PIT
PARKING LTG	1160	15A	15	16	15A	1Φ	ELEV. PIT
PARKING LTG	1290	15A	17	18	15A	2Φ	ELECT. RM
PARKING LTG	1220	15A	19	20	15A	3Φ	ELECT. RM
MECH. ROOM	590	15A	21	22	15A	2Φ	AUDIO STUDIO
SPARE		15A	23	24	15A	2Φ	AUDIO STUDIO
			25	26	15A	4Φ	OFFICE
			27	28	15A	100	CONTROL
			29	30	15A		SPARE
LTG	510	15A	31	32	15A		SPARE
LTG	320	15A	33	34	15A		SPARE
OPER. OFFICE	930	15A	35	36	20A 2P	1000	EH-10
ELECT. ROOM	750	15A	37	38			
			39	40	20A 2P	3000	EH-4 EH-5 EH-6
			41	42			
SUBTOTAL x	8.050kW				9.430kW		SUBTOTAL x

MAINS: 225A
MOUNTING: SURFACE
A.I.C.: 22KA
FEEDER: 2 1/2"-4#4/0
VOLTS: 120/208V-3Φ-4W
LOCATION: ELECT. RM
CONN. LOAD: 26.430KW
DEMAND LOAD: 26.430KW

PANEL EMA - (1)

DESCRIPTION	W/kW	BKR	CIRCUIT NO.	CIRCUIT NO.	BKR	W/kW	DESCRIPTION
SPARE		15A	1	2	20A	0.5	O/H GRILLE
PARKING LTG	600	15A	3	4	20A	0.5	O/H GRILLE
PARKING LTG	550	15A	5	6	15A	1/4	EF-2
SPARE		15A	7	8	15A		SPARE
STAIR LTG	740	15A	9	10	15A	100	FSD-1
STAIR LTG	790	15A	11	12	15A	100	FSD-2
STAIR LTG	690	15A	13	14	15A	150	CAR LITE & SIGNAL
SPARE		15A	15	16	15A	150	CAR LITE & SIGNAL
ELECT. RM	380	15A	17	18	15A	600	SNOW MELTING
PAINTING STUDIO	190	15A	19	20	15A	1200	SNOW MELTING
SCENE SHOP	540	15A	21	22	15A	135	EF-12
SCENE SHOP	280	15A	23	24	15A	100	MD-1, MD-2
CORRIDOR	480	15A	25	26	15A	100	FSD-32,33
CORRIDOR	380	15A	27	28	20A	0.5	DOOR OPERATOR
SPARE		15A	29	30	20A	0.5	DOOR OPERATOR
LTG	510	15A	31	32	15A		SPARE
LTG	320	15A	33	34	15A		SPARE
RAMP LTG	330	15A	35	36	15A		SPARE
WASH RM	200	15A	37	38	15A	180	EXIT SIGN
EXIT SIGN	12	15A	39	40	15A	140	EXIT SIGN
EXTERIOR	170	15A	41	42	15A	220	EXIT SIGN
SUBTOTAL x	6.420kW					5.175kW	SUBTOTAL x

MAINS: 225A
MOUNTING: SURFACE
A.I.C.: 10KA
FEEDER: 2"-4#3/0
VOLTS: 120/208V-3Φ-4W
LOCATION: ELECT. RM
CONN. LOAD: 17.18KW
DEMAND LOAD: 17.18KW

Figure 31: Arena Stage Panel Boards HPA(1) and EMA(1)

The panel boards reflect that the parking garage lighting load is:

1080 W
1160 W
1290 W
1220 W
600 W
550 W

Total: 5900 W = 5.9 kW

An array will be designed to provide approximately 6kW in order to counter this load.

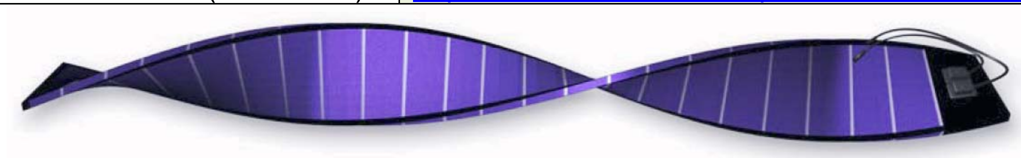
Selecting a Photovoltaic Panel

The type of roof surface and its slope will dictate the types of mounting systems and attachment methods that are feasible. Arena Stage's main roof is made of the following materials:

- SBS-Modified Bituminous Membrane Roofing
- Hot Rubberized Asphalt Protected Roofing Membrane
- Fully-adhered fabric reinforced TPO sheet membrane roofing

Since Arena Stage and Bing Thom Architects have already made several design sacrifices due to value engineering, it is important that the PV array not alter the appearance of the roof. For this reason, a building-integrated photovoltaic (BIPV) module is going to be used. It is thin, "peel and stick" solar laminate module from Uni-Solar, model PVL-144. This type of panel can be used on TPO and hot fluid applied roofs like Arena Stage.

General Product Information	
Company	United Solar Ovonic (Uni-Solar)
Name / Model	144 Watt Solar Laminate PVL-Series / PVL-144
Unique Features - Integration with building, mounting, collection	BIPV
Company URL	http://www.uni-solar.com/index.asp
Product Data Sheet URL (if available)	http://www.uni-solar.com/uploadedFiles/PVL-144-EN.pdf

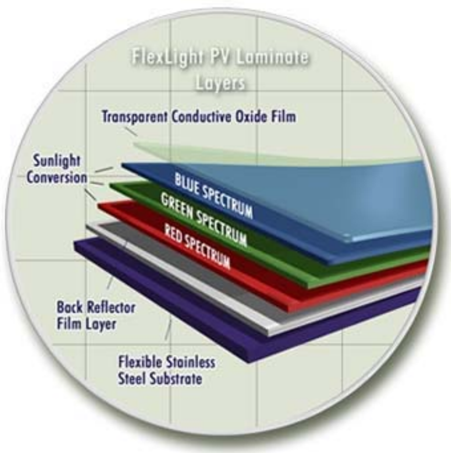


Product Details	
Weight	17 lb
Type (thin-film, poly-crystal, CIGS, CeTe, etc.)	22 triple junction amorphous silicon solar cells connected in series
Connectors	Quick-connect terminals and adhesive backing
Operating temperature	-40ºC to +85ºC
Temperature Coefficient (Pmp)	(-)0.21%/ºC
Temperature Coefficient (Voc)	(-)0.38%/ºC
Temperature Coefficient (Vmp)	(-)0.31%/ºC
Temperature Coefficient (Isc)	0.10%/ºC
Temperature Coefficient (Imp)	0.10%/ºC
Max power current (Imp)	4.36 A
Short-circuit current (Isc)	5.3 A
Rated power at PTC (Pptc)	136.4 W
Durability features	All weather construction
Module Construction/Materials	Photovoltaic laminate with potted terminal housing assembly with output cables and quick-connect terminals Encapsulation: durable ETFE high light-transmissive polymer Adhesive: Ethylene propylene copolymer adhesive-sealant with microbial inhibitor

(The specification sheets for Uni-Solar Laminate PVL-Series model PVL-144 are located on the next two pages.)

Features of the Uni-Solar PVL-144:

- High temperature and low light performance
- Flexible and lightweight
    - Virtually unbreakable
    - Weighs less than 1 lb/sf, compared to 5 lb/sf for a traditional solar system
- Adheres directly to the roof without penetrations
    - Approved for roofing manufacturers warranties
- Triple junction technology
    - Captures to complete solar spectrum more efficiently
- Generates electricity at low light levels
    - Produces more electricity per watt than any other system
- Approved by state revenue departments for tax incentives and rebates
- Bypass diode across ever solar cell
    - Protects solar laminate from total power loss in case of partial shading or damage of individual solar cells while other cells are exposed to full sunlight



UNI-SOLAR

Solar Laminate PVL-Series
Model: PVL-144

- High Temperature and Low Light Performance
- 20 Year Warranty on Power Output at 80%
- Quick-Connect Terminals* and Adhesive Backing
- Bypass Diodes for Shadow Tolerance
- UL 1703 Listed to 600 VDC
- IEC 61646 v1 certified
- IEC 61646 v2 and 61730, TUV certification pending

Performance Characteristics

Rated Power (P_{max}): 144 Wp
Production P_{max} Tolerance: ± 5 %

Construction Characteristics

Dimensions:	Length: 5486 mm (216"), Width: 394 mm (15.5"), Depth: 4 mm (0.2"), 16 mm (0.6") including potted terminal housing assembly
Weight:	7.7 kg (17.0 lbs)
Output Cables:	4 mm^2 (12 AWG) cable with weatherproof DC rated quick-connect terminals* 560mm (22") length.
By-pass Diodes:	Connected across every solar cell
Encapsulation:	Durable ETFE high light-transmissive polymer
Adhesive:	Ethylene propylene copolymer adhesive-sealant with microbial inhibitor
Cell Type:	22 triple junction amorphous silicon solar cells 356 mm x 239 mm (14" x 9.4") connected in series

Qualifications and Safety

Listed by Underwriter's Laboratories for electrical and fire safety (Class A Max. Slope 2/12, Class B Max. Slope 3/12, Class C Unlimited Slope fire ratings) for use in systems up to 600 VDC.

Laminate Standard Configuration

Photovoltaic laminate with potted terminal housing assembly with output cables and quick-connect terminals*

Application Criterion

- New or qualified new roof installations
- Installation by certified installers only
- Installation temperature between 10 °C - 40 °C (50 °F - 100 °F)
- Maximum roof temperature 85 °C (185 °F)
- Minimum slope: 5/8:12 (3°)
- Maximum slope 21:12 (60°)
- Membrane: Select EPDM and TPO substrates from approved manufacturers only
- Metal: PVDF Coated (Galvalume® or Zincalume®) steel metal roofing pan with flat surface (without pencil beads or decorative stippling) and 406 mm (16") minimum width

Refer to manufacturers installation guide for approved substrates and installation methods

*e.g., Multi-Contact (MC®) Connectors

Flexible
Lightweight
No-Glass
Durable
Shadow Tolerant
High Temp Performance

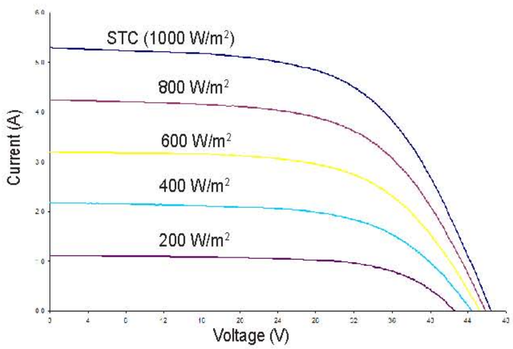
Technical Data Sheet

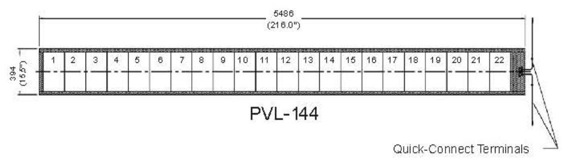
#AA5-3636-02

UNI-SOLAR

Solar Laminate PVL-Series
Model: PVL-144

IV Curves at various Levels of Irradiance at Air Mass 1.5 and 25 °C Cell Temperature





All measurements in mm.
Inches in parentheses.
Tolerances: Length: ± 5 mm (1/4"), Width: ± 3 mm (1/8")

Electrical Specifications

STC

(Standard Test Conditions)
(1000 W/m², AM 1.5, 25 °C Cell Temperature)

Maximum Power (P_{max}): 144 W
Voltage at Pmax (V_{mp}): 33.0 V
Current at Pmax (I_{mp}): 4.36 A
Short-circuit Current (I_{sc}): 5.3 A
Open-circuit Voltage (V_{oc}): 46.2 V
Maximum Series Fuse Rating: 8 A

NOCT

(Nominal Operating Cell Temperature)
(800 W/m², AM 1.5, 1 m/sec. wind)

Maximum Power (P_{max}): 111 W
Voltage at Pmax (V_{mp}): 30.8 V
Current at Pmax (I_{mp}): 3.6 A
Short-circuit Current (I_{sc}): 4.3 A
Open-circuit Voltage (V_{oc}): 42.2 V
NOCT: 46 °C

Temperature Coefficients

(at AM 1.5, 1000 W/m² irradiance)

Temperature Coefficient (TC) of I_{sc}: 0.001/°K(0.10%/°C)
Temperature Coefficient (TC) of V_{oc}: -0.0038/°K (-0.38%/°C)
Temperature Coefficient (TC) of P_{max}: 0.0021/°K (-0.21%/°C)
Temperature Coefficient (TC) of I_{mp}: 0.001/°K (0.10%/°C)
Temperature Coefficient (TC) of V_{mp}: -0.0031/°K (-0.31%/°C)

y = yreference • [1 + TC • (T- Treference)]

Notes:
1. During the first 8-10 weeks of operation, electrical output exceeds specified ratings. Power output may be higher by 15 %, operating voltage may be higher by 11 % and operating current may be higher by 4 %.
2. Electrical specifications are based on measurements performed at standard test conditions of 1000 W/m² irradiance, Air Mass 1.5, and cell temperature of 25 °C after stabilization.
3. Actual performance may vary up to 10 % from rated power due to low temperature operation, spectral and other related effects. Maximum system open-circuit voltage not to exceed 600 VDC per UL.
4. Specifications subject to change without notice.

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#AA5-3636-02

Selecting an Inverter and Sizing the Array to Match

Now that a PV panel has been chosen, an inverter is required to convert the DC power that the array produces to utility-grade AC power. The inverter that was selected for this analysis is the Fronius IG Plus 6.0-1 because it has a recommended PV power of 5100-6900 W, which is a good range for the amount of power that the array has to substitute.

An exercise that was performed in EDSGN 498A was developed and created using John Berdner's article in the December/January 2009 SolarPro magazine entitled *Array to Inverter Matching: Mastering Manual Design Calculations.* From that article, Penn State student, Andrew Mackey, created an Excel spreadsheet that matches arrays to inverters using select information from each of the products.

The following tables represent the input information needed to run the simulation of the hand-calculations in Excel:

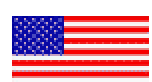
Panel Characteristics at STC				
Rated power at STC (Pmp)	144	W	Temp Coefficient of Pmp (/°C)	-0.0021
Open circuit voltage (Voc)	46.2	V	Temp Coefficient of Voc (/°C)	-0.0038
Maximum power voltage (Vmp)	33	V	Temp Coefficient of Vmp (/°C)	-0.0031
Short-circuit current (Isc)	5.3	A	Temp Coefficient of Isc (/°C)	0.0010
Maximum power current (Imp)	4.36	A	Temp Coefficient of Imp (/°C)	0.0010
Rated power at PTC (Pptc)	136.4	W	UL series fuse rating (amps)	8

Inverter	
Power (W)	6000
Number	1
Input V_min	230
Input V_max	600
MPPT min	230
MPPT max	500
Input I_max	28.1
Efficiency	0.962
Derate Factor	0.95

Environment	
	Temp (°C)
Min	-20
Max	40
STC	25
T_rise	40

The environmental temperature information was obtained from www.weatherbase.com.

Washington, District of Columbia
Elevation: 3 meters Latitude: 38 51N Longitude: 077 02W



Highest Recorded Temperature Years on Record: 51

	YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
°C	40	26	27	31	35	37	38	40	39	38	34	30	23

Lowest Recorded Temperature Years on Record: 51

	YEAR	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
°C	-20	-20	-15	-10	-4	1	8	12	9	3	-1	-8	-16

Specification Sheet for the Fronius IG Plus 6.0-1:

INPUT DATA Fronius IG Plus		3.0-1 UNI	3.8-1 UNI	5.0-1 UNI	6.0-1 UNI	7.5-1 UNI	10.0-1 UNI	11.4-1 UNI	11.4-3 Delta	12.0-3 WYE277
Recommended PV-Power (Wp)		2500-3450	3200-4400	4250-5750	5100-6900	6350-8600	8500-11500	9700-13100	9700-13100	10200-13800
MPPT-Voltage Range		230 ... 500 V								
Max. Input Voltage (at 1000 W/m² 14°F (-10°C) in open circuit operation)		600 V								
Nominal Input Current		8.3 A	10.5 A	13.8 A	16.6 A	20.7 A	27.6 A	31.4 A	31.4 A	33.1 A
Max. usable Input Current		14.0 A	17.8 A	23.4 A	28.1 A	35.1 A	46.7 A	53.3 A	53.3 A	56.1 A
Admissible conductor size (DC)		No. 14 - 6 AWG								

OUTPUT DATA Fronius IG Plus		3.0-1 UNI	3.8-1 UNI	5.0-1 UNI	6.0-1 UNI	7.5-1 UNI	10.0-1 UNI	11.4-1 UNI	11.4-3 Delta	12.0-3 WYE277
Nominal output power ($P_{AC nom}$)		3000 W	3800 W	5000 W	6000 W	7500 W	9995 W	11400 W	11400 W	12000 W
Max. continuous output power 104°F (40°C) 208 V / 240 V / 277 V		3000 W	3800 W	5000 W	6000 W	7500 W	9995 W	11400 W	11400 W	12000 W
Nominal AC output voltage		208 V / 240 V / 277 V							208 V / 240 V	277 V
Operating AC voltage range (default)	208 V	183 - 229 V (-12 / +10 %)								
	240 V	211 - 264 V (-12 / +10 %)								
	277 V	244 - 305 V (-12 / +10 %)								
Nominal output current	208 V	14.4 A	18.3 A	24.0 A	28.8 A	36.1 A	48.1 A	54.8 A	31.6 A*	n.a.
	240 V	12.5 A	15.8 A	20.8 A	25.0 A	31.3 A	41.7 A	47.5 A	27.4 A*	n.a.
	277 V	10.8 A	13.7 A	18.1 A	21.7 A	27.1 A	36.1 A	41.2 A	n.a.	14.4 A*
Max. output current	208 V	16.4 A	18.5 A	27.3 A	32.8 A	37.0 A	54.6 A	55.5 A	32.0 A*	n.a.
	240 V	14.2 A	14.4 A	23.7 A	28.4 A	35.5 A	47.4 A	54.0 A	31.2 A*	n.a.
	277 V	12.3 A	15.6 A	20.5 A	24.6 A	30.7 A	40.9 A	46.7 A	n.a.	16.4 A*
Admissible conductor size (AC)		No. 14 - 4 AWG								
Max. continuous utility back feed current		0 A								
Nominal output frequency		60 Hz								
Operating frequency range		59.3 - 60.5 Hz								
Total harmonic distortion		< 3 %								
Power factor		1								

GENERAL DATA Fronius IG Plus		3.0-1 UNI	3.8-1 UNI	5.0-1 UNI	6.0-1 UNI	7.5-1 UNI	10.0-1 UNI	11.4-1 UNI	11.4-3 Delta	12.0-3 WYE277
Max. Efficiency		96.2 %								
CEC Efficiency	208 V	95.0 %	95.0 %	95.5 %	95.5 %	95.0 %	95.0 %	95.5 %	95.5 %	n.a.
	240 V	95.5 %	95.5 %	95.5 %	96.0 %	95.5 %	95.5 %	96.0 %	96.0 %	n.a.
	277 V	95.5 %	95.5 %	96.0 %	96.0 %	96.0 %	96.0 %	96.0 %	n.a.	96.0 %
Consumption in standby (night)		< 1 W								
Consumption during operation		8 W		15 W			22 W			
Cooling		Controlled forced ventilation, variable fan speed								
Enclosure Type		NEMA 3R								
Unit Dimensions (W x H x D)		17.1 x 24.8 x 9.6 in.		17.1 x 36.4 x 9.6 in.			17.1 x 48.1 x 9.6 in.			
Inverter Weight		31 lbs. (14 kg)		57 lbs. (26 kg)			82 lbs. (37 kg)			
Wiring Compartment Weight		24 lbs. (11 kg)		26 lbs. (12 kg)			26 lbs. (12 kg)			
Admissible ambient operating temperature		-4 ... 122°F (-20 ... +50°C)								
Compliance		UL 1741-2005, IEEE 1547-2003, IEEE 1547.1, ANSI/IEEE C62.41, FCC Part 15 A& B, NEC Article 690, C22. 2 No. 107.1-01 (Sept. 2001)								

INPUT DATA Fronius IG Plus	3.0-1 UNI	3.8-1 UNI	5.0-1 UNI	6.0-1 UNI	7.5-1 UNI	10.0-1 UNI	11.4-1 UNI	11.4-3 Delta	12.0-3 WYE277
Ground fault protection	Internal GFDI (Ground Fault Detector/Interrupter); in accordance with UL 1741-2005 and NEC Art. 690								
DC reverse polarity protection	Internal diode								
Islanding protection	Internal; in accordance with UL 1741-2005, IEEE 1547-2003 and NEC								
Over temperature	Output power derating / active cooling								

* per Phase

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40,0006,2981,AE v01 2008 as01

From the input information, the following tables calculated the limitations of the array.

Maximum Modules in Series (Manual)	
Voc max =	Voc + (temp differenetial * temp coefficient of Voc)
=	**54.1002**
Nmax ≤	Inverter input Vdc_max ÷ Voc_max
≤	11.090532
	11

Maximum Modules in Series (NEC)	
Voc max =	Voc * Factor from NEC Table 690.7
=	**50.82**
Nmax ≤	Inverter input Vdc_ max ÷ Voc_max
≤	11.8063754
	11

Minimum Modules in Series	
Vmp_min =	Vmp + (temp differential * temp coefficient of Vmp)
=	Vmp + ((Trise + Tmax – Tstc)*(temp coef. Of Vmp * Vmp)
Vmp_min =	**26.103**
Nmin ≥	Inverter input Vdc_min ÷ Vmp_min
≥	8.81124775
Nmin =	**9**

Max Strings in Parallel	
N ≤	Inverter Input I_max ÷ Imp
≤	6.44495413
N =	**6**

Maximum Array Capacity	
Inverter power ≤	N * PTC * CEC weighted efficiency
N ≤	Power ÷ PTC ÷ CEC weighted efficiency
≤	45.7258522
N ≤	**45 modules**
With Additional Derate Factor	
Inverter power ≤	N * PTC * CEC weighted efficiency * Derate Factor
N ≤	Power ÷ PTC ÷ CEC weighted efficiency ÷ Derate Factor
≤	48.132476
N ≤	**48 modules**

These tables show that the maximum number of modules allowed in series, according to both manual calculations and the NEC, is 11. Similarly, the minimum number of modules allowed in series is 9. Therefore, each string in the array can only have between 9 and 11 modules.

A maximum of 6 strings are allowable in parallel and a there can be up to 48 modules in the array when the derate factor is taken into consideration. A derate factor accounts for losses from the DC nameplate power rating and is the product of the derate factors for the components of the PV system (including dirt, shadows, etc.). It determines the AC power rating at Standard Test Conditions (STC).

On the next page is a matrix that shows the allowable string configurations for the chosen inverter. The shaded areas are the regions that are most favorable because they utilize at least 80% of the inverter's power.

String Configurations for the Chosen Inverter

Number of modules in series	1 String			2 Strings			3 Strings			4 Strings		
	#	Pac out (W)	% of max	#	Pac out (W)	% of max	#	Pac out (W)	% of max	#	Pac out (W)	% of max
1	1	125	2	2	249	4	3	374	6	4	499	8
2	2	249	4	4	499	8	6	748	12	8	997	17
3	3	374	6	6	748	12	9	1122	19	12	1496	25
4	4	499	8	8	997	17	12	1496	25	16	1994	33
5	5	623	10	10	1247	21	15	1870	31	20	2493	42
6	6	748	12	12	1496	25	18	2244	37	24	2992	50
7	7	873	15	14	1745	29	21	2618	44	28	3490	58
8	8	997	17	16	1994	33	24	2992	50	32	3989	66
9	9	1122	19	18	2244	37	27	3366	56	36	4488	75
10	10	1247	21	20	2493	42	30	3740	62	40	4986	83
11	11	1371	23	22	2742	46	33	4114	69	44	5485	91
12	12	1496	25	24	2992	50	36	4488	75	48	5983	100
13	13	1621	27	26	3241	54	39	4862	81	52	6482	108
14	14	1745	29	28	3490	58	42	5236	87	56	6981	116
15	15	1870	31	30	3740	62	45	5610	93	60	7479	125
16	16	1994	33	32	3989	66	48	5983	100	64	7978	133
17	17	2119	35	34	4238	71	51	6357	106	68	8477	141
18	18	2244	37	36	4488	75	54	6731	112	72	8975	150

Number of modules in series	5 Strings			6 Strings			7 Strings			8 Strings		
	#	Pac out (W)	% of max	#	Pac out (W)	% of max	#	Pac out (W)	% of max	#	Pac out (W)	% of max
1	5	623	10	6	748	12	7	860	17	8	860	17
2	10	1247	21	12	1496	25	14	1720	34	16	1720	34
3	15	1870	31	18	2244	37	21	2580	52	24	2580	52
4	20	2493	42	24	2992	50	28	3440	69	32	3440	69
5	25	3116	52	30	3740	62	35	4300	86	40	4300	86
6	30	3740	62	36	4488	75	42	5160	103	48	5160	103
7	35	4363	73	42	5236	87	49	6021	120	56	6021	120
8	40	4986	83	48	5983	100	56	6881	138	64	6881	138
9	45	5610	93	54	6731	112	63	7741	155	72	7741	155
10	50	6233	104	60	7479	125	70	8601	172	80	8601	172
11	55	6856	114	66	8227	137	77	9461	189	88	9461	189
12	60	7479	125	72	8975	150	84	10321	206	96	10321	206
13	65	8103	135	78	9723	162	91	11181	224	104	11181	224
14	70	8726	145	84	10471	175	98	12041	241	112	12041	241
15	75	9349	156	90	11219	187	105	12901	258	120	12901	258
16	80	9972	166	96	11967	199	112	13761	275	128	13761	275
17	85	10596	177	102	12715	212	119	14621	292	136	14621	292
18	90	11219	187	108	13463	224	126	15481	310	144	15481	310

This output table shows that 3-string, 4-string, 5-string, and 6-string configurations produce the acceptable amount of power. However, the range of modules allowable in series is only 9 to 11. This eliminates the option of using 3-strings and 6-strings, as they both require a number of modules outside of that range.

Now, when reviewing the options for 4-strings and 5-strings, the following combinations are possible:

4-strings:
1.) 10 in series 40 modules total 83% of max
2.) 11 in series 44 modules total 91% of max

5-strings:
3.) 9 in series 45 modules total 93% of max
4.) 10 in series 50 modules total 104% of max

Taking into account the fact that the maximum number of modules allowed in the array is 48, this eliminates the option of using combination #4, since it exceeds 48 modules.

This means a configuration needs to be chosen out of combinations #1, #2, and #3. When reviewing, their percentage of maximum output, combination #3 is the best option at 93% of max.

For this analysis, combination #3 is going to be used:

5-strings
9 modules in series
45 modules total
93% of inverter max output

Placement of the Array

The most logical place to place a photovoltaic array is on the roof of Arena Stage due to the fact there is insufficient space to place it on the ground and because it is surrounded by buildings that are of similar, or slightly larger, height. By looking at the snapshots from Google Sketch Up, it is clear that very few substantial shadows are cast onto Arena Stage throughout the year. The surrounding buildings are not tall enough to cause significant shading on Arena Stage between 09:00 am and 03:00 pm. With the exception of shadows cast by the Cradle, the roof is relatively clear of obstructions, making it able to receive direct sunlight. However, this not taking the potential effects that trees and clouds could have into account.

The bulk of the roof is flat, supported by a steel-framed truss system, but the perimeter elevation of the roof varies due to an architectural soffit made of EIFS. EIFS stands for Exterior Insulation and Finishing Systems, which is a type of synthetic stucco. This portion of the roof undulates, so it will be important to make sure that the array is placed toward the center of the roof, away from the parapet. In this way, both the shadows from the Cradle and any slight elevation change made by the soffit can be avoided.

It was decided that the array should be placed on the north edge of the upper roof, as shown in Figure 32, for two reasons. First, it is far enough away from the Cradle that the shadows should not be cast onto the array and second, it is close to the main electrical room in the BOH where the panel boards are located. Figure 32 also provides an idea of how much space is available on the roof for PV panels. The array that matches the parking garage lighting load takes up a small amount of space, meaning that, if desired, a larger array could be designed to produce more electricity.

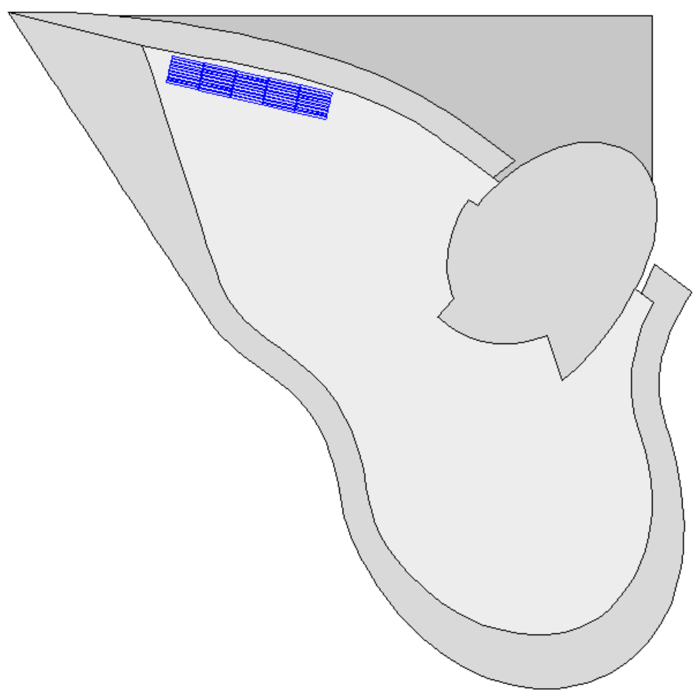


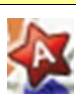
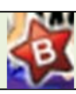
Figure 32: Placement of the Array on the Arena Stage Roof

Finding a Material Provider and Installer

Figure 33: Map of Material Providers (left) and Installers (right)

Figure 33 is a map identifying companies that supply and install Uni-Solar's PVL-144 module and Fronius's IG Plus 6.0-1 inverter. SunWize is a company that provides the Fronius inverter. They have a distributer in Kingston, NY and a certified installer located in Columbia, MD. Advanced Green Technologies (AGT) provides the Uni-Solar PV panel. AGT is based out of Fort Lauderdale, FL with a certified installer located in Falls Church, MD. Installers for both products are located within a close range of Arena Stage.

Table 8: PV Module / Inverter Installers (Consistent with right map above)

Label	Company	City	State	Distance from Arena Stage
	SunWize Technologies (Inverter)	Columbia	MD	37 miles
	**Arena Stage**	**Washington**	**DC**	–
	Advanced Green Technologies (PV module)	Falls Church	MD	10.25 miles

COST IMPACT

Figure 34: Uni-Solar PVL-144

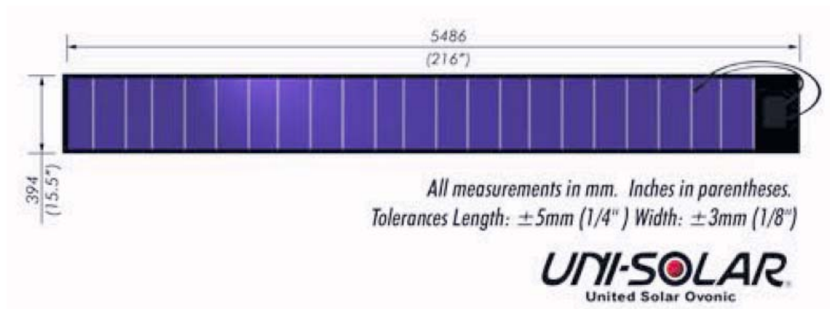


Table 9: Area of the PVL-144

Panel Size			
Length (in)	**Width (in)**	**Area (in^2)**	**Area (ft^2)**
216	15.5	3348	23.25

Table 10: 6 kW Array Estimate

6 kW Array Estimate							
Company	**Panel**				**Area for 6kW (ft^2)**	**# of Panels**	**System Price ($)**
	Model	**Power (W)**	**Size (ft^2)**	**Price ($)**			
Uni-Solar	PVL-144	144	23.25	$800*	1046.25	45	**$36,000**

**Unit Price provided by Advanced Green Technologies*

After performing a quick calculation, it was determined that a total of 42 modules would be able to form a 6kW array. However, in accordance with the sizing configurations with the Fronius inverter, a total of 45 Uni-Solar PVL-144 series modules are required. The table above shows that, at a unit price of $800 per panel roll, the material cost for the entire system is $36,000. This does not include the cost of installation.

Figure 35: Fronius IG Plus 6.0-1 Inverter

The inverter is somewhat simpler to price. Since only one inverter is required for the system, just the material cost is necessary. Affordable Solar (http://www.affordable-solar.com/home.htm) has a product list price of $4,409 for the Fronius IG Plus 6.0-1 inverter, as does Kully Solar (http://kullysolar.com/index.html).

Therefore, the material cost of the PV modules and the inverter is:

Table 11: Inverter Estimate

Inverter Estimate		
(1) Fronius IG Plus 6.0-1 Inverter	(45) Uni-Solar PVL-144 modules	Total
$4,409	$36,000	**$40,409**

Determining the Payback Period

The life-cycle cost of this system is going to be assumed as the initial cost of the system at $40,409. This value obviously does not include the costs incurred throughout the life of the system, which would include maintenance, repair, and replacement costs. To determine the payback period, a program from the National Renewable Energy Laboratory (NREL) website called PV Watts (http://www.nrel.gov/rredc/pvwatts/) is going to be used. Although this program is very basic, it does give a general idea of how quickly a solar array will be able to pay itself off.

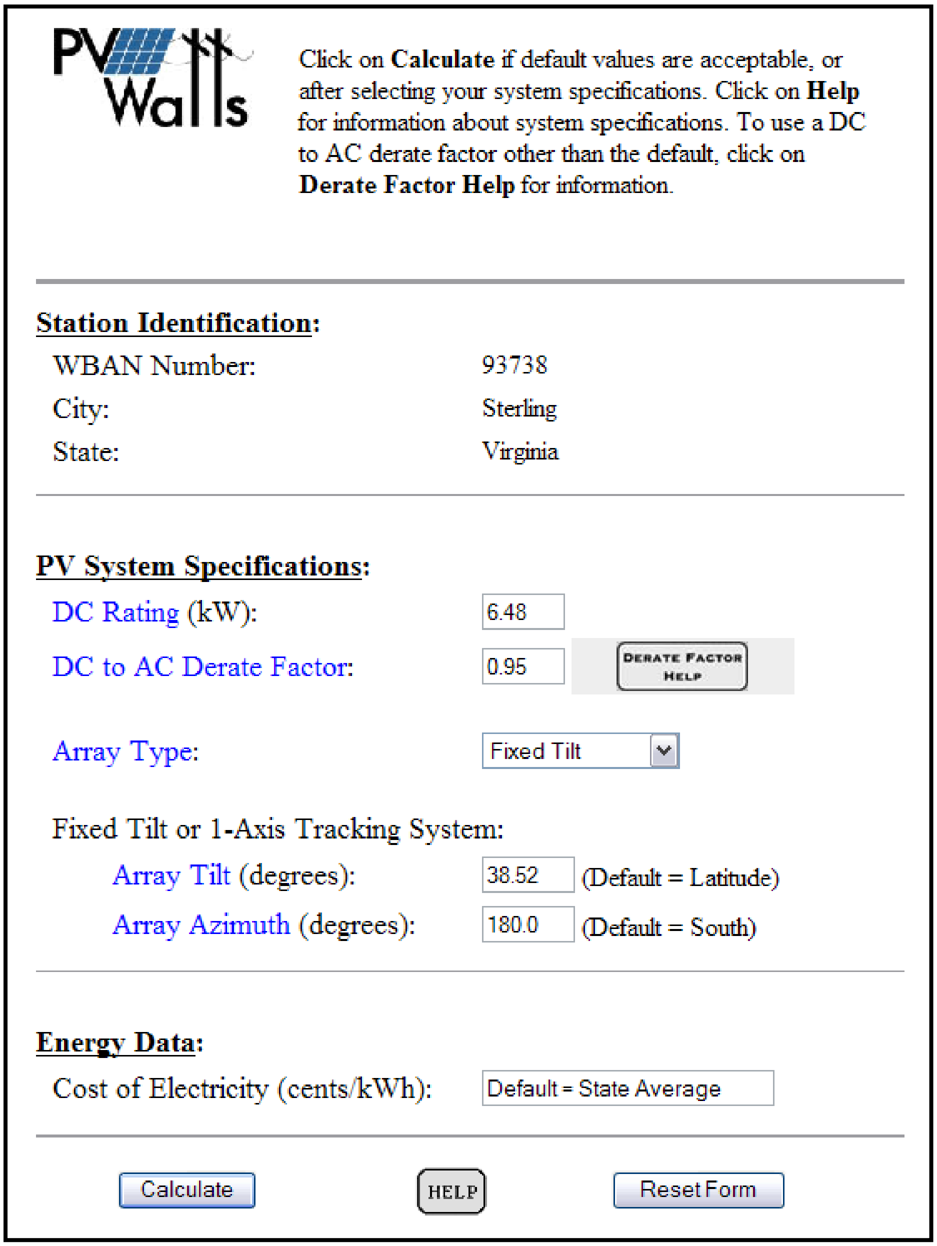


Figure 36: Input Data Screen from PV Watts

PV Watts does not recognize Washington, DC as a link on their map, so Sterling, VA (similar longitude/latitude) was chosen as the station for site analysis.

With 45 Uni-Solar PVL-144 modules, a DC rating of 6.48kW was input.

A derate factor of 0.95 was used to remain consistent with value used for matching the inverter to the array.

Since the modules are going to be directly adhered to the roof of Arena Stage, the array type was chosen as "Fixed Tilt."

The array tilt was left as the default for the location's decimal latitude value of 38.52°, as was the array azimuth at180°.

Since the cost of electricity is unknown, the default was kept at $0.08/kWh.

PV Watts — AC Energy & Cost Savings

Cautions for Interpreting the Results

Station Identification	
City:	Sterling
State:	Virginia
Latitude:	38.95° N
Longitude:	77.45° W
Elevation:	82 m
PV System Specifications	
DC Rating:	6.5 kW
DC to AC Derate Factor:	0.950
AC Rating:	6.2 kW
Array Type:	Fixed Tilt
Array Tilt:	38.5°
Array Azimuth:	180.0°
Energy Specifications	
Cost of Electricity:	8.0 ¢/kWh

Results			
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value ($)
1	3.58	709	56.72
2	4.27	745	59.60
3	4.80	900	72.00
4	5.34	934	74.72
5	5.33	916	73.28
6	5.68	944	75.52
7	5.48	919	73.52
8	5.39	920	73.60
9	5.07	855	68.40
10	4.71	847	67.76
11	3.55	644	51.52
12	3.02	572	45.76
Year	4.69	9903	792.24

Output Hourly Performance Data — Output Results as Text

About the Hourly Performance Data — Saving Text from a Browser

Figure 37: Output Data Screen from PV Watts

After calculating the output from the frame on the previous page, the frame above displays the program results. It shows that during a one year time period, $792.24 of energy cost savings can be expected by the owner. This is determined through the product of the number of kilowatt hours (kWh) and the cost of electricity per kilowatt ($0.08/kWh).

Table 12: PV Watts Summary

Initial (Life-Cycle) Cost of System	Energy Savings per Year	Payback Period
$40,409	$792.24	**51 years**

Taking the life-cycle cost of the system and dividing it by the energy savings per year, a projected payback period of 51 years was determined.

Incentives

The District Department of the Environment (DDOE) recently announced the Renewable Energy Incentive Program (REIP) to support the installation of renewable energy systems in the District of Columbia. REIP is supported through the Sustainable Energy Trust Fund (SETF), with allocations of $2 million per year through 2012, and administered by the DDOE.

Arena Stage is an eligible participant according to the following criteria:

- Photovoltaic installation
- Pepco retail electric account holder
- Connected to Pepco's electricity distribution system
- Site within the District of Columbia
- Not-for-profit organization

There are several other technical requirements as spelled out by the *Guide to Solar Photovoltaic Incentives*, but providing that Arena Stage was accepted upon application, it would be eligible to receive a portion of these funds. PV incentives are based on the combined system rating in kilowatt (DC) output:

- $3 for each of the first 3,000 installed watts of capacity
- $2 for each of the next 7,000 installed watts of capacity
- $1 for each of the next 10,000 installed watts of capacity

Rebates are capped at a maximum of $33,000 (for 20kW) for each applicant site per program year.

In the case of Arena Stage and the PV array designed through this analysis, it could potentially receive a $15,000 rebate for installing the proposed system.

Table 13: Incentive Rebate

Potential Incentive Rebate for Arena Stage	
$3 x 3,000 W	$9,000
$2 x 3,000 W	$6,000
Total	**$15,000**

In this scenario, the $15,000 rebate would decrease the life-cycle cost of the PV array to $25,409, meaning that it would then take 32 years for the system to pay itself off.

Table 14: Payback Period Adjusted to Include the Incentive Rebate

Rebated (Life-Cycle) Cost of System	Energy Savings per Year	Payback Period
$25,409	$792.24	**32 years**

CONCLUSION AND RECOMMENDATION

The installation of a solar photovoltaic system provides the owner with greater energy independence and allows for a reduction in fossil fuel usage and air pollution. Due to the recent effects of global warming, it is very important that renewable energy technology be implemented on all scales of consumption. While is it something that everyone is capable of contributing to, this particular system is not a reasonable method of application for Arena Stage. I would not suggest installing the proposed PV array to the project.

Although the initial cost of $40,409 is minimal in relation to the overall cost of the building, $125 million, the payback period for the system is much higher than anticipated (51 years), even when taking incentive rebates into consideration (32 years). It is possible that an alternate solar PV system would be more suitable for Arena Stage. If it proved to be a smart investment with a reasonable payback period, I would definitely suggest that Arena Stage construct a solar PV array on their roof.

The use of “peel and stick” PV modules may have also been a reason that the cost of the system was so high. Solar laminates are a relatively new technology and they are not prevalent in the market yet. An array of these modules would have minimal impact on the architecture of the building, but a different type of module might cause a slight alteration to the look of the building. If a solar PV system was designed and worth implementing on Arena Stage, it would be up to them to decide if the addition of the array was worth the aesthetic harm.

Not only would a PV system give Arena Stage some self-sufficiency, it would probably attract numerous donors for the Next Stage Campaign. Since this project is part of the Anacostia Waterfront Initiative, any enhancements to the building would most likely be readily welcomed by patrons and all advocates of Green Energy DC. Implementing PV panels, or other green systems, should be something that Arena Stage considers once the project is complete.

Analysis III: Redesign of the Fichandler Stage Air Distribution System

[Mechanical Breadth]

BACKGROUND

The Fichandler was originally built in 1960 and is the most well known icon of Arena Stage. The style of the theater is known as a "theater-in-the-round" where the stage is surrounded by audience seating on all four sides. To maximize comfort, the refurbished mechanical system of the Fichandler is being served by two separate constant volume air handling units: one for the seating area and one for the stage. The seating is being retrofit with under-seat air distribution, while the air to the stage is being distributed by a ring duct plenum and branch ducts located above the wood ceiling.

PROBLEM STATEMENT

The sheet metal duct work that makes up the ring duct plenum and the branch ducts is difficult to install. Installation consists of the removal of the front face paneling of the wall, followed by the placement of 3-sided bar slip sheet metal duct which is placed along the beam that makes up the exterior wall. Once the entire run is in place and joined together, the front face of the duct is then screwed on. Hinged air deflectors are at the terminal end of the (8) branch ducts which will be directed to distribute air toward the stage. This system is then hidden behind a refurbished wood ceiling and requires a high-throw to supply air to the stage below.

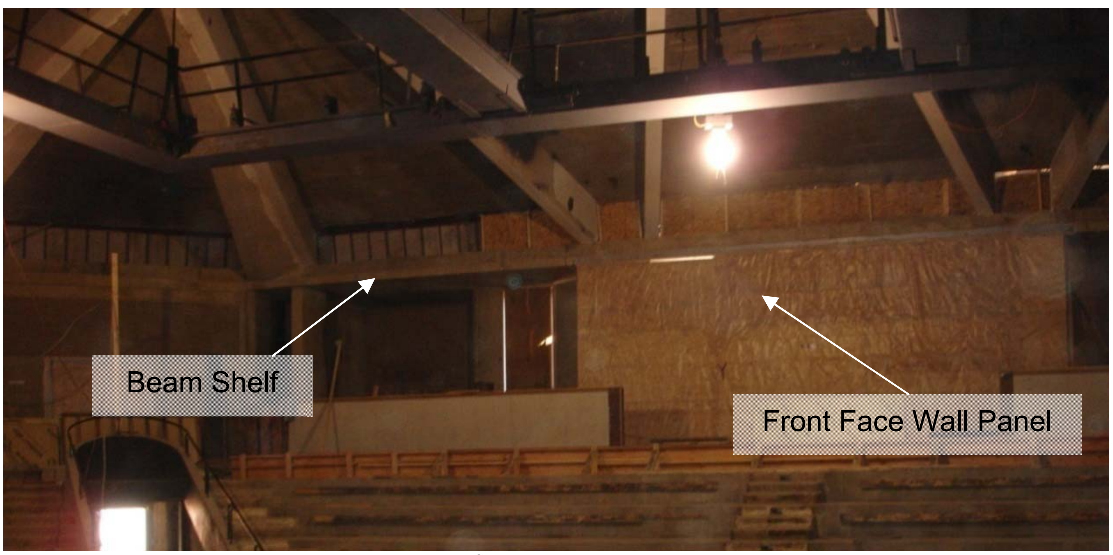


Figure 38: Inside of the Fichandler during Renovation

Another issue with this design is that it is also going to be very difficult to perform maintenance on the entire run of ring duct since it is going to be enclosed by the wood roof and access to this area is not only tight, but limited. Similarly, sheet metal duct is expensive to furnish and install and it has the potential to be very noisy at such a high-throw. This is unfavorable for Arena Stage since it is running on a tight budget and, as a theater, it has strict acoustical requirements.

OBJECTIVE

To redesign the current mechanical system of the Fichandler stage using fabric duct, specifically DuctSox, to ease installation, reduce installation time, and reduce the overall cost of the system.

METHODOLOGY

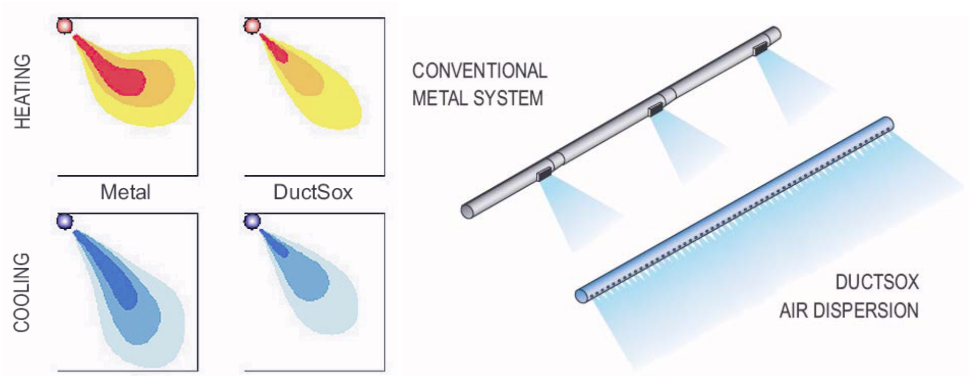
1. Perform a quantity take-off of the current mechanical design, primarily the ring duct plenum and the branch ducts
2. Determine air flow requirements for the Fichandler stage
3. Determine the cost and installation time of the current design
4. Redesign the system with fabric duct while maintaining supply air requirements
5. Determine the cost and installation time of the new design
6. Research the benefits of using fabric duct over standard sheet metal duct
7. Find a fabric duct material provider and installer near Washington, DC
8. Compare the two systems, focusing primarily on the ease of installation, cost of the systems, and duration of installation
9. Make a recommendation on whether changing the current design to a fabric duct system is a beneficial adjustment for Arena Stage

TOOLS / RESOURCES

- Southland Industries
- Clark Construction Group, LLC
- Arena Stage Construction Documents/Specifications
- DuctSox website
- 2005-2008 ASHRAE HandbookCD+
- Trane Ductulator
- Penn State AE Faculty

EXPECTATIONS

By implementing fabric duct and reducing the amount of sheet metal duct used to condition the Fichandler stage, I expect that the installation of the mechanical system will be simplified. In addition, I expect that furnishing and installation costs will be reduced, as well as installation time.



ANALYSIS

Current Design of the Fichandler Stage Mechanical System

- Service provided by (1) Air Handling Unit

  Location: Fichandler Mechanical Room
  Supply Air Flow: 10,500 cfm (900 cfm outside air)
  (16) Diffusers: 650 cfm each

Table 15: Stage Ventilation Criteria

Ventilation Criteria	
Occupancy Density:	25 sf/person
Minimum OSA Ventilation:	15 cfm/person

- Standard Sheet Metal Duct

  Ring duct plenum
  3-sided bar slip sheet metal duct, front piece screwed on
  (8) Branch ducts above wood ceiling
  (16) Open diffusers with hinged air deflectors

- Quantity Take-Off

Table 16: Take-Off of the Sheet Metal Duct

Duct Size	Length (LF)
16x16	55
20x20	140
20x26	75
20x40	245
38x11	55
45° Angles	(16) 3
Total Run of Duct (LF)	**618**

- Installation Time

Table 17: Installation Criteria

Man Hours	Week(s)	Crew Size (men)
532	3	4

- Cost

Table 18: Cost of the Current Mechanical Design

	Unit	Multiplier	Expanded
Material	$28/LF	618 LF	$17,304
Labor	$57.68/hr (budgeted labor rate)	532 hrs	$30,686
Total Cost (to engineer, furnish, and install)			**$47,990**

Figure 39: Rendering of the Fichandler Catwalk (Provided by Bing Thom Architects)

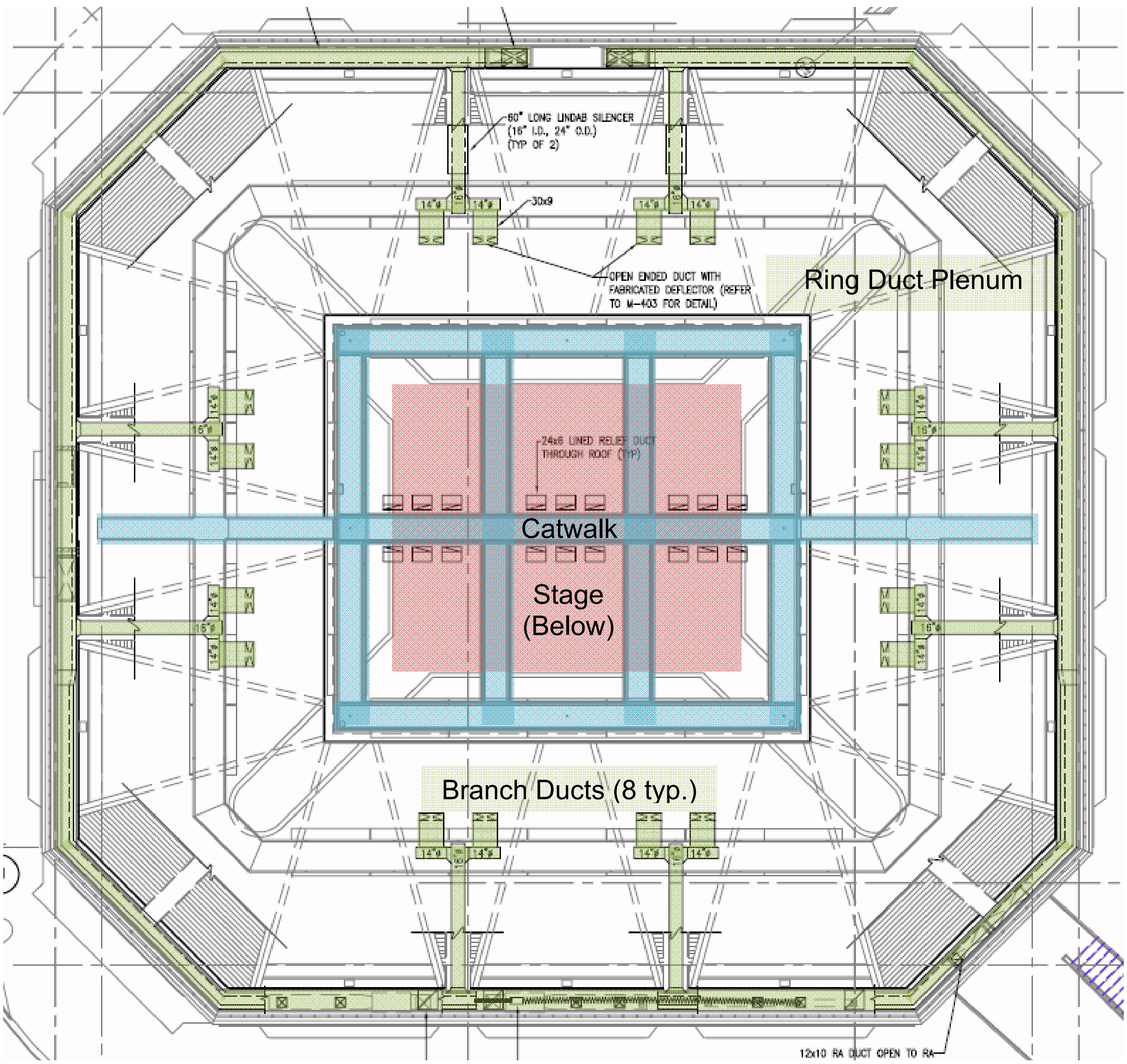


Figure 40: Fichandler Plan showing the current design with the Catwalk (blue), Stage (red), Ring Duct and Branch Ducts (green)

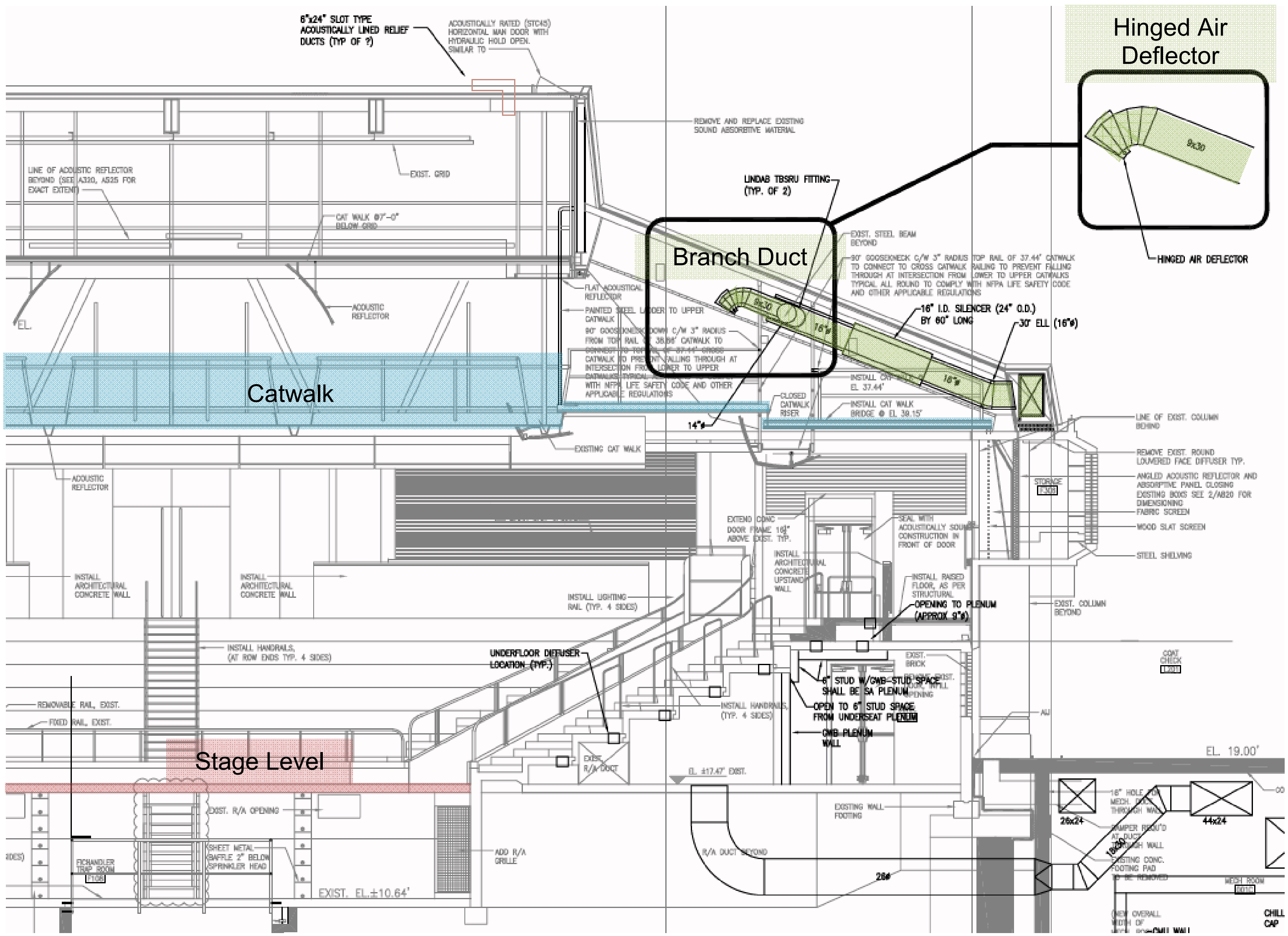


Figure 41: Fichandler Section showing the Catwalk (blue), Stage (red), Ring Duct and Branch Ducts (green)

Redesign with Fabric Duct

DuctSox® Fabric Air Dispersion Products *Engineering & Design Manual* uses a five step process for designing a DuctSox system. These steps include making the following decisions about the system:

1. Series/Shape
    - Cylindrical
    - Surface Mount
2. Design Layout
    - Location
    - Diameter Lengths
    - Required Fittings
3. Fabric
    - Porosity
    - Color
    - Quality
        - Premium, Commercial, Economy, or Specialty Fabric
4. Air Dispersion
    - Comfort-Flow
    - High-Throw
    - Low-Throw
5. Suspension
    - Tension Cable
    - 3x1 (4x2) Suspension
    - Suspended H-Track
    - Surface Mount

Step 1: Series/Shape

DuctSox offers two different shapes of fabric duct: cylindrical and surface mount (or D-shape). The cylindrical shape is intended to be suspended and exposed in open ceiling architecture, while D-shape is intended to be flush mounted to walls or ceilings, especially those lower than 14 feet. Since the Fichandler Theater at Arena Stage has a high open ceiling free from major obstructions, the cylindrical series is the best option.

Figure 42: Cylindrical Series

Figure 43: Surface Mount (D-Shape)

Step 2: Design Layout

Normally, when designing a fabric duct system, the fabric duct can directly replace standard sheet metal. In such case, the list of sheet metal cross sectional sizes would simply have to be converted to round duct sizes to come up with size of fabric duct. However, in the case of Arena Stage, the current layout of the mechanical duct in the Fichandler is not being maintained. The amount of sheet metal duct that makes up the ring duct plenum is being reduced and the branch ducts are being eliminated entirely. A run of sheet metal duct will be kept along the beam shelf and once it reaches the catwalk bridge, will terminate. From that point, fabric duct will be suspended from the catwalk to provide closer air distribution to the Fichandler stage.

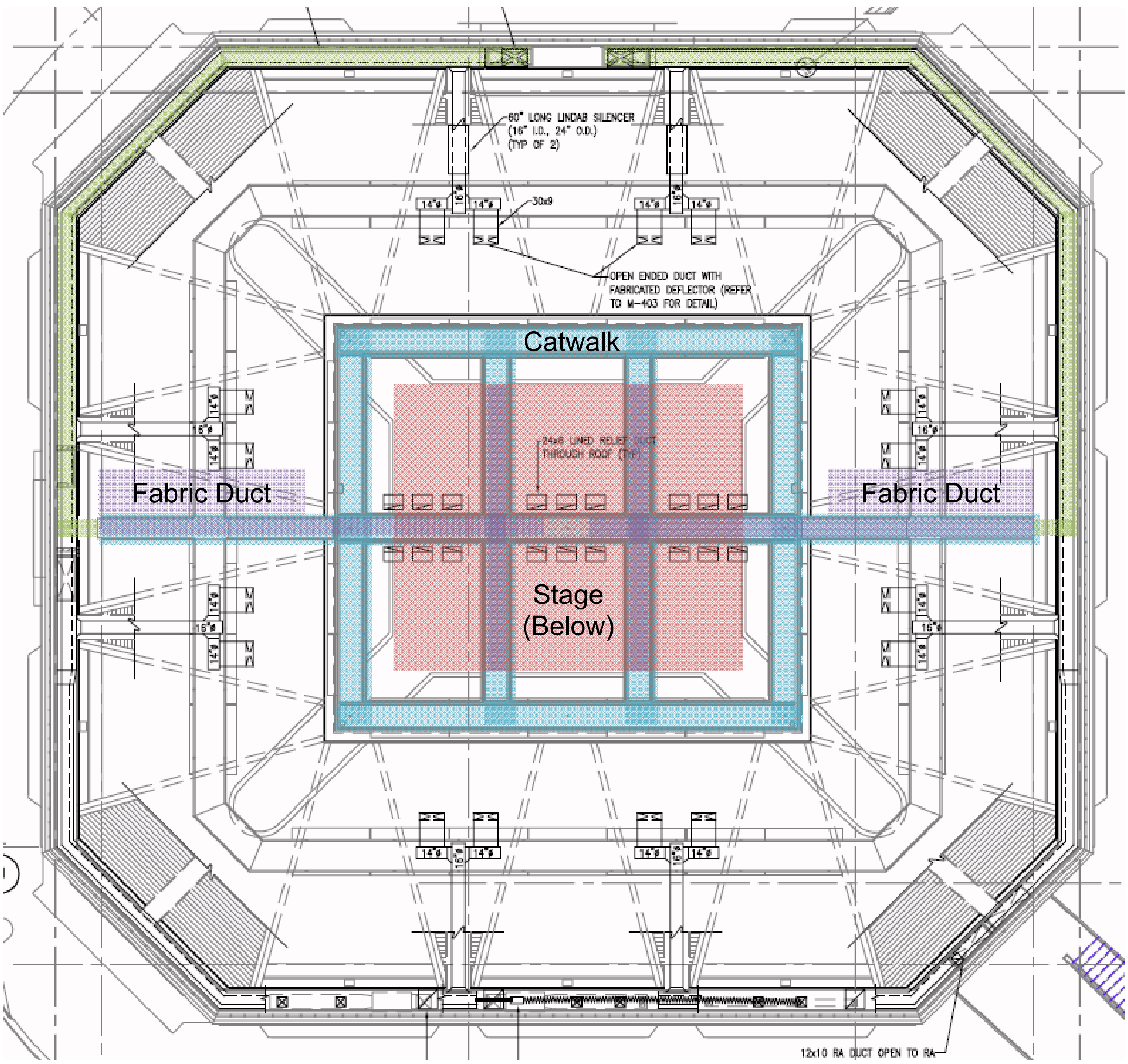


Figure 44: Fichandler Plan showing the redesign with the Catwalk (blue), Stage (red), Sheet Metal Duct (green), and Fabric Duct (purple)

There is going to be 186 LF of sheet metal duct remaining on the beam shelf:

Table 19: New Calculation of Sheet Metal Duct

Duct Size	Length (LF)
20x40	170
45° Angles	(4) 3
Rectangular to Round Duct Transition	(2) 2
Total Run of Sheet Metal Duct (LF)	**186**

Diameter Selection

Next, a fabric duct diameter must be selected. The size of the sheet metal duct that terminates at the catwalk is 20x40.

Diameter	Inlet Velocity			
	1,000	1,200	1,400	1,600
8	349	419	489	559
10	545	654	764	873
12	785	942	1,100	1,257
14	1,069	1,283	1,497	1,710
16	1,396	1,676	1,955	2,234
18	1,767	2,121	2,474	2,827
20	2,182	2,618	3,054	3,491
22	2,640	3,168	3,696	4,224
24	3,142	3,770	4,398	5,027
26	3,687	4,424	5,162	5,899
28	4,276	5,131	5,986	6,842
30	4,909	5,890	6,872	7,854
32	5,585	6,702	7,819	8,936
34	6,305	7,566	8,827	10,088
36	7,069	8,482	9,896	11,310
38	7,876	9,451	11,026	12,601
40	8,727	10,472	[illegible]	[illegible]
42	9,621	11,545	[illegible]	[illegible]
44	10,559	12,671	[illegible]	[illegible]
46	11,541	13,849	[illegible]	[illegible]
48	12,566	15,080	[illegible]	[illegible]
50	13,635	16,362	[illegible]	[illegible]
52	14,748	17,698	[illegible]	[illegible]
54	15,904	19,085	[illegible]	[illegible]
56	17,104	20,525	[illegible]	[illegible]
58	18,348	22,017	[illegible]	[illegible]
60	19,635	23,562	[illegible]	[illegible]
62	20,966	25,159	[illegible]	[illegible]
64	22,340	26,808	31,276	35,744
66	23,758	28,510	33,262	38,013
68	25,220	30,264	35,308	40,352
70	26,725	32,070	37,415	42,761
72	28,274	33,929	39,584	45,239

CYLINDRICAL SERIES

Diameter based on airflow and inlet conditions. Lower inlet velocities (1,000-1,200 FPM) reduce stress, noise and yield a better balanced system.

1,600 FPM Maximum: Straight Run
1,400 FPM Maximum: Inlet with Fittings

If the required diameter is too large for the space - consider breaking the system down into multiple runs.

Inlet velocities greater than 1,600 FPM is not covered by warranty program.

Figure 45: Diameter Selection Table from DuctSox

The two side units of sheet metal duct will be exposed at the catwalk bridge and will have a rectangular duct to round duct transition. The fabric duct will be connected and angled to reach the underside of the catwalk, which is 21'-6" above the stage level.

Based on the need for low noise, a diameter is selected for low inlet velocity (< 1,200 fpm):
Diameter: 30" at 1070 fpm

Fabric Duct Layout

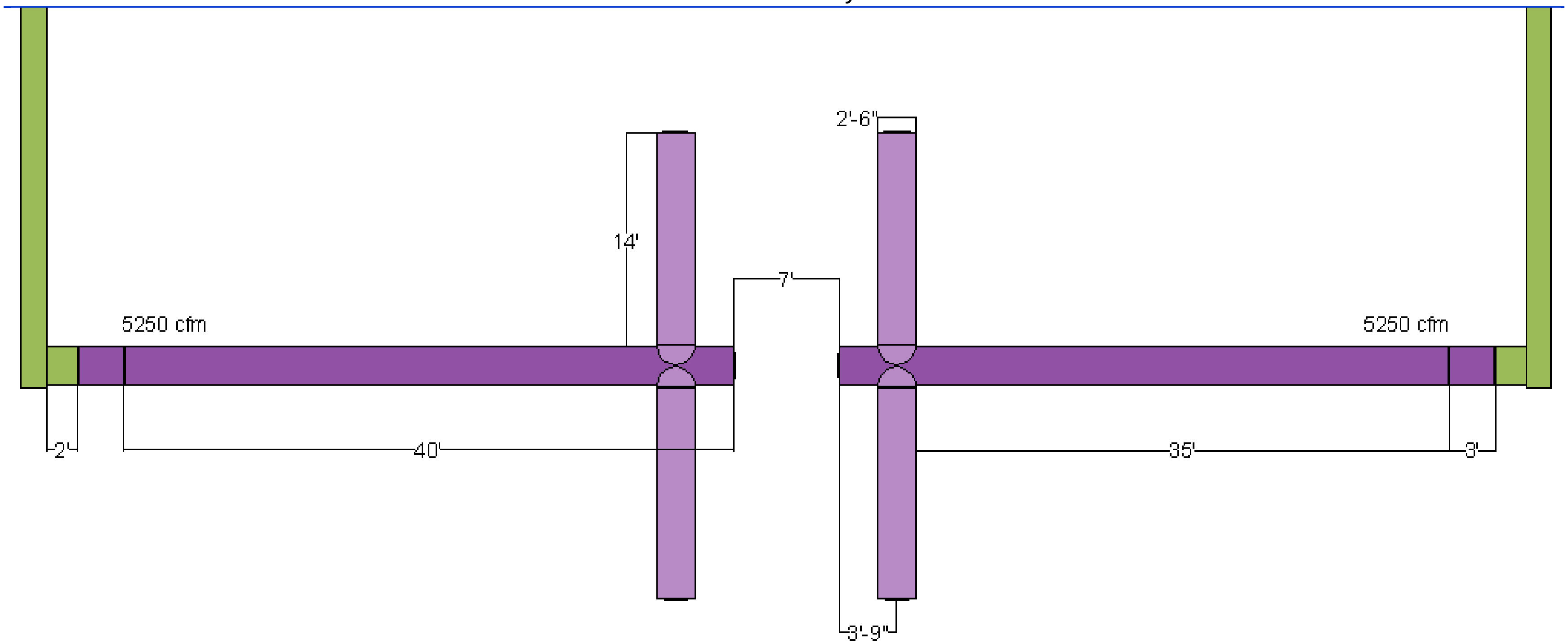


Figure 46: Plan of the Fabric Duct Layout

Table 20: Fabric Duct Dimensions

Inlet Duct: (2) 20x40 @ 5250 cfm each			
Rectangular to Round Duct Transition: (2) 2’			
Catwalk Dimensions		Fabric Duct Dimensions	
Width	2’-6”	Diameter	2’-6” (30”)
Long Run (including bridge)	97’	Elevation Transition	(2) 3’
Short Run	(2) 36’	Long Run	(2) 40’ (7’ gap between)
		Short Run	(4) 14’
		Total Length	**142’**

Fittings & Zippers

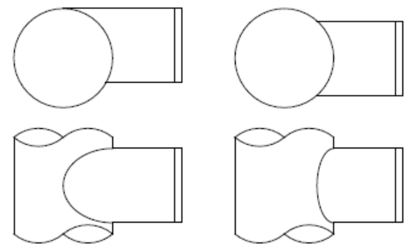
Zippers

Straight lengths and/or fittings are connected together using a radial zipper. The zipper is affixed with the start/stop located at the bottom center - and each includes a 2" fabric overlap to conceal the zipper.

The following table indicates maximum sectional length of a straight run. Longer sections are broken into equal lengths: 60 ft of 36" Dia would be constructed of two 30 foot long sections.

Cylindrical		D-Shape	
Diameter	Max Length	Dia	Max Length
6"	15'	14"	25'
8"-10"	20'	18"	25'
12"-16"	25'	22"	30'
18"-20"	30'	26"	35'
22"-26"	35'	30"	35'
28"-40"	40'	34"	40'
42"-44"	35'		
46"-50"	30'		
52"-56"	25'		
58"-60"	20'		
62"+	15'		

Economy (PolyTex) max sectional length: 50 ft (all dia)



TAKE-OFF (T's)

When designing complicated systems, efficiency take off fittings direct air to areas perpendicular to the main run. Shown above in Top Flat and Concentric options (Bottom Flat available). The branch duct will require a zipper for attachment.

For better airflow management, branch ducts should be positioned at least 1.5 times the outlet diameter from endcaps.

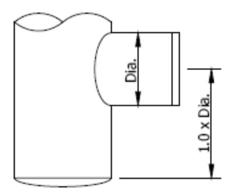


Figure 47: Fitting and Zipper Guide from DuctSox

As shown in Figure 47, the longest run allowable for the 30" diameter fabric duct is 40'. Since the two longer runs of the new fabric duct design are 40', they will not require any zippers to connect runs. It is suggested that the branch ducts are positioned at least 1.5 times the outlet diameter from the main endcaps. Since the main duct is 30" in diameter, the branch ducts were positioned 3'-9" away from the main endcaps. These 4 branch ducts will require a total of 4 concentric take-off T's and 4 connection zippers. Similarly, there will be zippers located at the 2 elevation transitions.

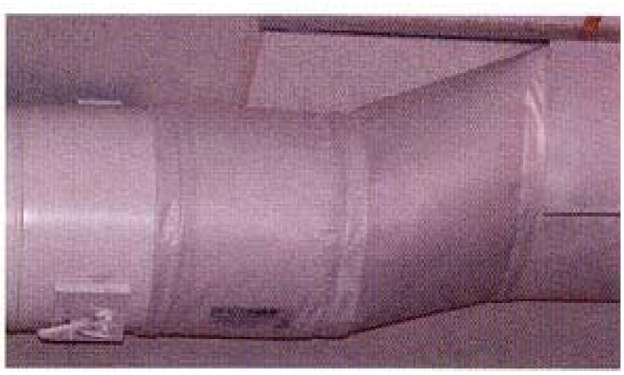


Figure 48: Example of an Elevation Transition from DuctSox

In summary, a total of 6 zippers and 4 take-off T's are required for the fabric duct layout of the Fichandler Stage.

Table 21: System Recommendation from DuctSox

Application	Fabric Options	Model Options	Suspension and Attachment Options
Food Processing	Microbe-X	LT or CF	Stainless Steel Cable and Snap Clips
	Sedona-Xm or Verona	CF	
Industrial, Manufacturing, Warehousing, & Distribution	Verona	CF	Galvanized Cable and Snap Clips; Aluminum Track and Snap Tabs
	Sedona-Xm or DuraTex	CF or HT	
	EkoTex (36” dia. max)	HT	
Pools	Coronado Sedona-Xm, Verona	CF	Stainless Steel Cable and Snap Clips; Aluminum Track and Snap Tabs or Cord-In
Gymnasium	Coronado, Verona	CF	Galvanized Cable and Snap Clips
	TufTex or DuraTex Sedona-Xm	CF or HT	
Office Space, Telemarketing	Coronado Sedona-Xm or Verona	CF	Aluminum Track and Snap Tabs or Cord-In
	TufTex or DuraTex	CF or HT	
Retail, Grocery Store	Sedona-Xm or Verona	CF	Galvanized Cable and Nylon Snap Clips; Aluminum Track and Snap Tabs or Cord-In
	TufTex or DuraTex	CF or HT	
Restaurant, Bar, Cafeteria	Coronado Sedona-Xm or Verona	CF	Galvanized Cable and Snap Clips; Aluminum Track and Snap Tabs or Cord-In
	TufTex or DuraTex	CF or HT	
Library, School Classroom	Sedona-Xm or Verona	CF	Galvanized Cable and Snap Clips; Aluminum Track and Snap Tabs or Cord-In
	TufTex or DuraTex	CF or HT	
Telecommunication & Electronics Hub	Stat-X	CF	Galvanized Cable and Nylon Snap Clips
Auditorium, Sports Arena, Convention Center, Church	Verona	CF	Galvanized Cable and Nylon Snap Clips
	TufTex or DuraTex Sedona-Xm	CF or HT	
Tent, Temporary Structure, Animal Housing	Verona	CF	Galvanized Cable and Snap Clips
	DuraTex	CF or HT	
	EkoTex (36” dia. max)	HT	
Clean Room, Test Lab	Stat-X or Verona	CF	Galvanized Cable and Snap Clips
	Sedona-Xm	CF or LT*	
	Microbe-X	CF or LT	

Model / Airflow Description:
CF = Comfort Flow Model / L-Vent, S-Vent, or Mesh Vents
HT = High Throw Model / Engineered Orifices or SG (Diffusers in Sedona-Xm only)
LT = Low Throw Model / Porous Fabric

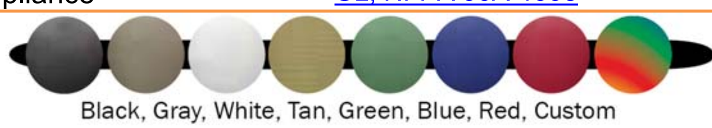
Step 3: Fabric

According to the DuctSox System Recommendation table (Table 21), the best types of fabric to use in a theater are Verona, TufTex, DuraTex, and Sedona-Xm. After reviewing the product information on each of the four fabrics listed above, the best type of fabric to apply at Arena Stage is Verona. It is an all-purpose, air permeable, commercial-quality fabric. Some features of Verona fabric are:

1. Finished (interior) seam construction
2. Positive inlet anchoring system
3. Zippered inlet collar
4. 8 Color options
5. Launderable
6. 5-year warranty

Table 22: Verona Specifications from DuctSox

Specifications	
Type	Fire retardant polyester fabric
Weight	5.2 oz/yd2
Porosity	1.5 CFM/ft2 @ 0.5 w.g.
Weave	2x2 Twill FR Polyester
Colors	black, gray, white, tan, green, blue, red, custom
Compliance	UL, NFPA 90A-1993



The best color to choose for the fabric duct in the Fichandler Theater is black. In general, the ceiling of the theater is dark to hide all of the obstructions above the stage including theater rigging, catwalks, acoustical reflectors, and lighting fixtures.

Step 4: Air Dispersion

The only type of air dispersion available with Verona fabric is Comfort-Flow. A gentle air flow is delivered through linear vents, called L-Vents, whose sizes and locations can be custom designed. Comfort-Flow is best applied in high occupancy spaces where emphasis is on optimum air diffusion and mixing, creating comfortable and pleasing environments, which is ideal for Arena Stage.

Figure 49: Comfort-Flow

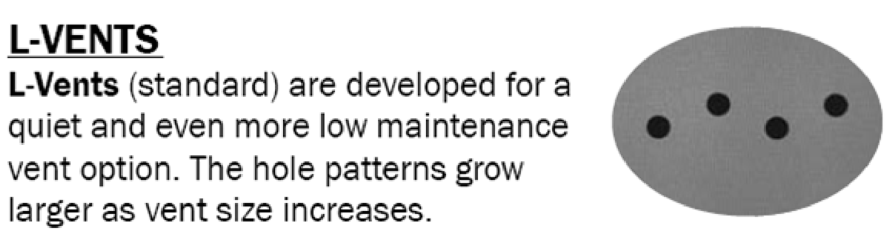


Figure 50: L-Vents

The following data reports are from the DuctSox Designer spreadsheet, which calculate the necessary vent sizes from the design criteria.

DUCTSOX® COMFORT FLOW DESIGN

Main 43' Runs

Project: **Arena Stage**
Reference: Fichandler Stage - Main Runs

Airflow	5250	cfm
Diameter	30	inch
Length	43	feet
Inlet Velocity	1070	fpm
Inlet Static Pressure	0.50	in of H_20
Velocity Pressure	0.07	in of H_20
Frictional Losses	0.01	in of H_20
Average Pressure	0.54	in of H_20
Maximum Pressure	0.56	in of H_20
Fabric Porosity	1.50	cfm/ft^2
Fabric CFM	549	cfm

Diameter (inches)	Velocity (ft/min)	Application
32	1000	Low Velocity
30	1200	Low Noise
28	***1400***	***Max Through Fittings***
26	***1600***	***Max in Straight Sections***
24	1800	High Velocity

# of Zippers in Sect.
1 Zips

	Vent Set #1		Vent Set #2		Vent Set #3	
% of Air to Disperse	100%					
Number of Vents	1	Vents		Vents		Vents
Total Vent CFM	4701	cfm	0	cfm	0	cfm
Standard L-Vent Size	105	cfm/ft	#DIV/0!	cfm/ft	#DIV/0!	cfm/ft
Optional M-Vent Size	1.19	inches	#DIV/0!	inches	#DIV/0!	inches

DUCTSOX® COMFORT FLOW DESIGN

14' Branch Runs

Project: **Arena Stage**
Reference: Fichandler Stage - Branch Runs

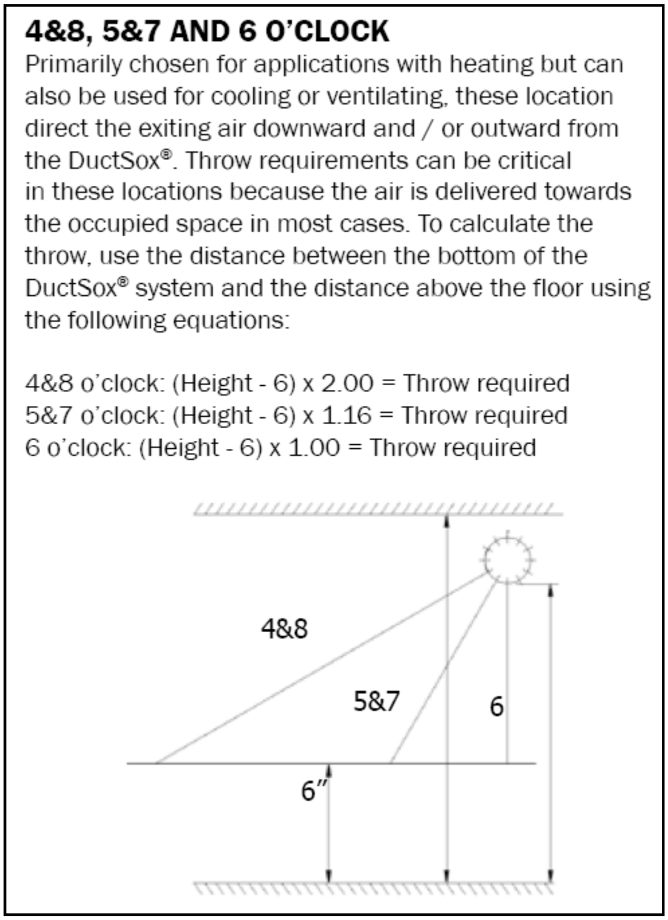
Airflow	4701	cfm
Diameter	30	inch
Length	14	feet
Inlet Velocity	958	fpm
Inlet Static Pressure	0.50	in of H_20
Velocity Pressure	0.06	in of H_20
Frictional Losses	0.00	in of H_20
Average Pressure	0.54	in of H_20
Maximum Pressure	0.56	in of H_20
Fabric Porosity	1.50	cfm/ft^2
Fabric CFM	177	cfm

Diameter (inches)	Velocity (ft/min)	Application
30	1000	Low Velocity
28	1200	Low Noise
26	***1400***	***Max Through Fittings***
24	***1600***	***Max in Straight Sections***
22	1800	High Velocity

# of Zippers in Sect.
0 Zips

	Vent Set #1		Vent Set #2		Vent Set #3	
% of Air to Disperse	100%					
Number of Vents	2	Vents		Vents		Vents
Total Vent CFM	4524	cfm	0	cfm	0	cfm
Standard L-Vent Size	156	cfm/ft	#DIV/0!	cfm/ft	#DIV/0!	cfm/ft
Optional M-Vent Size	1.77	inches	#DIV/0!	inches	#DIV/0!	inches

Figure 51: Output Data from the DuctSox Designer

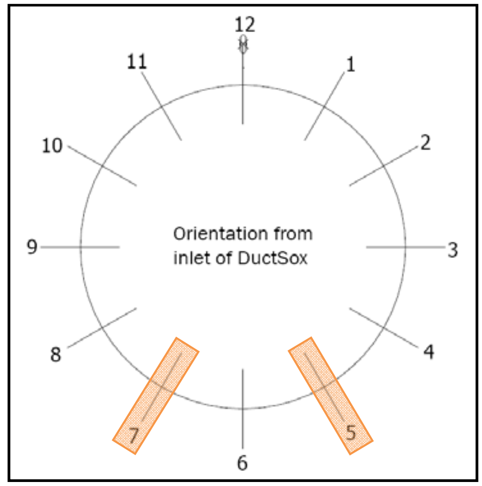


4&8, 5&7 AND 6 O'CLOCK

Primarily chosen for applications with heating but can also be used for cooling or ventilating, these location direct the exiting air downward and / or outward from the DuctSox®. Throw requirements can be critical in these locations because the air is delivered towards the occupied space in most cases. To calculate the throw, use the distance between the bottom of the DuctSox® system and the distance above the floor using the following equations:

4&8 o'clock: (Height - 6) x 2.00 = Throw required
5&7 o'clock: (Height - 6) x 1.16 = Throw required
6 o'clock: (Height - 6) x 1.00 = Throw required

Figure 52: Vent Orientation Guide from DuctSox



In order to figure out the orientation of the fabric duct vents, throw calculations provided by DuctSox are performed to figure out how far the air needs to be dispersed to provide adequate supply air to the Fichandler Stage.

Vertical distance from stage level to underside of catwalk: 21'-6" (258")

4&8 o'clock: (258" – 6") x 2.00 = 42'
5&7 o'clock: (258" – 6") x 1.16 = 24'-4"
6 o'clock: (258" – 6") x 1.00 = 21'

Since the dimension of the stage is 35'-6" x 29'-6", the 4&8 o'clock option has a far throw requirement of 42'. This would greatly exceed the length and width of the stage. The 6 o'clock option only disperses air to the area directly beneath the vents, so the stage would not be fully covered if this option was used. Therefore, the best option to use is the 5&7 o'clock option, which provides supply air to all corners of the stage.

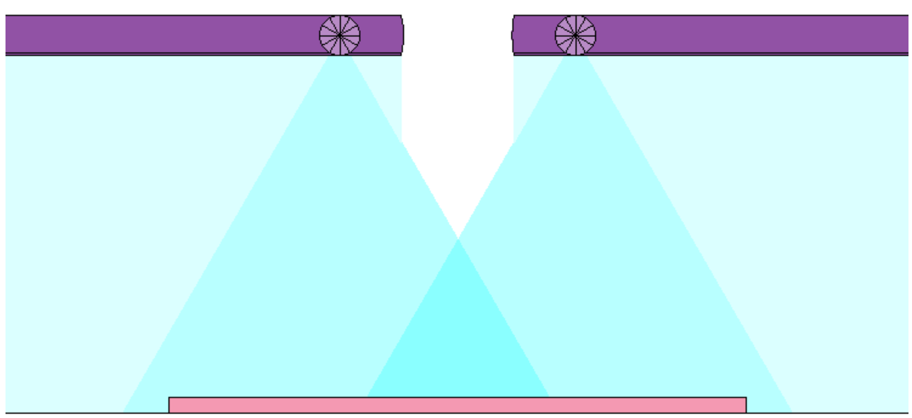


Figure 53: Air Dispersion of the Fabric Duct at 5&7 o'clock

Step 5: Suspension

Again, according to the DuctSox System Recommendation table (Table 21), the best type of suspension accessories to use in a theater are the galvanized cable and nylon snap clips. As stated before, there are four options for DuctSox suspension:

1. Tension Cable
2. 3x1 (4x2) Suspension
3. Suspended H-Track
4. Surface Mount

For this application, the 3x1 Hanger Suspension System is a good option since it provides the best aesthetics, smooth inflation, and easy installation. This suspension system requires that hangers be spaced every 36" along straight sections, 18" past the endcaps of any straight section, and that none be placed per transitions. This results in a total of (44) hangers at 31 1/16" wide to support the entire layout. Only one row of tension cable per branch is needed to suspend the hangers. This project would require 4 rows of cable; 2 at 43' long, 2 at 31' long, and 8 bracket supports.

3x1 Sizing Reference Table

Dia.	Width
16	18 7/8
18	20 11/16
20	22 3/8
22	24 1/16
24	25 13/16
26	27 5/8
28	29 5/16
30	31 1/16
32	32 3/4
34	34 1/2
36	36 7/16
38	38 3/16
40	39 7/8
42	41 5/8
44	43 5/16
46	45 1/8
48	46 13/16

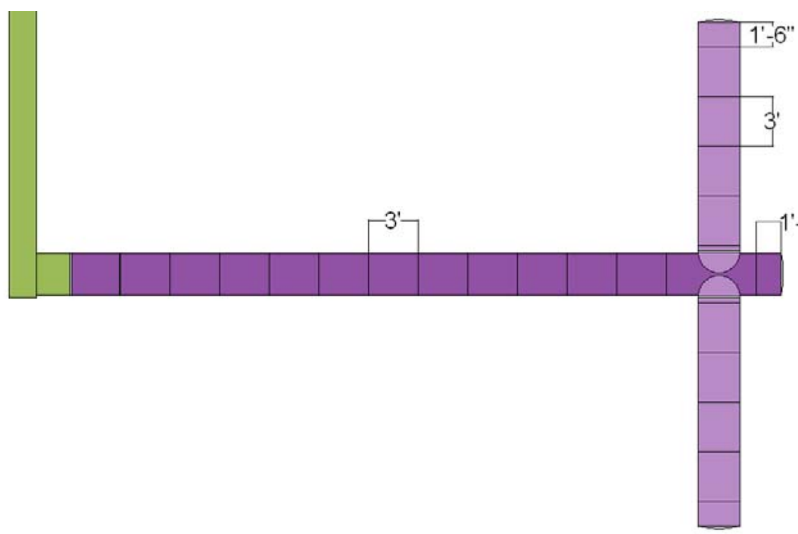
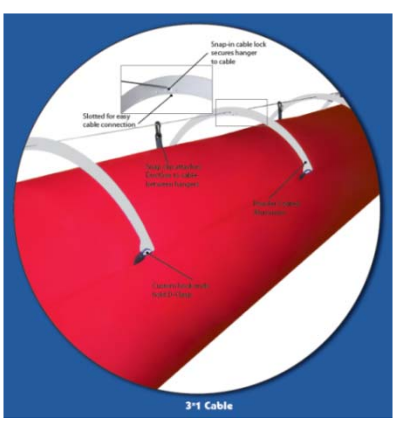
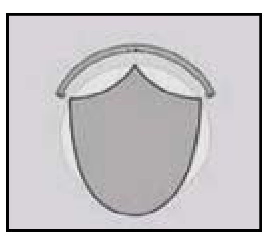


Figure 54: Size and Layout of the 3x1 Hangers

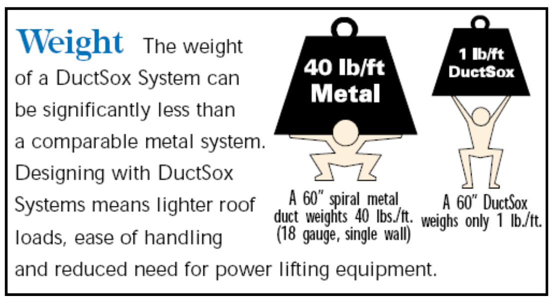




The 3x1 hanger also provides the least visual difference between inflation and deflation. When the fabric duct is deflated, the 3 suspension points make it appear as if it is 83% inflated. Then, once the duct becomes inflated, the transition is much faster and quieter since there is no "pop" associated with filling the duct with air as there often is when the duct is only supported by cables and snaps.

Benefits of using Fabric Duct

- Superior air dispersion
  - Discharge air uniformly along entire length of system
  - Provides consistent and uniform air dispersion to the occupied space
- Simple and easy installation
  - Simple suspension systems reduce installation time (about 90% less)
    - Hang cable
    - Attach DuctSox via 1 of 4 suspension options
    - Balance the duct
- Balancing
  - Little if any downstream from the inlet collar
- Lightweight
  - Fabric weighs much less than the conventional system
  - Lighter roof loads, ease of handling, and reduced need for power lifting equipment



According to DuctSox, 60" fabric duct weighs 1 lb/ft. Therefore, the 30" fabric duct that is being proposed for Arena Stage weighs approximately ½ lb/ft. With a total of 142 feet, the DuctSox design for the Fichandler stage weighs only 71 lbs!

- Shipping
  - Smaller and lighter packages
  - Reduces transportation costs and minimizes risk of damage
- Flexible
  - Will not dent or scratch like metal
- Quiet Air Delivery
  - Does not have resonating properties found in metal
  - Provides noise absorption benefits in the occupied space
- Air porous fabric
  - Air passing through eliminates risk of condensation and deflects air-borne dust from accumulating on surfaces
- Hygienic
  - Woven fabrics do not absorb moisture (bacteria and mold)
  - Antimicrobial treatments (on certain models) increase the hygienic benefit

Finding a Material Provider and Installer

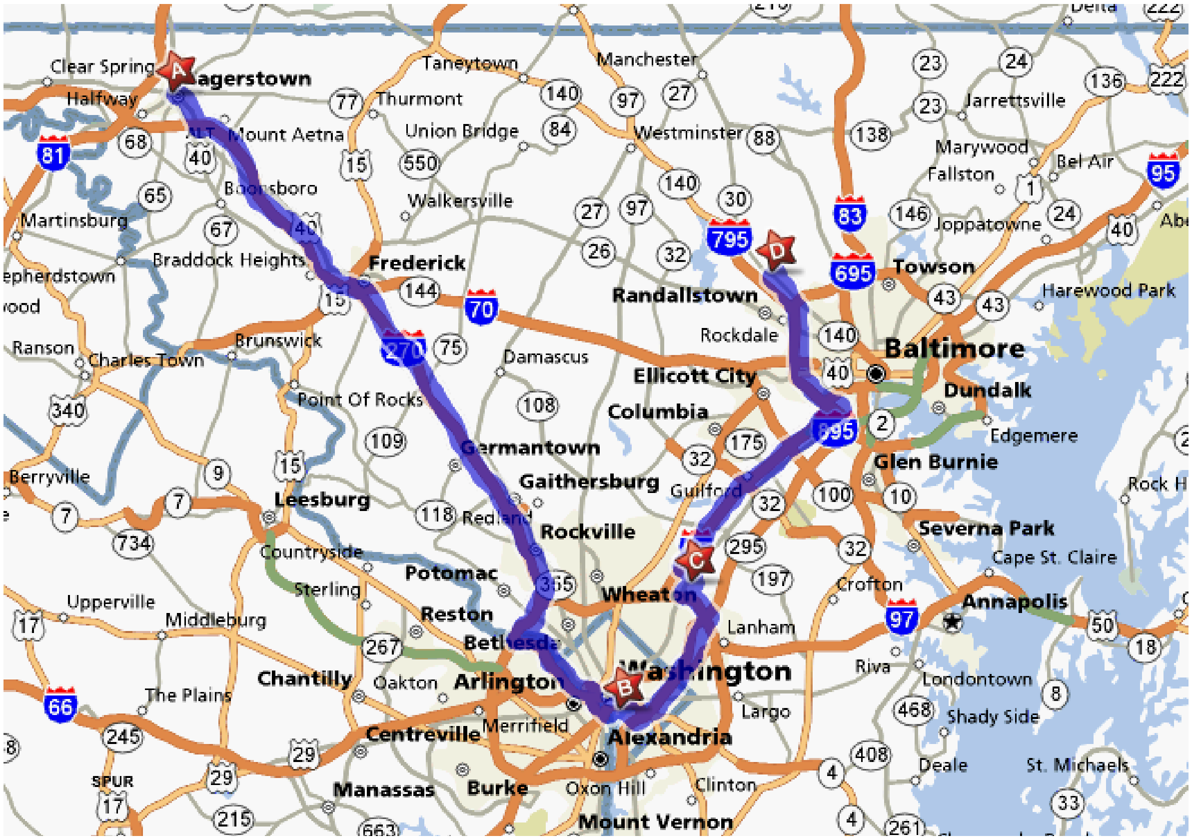


Figure 55: Map of DuctSox Material Providers and Installers

Figure 55 is a map that identifies companies that supply and install DuctSox. There are three companies that are within the close proximity to Arena Stage.

Table 23: DuctSox Providers and Installers

Label	Company	City	State	Distance from Arena Stage
A	Ward Boland	Hagerstown	MD	74 miles
B	**Arena Stage**	**Washington**	**DC**	–
C	C.G. Wood Company	Beltsville	MD	19 miles
D	Ward Boland	Owings Mills	MD	52 miles

As shown in Table 23, C.G. Wood Company is only 19 miles away from Arena Stage and would be an excellent company to contact if DuctSox was implemented in the Fichandler or anywhere else in the building.

COST AND SCHEDULE IMPACT

Sheet Metal Duct

The first component that needs to be considered is the amount of sheet metal duct that is still going to be a part of the Fichandler Stage mechanical system. It was previously determined that 186 LF of sheet metal duct was going to remain as a part of the ring duct which will feed air to the fabric duct. Using the information from before, ratios were used to determine the proper installation time and cost associated with the remaining 186 LF of sheet metal duct.

- Installation Time

Table 24: Installation Time of Remaining Sheet Metal Duct

Man Hours	Week(s)	Crew Size (men)
160	1	4

- Cost

Table 25: Cost of Remaining Sheet Metal Duct

	Unit	Multiplier	Expanded
Material	$28/LF	186 LF	$5,210
Labor	$57.68/hr (budgeted labor rate)	160 hrs	$9,230
Total Cost (to engineer, furnish, and install)			**$14,440**

DuctSox

Now, the impact that the DuctSox will have on the installation time and cost can be determined using information provided by DuctSox and C.G. Wood Company.

- Installation Time

Connecting the DuctSox to the inlet:

For an inlet diameter of 30", each inlet requires 0.75 man hours. Since there are (2) inlet locations, this results in **1.5 man hours**.

Hanging the Suspension System:

Since the 3x1 Hanger Suspension system requires a one-row cable, each straight section requires 2 base hours and 0.5 hrs for every 25' of length. Therefore:

43' long straight sections: 2 hrs + 0.86 hrs = 2.86 hrs
31' long straight sections: 2 hrs + 0.12 hrs = 2.12 hrs
Total: 4.98 hrs

A 10% increase needs to be added since the diameter is 30", making it 5.5 hrs. There are two of each length of straight sections, therefore the suspension system for the (4) straight runs is going to require approximately **11 man hours** to install.

Total:

It would take approximately **12.5 man hours** to install the entire DuctSox system.

Table 26: Installation Time of DuctSox

Man Hours	Day(s)	Crew Size (men)
12.5	1	2

- Cost

Table 27: Cost of DuctSox

	Item		Cost
Material	Duct and Fittings		$6,095
	Knee Braces and Bar Joist Angle Irons		$250
	Freight		$175
Labor	**Unit**	**Multiplier**	
	$72.50/hr (budgeted labor rate)	12.5 hrs	$907
Total Cost (to engineer, furnish, and install)			**$7,427**

Combined System

The combination of the sheet metal and the fabric duct system would result in the following installation time and cost:

- Installation Time
  Two separate crews would need to be used when installing this system because the sheet metal system would still be installed by Southland Industries, while the DuctSox system would be installed by C.G. Wood Company. Therefore, the two different crews could be working simultaneously.

Table 28: Total Installation Time of Proposed Mechanical System

	Man Hours	Week(s)	Crew Size (men)
Sheet Metal	160	1	4
DuctSox	12.5	0.2	2

- Cost

Table 29: Total Cost of Proposed Mechanical System

	Material	Labor
Sheet Metal	$5,210	$9,230
DuctSox	$6,520	$907
Combined	$11,730	$10,137
Total Cost (to engineer, furnish, and install)	**$21,867**	

- Comparison

Table 30: Direct Comparison of the Two Designs

Current Sheet Metal Design				New Design with DuctSox				
Duration			**Cost**	**Duration**				**Cost**
Man Hours	**Week(s)**	**Crew Size (men)**	**Total**	**Man Hours**	**Week(s)**	**Crew Sizes (men)**		**Total**
532	3	4	$47,990	172.5	1	4	2	$21,867

As shown in the tables above, the hybrid sheet metal-DuctSox system is estimated to take 2 weeks less than the current mechanical system and produce a total cost savings of $26,123, which is a 54% cost cut on the mechanical system.

CONCLUSION AND RECOMMENDATION

Implementing fabric duct in the Fichandler Theater is a practical decision. By reducing the current 3-sided bar slip sheet metal duct that makes up the ring duct and replacing the branch ducts with a DuctSox system, the objectives of this analysis were fully achieved. The difficult installation of the ring duct would be partially avoided since only half of the ring duct would have to be constructed. Similarly, the installation time of the entire system was reduced by 67% since the new system would only require a week to install by crews from both Southland Industries and C.G. Wood Company. It is convenient that several material providers and installers were located close to Arena Stage as well.

Cost wise, it would be a huge benefit for Arena Stage to implement fabric duct. The 54% cost savings achieved by using the proposed system is very attractive on a project like Arena Stage, which is only being funded by donations. Considering the fact that there are multiple locations in the complex that have the potential to use fabric duct in lieu of standard sheet metal, the Fichandler Stage is not the only area that could save them money. While $26,123 is not large percent of the overall cost of the project, it is an example of how a small adjustment to the mechanical system can significantly reduce the cost of individual systems.

DuctSox also provides many other benefits that sheet metal does not. The hinged air deflectors at the end of the branch ducts of the current system had the potential to make some noise while conditioning the space. DuctSox has quiet air delivery and can have some absorptive acoustical properties. Maintenance on the DuctSox system is going to be much easier as well. Not only is the system no longer going to be hidden behind the wood ceiling, but the 3x1 Suspension system is going to make cleaning and maintenance much easier. The D-clasp hooks that hold the fabric duct make its removal easy to take down, launder, and reconnect.

Arena Stage would definitely benefit from using the DuctSox system in the Fichandler Theater. By using the proposed system, it relieves two of the owner's primary concerns: cost and schedule. They are not willing to cut cost for quality, so DuctSox is an excellent solution. It provides excellent air distribution and also has aesthetic and environmental benefits. Similarly, Arena Stage wants the new building to be open in time for the 2010-2011 season, so finding small opportunities to reduce the project's schedule are of crucial importance. Switching the current mechanical system from standard sheet metal duct to fabric duct is a logical and advantageous choice for Arena Stage.

Figure 56: Hill Country Bible Church (Dallas, TX) from DuctSox

Summary and Closing Remarks

The results of the three analyses listed above proved that even small value engineering ideas can make a big difference on a project. While the proposed change to the curtain wall resulted in a significant redesign of the system, the concept of making a 4 degree slope reduce to 0 degrees is a relatively basic suggestion. It is not farfetched, nor does it take serious engineering intellect to understand how big of an impact it can make on such a large system. Applying a small, 6kW solar array was a means of testing how/if Arena Stage would benefit from the use of solar energy, even if it was on a much bigger scale. The modification to the Fichandler stage air distribution system was also a small scale representation of how fabric duct has the ability to make a big impact on the cost and schedule of the project.

Quantifying the results of all three analyses is the best way to understand how these ideas would influence Arena Stage. The table below shows the total cost of Arena Stage if all three analyses ideas were to be implemented:

Table 31: Total Cost Impact of the Analyses

Cost Impact of Analyses	
Total Cost of Arena Stage	$125,000,000
Analysis I: Curtain Wall	(–) $1,174,600
Analysis II: PV System (including incentives)	(+) $25,409
Analysis III: Mechanical	(–) $21,867
Total Cost of Arena Stage with Proposed Ideas	**$123,828,942**

A total cost savings of $1,196,467 was achieved, but with the addition of the PV panels, it is reduced to $1,171,058. Although the results of the solar analysis resulted in a recommendation to not utilize the system, this shows that if the owner did decide to consider a PV array, he could use the money that was saved through the curtain wall and mechanical system adjustments.

Similarly, the calculated schedule impact is shown below in the form of durations:

Table 32: Total Schedule Impact of Analyses I and III

Schedule Impact of Analyses I and III	
Analysis I: Curtain Wall	(–) 66.5 days
Analysis III: Mechanical	(–) 10 days
Total Schedule Reduction with Proposed Ideas	**76.5 days**

The schedule could be reduced by 76.5 days if the curtain wall was straightened and if fabric duct was used in the Fichandler Theater. A schedule investigation was not done for the solar analysis because after a cost analysis was completed, it was not recommended as a favorable upgrade for Arena Stage. However, the other two analyses offer a 2.5 month schedule reduction, which would be a huge push toward the completion of the project. The project could potentially finish early, which would give the owner more time to prepare for a grand opening of the theater for the 2010-2011 season.

The main goal of this thesis was to suggest solutions that would enhance Arena Stage without losing any quality in the outcome of the building. This was done through value engineering ideas that not only cut cost and reduced the construction schedule, but that also increased constructability. It was important that the analyses were realistic, lucrative, and attractive to the owner. The curtain wall analysis and the mechanical analysis were strictly design based, while the solar analysis was seen as a method to put Arena Stage on the map as an energy conscious building. While it ended up costing more money and adding time to the schedule, it's a potential way to attract donors, which is how Arena Stage had the ability to undergo renovation in the first place. Both the mechanical and solar analyses could be expanded to a large scale application. Fabric duct could be used in all high ceiling locations in the building, such as the lobby and other theater spaces. Using it in multiple locations could end up saving Arena Stage more time and money. Similarly, a much larger solar PV array could be designed to provide more than 6kW of energy to the building. A different design may prove to be more realistic with relation to cost and payback period.

This thesis has helped me realize that I have learned a lot from the Architectural Engineering program in the last 4 years and I am pleased with the outcome of this document. The analyses that I chose to perform were of personal interest to me, making it enjoyable to complete. This thesis also further enhanced my belief that communication is the most crucial ingredient in construction. Without the help of the people mentioned in my Acknowledgements, my understanding of this project from a construction standpoint would have been severely lacking. I want to thank them again for taking the time to educate me about this amazing building and wish them the best of luck on completing the project.