2013

Updated Final Report

American Art Museum

Hybrid Cooling System Analysis
and
Acoustical and Structural Analysis of New Mechanical Ductwork Layout

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04/21/2013

AMERICAN ART MUSEUM
NEW YORK, NY

Owner Representative: Withheld by the owner
Architect: Cooper, Robertson & Partners
Renzo Piano Building Workshop
Lighting Consultant: Arup Lighting
MEP Consultant: Jaros, Baum & Bolles
Structural Consultant: Robert Silman Associates, P.C.
Construction Manager: Turner Construction Company

Total Size: 195, 000 sq ft
Levels above Grade: 9 levels
Cost: ~$270M

CHEUK TSANG | MECHANICAL

Architecture
- Asymmetrical form
- Cantilevered entrance
- The largest column-free museum gallery
- Outdoor galleries on the rooftops

Structural System
- Caisson pile-supported foundation
- Long span beams framing system with the deck framing
- A saw tooth profiled roof with support trusses @ 4' spacing

Lighting/Electrical:
- Skylight & Motorized daylight shading device
- Centrol Lighting Control
- Building Voltage: 208Y/120 V
- Cogeneration system

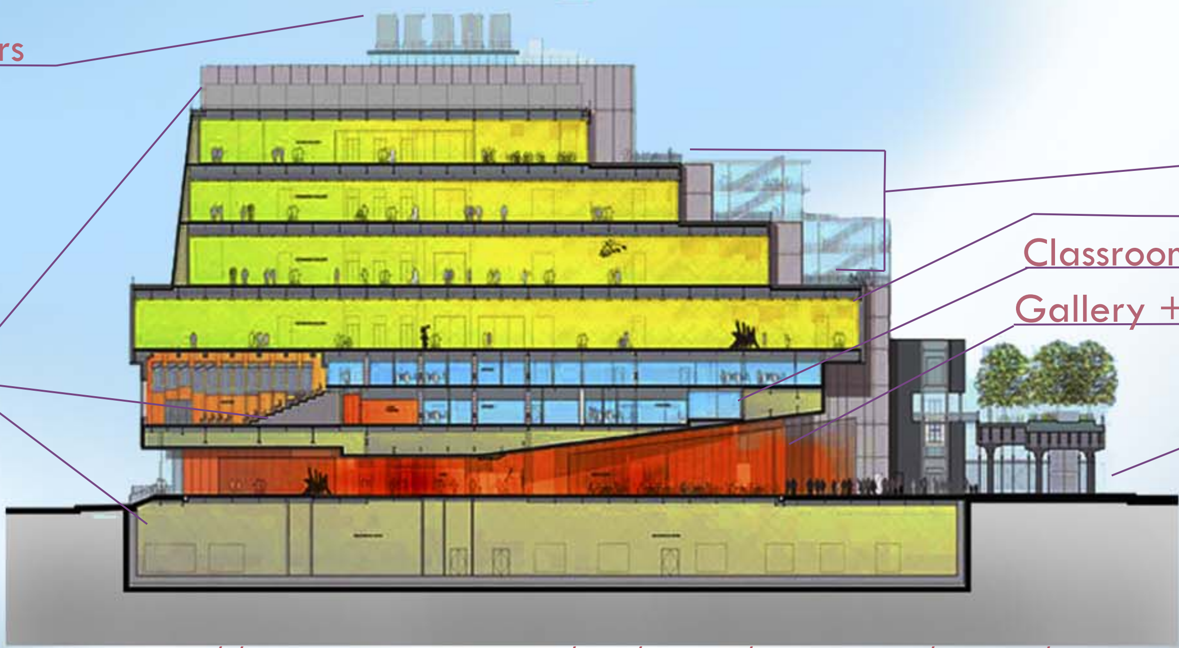
Mechanical System:

Cooling System
- 2 primary air conditioning systems
- Cold fluid applied roofing & greenroofs

Heating System
- Natural Gas Condensing Firetube Boilers
- Finned Tubed Hot Water Convectors

Ventilation
- VAV and CAV system for different zones

Control System
- Direct Digital Control (DDC)



My CPEP Web Add.: http://www.engr.psu.edu/ae/thesis/portfolios/2013/cyt5046/index.html

Contents

Thank you.

	For …
Turner Construction Company	**Offering** American Art Museum for my thesis project
Mr. Benjamin Gordon	**Providing** us building information
All the AE Professors	**Helping** and **Supporting** me in these years
Corey Wilkinson and Copy Center	**Computer troubleshooting**
Students shared the same thesis project with me (Sean Felton, Chang Liu, and Vincent Rossi)	**Sharing** news and ideas of AAM thesis project
Class of AE 222	**Building** a Revit model of AAM
My family and My Studio Roommates	**(Andrew Voorhees, Brice Ohl, Daniel Bodde, Jonathan Fisher, Jonathan Gallis, Mingao Li, Sarah Bednarick, etc.)**

Executive Summary

After analyzing the mechanical system of American Art Museum (AAM), two proposed ideas are conducted a further and detail analyses. The overall report is focused on the cost effectiveness of mechanical system.

Mechanical Depth – Hybrid Cooling System

Today, the price of No.2 oil is increasing. And, the utility company, ConEd, which is contracted with AAM, generates electricity by fueling oil. As other fuels, the applications provide either attractive incentive and/or rebate programs or relatively lower price. Therefore, a hybrid cooling system is suggested to seek for further saving with the highly energy efficient mechanical system. After conducting an exhaust search of the best hybrid system, it found that the best system is two natural gas-fired single stage absorption chillers and one electric centrifugal chiller with 5 year payback period.

Structural and Acoustical Breadths – New Ductwork layouts

AAM will consist of 3 mechanical floors. Two out of three floors will hold ventilation systems, which will serve different floor levels. The ventilation system on cellar level will serve conditioned air from cellar level to 7th floor, and the ventilation system on 9th floor will deliver air to 8th floor only. So, the proposed idea is to bring more AHU closer to the load with the consideration of minimizing the structural impact and acoustical impact. Overall, the result shows that the proposed duct work layout will save about $36,000 by reducing the amount of ducts.

After conducting the studies of two ideas, it shows that there are more potential savings of AAM mechanical system. For example, the fuel type of AAM should be more toward natural gas. And, the area of 9th floor would be increased and more AHUs can be put on 9th floor to be closer to the load, if the aesthetics of AAM is not affected.

Project Background

Name	American Art Museum
Location	New York, NY
Occupancy Type	Group A-3 Museum
Size	195000 sq. ft.
Function	Gallery, Classroom, Office, Auditorium, Restaurant
Floors	9 levels with cellar mezzanine and cellar level underground
Construction	Start in February 2012, End in late 2014
Main Architectural Feature(s)	1. Cantilevered entrance 2. The Biggest column-free gallery in New York 3. Ground floor restaurant and top floor café 4. Rooftops on Multiple levels for outdoor exhibition 5. Glazing system, pre-cast concrete, and stud wall as façade
Sustainability	Goal: LEED Gold Certification

Figure 1 Courtesy of the owner

Figure 2 Courtesy of the owner

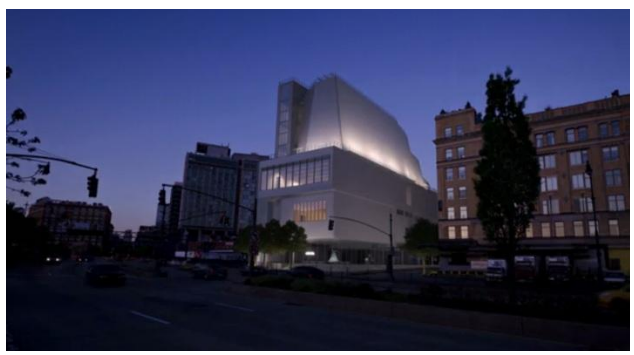


Figure 3 Courtesy of the owner

Mechanical overview

Heating and Cooling System

Cooling System

The main cooling system will consist of three 300 tons electrically driven centrifugal chillers with utilizing refrigerants R-123 or R-134a. This cooling system design of AAM takes a big advantage of free cooling. On the roof, there will be 5 cooling towers, and each of them will hold 200 ton cross-flow or counter-flow typed cells. A plate and frame free cooling heat exchange will be installed in this system.

The following figure is the monthly cooling load profile of AAM. The cooling load profile is similar to a profile of a typical commercial, because the AAM will be operated with the schedule similar to a commercial building.

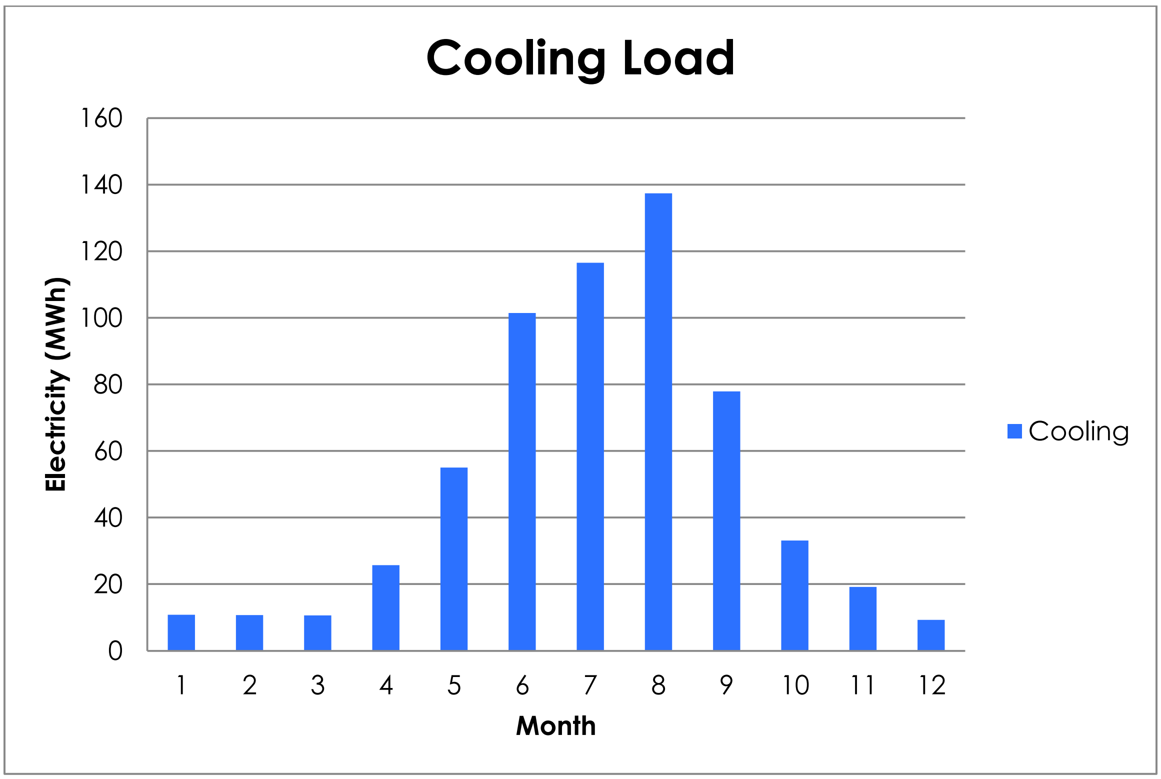


Figure 4 cooling load profile of AAM

Heating System

A hot water heating boiler plant also will be located on Cellar level. This plant will consist of 5 condensing boilers generating hot water with 150 °F supply water and 120 °F return water. The system will lower its pollution by built-in water treatment and a combustion chamber with gas filters.

Similar to the cooling system, the heating system will also have energy saving components. First, the waste heat will be sent to a 75kW cogeneration unit to produce extra electricity. Second, the radiation heaters will be conducted in finned tube convector along the exterior walls to reduce heat losses.

The heating load profile of AAM is shown as the following figure. This profile doesn't include the data of domestic water heating, because the domestic water load profile is not provided.

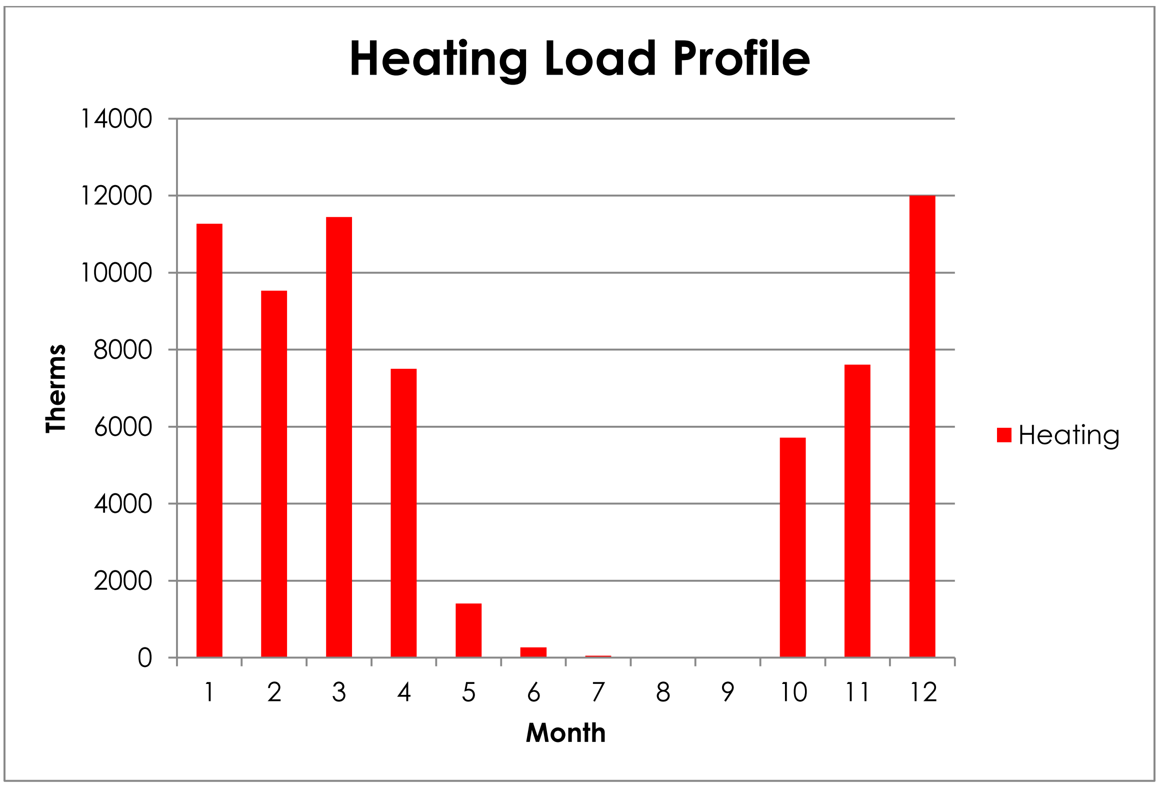


Figure 5 heating load profile of AAM

Ventilation

In American Art Museum, there will be 3 air conditioning systems as cooling systems located on the cellar Level (-1). Each of them will handle 1/3 of the load generated from Cellar to 7th levels. The other system is located in Level 9, which only manages the air condition in 8th floor. Because of the moisture sensitivity of artwork in AAM, both of the main air condition system will consist of fogged type humidifier systems. Also, the system will consist of 95% efficient filters, which stabilize the contaminant concentration levels. For energy saving purpose, some particular zones will be treated with variable air volume boxes, such as galleries.

Control System

The control system of American Art Museum, Direct Digital Control (DDC), will be programed to switch modes automatically, called "Auto" mode. DDC will also receive the data from all sensors, gradually adjust the damper position and provide the needed de/humidification. Moreover, the control system can be remotely controlled outside of AAM, which greatly increases the convenience.

Building Envelope

Finally, the AAM will gain good amount of LEED point on energy efficiency by developing a well-insulated building envelope. The building envelope is particularly designed to block solar heat gain from the sun. First, all the windows will be installed with motorized roller shades. Second, all the windows will be applied a layer low-e glazing.

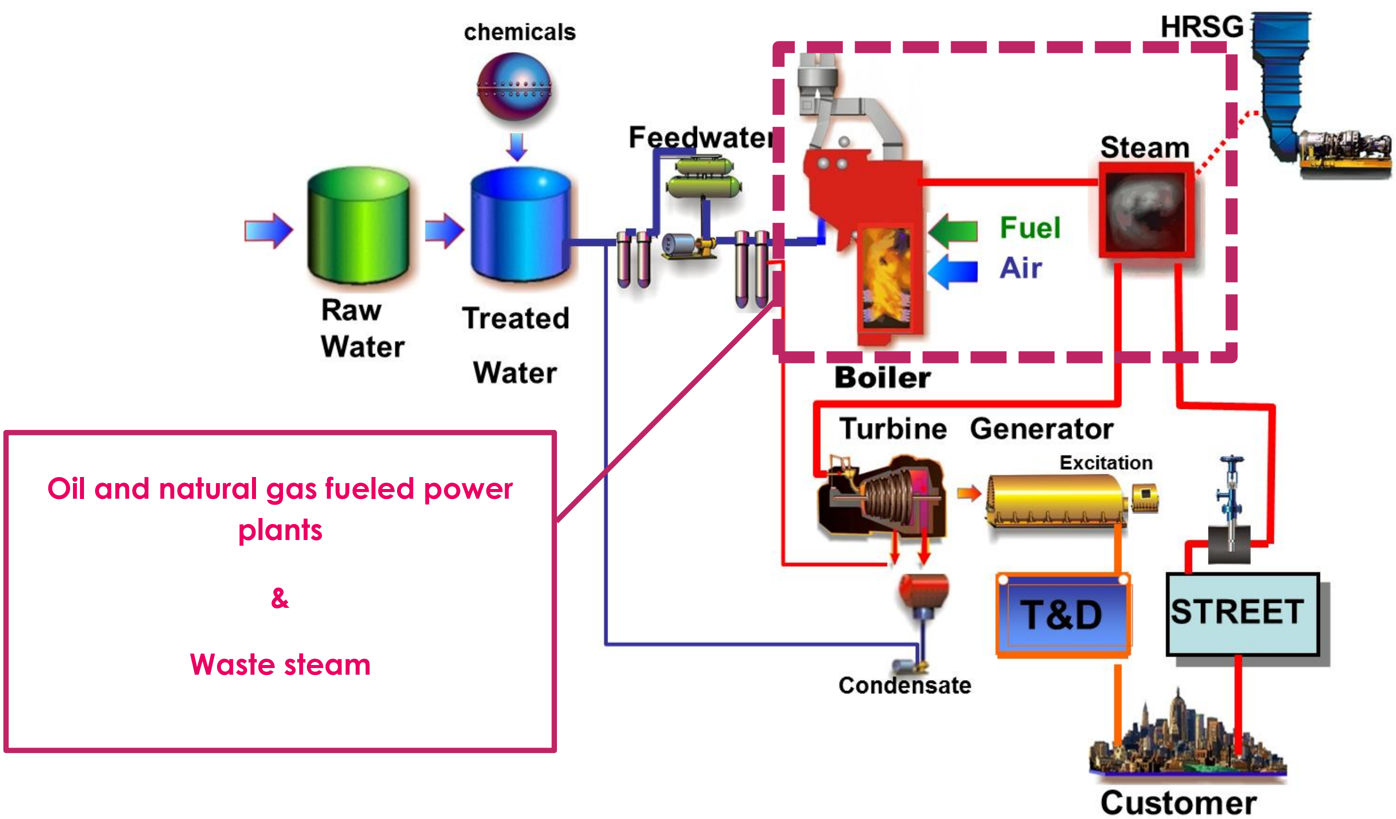
Proposed Cooling System --- Hybrid Cooling System

Purposes

In 2000s, there are several ASHRAE articles related to hybrid system (Smith, 2002). A hybrid system is a combination of cooling system with electricity and other fuel. The articles introduce a new combination of different chiller type to increase the capital cost and decrease the long term utility cost. This is the starting point of the hybrid system analysis.

This study conducts a hybrid system analysis with 3 fuel choices.

(1) Electricity is the original fuel choice of AAM cooling system.
(2) The steam is the most attractive choices, because of three rebate and incentive programs provided by ConEdison and the greenness of steam--- the steam is the waste heat produced from the oil power plant of ConEdison.



(3) Figure 6 'How steam is generated' from ConEdison

Although the LEED point in Energy and Atmosphere is fully obtained, the application of steam driven cooling system with the waste heat of ConEdison significantly lower the emission rate.

(4) Natural gas. Recently, as the price of electricity increase, the cost of natural gas decreases.

This analysis is focused on the cost effectiveness and the workability of the AAM cooling system. The workability of the cooling system should be ensured that installing a new type of chiller doesn't damage the cooling system as a whole. For example, the size of the chiller room should be fit for new chiller(s), and the supply temperature of a new chiller should match with the supply temperature of the electric chiller.

Since this analysis is to seek for a more economical hybrid system, the change of cooling system and mechanical room will be designed to make future saving within a short payback period.

Design Criteria

According to install a hybrid cooling system, there are two limitations:

(1) The selection of fuels. The fuel options in New York are electricity, natural gas and steam. The steam is an interesting fuel option, because of the incentive programs offered by ConEdison, which is the only company. Since AAM already has contracted with ConEdison for supplying natural gas and electricity. The cost prediction, which is used to conduct the sensitive analysis, is applied on the historical rate provided by the website of ConEdison.

(2) By adding a new type of chiller to the cooling system, it changes the characteristics of the cooling system, such as condenser inlet and outlet water temperatures. But, the characteristic changes do not include in this section. The change is concluded in the water.

Programs of Utility Rates and Installation Provided ConEd Steam

This section details the programs of ConEd steam. These programs convince building owners and mechanical engineers to consider the potential application of cooling system. Also, ConEd has a large amount of case studies and related information in its website. Therefore, the analysis in this report is conducted with these programs and determines if the offers are beneficial to AAM.

Incentive Program of Steam Cooling System

Comparing to the cost differences with an electric centrifugal chiller and other steam driven cooling equipment, the capital costs of a steam turbine and a steam driven double stage chiller are triple the cost of electric centrifugal chiller (Spanswick, 2003), and the cost of a single stage chiller is 30% more than the cost of an electric chiller (RSMeans Engineering Department, 2013). The incentive program helps the owner of a building to decrease the capital cost of steam cooling system. However, this amount of incentive only covers about 15~20% of the capital cost and doesn't include any single stage steam chiller.

Incentives

Steam AC Equipment Type	Capacity Range	Incentive Level ($ per ton)	Incentive Limit
Steam Turbine Chiller	Less than or equal to 1700 tons	$525	Up to 65% of the delivered equipment cost*
	Greater than 1700 tons	$470	
Double Stage Steam Absorption Chiller	All	$430	
Single Stage Steam Absorption Chiller	not eligible for incentives		

Notes:*Delivered equipment cost represents the total invoiced cost associated with purchase of the chiller equipment. This cost includes all delivery, labor, equipment, and taxes associated with purchasing the chiller equipment and delivering it to the property. Any additional customer costs including but not limited to site preparation, rigging, demolition, and equipment removal are not to be included in the total invoiced cost.

Table 1 Incentive program of installing a steam cooling system

Operation Saving: Steam Air Conditioning Summer Discount Program

The steam air conditioning summer discount program in ConEd offers a rate reduction in 2012 to promote their steam client addition or/and replacement of steam driven air conditioning equipment. 'Con Edison: steam operations - steam rates: incentive programs, it states that

> ***Steam Air-Conditioning Summer Discount Program***
>
> *"As described in SC 2 and SC 3 tariff Special Provisions D and E, when a customer installs a new or replacement steam air conditioning system, Con Edison will provide a $2.00 per 1,000 pounds discount for cooling steam."*
>
> *------- ConEd.*

This discount program is not cost effective, because the utility rates of steam in Service Classification No. 2 and No. 3 tariff are about $20~$50 per 1,000 lbs. steam.

Maintenance Service and Annual Incentive of a Steam Cooling System

There are difficulties of maintaining the steam cooling equipment due to the complexity. ConEd provides 24/7 steam maintenance and services, including flange, piping, and trap repair, and another incentive program of steam cooling system.

With high convenience and no profit making, the bill will be charged in the following month bill. In the ConEd website of 'Why Steam FQA', it claims that

> *"Labor cost: - $93 per hour from 7:30 a.m. to 3 p.m., Monday through Friday, excluding holidays, and $111 at all other times." ---- ConEd*
>
> (The list of Steam Repair Service is shown on the web page of ConEd, Con Edison: steam operations - maintenance & services.)

As the steam cooling system, ConEd also provides an incentive program associated with the service. Based on the claim of ConEd Maintenance Cost in 'Why Steam FQA', the incentive program doesn't significantly reduce the maintenance cost of a new steam cooling system. But, providing the service of remote monitoring steam trap behind the steam meter, it gives the client of ConEd a fully secured and trusted maintenance system.

Maintenance Incentive Type	Incentive Level ($ per ton)	Incentive Annual Limit*	Term Limit
Maintenance Service Contract	$5	up to $3000	Up to ten years on an annual schedule
Remote Monitoring Bonus	$2	Up to $1000	

**Or up to the amount of the actual service contract, whichever is less*

Notes: The maintenance incentive funding shall only be used to maintain the applicable chiller included under the Steam AC Chiller Incentive Program. The funding can be used for any and all maintenance activities associated with the particular chiller.

Table 2 an annual maintenance incentive of a steam cooling system[1]

However, due to lack the maintenance cost of the 2 chiller types, this analysis neglects the maintenance cost study and assumes that the maintenance cost of both system are the same.

Process of Utility Cost Predictions

Since this study heavily focus on the cost effectiveness of cooling system and associated with the utility cost, the prediction of utility must be accurate and closed to the future predictions provided by ConEdison and other related organizations. The approach of predicting is to find a regression equation with a reasonably high coefficient of determinant of utility cost. There are about 10 combinations of hybrid systems and 4 utility costs of each combination (electricity, natural gas, steam and water).

In the following sections, it explains in detail of conducting each utility prediction. The figures and the regression equations posted in this section are the calculations of the original cooling system, which predicts the utility cost from 2015 to 2035. Every combination has 3 common regression equation to calculation the monthly cost of water, steam, and natural gas and individual equation of electricity in order to restore accuracy.

[1] It is only eligible for the application of steam turbine or double stage absorption chiller.

Electric Cost prediction

AAM will have a contract with the ConEd for electricity supply. Therefore, the historical rates of ConEd can be used in detail utility prediction. Then, the future electricity bill is predicted from 2012 to 2035, which is a typical lifetime of a chiller.

Since in every few years, ConEd increases the electric rates and changes the structure of electricity cost. The prediction applies the regression with annual electricity bills in past and find the future electricity bills. For example, in the following figure, the total annual electricity bill first is calculated the past electricity rates from 2005 to 2012. Second, the regression is generated and based on the past electricity bill, which the regression equation of original cooling system is shown in Figure 7. The regression equation is a 2nd order equation and the function of year.

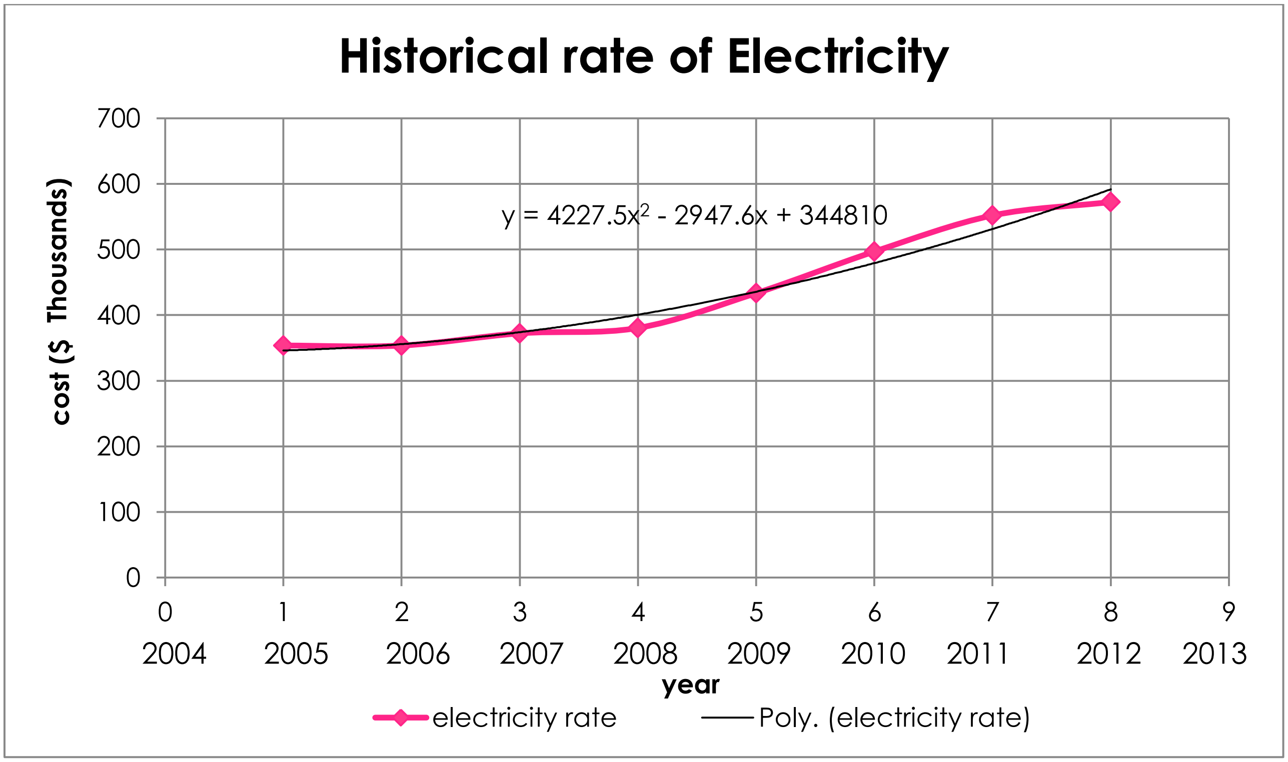


Figure 7 Electricity prediction of original cooling system

Every combination obtains its own regression equation to predict the electricity cost. All regression equations of combinations are in Appendix. C.

Although the error ranges of all the electricity bill predictions are less than 5%, the payback must be within a reasonable time period. It is because the error increases while the number of year is increasing.

Prediction of Steam Utility Rate

The data that ConEd provides in public is from past 4 years. Since the steam utility rate in all these years remains same billing structure, the calculation of the steam utility prediction is done on every basic items of the bill, such as customer charge and steam base rate.

The equations shown in the following 2 tables are used in the prediction of all combinations. Since the prediction is based on the rates in last 4 years, the regression of each item behaves linearly. It provides a more accurate prediction than using overall regression equation. Therefore, every combination has the same regression equation set.

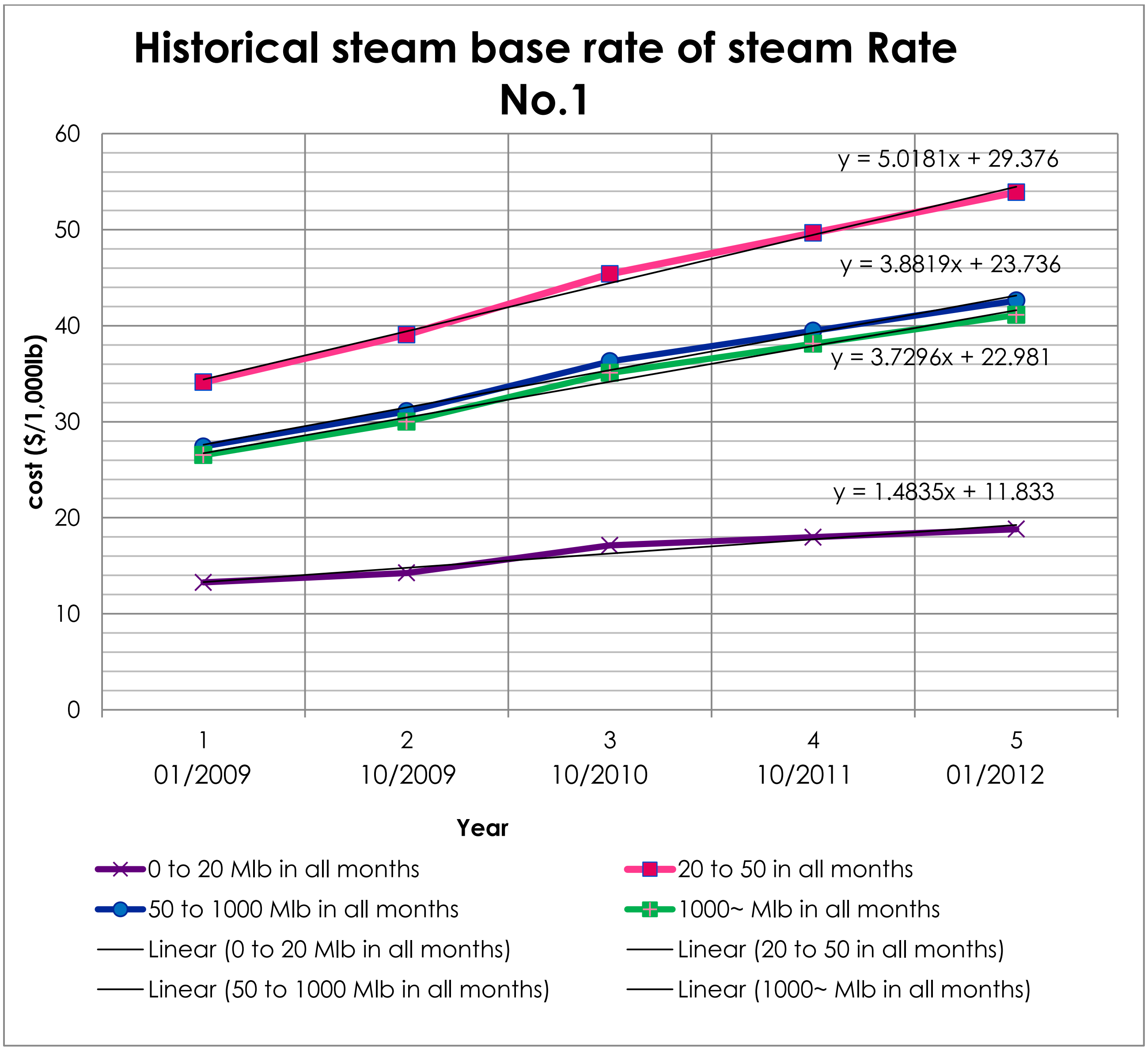


Table 3 Base rate of steam rate No.1

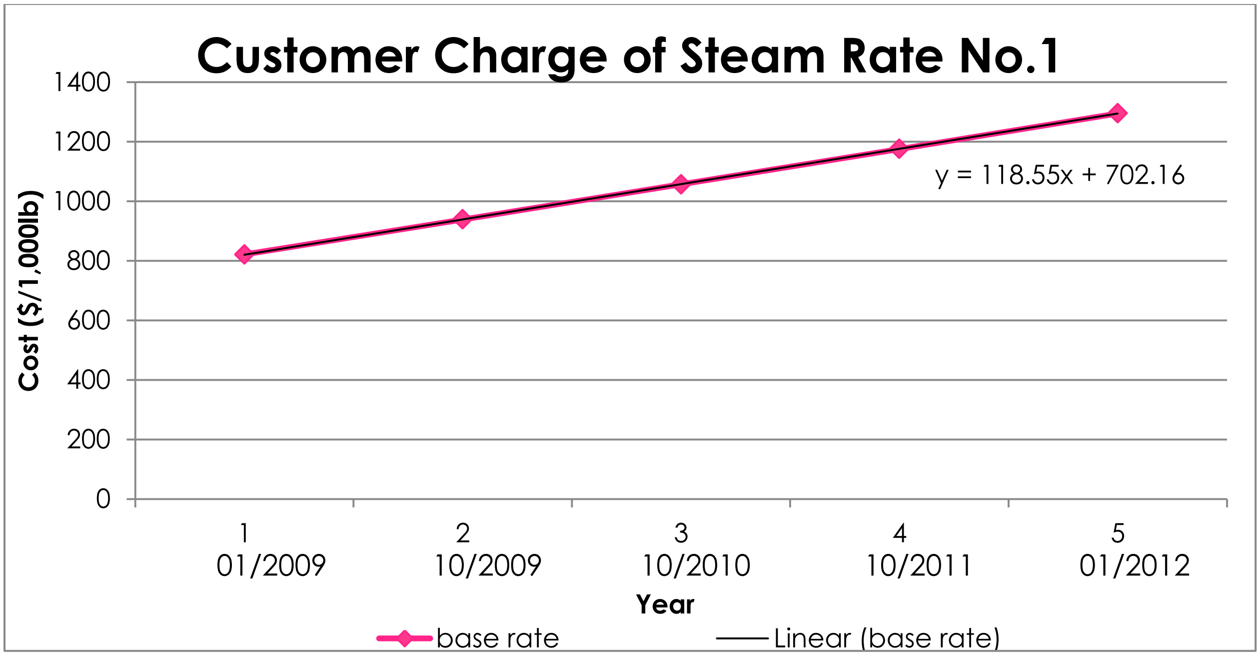


Table 4 Customer charge of steam rate No.1

The Calculation of Steam Utility Cost

Steam:

First 0~20 Mlb (1Mlb = 1000 lb.)

$$Cost/Mlb = 1.4835 \times (Year - 2009) + 11.833$$

Next 30 Mlb

$$Cost/Mlb = 5.0181 \times (Year - 2009) + 29.376$$

Next 950 Mlb

$$Cost/Mlb = 3.8819 * (Year - 2009) + 23.736$$

More than 1000 Mlb

$$Cost/Mlb = = 3.7296 * (Year - 2009) + 22.981$$

Customer Charge

$$Cost = 118.55 * (Year - 2009) + 702.16$$

Total: The sum of all charges = monthly steam cost

Prediction of Natural Gas Utility Price

The cost prediction of natural gas utility price is slightly different than the previous predictions. It is because it is difficult to stimulate a regression equation of natural gas utility cost. In 2012, the utility cost of natural gas behaves irregularly that the cost in 2012 is significantly lower than the previous and further years. So, the natural gas historical rate applied in the regression only takes the data after 2012 in order to restore the accuracy.

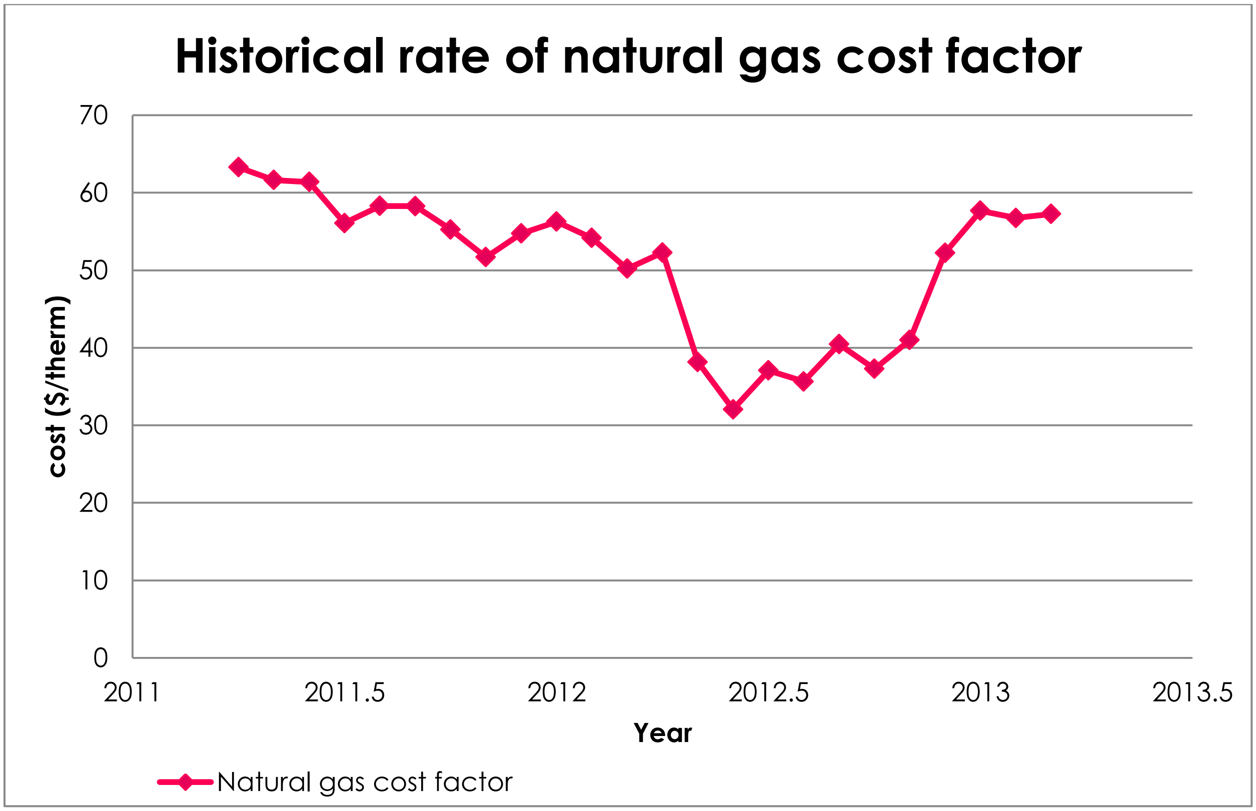


Figure 8 Historical rate of natural gas cost factor

As Figure 8 Historical rate of natural gas cost factor it shows that the natural gas cost of ConEdison consists of many large range fluctuations. After applying the shortened range of historical rates, the coefficient of determination, R^2 value, doesn't fall above 0.9. It is impossible to predict the future natural gas cost accurate. So, the other approach is conducted.

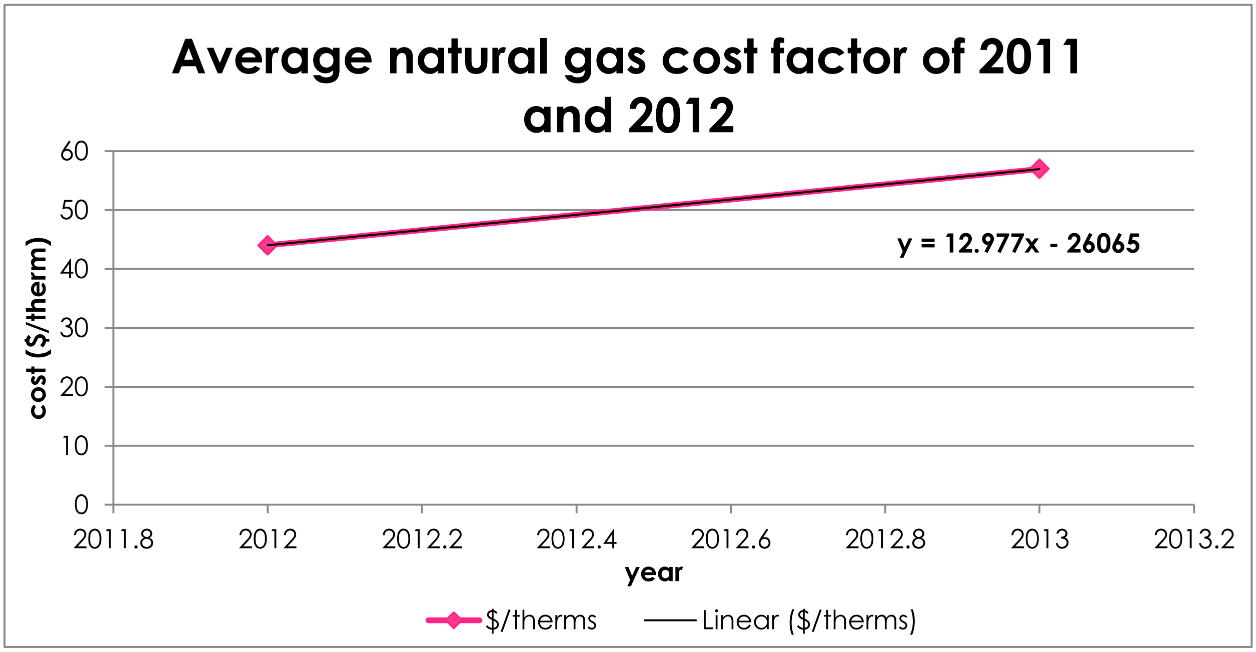


Figure 9 Average natural gas cost factor of 2011 and 2012

The approach is to average the cost factor of 2011 and 2012 and generate regression equations. So that, the prediction of natural gas cost factor behaves more stable and similar to the prediction of the ConEdison's Citygate cost of natural gas, Figure 10.

Con Edison's Citygate Cost of Gas for Firm Customers

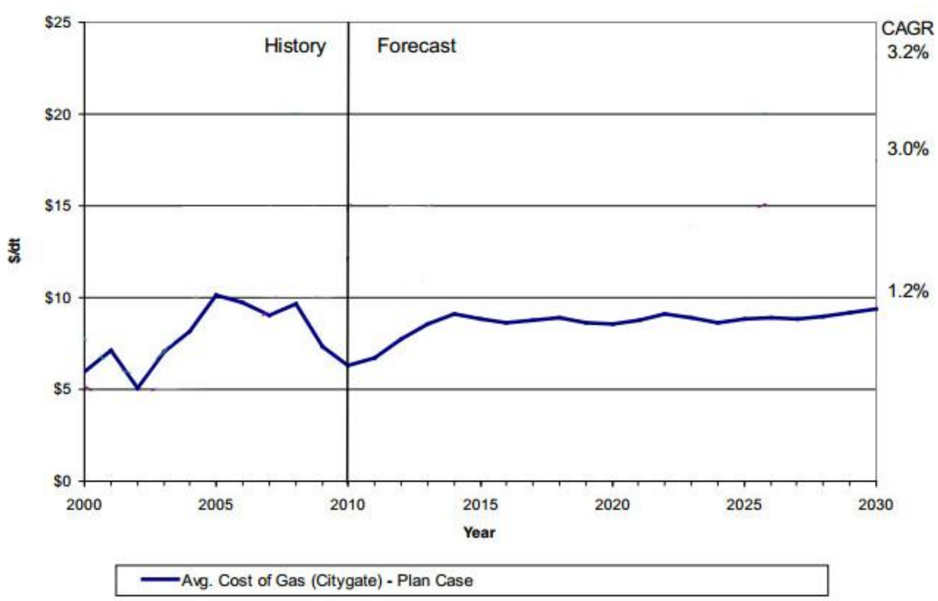


Figure 10 Con Edison's Citygate Cost of Gas for Firm Customers (ConEdison , 2010)

Water Cost prediction

According to the New York City Water Board, it provides the historical rate of water at least 50 years. And, this calculation of water prediction is applied with the historical rates in past 10 years. Figure 11 shows both water rate and sewer rate. Both rates are summed up and calculated the total cost of water used. Finally, the difference between the calculated cost of the 2nd power regression equation and the actual historical rate of water is with 5%. The water cost is well-predicted.

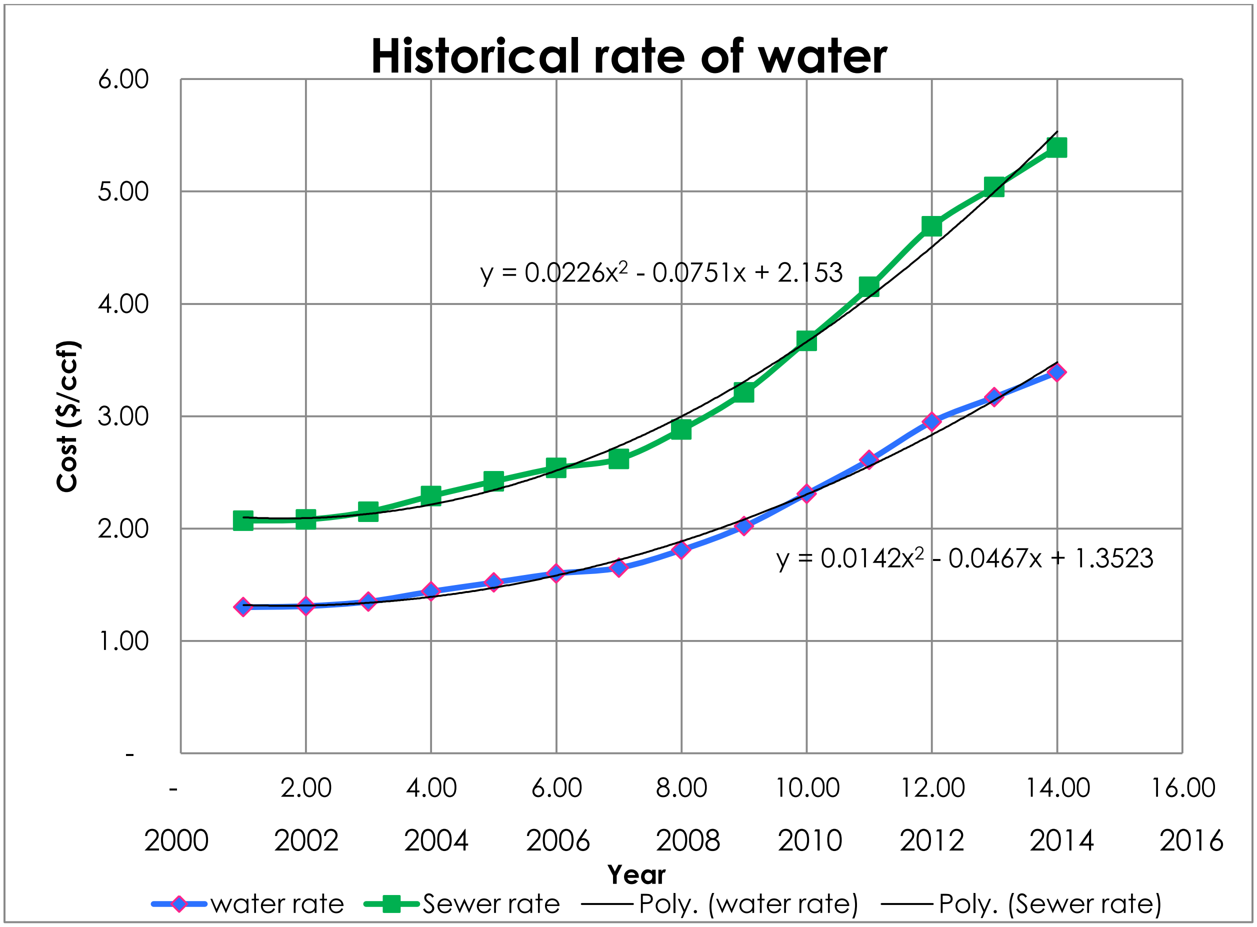


Figure 11 Historical rate of water

Water:

Water rate

$$Cost/748Gal = 0.0226 * (Year - 2000)^2 - 0.0751 * (Year - 2000) + 2.153$$

Sewer rate

$$Cost/748Gal = 0.0142 * (Year - 2000)^2 - 0.0467 * (Year - 2000) + 1.3523$$

Settings of Energy Stimulation

In this section, it provides information of energy stimulation and explains the uncertainty of the energy model used in this analysis.

Energy Model

The cooling system alternatives built in the energy stimulation are assumed that there is no other change of components, beside the chiller types. The cooling systems are includes all the major components of the original cooling system:

- Parallel piping layout with load distributed evenly
- Cooling towers
- A plate and frame free cooling heat exchanger
- 75 kW co-generator unit

And, the chiller types considered are straightly from the default items in Trace 700.

Assumptions Made in Analysis

Cooling system

The assumptions made in all energy models are:

- No secondary cooling and heating system
- No domestic water heating load
- The humidification system is not added
- No advance control system added
- The piping system of AAM is a primary/secondary variable flow piping layout, but the piping is treated as parallel piping in the models.
- The data of chiller will be based on the value of Trane catalog
- If the information needed for energy modeling is missing, the default value of Trace700 will be applied.

Prediction of utility cost

The assumption made in the utility cost predictions are:

- Although ConEd increases the utility every few years and changes the structure of utility costs, the predictions assume that the utility cost increase gradually. For example, the electricity utility structure was changed twice in past 20 years. In the prediction, it assumes that the electricity rate increase gradually.

Conclusion Potential inaccuracy of the stimulation

The assumptions simplify the energy stimulations, but these assumptions may cause inaccuracy of the results. And, it is unavoidable.

Result of the Hybrid Cooling System Analysis

In this analysis, it conducted an exhaust search associated with the absorption chiller without changing the number of chillers. So, the new cooling system doesn't affect the size of the chiller room in Cellar level. It shows that the best hybrid system is one electric and two natural gas chillers. And, the payback period is about 5 years.

The combinations of hybrid system studied are in the following layouts

Combinations of Hybrid System		
	Electric Chillers	Chillers of other fuel
Combination 1	3	0
2	2	1
3	1	2
4	0	3

Table 5 Combinations of hybrid system

The results and analyses of all hybrid system combination types are shown in the unit of "dollars", since "dollars" is a universe unit of utility.

The following figure shows the annual utility costs of all studied combinations in 2015, the first year after completing construction. The figure concludes that the hybrid system with the most potential saving is with natural gas, and the combination is No. 9, one electric chiller and 2 natural gas absorption chillers.

Combination Legend of Figure 12 Total Utility Cost in 2015 of All Combinations		
Combination No. #	Amount of … …	
	Electric chiller	Chiller of other fuel
1	3	0
	Electric chiller	**Steam** driven **single** stage absorption chiller
2	2	1
3	1	2
4	0	3
	Electric chiller	**Steam** driven **double** stage absorption chiller
5	2	1
6	1	2
7	0	3
	Electric chiller	**Natural gas** absorption chiller
8	2	1
9	1	2
10	0	3

Table 6Combination Legend of Total Utility Cost in 2015 of All Combinations

Best hybrid combination

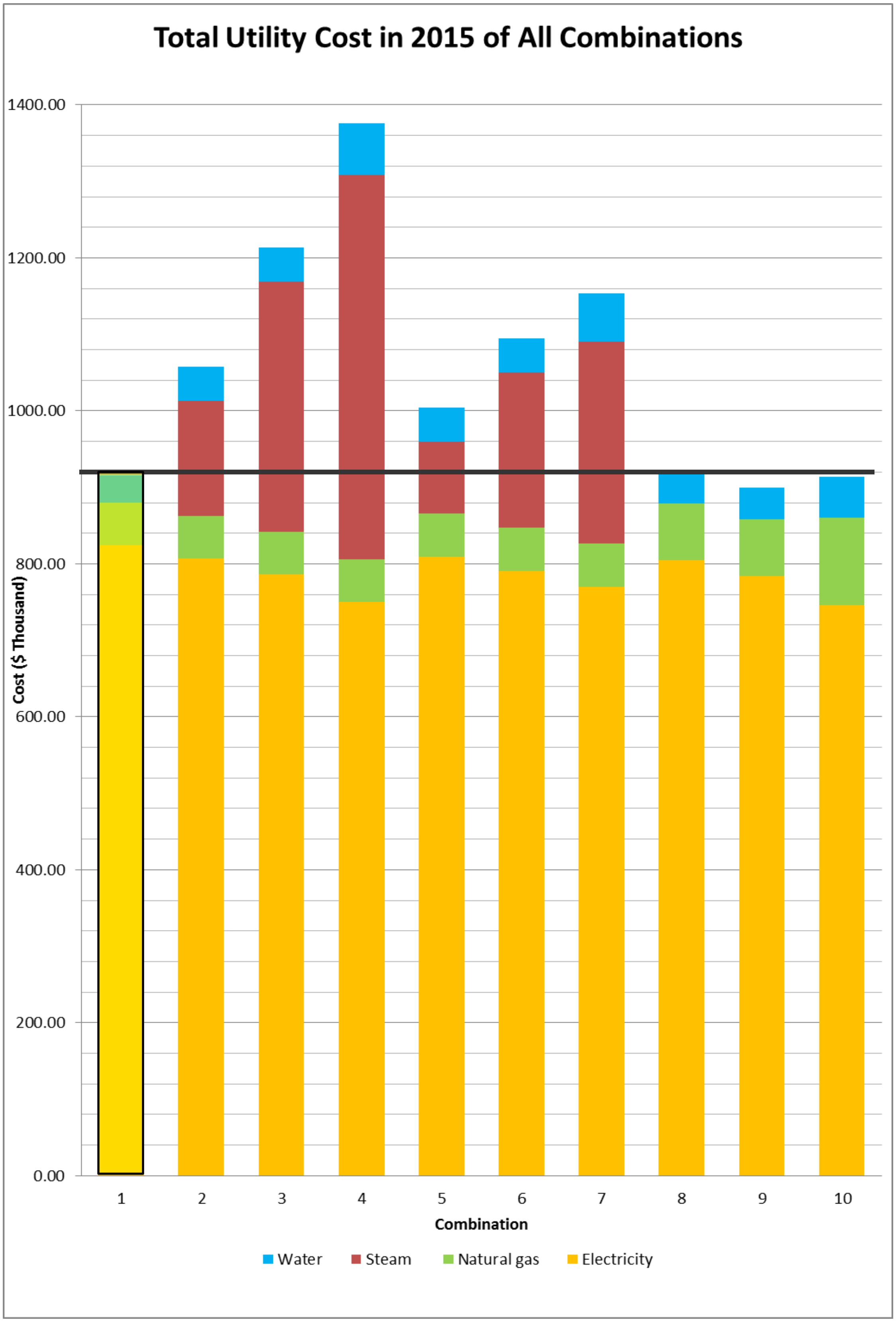


Figure 12 Total Utility Cost in 2015 of All Combinations

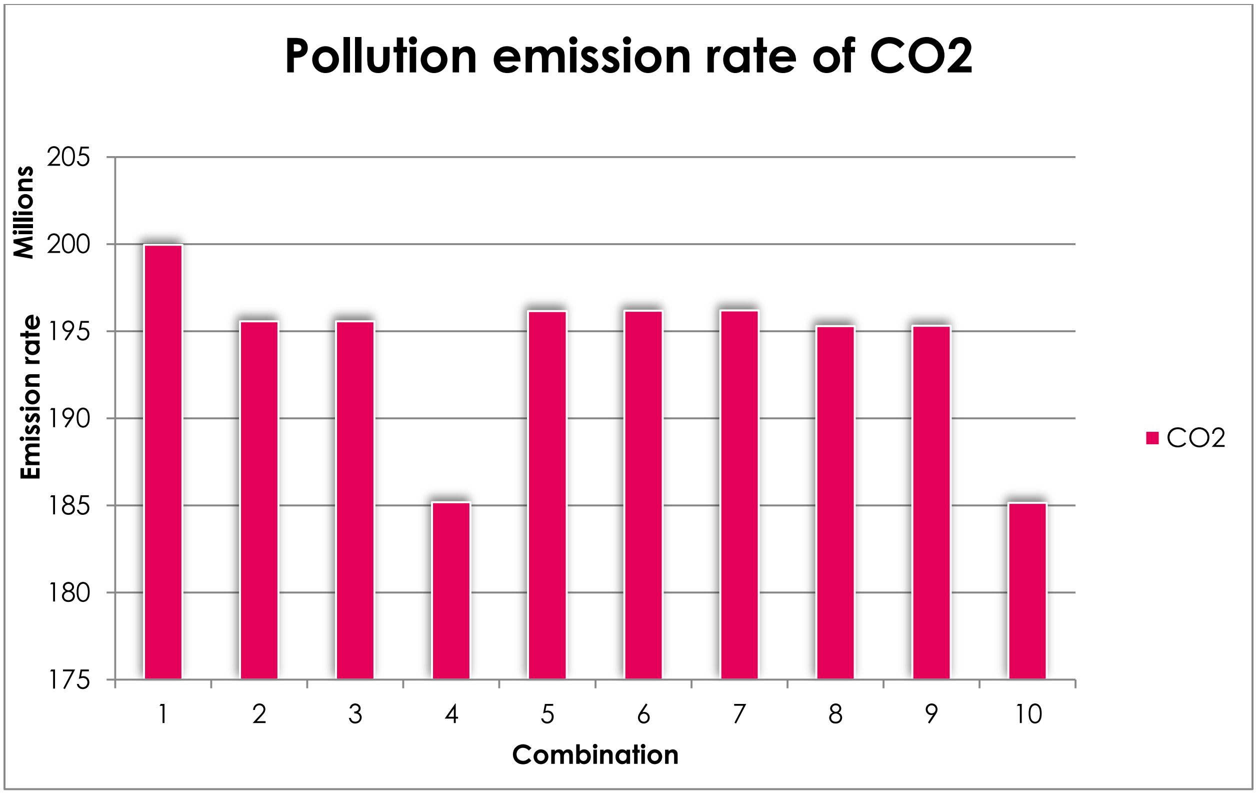


Figure 13 Pollution emission rate of CO2

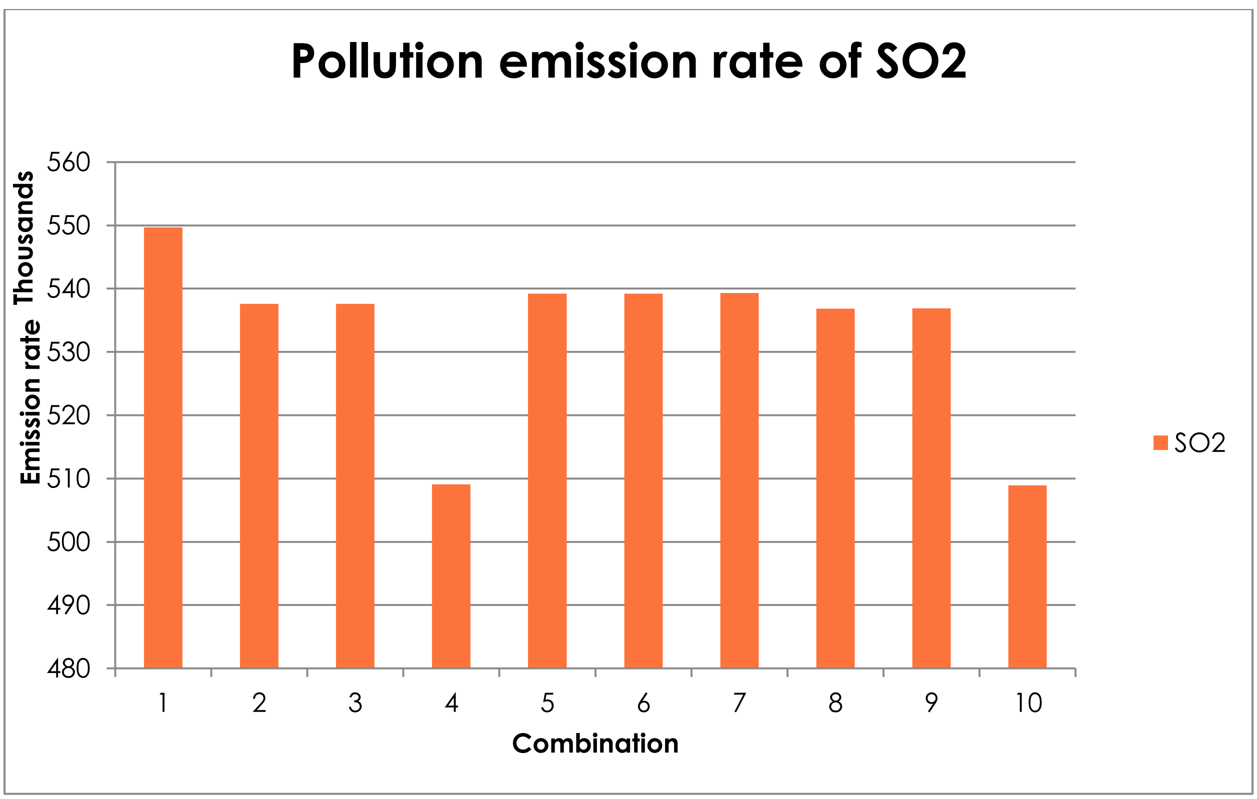


Figure 14 Pollution emission rate of SO2

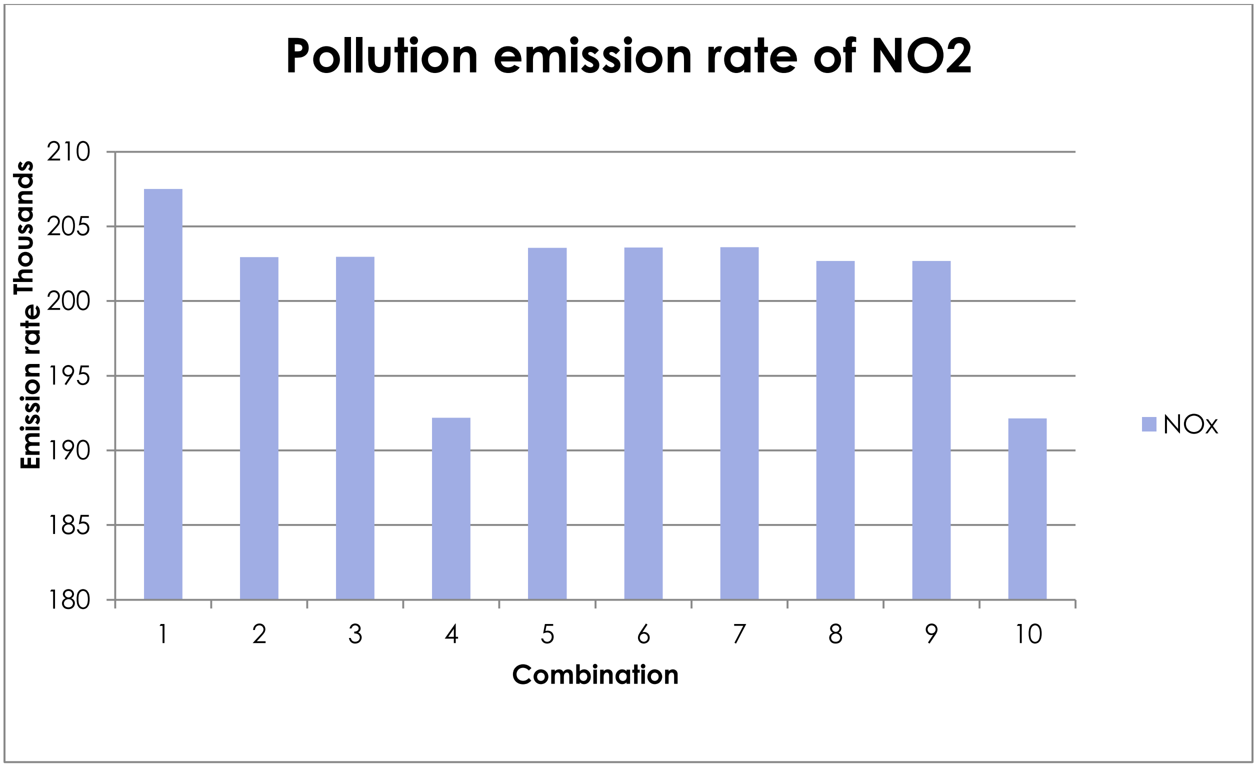


Figure 15 Pollution emission rate of NO2

Based on the sensitive analysis and lifecycle cost analysis, the combination of natural gas hybrid system with shortest payback period also is combination No. 9. It is able to recover the exceed capital cost within 5 years.

The following figure shows the profit made in a new cooling system compared to the original cooling system. The shaded area is the loss of the system. If the line of the combination falls in the white region, the combination will make profit. The calculation of profit is the saving with inflation rates subtracting the difference of capital cost between new and original cooling systems. In the calculation, the inflation rates applied are:

Inflation rates used in prediction calculations	
General inflation rate (Single present value)	2.3 %
Utility interest rates	Projected fuel price indices (including general inflation) in *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis –2011*

Table 7 Inflation rates used in prediction calculations (U.S. DEPARTMENT OF COMMERCE, 2011)

And, the capital costs are only included the cost of chillers, which references from the RS Mean (RSMeans Engineering Department, 2013).

Capital cost of Chillers					
Item No.#	Description	Capacity (tons)	Material ($/unit)	Labor ($/unit)	Total ($/unit)
	Centrifugal Typed Water Chiller				
0280	electric chiller	400	129500	15300	144800
	Steam Indirect-Fired Absorption Water Chillers				
0300	Single stage absorption	354	325500	16400	341900
0300	Double stage absorption chiller	354	585900	20500	606400
	Natural Gas Direct Fire Absorption Water Chillers				
4150	Water cooled, duplex chiller	300	219500	16100	235600

Table 8 Capital cost of Chillers (RSMeans Engineering Department, 2013)

The figure describes that the only combination with profits are combination No. 9 and No. 5. Combination No.9 has two natural gas chillers and one electric chiller, and the payback period of it is about 5 years. Next, Combination No.5 has one single staged absorption chiller and two electric chillers. But, the payback period is 19 years, which is too long.

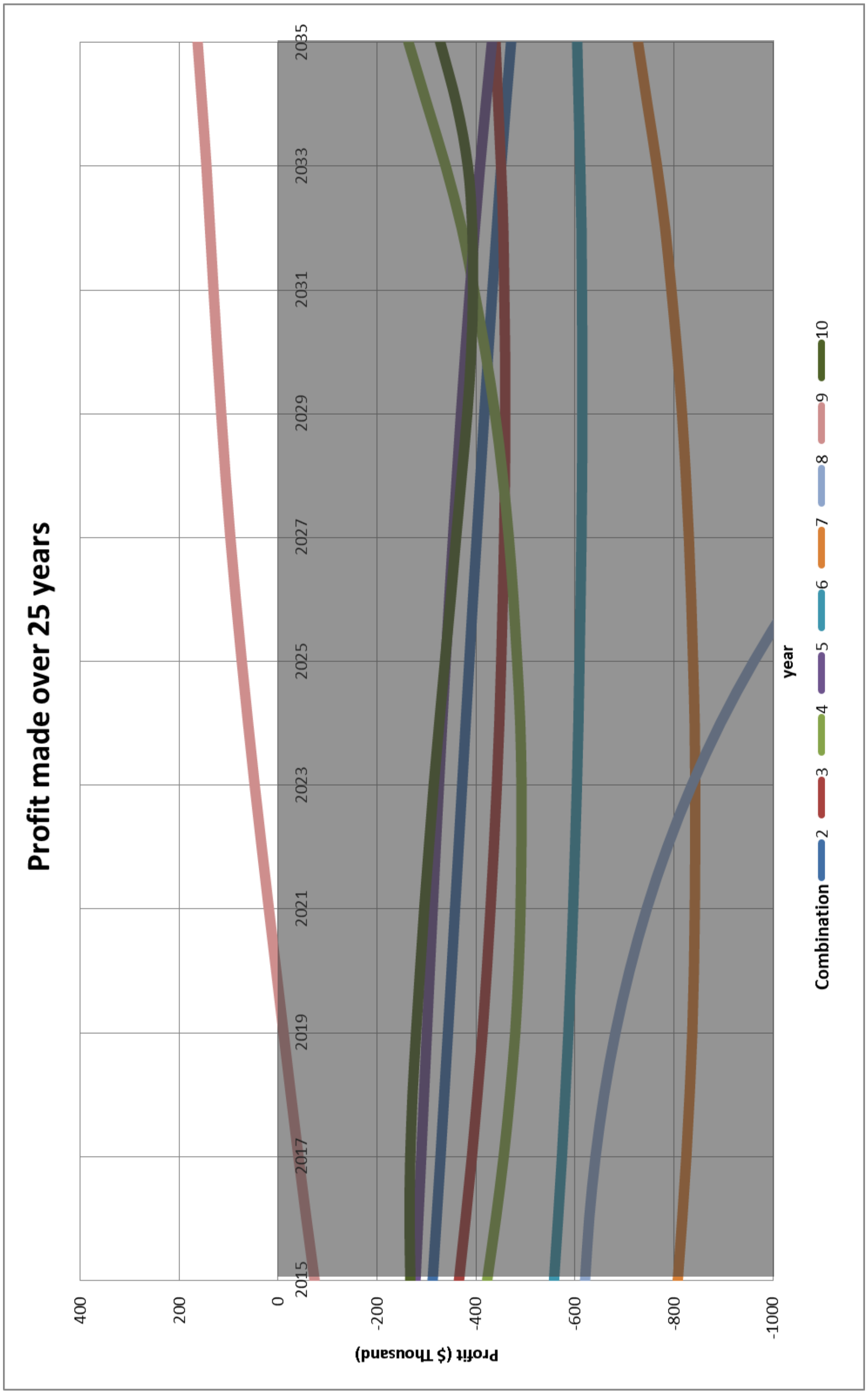


Figure 16 Profit made over 25 years

Natural Gas Hybrid System vs. Electric Cooling System

Combination No. 9 is the best of overall combinations. It is because the price of natural is cheaper than the price of electricity now and in the future. The reason why the HVAC engineers may neglect this selection is that it is difficult to compare the prices of these two utility with different utility companies. Also, the calculation of these two utility cost is tedious, since the structure of utility cost calculation and the cost itself are changed every few years. In order to predict the future utility cost of a particular company, it requires historical rates of several years, which sometimes isn't opened to public. Therefore, the extra cost of natural gas fired chiller can be made up within 5 years.

Natural Gas Hybrid System vs. Steam Hybrid System

The natural gas hybrid system in this analysis is more energy efficient and cheaper than the steam hybrid system, because

- A natural gas fired absorption water chiller is cheaper than both single and double staged steam absorption chillers.

Cost Different Between Natural Gas and Steam Absorption Chillers

Chiller types	Cost	Δ %
Natural gas direct-fired (300 tons)	$ 235,600	---
Single stage indirect fired (354 tons)	$ 341,900	+45%
Double stage indirect fired (354 tons)	$ 606,400	+157%

Table 9 Cost different between natural gas and steam absorption chillers

- The coefficient of performance (COP) of natural gas chiller is higher.

Coefficient of Performance of Natural Gas and Steam Absorption Chillers

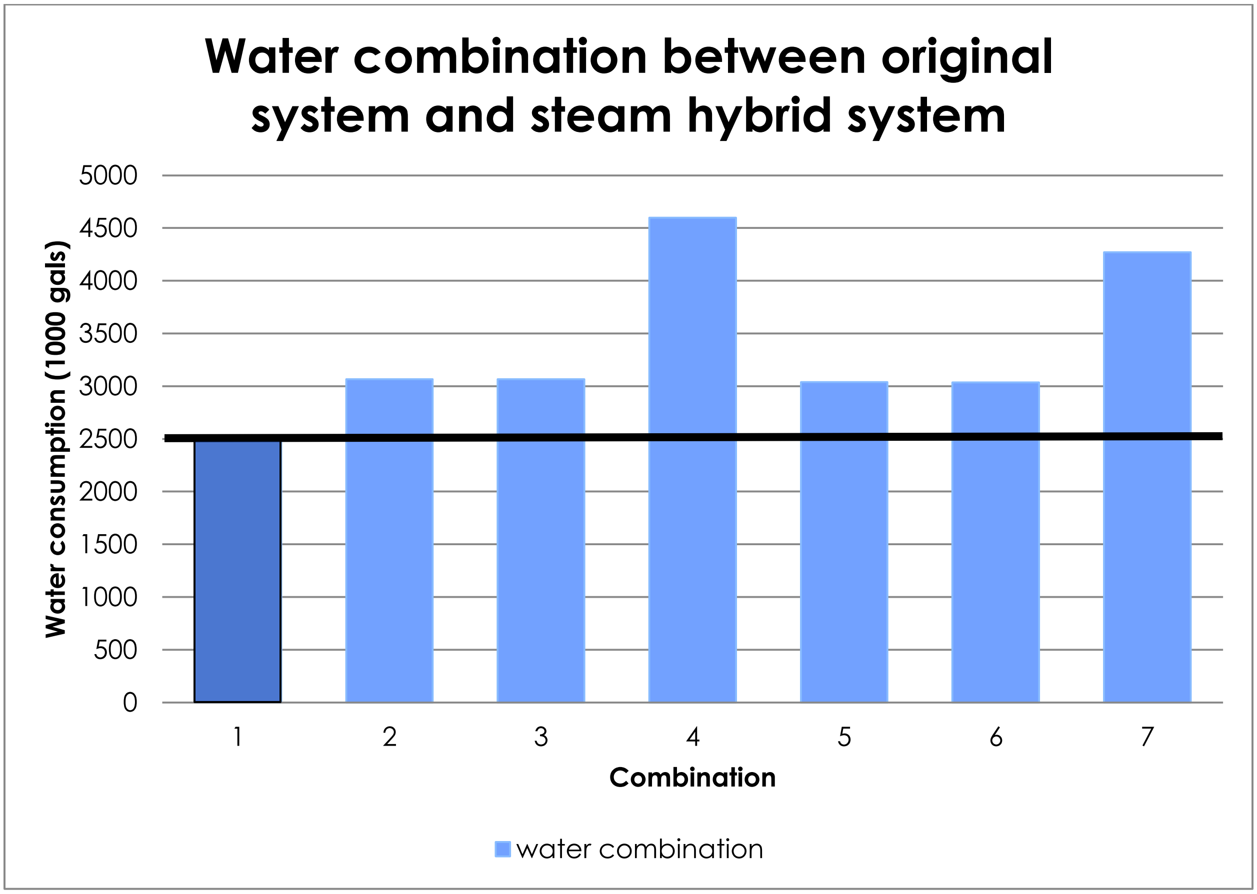
Chiller types	Coefficient of Performance
Natural gas direct-fired (300 tons)	1.01
Single stage indirect fired (354 tons)	0.7
Double stage indirect fired (354 tons)	1.23

Table 10Coefficient of Performance of Natural Gas and Steam Absorption Chillers

Steam Hybrid System vs. Electric Cooling System

The reasons why the combinations with steam chillers are not economical are:

- AAM will not be eligible for Steam Air-Conditioning Summer Discount Program, because AAM is only eligible for No.1 steam rate.
- Both single and double staged steam absorption chillers have too low COPs, because the COP of an electric chiller is 0.63.
- Since waste heat steam provides low quality heat, the system requires relatively large amount.
- Due to the difference of COPs, the makeup water consumption of cooling towers.



Steam Hybrid Systems - Double Staged vs. Single Staged Absorption Chiller

Although both sets of combinations are unable to overcome the original system, Combination No.1, the result shows that the combinations with single staged absorption chillers is more economical than the ones with double staged absorption. It is because the capital cost of a double staged absorption chiller is 100% higher than the cost of single staged absorption chiller. And, the Incentive Program of Steam Cooling System only covers 20% of the capital cost of a double staged steam absorption chiller, which is not enough to recover both capital cost by lowered steam usage.

Change of Cooling System Needed to Adopt the New Chiller

This section ensures if the characteristic of the best combination, No. 9, is able to work well in the cooling system of AAM without damaging other components. And, the information of original cooling system is provided by the mechanical drawing given by AAM. Then, the information of combination No. 9 is recommended from Trane website. It is because the characteristic of an absorption chiller in Trane website can well match with the energy stimulation of Trace 700, which is the product of Trane. If the new chiller doesn't match the parameter of system, the change of system or chillers will be needed.

Performance data comparison between electric and Trane natural gas chiller.1

	Chiller Type	Electric centrifugal chiller	Trane natural gas absorption chiller
	Cooling Capacity (Ton)	300	321
	Heating Capacity (MBH)	--	2799.3
	Refrigerant	R134-a	Absorbent: Lithium Bromide (LiBr) Refrigerant: Water
	Dimension (in)	172(L)x67(W)x82.1(H)	187.4(L)x113.4(W)x111.4(H)
	Operating weight (lbs.)	22436	27800
Chiller	Flow rate (GPM)	450	777.1
Chiller	Inlet water temperature (°F)	58	54
Chiller	Outlet water temperature (°F)	42	44
Chiller	Max. pressure drop (ft. H_2O)	8.9	25.6
Chiller	Number of passes	2	2
Condenser	Flow rate (GPM)	900	1391.3
Condenser	Inlet water temperature (°F)	85	85
Condenser	Outlet water temperature (°F)	95	94.46
Condenser	Max. pressure drop (ft. H_2O)	17	22.3
Condenser	Working pressure (Psig)	150	--
Condenser	Number of passes	2	Absorber: 2 Condenser: 1

Performance data comparison between electric and natural gas chiller.1			
Electrical	kW (Power factored)	195	--
	Voltage	208	460
	Phase	3	3
	Frequency	60	60
	kW/ton	.6	--
	Total full load Amp	631	10.6

Table 11 Performance data comparison between electric and Trane natural gas chiller.1

In this comparison, the highlighted rows show the major differences between two chillers.

Different Refrigerants

Both chiller types consist of different refrigerants. The electric chillers of AAM contain a safer refrigerant, R134a, and a natural gas fired chiller has lithium bromine as an absorbent and water as a refrigerant. However, lithium bromide is a corrosive solution, so it is requires an extra sensor and stricter mechanical room design for safety purposes. Therefore, the catalog referenced from Trane mentions a built-in inhibitor and a design suggestion of a mechanical room, which is similar to ASHRAE Standard 15—Safety Standard for Refrigeration Systems (Thermax Ltd.).

- The absorption chiller of Trane has a built-in corrosion inhibitor, lithium molybdate, and factory mounted on-line purging system. The on-line purging system is to purge any non-condensable gas into a storage tank to keep the corrosion rates low.
- The following table shows the major consideration of mechanical room layout.

Machine room layout consideration	
Electrical	All conductors should be made of copper.
Piping	Far gas fire system, the piping design pressure should be higher than the operation pressure.
	The piping should be installed with a stop valve, safety device, drain and sampling connections.
	If a cooling water pump is not installed with each chiller, this chiller should be connected with an auto-operated butterfly valve.
Control system	The chiller control panel should interlocking chilled water and cooling water of the absorption chiller.

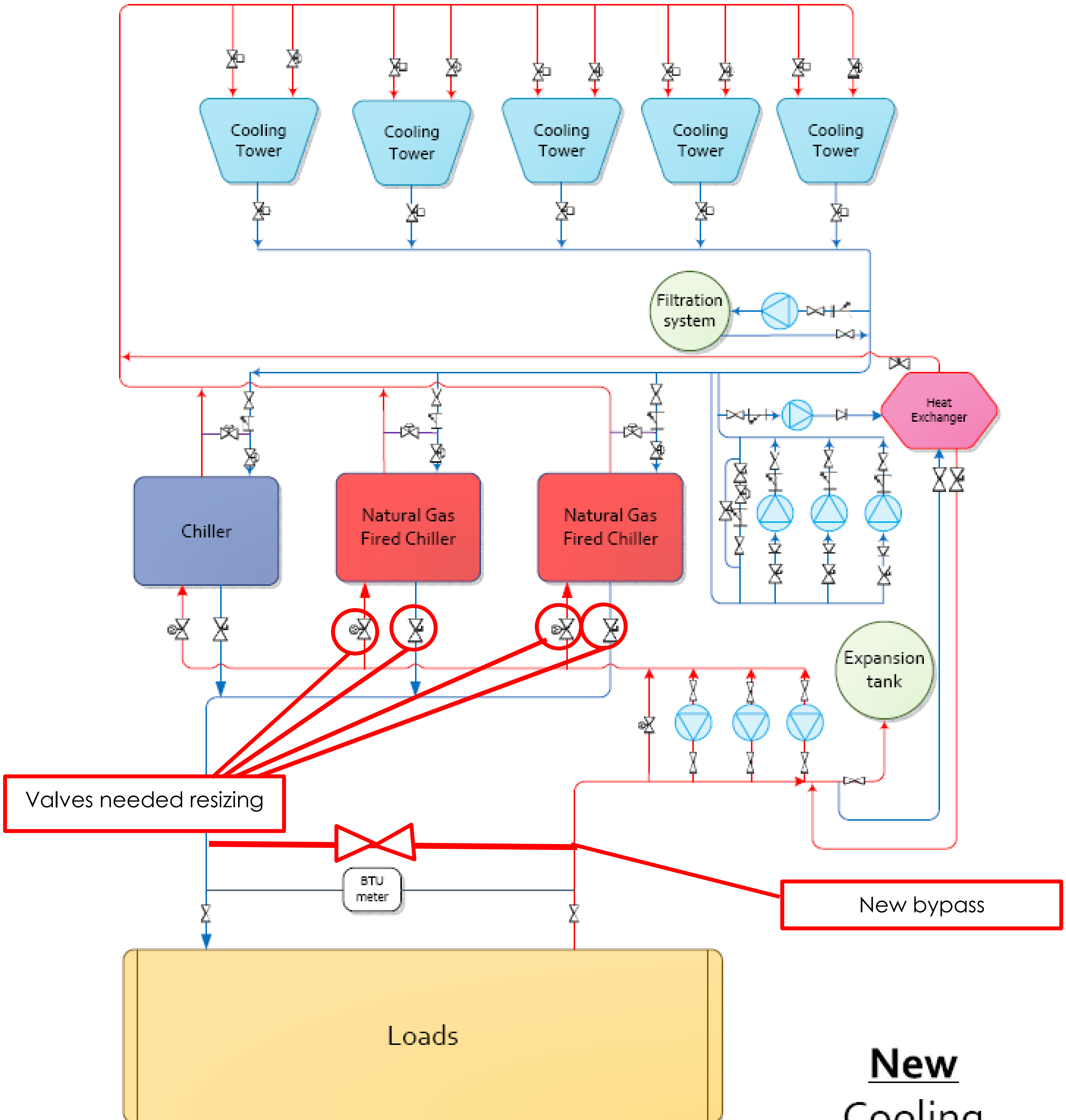
Table 12 Machine room layout consideration (Thermax Ltd.)

- ASHRAE Standard 15 states that
  - The door of the chiller room should be tight-fitting and opened outward.

- o There should be refrigerant sensors. The sensors should be located where refrigerant concentrates and coupled to alarm and mechanical ventilation.
- o The purge system and its relief must be vented outside, minimum 20 ft. away from ventilation openings and minimum 15 ft. above ground.

Different Flow Rates

In the comparison, the GPMs of both chillers are different. Therefore, the valves of the new chillers must be resized in order to handle bigger amount of flow. The following figure illiterates the new cooling system with two natural gas chillers, and the circled components are required resizing. The changes of cooling system are not significant, because the chosen absorption chillers are designed for variable frequency control. And also, the original piping system is Primary/Secondary Variable flow piping designed. This system is "desirable to have the flow rate in primary loop equal to or greater than the flow rate in the secondary loop". (Vogelsang, 2000)Although the natural gas chillers provide much higher flow rate, the flow can be regulated by the piping loop. Moreover, if needed, a new bypass between returning and supplying chilled water to load will be added.



New Cooling system

Figure 17 New cooling system of Combination No. 9

Different Voltages

The voltage of a natural gas chiller in Trane is 406 V, which is not a typical voltage in a commercial building. So, the solutions are

- To purchase a transformer.
- Buy an absorption chiller from other company, which has the same voltage applied in AAM. For example, the Model No. 3B3 in Johnson Controls is powered by 208 volt, which has similar characteristics of a Trane natural gas absorption chiller (Johnson Controls, Inc, 2010).

Performance data comparison between electric and natural gas chiller.2

	Chiller Type	Electric centrifugal chiller	Johnson controls natural gas absorption chiller
	Cooling Capacity (Ton)	300	311
	Refrigerant	R134-a	Absorbent: Lithium Bromide (LiBr) Refrigerant: Water
	Dimension (in)	172(L)x67(W)x82.1(H)	242.5(L)x59(W)x103.75(H)
	Operating weight (lbs.)	22436	21857
Chiller	Flow rate (GPM)	450	746.4
	Inlet water temperature (°F)	58	54
	Outlet water temperature (°F)	42	44
	Max. pressure drop (ft. H_2O)	8.9	25.0
	Number of passes	2	2
Condenser	Flow rate (GPM)	900	1120
	Inlet water temperature (°F)	85	85
	Outlet water temperature (°F)	95	101.1
	Max. pressure drop (ft. H_2O)	17	10.4
	Working pressure (Psig)	150	--
	Number of passes	2	Absorber: 2 Condenser: 1

Table 13 Performance data comparison between electric and Johnson Controls natural gas chiller.2

Different Dimensions

The dimension difference of the electric chiller and the absorption chillers is significant.

Dimension of different chillers			
Dimension	Electric Chiller	Trane Absorption Chiller	Johnson Controls Chiller
Length	172	187.4	242.5
Width	67	113.4	59
Height	82.1	111.4	103.75

Table 14 Dimension of different chillers

Luckily, the height of chiller room is 20 ft., which is tall enough to hold the natural gas chillers. But, the width of new chillers may cause the width or length of chiller room to increase, due to accessibility and the recommendation of the Trane absorption chiller catalog. It says that

- The clearance space on all sides of chiller should be at least 3.3 ft.
- The clearance on the panel side of the chiller should be at least 3.95 ft.
- The space above the chiller should be more than 0.7 ft.

Original chiller room layout

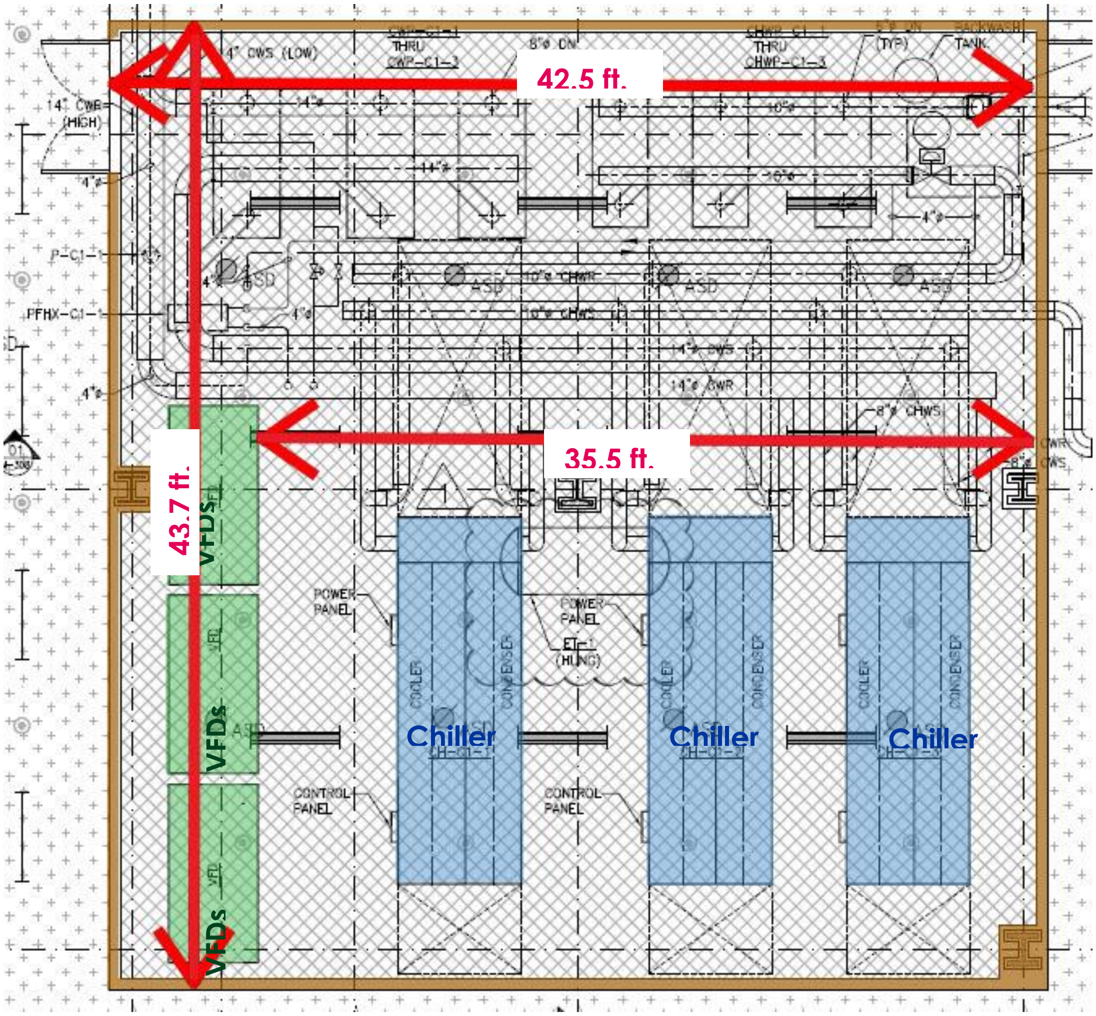


Figure 18 Original chiller room of AAM

New chiller room layout with Trane absorption chillers

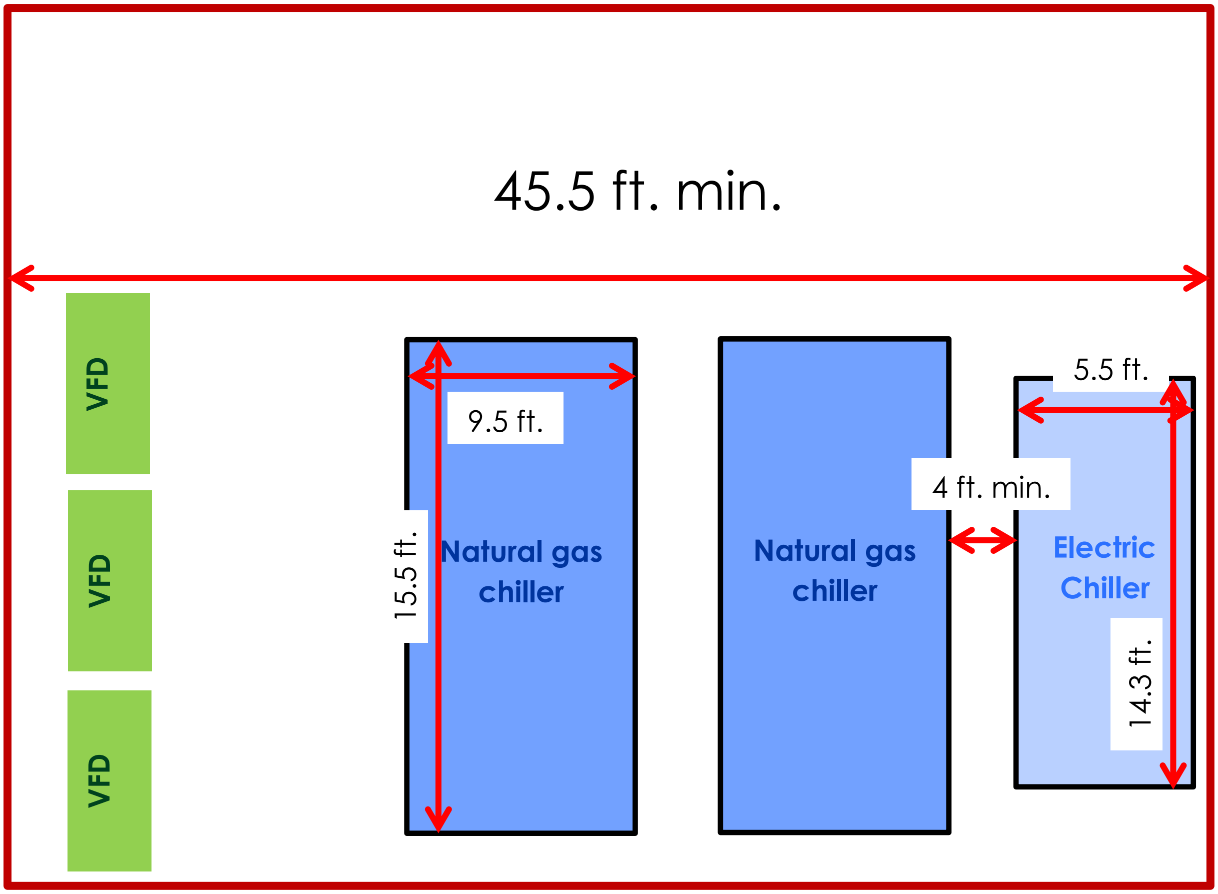


Figure 19 New chiller room layout of AAM with Trane absorption chillers

And, the minimum width of the new chiller room is 45.5 ft.

New chiller room layout with Johnson Controls absorption chillers

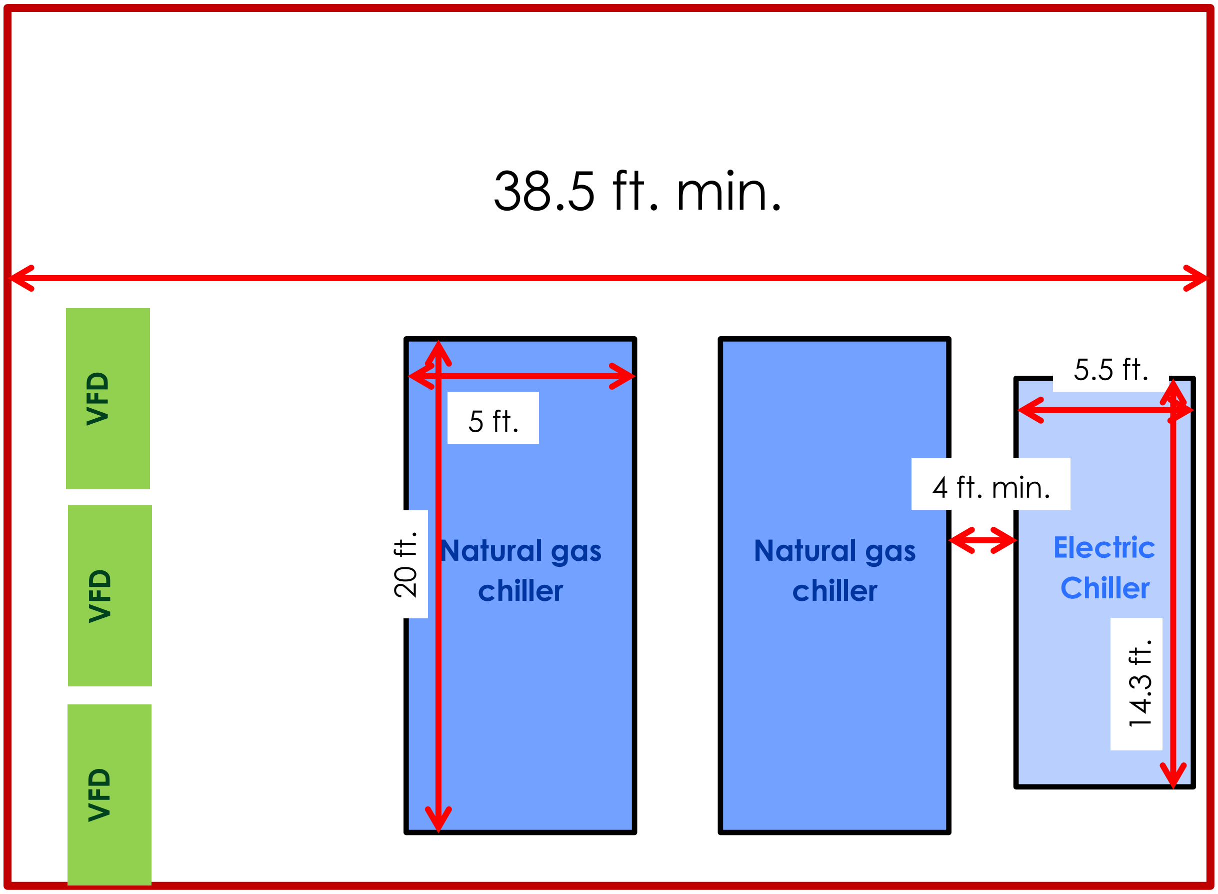


Table 15 New chiller room layout with Johnson Controls absorption chillers

The size of original mechanical room doesn't need to be changed, because the minimum width is achieved.

Analysis of Operation Sequences for Hybrid System

Purpose

Since the analysis of hybrid system results the most cost efficient system is the combination of natural gas hybrid system with two natural gas chillers and one electric chiller. And, the following study is to seek for the most cost effective operation of sequence. This study is inspired by a question asked in Architectural Engineering Thesis Capstone Project presentation related to the sequence of chiller operation. The search method of the operation sequence study is the same with the search method of the pervious analysis. It is because it significantly reduces the time consumption of calculation and brain storming.

Analysis of Operation Sequence

This section describes the setup of energy model and the result of the stimulations. The energy model was built on the model of the most cost effective hybrid system found in the previous analysis. In this analysis, there are 7 types of operation sequences studied.

Progress of Building Energy Model and Calculating Annual Utility Cost

Setup and Assumptions Energy Model

According to the assumption, because the energy model was built based on the energy model of the hybrid system combination, 2 natural chillers and 1 electric chiller, the same assumption also are kept in the model except the sequence of operation.

Next, the default characteristics of both chillers are also kept in this model, due to lack of information. It is difficult In Trace 700, the 2 models of chillers are

- 90.1-04 Min Centrifugal 150-300 tons as the electric chiller
- Direct Fired Absorption – Horizon as the two natural gas absorption chillers

Both chillers are set that the power consumption and the load ratio are linearly proportional.

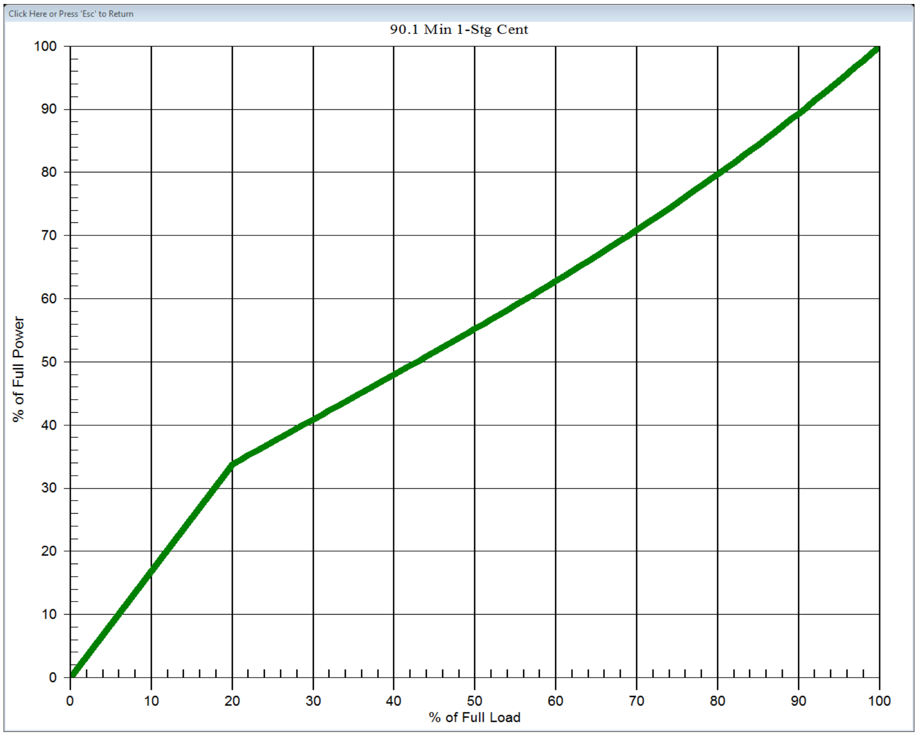


Figure 20 Power consumption vs. full load of a Trace 700 electric chiller model

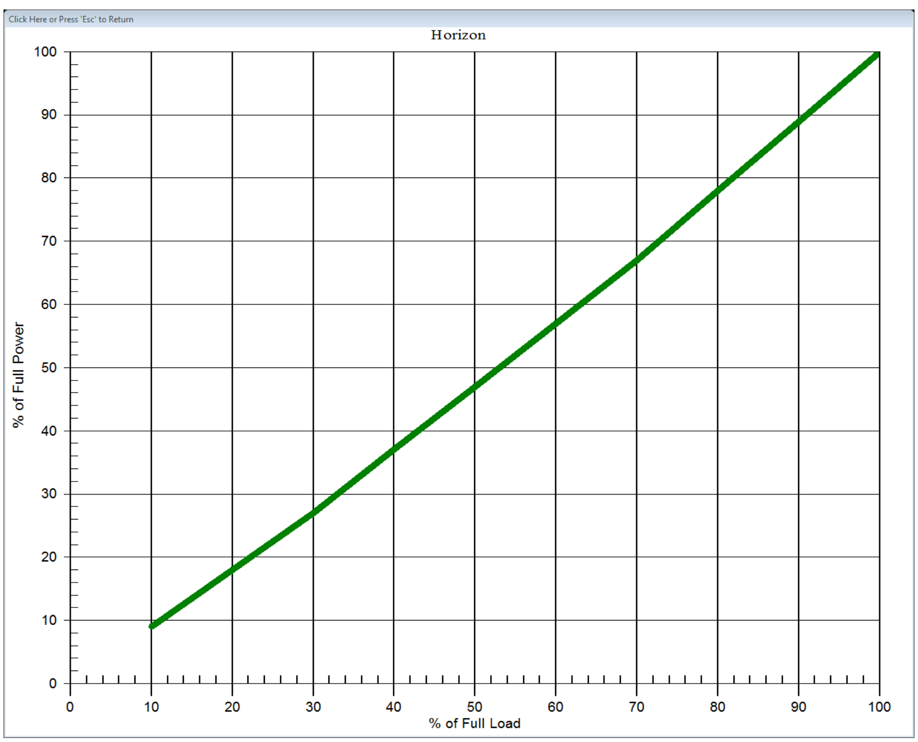


Figure 21 Power consumption vs. full load of a Trace 700 natural gas direct fired chiller model

Annual Utility Cost

The annual utility costs of each sequence over 20 years are conducted. The data of energy consumption is inputted into the calculation of utility cost prediction with utility regression equations. The regression equations of natural gas and water are the same set of pervious study, and the electricity is generated with the same approach, which the regression equation is generated by the annual electricity cost from 2004 to 2012, instead of every item of a utility cost.

Operation Sequences of the Hybrid System Studied

There are 7 sequences of chiller operation studied in this analysis.

No. 1 Chillers Operating in Parallel

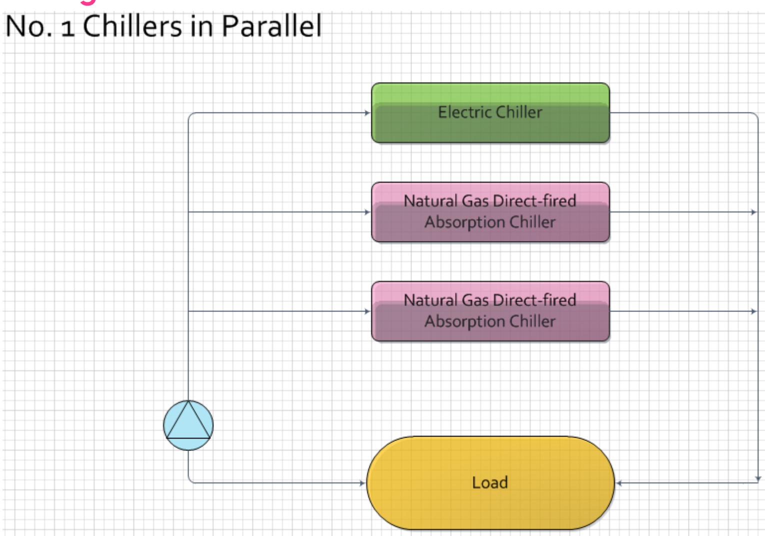


Figure 22 No.1 Chillers in Parallel

This sequence allows the chillers running at all the time mostly part load.

No. 2 Chillers Operating in Single

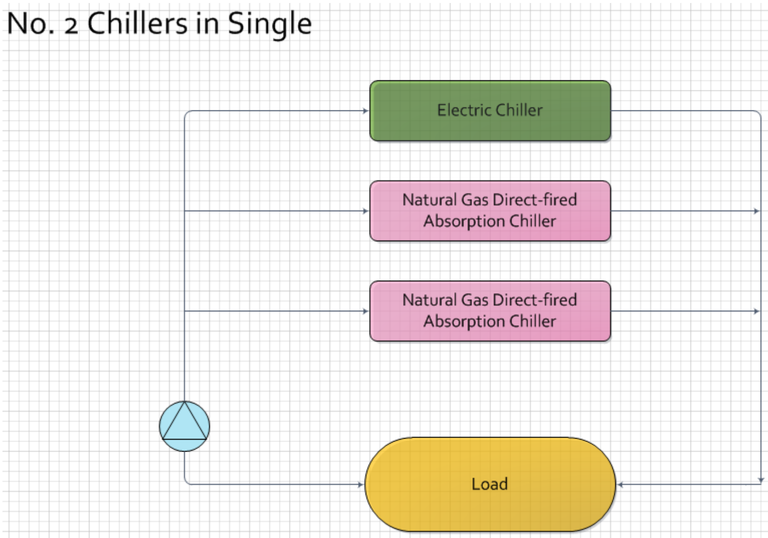


Figure 23 No.2 chillers in single

This sequence is to operate the electric chiller first, until the capacity of the electric chiller is reached. Then, one of the natural gas chillers will be turned on, if the capacity of the electric chiller is exceed.

No. 3 Chillers Operating in Single-2

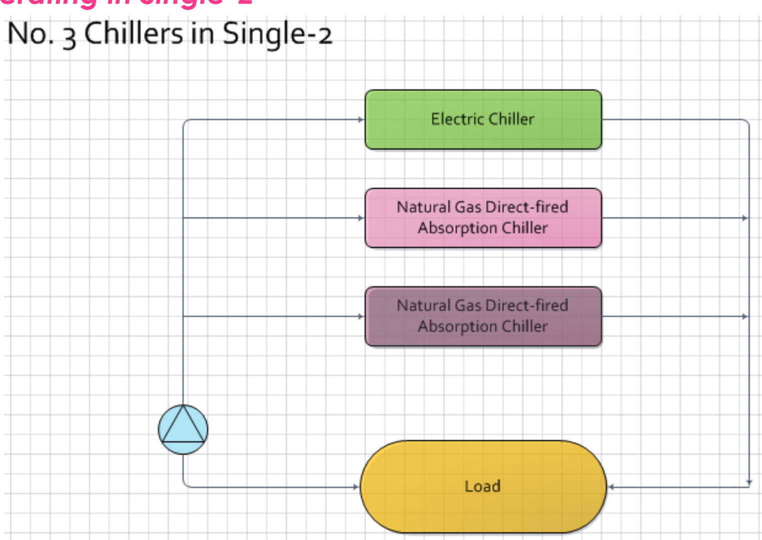


Figure 24 No. 3 Chillers Operating in Single-2

This sequence is similar to the No.2 sequence, but the first chiller starting is natural gas direct fired absorption chiller.

No. 4 Electric Chiller Operating in Sidecar

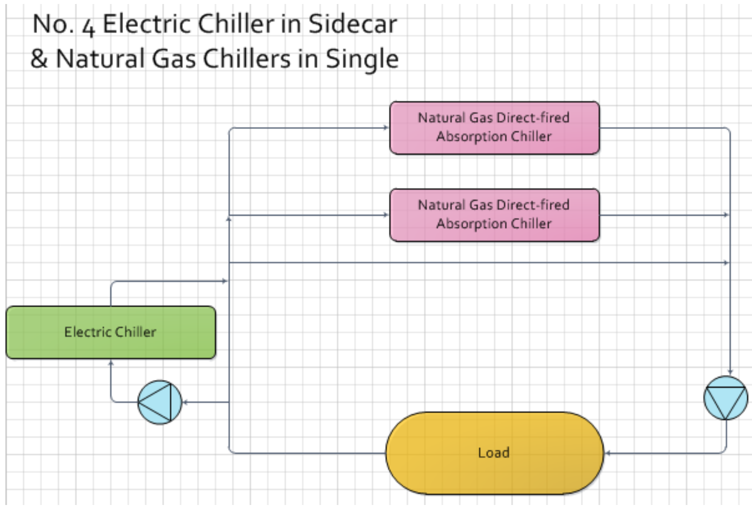


Figure 25 No. 4 Electric Chiller Operating in Sidecar

This sequence is required no valves and the flow in bypass is driven by the pressure difference. The electric chiller in the sequence is in the Sidecar sequence.

No. 5 Natural Gas Chiller Operating in Sidecar

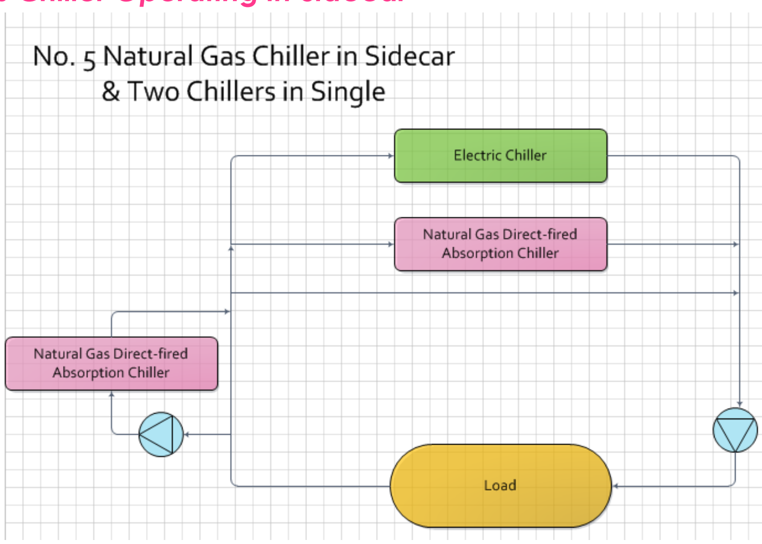


Figure 26 No. 5 Natural Gas Chiller Operating in Sidecar

In this sequence, a natural gas chiller in the sequence is in the Sidecar sequence.

No. 6 Chillers in Decouple Parallel

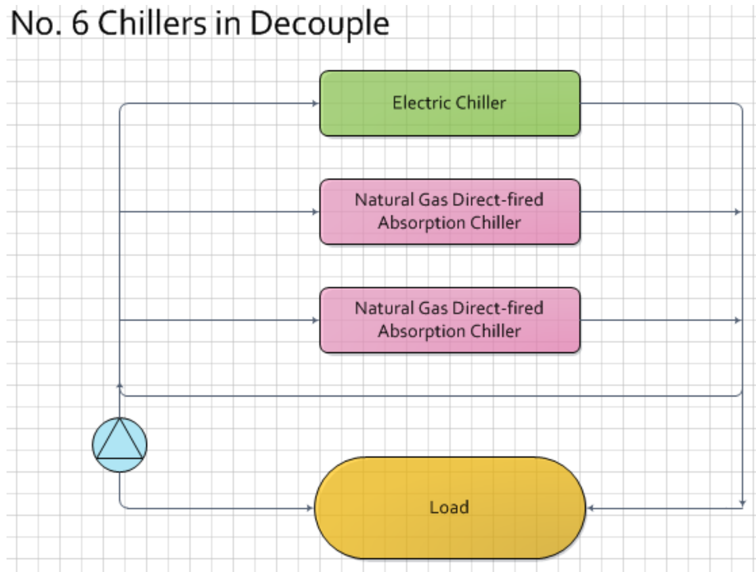


Figure 27 No. 6 Chillers in Decouple

This sequence is that all three chillers operate all the time. And, the cooling load is evenly distributed, since the tonnage of each chiller is the same. The water flow through the electric chiller first.

No. 6 Chillers in Decouple Parallel-2

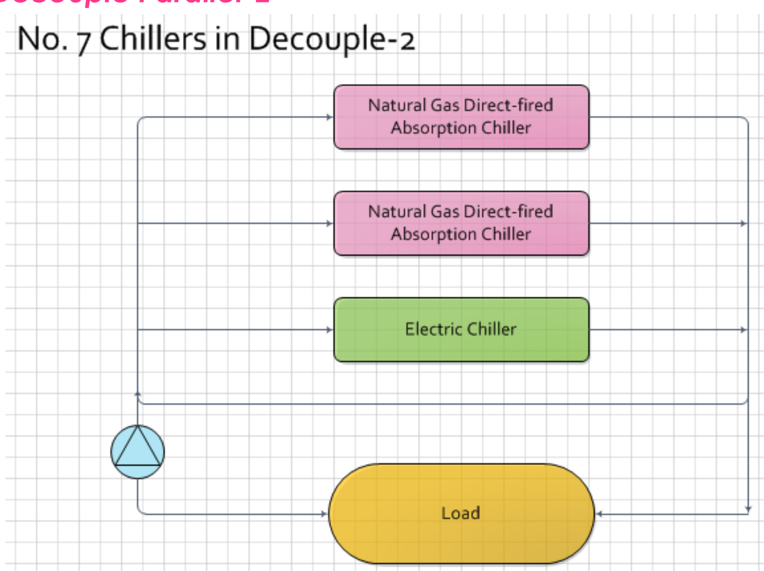


Figure 28 No. 6 Chillers in Decouple Parallel-2

This sequence is similar with Sequence No. 6. However, because there are two types of chillers in this hybrid system, the water temperatures of evaporators and condensers are also different. And, because the water flows through natural gas chiller first, the result of energy consumptions between Sequence No. 6 and No. 7 are different.

Result of Operation Sequence Analysis

By comparing the payback period (Figure. 29), it shows the best operation sequences are

- No. 1 Chillers Operating in Parallel.
  All the chillers operate with evenly load during all the time.
- No. 2 Chillers Operating in Single.
  The electric chiller operates first until it reaches its full capacity.
- No. 6 Chillers Operating in Decouple.
  The chillers operate with load proportional to the capacity of each chiller.

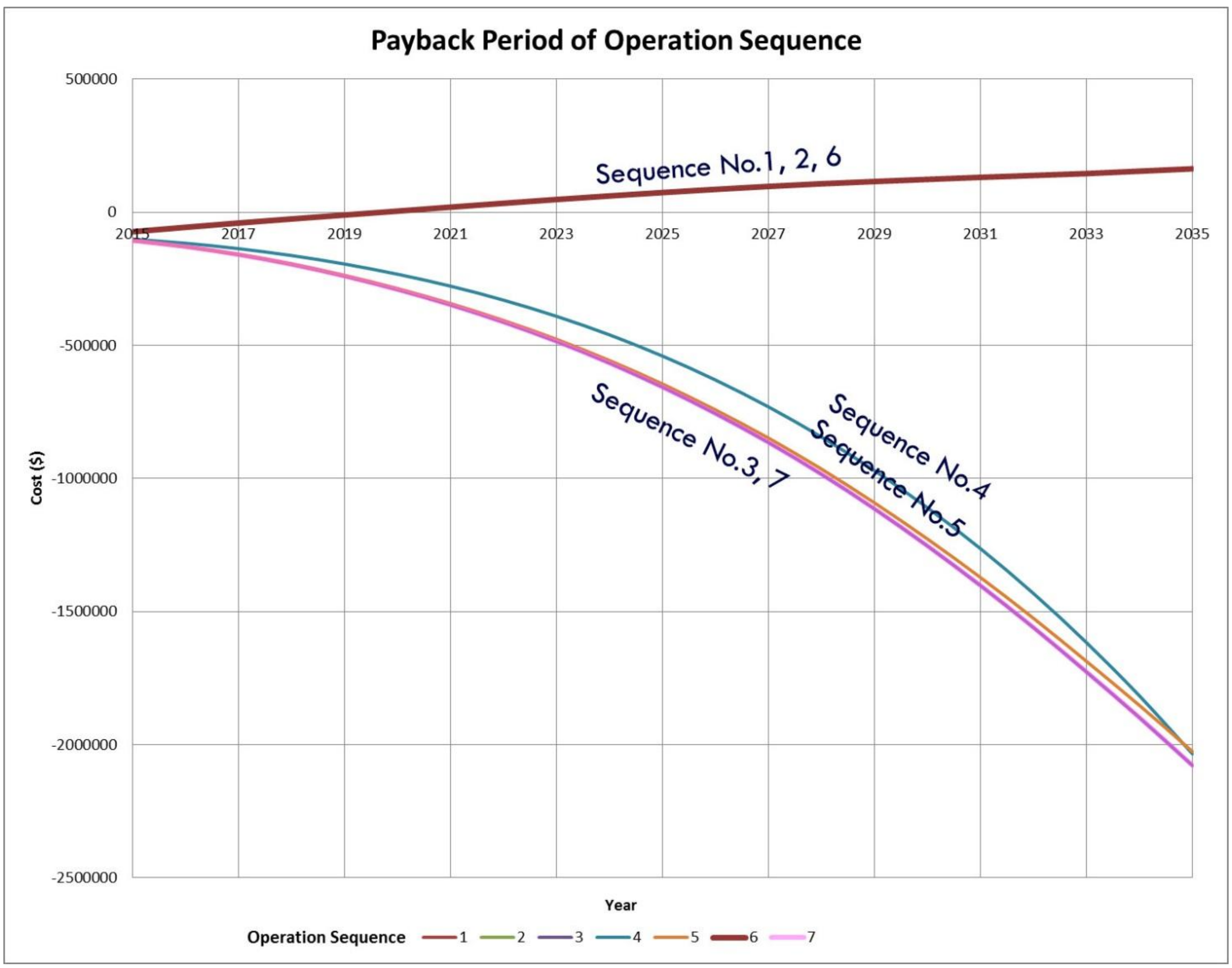


Figure 29 Payback Period of Operation Sequence

Conclusion

The result shows that the most cost effective operation sequences are:

- Parallel.
  The chillers operate with evenly distributed load.
- Single.
  The electric chiller operates first, than the natural gas chiller start operating.

There are suggestions of operation sequences. Because it is difficult to obtain the IPLV data of a chiller in the catalog of manufacturer, the decision of selecting the suitable operation sequence cannot be made without the corresponding IPLA data of the selected chillers.

The decoupling piping system is needed. Since the analysis of hybrid system concludes that the flow rates of both chillers are very different, a bypass should be placed between return and supply pipelines. This approach is similar to the decoupling piping system. The decouple system is used to solve the pressure and temperature differences between the components in a mechanical system.

Between the chillers operating in single and parallel, it should be based on efficiency at part load. Some of the chillers have relatively high efficiency at part load, and some are more efficient at full load. It is important to understand the energy consumption of a chiller under different ratio of load. Since the characteristic of Johnsons' Control Chiller is that the efficiency also is linearly proportional to the design load, it suggests the single in decoupling piping system is a better choice.

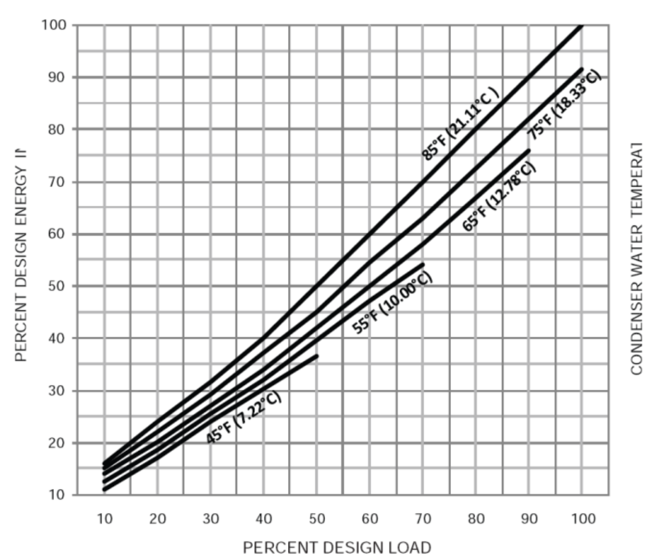


Figure 30Energy consumption vs load of a Johnsons' Control Chiller

However, it is important to input the IPLV data into the energy model stimulation in order to ensure the potential saving.

Economic Analysis

Current Condition of Utility Rate

Based on the current condition, the rate of electricity is increasing significantly, because the fuel of major power plants in ConEdison is oil and the prices of No. 2 and 6 oils are increasing. And, the rate of natural gas is more still and stable. It is because the shale technology is well developed to supply a reliable amount of supply nowadays.

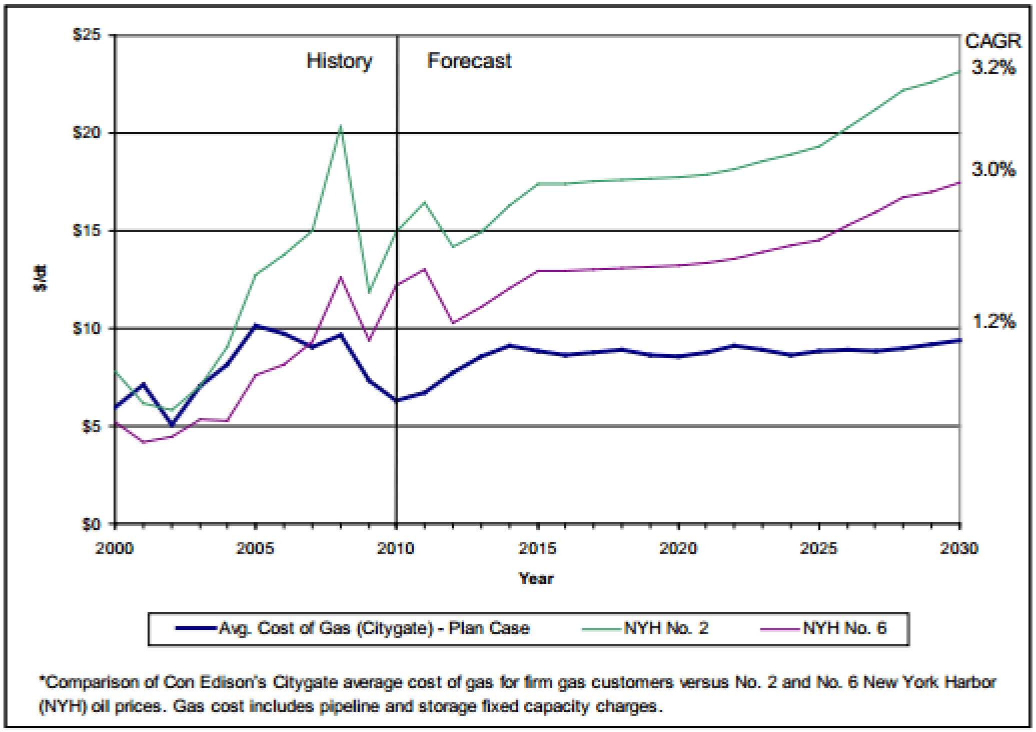


Figure 31 Con Edison's Citygate Cost of Gas for Firm Customers Versus #2 & #6 Oil (ConEdison , 2010)

In the website of ConEdison, there are several reasons why ConEdison would like to generate power with oil fueled power plants.

- *"While natural gas is currently the less expensive fuel, it has not always been so. There have been times when oil was less expensive than natural gas."*
- *"During the winter season, there are some days when natural gas is in short supply. When natural gas is in short supply, it must be given to Con Edison's gas customers before any is used in Con Edison's own facilities."*
- *"Because Con Edison has the capability to produce steam from two different fuels, Con Edison can reliably produce steam at the best price."*

---- ConEd (Con Edison, 2012)

It is less likely that the electric price will decrease, if the current condition of the ConEdison power generation system remains the same.

Future Plant of ConEdison Power Generation and Other Utilities

The biggest problem of a hybrid system is high sensitivity of utility cost. It is difficult to predict the future utility cost throughout the lifetime of a chiller precisely. ConEdison is planning to switch the fuel type of power generation system and promote CHP (Combined Heat and Power) System. The main advantage of CHP toward the utility company is the stable and consistent amount of demanded fuel over time.

Currently, the power plants are fueled by oil and back up with natural gas. In the Gas Long Range Plan, 2010-2030, of ConEdison, it shows that ConEdison is willing to switch the fuel of major power plants from No. 2 and 6 to natural gas. And, all the power plants are switchable from oil to natural gas. But, this report doesn't state clearly about when or how the power plants operate with different fuels.

ConEdison is planning to change the fuel of power plant, because of two reasons:

- The price of natural gas is decreasing in the future 30 years. And, the prices of No. 2 and 6 oils have gone over the price of natural gas.
- The NOx RACT regulation will be settled and limit the NOx emission from buildings and facilities. One of the alternative solutions is to switch the fuel type of the major power plants.

There are also drawbacks of changing fuels:

- Since ConEdison planned to change the fuel of power plant, it will lower the production of steam. In order to balance the demand and supply of steam, ConEdison plans to start incentive program to convince the steam customers to replace steam heating system with natural gas CHP (Combined Heat and Power) system. But, a CHP system consists of high capital cost and stable thermal load profile. ConEdison will require big amount of funding to convince the steam customer.
- In the Gas Long Range Plan of ConEdison, it shows that if the power generation system switches the fuel type, the load will be increased by 400 thousand dekatherms per day (Mdt/day).
- According to the damage of Sandy, ConEdison seeks for $400 million from customers to repair the damage of Sandy and prepare for the natural disaster in future. ConEdison will increase the rate of natural gas by 1.3 percent and the rate of electricity by 3.3 percent. Since the electric delivery system received

more damage from Sandy, the funding requested will be more and used for "increase the height of flood walls for certain facilities; raise the level of critical equipment; install submersible equipment; install additional switches and related smart grid technology; and reconfigure certain distribution networks." (McGeehan, 2013) And, the funding corresponding to natural gas will be used for "the connection to a new gas transmission pipeline, projects for cover plates and remote emergency generators to address possible tunnel flooding and check valves to prevent water infiltration that could lead to over-pressurization of piping and equipment." (McGeehan, 2013)

It is more likely that the electric price will be increased in order to get the funding for repairing the damage caused by Sandy, because ConEdison needs more funding and time to switch the fuel of power plants. In conclusion, it suggests that the hybrid system will more likely make up the difference of capital cost. Next, when the incentive/rebate program of CHP system from ConEdison is offered, it is important to investigate the potential of CHP system. It highly recommends the investigation to be conduct at the end of natural gas absorption chillers' lifespan. There are three reasons why CHP system may benefit to AAM in future:

- AAM will obtain a good amount of utility usage data. The data is required to design the best fit CHP system, because CHP satisfies the thermal and electric loads of a building in the most cost effective setup.

- In AAM, there will be a co-generation unit on the second floor. To setup the CHP system, the co-generation unit will be replaced with a bigger sized unit without changing the loop of piping system on the heating side.

- According to the CHP design, it is necessary to have flat thermal load over time in a day. So, it recommends the application of hot water absorption chillers and replacing the natural gas absorption chillers after 20 years (which is the typical lifespan of a chiller). It results with a higher electricity output of CHP system. The change of the piping system on cooling side of HVAC system is that the natural gas supply pipes of the original natural gas will be cut off and the hot water supply pipes will be added and connected to the new hot water absorption chillers. Since the size of the selected natural gas absorption chiller is as same as the size of a hot water absorption chiller in Johnson's Control, the arrangement of piping will be minimized.

Overall Conclusion

This analysis is to seek a hybrid system with the variation of fuel types. It found that the combination No. 9 with two natural gas chillers and one electric chiller is more economical than the original cooling system, because the natural gas price is cheaper than the price of electricity nowadays. As a conclusion, it is presented in 2 ways: technical and economical perspectives.

Technical Conclusion—Why Natural Gas Fired Absorption Chillers?

This section is about pros and cons of the combination No. 9.

One of the reasons that the natural gas hybrid system is more economical in AAM than the electric cooling system and the steam hybrid system are that the price of natural gas is getting lower. It is caused by the supply in shale gas in United States is increasing recently. The technology of collecting shale gas is becoming more economical. As the cost of natural gas extraction is more, the supply of natural gas increases. Comparing to the COP of all chillers, although the COP of natural gas fired absorption chiller is lower than the electric chiller, it is higher than the one of steam absorption chiller. It is because the steam in double and single staged absorption chillers cannot carry a lot of heat. Also, the power plant of ConEdison produces low quality of heat. Therefore, using natural gas fired absorption chillers is a better choice.

The impact of this hybrid system is that the size of an absorption chiller is at least 25 % larger than an electric chiller. It may cause the size of a chiller room to increase due to the minimum clearance. The other solution is to select an optimal size of chiller. However, in this energy analysis, it is not conducted with the preferred chiller, but a Trane absorption chiller. It is because Trace700 is design for operating with Trane equipment. When a chiller of other brand is used, the built-in function should be modified in Trace700, such as integrated part load values, for matching the load characteristics.

As conclusion, the preferred natural gas chiller has similar characteristics with the Trane chiller and optimal size. So, this hybrid system doesn't impact the cooling system significantly. Next, based on the analysis of operation sequence, it recommends the application of "single in decoupling" sequence for minimizing the weariness of the equipment and maximizing the cost effectiveness of it.

Economical Conclusion—Price of Natural Gas and Future Plan of AAM Mechanical System

After conducting an economic study, there are one conclusion and one suggestion of the future mechanical system in AAM:

- Hybrid system is recommended due to the current fuel economic condition.
- The potential of CHP system should be investigated in the end of the absorption chiller lifespan.

These two ideas are based on the short term and long term predictions of ConEdison utility system and plans.

Short term economic prediction

According to Gas Long Range Plan of ConEdison, the rate of electricity remains high and the natural gas costs lower in these recent years. It is because the price of oil is increasing, and the shale gas technology is well developed that increases the amount of natural gas supply. It results that the hybrid system is recommended.

Long term economic prediction

The report of ConEdison's plan states that in next 30 years, ConEdison invests on expanding the natural gas delivery system and promoting the natural CHP system. In these 30 years, the supply and demand of natural gas will be balance. Therefore, the consideration of CHP system is suggested to be the replacement of hybrid system.

This economic analysis does not require the long term prediction. However, the prediction can provide the owner better and greener ideas of the future mechanical system.

Structural and Acoustical Breadths-- New Mechanical Ductwork Layout

Purposes

The mechanical area in AAM will be around 1/3 of gross area, because there will be 3 mechanical floors in AAM. Two out of three floors will hold the major equipment of cooling, heating and ventilation systems, then another floor will locate the cogeneration system. The main idea in this analysis is to seek for capital saving of ductwork by relocating a part of the ventilation systems in two floors with the consideration of structural and acoustical impact. The approach of this analysis is to increase the size of ventilation system on 9th floor and lower the capacity of the one on cellar level in order to minimize the amount of ductwork.

Design Criteria

In this section, it states the existing conditions of the current mechanical ductwork layout.

Placement of Mechanical Equipment

The 3 mechanical floors will be:

Mechanical floor	Mechanical room(s) and equipment located in this floor
Cellar level	Chiller room Boiler room Ventilation systems serving cellar level to 7th floor
2nd floor	Cogeneration System room
9th floor	Ventilation systems serving 8th floor

Table 16 Location of Mechanical rooms and equipment

As the table shown, the major equipment will be located in the cellar level. And, the longest ductworks will be the ones of supplying and returning the conditioned air from 7th floor to cellar level.

Redundancy of Ventilation Systems in AAM

This analysis is focused on the major air condition systems, which will serve the gallery and office zones throughout the whole buildings. There will be three 42000 cfm AHUs (air handling units) on cellar level that will supply and return the air up to 7th floor, then only 1 AHU on 9th floor. Therefore, if the ventilation system on 9th floor is shut down due to maintenance and equipment failure, 8th floor will not have conditioned air served.

Structural System of AAM

The structural system of AAM will be a partially composited steel system. The beam which will support the weight of façade will be a composite beam, and most of the column in AAM also will be a composite column.

Acoustical control of AAM

In AAM, there will be noise sensitive rooms, such as a classroom and a theater. Therefore, the mechanical equipment will be specifically selected based on sound level.

- On 8th floor, every fan power VAV unit will be installed with a sound trap.
- In the specification of AAM, all fans, diffusers and VAV boxes must operate below the maximum sound level.

Proposed Air Handling Unit Locations and Ductwork Layout

The proposed air handling units and the location are two 50,000 cfm AHUs in cellar level and two 20,000 cfm AHUs on 9th floor. The considerations that this combination is picked are:

- Having two AHUs on each mechanical floor provides better reliability.
- Since the usable area of 9th floor is limited, two units of AHUs are the maximum number of AHUs, which can be located on 9th floor.

The two 50,000 cfm AHUs will serve the galleries and offices from cellar level to 6th floor, and the other two 20,000 cfm AHUs will supply and return the air to 7th and 8th floors. To avoid unnecessary structural and acoustical change, the addition supply and return ducts on 9th floor that will deliver conditioned air to 7th floor should be connected to the original supply and return ducts. As the original ducts that will send air to 7th floor from cellar level will be cancelled in this analysis, the return and supply ducts on 7th floor will be expanded to 9th floor. Therefore, the length of ductwork saved will be at least160 feet.

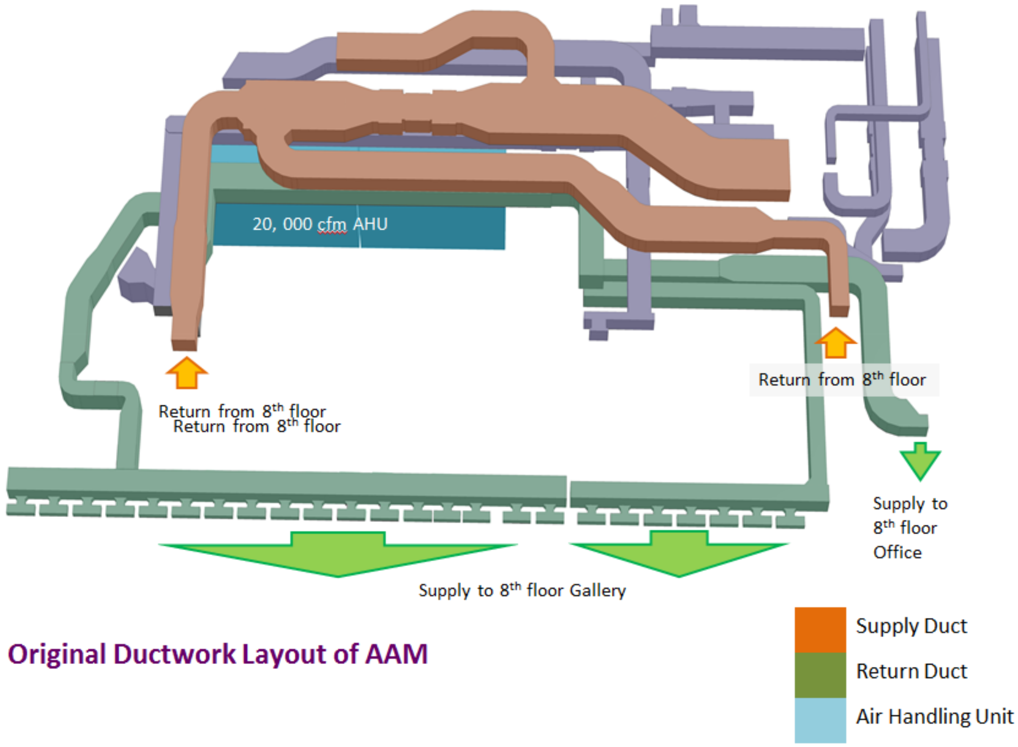


Figure 32 Original Ductwork Layout of AAM

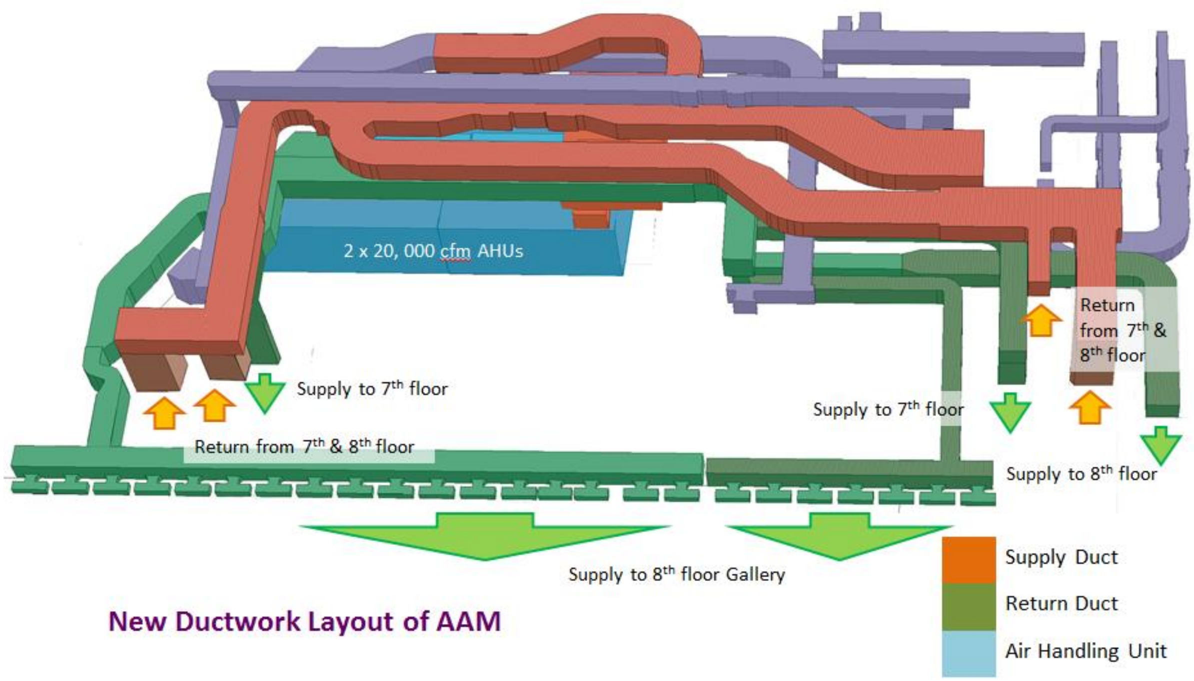


Figure 33 New ductwork layout of AAM

Result with 3 perspectives: Mechanical, Structural and Acoustical

The result of 3 analyses (duct sizing, structural system check and acoustical performance stimulation) shows that moving an AHU to 9th floor reduces the capital cost of ductwork by $36,000 without causing structural and acoustical impacts.

Mechanical Perspective

By changing the ventilation distribution, the capital cost of ventilation system decreases.

After moving an AHU to 9th floor, the size of ductworks is reduced, because of decreasing the pressure drop in the ductwork. Also, it increases the amount of piping, which the pipes of chilled water supply and return and the pipes of hot water supply and return. The reason why shifting the AHUs closed to the loads is that the cost of ductwork is greater than the cost of piping.

Capital Cost Analysis							
Cost lost				Cost gained			
Item	Quantity	Cost/unit	Cost	Item	Quantity	Cost/unit	Cost
AHUs				AHUs			
AHU 42,000 cfm	3	74500	223500	AHU 50,000 cfm	2	96000	192000
AHU 20,000 cfm	1	37100	37100	AHU 20,000 cfm	2	37100	74200
Duct				Duct			
Cellar Level			128851.3	Cellar Level			22501.54
9th floor			9880.043	9th floor			70583.48
Pipe				Pipe			
				9th floor			3550
Total				Total			
			399331.34				362835.02
Saving (Cost lost - Cost gained)							
							36496.32

Table 17 Capital Cost Analysis

According to Table.17, the saving is about $36,000.

Also, it increases redundancy of the ventilation on 9th floor. It is because if either one of the AHUs on a floor fails, the second AHU will still operate and provide minimum air flow.

Structural Perspective

Since a ~9,000 pounds weighted AHU will be moved to the 9th floor, it may affect the building structural load. It is required to check the capacity of the major structural components: composite deck, beams, and columns.

In the structural system check, the load distribution based on the drawings and the calculated weight of AHUs and other ventilation equipment is the following:

Load distribution calculation				
Loads	Load distribution			
live load	75	psf	from drawing	
ductwork and pipe	15	psf		
Steel	12	psf		
Mechanical equipment load				
equipment	weight	quantiity	total	
	lbs		lbs	
fan	1000	3	3000	
AHU	9000	2	18000	
HVs	1500	3	4500	
		total	25500	lbs
		total/total area	5.73	psf
total distributed load	107.73	psf		

Table 18 Load distribution calculation

Next, the area of 9th floor conducted in this check is:

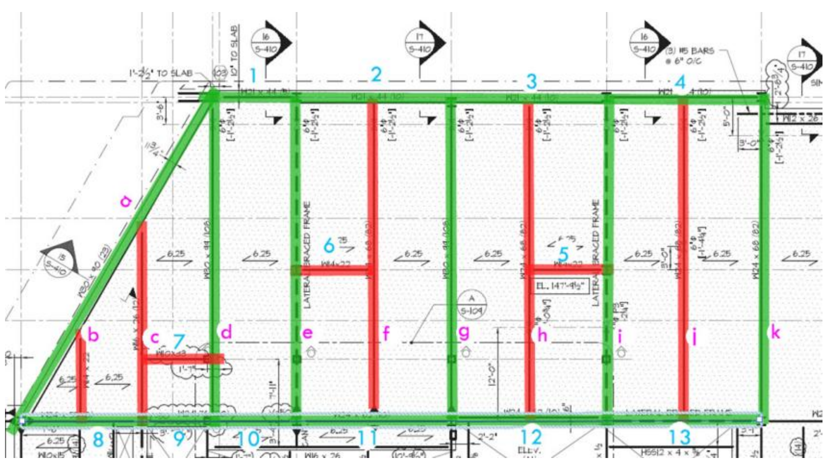


Figure 34 Area of 9th floor conducted in this check

The structural check shows that the major structural components are all capable to support the additional structural load. Finally, there is an additional check by applying the point load to the columns under the AHUs in the calculation. And, all the columns also achieve the minimum load requirement.

Acoustical Perspective

The acoustical performance should be checked and ensured if the minimum noise criteria (NC) are achieved. Also, as the duct is resized, the sizing should follow the 'Rules of Thumb" (McQuiston, 2005):

- The air velocity in each duct should be less than 2400 fpm
- The pressure drop must also be less than 0.1 in. wg.

It prevents turbulence flow inside the duct and minimizes the noise generation.

The galleries on 7th & 8th floors and the office areas (Rm 803 and Rm 703) on these two floors with the shortest flanking path should conducted in acoustical performance stimulation. The result shows that the noise generated by the AHUs is mostly dissipated inside the ducts before the air reaching the diffuser. The loudest noise generated and reaching out of the diffuser is from a fan powered VAV units with sound trap. After leaving from a sound trap, the noise will be high frequency sound. Next, when the noise leaves from the diffusers and reach to the ceiling, gypsum board tiles, the high frequency noise is dissipated inside the tiles. It reduces the noise on 8th floor below the minimum NC value.

The acoustical performance of Rm703, opened office

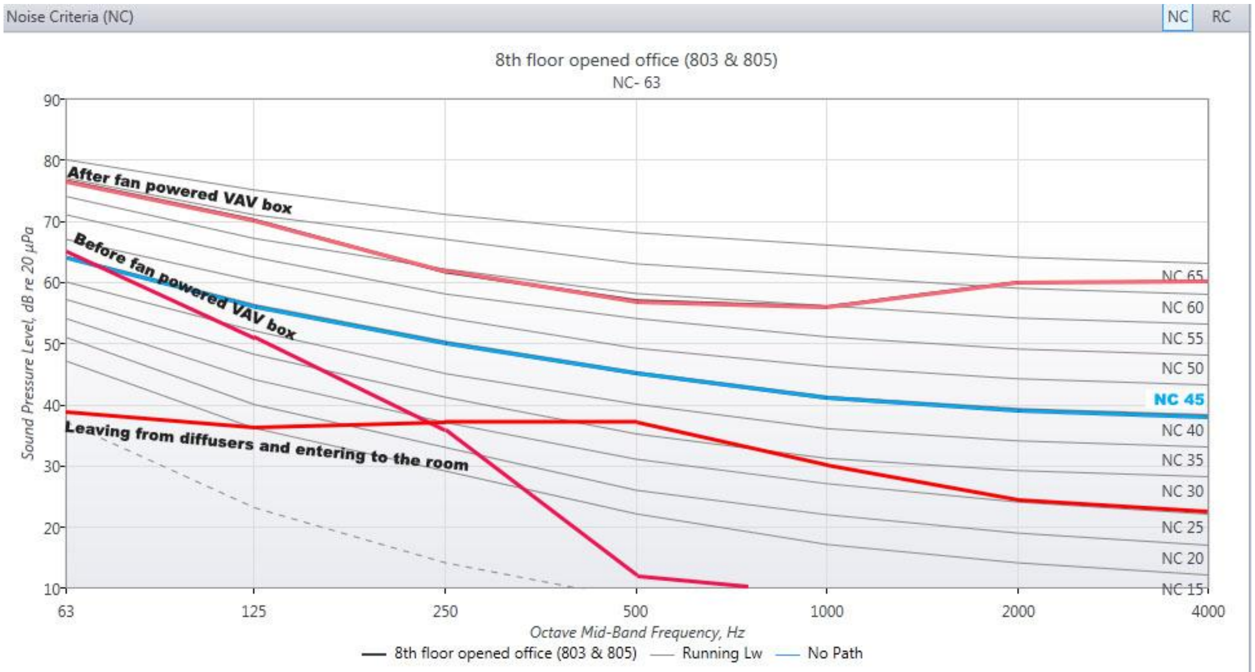


Figure 35 Acoustical performance before fan powered VAV box

Acoustical performance of Rm 803 and Rm 805, opened office

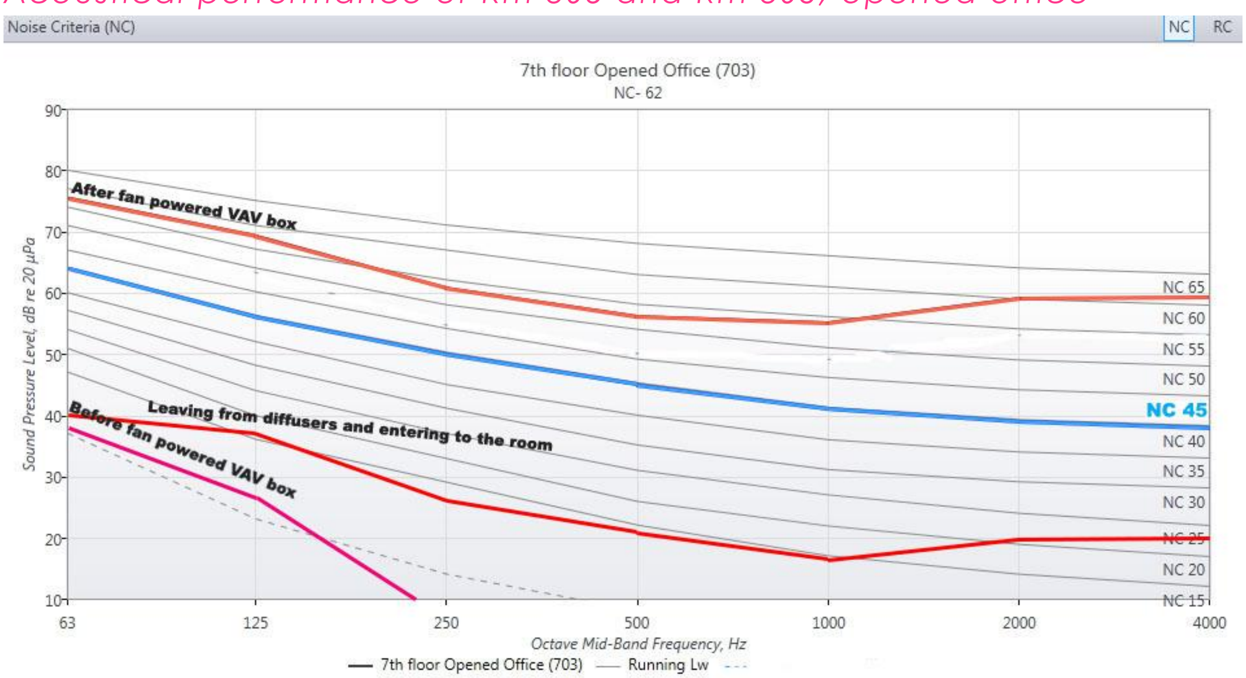


Figure 36 Acoustical performance before fan powered VAV box

Conclusion

Having multiple floors of "Mechanical floor" is unusual, because it reduces the usable space of the building. But, the application of mechanical floor brings the AHU closer to the load, which decreases the amount of ducts. In AAM, there will be 3 mechanical floors. And, the engineer brought the AHU of serving 8th floor ventilation much closer to the load. In this analysis, the proposed idea is to bring more AHUs closer to the load and increase the redundancy of the system.

Mechanical floor has several disadvantages. And, the proposed ductwork layout in this report is focus on minimizing the side effect to the structural system and the acoustical performance. Fortunately, after all the checks, it shows that the structure of AAM will be capable to support the extra weight of an AHU. The columns of AAM will be able to carry the weight of both new AHUs individually.

According to the acoustics treatment in AAM, the treatment is slightly over designed. It is because after placing linings in the ducts on 9th floor, the sound level of noise generated by AHUs decreases significantly. The NC value before reaching another noise generated device is about 20.

As the conclusion, new placement of AHUs saves about $36,000 with the resized ducts and piping. And, it will bring zero structural impact and no disturb of acoustical performance.

MAE Course Relation

The MAE courses related to this project are:

AE 557 Centralized Cooling System:

The ideas of absorption refrigeration in this course help to understand the impact to other mechanical components and the installation requirement of absorption chillers. Also, the lecture of AHRI Standard 550/590 and ASHRAE Standard 90.1 explains the potential energy saving of operating with multiple chillers instead of one.

AE 555 Building Control System:

This course provides different search methods that can be applied on HVAC operation, such as increasing the efficiency of HVAC system by changing the combination of mass flow rates, temperature setpoints, and part load ratios. This concept helps to find the cost effective combination of electric and absorption chillers, and also the well balanced layout of the mechanical room on 9th floor.

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Appendix. A Hybrid System Combination List

Combination Legend of Figure 12 Total Utility Cost in 2015 of All CombinationsTotal Utility Cost in 2015 of All Combinations		
	Amount of … …	
Combination No. #	Electric chiller	Chiller of other fuel
1	3	0
	Electric chiller	**Steam** driven **single** stage absorption chiller
2	2	1
3	1	2
4	0	3
	Electric chiller	**Steam** driven **double** stage absorption chiller
5	2	1
6	1	2
7	0	3
	Electric chiller	**Natural gas** absorption chiller
8	2	1
9	1	2
10	0	3

Appendix. B Consumption of Hybrid System Combinations

Combination No. 1														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1717	1759	1718	1941	2169	2298	2347	2387	2248	2045	1846	1718	2387
Electric	kWh	306906	277905	327913	307668	356603	393446	386044	438917	350989	337477	313756	295507	4093131
Gas	therms	11267	9529	11444	7504	1407	265	50	5	6	5715	7608	12001	66801
Steam	Mlb	0	0	0	0	0	0	0	0	0	0	0	0	0
Water	1000gals	44	45	46	112	241	412	464	533	323	154	84	40	2498

Combination No. 2														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1717	1759	1718	1879	2074	2168	2204	2233	2132	1938	1846	1718	2233
Electric	kWh	306906	277905	327913	307668	354417	374571	361767	406300	339011	337477	313756	295507	4003198
Gas	therms	11267	9529	11444	7504	1407	265	50	5	6	5715	7608	12001	66801
Steam	Mlb	0.0	0.0	0.0	0.0	72.3	551.5	700.3	933.4	350.4	0.0	0.0	0.0	2607.917
Water	1000gals	44	45	46	112	256	533	617	737	399	154	84	40	3067

Combination No. 3														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1717	1759	1718	1879	1980	2039	2061	2079	2016	1938	1846	1718	2079
Electric	kWh	306906	277905	327913	307668	354428	374621	361822	406364	339046	337477	313756	295507	4003413
Gas	therms	11267	9529	11444	7504	1407	265	50	5	6	5715	7608	12001	66801
Steam	Mlb	0.0	0.0	0.0	0.0	72.3	551.5	700.3	933.4	350.5	0.0	0.0	0.0	2607.908
Water	1000gals	44	45	46	112	256	533	617	737	399	154	84	40	3067

Combination No. 4														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1706	1711	1708	1813	1886	1910	1919	1925	1900	1832	1760	1707	1925
Electric	kWh	302777	273891	323838	292640	330065	344575	328137	365314	316169	319825	301397	292226	3790854
Gas	therms	11287	9557	11453	7611	1422	282	65	6	6	5762	7748	12007	67206
Steam	Mlb	119.79	138.43	132.98	379.13	889.56	1633.71	1898.03	2303.11	1235.82	522.06	305.51	99.17	9657.283
Water	1000gals	74	79	79	194	429	764	875	1033	587	265	154	65	4598

Combination No. 5														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1717	1759	1718	1899	2092	2178	2211	2237	2145	1951	1846	1718	2237
Electric	kWh	306906	277905	327913	307668	355545	377822	364633	408590	341694	337477	313756	295507	4015416
Gas	therms	11267	9529	11444	7504	1407	265	50	5	6	5715	7608	12001	66801
Steam	Mlb	0.0	0.0	0.0	0.0	43.4	322.3	403.5	525.9	207.4	0.0	0.0	0.0	1502.583
Water	1000gals	44	45	46	112	257	529	609	720	398	154	84	40	3038

Combination No. 6														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1717	1759	1718	1899	2015	2058	2074	2088	2041	1951	1846	1718	2088
Electric	kWh	306906	277905	327913	307668	355551	377849	364663	408625	341713	337477	313756	295507	4015533
Gas	therms	11267	9529	11444	7504	1407	265	50	5	6	5715	7608	12001	66801
Steam	Mlb	0.0	0.0	0.0	0.0	43.4	322.3	403.5	525.9	207.4	0.0	0.0	0.0	1502.583
Water	1000gals	44	45	46	112	256	529	609	720	398	154	84	40	3037

Combination No. 7														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1759	1761	1760	1857	1938	1938	1938	1938	1938	1857	1776	1759	1938
Electric	kWh	324551	293856	346843	313270	345915	359871	343964	380288	331149	339621	323551	313378	4016257
Gas	therms	11287	9557	11453	7611	1422	282	65	6	6	5762	7748	12007	67206
Steam	Mlb	28.49	36.48	32.78	144.93	451.49	894.49	1036.88	1246.68	657.58	231.48	95.63	22.27	4879.158
Water	1000gals	57	62	61	165	406	736	836	976	562	239	121	50	4271

Combination No. 8														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1717	1759	1718	1879	2068	2162	2198	2227	2126	1932	1846	1718	2227
Electric	kWh	306906	277905	327913	307668	354139	373321	360377	404703	338127	337477	313756	295507	3997799
Gas	therms	11254	9519	11431	7495	2031	4885	5836	7568	2979	5708	7599	11987	88292
Steam	Mlb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Water	1000gals	55	45	46	112	251	491	563	662	373	154	84	40	2876

Combination No. 9														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1717	1759	1718	1879	1967	2026	2049	2067	2003	1932	1846	1718	2067
Electric	kWh	306906	277905	327891	307668	354136	373365	360414	404724	338164	337477	313756	295507	3997913
Gas	therms	11242	9507	11418	7487	2032	4901	5854	7579	2991	5701	7590	11973	88275
Steam	Mlb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Water	1000gals	44	45	46	112	251	491	563	662	374	154	84	40	2866

Combination No. 10														
	Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Peak	kW	1708	1711	1709	1800	1867	1891	1900	1906	1881	1819	1754	1708	1906
Electric	kWh	307519	278130	329949	292396	327616	340158	323675	360382	312314	318930	301527	299399	3791995
Gas	therms	11329	9794	11537	9697	7946	13192	15029	17998	9496	9115	9106	11994	136233
Steam	Mlb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Water	1000gals	46	51	48	144	341	624	711	831	475	205	108	42	3626

Appendix. C Utility Cost Predictions Equations of All Hybrid System Combinations

The following equations are to calculation the monthly utility costs.

Common Regression Equations Used in All Hybrid System Combinations

Steam:

First 0~20 Mlb (1Mlb = 1000 lb)

$$\boldsymbol{Cost/Mlb = 1.4835 \times (Year - 2009) + 11.833}$$

Next 30 Mlb

$$\boldsymbol{Cost/Mlb = 5.0181 \times (Year - 2009) + 29.376}$$

Next 950 Mlb

$$\boldsymbol{Cost/Mlb = 3.8819 * (Year - 2009) + 23.736}$$

More than 1000 Mlb

$$\boldsymbol{Cost/Mlb = = 3.7296 * (Year - 2009) + 22.981}$$

Customer Charge

$$\boldsymbol{Cost = 118.55 * (Year - 2009) + 702.16}$$

Natural gas:

$$\frac{¢}{therms} = 12.977 * year - 26065$$

Water:

Water rate

$$\boldsymbol{Cost/748Gal = 0.0226 * (Year - 2000)\text{^}2 - 0.0751 * (Year - 2000) + 2.153}$$

Sewer rate

$$\boldsymbol{Cost/748Gal = 0.0142 * (Year - 2000)\text{^}2 - 0.0467 * (Year - 2000) + 1.3523}$$

Combination No.1

Electricity:

$$Cost = 4227.5 \times (Year - 2004) - 2947.6 \times (Year - 2004) + 344810$$

Combination No.2

Electricity:

$$Cost = 4299.1 * ((Year - 2004)^2) - 3983.7 * (Year - 2004) + 330264$$

Combination No.3

Electricity:

$$Cost = 4199.3 * (Year - 2004)^2 - 4086.1 * (Year - 2004) + 323349$$

Combination No.4

Electricity:

$$Cost = 3984.6 * ((Year - 2004)^2) - 3719 * (Year - 2004) + 308587$$

Combination No.5

Electricity:

$$Cost = 4315.4 * ((Year - 2004)^2) - 4001.8 * (Year - 2004) + 331375$$

Combination No.6

Electricity:

$$Cost = 4223.1 * ((Year - 2004)^2) - 4095.9 * (Year - 2004) + 324967$$

Combination No.7

Electricity:

$$Cost = 4120.4 * ((Year - 2004)^2) - 4200.7 * (Year - 2004) + 317891$$

Combination No.8

Electricity:

$$Cost = 4291.9 * ((Year - 2004)^2) - 3976.2 * (Year - 2004) + 329765$$

Combination No.9

Electricity:

$$Cost = 4186.9 * ((Year - 2004)^\wedge 2) - 4083.5 * (Year - 2004) + 322494$$

Combination No.10

Electricity:

$$Cost = 3966.4 * ((Year - 2004)^\wedge 2) - 3739.2 * (Year - 2004) + 307347$$

Appendix. D Annual Utility Cost without Inflation Rates of Hybrid System Combinations

Combination	1				2			
Year	Electricity	Steam	Natural gas	Water	electricity	steam	Natural gas	Water
2015	823913.90	0.00	55882.37655	36659.49	806634.4	150321.162	55882.37655	45009.86511
2016	918198.80	0.00	64551.14232	40308.30	901530.0	161798.0237	64551.14232	49489.81725
2017	1020938.70	0.00	73219.90809	44202.91	1005023.8	173274.8854	73219.90809	54271.54906
2018	1132133.60	0.00	81888.67386	48343.31	1117115.8	184751.7471	81888.67386	59355.06056
2019	1251783.50	0.00	90557.43963	52729.51	1237806.0	196228.6088	90557.43963	64740.35174
2020	1379888.40	0.00	99226.2054	57361.49	1367094.4	207705.4705	99226.2054	70427.42259
2021	1516448.30	0.00	107894.9712	62239.27	1504981.0	219182.3322	107894.9712	76416.27313
2022	1661463.20	0.00	116563.7369	67362.84	1651465.8	230659.1939	116563.7369	82706.90334
2023	1814933.10	0.00	125232.5027	72732.21	1806548.8	242136.0556	125232.5027	89299.31324
2024	1976858.00	0.00	133901.2685	78347.37	1970230.0	253612.9173	133901.2685	96193.50281
2025	2147237.90	0.00	142570.0343	84208.31	2142509.4	265089.779	142570.0343	103389.4721
2026	2326072.80	0.00	151238.8	90315.06	2323387.0	276566.6408	151238.8	110887.221
2027	2513362.70	0.00	159907.5658	96667.59	2512862.8	288043.5025	159907.5658	118686.7496
2028	2709107.60	0.00	168576.3316	103265.92	2710936.8	299520.3642	168576.3316	126788.0579
2029	2913307.50	0.00	177245.0973	110110.04	2917609.0	310997.2259	177245.0973	135191.1459
2030	3125962.40	0.00	185913.8631	117199.95	3132879.4	322474.0876	185913.8631	143896.0135
2031	3347072.30	0.00	194582.6289	124535.65	3356748.0	333950.9493	194582.6289	152902.6608
2032	3576637.20	0.00	203251.3946	132117.15	3589214.8	345427.811	203251.3946	162211.0878
2033	3814657.10	0.00	211920.1604	139944.44	3830279.8	356904.6727	211920.1604	171821.2945
2034	4061132.00	0.00	220588.9262	148017.52	4079943.0	368381.5344	220588.9262	181733.2809
2035	4316061.90	0.00	229257.692	156336.39	4338204.4	379858.3961	229257.692	191947.0469

Combination	3				4			
Year	electricity	steam	Natural gas	water	electricity	steam	Natural gas	water
2015	786517.2	326608.3371	55882.37655	45009.86511	749814.60	502445.2705	55882.37655	67478.10882
2016	879015.0	351528.5818	64551.14232	49489.81725	837741.40	540722.2334	64551.14232	74194.38529
2017	979911.4	376448.8265	73219.90809	54271.54906	933637.40	578999.1963	73219.90809	81363.08529
2018	1089206.4	401369.0712	81888.67386	59355.06056	1037502.60	617276.1592	81888.67386	88984.20882
2019	1206900.0	426289.3159	90557.43963	64740.35174	1149337.00	655553.1221	90557.43963	97057.75588
2020	1332992.2	451209.5606	99226.2054	70427.42259	1269140.60	693830.085	99226.2054	105583.7265
2021	1467483.0	476129.8053	107894.9712	76416.27313	1396913.40	732107.048	107894.9712	114562.1206
2022	1610372.4	501050.05	116563.7369	82706.90334	1532655.40	770384.0109	116563.7369	123992.9382
2023	1761660.4	525970.2947	125232.5027	89299.31324	1676366.60	808660.9738	125232.5027	133876.1794
2024	1921347.0	550890.5394	133901.2685	96193.50281	1828047.00	846937.9367	133901.2685	144211.8441
2025	2089432.2	575810.784	142570.0343	103389.4721	1987696.60	885214.8996	142570.0343	154999.9324
2026	2265916.0	600731.0287	151238.8	110887.221	2155315.40	923491.8625	151238.8	166240.4441
2027	2450798.4	625651.2734	159907.5658	118686.7496	2330903.40	961768.8254	159907.5658	177933.3794
2028	2644079.4	650571.5181	168576.3316	126788.0579	2514460.60	1000045.788	168576.3316	190078.7382
2029	2845759.0	675491.7628	177245.0973	135191.1459	2705987.00	1038322.751	177245.0973	202676.5206
2030	3055837.2	700412.0075	185913.8631	143896.0135	2905482.60	1076599.714	185913.8631	215726.7265
2031	3274314.0	725332.2522	194582.6289	152902.6608	3112947.40	1114876.677	194582.6289	229229.3559
2032	3501189.4	750252.4969	203251.3946	162211.0878	3328381.40	1153153.64	203251.3946	243184.4088
2033	3736463.4	775172.7416	211920.1604	171821.2945	3551784.60	1191430.603	211920.1604	257591.8853
2034	3980136.0	800092.9863	220588.9262	181733.2809	3783157.00	1229707.566	220588.9262	272451.7853
2035	4232207.2	825013.231	229257.692	191947.0469	4022498.60	1267984.529	229257.692	287764.1088

Combination	5				6			
Year	electricity	steam	Natural gas	water	electricity	steam	Natural gas	water
2015	809518.6	93959.92581	55882.37655	44584.2746	790907.2	203080.5133	55882.37655	44569.59906
2016	904771.0	101138.5141	64551.14232	49021.86658	883942.6	218675.056	64551.14232	49005.73035
2017	1008654.2	108317.1023	73219.90809	53758.38476	985424.2	234269.5987	73219.90809	53740.68944
2018	1121168.2	115495.6906	81888.67386	58793.82914	1095352.0	249864.1414	81888.67386	58774.47634
2019	1242313.0	122674.2788	90557.43963	64128.19973	1213726.0	265458.6841	90557.43963	64107.09104
2020	1372088.6	129852.8671	99226.2054	69761.49652	1340546.2	281053.2269	99226.2054	69738.53356
2021	1510495.0	137031.4554	107894.9712	75693.71952	1475812.6	296647.7696	107894.9712	75668.80388
2022	1657532.2	144210.0436	116563.7369	81924.86872	1619525.2	312242.3123	116563.7369	81897.90201
2023	1813200.2	151388.6319	125232.5027	88454.94412	1771684.0	327836.855	125232.5027	88425.82794
2024	1977499.0	158567.2201	133901.2685	95283.94572	1932289.0	343431.3977	133901.2685	95252.58168
2025	2150428.6	165745.8084	142570.0343	102411.8735	2101340.2	359025.9405	142570.0343	102378.1632
2026	2331989.0	172924.3967	151238.8	109838.7275	2278837.6	374620.4832	151238.8	109802.5726
2027	2522180.2	180102.9849	159907.5658	117564.5078	2464781.2	390215.0259	159907.5658	117525.8098
2028	2721002.2	187281.5732	168576.3316	125589.2142	2659171.0	405809.5686	168576.3316	125547.8747
2029	2928455.0	194460.1614	177245.0973	133912.8468	2862007.0	421404.1114	177245.0973	133868.7675
2030	3144538.6	201638.7497	185913.8631	142535.4056	3073289.2	436998.6541	185913.8631	142488.4881
2031	3369253.0	208817.3379	194582.6289	151456.8906	3293017.6	452593.1968	194582.6289	151407.0365
2032	3602598.2	215995.9262	203251.3946	160677.3019	3521192.2	468187.7395	203251.3946	160624.4127
2033	3844574.2	223174.5145	211920.1604	170196.6393	3757813.0	483782.2822	211920.1604	170140.6167
2034	4095181.0	230353.1027	220588.9262	180014.9029	4002880.0	499376.825	220588.9262	179955.6485
2035	4354418.6	237531.691	229257.692	190132.0928	4256393.2	514971.3677	229257.692	190069.5082

Combination	7				8			
Year	electricity	steam	Natural gas	water	electricity	steam	Natural gas	water
2015	770251.70	264269.8744	55882.37655	62679.20896	805346.7	0	73860.6726	42206.83797
2016	860820.20	284423.1105	64551.14232	68917.8381	900084.2	0	85318.32544	46407.79733
2017	959629.50	304576.3466	73219.90809	75576.71537	1003405.5	0	96775.97828	50891.74278
2018	1066679.60	324729.5826	81888.67386	82655.84078	1115310.6	0	108233.6311	55658.67433
2019	1181970.50	344882.8187	90557.43963	90155.2143	1235799.5	0	119691.284	60708.59198
2020	1305502.20	365036.0548	99226.2054	98074.83596	1364872.2	0	131148.9368	66041.49572
2021	1437274.70	385189.2908	107894.9712	106414.7057	1502528.7	0	142606.5896	71657.38556
2022	1577288.00	405342.5269	116563.7369	115174.8237	1648769.0	0	154064.2425	77556.2615
2023	1725542.10	425495.763	125232.5027	124355.1897	1803593.1	0	165521.8953	83738.12353
2024	1882037.00	445648.9991	133901.2685	133955.8039	1967001.0	0	176979.5482	90202.97166
2025	2046772.70	465802.2351	142570.0343	143976.6662	2138992.7	0	188437.201	96950.80588
2026	2219749.20	485955.4712	151238.8	154417.7766	2319568.2	0	199894.8538	103981.6262
2027	2400966.50	506108.7073	159907.5658	165279.1352	2508727.5	0	211352.5067	111295.4326
2028	2590424.60	526261.9433	168576.3316	176560.7418	2706470.6	0	222810.1595	118892.2251
2029	2788123.50	546415.1794	177245.0973	188262.5967	2912797.5	0	234267.8124	126772.0037
2030	2994063.20	566568.4155	185913.8631	200384.6996	3127708.2	0	245725.4652	134934.7684
2031	3208243.70	586721.6515	194582.6289	212927.0507	3351202.7	0	257183.118	143380.5193
2032	3430665.00	606874.8876	203251.3946	225889.6499	3583281.0	0	268640.7709	152109.2561
2033	3661327.10	627028.1237	211920.1604	239272.4972	3823943.1	0	280098.4237	161120.9791
2034	3900230.00	647181.3597	220588.9262	253075.5926	4073189.0	0	291556.0766	170415.6882
2035	4147373.70	667334.5958	229257.692	267298.9362	4331018.7	0	303013.7294	179993.3834

Combination	9				10			
Year	electricity	steam	Natural gas	water	electricity	steam	Natural gas	water
2015	784190.4	0	73846.45125	42060.08262	746150.20	0	113965.7161	53213.48904
2016	876405.6	0	85301.898	46246.43503	833638.20	0	131644.6726	58509.96979
2017	976994.6	0	96757.34475	50714.78957	929059.00	0	149323.629	64163.23342
2018	1085957.4	0	108212.7915	55465.14626	1032412.60	0	167002.5854	70173.27995
2019	1203294.0	0	119668.2383	60497.50508	1143699.00	0	184681.5418	76540.10936
2020	1329004.4	0	131123.685	65811.86604	1262918.20	0	202360.4982	83263.72166
2021	1463088.6	0	142579.1318	71408.22914	1390070.20	0	220039.4546	90344.11684
2022	1605546.6	0	154034.5785	77286.59439	1525155.00	0	237718.411	97781.29492
2023	1756378.4	0	165490.0253	83446.96176	1668172.60	0	255397.3674	105575.2559
2024	1915584.0	0	176945.472	89889.33128	1819123.00	0	273076.3238	113725.9997
2025	2083163.4	0	188400.9187	96613.70294	1978006.20	0	290755.2802	122233.5265
2026	2259116.6	0	199856.3655	103620.0767	2144822.20	0	308434.2367	131097.8361
2027	2443443.6	0	211311.8123	110908.4527	2319571.00	0	326113.1931	140318.9286
2028	2636144.4	0	222767.259	118478.8307	2502252.60	0	343792.1495	149896.804
2029	2837219.0	0	234222.7058	126331.211	2692867.00	0	361471.1059	159831.4623
2030	3046667.4	0	245678.1525	134465.5933	2891414.20	0	379150.0623	170122.9035
2031	3264489.6	0	257133.5993	142881.9778	3097894.20	0	396829.0187	180771.1275
2032	3490685.6	0	268589.046	151580.3644	3312307.00	0	414507.9751	191776.1345
2033	3725255.4	0	280044.4928	160560.7532	3534652.60	0	432186.9315	203137.9243
2034	3968199.0	0	291499.9395	169823.1441	3764931.00	0	449865.8879	214856.4971
2035	4219516.4	0	302955.3863	179367.5372	4003142.20	0	467544.8444	226931.8527

Appendix. E Interest Rates and Projected furl price indices Used in Sensitive Analysis

	inflation rate 3%		
	interest rate	projected fuel price indices	
Year	SPV	Electricity	Natural Gas
2012	1	0.99	1.01
2013	0.978	0.98	1.01
2014	0.956	1	1
2015	0.934	1.02	1.01
2016	0.913	1.05	1.05
2017	0.893	1.08	1.09
2018	0.872	1.11	1.13
2019	0.853	1.15	1.18
2020	0.834	1.2	1.23
2021	0.815	1.25	1.28
2022	0.797	1.3	1.34
2023	0.779	1.34	1.39
2024	0.761	1.38	1.45
2025	0.744	1.43	1.52
2026	0.727	1.47	1.58
2027	0.711	1.51	1.64
2028	0.695	1.55	1.71
2029	0.679	1.59	1.78
2030	0.664	1.64	1.85
2031	0.649	1.69	1.92
2032	0.635	1.74	1.99
2033	0.62	1.8	2.07
2034	0.606	1.87	2.14
2035	0.593	1.93	2.22

Appendix. F Sensitive Analysis Results of All Combinations

Combination	1					2							
Year	Electricity	Steam	Natural ga	Water	Total	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?
2015	840392.2	0	56441.2	34239.96	931073.3	822767.1	140400	56441.2	42039.21	1061647	14.02404	-130574	NO
2016	964108.7	0	67778.7	36801.48	1068689	946606.5	147721.6	67778.7	45184.2	1207291	12.96936	-138602	NO
2017	1102614	0	79809.7	39473.2	1221897	1085426	154734.5	79809.7	48464.49	1368434	11.99264	-146538	NO
2018	1256668	0	92534.2	42155.37	1391358	1239999	161103.5	92534.2	51757.61	1545394	11.07091	-154036	NO
2019	1439551	0	106857.8	44978.27	1591387	1423477	167383	106857.8	55223.52	1752941	10.15178	-161554	NO
2020	1655866	0	122048.2	47839.49	1825754	1640513	173226.4	122048.2	58736.47	1994524	9.243883	-168771	NO
2021	1895560	0	138105.6	50725.01	2084391	1881226	178633.6	138105.6	62279.26	2260245	8.436696	-175854	NO
2022	2159902	0	156195.4	53688.19	2369786	2146906	183835.4	156195.4	65917.4	2552854	7.725085	-183068	NO
2023	2432010	0	174073.2	56658.39	2662742	2420775	188624	174073.2	69564.17	2853037	7.146573	-190295	NO
2024	2728064	0	194156.8	59622.35	2981843	2718917	192999.4	194156.8	73203.26	3179277	6.621197	-197434	NO
2025	3070550	0	216706.5	62650.99	3349908	3063788	197226.8	216706.5	76921.77	3554643	6.111686	-204736	NO
2026	3419327	0	238957.3	65659.05	3723943	3415379	201063.9	238957.3	80615.01	3936015	5.694818	-212072	NO
2027	3795178	0	262248.4	68730.66	4126157	3794423	204798.9	262248.4	84386.28	4345856	5.32456	-219700	NO
2028	4199117	0	288265.5	71769.81	4559152	4201952	208166.7	288265.5	88117.7	4786502	4.986668	-227350	NO
2029	4632159	0	315496.3	74764.71	5022420	4638998	211167.1	315496.3	91794.79	5257456	4.679748	-235037	NO
2030	5126578	0	343940.6	77820.77	5548340	5137922	214122.8	343940.6	95546.95	5791533	4.383165	-243193	NO
2031	5656552	0	373598.6	80823.64	6110974	5672904	216734.2	373598.6	99233.83	6362471	4.115486	-251496	NO
2032	6223349	0	404470.3	83894.39	6711713	6245234	219346.7	404470.3	103004	6972055	3.87891	-260341	NO
2033	6866383	0	438674.7	86765.55	7391823	6894504	221280.9	438674.7	106529.2	7660988	3.641394	-269165	NO
2034	7594317	0	472060.3	89698.62	8156076	7629493	223239.2	472060.3	110130.4	8434923	3.418893	-278848	NO
2035	8329999	0	508952.1	92707.48	8931659	8372734	225256	508952.1	113824.6	9220767	3.236892	-289108	NO
Total:	75388246	0	5051371	1321467	81761085	75393945	4031065	5051371	1622474	86098855		-4337770	

Combination	3								4							
Year	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?
2015	802247.5	305052.2	56441.2	42039.21	1205780	29.50431	-274707	NO	764810.9	469283.9	56441.2	63024.55	1353561	45.37636	-422487	NO
2016	922965.8	320945.6	67778.7	45184.2	1356874	26.96625	-288185	NO	879628.5	493679.4	67778.7	67739.47	1508826	41.18477	-440137	NO
2017	1058304	336168.8	79809.7	48464.49	1522747	24.62161	-300851	NO	1008328	517046.3	79809.7	72657.24	1677842	37.31452	-455945	NO
2018	1209019	349993.8	92534.2	51757.61	1703305	22.42032	-311947	NO	1151628	538264.8	92534.2	77594.23	1860021	33.68388	-468663	NO
2019	1387935	363624.8	106857.8	55223.52	1913641	20.24988	-322254	NO	1321738	559186.8	106857.8	82790.27	2070572	30.11117	-479185	NO
2020	1599591	376308.8	122048.2	58736.47	2156684	18.12568	-330930	NO	1522969	578654.3	122048.2	88056.83	2311728	26.61773	-485974	NO
2021	1834354	388045.8	138105.6	62279.26	2422784	16.23464	-338393	NO	1746142	596667.2	138105.6	93368.13	2574283	23.50287	-489892	NO
2022	2093484	399336.9	156195.4	65917.4	2714934	14.56453	-345148	NO	1992452	613996.1	156195.4	98822.37	2861466	20.74787	-491680	NO
2023	2360625	409730.9	174073.2	69564.17	3013993	13.19134	-351251	NO	2246331	629946.9	174073.2	104289.5	3154641	18.4734	-491899	NO
2024	2651459	419227.7	194156.8	73203.26	3338047	11.94575	-356203	NO	2522705	644519.8	194156.8	109745.2	3471127	16.40876	-489283	NO
2025	2987888	428403.2	216706.5	76921.77	3709919	10.74692	-360012	NO	2842406	658599.9	216706.5	115319.9	3833032	14.42203	-483125	NO
2026	3330897	436731.5	238957.3	80615.01	4087200	9.754631	-363257	NO	3168314	671378.6	238957.3	120856.8	4199506	12.77041	-475563	NO
2027	3700706	444838.1	262248.4	84386.28	4492178	8.870763	-366022	NO	3519664	683817.6	262248.4	126510.6	4592241	11.29584	-466084	NO
2028	4098323	452147.2	288265.5	88117.7	4926854	8.065126	-367701	NO	3897414	695031.8	288265.5	132104.7	5012816	9.95062	-453664	NO
2029	4524757	458658.9	315496.3	91794.79	5390707	7.332857	-368287	NO	4302519	705021.1	315496.3	137617.4	5460654	8.725559	-438234	NO
2030	5011573	465073.6	343940.6	95546.95	5916134	6.62891	-367794	NO	4764991	714862.2	343940.6	143242.5	5967037	7.54635	-418697	NO
2031	5533591	470740.6	373598.6	99233.83	6477164	5.992322	-366189	NO	5260881	723555	373598.6	148769.9	6506805	6.477365	-395830	NO
2032	6092070	476410.3	404470.3	103004	7075954	5.426942	-364241	NO	5791384	732252.6	404470.3	154422.1	7082529	5.524896	-370815	NO
2033	6725634	480607.1	438674.7	106529.2	7751445	4.865134	-359622	NO	6393212	738687	438674.7	159707	7730281	4.578815	-338458	NO
2034	7442854	484856.3	472060.3	110130.4	8509901	4.338184	-353826	NO	7074504	745202.8	472060.3	165105.8	8456872	3.688008	-300797	NO
2035	8168160	489232.8	508952.1	113824.6	9280169	3.901967	-348510	NO	7763422	751914.8	508952.1	170644.1	9194933	2.947653	-263274	NO
Total:	73536436	8756135	5051371	1622474	88966416		-7205331		69935443	13461569	5051371	2432389	90880772		-9119688	

Combination	5								6							
Year	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?
2015	825709	87758.57	56441.2	41641.71	1011550	8.643478	-80477.1	NO	806725.3	189677.2	56441.2	41628.01	1094472	17.54947	-163398	NO
2016	950009.6	92339.46	67778.7	44756.96	1154885	8.065561	-86195.8	NO	928139.7	199650.3	67778.7	44742.23	1240311	16.05912	-171622	NO
2017	1089347	96727.17	79809.7	48006.24	1313890	7.528701	-91992.9	NO	1064258	209202.8	79809.7	47990.44	1401261	14.67917	-179364	NO
2018	1244497	100712.2	92534.2	51268.22	1489011	7.018575	-97653.5	NO	1215841	217881.5	92534.2	51251.34	1577508	13.37901	-186150	NO
2019	1428660	104641.2	106857.8	54701.35	1694860	6.502074	-103473	NO	1395785	226436.3	106857.8	54683.35	1783762	12.08852	-192375	NO
2020	1646506	108297.3	122048.2	58181.09	1935033	5.985425	-109279	NO	1608655	234398.4	122048.2	58161.94	2023264	10.81801	-197510	NO
2021	1888119	111680.6	138105.6	61690.38	2199595	5.527005	-115204	NO	1844766	241767.9	138105.6	61670.08	2286309	9.687164	-201918	NO
2022	2154792	114935.4	156195.4	65294.12	2491217	5.124136	-121431	NO	2105383	248857.1	156195.4	65272.63	2575708	8.689484	-205922	NO
2023	2429688	117931.7	174073.2	68906.4	2790600	4.80173	-127858	NO	2374057	255384.9	174073.2	68883.72	2872398	7.873705	-209656	NO
2024	2728949	120669.7	194156.8	72511.08	3116286	4.50872	-134443	NO	2666559	261351.3	194156.8	72487.21	3194554	7.133539	-212711	NO
2025	3075113	123314.9	216706.5	76194.43	3491329	4.22164	-141421	NO	3004916	267115.3	216706.5	76169.35	3564908	6.418086	-215000	NO
2026	3428024	125716	238957.3	79852.75	3872550	3.99057	-148607	NO	3349891	272349.1	238957.3	79826.47	3941024	5.829325	-217081	NO
2027	3808492	128053.2	262248.4	83588.37	4282382	3.78622	-156225	NO	3721820	277442.9	262248.4	83560.85	4345072	5.305543	-218915	NO
2028	4217553	130160.7	288265.5	87284.5	4723264	3.599617	-164112	NO	4121715	282037.7	288265.5	87255.77	4779274	4.828132	-220122	NO
2029	4656243	132038.4	315496.3	90926.82	5194705	3.43032	-172285	NO	4550591	286133.4	315496.3	90896.89	5243118	4.394252	-220698	NO
2030	5157043	133888.1	343940.6	94643.51	5729516	3.265406	-181176	NO	5040194	290167.1	343940.6	94612.36	5768914	3.975507	-220575	NO
2031	5694038	135522.5	373598.6	98295.52	6301454	3.117011	-190480	NO	5565200	293733	373598.6	98263.17	6330795	3.597136	-219820	NO
2032	6268521	137157.4	404470.3	102030.1	6912179	2.986797	-200465	NO	6126874	297299.2	404470.3	101996.5	6930640	3.261865	-218927	NO
2033	6920234	138368.2	438674.7	105521.9	7602798	2.854172	-210975	NO	6764063	299945	438674.7	105487.2	7608170	2.926846	-216347	NO
2034	7657988	139594	472060.3	109089	8378732	2.729941	-222656	NO	7485386	302622.4	472060.3	109053.1	8369121	2.612109	-213046	NO
2035	8404028	140856.3	508952.1	112748.3	9166585	2.630257	-234926	NO	8214839	305378	508952.1	112711.2	9141880	2.353663	-210221	NO
Total:	75673553	2520363	5051371	1607133	84852420		-3091335		73955658	5458831	5051371	1606604	86072464		-4311379	

Combination	7								8							
Year	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?
2015	785656.7	246828.1	56441.2	58542.38	1147468	23.24146	-163398	NO	821453.6	0	74599.28	39421.19	935474.1	0.472655	-4400.76	No
2016	903861.2	259678.3	67778.7	62921.99	1294240	21.10542	-171622	NO	945088.4	0	89584.24	42370.32	1077043	0.78171	-8354.05	No
2017	1036400	271986.7	79809.7	67490.01	1455686	19.13333	-179364	NO	1083678	0	105485.8	45446.33	1234610	1.040463	-12713.4	No
2018	1184014	283164.2	92534.2	72075.89	1631789	17.2803	-186150	NO	1237995	0	122304	48534.36	1408833	1.255986	-17475.3	No
2019	1359266	294185	106857.8	76902.4	1837211	15.44717	-192375	NO	1421169	0	141235.7	51784.43	1614190	1.432869	-22802.5	No
2020	1566603	304440.1	122048.2	81794.41	2074885	13.64541	-197510	NO	1637847	0	161313.2	55078.61	1854238	1.560158	-28484.6	No
2021	1796593	313929.3	138105.6	86727.99	2335356	12.04022	-201918	NO	1878161	0	182536.4	58400.77	2119098	1.665097	-34707.1	No
2022	2050474	323058	156195.4	91794.33	2621522	10.62275	-205922	NO	2143400	0	206446.1	61812.34	2411658	1.766926	-41872.4	No
2023	2312226	331461.2	174073.2	96872.69	2914633	9.459856	-209656	NO	2416815	0	230075.4	65232	2712122	1.854489	-49380.3	No
2024	2597211	339138.9	194156.8	101940.4	3232447	8.40433	-212711	NO	2714461	0	256620.3	68644.46	3039726	1.941181	-57883	No
2025	2926885	346556.9	216706.5	107118.6	3597267	7.384063	-215000	NO	3058760	0	286424.5	72131.4	3417316	2.012231	-67407.9	No
2026	3263031	353289.6	238957.3	112261.7	3967540	6.541362	-217081	NO	3409765	0	315833.9	75594.64	3801194	2.074425	-77250.4	No
2027	3625459	359843.3	262248.4	117513.5	4365065	5.790081	-218915	NO	3788179	0	346618.1	79131.05	4213928	2.127184	-87770.9	No
2028	4015158	365752.1	288265.5	122709.7	4791885	5.10475	-220122	NO	4195029	0	381005.4	82630.1	4658665	2.182704	-99512.8	No
2029	4433116	371015.9	315496.3	127830.3	5247459	4.480687	-220698	NO	4631348	0	416996.7	86078.19	5134423	2.230061	-112003	No
2030	4910264	376201.4	343940.6	133055.4	5763461	3.877221	-220575	NO	5129441	0	454592.1	89596.69	5673630	2.258162	-125290	No
2031	5421932	380782.4	373598.6	138189.7	6314503	3.330533	-219820	NO	5663533	0	493791.6	93053.96	6250378	2.281201	-139404	No
2032	5969357	385365.6	404470.3	143439.9	6902633	2.844571	-218927	NO	6234909	0	534595.1	96589.38	6866093	2.300159	-154380	No
2033	6590389	388757.4	438674.7	148348.9	7566170	2.358645	-216347	NO	6883098	0	579803.7	99895.01	7562796	2.313005	-170973	No
2034	7293430	392191.9	472060.3	153363.8	8311046	1.90006	-213046	NO	7616863	0	623930	103271.9	8344065	2.304902	-187990	No
2035	8004431	395729.4	508952.1	158508.3	9067621	1.522248	-210221	NO	8358866	0	672690.5	106736.1	9138293	2.313497	-206634	No
Total:	72045759	7083356	5051371	2259402	86439888		-4311379		75269858	0	6676482	1521433	83467774		-1706689	

Combination	9								10							
Year	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?	Electricity	Steam	Natural ga	Water	Total	Δ%	Saving $	Saving?
2015	799874.2	0	74584.92	39284.12	913743.2	-1.8613	17330.1	YES	761073.2	0	115105.4	49701.4	925880	-0.55778	5193.362	YES
2016	920225.9	0	89566.99	42223	1052016	-1.56014	16673.05	YES	875320.1	0	138226.9	53419.6	1066967	-0.16116	1722.301	YES
2017	1055154	0	105465.5	45288.31	1205908	-1.30852	15988.71	YES	1003384	0	162762.8	57297.77	1223444	0.126651	-1547.55	NO
2018	1205413	0	122280.5	48365.61	1376059	-1.09958	15299.09	YES	1145978	0	188712.9	61191.1	1395882	0.32516	-4524.14	NO
2019	1383788	0	141208.5	51604.37	1576601	-0.92913	14786.08	YES	1315254	0	217924.2	65288.71	1598467	0.444877	-7079.71	NO
2020	1594805	0	161282.1	54887.1	1810975	-0.80949	14779.29	YES	1515502	0	248903.4	69441.94	1833847	0.443291	-8093.4	NO
2021	1828861	0	182501.3	58197.71	2069560	-0.71154	14831.2	YES	1737588	0	281650.5	73630.46	2092869	0.406726	-8477.76	NO
2022	2087211	0	206406.3	61597.42	2355214	-0.61488	14571.42	YES	1982702	0	318542.7	77931.69	2379176	0.396243	-9390.11	NO
2023	2353547	0	230031.1	65005.18	2648583	-0.53173	14158.55	YES	2235351	0	355002.3	82243.12	2672597	0.370101	-9854.83	NO
2024	2643506	0	256570.9	68405.78	2968483	-0.44806	13360.59	YES	2510390	0	395960.7	86545.49	2992896	0.370666	-11052.7	NO
2025	2978924	0	286369.4	71880.59	3337174	-0.38013	12733.98	YES	2828549	0	441948	90941.74	3361439	0.344218	-11531	NO
2026	3320901	0	315773.1	75331.8	3712006	-0.32055	11937.11	YES	3152889	0	487326.1	95308.13	3735523	0.310947	-11579.5	NO
2027	3689600	0	346551.4	78855.91	4115007	-0.27022	11149.62	YES	3502552	0	534825.6	99766.76	4137145	0.266298	-10987.9	NO
2028	4086024	0	380932	82342.79	4549299	-0.21613	9853.499	YES	3878492	0	587884.6	104178.3	4570554	0.250096	-11402.3	NO
2029	4511178	0	416916.4	85778.89	5013874	-0.17016	8546.395	YES	4281659	0	643418.6	108525.6	5033603	0.222657	-11182.7	NO
2030	4996535	0	454504.6	89285.15	5540324	-0.14447	8015.476	YES	4741919	0	701427.6	112961.6	5556309	0.143624	-7968.76	NO
2031	5516987	0	493696.5	92730.4	6103414	-0.12371	7560.135	YES	5235441	0	761911.7	117320.5	6114673	0.060529	-3698.9	NO
2032	6073793	0	534492.2	96253.53	6704539	-0.1069	7174.716	YES	5763414	0	824870.9	121777.8	6710063	-0.02459	1650.497	YES
2033	6705460	0	579692.1	99547.67	7384699	-0.09637	7123.577	YES	6362375	0	894626.9	125945.5	7382947	-0.12008	8875.923	YES
2034	7420532	0	623809.9	102912.8	8147255	-0.10815	8820.934	YES	7040421	0	962713	130203	8133337	-0.2788	22738.75	YES
2035	8143667	0	672561	106364.9	8922593	-0.10151	9066.466	YES	7726064	0	1037950	134570.6	8898585	-0.37031	33074.44	YES
Total:	73315985		6675197		81507325		253760		69596316		10301694	1918191	81816201		-55115.9	

Appendix. G Sensitive Analysis Results of All Operation of Sequences

		Original cost				Altnerative 1 - natural gas x2+ electric x1 (parallel)							
No. # year	Year	Electricity	Natural Ga	Water	Total	Electricity	Natural Ga	Water	Total	Saving (+)		Payback	Profit?
0	2015	840392.2	56441.2	34239.96	931073.3	799874.2	74584.92	39284.12	913743.2	17330.1	73469.9	-73469.9	NO
1	2016	964108.7	67778.7	36801.48	1068689	920225.9	89566.99	42223	1052016	16673.05	56796.85	-56796.9	NO
2	2017	1102614	79809.7	39473.2	1221897	1055154	105465.5	45288.31	1205908	15988.71	40808.14	-40808.1	NO
3	2018	1256668	92534.2	42155.37	1391358	1205413	122280.5	48365.61	1376059	15299.09	25509.05	-25509	NO
4	2019	1439551	106857.8	44978.27	1591387	1383788	141208.5	51604.37	1576601	14786.08	10722.97	-10723	NO
5	2020	1655866	122048.2	47839.49	1825754	1594805	161282.1	54887.1	1810975	14779.29	-4056.32	4056.324	YES
6	2021	1895560	138105.6	50725.01	2084391	1828861	182501.3	58197.71	2069560	14831.2	-18887.5	18887.52	YES
7	2022	2159902	156195.4	53688.19	2369786	2087211	206406.3	61597.42	2355214	14571.42	-33458.9	33458.95	YES
8	2023	2432010	174073.2	56658.39	2662742	2353547	230031.1	65005.18	2648583	14158.55	-47617.5	47617.5	YES
9	2024	2728064	194156.8	59622.35	2981843	2643506	256570.9	68405.78	2968483	13360.59	-60978.1	60978.09	YES
10	2025	3070550	216706.5	62650.99	3349908	2978924	286369.4	71880.59	3337174	12733.98	-73712.1	73712.07	YES
11	2026	3419327	238957.3	65659.05	3723943	3320901	315773.1	75331.8	3712006	11937.11	-85649.2	85649.18	YES
12	2027	3795178	262248.4	68730.66	4126157	3689600	346551.4	78855.91	4115007	11149.62	-96798.8	96798.8	YES
13	2028	4199117	288265.5	71769.81	4559152	4086024	380932	82342.79	4549299	9853.499	-106652	106652.3	YES
14	2029	4632159	315496.3	74764.71	5022420	4511178	416916.4	85778.89	5013874	8546.395	-115199	115198.7	YES
15	2030	5126578	343940.6	77820.77	5548340	4996535	454504.6	89285.15	5540324	8015.476	-123214	123214.2	YES
16	2031	5656552	373598.6	80823.64	6110974	5516987	493696.5	92730.4	6103414	7560.135	-130774	130774.3	YES
17	2032	6223349	404470.3	83894.39	6711713	6073793	534492.2	96253.53	6704539	7174.716	-137949	137949	YES
18	2033	6866383	438674.7	86765.55	7391823	6705460	579692.1	99547.67	7384699	7123.577	-145073	145072.6	YES
19	2034	7594317	472060.3	89698.62	8156076	7420532	623809.9	102912.8	8147255	8820.934	-153894	153893.5	YES
20	2035	8329999	508952.1	92707.48	8931659	8143667	672561	106364.9	8922593	9066.466	-162960	162960	YES

		Altnerative 2 - electric in single x1, natural gas in single x2							Altnerative 3 - natural gas in single (1st), electric and natural gas in single						
No. # year	Year	Electricity	Natural Ga	Water	Total	Saving (+)	Payback	Profit?	Electricity	Natural Ga	Water	Total	Saving (+)	Payback	Profit?
0	2015	799874.2	74584.92	39284.12	913743.2	17330.1	-73469.9	NO	782524.4	115043.7	49632.86	947201	-16127.6	-106928	NO
1	2016	920225.9	89566.99	42223	1052016	16673.05	-56796.9	NO	900033.3	138152.8	53345.94	1091532	-22843.2	-129771	NO
2	2017	1055154	105465.5	45288.31	1205908	15988.71	-40808.1	NO	1031734	162675.5	57218.76	1251628	-29731.8	-159503	NO
3	2018	1205413	122280.5	48365.61	1376059	15299.09	-25509.1	NO	1178360	188611.8	61106.72	1428078	-36720.2	-196223	NO
4	2019	1383788	141208.5	51604.37	1576601	14786.08	-10723	NO	1352402	217807.4	65198.68	1635408	-44021.4	-240244	NO
5	2020	1594805	161282.1	54887.1	1810975	14779.29	4056.32	YES	1558272	248770	69346.19	1876388	-50634.2	-290878	NO
6	2021	1828861	182501.3	58197.71	2069560	14831.2	18887.5	YES	1786573	281499.6	73528.92	2141602	-57210.8	-348089	NO
7	2022	2087211	206406.3	61597.42	2355214	14571.42	33458.9	YES	2038528	318372	77824.23	2434724	-64938.4	-413028	NO
8	2023	2353547	230031.1	65005.18	2648583	14158.55	47617.5	YES	2298206	354812.1	82129.72	2735148	-72406	-485434	NO
9	2024	2643506	256570.9	68405.78	2968483	13360.59	60978.1	YES	2580877	395748.5	86426.15	3063052	-81208.8	-566642	NO
10	2025	2978924	286369.4	71880.59	3337174	12733.98	73712.1	YES	2907853	441711.2	90816.34	3440381	-90473.1	-657116	NO
11	2026	3320901	315773.1	75331.8	3712006	11937.11	85649.2	YES	3241155	487065	95176.7	3823397	-99453.7	-756569	NO
12	2027	3689600	346551.4	78855.91	4115007	11149.62	96798.8	YES	3600463	534539.1	99629.19	4234631	-108474	-865043	NO
13	2028	4086024	380932	82342.79	4549299	9853.499	106652	YES	3986752	587569.6	104034.6	4678356	-119204	-984248	NO
14	2029	4511178	416916.4	85778.89	5013874	8546.395	115199	YES	4401001	643073.8	108375.9	5152450	-130031	-1114278	NO
15	2030	4996535	454504.6	89285.15	5540324	8015.476	123214	YES	4873904	701051.8	112805.8	5687762	-139422	-1253700	NO
16	2031	5516987	493696.5	92730.4	6103414	7560.135	130774	YES	5380963	761503.4	117158.7	6259625	-148650	-1402351	NO
17	2032	6073793	534492.2	96253.53	6704539	7174.716	137949	YES	5923397	824428.9	121609.9	6869436	-157723	-1560073	NO
18	2033	6705460	579692.1	99547.67	7384699	7123.577	145073	YES	6538756	894147.6	125771.8	7558675	-166852	-1726926	NO
19	2034	7420532	623809.9	102912.8	8147255	8820.934	153894	YES	7235355	962197.1	130023.5	8327576	-171500	-1898426	NO
20	2035	8143667	672561	106364.9	8922593	9066.466	162960	YES	7939724	1037393	134385	9111503	-179844	-2078270	NO

		Altnerative 4 - natural gas x2 in single + electric x1 in sidecar							Altnerative 5 - natural gas x1 in sidcar, others in single						
No. # year	Year	Electricity	Natural Ga	Water	Total	Saving (+)	Payback	Profit?	Electricity	Natural Ga	Water	Total	Saving (+)	Payback	Profit?
0	2015	812369.9	82175.64	47001.13	941546.7	-10473.4	-101273	NO	781249.2	115635.1	49838.47	946722.8	-15649.5	-106449	NO
1	2016	934713.6	98682.48	50517.32	1083913	-15224.5	-116498	NO	898565.4	138863.1	53566.93	1090995	-22306.5	-128756	NO
2	2017	1071887	116199	54184.79	1242271	-20374.1	-136872	NO	1030052	163511.9	57455.79	1251020	-29123.1	-157879	NO
3	2018	1224657	134725.3	57866.6	1417249	-25891	-162763	NO	1176441	189581.5	61359.86	1427382	-36024.5	-193904	NO
4	2019	1406017	155579.7	61741.59	1623338	-31951.3	-194714	NO	1350205	218927.2	65468.77	1634601	-43213.5	-237117	NO
5	2020	1620570	177696.3	65669.17	1863935	-38181.2	-232895	NO	1555746	250049	69633.46	1875428	-49674.1	-286791	NO
6	2021	1858560	201075	69630.12	2129265	-44874	-277769	NO	1783685	282946.8	73833.52	2140465	-56073.8	-342865	NO
7	2022	2121266	227412.9	73697.68	2422377	-52591.2	-330361	NO	2035241	320008.7	78146.62	2433396	-63610.6	-406476	NO
8	2023	2392116	253442.1	77774.87	2723333	-60590.9	-390951	NO	2294511	356636.2	82469.94	2733617	-70875.4	-477351	NO
9	2024	2686999	282682.9	81843.48	3051526	-69682.5	-460634	NO	2576740	397783	86784.17	3061307	-79464.1	-556815	NO
10	2025	3028115	315514	86000.89	3429630	-79722.5	-540357	NO	2903205	443982.1	91192.55	3438380	-88472.4	-645288	NO
11	2026	3375925	347910.2	90130.05	3813965	-90021.6	-630378	NO	3235990	489569	95570.97	3821130	-97186.4	-742474	NO
12	2027	3750921	381820.9	94346.45	4227089	-100932	-731310	NO	3594741	537287.1	100041.9	4232070	-105913	-848387	NO
13	2028	4154128	419700.6	98518.29	4672347	-113195	-844505	NO	3980434	590590.3	104465.6	4675490	-116338	-964725	NO
14	2029	4586567	459347.2	102629.4	5148544	-126124	-970629	NO	4394045	646379.8	108824.9	5149249	-126829	-1091554	NO
15	2030	5080239	500760.8	106824.4	5687824	-139484	-1110113	NO	4866220	704655.9	113273.1	5684149	-135810	-1227364	NO
16	2031	5609620	543941.4	110946.5	6264508	-153534	-1263647	NO	5372501	765418.3	117644	6255563	-144589	-1371952	NO
17	2032	6175990	588889	115161.7	6880040	-168327	-1431974	NO	5914105	828667.3	122113.7	6864886	-153173	-1525125	NO
18	2033	6818506	638689	119102.9	7576298	-184475	-1616449	NO	6528522	898744.4	126292.9	7553559	-161736	-1686861	NO
19	2034	7545863	687296.8	123129.1	8356289	-200213	-1816662	NO	7224057	967143.8	130562.1	8321763	-165687	-1852548	NO
20	2035	8281447	741009.4	127259.4	9149716	-218057	-2034719	NO	7927353	1042727	134941.7	9105021	-173362	-2025910	NO

		Altnerative 6 - decoupling, electric (1st)							Altnerative 7 - decoupling, natural gas (1st)						
No. # year	Year	Electricity	Natural Ga	Water	Total	Saving (+)	Payback	Profit?	Electricity	Natural Ga	Water	Total	Saving (+)	Payback	Profit?
0	2015	799874.2	74584.92	39284.12	913743.2	17330.1	-73469.9	NO	782524.4	115036.1	49632.86	947193.4	-16120	-106920	NO
1	2016	920225.9	89566.99	42223	1052016	16673.05	-56796.9	NO	900033.3	138143.7	53345.94	1091523	-22834.1	-129754	NO
2	2017	1055154	105465.5	45288.31	1205908	15988.71	-40808.1	NO	1031734	162664.8	57218.76	1251618	-29721	-159475	NO
3	2018	1205413	122280.5	48365.61	1376059	15299.09	-25509	NO	1178360	188599.3	61106.72	1428066	-36707.8	-196183	NO
4	2019	1383788	141208.5	51604.37	1576601	14786.08	-10723	NO	1352402	217793	65198.68	1635394	-44007	-240190	NO
5	2020	1594805	161282.1	54887.1	1810975	14779.29	4056.324	YES	1558272	248753.6	69346.19	1876372	-50617.7	-290808	NO
6	2021	1828861	182501.3	58197.71	2069560	14831.2	18887.52	YES	1786573	281481	73528.92	2141583	-57192.2	-348000	NO
7	2022	2087211	206406.3	61597.42	2355214	14571.42	33458.95	YES	2038528	318350.9	77824.23	2434703	-64917.3	-412917	NO
8	2023	2353547	230031.1	65005.18	2648583	14158.55	47617.5	YES	2298206	354788.7	82129.72	2735125	-72382.6	-485300	NO
9	2024	2643506	256570.9	68405.78	2968483	13360.59	60978.09	YES	2580877	395722.3	86426.15	3063026	-81182.6	-566482	NO
10	2025	2978924	286369.4	71880.59	3337174	12733.98	73712.07	YES	2907853	441682	90816.34	3440352	-90444	-656926	NO
11	2026	3320901	315773.1	75331.8	3712006	11937.11	85649.18	YES	3241155	487032.8	95176.7	3823365	-99421.5	-756348	NO
12	2027	3689600	346551.4	78855.91	4115007	11149.62	96798.8	YES	3600463	534503.7	99629.19	4234596	-108439	-864787	NO
13	2028	4086024	380932	82342.79	4549299	9853.499	106652.3	YES	3986752	587530.7	104034.6	4678318	-119165	-983952	NO
14	2029	4511178	416916.4	85778.89	5013874	8546.395	115198.7	YES	4401001	643031.3	108375.9	5152408	-129988	-1113940	NO
15	2030	4996535	454504.6	89285.15	5540324	8015.476	123214.2	YES	4873904	701005.4	112805.8	5687715	-139376	-1253316	NO
16	2031	5516987	493696.5	92730.4	6103414	7560.135	130774.3	YES	5380963	761453.1	117158.7	6259575	-148600	-1401916	NO
17	2032	6073793	534492.2	96253.53	6704539	7174.716	137949	YES	5923397	824374.4	121609.9	6869382	-157668	-1559584	NO
18	2033	6705460	579692.1	99547.67	7384699	7123.577	145072.6	YES	6538756	894088.5	125771.8	7558616	-166793	-1726377	NO
19	2034	7420532	623809.9	102912.8	8147255	8820.934	153893.5	YES	7235355	962133.5	130023.5	8327512	-171437	-1897814	NO
20	2035	8143667	672561	106364.9	8922593	9066.466	162960	YES	7939724	1037325	134385	9111434	-179775	-2077589	NO

Appendix. H Ventilation Distribution of Supplying Air to Galleries and Offices

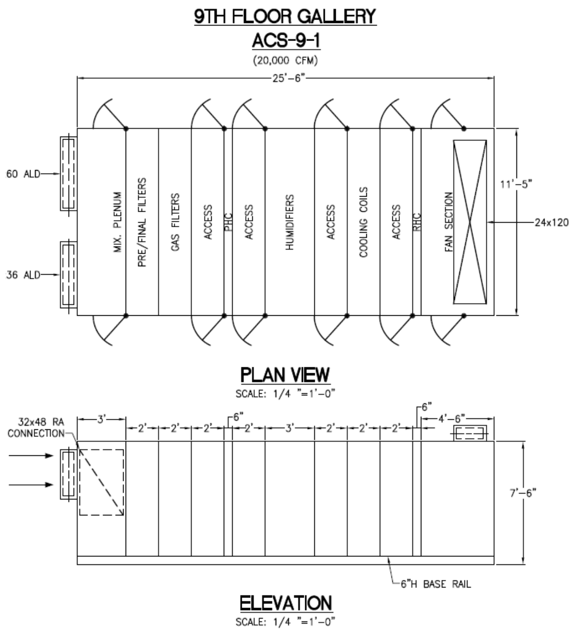
Ventilation System on Cellar Level

Cellar level										
Supply to	Level 7	Level 6	Level 6	Level 5	Level 5	Level 4	Level 4	Level 3	Level 3	Level 1	Total
Duct size	54 x 16	54 x 16	42 x 16	60 x 20	72 x 16	30 x 18	36 x 16	72 x 12	30 x 18	24 x 12	
Airflow rate	9040	6760	5760	12080	12400	5600	7155	6900	3680	1900	92815

Ventilation System on 9th floor

9th level			
Supply to	Level 8		
Duct size	36 x 18	20 x 12	20 x 16
Airflow rate	6760	1120	4120

Appendix. I Information of New Air Handling Units Referenced by Trane

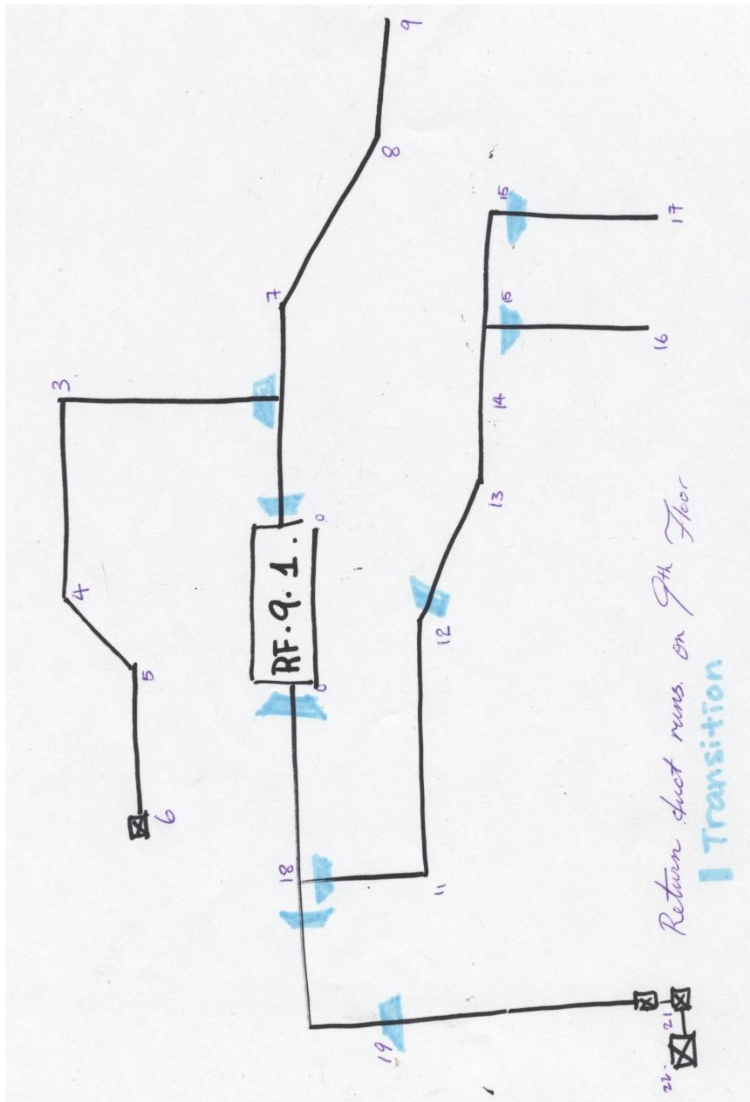


Air Handling Units of Proposed Ventilation System									
size	Width (in)	Height (in)	Order	item	description	Length (in)	Weight/length (lbs/in)	Weight	
40	112.5	75	1	Discharge	horitizonal	48	677.47	677.47	
			2	Filter	2 in. MERV 8	14	358.18	358.18	
			3	Filter	HEPA	40	1128	1128	
			4	access	Medium	14	260.24	260.24	
			5	Coils	2 rows, Heating	10	754.61	754.61	
			6	Access	Medium	14	260.24	260.24	
			7	Humidifier	Atmospheric	19	665	665	
			8	Access	Medium	14	260.24	260.24	
			9	Coils	2 rows, Cooling	10	754.61	754.61	
			10	Coils	2 rows, Reheating	10	754.61	754.61	
			11	Access	Medium	14	260.24	260.24	
			12	Fan	Belt Driven	53.5	2740.37	2740.37	
			Total			21.71	ft	8873.81	lbs
100	154.5	124.88	1	Discharge	horitizonal	60	1423.88	1423.88	
			2	Filter	2 in. MERV 8	27.5	1157.16	1157.16	
			3	Filter	HEPA	40	2554	2554	
			4	access	Medium	15	493.59	493.59	
			5	Coils	2 rows, Heating	15	3094.04	3094.04	
			6	Access	Medium	15	493.59	493.59	
			7	Humidifier	Atmospheric	19	570	570	
			8	Access	Medium	15	493.59	493.59	
			9	Coils	2 rows, Cooling	15	3094.04	3094.04	
			10	Coils	2 rows, Reheating	15	3094.04	3094.04	
			11	Access	Medium	15	493.59	493.59	
			12	Fan	Belt Driven	73.75	6223.51	6223.51	
			Total			27.10	ft	23185.03	lbs

Appendix. J Duct Sizing of New Ductwork layout

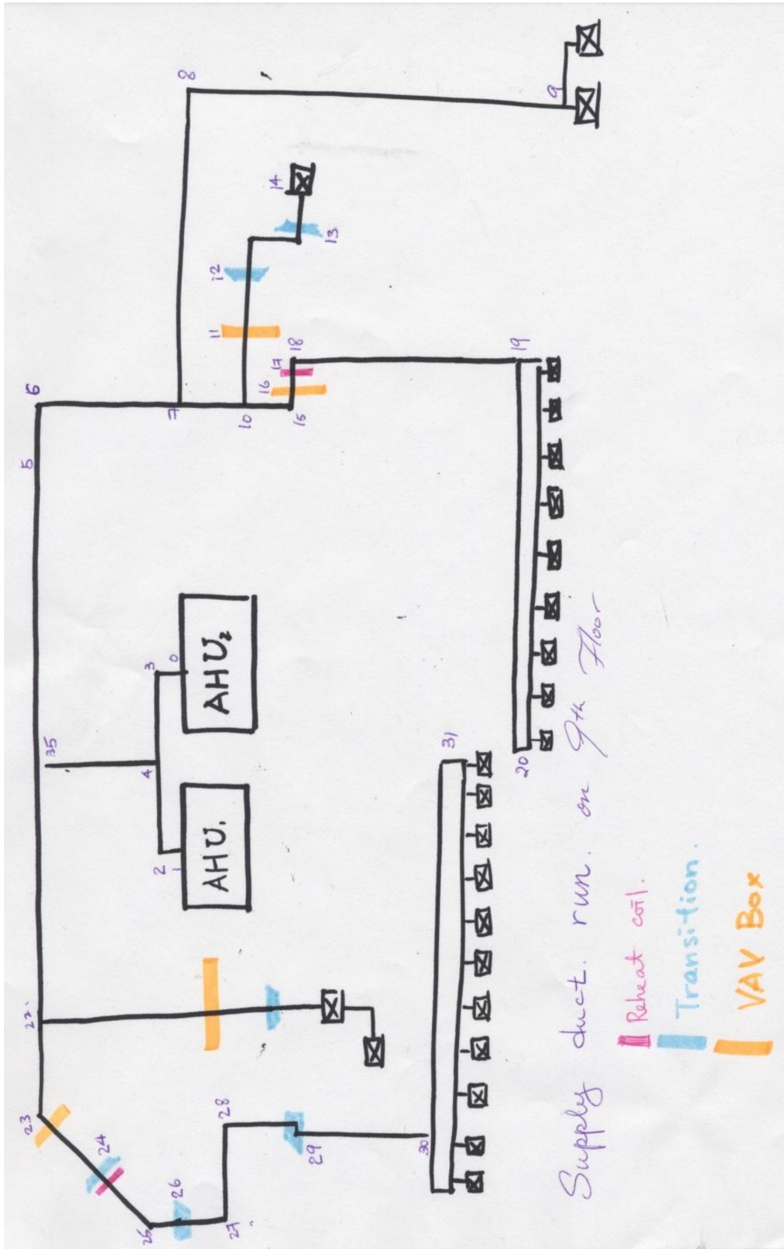
Ductwork sizing of new layout in cellar level

Section	Length (ft)	Airflow (cfm)	Diameter (in)	width (in)	Height (in)	Velocity (fpm)	>2400fpm ?	Frictionloss (in wg)	>0.1 w.g.?
120 x 96	13	73611	102	90	90	1298	Yes,Good	0.01	No,Good
40 x 34	28	22580	40	60	20	2589	Yes,Good	0.06	No,Good


RF-9-1
Return duct runs on 9th Floor
Transition

Return uctwork sizing of new layout

Section	Length (ft)	Airflow (cfm)	Diameter (in)	width (in)	Height (in)	Velocity (fpm)	>2400fpm ?	Frictionloss (in wg)	>0.1 w.g.?	Pressure Loss Path 1 (in wg)	Pressure Loss Path 2 (in wg)	Pressure Loss Path 3 (in wg)	Pressure Loss Path 4 (in wg)	Pressure Loss Path 5 (in wg)	Pressure Loss Path 6 (in wg)	Added
0-7	25.00	40000	60	32	88	2038.217	Yes,Good	0.03	No,Good	0.03	0.03					
7-8	8.50	31256	60	32	88	1592.662	Yes,Good	0.01	No,Good	0.01						
8-9	11	31256	60	32	88	1592.662	Yes,Good	0.01	No,Good	0.01						
1-3	2.5	7814	44	48	32	740.3906	Yes,Good	0.01	No,Good		0.01					
3-4	8	7814	44	48	32	740.3906	Yes,Good	0	No,Good		0					
4-5	7	7814	44	48	32	740.3906	Yes,Good	0	No,Good		0					
5-6	12	7814	44	48	32	740.3906	Yes,Good	0	No,Good		0					
0-18	14	39070	60	32	88	1990.828	Yes,Good	0.04	No,Good			0.04				
18-19	13	19535	39	40	30	2356.009	Yes,Good	0.04	No,Good			0.04				
19-21	16	19535	39	40	30	2356.009	Yes,Good	0.04	No,Good			0.04				Y
21-22	13.5	9835	33	48	18	1656.683	Yes,Good	0.02	No,Good			0.02				Y
11-12	40	19535	43	48	30	1938.069	Yes,Good	0.05	No,Good				0.05	0.05		
12-13	4.5	19535	43	40	14	1938.069	Yes,Good	0.01	No,Good				0.01	0.01		
13-14	16.5	19535	39	60	24	2356.009	Yes,Good	0.01	No,Good				0.01	0.01		
14-15	15	19535	43	60	24	1938.069	Yes,Good	0.07	No,Good				0.07	0.07		Y
15-16	7	9700	32	46	18	1737.659	Yes,Good	0.05	No,Good				0.05			Y
15-17	18.5	9835	30	30	25	2004.586	Yes,Good	0.1	No,Good					0.1		Y
Total										0.06	0.05	0.15	0.2	0.25		


AHU1
AHU2
Supply duct run on 9th Floor
Reheat coil
Transition
VAV Box

Supply ductwork sizing of new layout

Section	Length (ft)	Airflow (cfm)	Diameter (in)	width (in)	Height (in)	Velocity (fpm)	>2400fpm ?	Frictionloss (in wg)	>0.1 w.g.?	Pressure Loss Path 1 (in wg)	Pressure Loss Path 2 (in wg)	Pressure Loss Path 3 (in wg)	Pressure Loss Path 4 (in wg)	Pressure Loss Path 5 (in wg)	Added
0-3	3	19535	43	48	30	1938	Yes,Good	0	No, Good	0.00	0.00	0.00	0.00	0.00	Y
3-4	12	19535	43	48	30	1938	Yes,Good	0.01	No, Good	0.01	0.01	0.01	0.01	0.01	Y
4-35	0.5	39070	72	72	60	1383	Yes,Good	0.02	No, Good	0.02	0.02	0.02	0.02	0.02	Y
35-21	40	16190	43	48	30	1606	Yes,Good	0.08	No, Good	0.08	0.08				
21-22	2	16190	43	48	30	1606	Yes,Good	0	No, Good	0.00	0.00				
22-32	2.5	12690	43	60	24	1259	Yes,Good	0.01	No, Good	0.01	0.01				
32-33	8.5	12690	43	60	24	1259	Yes,Good	0	No, Good	0.00	0.00				
VAV							Yes,Good	0.2	Yes, Bad	0.20					
33-34	10	12690	37	54	20	1700	Yes,Good	0.01	No, Good	0.01					
22-23	2	3500	21	30	12	1456	Yes,Good	0	No, Good		0.00				
23-24	7.5	3500	21	30	12	1456	Yes,Good	0.01	No, Good		0.01				
RHC							Yes,Good	0.15	Yes, Bad		0.15				
24-25	2	3500	33	36	24	590	Yes,Good	0	No, Good		0.00				
25-26	7	3500	33	36	24	590	Yes,Good	0	No, Good		0.00				
26-27	2	3500	24	18	26	1115	Yes,Good	0.03	No, Good		0.03				
27-28	6	3500	24	18	26	1115	Yes,Good	0.01	No, Good		0.01				
29-30	6.75	3500	24	18	26	1115	Yes,Good	0.04	No, Good		0.04				
30-31	80	3500	26	30	18	950	Yes,Good	0.04	No, Good		0.04				
35-5	12.5	16420	43	48	30	1629	Yes,Good	0.01	No, Good			0.00	0.01	0.01	Y
5-6	2	16420	36	36	28	2324	Yes,Good	0	No, Good			0.00	0.00	0.00	Y
6-7	3	16420	36	36	28	2324	Yes,Good	0.01	No, Good			0.00	0.01	0.01	Y
7-8	48	11180	43	48	30	1109	Yes,Good	0.02	No, Good			0.00			Y
8-9	37.5	11180	43	48	30	1109	Yes,Good	0.02	No, Good			0.00			Y
7-10	2	5240	33	36	24	883	Yes,Good	0	No, Good				0.00	0.00	
10-11	8.75	4120	23	26	16	1429	Yes,Good	0.07	No, Good				0.07		
VAV							Yes,Good	0.2	Yes, Bad						
11-12	0.5	4120	23	26	16	1429	Yes,Good	0.01	No, Good				0.01		
12-13	14.5	4120	36	40	26	583	Yes,Good	0.01	No, Good				0.01		
13-14	24.5	4120	30	40	18	840	Yes,Good	0.01	No, Good				0.01		
10-15	7.5	1120	33	36	24	189	Yes,Good	0	No, Good					0.00	
15-16	11	1120	20	20	16	514	Yes,Good	0	No, Good					0.00	
RHC							Yes,Good	0.15	Yes, Bad					0.15	
16-17	10	1120	20	20	16	514	Yes,Good	0	No, Good					0.00	
VAV							Yes,Good	0.2	Yes, Bad					0.20	
17-18	10.5	1120	20	20	16	514	Yes,Good	0	No, Good					0.00	
18-19	24.5	1120	20	20	16	514	Yes,Good	0.01	No, Good					0.01	
19-20	36	1120	17	20	12	711	Yes,Good	0.02	No, Good					0.02	
Total										0.33	0.40	0.03	0.15	0.43	

Appendix. K Structural System Check

Deck Check

Area		
9th floor	4454	sf

Load assumption		
ductwork and	15	psf
fan	1000	lbs/ea
AHUs	9000	lbs/ea
HV	1500	lbs/ea

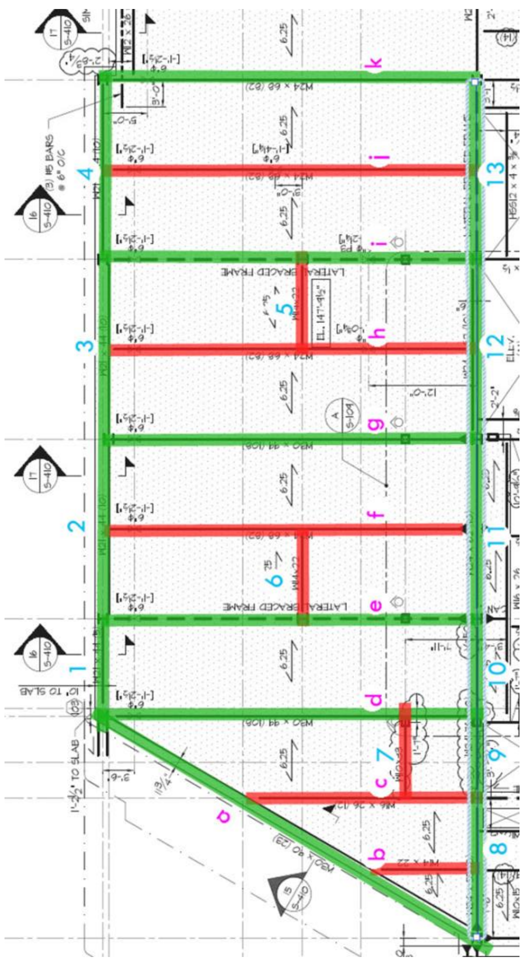
Load calculation				
live load	75	psf	from drawing	
ductwork and	15	psf		
Steel	12	psf		
Mechanical equipment load				
equipment	weight	quantiity	total	
	lbs		lbs	
fan	1000	3	3000	
AHU	9000	2	18000	
HVs	1500	3	4500	
		total	25500	lbs
		total/total area	5.72519084	psf
total distribut	107.7251908			

Original deck	3"-18 guage composite metal deck	
	3.25 " lightweight concrete	
	total thickness	6.25

		Deck Check		
Deck type	thickness (in)	V_a (lbs/ft)	F_y (ksi)	
3VLI 18	0.0474	4729	50	
Total slab depth	deck type	SDI Max unshored clear span (ft)	superimposed live load (psf)	
6.25	3VLI 18	15	191	11.5'
AAM layout				
6.25	3" 18 guage	11.5	107.7251908	
Conclusion:	Checked	OK		

Beams

Influence Area of Beams



Dead Load Distribution

Dead load		
ductwork and pipe	15	psf
Deck	46	psf
slab	50	psf
Mechanical equipment load	5.72519084	psf
total distributed load	116.7251908	psf

Live Load Distribution

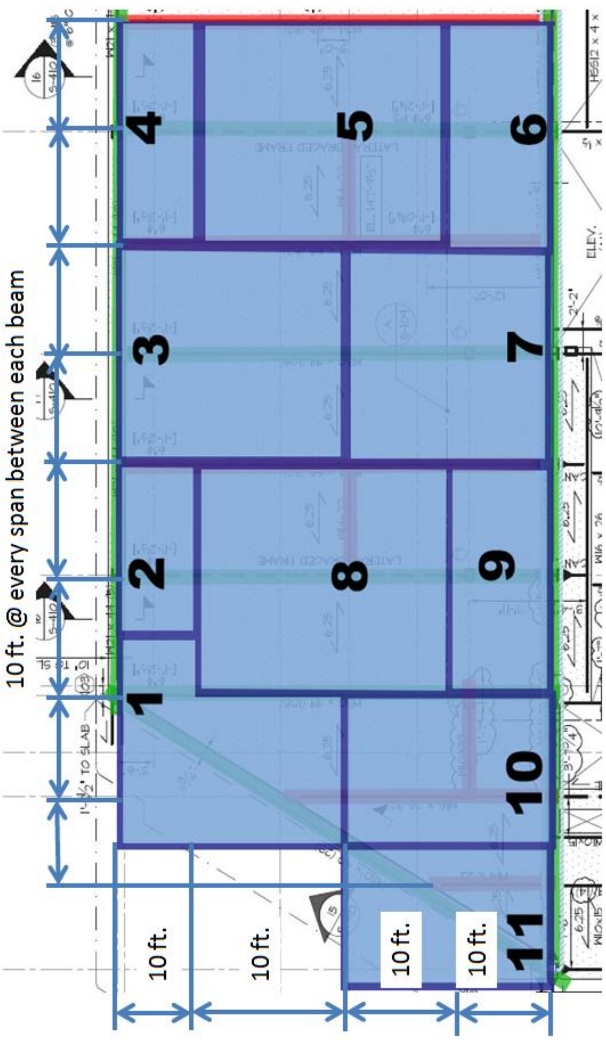
Live load		
live load	75	psf

Beam																
		distributed load														
beam	shape	self weight (lb)	Span	Length	Dead load (psf)	Dead load of wall	additional load	wL Total	Vu Equation	Mu Equation	Vu	ϕ_v V_px	Yes/No	Mu	ϕ_n M_px	Yes/No
a	W 30 x 90	90	15.5	48	0	15	0.719132	2.117132	(wL)*L/2	(wL)*L^2/	50.81117	463	Yes	609.734	1170	Yes
b	W 14 x 22	22	10	10	116.7252	0	0	2.027102	(wL)*L/2	(wL)*L^2/	10.13551	94.5	Yes	25.33878	125	Yes
c	W 16 x 26	26	10	24	116.7252	0	0	2.031902	(wL)*L/2	(wL)*L^2/	24.38283	105	Yes	146.297	166	Yes
d	W 30 x 90	90	10	40	116.7252	0	0	2.108702	(wL)*L/2	(wL)*L^2/	42.17405	463	Yes	421.7405	1170	Yes
e																
f	W 24 x 68	68	10	40	116.7252	0	0	2.082302	(wL)*L/2	(wL)*L^2/	41.64605	295	Yes	416.4605	664	Yes
	W 27 x 84	84	10	40	116.7252	0	0	2.101502	(wL)*L/2	(wL)*L^2/	42.03005	368	Yes	420.3005	915	Yes
g	W 30 x 90	90	10	40	116.7252	0	0	2.108702	(wL)*L/2	(wL)*L^2/	42.17405	463	Yes	421.7405	1170	Yes
h	W 24 x 68	68	10	40	116.7252	0	0	2.082302	(wL)*L/2	(wL)*L^2/	41.64605	295	Yes	416.4605	664	Yes
i																
j	W 24 x 68	68	10	40	116.7252	0	0	2.082302	(wL)*L/2	(wL)*L^2/	41.64605	295	Yes	416.4605	664	Yes
k	W 24 x 68	68	10	40	116.7252	0	0	2.082302	(wL)*L/2	(wL)*L^2/	41.64605	295	Yes	416.4605	664	Yes

Beam																
		distributed load														
beam	shape	self weight (lb)	Span	Length	Dead load (psf)	Dead load of wall	additional load	wL Total	Vu Equation	Mu Equation	Vu	ϕ_v V_px	Yes/No	Mu	ϕ_n M_px	Yes/No
1	W21x44	44	40	10	116.7252	15	0	2.4708	(wL)*L/2	(wL)*L^2/	12.354	217	Yes	30.885	358	Yes
2	W21x44	44	40	20	0	15	2.082302	4.895102	(wL)*L/2	(wL)*L^2/	48.95102	217	Yes	244.7551	358	Yes
3	W21x44	44	40	20	0	15	2.082302	4.895102	(wL)*L/2	(wL)*L^2/	48.95102	217	Yes	244.7551	358	Yes
4	W21x44	44	40	20	0	15	2.082302	4.895102	(wL)*L/2	(wL)*L^2/	48.95102	217	Yes	244.7551	358	Yes
5	W21x44	44	20	10	116.7252	0		2.053502	(wL)*L/2	(wL)*L^2/	10.26751	94.5	Yes	25.66878	125	Yes
6	W21x44	44	20	10	116.7252	0		2.053502	(wL)*L/2	(wL)*L^2/	10.26751	94.5	Yes	51.33756	125	Yes
7	W10x33	33	18	10	116.7252			1.840232	(wL)*L/2	(wL)*L^2/	9.20116	84.7	Yes	46.0058	145	Yes

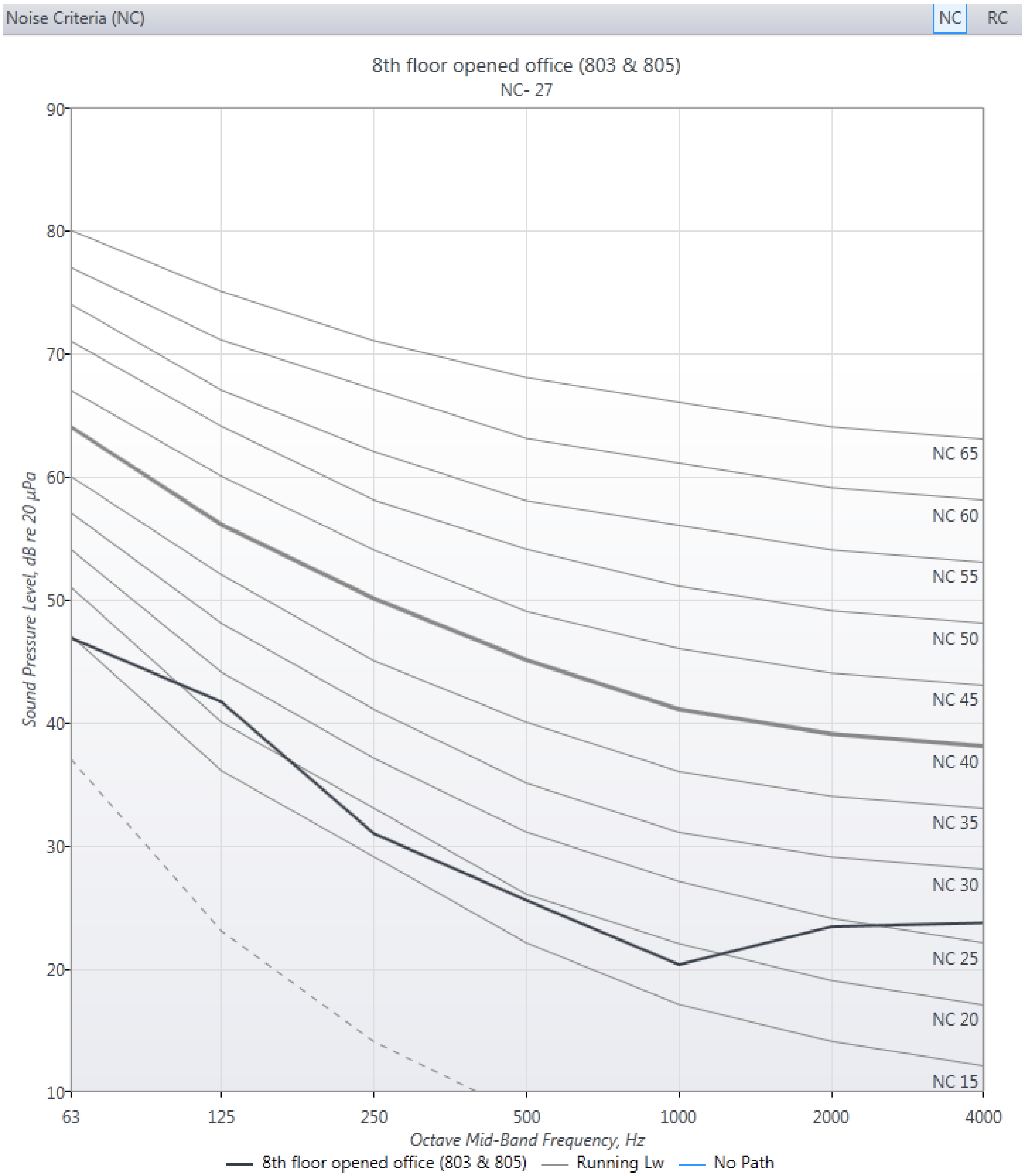
Columns

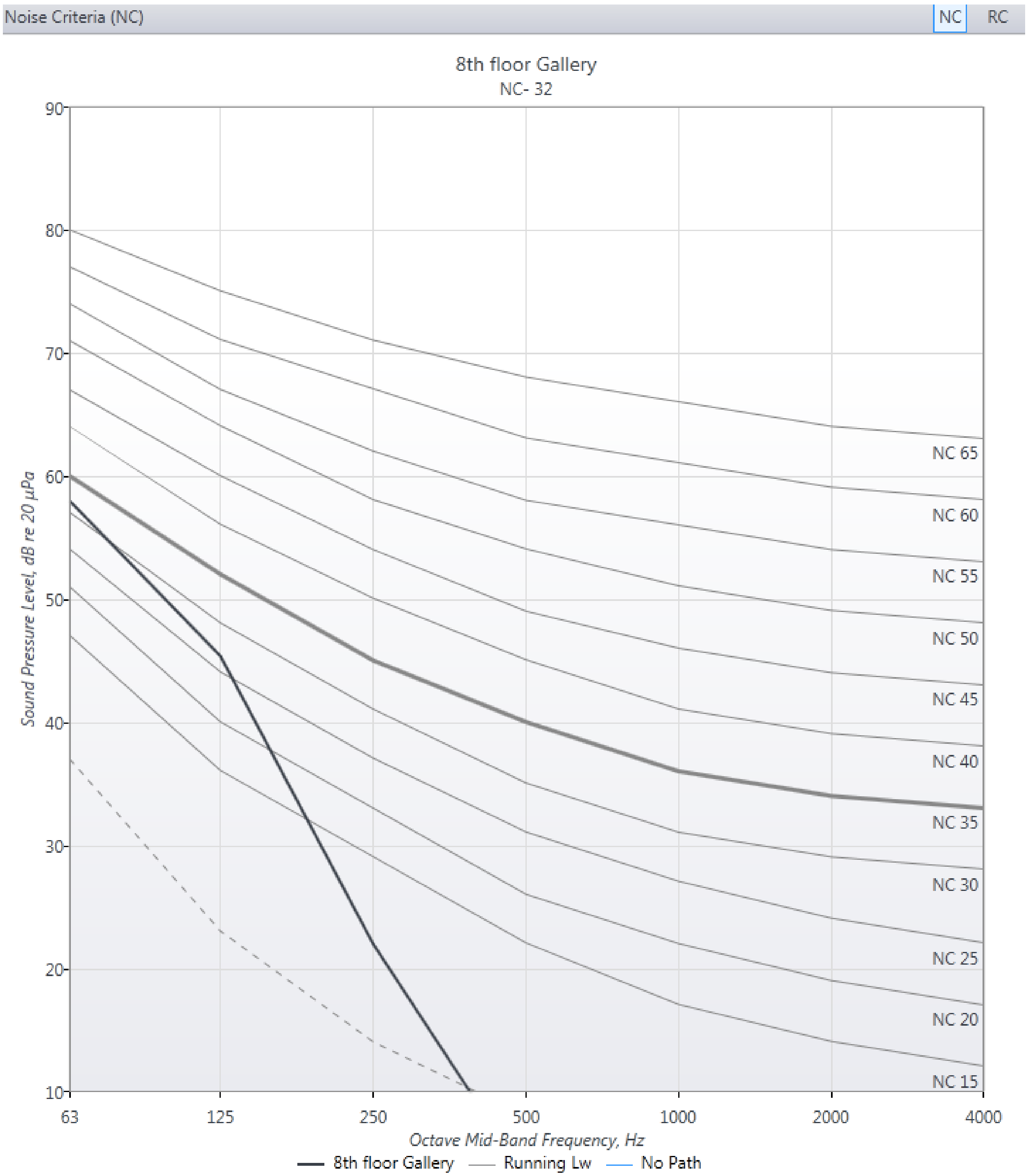
Influence Area of Columns

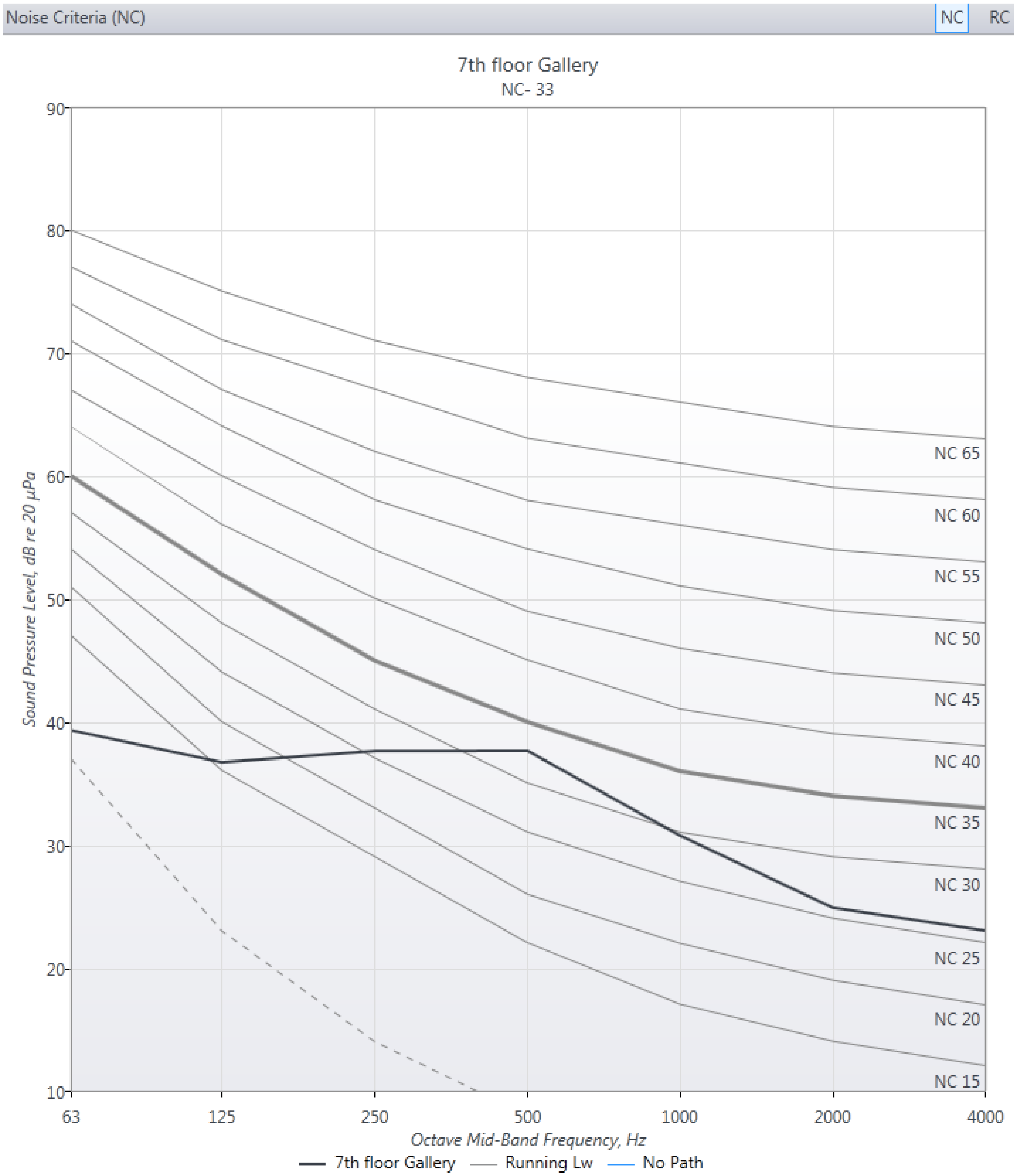


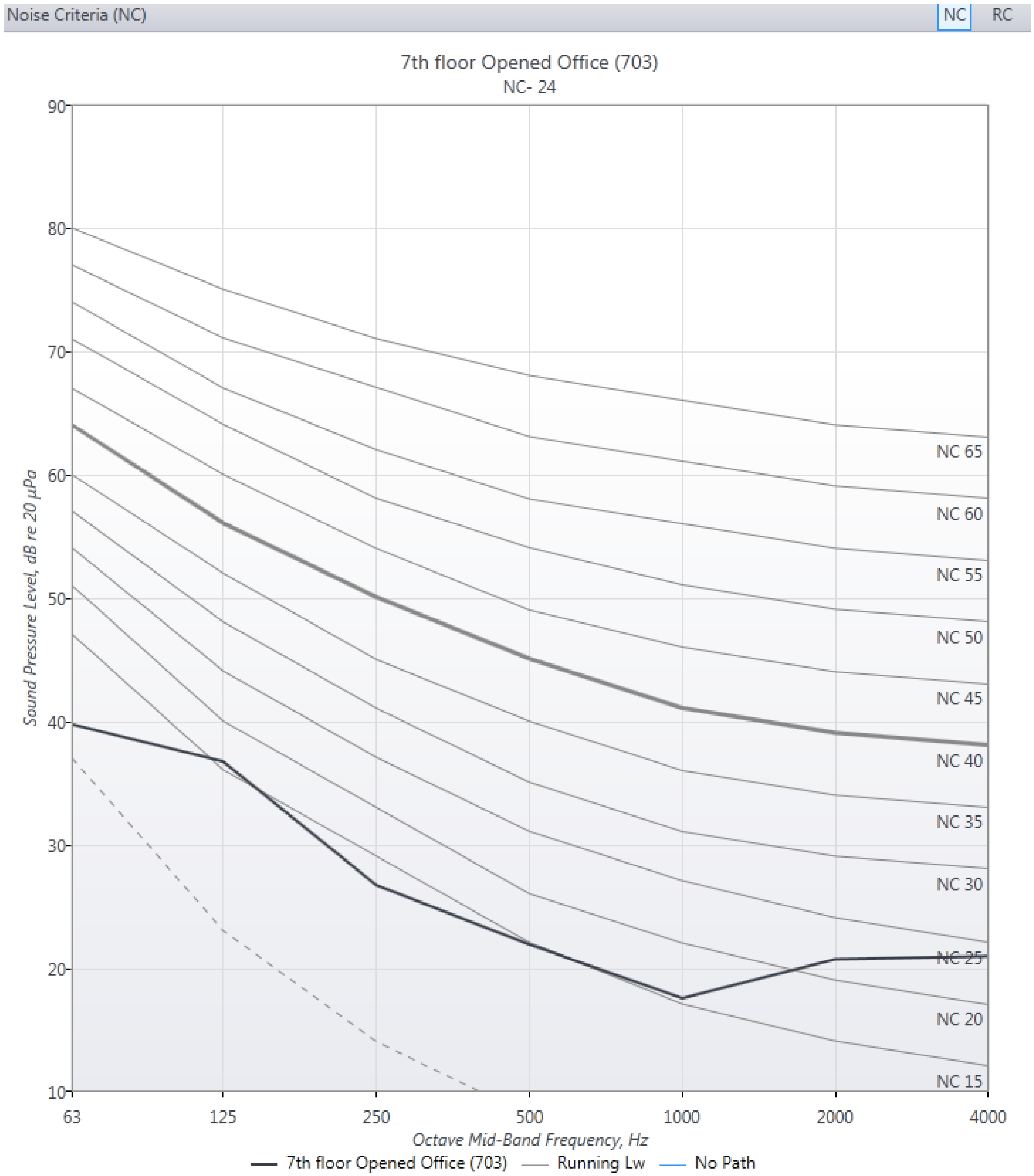
Column Load											
distributed load											
shape	self weight (lb)	Width	Length	height (ft)	Dead load (psf)	Dead load of wall (psf)	Wall area (sf)	additional load (lb)	P Total (Mlb)	ϕ_v V_px	Yes/No
W12 x 65	65	10	20	21.667	238.7252	15	216.6667		87.29077	492	Yes
W 12 x 65	65	10	20	21.667	238.7252	15	216.667	9000	98.09078	492	Yes
W12 x 65	65	15	10	21.667	238.7252	15	325		68.81558	492	Yes
W 12 x 65	65	15	10	21.667	238.7252	15	325	4500	74.21558	492	Yes
W12 x 65	65	20	20	21.667	238.7252	15	433.3333		172.8915	492	Yes
W12 x 65	65	15	10	21.667	238.7252	15	325		68.81558	492	Yes
W 12 x 53	53	20	20	21.667	238.7252	0	433.3333		164.7795	307	Yes
W 14 x 53	53	20	13.75	21.667	238.7252	0	433.3333		113.7166	186	Yes
W 14 x 53	53	20	17	21.667	238.7252	0	433.3333		140.2693	186	Yes
W 12 x 53	53	20	20	21.667	238.7252	0	433.3333		164.7795	492	Yes
W 12 x 53	53	20	20	21.667	238.7252	0	433.3333	4500	170.1796	492	Yes
W 14 x 53	53	20	13.75	21.667	238.7252	0	433.3333		113.7166	186	Yes
W 14 x 53	53	20	17	21.667	238.7252		433.3333		140.2693	186	Yes
W 14 x 53	53	14.5	17	21.667	238.7252	15	314.1667		107.7292	186	Yes

Appendix. L Noise Criteria Charts




Noise Criteria (NC)
NC
RC
8th floor Gallery
NC- 32
Sound Pressure Level, dB re 20 µPa
90
80
70
60
50
40
30
20
10
NC 65
NC 60
NC 55
NC 50
NC 45
NC 40
NC 35
NC 30
NC 25
NC 20
NC 15
63
125
250
500
1000
2000
4000
Octave Mid-Band Frequency, Hz
8th floor Gallery
Running Lw
No Path


Noise Criteria (NC)
NC
RC
7th floor Gallery
NC- 33
90
80
70
60
50
40
30
20
10
Sound Pressure Level, dB re 20 µPa
NC 65
NC 60
NC 55
NC 50
NC 45
NC 40
NC 35
NC 30
NC 25
NC 20
NC 15
63
125
250
500
1000
2000
4000
Octave Mid-Band Frequency, Hz
7th floor Gallery
Running Lw
No Path


Noise Criteria (NC)
NC
RC
7th floor Opened Office (703)
NC- 24
90
80
70
60
50
40
30
20
10
Sound Pressure Level, dB re 20 μPa
NC 65
NC 60
NC 55
NC 50
NC 45
NC 40
NC 35
NC 30
NC 25
NC 20
NC 15
63
125
250
500
1000
2000
4000
Octave Mid-Band Frequency, Hz
7th floor Opened Office (703)
Running Lw
No Path

MAE Course Relation

The MAE courses related to this project are:

AE 557 Centralized Cooling System:

The ideas of absorption refrigeration in this course help to understand the impact to other mechanical components and the installation requirement of absorption chillers. Also, the lecture of AHRI Standard 550/590 and ASHRAE Standard 90.1 explains the potential energy saving of operating with multiple chillers instead of one. Third, this course mentions the requirements and needs of mechanical room layout.

AE 555 Building Control System:

This course provides different search methods that can be applied on HVAC operation, such as increasing the efficiency of HVAC system by changing the combination of mass flow rates, temperature setpoints, and part load ratios. This concept helps to find the cost effective combination of electric and absorption chillers, and also the well balanced layout of the mechanical room on 9th floor.

AE 551 Combined Heat and Power:

This course provides information of today fuel economy and theories of different cogeneration operations. It significantly gives the analysis of this project more alternatives of redesigning the HVAC system.