architectual engineering thesis

[final report]

PHIPPS
center for sustainable landscapes

mechanical system redesign
April 4, 2012
thesis.joshwentz.net

option. mechanical
advisor. Dr. William Bahnfleth
building location. Pittsburgh, PA

by JOSHWENTZ

PHIPPS
center for sustainable landscapes

PENNSTATE
architectural engineering thesis
[mechanical option]

by JOSH WENTZ

statistics

location. Pittsburgh, PA, Schenley Park
function. education, administration, research
occupants. Phipps employees / researchers
size. 24, 350 square foot, 3 stories
cost. $ 20 million
construction dates. Dec. 2010 - Apr. 2012
delivery method. lump sum with contractor

team

owner. Phipps Conservatory
architect. The Design Alliance
structural. Atlantic Engineering Services
MEP. CJL Engineering
contractor. Turner Construction
landscape. Andropogoan Associates
integrated design process required by owner

architecture

sustainability. LEED Platinum
materials. regional, salvaged barn siding, motorized low-e glazing, metal light shelves
Living Building Challenge. + green roof
site. rainwater harvesting, constructed wetland
façade. high thermal mass
net zero. energy & water consumption

structural

substructure. cast –in-place concrete
foundation. 12" concrete wall reinforcement, 30" diameter concrete column reinforcement
superstructure. structural steel
strip & spread footings
frame construction. with composite slab on deck

mechanical

heating & cooling. geothermal ground source
rooftop energy recovery unit. 12,400 cfm VAV with enthalpy wheel, desiccant dehumidification
raised floor distribution. 4,860 cfm open office
100% passively cooled atrium
ventilating. CO2 sensors, demand controlled
controls. building management system

lighting / electrical

lights. mainly 4' T8 or T540 direct/indirect high efficiency ecosystem dimming ballast
natural daylighting, occupancy sensors
photovoltaics. 36 kW PV arrary
vertical access wind turbine
transformer. 75 kV
main distribution panel. 600A

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1.0 Executive Summary

New energy efficiency policies, a global social responsibility to "live greener", information technology advancements, and energy efficiency pressures from other industries have all raised the standard to which mechanical systems in buildings are expected to perform. The owner of Phipps Conservatory expected the highest performing, sustainable building that technology has to offer with a new facility currently under construction.

Phipps Center for Sustainable Landscapes (CSL) is a new 24,350 square foot building in Pittsburgh, Pennsylvania. The building will be comprised of classrooms, offices, and conference rooms for Phipps employees and university researchers. The estimated date of construction completion is April 2012. Phipps strives for CSL to exceed the United States Green Building Council's highest certification, LEED (Leadership in Energy and Environmental Design) Platinum.

The **objective** of this report is to analyze a proposed redesign for the Center for Sustainable Landscapes. **Sections discuss**: building overview, existing mechanical system overview, proposed redesign, mechanical depths, construction management breadth, electrical breadth, energy and cost analysis, and conclusions / recommendations.

Currently, the mechanical system of CSL has a full geothermal ground source closed loop system, a 12,400 cfm rooftop energy recovery unit, a demand control ventilation system, an underfloor air distribution to supply air directly to the space, and a direct digital control building management system. It was simulated to consume 19,926 BTU/SF annually for electricity, 75% less than a building of its size, function, and location. The main goal of the redesign was to decrease initial costs while maintaining similar energy performance.

The first mechanical depth was to replace the $114,329 priced green roof with a **spray cooled roof**. The spray cooled roof works by misting water onto the roof during the summer months. Cooling is provided to the envelope through the evaporation process. This alternative proved to cost 94% less in up-front costs and to save more energy through cooling months than a green roof. Yet, through heating months (October to March) the green roof performed better due to adding an additional layer of insulation.

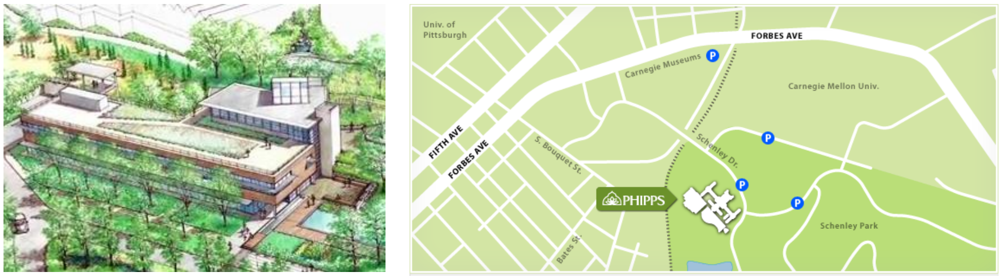
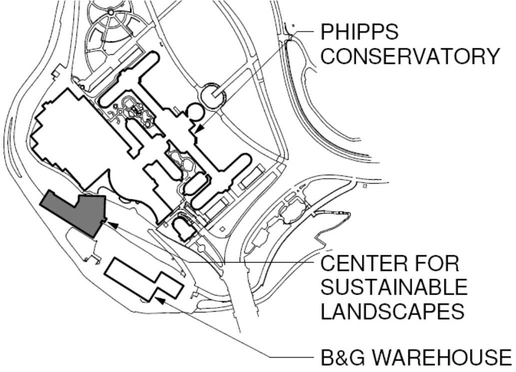
The second mechanical depth was to redesign the $100,000 full geothermal system with a **hybrid geothermal system**. Since CSL is cooling dominated, a cooling tower was added to provide heat rejection during peak conditions. Through this depth and a construction management breadth of optimizing the most economical number of boreholes it was determined that a 10 ton cooling tower with a reduced borehole depth could cost $46,458 less to install while only nominally increasing annual utility costs by $352.

The final electrical breadth attempted to capitalize on the 946 solar panels on site. Through a direct current distribution system as opposed to an alternating current, DC-AC and AC-DC inefficiencies could be removed. Results show that by having a DC microgrid within CSL's building, photovoltaics could produce an additional 53,966 kWh having a value of $4,390 annually.

Overall, the redesign met the goal of decreasing initial costs by a total of $183,286 and only slightly increasing the energy performance by 2,561 kWh.

2.0 Building Overview

2.1 Statistics

Name	**Phipps Conservatory, Center for Sustainable Landscapes (CSL)**  Figure 1 Rendering & Location Map
Location	One Schenley Park Drive; Pittsburgh, PA 15213 
Occupant	Phipps Employees / University Researchers 367 persons [*1st: 140, 2nd: 112, 3rd: 115*]
Function	Classroom / Office / Conference Education / Administration / Research
Size	24,350 SF [*1st: 11,209 SF, 2nd: 11,151 SF, 3rd: 1,990 SF*]
Floors	3 stories
Construction	Dec. 2010 - Apr. 2012
Cost	$20 million
Team	Integrated Project Delivery (IPD) required by the owner
Sustainability Goals	1. Net-Zero Energy Building 2. LEED Platinum 3. Living Building Challenge 4. SITES Certification for landscapes

2.2 Architecture

Influences	Center for Sustainable Landscapes is a part of Phipps Conservatory and Botanical Gardens, which are a complex of buildings and grounds set in Schenley Park, Pittsburgh, Pennsylvania (near the Carnegie Museums in Oakland). Phipps is a Pittsburgh historic landmark and is listed on the National Register of Historic Places. The conservatory's overall purpose is to educate and entertain the people of Pittsburgh with formal gardens (Roman, English, etc.) and various species of exotic plants (palm trees, succulents, bonsai, orchids, etc.). Center for Sustainable Landscapes must conform to Phipps high green standards and progressive architecture, yet, unlike the rest of the campus, is not open to the public.
Codes	● IBC 2006 ● Uniform Construction Code (UCC) of Pennsylvania ○ Building Code (2006) ○ Mechanical Code (2006) ○ Plumbing Code (2006) ○ Fire Code (2006) ○ Energy Conservation Construction Code (2006) ● National Electric Code ● NFPA-70 ● Americans with Disabilities Act (ADA)
Zoning	"P" Parks District
Historical Requirements	Schenley Park National Register District: Thus, the design must comply with the compliant architecture of the park.
Landscape	*Sustainable Landscape* ● Sustainable landscape features all non-invasive, native plants. Click here to view the proposed plant list. ● Plants will use rain water as irrigation - no additional irrigation will be installed ● A walking trail and boardwalk lead through a variety of landscape communities including wetland, rain garden, water's edge, shade garden, lowland hardwood slope, successional slope, oak woodland and upland groves ● Restores natural landscape function, provides wildlife habitat, and offers educational opportunity

Rainwater Harvesting

- Stormwater from upper campus glass roofs and lower site will be captured
- Stored in two 1,700 gallon underground cisterns
- Rainwater will be used for toilet flushing, as well as interior irrigation and maintenance as required
- Ultralow flow plumbing fixtures include waterless urinals and dual-flush toilets for water conservation
- Greatly reduces impact on municipal sewage treatment and energy-intensive potable water systems

Constructed Wetland

- Treat all sanitary water from CSL and adjacent maintenance building
- Subsurface flow constructed wetland system
- 2-stage wetland treatment cell system
- Sand filtration provides additional treatment of the wetland effluent
- Ultraviolet process disinfects water to gray water standards
- Greatly reduces impact on municipal sewage treatment and energy-intensive potable water systems

2.3 Enclosure

Facade

Facade is a combination of:

- Salvage barn siding
- Motorized upper glazing

	- Metal light shelf - Operable windows - Glass Fiber Reinforced Concrete Precast Panels - Backup of exterior studs **Robust Building Envelope** - Provides optimal energy efficiency - Building envelope reduces thermal heating losses and solar cooling loads, and maximizes natural daylighting - High performance wall and roof insulation reduce winter heat losses and summer heat gains - High performance, low-e (low-emissivity) windows provide state-of-the-art solar and thermal control and energy efficiency, while admitting maximum daylight
Roofing	 The following is the weather resistant covering as part of the exterior enclosure. **Insulation** - The white surface of the roof (including the atrium) consists of rigid foam insulation and *Thermoplastic PolyOlefin (TPO)* . - The Green Roof that covers the majority of the roof provides added insulation from outdoor to indoor conditions. **Drainage** - *Tapered roof* directs water to gutters that leads to on-site water treatment for grey water. - The *Green Roof* acts as roofing membrane similar to TPO, but is applied to the concrete, followed by soil, plants. - The secondary drainage system consists of *overflow scuppers*, which are simply holes in the parapet wall.

	The NE shaft wall & NE stairs seen on the bottom of the picture is also covered with TPO.

2.3 Engineering Systems

Mechanical	Discussed in Section 3.
Electrical	Due to CSL's close proximity to the existing Phipps Conservatory; a 600 amp 3 phase electrical service connects this new building directly to the third floor with existing adjacent facilities. Standard voltages of 120/208 and 277/480 are distributed as needed throughout the building via the raised access floor system. CSL also strives to be a net-zero building with respect to electricity use. A vertical axis wind turbine as well as 36kW solar panel arrays contribute both to building electricity demands as well as supplying back to Duquense Light's grid.
Lighting	The Center for Sustainable Landscapes uses a variety of lighting methods including national daylighting, fluorescent lighting, and energy efficient LEDs. The typical fixture is a 4' T8 or T540 direct/indirect with high efficiency ecosystem dimming ballasts. Dynamic light shelves along the facade control the natural daylighting into the spaces. There are also occupancy sensors in the offices that help save energy during unoccupied periods.
Structural	The primary structural building material for the CSL is structural steel. The substructure consists of cast-in-place concrete with a 12" concrete wall reinforcement and 30" diameter concrete column reinforcement. Beam sizes consist primarily of types W12 and W16 made of ASTM A992 steel with yield strength of 50 ksi. Column sizes consist primarily of HSS 4x4 and HSS 6x6 shapes made with ASTM A500 Grade B with yield strength of 36 ksi. In addition, CSL is unique in that it is being constructed against a steeply sloped hill.
Construction	The project delivery method is a lump sum contract with Turner Construction as the construction manager. Construction of the Center for Sustainable Landscapes began in December of 2010 and is scheduled to be complete in April 2012 with a total cost of $20 million. A separate contract was created between the controls manufacturer and the owner, which is completely detached from the contractor.

2.4 Support Systems

Fire Protection	The Center for Sustainable Landscapes comprises of active and passive system as appropriate. Primary fire construction type is defined by Construction Type 2B. The fire protection system has an 8" fire service entrance with a double check detector assembly before it reaches a 60 HP, 1000 GPM fire pump. All standpipes are located within the stairwells.
Transportation	A hydraulic elevator is located in the northeast corner of building spanning from the first to third floors.
Telecommunication	The Center for Sustainable Landscapes telecommunication system is a series of CAT-6 cables distributed from the main electrical room on the first floor for individual floor distribution. The CAT-6 cables end at wall-mounted outlets that are designated as telephone or Ethernet connections. There are also WiFi access points mounted in the ceiling throughout the building. The audio-visual system contains a combination of projectors and speaker system integrated into each classroom and conference room. The security for the Center for Sustainable Landscapes is comprised of a series of cameras strategically placed throughout the building as well as magnetic swipe card access to specific rooms of the building. Security cameras are placed at each entrance of the building and in the stairwells.
Special Systems/ Uses	The Center for Sustainable Landscapes will be used as a living laboratory for research throughout its life. Software with algorithms for a direct digital controls system will be used to optimize the performance of the building. Advanced controls and metering will be led by Carnegie Mellon University.

3.0 Existing Mechanical System

3.1 Overview

Objectives	The primary factor in the mechanical system design was Phipps' ambition to achieve the **three highest green standards**: the ILBI (International Living Building Institute) Living Building Challenge, LEED Platinum, and SITES Certification for landscapes (all of which were required by the owner in the building program). These standards are expected to be a way to emphasize more green and sustainable building practices and operations. Phipps' new center for education, research, and administration will **generate all of its own energy** and capture and treat all of its own water on site. Other compliance factors included the Uniform Construction Code of Pennsylvania 2006, International Building Code 2006, National Electric Code, and ASHRAE ventilation requirements.
Heating & Cooling	A **geothermal ground-source closed-loop system** satisfies 70% of CSL's heating and cooling loads. Geothermal wells, bored into the ground sink, create a ground source heat exchanger by remaining at a consistent temperature of 55 °F. In winter, warmth stored over the course of the summer season is recovered from the wells to heat the building spaces. In summer, heat removed from the heat pump refrigeration cycle is absorbed by the water circulated in the wells and the cool ground. A 12,400 cfm capacity **rooftop energy recovery unit** supports the geothermal system in heating, cooling, ventilating, and dehumidification. A desiccant wheel in the energy recovery unit pre-cools and dehumidifies outside air to reduce cooling loads by removing the humidity from warmer incoming air. Air is distributed throughout the majority of the building (offices, classrooms, conference rooms) through an **under floor air distribution** variable air volume (VAV) with baseboard diffusers. This system was chosen to reduce duct costs while accommodating for fluctuations in occupancies throughout the day. The large, three-story atrium/lobby is 100% passively cooled. Passive heating strategies are supplemented by **radiant floors** heated by an evacuated tube solar hot water system and heat from the upper campus conservatory and green house. To provide both insulation and thermal storage a **green roof** was added to CSL.
Ventilating	A **demand controlled ventilation system** (DCV) uses **CO2 sensors** throughout the building to track building occupancy levels and tailors the ventilation rate to provide for the current occupancy level. **Ultraviolet duct lamps** were also added to increase the indoor air quality in response to the tighter, high performance envelope. A **natural ventilation sensor system** inside the building automatically notifies building occupants when conditions are appropriate to open the operable windows. Through natural ventilation and humidity reduction, a comfort set point of 78°F reduces the mechanical cooling load and HVAC system fan energy usage.
Controls	A **direct digital control (DDC) Building Management System** will monitor, control, and provide feedback to various building systems for optimal energy efficient operations. The DDC uses past historical weather patterns and current conditions to predict daily ambient temperatures, humidity

	swings and optimize building systems. **Energy data meters** will also provide building managers and occupants building operating profiles and trend data to monitor energy efficiency.

3.2 Loads

The main load sources on the building are weather (ambient conduction/convection & direct solar gain), occupancy (# people in a space), and lighting / electrical / mechanical power densities (including equipment, appliances, & computers). Factors that affect the total load include schedules (percent of total load in relation to the time of day), airflow (ventilation & infiltration), and construction. The software used to simulate block loads of the building was Trane TRACE 700. Table 1 summarizes heating, cooling, ventilating loads of CSL (which was discussed in more detail in Technical Report one and two).

Table 1 Heating, Cooling, Ventilating Factors Contributing to Building Load

Weather	Design Outdoor Conditions • Dry Bulb Temp: 87 F (summer), 9 F (winter) • Wet Bulb Temp: 71 F (summer) Desired Indoor Conditions • Heating & Cooling Setpoint: 75 F • Relative Humidity: 50%
Occupancy	367 persons [*1st: 140, 2nd: 112, 3rd: 115*] • Atrium: 200 sqft/person • Break Room: 16 people • Classroom: 31 people • Conference: 10 people • Lobby: 200 sqft/person • Office: 20 people • Reception: 143 sqft/person
Schedules	Office (Weekdays Year-Round) • 6am-8am: 50% load • 8am-5pm: 100% load • 5pm-7pm: 50% load
Power Densities *Lighting, Electrical, Mechanical*	Lights for the open office areas are high performance, energy efficient T-5 fluorescents or LEDs. • Classrooms: 1.4 W/sqft, 2 workstations • Conference: 1.3 W/sqft, 1 workstation • Mechanical: 20 W/sqft • Open Office: 1.1 W/sqft, 20 workstations (based upon the number of chairs from design documents) • Reception: 1.3 W/sqft, 1 workstation

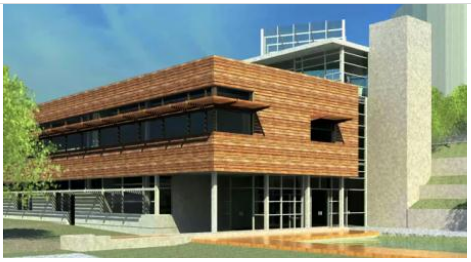
Envelope Construction	The facade is a combination of: • Salvage barn siding • Motorized upper glazing • Metal light shelf • Operable windows: High performance, low-e (low-emissivity) windows provide solar and thermal control and energy efficiency, while admitting maximum daylight. • Glass Fiber Reinforced Concrete Precast Panels • Backup of exterior studs • High performance wall and roof insulation reduce winter heat losses and summer heat gains  Figure 2 Facade of CSL

Table 2 below provides various heating and cooling design load results. Engineering check values for the designed Center for Sustainable Landscapes were not provided by the mechanical engineer. Therefore, the calculated cooling and heating loads were compared to the ASHRAE 2009 Pocket Guide. The computed/simulated cooling [SF/ton] falls within this range. The supply air rate [cfm/SF] computed also falls within the standard range for office facilities as expected. The atrium radiant floors, which is a supplemental system provided by evacuated tube solar hot water, is higher than expected at 324,341 BTU/hr. This may be due to its roof façade being covered entirely by glazing.

Table 2 Simulated vs. Typical Load & Ventilation for Entire Building

SYSTEM		Simulated	Typical for Office Buildings (General)
Underfloor Air Distribution & Geothermal Heating/Cooling	Cooling [SF/ton]	666.78	690-490
	Heating [BTU/hr SF]	24.58	-
	Supply & Ventilation Air [cfm/SF]	1.08	0.9-2.0
	Cooling Coil Peak [BTU/hr]	605,880	-
	Heating Coil Peak [BTU/hr]	397,007	-
Atrium Radiant Floors	Heating Coil Peak [BTU/hr]	324,341	-

3.3 Schematics & Equipment

The heating and cooling systems in the building are designed to ensure optimal comfort for the occupant. The following series of figures and tables outline the mechanical system configuration as well as major hardware / equipment components of the building.

Geothermal Heating/Cooling

Figure 3 is a schematic of the water side pipes and equipment that run throughout the building. The right side of the schematic depicts the pipes that travel to and from the ground wells to the mechanical room. P-1 and P-2 represent the water pumps in the mechanical room that take water from the first floor to the rooftop air handling unit (depicted on the left side of the diagram). Only one pump is on duty at a time, while the other is on stand-by. The controls sequence shows that the pump on duty will alternate operation at least daily.

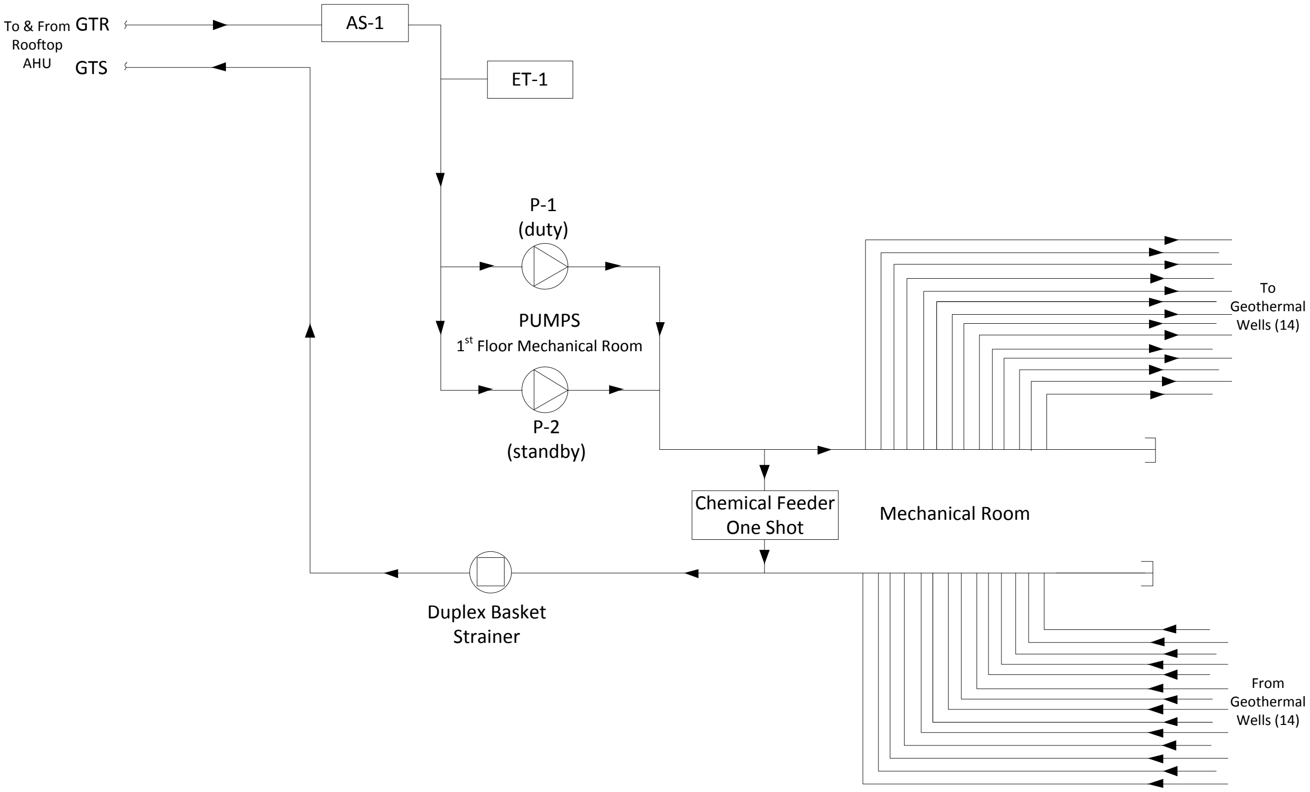


Figure 3 Water Side Schematic

Air Handling Unit (AHU) / Energy Recovery Ventilator (ERV)

The air handing unit (AHU) (which is also an energy recovery ventilator) is located on the roof of CSL in the northwest corner. Table 3 shows the 12,400 cfm capacity of this Berner Energy Recovery Unit, Model 9812.

Table 3 Rooftop Air Handling Unit (AHU) / Energy Recovery Unit (ERV)

UNIT NO.	TOTAL CFM	MIN OA CFM	MAKE, MODEL
AHU-1	12,400	2,720	Berner Energy Recovery, 9812

Figure 4 below shows the air side schematic of this rooftop air handling unit. After the water enters from the geothermal pipes in the upper left corner of the schematic, it enters the water source heat pump where heat is exchanged from the water into entering air from return air (RA) ducts and outside air (OA). After air travels through the air handling unit, it is then supplied to the space (SA).

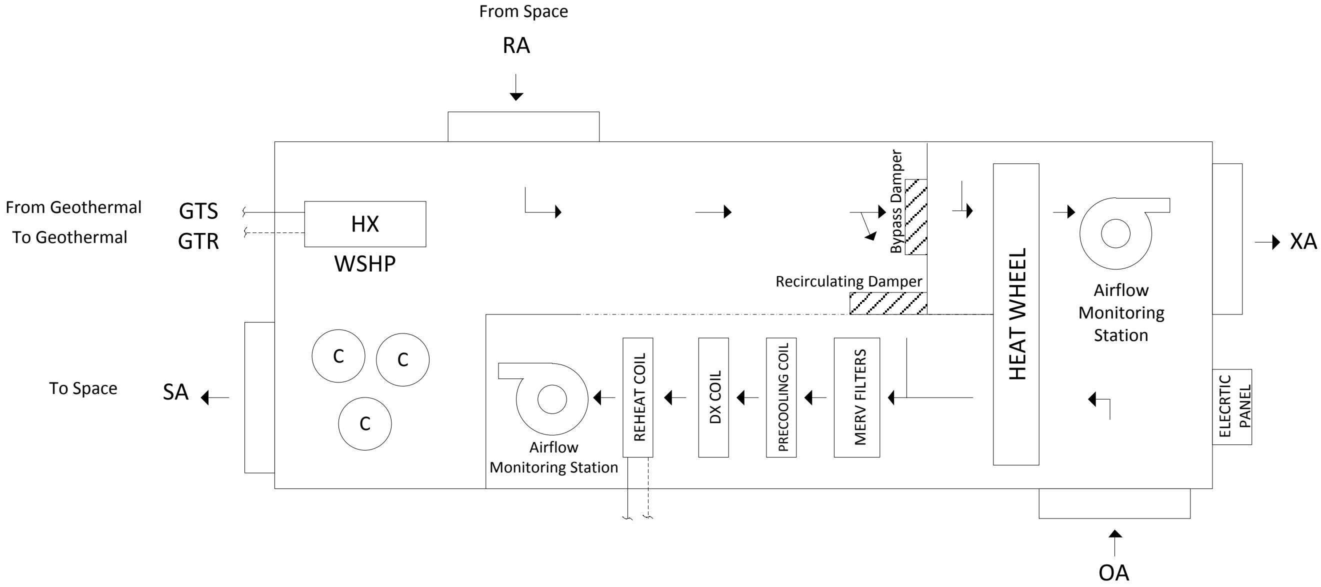


Figure 4 Air Side Schematic: Air Handling Unit (AHU) / Energy Recovery Ventilator (ERV)

3.4 Energy

The fraction of electric energy consumed by subsystems (HVAC, lighting, office equipment) is desirable to provide a basis for energy efficiency improvement claims of redesign. Table 4 and Figure 5 highlight CSL's energy consumption by subsystem. In total, CSL consumes 485,206 kBTU/yr. The total end use and source energy consumption by subsystem was calculated by Trane TRACE.

Table 4 Energy Consumption by Subsystem

SUBSYSTEM	Electrical Consumption (kWh)	Total Building Energy [kBTU/yr]	Total Source Energy [kBTU/yr]
Primary Heating	5,230	17,849	53,551
Primary Cooling	15,017	51,5253	153,774
Supply Fans	16,197	55,280	165,855
Pumps & Equipment	31,920	108,183	326,867
Lighting	40,141	137,000	411,041
Receptacles	33,660	114,880	344,675
TOTAL	**142,164**	**485,206**	**1,455,762**

Figure 5 depicts a much different energy consumption distribution than the traditional building. Amongst many other factors, a geothermal system eliminates the need for inefficient fans which decrease the consumption percentage of heating & cooling in CSL. Yet, the heating consumption seems low for a typical Pittsburgh office. An explanation for this may be CSL's high performance building envelope. Higher than expected, the energy percentage consumed by pumps & equipment is likely larger than traditional designs due to various water management systems. Receptacles (dominated by the computers of the office building) and lighting distributions result as expected.

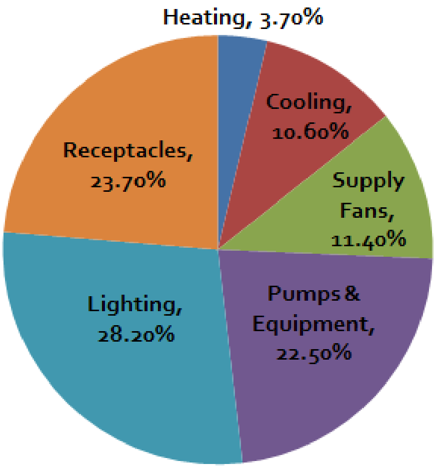


Figure 5 Subsystem Energy Consumption

The energy costs for the building are determined by resource providers. Phipps' new center for education, research and administration has ambitions of generating all of its own energy while capturing and treating all of its own water on site. This, coupled with the geothermal heating & cooling system (which eliminates the need for natural gas in a boiler), has resulted in CSL only using one utility, electricity, for mechanical systems. Shown below in Figure 6 is the distribution map of electricity providers for Pennsylvania. Pittsburgh is located in the region shaded in orange. CSL's utility providers are Duquesne Light & Columbia Gas. Table 5 shows the $7.07 /kW electricity demand price charged by Duquesne Light.

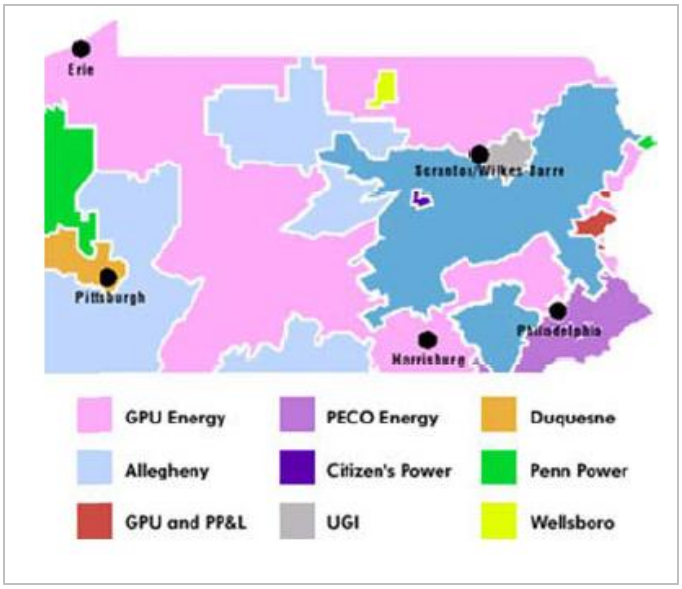


Figure 6 Pennsylvania Power Distribution

Table 5 Duquesne Light Electricity Rates

DEMAND	USAGE
$7.07 /kW	0.1236 cents/kWh

The monthly operating cost for a full year for the Center for Sustainable Landscapes can be viewed in Table 6 and Figure 7 below. Proving that CSL's progressive green design discussed throughout this report is in fact worth its upfront cost, the total cost of electricity at CSL totals only $14,216.

Table 6 Monthly Utility Costs [Electricity]

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
$1,097	$919	$1,144	$1,097	$1,281	$1,396	$1,422	$1,476	$1,173	$1,171	$1,015	$1,027	$14,216

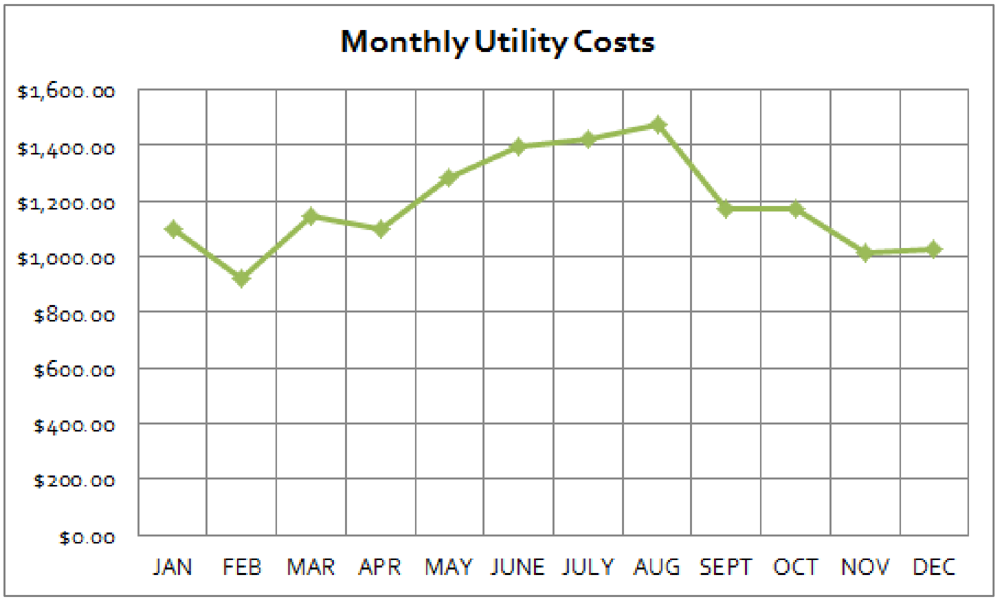


Figure 7 Monthly Utility Costs [Electricity]

In addition to the above data, Trane TRACE also predicted that the annual cost / square foot to operate building is only 0.68 $ / SF. Unfortunately, actual utility billing data to test the validity of these simulated costs were unavailable since the building is under construction during the writing of this report and will be until April 2012.

3.5 LEED Sustainability

With "sustainable" being in the name of the building, Phipps's main objective with the design of the building was making a statement about being one of the most sustainable buildings ever built. As a way to measure this, the owner required that the design achieve three nationally recognized green standards (all focused around sustainability):

1. the ILBI (International Living Building Institute)Living Building Challenge
2. LEED Platinum
3. SITES Certification for landscapes

To ensure that all were met, Phipps hired Evolve, LLC to perform and coordinate the LEED Certification process. In total, there were ten different companies, summarized in Table 7, involved in CSL achieving LEED Platinum. The specific involvement of each party is noted in the right column of the LEED Analysis in Table 8 on the next page. Additional costs associated with hiring these consultants were not captured in the initial costs estimate because the amount to which each will be reimbursed for their services is undisclosed. Yet, it can be inferred that these services that were needed to ensure green certification are an added cost above traditionally designed buildings.

Table 7 LEED Analysis Team [with Mechanical System Focus]

	COMPANY / RESPONSIBLE PARTIES		ROLE
1	evolve Environment:Architecture	eEA	LEED Certification Consultants
2	7 Group	7G	Energy, Daylight and Materials Consultants
3	Carnegie Mellon University - Center for Building Performance and Diagnostics, Advanced Infrastructure Systems	CMU	Advanced Measurement & Verification
4	Civil & Environmental Consultants, Inc.	CEC	Civil Engineering
5	CJL Engineering	CJL	MEP Engineering
6	Design Alliance Architects	DAA	Architecture
7	Energy Independent Solutions	EIS	Photovoltaic Array
8	H.F. Lenz	HFL	Commissioning
9	Pitchford Diversified	PFD	Enhanced Commissioning
10	Turner Construction	TC	General Contractor

LEED criteria directly affected by the mechanical design include:

1. Energy and Atmosphere
2. Indoor Environmental Quality

Both of these criteria are further analyzed with respect to the Center for Sustainable Landscapes in Table 8. The LEED Analysis shows how the designers and engineers executed each prerequisite and credit in order to achieve every point within Energy & Atmosphere (17/17) as well as Indoor Environmental Quality (15/15).

Table 8 LEED Analysis

CREDIT	DESCRIPTION	PTS	EXECUTION	Responsible Party
Energy & Atmosphere		**17/17**	*(earned / available)*	
EA Prerequisite 1	Fundamental Commissioning of the Building Energy Systems	Rqd	Commissioning plan draft and construction document review of energy systems were completed by HFL & Pitchford. Coordination between the two is managed by Evolve.	HFL PFD
EA Prerequisite 2	Minimum Energy Performance	Rqd	ASHRAE Standard 90.1-2004 (Sections 5.5, 6.5, 7.5, and 9.5) is met as outlined in Technical Report 1. The MEP Engineer, CJL Engineering performed an initial and final energy model. CSL's yearly energy use is projected to be greater than the minimum 10% energy improvement from the baseline building as outlined by ASHRAE Standard 90.1.	CJL
EA Prerequisite 3	Fundamental Refrigerant Management	Rqd	CJL Engineering ensured that the mechanical system for does not use any CFC-based refrigerants.	CJL
EA Credit 1.1-1.5	Optimize Energy Performance	10/10	The simulated energy model in Section 7.3 shows that CSL will perform on average 75% better than typical buildings of its size, function, and location (beyond the required 10.5-42% reduction range).	7G
EA Credit 2.1-2.3	On-Site Renewable Energy 2.5 / 7.5 / 12.5 % reduction	3/3	Solar photovoltaics were added to an adjacent facilities building & special events hall roof surfaces at a near-southern orientation. Vertical Axis Wind Turbines were also added on site to contribute to the net zero approach of	CSL EIS

			offsetting 100% of the annual energy consumption.	
EA Credit 3	Enhanced Commissioning	1/1	Throughout construction document phase & through completion, work scope for enhanced commissioning was broken down into two third party commissioning agents: H.F Lenz &Pitchford.	HFL PFD
EA Credit 4	Enhanced Refrigerant Management	1/1	Documented analysis of HVAC equipment shows a LCGWP (Lifecycle Direct Global Warming Potential) lower than 100, which meets the maximum threshold for refrigerant impact in order to achieve this LEED credit.	CJL
EA Credit 5	Measurement & Verification	1/1	Product data and wiring diagrams for sensors and data collection system used to provide continuous metering of building energy-consumption performance is shown in Section 6.2. Carnegie Mellon University also partnered with CSL in order to provide future advanced measurement & verification for research purposes.	CJL CMU
EA Credit 6	Green Power	1/1	Greater than the required 35% of electricity is received from renewable sources including generation from on-site photovoltaics as well as a wind mill. eEA will determine equivalency for on-site renewables .	CJL EIS eEA
Indoor Environmental Quality		**15/15**	*(earned / available)*	
EQ Prerequisite 1	Minimum IAQ Performance	Rqd	The project has been designed to meet the minimum requirements of ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, using the discussed Ventilation Rate Procedure in Technical Report 1.	CJL
EQ Prerequisite 2	Environmental Tobacco Smoke (ETS) Control	Rqd	Smoking is prohibited inside the building. Any designated smoking areas are at least 25 feet away from any building openings.	eEA
EQ Credit 1	Outdoor Air Delivery Monitoring	1/1	There is a permanent CO2 monitoring system with lights cuing occupants that outside conditions are favorable for opening windows.	CJL
EQ Credit 2	Increased Ventilation	1/1	As previously mentioned in Section 5.3 of this report, the rooftop air handling unit contains the capacity for 12,400 cfm of primary air, and 2843 cfm of outdoor air, which exceeds the requirements set forth by ASHRAE Standard 62.1	CJL
EQ Credit 3.1	Construction IAQ Management Plan: During Construction	1/1	An Indoor Air Quality plan is documented within the specification and summarized in Section 5.3. In addition, filters with a minimum rating of MERV 8 were used during construction to maintain air quality as well.	TC
EQ Credit 3.2	Construction IAQ Management Plan: Before Occupancy	1/1	Phipps has required Turner Construction to schedule & implement a building and duct flush-out prior to occupancy.	TC
EQ Credit 4.1	Low-Emitting Materials: Adhesives & Sealants	1/1	Product data for adhesives and sealants used inside the weatherproofing system indicate complying VOC content.	TC
EQ Credit 4.2	Low-Emitting Materials: Paints & Coatings	1/1	Product data for paints and coatings used inside the weatherproofing system indicate complying VOC content.	TC
EQ Credit 4.3	Low-Emitting Materials: Carpet Systems	1/1	Product data for carpet systems complying with testing and product requirements of Carpet and Rug Institutes Green Label Plus program for carpet and Green Label program for cushion and pad.	TC
EQ Credit 4.4	Low-Emitting Materials: Composite Wood & Agrifiber Products	1/1	Product data for products containing composite wood or agrifiber products or wood glues indicate that they do not contain urea-formaldehyde resin.	TC
EQ Credit 5	Indoor Chemical & Pollutant Source Control	1/1	Provided by Design Alliance Architects, entryway systems employed are of at least six feet in length in order to prevent dirt and particulates from entering the building. Also, Turner is to provide air filters of MERV 13 rating or higher.	DAA CJL TC eEA
EQ Credit 6.1	Controllability of Systems, Lighting	1/1	Individual lighting controls for at least 90% of the occupants was installed. An advanced lighting network control system discussed in section 6.3 will use Lutron's Ecosytem. In addition, occupancy sensors turn off lights in unoccupied rooms.	CJL
EQ Credit 6.2	Controllability of Systems, Thermal Comfort	1/1	Each multi-occupant space, including offices and classrooms, is provided with its own individual space controls. Additional HVAC controls are to be controlled by an Argus Control system.	CJL
EQ Credit 7.1	Thermal Comfort, Design	1/1	The rooftop air handling unit distributes 55° F supply air and the desiccant dehumidification system allows for a higher comfortable indoor temperature setpoint of 78° F. The building envelope and HVAC design also meets ASHRAE Standard 55.	CJL
EQ Credit 7.2	Thermal Comfort: Verification	1/1	eEA is to administer a comfort survey assuring adequate assessment of building thermal comfort during post completion.	eEA
EQ Credit 8.1	Daylight & Views: Distribution Quality to 75-90% of Spaces	1/1	For the windows on the exterior of the building, there is at least a 2% daylighting factor in only 18% of regularly occupied spaces. In addition, ceiling cloud surface & interior finish color schemes provide high reflectance values. This along with light shelves maximizes the depth of daylight	DAA eEA

			penetration into the space.	
EQ Credit 8.2	Daylight & Views: Views for Seated Spaces	1/1	Of the total regularly occupied area, 100% of seated spaces have access to views (exceeding the 90% requirement).	DAA eEA
Total Energy & Atmosphere, Indoor Environmental Quality		**32 earned** / 32 available points for the mechanical systems		
Total Overall		**55 earned** / 69 available points for this site		

Overall CSL is predicted to achieve 55 likely earned + 8 maybe = **63 total points** in play. All points are "likely" until submitting to LEED Online (LOL). Evolve LEED Consultants considered this point cushion sufficient to maintain Certification Goal of Platinum. Appendix A1 shows the full LEED Scorecard created by Evolve, LLC. For reference, LEED Certification Levels and points associated with each are shown in Table 9. Note that LEED Certification is ultimately a determination of the USGBC, but it is clear through this LEED analysis that CSL's design is well on its way to achieving LEED Platinum.

Table 9 LEED Certifications & Points	
LEED Certified	26-32 points
LEED Silver	33-38 points
LEED Gold	39-51 points
LEED Platinum	52+ points

4.0 Proposed Redesign

Mechanical depth redesigns include:

- **Spray Cooled Roof**: Green roofs are an expensive initial cost and its energy savings through the thermal barrier that it creates is not proven over time. As a way to decrease costs, water sprayed on the roof, which acts as an ecologically sound cooling agent, could offer similar benefits at lower costs. In pursuit of figuring out which rooftop design would be the most energy conscious throughout its life, the green statement criterion of the owner will be relaxed.
- **Hybrid Geothermal System**: Ground source heat pumps have higher first costs than conventional systems making short-term economics unattractive. An alternative, lower cost approach for such applications can be use of a hybrid GSHP design. In hybrid geothermal systems, the ground heat exchanger size is reduced and an auxiliary heat rejecter (e.g., a cooling tower or some other option) is used to handle the excess heat rejection loads during building cooling operation. This depth will analyze the function of life cycle costs vs. ground loop size.

Breadth redesigns include:

- **Construction Management, Bore Hole Optimization**: The installation of a hybrid geothermal system will dramatically affect the construction time, installation cost, and equipment. In particular bore hole depth and corresponding bore drilling costs will presumably be reduced due to the ground heat exchanger reduction. Bore hole optimization will be analyzed and weighted to see if the proposed hybrid geothermal system is worthwhile to the owner.
- **Electrical, Direct Current Distribution**: To accommodate the controls system and eliminate PV inefficiency, it is proposed to study the alternative of a DC distribution system within the building. This was not to be considered as an alternative after completion but to be considered as an initial design consideration.

5.0 Mechanical Depth 1: Roof Spray Cooling System vs. Green Roof

5.1 Objective

Green roofs are an expensive initial cost and its energy savings through the thermal barrier that it creates is not proven over time. As a way to decrease costs, water sprayed on the roof, which acts as an ecologically sound cooling agent, could offer similar benefits at lower costs. In pursuit of figuring out which rooftop design would be the most energy conscious throughout its life, the green statement criterion of the owner will be relaxed. The owner's desire to create a "green statement" is exhibited through his requirement for the building to achieve three of the highest green standards (LEED Platinum, Living Building Challenge, & SITES Certification for landscapes).

5.2 Existing Green Roof

The green roof currently designed for the roof of the Center for Sustainable Landscapes includes numerous components, an intricate installation, and an incredibly high price tag. It's expensive initial cost was the stimulus for this redesign. Figure 8 below shows the occupant accessible green roof atop the building.

Figure 8 CSL Existing Green Roof

By design, it is an intensive green roof with 8 inches of growing medium including a variety of plants, edibles, and ornamentals. The manufacturer selected for the design and installation was American Hydrotech. Figure 9 below shows the roof area coverage by the green roof, totaling 3216.2 sqft (48.1% of the total roof). The pathways surrounding the green roof act as a way for the building occupants to use the space for office time breaks or special events.

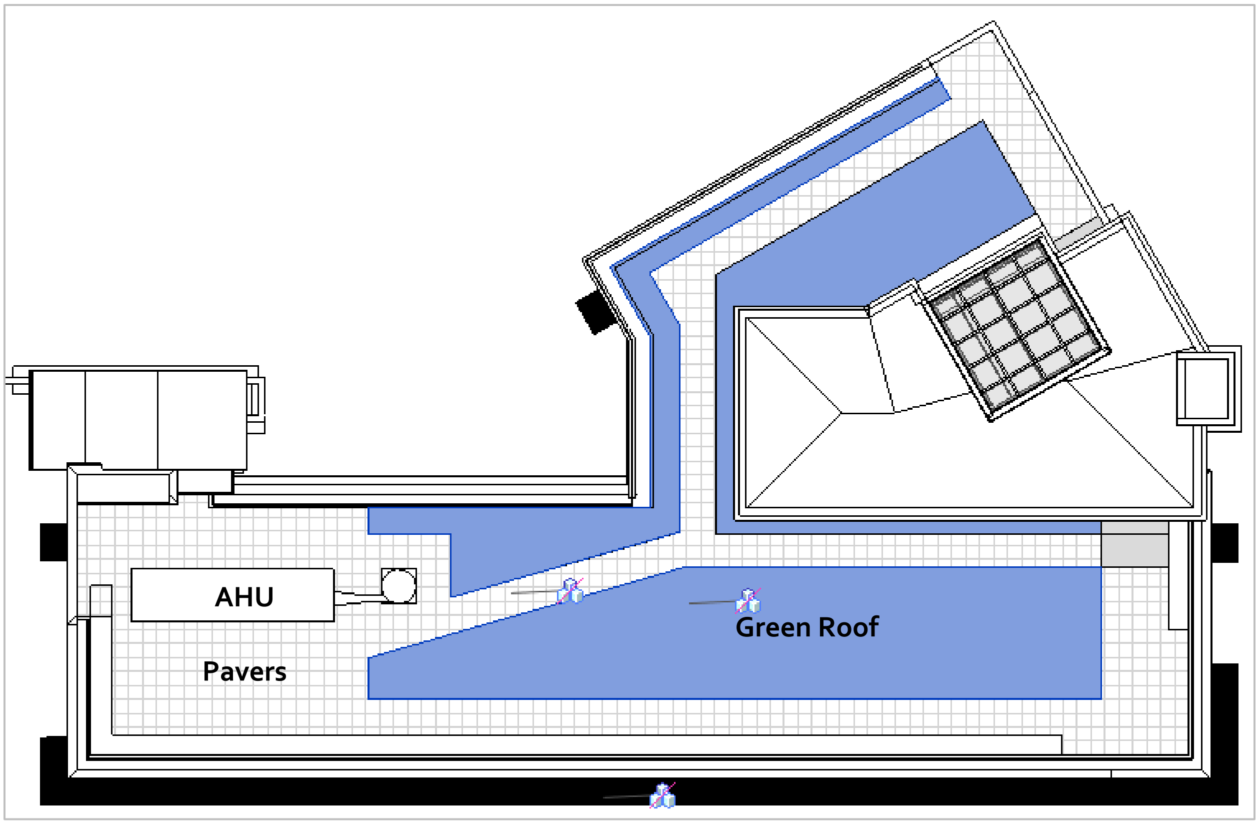


Figure 9 Green Roof Area

The cross section of the green roof is needed in order to compare this design to the spray cooled roof redesign. The submittal for the green roof, obtained from the contractor included all of the components that make up this cross section. The layers of the vegetated roof are shown in Table 10.

Table 10 Vegetated Roof Components

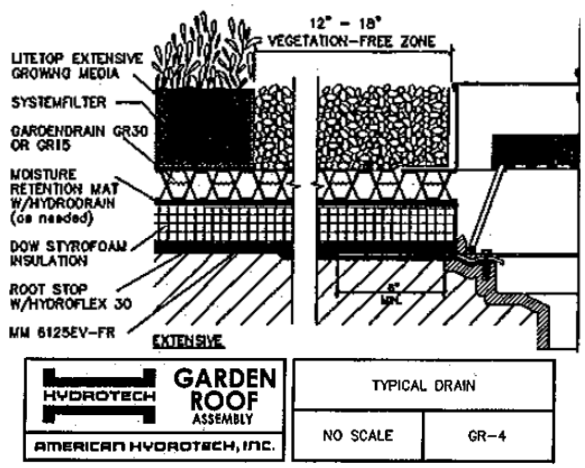
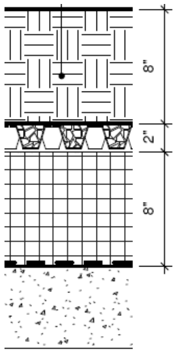
	• Lifetop Aggregate • System Filter • 2nd layer of hot, fluid applied, asphalt • Hydroflex 30 • 1st layer of hot, fluid applied, asphalt • Flex flash F (reinforcing fabric) • Surface conditioner • Gardendrain GR-30 • 2 layer of 4" extruded polystyrene insulation • Root Stop HD • 3-1/2" LW Concrete Slab

Table 11 below shows the depth, material, and thermal peformance of the 3216.2 sqft of the green roof cross section. There is great debate on the actual thermal peformance of a green roof. Many (including sales representatives from American Hydrotech) claim that the an overall R-value cannot be estimated due to the number of parameters taken into account as well as its inconsistent performance throughout the year. Researchers at Columbia have claimed that green roofs can have an R-value up to R-100 in the summer and R-7 in the summer (Gaffin et al. 2010). For modeling purposes, the green roof (or growing medium) was conservatively considered in have an overall R-value of R-7.

Table 11 Green Roof Section [3216.2 SF]

SECTION	DEPTH	MATERIAL	R-VALUE	
	8″	Growing Media	Low Estimate	R-7 (R~100 in summer)
	2″	Drainage Course	R-0/in	R-0
	8″	Rigid Insulation	R-5/in	R-40
	3-1/2″ 2″	Concrete Slab Composite Steel Deck	R-0.3/in R-0/in	R-1.5 R-0
		TOTAL		R-48.5

Notice that the majority of the thermal peformance is obtained by the two layers of 4″ extruded polystryrene not by the growing medium. Together they are extremely expensive with the insulation and growing medium components contributing $44,426 and $83,137 respectively. Surrounding the green roof, covering the remaining area of the roof, are pavers (or lightwight concrete) to be used as an occupant pathway. Figure 10 below shows this area in blue.

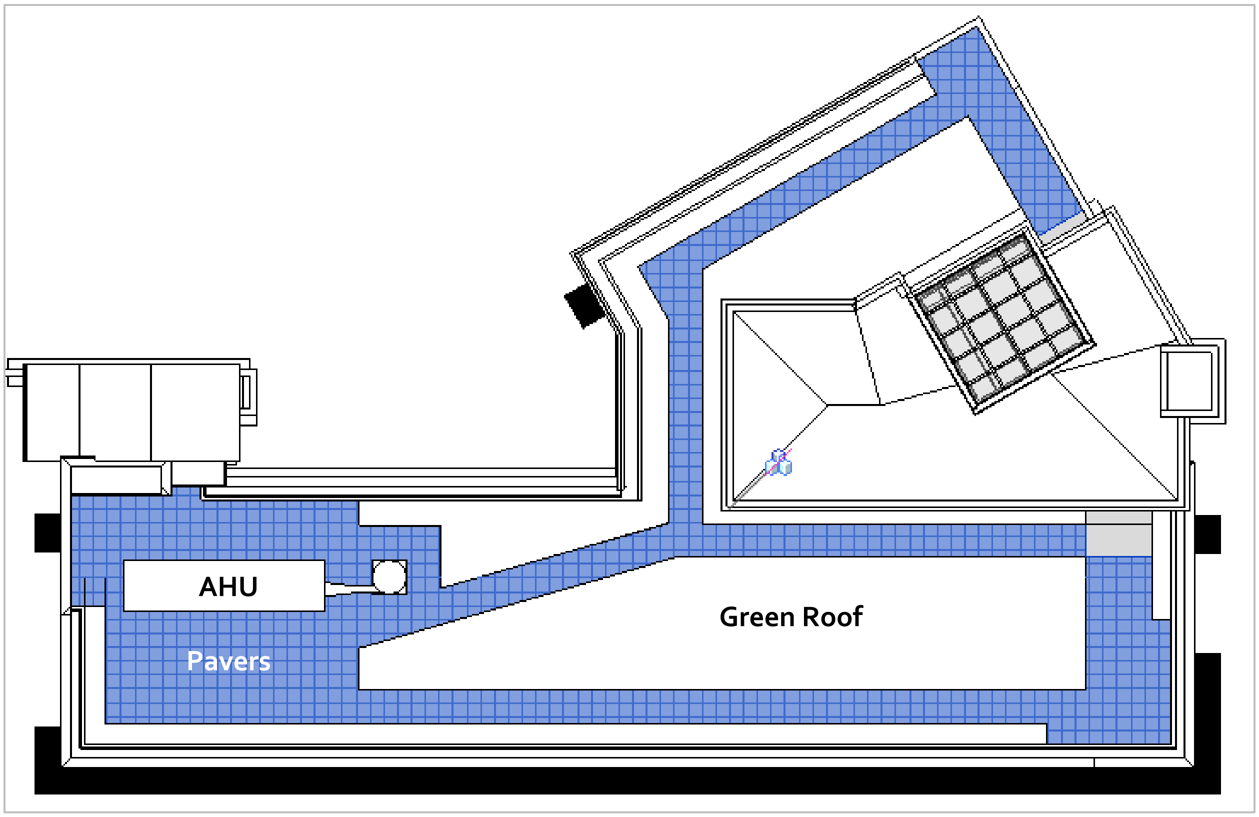
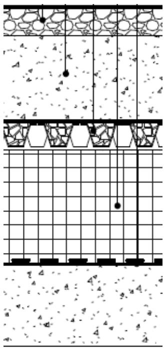


Figure 10 Pavers Area

The cross section of this portion of the roof is summarized in Table 12. The only real difference between here is that the growing medium is replaced with cast-in-place concrete and aesthetic pavers. This adds an additional price tag of $58,301 for the majority of the roof that it covers.

Table 12 Pavers Section [3469.7 SF]

SECTION	DEPTH	MATERIAL	R-VALUE	
	2″	Pavers (lightweight concrete)	R-0.3/in	R-0.6
	6″	Cast-in-place Concrete	R-0.3/in	R-1.8
	2″	Drainage Course	R-0/in	R-0
	8″	Rigid Insulation (extruded polystyrene)	R-5/in	R-40
	3-1/2″ 2″	Concrete Slab Composite Steel Deck	R-0.3/in R-0/in	R-1.5 R-0
		TOTAL		R-43.9

Benefits of the spray cooling redesign are that initial costs are lower and components are much simpler in comparison. A disadvantage is that due to the misting throughout summer days, the roof can no longer be an occupiable space. The positive to this is that the $58,000 aesthetic pavers above the concrete can be removed. The blue area in Figure 11 shows the resulting area potential for the spray cooling system, totaling 5645.5 SF or 84.5% of the 6685.98 SF of roof.

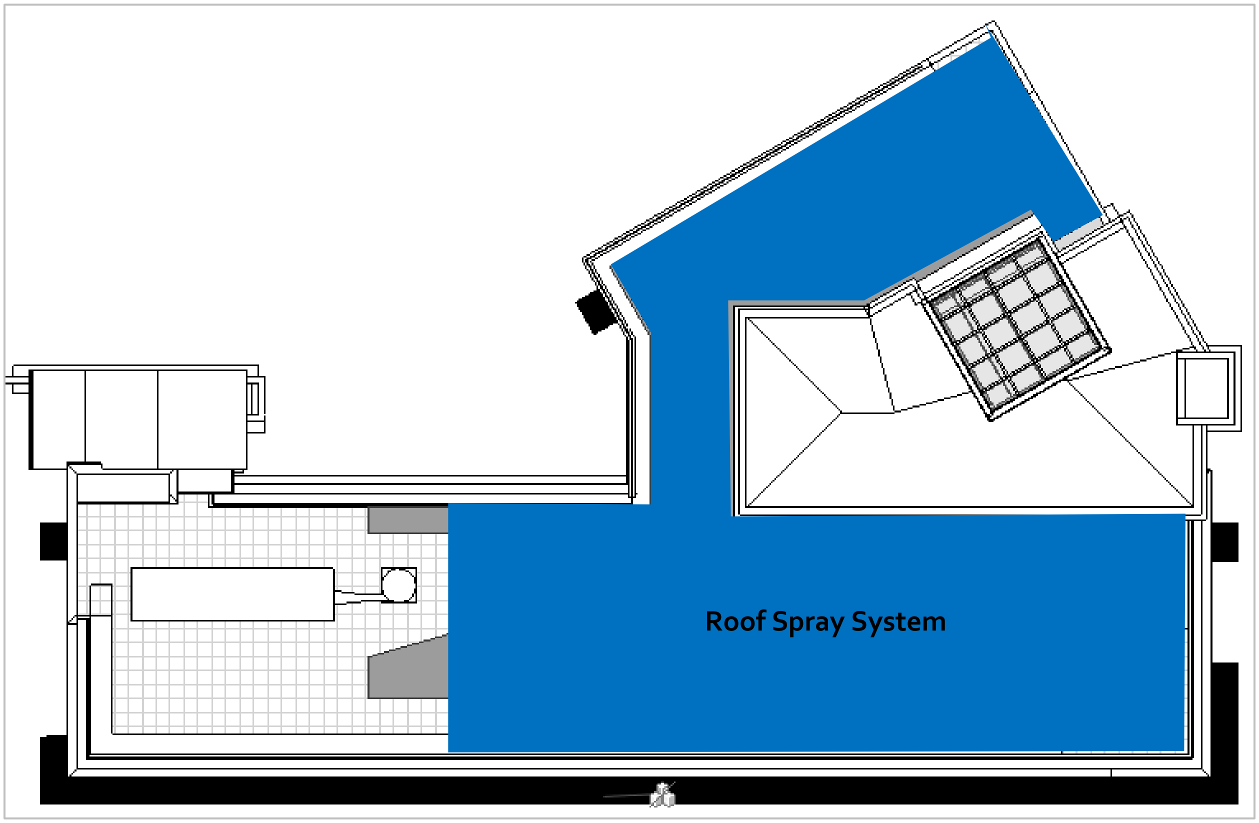


Figure 11 Spray Cooling Area

5.3 Vendors for Roof Spray Cooling

Next, a vendor for the roof spray cooling system was chosen. Despite the spray cooled system's simple design and control, there have only been a limited number of installations compared to green roofs. Certain engineers attribute this to the lack of elegance of the system and a crude, unsophisticated approach by manufacturers (Smith 1985). Nevertheless, the two vendors considered were:

1. Whitecap Roof Spray Cooling System: Whitecap is an integrated roof surface and spray cooling system suitable for warm, dry climates. WhiteCap made installations throughout the 80s and 90s but its company website could not be found. Since this system was mostly recommended for the Midwest climate, it was not used for CSL (located in Pittsburgh, PA).

2. Sprinkool System: Sprikool has been cooling buildings since 1981 and covered over 60 million square feet of commercial, industrial, and residential buildings with its roof evaporative cooling systems.

In 1940, Houghton, et al, analyzed the performance of a system that the Sprinkol System was based off of. The research was conducted at the ASHVE Research Lab in Pittsburgh, PA. Since the Center for Sustainable Landscapes is also in Pittsburgh, Houghton's research results are relevant to the same location. Just as in the case of CSL, the measured building had an outdoor dry bulb temperature ranged from 77 F to 95 F, while the wet bulb ranged from 68 F to 75 F. The roof spray cooling summary showed that the maximum heat flow without spray was 18.0 BTU/sqft/hour, while with spray was 2.1 BTU/sqft/hour (Houghton 1940). Thus, the effect of water in the case of the sprinkled roof greatly reduced the rate of heat flow and absorbed a large part of the radiant heat. Solar heat is then dissipated back into the air through the latent heat of evaporation rather than into the building. Due to its history of experience and proven performance, the Sprikool System was selected.

Figure 12 below shows an image of the Sprinkool System installation to the left and a close up of the water nozzles to the right.

Figure 12 Sprinkool System Installation

5.4 Schematics & Equipment

The roof spray cooling system consists of water being pumped up to the roof and sprayed incrementally throughout the day. Water can come from any source. The Center for Sustainable Landscapes conveniently has an underground water basin that is meant to harvest rainwater from the site. Its initial purpose was for use in flushing toilets. This, along with Pittsburgh Water Authority city water will be piped up to the roof via a ¾" pipe to provide water for the misting. The spray piping array will connect into one of the three hydrants that exist on the roof (originally used for watering plants of the green roof). The hydrant should be a Zurn Z1360 (accommodating the ¾" pipe from the 2nd floor ceiling below). Figure 13 below shows a schematic of flow of water for this mechanical system.

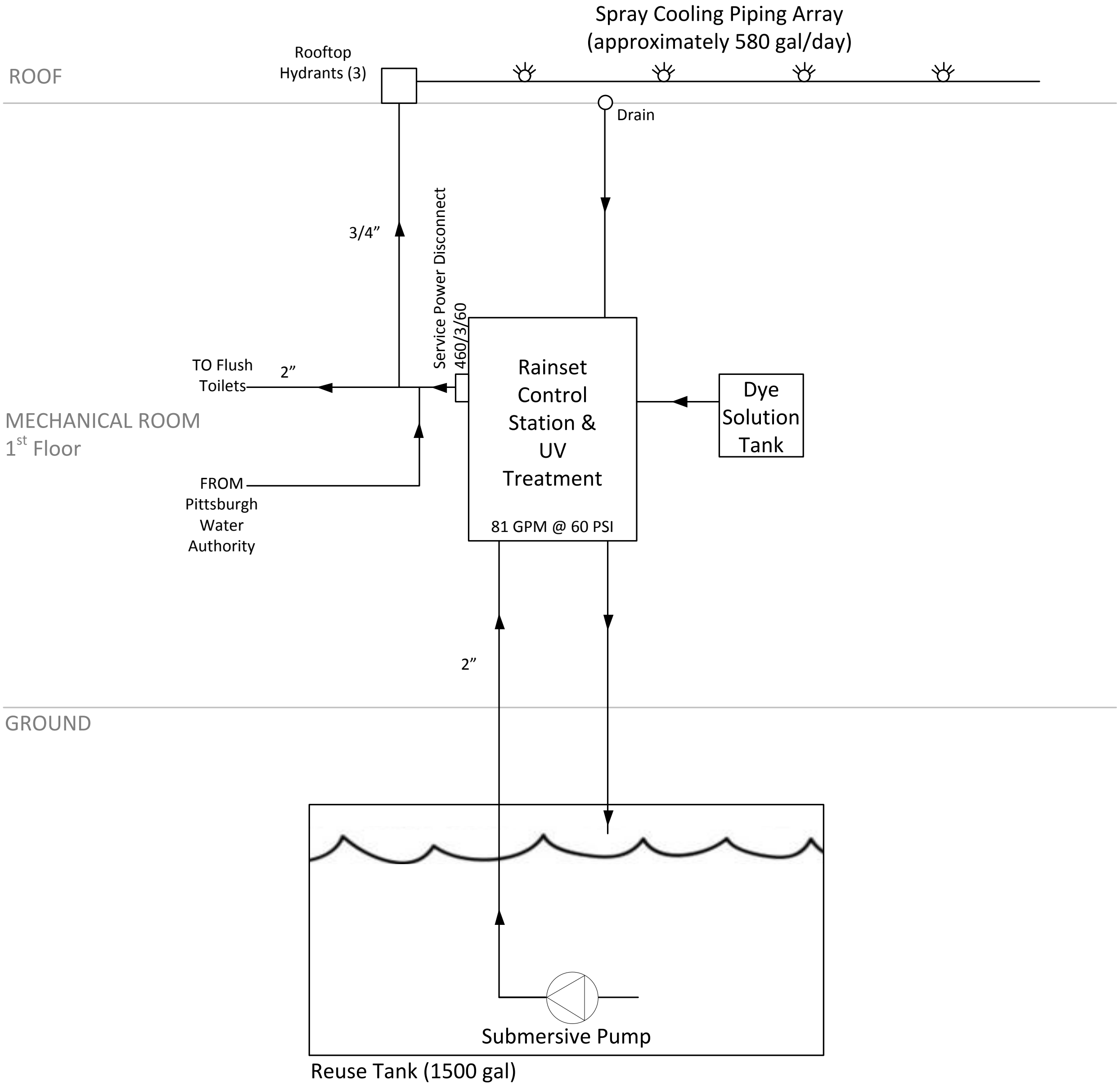


Figure 13 Spray Cooling Water Flow Schematic

The pumping and piping system manufacturer was selected to be BRAE Rainwater System. The head for this distance was determined to be 227 ft and required flow to be 78.6 gpm. An equipment summary of the schematic above is summarized in Table 13. During the summer months, approximately 580 gallons per day is used in spray cooling. Thus, city water will be used as a backup system for when the reuse tank is depleted.

Table 13 Equipment Summary for Spray Roof

EQUIPMENT	DETAILS
Water Storage (Reuse) Tank	1500 gallons capacity
Submersive Pump	Model#75S75-11, 7.5 HP, 460/3/60 V, 95gpm max flow, includes discharge piping and floating extractor
Rainset Control Station	Model#H2-ID2, 81 gpm at 60 psi
Ultraviolet Water Purifier 	This unit utilizes germicidal ultraviolet lamps that produce short wave radiation lethal to microorganisms present in water such as bacteria and viruses. Operating pressure range of 5-100 psi. Electrical voltage at 120 V. 140W power consumption.
Dye Solution Tank 	This injects blue or green dye for code compliance. Capacity is 35 gallons.
Sprinkool Misting System	For 5645.5 SF of the roof coverage.

The specific layout of the piping system followed the guidelines recommended by the Sprinkool vendor, which recommends 12 feet between all nozzles. The layout for CSL was designed with 12 foot typical between nozzles (circles) and between piping lines shown in Figure 14. To ensure that the humidity from the water spray system does not affect the intake of the air handling unit, the system was placed 16 feet away (compliant with ASHRAE Standard 62.1).

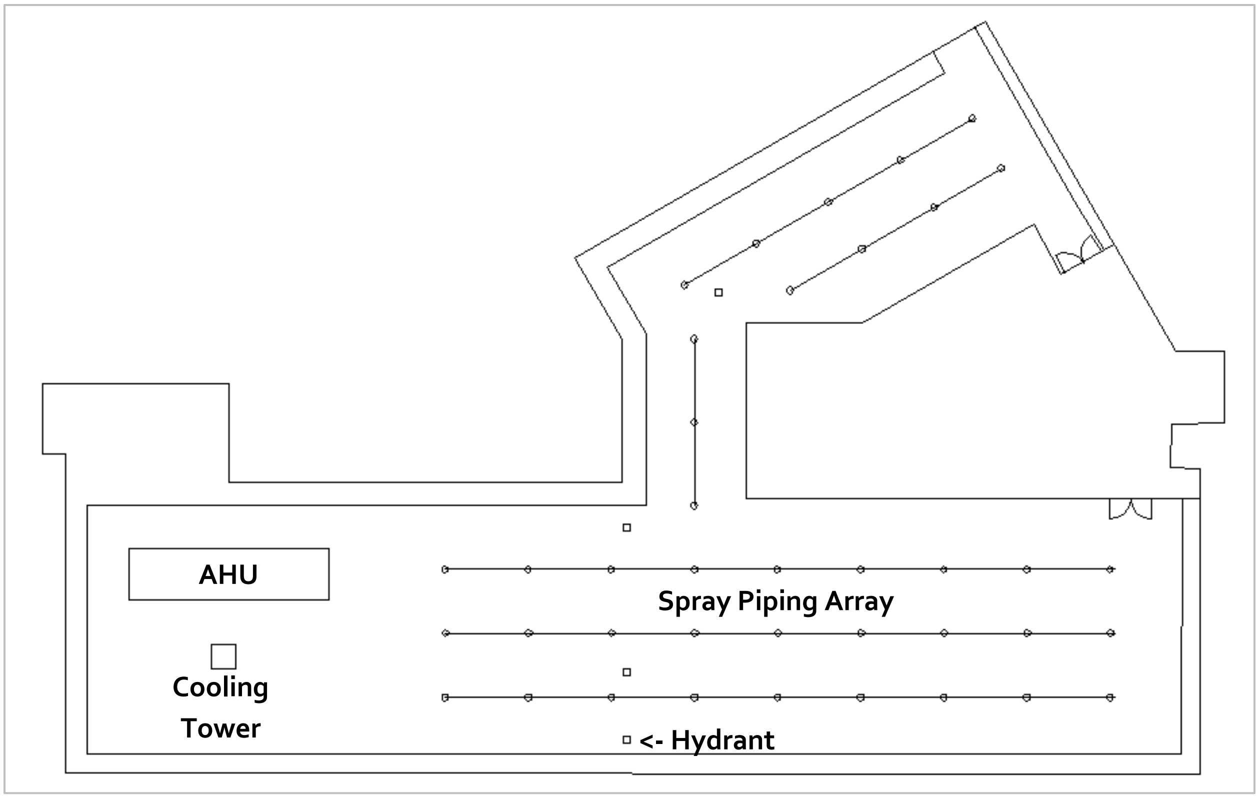


Figure 14 Spray Piping Array Layout

Due to its simple setup, properly designed systems have relatively low maintenance requirements. This will be a great advantage to the existing green roof – which will require extensive care by the maintenance staff. The advanced control system monitors temperature variation throughout every day of the cooling season and alters the amount of water as the conditions for optimal evaporation changes.

5.5 Modeling Considerations

There is no one accepted way to create an energy model of a spray cooled system. Several energy modeling techniques were considered through recommendations of professors and professional engineers. Methods 3 through 5 were attempted and discussed in the following few sections.

1. eQUEST: A front end software to Energy Plus's back end algorithms, eQUEST, was considered as a way of looking at the portion of cooling load due to roof conduction. Energy savings could be equated based on if the roof conduction was eliminated. This method was recommended by a LEED consultant of the Center for Sustainability but was eliminated due to lack of experience with the software. If there was additional time, this modeling method could very well provide additional, unique results.
2. Trane TRACE: The energy performance of the existing building was simulated using Trance TRACE. The green roof was equated to a super insulated roof with an R-value of 43. An engineering consultant suggested running an additional simulation with a varied insulation value to reflect the spray cooling. Ultimately, this method was not used due to its lack of solar benefits functionality.
3. Engineering Equation Solver (EES)
4. Green Roof Energy Calculator

5. Cooling Load Temperature Differential with Solar Load Factors (CLTD/CLF)

5.6 Model #1: EES

Engineering Equation Solver or EES is a general equation solver program that can numerically solve thousands of coupled non-linear algebraic and differential equations. In order to model the cooling benefits of the spray roof system on CSL, a 1D model including solar, evaporation, and indoor conditions could be used. In this 1-dimensional equation, heat transfer effects through the edges are ignored and the same flux per unit area is assumed. Governing equations listed in the following section was attempted to be run over the cooling season with and without wetting. The physics of this evapotranspiration simulation of the spray cooled roof are outlined below.

Assumptions

- 1 dimensional heat flow calculation (the saturated water vapor pressures and temperature are correlated in a linear fashion)
- Sun's radiation is constant
- Inside temperature = 78 F
- Quasi-steady state (varying ambient temperatures & solar flux in the form of a Fourier series)
- All water lost by way of evaporation is instantly replenished by an external source (i.e. water level remains constant with time)
- No capacitance effects due to the thermal mass of the water film or roof
- Weather data is assumed for a typical summer day via TMY3 weather data
- No wind effects
- The temperature of the water is of little importance as it is the latent heat rather than the sensible heat that determines the cooling effect of the system.
- Evaporative heat transfer coefficient of 5.678 W/m2
- The Sun delivers 344 BTU/ft2/Hr to the Earth's surface
- An average roof, on a 90 degree day, can reach 185 degrees F

Conversions

- 1 gallon of water absorbs 8,265 BTUs in evaporation
- 1 Ton of air conditioning = 12,000 BTUs
- 1 Ton of air conditioner operating for one hour, consumes about 1.25 KwH

Governing Equations

Energy balances result in three problems which need to be solved simultaneously. A schematic for this roof spray problem is shown in Figure 15.

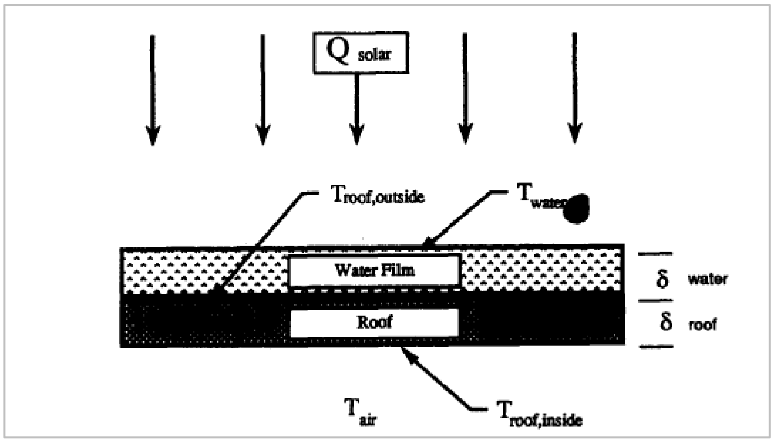


Figure 15 Roof Spray Schematic

1) **Water Surface**: The gain in solar energy on the water surface is complemented with losses in radiation, convection, conduction, and evaporation. The expression for evaporative loss and the linear relationship between pressure and temperature are taken from Tiwari et al. Figure 16 shows this energy balance at the water surface node.

$$q_{solar} = q_{evqp} + q_{rad} + q_{conv} + q\ _{cond}$$

$$q_{evqp} = 0.073814(P_w - \ \phi P_a)$$

$$q_{rad} = \epsilon\sigma(T_w^4 - \ T_c^4)$$

$$q_{conv} = h_0(T_w - \ T_c)$$

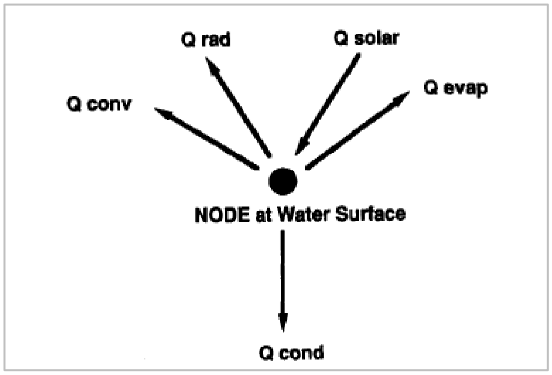
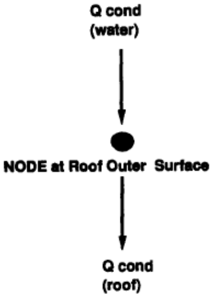


Figure 16 Water Surface Node Energy Balance

$$q_{cond} = (T_w - \ T_o)/R_w$$

$$P_w = 325.17T - 5154.87$$

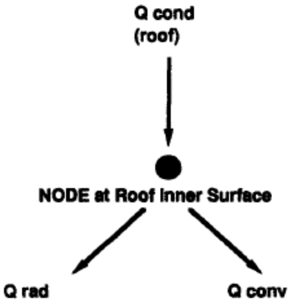
2) **Roof Outer Surface**: The thermal conduction through the water is equal to the heat flux passing through the roof allowing for the inside roof temperature to be evaluated as a function of the water surface and water, roof thermal resistances.



$$q_{cond(water)} = q_{cond(roof)}$$

$$\frac{T_w - T_o}{R_w} = (T_o - T_i)/R_r$$

3) **Roof Inner Surface**: The heat flux through the roof is dissipated indoors by convection and radiation to the air inside the room.



$$q_{cond(roof)} = q_{rad(inside)} + q_{conv(inside)}$$

$$q_{rad(inside)} = \epsilon\sigma(T_i^4 - T_a^4)$$

$$q_{conv(inside)} = h_i(T_i - T_a)$$

4) **Iteratively Solve for Temperatures:** The following expression is to be solved iteratively in conjunction with equations in steps 1 through 3 to obtain To, Tw, and Ti for the weather conditions of Pittsburgh, PA.

$$\begin{aligned} T_o = {} & (1 + h_i R_r)[(T_o - T_w)(R_r/R_w) + T_o] \\ & + \epsilon\sigma R_r[(T_o - T_w)(R_r/R_w) + T_o]^4 \\ & - R_r(h_i T_a + \sigma\epsilon T_a^4). \end{aligned}$$

5) **Simple Computer Program:** Kondepudi 1992 uses a custom built computer program to solve for the various parameters in an iterative fashion where the design parameter was the inside temperature (which is 78 F for CSL). Due to errors in the EES simulation setup, the results from this analysis were not able to be used. If more time and experience with EES was available, this custom built physics engine could provide a reasonable baseline to other methods.

Results from this methodology with and without spray cooling for a case study in Pittsburgh, PA (the same location as CSL), show that the roof surface temperature is on average 10 C or 25 F cooler with water misting. The study was performed for a day in August. Figure 17 shows the temperature profile throughout the day.

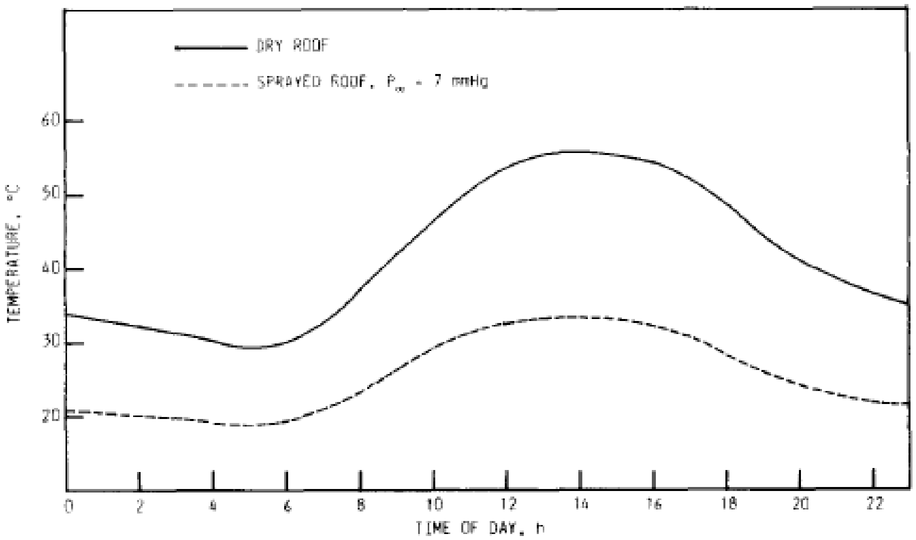


Figure 17 Comparison of roof surface temperatures for sprayed and unsprayed roof conditions

5.7 Model #2: Green Roof Calculator

Modeling methods discussed earlier did not provide the functionality to edit the properties of a roof in the detail needed for this depth analysis. Thus, this simulation was used as a performance baseline for comparison results discussed in Section 9 and 10. **Green Roof Energy Calculator** allows engineers to compare the annual energy performance of a building of a white roof and dark roof with a vegetative green roof. This physically based energy balance was developed by researchers at Portland State University and the University of Toronto. In April 2007 this module became part of the standard release of the US Department of Energy's EnergyPlus model. The calculator incorporates a vegetation canopy and soil transport model that represents the following green roof physics:

- long and short wave radiation exchange within the canopy (multiple reflections, shading)
- effect of canopy on sensible heat exchange among the ambient air, leaf, and soil surfaces
- thermal and moisture transport in the growing media with moisture inputs from precipitation (and irrigation if desired)
- evaporation from the soil surface and transpiration from the vegetation canopy

Table 14 shows the simulation inputs. EnergyPlus weather files used for Pittsburgh, PA are based on Typical Meteorological Year 3 (TMY3) data. The green roof only covers 48% of the roof while pavers (dark concrete panels) cover the rest. This highlights that green roof thermal performance was not the main goal. The 8 inches of growing media was pulled from the building drawings. The growing media characteristics for were set as follows: thermal conductivity 0.35 W/mK; density 1100 kg/m3; specific heat 1200 J/kgK; saturation volumetric moisture 0.3; residual volumetric moisture 0.01; initial volumetric moisture 0.1. The leaf area index was estimated to be 2 based on approximating between zero for bare ground and 6 for dense forest. The same utility rate structure from section 3 was used.

Table 14 Green Roof Energy Calculator Inputs	
State	Pennsylvania
City	Pittsburgh
Type	New Office Building
Total Roof Area	6685.98 sqft
Green Roof Area	3216.28 sqft
Percentage	48.1%
Rest of Roof	Dark (0.15 albedo) Concrete Pavers
Growing Media Depth	8 inches
Leaf Area Index	2
Roof Irrigated?	Yes

Simulations were carried out using the standard conduction transfer function solution scheme. Energy and cost savings were determined on a per square foot of roof basis. The savings were multiplied by the 6685.98 SF roof area and 48% of percent green roof to determine the total savings. Results below were compared to a dark roof as a baseline. Table 15 and Table 16 show simulation outputs. Compared to a dark roof (or a full roof of the concrete pavers), the existing green roof on CSL saves 1213.7 kWh in energy resulting in $181.18 of savings annually. This is relatively low amount of annual savings compared to the near $140,000 up front cost and staff maintenance wages that are inevitable to incur.

Table 15 Annual Energy Savings Compared to Dark Roof	
Electrical Savings	1213.7 kWh
Total Cost Savings	$181.18

Table 16 Average Sensible Heat Flux to the Environment		
	DARK ROOF	48% GREEN ROOF
Summer Average [W/m2]	51.1	37.4
Summer Daily Peak Average [W/m2]	297.4	190.3

5.8 Model #3: CLTD

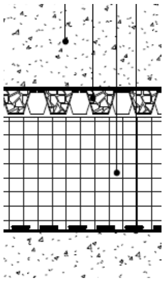
Cooling Load Temperature Differential with Solar Load Factors (CLTD/CLF): This ASHRAE analysis (first published in 1989 Fundamentals) was devised to account for the effects of wall mass on transmission, solar gain, and other load components. A design day in August is considered, but an effective cooling load temperature difference (CLTD) is used in place of the standard outside/inside design temperature difference. These CLTD values are calculated using a transfer function analysis of a room containing the roof section under consideration. The TFM of the roofs was used to compute one-dimensional transient heat flow. This technique modifies the temperature difference of the hourly loads, rather than the U-values, to arrive at an equivalent thermal transfer across a wall section. The results are approximate cooling load values rather than simple heat gain values. This modeling method was selected because it was recommended by the Sprinkol System roof misting vendor. A reference to the first page of this ASHRAE Fundamentals 1989, chapter 26, procedure is in [A2] CLTD/CLF Calculation Procedure.

The basic cooling load equation for the exterior roof surface is:

- q = UA(CLTD)
- where
  - q = cooling load, W
  - U = roof design heat transfer coefficient
  - A = area of roof calculated from the building plans
  - CLTD = cooling load temperature difference, roofs (base value)

A low to high range of the R-value used in the CLTD calculation is summarized in Table 17.

Table 17 Spray Cooling Roof Section

SECTION	DEPTH	MATERIAL	R-VALUE	
	<1"	Layer of Misted Water in the Summer	R ~ 100 during day R=0 at night	
	6"	Cast-in-place Concrete	R-0.3/in	R-1.8
	2"	Drainage Course	R-0/in	R-0
	8"	Rigid Insulation (extruded polystyrene)	R-5/in	R-40
	3-1/2" 2"	Concrete Slab Composite Steel Deck	R-0.3/in R-0/in	R-1.5 R-0
		TOTAL	R-43 to R-143	

Thus, its U-value is the inverse which is 0.023 BTU/hr*ft2F. The total area of the roof is 6,686 SF while the total area to be spray cooled is 5645.5 SF. This reduction in the spray area was to ensure that the rooftop air handling unit and added cooling tower were not affected by the added humidity.

CLTD is adjusted for latitude-month correction, exterior surface color, indoor design temperature, outdoor design temperature, solar radiation, attic conditions, U-values, and insulation. Steps one through four below outline adjustments and corrected values for the Center for Sustainable Landscapes.

1. Hourly Temperature Variation

The hourly temperature variation is based off of the design month and daily range of the Center for Sustainable Landscapes. Table 18 shows the weather data used for the building site in Pittsburgh, PA.

Table 18 Weather Data for CLTD Procedure	
Latitude	40.5
Design Month	August
Summer Dry Bulb	87 F
Summer Wet Bulb	71 F
Daily Range	23

Only hours 9 through 18 were considered in this calculation, since those are the main daily cooling hours. Appendix [A3] Hourly Temperature Variation shows the calculations for step one. The ten hour average was calculated to be 81.55 F. This value represents 'To' in steps two through four.

2. Hourly Cooling Load Temperature Differential (corrected)

Steps two through four use the following CLTD equation as a way to correct calculation values:

- CLTD(c) = [(CLTD(unc)) + LM) * K + (78 F – Tr) + (To – 85 F)] *f
- where
    - CLTD (c) = CLTD corrected
    - CLTD (unc) = CLTD uncorrected (Roof#1 at 1400 hrs. was used for CSL's super insulated office building)
    - LM = Latitude / month solar radiation correction
    - K = color correction factor (K was selected to be 1 for CSL)
    - To = ten hour average for temperature variation (calculated in step one)

This step uses August as the design month for the hourly calculations. Appendix [A4] Hourly Cooling Load Temperature Differential (corrected) shows the calculations for step two. The ten hour average CLTD uncorrected value was calculated to be 62.3 F. This value is used as the CLTD (uncorrected) for step three.

3. Monthly Cooling Load Temperature Differential (corrected)

This step calculates the monthly cooling load temperature differential for cooling months April through October. As a conservative approach recommended by a mechanical engineer in the industry, only 90% of the CLTD corrected value was used. Appendix [A5] Monthly Cooling Load Temperature Differential (corrected) shows the calculations for step three. The seven month CLTD corrected average was calculated to be 50 F.

4. Peak Monthly Cooling Load Temperature Differential (corrected)

This step is very similar to step three in calculating peaks for April through October but uses the peak temperatures. Appendix [A6] Peak Monthly Cooling Load Temperature Differential (corrected) shows the calculations for step four. The seven month peak CLTD corrected average was calculated to be 65 F. The peak CLTD was 70 F.

5.9 Energy & Cost Reduction

The monthly average CLTD corrected values calculated in step 3 and Appendix [A5] Monthly Cooling Load Temperature Differential (corrected) as well as those calculated in step 4 and Appendix [A6] Peak Monthly Cooling Load Temperature Differential (corrected) was used. Hours per month of cooling was assumed to be 300. The EER (energy efficient ratio) of the existing system was assumed to be 3.56 due to its high energy performance discussed in Section 3.

Usage Reduction and Demand were calculated by the following equations:

- **Usage Reduction (kWh/Mo)** = U*A*CLTD(c)*(Hrs/Mo.) / [EER*1000]
- **Peak Demand Reduction (kW)** = U*A*CLTD(c)/ [EER*1000]

MONTH	MONTHLY AVERAGE CLTD (c)	USAGE per MONTH [kWh]	PEAK MONTHLY CLTD	DEMAND [kW]
APR	50	649	66	3
MAY	54	701	69	3
JUNE	55	714	70	3
JULY	54	701	69	3
AUG	50	649	66	3
SEPT	46	597	61	3
OCT	41	529	55	3
TOTAL		**4540**		**20**

Results show that the reduction totals to be 4,540 kWh for the cooling season. Note that Kwh savings due to demand reduction was 150 Kwh/1Kw.

Combining the energy seasonal usage and demand with the utility billing information from Section 3.3, the electrical savings for the season is as follows:

- **Usage Energy Reduction Savings**: 4540 KWh / season * 0.01236/kWh = $561.14 / season
- **Demand Billing Reduction Savings**: 20 kW/season * 7.07 /kW = $141.40 / season
- **Total Electrical Savings** = $702.54 / season

Based on the total roof area to be sprayed (5,645.5 SF), the average cooling savings equated to be 7,689 BTU/hr (or 0.64 tons) while the peak savings equaled 10,746 BTU/hr (or 0.90 tons). These were calculated via the load equation for a roof surface above as well as the average CLTD (C) [50 F] from step 3 and peak CLTD (c) [70 F] in step 4.

Although the energy tonnage savings is minimal compared to the total energy consumption of the building discussed in section 3, the total electrical savings is a sizeable amount of money to save annually by adding the spray cooled system. When it comes to maintenance, the existing intensive green roof would cost a significant amount to maintain in staff wages. The spray cooled roof on the other hand does not have any regular maintenance requirements. An additional energy and costs summary is discussed later in this report.

5.10 Installation Costs

Costs for installing the Sprikool system are summarized in Table 19. The $1.55 / sqft cost structure for the system is from the vendors' website as a general estimate. The above grade storage tank is not needed since there is an underground rainwater harvesting basin already exists. The pipe connecting water to the roof is also not needed because the green roof was already designed with it for watering purposes. Initial and installation costs for the spray cooling system sums to be $8,750.53. Compared to the green roof's price tag, this is $132,688.47 less in upfront costs.

Table 19 Spray Cooling System Installation Costs

ITEM	COST	CSL SPECIFICS	COSTS
Sprikool Roof Spray System (Piping & Controls)	$1.55 / sqft	Installed onto 85% of the Roof (5645.5 SF)	$8,750.53
Above-Grade Storage Tank	$1500 per 1000 gallons	Unground Water Basin Already Exists	0
Connecting Pipe	$16 per lineal foot drain to coil	Connecting Pipe to Roof Already Exists due to Green Roof	0

5.11 Water Usage

The above underground water basin should be able to provide the water for the spray cooled system. Yet, a consulting engineer claimed that spray cooling the outside of an R-20+ roof could cost more in water than it's going to save in energy. Thus, a more in depth analysis of the water usage of this spray cooled system was conducted. If the previously explained greywater system does not provide the needed demand, potable water purchased from the city could be piped up to the roof. Table 20 calculates water usage throughout the seven months of spray cooling operation. Assumptions for the calculation were as follows:

- **Hrs./Day**: Hours of cooling per day Pittsburgh, PA are from the U.S. Naval Observatory.
- **Solar Radiation BTU / sqft per day**: Theses values for Pittsburgh, PA are from NASA's
- **Gal / sqft per day**: This value is calculated by dividing the solar radiation BTU's by 8532 (a recommended water rate by the manufacturer).
- **Usage days per month**: 30 days per month was assumed for April through October.
- **Usage hours per day**: The spray system would cool the building for approximately 10 hours per day during the months listed above.
- **H20 $ / 1000 gal**: An average of $1.00 per 1000 gallons was assumed based off of the Pittsburgh Water Authority.

Table 20 Water Usage

MONTH	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	TOTAL
Hrs./Day (Pittsburgh, PA)	13.33	14.48	15.05	14.73	13.72	12.42	11.07	
Solar Radiation BTU / sqft	830	952	1043	1045	919	775	586	

per day								
Gal / sqft per day	0.1	0.11	0.12	0.12	0.11	0.09	0.07	
Gal / sqft per hour	0.01	0.01	0.01	0.01	0.01	0.01	0.01	
Usage days per month	30	30	30	30	30	30	30	
Usage hours per day	10	10	10	10	10	10	10	
Gal / sqft per month	2.19	2.31	2.44	2.49	2.36	2.19	1.86	
H20 gal / month	14631	15446	16292	16672	15755	14666	12452	**105914**
H20 $ / 1000 gal	1	1	1	1	1	1	1	
H20 $ / month	14.63	15.45	16.29	16.67	15.76	14.67	12.45	**$ 105.92**

It was found that for the 5645.5 square footage of roof to be misted, a total of 105,914 gallons of water equaling $105.92 would be used per year. Being only an average of 15,000 gallons and $15 / month, this is a low cost compared to the watering and maintenance costs that would incur with a green roof.

6.0 Mechanical Depth 2: Hybrid Geothermal System vs. Full Ground Coupled

6.1 Objective

Ground source heat pumps (GSHP) have higher first costs than conventional systems making short-term economics unattractive. An alternative, lower cost approach for such applications can be use of a hybrid GSHP design. In hybrid geothermal systems, the ground heat exchanger size is reduced and an auxiliary heat rejecter (e.g., a cooling tower or some other option) is used to handle the excess heat rejection loads during building cooling operation. This depth will analyze the function of life cycle costs vs. ground loop size.

6.2 Background

The Center for Sustainable Landscapes was initially designed with a full geothermal ground source heat pump, which resulted in an extremely high initial price tag of $100,000 or $29.32 per SF. Located in Pittsburgh, it is also cooling dominated. As a way to reduce costs without dramatically changing the operating costs, the addition of a cooling tower will be analyzed as a supplemental heat rejecter. This allows for smaller borehole fields (which results in lower first costs, reduced total field area, and less installation time during construction). Degradation of the heat pump performance is avoided by offsetting the annual load imbalance in the bore field.

6.3 Site

The site conditions are a very important part of a geothermal a ground source heat pump design. The earth layers must be predetermined in order to choose the best area on the site for the bore field and to prepare for well drilling. Figure 18 below shows the geologic map of Pennsylvania. The Center for Sustainable Landscapes is located at the red star in Pittsburgh, Allegheny County. The geology for this area is depicted in the figure as a light blue. Pennsylvanian geology consists of cyclic sequences of sandstone, red, and gray shale, conglomerate, clay, coal, and limestone.   This soil has a resistance of 0.25 hr-ft-F/BTU (calculated by taking the invers to the rock and soil types listed in ASHRAE Handbook – HVAC Applications, Ch. 32).

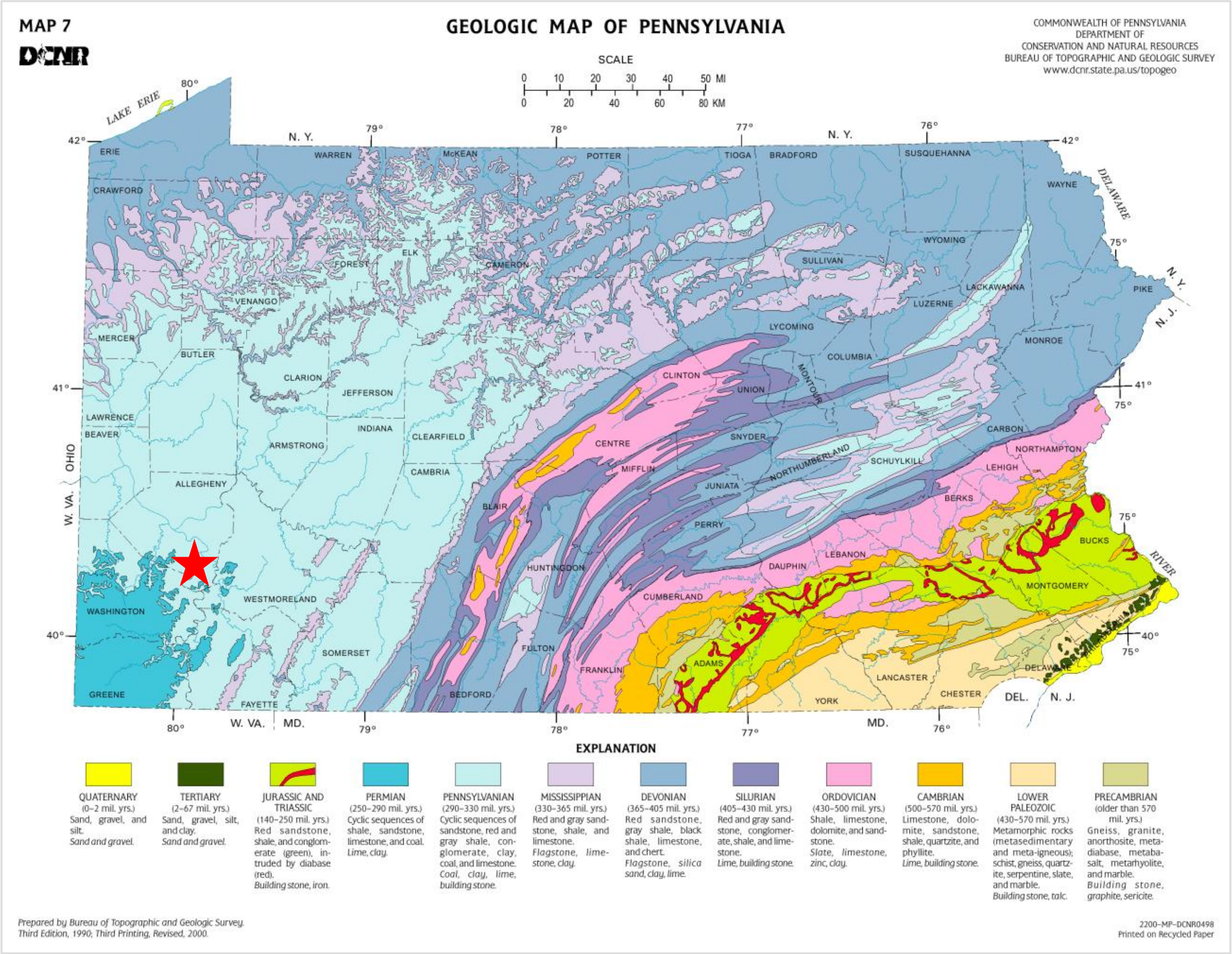


Figure 18 Geologic Map of Pennsylvania

An additional in depth study of CSL's site was performed by Civil and Environmental Consultants. Appendices A11 & A12 shows the analysis in detail.

The bore fields of the ground loop heat exchanger typically occupy a large area of a building site. CSL sits on a slope, which limits the flat area needed to drill the geothermal wells. Shown in Figure 19 below, the location of the building is highlighted by a red start. The driveway (circled in yellow) leading up to the building provides the most flat space for the field without interfering with existing buildings. The bore field area potential is approximately 35,000 square feet.

Figure 19 CSL Site & Bore Field Area

The ground and borehole grout properties for the site are summarized in Table 20.

Table 20 Ground Properties

GROUND	Type	Dry Density [lb/ft3]	Conductivity [Btu/h-ft-F]	Diffusivity [ft^2/day]
Soils	Heavy Clay 5% Water	120	0.6 - 0.8	0.5 - 0.65
	Light Sand 5% Water	80	0.5 - 1.1	0.6 - 1.3
Rock	Sandstone	-	1.2 - 2.0	0.7 - 1.2
Grout	15% bentonite/85% SiO_2 sand	-	1.00 - 1.10	-

6.4 Modeling

A hybrid geothermal system includes a supplemental heat rejecter in order to downsize the ground loop heat exchanger. This supplemental heat rejecter is sized so that the annual heat rejection to the ground approximately balances the annual heat extraction from it. Excess heat is then rejected through the cooling tower resulting in a smaller ground-loop heat exchanger. The size of the ground loop heat exchanger as well as the supplemental cooling tower is dictated by the cooling peak load of the building. Simulated in Trane TRACE 700, Table 21 shows the calculated cooling coil peak and heating coil peak for CSL.

Table 21 Simulated Cooling & Heating Load

	BTU/hr	Tons
Cooling Coil Peak	605,880	50.49
Heating Coil Peak	397,007	33

The load profile shows that this commercial office building is cooling dominated, which opens an opportunity to add a supplemental heat rejecter. A building also very rarely runs at peak load. Thus the cooling tower will likely only be needed during extreme conditions.

This redesign depth focuses on a hybrid geothermal system vs. a full ground loop heat exchanger. In order to analyze the performance of various sized cooling towers for a hybrid geothermal system, the load demand on the ground loop heat exchanger was decreased by 10% increments. Table 22 shows the load reduction and the resulting cooling tower sizes to be further analyzed: 5 tons, 10 tons, and 15 tons. At a 30% reduction, the ground loop is sized to meet the building heating loads, while the cooling load in excess of the heating load is met through a 15 ton cooling tower supplemental heat rejection. This methodology is also used by Yavuzturk and Spitler 2000 as well as Sagia, Rakopoulous, Kakaras 2011. Any further incremental reduction would drop the load coverage below the heating coil peak of 397,007 BTU/hr which would require heat absorption (the addition of a boiler). Continuing to reduce the load in this manner could be an area of further research.

Table 22 Full Load Reduction for Hybrid Geothermal

	LOAD COVERAGE BY GROUND LOOP HEAT EXCHANGER	RESULTING COOLING TOWER SIZE
Cooling Coil Peak [Existing]	605,800 BTU/hr	0 tons
10% reduction	545,400 BTU/hr	5 tons
20% reduction	485,800 BTU/hr	10 tons
30% reduction	425,880 BTU/hr	15 tons

6.5 Cooling Tower

There are two types of cooling towers, open and closed; each of which has its own advantages and disadvantages.

- Open Cooling Tower
  - Water to be chilled is open to the atmosphere and cooled by evaporation.
  - “Fill” (structured packing material) can be added to increase the evaporation rate, thus increasing the surface temperature of falling water.
  - Must be isolated from the ground loop with a plate heat exchanger (prevent contamination by debris in the cooling tower air stream, which otherwise would lead to corrosion and clogging of the building heat pump units).
  - TWO TYPES include:
    - Induced Draft: use a suction fan to pull air up through the fill ("counterflow") or across the fill ("crossflow"). Counterflow towers are the most compact and thermally efficient.

        - Forced Draft: use bottom mounted centrifugal blowers. These consume twice the power of induced draft.
- Closed Cooling Tower
    - Water to be chilled is in an isolated pipe.
    - These are typically larger, cost more, and consume more power than open towers of the same cooling capacity.
    - Closed tower are typically recommended for new hybrid geothermal systems. Due to their larger size, it was difficult to find a cooling tower at the small capacity needs of CSL.

The cooling tower type ultimately chosen was an open cooling tower (based on vendor size availability) that is counterflow induced draft with fill (which provides a compact size and thermal efficiency). Figure 20 shows a diagram of this specific cooling tower.

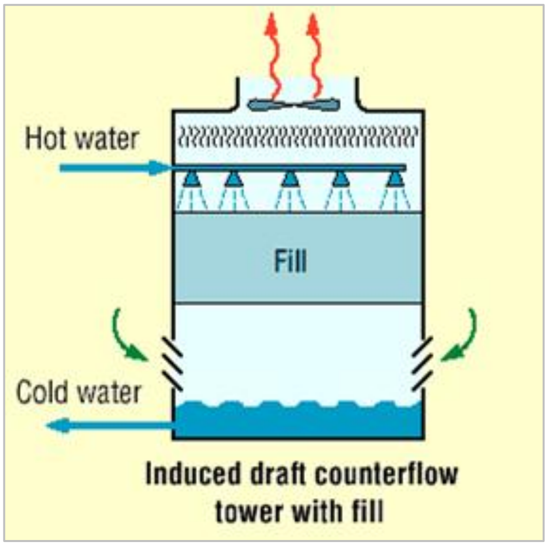


Figure 20 Induced Draft Counterflow Tower with Fill

The peak cooling load of the Center for Sustainable Landscapes is 605,800 BTU/hr . The steps in selecting the correct cooling tower are based off of Yavuzturk 1999.

The heat rejection requirement as well as the peak ground loop entering fluid temperature was used to size an induced draft counterflow cooling tower as follows:

1) Select the **maximum wet bulb temperature** for Pittsburgh, PA. According to ASHRAE the summer design Twb for Pittsburgh is 73 F. Selecting this wet bulb will oversize the cooling tower because the max design wet bulb rarely ever coincides with the peak entering fluid temperature.
2) Set the **cooling range** (or the difference between fluid entering and exiting fluid temperatures of the cooling tower) at design conditions. 95 F and 85 F entering and leaving water temperatures were selected based upon recommendation from a mechanical engineer.
    - Cooling Range = T entering – T leaving = 95 F – 85 F = 10 F

3) Set the **approach temperature** (or the difference between the exiting fluid temperature of the cooling tower and the design wet blub temperature). Again, the cooling tower leaving fluid temperature was assumed to be 85 F under design conditions.
    - Approach Temperature = T water exit – T wb air = 85 F – 73 F = 12 F

4) Adjust the required fluid flow based on the required cooling tower capacity. The fluid flow equation is as follows:

$$\dot{m}_{H20} = \frac{\dot{q}}{Cp * \Delta\, T_{cooling\ range}}$$

    - where:
        - m = the flow of the fluid to and from the cooling tower [gpm]
        - q = the cooling tower capacity [BTU/hr]
        - Cp = specific heat [BTU/lbm-F]
        - ΔT = cooling range calculated in step 2 [F]

Table 23 shows the calculated required flow based on the capacity of the three cooling towers under analysis.

Table 23 Required Flow of Cooling Towers

TOWER	CAPACITY [BTU/hr]	REQUIRED FLOW [gpm]
5 ton	60,000	13.1
10 ton	120,000	26.1
15 ton	180,000	39.3

5) Choose a "cooling tower selection factor" from a table produced by the cooling tower manufacturer based on the design wet bulb temperature, approach temperature, and cooling range. Figure 21 below shows the ideal cooling tower performance and standard design from McQuinston, Parker, and Spitler's HVAC Analysis and Design . The design for this cooling tower (lowered by the wet bulb temperature) is highlighted in red.

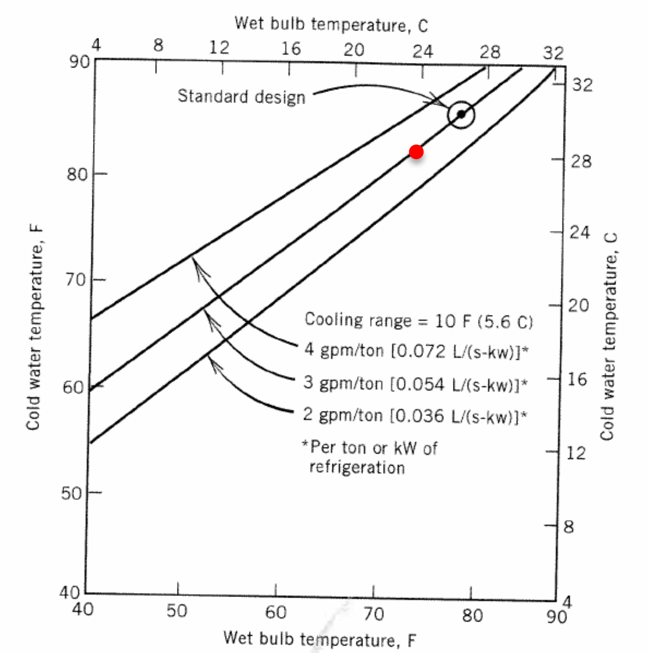


Figure 21 Ideal Cooling Tower Performance

6) Select a cooling tower based on the above outlined properties, maximum het rejection at the time where the maximum entering fluid temperature occurs.

There are numerous cooling tower vendors, but only a few accommodate the small capacity requirements of the three potential cooling towers. Cooling Tower Systems (CTS) have manufactured cooling tower lines and related equipment for 40 years. They range in sizes from 5 tons to 200 tons, take up minimal space, have a nominal operating weight, and offer reasonable prices. Each of their specified water flows falls above the calculated requirement. **Table 24** summarizes the details of the cooling tower options.

Table 24 Cooling Tower Options

	CAPACITY	5 ton	10 ton	15 ton
	Model	T-25	T-210	T-215
	Fan Motor [HP]	1/6	1/4	1/4
	Volt Single Phase [V]	110/220	110/220 V	110/220
	Flow [gpm]	15	30	44
	Operating Weight [lbs]	251	443	536
	Size Diameter [inches]	28"	36"	60"
	Price	$ 1,185.43	$ 1,561.71	$ 1,855.71

A preliminary hybrid geothermal energy model was conducted using Trane TRACE 700. The three alternatives considered varied in cooling tower capacity by 5 ton increments. Each alternative compared to a full geothermal system consumes only nominally more energy. Figure 22below shows the energy consumption of just the cooling tower equipment in Trane TRACE. The curves resulted as expected, with the cooling towers only operated during heating months. With a 10% reduction in the full geothermal system, the 5 ton system would operate only in July, August, and September (when the load demand exceeds 90% of design conditions) and consume only 17.5 kWh. With a 20% reduction in the full geothermal system, the 10 ton cooling tower would consume 69% more energy annual 56.5 kWh throughout June, July, August, and September. With a 30% reduction in the full geothermal, the 15 tons cooling tower would operate May through October consuming 104.4 kWh to meet demands that the downsized ground loop would not be able to meet. This is a 49% increase from the 10 tons and 83% more than the 5 ton. This analysis is used later in this section in conjunction with the corresponding borehole heat exchanger length / costs.

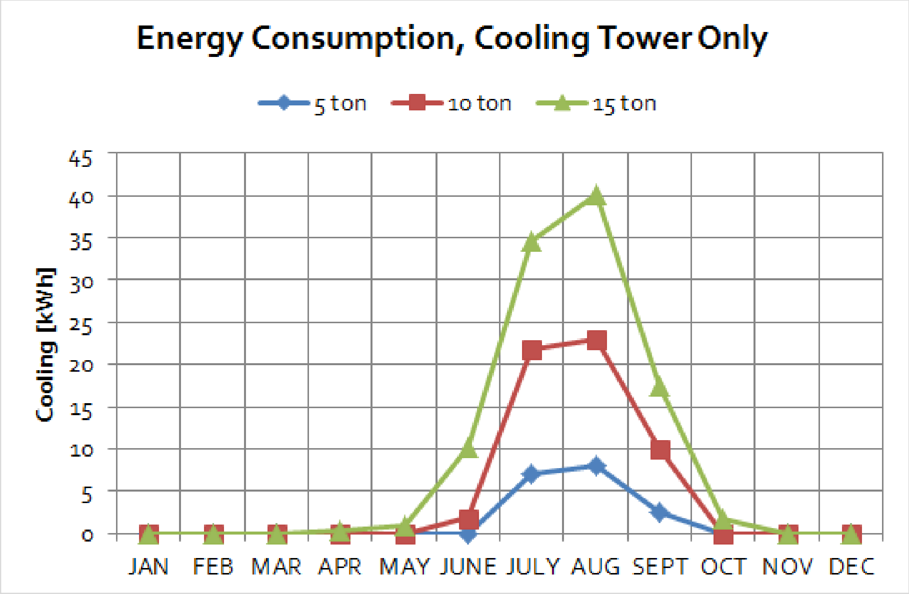


Figure 22 Preliminary Energy Simulation of Cooling Towers

Note that if the outside wet bulb temperature drops below the rated degrees, the cooling tower will improve in performance. As a way to further improve the performance, it is recommended that the cooling tower be run at night in order to condition the field for the day. In a way, this will reset the temperature of the ground for to ensure optimal performance of the hybrid geothermal system during peak daytime demand.

6.6 Bore Holes

To calculate the heat exchanger length as well as the corresponding number of bores and potential depths, two methods were used. The first methodology was from Chapter 32 of the ASHRAE Handbook-HVAC Applications. This was used to setup assumptions while the McClure Company's heat exchanger length spreadsheet computer program was used to run various ground loop load requirement calculations. This ASHRAE Handbook provides the equations to calculate the needed bore length to meet the load requirements. Design heating and cooling block loads were calculated via Trane TRACE 700. For the hybrid geothermal system, ground loop heat exchanger load requirements were decreased as cooling tower capacity was increased. The equations account for the variable heat rate of a ground heat exchanger by using a series of constant-heat-rate "pulses."

The equation for the required length for cooling loads:

$$Lc = \frac{q_a R_{ga} + (q_{lc} - 3.41W_c)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p}$$

The equation for the required length for heating loads:

$$L_h = \frac{q_a R_{ga} + (q_{lh} - 3.41W_h)(R_b + PLF_m R_{gm} + R_{gd} F_{sc})}{t_g - \frac{t_{wi} + t_{wo}}{2} - t_p}$$

- where:
    - F_{sc} = short-circuit heat loss factor
    - L_c = required bore length for cooling, ft
    - L_h = required bore length for heating, ft
    - PLF_m = part-load factor during design month
    - q_a = net annual average heat transfer to ground, Btu/h
    - q_{lc} = building design cooling block load, Btu/h
    - q_{lh} = building design heating block load, Btu/h
    - R_{ga} = effective thermal resistance of ground (annual pulse), h-ft-°F/Btu
    - R_{gd} = effective thermal resistance of ground (peak daily pulse), h-ft-°F/Btu
    - R_{gm} = effective thermal resistance of ground (monthly pulse), h-ft-°F/Btu
    - R_b = thermal resistance of bore, h-ft-°F/Btu
    - t_g = undisturbed ground temperature, °F
    - t_p = temperature penalty for interference of adjacent bores, °F
    - t_{wi} = liquid temperature at heat pump inlet, °F
    - t_{wo} = liquid temperature at heat pump outlet, °F
    - W_c = system power input at design cooling load, W
    - W_h = system power input at design heating load, W

Assumptions

- **Short-Circuit Heat Loss Factor:** A flow rate of 3 gpm/ton was assumed since there is only one bore per loop. Using the table in ASHRAE Handbook Chapter 34 shown below, a short-circuit heat loss factor of 1.04 was chosen.

	F_{sc}	
Bores per Loop	**2 gpm/ton**	**3 gpm/ton**
1	1.06	1.04
2	1.03	1.02
3	1.02	1.01

- **Part Load Factor**: A worst case PLF of 1.0 was used.
- **Ground Effective Thermal Resistance**

$$R_{ga} = \frac{(G_f - G_1)}{k_g} \qquad R_{gm} = \frac{(G_1 - G_2)}{k_g} \qquad R_{gd} = \frac{G_2}{k_g}$$

    - where:

  - k_g = ground thermal conductivity found in Table 5 of the ASHRAE Handbook,
  - G_n = G-Factors found in Fig. 15 in the ASHRAE Handbook using Fourier numbers:

$$Fo_f = \frac{4\alpha\tau_f}{d_b^2} \qquad Fo_1 = \frac{4\alpha(\tau_f - \tau_1)}{d_b^2} \qquad Fo_f = \frac{4\alpha(\tau_f - \tau_2)}{d_b^2}$$

- where:
  - α = thermal diffusivity of the ground, ft^2/day, found in Table 5 of the ASHRAE Handbook,
  - d_b = bore diameter, ft. A bore diameter of 6" was chosen for this application,
  - τ = time of operation, days (τ_1 = 3650 days, τ_2 = 3680 days, τ_f = 3680.25 days)

- **Thermal Resistance of Bore**: A 1-1/4" U-Tube was used in a 6" borehole with a conductivity of 1.0 BTU/ h-ft-°F. Using Table 6 in the 2012 ASHRAE Handbook – HVAC Applications Chapter 34, this provides a thermal resistance (R_b) of 0.048 h-ft-°F/BTU.

- **Temperature Penalty for Interference of Adjacent Bores:** This value was determined using Table 7 and Table 8 of the 2012 ASHRAE Handbook, HVAC Applications Chapter 34. An $EFLH_c$ and $EFLH_h$ of 750 and 750, respectively, were used.

- **Grout resistance**: Assumed to be 0.25 F/(BTU/(hr*ft)) according to a mechanical engineering in the building industry.

- A summary of other assumptions and calculation inputs can be found in **Table 25**. The ground loop load was decreased in different iterations of the hybrid geothermal calculations. Outdoor, indoor, and balance design temperatures are from CSL design documents. The Berner Energy Recovery Unit (ERV/AHU) manufacturer's data was used for COP cooling and mean water temperature. BIN data from ASHRAE Handbook HVAC Applications was used for the spreadsheet computer program. Appendix **Error! Reference source not found.** shows the full spreadsheet of data inputs and outputs for the geothermal system at full load.

Table 25 Bore Hole Length Inputs	
Building Area [SF]	24,350
Ground Loop Load [ton]	50.49, 45.49, 40.49, 35.49
Outdoor Design Temp [F] Indoor Design Temp [F] Balance Temp [F]	90 75 65
Total Heat Pump Capacity [ton] COP cooling	109.8 6.24
Pipe Resistance [hr-ft-F/BTU] Soil Resistance [hr-ft-F/BTU]	0.048 0.25
Mean Water Temp [F] Mean Earth Temp [F]	70 55

After running the bore length sizing computer program, the ground loop heat exchanger lengths shown in **Table 26** were found for the three different cooling towers. For the full geothermal system (0% cooling tower coverage), the actual number of bores and depth is shown. For the downsized hybrid geothermal system, a depth of 320 feet was selected. Reasoning for this depth is discussed later during the construction management breadth. Ground loop heat exchanger length for the 5 ton, 10 ton, and 15 ton cooling towers were calculated to be 5377 ft, 4055 ft, and 2919 ft respectively.

Table 26 Borehole Sizing Outputs

	Load Coverage by Cooling Tower*			
	0%	**10%**	**20%**	**30%**
Ground Loop Heat Exchanger Length [ft]	6885	5377	4055	2919
# Boreholes	14	17	13	9
Borehole Depth [ft]	500	320	320	320

6.7 Schematics

With the addition of a cooling tower to the hybrid geothermal system, the flow of water may change throughout the year during peak conditions. Figure 23 shows that in a typical hybrid geothermal system, the added cooling tower is located after the air handling unit / heat pump, before entering the ground loop. The cooling tower is connected in series with the ground heat exchanger and is isolated from the building and ground piping loops with a plate heat exchanger. The plate heat exchanger is added for open cooling towers only to prevent debris contamination. Thus, the purpose of the cooling tower in this configuration is to lower the entering ground loop temperature.

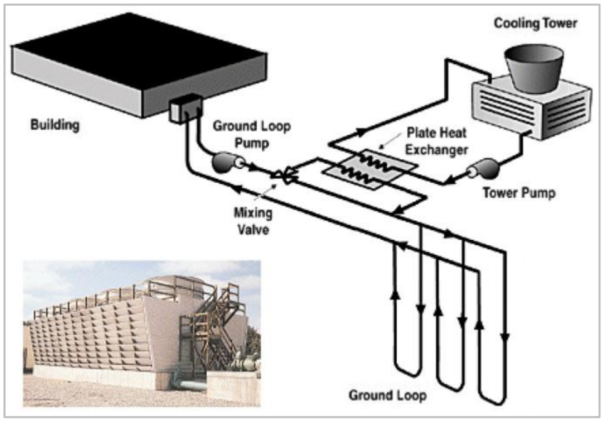


Figure 23 Cooling Tower Located Directly Before Ground Loop

Figure 24 shows the water-side schematic for the system redesign. Water is conditioned through the 1-1/4" ground loops in order for the leaving water temperature to be 55 F. From the wells, water is piped to the mechanical room where water is pumped up to the rooftop air handling unit via a 3" pipe. During peak conditions, the leaving water temperature from the heat pump would be 70.6 F. The diverter valve would be activated when the temperature exceeds a certain temperature explained in the controls section that follows. Cooling tower entering and leaving temperature as well as flow was calculated earlier in this section. Water is then continues down to the mechanical room, where two pumps (one duty and one backup) sustain the 151.5 gpm throughout the ground loop system. Electric, pressure, and temperature controls meters are depicted as a small square in the following schematic.

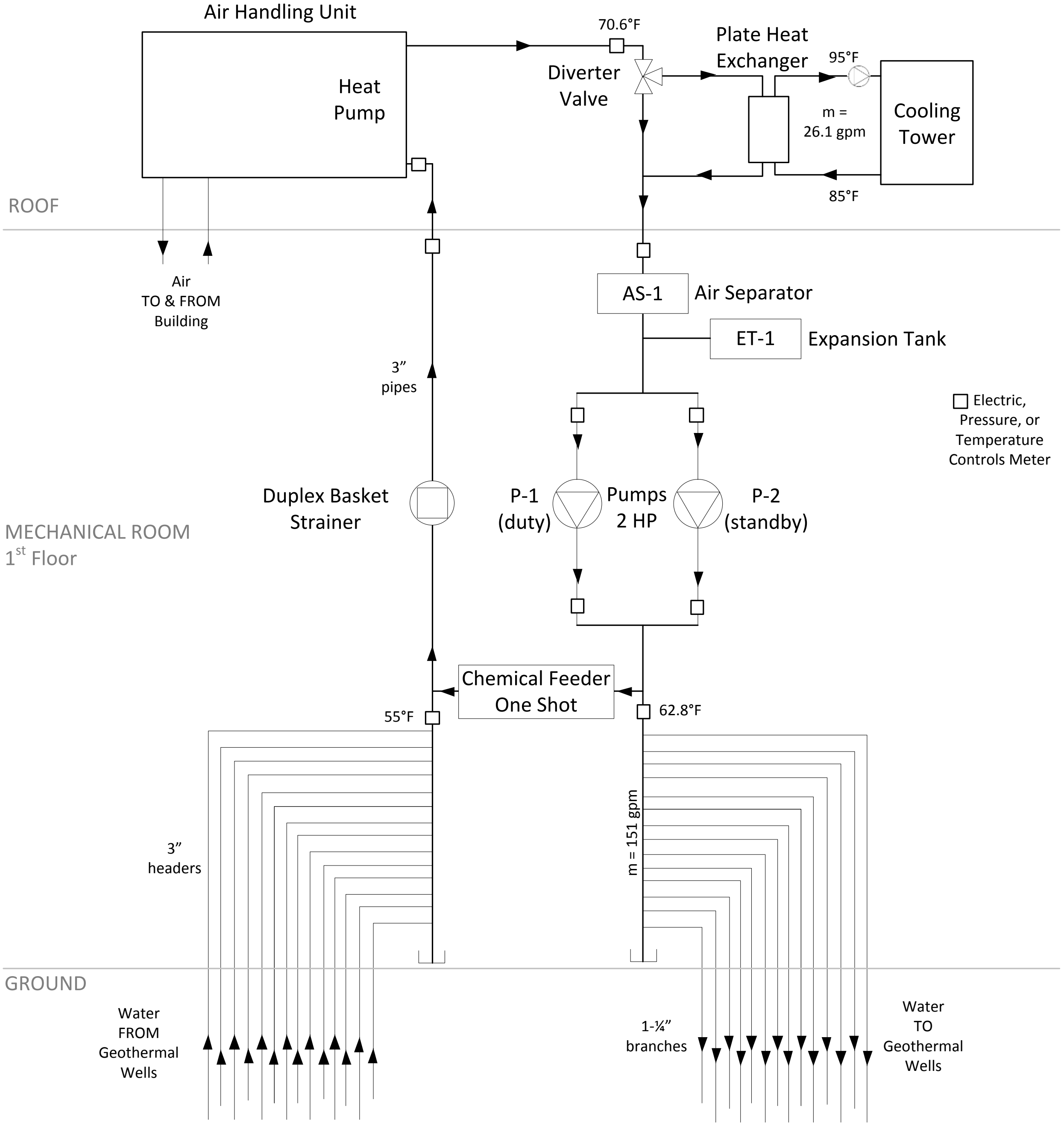


Figure 24 Redesign Water-side Schematic

The specific site layout for the 13 hole hybrid geothermal system is explained further in the construction management breadth and copied below for reference.

Figure 25 Hybrid Geothermal Borefield Layout

With the addition of a spray cooled roof in the first depth and a hybrid geothermal in this depth, there are no changes to the air side of the mechanical system.

6.8 Controls

The differential control scheme operates the cooling tower based on the temperature difference between the entering or exiting heat pump temperatures and the ambient wet bulb temperatures. Yet, the control scheme would change for the three different hybrid geothermal systems under investigation.

To find the required entering ground temperature during cooling months for the three different sized cooling towers, load capacity information was inputted into the following heat transfer equation:

$$\dot{q} = \dot{m} * C_p * \Delta T$$

- where:
  - q = downsized ground loop capacity corresponding to the cooling tower coverage [BTU/hr]
  - m = fluid flow [gpm]
    - 3 gpm/ton assumed based on ASHRAE recommendation
    - max cooling load for CSL = 50.49 ton (calculated via Trane TRACE)
  - Cp = specific heat for 20% ethylene glycol solution [0.917 BTU/lbm-F] (using this solution in the pipes is recommended by ASHRAE due to its lower freezing temperature)
  - ΔT = T in – Tout of the ground loop heat exchanger
    - Tout during cooling months assumed to be 55 F based on the ground temperature and required temperature needed by the heat pump
- Example Calculation at Full Load:
  - 605880 BTU/hr = (3 gpm/ton * 50.49 ton * 60 min/hr * 8.33lbm/gal) * 0.917 BTU/lbm-F *(Tin – 55)
  - Tin = 63.7 F for existing full geothermal system (this is the temperature that the entering water temperature must be in order for it to exit at 55 F)

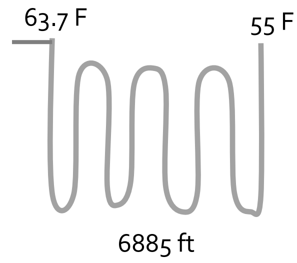
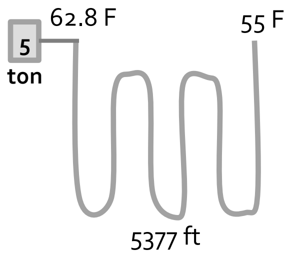
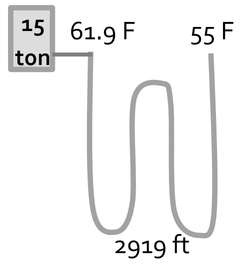
The set point control activates the cooling tower when the entering leaving heat pump temperature exceeds the following temperatures. Calculations are summarized in Table 27.

Table 27 Controls for Temperature Entering Downsized Ground Loop

	Load Coverage by Cooling Tower			
	0%	10%	20%	30%
Load on Ground Loop [BTU/hr]	605,880	545,400	485,880	425,880
Required Temperature Entering Ground Loop [F]	63.7	62.8	61.9	61.0
Activate Cooling Tower IF Temp. from Heat Pump Towards Ground is:	-	> 62.8	> 61.9	> 61.0

Results show that the required entering water temperature for the downsized ground loop would incrementally decrease in order to ensure that the exiting ground loop temperature is 55 F. This makes sense, because as the ground loop length decreases, the pipe area to reject heat to the cool earth becomes smaller. Table 28 shows diagrams of how when the ground loop length decreases, the entering temperature must be lower. If the entering temperature is ever above this, the cooling tower must be activated.

Table 28 Required Entering Ground Temperatures Diagram

Ground Loop 100% Cooling Tower 0%		Ground Loop 90% Cooling Tower 10%		Ground Loop 70% Cooling Tower 30%	
T entering	T exit	T entering	T exit	T entering	T exit
					
Length Ground Loop		Length Ground Loop		Length Ground Loop	

6.9 Selected Cooling Tower

Of the three different cooling towers under analysis for the hybrid geothermal depth and construction management breadth, seven variables were taken into account when deciding which combination would be the most cost effective initially as well as energy efficient throughout its life. Balanced variables included length, depth, # bore holes, area, time, and energy. The 20% reduction in the full geothermal system with a 10 ton cooling tower was ultimately selected based on the following criteria.

1. Depth & Cost: In order to decrease the initial costs, the depth of the boreholes had to be decreased below 325 feet to be able to use a cheaper auger. But, as depth of bores decreased, the space needed for boreholes increased.
2. Area: Space available for the boreholes was limited for CSL due to the steep hill that it site sits upon.

3. 10% Coverage by Cooling Tower: At the 320 foot bore depth, this option, which only had a 5 ton cooling tower, ended up being so small that it was difficult to decrease the area needed for bore holes up-front installation cost of the still 5377 ft of ground heat exchanger. The majority of options below the 3200 were still within the $90,000 up front cost range.
4. 30% Coverage by Cooling Tower: Between this 15 ton and 10 ton cooling tower, the preliminary energy simulation of simply the cooling tower showed that the 15 ton cooling tower would consume about twice amount of energy as the 10 ton throughout the year. This is mostly due to the fact that a 15 ton cooling tower would need to be operating for two more months than the 10 ton cooling tower.
5. 20% Coverage by Cooling Tower: At the 320 ft depth, the 10 ton cooling tower would only need 13 boreholes and cover 3010 sqft. It utilizes a reasonable area of the site without causing other construction management problems that the 5 ton cooling tower would cause while consuming 45% less energy than the 15 tons cooling tower.

Table 29 shows the mechanical bore hole / cooling tower optimization used in conjunction with the construction management optimization to select the most cost and space effective hybrid geothermal system.

Table 29 Mechanical Bore Hole / Cooling Tower Optimization

VARIABLES	Load Coverage by Cooling Tower*			
	0%	10%	20%	30%
Borehole Length [ft]	6885	5377	4055	2919
# Boreholes	14	17	13	9
Borehole Depth [ft]	500	320	320	320
Cooling Tower Capacity [tons]	0	5	10	15
Cooling Tower Water Flow Rate [gpm]	-	13.1	26.1	39.3
Temperature Entering Ground Loop [F]	63.7	62.8	61.9	61.0
Annual Cooling Tower Consumption [kWh]	-	17.5	56.5	104.4
* Peak Cooling Load 605,880 [BTU/hr]				

The function of the cooling tower is to reject heat to the atmosphere by reducing the temperature of water circulated through ground loop. According to a preliminary Trane TRACE energy simulation of the 10 ton cooling tower hybrid geothermal system, the total heat rejected specifically by the auxiliary cooling tower throughout the year was calculated to be 3312 kBTU. The energy rejection profile resulted as expected, with cooling tower heat rejection only occurring in June through August.

Table 30 Heat Rejected to Auxiliary Cooling (10 ton cooling tower) [kBTU]

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
0	0	0	0	0	14	1067	1493	437	0	0	0	3312

6.10 Piping & Pump

When downsizing the geothermal system, the resulting ground loop heat exchanger length has decreased. Thus, the piping calculations were redone in order to size the pump off of the new corresponding head and flow. The same water pump that circulates the water throughout the geothermal wells is also used throughout the building to pump conditioned water up to the heat pump in the rooftop AHU. The longest run out to the furthest borehole of the new hybrid geothermal system is now a total of 730 feet, shown in Figure 26. This is a decrease of 210 feet from the previous full geothermal.

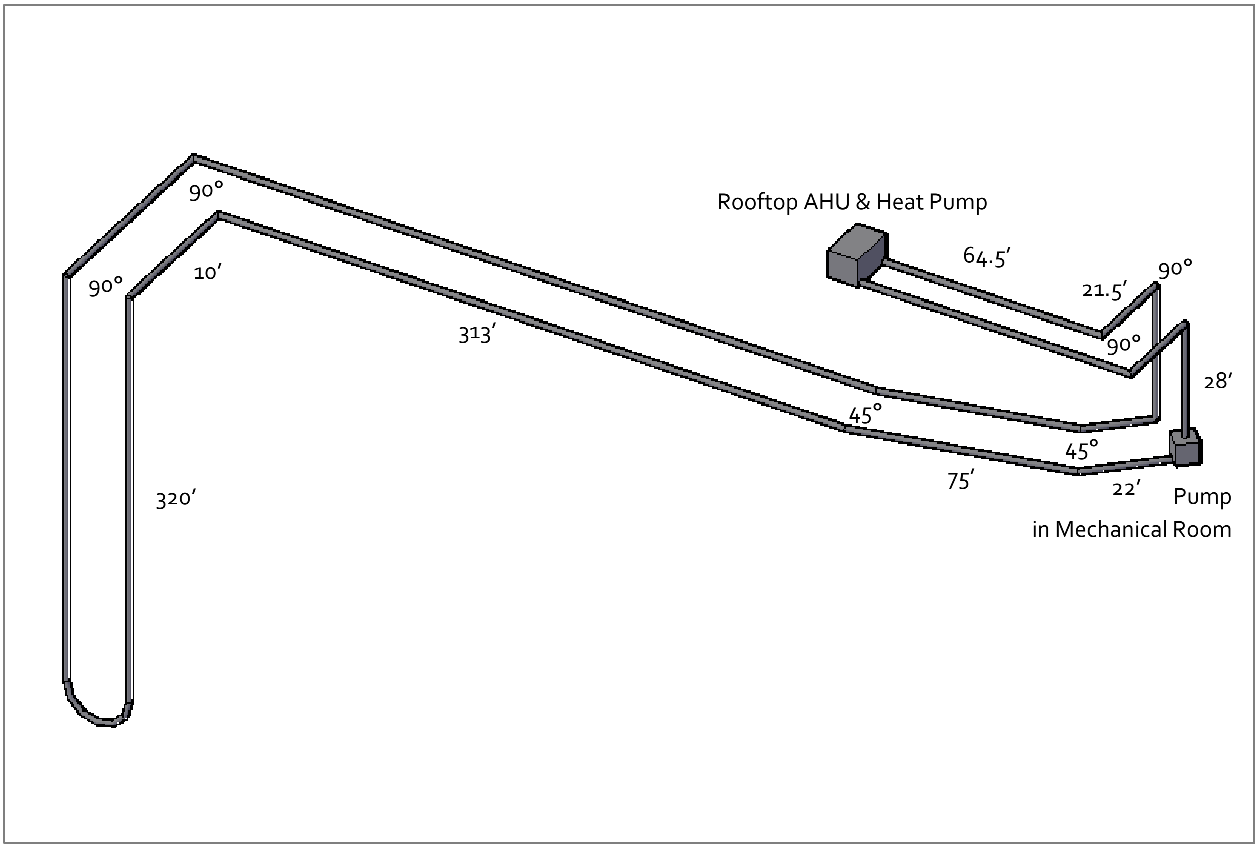


Figure 26 Piping Static Pressure Diagram

Note that isolation valves are not depicted in the figures but were not taken into account in the calculations. From the above diagram, system head pressure was calculated based on losses due to friction and fittings. Discussed in the schematics section above, the piping in the geothermal loops is 1-1/4" while the piping through the building is 3". During the ground loop sizing and controls analysis, the whole system flow was determined to be 151 gpm (based on 3 gpm/ton). The resulting total head for the entire system was calculated to be 34 feet. Full head loss and equivalent length calculations can be found in Appendix [A8] Head Loss Calculations.

The resulting pump (and backup pump) was selected using pump curves from Bell & Gossett. The resulting selected pump was a 4 base mounted, end suction Series 1510 2AC pumps. Table 31 shows the pump equipment details which have a pump speed of 1750 rpm and 67% efficiency.

Table 31 Pump Schedule

EQUIP. NO.	FLOW RATE [GPM]	TOTAL HEAD [ft]	MOTOR POWER [HP]	PUMP SPEED [RPM]	FLA [460V]	EFFICIENCY	MAKE, MODEL
P-1	152	34	2	1750	4	67%	Bell & Gossett, Series 1510 2AC
P-2	152	34	2	1750	4	67%	Bell & Gossett, Series 1510 2AC

6.11 Structural Concerns

Adding a cooling tower to the roof typically adds structural concerns of whether the currently designed beams and columns can withstand the adding weight. The spray cooled roof depth explains the removal of an intensive green roof. An intensive green roof adds a significant amount of weight to the roof. Removing it would reduce the overall distributed roof load. The cooling tower on the other hand would be a point load. CSL's roof is composed of a concrete slab on composite steel deck. Figure 27 shows the roof beam layout, the cooling tower location (in blue), and a cross section of the roof. Design drawings reveal that typical beam sizes across the roof are W12x19 and W24x62. According to the manufacturer spec sheet, the 10 ton cooling tower selected has an operating weight of only 442 lbs. This point load is nominal compared to the energy recovery unit beside it on the roof, which weighs 5,012 lbs. Thus, with the green roof being removed and the ERV/AHU being 91% more weight than the added cooling tower, the added cooling tower was not considered to be a structural concern.

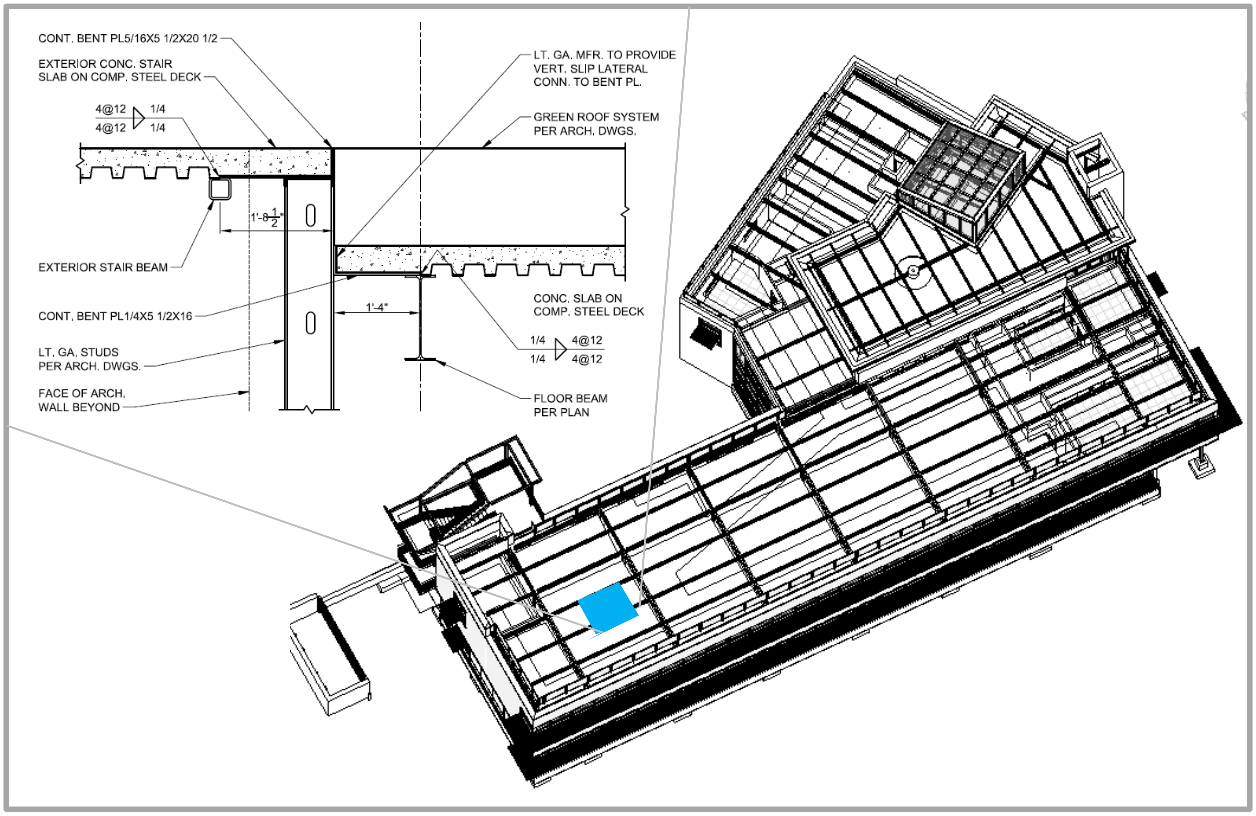


Figure 27 Roof Structural System

6.12 Mechanical Room

With the two mechanical depths, there are very few differences to the mechanical room located on the first floor. The majority of changes affected the roof layout and aesthetics. The spray cooled system includes a rainset control station and UV treatment pumping system. It also includes a dye solution tank for sanitizing graywater. Geothermal pipes are pumped to the mechanical room and then up to the air handling unit, just as in the existing full geothermal system. The water pumps are nearly the same size as the existing system but with different criteria highlighted earlier in this section. Figure 28 depicts the mechanical room equipment related to the spray cooled and hybrid geothermal depths.

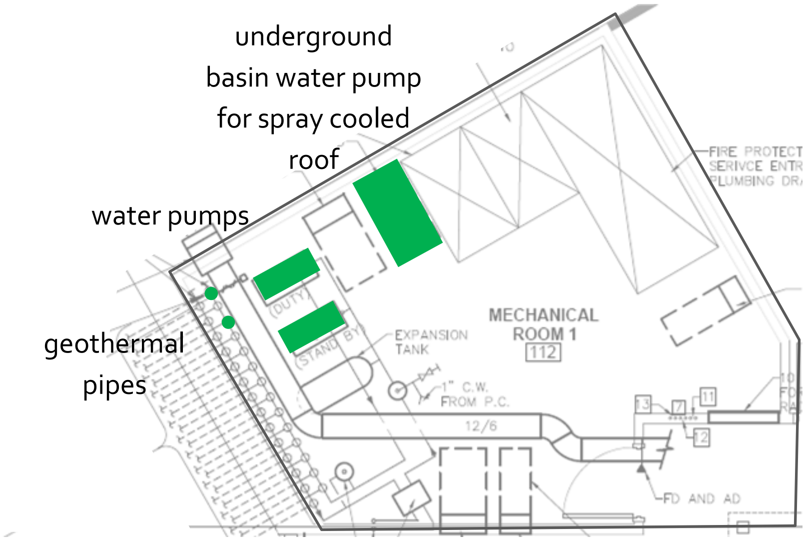


Figure 28 Mechanical Room Geothermal Pipes & Water Pumps

7.0 Construction Management Breadth: Bore Hole Optimization

7.1 Objective

The installation of a hybrid geothermal system will dramatically affect the construction time, installation cost, and equipment. In particular borehole depth and corresponding bore drilling costs will presumably be reduced due to the ground heat exchanger reduction. Borehole construction is a key design factor for geothermal heat pump systems. How it is done dramatically changes construction coordination as well as thermal performance. Borehole optimization will be analyzed and weighted to see if the proposed hybrid geothermal system is worthwhile to the owner.

7.2 Installation

Prior to construction, multiple site analyses must be done in order to identify the earth layers that need to be drilled through. This analysis was performed prior to building construction and begins with drilling a hole to the desired depth. Next, the ground loop will be installed by putting a weight on the 'U' bend and feeding it down to the designed depth. After, the hole is backfilled with a thermally enhanced bentonite grout to ensure maximum conductivity of heat between the ground and the liquid in the pipe.

7.3 Field Arrangement

Arrangement of the boreholes throughout the site is an important part of the installation process. The mechanical engineering and construction manager should collaboratively decide this based on cost, space, and time. The two different closed loop designs are horizontal and vertical, shown in Figure 29. The original geothermal design of the Center for Sustainable Landscapes was a closed loop system. For the redesign, a horizontal closed loop system was considered due to its lower trenching and well drilling costs. Further investigation of this original idea proved that the area requirement for the horizontal system would be too great for the building site (which sits on a hill). The rest of this breadth investigates the optimization of vertical boreholes at various depths.

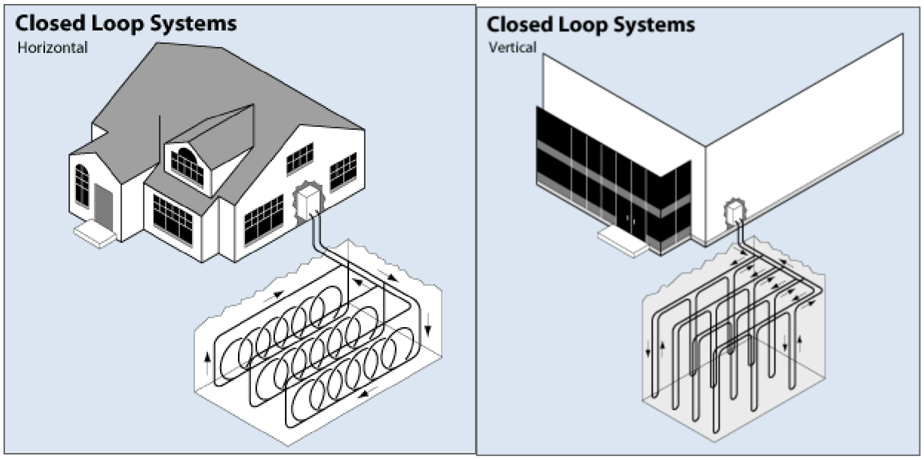
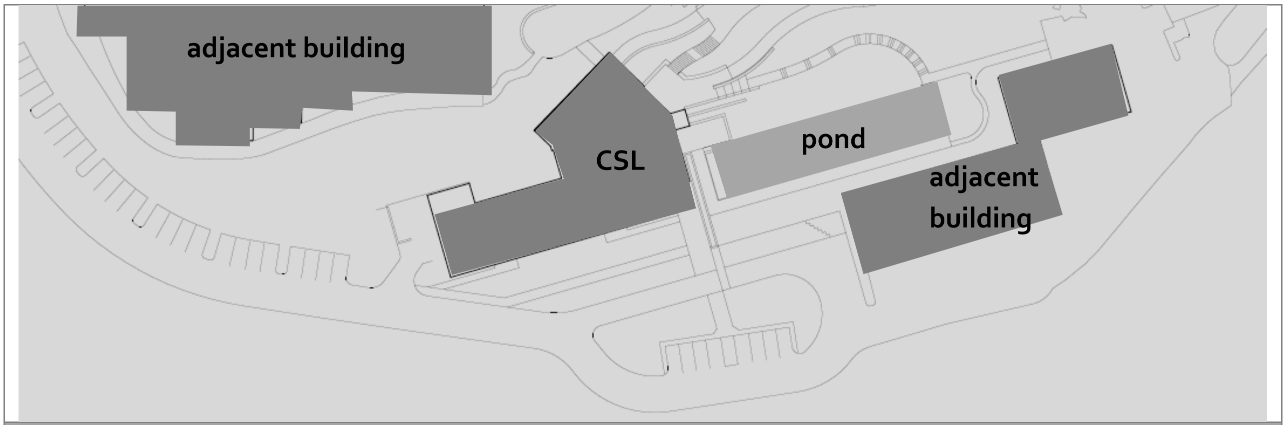


Figure 29 Closed Loop Geothermal System Arrangements

7.4 Site

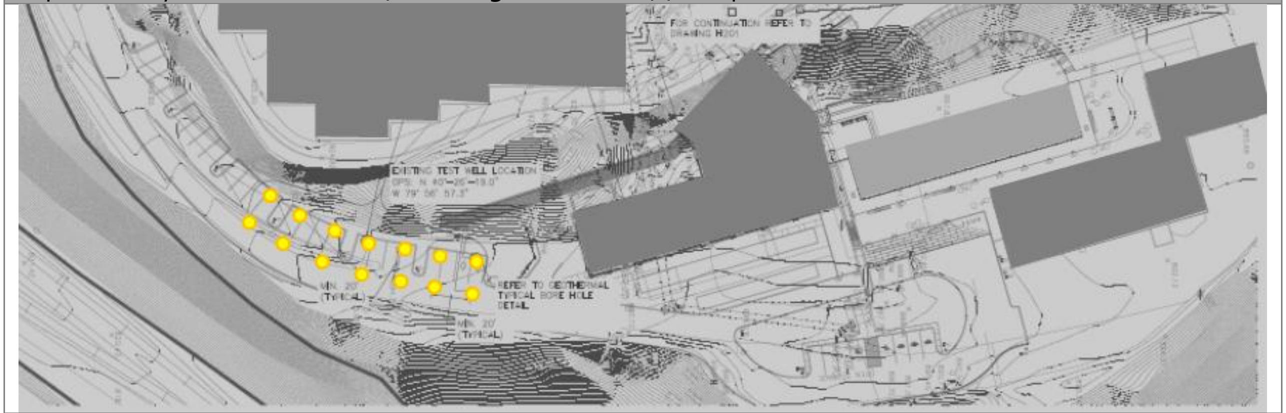
The site to which the Center for Sustainable Landscapes is located posed a difficult construction management problem. The building is built directly along a steep hill, making the area for a borehole field limited. Table 32 shows the steps taken in determining the ideal size and location for the borehole wells.

Table 32 Steps to Borefield Layout
1) SITE LAYOUT The diagram below shows a simplified version of CSL's site plan. Limiting factors in the borefield layout here are Phipps Tropical Rainforest building to the northwest and Phipps B&G Warehouse to the east. There is also an aesthetic water treatment pond directly east of the building. It would not be able to drill boreholes in these areas or directly surrounding them.



2) SITE TERRAIN & EXISTING BOREHOLES

The image below shows the terrain lines surrounding the building. Note that the northside of the building is built into an earth bank. The southside of the building, below the driveway, consists of a steep grade that extends hundreds of feet. Yellow dots show the 14 existing boreholes that are separated by 20 feet on center, covering an area of 2,400 sqft.



3) AREA POTENTIAL FOR THE GEOTHERMAL WELLS

The red line below outlines the site area that has the potential for geothermal wells to be drilled. This mostly covers the area of the entering driveway as well as the rain gardens and bioswales directly in front of the building. In total this area covers 50,715 square foot.

4) AREA PLOTS FOR BOREHOLES

Further analysis of this 50,715 sqft shows that that total area is not an adequate estimate of the maximum field potential. Since boreholes must be distanced 20 feet, the diagram below lays out 20' x 20' plots throughout the same area as above. 49 plots fit at 400 sqft, conservatively totaling 19,000 square feet of area potential (a much more reasonable estimate that compensates for the awkward shape compared to the previous estimate).

5) TOTAL MAX BOREHOLES & AREA per BORE

Boreholes can be placed at each of the corners of the above plots. Shown below in yellow, 80 total bores can fit on the constrained site. An area function that provides an estimation of space per bore is:

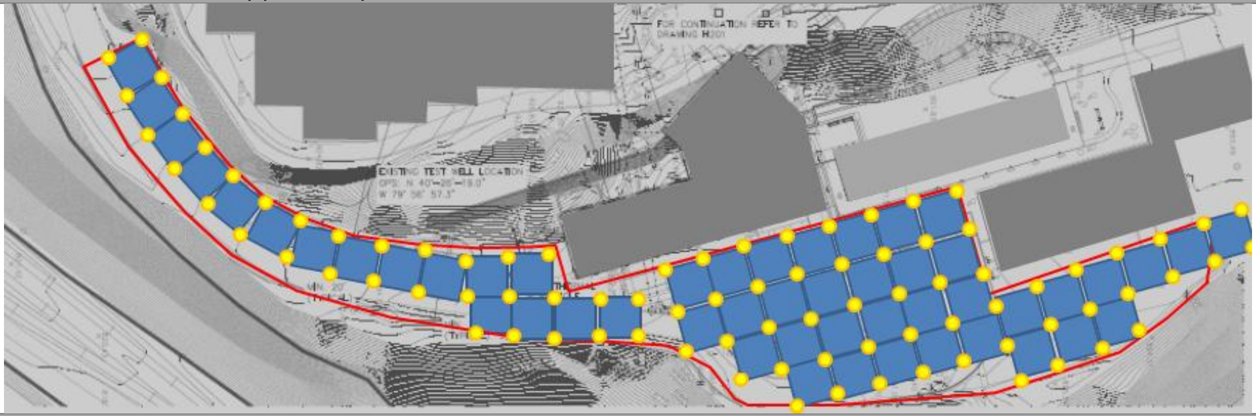
- Area/borehole = $\pi * r^2$, where r = 10 ft (by dividing the recommended spacing of 20 ft in half)
- Area/borehole = 314 sqft/bore (as an over estimate)

This estimation proved to be an over estimation for the site shape. Square footage for bore plots equals 19,000 sqft max divided by the 80 total bores, which equals 238 sqft per bore (specific to this site's shape). This approximation of one bore area is used later in this section to optimize various combinations of bore number and depth.

This step also reveals an interesting opportunity to which Phipps could have capitalized. Using the bore hole number and depth spreadsheet based on tonnage in reverse (discussed in section 6), adding this many bores at varying depths could provide extra cooling or heating capacity. Being a geothermal ground loop, the system performance is much more efficient than existing mechanical systems on the rest of Phipps' campus. Eighty bores could serve:

- 105 tons @ 500 depth
- 84 tons @ 320 depth
- 65 tons @ 220 depth

While CSL only needs approximately 50 tons of cooling and 35 tons of heating, capacity exceeding this could be routed to upper campus needs.



6) HYRBRID GEOTHERMAL FIELD SELECTION

Through mechanical and construction management borehole optimization later in this section, it will be determined that 13 boreholes were needed at a 320 ft depth. Theplot selected was a more compact area, closer to the mechanical room (in green below) than the original design. Bores and their 20' spacing covers a total area of 2,400 square feet.

7) GEOTHERMAL PIPING

The piping layout below for the resulting ground loop heat exchanger starts and ends in the green mechanical room. Piping (shown in yellow) routes 5 feet below the earth surface to the 13 bores (shown in orange) and then dive 320 feet into the ground. The maximum distance from the mechanical room to the furthest hole is 730 feet, which is 210 feet less than the original design. Discussed further in the section, this reduction in piping length and hole depth have resulted in a significant decrease in initial costs.

7.5 Drilling

Costs involved with drilling the boreholes include the mobilization excavator, support crew / equipment, and drill rig. Total drilling costs is function of the depth that the bore holes need to be drilled. This study compares three different augers of varying depth capabilities. The drill log for test well showed that the earth surrounding the Center for Sustainable Landscapes mostly consisted of brown shale & clay, red shale, gray sandy shale, dark gray shale, and red & gray shale. A different drill must be used at 225 feet when the earth consists of gray sand shale and yet another must be used at depths deeper than 325 feet which must penetrate sand rock. The full drill log test can be found in Appendix [A13] Borehole Test. Table 33 compares drill rig rental costs and daily drill output. Costs were based off of RS Means Mechanical Cost Data 2010 and then adjusted based on the actual cost of the full geothermal system installation costs. According to the contractor, it took 2 days per borehole at 510 depths. The resulting daily output for a drilling depth greater than 325 feet depth was assumed to be

250 ft of depth / day. This daily output is less than the estimates given by RS Means but are more accurate for the site under investigation. Lower borehole depth daily outputs were proportionally increased based on original estimates. These cost ranges will later be used to optimize the borehole selection.

Table 33 Drill Rig Rental & Daily Output

Bore Hole Depth (D) in [ft]	Drill Rig Rental Cost / Day	Typical Daily Output [ft of depth/day]	Adjusted Daily Output [ft of depth/day]
D < 225	$ 1,737.00	1800	500
225 < D < 325	$ 2,115.00	1200	333
D > 325	$ 2,417.00	900	250

For this range of borehole length, the contractor recommended Atlas Copco Cyclone Operating System drills. These drills focus on speed with safety and reducing manual labor. Their hydraulic system and compressor are coupled directly to the deck engine making power efficiency higher with fewer drive train components. Three drills that fit the need of the borehole drilling for this site include the T3W, T3WDH, or the TH60DH Water well drill. Figure 30 below depicts images of these drills. Appendix [A15] Borehole Drills shows the specifications of the drills.

Mid-weight, truck powered, hydraulic tophead drive drill rig

T3W

TH60

Figure 30 Drill Rig

7.6 Piping, Grouting, Labor, Cooling Tower

The piping for the hybrid geothermal installation consists of 1-1/4" high density polyethylene (HDPE) piping which is priced at $0.59 per foot based on PowerFlex Fence manufacturer. Connection methods for HDPE piping can either be butt welding or electro fusion welding. RS Means notes that every 40 ft of pipe must be welded together costing $25/weld and $55/day to rent the welding equipment. Grouting pricing was also based off of the full geothermal system, which took 1 day to grout 7 holes or 0.14 days per hole. Labor costs for hybrid geothermal variations were also based off of actual existing design costs. Labor for the existing full geothermal system installation required 2 people at $70 / hour.

Thus, Initial Labor = $70 / hour * 8 hours / day * 2 days/ hole * 14 holes * 2 people = $31,360.

The resulting labor function for optimization is $70 / hour * 8 hours / day * 2 people = $1120 / day.

Also included in total pricing was the up-front costs for the 5 ton, 10 ton, and 15 ton cooling towers ($1,185.43, $1,561.71, and $1,855.71 respectively).

7.7 Bore Hole Optimization

Borehole optimization combined 6 different variables including geothermal length, borehole depth, number of boreholes, space required, time, and costs. A custom built spreadsheet computer program was developed to balance all variables and graph outputs. Each variable, which included various ranges, was either an input or output of the optimization. Table 34 summarizes variables tracked, inputs, and post-optimization resulting output ranges.

Table 34 Bore Hole Optimization Variables, Inputs, Outputs

VARIABLE		UNIT	INPUT RANGES	RESULTING OUTPUT RANGES
1	Length	ft	6885, 5377, 4055, 2919 (for varying cooling tower capacities)	
2	Depth	ft	(Bores) 140 ft to 500 ft (Drills) D<225, 225<D<325, D>325	
3	# Bore Holes	#	6 to 49 (depending on length & depth)	
4	Area	SF	1,387 to 11,680 SF (linear with # bore holes & depth)	
5	Time	days		8 to 30 days
6	Cost	$		$28,541 to $119,194

A seventh variable taken into consideration during cooling tower selection was the annual cooling tower specific energy consumption.

The output graphs can be seen in Figures 31 to 34 below. Note the significant spiked in total costs as the drilling depth range increases. These drops are due to the rental costs and corresponding required days of rental of the three different types of augers being analyzed. Auger costs are lower at the lower depths because the earth is softer. Thus, the drill is more efficient and faster. The red point in Figure 31 shows the location of the existing full geothermal system. The red point in Figure 33 shows the point of the selected configuration (explained at the end of this section). Full tables of borehole optimization data can be found in Appendix [A16] Bore Hole Optimization Data.

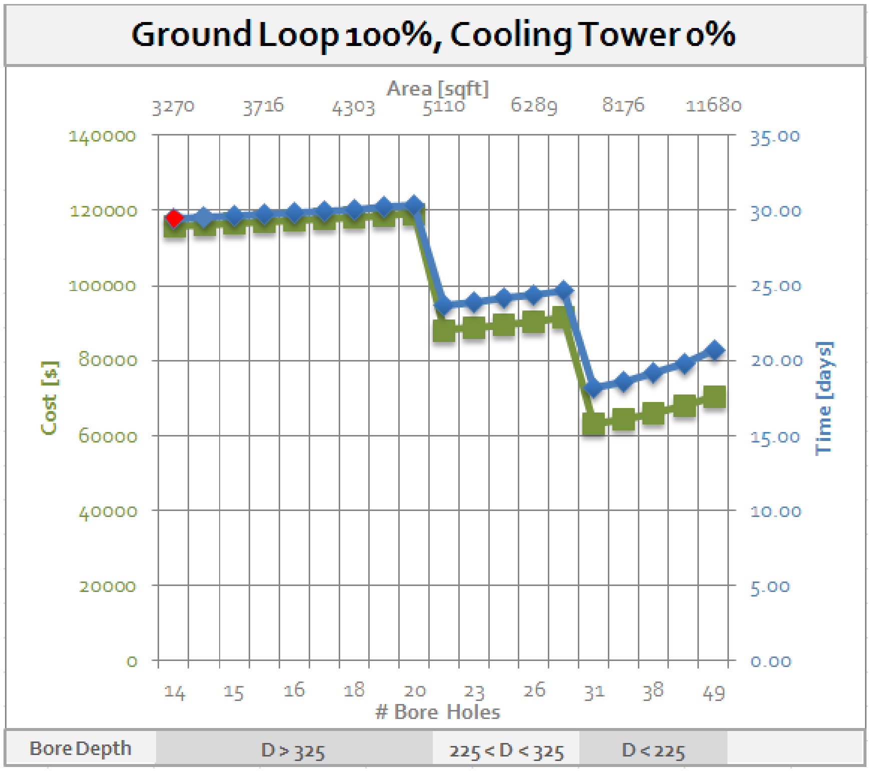


Figure 31 Bore Hole Optimization for Existing 6885 ft Full Geothermal System

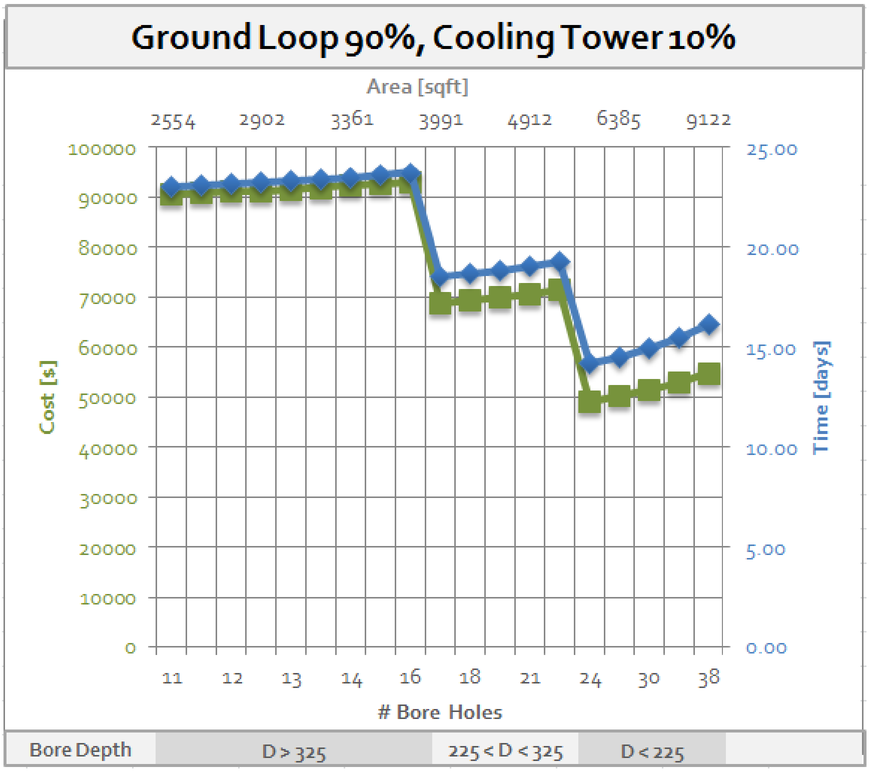


Figure 32 Bore Hole Optimization for 5377 ft Hybrid with 5 ton Cooling Tower

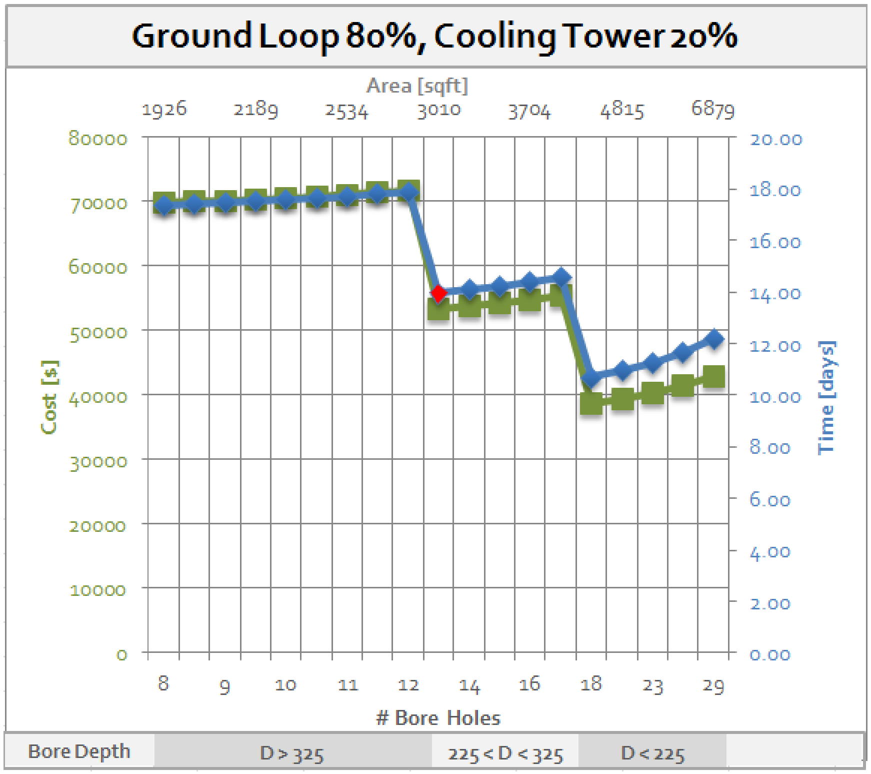


Figure 33 Bore Hole Optimization for 4055 ft Hybrid with 10 ton Cooling Tower

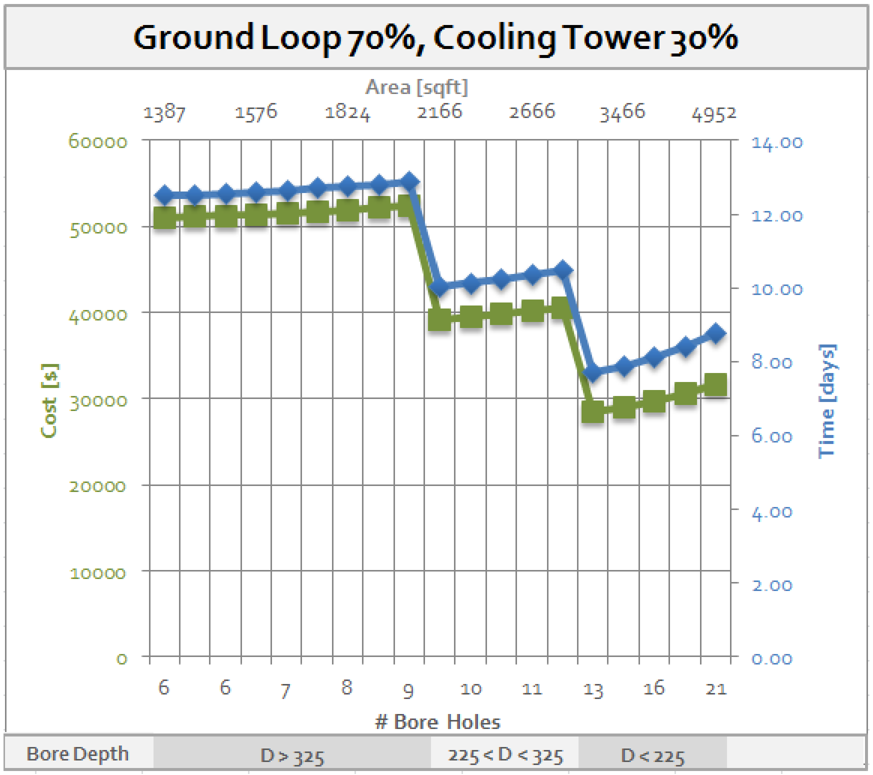


Figure 34 Bore Hole Optimization for 2919 ft Hybrid with 15 ton Cooling Tower

Table 35 shows a summary of the existing design and exact costs (obtained from the contractor) as well as the optimized selection for a cooling tower ranging from 5 tons to 15 tons. The 320 foot depth was chosen due to its balance between costs and space requirements among all configurations. This graphing format could be used in future research to optimize lengths of many different sizes and varying field shapes / arrangements. This methodology has effectively determined:

- Approximate Area Needed / Borehole
- Cost / Square Foot of Bores
- Cost / heat exchanger foot length

Table 35 Construction Management Bore Hole / Cooling Tower Optimization

VARIABLES	Load Coverage by Cooling Tower*			
	0%	10% (5 ton)	20% (10 ton)	30% (15 ton)
Borehole Length [ft]	6885	5377	4055	2919
# Boreholes	14	17	13	9
Borehole Depth [ft]	500	320	320	320
Days of Installation	30	18.5	14	10
Initial Cost [$]	$100,000	$68,741	$53,402	$39,173
Space Needed [sqft]	3270	3991	3010	2166
$ / Square Foot Bores	$30.50	$17.22	$17.74	$18.08
$ / Foot Length	$14.52	$12.70	$13.10	$13.42
* Peak Cooling Load 605,880 [BTU/hr]				

The Geothermal Loop at 80% load / Cooling Tower at 20% load / 10 ton capacity / 320 ft depth (which is displayed by the red point in Figure 33 / the red column in Table 35) was ultimately selected based on the following reasoning (which was previously discussed in section 6):

1. Depth & Cost: In order to decrease the initial costs, the depth of the boreholes had to be decreased below 325 feet to be able to use a cheaper auger. But, as depth of bores decreased, the space needed for boreholes increased.
2. Area: Space available for the boreholes was limited for CSL due to the steep hill that it site sits upon.
3. 10% Coverage by Cooling Tower: At the 320 foot bore depth, this option, which only had a 5 ton cooling tower, ended up being so small that it was difficult to decrease the area needed for bore holes up-front installation cost of the still 5377 ft of ground heat exchanger. The majority of options below the 3200 were still within the $90,000 up front cost range.
4. 30% Coverage by Cooling Tower: Between this 15 ton and 10 ton cooling tower, the preliminary energy simulation of simply the cooling tower showed that the 15 ton cooling tower would consume about twice amount of energy as the 10 ton throughout the year. This is mostly due to the fact that a 15 ton cooling tower would need to be operating for two more months than the 10 ton cooling tower.
5. 20% Coverage by Cooling Tower: At the 320 ft depth, the 10 ton cooling tower would only need 13 boreholes and covers 3010 sqft. It utilizes a reasonable area of the site without causing other construction management problems that the 5 ton cooling tower would cause while consuming 45% less energy than the 15 tons cooling tower.

8.0 Electrical Breadth: Direct Current Distribution

8.1 Objective

The Center for Sustainable Landscapes uses various energy producing tactics including photovoltaics as well as a wind turbine on site. Energy produced from both systems contributes to the net-zero design of the building. Yet, an area for improvement would be the elimination of the electric conversion from DC to AC. In order to accommodate the advanced controls system and eliminate PV inefficiency, it is proposed to study the alternative of a DC distribution system within the building. This was not to be considered as an alternative after completion but to be considered as an initial design consideration.

8.2 Background

In the 19th century, Thomas Edison developed the first power systems which were based off of direct current distribution. Shortly after, George Westinghouse developed the alternating current distribution counterpart. AC was considered superior to DC mainly because it enables efficient long-distance power transmission. Although AC remains the ruling standard transmission, most devices that consume electricity (computers, motors, electronics, and most anything with a battery) actually run on DC. At the same time, solar panels and wind turbines, natively produce DC power. With AC distribution, power is lost due to this DC-AC and AC-DC conversions between the DC Source (the grid or solar panels) and the DC-internal appliance (LEDs, etc.). With DC distribution, power is sent directly to the load. Heat coming off of laptop bricks is actually a waste product of an AC-DC conversion.

Offices are great candidates for DC distribution for many of the devices within are already DC powered. DC powered devices that the Center for Sustainable Landscapes will hold include:

- Computer and Information Technology Equipment
- Advanced energy management & control systems
- Electronic ballasts and drivers for LED Solid State lighting
- Adjustable speed drives for HVAC & pumping

In solar panels, DC power produced becomes AC in an inverter and DC again within device / appliance converters. Figure 35 shows AC Distribution (with an inverter) on the left and DC Distribution to the right. DC modules include the PV Array & mounting racks, a DC isolation switch, a PV generation motor, and the main electrical panel. From there, DC power can be sent to equipment.

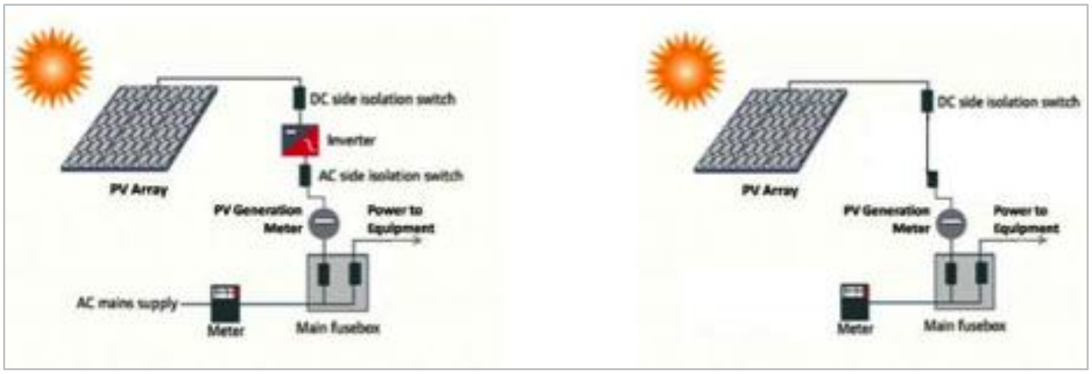


Figure 35 PV Schematic with AC vs. DC Distribution

Having to convert produced DC power to AC through the inverter creates added, unnecessary inefficiencies. Lawrence Berkeley's National Lab highlights losses through the DC/AC and AC/DC converter in Figure 36.

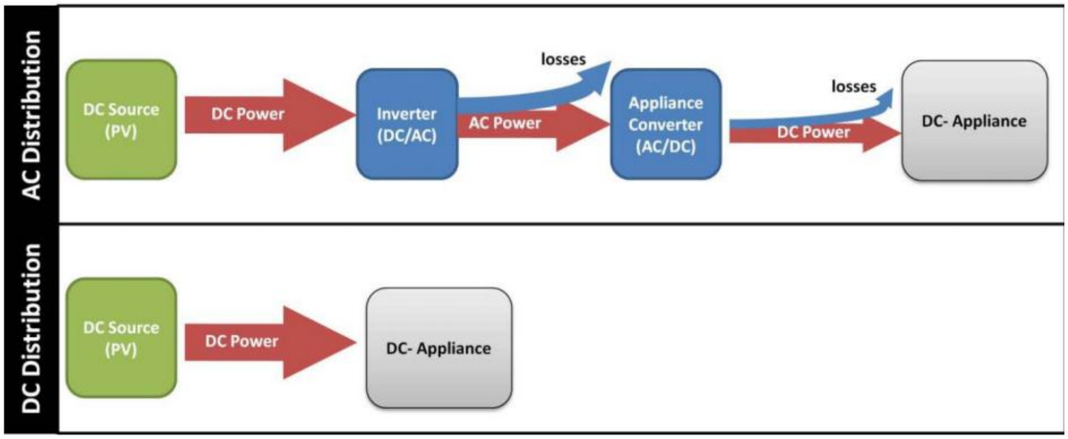


Figure 36 Energy Losses in AC Distribution

This redesign investigates the elimination of the inverters so that DC electricity can flow directly from photovoltaics to the fuse box and building equipment. To retrofit a building with a DC system can be costly, so to keep the feasibility in a positive light a DC system is being considered as part of the original renovation intentions.

8.3 Existing Photovoltaics

To contribute to its net-zero design, the Center for Sustainable Landscapes has had hundreds of photovoltaic panels installed at the very beginning of construction. The owner's goal was to produce energy throughout and after the construction process. For reference, Figure 37 shows the location of the solar panels in relation to the Center for Sustainable Landscapes. PVs are to be installed above the Phipps Events Hall to the direct northeast, the Phipps B&G Warehouse, and on the cusp of the hill below the warehouse. Electricity collected through the PVs is routed through the Center for Sustainable Landscapes (supporting electricity demands of the building as well as donating extra electricity back to the grid).

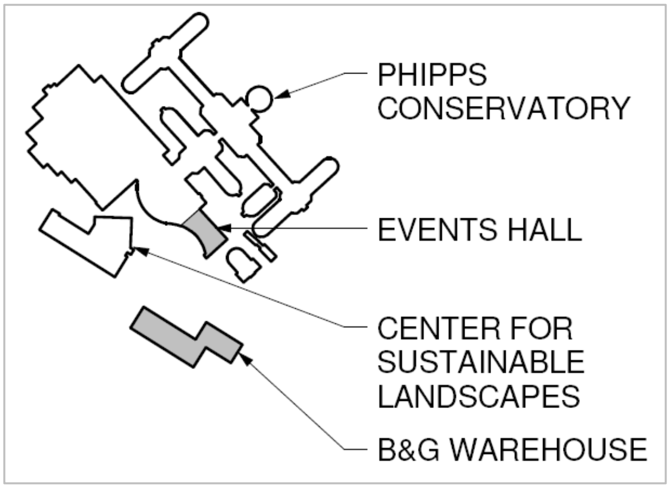
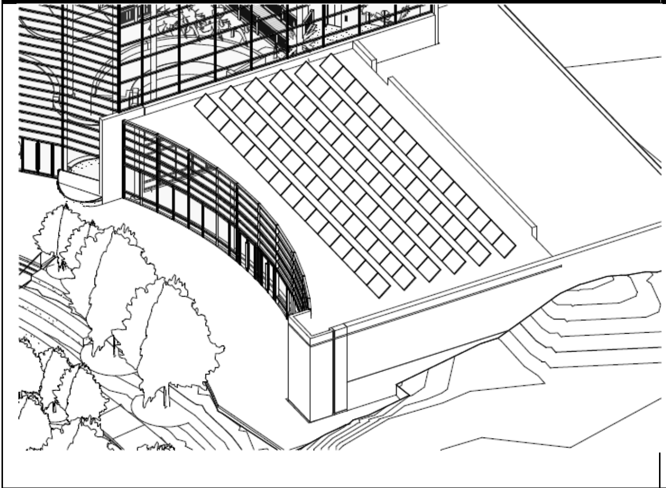
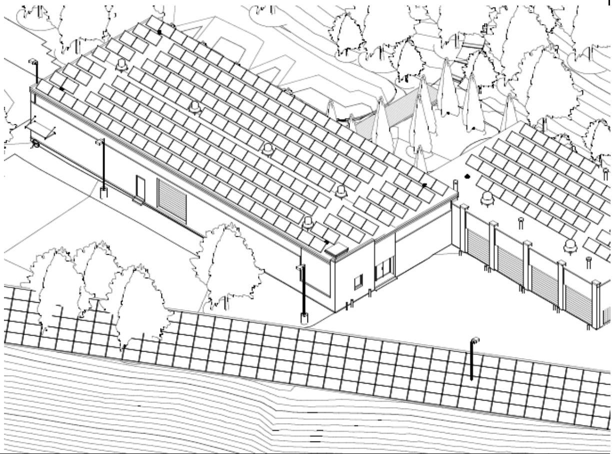


Figure 37 Photovoltaics Relative to CSL

Table 36 shows renderings, locations, number, and wattage of the solar panels. These 946 solar panels having a total rated voltage of 189.2 kW was the stimulus of this redesign. There is great potential in eliminating the DC/AC inverter in the process highlighted above in order to take advantage of all of the DC power produced. The following sections discuss the modeling of direct DC vs. DC/AC converted photovoltaics.

Table 36 Existing Photovoltaic Wattage

EVENTS HALL	B&G WAREHOUSE
	
368 solar panels @ 200W	578 solar panels @ 200W
189,200 total rated wattage	

8.4 Model: PVWatts

The National Renewable Energy Laboratory (NREL) developed a calculator that determines the energy production and costs savings of grid connected photovoltaic energy systems. The calculator, named PVWatts, creates an hour-by hour performance simulation that provides estimated monthly and annual energy production in kilowatts and energy value. The direct current energy for each hour is calculated from the PV system DC rating and the incident solar radiation and then corrected for the PV cell temperature. The AC energy is calculated by multiplying the DC energy by the overall DC-to-AC derate factor and adjusting for inverter inefficiency as a function of load.

NREL developed a Photovoltaic Solar Resource potential map for the same flat-plate technology as on CSL. The map is shown in Figure 38. Pittsburgh sits in the yellow to green region, which is in the mid potential range around 4.5 kWh/m2/day. Although there are other areas of the US with greater solar potential, the owner requested that solar panels be installed on site.

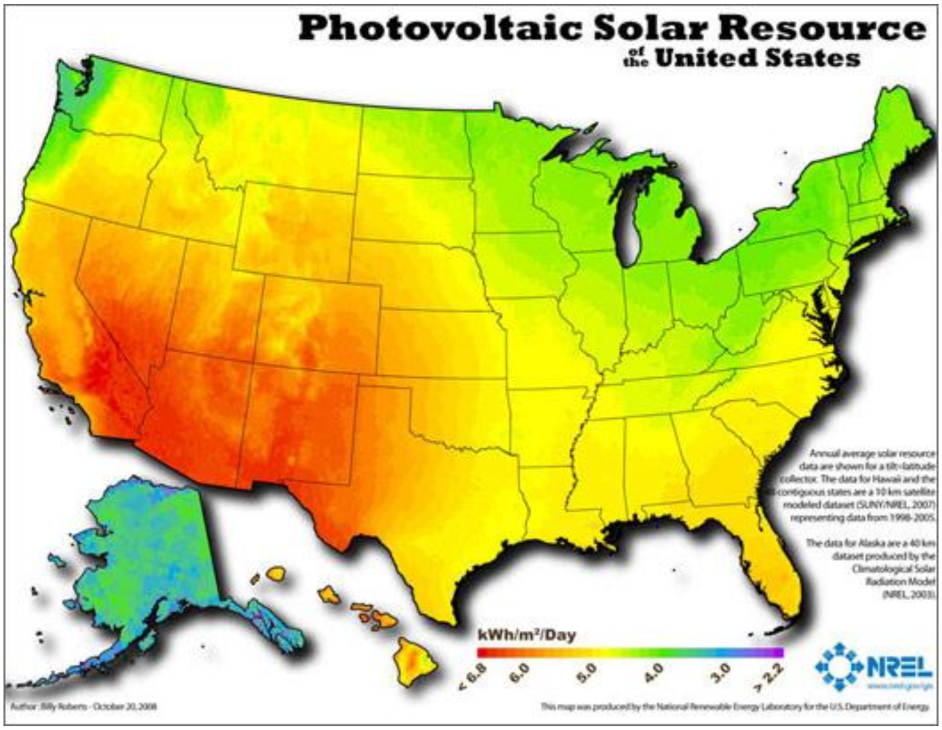


Figure 38 NREL Photovoltaic Solar Resource Map

8.5 DC-to-AC Derate Factor

The overall DC-to-AC derate factor accounts for losses from the DC nameplate power rating and is the mathematical product of the derate factors for the components of the PV system. The default component derate factors used by the PVWatts calculator and their ranges are listed in the table below.

Table 37 Derate Factors for AC Power Rating at STC

COMPONENT DERATE COMPONENTS	FACTOR	RANGE

PV module nameplate DC rating	0.95	0.80–1.05
Inverter and transformer	0.92	0.88–0.98
Mismatch	0.98	0.97–0.995
Diodes and connections	0.995	0.99–0.997
DC wiring	0.98	0.97–0.99
AC wiring	0.99	0.98–0.993
Soiling	0.95	0.30–0.995
System availability	0.98	0.00–0.995
Shading	1.00	0.00–1.00
Sun-tracking	1.00	0.95–1.00
Age	1.00	0.70–1.00
Overall DC-to-AC derate factor	0.77	0.09999–0.96001

The overall DC-to-AC derate factor is calculated by multiplying the component derate factors.

- Overall DC to AC derate factor

    = 0.95 x 0.92 x 0.98 x 0.995 x 0.98 x 0.99 x 0.95 x 0.98 x 1.00 x 1.00 x 1.00
    = 0.77

After adding the DC Rating of the PV array for CSL and calculating the DC-to-AC Derate factor, then inputting the location information as well as the cost rate for Duquesne Light Electricity, the simulation could be run. For the DC Energy simulation, the derate factor was assumed to be 0.94 since only the PV module nameplate DC rating and DC wiring apply. **Table 38** summarizes inputs for the PVWatts simulation.

Table 38 Building Inputs for PV Watts Simulation

STATION IDENTIFICATION	
State	Pennsylvania
Latitude	40.3 ° N
Longitude	80.2 ° W
PV SYSTEM SPECIFICATIONS	
DC Rating	189.2 kW
DC to AC Derate Factor	0.770
AC Rating	145.7 kW
Array Type	Fixed Tilt
Array Tilt	40.3 °
Array Azimuth	180.0 °
ENERGY SPECIFICATIONS	
Cost of Duquesne Light Electricity	0.1236 cents/kWh

Results from the simulation show the energy and value potential of collecting using DC vs. AC. The energy amount mostly represents the electricity wasted in DC-AC and AC-DC conversions. Table 39 shows that annually, CSL could produce 53,966 kWh more with DC. This increase in energy production results in $4,390.67 more money that Phipps could be reimbursed yearly by Duquesne Light electricity.

Overall, installing a DC distribution system to supplement the hundreds of solar photovoltaics on site would be a cost-generating alternative to the traditional and existing AC distribution.

Table 39 PV Energy Production AC vs. DC

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	DC Energy (kWh)	AC Energy Value ($)	DC Energy Value ($)
JAN	2.55	11781	14822	958.50	1205.92
FEB	3.27	13568	17011	1103.89	1384.01
MAR	4.55	20165	25278	1640.62	2056.62
APR	5.06	21154	26500	1721.09	2156.04
MAY	5.15	21381	26812	1739.56	2181.42
JUNE	5.43	21232	26625	1727.44	2166.21
JULY	5.31	21323	26763	1734.84	2177.44
AUG	5.36	21687	27179	1764.45	2211.28
SEPT	4.93	19592	24559	1594.01	1998.12
OCT	4.15	17689	22165	1439.18	1803.34
NOV	2.80	11830	14922	962.49	1214.05
DEC	2.37	10201	12932	829.95	1052.15
Year	4.25	211603	265569	17216.02	21606.69
Difference *with DC*		+ 53,966 kWh *more energy produced*		+ $4,390.67 *added cash value*	

8.6 DC Equipment

As direct current distribution would allow the photovoltaic system on site to produce more energy, it would also allow certain equipment throughout the building to consume less. Much of the electrical and mechanical equipment is already DC-internal and currently uses AC-DC converters at their input stage. Motors, compressors, pumps, and fans have been proven to be most efficient in their DC-internal form (Garbesi et al 2011). This DC microgrid within the building would consist of safe, low voltage 24V DC power at the device interface. According to a 2011 study by Lawrence Berkeley National Laboratory, the percentage of energy savings of DC compared to an AC power source can be broken down by function. Table 40 shows the existing AC technology within the Center for Sustainable Landscapes, the new DC-internal technology replacement, and the corresponding energy savings. Energy savings of DC compared to an AC power source are significant.

Table 40 Equipment Savings with Direct Current

Function	Existing AC Technology	Location	New DC-internal Technology	Energy Savings Compared to AC Power Source
Lighting	Fluorescent & LED	Offices & Classrooms	Electronic Fluorescent & LED	73%

Heating	Electric Resistance Heat Pump	Roof	Heat Pump operated by BDCPM (for space & water)	50%
Cooling	Induction motor, single speed compressor, pumps, & UFAD fans	Mechanical Room	BDCPM operating variable speed	30-50% (VSD)
Miscellaneous	Water Pumps, Induction Motor	Mechanical Room, Underground Basin	BDCPM	5-15%
*BDCPM = Brushless DC permanent magnet motor, *VSD = Variable Speed Drive				

9.0 Energy

An overall energy analysis comparing the mechanical system redesigns with the baseline (or existing system) provides a way to gauge whether it would be beneficial from the owner's perspective to pursue them. As in any energy analysis, these values are estimates and accuracy is affected by the software used.

9.1 Spray Cooled Roof

Due to the nature of modeling the spray cooled roof, the same modeling program was not able to be used for the existing and redesign. No single software provided enough functionality to manipulate the roof properties the amount of detail needed. Thus, both the existing green roof and spray cooled roof were compared to a dark roof as a baseline. First comparing each of them to a dark roof was a way to then compare them directly.

The CLTD/CLF method was used to model the spray cooled roof. Shown in Table 41, this method reveals that the evaporative mist cooling reduces the usage by 4540 kWh annually in comparison to a dark roof.

Table 41 Energy Usage Reduction by Spray Cooling

MONTH	MONTHLY AVERAGE CLTD (c)	USAGE per MONTH [kWh]	PEAK MONTHLY CLTD	DEMAND [kW]
APR	50	649	66	3
MAY	54	701	69	3
JUNE	55	714	70	3
JULY	54	701	69	3
AUG	50	649	66	3
SEPT	46	597	61	3
OCT	41	529	55	3
TOTAL		**4540**		**20**

The Green Roof Calculator simulated the existing green roof in comparison to a dark roof, showing that the savings annually would total approximately 1213.7 kWh.

Figure 39 depicts these savings with respect to a dark roof. This shows that the spray cooling throughout the summer months is predicted to save an average of 73% more energy than the green roof. A reason for this difference is likely due to the green roof only covering 48% of the roof. The spray cooled roof on the other hand was designed to evaporatively cool 85% of the surface area. A point not captured through this output and graphic is the winter months. Although the energy savings throughout the summer for evaporative cooling seems to be a more consistent way of cooling, the green roof provides an added R-value to insulate the building heat during the winter. The spray cooling system is rendered inactive throughout October through February in Pittsburgh, limiting its benefits to only six months out of the year.

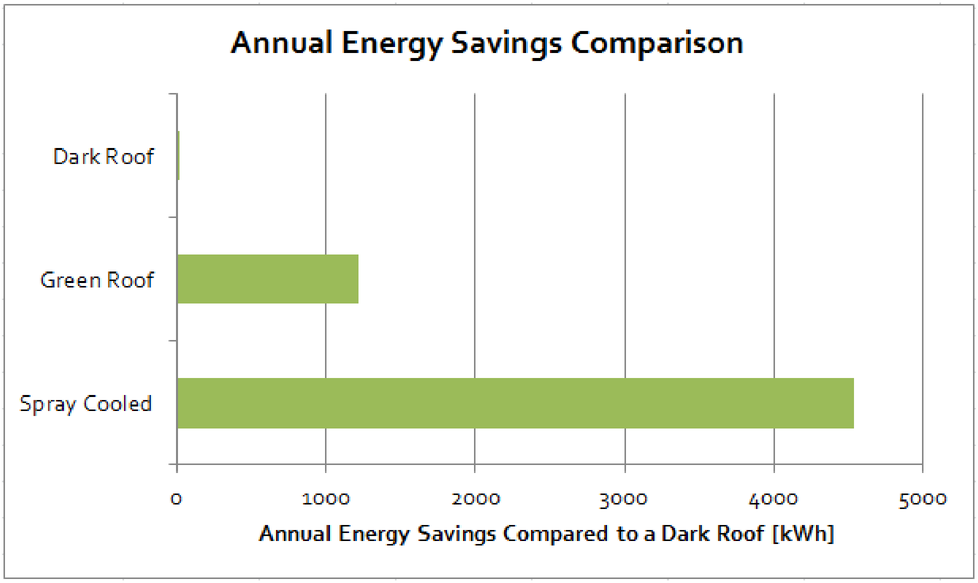


Figure 39 Roof Cooling Energy Savings Comparison

9.2 Hybrid Geothermal

Both the full geothermal and hybrid geothermal were able to be modeled in the same program, Trane TRACE 700. The goal of adding the hybrid geothermal was to significantly reduce the up-front costs while only slightly increasing the energy consumption throughout the year. Table 42 shows that the energy consumption (which only consists of electricity) totaled to be 144,735 kWh for the 20% reduced full geothermal system. This size hybrid geothermal system only consumed 2,571 kWh or 7,855 kBTU per year more than the full geothermal. Overall, this is only a very slight increase as intended with the redesign.

Table 42 Energy Consumption by Subsystem

	Electrical Consumption [kWh]		Total Building Energy [kBTU/yr]		Total Source Energy [kBTU/yr]	
	EXISTING	REDESIGN	EXISTING	REDESIGN	EXISTING	REDESIGN
Heating	5230	4983	17849	17007	53551	51026
Cooling	15017	16263	515253	55505	153774	166532
Supply Fans	16197	16272	55280	55537	165855	166627
Pumps & Equipment	31920	33148	108183	113132	326867	339431
Lighting	40141	40141	137000	137000	411041	411041
Receptacles	33660	33660	114880	114880	344675	344675
TOTAL	**142164**	**144735**	**485206**	**493061**	**1445762**	**1479332**
DIFFERENCE	**+2,571**		**+7,855**		**+33,570**	

Figure 40 depicts subsystem energy consumption of the hybrid geothermal system. Just as in the original design, the total heating and cooling is much less than a more traditional building. This is mostly due to the geothermal system eliminating the need for inefficient fans. The cooling is noticeably larger than the existing design. This was expected due to the induced draft counterflow cooling tower added.   Still, the heating consumption seems low for a typical Pittsburgh office. An explanation for this may be CSL's high performance building envelope and roof at an R-value of 43. Pumps & equipment, lighting, and receptacles remained the same as the existing design.

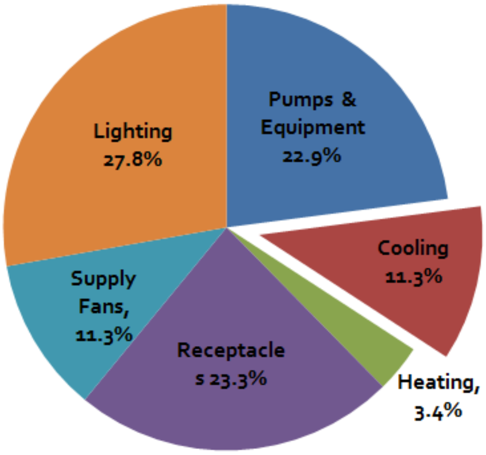


Figure 40 Subsystem Energy Consumption

Table 43 compares the monthly energy consumption of the existing vs. redesign. Summer months have a noticeably higher energy consumption, which was expected due to the cooling tower activating during this time.

Table 43 Monthly Energy Consumption [kWh]

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
Existing 100% Full GSHP												
10973	9185	11437	10965	12806	13959	14224	14759	11726	11707	10153	10271	142165
Redesign with 80% GSHP, 20% Cooling Tower												
10936	9214	11615	11184	13162	14340	14466	15205	12304	11930	10193	10186	144735

9.3 Pollution

The hybrid geothermal system redesign slightly increases annual emissions. Emissions profiles associated with any on-site combustion system [such as electricity] are desirable in order to estimate a building's carbon footprint. The emission factors were taken from tables found in the National Renewable Energy Laboratory (NREL). As is shown in Table 44, CO_2 pollution is expected to be the major product of electric utilization with 214,208 lbs/year, while Lead, Mercury, and N_2O pollutants emit the least annually. This also reveals that compared to the original design, the hybrid geothermal would produce 4,302 lbs more pollutants per year.

Table 44 Emissions from Delivered Electricity

POLLUTANT	Emission Factor for PA [lb/kWh]	Electric Consumption [kWh/year]	Electric Total [lbs/year]
CO_2	1.48E+00	144,735	214,208
CH_4	2.70E-03	144,735	391
N_2O	3.22E-05	144,735	5
NO_x	2.91E-03	144,735	421
Sox	8.88E-03	144,735	1,285
CO	6.01E-04	144,735	87
TNMOC	5.46E-05	144,735	8
Lead	1.17E-07	144,735	0
Mercury	2.70E-08	144,735	0
PM10	7.14E-05	144,735	10
Solid Waste	1.78E-01	144,735	25,763
CO_2	1.48E+00	144,735	214,208
TOTAL			**242,178**
DIFFERENCE			**+ 4,302 lbs/year** more than the existing design

10.0 Costs

While operating costs were lower than a typical building, the initial costs of the existing design of CSL were much higher than most. The owner was willing to spend much more money upfront in order to create the most energy efficient building throughout its life. Reducing the initial cost of the systems was the main driver of the mechanical system redesign.

10.1 Initial Costs

Spray Cooled Roof vs. Green Roof

Most green roofs cost anywhere between $8 - $25 per square foot. The intensive type green roof that is installed on CSL is typically on the higher end due to plant complexity and maintenance requirements. After analyzing the assembly for the green roof, received from the contractor, it was found that CSL's green roof cost a total of $114,439 equaling $20 per square foot of the entire roof. The total initial cost breakdown for the green roof is shown in Table 45. A large portion of the green roof costs was due to the aesthetic lightweight concrete pavers that were to surround the green roof as pathways for building occupants. Overall, choosing a system that would be cheaper than this was not very difficult.

Table 45 Green Roof Initial Costs

ITEM	COST
Flashing Flex Flash F	1878
Flashing Flex Flash UN reinforcing	7321
Gardendrain GR30	10476
Hydrodrain 300 Panels	2337
Hydroflex 30	3559
Lite Top Soil	8956
Lite Top Aggregate	883
Lite Top Growing Media / Manufactured Growing Media	8956
Metal Edge Restraint Soil Retainer	9334
Root Stop Root Barrier	8860
Surface Conditioner for Vegetated Roof	449
Walkway Pavers & Adjustable Pedestal	34011
Holover Pavers	24300
Monolithic Membrane	6919
Adhesives Sealant	5632
System Filter	2568
Aluminum Flat Sheets	5000
TOTAL	**$141,439**

A general estimate of the installation costs for the sprinkool spray cooling system was provided on the vendor website of being $1.55 / sqft. For the 5645.5 SF covered, the lightweight and simple spray cooled system would only cost $8750.53. This is an initial savings of $132,688.47 by installing the spray cooled roof as opposed to the green roof.

Table 46 Spray Cooling System Installation Costs

ITEM	COST	CSL SPECIFICS	COSTS
Sprikool Roof Spray System (Piping & Controls)	$1.55 / sqft	Installed onto 85% of the Roof (5645.5 SF)	$8,750.53
Above-Grade Storage Tank	$1500 per 1000 gallons	Unground Water Basin Already Exists	0
Connecting Pipe	$16 per lineal foot drain to coil	Connecting Pipe to Roof Already Exists due to Green Roof	0

Hybrid Geothermal vs. Full Geothermal Comparison

Although the full geothermal system had an highly efficient performance, it was complemented with an extremely high price tag. While the hybrid geothermal redesign added costs through the cooling tower equipment, it greatly reduced costs through optimizing its installation costs. Shown in Table 47, the hybrid geothermal system overall would save $46,598.14 in upfront costs. An additional estimate of the individual components that made up the geothermal system can be found in Appendix [A15].

Table 47 Initial Costs Comparison of Geothermal Systems

	Full Geothermal	Hybrid Geothermal
Drilling	$ 61,434.21	$ 29,506.87
Piping	$ 8,613.46	$ 5,694.14
Grouting	$ 1,484.67	$ 1,013.75
Labor	$ 28,467.66	$ 15,625.39
Cooling Tower	$ -	$ 1,561.71
TOTAL	**$ 100,000.00**	**$ 53,401.86**
DIFFERENCE	**- $46,598.14**	

10.2 Operating Costs

The monthly operating costs for a full year for the Center for Sustainable Landscapes can be viewed in Table 48 and Figure 41 below. The total energy consumption and energy costs were expected to increase with the addition of a cooling tower in the hybrid geothermal, but were hoped to not significantly change the monthly and annual costs for the building. Through the energy simulation, this was proven to be true, with only a 3% increase in annual energy costs. This small increase in operating costs makes the choice to select the redesign from strictly an energy consumption point of view an easy choice.

Table 48 Monthly Utility Costs [Electricity & Water]

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
Existing Full GSHP & Green Roof												
1097	919	1144	1097	1281	1396	1422	1476	1173	1171	1015	1027	$14,218.00
Redesign with Cooling Tower & Spray Cooling												
1093	922	1162	1134	1332	1450	1463	1536	1245	1206	1019	1019	$14,580.97

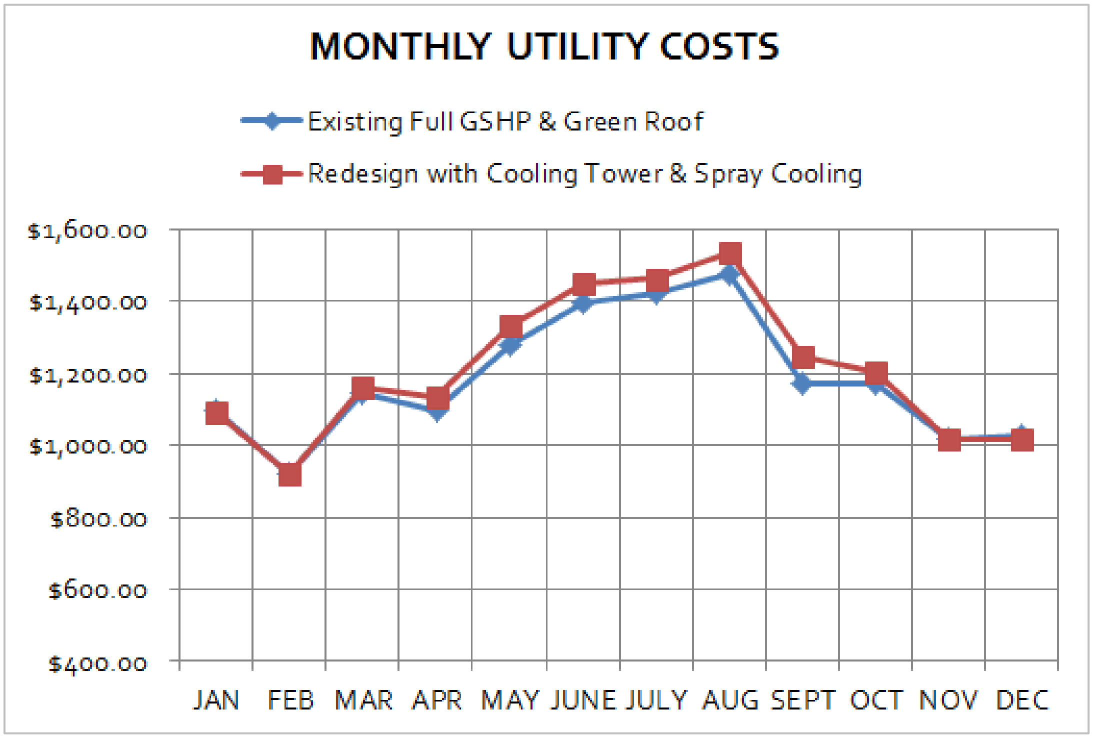


Figure 41 Monthly Utility Costs for Redesign

10.3 Life Cycle Analysis

Spray Cooled

The payback for the spray cooled system was calculated to be about 15 cooling seasons (or years) below in Table 49. The Green Roof on the other hand, which costs $114,439 and saves only $181.18 in energy costs annually, has a payback period of hundreds of years away from installation. The incredibly high cost of the green roof does not seem economically rational for its nominal energy savings.

Table 49 Spray Cooled Roof Payback Analysis	
Cost of Implementation	
Initial Cost of Sprinkool Roof Spray System	$8,750.53 ($1.55 /sqft)
Operating Cost Per Season	
Water Usage Annually	$105.92
Net Savings per Season	
Annual Savings	$702.54
Less Annual Costs	$105.92
Net Annual Savings	$596.62
Payback	
Cost of Implementation / Net Savings per Season	14.6 seasons

Hybrid Geothermal

Compared to the full geothermal system, the hybrid geothermal costs $46,598.14 less in up-front costs. The energy simulation shows that the addition of the 10 ton cooling tower in this hybrid geothermal system (which would only operate only in June, July, August, and September) would only cost $362.97 more per year. Thus, it would take approximately 120 years for the additional energy costs of the hybrid geothermal system to equal the difference saved in up-front costs. This amount of time seems larger than expected. This may be due to an energy model simulation issue that was a result of how Trane TRACE models cooling tower.

11.0 Conclusions

Through the initial energy analysis, the Center for Sustainable Landscapes proved to have a highly energy efficient performance. It was simulated to consume 19,926 BTU/SF annually for electricity. Compared to other buildings of its size, function, and location from an Energy Information Administration study, CSL consumed an average of 75% less energy. But, increased energy performance comes with a cost. The budget for this high performance was much higher than typical building projects. The main goal of the redesign was to decrease initial costs while maintaining similar energy performance. The evaluation for the redesign was conducted using various criteria and grades A through F.

Spray Cooled Roof vs. Green Roof

The green roof was one of many different added "green" components of the original CSL design that came with a high price tag. The following table summarizes the comparison of results.

EXISTING: Green Roof	CRITERIA	REDESIGN: Spray Cooled
B For providing nominal energy savings throughout the summer, yet adding an additional layer of insulation in the winter.	Energy	**A** For saving a total of 4540 kWh throughout the summer months by maximizing cooling coverage to 85% of the roof.
D For costing $114, 439 for the complete green roof system.	Cost	**A** For only costing $8,750 to install, 94% less than the green roof.
A For creating a pleasant roof space for occupants to enjoy	Aesthetics	**C** For having a piping array in place of a green space

Recommendation: If energy consumption is the only criteria the owner is interested in, then the spray cooled roof is the best option. But, from the owner's perspective, who is selling the project as a "green model for the future," aesthetics is likely the most important criteria, making the initial investment worth it.

Hyrbid Geothermal vs. Full Geothermal

Unlike most building redesigns, where the main goal is to decrease energy, changing a full geothermal to a hybrid was basically taking an opposite approach. Since the performance of the building would be difficult to improve beyond its existing system, this investigated slightly increasing the energy consumption while dramatically decreasing costs. Results shows that the best option for this would be to downsize the ground loop by 20% and install a 10 ton cooling tower. The following table summarizes the comparison.

EXISTING: Full Geothermal	CRITERIA	REDESIGN: Hybrid Geothermal
A For only consuming $14,218 per year in electricity	Energy	**B** For causing an increase of only a few hundred dollars more annually
D For costing $100,000 in installation fees	Cost	**A** For reducing initial costs by nearly $47,000

Recommendation: Although energy consumption slightly increases, the savings in initial costs make the hybrid geothermal more economically sensible compared to the high price of the existing geothermal system.

12.0 Acknowledgements

I would like to thank the following people and companies for helping me throughout my senior thesis semesters (Fall 2011 – Spring 2012).

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- Dr. William Bahnfleth
- Dr. Jelena Srebric
- AE Students from the Class of 2012

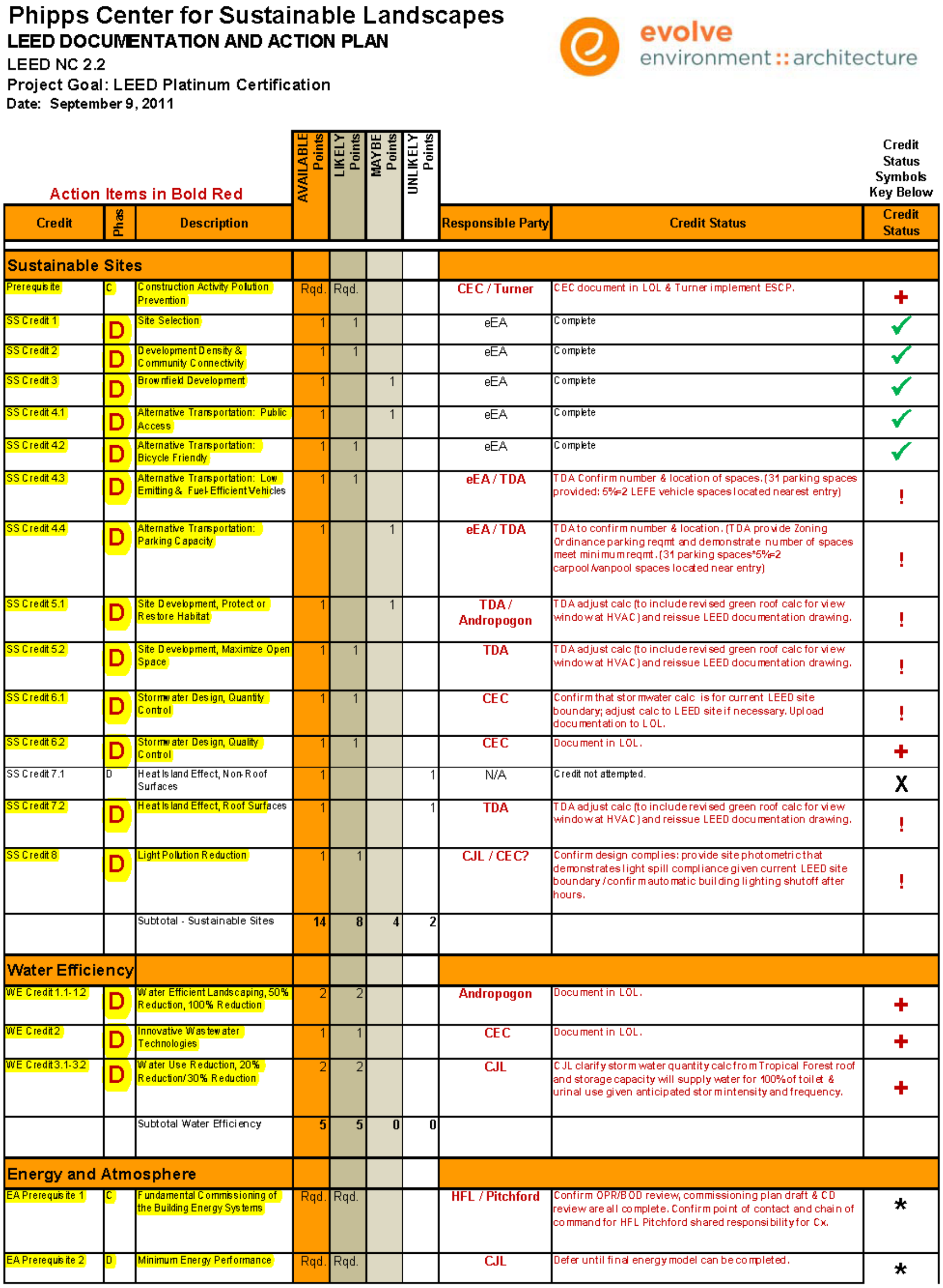
CJL Engineering
- Craig Duda

Sprinkool Systems
- Jim & Sean Smith

Thank you to all of my friends and family for providing support and confidence during the Spring 2012 semester.

13.0 Appendix

[A1] LEED Scorecard



Phipps Center for Sustainable Landscapes
LEED DOCUMENTATION AND ACTION PLAN
LEED NC 2.2
Project Goal: LEED Platinum Certification
Date: September 9, 2011

evolve
environment :: architecture

Action Items in Bold Red

Credit Status Symbols Key Below

Credit	Phas	Description	AVAILABLE Points	LIKELY Points	MAYBE Points	UNLIKELY Points	Responsible Party	Credit Status	Credit Status
Sustainable Sites									
Prerequisite	C	Construction Activity Pollution Prevention	Rqd.	Rqd.			**CEC / Turner**	CEC document in LOL & Turner implement ESCP.	✚
SS Credit 1	D	Site Selection	1	1			eEA	Complete	✓
SS Credit 2	D	Development Density & Community Connectivity	1	1			eEA	Complete	✓
SS Credit 3	D	Brownfield Development	1		1		eEA	Complete	✓
SS Credit 4.1	D	Alternative Transportation: Public Access	1		1		eEA	Complete	✓
SS Credit 4.2	D	Alternative Transportation: Bicycle Friendly	1	1			eEA	Complete	✓
SS Credit 4.3	D	Alternative Transportation: Low Emitting & Fuel-Efficient Vehicles	1	1			**eEA / TDA**	TDA Confirm number & location of spaces. (31 parking spaces provided: 5%=2 LEFE vehicle spaces located nearest entry)	!
SS Credit 4.4	D	Alternative Transportation: Parking Capacity	1		1		**eEA / TDA**	TDA to confirm number & location. (TDA provide Zoning Ordinance parking reqmt and demonstrate number of spaces meet minimum reqmt. (31 parking spaces*5%=2 carpool/vanpool spaces located near entry)	!
SS Credit 5.1	D	Site Development, Protect or Restore Habitat	1		1		**TDA / Andropogon**	TDA adjust calc (to include revised green roof calc for view window at HVAC) and reissue LEED documentation drawing.	!
SS Credit 5.2	D	Site Development, Maximize Open Space	1	1			**TDA**	TDA adjust calc (to include revised green roof calc for view window at HVAC) and reissue LEED documentation drawing.	!
SS Credit 6.1	D	Stormwater Design, Quantity Control	1	1			**CEC**	Confirm that stormwater calc is for current LEED site boundary; adjust calc to LEED site if necessary. Upload documentation to LOL.	!
SS Credit 6.2	D	Stormwater Design, Quality Control	1	1			**CEC**	Document in LOL.	✚
SS Credit 7.1	D	Heat Island Effect, Non-Roof Surfaces	1			1	N/A	Credit not attempted.	X
SS Credit 7.2	D	Heat Island Effect, Roof Surfaces	1			1	**TDA**	TDA adjust calc (to include revised green roof calc for view window at HVAC) and reissue LEED documentation drawing.	!
SS Credit 8	D	Light Pollution Reduction	1	1			**CJL / CEC?**	Confirm design complies: provide site photometric that demonstrates light spill compliance given current LEED site boundary / confirm automatic building lighting shutoff after hours.	!
		Subtotal - Sustainable Sites	**14**	**8**	**4**	**2**			
Water Efficiency									
WE Credit 1.1-1.2	D	Water Efficient Landscaping, 50% Reduction, 100% Reduction	2	2			**Andropogon**	Document in LOL.	✚
WE Credit 2	D	Innovative Wastewater Technologies	1	1			**CEC**	Document in LOL.	✚
WE Credit 3.1-3.2	D	Water Use Reduction, 20% Reduction/30% Reduction	2	2			**CJL**	CJL clarify storm water quantity calc from Tropical Forest roof and storage capacity will supply water for 100% of toilet & urinal use given anticipated storm intensity and frequency.	✚
		Subtotal Water Efficiency	**5**	**5**	**0**	**0**			
Energy and Atmosphere									
EA Prerequisite 1	C	Fundamental Commissioning of the Building Energy Systems	Rqd.	Rqd.			**HFL / Pitchford**	Confirm OPR/BOD review, commissioning plan draft & CD review are all complete. Confirm point of contact and chain of command for HFL Pitchford shared responsibility for Cx.	*
EA Prerequisite 2	D	Minimum Energy Performance	Rqd.	Rqd.			**CJL**	Defer until final energy model can be completed.	*

Action Items in Bold Red

Credit Status Symbols Key Below

Credit	Phas	Description	AVAILABLE Points	LIKELY Points	MAYBE Points	UNLIKELY Points	Responsible Party	Credit Status	Credit Status
EA Prerequisite 3	D	Fundamental Refrigerant Management	Rqd.	Rqd.			**CJL**	**LOL documentation appears complete; CJL to confirm.**	+
EA Credit 1.1-1.5	D	Optimize Energy Performance, 10.5%-42% Reduction	10	10			**7 Group**	**Defer until final energy model can be completed.**	*
EA Credit 2.1-2.3	D	On-Site Renewable Energy, 2.5%/7.5%/12.5% Reduction	3	3			**CJL / EIS**	**Defer until energy model complete. Document in LOL.**	*
EA Credit 3	C	Enhanced Commissioning	1	1			**HFL / Pitchford**	**Assure work scope breakdown between HFL & Pitchford is clear (see EAp1).**	*
EA Credit 4	D	Enhanced Refrigerant Management	1	1			**CJL**	**CJL to complete calc in LOL template.**	+
EA Credit 5	D	Measurement and Verification	1	1			**CJL / CMU**	**CJL provide proposed M&V plan and confirm metering is included in CD's.**	+
EA Credit 6	C	Green Power	1	1			**CJL / EIS / Phipps / eEA**	**Defer until energy model is complete. eEA to determine equivalency for onsite renewables. Document in LOL.**	*
		Total Energy and Atmosphere	17	17	0	0			
Materials and Resources									
MR Prerequisite 1	D	Storage and Collection of Recyclables	Rqd.	Rqd.			eEA / Phipps	Complete	✓
MR Credit 1.1	C	Building Reuse, Maintain 75% of Walls, Floor & Roof	1			1	N/A	Credit not attempted.	X
MR Credit 1.2	C	Building Reuse, Maintain 95% of the Existing Walls, Floor & Roof	1			1	N/A	Credit not attempted.	X
MR Credit 1.3	C	Building Reuse, Maintain 50% of Interior Non-Structural Elements	1			1	N/A	Credit not attempted.	X
MR Credit 2.1-2.2	C	Construction Waste Management, Divert 50% or 75% from Disposal	2	2			**Turner**	**Implement & document waste management plan.**	*
MR Credit 3.1-3.2	C	Materials Reuse, Specify 5% - 10%	2		2		**Turner / TDA**	**Continue effort to maximize material reuse. Document value of reused items.**	*
MR Credit4.1-4.2	C	Recycled Content, 10% or 20% (post-consumer + 1/2 pre-consumer)	2	1	1		**Turner**	**Continue effort to maximize recycled material use. Document value of recycled materials.**	*
MR Credit 5.1-5.2	C	Regional Materials, 10% or 20% Extracted, Processed & Manufactured Regionally	2	2			**Turner**	**Continue effort to maximize regional material use. Document value of regional materials. (LBC requirements likely to help.)**	*
MR Credit 6	C	Rapidly Renewable Materials	1			1	N/A	Credit not attempted.	X
MR Credit 7	C	Certified Wood	1	1			**Turner**	**Continue effort to use 100% certified wood per LBC. Document value of certified wood and develop action plan. (100% FSC will result in an ID credit)**	*
		Total Materials and Resources	13	6	3	4			
Indoor Environmental Quality (IEQ)									
EQ Prerequisite 1	D	Minimum IAQ Performance	Rqd.	Rqd.			**CJL**	**Document in LOL.**	+
EQ Prerequisite 2	D	Environmental Tobacco Smoke Control	Rqd.	Rqd.			eEA / Phipps	Complete	✓
EQ Credit 1	D	Outdoor Air Delivery Monitoring	1	1			**CJL**	**Document in LOL.**	+
EQ Credit 2	D	Increased Ventilation	1		1		**CJL**	**CJL to determine if this is desirable / achievable?**	!
EQ Credit 3.1	C	Construction IAQ Management Plan, During Construction	1	1			**Turner**	**Implement & document IAQ plan.**	*
EQ Credit 3.2	C	Construction IAQ Management Plan, Before Occupancy	1	1			**Turner**	**Coordinate testing with LBC testing. Schedule and implement flushout only if Phipps requests..**	*
EQ Credit 4.1	C	Low Emitting Materials, Adhesives and Sealants	1	1			**Turner**	**Document use of VOC complying materials..**	*
EQ Credit 4.2	C	Low Emitting Materials, Paints & Coatings	1	1			**Turner**	**Document use of VOC complying materials..**	*
EQ Credit 4.3	C	Low Emitting Materials, Carpet Systems	1	1			**Turner**	**Document use of complying carpet systems.**	*
EQ Credit 4.4	C	Low Emitting Materials, Composite Wood & Agrifiber Products	1	1			**Turner**	**Document use of composite wood and agrifiber products containing no added no urea-formaldehyde.**	*

Action Items in Bold Red

Credit Status Symbols Key Below

Credit	Phas	Description	AVAILABLE Points	LIKELY Points	MAYBE Points	UNLIKELY Points	Responsible Party	Credit Status	Credit Status
EQ Credit 5	C	Indoor Chemical and Pollutant Source Control	1	1			**TDA / CJL / Turner / eEA**	**CJL confirm complying ventilation for janitor's closets. Turner provide MERV 13 filter documentation. TDA to provide plans showing walk off mats at entries. eEA document in LOL.**	*
EQ Credit 6.1	D	Controllability of Systems, Lighting	1	1			**CJL**	**Document in LOL.**	+
EQ Credit 6.2	D	Controllability of Systems, Thermal Comfort	1	1			**CJL**	**Confirm controls in open office area. Document in LOL.**	+
EQ Credit 7.1	D	Thermal Comfort, Design	1	1			**CJL**	**Document in LOL.**	+
EQ Credit 7.2	D	Thermal Comfort, Verification	1	1			eEA	Complete	✓
EQ Credit 8.1	D	Daylight and Views, Distribution Quality to 75%/90% of Spaces	1	1			**TDA / eEA**	**Document in LOL.**	+
EQ Credit 8.2	D	Daylight and Views, Views for Seated Spaces	1	1			**TDA / eEA**	**Document in LOL.**	+
		Total Indoor Environmental Quality	15	14	1	0			
Innovation in Design									
ID Credit 1.1	D	Innovation in Design	1	1			**CJL / EIS**	**EP onsite renewable energy. Defer until final energy model is completed. Document in LOL.**	*
ID Credit 1.2	D	Innovation in Design	1	1			**CJL**	**EP reuse or infiltrate 100% of waste water. Document in LOL.**	+
ID Credit 1.3	D	Innovation in Design	1	1			**CEC**	**EP manage all storm water on site. Document in LOL.**	+
ID Credit 1.4	D	Innovation in Design	1	1			eEA / Phipps	SITES pilot participation. Complete	✓
ID Credit 2	D	LEED Accredited Professional	1	1			eEA	Complete	✓
		Total Innovation in Design	5	5	0	0			
		Total Points	**69**	**55**	**8**	**6**			

LEED Certified LEED Silver LEED Gold LEED Platinum	26 - 32 Points 33 - 38 Points 39 - 51 Points 52 + Points	LEED Status: 55 Likely + 8 Maybe = 63 Total Points in Play Point cushion sufficient to maintain Certification Goal of Platinum.

Notes:

1. D indicates Design Phase LEED Online documentation required ASAP. Goal for LEED Design Phase Certification Submission is October 15, 2011.

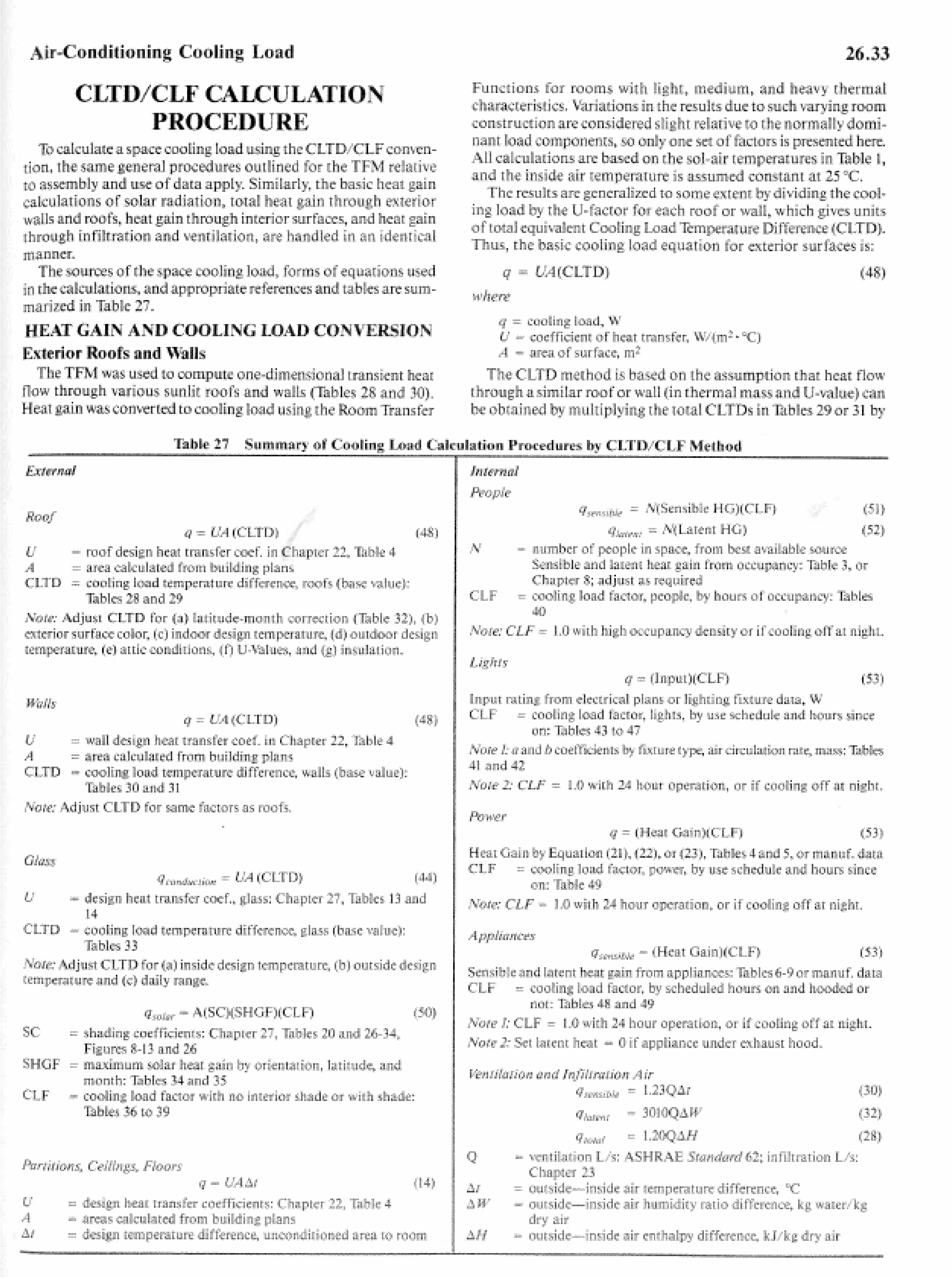
2. Possible other ID Credits include : Non-toxic material use, non-chemical water treatment, carbon offset for construction, EP construction waste management / over 95%, EP certified wood / over 95% - continue tracking performance of these credits.

3. Staff FTE 77 weekdays /34 weekends; Transient Visitors 50 weekdays / 200 weekends; Average Transient Visitors 100/day; Parking Spaces 31

CREDIT STATUS KEY	
Documentation Complete	✓
Documentation Required	!
Upload LOL Documentation	+
Defer Until Later	*
Credit Not Attempted	X

This LEED credit evaluation represents the project team's best determination of the likelihood of attaining the evaluated credits. LEED Certification is a determination of the USGBC and can not be assured by evolveEA or the project team.

[A2] CLTD/CLF Calculation Procedure



CLTD/CLF CALCULATION PROCEDURE

To calculate a space cooling load using the CLTD/CLF convention, the same general procedures outlined for the TFM relative to assembly and use of data apply. Similarly, the basic heat gain calculations of solar radiation, total heat gain through exterior walls and roofs, heat gain through interior surfaces, and heat gain through infiltration and ventilation, are handled in an identical manner.

The sources of the space cooling load, forms of equations used in the calculations, and appropriate references and tables are summarized in Table 27.

HEAT GAIN AND COOLING LOAD CONVERSION

Exterior Roofs and Walls

The TFM was used to compute one-dimensional transient heat flow through various sunlit roofs and walls (Tables 28 and 30). Heat gain was converted to cooling load using the Room Transfer Functions for rooms with light, medium, and heavy thermal characteristics. Variations in the results due to such varying room construction are considered slight relative to the normally dominant load components, so only one set of factors is presented here. All calculations are based on the sol-air temperatures in Table 1, and the inside air temperature is assumed constant at 25 °C.

The results are generalized to some extent by dividing the cooling load by the U-factor for each roof or wall, which gives units of total equivalent Cooling Load Temperature Difference (CLTD). Thus, the basic cooling load equation for exterior surfaces is:

$$q = UA(\mathrm{CLTD}) \qquad (48)$$

where

q = cooling load, W
U = coefficient of heat transfer, W/(m^2 · °C)
A = area of surface, m^2

The CLTD method is based on the assumption that heat flow through a similar roof or wall (in thermal mass and U-value) can be obtained by multiplying the total CLTDs in Tables 29 or 31 by

Table 27 Summary of Cooling Load Calculation Procedures by CLTD/CLF Method

External

Roof

$$q = UA\,(\mathrm{CLTD}) \qquad (48)$$

U = roof design heat transfer coef. in Chapter 22, Table 4
A = area calculated from building plans
CLTD = cooling load temperature difference, roofs (base value): Tables 28 and 29

Note: Adjust CLTD for (a) latitude-month correction (Table 32), (b) exterior surface color, (c) indoor design temperature, (d) outdoor design temperature, (e) attic conditions, (f) U-Values, and (g) insulation.

Walls

$$q = UA\,(\mathrm{CLTD}) \qquad (48)$$

U = wall design heat transfer coef. in Chapter 22, Table 4
A = area calculated from building plans
CLTD = cooling load temperature difference, walls (base value): Tables 30 and 31

Note: Adjust CLTD for same factors as roofs.

Glass

$$q_{conduction} = UA\,(\mathrm{CLTD}) \qquad (44)$$

U = design heat transfer coef., glass: Chapter 27, Tables 13 and 14
CLTD = cooling load temperature difference, glass (base value): Tables 33

Note: Adjust CLTD for (a) inside design temperature, (b) outside design temperature and (c) daily range.

$$q_{solar} = A(\mathrm{SC})(\mathrm{SHGF})(\mathrm{CLF}) \qquad (50)$$

SC = shading coefficients: Chapter 27, Tables 20 and 26-34, Figures 8-13 and 26
SHGF = maximum solar heat gain by orientation, latitude, and month: Tables 34 and 35
CLF = cooling load factor with no interior shade or with shade: Tables 36 to 39

Partitions, Ceilings, Floors

$$q = UA\Delta t \qquad (14)$$

U = design heat transfer coefficients: Chapter 22, Table 4
A = areas calculated from building plans
Δt = design temperature difference, unconditioned area to room

Internal

People

$$q_{sensible} = N(\text{Sensible HG})(\mathrm{CLF}) \qquad (51)$$

$$q_{latent} = N(\text{Latent HG}) \qquad (52)$$

N = number of people in space, from best available source
Sensible and latent heat gain from occupancy: Table 3, or Chapter 8; adjust as required
CLF = cooling load factor, people, by hours of occupancy: Tables 40

Note: CLF = 1.0 with high occupancy density or if cooling off at night.

Lights

$$q = (\text{Input})(\mathrm{CLF}) \qquad (53)$$

Input rating from electrical plans or lighting fixture data, W
CLF = cooling load factor, lights, by use schedule and hours since on: Tables 43 to 47

Note 1: a and b coefficients by fixture type, air circulation rate, mass: Tables 41 and 42

Note 2: CLF = 1.0 with 24 hour operation, or if cooling off at night.

Power

$$q = (\text{Heat Gain})(\mathrm{CLF}) \qquad (53)$$

Heat Gain by Equation (21), (22), or (23), Tables 4 and 5, or manuf. data
CLF = cooling load factor, power, by use schedule and hours since on: Table 49

Note: CLF = 1.0 with 24 hour operation, or if cooling off at night.

Appliances

$$q_{sensible} = (\text{Heat Gain})(\mathrm{CLF}) \qquad (53)$$

Sensible and latent heat gain from appliances: Tables 6-9 or manuf. data
CLF = cooling load factor, by scheduled hours on and hooded or not: Tables 48 and 49

Note 1: CLF = 1.0 with 24 hour operation, or if cooling off at night.

Note 2: Set latent heat = 0 if appliance under exhaust hood.

Ventilation and Infiltration Air

$$q_{sensible} = 1.23Q\Delta t \qquad (30)$$

$$q_{latent} = 3010Q\Delta W \qquad (32)$$

$$q_{total} = 1.20Q\Delta H \qquad (28)$$

Q = ventilation L/s: ASHRAE *Standard* 62; infiltration L/s: Chapter 23
Δt = outside—inside air temperature difference, °C
ΔW = outside—inside air humidity ratio difference, kg water/kg dry air
ΔH = outside—inside air enthalpy difference, kJ/kg dry air

[A3] Hourly Temperature Variation

Solar Time [hrs]	1-9	9	10	11	12	13	14	15	16	17	18	19-24	10 hr. Avg.
Daily Range Ratio	0	0.7	0.6	0.4	0.2	0.1	0	0	0	0.1	0.2	0	
Dry Bulb [F]	0	87	87	87	87	87	87	87	87	87	87	0	
Daily Range	0	23	23	23	23	23	23	23	23	23	23	0	
To=Dry Bulb - Range*Ratio	0	71	74	78	82	84	86	87	86	85	82	0	81.55

[A4] Hourly Cooling Load Temperature Differential (corrected)

Solar Time [hrs]	1-8	9	10	11	12	13	14	15	16	17	18	19-24	10 hr. Avg.
CLTD (uncorrected) @1400 hours	0	34	49	61	71	78	79	77	70	59	45	0	62.3
LM (Latitude/Month correction) JUNE	0	2	2	2	2	2	2	2	2	2	2	0	
CLTD & LM	0	36	51	63	73	80	81	79	72	61	47	0	
K = 1	0	1	1	1	1	1	1	1	1	1	1	0	
(CLTD & LM)K	0	36	51	63	73	80	81	79	72	61	47	0	
78 F - Tr Tr = 78 F	0	0	0	0	0	0	0	0	0	0	0	0	
To - 85 To = 81.55 F	0	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	0	
f = 1	0	1	1	1	1	1	1	1	1	1	1	0	
CLTD (corrected)	0	33	48	60	70	77	78	76	69	58	44	0	61.3

[A5] Monthly Cooling Load Temperature Differential (corrected)

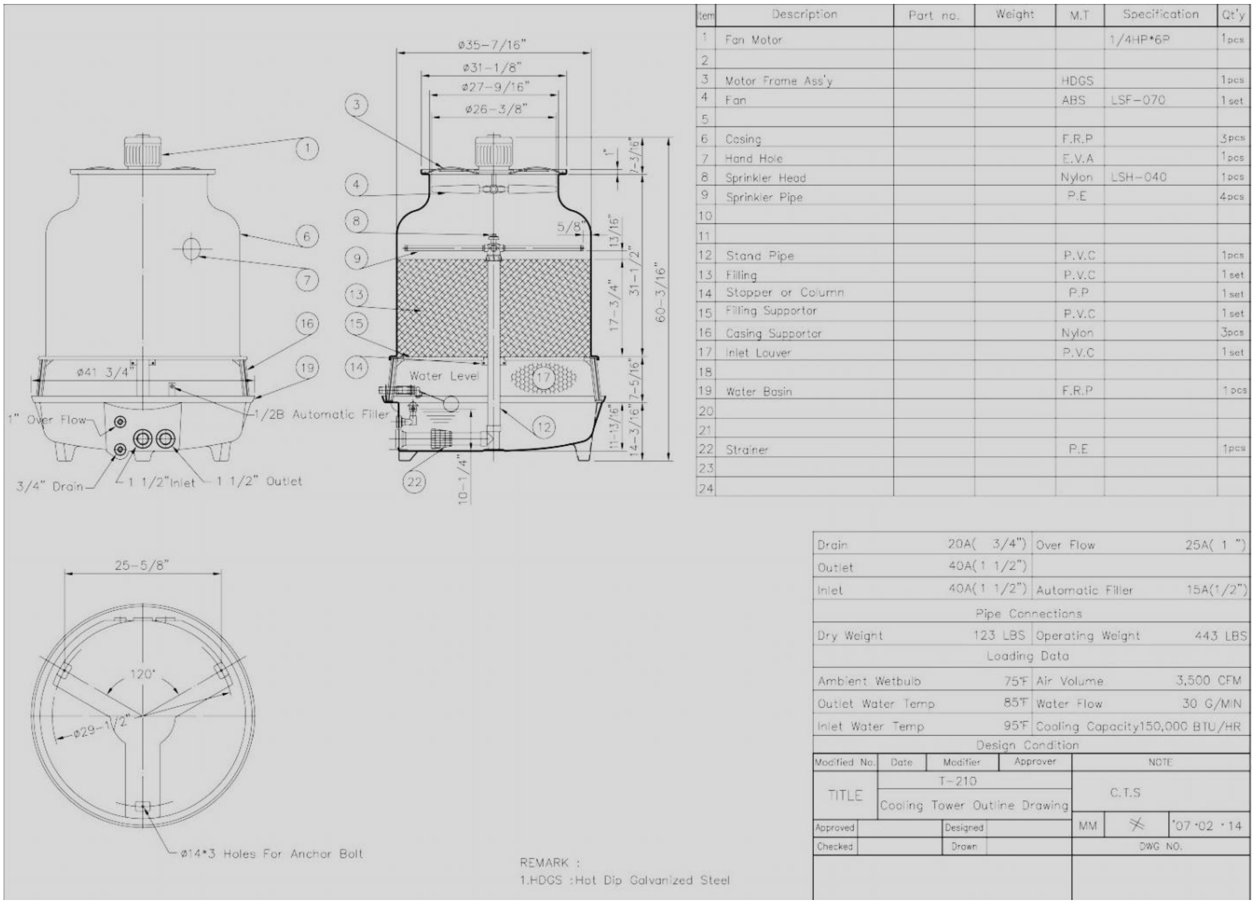
MONTH	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	MO. AVG.
CLTD (uncorrected) 10 hr. average	62.3	62.3	62.3	62.3	62.3	62.3	62.3	
LM (Latitude/Month correction)	-3	1	2	1	-3	-8	-14	
CLTD & LM	59	63	64	63	59	54	48	
K = 1	1	1	1	1	1	1	1	
(CLTD & LM)K	59	63	64	63	59	54	48	
78 F - Tr Tr = 78 F	0	0	0	0	0	0	0	

To - 85 **To = 81.55 F**	-3	-3	-3	-3	-3	-3	-3	
f = 1	1	1	1	1	1	1	1	
CLTD (corrected)	50	54	55	54	50	46	41	**50**

[A6] Peak Monthly Cooling Load Temperature Differential (corrected)

MONTH	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	MO. AVG.
CLTD (uncorrected) 10 hr. average				79	79	79	79	79	79	79			
LM (Latitude/Month correction)	-19	-14	-8	-3	1	2	1	-3	-8	-14	-19	-21	
CLTD & LM				76	80	81	80	76	71	65			
K = 1				1	1	1	1	1	1	1			
(CLTD & LM)K				76	80	81	80	76	71	65			
78 F - Tr **Tr = 78 F**				0	0	0	0	0	0	0			
To - 85 **To = 81.55 F**				-3	-3	-3	-3	-3	-3	-3			
f = 1				1	1	1	1	1	1	1			
CLTD (corrected)				66	69	70	69	66	61	56			**65**

[A7] Cooling Tower Specification Sheet



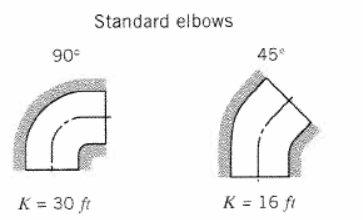
Item	Description	Part no.	Weight	M.T	Specification	Qt'y
1	Fan Motor				1/4HP*6P	1pcs
2						
3	Motor Frame Ass'y			HDGS		1pcs
4	Fan			ABS	LSF-070	1set
5						
6	Casing			F.R.P		3pcs
7	Hand Hole			E.V.A		1pcs
8	Sprinkler Head			Nylon	LSH-040	1pcs
9	Sprinkler Pipe			P.E		4pcs
10						
11						
12	Stand Pipe			P.V.C		1pcs
13	Filling			P.V.C		1set
14	Stopper or Column			P.P		1set
15	Filling Supportor			P.V.C		1set
16	Casing Supportor			Nylon		3pcs
17	Inlet Louver			P.V.C		1set
18						
19	Water Basin			F.R.P		1pcs
20						
21						
22	Strainer			P.E		1pcs
23						
24						

Drain	20A(3/4")	Over Flow	25A(1 ")
Outlet	40A(1 1/2")		
Inlet	40A(1 1/2")	Automatic Filler	15A(1/2")
Pipe Connections			
Dry Weight	123 LBS	Operating Weight	443 LBS
Loading Data			
Ambient Wetbulb	75°F	Air Volume	3,500 CFM
Outlet Water Temp	85°F	Water Flow	30 G/MIN
Inlet Water Temp	95°F	Cooling Capacity	150,000 BTU/HR
Design Condition			

Modified No.	Date	Modifier	Approver	NOTE
TITLE	T-210 Cooling Tower Outline Drawing			C.T.S
Approved		Designed		MM ✕ '07 ·02 ·14
Checked		Drawn		DWG NO.

REMARK :
1.HDGS :Hot Dip Galvanized Steel

[A8] Head Loss Calculations

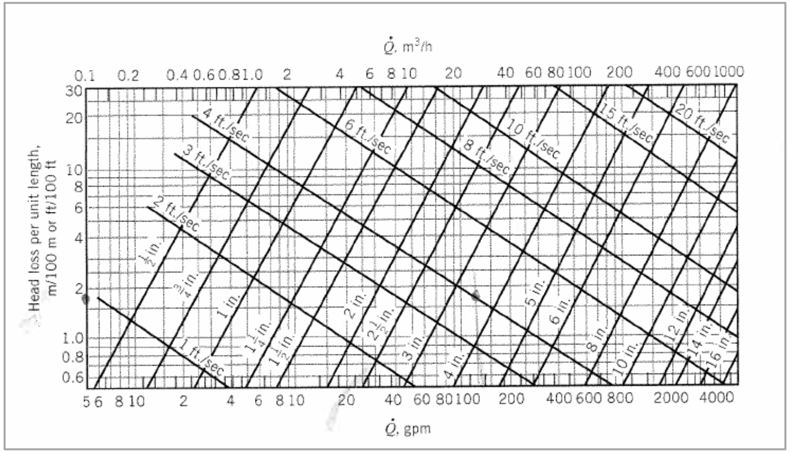
<table>
<tr><td colspan="3">Head Loss Calculations</td></tr>
<tr><td>Location</td><td>Ground</td><td>Building</td></tr>
<tr><td>Piping Diameter</td><td>1-1/4”</td><td>3”</td></tr>
<tr><td>1-way</td><td>730’</td><td>114’</td></tr>
<tr><td>2-way</td><td>1460’</td><td>228’</td></tr>
<tr><td>Elbows


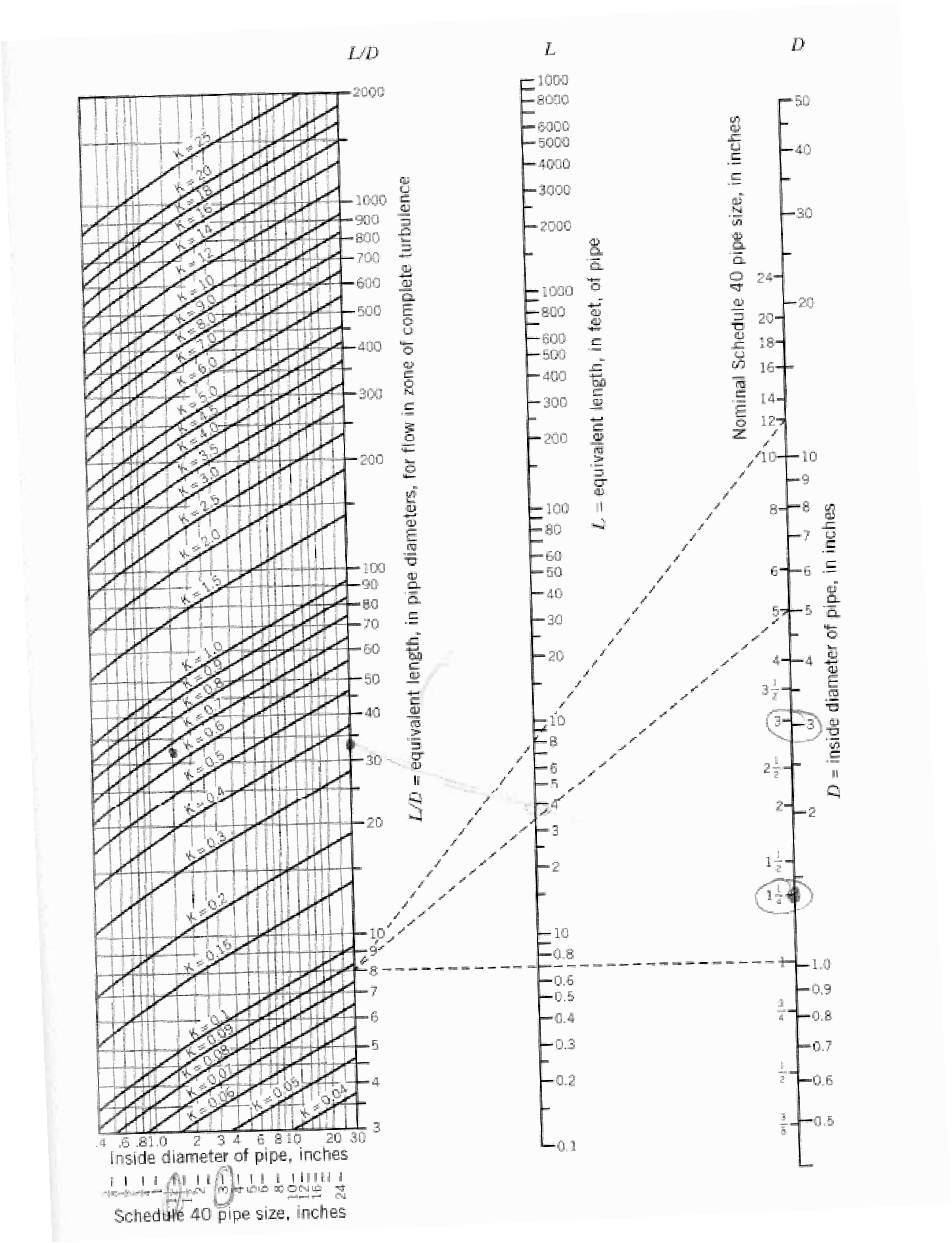
<table><tr><td>Nominal Size, in.</td><td>Friction Factor f_t</td><td>Nominal Size, in.</td><td>Friction Factor f_t</td></tr><tr><td>$\frac{1}{2}$</td><td>0.027</td><td>4</td><td>0.017</td></tr><tr><td>$\frac{3}{4}$</td><td>0.025</td><td>5</td><td>0.016</td></tr><tr><td>1</td><td>0.023</td><td>6</td><td>0.015</td></tr><tr><td>$1\frac{1}{4}$</td><td>0.022</td><td>8–10</td><td>0.014</td></tr><tr><td>$1\frac{1}{2}$</td><td>0.021</td><td>12–16</td><td>0.013</td></tr><tr><td>2</td><td>0.019</td><td>18–24</td><td>0.012</td></tr><tr><td>$2\frac{1}{2}$, 3</td><td>0.018</td><td></td><td></td></tr></table></td><td>45 Degree Elbow
K=16*ft
K=16*0.022 = 0.35

Equivalent Length
L=2 ft
x 2 = 4’

90 Degree Elbow
K = 30*ft
K = 30*0.0222 = 0.66

Equivalent Length
L = 3.5 ft
x 4 = 14’</td><td>90 Degree Elbow
K = 30*ft
K = 30*0.0222 = 0.66

Equivalent Length
L = 10 ft
x 4 = 40’</td></tr>
<tr><td>Total Length</td><td>1478’</td><td>268’</td></tr>
<tr><td>Flow</td><td>151.5 gpm</td><td>151.5 gpm</td></tr>
<tr><td rowspan="2">Head Loss [ft/100ft]</td><td colspan="2">
 </td></tr>
<tr><td>1.7 / 100</td><td>3.5/100</td></tr>
<tr><td>Head</td><td>25.1 ft</td><td>9.38 ft</td></tr>
<tr><td>Total Head</td><td colspan="2">34 feet</td></tr>
</table>


L/D
L
D
K = 25
K = 20
K = 18
K = 16
K = 14
K = 12
K = 10
K = 9.0
K = 8.0
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K = 4.5
K = 4.0
K = 3.5
K = 3.0
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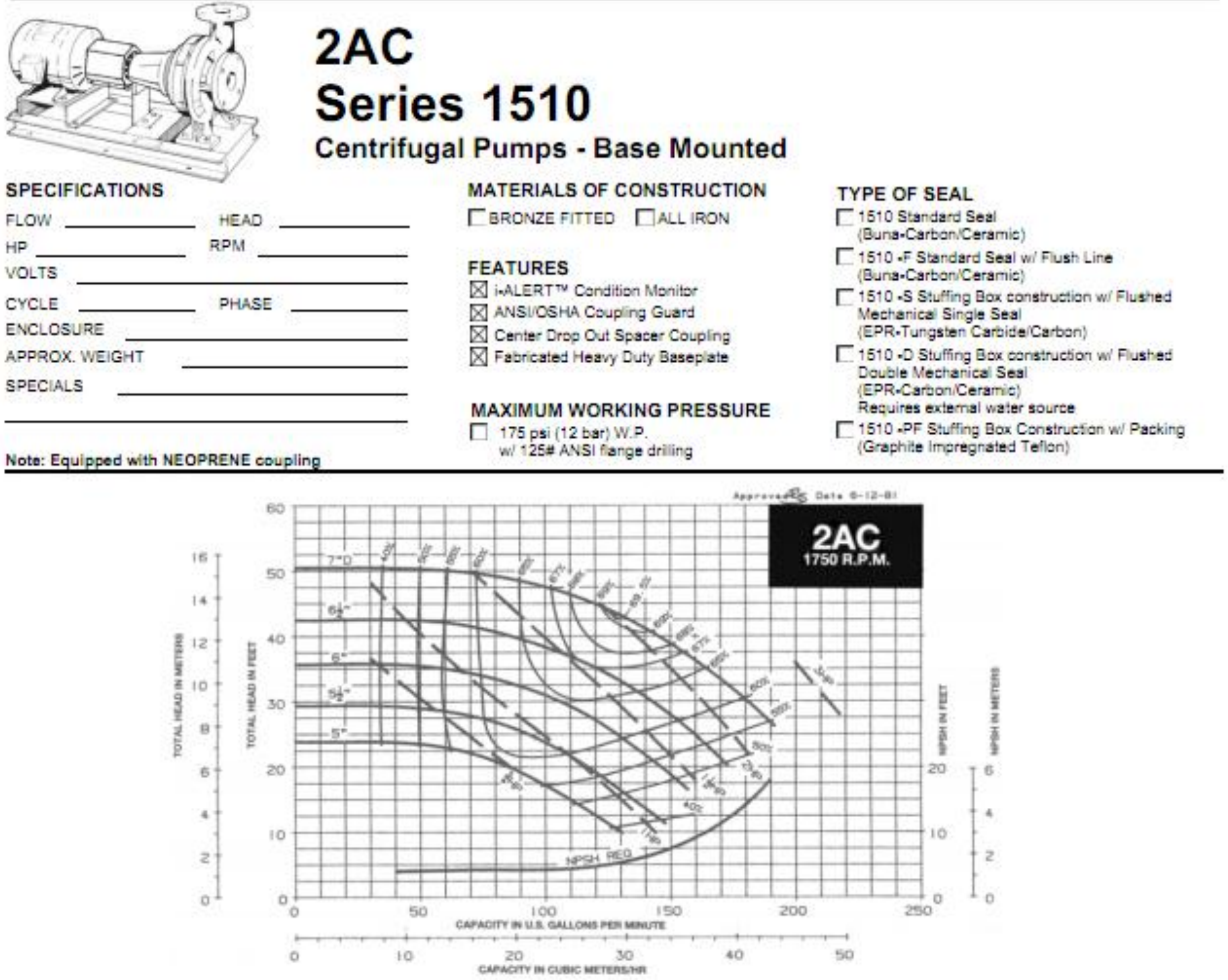
K = 2.0
K = 1.5
K = 1.0
K = 0.9
K = 0.8
K = 0.7
K = 0.6
K = 0.5
K = 0.4
K = 0.3
K = 0.2
K = 0.15
K = 0.1
K = 0.09
K = 0.08
K = 0.07
K = 0.06
K = 0.05
K = 0.04
L/D = equivalent length, in pipe diameters, for flow in zone of complete turbulence
L = equivalent length, in feet, of pipe
Nominal Schedule 40 pipe size, in inches
D = inside diameter of pipe, in inches
Inside diameter of pipe, inches
Schedule 40 pipe size, inches
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
10000
8000
6000
5000
4000
3000
2000
1000
800
600
500
400
300
200
100
80
60
50
40
30
20
10
8
6
5
4
3
2
1.0
0.8
0.6
0.5
0.4
0.3
0.2
0.1
50
40
30
24
20
18
16
14
12
10
9
8
7
6
5
4
3 1/2
3
2 1/2
2
1 1/2
1 1/4
1
1.0
0.9
3/4
0.8
0.7
1/2
0.6
3/8
0.5
.4
.6
.8
1.0
2
3
4
6
8
10
20
30

[A9] Pump Selection



2AC
Series 1510
Centrifugal Pumps - Base Mounted

SPECIFICATIONS

FLOW ____________ HEAD ____________
HP ____________ RPM ____________
VOLTS ____________
CYCLE ____________ PHASE ____________
ENCLOSURE ____________
APPROX. WEIGHT ____________
SPECIALS ____________

Note: Equipped with NEOPRENE coupling

MATERIALS OF CONSTRUCTION

☐ BRONZE FITTED ☐ ALL IRON

FEATURES

- ☒ i-ALERT™ Condition Monitor
- ☒ ANSI/OSHA Coupling Guard
- ☒ Center Drop Out Spacer Coupling
- ☒ Fabricated Heavy Duty Baseplate

MAXIMUM WORKING PRESSURE

☐ 175 psi (12 bar) W.P.
w/ 125# ANSI flange drilling

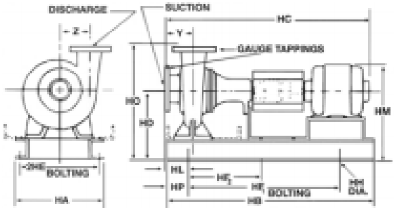
TYPE OF SEAL

- ☐ 1510 Standard Seal (Buna-Carbon/Ceramic)
- ☐ 1510 -F Standard Seal w/ Flush Line (Buna-Carbon/Ceramic)
- ☐ 1510 -S Stuffing Box construction w/ Flushed Mechanical Single Seal (EPR-Tungsten Carbide/Carbon)
- ☐ 1510 -D Stuffing Box construction w/ Flushed Double Mechanical Seal (EPR-Carbon/Ceramic) Requires external water source
- ☐ 1510 -PF Stuffing Box Construction w/ Packing (Graphite Impregnated Teflon)

Approved Date 6-12-81

Series 1510 2AC Centrifugal Pump Submittal

B-224.2H



FLANGE DIMENSIONS IN INCHES (MM)			
	SIZE	THICKNESS	O.D.
Discharge	2"	5/8" (16)	6" (152)
Suction	2-1/2"	11/16" (17)	7-1/8" (181)

FLANGES ARE 125# ANSI - STANDARD

DIMENSIONS – Inches (mm)

STANDARD SEAL 1510, 1510-F

MOTOR FRAME	HA	HB	HC MAX	HD	2HE	HF_1	HF_2	HH	HL	HM MAX	HO	HP	Y	Z
	"S" FRAME													
56	12 (305)	28-3/4 (730)	28-7/8 (733)	9-3/4 (248)	10-1/4 (260)	22-1/2 (572)	-	3/4 (19)	3-9/16 (90)	13-3/8 (340)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
143T	12 (305)	28-3/4 (730)	29 (737)	9-3/4 (248)	10-1/4 (260)	22-1/2 (572)	-	3/4 (19)	3-9/16 (90)	13-1/2 (343)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
145T	12 (305)	28-3/4 (730)	30 (762)	9-3/4 (248)	10-1/4 (260)	22-1/2 (572)	-	3/4 (19)	3-9/16 (90)	13-1/2 (343)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
182T	14-5/8 (371)	31 (787)	32-5/8 (829)	9-3/4 (248)	12-7/8 (327)	25 (635)	-	3/4 (19)	2-3/16 (56)	15 (381)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
184T	14-5/8 (371)	31 (787)	33-3/8 (848)	9-3/4 (248)	12-7/8 (327)	25 (635)	-	3/4 (19)	2-3/16 (56)	15 (381)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
213T	14-5/8 (371)	34-5/8 (879)	36 (914)	9-3/4 (248)	12-7/8 (327)	28-5/8 (727)	-	3/4 (19)	2-3/16 (56)	15-5/8 (397)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
215T	14-5/8 (371)	34-5/8 (879)	37-1/2 (953)	9-3/4 (248)	12-7/8 (327)	28-5/8 (727)	-	3/4 (19)	2-3/16 (56)	15-5/8 (397)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
254T	14-5/8 (371)	39-3/8 (1000)	41-1/4 (1048)	10-3/4 (273)	12-7/8 (327)	33-3/8 (848)	-	3/4 (19)	2-3/16 (56)	17-5/8 (448)	17-1/4 (438)	3 (76)	3-1/2 (89)	4-3/4 (121)
256T	14-5/8 (371)	39-3/8 (1000)	43 (1092)	10-3/4 (273)	12-7/8 (327)	33-3/8 (848)	-	3/4 (19)	2-3/16 (56)	17-5/8 (448)	17-1/4 (438)	3 (76)	3-1/2 (89)	4-3/4 (121)

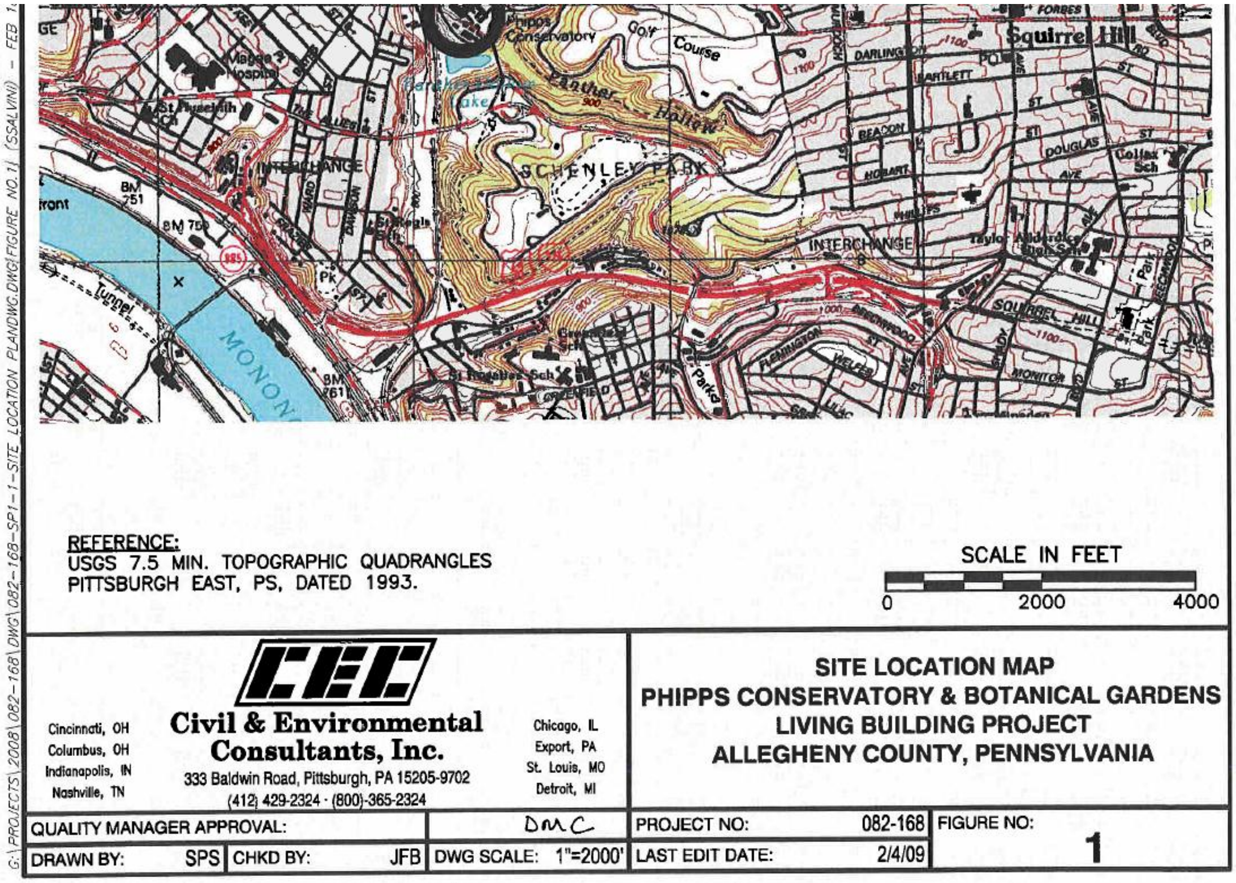
STUFFING BOX 1510-PF, 1510-S, 1510-D

MOTOR FRAME	HA	HB	HC MAX	HD	2HE	HF_1	HF_2	HH	HL	HM MAX	HO	HP	Y	Z
	"S" FRAME													
56	14-5/8 (371)	34-5/8 (879)	32-3/8 (822)	9-3/4 (248)	12-7/8 (327)	28-5/8 (727)	-	3/4 (19)	2-3/16 (56)	13-3/8 (340)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
143T	14-5/8 (371)	34-5/8 (879)	32-1/2 (826)	9-3/4 (248)	12-7/8 (327)	28-5/8 (727)	-	3/4 (19)	2-3/16 (56)	13-1/2 (343)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
145T	14-5/8 (371)	34-5/8 (879)	33-1/2 (851)	9-3/4 (248)	12-7/8 (327)	28-5/8 (727)	-	3/4 (19)	2-3/16 (56)	13-1/2 (343)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
182T	14-5/8 (371)	34-5/8 (879)	36-1/4 (921)	9-3/4 (248)	12-7/8 (327)	28-5/8 (727)	-	3/4 (19)	2-3/16 (56)	15 (381)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
184T	14-5/8 (371)	34-5/8 (879)	37 (940)	9-3/4 (248)	12-7/8 (327)	28-5/8 (727)	-	3/4 (19)	2-3/16 (56)	15 (381)	16-1/4 (413)	3 (76)	3-1/2 (89)	4-3/4 (121)
	"L" FRAME													
213T	16 (406)	46-1/2 (1181)	42-3/4 (1086)	11 (279)	14 (356)	36-1/2 (927)	18-1/4 (464)	7/8 (22)	3-5/16 (84)	16-7/8 (429)	17-1/2 (445)	5 (127)	3-1/2 (89)	4-3/4 (121)
215T	16 (406)	46-1/2 (1181)	44-1/4 (1124)	11 (279)	14 (356)	36-1/2 (927)	18-1/4 (464)	7/8 (22)	3-5/16 (84)	16-7/8 (429)	17-1/2 (445)	5 (127)	3-1/2 (89)	4-3/4 (121)
254T	16 (406)	51-3/4 (1314)	48 (1219)	12 (305)	14 (356)	41-3/4 (1060)	20-7/8 (530)	7/8 (22)	3-5/16 (84)	18-7/8 (479)	18-1/2 (470)	5 (127)	3-1/2 (89)	4-3/4 (121)
256T	16 (406)	51-3/4 (1314)	49-3/4 (1264)	12 (305)	14 (356)	41-3/4 (1060)	20-7/8 (530)	7/8 (22)	3-5/16 (84)	18-7/8 (479)	18-1/2 (470)	5 (127)	3-1/2 (89)	4-3/4 (121)

Dimensions are subject to change. Not to be used for construction purposes unless certified.

ITT
8200 N. Austin Avenue
Morton Grove, IL 60053
Phone (847)966-3700
Facsimile (847)966-9052
www.bellgossett.com

[A11] Vicinity Geological Report



G:\PROJECTS\2008\082-168\DWG\082-168-SP1-1-SITE LOCATION PLANDWG.DWG\FIGURE NO.1\ (SSALVINI) - FEB 1

REFERENCE:
USGS 7.5 MIN. TOPOGRAPHIC QUADRANGLES
PITTSBURGH EAST, PS, DATED 1993.

CEC
Civil & Environmental Consultants, Inc.
333 Baldwin Road, Pittsburgh, PA 15205-9702
(412) 429-2324 · (800)-365-2324

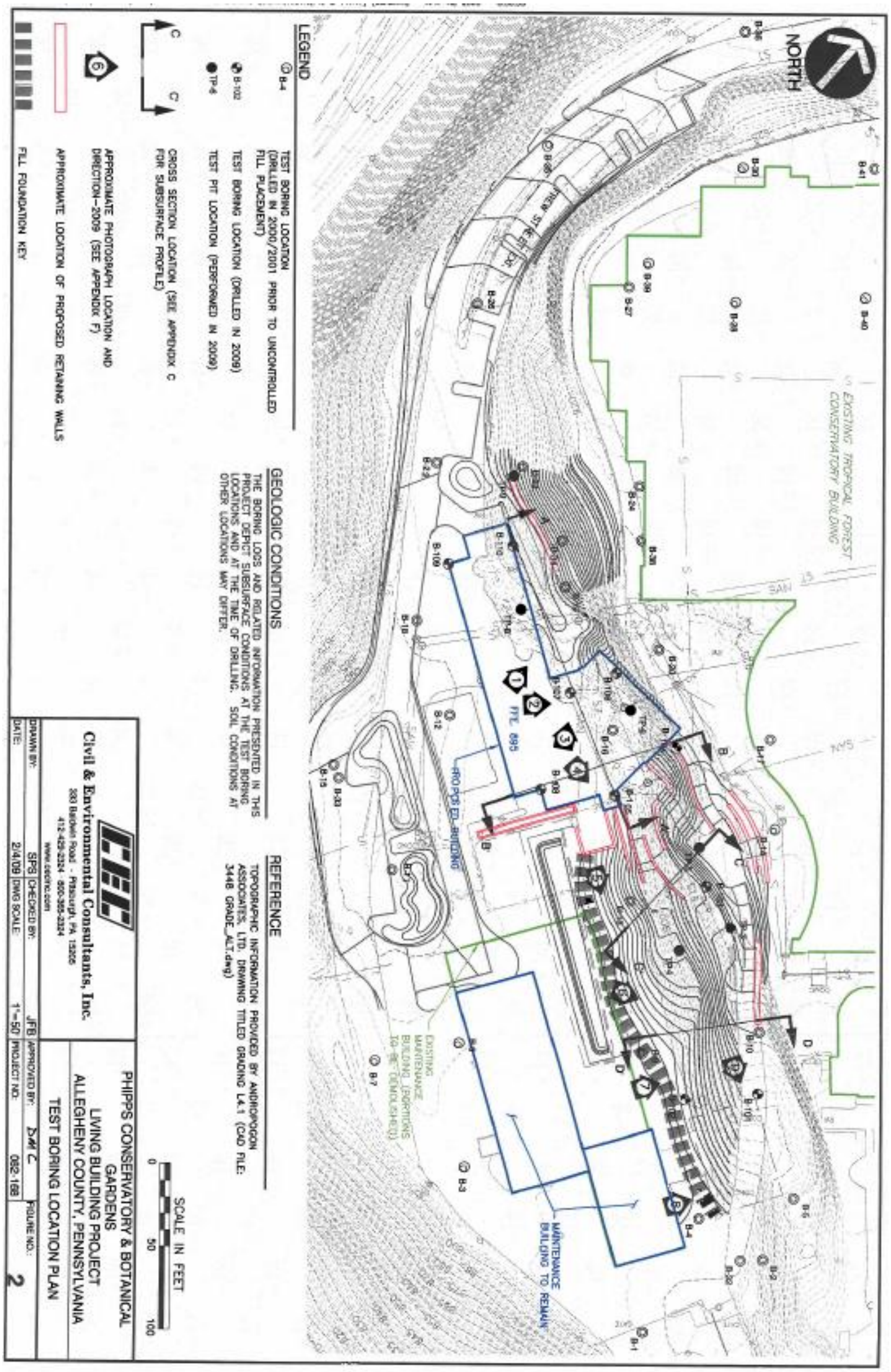
Cincinnati, OH
Columbus, OH
Indianapolis, IN
Nashville, TN

Chicago, IL
Export, PA
St. Louis, MO
Detroit, MI

SITE LOCATION MAP
PHIPPS CONSERVATORY & BOTANICAL GARDENS
LIVING BUILDING PROJECT
ALLEGHENY COUNTY, PENNSYLVANIA

QUALITY MANAGER APPROVAL: DMC
DRAWN BY: SPS
CHKD BY: JFB
DWG SCALE: 1"=2000'
PROJECT NO: 082-168
LAST EDIT DATE: 2/4/09
FIGURE NO: 1

[A12] Site Geological Report



LEGEND

B-4	TEST BORING LOCATION (DRILLED IN 2000/2001 PRIOR TO UNCONTROLLED FILL PLACEMENT)
B-102	TEST BORING LOCATION (DRILLED IN 2009)
● TP-6	TEST PIT LOCATION (PERFORMED IN 2009)
C C	CROSS SECTION LOCATION (SEE APPENDIX C FOR SUBSURFACE PROFILE)
6	APPROXIMATE PHOTOGRAPH LOCATION AND DIRECTION–2009 (SEE APPENDIX F)
▭	APPROXIMATE LOCATION OF PROPOSED RETAINING WALLS
▮▮▮▮▮	FILL FOUNDATION KEY

GEOLOGIC CONDITIONS

THE BORING LOGS AND RELATED INFORMATION PRESENTED IN THIS PROJECT DEPICT SUBSURFACE CONDITIONS AT THE TEST BORING LOCATIONS AND AT THE TIME OF DRILLING. SOIL CONDITIONS AT OTHER LOCATIONS MAY DIFFER.

REFERENCE

TOPOGRAPHIC INFORMATION PROVIDED BY ANDROPOGON ASSOCIATES, LTD. DRAWING TITLED GRADING L4.1 (CAD FILE: 3448 GRADE_ALT.dwg)

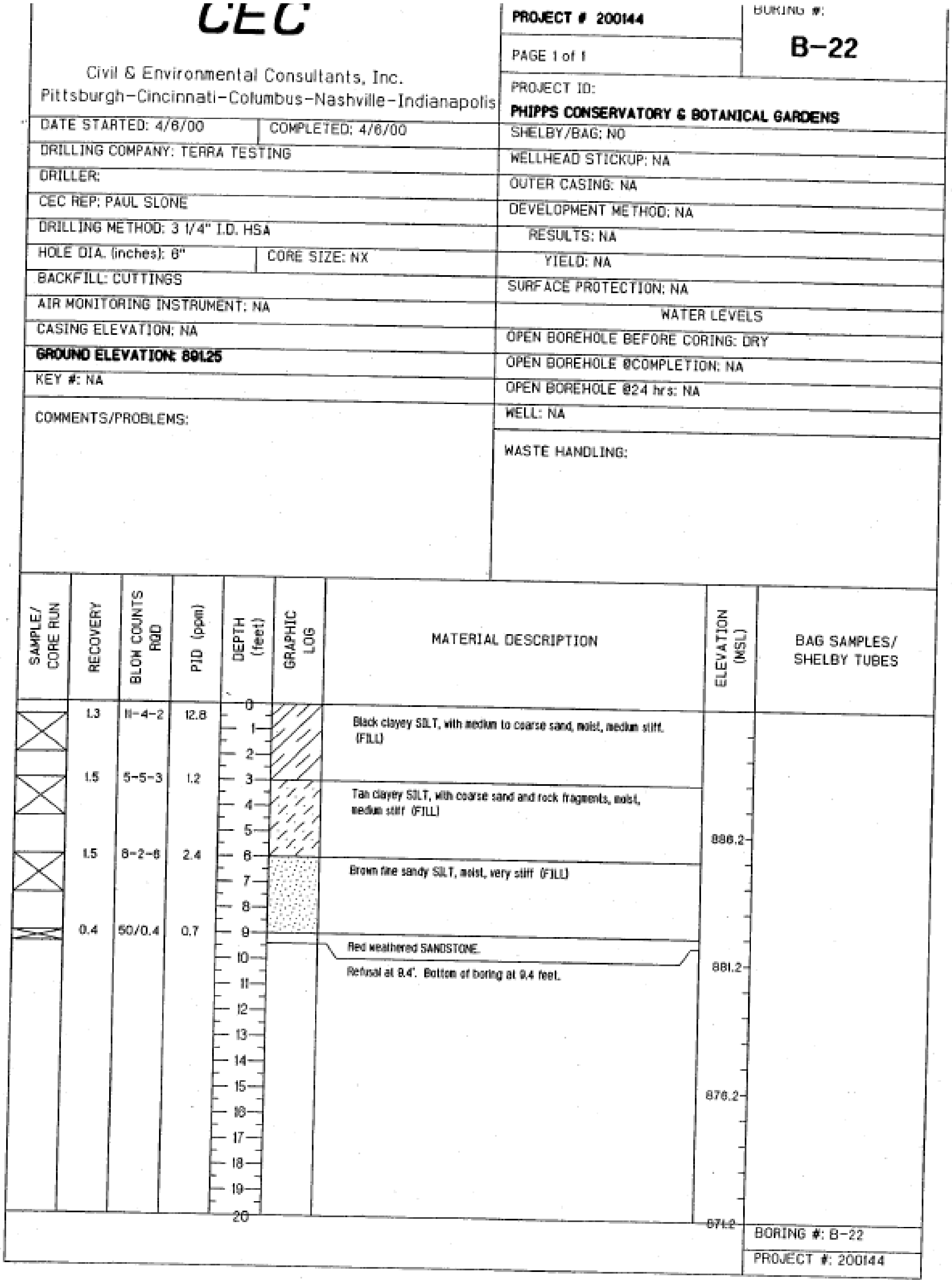
Civil & Environmental Consultants, Inc.
333 Baldwin Road - Pittsburgh, PA 15205
412-429-2324 · 800-365-2324
www.cecinc.com

PHIPPS CONSERVATORY & BOTANICAL GARDENS
LIVING BUILDING PROJECT
ALLEGHENY COUNTY, PENNSYLVANIA
TEST BORING LOCATION PLAN

DRAWN BY:	SPS	CHECKED BY:	JFB	APPROVED BY:	DMC
DATE:	2/4/09	DWG SCALE:	1"=50'	PROJECT NO:	082-168

FIGURE NO.: 2

[A13] Borehole Test



CEC

Civil & Environmental Consultants, Inc.
Pittsburgh–Cincinnati–Columbus–Nashville–Indianapolis

PROJECT # 200144
PAGE 1 of 1
BORING #: **B–22**
PROJECT ID:
PHIPPS CONSERVATORY & BOTANICAL GARDENS

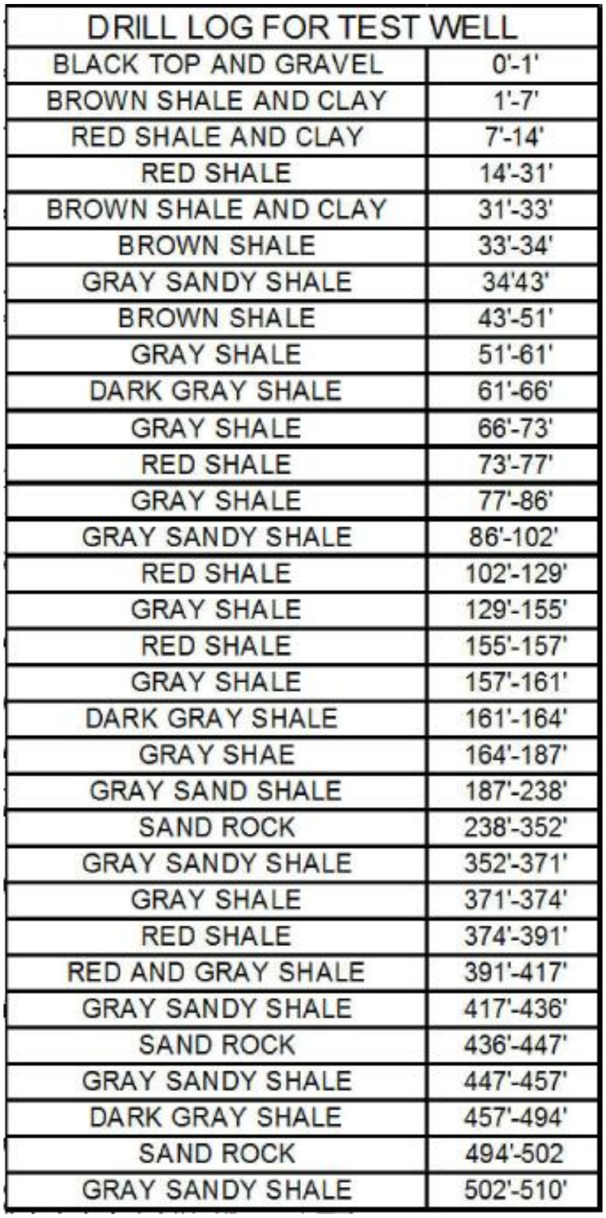
DATE STARTED: 4/6/00
COMPLETED: 4/6/00
DRILLING COMPANY: TERRA TESTING
DRILLER:
CEC REP: PAUL SLONE
DRILLING METHOD: 3 1/4" I.D. HSA
HOLE DIA. (inches): 8"
CORE SIZE: NX
BACKFILL: CUTTINGS
AIR MONITORING INSTRUMENT: NA
CASING ELEVATION: NA
GROUND ELEVATION: 891.25
KEY #: NA
COMMENTS/PROBLEMS:

SHELBY/BAG: NO
WELLHEAD STICKUP: NA
OUTER CASING: NA
DEVELOPMENT METHOD: NA
RESULTS: NA
YIELD: NA
SURFACE PROTECTION: NA

WATER LEVELS
OPEN BOREHOLE BEFORE CORING: DRY
OPEN BOREHOLE @COMPLETION: NA
OPEN BOREHOLE @24 hrs: NA
WELL: NA
WASTE HANDLING:

SAMPLE/ CORE RUN	RECOVERY	BLOW COUNTS RQD	PID (ppm)	DEPTH (feet)	GRAPHIC LOG	MATERIAL DESCRIPTION	ELEVATION (MSL)	BAG SAMPLES/ SHELBY TUBES
				0				
☒	1.3	11–4–2	12.8	1	▨	Black clayey SILT, with medium to coarse sand, moist, medium stiff. (FILL)		
				2				
☒	1.5	5–5–3	1.2	3	▨	Tan clayey SILT, with coarse sand and rock fragments, moist, medium stiff (FILL)		
				4				
				5			886.2	
☒	1.5	8–2–8	2.4	6	░	Brown fine sandy SILT, moist, very stiff (FILL)		
				7				
				8				
☒	0.4	50/0.4	0.7	9		Red weathered SANDSTONE. Refusal at 9.4'. Bottom of boring at 9.4 feet.		
				10			881.2	
				11				
				12				
				13				
				14				
				15			876.2	
				16				
				17				
				18				
				19				
				20			871.2	

BORING #: B–22
PROJECT #: 200144



DRILL LOG FOR TEST WELL	
BLACK TOP AND GRAVEL	0'-1'
BROWN SHALE AND CLAY	1'-7'
RED SHALE AND CLAY	7'-14'
RED SHALE	14'-31'
BROWN SHALE AND CLAY	31'-33'
BROWN SHALE	33'-34'
GRAY SANDY SHALE	34'43'
BROWN SHALE	43'-51'
GRAY SHALE	51'-61'
DARK GRAY SHALE	61'-66'
GRAY SHALE	66'-73'
RED SHALE	73'-77'
GRAY SHALE	77'-86'
GRAY SANDY SHALE	86'-102'
RED SHALE	102'-129'
GRAY SHALE	129'-155'
RED SHALE	155'-157'
GRAY SHALE	157'-161'
DARK GRAY SHALE	161'-164'
GRAY SHAE	164'-187'
GRAY SAND SHALE	187'-238'
SAND ROCK	238'-352'
GRAY SANDY SHALE	352'-371'
GRAY SHALE	371'-374'
RED SHALE	374'-391'
RED AND GRAY SHALE	391'-417'
GRAY SANDY SHALE	417'-436'
SAND ROCK	436'-447'
GRAY SANDY SHALE	447'-457'
DARK GRAY SHALE	457'-494'
SAND ROCK	494'-502
GRAY SANDY SHALE	502'-510'

[A14] Borehole Sizing

GEOTHERMAL VERTICAL GROUND LOOP DESIGN

Project: Phipps Center for Sustainable Landscapes
Job Number:
Date: 02/25/12
User: Wentz

INPUT DATA

Total Building Load (Ton)=	50.49	**Bldg Area**	24000	Sq Ft
Outdoor Design Temp. (°F)=	90	**Sq. Ft / Ton**	558	
Indoor Design Temp. (°F)=	75			
Balance Temp. (°F)=	65			
Total Heat Pump Capacity (Ton)=	33			
$\text{COP}_{\text{COOLING}}$=	3			
Pipe Resistance (Hr-Ft-°F/BTU)=	0.048			
Soil Resistance (Hr-Ft-°F/BTU)=	0.25			
Average Water Temp. (°F)=	70			
Mean Earth Temp.(°F)=	55			

BIN DATA

Design Month: July
Location: PITTSBURGH

BIN Range		**Mean**	**Hours**	**WB(°F)**
95	99	97	0	0.0
90	94	92	6	71.3
85	89	87	14	70.1
80	84	82	89	69.7
75	79	77	98	66.5
70	74	72	125	64.8
65	69	67	140	63.2
60	64	62	187	60.9
			659	

CALCULATIONS

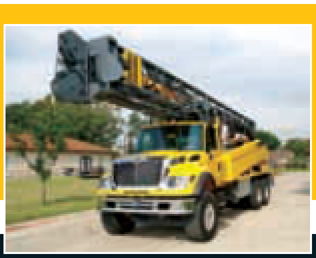
BIN Range	**Bldg Load Tons**	**Heat Pump Hours**
95/100	91.73	0.00
90/95	77.40	14.07
85/90	63.07	26.76
80/85	48.73	131.43
75/80	34.40	102.16
70/75	20.07	76.01
65/70	5.73	24.32
		374.75

Run Fraction= 0.50
Ground Loop Heat Exchanger Length(Ft/Ton)= 160.11
Total Ground Loop Length= 6884.68

Bores Required:	**Depth (Ft)**	**Number**
	400	17
	375	18
	350	20
	325	21
	300	23
	250	28
	200	34
	600	11
	500	13.76936

[A15] Borehole Drills

T3W and T3WDH



GENERAL SPECIFICATIONS

	T3W	T3WDH
Pullback Options	**Pullback** – 40,000 lb / 18 144 kg **Pulldown** – 25,000 lb / 11 340 kg	**Pullback** – 70,000 lb / 31 751 kg **Pulldown** – 30,000 lb / 13 608 kg
Feed System	Single Cylinder, Cable Feed D:d Ratio 28:1, ⅞ in. / 22 mm cable Drill Feed Rate: 20 ft./min. / 6.1 m/min. Fast Feed Up/Down: 150 ft./min. / 45.7 m/min.	Twin Cylinder, Cable Feed D:d Ratio 28:1, ⅞ in. / 22 mm cable Drill Feed Rate: 20 ft./min. / 6.1 m/min. Fast Feed Up/Down: 150 ft./min. / 45.7 m/min.
Derrick	Capacity: 45,000 lb. / 20 412 Kg Main Cord Length: 35 ft. 6 in. / 10 820 mm Head Travel: 27 ft. 4 in. / 8 330 mm Width: 36 in. / 914 mm Depth: 28 in. / 711 mm	Capacity: 75,000 lb. / 34 019 Kg Main Cord Length: 37 ft. 6 in. / 11 430 mm Head Travel: 27 ft. 4 in. / 8 330 mm Width: 36 in. / 914 mm Depth: 28 in. / 711 mm
Standard Carrier	**Standard** – Navistar 7600, 6 x 4 Caterpillar C13 Diesel Engine 380 hp / 283 kW @ 2100 RPM 21 ft. 2 in. / 6 452 mm wheelbase 68,000 lbs. / 30 844 kg GVWR **Optional** – 410 hp, 908LL Transmission	**Standard** – Navistar Paystar 5600i, 6 x 4 Caterpillar C13 Diesel Engine 380 hp / 283 kW @ 2100 RPM 21 ft. 2 in. / 6 452 mm wheelbase 68,000 lbs. / 30 844 kg GVWR **Optional** – 410 hp, 908LL Transmission
Drawworks **Single Line** **Bare Drum**	**Standard** – 18,000 lbs. / 8 165 kg 165 ft./min. / 50 m/min **Optional** – 30,000 lbs. / 13 608 kg 150 ft./min. / 45 m/min	**Standard** – 18,000 lbs. / 8 165 kg 165 ft./min. / 50 m/min **Optional** – 30,000 lbs. / 13 608 kg 150 ft./min. / 45 m/min
Rotary Head	**Standard** – 5,500 ft.-lbs. / 7 458 Nm @ 145 RPM Single-Speed Rotary Head **Optional** – 5,500 ft.-lbs. / 7 458 Nm @ 145 RPM Two-Speed Rotary Head (Second Speed) 4,000 ft.-lbs. / 5 424 Nm @ 196 RPM **Optional** – 6,250 ft.-lbs. / 8 475 Nm @ 134 RPM Single-Speed Rotary Head **Optional** – 6,250 ft.-lbs. / 8 475 Nm @ 134 RPM Two-Speed Rotary Head (Second Speed) 4,650 ft.-lbs. / 6 310 Nm @ 180 RPM **Optional** – 8,000 ft.-lbs. / 10 848 Nm @ 105 RPM Single-Speed Rotary Head **Optional** – 8,000 ft.-lbs. / 10 848 Nm @ 105 RPM Two-Speed Rotary Head (Second Speed) 5,500 ft.-lbs. / 7 458 Nm @ 145 RPM	
Powerpack	**Option 1 – 900 CFM @ 350 PSI** – Caterpillar C15 diesel engine, 475 hp / 354 kW @ 1800 RPM IR HR2.5 over-under screw compressor, 900 CFM / 425 L/s flow, direct coupled 120 to 350 PSI / 8.3 to 24.1 bar, optional in/out compressor disconnect **Option 2 – 1070 CFM @ 350 PSI** – Caterpillar C15 diesel engine, 575 hp 421 kW @ 1800 RPM IR HR2.5 over-under screw compressor, 1070 CFM / 505 L/s flow with standard in/out box 120 to 350 PSI / 8.3 to 24.1 bar	
Options	Mud pumps Floating-spindle hub 6 x 6 Heavy-duty trucks Pipe spinner Sand reel Water injection	Single-pipe loader Service hoist DHD lube injection High-pressure air piping Drop-down axle Deck engine starting aid

Atlas Copco Drilling Solutions LLC.
2100 North First Street Garland, TX 75040
Phone: **1 972-496-7400**
Website: **www.atlascopco.com/ads**

[A16] Bore Hole Optimization Data

GSHP @ 100% Load | Cooling Tower @ 0% Load

Drill Depth	Total Length	# Boreholes	Depth Borehole	Days	Drilling $	Piping $	Grouting $	Labor $	Cooling Tower $	Total $	Area [sqft]
D > 325	6885	14	500	29.47	71224	9986	1721	33004	0.00	115935	3270
	6885	14	480	29.55	71418	9990.42	1721	33094	0.00	116223	3407
	6885	15	460	29.64	71629	9995.22	1721	33192	0.00	116537	3555
	6885	16	440	29.73	71859	10000.5	1721	33298	0.00	116879	3716
	6885	16	420	29.84	72111	10006.2	1721	33415	0.00	117254	3893
	6885	17	400	29.95	72389	10012.5	1721	33544	0.00	117666	4088
	6885	18	380	30.08	72695	10019.5	1721	33686	0.00	118122	4303
	6885	19	360	30.22	73036	10027.2	1721	33844	0.00	118628	4542
	6885	20	340	30.38	73416	10035.9	1721	34020	0.00	119194	4809
225 < D < 325	6885	22	320	23.69	50100	9668.11	1721	26530	0.00	88020	5110
	6885	23	300	23.89	50525	9679.15	1721	26755	0.00	88680	5451
	6885	25	280	24.12	51010	9691.77	1721	27012	0.00	89435	5840
	6885	26	260	24.38	51570	9706.34	1721	27309	0.00	90307	6289
	6885	29	240	24.69	52223	9723.33	1721	27655	0.00	91323	6813
D < 225	6885	31	220	18.15	31529	9363.6	1721	20330	0.00	62943	7433
	6885	34	200	18.59	32290	9387.7	1721	20820	0.00	64219	8176
	6885	38	180	19.13	33220	9417.15	1721	21420	0.00	65779	9084
	6885	43	160	19.79	34383	9453.97	1721	22170	0.00	67728	10220
	6885	49	140	20.66	35878	9501.3	1721	23134	0.00	70234	11680

GSHP @ 90% Load | Cooling Tower @ 10% Load [5 tons]

Drill Depth	Total Length	# Boreholes	Depth Borehole	Days	Drilling $	Piping $	Grouting $	Labor $	Cooling Tower $	Total $	Area [sqft]
D > 325	5377	11	500	23.01	55624	7798.8	1344	25775	1185.43	90542	2554
	5377	11	480	23.08	55775	7802.25	1344	25845	1185.43	90767	2660
	5377	12	460	23.14	55940	7806	1344	25922	1185.43	91012	2776
	5377	12	440	23.22	56120	7810.09	1344	26005	1185.43	91279	2902
	5377	13	420	23.30	56317	7814.57	1344	26096	1185.43	91572	3041
	5377	13	400	23.39	56534	7819.5	1344	26197	1185.43	91894	3193
	5377	14	380	23.49	56773	7824.95	1344	26308	1185.43	92250	3361
	5377	15	360	23.60	57039	7831	1344	26431	1185.43	92645	3547
	5377	16	340	23.72	57336	7837.77	1344	26569	1185.43	93087	3756
225 < D < 325	5377	17	320	18.50	39127	7550.53	1344	20720	1185.43	68741	3991
	5377	18	300	18.66	39458	7559.16	1344	20895	1185.43	69257	4257
	5377	19	280	18.84	39837	7569.02	1344	21096	1185.43	69847	4561
	5377	21	260	19.04	40275	7580.39	1344	21328	1185.43	70527	4912
	5377	22	240	19.28	40785	7593.66	1344	21598	1185.43	71321	5321
D < 225	5377	24	220	14.18	24623	7312.72	1344	15877	1185.43	49157	5805
	5377	27	200	14.52	25218	7331.54	1344	16260	1185.43	50153	6385
	5377	30	180	14.94	25944	7354.54	1344	16728	1185.43	51371	7095
	5377	34	160	15.46	26852	7383.29	1344	17314	1185.43	52894	7981
	5377	38	140	16.13	28020	7420.26	1344	18067	1185.43	54851	9122

GSHP @ 80% Load | Cooling Tower @ 20% Load [10 tons]

Drill Depth	Total Length	# Boreholes	Depth Borehole	Days	Drilling $	Piping $	Grouting $	Labor $	Cooling Tower $	Total $	Area [sqft]
D > 325	4055	8	500	17.36	41948	5881.37	1014	19438	1561.71	69843	1926
	4055	8	480	17.40	42062	5883.97	1014	19491	1561.71	70013	2006
	4055	9	460	17.45	42187	5886.8	1014	19549	1561.71	70198	2094
	4055	9	440	17.51	42322	5889.89	1014	19611	1561.71	70399	2189
	4055	10	420	17.57	42471	5893.27	1014	19680	1561.71	70620	2293
	4055	10	400	17.64	42634	5896.98	1014	19756	1561.71	70862	2408
	4055	11	380	17.71	42815	5901.09	1014	19840	1561.71	71131	2534
	4055	11	360	17.80	43015	5905.66	1014	19933	1561.71	71429	2675
	4055	12	340	17.89	43239	5910.76	1014	20036	1561.71	71762	2833
225 < D < 325	4055	13	320	13.95	29507	5694.14	1014	15625	1561.71	53402	3010
	4055	14	300	14.07	29757	5700.65	1014	15758	1561.71	53791	3210
	4055	14	280	14.20	30043	5708.08	1014	15909	1561.71	54236	3440
	4055	16	260	14.36	30373	5716.66	1014	16084	1561.71	54749	3704
	4055	17	240	14.54	30758	5726.67	1014	16288	1561.71	55347	4013
D < 225	4055	18	220	10.69	18569	5514.8	1014	11973	1561.71	38633	4378
	4055	20	200	10.95	19018	5528.99	1014	12262	1561.71	39384	4815
	4055	23	180	11.26	19565	5546.34	1014	12616	1561.71	40303	5350
	4055	25	160	11.66	20250	5568.02	1014	13057	1561.71	41451	6019
	4055	29	140	12.17	21131	5595.9	1014	13625	1561.71	42927	6879

GSHP @ 70% Load | Cooling Tower @ 30% Load [15 tons]

Drill Depth	Total Length	# Boreholes	Depth Borehole	Days	Drilling $	Piping $	Grouting $	Labor $	Cooling Tower $	Total $	Area [sqft]
D > 325	2919	6	500	12.49	30196	4233.72	730	13993	1,855.71	51008	1387
	2919	6	480	12.53	30279	4235.59	730	14031	1,855.71	51130	1444
	2919	6	460	12.56	30368	4237.63	730	14072	1,855.71	51263	1507
	2919	7	440	12.60	30466	4239.85	730	14117	1,855.71	51408	1576
	2919	7	420	12.65	30573	4242.28	730	14167	1,855.71	51567	1651
	2919	7	400	12.70	30690	4244.96	730	14221	1,855.71	51742	1733
	2919	8	380	12.75	30820	4247.91	730	14282	1,855.71	51935	1824
	2919	8	360	12.81	30965	4251.2	730	14349	1,855.71	52150	1926
	2919	9	340	12.88	31126	4254.87	730	14423	1,855.71	52390	2039
225 < D < 325	2919	9	320	10.04	21241	4098.94	730	11248	1,855.71	39173	2166
	2919	10	300	10.13	21421	4103.62	730	11343	1,855.71	39453	2311
	2919	10	280	10.23	21626	4108.97	730	11452	1,855.71	39773	2476
	2919	11	260	10.34	21864	4115.15	730	11578	1,855.71	40143	2666
	2919	12	240	10.47	22141	4122.35	730	11725	1,855.71	40573	2889
D < 225	2919	13	220	7.70	13367	3969.84	730	8619	1,855.71	28541	3151
	2919	15	200	7.88	13690	3980.06	730	8827	1,855.71	29082	3466
	2919	16	180	8.11	14084	3992.54	730	9081	1,855.71	29744	3851
	2919	18	160	8.39	14577	4008.15	730	9399	1,855.71	30570	4333
	2919	21	140	8.76	15211	4028.22	730	9808	1,855.71	31632	4952

[A17] Existing Full Geothermal Components Costs

COMPONENT	QTY	COST
Mobilization excavator	2.000	492
Mobilization support crew & equip.	2.000	344
Mobilization drill rig	2.000	160
Drill wells 6" diameter	14.000	9,030
Pipe loops 1 1/4" diameter	200.000	61,600
Pipe headers 2" diameter	1600.000	6,480
U-fittings for loops	14.000	300
Header tee fittings	100.000	3,795
Header elbow fittings	10.000	241.50
Excavate trench for pipe header	475.000	3,310.75
Backfill trench for pipe header	655.000	1,755.40
Compact trench for pipe header	475.000	1,111.50
Circulation pump 2 HP	1.000	9,765
Pump control system	1.000	1,885
Pump gauges	2.000	121
Pump gauge fittings	2.000	230
Pipe insulation for pump connection	12.000	111.24
Pipe for pump connection	12.000	683.40
Pipe fittings for pump connection	1.000	206.80
Pipe strainer for pump	1.000	426
Shut valve for pump	1.000	883
Expansion joints for pump	2.000	872
TOTAL		**103,803.59**

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