AEI Student Design Competition 2016

Structural Group I - Concrete Design

Major Qualifying Project

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AEI Student Design Competition

A Major Qualifying Project

Submitted to the Faculty of

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in

Architectural Engineering

By

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Date: 3/4/2016

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Abstract

This project is based on the 2016 Architectural Engineering Institute Student Design Competition. The proposal is a new structural design for the building that is being constructed on 888 Boylston Street, Boston. With the help of software tools and various design methods, the team worked on designing the architectural, structural, and integrated systems of a LEED certified building with a near net zero output of energy, emission, water, and waste. The project addresses the engineering challenges involved in high-rise building design, specifically through the use of a concrete slab structure called Bubbledeck, as well as construction planning, energy efficiency, adaptability, and resiliency.

Acknowledgements

We would like to thank the Architectural Engineering Institute for hosting the student design competition and providing this opportunity for students to gain real-world experience in the engineering field. We would like to thank Worcester Polytechnic Institute for allowing us the opportunity to enter into the competition, and for supplying the software and references necessary to complete the project. Finally, we would like to thank our advisors, Professor Leonard D. Albano and Professor Leffi E. Cewe-Malloy, who oversaw our work and offered their expert advice along the way. Much appreciation and thanks goes to Professors Steven Van Dessel, Kenneth Elovitz, Clyde Robinson, and John Sullivan for all of your advice, guidance and commitment to this project. We would also like to thank PES Structural Engineers, Bubbledeck North America, and BL Companies industry professionals who assisted us with their expertise.

Authorship

All members of the team contributed equally to the completion of this Major Qualifying Project in Architectural Engineering. Every member was responsible for a portion of written work and calculations, and for editing and formatting the final report. Each student's individual tasks are detailed below:

Caroline Bartlett

- Preliminary research on lateral load systems,
- Preliminary design of a concrete column system including layout, calculations, and sizing,
- Preliminary modeling in Bentley RAM and Autodesk Robot,
- Design of shear wall system,
- Design of building envelope system and connection details between curtain wall and slab edge,
- Assisted with architectural and lighting designs.

Andrea Goldstein

- Design and detailing of the building's foundation,
- Flood protection research and other hazard mitigation options for building resiliency,
- Working on the central Revit model, placing, creating, and editing objects to create architectural renderings,
- Research on the sustainability and constructability of concrete compared to steel in construction.

Ali Yalaz

- Preliminary research on slab systems,
- Preliminary research on,
- Design and analysis of the structural model,
- Design of Bubbledeck structure,
- Redesign of the architectural layout of office and retail floors,
- Assisted with the design of building envelope systems.

Capstone Design Statement

This Major Qualifying Project demonstrates the application of academic coursework to realistic engineering practices. The use of engineering theory and practice was a key factor in the development of this project. The capstone design requirement of the MQP was met through the proposal of an alternate design of the multi-story, mixed-use building located at 888 Boylston Street in Boston, Massachusetts. The new design focuses on the integration of the structural, mechanical, and architectural systems of the building with a focus on resiliency, sustainability, and limiting the impact to the building's surroundings. The main goal of the project was to achieve a sustainable, innovative and cost beneficial solution for this building. Throughout the design process, realistic constraints were considered in various aspects of the project, including economics, constructability, social impact, environmental impact and sustainability, and safety and politics. These considerations are described in greater detail below.

Economic

In addition to designing 888 Boylston Street to be as sustainable and resilient as possible, the economic impact of the building was also taken into consideration. Local materials were selected, which reduced the time and cost of transportation. Construction methods were streamlined to ensure that the building could be built as efficiently as possible. Where possible, economically advantageous materials were selected over other options, such as the innovative Bubbledeck slab system and the use of sustainable concrete. Another measurement taken in order to reduce the project duration was the selection of prefabricated systems where possible, such as the Bubbledeck system and the unitized curtain wall system chosen for the curtain wall, which decreases the installation time and number of workers required.

Constructability

As a requirement of the competition, the impact of the construction of 888 Boylston Street on the surrounding buildings and infrastructure was taken into consideration. The site is located in the urban setting of downtown Boston; therefore, the design efforts were directed at minimizing the impact the building would have on the surroundings. The space needed for staging areas was minimized in the site logistics considerations, and prefabricated systems were chosen wherever possible.

Sustainability

The new design for 888 Boylston Street incorporates resilient and sustainable elements that can qualify towards LEED Platinum accreditation. The design incorporates PV panels, storm water and greywater reuse systems, high efficiency fixtures, and wind turbines. In addition, green spaces are included in the design of each office floor of the building to increase the indoor air quality and make the space more enjoyable for occupants.

Safety and Politics

The safety and political considerations were comprised throughout several aspect of the project. One of them was safety during construction. Through the site plan developed, the effects of the construction project on the surroundings were minimized by placing chain link fences around the perimeter of the property during the construction phase. The plan also separated the construction area from the existing buildings and adjacent dwelling. In addition, the *International Building Code*, American Institute of Steel Construction (AISC) *Code of Standard Practice*, American Concrete Institute (ACI) 318 *Building Code Requirements for Structural Concrete*, the *Massachusetts Building Code*, and *780 CMR: Massachusetts Amendments to the International Building Cod*e were used in the design of this building.

Executive Summary

This year's Architectural Engineering Institute (AEI) student design competition required a team of students to submit design solutions for a new 17 story multiuse building in Boston, Massachusetts. The goal for the competition is to create an innovative, integrated, and original solution for the building based off of initial plans given by the organization.

WPI organized a team of nine students to work on completing a submission competition. In addition to Building Integration, there are a four additional disciplines that each team has the option to submit designs for; Structural Systems, Mechanical Systems, Electrical Systems, and Construction Development. All nine students worked together to create the submittals for each discipline and followed AEI's strict guidelines for the report. Unfortunately, the team was not selected as finalists to present at the 2016 AEI Forum.

The WPI team submitted design ideas for the Integration, Structural, and Mechanical categories. The students were divided into three MQP groups of three students each based on their main focus for research and design. There was one mechanical focused team, and two structural focused team. The following report explains the results of one of the structural teams that focused primarily on the concrete based systems such as the shear wall, foundation, and floor slab. In addition, each of the three members did additional research on the integration category in collaboration with members from the two other MQP groups. Therefore, some of the information found in this report may overlap or reference ideas further developed in one of other documents.

The team developed the following goals to complete over the course of this project:

- Envelope Design
- Architectural Design
- Resiliency
- Sustainability

To achieve these goals, the following design solutions were developed:

Slab Structure

888 Boylston Street adopts the Bubbledeck reinforced concrete structure as the overall slab system. The Bubbledeck floor system is one of the most innovative features in the structural design of 888 Boylston Street. The criteria for choosing the most suitable floor system consisted of providing a minimum, clear, two-way slab span of 60 feet in both retail and office areas; integrating structural and mechanical systems to be able to create an additional floor as requested by the resiliency team; minimizing disturbance of the neighboring buildings and the inhabitants; and achieving cost efficiency.

Lateral Load Resisting System

In order to resist lateral loads, the team decided to use a reinforced concrete shear wall around the core of the building. Other options considered included steel bracing (eliminated as an option once the Bubbledeck was chosen), and an exterior shear wall (eliminated as an option due to the decision to enclose the building with a curtain wall). However, the footprint of the existing shear wall was changed to accommodate changes to the architectural design of the building. The proposed footprint is depicted in Figure XX.

Foundation

The foundation design for 888 Boylston Street had a lot of considerations to take into account such as the impact on the adjoining buildings and the interstate tunnel running under a portion of the building as well as supporting the large loads that the building produces. Drilled Shafts were chosen as the solution because of the minimal disturbance they posed to the foundations of the buildings next to it. A total of forty drilled shafts are needed at each column location in the parking garage, 80% of these have a 6ft. diameter while the remaining 20% need an 8ft. diameter to accommodate a larger capacity.

Building Envelope System

The façade of a building plays an important role in the building's function, in that it controls the flow of air, moisture, hear, and vapor between the interior of the building and the exterior environment. It also plays an important aesthetic role, in that it is the first thing that distinguishes one building from another to the public eye; therefore the facade must be aesthetically pleasing and must complement the architecture and surroundings of the building.

For the envelope, the team chose to use a unitized curtain wall system, which is a factory-assembled and factory glazed system shipped in units to the job site in custom built A-frame racks, facilitating unloading, hoisting, and distribution onsite. Once on site, the units are hung onto an edge-of-slab rail that is anchored with T-bolts into cast-in-channels that are pre-mounted onto the Bubbledeck at the factory. The entire process is designed to expedite installation and to minimize every aspect of onsite labor. Since a shorter construction schedule was a goal of the project, this system best met the team's requirements. It is widely used for high-rise building applications.

Architectural Layout

The architectural layouts of the interior and exterior spaces were redesigned according to the new structural and mechanical systems adopted by the building.

Office Floor

The layout of the typical floors was redesigned taking into account productivity elements, circulation, daylighting and indoor air quality, to achieve a tenant-friendly, highly productive office space. In order to utilize the daylight in the most efficient way, all the enclosed rooms are gathered around the central core area and provide open space around the perimeter of the open office area.

Front Plaza

The front plaza is a very important feature of the building, in that it conveys the ideology of the building to those passing by. Therefore, it was necessary to design a front plaza that properly reflects the sustainable features of the building to the general public. The plaza will feature various native vegetation such as Eastern Redbud, sweetgums, and black birch. It is important to use native plants to minimize the maintenance and reduce irrigation requirements. The planting areas will be surrounded by monumental seating areas made of concrete and welded steel to allow artists to engage with the public in different ways. The walkways through the plaza will be comprised of walkable PV panel grids provided by Onyx Solar Group to reflect the energy efficiency and sensitivity of the building. The area in front of the restaurant is reserved for outdoor seating that can fit 18 tables without compromising the building circulation.

Resiliency

One of the major goals of this project was to design a building that would be resilient to any major hazards that are likely for its location. For 888 Boylston Street, the biggest threat is water damage due to flooding. Floodgates are installed around the exterior of the building by the plaza to prevent any water from getting to the building. These floodgates are normally flush with the ground level, however water is detected, they automatically raise up to 90 degrees to prevent up to 3ft. of water from getting to the building. These floodgates do not require any source of power or human interaction to operate, making them an ideal solution.

However, if any water does get into the building, the critical electrical and mechanical systems would not be affected because they have been relocated from the below ground parking garage to an additional floor. This new floor is located between the office floors and the retail floors. This floor was made possible due to the use of the Bubbledeck system because it minimized the required floor to floor height, allowing an additional floor to be added without adding to the overall original height of the building.

Sustainable Features

In order to provide an environmental friendly and sustainable building, 888 Boylston Street proposes several sustainable features such as:

- Greywater filtration
- PV panels
- Wind turbines
- Green gardens
- Bike storage and sharing
- Water efficient fixtures

1.0 Introduction

The Architectural Engineering Institute's Student Design Competition is an annual competition that brings Architectural Engineering program from universities in the US together to test their skills of design and problem solving. This year's competition subject is a high-rise, multipurpose building in downtown Boston area. The building has two garage floors, 3 retails floors that houses retail stores, food court and a restaurant, and 14 office floors (34,000 SF each). Additional to the interior spaces, the building has a front and rear plaza that are open to public access and aiming to be the gathering point of the citizens. The students were given relevant material regarding the structural, mechanical, and the architectural information for the building and asked to improve the current design considering several challenges. The challenges that the students were asked to address in this year's competition were:

1. Sustainable design and construction
2. Provide resiliency with respect to local environmental considerations
3. Consider integration and impact on adjoining structures and public ways.[1]

Design Goals

For the purpose of the competition, this MQP team was one of three teams that comprised a larger team of nine members who each worked on multiple different components of the building. This MQP team focused on the concrete structural elements of the building as well as several other features such as architectural design, building envelope, resiliency precautions, and sustainability features. The goals of this report were decided not only considering the focus of this report, but also the goals decided for the AEI student design project as a whole.

The AEI Student Design Competition guidelines provided three major design concepts: sustainability, resiliency, and constructability. From these concepts, the following design goals were developed to ensure maximum building performance:

- Achieve a structural design that successfully integrates the structural, mechanical, and electrical elements with the architectural systems in order to create an integrated design.

[1] Architectural Engineering Institute. "2016 Project Guidelines." *ASCE Charles Pankow Foundation, Annual Architectural Engineering Student Competition*. Architectural Engineering Institute, n.d. Web. 23 Mar. 2016.

- Select design and construction methods that minimize the disturbances to neighboring buildings and the Massachusetts Turnpike.
- Plan site logistics in a way that will successfully coordinate the construction phase without negatively affecting the local environment.
- Design a structure that, in addition to resisting gravity loads, will be able to resist design wind loads, which is an important consideration in the City of Boston.
- Design every aspect of the building sustainably.
- Design all aspects of the building, including the building envelope, to contribute to an overall building energy usage that is at least 50% below ASHRAE requirements.

As stated before, the members of this MQP team worked with six other students for the AEI Student Design Competition. As well as the structural systems, each member worked on several other topics. On top of the structural system, the report presents the background, methodology, and results of each topic. These topics include:

- Envelope Design
- Architectural Design
- Resiliency
- Sustainability

The following section includes the research process of the relevant structural and other building systems that the team decided to adopt. The methodology section includes engineering work related to the design process of structural systems, sustainability features and architectural layouts that were mentioned in the background section. The results section provides the final designs of each structural systems discussed in the report, the architectural designs of the retail and office spaces, and energy production information regarding the on-site energy features and other sustainability features.

2.0 Background

The background chapter provides an overview to the building that is being redesigned and background information necessary for the design of the systems that are mentioned. The informational section includes static information essential to the project execution, and the options that were considered before deciding on the best possible option.

2.1 Structural Design Decisions

In general, high-rise buildings consist of steel, concrete or a system that combines both of these construction materials. The design of high-rise buildings includes structural systems to resist gravity and lateral loads. While deciding on the structural systems that will be used in the building, there were several considerations that were taken into account, such as the purposes of the interior spaces, the wind and seismic loads, and the geological features of the site. Even though the structural factors were given the first priority for making decisions regarding the usage of appropriate systems, environmental factors such as sustainability were also a concern in the decision making process. There are several other specific considerations in the decision process for the systems to be used, which will be furthermore discussed in the related sections.

2.2 Structural Systems

The subsystems of a building that aim to resist the expected loads are referred to as “structural systems”. These structural systems are broken into two categories according to the type of loads that they are resisting: gravity load systems and lateral load systems. These systems are specifically designed to resist certain loads acting on certain axes, and for this reason the systems that are related with these loads have to be specifically designed to behave in those axes. The lateral load systems are mainly directed at the wind and seismic loads, while the dead and live load acting in a vertical direction are the main concern for the gravity load systems.

2.2.1 Gravity Load Systems

There are four systems that are designed to resist the gravity loads acting on the structure, which are floor system, foundation system, walls, and columns. As the names suggests, the floor systems are the floor areas in the buildings. Their purposes are creating a dead load resisting element and providing useful flat area.

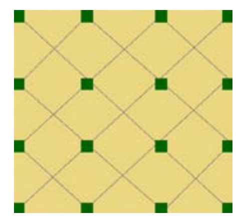
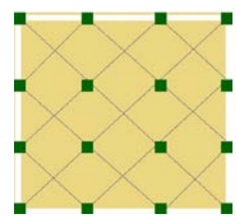
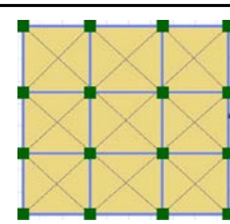
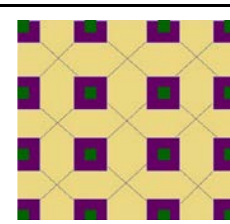
Floor Systems

The purpose of the floor system is to resist the dead and live loads acting on the building. The main concerns in deciding on the proper floor system can be listed as:

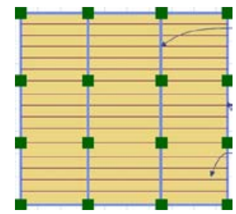
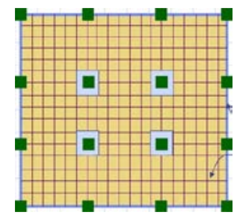
- Magnitude of the design loads
- Span lengths and bay size
- Aesthetics

The table below is the summary of the floor systems that were investigated in the process of selecting the proper system for the proposed 17-story building. The decision was made according to the results gathered in the table.

Table 1: Common Floor Systems Used in Buildings[2]

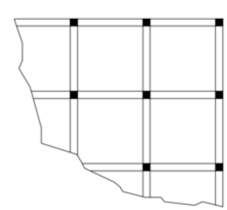
Type	Advantage	Use	Diagram
Flat Plate	-Simple Construction -Flat Ceilings (reduced finishing costs) -Low story heights due to shallow floors	Short-medium spans with light loading	
Flat Plate w/ Spandrel Beam	Same as flat plate, plus -Increased gravity & lateral load resistance -Increased torsional resistance -Decreased slab edge displacements	Short-medium spans with light loading	
Flat Plate w/ Beams	-Increased gravity & lateral load resistance -Simple Construction -Flat Ceilings (reduced finishing costs)	Medium spans with light loading	
Flat Plate w/ Drop Panels	-Reduced slab displacements -Increased slab shear resistance -Relatively flat ceilings -Low story heights due to shallow floors	Medium spans with moderate to heavy loading	

[2] Sandt, Edward, Dr. "Structural Concrete Design." CVEN 444. Texas A&M, College Station. *Slideshare*. Web. 6 Oct. 2015. <http://www.slideshare.net/gloryglow/structural-system-overview>.

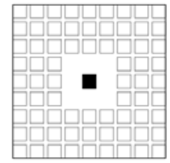
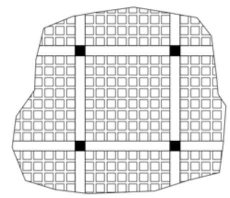
One-Way Joist	-Longer spans with heavy loads -Reduced dead load due to voids -Electrical, mechanical can be placed between voids -Good vibration resistance	Medium-long spans with heavy loading	
Two-Way Joist	-Longer spans with heavy loads -Reduced dead load due to voids -Electrical, mechanical can be placed in voids -Good vibration resistance -Aesthetic look	Long spans with heavy loading	

In the table above, the most important feature that was considered was the provided span length and the magnitude of load that can be supported. The best possible option from the list was two-way joist system. Two-way joist systems also break down into several categories on their own. These are two-way edge-supported slab systems, waffle slabs, and two-way edge-supported ribbed slab systems. The table below presents the descriptions and a graphical representation of each type of two-way joist system.

Table 2: Summary of Two-way Slabs[3]

	Type	Description	Figure
	Two-way Edge-supported Slab	o The overall slab thickness is greater because beams project downward, thus the system becomes inflexible in terms of mechanical layout. o Economical for spans up to 7.0 meters.	

[3] *TWO-WAY SLABS* (2007): n. pag. *Iugaza.edu*. Web. 13 Oct. 2015. <http://site.iugaza.edu.ps/sshihada/files/2012/09/Slabs-11.pdf>.

Two-way Ribbed Slab	**Waffle Slab**	o Provides the largest spans of the conventional concrete floor systems and can be economically used for spans up to 12.0 meters.	
	Two-way Edge-supported ribbed Slab	o This system can be economically used for spans up to 7.0 meters. o It is similar to the waffle slab but the voids between ribs are filled with hollow blocks. o Hidden or drop beams can be used with this system depending on their spans.	

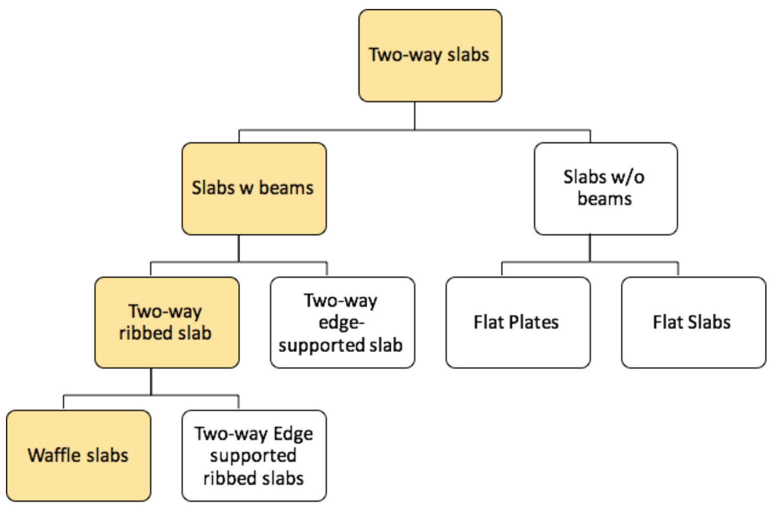


Figure 1: Preliminary Decision making for Floor System Selection

The current design of the office and retail areas contains large open spaces with only a core in the middle around the elevator shafts as the only structural component in between two columns with the longest span. Since the new architectural design will also require large spans due to the function of the office and retail spaces, the floor systems with large spans were preferred. Besides the span length, the load that the systems can be resisting was an important factor since the type of building that is being addressed is a high-rise office building with large dead and live load acting on it. These two factors left two possible floor systems that fits the requirements: One-way joist floor system and two-way joist floor system. The characteristics of both of these systems are highly similar, but in fact the two-way joist systems are able to provide a longer span in between columns, which is highly valuable for the architectural design of the building.

Table 3: In-depth analysis of the Waffle Slabs[4]

ADVANTAGES	DISADVANTAGES
Savings on weight and materials	Depth of slab between the ribs may control the fire rating
Long Spans	Requires special or proprietary formwork
Economical when reusable formwork pans used	Greater floor-to-floor height
Vertical penetrations in slab sections between ribs are easy	Large vertical penetrations are more difficult to handle

As a result, waffle slabs were decided to be the best system for this particular building. Narrowing down the options to waffle slabs was helpful but the type of waffle slab systems was still to be determined. Figure 2 is the graphical representation of the two different kinds of waffle slabs that are available.

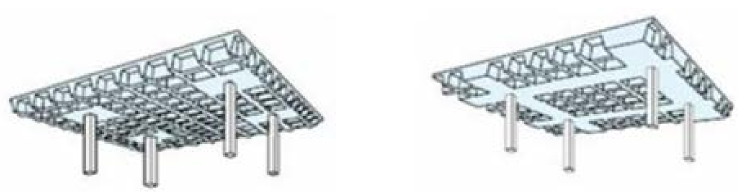


Figure 2: Waffle Slab with Solid Heads (left), Waffle Slab with Band Beams (right) [2]

The factor that differentiates these two different waffle slabs is the live load that they can resist. Compared to solid heads, band beam design is optimal for highly varying live loads. In the case of 888 Boylston, the floors above the fifth floor are utilized as office spaces, which are less likely to encounter highly varying live load patterns. At the same time, for same span length, it is found that the total cost of

[4] Cornell, Matt. "Beware Waffle Slabs." *Cornell Engineers*. N.p., 16 Apr. 2014. Web. 13 Oct. 2015. <https://www.cornellengineers.com.au/beware-waffle-slabs/>.

waffle slab with band beams along columns centerlines is (10%--12%) higher than the total cost of waffle slab with solid heads.[5] For these reasons, waffle slabs with solid heads were decided to be used.

The preliminary design of the waffle slab was done using several design aid materials. The table in *the Architect's Studio Companion* was used in order to determine an estimated slab thickness that could be used with the given column layout. Figure below represents the estimated slab thickness for the 60 feet span, which is the maximum span that is encountered in the office and retail areas.

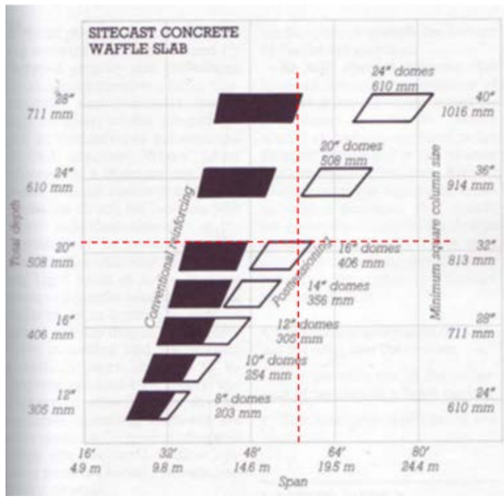


Figure 3: Site cast concrete waffle slab design chart[6]

The chart above states that the suitable waffle slab thickness for the span of 60 feet is roughly 21-22". The integration of the waffle slab and the MEP systems are challenging due to small sized ribs. The preliminary depth of the design of MEP systems acquired from the mechanical team was 2'10" and this led to a total minimum thickness of 4' (slab + MEP systems). One of the major goals of the structural system was to design a slab system that can be highly integrated with the MEP systems and also provide a lower floor to floor height due to the possible additional floor idea that was proposed by the mechanical team.

The fact that waffle slab was not able to provide the design a thinner slab and integration options, the team decided to search for an alternative design. The new criterion determined for the slab design were:

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[5] Galeb, Alaa C., and Zainab F. Atiyah. "Optimum Design of Reinforced concrete waffle slabs." *International Journal of Civil and Structural Engineering* 1.4 (2011): n. pag. Web. 29 Sept. 2015.

[6] Allen, Edward, and Joseph Iano. *The Architect's Studio Companion: Rules of Thumb for Preliminary Design*. 5th ed. Hoboken, NJ: John Wiley & Sons, 2012. Print.

- Low floor to floor height
- Smaller depth
- Integration options
- Cost efficiency
- Sustainability

After doing further research to find an alternative slab system, the team came across a relatively new system. This slab system is called "Bubbledeck". It is a biaxial concrete slab that houses hollow high density polyethylene (HDPE) spheres to replace the concrete in the areas falling in between the columns that are not structurally supporting the gravity loads.

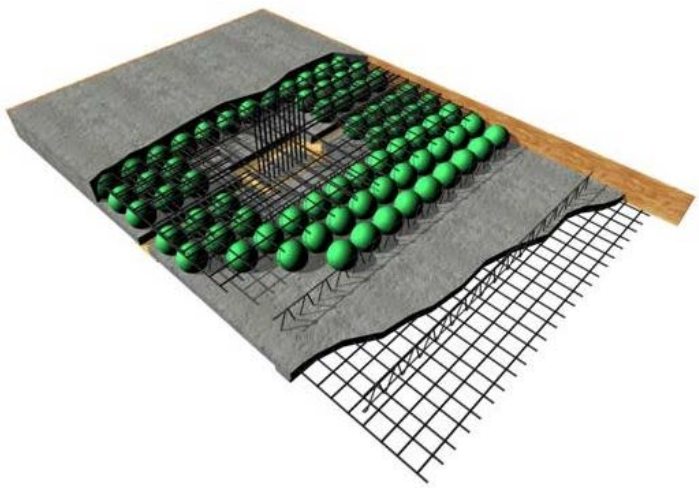


Figure 4: Representation of the components of a typical Bubbledeck system[7]

Bubbledeck consists of concrete, reinforcement steel and HDPE spheres. The slab is considered a semi-precast structure due to the fact that the bottom concrete panel, placement of the spheres and the reinforcement bars are completed in a factory environment.

Concrete: The concrete part of the slab is either standard Portland cement or structurally sufficient substitute with a maximum aggregate size of ¾ inches.

Plastic hollow spheres: The hollow spheres are made up of high density polyethylene. As well as the HDPE, recycled plastics can be used for the same purpose in order to reduce cost and minimize the environmental impact.

[7] "Perth Precast." *Bubbledeck*. Precast Australia, n.d. Web. 23 Mar. 2016.

Steel: The concrete slab includes reinforcement bars of Grade Fy60 or higher. Two layers of meshes are created for lateral support. The bubbles are vertically supported with the help of diagonal girders running alongside.

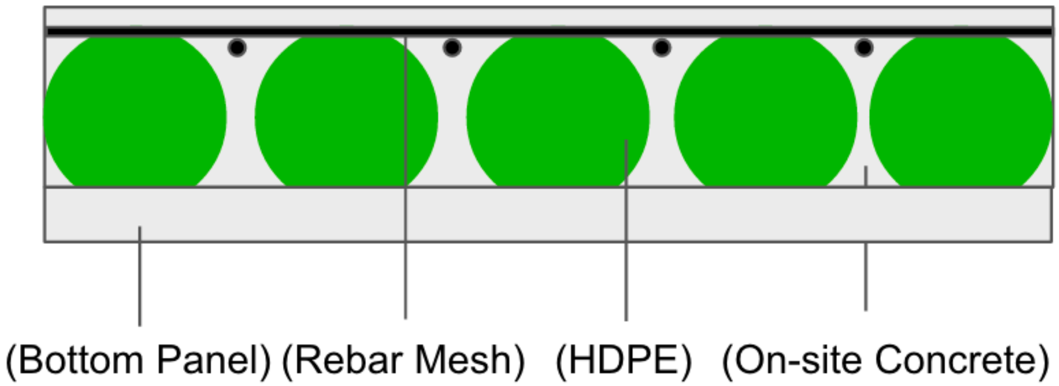


Figure 5: Bubbledeck Components

Once the panels are brought to the construction site, they are placed in place with shores that temporarily support the slabs during the installation of HVAC components, formation of edge formwork for concrete, and on-site concrete casting. The top panel of the concrete slab is responsible for resisting the flexural compression forces acting on the slab, and the rebar mesh placed at the bottom panel is responsible for the flexural tension forces acting on the structure. This feature is important in order to determine the reinforcement required to support the concrete slab.

Figure 6: Bubbledeck in factory setting
**courtesy of Bubbledeck North America*

The structural specifications of the slab are different from the traditional solid concrete slab due to its unique structural components. In order to be used for the design and make cost and performance comparisons with other slab systems, the structural characteristics of the Bubbledeck are presented in the following subsection.

Bending Stiffness and Deflection

The usage of hollow plastic spheres in the middle sections of the concrete slab allows the system to avoid using significant volume of unnecessary concrete. In concrete slabs, the depth of the section that undergoes flexural compressive forces is relatively very low.[8] This section that is affected by compression falls between the plastic bubbles and the panel surface, which is filled with solid concrete and reinforcement bars. For this reason, the behavior of the Bubbledeck system is same as a solid slab in this subject.

Table 4: Comparison of bending strength of Bubbledeck and solid concrete slab[9]

*In % of a **solid** deck*	**BubbleDeck vs. solid deck**		
	Same strength	Same bending stiffness	Same concrete volume
Strength	*100*	105	150 *
Bending stiffness	87	*100*	300
Volume of concrete	66	69	*100*

* On the condition of the same amount of steel. The concrete it self has 220 % greater effect.

Shear Strength

The shear strength of the slab is dependent on the volume of concrete used. Since the hollow spheres are being used in certain areas of the slab, the shear strength of these particular areas is lower than the shear capacity of the solid slab areas, which happen to be the area around the columns. The test data gathered for the shear capacity values of a Bubbledeck and a solid slab is shown below for comparison. In Table 4 Comparison of bending strength of Bubbledeck and solid concrete slab, the Bubbledeck capacity is presented as a percentage of that for the solid slab.

The highest shear observed in the slab structure is in the areas where column are connecting to the slab. In order to avoid any failure in these areas of the slab, these areas are designed as solid slabs or the number of voids used will be decreased. Applied shears will be determined in these areas and

[8] Martina Schnellenbach-Held and Karsten Pfeffer,"Punching behavior of biaxial hollow slabs" Cement and Concrete Composites, Volume 24,Issue 6, Pages 551-556,December 2002
[9] Sergiu Călin, Roxana Gînţu and Gabriela Dascălu, "Summary of tests and studies done abroad on the Bubbledeck slab system", The Buletinul Institutului Politehnic din Iaşi, t. LV (LIX), f. 3, 2009.

according to its relation with the shear capacity of the slab with the certain depth and dimensions, the size of the solid slab are will be determined.

Table 5: Comparison of shear capacity in girders with solid deck and Bubbledeck slab[10]

Shear capacity (in % of solid deck)	a/d=2.15	a/d=3
Solid deck	100	100
Bubble deck, secured girders	91	78 (81)*
Bubble deck, loose girders	77	
*Corrected for test elements with longer time for hardening		

Punching Shear

Due to the critical relation between the slab and the column in the connection area of the flat plate slab systems, punching shear is an important concern. Once the shear check is completed, additional reinforcement may be required in the column connection areas. The design of the connection area for punching shear can be seen in Figure 7: Bubbledeck column-slab connection area.

Figure 7: Bubbledeck column-slab connection area[11]

Integration

[10] Sergiu Călin, Roxana Gînţu and Gabriela Dascălu, "Summary of tests and studies done abroad on the Bubbledeck slab system", The Buletinul Institutului Politehnic din Iaşi, t. LV (LIX), f. 3, 2009.
[11] University of Sheifield. "Information Commons." *Construction 8*. University of Sheifield, n.d. Web. 23 Mar. 2016.

The physical integration of the MEP system within the thickness o the slab is highly possible with the Bubbledeck. Heating/ Cooling and electrical components of the systems can be laid out through the slab in the spaces between the plastic spheres. First step is to cut openings in the bottom mesh that are approximately 1" apart on all sides of the equipment (This procedure is done in the factory setting before the bottom panel concrete is casted). Once the mesh is open, the supplemental steel is added following the simple rule of "one new rebar for every bar cut". The development length of each bar is determined by a number of factors but principally by the size of the opening and the size of the positive moment steel. The figure below represents the radiant floor system being prepared to be integrated into the reinforcement mesh that will be created on the Bubbledeck panels.

Figure 8: Radiant heating and cooling system implemented in the factory setting
**courtesy of Bubbledeck North America*

Similar to the HVAC systems, it is possible to construct the electrical cables and equipment into the Bubbledeck.

Figure 9: Integrated electrical system to the in the Bubbledeck before the onsite concrete is casted.
**courtesy of Bubbledeck North America*

The important factor in the integration of MEP systems into the Bubbledeck slab is the volume of concrete that will be removed in order to place large ductworks. The shear capacity of the slab is decreased down to 60% compared to the capacity of a solid slab with the same thickness, and any additional loss in the capacity can lead to failure in the structure.

Cost

The unique features of the Bubbledeck allow the consumers to save money on several aspects of the construction. The hollow plastic spheres result in decrease in the weight and materials which results in lower transportation costs and lower cost of building frame elements since the overall dead load of the slab is decreased when it is compared to a solid slab. As a result of decreased on-site concrete placement, field labor cost is decreased and the construction time is less, which results in lower overhead costs.

Sustainability

The usage of Bubbledeck has direct and indirect impacts on the sustainability aspect. The usage of hollow spheres results in a significant reduction in the amount of concrete. To estimate on the impact of usage of less concrete, one can investigate a 54,000 ft^2 Bubbledeck. Compared to a solid concrete slab with the same dimensions, with the Bubbledeck it is possible to save up 35,000ft^3 of onsite concrete, 166 ready-mix cement truck trips, 1,798 tons of foundation loads (due to the fact that the structural dead load of the building decreases with the Bubbledeck), 1,745 GJ energy that would have been used in order to prepare the solid slab, and 287 tons of CO2 emission that is saved from the cement preparation process.[12]

Foundation Systems

Compared to floor systems, foundations system selection involves several external factors such as the existing foundation in the already developed site, the soil characteristic and the existing structures around the building site. As well as these factors, the dead load and live load that will be acting on the building is important in determining the type of foundation that will be used for this high-rise building.

The foundation systems are broken into two main categories: deep and shallow foundations. The factors listed above are used to decide which category of foundation should be investigated in order to determine the most suitable foundation.

[12] Bubbledeck North America. ® *Product* (n.d.): n. pag. *Bubbledeck*. Bubbledeck North America, 02 Oct. 2012. Web. 23 Mar. 2016.

Table 6: Comparison of Deep and Shallow Foundations

Type	Advantages	Disadvantages
Deep Foundation	-Can resist higher loads	-More expensive
Shallow Foundation	-Lower cost -Easy construction procedure -Lower skill level	-Total settlement and differential settlement -Proper for lightweight buildings only

Shallow foundations are suitable for low-rise buildings (around 3-4 stories). Since the raft is acting as both foundation and ground floor slab, it is an economical option. The raft is ideal for areas that require good protection against ground settlements and heave due to the design and good choice for sites where the bedrock layer is relatively close to the surface.

The category that the proposed building falls under is the first step in determining what kind of foundations that will be considered. 888 Boylston Street is a 17 story high-rise building, which is unsuitable to use a shallow foundation considering the dead loads that the building will be facing. At this point the decision making will be done among the deep foundations, which are driven piles, well foundations, and drilled (caisson) foundations. The table below summarizes each alternative of possible deep foundations.

Table 7: Summary of Commonly Used Deep Foundations[13]

Type	Advantage	Disadvantages	Use
Drilled Piles	-Can transmit heavy loads. -Larger diameter of piles mean less piles needed. -No need to support borehole as concrete replaces the void created. -Almost vibration free. -Almost noise free. -Not susceptible to boulders	-Require reasonably good soil content to avoid borehole collapsing. -Large plant needed to excavate earth.	-Heavy buildings with large loads. -When there is a risk of damage to surrounding buildings through vibration. -Bearing stratum is deep below the surface.

[13] *Foster, Thomas Elliott. "Case Study Done for J & W Lowry Limited." A Case Study Identifying the Advantages and Disadvantages of Certain Foundation Types (n.d.): n. pag. J. & W. LOWRY LIMITED. 9 Mar. 2013. Web. 6 Oct. 2015. <http://www.jwlowry.co.uk/wp-content/uploads/Brown-Field-Site-and-Suitable-Foundation-Types.pdf>.*

	or debris below ground. -Can transfer loads to deep bearing stratum on tight sites.		
Driven Piles	-Can transfer loads to deep bearing stratum -Suitable to tight sites. -Can transfer loads to deep bearing stratum. Made off site and quality maintained due to factory production. -No excavation required. No need to support excavated holes. Suited to framed construction.	-Problematic when dimensional stability of the ground is an issue. -Problematic when there is demolition debris or boulders in the ground. -Noisy installation method can cause environmental impact -Vibration can affect neighboring properties -Can cause ground heave	-Sites with poor ground conditions. -Soils that have low bearing capacity but offer good friction forces. -Bearing stratum is deep below the surface.
Raft Foundation	-Financially cheap due to the combined use of the foundation as the floor. -Shallow depth of foundation means little excavation. -Can cope with poor/mixed ground conditions.	-Weak when supporting point loads, specific treatment required. -Susceptible to edge erosion.	-Lightweight structures on poor ground with low bearing capacity. -Used in areas with mixed bearing capacity usually filled ground.
Well Foundation	-Feasibility to be sunk to great depths -Economical	-Possible delays in excavation process -Built-up water in concrete seal	

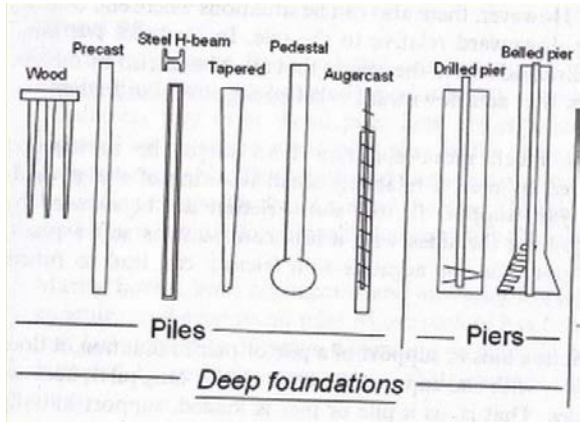


Figure 10: Deep Foundations graphical representations[14]

The first step in deciding on the building foundation was examining the land characteristics of the area. Sources from the city of Boston was useful to develop a general idea about what sort of layers occur in the area. Although to have a better understanding of the building site, the geotechnical report provided by Haley and Aldrich Engineering, a consultant company, was reference since the geotechnical report provided by the company was highly specific and detailed. The figure below is the representation of layers found in certain parts of the city of Boston. 888 Boylston Street is located in the Prudential Center area, which is marked in red.

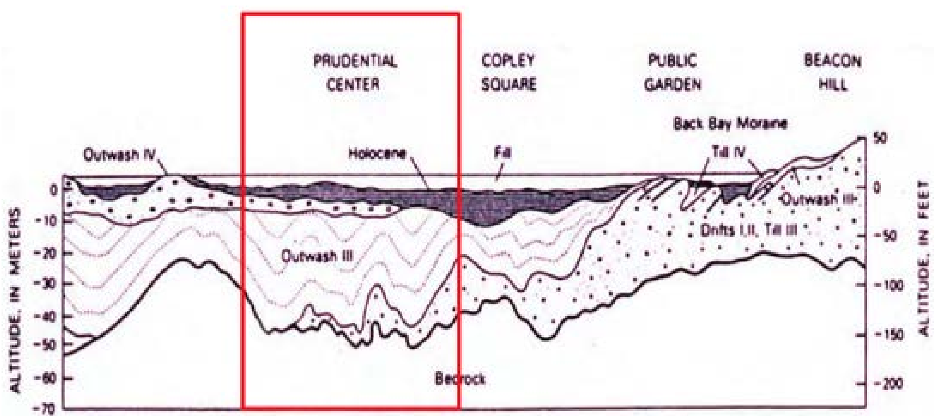


Figure 11: Earth Layers of Major Districts in Boston

As stated before, the location of 888 Boylston Street is affected by two criteria: being extremely close to surrounding buildings and the highway tunnel passing underneath. Based on the examinations

[14] Siong, Wei. *Deep, Intermediate and Shallow Foundation*. Digital image. *Scribd*. N.p., 28 Aug. 2011. Web. 6 Oct. 2015. <http://www.scribd.com/doc/63429538/Shallow-Foundation-and-Deep-Foundation#scribd>.

done by the Haley and Aldrich Engineering, and the matrix provided in this section, driven pile foundations have a high risk at this building site. As stated in the report, considering the vibration due to the construction of the driven piles might result in the settlement of the existing mat foundation, therefore the driven piles are not the best option. Also looking at the disadvantages of driven piles, noise and vibration are possible causes of problems considering the surrounding buildings and the tunnel passing right underneath.

Table 8: Soil Profile of 888 Boylston Street[15]

Strata	Top Level of Stratum (ft.)	Average Thickness (ft.)
Fill		6.0
Organics		NA
Sand		10.0
Clay		123.0
Till		5.5
Bedrock	-144.7	NA

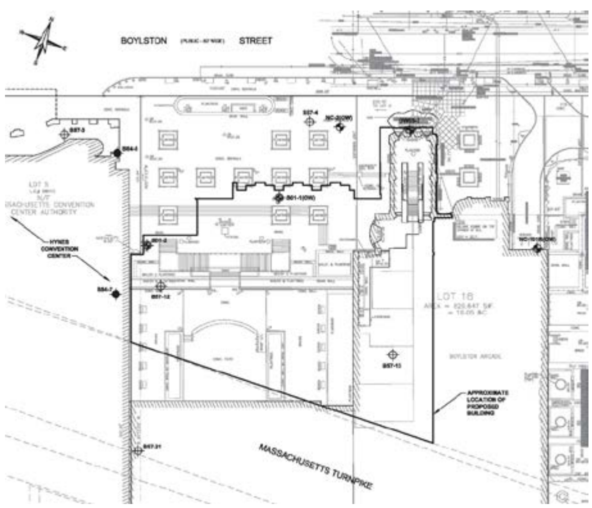


Figure 12: Map representing the location of Turnpike
**courtesy of FX Fowle Architecture*

[15] Haley & Aldrich, Inc. Boston, Massachusetts, comp. *REPORT ON SUBSURFACE CONDITIONS AND FOUNDATION DESIGN RECOMMENDATIONS PROPOSED 888 BOYLSTON STREET PRUDENTIAL CENTER BOSTON, MASSACHUSETTS*. Boston: n.p., May 2014. Print.

As a result, it has been decided to use drilled foundation for 888 Boylston Street. Drilled foundations are highly efficient in high-rise buildings due to their capability to transmit heavy loads and no noise and vibration features. Since there is a possibility for the soil underneath the building to settle over time, the caisson foundation will help to prevent the soil from moving in the vertical direction. At the same time, the reduced noise and vibration level of the installment process diminish the issue with the surrounding buildings and the highway tunnel.

The methods above are the steps that have been followed in order to determine gravity systems that are suitable for the 888 Boylston. To summarize the decisions, the table below lists the systems that were decided on:

Table 9: Gravity System Summary

System	Decided Type
Floor System	Bubbledeck slab
Foundation System	Drilled Piles

2.2.2 Lateral Load Systems

A lateral load, such as a wind or seismic load, is any effect that creates a load in any direction other than vertically downward. Wind creates horizontal forces on the walls of a building and upward suction on the roof. These loads cause lateral displacements on a building, which are zero at the base and increase with height. Earthquakes also create horizontal forces. Other lateral loads include earth pressure, water pressure, and blast and impact loads; earth pressure on a retaining wall creates a displacement that is large at the base and reduces to zero at the top of the soil. Similarly, hydrostatic pressure increases with depth and is zero at the fluid’s free surface. Lateral displacements are clearly detrimental to the integrity of the building and can cause extensive damage, so it is necessary to design systems to resist lateral loads. Examples of lateral load systems include shear walls, continuous rigid frames, pin supported frames, portal method, or unbraced frames.

Shear walls with large bending stiffness can be used to carry all wind and seismic loads to the foundation. Diaphragm action transmits loads from continuous floor slabs to the walls. Shear walls can be located on the interior or exterior of the building. The wall only resists flexure in-plane, so shear walls are required in both directions.

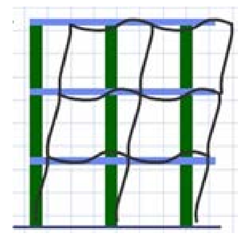
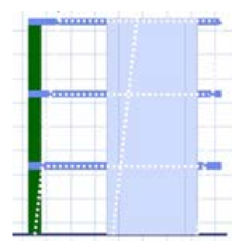
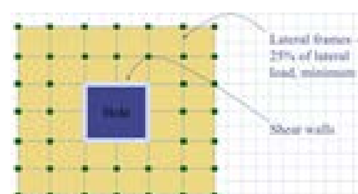
Continuous rigid frames are often used in cast-in-place concrete buildings since they have continuous joints. Rigid frames make use of beams and columns that are already there for gravity loads.

When these continuous joints are designed to carry lateral loads they usually require additional depth, however. Rigid frames are not as stiff as shear wall construction, so they are less susceptible to earthquake failures.

Dual shear wall-frame interaction combines aspects of continuous rigid frames with shear walls. The frame deflects in shear while the shear wall reacts by bending as a cantilever.

Each of these lateral load systems is summarized and depicted in Table 11 Lateral Load Systems.

Table 10: Lateral Load Systems

Type	Advantage	Use	Diagram
Continuous Rigid Frame	· Optimum use of floor space · Simple and experienced construction process · Continuity at joints · Economical for <20 stories · Offsite manufacture (less on site labor costs)	Low- to mid-rise construction	
Shear Wall	· Increases applicable height range of slab and shear walls	Taller than 10 stories	
Dual	· Enhanced stiffness because wall is restrained by frame at upper levels while at lower levels frame is restrained by shear wall	10 to 50 stories	

2.3 Envelope

The original building had an envelope that was comprised entirely of a glass curtain wall. Following the decision to preserve the overall architectural style of 888 Boylston Street, it was decided that the new building should also have a unitized curtain wall system, which is a factory-assembled and factory glazed system shipped in units to the job site in custom built A-frame racks, facilitating unloading, hoisting, and distribution onsite. Once on site, the units are hung onto an edge-of-slab rail that is anchored with T-bolts into cast-in-channels that are pre-mounted onto the Bubbledeck at the factory. The entire process is designed to expedite installation and to minimize every aspect of onsite labor (Addonisio, et.al. 2016).

A unitized curtain wall is a glazed wall system constructed of pre-manufactured glass and aluminum mullions. These mullions hold the facade in place and are designed to protect against factors such as water leakage, air infiltration, sound infiltration, and vertical loads. Their dimensions tend to be slightly larger than a stick system due to their open section as compared to the tube shape of a standard stick curtain wall section. An important advantage of aluminum mullions that contributes to the reliability of the system are the watertight seals achievable from factory construction and the reduced cost of labor in the factory versus that of high rise field labor. These units are assembled in a factory while the structural frame of the building is being constructed as well as require less space on the site for layout which ultimately provides an advantage for urban sites with space limitations (Addonisio, et.al. 2016).

Unitized curtain wall systems accommodate for different movements between the building's structure and the thermal movement of the frame at the joints between each curtain wall unit. The amount of movement the system is expected to accommodate for can be carefully engineered into the system since these systems are frequently custom designed. Vertical mullions typically span two floors which increases the dead load reactions at every other floor line. For support, these vertical mullions would be anchored to each slab edge on the structure as they extend past them. The anchors occur at each pair of vertical mullions along the edge of slab or spandrel beam. To accommodate for lateral loads, unitized systems span from a horizontal stack joint located at approximately desk height up to the anchor at the floor line above and then cantilevering past each floor to the next horizontal stack joint. This type of joint is designed to resist lateral loads while the two floors anchors resist gravity and lateral loads (Addonisio, et.al. 2016).

2.4 Resiliency

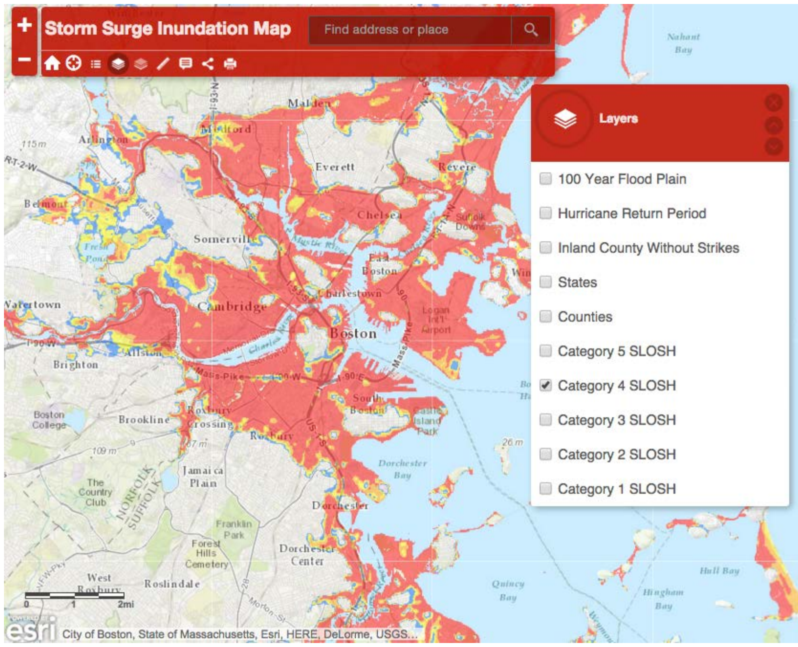


Figure 13 Storm Surge Inundation Map[16]

888 Boylston Street is located in the Boston Back Bay Architectural District, an area highly prone to storms and flooding. The Environmental Protection Agency (EPA) provides a Storm Surge Inundation Map which shows the possibilities of different intensity storms hitting a specific area of the country. The map in Figure 23 shows that any category 1-4 hurricanes would be likely to hit the Boston area.

[16] United States Environmental Protection Agency. *See Coastal Storm Surge Scenarios for Water Utilities*. Web.

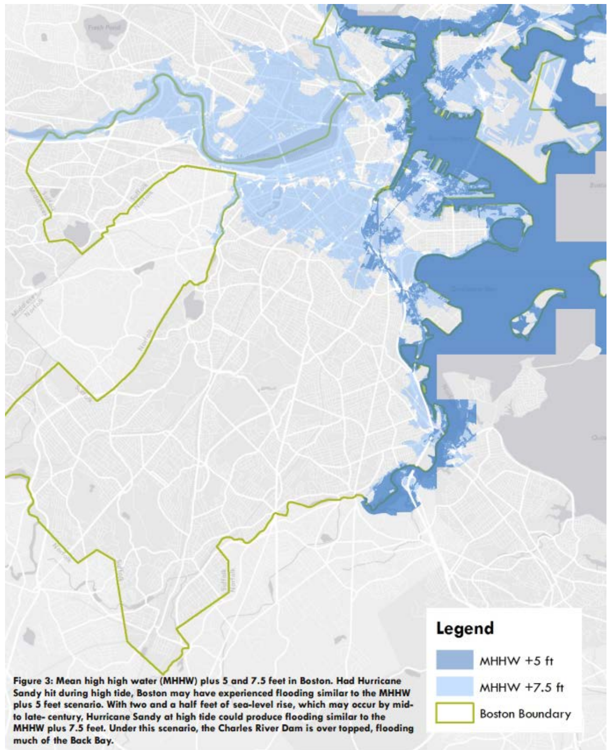


Figure 14 Storm Map[17]

It is positioned in the light blue colored zone on the map shown in Figure 23, which indicates that the mean high water height could reach over 7.5 feet during large storms when in high tide. To limit and prevent damages from these natural disasters to the building, and its occupants, multiple mitigation strategies were developed and implemented in the final design.

2.5 Sustainability in Buildings

2.5.1 Solar Energy

Light and heat from the sun are excellent sustainable resources that humans can utilize. With the help of technologies such as photovoltaics, solar heating, and solar thermal energy, the radiated heat and

[17] Schwartz, Kurt, and John P. Murray. *State Hazard Mitigation Plan*. Rep. Commonwealth of Massachusetts, Sept. 2013. Web.

light can be harvested and stored to be used in the building systems.[18] These technologies are categorized into two groups according to their processes of capturing and distributing solar energy or converting it into solar power.[19]

Active Solar	Passive Solar
Photovoltaics Concentrated Solar Power Solar Hot Water Solar Process Heating and Cooling	Orientation of the Building Material Selection Design of Spaces for natural air circulation

Photovoltaics (PV)

PV systems are one of the most efficient solar energy solutions due to their direct conversion of sunlight into electricity using solar cells.[20] As a simple example, “A 10-kW system that produces 1,500 kWh per kW capacity per year could thus produce 15,000 kWh annually. In a 20,000 square foot office building that uses 15.5 kWh per square foot, this system could reduce grid-based electricity purchases by approximately 5%.”[9]

Several factors affect the performance of PV units. These factors are:

- Cable Thickness
- Temperature
- Shading
- Charge Controller and Solar Cell’s IV Characteristics
- Inverter Efficiency
- Battery Efficiency[21]

[18] "About Solar Energy: Passive Solar, Solar Thermal, and Photovoltaic." *Energy and Environmental Affairs*. N.p., 2015. Web. 10 Oct. 2015. <http://www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/solar/about-solar-energy.html>.

[19] "Energy." *Energy*. Royal Society of Chemistry, n.d. Web. 10 Oct. 2015. <http://www.rsc.org/campaigning-outreach/global-challenges/energy/#solar>.

[20] "Renewable Power Generation 2010." *Renewable Energy Focus* 12.4 (2011): 38-41. *EPA*. US Environmental Protection Agency, 15 May 2008. Web. 10 Oct. 2015. <http://www3.epa.gov/statelocalclimate/documents/pdf/on-site_generation.pdf>.

[21] "6 Factors That Effect Solar PV System Efficiency." *Solar Power for Ordinary People*. Living on Solar Power, 06 Mar. 2013. Web. 10 Oct. 2015. <https://livingonsolarpower.wordpress.com/2013/03/06/6-factors-that-effect-solar-pv-system-efficiency/>.

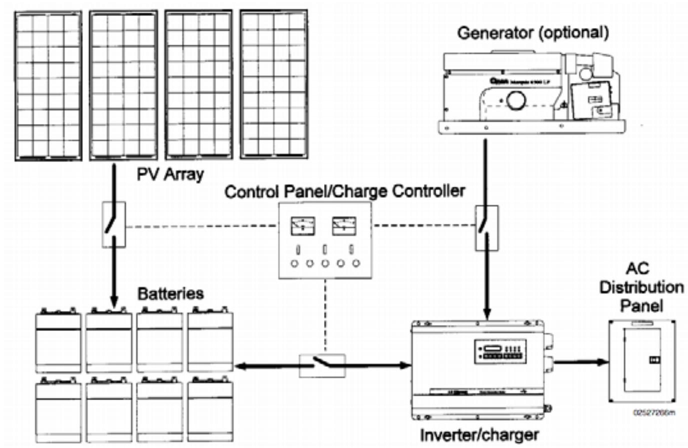


Figure 15: Schematic of a typical stand-alone PV System[22]

Roof Top Solar Panels

Rooftop solar panels are the most common form of solar cell placement around the globe because normally rooftops are unutilized and much more open for installation, and due to the positioning, they can harvest solar energy from many angles.

Building Integrated Photovoltaics (BIPV)

Besides the most general usage of photovoltaic panels in commercial buildings, there are many different applications available in the industry today. The square footage of rooftops are limited and not always available for solar panel installation, so it is important to take advantage of other surfaces on the exterior façade of the building to harvest solar energy. A list of available BIPV systems is shown in the table below.

Table 11: List of Building Integrated PV Systems

System	Description
Transparent PV Panels/Curtain Walls	• Layer of PV panels in between two thin panes of glass.[23] • High Radiation Filtering

[22] Eiffert, Patrina, and Gregory J. Kiss. *Building-integrated Photovoltaic Designs for Commercial and Institutional Structures: A Sourcebook for Architects*. Golden, CO: National Renewable Energy Laboratory, 2000. Print.

[23] "Energy Efficiency & Environmental News: Transparent PV Panel." *F Energy Efficiency and Environmental News* (Nov. 1992): n. pag. *Http://p2ric.org/*. Florida Energy Extension Service, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida., 2014. Web. 11 Oct. 2015.

	• Low U-Value[24]
Louvers	• Louvers with integrated PV panels • Both acts as shading device and solar energy harvesting • Effective in reducing air conditioning loads • Aesthetic architectural impact
Rain Screens	• The cavity wall format of rain screen cladding improves the efficiency of PV panels. • Ventilation zone allows thermal currents to circulate and prevent overheating.[25]
Flooring	• Floor systems integrated with PV panels to utilize every space possible. • Able to support up to 400 kg in point load.[26]

Certain factors play a role in the efficiency of the BIPV systems in multi-story buildings. These factors include site and location, orientation, tilt angle, inverters, wiring, dirt and dust, and shading.

Site and Location Consideration

[24] "Photovoltaic Transparent Glass for BIPV." *OnyxSolar BIPV*. OnyxSolar, n.d. Web. 11 Oct. 2015.
[25] "Solar PV - Solar PV Facades - Rainscreen Cladding." *Solar PV - Solar PV Facades - Rainscreen Cladding*. N.p., n.d. Web. 12 Oct. 2015. <http://www.solarpv.co.uk/solar-pv-facades.html>.
[26] "Walkable Photovoltaic Floor (For BIPV) - Onyx Solar - PV Floor." *Walkable Photovoltaic Floor (For BIPV)-Onyx Solar*. N.p., n.d. Web. 12 Oct. 2015. <http://www.onyxsolar.com/walkable-photovoltaic-roof.html>.

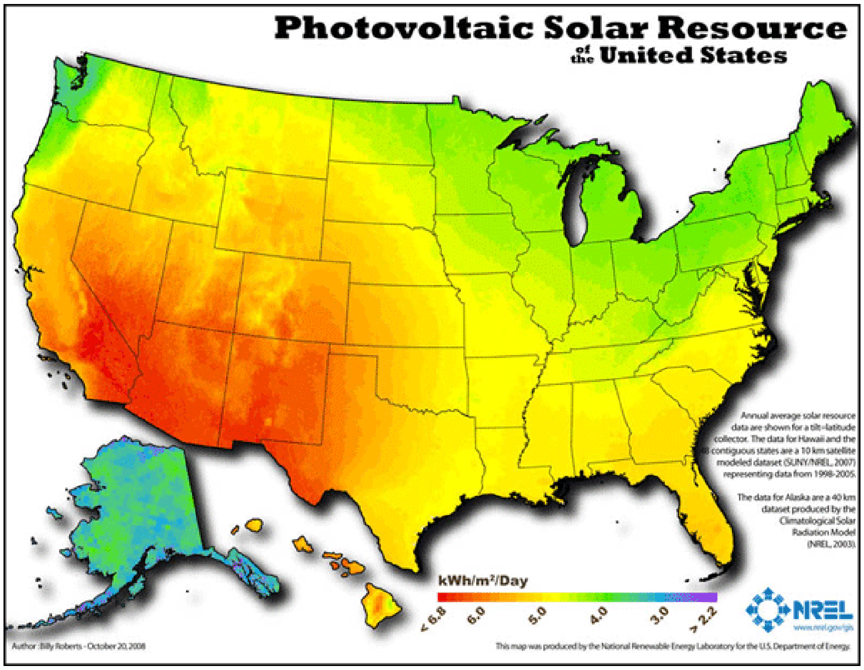


Figure 16: Photovoltaic Solar Resources of the United States[27]

The map above represents how much energy that PV resources can produce in different regions of United States. As can be seen, Massachusetts is falling under the category of 4kWh/m^3 per day. Compared with states located in southwest of United States, this value is less than half of what can be produced. This fact, however, should not be limit PV panel integration for commercial buildings in the Massachusetts area because any possible gain from renewable energy, such as solar energy, reduces the carbon footprint of the building.

The location is the primary factor in determining the efficiency of the PV panels. The climate has an effect on temperature, amount of irradiance, and utility rates.[28]

The impact of temperature can be observed under two conditions. First is effect on the circuit voltage change, where increased temperatures result in greater voltage drop. Second is the effect on operating temperature. Increased temperature can result in overheating the system, which can lead to hardware problems. This situation is alterable by implementing efficient cooling systems to keep the panels at a constant operating temperature.

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[27] WebUrbanist. "Invisible Bicycles: Tokyo's High-Tech Underground Bike Parking." *WebUrbanist RSS*. N.p., 26 Mar. 2015. Web. 10 Oct. 2015. <http://weburbanist.com/2015/03/26/invisible-bicycles-tokyos-high-tech-underground-bike-parking/>.

[28] Kayal, Sarah. "Application of PV Panels in Large Multi-Story Buildings." *CalPoly*. N.p., June 2009. Web. 12 Oct. 2015.

Orientation

Optimum performance is usually achieved when the panels are oriented properly towards true south.[22] Table 12 shows the efficiency of panels tilted 90 degrees and oriented in different directions at the same latitude.

Table 12: PV panel production vs. Tilt angle

Orientation	KWh/ yr.
South	18000
SE & SW	20000
North	13000
East, West	17000

Tilt

The overall yearly output shows that PV panels with the tilt angle equal to the latitude (40º) have a 28% higher efficiency compared with 90 º-installed panels. However, this factor is not the same through the whole year. Nevertheless, the tilt angle is also proportional to the amount of diffuse sunlight, because diffused radiation is less direction dependent. [23]

Wiring and Mismatch

Wire resistance adds a factor of approximately 0.97 to the output efficiency of the PV cells. Thus, it is important to be accurate in determining the cable lengths used to minimize the resistance throughout the system. Mismatch will also occur in a series of cells that do not have the same I-V characteristics. This situation also adds a factor of 0.95 to the efficiency.[29]

Dirt and Dust

Since PV panels are usually located in areas that are not under constant maintenance, it is likely for dust and dirt to build up on the panels, which results in the blockage of solar rays, and therefore, a drop in efficiency. According to research on the topic, this factor can reduce the efficiency by 7% to 25%.[23]

[29] Kayal, Sarah. "Application of PV Panels in Large Multi-Story Buildings." *CalPoly*. N.p., June 2009. Web. 12 Oct. 2015.

Economics of PV Systems

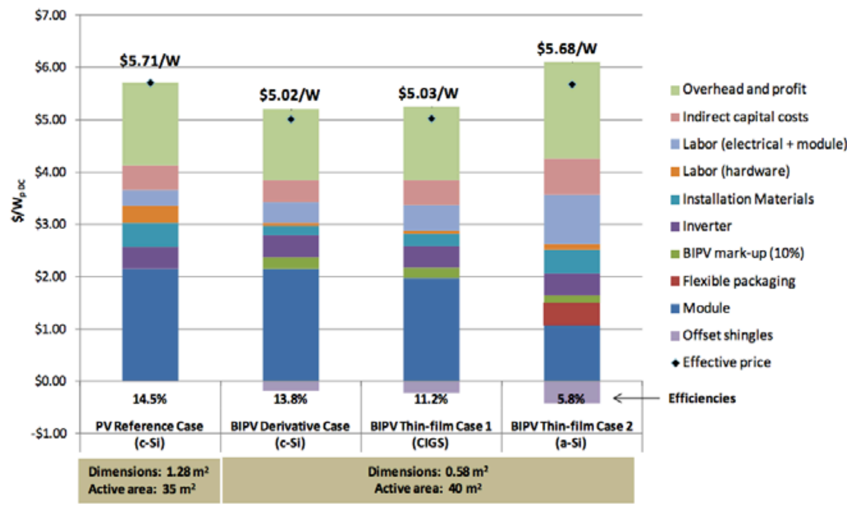

Figure 17: Comparison of rooftop prices for a rack-mounted PV Reference Case and three BIPV cases[30]

Design Issues for Photovoltaics

The climate in Boston is a real issue. Removal of snow from rooftops is expensive and difficult when PV panels are installed, and the panels may be damaged.

2.6 Wind Energy

Wind power is one of the most popular energy harvesting ideas in the United States today. According to mass.gov, as of 2008, 29,440 megawatts of wind energy were installed in the country, making up 1.25 percent of the national electricity supply[31]. There are two commercially sold wind turbines pictured in Figure 12: horizontal axis turbines and vertical axis turbines[32].

Wind turbines consist of a generator connected to turbine blades (usually three fiberglass blades), which catch the wind and rotate, thus turning the magnet inside the generator. The power generated by a wind turbine is dependent on wind speed and direction, the swept area of the blades, turbulence in the area, and wind consistency. The turbines can only generate power if the wind is blowing, which can cause

[30] James, T., A. Goodrich, M. Woodhouse, R. Margolis, and S. Ong. "Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis of Installed Rooftop System Prices." (2011): n. pag. *NREL*. Web. 12 Oct. 2015. <http://www.nrel.gov/docs/fy12osti/53103.pdf>.

[31] "Wind Energy: Facts." *Energy and Environmental Affairs*. Commonwealth of Massachusetts, 2015. Web. 11 Oct. 2015. <http://www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/wind/wind-energy-facts.html#a>.

[32] Meyers, C. Bracken. "Types of Wind Turbines." *Centurion Energy*. N.p., 09 Dec. 2013. Web. 11 Oct. 2015. <http://centurionenergy.net/types-of-wind-turbines>.

difficulties if, as the U.S. Department of Energy predicts, the electric grid is 20 percent of total supply power. With any intermittent energy source (such as solar power), there must always be backup power if wind speeds decrease.

There are many innovative wind turbine designs being explored today, each seeking to improve wind turbine efficiency or to make wind power more convenient for today's consumers. Many are also exploring energy storage in the form of batteries and compressed gas, which may solve the problem of intermittent power. The most efficient design commercial sold today is pictured on the left in Figure 12, but each design has pros and cons and is more applicable to certain situations. The advantages and disadvantages of the horizontal axis and vertical axis designs are detailed in the following sections.

2.6.1 Horizontal Axis Wind Turbines

The horizontal axis wind turbines are the most efficient wind turbines on the market, but they have their disadvantages too. The following chart lists the advantages and disadvantages of the horizontal axis turbines in comparison with the vertical axis wind turbines (see 2.2.2.2 Vertical Axis Wind Turbines).

Advantages	Disadvantages
• Higher efficiency • Easily mountable on towers • Taller tower allows access to higher winds • No rotation drag (always perpendicular)	• Sensitive to variable wind direction (requires a wind vane or motor) • Sensitive to turbulence • Heavier tower construction • Installation of gearbox, generator, etc. • Downwind designs suffer extra fatigue • Yaw control mechanism to turn blades • Safety braking or yaw for high winds • Turning into wind causes extra stresses • Higher start-up wind speed

Note: Sensitive in this context means not adaptable

2.6.2 Vertical Axis Wind Turbines

The vertical axis wind turbines have advantages when the available wind changes directions frequently or is very turbulent.

Advantages	Disadvantages

• High adaptability to wind direction • High adaptability to turbulence • Lighter towers (less equipment) • Better rooftop adaptability • Easier maintenance (equipment near ground) • No yaw mechanism • Lower start-up wind speed • Can take advantage of geometric “tunnels”*	• Lower efficiency • Difficult to mount on towers • Tower height restriction (less energy available) • Rotation drag (backtracking against wind) • More turbulence (due to more obstructions)

*low enough to take advantage of locations where buildings, hills, trees, ridges, etc. create a path for the wind to follow

Even with these various advantages, there are other disadvantages associated with wind energy in general. Previously mentioned was the intermittent nature of the wind, restricting wind turbines from producing a constant source of power. This problem may eventually be hurdled by increases in the effectiveness of battery storage. Other surmountable problems are injury to wildlife, which may be solved by mapping out migration patterns, noise pollution, initial manufacturing pollution, high manufacturing cost, and high cost of general maintenance. The vibration in the turbines due to turbulence, and generator noise causes noise pollution in nearby neighborhoods. Initially manufacturing pollution may eventually be reduced by using other renewable energy forms, or wind energy itself, to manufacture the turbines. Finally, the costs of manufacturing and maintenance will go down as wind power becomes more and more generally available and as manufacturing technologies improve.

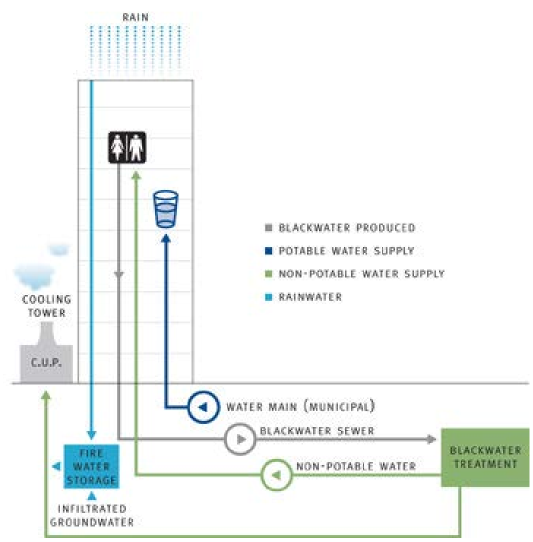

Figure 18: Rain Harvesting Systems Diagram

2.7 Rain Harvesting Systems

Figure 19: Informative Signage

Water is the most precious natural resource. With its limited supply, the rainwater harvesting technique is one of the alternatives to manage and conserve water for a secure and sustainable future. In this case, Boston gets a sufficient amount of rain and snow throughout the year, which makes rain-harvesting systems highly efficient. This harvested rainwater can be used in many different MEP systems in the building, which will drastically reduce the amount of water being used from the grid.

The rain harvesting system consists of several different components: collection area, storage tank, pumps, filters, and controls.

Collection area: The collection area of a rain-harvesting unit is usually located on the roof. In case of using the rainwater as potable water, the

Storage Tank: The tanks are mostly located underground and made out of materials such as epoxy steel, fiberglass, pre-cast concrete, polyethylene or poured-in-place concrete.[33] The factors affecting the selection of the materials are the location and size of the tank, and the specific purposes of the water that will be stored in the tank. The calculation of the tank size includes the information from annual rainfall, intended use of rainwater, and cost. In cities like Boston, it is possible to collect 80% of the rain that falls on the roof of a building. A rough estimate for the tank size can be made by assuming 600 gallons of water per inch of annual rainfall per 1,000 square feet of roof area is gatherable.

Pumps, filters, treatment, valves, piping and controls: in most of the rain harvesting systems in high-rise buildings, a duplex pump system is required to distribute the rainwater from the tank to the specific fixtures. There are several filtering techniques to consider such as ultraviolet treatment, and physical.

[33] Gray, Jonathan, and Jerry Yudelson. "Rainwater Harvesting Systems. Code of Practice." (n.d.): n. pag. *Stark Environmental*. Web. 15 Oct. 2015. <http://www.starkenvironmental.com/downloads/Interface_Engineering.pdf>.

3.0 Methodology

In order to design a structural system that would be strong enough for the proposed building, it was first necessary to determine and analyze the required design. The initial design for the structure of the building was given, the first activity was to model and analyze the existing design in Bentley RAM to determine the design loads and their structural behavior.

3.1 Preliminary Design Phase

3.1.1 Codes and Standards

Prior to design, the team researched and consulted local and national building codes and industry standards relevant to the structural design of 888 Boylston Street. These included the International Building Code (IBC), American Institute of Steel Construction (AISC) Code of Standard Practice, American Concrete Institute (ACI) 318 Building Code Requirements for Structural Concrete, the Massachusetts Building Code, and 780 CMR: Massachusetts Amendments to the International Building Code. The local codes limited both the roof design and wind design because Boston is in a high wind zone and can be subject to significant snowfall during the winter months. Additional codes and standards are listed in the bibliography.

3.1.2 Material Selection

For the competition purposes, the structural team divided into two groups to conduct research on the suitable materials that would fulfill the predetermined design criteria. The main focuses were on structural steel, reinforced concrete and combined systems. To get an idea of which type of column would best suit the building layout, design calculations were run on both steel and concrete columns to determine how large of a cross sectional area each material would require to support the building. A smaller cross sectional area is preferable to limit the disturbance of the floor plan caused by the columns.

3.1.3 Preliminary Column Load Calculations

When calculating preliminary design loads of the building, certain assumptions were taken to simplify initial calculations. The following assumptions in Table 13: Concrete Calculation Assumptions and Table 14: Concrete Calculation Equations were used in the calculation of the size of the concrete columns.

Table 13: Concrete Calculation Assumptions

Factor	Assumption
Area of Steel	3% of concrete area
Strength of Steel, fy	60 ksi
Strength of Concrete, f'c	5000 ksi
Dead Load	85 lb/ft^2
Live Load	50 lb/ft^2
Snow Load	40 lb/ft^2

Table 14: Concrete Calculation Equations

Live Load Reduction Factor	$LL = L_o\left(.25 + \frac{15}{\sqrt{K_{LL}A_t}}\right)$
Wind Load (lb/sf)	WL= $.00256V^2IK_zK_{zt}K_dGC_p$
Seismic Story Force (lb/sf)	$EL = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i w_i^k} V$

For the competition, each of the two structural groups was responsible for the preliminary design of column sizes for their assigned material. To give the teams a comparable starting point, the provided drawings of 888 Boylston Street were used to establish an initial grid. The columns were kept in the same locations as in the existing building, so that the sizes calculated for concrete and steel would be comparable.

Once the initial grid was established, preliminary column loads were calculated based on tributary areas, the design assumptions listed in Table 13: Concrete Calculation Assumptions, and the equations listed in Table 14: Concrete Calculation Equations. For influence areas ($K_{LL}A_T$) greater than 400 square feet, a live load reduction factor was used, since the member supporting a large tributary area is not likely to be loaded by the maximum live load at all points. Both the steel design and the concrete design incorporated the live load reduction factor in their calculations.

3.1.4 Column Sizing

Once column loads were calculated for the various sources of load (D, L, S, W, E), different load combinations with appropriate load factors were tested to see which provided the maximum design force. Using the column strength equation

$$\Phi Pn_{max} = .8(.85f'_c(A_g-A_{st})+f_yA_{st}),$$

the maximum design force and the assumptions listed above in Table 15: Concrete Calculation Assumptions were used to calculate the square foot area of each column necessary to support its design force.

3.2 Software

3.2.1 Structural Model

Structural Model: First Iteration

The next step in the analysis of the existing structure was to enter the information gained from the tributary area calculations into an analysis software. There are many different softwares available in the market such as Bentley RAM, Autodesk Robot, and STAAD. Bentley RAM was chosen because of its rich visual feedback options and status as a leading software in the industry. Initially, existing columns from the provided plans were laid out in the software. It was assumed that the interior walls around the elevator core were shear walls and that the exterior walls were gravity walls.

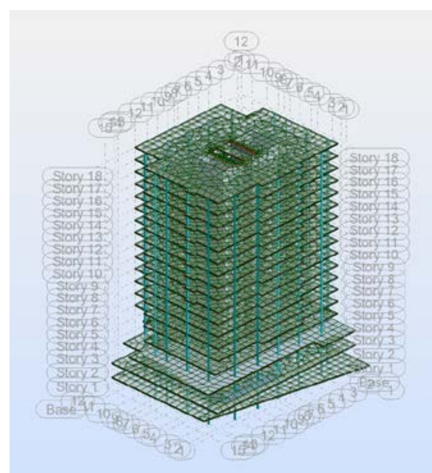

Figure 20: Robot Model of the Structural System

Once the existing structure was laid out, the material, size, and strength of each column was assigned. Basic load combinations for dead load, live load, wind, and seismic were assigned to the model.

Structural Model: Second Iteration

Following the decision to use composite columns, the team discovered that Bentley RAM did not have the capability of analyzing a composite system. In order to design for composite columns and the concrete Bubbledeck slab, the analysis shifted to the use of the Autodesk Robot Structural Analysis software. With the help of the Robot software, the team investigated the slab structure in order to determine the reinforcement requirements.

3.2.2 Revit Model

The team utilized an Autodesk Revit model given by the design competition to coordinate all changes made to the original design. This was made possible by the use of a network drive on WPI's server that allowed all members of the team to access a central file for the Revit model. Autodesk software allows for collaboration on the model through the use of localized files that are constantly synced with the central one so that multiple users can work on the model at the same time. The Revit file allowed for all the team members to be constantly updated on how their design affects the entire building. The model was also used to create architectural renderings of the building such as the ones shown in the Architectural Design Section, 3.7. This was done by placing model families of furniture, light fixtures, and other details along with adjusting the finishes of the walls and floors. Then a camera view was created that showed the desired area. Autodesk allows students to make a free A360 account, which supports an infinite number of full quality images to be rendered using their cloud services. This service gave us the opportunity to continuously revise rendered images as model updates were made.

3.3 Bubbledeck System

The main goal of this project is to incorporate smooth system integration between the architectural, structural, and mechanical systems of the building. Therefore, much research was done to find the best way to accommodate each of these systems. As a result, it was decided to use a new structural slab system called Bubbledeck, which is described in the background chapter of this report. Since the Bubbledeck is fairly new in the industry and much different than the traditional concrete slabs, design guides provided by the companies were used for preliminary design purposes. The published data was acquired from series of experiments, mostly done in Europe, over the course of twenty years.[34]

[34] Concrete Reinforcing Steel Institute. "Design Guide for Voided Concrete Slabs." *Builder's Book, Inc. Bookstore*. CRSI, 2014. Web. 04 Jan. 2016.

The first step was to determine a preliminary value for the required the preliminary slab thickness based on the column layout. Using the provided floor plans, the column layout was investigated and it was concluded that the maximum span in the column system is 58 feet. Using the spans guide table (Table 15) provided by Bubbledeck North America, it was decided to initiate the preliminary design calculations with a slab thickness of 20 inches.

Table 15: Spans guide for Bubbledeck systems[36]

Slab Thickness (in)	Steel (in^2/ft)	Span (ft)	Span Data Low	Span Data High	Moment Strength Data Low	Moment Strength Data High
9	0.15-0.5	10	16	22	6	22.4
11	0.18-0.54	20		29,5	7	30
13.5	0.22-0.59	30		36,5	16	42
15.5	0.26-0.64	40		44	22	53
18	0.29-0.69	50		51,5	30	68
20	0.31-0.82	60		59,5	34	90
24	0.42-0.96	70	58	68	39	127

The next step of the preliminary design was to check for the deflection limitations. The limits for the appropriate values were acquired from the ACI Table 8.1.1.1

Table 16: ACI Table 8.1.1.1[35]

Table 1: Min. Thickness of Slabs without interior beams						
	Without Drop Panels(b)			With Drop Panels(b)		
	Exterior Panels		Interior Panels	Exterior Panels		Interior Panels
f_y (psi)	Without Edge Beams	With Edge Beams(a)		Without Edge Beams	With Edge Beams(a)	
40,000	$l_n/33$	$l_n/36$	$l_n/36$	$l_n/36$	$l_n/40$	$l_n/40$
60,000	$l_n/30$	$l_n/33$	$l_n/33$	$l_n/33$	$l_n/36$	$l_n/36$
75,000	$l_n/28$	$l_n/31$	$l_n/31$	$l_n/31$	$l_n/34$	$l_n/34$

35 *Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary*. Farmington Hills, MI: American Concrete Institute, 2011. *Public Resource*. Https://law.resource.org/pub/us/cfr/ibr/001/aci.318.1995.pdf, 2011. Web. 5 Jan. 2016.

Assuming the f_y=60,000 psi, the limit value of l_n/36 was used for preliminary purposes. According to the maximum span of 58 ft in the column layout, the minimum thickness of slab allowed by the ACI code was found to be 19 inches, which is less than the value obtained from the design guide for the Bubbledeck systems. Therefore, a 20-inch slab thickness was adopted.

The next step was to run a structural model analysis to obtain the moment contour maps in order to determine the shear force observed on the slab and required steel reinforcements. Figure 21 represents the structural model created in Autodesk Robot Structural Analysis software. The structural behavior was investigated for three different categories in terms of usage; garage floor, retail floor, and the typical office floor. Moment analysis was done for each of these slab structures and the moment values for edge middle strip, and core areas were determined. These moment values were then used in order to calculate the required steel area for each section. Once the required steel area was determined, the value was compared to the minimum steel area. For the sections where the minimum steel area was larger than the required steel area, the reinforcement bar configuration was defined according to the larger value.

In order to resist the punching shear, it was decided to use solid heads around the column connection areas where there will be no HDPE bubbles in present. The moment maps and two-way shear requirement calculations were used to determine the minimum solid head area for each column heads.

Once the solid head areas were determined, the Bubbledeck layouts were designed using the spacing specifications and maximum panel sizing. Figure 15 represents the bubble layout of a typical office slab.

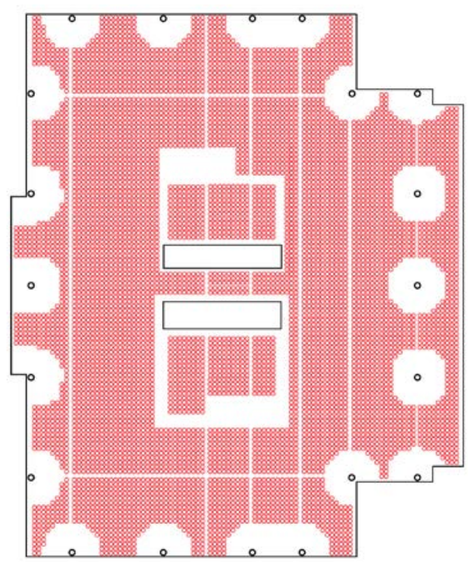

Figure 21: Bubbledeck layout for typical office floor

3.4 Shear Wall

Rationale

The review of various lateral load systems indicated that the shear wall system utilized in the initial design of 888 Boylston Street best met the needs of the redesigned building. That is, a reinforced concrete shear wall around the core of the building was selected to resist lateral loads. Other options considered included steel bracing (eliminated as an option once the Bubbledeck was chosen), and an exterior shear wall (eliminated as an option due to the decision to enclose the building with a curtain wall). The footprint of the existing shear wall was changed to accommodate changes to the architectural design of the building. The proposed footprint is depicted in Figure 20.

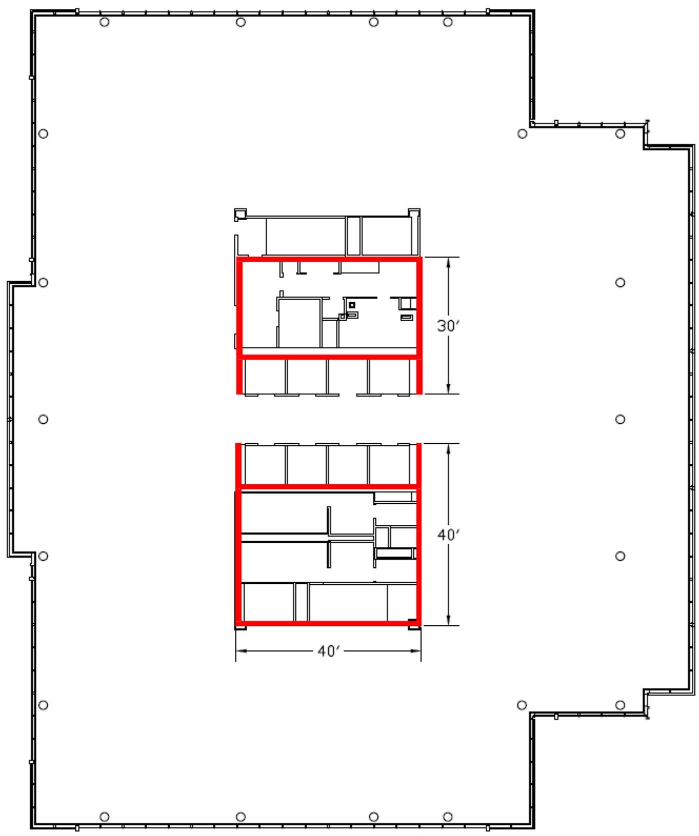

Figure 22: Shear Wall Footprint

Design Approach

Due to the proposed changes to the shear wall footprint from that of the existing building, as well as changes to the loading of the structure, it was necessary to run calculations to ensure that the proposed shear wall design would withstand the lateral loads placed on the building. The shear wall was designed based on design code ACI 318-05, using an example from ce.ref.com. Using the loads that were calculated and input to the concrete column design, the reinforcement of a twelve-inch wide wall was designed. The design calculations for the reinforcement assumed that the out-of-plane moment is negligible and that the wall was an interior wall.

Calculations were completed according to the steps detailed on CivilReferences.com (ce.ref.com):

- Calculated maximum vertical and shear force at first floor
- Checked maximum shear strength permitted
- Calculated factored overturning moment and weight of wall at critical section
- Calculated shear strength of concrete
- Design horizontal shear reinforcement (guess and check)
- Designed vertical reinforcement
- Designed flexural reinforcement
- Calculated factored moment at base
- Checked effective depth
- Recalculated reinforcement
- Checked clear spacing between bars

In addition to hand calculations, an interaction diagram was developed to check the design of the shear wall. An interaction diagram is a chart developed from iterations of calculations that is used as a quick, graphical means of analyzing a concrete column for combined axial and bending effects. It is constructed using a series of values for P_n and M_n, and checks the flexural failure mechanism of the concrete shear wall. Pure flexure is where there is no axial force, and is represented by the x-intercept on the interaction diagram. The interaction diagram also produces a performance ratio, which is a ratio comparing the factored design load to the factored capacity. If the performance ratio is greater than 100%, the member is past maximum load. If less than or equal to 100%, the member is within the operable range of force effects.

3.5 Foundation Design

Design Considerations

Due to the urban setting of 888 Boylston Street, it was important to consider construction technologies that pose limited disruption to neighboring buildings and to the Massachusetts Turnpike tunnel. A deep foundation with drilled shafts was chosen for the structural system based on the capacity the system provides and its ability to limit disturbance. Specifically, round drilled shafts were selected for this project as opposed to rectangular load bearing elements (LBEs) due to the concrete savings they would provide.

A section of the underground parking garage that served the neighboring Prudential Center was located under the plot of land where 888 Boylston Street is currently being constructed. This section of the garage was demolished, and the new structure is being built using the existing mat foundation as the floor slab for the lowest garage level. The mat foundation must be cut in the locations of the columns to allow for installation of the deep foundation elements underneath. During the construction of the Prudential Center, an interlocking steel sheet pile cutoff wall was installed that serves as a groundwater barrier for the surrounding area, including the 888 Boylston Street site. According to the geotechnical report from Haley & Aldrich, because of this wall, the typical elevation range of groundwater levels was between -3'-9 to 2'-8" while the elevation of the existing mat foundation is around 2'-8". Therefore, all new, below grade structures are to be waterproofed and other waterproofing measures are to be taken into consideration during the foundation installation process.[36]

Design Process

The design of the foundation elements was completed based on the findings and recommendations of the geotechnical report by Haley & Aldrich. The reaction forces of the columns on the bottom garage floor determined the required capacity of the drilled shafts. The total capacity of the drilled shaft equaled the summation of the contributions from skin friction and end bearing capacity. However, the end bearing capacity cannot make up more than 50% of the total design capacity of the pier.

Table 17: Max. Bearing Capacity by Shaft Diameter

Diameter (ft.)	Area (SF)	Max. Bearing Capacity (k)
4	12.57	1256.64
5	19.63	1963.50
6	28.27	2827.43
7	38.48	3848.45

[36] Haley & Aldrich, Inc. *REPORT ON SUBSURFACE CONDITIONS AND FOUNDATION DESIGN RECOMMENDATIONS PROPOSED 888 BOYLSTON STREET PRUDENTIAL CENTER BOSTON, MASSACHUSETTS*. Boston, MA, May 2014. Print.

8	50.27	5026.55

The end bearing capacity of the shafts varied by the diameter. It was found by multiplying the gross area of the shaft by the end bearing capacity in competent bedrock given by the geotechnical report. The reported values for bearing capacity in kips per square foot (ksf) were based on a depth of 5' into the bedrock. Table 17: Max. Bearing Capacity by Shaft Diameter shows how the maximum bearing capacity varies by the diameter of the shaft. These values do not take into account the maximum allowed capacity based on the design limitations.

Table 18: Skin Friction Capacity by Bedrock Depth

Depth (ft.)	Skin Friction Capacity (k)
6	1628.60
7	1900.04
7.5	2035.75
8	2171.47
9	2442.90
10	2714.34
10.5	2850.05

The skin friction capacity varies due to the amount of weathered bedrock found at the location of the shaft. It is calculated by multiplying the skin friction force given by the geotechnical report by the circumference of the shaft and the depth of competent and weathered bedrock beneath the soil. For the depth, it was given that there was 5' of competent bedrock, and an assumption was made that there would be on average, 2'-6" of weathered bedrock at a typical column location. The geotechnical report stated that, based on the conditions of the surrounding sites, there would be an estimated 1' to 5'-6" of weathered bedrock above the competent bedrock in a given column location. Table 18: Skin Friction Capacity by Bedrock Depth shows the how the skin friction capacity varies based on the depth of the weathered bedrock for a 6' diameter shaft.

Due to the large capacity requirements and the large diameter of the shafts, the minimum requirement for the amount of steel per AISC 318 10.9.1 was used for reinforcing. The amount of steel needed is 0.1% of the gross area of the column. Therefore the largest reinforcing bar size, number 18, was selected. The number of bars was calculated by dividing the required minimum area of steel by the area of one number 18 bar and rounded up to the nearest whole number. To hold this vertical rebar in place, a spiral cage made of number 4 rebar ties was chosen based on their ease of constructability and installation for large shafts.

3.6 Building Envelope Design

The building envelope is an important piece of the design of the building for many reasons. Perhaps most important architecturally is that it is the first thing that distinguishes one building from another to the public eye. Therefore, the facade must be aesthetically pleasing and must complement the architecture and surroundings of the building. Just as important is the fact that the envelope is the barrier between the interior of the building and the outside elements. One goal of the competition team was to achieve an energy load of 50% less than code; much of this reduction in energy load falls to the proper design of the building envelope.

When deciding on which system to use for the curtain wall, the available options were evaluated based on the following criteria: project size, wall configuration, joint pattern, glazing, inter-story movement, quality control, modification, sealing, field labor cost, field labor duration and access, and safety. Having settled with a curtain wall as the building enclosure, two applications were evaluated: stick and unitized curtain wall systems. 888 Boylston Street is a high-rise building, which makes it a large project size for curtain wall installations, and ultimately too large of an installation project for a stick-built curtain wall. A stick-built system consists of horizontal mullions to form a grid with long aluminum mullions inserted between floors vertically and fixed to floor edges by brackets to provide wind resistance. The structure has a monotonic exterior which makes a unitized system a better choice. Additionally, this system is high-quality since it is pre-manufactured and glazed in a climate-controlled environment. Due to Boston being a high-traffic city and the tight building site having minimal storage space, a unitized system is more ideal, considering its installation requires only 75 ft^2 per unit, set from the interior using suction robots and stored on dolly-crates inside the structure as well as outside. Having a recorded installation speed of 50 units per day, a unitized system can be installed in a third of the time required for a stick-built system.

3.7 Architectural Design

3.7.1 Typical Office Floor Design

The change in shear wall design and the column layout (information acquired from the steel design group) resulted in changes in the typical office floor layout. With the new structural design, and other considerations such as sustainable design, egress requirements and daylight harvesting, the team designed a new layout for 888 Boylston. The design of the office floor can be seen in the Results section.

3.7.2 Front Plaza and Green Garden

888 Boylston building is intended to be a location where the public will gather together and use the space for multiple purposes. The building site includes a large front plaza and a rear garden that can be utilized for different purposes, such as public gatherings and live events. The front plaza was redesigned considering events that can be organized in the building site, as well as the resiliency precautions determined.

The redesign of the green garden on the rear side of the building was also done considering the public use factor. It was decided that green garden area would include beehive colonies, community gardens, and outside seating area for the restaurant located inside the retail floors.

3.8 Resiliency

Hazard Considerations

Flooding is the most likely hazard to occur in the Boston Back Bay area that would threaten the resiliency of 888 Boylston. Numerous options for water proofing and flood prevention were researched that would prevent any water that got inside the building from damaging any critical systems as well as methods that would prohibit the water from getting near the building in the first place.

Another major hazard consideration is the loss of power, water, or gas usage in the building. The building must be able to maintain operation for a minimum of 48 hours in case of disconnect from the city's resources. To allow for this capability, backup generators and other sources of power for the building were explored. In addition, supplementary systems and tanks that could hold excess water and gas needed to support building functions were investigated as means of making the building more resilient.

Many other hazards have the possibility of affecting the new building. Appendix 04 is from the Commonwealth of Massachusetts 2013 Hazard Assessment (State Hazard Mitigation Plan) and lists the likelihood and severity of impact of potential hazards. The resiliency team focused on providing mitigation strategies for the events that have a higher probability of occurrence and will have the most impact on the building such as flood, high wind, and snow events. To protect from these conditions, the structural and envelope teams designed for loads that exceeded minimum code requirements in order to ensure their durability. Appendix 04 offers numerous potential mitigation strategies that were discussed during the development of the building design.

3.9 Sustainability Features

3.9.1 PV Panels

For the estimated output of the rooftop PV panels was calculated using the following equation:

$$E = A * r * H * PR$$

where;

E = Energy (kWh)

A = Total solar panel Area (m^2)

r = solar panel yield (%)

H = Annual average solar radiation on tilted panels (shadings not included)

PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

In order to obtain more accurate results for the output, monthly averages values were used instead of annual average solar ra. The results of the average monthly energy production by the PV panels can be seen in section 4.7.1.

3.9.2 Wind Turbines

The selection of the wind turbines was the first step in this process. The three determining factors in this process are minimum vibration, noise production and efficiency. Conventional wind turbines are known for high vibration and noise production, which makes them unsuitable for urban areas. For this reason, the team started looking into curved vertical blade wind turbines, which are well known are increased aerodynamic performance and low noise and vibration generation. Once the product is determined, the team investigated the wind profile in Boston and the monthly values. Using this data, the monthly energy production by 14 wind turbines was calculated.

3.9.3 High Efficiency Fixtures

In order to justify the usage of high efficiency fixtures, the team investigated two different scenarios; the base case and the design with new fixtures. First the total number of fixtures was determined for different usages such as retail and office use. Once these values were obtained, the specifications given by LEED Green Council for generic water usage of each gender were used to determine the GPM (gallons per minute) and the GPF (gallons per flush) values for each fixture type. The results for both cases were compared to see the impact of using high fixture selection on the water consumption of the entire building. This comparison can be seen in the result section 4.7.4.

4.0 Results

4.1 Composite Columns

Based on the calculations detailed in the preliminary design section of the Methodology, the largest column size found was approximately 5.5’x5.5’, which is not an acceptable size for the floor plan, as a 5.5-foot column would greatly disturb both the retail and the office floor layouts. See Appendix 01 for detailed calculations.

For the other structural group that focused on steel design, the goal was to use compression members with an available strength equal to or exceeding the required strength for that column location. Having calculated all loads for each designated tributary area, load calculations were used to calculate the maximum required capacity (**Φ**c*Pn). Using Table 4.1 in the *Steel Construction Manual 14th Edition* by AISC, the team selected the smallest column size that would sufficiently meet loading requirements. The selected column size was W14x665, which, once covered with fireproofing and/or a concrete shell for aesthetics, would have gross dimensions of 25.6”x 22.7”.

Based on these preliminary calculations, it was decided that the structural steel team would proceed with the design of steel columns, due to their smaller column footprint compared to that of concrete columns. After further calculations, described in the Structural Team II report (Addonisio et al, 2016), the structural group selected composited columns for the gravity load system of the building.

4.2 Bubbledeck

The moment maps for each category can be seen in Appendix 01. In these areas of the slab, depicted in Figure 6, no hollow bubbles were placed to achieve the required shear strength. In the model, the areas that are covered with HDPE bubbles were affected by the weight reduction caused by the usage of hollow bubbles and the critical areas where the shear capacity was exceeded, the slab was detailed as a solid concrete slab.

Table 19: Reinforcement Schedule of the Bubbledeck Slab Systems

		OFFICE	RETAIL	GARAGE
	Top	#4 @ 8" OC	#5 @ 8" OC	#3 @ 8" OC
Edge	**Bottom**	#4 @ 10" OC	#5 @ 10" OC	#3 @ 10" OC
Core		#5 @ 10" OC	#6 @ 10" OC	#5 @ 10" OC
Corner		#4 @ 10" OC	#5 @ 10" OC	#4 @ 10" OC

Integrating the ductwork into the slab system was the next topic to consider. The ductwork layout was obtained from the mechanical group from the competition team, and the areas that the ductwork would impact were established. Once the layouts of the ducts were finalized, the areas that required extra reinforcement were obtained using the moment maps for each floor. While integrating the ductwork into the slab structural system, the first step is to cut openings in the bottom mesh that are approximately 1" apart on all sides of the equipment. Once the mesh is open, supplemental steel is added following the simple rule of "one new rebar for every bar cut". The development length of each bar was determined by a number of factors but principally by the size of the opening and the size of the positive moment steel. An example for this case can be seen in the figure below.

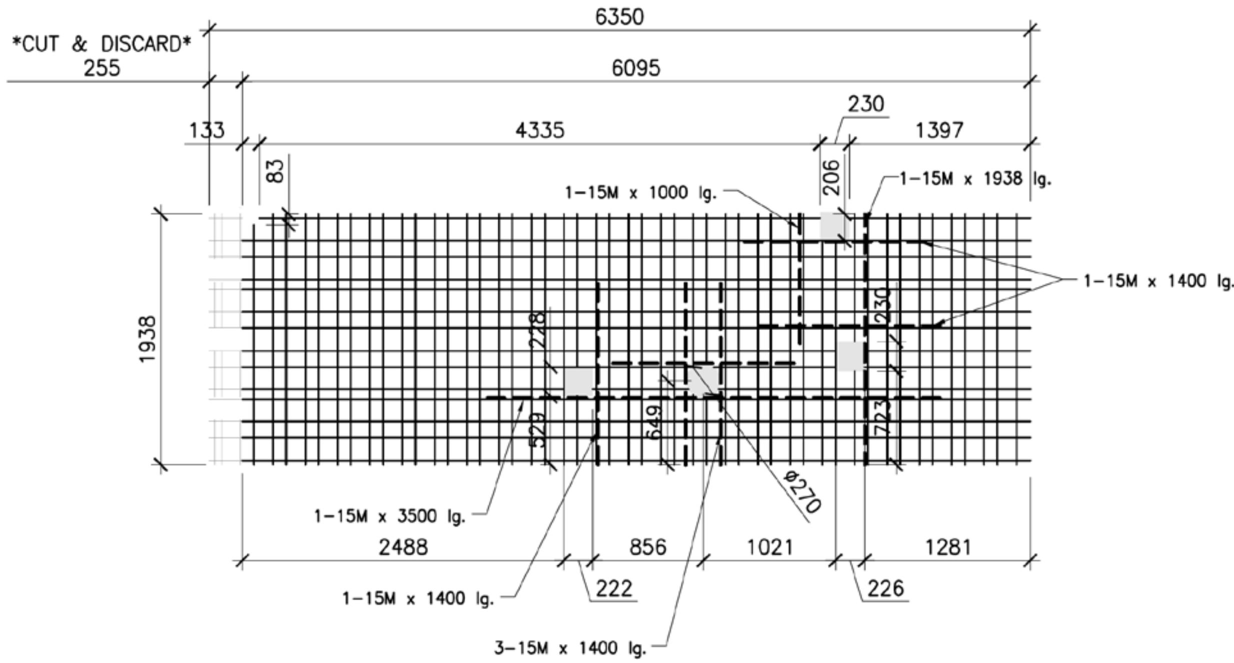

Figure 23: Rebar cutting for the ductwork placement

hollow HDPE bubbles, the reinforcement mesh did not require any major additional of support. This way the integration goals of the team were achieved and enough plenum space was saved to add an additional floor to the building. The maximum size of precast panels that can be produced is 40 feet by 10 feet (see Drawing D01 and D02). The schedules provided in Drawing D01 and D02 were created based on these dimensions and with the objective of minimizing the number of individual panels, which would minimize the number of trips required between the construction site and the prefabrication factory.

The half precast, half site cast nature of the Bubbledeck provides advantages in the construction of the building as well. Once the precast panels arrive to the construction site, they are placed on shores that are placed no more than 7 feet apart. Once the precast panels are in place, required formwork for the perimeter of the slab is installed alongside the additional reinforcement bars. Once every component is in place, the site-casting of the concrete is done. This fast-phased construction cycle leads to minimum amount of work on-site and less time spent for site-cast concrete placement.

Using Bubbledeck panels saved 1,566,136 square feet of concrete when compared to a solid slab with an equivalent carrying capacity. This difference leads to a 96.79 square feet reduction in CO_2 emission caused during the material production and $4,640,403 in the cost of the slab systems. These results demonstrate that Bubbledeck systems are highly cost efficient and environmentally friendly compared to other conventional concrete slab systems.

4.3 Shear Wall

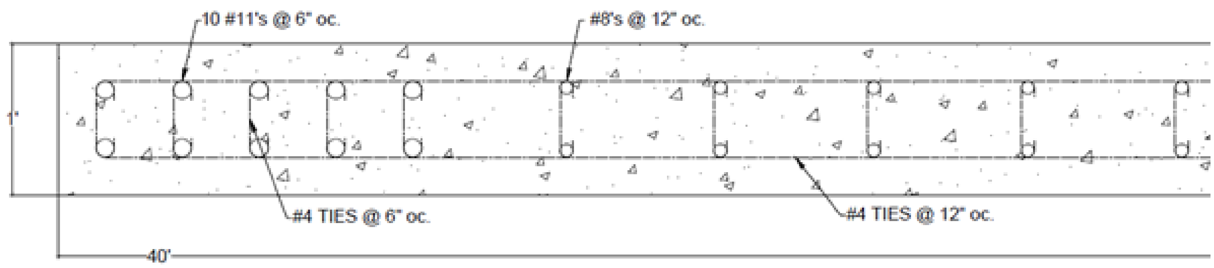

Figure 24: Shear Wall Section View

Based on the calculations, it was determined that the shear wall should be twelve inches thick. It should be reinforced at each end with ten #11 bars at six inches on center and #4 ties at six inches on center. Figure 16 Shear Wall Section View shows the proposed layout of reinforcement bars and ties. This design was confirmed by the interaction diagram, which is depicted in Figure 17 Shear Wall Interaction Diagram.

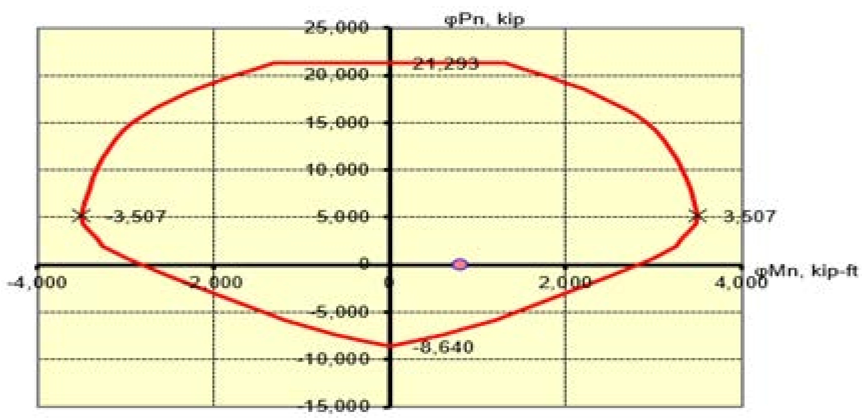

Figure 25: Shear Wall Interaction Diagram

4.4 Foundation

Appendix 03 displays the results of the design calculations for each recommended size drilled shaft and LBE. The table lists the columns on the lowest floor in the parking garage and their corresponding reaction forces. It also shows the number of piles at each diameter size that would be needed to support the load from each column. Steel baseplates were designed by the other structural team to connect the columns to the foundation and were checked for bending and bearing stress.

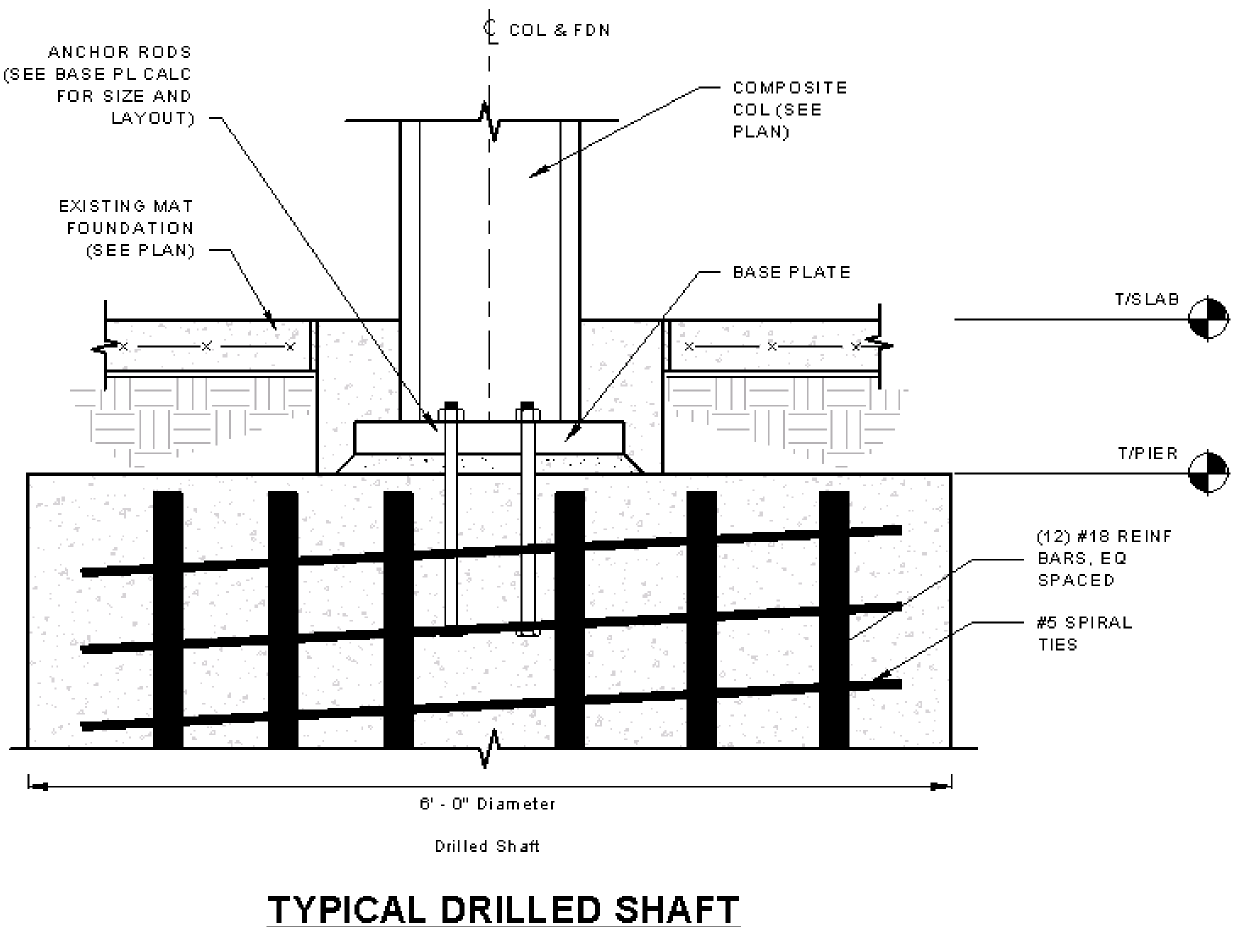

Figure 26: Typical drilled shaft section

A total of forty drilled shafts are required to support the structural frame of the building. Based on the depth assumption above, 80% of the shafts have a 6' diameter while the other 20% have an 8' diameter. This is due to the capacity of the 6' diameter not being enough to support the larger loaded columns. However, even with the largest recommended diameter shafts, 3 columns exceed the maximum capacity under the assumption of a depth that only contains the average 2'-6" of weathered bedrock. When that assumption increases to the largest estimated depth of 5'-6", the capacity is sufficient. The layout of the drilled shafts and their sizes can be seen in Figure 29. A smaller sized shaft would also be acceptable at all the locations; however, multiple column locations would require more than one shaft to be installed to meet capacity. While the smaller size reduces the amount of concrete needed for the piers, the amount of work needed to install the additional shafts and pile caps would have a greater impact on the cost and schedule for construction. The piers each have 12 or 20 #18 bars of vertical reinforcement based on the minimum steel calculation in addition to #5 spiral ties. Figure 28 shows a detailed section of a typical drilled shaft.

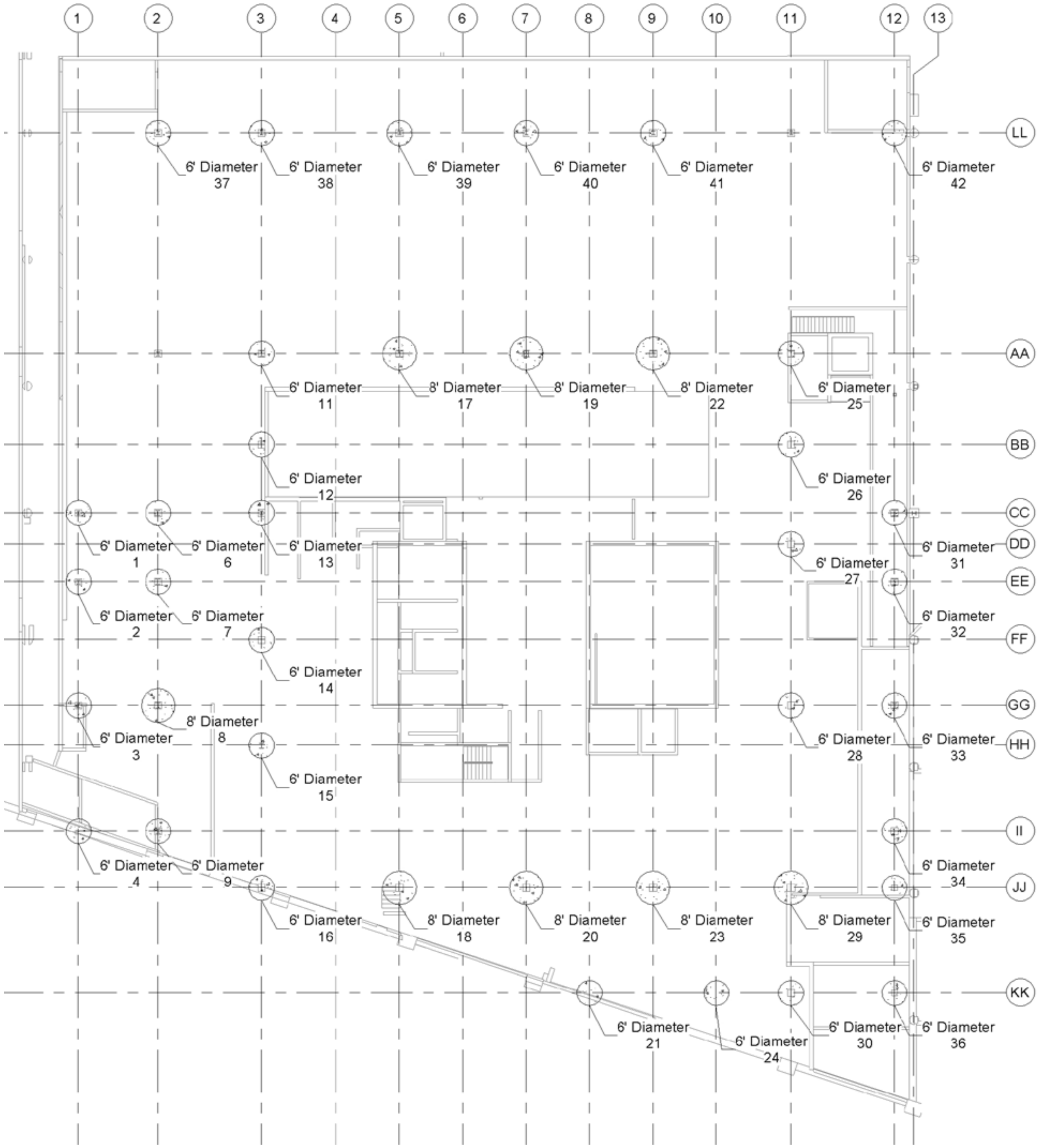

Figure 27: Location of Drilled Shafts

To install a drilled shaft, a hole must be cut out of the floor slab, water stops need to be used at construction joints, and temporary casing is required to be used during excavation to maintain stability of the ground. In addition, based on drillings in surrounding buildings, it is expected that the construction team will encounter cobble and boulders during the excavation process.

4.5 Building Envelope

A unitized curtain wall system provides many architectural and structural benefits to the building. Aesthetically, it allows the building to appear to have a very thin thickness of each floor, as the Bubbledeck was tapered on the edges to give this appearance. See Drawing D06 for a section view of the tapered edges.

Structurally, the team ensured that no gravity loads would be transferred to the glass of the curtain wall. The maximum deflection of each floor slab was calculated in Autodesk Robot to be 0.13 inches, taking the 15-foot cantilever into account. The selected curtain wall system includes a 1-inch gap between the glass panels, filled with a flexible rubber gasket, which will absorb the predicted deflection of the slab and isolate the curtain wall from the flexural response of the slab.

Product specification for the selected curtain wall system can be found in Appendix 08. The envelope system consists of multiple components that offer various solutions depending on the user's preference. Figure 19 Axonometric View of the Envelope Components depicts an exploded axonometric view of the individual pieces forming the mullion system and other components. Item (1) represents the mullion system that is 13 feet tall and 8 feet wide on the office floors. Every mullion includes a casing for shading devices (Item 2) that are readily available in case the occupants would like to include a shading device after removing the detachable shadow box (3) which is a 12-inch thick sandwich panel with foam insulation compressed in between two 3/32-inch thick aluminum panels. Item (4) represents the conduit box where the required electrical equipment for the shading devices can be placed. The conduit box will be cast inside the precast top of the Bubbledeck panel. The shadow boxes consist of three individual sections to provide an effortless installation process. The top (5) and bottom (6) of the shadow box clip to the hooks (7) located on the ceiling and floor finishes and the middle section (8) fits in between these two pieces. See Drawing D05 and D06 for section drawings.

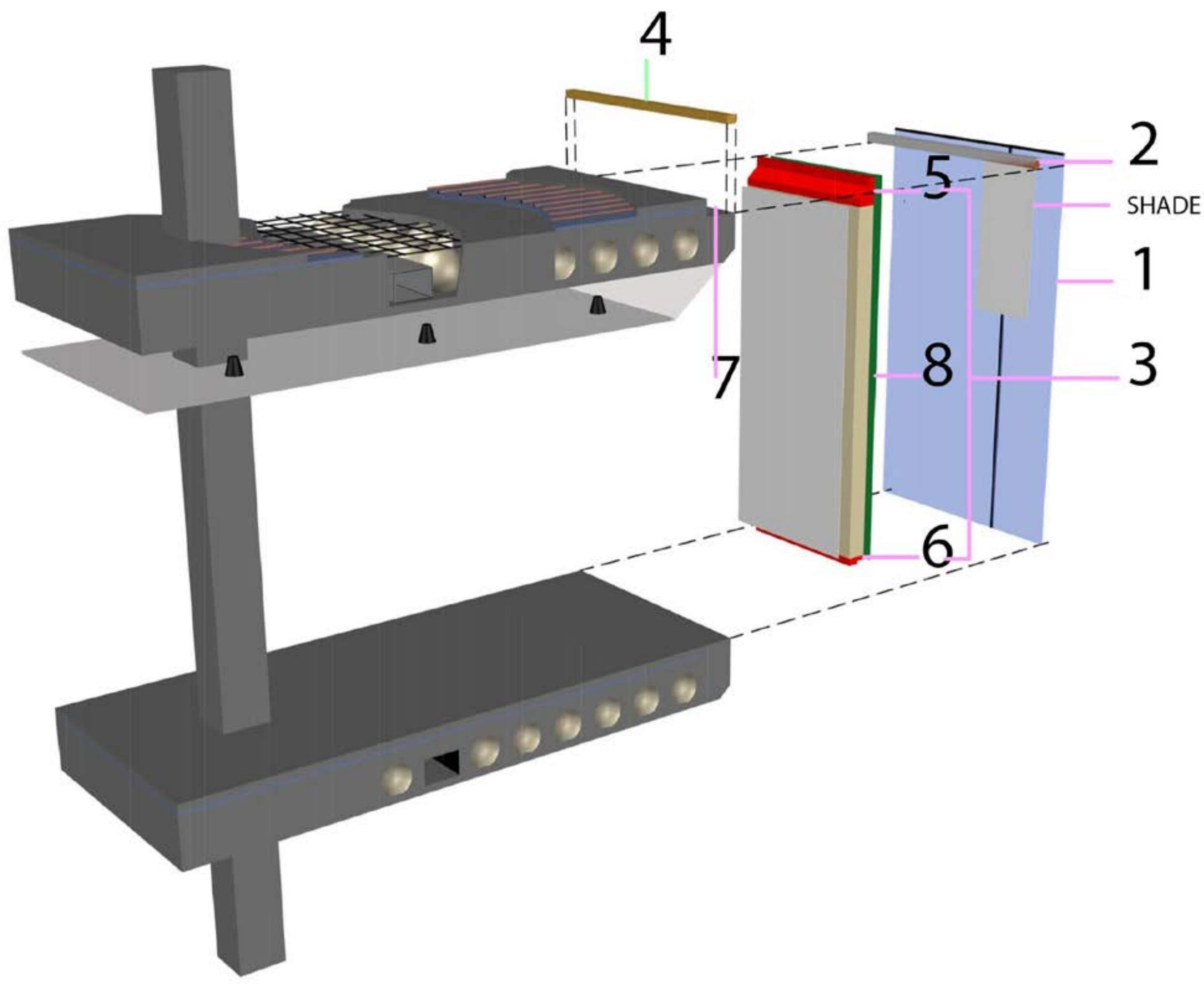

Figure 28: Axonometric View of the Envelope Components

4.6 Architectural Design

4.6.1 Retail Floors

The first three floors of the building serves for retail purposes. The first floor contains a large retail store (about 35,000 square feet) that can be accesses from the front plaza. The upper section of the first floor houses a set of escalators that leads to the second floor retail area. The second floor contains the rest of the retail store and a food court that can house multiple food vendors and around 100 people in the designated seating area. The third floor of the building holds a restaurant, and a lobby area that leads to the offices on the upper floors. The lobby area separates the publicly accessed restaurant area from the offices for security purposes. The detailed layout of the retail floor can be seen in the Drawing 4 and Drawing 5.

4.6.2 Typical Office Floor Design

The layout of the typical office floor plans was redesigned to achieve a tenant-friendly, highly productive office space. The design process took into account productivity elements, circulation, daylighting, and indoor air quality office space. The first step in the redesign of the office floor was deciding on the placement of six standard offices, four executive offices, three meeting rooms, and storage and kitchen areas. In order to utilize the daylight in the most efficient way, the architectural design and daylighting design teams decided to gather all the enclosed rooms around the central core area and provide open space around the perimeter of the open office area. The central core area is enclosed by the shear wall, this area also houses the restrooms, elevator shafts, and exit stairs. The offices round the central core are placed in a symmetrical manner to keep the layout organized. The executive offices are placed on the opposite side of the core from the reception area to minimize traffic around these offices. The first layout was done assuming there will be only one tenant on each floor. To emphasize the flexibility of the space, the architectural team worked on an alternative layout that will be suitable to hold two tenants on one floor. While the one-tenant layout included one large kitchen with one large storage area, the two-tenant alternative includes two storage and two kitchen areas that can be rented for different firms. A larger layout can be seen in Drawing 04.

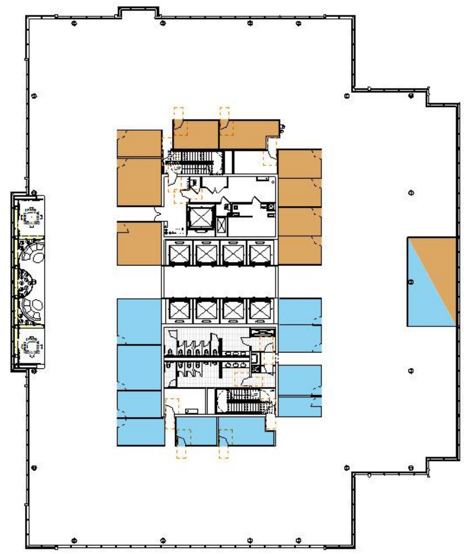

Figure 29: Typical Office Floor Plan

4.6.3 Front Plaza

Figure 31: Front Plaza

The front plaza is a very important feature of the building, in that it conveys the ideology of the building to those passing by. Therefore, it was necessary to design a front plaza that properly reflects the sustainable features of the building to the general public. The plaza will feature various native vegetation such as Eastern Redbud, sweet gums, and black birch. It is important to use native plants to minimize the maintenance and reduce irrigation requirements. The planting areas will be surrounded by seating areas made of concrete and welded steel to allow local artists artists to engage with the public in different ways. The walkways through the plaza will be comprised of walkable PV panel grids provided by Onyx Solar Group to reflect the energy efficiency and sensitivity of the building. The area in front of the restaurant is reserved for outdoor seating that can fit 18 tables without compromising the building circulation.

Figure 30: 3D View of the Front Plaza

4.6.4 Green Garden

A 30,000 ft^2 public-access green area is located on the third floor, in the south section of the property. This green area is intended to minimize the square footage affected by the urbanization in the area and to provide a garden that both tenants and the public can benefit from. The garden will consist of three sections: community garden (a planting area of 4300 ft^2) that can be rented by individuals or the restaurant that will be housed in the retail area, a public access area, and a bee hive colony section. The public area will contain native vegetation, and for this reason, the irrigation systems were chosen as micro spray and standard drip systems to minimize the irrigation water usage. As a result, the water budgeting for irrigation systems decreased the water usage by 80%, compared to a baseline system.

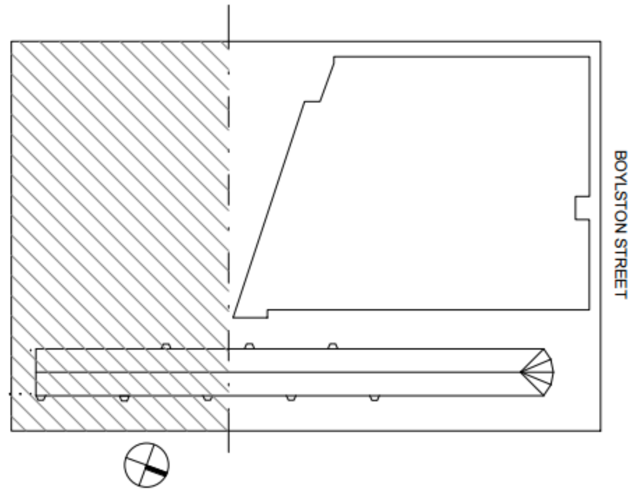

Figure 32: Location of the Green Garden

Table 1. Landscape Water Requirement

Zone	Hydrozone/Landscape Feature Area (sq. ft.)	Plant Type or Landscape Feature	Landscape Coefficient (K_L)	Irrigation Type
1	140	Trees - Low water requirement	0.2	Drip - Standard
2	2,700	Turfgrass - Low water requirement	0.6	Micro Spray
3	19,154	Groundcover - Low water requirement	0.2	Micro Spray
4	1,744	Shrubs - Low water requirement	0.2	Drip - Standard

OUTPUT - DOES THE DESIGNED LANDSCAPE MEET THE WATER BUDGET?

YES If YES, then the water budget criterion is met.
If NO, then the landscape and/or irrigation system needs to be redesigned to use less water.

The designed landscape water requirement is a 80% reduction in water use from the baseline calculated in Part 1.

Figure 33: Water Savings from Irrigation Systems

4.7 Sustainability Features

4.7.1 PV Panels

888 Boylston Street adopts both traditional rooftop and building integrated photovoltaic panels to harvest solar power. The rooftop houses (232) PV panels, with a size of 1560 mm x 1050 mm x 50 mm and a rated capacity of 327 Watts each. These panels are adjustable from a central control unit to accommodate the changing angle of the sun throughout the year, which maximizes their performance. The rooftop panels are responsible for the production of 62,234 kWh annually as seen in Appendix 05. The monthly production values vary every month according to environmental factors such snow coverage and radiation path.

4.7.2 Wind Turbines

There are fourteen UGE 9M (rated output of 14,500 kWh/yr each) wind turbines located on top of the building. These wind turbines were chosen to fulfill the design requirements such as low noise and vibration generation, and high energy output. The curved blade shape provides increased sweep area for each blade and minimizes noise generated by the blades since the tip speed of each turbine is less than for traditional turbine blades. In total, the turbines are generating 127,461 kWh annually on average. The performance calculations can be seen in Appendix 05.

Figure 34: UGE-9M Wind Turbine

4.7.3 Greywater Filtration

One of the important features of a smart building is to fulfill the water demands through harvested rainwater and treatment of greywater collected in the building. A 65,000-gallon tank was selected by considering the volume of rainwater that can be harvested monthly and the volume of greywater that will be recycled. The tank sizing information and product specifications can be found in Appendix 07.

4.7.4 High Efficiency Fixtures

Throughout the whole building, every plumbing fixture and appliance was selected from among the list of Water Sense labeled fixtures. Every fixture that was selected, offers greater flush and flow performance than the comparable baseline fixture. With the usage of high efficiency fixtures in the kitchen and bathroom areas, it has been calculated that the design water usage is 43% less than the baseline usage with conventional fixtures. The calculations considered average fixture usage by male and female tenants determined by the U.S Green Building Council. In Table 17 Annual Water Consumption for Baseline and Design Fixtures, the impact of using high efficiency fixtures can be seen for each type of fixture. More information can be found in the Appendix 06.

Table 20: Annual Water Consumption for Baseline and Design Fixtures

Fixture Type	Baseline (gal/yr)	Design (gal/yr)
Toilet	1,562,200	1,274,040
Urinal	976,375	0
Faucet	1,379,569	811,606.5
Total	3,918,144	2,087,196.5

4.7.5 Bike Storage and Sharing

A bike storage area will be included on the street level of the building to provide a safe space for the storage of the bikes. As well as the storage, showers will be located on the 5th floor with the necessary locker room area to provide privacy and comfort for the users of the building. As well as the storage area, bike sharing racks will be located in the front plaza of the building by Hubway Bike Sharing Company. This sharing system will be accessible for both the public and the tenants. This alternative way of transportation will contribute to lowering the emission of the tenants of the building and promote a healthier and sustainable life among the public as well.

4.8 Resiliency

4.8.1 Additional Floor

The most important measure to make the building more resilient was moving the mechanical and electrical rooms that were previously located below grade in the parking garages above the threat of flooding. Since there is limited space in the existing mechanical floor, moving this equipment into the main building area would take away about 3400 square feet of rentable space from the owner. However, through collaboration of both the mechanical and structural teams, a solution was developed that allowed for an entirely new floor to be added, without increasing the overall height of the building that would house this equipment and add even more usable space. The Bubbledeck is a precast concrete floor system which makes floor slabs lighter and stronger by incorporating large, hollow plastic balls in a lattice of steel. The use of this system instead of typical cast-in-place concrete floor slabs allowed mechanical ducts to be embedded within the slab and enabled a one foot reduction in floor-to-floor height on each level. As a result, an additional floor was added without exceeding the original designed building height. The new floor is located between the previously designed fourth and fifth floors. Not only does this solution provide a safer space for critical equipment to be located, it also provides an additional 10,000 ft^2 of leasable space on the 5th floor and several parking spots for the owner.

4.8.2 Flood proofing

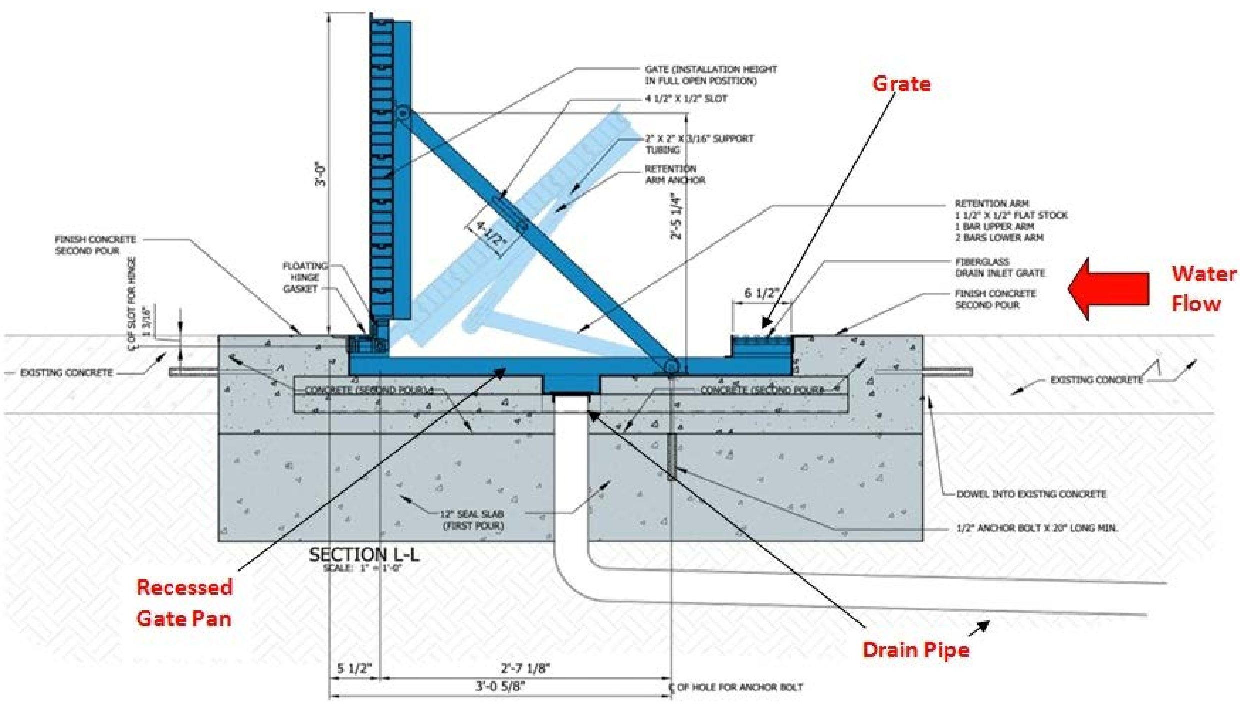

Figure 35: Floodgate Section[37]

Even though the critical mechanical and electrical equipment will no longer be located in a flood prone area of the building, another form of flood protection was established outside the building. While a flood will no longer will shut down the building, it could still cause serious damage to the lower floors of the structure, where all the retail merchandise is located. A retractable FloodBreak flood gate, as detailed

[37] FloodBreak. "How it works." *FloodBreak Revolutionary Flood Control*. Web.

in Figure 35, is to be implemented around the exposed perimeter of the building. When idle, the wall is flush with the pavement, but when water threatens to flood the building, the four-foot wall automatically rises to hold back the water.[38] From the product description on the Floodbreak website,

> ***"The concept is simple – the rising floodwater creates the hydrostatic pressure to float the buoyant aluminum beam and activate the self-sealing rubber gaskets. The higher the water rises, the higher the flood barrier is lifted until it reaches 90° and is held closed by the floodwater. When the water recedes, the flood barrier returns to its recessed location in front of the entry way, allowing vehicle and pedestrian passage to resume" (FloodBreak).***

This concept allows the device to be self-sustaining, not requiring any power or human interaction to be functional. All materials in the product are coated to protect the floodgate from rust or corrosion (FloodBreak).

Additional measures will be installed to assist in protecting the lower floors of the building from water damage. Equipment such as a sump pumps and backflow preventers will quickly remove any water that has accumulated in the bottom garage floors and prevent it from backing up the building's sewage system. The Resiliency team also proposes to install the retractable floodgate at other entrances to the parking lot such as that from the Prudential Center to avoid water flooding from other entrances that are not in the property of 888 Boylston Street.

[38] FloodBreak. "How it works." *FloodBreak Revolutionary Flood Control*. Web.

5.0 Conclusions

The structural system for 888 Boylston Street was designed to achieve the goal of a completely integrated, high-performance building. The use of the Bubbledeck system coordinated to include the radiant floor system, ductwork, and electrical wiring, and allowed for a reduction of floor to floor height, enabling the team to add an additional floor on to the building. The constructability of this system was monitored to reduce disturbance to neighboring buildings. Sustainable measures were implemented to help the building surpass the goal of energy consumption 50% below ASHRAE standards. Lastly, the building was designed to withstand the high wind, rain, and snow loads in the Boston area, making it more resilient and durable.

Goals that were met:

- Select design and construction methods that minimize the disturbances to neighboring buildings and the Massachusetts Turnpike.
    - Drilled piles
    - Half precast Bubbledeck
- Plan site logistics in a way that will successfully coordinate the construction phase without negatively affecting the local environment.
- Design a structure that, in addition to resisting gravity loads, will be able to resist design wind loads, which is an important consideration in the City of Boston.
    - Reinforced concrete shear wall
    - Bubbledeck
- Design every aspect of the building sustainably.
    - Concrete structural elements that use sustainable concrete
    - Sustainable features such as water filtration, green gardens, PV panels, wind turbines, bike sharing units.
- Design all aspects of the building, including the building envelope, to contribute to an overall building energy usage that is at least 50% below ASHRAE requirements.
    - PV panels
    - Wind Turbines
    - Unitized envelope design and shadowboxes

Sustainable Concrete

Concrete has become an increasingly more sustainable option as a building material. New technological developments have allowed for a decrease in the amount of carbon dioxide production caused by the manufacturing of cement along with the increasing use of more energy efficient plants which down on fuel consumption. Concrete can also become more durable by changing the aggregates used in the mixture of this material to more sustainable ingredients. It is also a much more flexible option as a building material and can be more easily manufactured to fit specific situations and minimize construction and material costs.

The World Business Council for Sustainable Development claimed that, "after water, concrete is the planet's most used material, and this year three tones (metric tons) of it will be used for every one of the six billion people on Earth"[39]. Many of these concrete mixtures use ingredients such as Portland cement as a binding agent in production. Portland Cements are also known as hydraulic cements and are defined by the fact that they set and harden due to a chemical reaction of water and hydrogen. In 2004, the EPA estimated that the world total annual production of hydraulic cement was 2 billion metric tons across over 150 different countries[40]. However, to manufacture just one ton of the Portland cement using the typical method, produces about one ton of carbon dioxide. About half of that is from the reaction that takes place when calcium carbonates in the mixture are heated in a kiln and the other half is from the fuel to power production. Recent technical developments have allowed production of cement to have about an 8% reduction in the amount of carbon dioxide from the chemical reaction. In addition, many manufacturers are using alternative sources of fuel such as recycled materials to reduce emissions even more[41].

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[39] Suderland, Charlie, Lorenzo H. Zambrano, Liam O'Mahony, Carlo Pesenti, Pramote Techasupatkul, N. S. Sekhsaria, Bernard Kasriel, Michio Kimura, Ricardo B. Horta, Bernd Scheifele, Carlos Alves, Dimitri Papalexopoulos, Francisco Reynés, Markus Akermann, M. K. Singhi, and Fábio Emírio De Moraes. *The Cement Sustainability Initiative Progress Report*. Rep. World Buisness Council for Sustainable Development, June 2005. Web. <http://www.wbcsdcement.org/pdf/csi_progress_report_2005.pdf>.

[40] *Appendix A: Overview of Portland Cement and Concrete*. Rep. Environmental Protection Agency, 6 Sept. 2013. Web. <http://www3.epa.gov/epawaste/conserve/tools/cpg/pdf/app-a.pdf>.

[41] Nasvik, Joe. "Sustainable Concrete Structures." *Concrete Construction*. N.p., 09 Apr. 2009. Web. <http://www.concreteconstruction.net/concrete-construction/sustainable-concrete-structures.aspx>.

The sustainability and even durability of concrete can be increased by altering the distribution of aggregate in the mixtures. One option is replacing some of the Portland cement used as a binding agent with fly ash and slag cement, materials that would otherwise go unused and end up in landfills. It has been discovered that replacing 15% - 40% of this ingredient can improve the features of concrete such as its strength and long term durability. Using less water can also have the same effects, and manufacturers have begun allowing the usage of grey water in mixing as long as it meets the standards for this process set by the American Society for Testing and Materials. These admixtures are making concrete a more viable option for a variety of situations including tall buildings[42].

Adaptability is one of the major benefits in choosing concrete over another structural building material. The size of structural elements can be reduced by the structural engineer calling for a higher performance mixture of concrete, or the mechanical engineer for a project can use the thermal mass capacity of the concrete element to store energy and reduce demand for heating and cooling. In addition, since these higher performance mixtures are so durable, they can be designed to resist extreme situations such as high winds or earthquakes and allow for a more resilient building[4]. While the cost for more sustainable concrete may be higher upfront, it can extend the useful life of the structure and allow for a more energy efficient building, making it a valuable option as a building material.

[42] Nasvik, Joe. "Sustainable Concrete Structures." *Concrete Construction*. N.p., 09 Apr. 2009. Web. <http://www.concreteconstruction.net/concrete-construction/sustainable-concrete-structures.aspx>.

Bibliography

"6 Factors That Effect Solar PV System Efficiency." *Solar Power for Ordinary People*. Living on Solar Power, 06 Mar. 2013. Web. 10 Oct. 2015. <https://livingonsolarpower.wordpress.com/2013/03/06/6-factors-that-effect-solar-pv-system-efficiency/>.

"About Solar Energy: Passive Solar, Solar Thermal, and Photovoltaic." *Energy and Environmental Affairs*. N.p., 2015. Web. 10 Oct. 2015. <http://www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/solar/about-solar-energy.html>.

"Energy Efficiency & Environmental News: Transparent PV Panel." *F Energy Efficiency and Environmental News* (Nov. 1992): n. pag. *Http://p2ric.org/*. Florida Energy Extension Service, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida., 2014. Web. 11 Oct. 2015.

"Energy." *Energy*. Royal Society of Chemistry, n.d. Web. 10 Oct. 2015. <http://www.rsc.org/campaigning-outreach/global-challenges/energy/#solar>.

"Perth Precast." *Bubbledeck*. Precast Australia, n.d. Web. 23 Mar. 2016.

"Photovoltaic Transparent Glass for BIPV." *OnyxSolar BIPV*. OnyxSolar, n.d. Web. 11 Oct. 2015.

"Renewable Power Generation 2010." *Renewable Energy Focus* 12.4 (2011): 38-41. *EPA*. US Environmental Protection Agency, 15 May 2008. Web. 10 Oct. 2015. <http://www3.epa.gov/statelocalclimate/documents/pdf/on-site_generation.pdf>.

"Solar PV - Solar PV Facades - Rainscreen Cladding." *Solar PV - Solar PV Facades - Rainscreen Cladding*. N.p., n.d. Web. 12 Oct. 2015. <http://www.solarpv.co.uk/solar-pv-facades.html>.

"Walkable Photovoltaic Floor (For BIPV) - Onyx Solar - PV Floor." *Walkable Photovoltaic Floor (For BIPV)-*

"Wind Energy: Facts." *Energy and Environmental Affairs.* Commonwealth of Massachusetts, 2015. Web. 11 Oct. 2015. <h ttp://www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/wind/wind-energy-facts.html#a>.

Allen, Edward, and Joseph Iano. *The Architect's Studio Companion: Rules of Thumb for Preliminary Design*. 5th ed. Hoboken, NJ: John Wiley & Sons, 2012. Print.

Appendix A: Overview of Portland Cement and Concrete. Rep. Environmental Protection Agency, 6 Sept. 2013. Web. <http://www3.epa.gov/epawaste/conserve/tools/cpg/pdf/app-a.pdf>.

Architectural Engineering Institute. "2016 Project Guidelines." *ASCE Charles Pankow Foundation, Annual Architectural Engineering Student Competition*. Architectural Engineering Institute, n.d. Web. 23 Mar. 2016.

Bubbledeck North America. *® Product* (n.d.): n. pag. *Bubbledeck*. Bubbledeck North America, 02 Oct. 2012. Web. 23 Mar. 2016.

Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary. Farmington Hills, MI: American Concrete Institute, 2011. *Public Resource*. Https://law.resource.org/pub/us/cfr/ibr/001/aci.318.1995.pdf, 2011. Web. 5 Jan. 2016.

Concrete Reinforcing Steel Institute. "Design Guide for Voided Concrete Slabs." *Builder's Book, Inc. Bookstore*. CRSI, 2014. Web. 04 Jan. 2016.

Cornell, Matt. "Beware Waffle Slabs." *Cornell Engineers*. N.p., 16 Apr. 2014. Web. 13 Oct. 2015. <https://www.cornellengineers.com.au/beware-waffle-slabs/>.

Eiffert, Patrina, and Gregory J. Kiss. *Building-integrated Photovoltaic Designs for Commercial and Institutional Structures: A Sourcebook for Architects*. Golden, CO: National Renewable Energy Laboratory, 2000. Print.

FloodBreak. “How it works.” *FloodBreak Revolutionary Flood Control*. Web.

Foster, Thomas Elliott. "Case Study Done for J & W Lowry Limited." A Case Study Identifying the Advantages and Disadvantages of Certain Foundation Types (n.d.): n. pag. J. & W. LOWRY LIMITED. 9 Mar. 2013. Web. 6 Oct. 2015. <http://www.jwlowry.co.uk/wp-content/uploads/Brown-Field-Site-and-Suitable-Foundation-Types.pdf>.

Galeb, Alaa C., and Zainab F. Atiyah. "Optimum Design of Reinforced concrete waffle slabs." *International Journal of Civil and Structural Engineering* 1.4 (2011): n. pag. Web. 29 Sept. 2015.

Gray, Jonathan, and Jerry Yudelson. "Rainwater Harvesting Systems. Code of Practice." (n.d.): n. pag. *Stark Environmental*. Web. 15 Oct. 2015. <http://www.starkenvironmental.com/downloads/Interface_Engineering.pdf>.

Haley & Aldrich, Inc. Boston, Massachusetts, comp. *REPORT ON SUBSURFACE CONDITIONS AND FOUNDATION DESIGN RECOMMENDATIONS PROPOSED 888 BOYLSTON STREET PRUDENTIAL CENTER BOSTON, MASSACHUSETTS*. Boston: n.p., May 2014. Print.

James, T., A. Goodrich, M. Woodhouse, R. Margolis, and S. Ong. "Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis of Installed Rooftop System Prices." (2011): n. pag. *NREL*. Web. 12 Oct. 2015. <http://www.nrel.gov/docs/fy12osti/53103.pdf>.

Kayal, Sarah. "Application of PV Panels in Large Multi-Story Buildings." *CalPoly*. N.p., June 2009. Web. 12 Oct. 2015.

Martina Schnellenbach-Held and Karsten Pfeffer,"Punching behavior of biaxial hollow slabs" Cement and Concrete Composites, Volume 24,Issue 6, Pages 551-556,December 2002

Meyers, C. Bracken. "Types of Wind Turbines." *Centurion Energy*. N.p., 09 Dec. 2013. Web. 11 Oct. 2015. <http://centurionenergy.net/types-of-wind-turbines>.

Nasvik, Joe. "Sustainable Concrete Structures." *Concrete Construction*. N.p., 09 Apr. 2009. Web. <http://www.concreteconstruction.net/concrete-construction/sustainable-concrete-structures.aspx>.

Onyx Solar. N.p., n.d. Web. 12 Oct. 2015. <http://www.onyxsolar.com/walkable-photovoltaic-roof.html>.

Sandt, Edward, Dr. "Structural Concrete Design." CVEN 444. Texas A&M, College Station. *Slideshare*. Web. 6 Oct. 2015. <http://www.slideshare.net/goryglow/structural-system-overview>.

Schwartz, Kurt, and John P. Murray. *State Hazard Mitigation Plan*. Rep. Commonwealth of Massachusetts, Sept. 2013. Web.

Sergiu Călin, Roxana Gînţu and Gabriela Dascălu, "Summary of tests and studies done abroad on the Bubbledeck slab system", The Buletinul Institutului Politehnic din Iaşi, t. LV (LIX), f. 3, 2009.

Siong, Wei. *Deep, Intermediate and Shallow Foundation*. Digital image. *Scribd*. N.p., 28 Aug. 2011. Web. 6 Oct. 2015. <http://www.scribd.com/doc/63429538/Shallow-Foundation-and-Deep-Foundation#scribd>.

Suderland, Charlie, Lorenzo H. Zambrano, Liam O'Mahony, Carlo Pesenti, Pramote Techasupatkul, N. S. Sekhsaria, Bernard Kasriel, Michio Kimura, Ricardo B. Horta, Bernd Scheifele, Carlos Alves, Dimitri Papalexopoulos, Francisco Reynés, Markus Akermann, M. K. Singhi, and Fábio Emírio De Moraes. *The Cement Sustainability Initiative Progress Report*. Rep. World Buisness Council for Sustainable Development, June 2005. Web. <http://www.wbcsdcement.org/pdf/csi_progress_report_2005.pdf>.

TWO-WAY SLABS (2007): n. pag. *Iugaza.edu*. Web. 13 Oct. 2015. <http://site.iugaza.edu.ps/sshihada/files/2012/09/Slabs-11.pdf>.

United States Environmental Protection Agency. *See Coastal Storm Surge Scenarios for Water Utilities*. Web.

University of Sheifield. "Information Commons." *Construction 8*. University of Sheifield, n.d. Web. 23 Mar. 2016.

WebUrbanist. "Invisible Bicycles: Tokyo's High-Tech Underground Bike Parking." *WebUrbanist RSS*. N.p., 26 Mar. 2015. Web. 10 Oct. 2015. <http://weburbanist.com/2015/03/26/invisible-bicycles-tokyos-high-tech-underground-bike-parking/>.

6.0 Appendices

1. Bubbledeck Calculations
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7.0 Drawings

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6. Additional Floor Architectural Layout
7. Office Floor Architectural Layout
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9. Building Envelope Details

APPENDIX 01: Bubbledeck Slab System Calculations

Design Data

Concrete	Compressive Strength (f'c)	4000	psi
	Density wc	156	pcf
Reinforcing Steel	Yield Strength	60000	psi
Loads	Superimposed Dead Loads	20	psf
	Live Load	50	psf

1) **As Calculation**

Step 1) **Assume tension-controlled section**

Phi 0.9

Step 2) **Determine the nominal strength coefficient of resistance R n**

Rn 95.59 psi

$$R_n = \frac{M_u}{\phi b d^2}$$

Step 3) **Determine the required reinforcement ratio p**

p 0.00016

Step 4) **Determine the required area of tension reinforcement A s**

$$A_s = \rho b d$$

As 4.042 in^2

Step 5) **Determine the minimum required area of reinforcement A s,min**

$A_{s,\,min}$ 4.45 in^2

$$A_{s,min} = 0.0018bh$$

Step 6) **Determine depth of equivalent rectangular stress block a**

a 1.19 in^2

$$a = \frac{A_s f_y}{0.85 f_c' b}$$

Step 7) **Determine β 1**

β 1 0.84 for f'c=4,000 psi -

Step 8) **Determine neutral axis depth c**

c 1.4152661 inch

$$c = \frac{a}{\beta_1}$$

Step 9) **Determine ε t**

ε_t 0.1029871 > 0.004 -

0.1029871 > 0.005 -

$$\varepsilon_t = 0.003\left(\frac{d}{c} - 1\right)$$

Step 10) **Choose size and spacing of reinforcing bars**

As 4.455 in^2

bar #4 0.44 -

amount 14 -

Moment transfer

b_1 27.375

b_2 36.75

γ_f 0.6347662

$\gamma_f M_u$ 126.00386

$$\gamma_f = \frac{1}{1 + (2/3)\sqrt{b_1/b_2}}$$

$$b_1 = c_1 + \frac{d}{2} =$$

$$b_2 = c_2 + d$$

2) **Check two-way shear requirements**

Solid area around column = Tributary area of column − $\frac{\text{(Shear reduction factor)(Allowable direct shear force)}}{\text{Total factored uniformly distributed load}}$

		Vc
11-31		699.28222
11-32	interior	349.5305
	edge	349.30815
	corner	349.08581
11-33		697.28

ΦV_c 522.96167

Solid Area Around Column 254.469 ft^2

Factored shear stress due to gravity	$V_u = q_u(A_t - b_1 b_2)$
At	415
b1	27.375
b2	36.750
Vu	168.12795

$0.3M_o$ 229.04348

γ_v 0.37

A_c 1715.625

$J_c c_{AB}$ 20931.225

v_u 145.95767

Allowable stress 189.73666

11.11.2.1 — For nonprestressed slabs and footings, V_c shall be the smallest of (a), (b), and (c):

(a) $$V_c = \left(2 + \frac{4}{\beta}\right)\lambda\sqrt{f_c'}\,b_o d \quad (11\text{-}31)$$

where β is the ratio of long side to short side of the column, concentrated load or reaction area;

(b) $$V_c = \left(\frac{\alpha_s d}{b_o} + 2\right)\lambda\sqrt{f_c'}\,b_o d \quad (11\text{-}32)$$

where α_s is 40 for interior columns, 30 for edge columns, 20 for corner columns; and

(c) $$V_c = 4\lambda\sqrt{f_c'}\,b_o d \quad (11\text{-}33)$$

13.6.3.6 — The gravity load moment to be transferred between slab and edge column in accordance with 13.5.3.1 shall be $0.3M_o$.

$$\gamma_v = 1 - \gamma_f$$

$$A_c = (2b_1 + b_2)d$$

$$J_c c_{AB} = \frac{2b_1^2 d(b_1 + 2b_2) + d^3(2b_1 + b_2)}{6b_1}$$

$$v_u = \frac{V_u}{A_c} + \frac{\gamma_v M_u}{J_c c_{AB}}$$

$$\phi v_c = \phi 4\lambda\sqrt{f_c'}$$

Table: Product Parameters for Bubbledeck Cage Only and Precast Panel

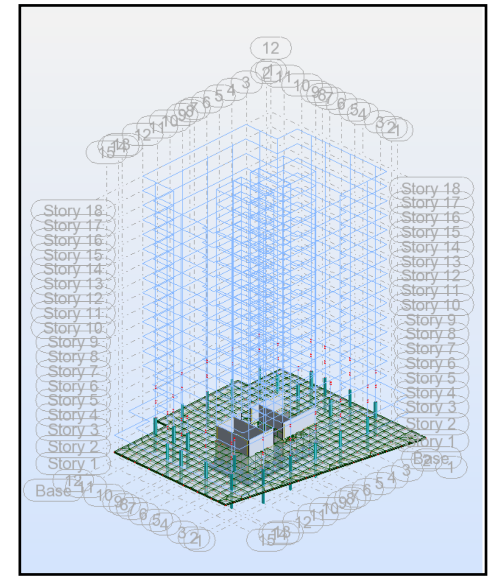
Slab Depth	[inch]	9	11	12	14	16	18	20	22	24	30
Dead Load Reduction	[psf]	30	41	46	52	66	73	82	94	103	122
Stiffness Correction Factor	[%]	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Shear Reduction Factor	[%]	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Ball Diameter	[inch]	7	8 7/8	9 3/4	10 5/8	12 3/8	14 1/8	16	17 3/4	19 1/2	23
Space between Balls	[inch]	1 5/8	1 5/8	1 3/4	1 3/4	1 3/4	1 7/8	2	2	2 1/8	2 3/4
On Center Spacing	[inch]	8 3/4	10 1/2	11 1/2	12	13 3/4	16	18	19 5/8	21 5/8	25 3/4
Balls psf	[psf]	1.37	1.14	1.04	0.98	0.87	0.75	0.67	0.61	0.55	0.47
Concrete Displacement	[ft^3/ft^2]	0.20	0.28	0.31	0.35	0.44	0.49	0.55	0.63	0.69	0.81
CAGE ONLY											
Nominal Cage Size	[ft (W x L)]	4 x 8	4 x 8	4 x 8	4 x 8	6 x 8	7 x 8	8 x 8	8 x 8	8 x 8	8 x 8
Balls per Cage	[-]	55	48	32	32	35	30	25	16	16	16
PRECAST PANEL											
Precast Size Maximum	[ft (W x L)]	11 x 40	11 x 40	11 x 40	11 x 40	11 x 40	11 x 40	11 x 40	11 x 40	11 x 40	11 x 40
Nominal Balls per Panel	[-]	810	540	450	440	315	240	190	145	130	110
Panel Thickness	[inch]	2 1/2	2 1/2	2 1/2	2 1/2	3	3	3	3	3	3

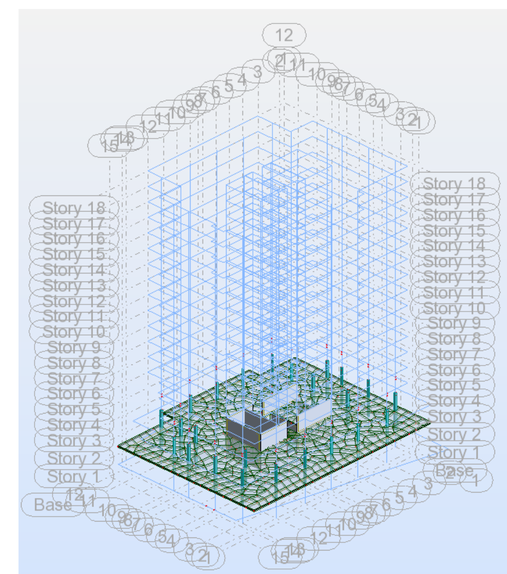
Note:
Precast Panel the site poured concrete is further reduced by the appropriate thickness of precast panel.
Precast Panel includes the positive moment bottom structural steel.

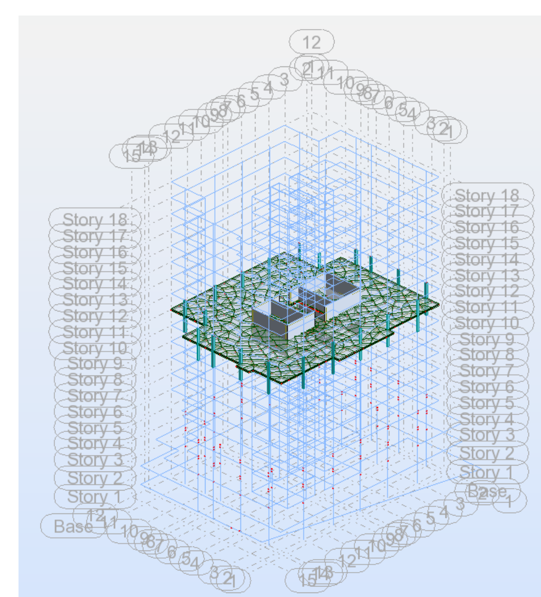
Courtesy of BubbleDeck.

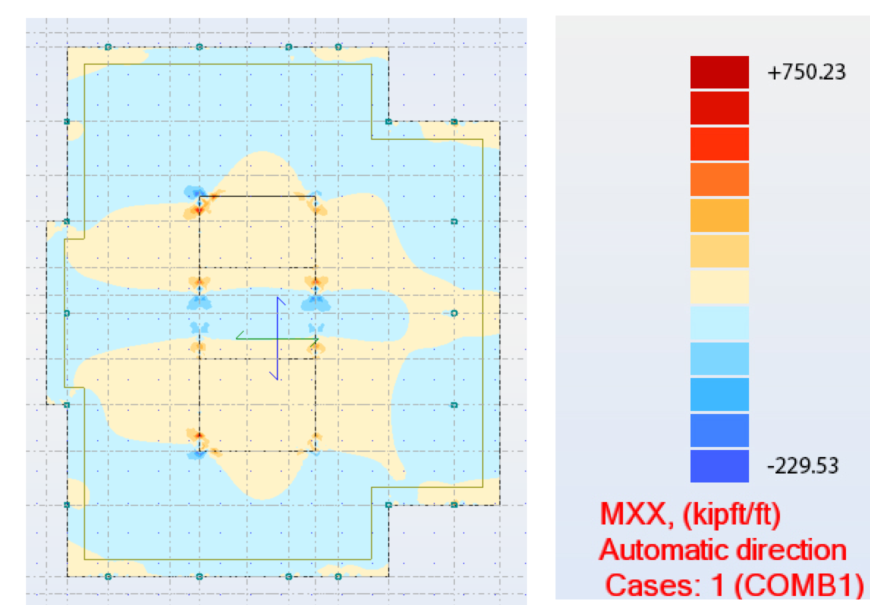
APPENDIX 01: Bubbledeck Slab System Calculations

GARAGE	FLEXURAL REINFORCEMENT TABLE									
Mu	245.6	298.121	509.651	0	201.959	163.481	201.959	471.179	134.639	153.855
b	132	132	132	132	132	132	132	132	132	132
As	2.942	3.579	6.176	0	2.414	1.951	2.414	5.700	1.605	1.835
Rn	70.565	85.655	146.432	0	58.026	46.971	58.026	135.378	38.684	44.205
p	0.001	0.001	0.002	0	0.001	0.001	0.001	0.002	0.001	0.001
As	2.942	3.579	6.176	0	2.414	1.951	2.414	5.700	1.605	1.835
A s, min	4.455	4.455	4.455	4.455	4.455	4.455	4.455	4.455	4.455	4.455
Bar #	4	4	5		3	3	3	5	3	3
Amount	14	14	14	14	14	14	14	14	14	14
Spacing	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125
RETAIL	FLEXURAL REINFORCEMENT TABLE									
Mu	643	780.503	1334.307	0	528.744	428.007	528.744	1233.584	352.496	402.803
b	180	180	180	180	180	180	180	180	180	180
As	7.779	9.486	16.528	0	6.373	5.142	6.373	15.226	4.224	4.835
Rn	135.480	164.452	281.138	0	111.406	90.181	111.406	259.916	74.271	84.870
p	0.002	0.003	0.005	0	0.002	0.002	0.002	0.005	0.001	0.001
As	7.779	9.486	16.528	0	6.373	5.142	6.373	15.226	4.224	4.835
A s, min	6.075	6.075	6.075	6.075	6.075	6.075	6.075	6.075	6.075	6.075
Bar #	6	6	6		5	5	5	6	5	5
Amount	18	18	18	18	18	18	18	18	18	18
Spacing	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125
OFFICE	FLEXURAL REINFORCEMENT TABLE									
Mu	336.2	408.095	697.658	0	276.460	223.789	276.460	644.994	184.307	210.610
b	132	132	132	132	132	132	132	132	132	132
As	4.043	4.923	8.528	0	3.316	2.678	3.316	7.865	2.202	2.519
Rn	96.596	117.253	200.449	0	79.432	64.298	79.432	185.318	52.955	60.512
p	0.002	0.002	0.003	0	0.001	0.001	0.001	0.003	0.001	0.001
As	4.043	4.923	8.528	0	3.316	2.678	3.316	7.865	2.202	2.519
A s, min	4.455	4.455	4.455	4.455	4.455	4.455	4.455	4.455	4.455	4.455
Bar #	5	5	6		4	4	4	6	4	4
Amount	14	14	14	14	14	14	14	14	14	14
Spacing	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125	10.125









APPENDIX 02: Foundation Design Calcualtions

Bottom Garage Floor Columns											
Bedrock Depth	7.5	ft									
						Number of Drilled Shafts Needed per Column					
Column #	Pu (k)	ASD (k)	LRFD (k)	MIN (k)		# 4' Dia	# 5' Dia	# 6' Dia	# 7' Dia	# 8' Dia	LBE
1	350.1	332.50	359	332.5		1	1	1	1	1	1
2	670.2	613.00	753	613		1	1	1	1	1	1
3	893.3	813.60	983	813.6		1	1	1	1	1	1
4	854.8	792.3	983	792.3		1	1	1	1	1	1
5											
6	3,368.10	3,268.60		3,268.60		2	1	1	1	1	1
7	3,547.60	3,398.30		3,398.30		2	2	1	1	1	1
8	4,746.10	4,614.40		4,614.40		2	2	2	1	1	1
9	3,132.50	3,030.40		3,030.40		2	1	1	1	1	1
10											
11	2,186.00	2,137.50	2300	2,137.50		1	1	1	1	1	1
12	2,541.60	2,483.80	2730	2,483.80		1	1	1	1	1	1
13	705.3	679.50	753	679.5		1	1	1	1	1	1
14	729.6	640.30	753	640.3		1	1	1	1	1	1
15	1,323.50	1,181.10	1460	1,181.10		1	1	1	1	1	1
16	4,159.80	4,031.50		4,031.50		2	2	1	1	1	1
17	6,822.20	6,510.00		6,510.00		3	2	2	2	2	2
18	5,027.30	4,830.10		4,830.10		2	2	2	2	1	1
19	7,131.20	6,831.50		6,831.50		3	3	2	2	2	2
20	5,461.80	5,252.10		5,252.10		3	2	2	2	1	1
21	507.4	401.1	658	401.1		1	1	1	1	1	1
22	7,399.90	7,099.70		7,099.70		3	3	2	2	2	2
23	5,250.60	5,039.50		5,039.50		2	2	2	2	1	1
24	852.4	673.70	868	673.7		1	1	1	1	1	1
25	2,524.70	2,437.40	2730	2,437.40		1	1	1	1	1	1
26	2,659.50	2,560.10	2730	2,560.10		1	1	1	1	1	1
27	891.2	757.30	983	757.3		1	1	1	1	1	1
28	1,111.00	933.50	1280	933.50		1	1	1	1	1	1
29	4,423.20	4,213.40		4,213.40		2	2	2	1	1	1
30	1,059.40	940.2	1110	940.20		1	1	1	1	1	1
31	2,874.10	2,795.90	3010	2,795.90		2	1	1	1	1	1
32	2,929.80	2,854.70	3010	2,854.70		2	1	1	1	1	1
33	3,833.90	3,733.30		3,733.30		2	2	1	1	1	1
34	2,671.20	2,600.20	2730	2,600.20		1	1	1	1	1	1
35	435.3	371.2	471	371.2		1	1	1	1	1	1
36	921.5	749.4	983	749.4		1	1	1	1	1	1
37	494.5	346.6	519	346.6		1	1	1	1	1	1
38	600.6	421	658	421		1	1	1	1	1	1
39	660.4	462.8	753	462.8		1	1	1	1	1	1
40	632.3	443.2	658	443.2		1	1	1	1	1	1
41	660.5	462.9	753	462.9		1	1	1	1	1	1
42	648.4	454.4	658	454.4		1	1	1	1	1	1
Avg	2442.32	2,304.80	1319.85	2304.8	1 Pile	25	29	32	34	37	37
Median	1754.75	1,659.30	983	1659.3	2 Piles	11	9	8	6	3	3
Max	7399.9	7,099.70	3010	7099.7	3 Piles	4	2	0	0	0	0
Min	350.1	332.50	359	332.5	Total	40	40	40	40	40	40
								628.319	961.327		
								402.124	301.593		
								1030.442	1262.920		

Foundation Design

End Bearing 5 ft into competent Bedrock*:	100	ksf	Skin Friction in weathered and competent Bedrock**:	14.4	ksf
* Cannot exceed 50% of design capacity			**5' in bedrock + assumed depth in weathered bedrock		
Depth in competent Bedrock:	5	ft	Assumed depth in weathered Bedrock:	2.5	ft

LBE

Length (ft)	Width (ft)	Total Depth** (ft)	Area, Ag (SF)	Circum. (ft)	Skin Friction (k)	Bearing Capacity* (k)	Total Capacity (k)	Min. Area of Steel, As (in2)	Vertical Reinf. Bar #	Reinf. Bar Amount	Ties #
10	3	7.5	30.00	26.00	2808.00	2808.00	5616.00	43.2	18	11	4

Drilled Shafts

Dia. (ft)	Total Depth** (ft)	Area, Ag (SF)	Circumf. (ft)	Skin Friction (k)	Bearing Capacity* (k)	Total Capacity (k)	Min. Area of Steel, As (in2)	Vertical Reinf. Bar #	Reinf. Bar Amount	Ties #
4	7.5	12.57	12.57	1357.17	1256.64	2613.81	18.10	18	5	5
5	7.5	19.63	15.71	1696.46	1696.46	3392.92	28.27	18	8	5
6	7.5	28.27	18.85	2035.75	2035.75	4071.50	40.72	18	11	5
7	7.5	38.48	21.99	2375.04	2375.04	4750.09	55.42	18	14	5
8	7.5	50.27	25.13	2714.34	2714.34	5428.67	72.38	18	19	5

APPENDIX 03: Integration of Systems Diagram

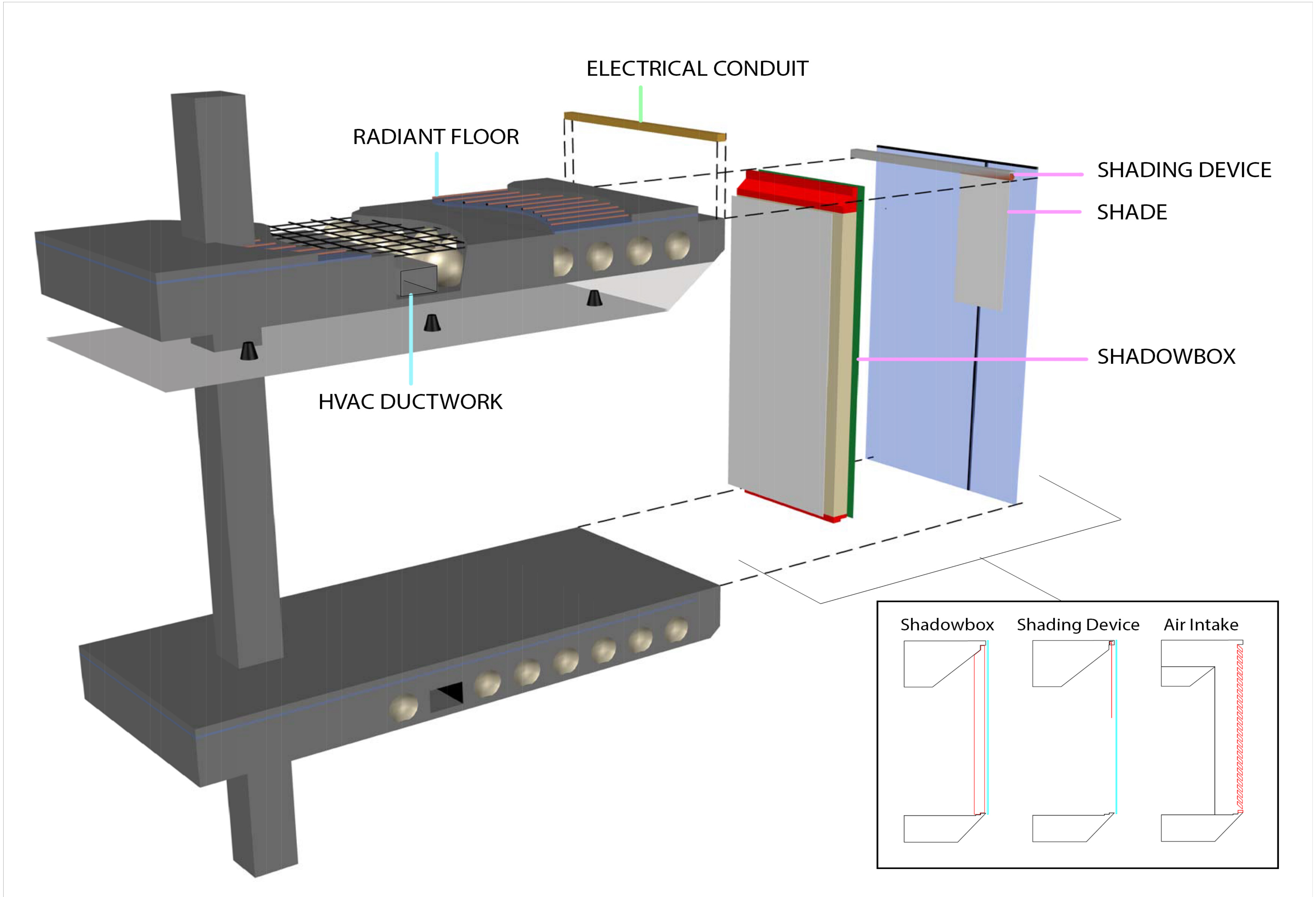


TABLE 5-1.
2013 HAZARD ASSESSMENT—HAZARDS OF GREATEST CONCERN

		Severity[a]			
Hazard	Frequency[b]	Likely Level	Potential Worst-Case	Area of Impact	Area of Occurrence
Natural Hazards					
Flood (including Ice Jam)	High	Serious	Catastrophic	Regional	Statewide
Dam Failure	Very low	Extensive	Catastrophic	Local	Regional
Coastal Hazards	High	Serious	Extensive	Regional	Regional
Hurricane/ Tropical Storm	Medium	Serious	Catastrophic	Widespread	Statewide
Nor'easter	High	Minor	Extensive	Widespread	Statewide
Earthquake	Very low	Serious	Catastrophic	Regional	Statewide
Landslide	Low	Minor	Extensive	Local	Statewide
Snow & Blizzard (Severe Winter Weather)	High	Minor	Extensive	Widespread	Statewide
Ice Storm (Severe Winter Weather)	Medium	Minor	Extensive	Regional	Statewide
Wildland Fire	Medium	Minor	Extensive	Local	Regional
Major Urban Fires	Low	Minor	Serious	Isolated	Statewide
Thunderstorm (Severe Weather)	High	Minor	Extensive	Regional	Statewide
High Wind (Severe Weather)	High	Minor	Extensive	Regional	Statewide
Tornado (Severe Weather)	Medium	Serious	Extensive	Local	Statewide
Drought (Severe Weather)	Low	Minor	Serious	Widespread	Statewide
Extreme Temperature (Severe Weather)	Medium	Minor	Serious	Widespread	Statewide
Tsunami	Very low	Extensive	Catastrophic	Widespread	Regional
Non-Natural Hazards of Concern – Not profiled in SHMP but data are available in Annex 1					
Public Health Hazard (epidemic or pandemic)		Extensive	Catastrophic	Widespread	Widespread
Blackout		Minor	Extensive	Widespread	Widespread
Bridge Failure		Minor	Extensive	Local	Regional
Commodity Shortage		Serious	Extensive	Widespread	Widespread
Nuclear Power Station Radiological Release		Serious	Catastrophic	Widespread	Regional
Transportation Accident		Minor	Serious	Isolated	Statewide
Terrorist Related Risk - Not profiled in SHMP - Privileged data					
Active Shooter		Minor	Serious	Isolated	Statewide
Biological Weapon		Serious	Extensive	Local	Statewide
Chemical Weapon		Serious	Extensive	Local	Statewide
Cyber Attack - Data		Serious	Extensive	Widespread	Statewide
Cyber Attack – Infrastructure		Serious	Extensive	Widespread	Statewide
Explosive Device (improvised or vehicle-borne)		Serious	Catastrophic	Widespread	Statewide
Radiological Device		Extensive	Catastrophic	Local	Statewide

a. Two severity ratings were assigned for each hazard: A likely level used in the risk assessment, and a potential worst-case defined for consideration in developing the THIRA and mitigation goals and actions.
b. Frequency analysis is not included for non-natural hazards; the criteria are specific for natural hazard frequency and are not transferable. See Annex 1 for details on the non-hazards.

- Area of Impact (extent of impact on any locality for a particular event):

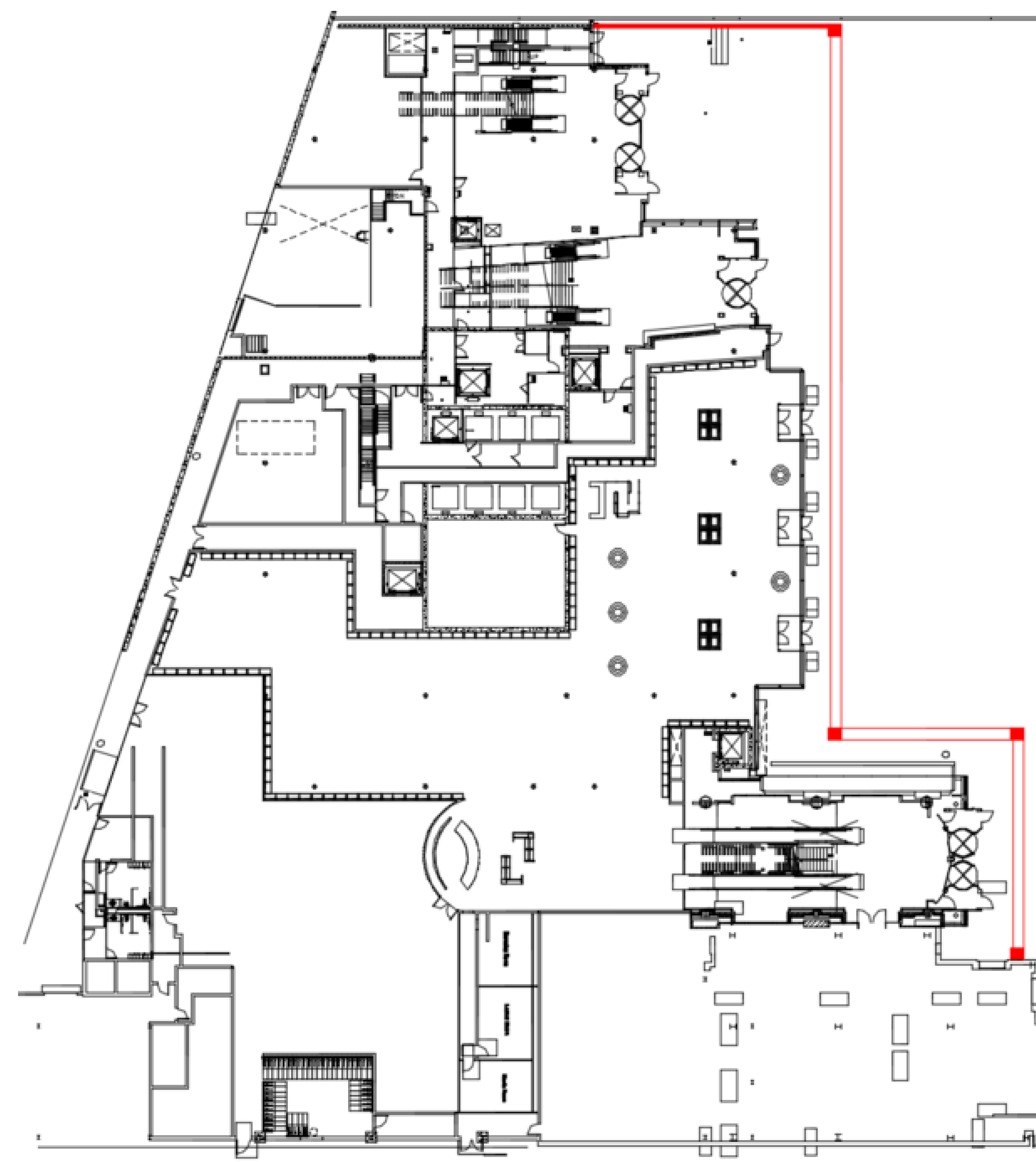


Figure: Location of the Floodproof Wall

APPENDIX 05: WIND TURBINE AND SOLAR PANEL PERFORMANCES

Table: Monthly Energy Production by the Wind Turbines

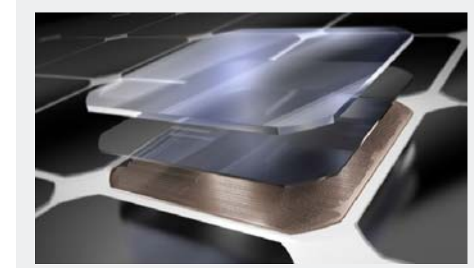
Month	Wind Speed (MPH)	Wind Speed (m/s)	Average Power (watts)	kWh per hour	kWh per day	kWh per month
January	13.6	6.080	1400	1.4	33.6	1008
February	13.5	6.035	1375	1.375	33	990
March	13.5	6.035	1375	1.375	33	990
April	13	5.812	1230	1.23	29.52	885.6
May	11.9	5.320	940	0.94	22.56	676.8
June	11.2	5.007	780	0.78	18.72	561.6
July	11	4.917	750	0.75	18	540
August	10.8	4.828	720	0.72	17.28	518.4
September	11.2	5.007	780	0.78	18.72	561.6
October	11.8	5.275	920	0.92	22.08	662.4
November	12.5	5.588	1100	1.1	26.4	792
December	13.2	5.901	1275	1.275	30.6	918
					Annual Total	9,104.40
				(14) Turbines	Annual Total	127,461.60

Table: Monthly Energy Production by the PV Panels

Month	Average Solar Radiaton (kWh/(m²)	Total Solar Panel Area (m²)	Solar Panel Yield	Performance Ratio	Energy Output (kWh/month)
January	1095	378.16	15%	0.69	42,857.82
February	1460			0.69	57,143.76
March	1642.5			0.75	69,876.88
April	1679			0.75	71,429.70
May	1679			0.75	71,429.70
June	1788.5			0.75	76,088.16
July	1861.5			0.75	79,193.79
August	1861.5			0.75	79,193.79
September	1679			0.75	71,429.70
October	1387			0.75	59,007.14
November	1131.5			0.75	48,137.40
December	1058.5			0.75	45,031.77
				Average	64,234.97

PV Panel Visuals

SPR-E20-327

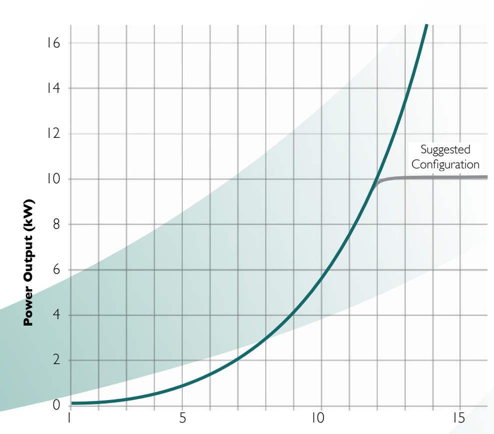


Maxeon® Solar Cells: Fundamentally better.

SPECIFICATIONS

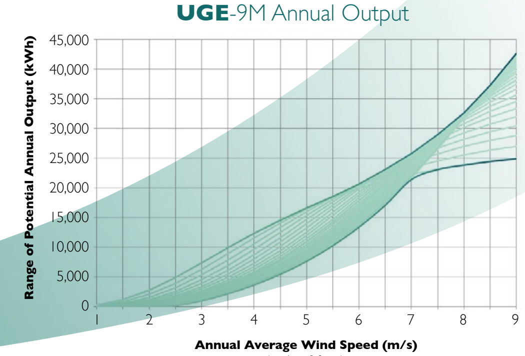
General

Axis _______ Vertical
Height _______ 9.6 m (31' 6")
Width _______ 6.4 m (21')
Swept Area _______ 61.4 m² (661.5 ft²)
Weight _______ 4000 kg (8816 lb)
Blade Materials _______ Carbon Fiber & Fiberglass with Steel reinforcement



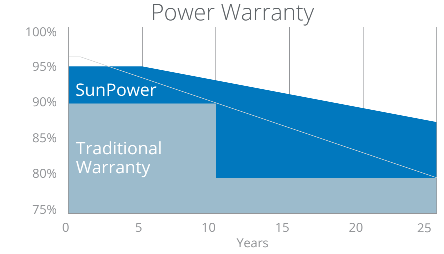
Performance

Energy Output _______ 14,500 kWh/yr (at 5.5 m/s)
Cut-In Wind Speed _______ 3.5 m/s (7.8 mph)
Cut-Out Wind Speed _______ 30 m/s (67 mph)
Rated RPM _______ 55 RPM
Survival Wind Speed _______ 50 m/s (110 mph)



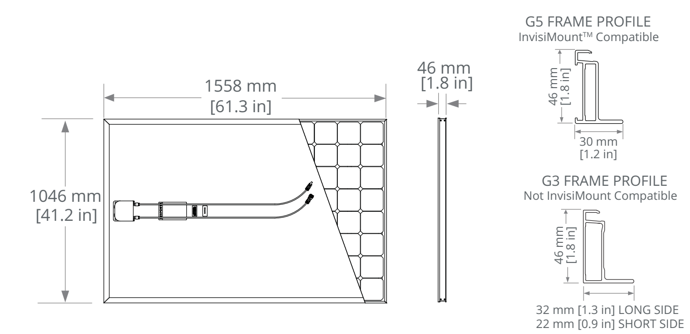
Electric Generation

PV Panel Specifications



More guaranteed power: 95% for first 5 years, -0.4%/yr. to year 25. [7]

Electrical Data	SPR-E20-327	SPR-E19-320
Nominal Power (Pnom)[11]	327 W	320 W
Power Tolerance	+5/−0%	+5/−0%
Avg. Panel Efficiency[12]	20.4%	19.9%
Rated Voltage (Vmpp)	54.7 V	54.7 V
Rated Current (Impp)	5.98 A	5.86 A
Open-Circuit Voltage (Voc)	64.9 V	64.8 V
Short-Circuit Current (Isc)	6.46 A	6.24 A
Max. System Voltage	600 V UL & 1000 V IEC	
Maximum Series Fuse	15 A	
Power Temp Coef.	−0.38% / °C	
Voltage Temp Coef.	−176.6 mV / °C	
Current Temp Coef.	3.5 mA / °C	



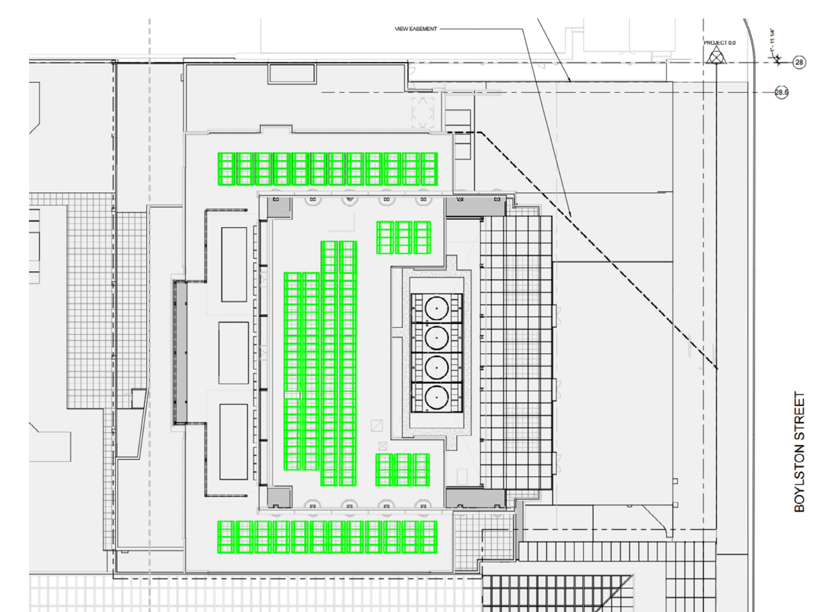


Figure: Rooftop PV Panel Layout

APPENDIX 06: Water Consumption and Fixture Selection

Table 1: Fixture Specifications for Baseline and Design

		# of Fixtues	Baseline	Design	Unit
RETAIL	Toilet	15	1.6	1.28	gpf
	Urinal	4	1	0	gpf
	Showerheads	8	2.5	2	gpm
	Bathroom Faucet	16	2.2	1.5	gpm
	Kitchen Faucet	5	2.2	1.5	gpm
OFFICE	Toilet	140	1.6	1.28	gpf
	Urinal	28	1	0	gpf
	Bathroom faucet	84	2.2	1.5	gpm

Table 2: Annual Water Consumption for Different Usage Areas

	Baseline (gallons/year)			Design (gallons/year)		
	Annual Flush Volume	Annual Flow Volume	Total Consumption	Annual Flush Volume	Annual Flow Volume	Total Consumption
Retail	195,275	156,344	351,619	105,120	106,598	211,718
Office	2,299,500	1,267,025	3,566,525	958,125	926,928	1,885,053
		Total=	3,918,144		Total=	2,096,772

Table 3:Flush and Flow Calculations for Fixtures

		person	day	flushes/day	flush/year	flush/year
FLUSH	female	100	365	2	73,000.0	82,125.00
	male	100	365	0.25	9,125.0	
		100	365	1.75	63,875.0	
	female	700	365	3	766,500.0	894,250.00
	male	700	365	0.5	127,750.0	
		700	365	2.5	638,750.0	
		person	day	minutes/day	minutes/year	minutes/year
FLOW	female	100	365	0.66	24,090.0	35,532.75
	male	100	365	0.066	2,409.0	
		100	365	0.248	9,033.8	
	female	700	365	0.33	84,315.0	333,427.50
	male	700	365	0.15	38,325.0	
		700	365	0.825	210,787.5	

STEP 1A - ENTER THE LANDSCAPED AREA (A)

23,738 Area of the designed landscape (square feet)

STEP 1B - ENTER THE AVERAGE MONTHLY REFERENCE EVAPOTRANSPIRATION (ET_o)

6.18 Average monthly reference ET (inches/month) for the site's peak watering month

Obtain from Water Budget Data Finder at www.epa.gov/watersense/nhspecs/wb_data_finder.html

OUTPUT - BASELINE FOR THE SITE

91,444 Monthly baseline (gallons/month) based on the site's peak watering month

OUTPUT - WATER ALLOWANCE FOR THE SITE

64,010 Monthly landscape water allowance (gallons/month) based on the site's peak watering month

Table 1. Landscape Water Requirement

Zone	Hydrozone/Landscape Feature Area (sq. ft.)	Plant Type or Landscape Feature	Landscape Coefficient (K_L)	Irrigation Type
1	140	Trees - Low water requirement	0.2	Drip - Standard
2	2,700	Turfgrass - Low water requirement	0.6	Micro Spray
3	19,154	Groundcover - Low water requirement	0.2	Micro Spray
4	1,744	Shrubs - Low water requirement	0.2	Drip - Standard

STEP 3A - REVIEW THE LWA AND LWR FROM PART 1 AND PART 2

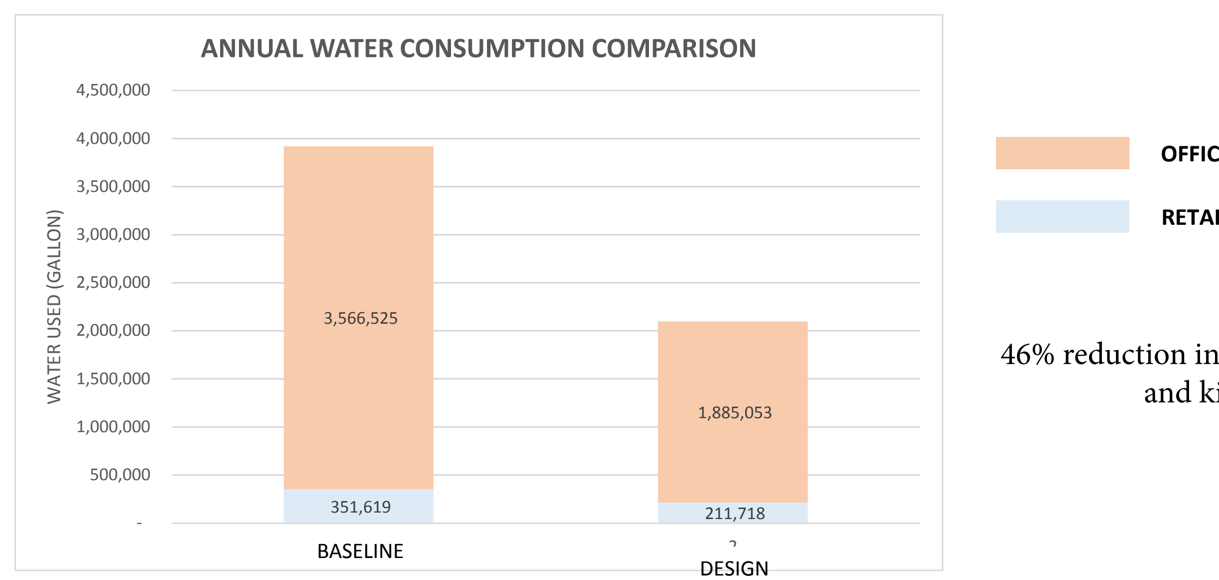
LWA 64,010 (gallons/month) LWR 17,908 (gallons/month)

OUTPUT - DOES THE DESIGNED LANDSCAPE MEET THE WATER BUDGET?

YES If YES, then the water budget criterion is met.

If NO, then the landscape and/or irrigation system needs to be redesigned to use less water.

The designed landscape water requirement is a 80% reduction in water use from the baseline calculated in Part 1.



46% reduction in water consumption by the bathroom and kitchen fixtures is achieved.

APPENDIX 07: Grey water and Rainwater Systems

Table: Rainwater and Tank Calculations

Input Values	
Catchment area (ft²):	26,208.00
Collection efficiency (%):	95.00
Initial tank volume (gal):	-
Tank size (gal):	65,000.00
Plant water use coeff:	3.00
Irrigated area (ft²):	23,000.00
Monthly indoor demand (gal):	2,575,834.00

	Avg. monthly rainfall (in)	Avg. PET (in)	AC Condensate (gal)
January:	3.35	2.02	0
February:	3.27	2.71	0
March:	4.33	3	0
April:	3.74	5.23	0
May:	3.5	7.48	0
June:	3.66	8.08	0
July:	3.43	7.79	0
August:	3.35	7.78	0
September:	3.43	6.06	0
October:	3.94	4.9	0
November:	3.98	3.06	0
December:	3.78	2.12	0
Total:	**43.76**	**60.23**	**0**

MINIMUM REQUIRED TANK SIZE CALCULATIONS:

	Rainwater (Gallons)	Greywater (Gallons)
January:	54,697.41	86,127.23
February:	53,391.20	86,127.23
March:	65,413.87	86,127.23
April:	61,065.16	86,127.23
May:	57,146.54	86,127.23
June:	59,758.96	86,127.23
July:	56,003.61	86,127.23
August:	54,697.41	86,127.23
September:	56,003.61	86,127.23
October:	64,330.68	86,127.23
November:	64,983.78	86,127.23
December:	61,718.27	86,127.23
Max Value	**65,413.87**	**86,127.23**

Minimum Tank Size (Gallons)	65,413.87

* Tank size for rainwater= avg. rainfall x cathment area x harvesting coefficient

Table: Rainwater Tank Product Specifications

SPECIFICATIONS							Processing Skid Dimensions (Inches)		
Model#	Processing Capacity (GPM)	Gallons Per Day*	Inlet PSI	Outlet Filtration (Microns)	Inlet Size (From Sump) Inches	Outlet Size (To Tank) Inches	Length	Width	Height
GW-600	10	7,200	35	10	2	1	72	36	84
GW-1200	20	14,400	35	10	2	1.5	72	36	84
GW-1800	30	21,600	35	10	2	1.5	96	36	96
GW-3000	50	36,000	35	10	2	2	96	36	96

Table: Greywater Filtration Product Specifications

Model	Diameter	Eave Height	Peak Height*	Capacity (Gallons)
WHS-FS/HR 602	6′	7′- 3″	8′ - 9″	1,400
WHS-FS/HR 603	6′	10′ - 9″	12′ - 4″	2,200
WHS-FS/HR 604	6′	14′ - 4″	15′ - 10″	2,900
WHS-FS/HR 801	8′	3′ - 8″	5′ - 10″	1,200
WHS-FS/HR 802	8′	7′ - 3″	9′ - 5″	2,500
WHS-FS/HR 803	8′	10′ - 9″	12′ - 11″	3,900
WHS-FS/HR 901	9′	3′ 8″	6′ 1″	1,500
WHS-FS/HR 902	9′	7′ - 3″	9′ 7″	3,200
WHS-FS/HR 903	9′	10′ - 9″	13′ 2″	4,900

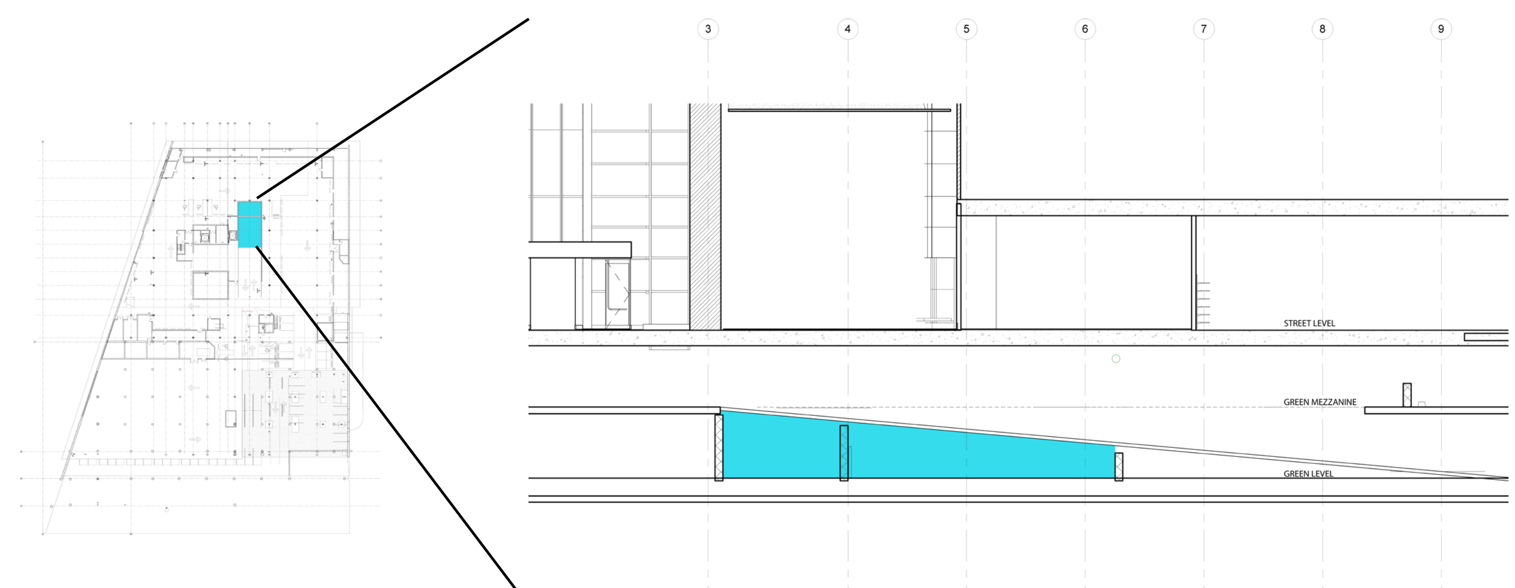
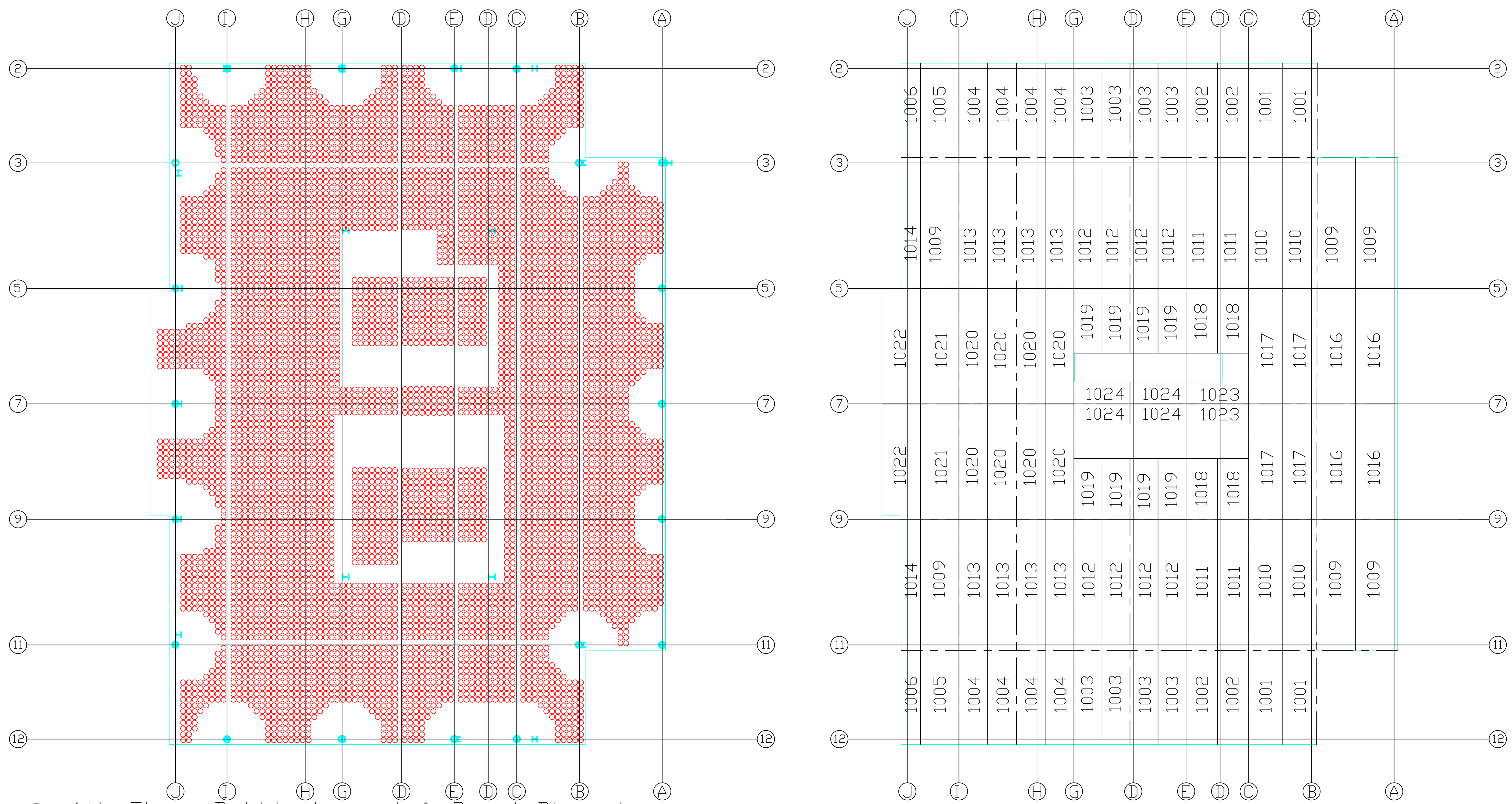
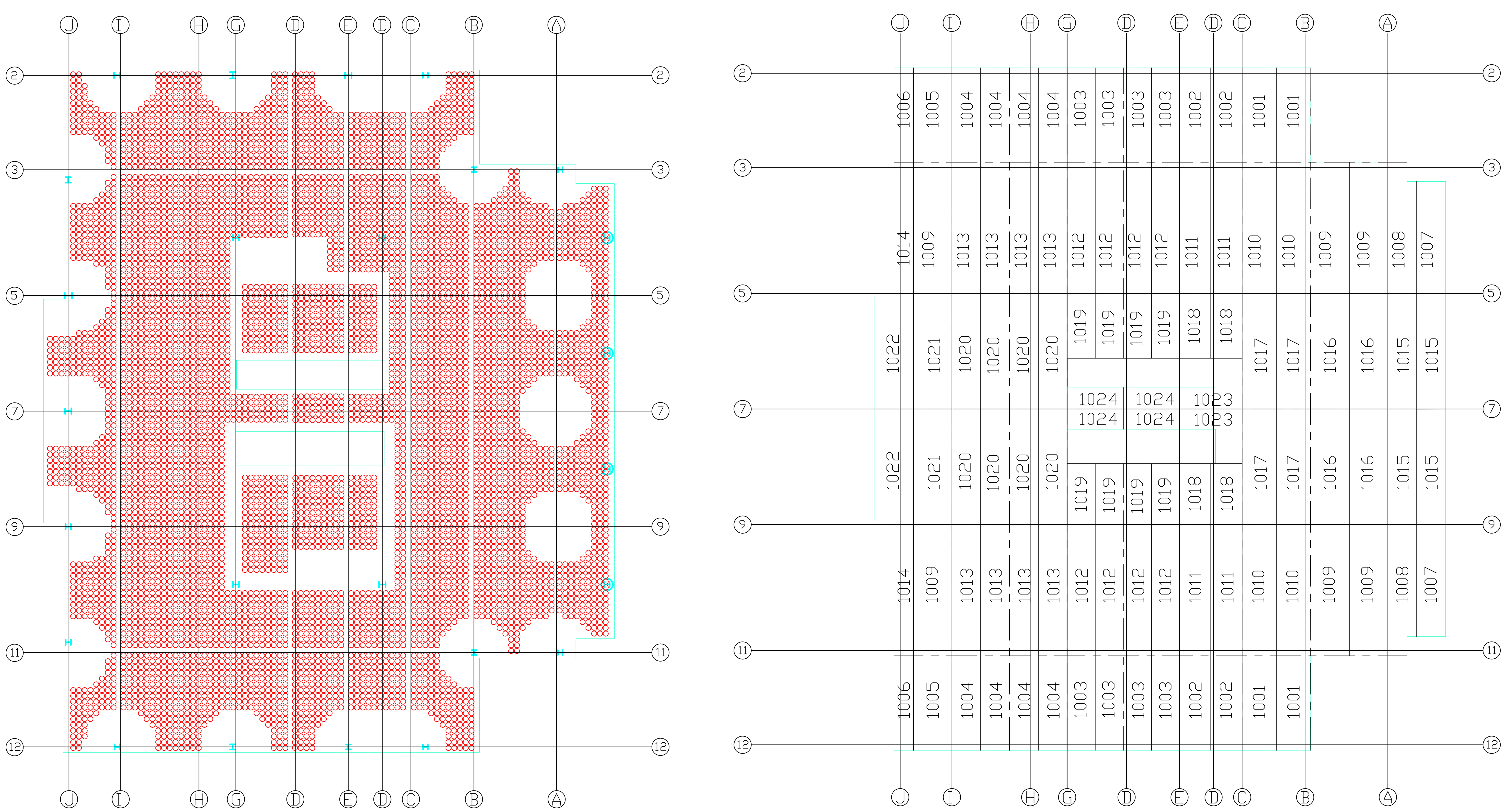


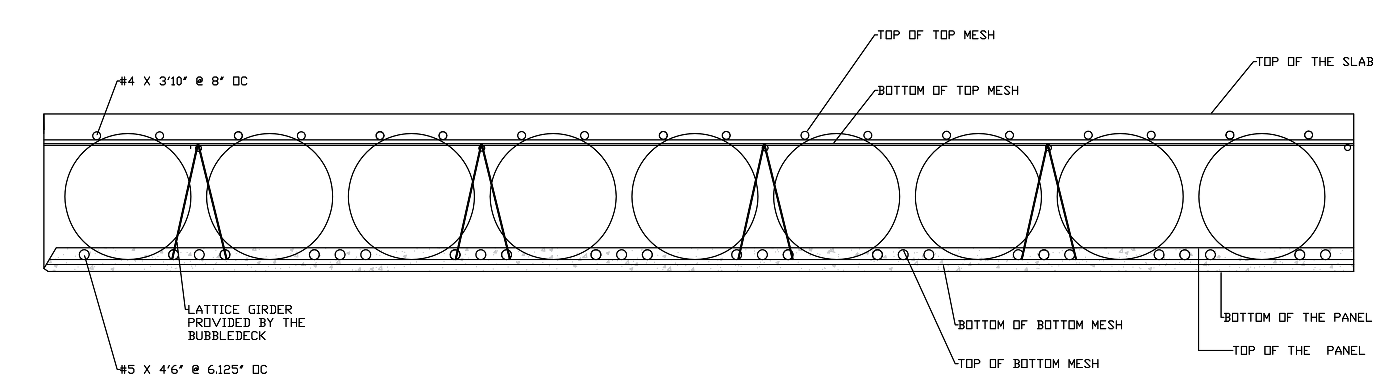
Figure: Tank Location in Green Level



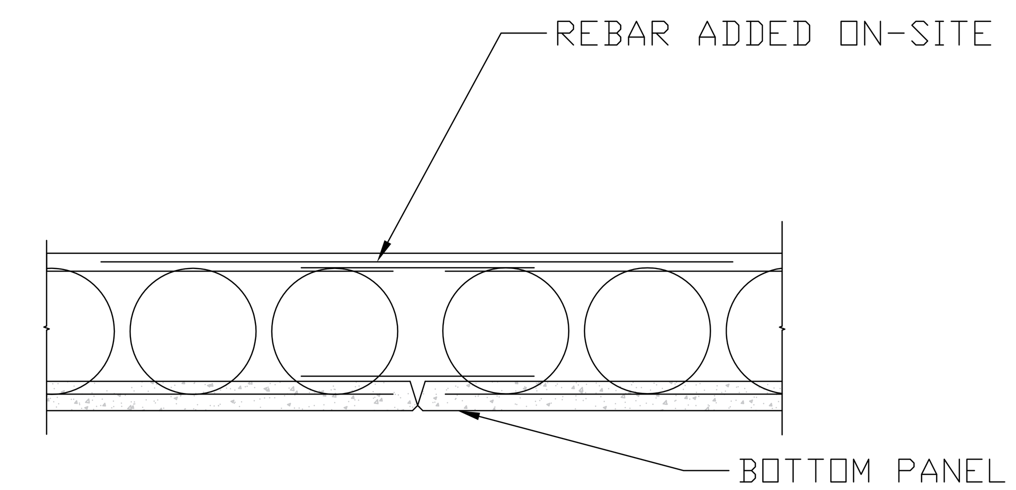
(1) 4th Floor Bubble Layout & Panel Dimensions
1/16"=1'-0"



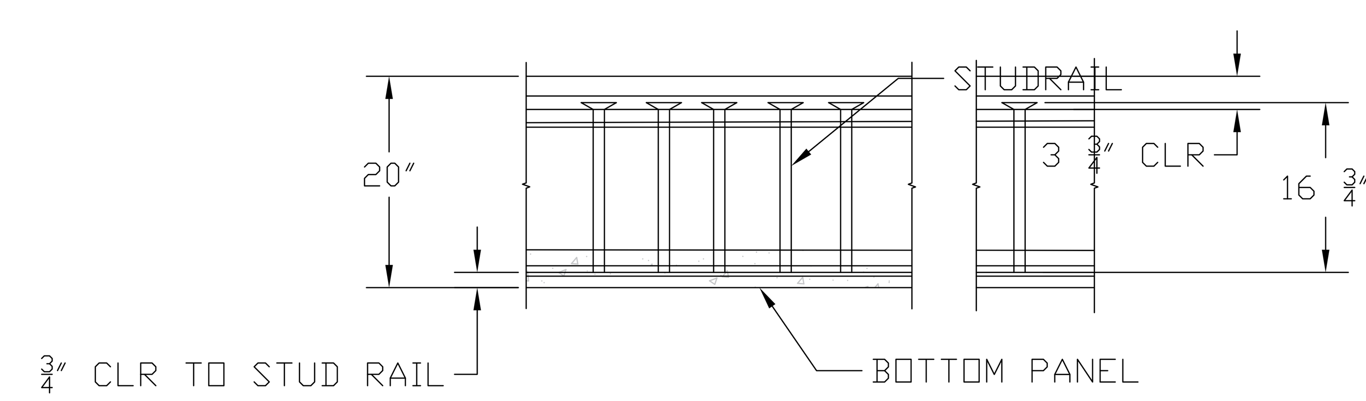
(2) Typical Office Floor Bubble Layout & Panel Dimensions
1/16"=1'-0"



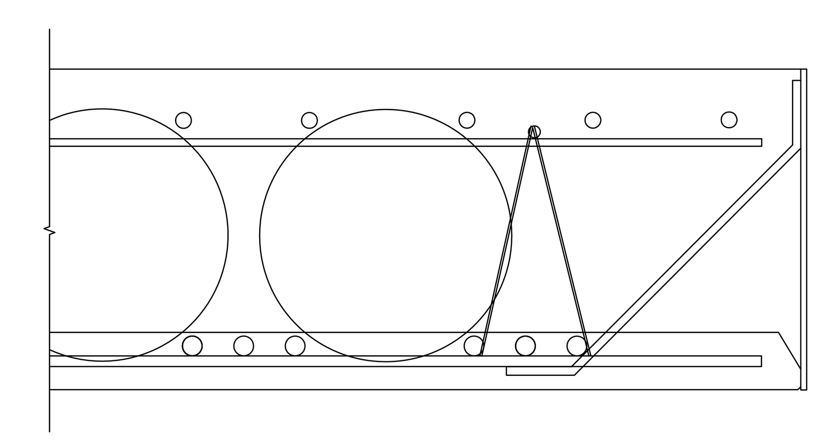
(3) Office Floor Edge Slab Section
3/4"=1'-0"



(4) Typical Longtudinal Closing Strip
3/4"=1'-0"



(5) Typical Studrail Cross-section
3"-0=1'-0"



(6) Edge Slab Section
1 1/2"=1'-0"

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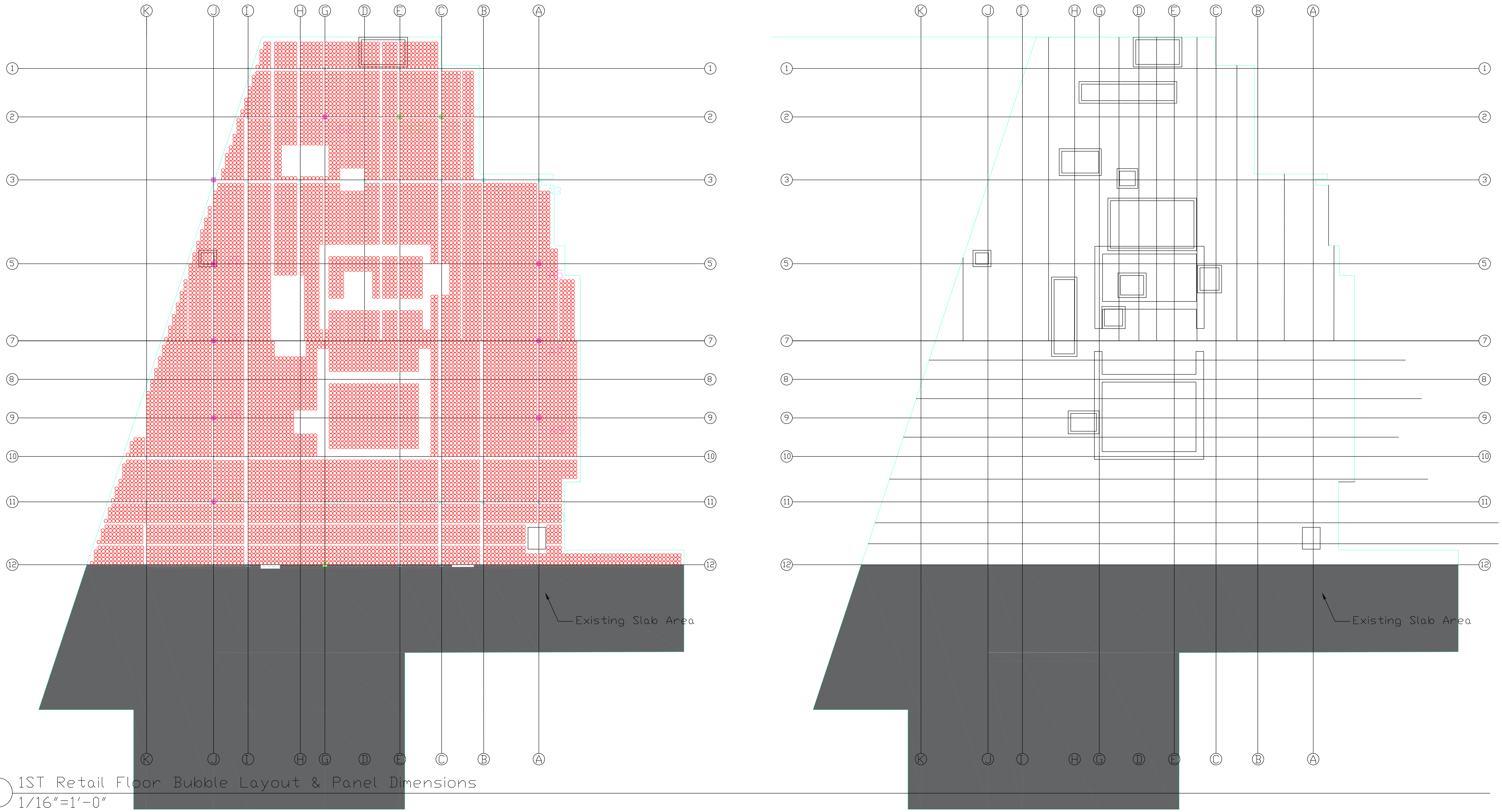
Bubbledeck Slab Details-I

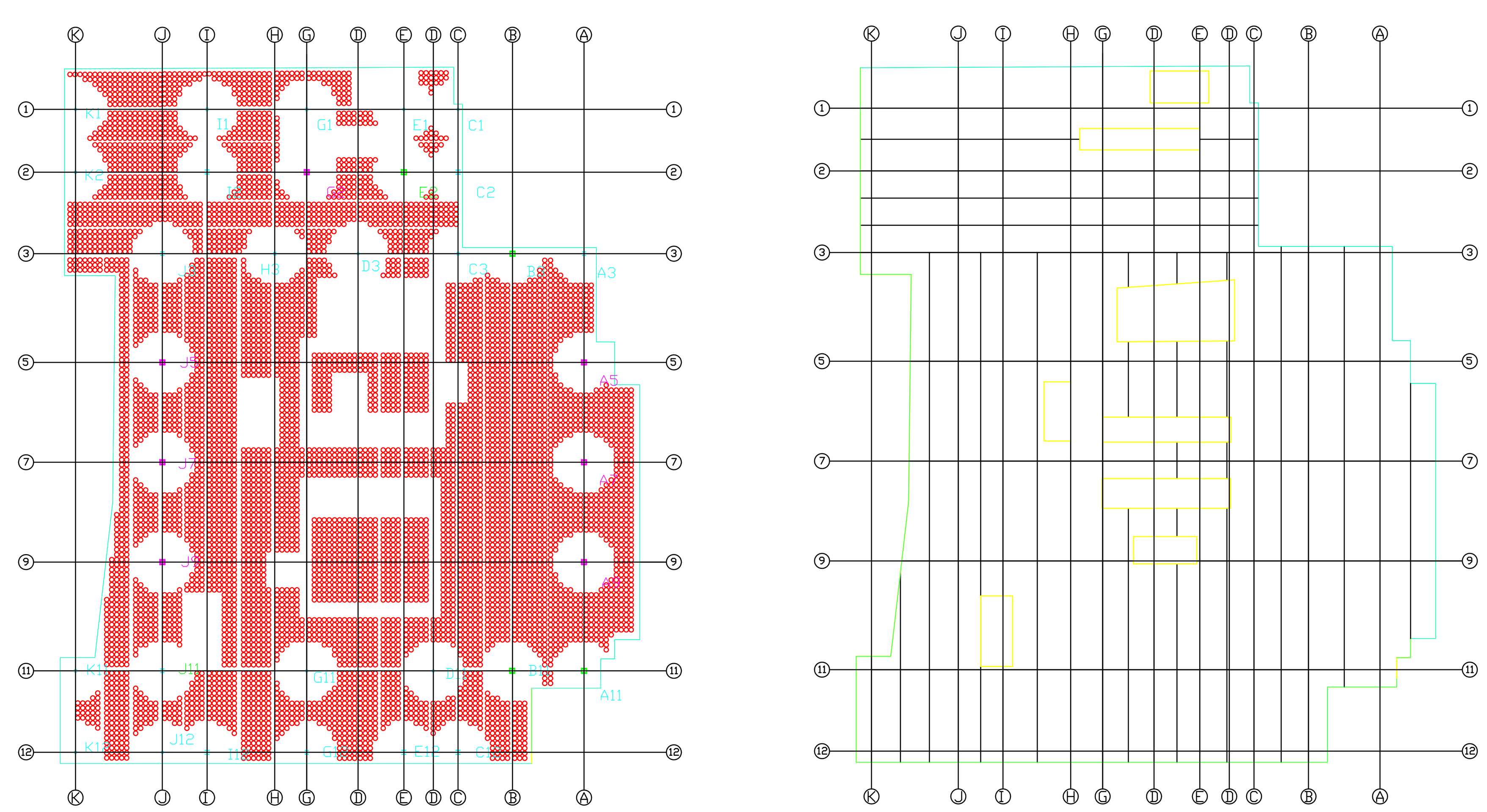
TEAM 05

02.17.16

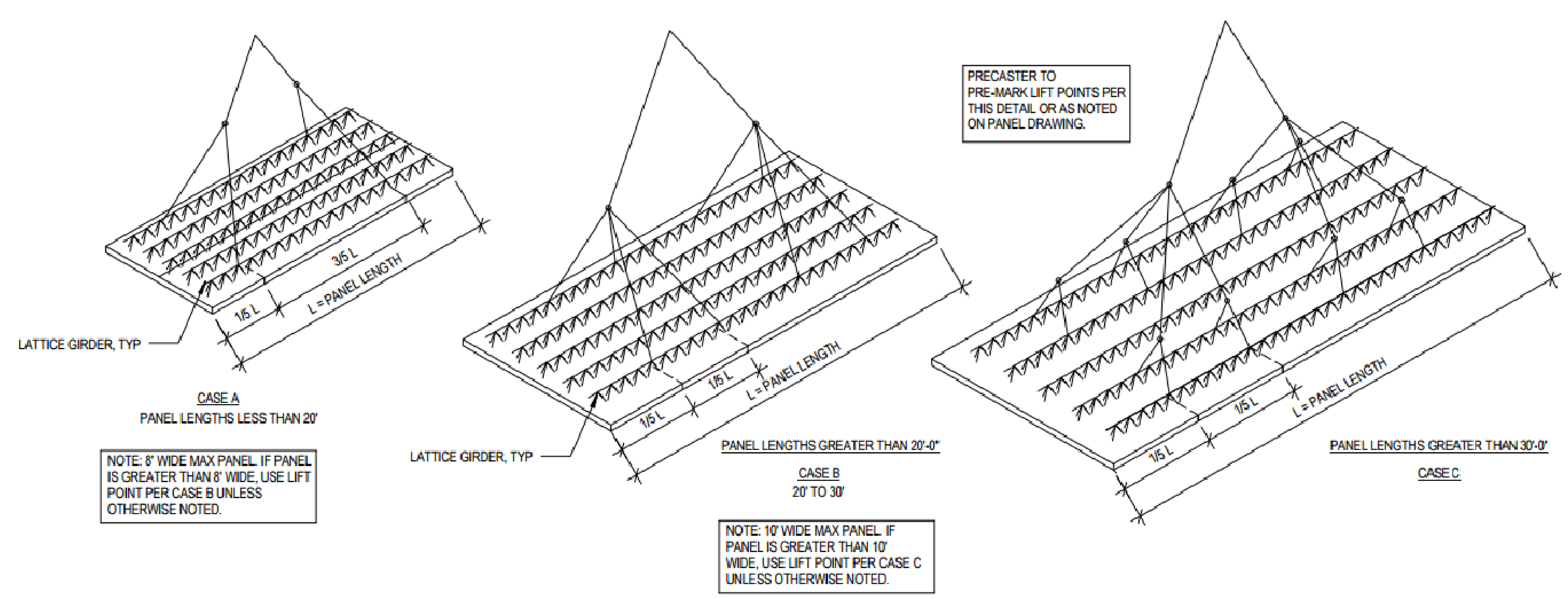
D01



1 1ST Retail Floor Bubble Layout & Panel Dimensions
1/16"=1'-0"



2 2nd Retail Floor Bubble Layout & Panel Dimensions
1/32"=1'-0"



4 Crane Raising Guidlines

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Bubbledeck Slab Details-II

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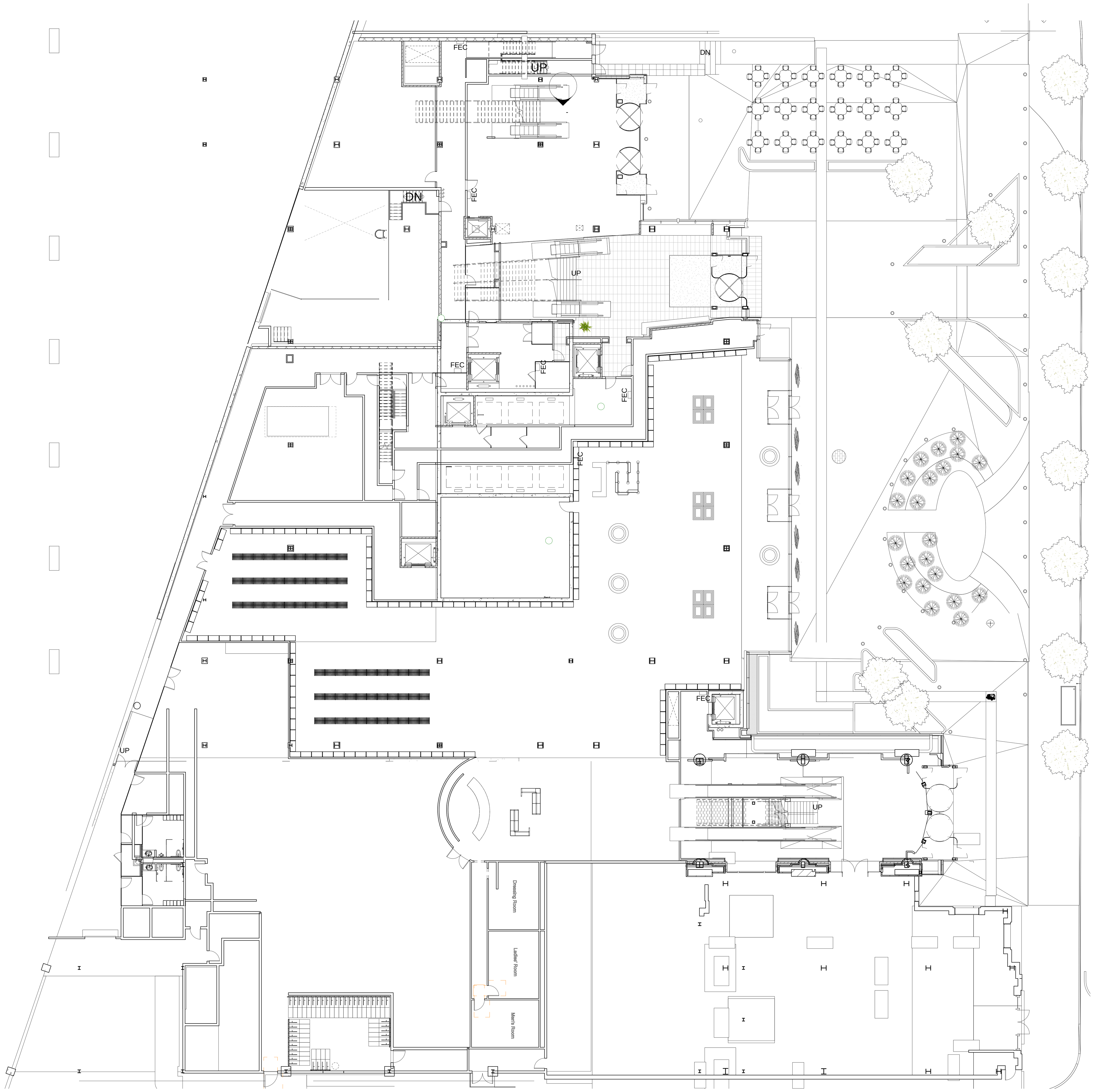
D02



1 LEVEL 01 (STREET LEVEL) FLOOR PLAN
1/16" = 1'-0"

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1st Floor Retail

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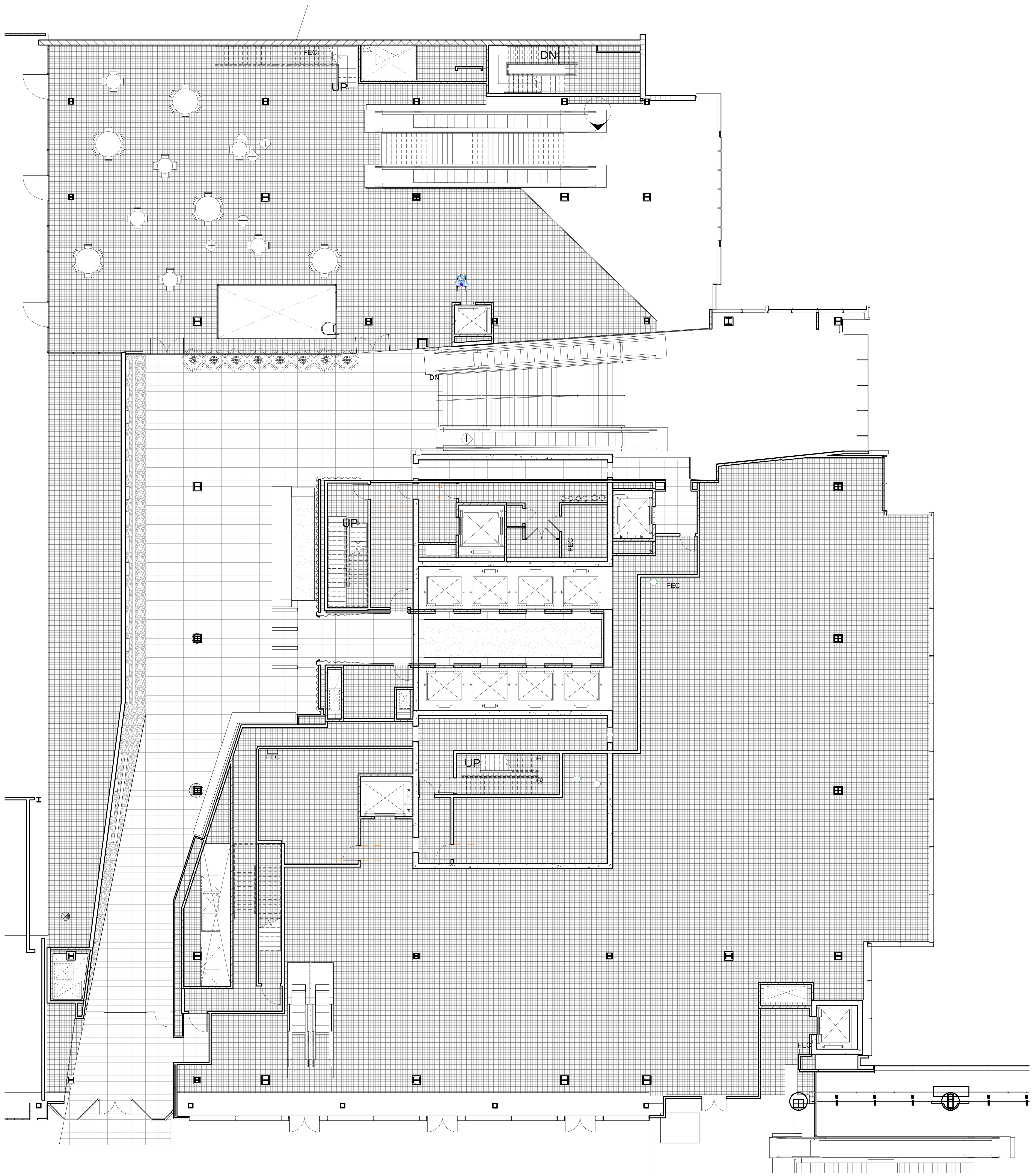
02.17.16

D01



1 LEVEL 02 FLOOR PLAN
3/32" = 1'-0"

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2nd Floor Retail

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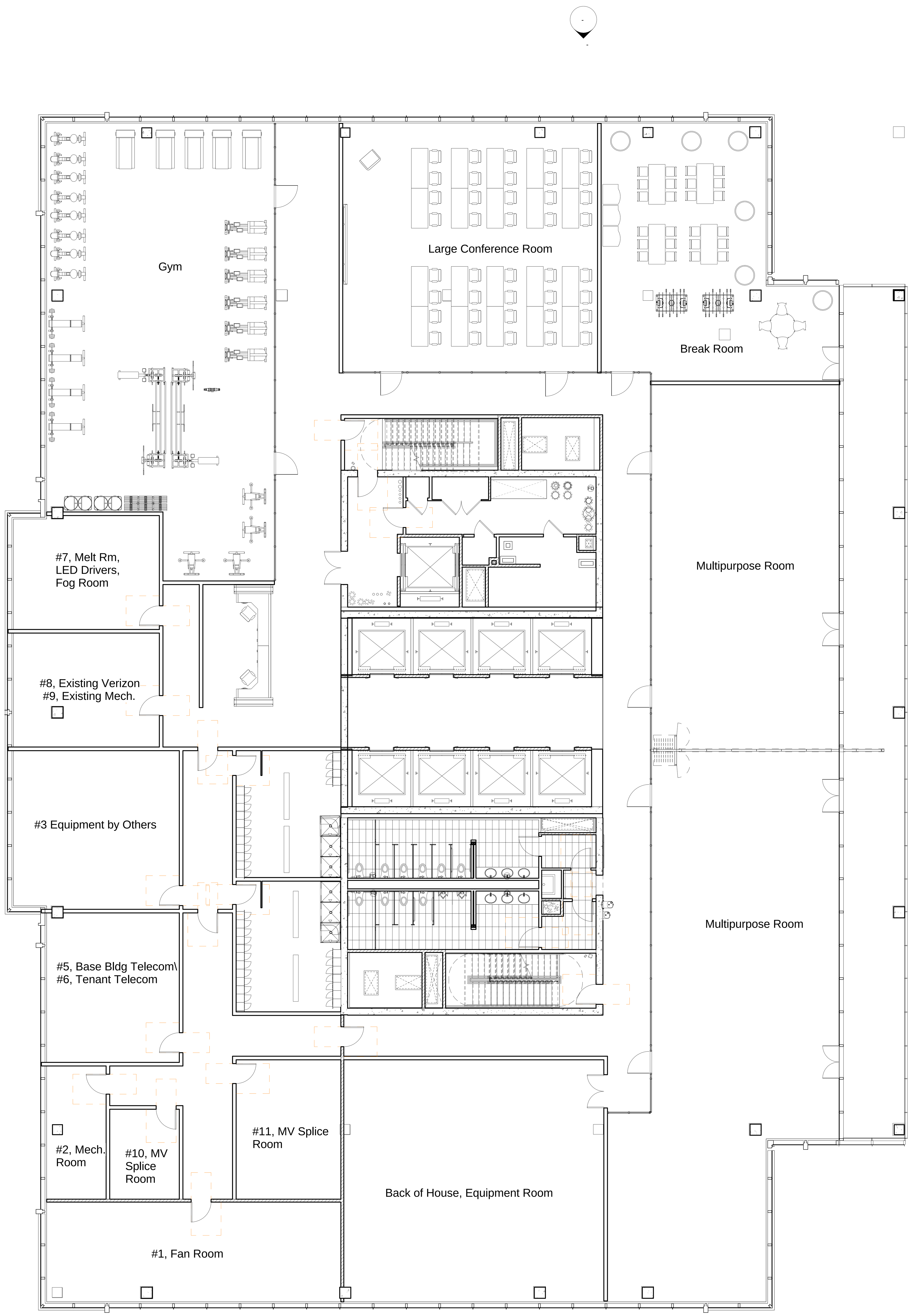
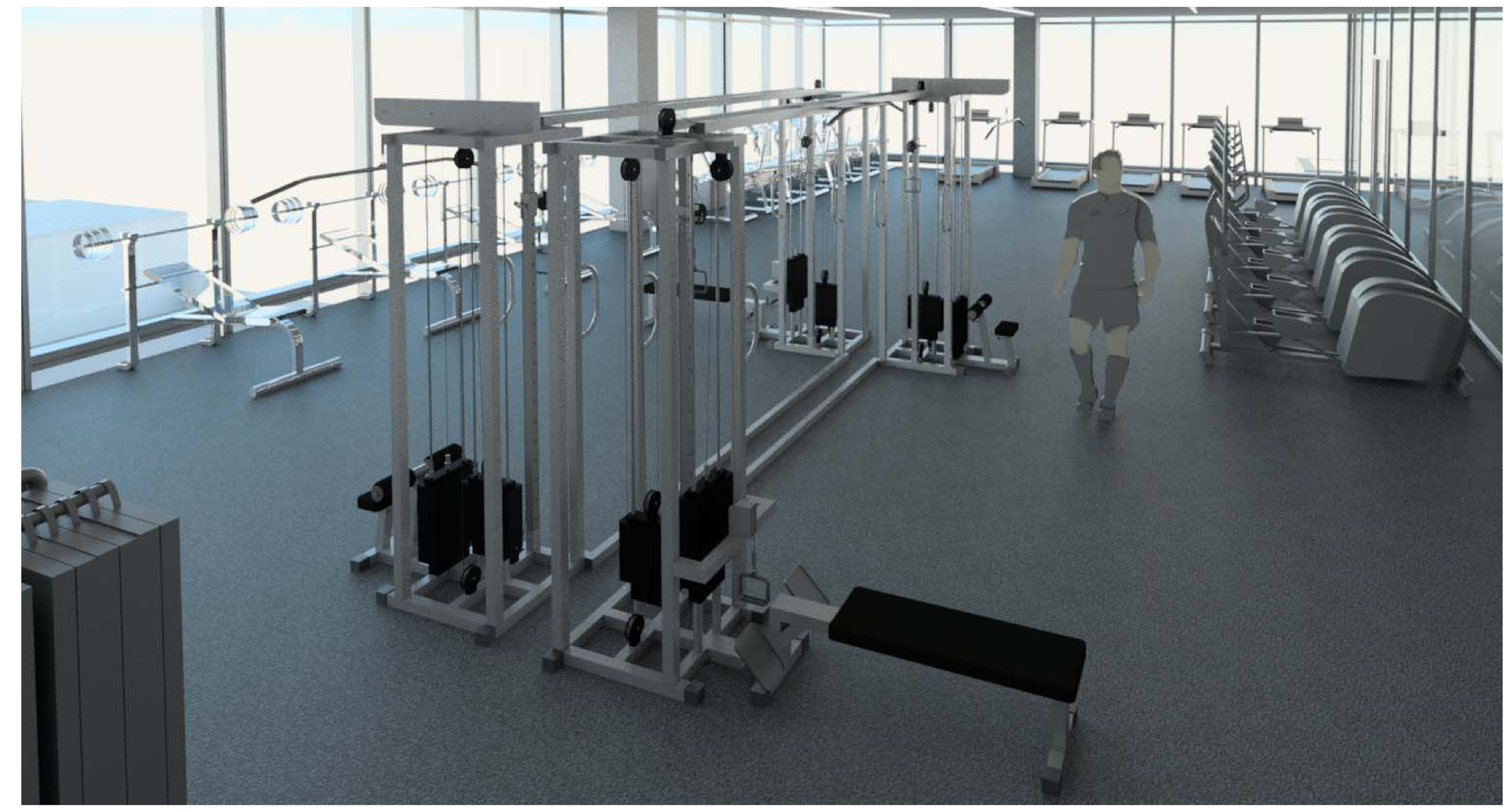
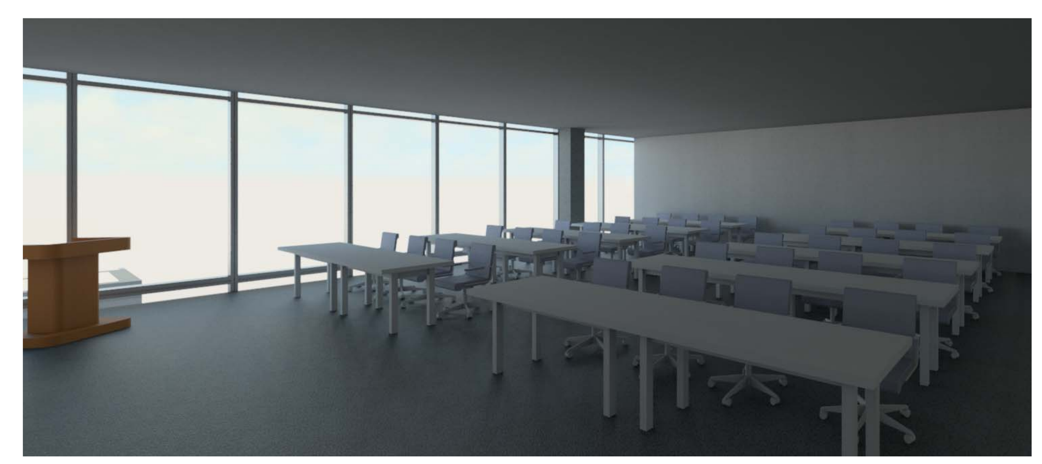
02.17.16

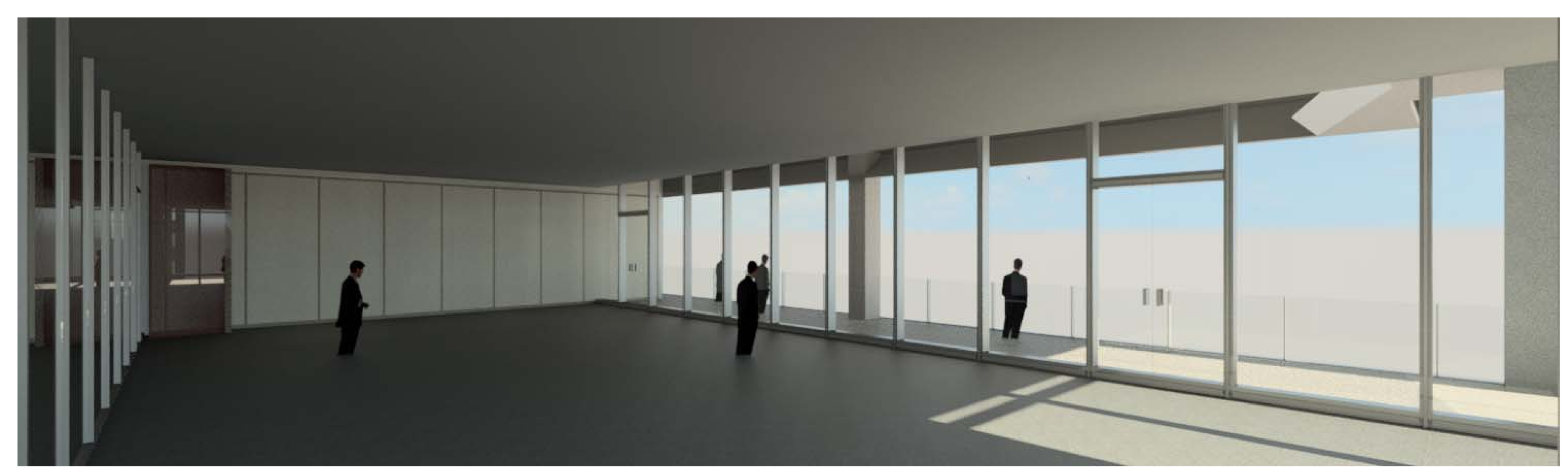
D02



1 LEVEL 05 FLOOR PLAN
1/8" = 1'-0"







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5th Floor (Additional Floor)

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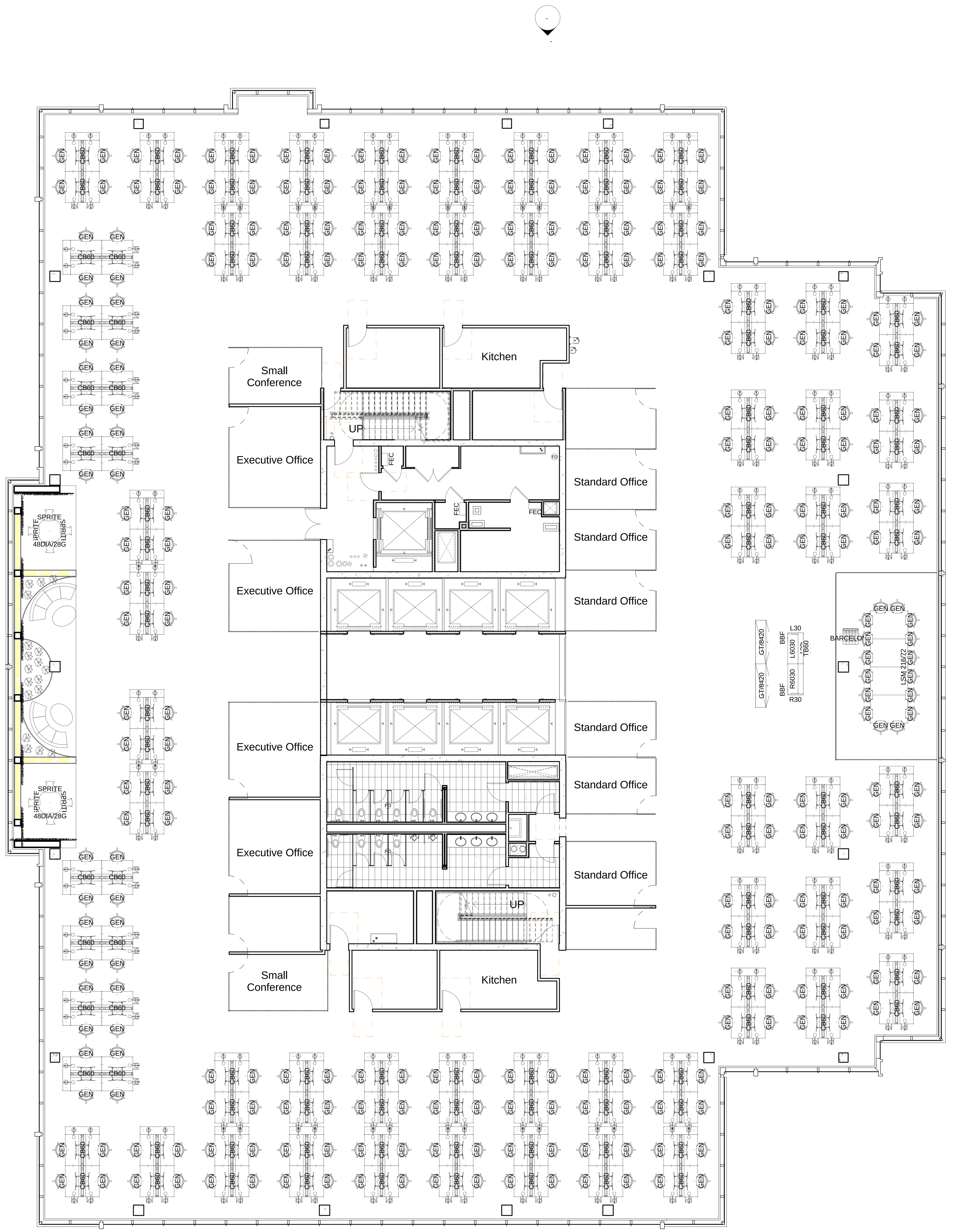
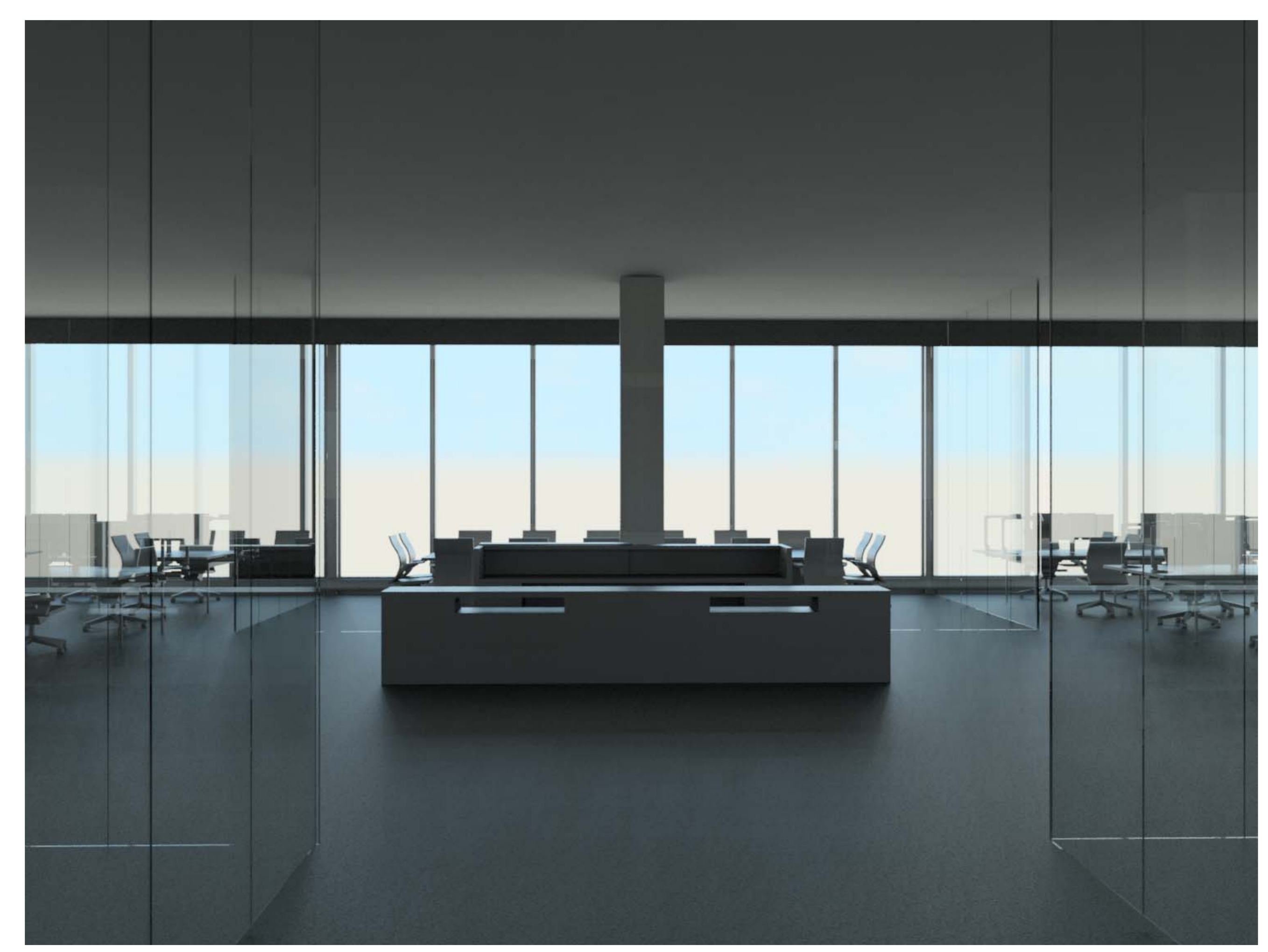
D03



1 LEVEL 17 FLOOR PLAN
1/8" = 1'-0"



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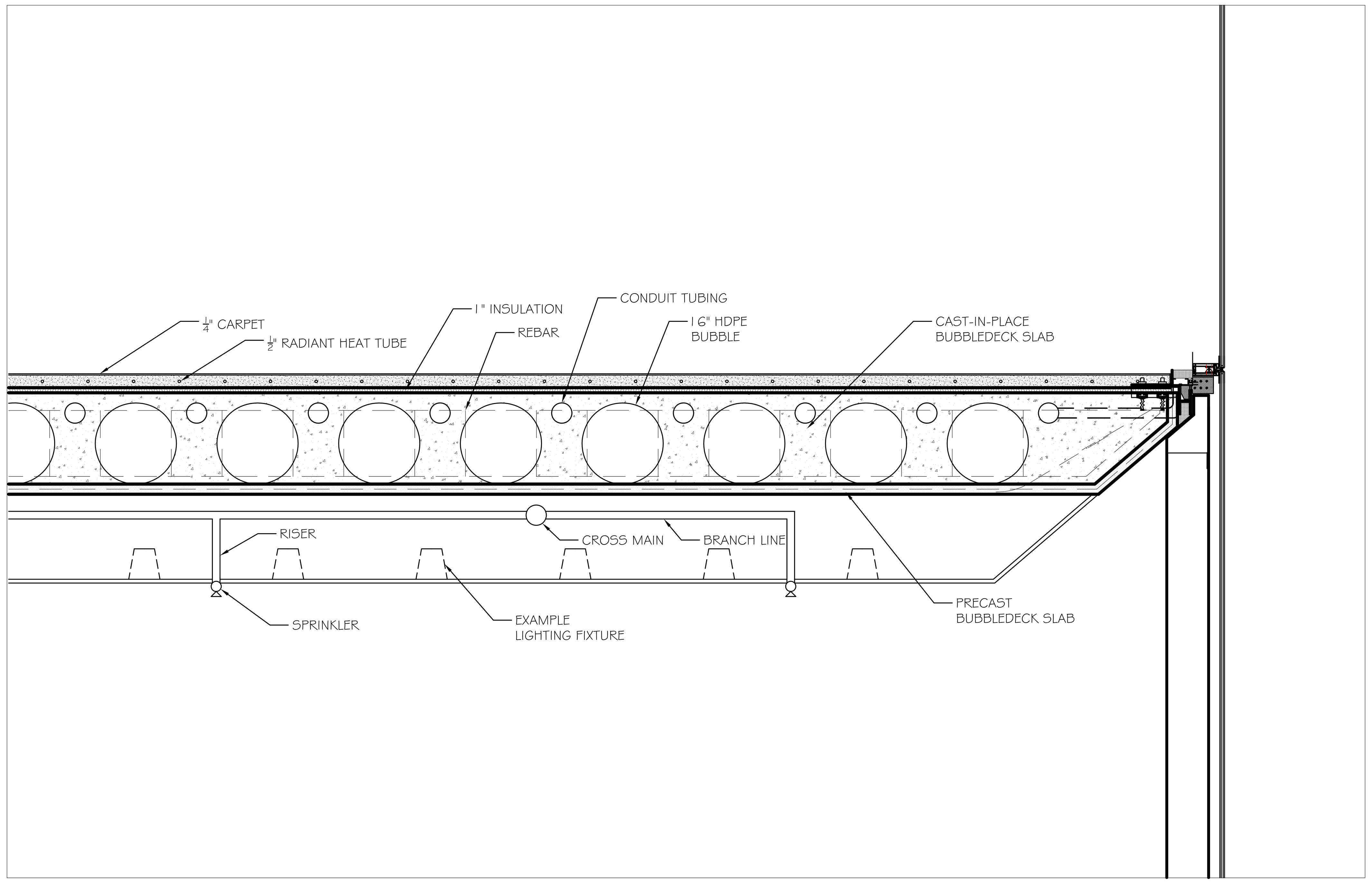
Typical Office Floor

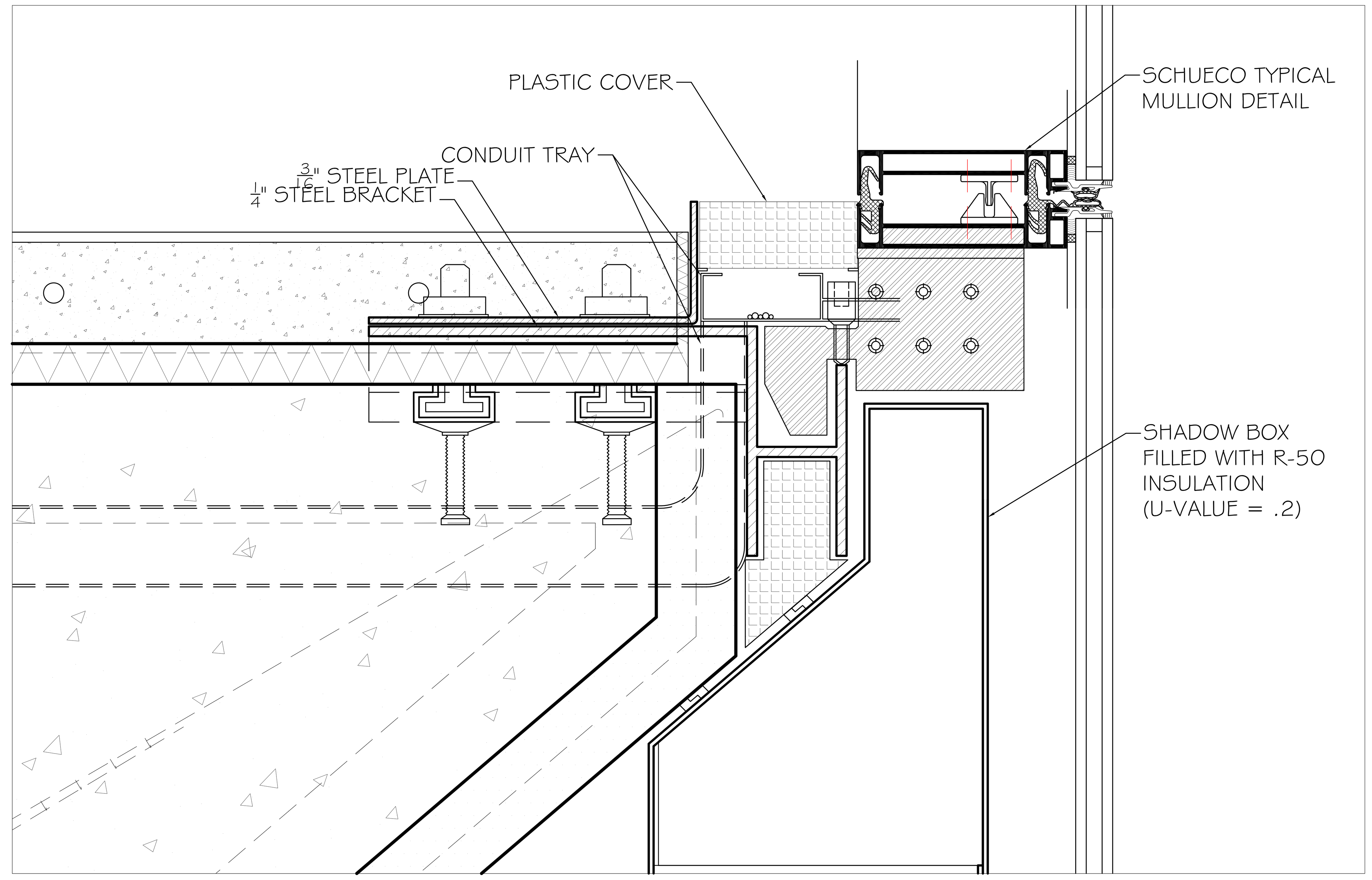
TEAM 05

02.17.16

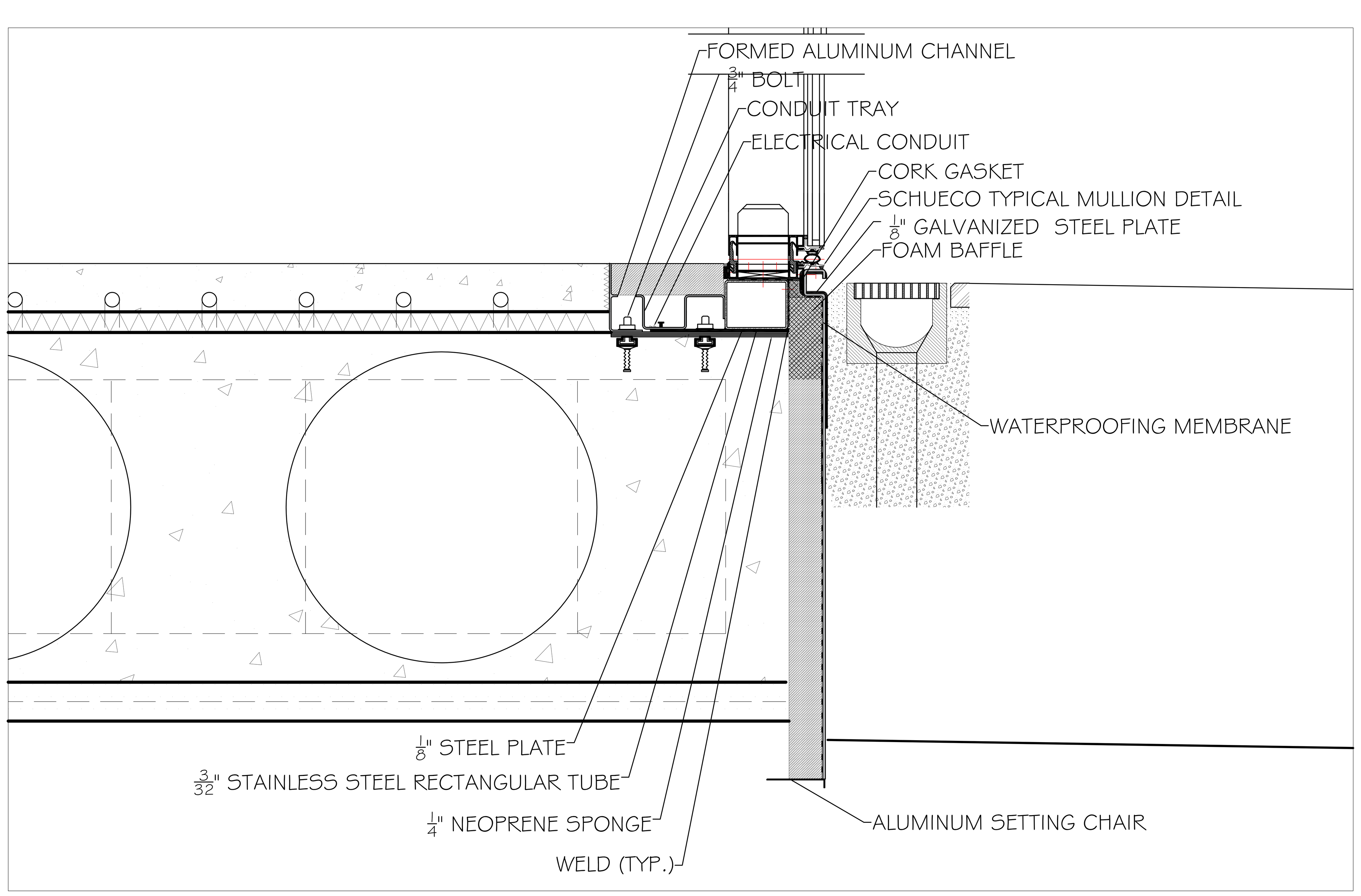
D04



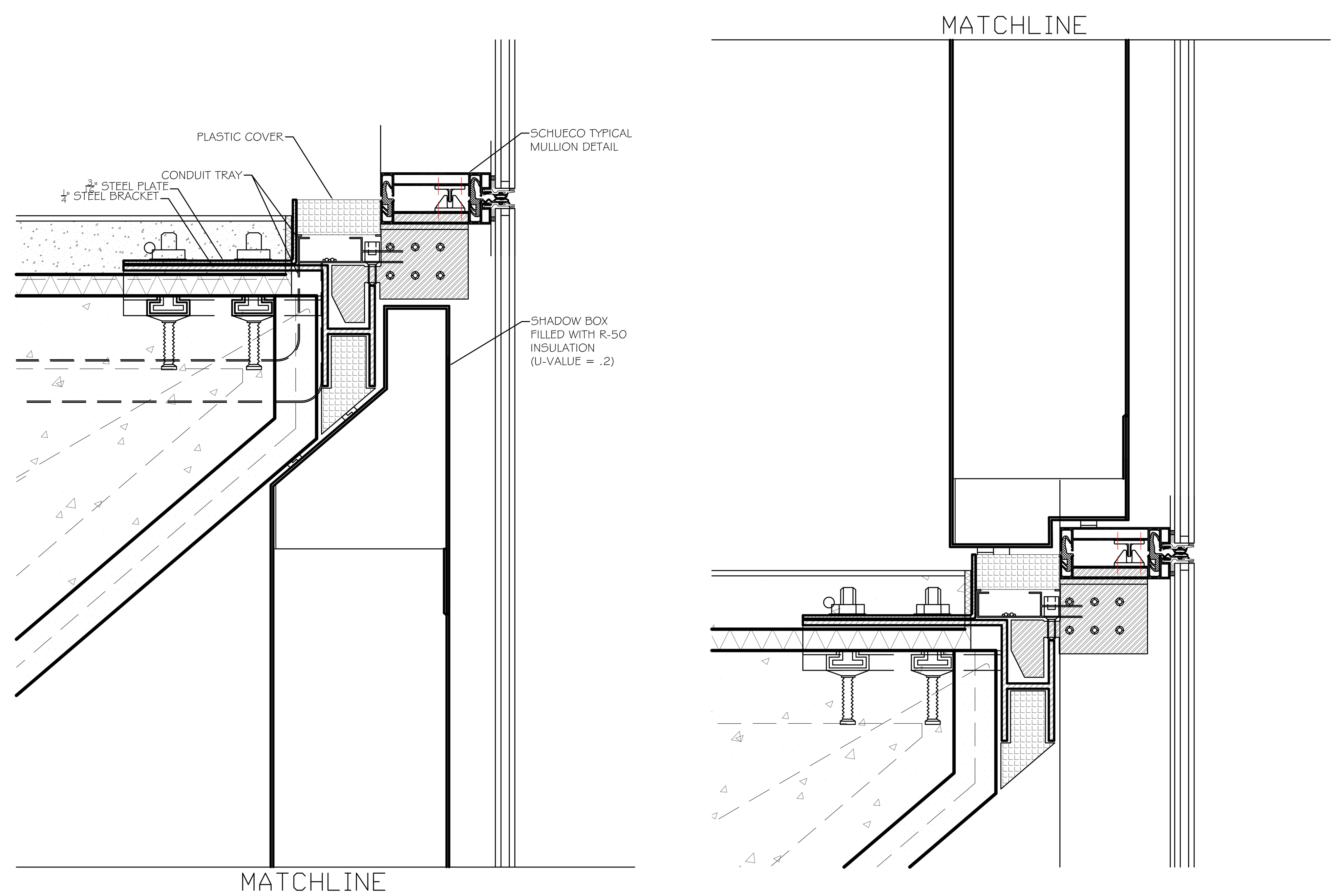
1 TYPICAL BUBBLEDECK SECTION (SCALE: 3/4" = 1'-0")



2 TYPICAL BUILDING ENVELOPE SECTION (SCALE: 6" = 1'-0")



3 BUILDING ENVELOPE TYPICAL CONNECTION TO PAVEMENT (SCALE: 3" = 1'-0")



1 BUILDING ENVELOPE TYPICAL SHADOWBOX DETAIL (SCALE: 3" = 1'-0")

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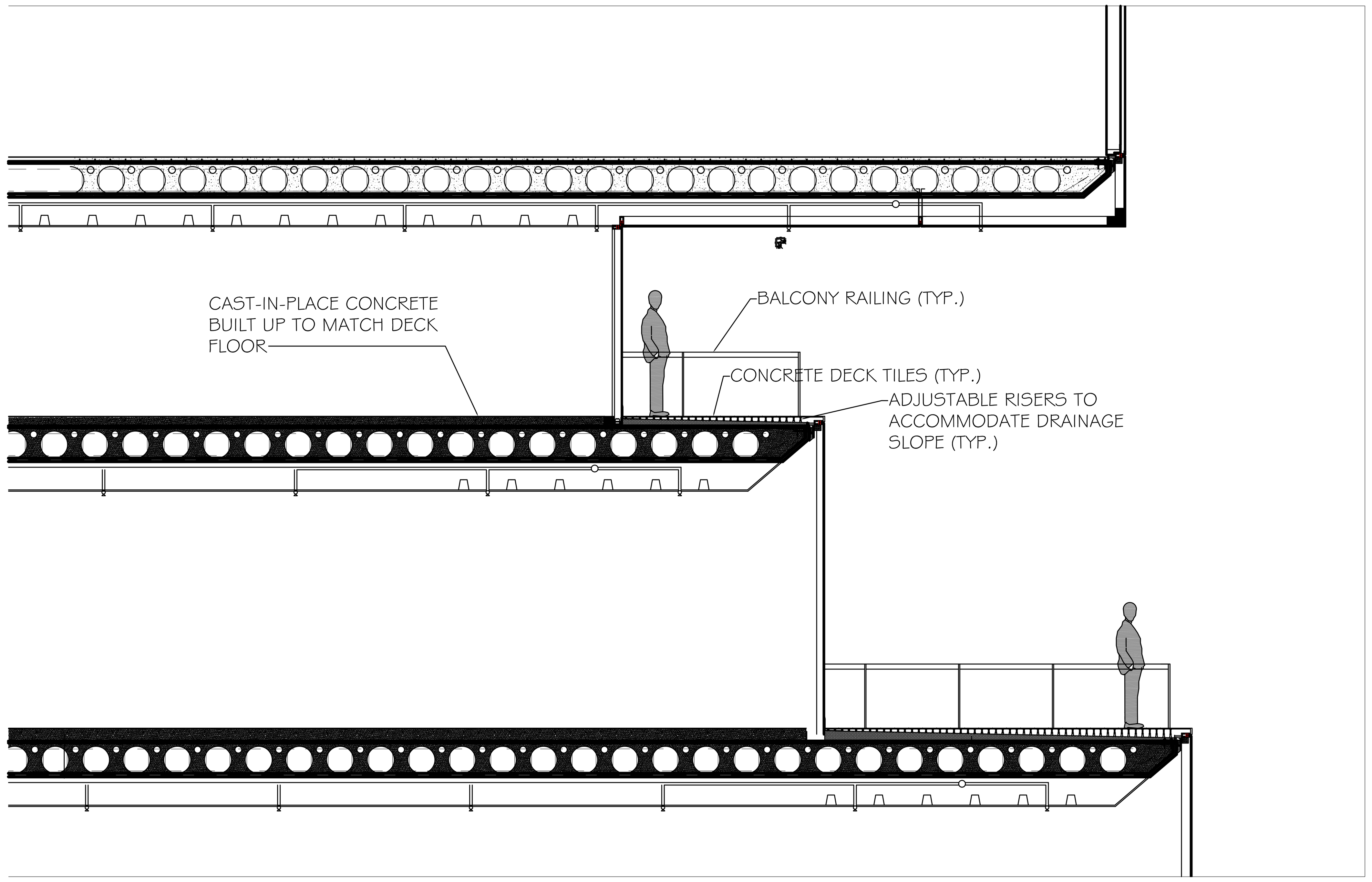
ENVELOPE DETAILS

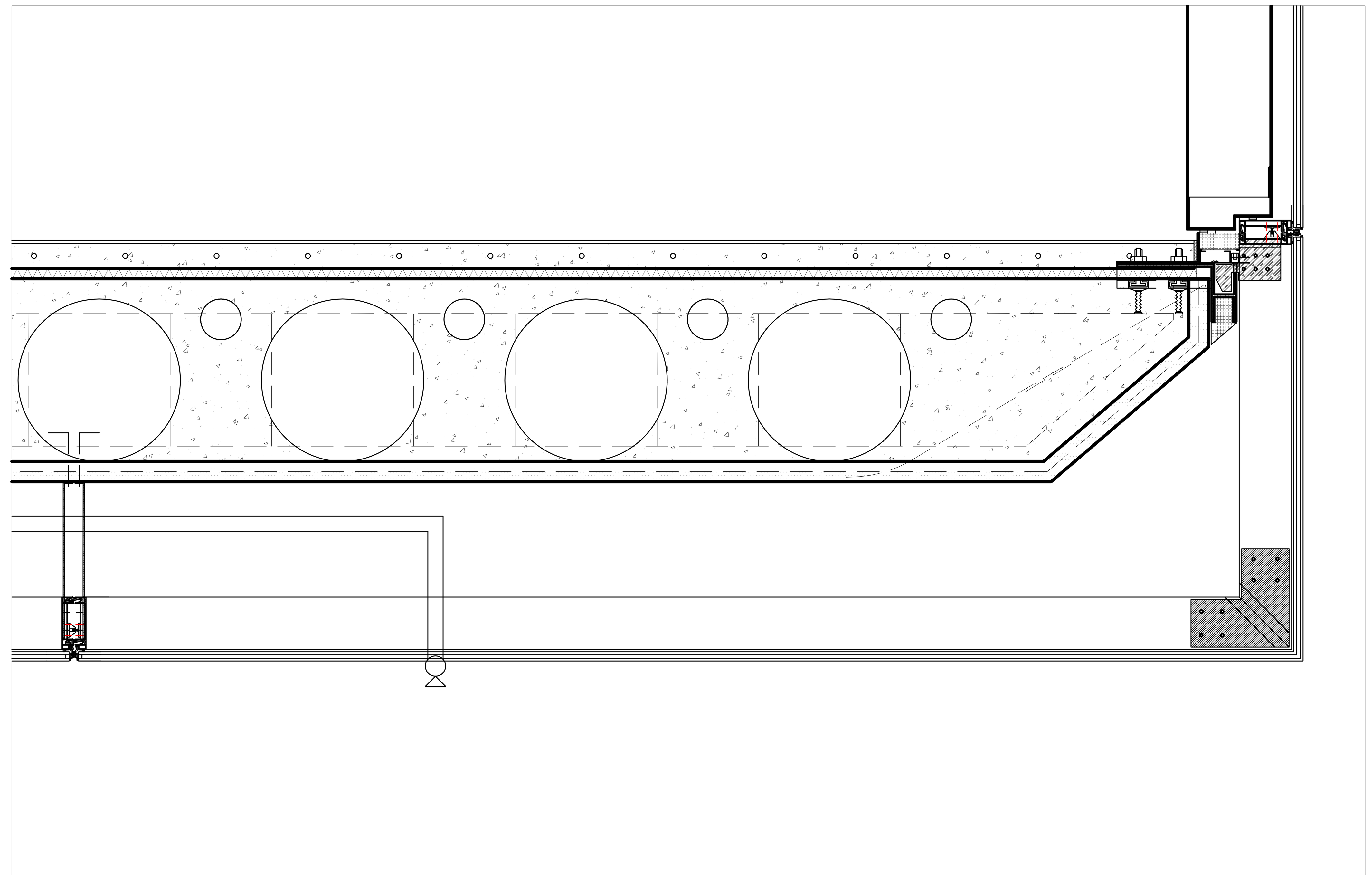
TEAM 05

2/17/16

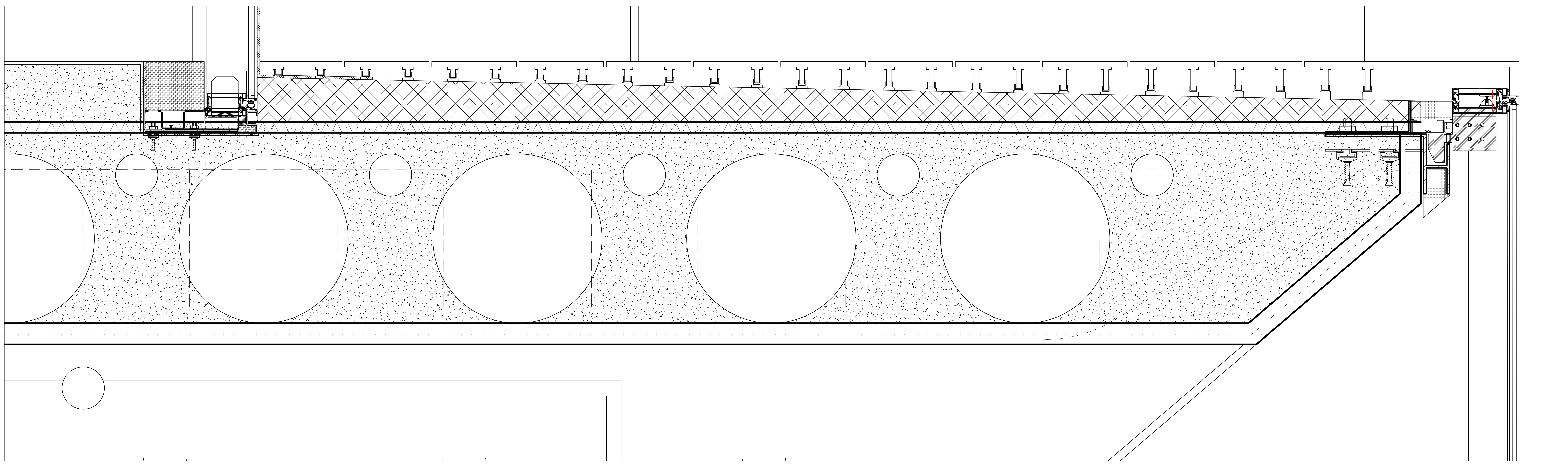
D05



1 SKY GARDEN SECTION (SCALE: 1/4" = 1'-0")



1 UPPER SKY GARDEN CEILING DETAIL SECTION (SCALE: 1-1/2" = 1'-0")



1 UPPER SKY GARDEN DETAIL SECTION (SCALE: 3" = 1'-0")

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ENVELOPE DETAILS

TEAM 05

2/17/16

D06