Green Roof Design

Background / Goals

In their initial investigation into pursuing LEED accreditation, Brookfield Properties considered incorporating a green roof into the 77 K Street project. After realizing that the building would not be able to achieve certain LEED benchmark requirements, the idea of adding a green roof was abandoned. Incorporating a green roof into the existing building would improve the facility in the following ways:

- Reduce storm water runoff into Washington, D.C.'s sewer system
- Reduce peak energy demands by decreasing heating and cooling loads
- Decrease the urban heat island effect
- Protect the waterproofing membrane from UV exposure and freeze-thaw cycles, thus extending its lifespan
- Help the environment through oxygen filtration and production
- Improve sound insulation
- Contribute a significant number of LEED points to help achieve accreditation
- Add recreational space for tenants to enjoy
- Increase property value

The following analysis will investigate the structural implications of adding a green roof to the project. A rudimentary energy study is performed as well in order to assess potential energy savings achieved through the green roof addition. Finally, a LEED assessment will be performed to evaluate contributions the green roof design would add towards LEED accreditation.

Analysis Methodology

1. Investigate various green roof alternatives.

2. Select an appropriate roofing system and components.
3. Assess cost impacts of the new roofing system.
4. Assess schedule impacts of the new roofing system.
5. Determine new roof loads.
6. Design new roof structural system based on the <u>Concrete Reinforcing Steel Design Handbook</u> (2002).
7. Assess plenum space implications of the one-way slab design.
8. Assess energy savings of the new roofing system.
9. Evaluate impact on LEED accreditation.

Resources and Tools

In order to perform the green roof analysis, a number of resources were utilized. After investing various green roof systems, it was decided that the Sika Sarnafil system would be utilized. Ryan Shaughnessy, a representative from Sika Sarnafil Inc., was an integral contact that helped guide my green roof design.

Once an appropriate system was selected and the new roof loads were calculated, the 2002 edition of the <u>Concrete Reinforcing Steel Institute Design Handbook</u> was used to

design the new structural system. Of note, the current roofing system uses a two-way post-tensioned slab. The redesigned system is based on a one-way slab system. The primary reason why a two-way post-tensioned system was not used was because of the complexity of post-tension design. Following discussions with Professor Parfitt, it was determined that a one-way slab would be the most appropriate design alternative for a construction management student. Results of this decision are further discussed later in the analysis.

Green Roof System Selection

Intensive vs. Extensive System

When determining what type of green roof system would be most appropriate for the 77 K Street project, the various benefits of a green roof design were assessed. What features does the owner want to incorporate? What components would the future tenants most value?

From the owner's perspective, the benefits of adding a green roof include large energy savings, more usable space, increased property value, prolonged roof lifespan, and valuable marketing. If the green roof was able to be used as a recreational, leisure space, the roof would be an attractive feature that could set the 77 K Street building apart from other similar commercial office buildings in the Washington, DC metro area.

Based on the following chart from the organization Green Roofs for Health Cities, a green roof type was selected.

EXTENSIVE	SEMI-INTENSIVE	INTENSIVE
Lightweight	Combines best features of extensive and intensive	Greater diversity of plants
Suitable for large areas	Utilizes roof areas with greater loading capacity	Best insulation and storm water management
Low maintenance costs and no irrigation required after fully established	Greater coverage at less cost than intensive	Greater range of design
Suitable for retrofit projects	Average maintenance	Usually accessible
Lower capital costs	Greater plant diversity than extensive	Greater variety of human uses
Easier to replace	Greater opportunities for aesthetic design than extensive	Greater biodiversity potential

Figure 4.1: Green Roof System Summary
(Source: *Green Roofs for Healthy Cities*)

| Extensive Roof | Semi-Intensive Roof | Intensive Roof |

(Source: *Sika Sarnifil*)

A semi-intensive system seemed to be the most appropriate for this commercial setting. The building would benefit from many of the advantages of an intensive roof without many of the added costs.

- The lighter loads would have a smaller impact on the existing structural system.
- The system still contributes significant energy savings to the building.
- The design would have fewer maintenance concerns in terms of irrigation and landscaping.
- The roofing system could incorporate areas for pedestrian access, thus allowing tenants of the building to enjoy the green space.
- The mid-range media depth allows for a wider range of small plant diversity as compared to an extensive design.
- The owner achieves a strong cost-benefit relationship.

After investigating various manufacturers of green roof systems, Sika Sarnafil Inc. was selected as the roofing system of choice.   Other manufacturers that were considered include Hydrotech and Icopal.

Select System Components

As seen on the next page in Figure 4.2, the Sarnafil green roof system includes a waterproofing membrane, protection and drainage layer, insulation layer, drainage composite, growth medium, and vegetation. Based on the proposed design parameters, the system could support grasses and small plant species.

Sarnafil Waterproofing Membrane (Sarnafil G476-15):
    The Sarnafil G476 waterproofing membrane is a PVC based fiberglass mat system. The membrane comes in a variety of thicknesses ranging from 60 mil to 120 mil. The 60 mil (1.5 mm) system was chosen in this design as an alternative to the 1.5 mm EPDM waterproofing membrane in the current roofing design. The G476 system is applied directly to the concrete surface and attaches by means of a pressure sensitive adhesive as well as fasteners. Edges of the membrane are heat-welded together to create a

single waterproofing membrane. Sections of the roof can be compartmentalized as well as a maintenance precaution in case of water penetration below the membrane.
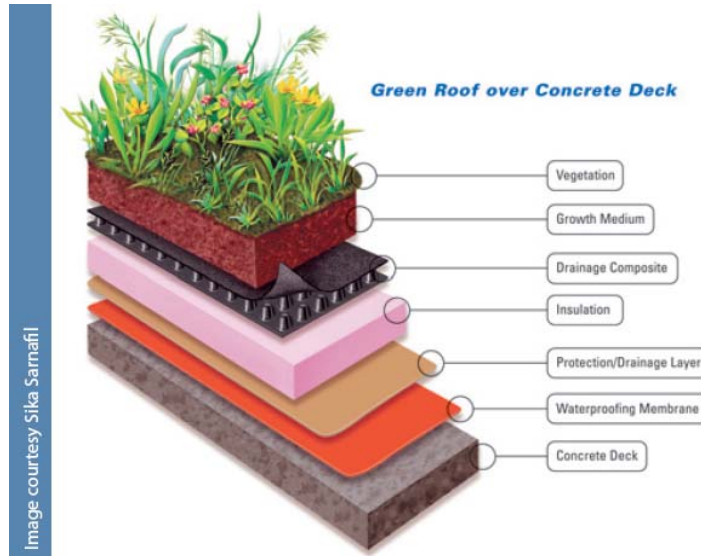

Figure 4.2: Green Roof Components
(Source: *Sika Sarnafil*)

Insulation (4" Sarnatherm XPS-400):
The extruded polystyrene (XPS) insulation board is installed above the waterproofing membrane. The XPS system is specifically designed for moist, buried environments. As a result, it need not be protected by an air or vapor barrier. The insulation does not lose thermal performance when exposed to moisture because of its closed cell design.

Drainage Panel 900:
The drainage panel has a three-dimensional core with a fabric covering that allows large amounts of water to pass freely out of the roofing system. The purpose of the panel is to allow water that flows through the soil medium to drain out of the system, thus protecting the waterproofing membrane from ponding and hydrostatic uplift. The panels also have pockets to store some water as well for the plant medium to absorb after it begins to lose some of its current moisture.

Growth Medium and Plant Vegetation:
It was decided that a semi-intensive green roof system would be incorporated into the building. Eight inches of soil medium will support small shrubberies and plant growth. This wider diversity of plant species will be more attractive than an extensive system that can only support grasses.

Cost and Schedule Comparison

In order to determine an accurate cost estimate for the green roof system, a number of sources were utilized. An attempt was made to receive an estimate from Sika Sarnafil but the company was unable to provide such a cost estimate. A supplier from the Philadelphia area was also contacted but again, they were unable to provide a cost estimate for the system. At which point it was decided to develop a cost estimate based on case studies and design guidelines. The cost estimate was developed from green roof systems of comparable size and scope. Additionally, the system breakdown was developed from the "Design Guidelines for Green Roofs" developed by the Ontario Association of Architects. The estimate of $22.50 falls within the anticipated cost range for a semi-intensive roofing system and the general guideline of being roughly twice the construction cost of a standard built-up roofing system.

	Component	Cost / SF
Green Roof	Green Roof System (curbing, drainage layer, filter cloth, growing medium, pavers, etc.)	$11.00
	Plants	$3.50
	Installation / Labor	$8.00
	Total	**$22.50**

The green roof design would cover approximately 24,000 square feet of the 32,000 square foot roof. The penthouse and second floor roofs will still be covered by the ballasted EPDM roof system. The primary factor governing the use of the EPDM system in these two areas is the difficulty of access. The green roof system does have additional landscaping and upkeep issues that require more extensive maintenance access.

Material and Installation Cost Summary:

Existing EPDM Roof System	**Green Roof Redesign**
32,000 SF @ $9.80/SF = $313,600	8,000 SF @ $9.80/SF = $78,400
	24,000 SF @ $22.50/SF = $540,000
Total Cost = $313,600	**Total Cost = $618,400**
Average Cost = $9.80/SF	**Average Cost = $19.32/SF**

Based on the proposed schedule below, the green roof system would add thirteen days to the existing roofing schedule. Though this adds duration to the roofing activities, it does not push back the overall construction schedule. The substantial completion date is not affected in any way.

Task Name	Duration	Feb 24, '08	Mar 9, '08	Mar 23, '08	Apr 6, '08	Apr 20, '08	May 4, '08	May 18, '08
Penthouse Roof Tar and Membrane	8 days							
Penthouse Roof Water Test	3 days							
Penthouse Roof Insulation and Ballast	4 days							
Main Roof Tar and Membrane	15 days							
Main Roof Water Test	5 days							
Main Roof Insulate and Ballast	15 days							
Penthouse Roof Tar and Membrane	8 days							
Penthouse Roof Water Test	3 days							
Penthouse Roof Insulation and Ballast	4 days							
Main Roof Waterproofing Membrane	8 days							
Main Roof Water Test	5 days							
Main Roof Protection Layer and Insulation	10 days							
Main Roof Drainage Composite	5 days							
Main Roof Pedestals and Pavers	8 days							
Main Roof Growth Medium and Vegetaion	12 days							

Green Roof Structural Design

Description

To accommodate the increased load on the roof structure, the existing structural system was redesigned to accommodate the additional dead loads associated with the green roof. Additionally, live loads were increased to 100 PSF on all portions of the roof to accommodate pedestrian access. A one-way concrete slab system with beams and girders was designed for a typical 30'-0" x 30'-0" bay with typical 24" x 24" columns. Both interior and end span bays were designed. Members were sized using _Concrete Reinforcing Steel Institute Design Handbook, 2002_. Detailed calculations for the design of the roofing system can be found in Appendix B. For this breadth study, torsional moments induced on end span spandrel beams were not considered. Additionally, the tributary area for a typical interior span was used in the calculation of end spans as well. A typical interior bay is shown in Figure 4.3.
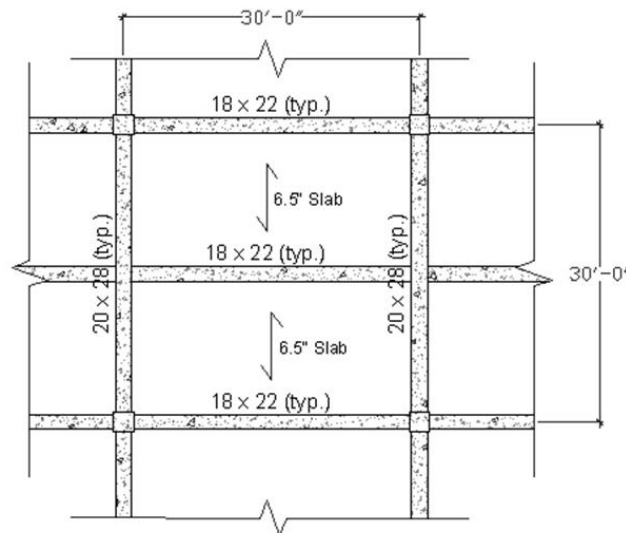
Figure 4.3:
Typical Interior Bay Design

Slab Design Procedure

1. Calculate live and dead loads being induced on the slab.
2. Calculate factored load, w_u.
3. Determine clear span, ℓ_n, between the column and beam.
4. Determine minimum allowable slab thickness based on $\ell/28$.
5. Determine slab thickness and ρ value based on minimum slab thickness, clear span, and factored loading. Use tables in chapter 7 of the CRSI Design Handbook.
6. Compare allowable interior span and end span slab thicknesses and use the greater of the two values. End span thickness will always control.
7. Check deflection and crack control.

The slab thickness for a typical bay was calculated to be 6.5".

Beam Design Procedure

1. Calculate live and dead loads being induced on the slab.
2. Calculate factored load, w_u, per square foot.
3. Calculate load per linear foot of beam stem.
4. Convert factored load into a line load on the beam and add to stem load.
5. Determine minimum beam size based on clear span and factored loading. Use tables in chapter 12 of the CRSI Design Handbook.
6. Adjust beam stem loading in step 3 and repeat steps 4 and 5 as necessary.
7. Compare allowable interior span and end span beam sizes and determine whether it is appropriate to use different sizes. End span size will always be greater given the same loading.

8. Determine stirrup requirements given in beam design based on tables provided on page 12-13 of the design handbook.

The design conditions dictated a beam size of 18" x 22". It is possible that interior span beams be reduced to 16" x 22" but for ease of construction, all beams were maintained at a 18" x 22" size. By keeping a uniform beam size throughout, the concrete contractor is able to use the same formwork throughout the slab system. Though interior and exterior spans have the same size beams, the reinforcing within the beams varies. Figures 4.4 and 4.5 show typical interior span beam sections.
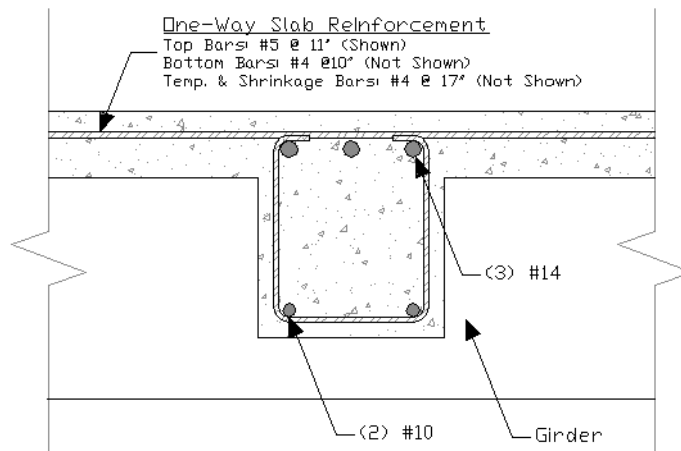
Figure 4.4:
Interior Span, Beam Section
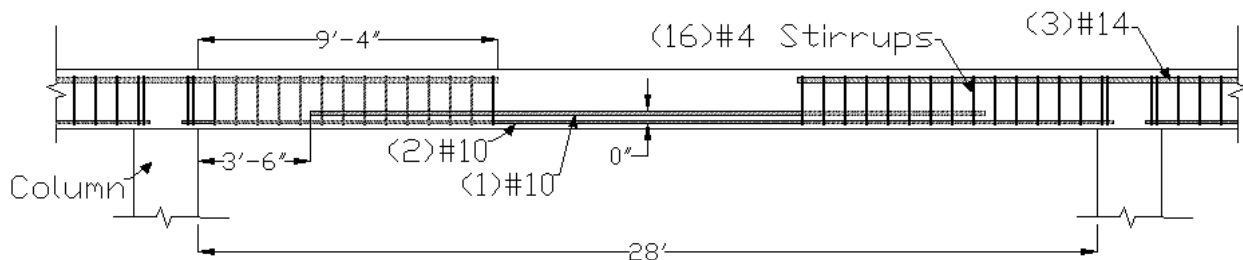
Figure 4.5:
Interior Span, Beam Section

Girder Design Procedure

1 Convert concentrated mid-span beam load to a point load.
2. Calculate load per linear foot of beam stem.
4. Calculate factored moment from concentrated load at mid-span, M.
5. Calculate equivalent uniform load based on factored moment, w.

6. Calculate total uniform factored load, w_u, for negative moment by adding w and girder stem load.
7. Calculate factored positive moment, $+M_u$.
8. Calculate total uniform factored load, w_u, for positive moment.
9. Determine minimum girder size based on clear span and total uniform factored load, w_u, for negative moment. Use tables in chapter 12 of the CRSI Design Handbook.
10. Adjust beam stem loading in step 2 and repeat the above steps as necessary.
11. Compare allowable interior span and end span beam sizes and determine whether it is appropriate to use different sizes. End span size will always be greater given the same loading.
12. Determine stirrup requirements given in girder design based on tables provided on page 12-13 of the design handbook.
13. Check that torsion requirements are met.
14. Check that shear requirements are met.
15. Check bottom bar positive moment capacity based on data in design tables.
16. Adjust initial stirrup spacing based on shear requirements.

The design conditions dictated a girder size of 20" x 28". It is possible that interior span girders be reduced to 18" x 28" but for ease of construction, all beams were maintained at a 20" x 28" size. By keeping a uniform beam size throughout, the concrete contractor is able to use the same girder framing formwork throughout the slab system. Though interior and exterior spans have the same size girders, the reinforcing within the girders varies. Figures 4.6 and 4.7 show typical interior span girder sections. Figure 4.8 illustrates a typical interior span intersection of a column, beam, and girder.
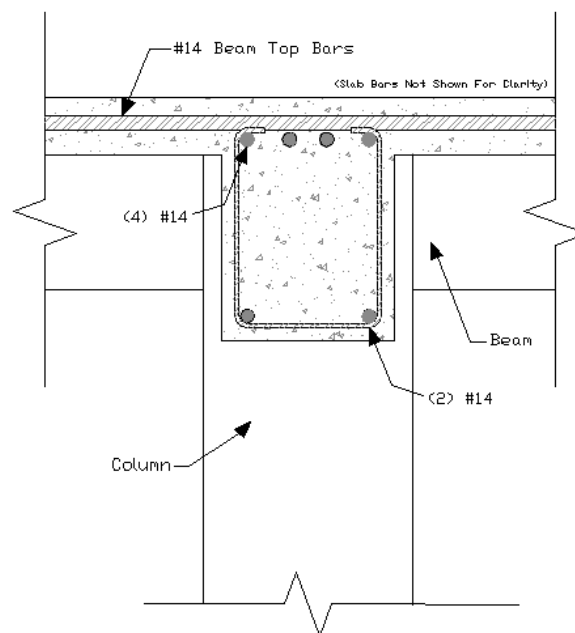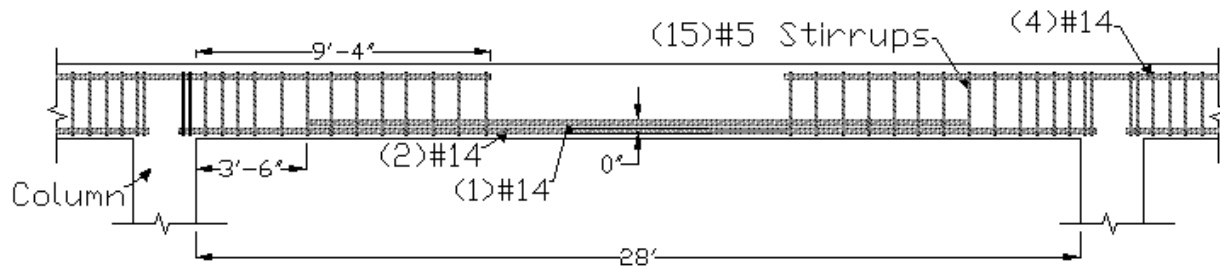

Figure 4.6:
Interior Span, Girder Section

Figure 4.7:
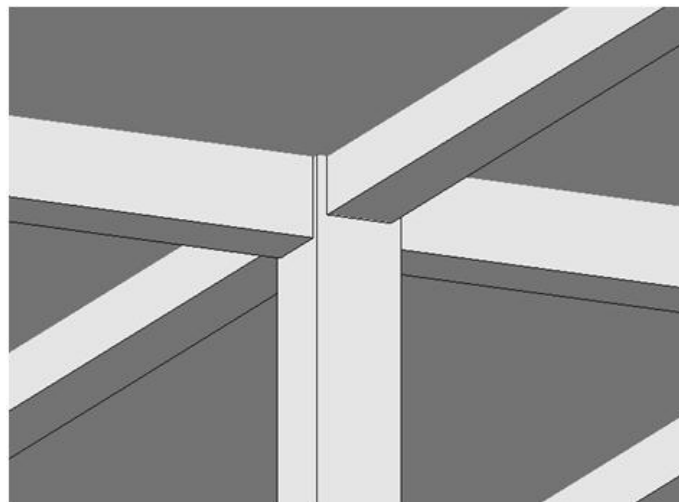Interior Span, Girder Section

Figure 4.8:
Structural Element Intersection

Plenum Space Implications

The decision to design a one-way reinforced slab system rather than a two-way traditional or post-tensioned system creates a construction coordination concern in terms of mechanical and plumbing coordination within the plenum space. The girders running in the north-south direction have a depth of 28", 17" deeper than the existing 11" slab. In the east-west direction, the beams have a depth of 22", again deeper than the existing conditions.

The existing finished floor to finished ceiling height on all typical floors, except for the eleventh floor, is 8'-7". The eleventh floor has a floor to ceiling height of 9'-1". By lowering the finished ceiling height to 8'-7" on the eleventh floor, an additional 4" is gained to account for some of the reduced plenum space.

As shown in the typical tenant space drawings in Figure 4.9, even with lowering the finished ceiling height, the reduced plenum space still poses a problem for installing the mechanical duct work. Additionally, raising the roof height is not an option. District of Columbia code mandates that the building not exceed a height of 130'-0". The building currently stands at 129'-11-1/2" and therefore it is not a feasible solution to add plenum space on the eleventh floor by raising the roof slab.

11th Floor Plenum Detail

Typical Floor Plenum Detail

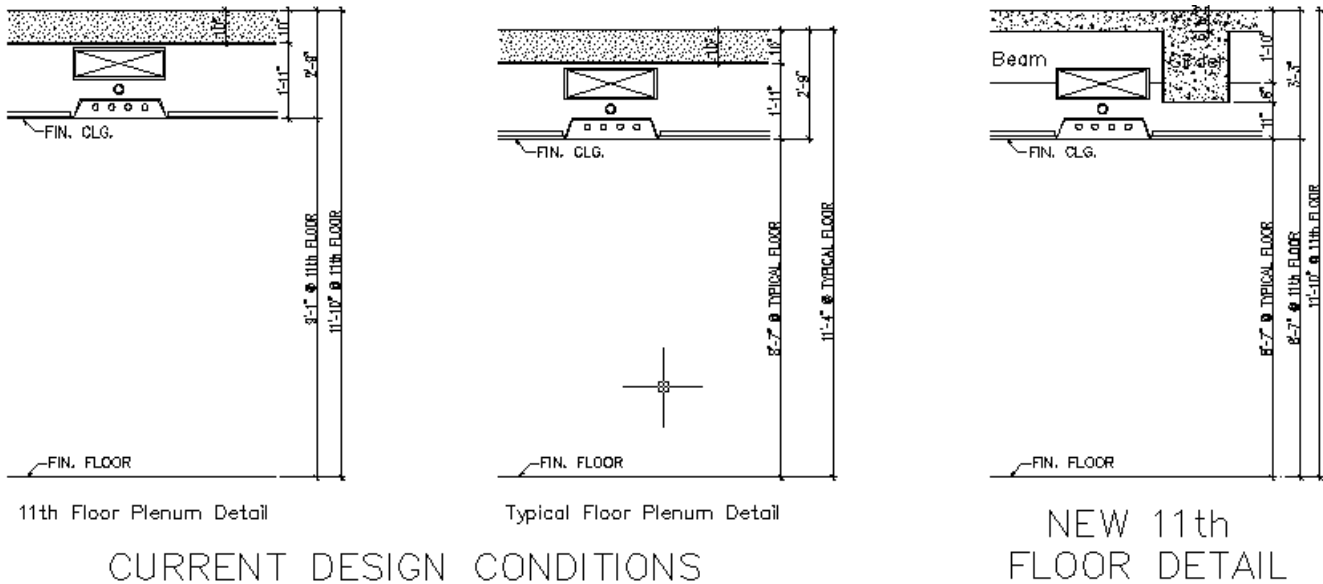CURRENT DESIGN CONDITIONS

NEW 11th FLOOR DETAIL

Figure 4.9:
Existing and Proposed Plenum Space Conditions

The current system has a plenum space of 1'-11". The redesigned roof slab system provides for a clearance of 1'-5" beneath the beams running in the east-west direction and only 11" beneath the girders in the north-south direction. From the core of the building, ducts are currently 16" deep extending 20' from the self contained air conditioning units. The 16" ducts are only located in the core of the building where the plenum space is 2'-5", 7" larger than in the tenant space. In the tenant space duct size is reduced to 12" maximum. Consequently, the major concern is fitting the ducts beneath the girders. The beam design does not have a hindering impact on the current duct design.

Possible solutions to the plenum space issue:
1. Resize ducts and minimize duct depth so as to fit beneath the girder and above the current finished ceiling height.
2. Lower the finished ceiling height.
3. Provide cutouts in the girders to accommodate ducts. Provide additional reinforcement at cutout locations to provide adequate load capacity at these locations.

Energy Analysis

Green roof systems have been proven to reduce heat transfer compared to a conventional roofing system. This in turn reduces heating and cooling loads induced on the building. In order to determine the energy savings of the green roof design, the heat transfer was first calculated for the existing roof. Heat transfer through a flat roofing system can be estimated using the equation:

$$Q = UA(\Delta T)$$

To begin, the thermal transmittance (U value) for the existing roofing system was tabulated and is shown in Figure 4.10.

		Unit Resistance (R)
	Inside surface (still air)	0.61
	Concrete slab, 11 in.	0.88
	Rigid roof deck insulation, 4"	20.00
	EPDM, 1.5 mm	0.05
	Ballast, 2"	1.70
	Outside surface (15 mph wind)	0.17
	Total Thermal Resistance (R)	23.41
U = 1/R	*Coefficient of Transmission (U)*	0.0427

Figure 4.10:
Roof Thermal Conductivity Analysis

The calculation of an effective U value for a green roof system is a bit more complex due to the changing thermal properties of the roof with fluctuations in temperature and moisture content. As a result, a study performed at the National Research Center in Toronto, Canada was used as a reference.   Their research found that over the two year study, green roofs had a 95% heat gain reduction and a 26% heat loss reduction compared to a reference roof of conventional roofing construction.

In the analysis below in Figure 4.11, a conservative value of 75% of each of these reductions was used (71.25% heat gain reduction and 19.5% heat loss reduction). Their research concluded that green roofs experienced larger heat transfer savings in the warmer, summer months. Being that Washington, DC is a more temperate climate than Toronto, the potential energy savings may be even greater than those estimated.
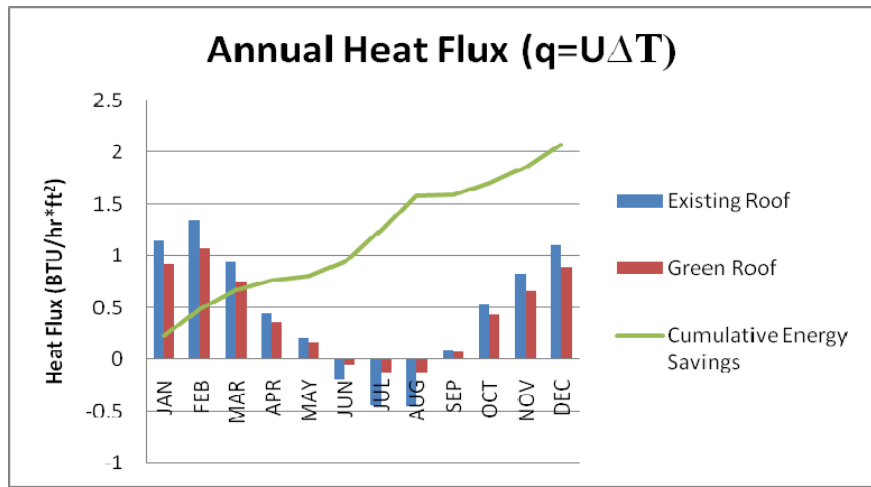
Figure 4.11:
Annual Heat Flux

Based on the above graph, the greatest energy savings will be achieved in August when the system will have a 7.5525 BTU/hr*ft^2 reduction in cooling load between the existing and green roof systems.

Existing Roofing System:

$Q_e = UA(\Delta T)$

$Q_e = (0.0427 \text{ BTU} / (hr*ft^2*°F))*(32,000 \text{ ft}^2)*(80.6 °F − 70 °F)$

$Q_e = 14,484 \text{ BTU} / hr$

    Q_e for 24,000 SF = 10,863 BTU / hr

    Q_e for 8,000 SF = 3,621 BTU / hr

Green Roof Design:

$Q_g = (10,863 \text{ BTU} / hr)*(1-(0.75*0.95)) + 3,621 \text{ BTU} / hr$

$Q_g = 6,744 \text{ BTU} / hr$

Savings = (14,484 BTU / hr − 6,744 BTU / hr) / (12,000 BTU / ton)
       = 0.645 ton/hr savings

Because the reduction in the maximum cooling load is less than a ton, the possibility of reducing the size of the self-contained air handling unit that cools the eleventh floor is not practical. Nonetheless, there is still a reduction in demand on the system. The McQuay SWP-080 system used in the building has an efficiency of SEER 14.

Annual Energy Savings:

Q = Area * Cum. Annual Savings * Hours Per Day * Days Per Year

Q = (24,000 ft^2) * (2.073 BTU / Hr. * ft^2) * 24 Hrs/Day * 365.25 Days/Year

Q = 436,126,032 BTUs/Year

$$\frac{\$}{yr} = \frac{(BTU/yr)(\$/kWh)}{(SEER)(1,000 \text{ W/kW})}$$

$$\frac{\$}{yr} = \frac{(436,126,032 \text{ BTUs/Year})(\$0.0672/\text{kWh})}{(14 \text{ BTUs/W})(1,000 \text{ W/kW})}$$

$$\frac{\$}{yr} = \$2,093/yr.$$

Life Cycle Cost Analysis

According to published data, the average expected life expectancy of the waterproofing membrane in an EPDM and ballast roofing system as is currently installed on the 77 K Street project is 17.7 years. Because the waterproofing in a green roof design is protected from UV exposure and more extreme surface temperatures, the life span is greatly extended. Estimates are that green roof systems can last between 35 and 50 years before the waterproofing membrane must be replaced.

The forty year cost analysis below shows that over the life span of the building, the green roof system is a slightly more cost effective solution as the roofing system has a lifespan of approximately twice that of the EPDM system. Replacement of the EPDM system is assumed to take place at year 20 and in year 40, both systems would need replacement. 8,000 square feet of roof will require replacement in the redesigned system as well because 100% of the roof was not redesigned to be green.   The owner will realize an equivalent cost at approximately year 20 and from that point forward will begin to realize a cost savings from the green roof design.

The rudimentary analysis below includes initial costs, replacement costs, and annual energy expenses associated with heat loss through the roofing system. Interest rates and changes of the dollar value over time are ignored. A more in depth cost assessment can be found in the final section of this report entitled "LEED for Core & Shell Development: Potential Status."   As shown above, the green roof system has an operating savings of $2,903 as compared to the existing system. Maintenance costs are not included in the analysis below but are relatively comparable between the two systems if an appropriate green roof design is incorporated.
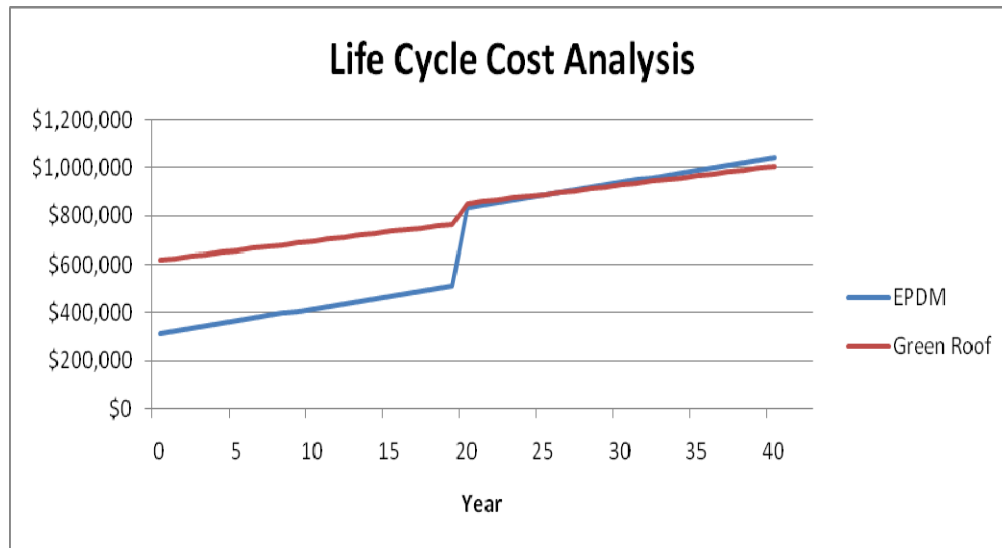
Figure 4.12:
Roofing Life Cycle Analysis

LEED Impact

The incorporation of a green roof into the 77 K Street project has the potential to contribute to four categories of the LEED rating system as outlined below.

# of Credits	LEED Credit	Likely	Possibly	Contributor
1	Sustainable Sites 6.1 *Stormwater Design: Quantity Control*	X		
1	Sustainable Sites 7.2 *Heat Island Effect: Roof*	X		
1	Water Efficiency 1.1 *Water-Efficient Landscaping*		X	
2-8	Energy and Atmosphere 1.0 *Optimizing Energy Performance*			X
1-2	Materials and Resources 4.1, 4.2 *Recycled Content*			X
1-2	Materials and Resources 5.1, 5.2 *Local and Regional Materials*			X

Sustainable Sites Credit 6.1,
Limit disruption of natural hydrology by reducing impervious cover, increasing on-site infiltration, and managing stormwater runoff.

    In order to meet the requirements for this credit, one must reduce stormwater runoff by a minimum of 25% for a given two-year 24-hour design storm. The incorporation of a green roof will most certainly meet this criterion.

Sustainable Sites Credit 7.2,
Reduce heat islands (thermal gradient differences between developed and undeveloped areas) to minimize impact on microclimate and human and wildlife habitat.

    Installing a green roof on at least 50% of the roof area meets the credit requirement.

Water Efficiency Credit 1.1,
Limit or eliminate the use of potable water, or other natural surface or subsurface water resources available on or near the project site, for landscape irrigation.

    Irrigation requirements for landscaping must be reduced by 50%. By selecting appropriate, indigenous plants for the roof, irrigation needs can be reduced or even completely eliminated.

Energy and Atmosphere Credit 1.0,
Achieve increasing levels of energy performance above the baseline in the prerequisite standard to reduce environmental and economic impacts associated with excessive energy use.

    Total building energy cost savings must equal 14% at minimum to receive the required 2 credits for certification. Incremental increases in building performance will lead to accruing more credits. The green roof will undoubtedly help contribute to this overall energy savings as shown in the energy analysis portion of this report.

Materials and Resources Credits 4.1, 4.2
Increase demand for building products that incorporate recycled content materials, thereby reducing impacts resulting from extraction and processing of virgin materials.

    Post-consumer content plus one-half pre-consumer content constitutes at least 10% of the total material value of the project to receive credit 4.1. By adding an additional 10% of the material value, the project will receive an additional credit under credit 4.2. Many green roof materials contain recycled content and thus can contribute to these credits.

Materials and Resources Credits 5.1, 5.2
Increase demand for building materials and products that are extracted and manufactured within the region, thereby supporting the use of indigenous resources and reducing the environmental impacts resulting from transportation.

    10% of all building materials, based on cost, must be produced within a 500 mile radius of the jobsite to receive credit 5.1. By purchasing an additional 10% of local materials, the project will receive an additional credit under credit 5.2. Many green roof materials are produced locally. Plants and medium, for example, are almost always indigenous to the project region.