6.0 Analysis 2: Chilled Beams Cost & Schedule Impact (Mechanical Breadth)

6.1 Background

The mechanical package for the JHH project accounts for 29.1% of the construction cost. The HVAC system alone totals [redacted] or 13.9% of the construction cost. The critical path of the project largely involves the installation of the HVAC system.

The JHH campus has a central utility plant that is capable of supplying the NCB with chilled water and high pressure steam. Therefore, the new facility does not include any boilers or chillers. The current HVAC system is a variable air volume (VAV) with reheat coils in each VAV box. On average each VAV box serves 3 rooms that are on one zone. There are 19 air handling units with sizes ranging from 11,000 – 133,000 CFM. They are primarily located on the 6^{th} and 7^{th} floor.

When designing a HVAC system for a healthcare facility, the engineer must consider infection control, filtration requirements, outdoor air requirements, recirculated air requirements, air change rates, etc. Hospitals have much stricter design criteria than typical buildings. A VAV system is the most common system used in invasive areas of healthcare facilities. However, non-invasive areas such as office space, waiting rooms, cafeterias, patient rooms, etc. do not have as strict of guidelines. For this reason, these areas have the potential to use a different HVAC system, such as chilled beams that could potentially save time and money.

6.2 Problem Statement

Analysis 1 showed that the top two goals for the owner, A/E, and contractor are to deliver the project on/under budget and on time.

Currently, the 1^{st} package of changes (CCD 1-38) has been evaluated by Clark/Banks and they have determined that the schedule will need to be extended [redacted] This is because the HVAC system was severely impacted by the changes. [redacted] This has caused JHH to not meet their top two goals.

6.3 Goal

The goal of this analysis is to demonstrate that chilled beam HVAC systems in non-invasive spaces have the *potential* to lower the cost (initial and life-cycle) and accelerate the construction schedule.

6.4 Resources

TROX USA – Ken Loudermilk
TROX USA – Chris Lawrence
DADANCO – Bill Rafferty
Pierce Associates, Inc. – Dan Donaghy
Clark Construction – Jim Salvino

Poole & Kent – Donald Campbell
United Sheet Metal – Mike Topper
Johns Hopkins Facility Group – Bob Singer
BR+A – Mark Octeau
SmithGroup – David Varner
Penn State – Moses Ling

6.5 Analysis

Chilled Beam System Background

An emerging technology from Europe is the chilled beam HVAC system. They have been successfully using chilled beam systems in healthcare facilities for the past 20 years (see Table 4 below for sample projects). Within the past few years, several projects have popped up in the USA with these systems such as Constitution Center in Washington D.C. and the Yale Hospital Expansion project in New Haven, CT.

Table 4: Healthcare Projects in Europe Using Chilled Beams (Source: Frenger Systems)

Hospital	Healthcare Trust	# of Chilled Beams	Year	Consulting Engineer
Royal Sussex, Brighton	Brighton & Sussex University Hospitals	450	2003	Whichloe Macfarlane
UCLH London	University College London Hospitals	1,100	2005	DSSR
Beatson Oncology	Greater Glasgow Health Board	500	2006	DSSR
QMC Nottingham	Nations Healthcare	200	2007	TB&A
ACAD Hospitals, Scotland	Greater Glasgow Health Board	1,000	2007	DSSR
Wakefield Hospitals	Mid Yorkshire Hospitals	350	2008	Buro Happold
Barts & Royal London	The London	4,500	2008-2013	TB&A and DSSR

Chilled beam units have finned chilled water heat exchanger cooling coils, capable of providing 1,000 BTU/hr of sensible cooling per foot of beam. They take advantage of the fact that water can move energy more efficiently than air. Figure 14 below shows that a 1" diameter water pipe can carry the same cooling capacity as an 18" x 18" air duct. Thus, chilled beams can dramatically reduce AHU and duct sizes.

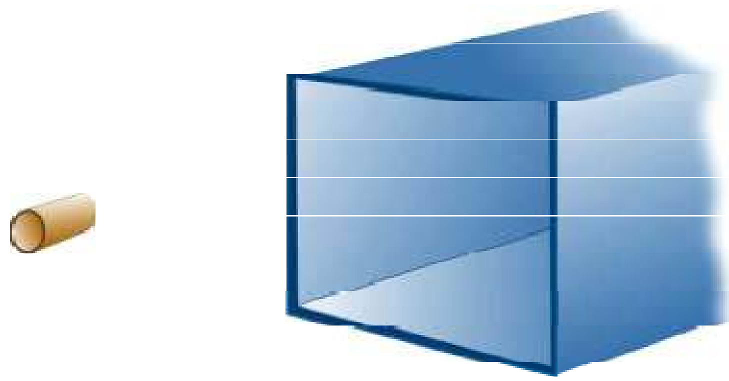

Figure 14: Cooling Energy Transport Economies of Air and Water

There are two main types of chilled beams – active and passive. Passive chilled beams use finned tube heat exchanger coil to provide convective cooling to the space. They do not use fans, ductwork, or any other component. Since they do not have a source of providing primary air to the space, another source of air is required for ventilation and humidity control.

Active chilled beams use a ducted primary air (conditioned) supply to induce room air across the cooling coil where it mixes with the primary air and discharges in the space. The chilled beam provides most of the sensible load while the primary air provides the ventilation and latent cooling. A Hygienic Active Chilled Beam is the recommended solution for this project (see Appendix A for product data sheets).

Figure 15 below shows a cross section through an active chilled beam. (1) Primary air is fed from a central AHU through a series of nozzles (2). The primary air creates an induction of room air (3) that passes through a cooling coil (4). The primary air and room air are then mixed and discharged to the space (5).

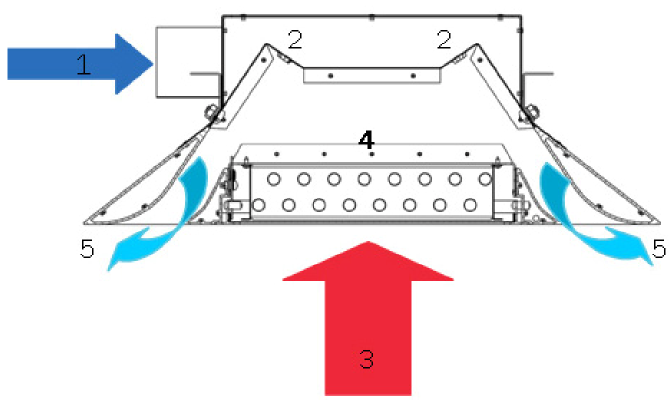

Figure 15: Active Chilled Beam Cross Section

Chilled beams have many advantages including low energy consumption, space savings, improved comfort, no regular maintenance, and easy commissioning. The design intent of chilled beams is to size the primary air to meet ventilation or latent load requirements and use the beams to provide the rest of the sensible cooling load. It is common to see 75-85% reduction in circulated air when using chilled beams compared to all air systems according to DADANCO. This reduction in air can reduce the ductwork, fans, AHUs, etc. by the same proportioned amount. The downsizing of fans and AHUs results in less energy consumption because it is much more energy efficient to move water instead of air. This can save significantly on the life-cycle cost of a building.

By reducing the ductwork by 75-85% it frees up space in the ceiling plenum. Therefore, the floor-floor height can be reduced. This can save money on structure and the façade. Another advantage could be in areas with height restrictions such as Washington, D.C. where it may be possible to add another floor. It also lends itself nicely to renovation projects where the ceiling plenum is restricted.

The room comfort is maintained by providing excellent air movement with uniform air temperatures (see Figure 16 and 17 below). This reduces unwanted drafts and hot spaces in the room. Full ventilation air requirements are delivered to the spaces at all times and loads. Humidity control is met as the constant volume primary air is delivered with the proper moisture content to satisfy the latent loads.

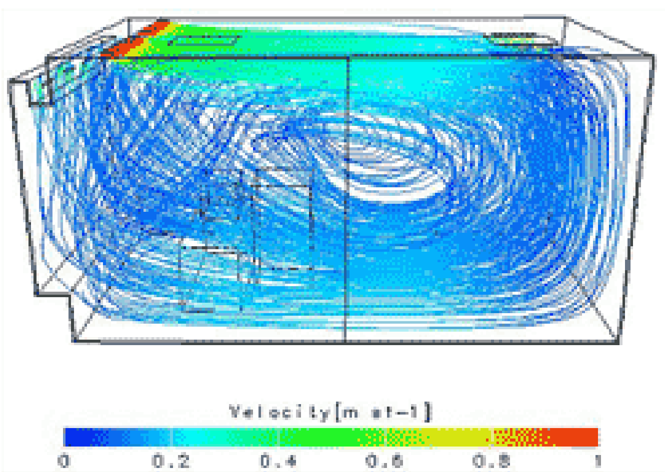

Figure 16: Air Movement Throughout the Room (Source: DADANCO)

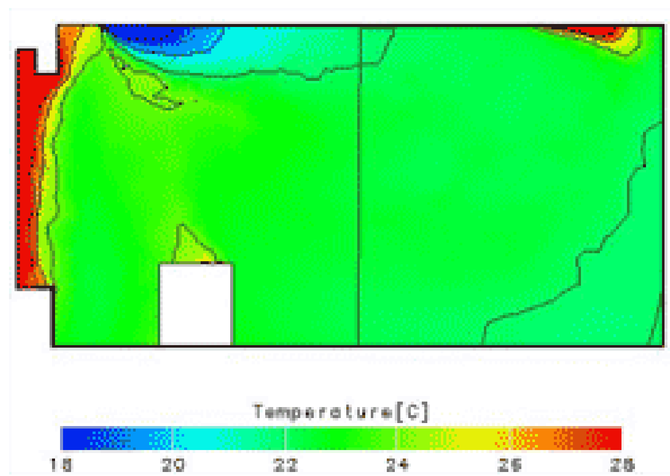

Figure 17: Uniform Temperature Throughout the Room (Source: DADANCO)

Chilled beams do not have any moving parts which reduces the maintenance costs. In the recommended Hygiene Chilled Beam for this project, there is an inbuilt filter which will capture all the airborne bacteria as the air is recirculated. This will need to be replaced every 6 months which is the same as the current VAV system. Figure 18 below shows maintenance personnel cleaning a chilled beam.

Figure 18: Maintenance Personnel Cleaning a Chilled Beam

The commissioning process is much easier than VAV systems. Chilled beams only require adjustments to the water balancing valves and primary air balancing dampers through static pressure readings. The adjustments can be made by turning regulating screws with an allen key with the underplate in position (see Figure 19 below).

Figure 19: Adjustment for Regulating Air Amount and Speed

Sizing the Chilled Beam System

For this analysis, the current VAV system design will be left untouched for the invasive spaces (i.e. operating rooms, trauma rooms, triage, exam rooms, etc.). The remaining non-invasive spaces will be analyzed to determine the cost and schedule impact of using chilled beams.

The sheer size and complexity of the HVAC system makes it virtually impossible to analyze each aspect of the HVAC system for this thesis. Therefore, representative and typical spaces will be analyzed and their results will be extrapolated to the rest of the spaces in question.

The two main spaces that are representative of the non-invasive spaces are the office and patient rooms. These areas make up the majority of the non-invasive spaces. They also represent the two extremes of the design criteria for the non-invasive spaces. The office spaces have the least amount of design restrictions while the patient rooms have the most. Analyzing these two spaces will provide a working average that can be used to analyze the entire impact.

Office Space

Level 6 was analyzed as the typical floor for the office spaces. The entire floor functions as faculty offices, meeting rooms, lounges, and filing rooms. Each VAV box serves a certain zone that ranges from 1- 9 rooms. The following assumptions were used for the calculation.

- The supply CFM shown on the drawings for each corresponding VAV box represents the design loads for that zone.
- Each room that is a part of the zone has similar loads.
- By examining the entire floor, including the north, south, east, west and inside rooms provide representative load conditions.
- The number of seats or area to a room was used to estimate the number of people that would occupy the room at maximum load.
- Sizing is based on cooling load, not heating load
  - Heating will only be required on perimeter spaces and can be accomplished by adding heating coils in the beams.

The following calculation is an example of how the chilled beams and primary air supply were sized.

VAV Box S6D-1

- Total Supply for this VAV = 300 CFM
- 6 people are expected to occupy the zone at maximum capacity
- 1 room is served by this VAV
- Room temperature design = 70˚F
- Supply primary air temperature = 55˚F

1. Total Sensible Design Load = 1.08 x Total Supply CFM x (Room Temp – Supply Temp)
= 1.08 x 300 CFM x (70˚F - 55˚F)
= 4,860 BTU/hr

2. Ventilation air required per ASHRAE 62.1 – 2007 is 25 CFM/person for patient rooms (see Figure 20 below). Office spaces are not shown. To be on the conservative side, 25 CFM/person will be used for both the office and patient rooms.

Application	Estimated Maximum** Occupancy P/1000 ft² or 100 m²	Outdoor Air Requirements cfm/ person	L/s · person	cfm/ft²	L/s · m²	Comments
Patient rooms	10	25	13			Special requirements or codes and pressure relationships may determine minimum ventilation rates and filter efficiency. Procedures generating contaminants may require higher rates.
Medical procedure	20	15	8			
Operating rooms	20	30	15			
Recovery and ICU	20	15	8			
Autopsy rooms	20			0.50	2.50	Air shall not be recirculated into other spaces.
Physical therapy	20	15	8			

* Table E-1 prescribes supply rates of acceptable outdoor air required for acceptable indoor air quality. These values have been chosen to dilute human bioeffluents and other contaminants with an adequate margin of safety and to account for health variations among people and varied activity levels.
** Net occupiable space.

Figure 20: ASHRAE 62.1 – 2007 Ventilation Air Requirements for Healthcare Facilities

3. Ventilation Air Required = 25 CFM/person x 6 persons = 150 CFM

4. Assume that ventilation air governs primary air supply right now and then check to see if it is greater than the latent load air requirement later.

5. Sensible Cooling Capacity of Primary Air = 1.08 x Vent. Air CFM x (Room Temp – Supply Temp)
= 1.08 x 150 CFM x (70˚F - 55˚F)
= 2,430 BTU/hr

6. Sensible Cooling by Chilled Beam = Total Sensible Load – Sensible Capacity of Primary Air
= 4,860 BTU/hr – 2,430 BTU/hr
= 2,430 BTU/hr

7. Latent load in the room can be approximated by the general rule of thumb that each person gives off 200 BTU/hr of latent load.

8. Latent Load = 200 BTU/hr/person x 6 person = 1,200 BTU/hr

9. Latent Cooling Capacity of Primary Air = 4,840 x Vent. Air CFM x (W_{Room} – $W_{Primary}$)
= 4,840 x 150 CFM (0.009 – 0.007)
= 1,452 BTU/hr

10. The latent cooling capacity of primary air is greater than the latent load. Therefore, the ventilation air is adequate in supporting the latent load for the zone.

11. On average, a chilled beam can produce 1,000 BTU/hr/ft of sensible cooling capacity.

12. Chilled Beam Size = 2,430 BTU/hr ÷ 1,000 BTU/hr/ft = 2.43 ft Chilled Beam ≈ 3 ft Chilled Beam

13. Primary Air Reduction = 1 – (Primary Air CFM ÷ Total Current Supply CFM)
= 1 – (150 CFM ÷ 300 CFM)
= 50%

Table 4 on the following page shows all of the calculations for the typical office rooms. Below is a summary of the findings:

- Percent Reduction in Primary Air = 79%
- Average Chilled Beam Size per Room = 5 ft
- Total Cost of VAVs for Typical Area = $15,078 = $0.61/SF
- Total Cost of Chilled Beams for Typical Area = $102,760 = $4.16/SF
- Percent Increase of Chilled Beams over VAV Boxes = 682%

Table 5: Chilled Beam Load Calculations for Office Space

Chilled Beam Design Calculations

Typical Office/Administration Space (24,719 SF)

VAV Box	Total Supply CFM/VAV	Population/VAV	# of Rooms/VAV	Delta-T[1]	Sensible Load (BTU/hr)[2]	Vent Air (cfm)[3]	Sensible Capacity(BTU/hr)[4]	Sensible Load by Beams(BTU/hr)[5]	Latent Load(BTU/hr)[6]	Latent Capacity(BTU/hr)[7]	Latent OK?[8]	Sensible Load/Room[9]	Chilled Beam Size/Room(ft)[10]
S6D-1	300	6	1	15	4,860	150	2,430.00	2,430.00	1,200	1452	Yes	2,430.00	2.43
S6D-2	800	10	5	15	12,960	250	4,050.00	8,910.00	2,000	2420	Yes	1,782.00	1.78
S6D-4	950	4	5	15	15,390	100	1,620.00	13,770.00	800	968	Yes	2,754.00	2.75
S6D-3	1,100	15	4	15	17,820	375	6,075.00	11,745.00	3,000	3630	Yes	2,936.25	2.94
S6D-5	500	7	3	15	8,100	175	2,835.00	5,265.00	1,400	1694	Yes	1,755.00	1.76
S6D-6	1,025	7	3	15	16,605	175	2,835.00	13,770.00	1,400	1694	Yes	4,590.00	4.59
S6D-8	225	2	1	15	3,645	50	810.00	2,835.00	400	484	Yes	2,835.00	2.84
S6D-31	725	6	4	15	11,745	150	2,430.00	9,315.00	1,200	1452	Yes	2,328.75	2.33
S6D-7	1,050	16	6	15	17,010	400	6,480.00	10,530.00	3,200	3872	Yes	1,755.00	1.76
S6D-9	175	2	1	15	2,835	50	810.00	2,025.00	400	484	Yes	2,025.00	2.03
S6D-10	475	6	2	15	7,695	150	2,430.00	5,265.00	1,200	1452	Yes	2,632.50	2.63
S6D-11	800	6	1	15	12,960	150	2,430.00	10,530.00	1,200	1452	Yes	10,530.00	10.53
S6D-12	775	7	3	15	12,555	175	2,835.00	9,720.00	1,400	1694	Yes	3,240.00	3.24
S6D-13	900	7	4	15	14,580	175	2,835.00	11,745.00	1,400	1694	Yes	2,936.25	2.94
S6D-17	300	3	1	15	4,860	75	1,215.00	3,645.00	600	726	Yes	3,645.00	3.65
S6D-16	250	3	1	15	4,050	75	1,215.00	2,835.00	600	726	Yes	2,835.00	2.84
S6D-15	350	3	2	15	5,670	75	1,215.00	4,455.00	600	726	Yes	2,227.50	2.23
S6D-14	375	7	3	15	6,075	175	2,835.00	3,240.00	1,400	1694	Yes	1,080.00	1.08
S6D-18	1,075	1	1	15	17,415	25	405.00	17,010.00	200	242	Yes	17,010.00	17.01
S6D-19	250	2	1	15	4,050	50	810.00	3,240.00	400	484	Yes	3,240.00	3.24
S6D-20	700	2	3	15	11,340	50	810.00	10,530.00	400	484	Yes	3,510.00	3.51
S6D-21	400	3	4	15	6,480	75	1,215.00	5,265.00	600	726	Yes	1,316.25	1.32
S6D-30	550	5	4	15	8,910	125	2,025.00	6,885.00	1,000	1210	Yes	1,721.25	1.72
S6D-22	775	9	4	15	12,555	225	3,645.00	8,910.00	1,800	2178	Yes	2,227.50	2.23
S6D-23	450	10	1	15	7,290	250	4,050.00	3,240.00	2,000	2420	Yes	3,240.00	3.24
S6D-27	500	10	1	15	8,100	250	4,050.00	4,050.00	2,000	2420	Yes	4,050.00	4.05
S6D-25	825	4	1	15	13,365	100	1,620.00	11,745.00	800	968	Yes	11,745.00	11.75
S6D-26	600	2	1	15	9,720	50	810.00	8,910.00	400	484	Yes	8,910.00	8.91
S6D-24	150	2	1	15	2,430	50	810.00	1,620.00	400	484	Yes	1,620.00	1.62
S6D-32	300	2	1	15	4,860	50	810.00	4,050.00	400	484	Yes	4,050.00	4.05
S6D-29	600	3	3	15	9,720	75	1,215.00	8,505.00	600	726	Yes	2,835.00	2.84
S6D-28	1,000	1	1	15	16,200	25	405.00	15,795.00	200	242	Yes	15,795.00	15.80
S6C-10	800	1	5	15	12,960	25	405.00	12,555.00	200	242	Yes	2,511.00	2.51
S6C-9	650	2	6	15	10,530	50	810.00	9,720.00	400	484	Yes	1,620.00	1.62
S6C-8	525	3	9	15	8,505	75	1,215.00	7,290.00	600	726	Yes	810.00	0.81
S6C-24	575	3	9	15	9,315	75	1,215.00	8,100.00	600	726	Yes	900.00	0.90
S6C-7	1,500	1	2	15	24,300	25	405.00	23,895.00	200	242	Yes	11,947.50	11.95
S6C-11	350	3	1	15	5,670	75	1,215.00	4,455.00	600	726	Yes	4,455.00	4.46
S6C-12	500	6	1	15	8,100	150	2,430.00	5,670.00	1,200	1452	Yes	5,670.00	5.67
S6C-13	1,575	11	1	15	25,515	275	4,455.00	21,060.00	2,200	2662	Yes	21,060.00	21.06
S6C-14	1,200	25	1	15	19,440	625	10,125.00	9,315.00	5,000	6050	Yes	9,315.00	9.32
S6C-15	700	6	1	15	11,340	150	2,430.00	8,910.00	1,200	1452	Yes	8,910.00	8.91
S6C-23	600	4	8	15	9,720	100	1,620.00	8,100.00	800	968	Yes	1,012.50	1.01
S6C-17	450	3	9	15	7,290	75	1,215.00	6,075.00	600	726	Yes	675.00	0.68
Total 44	**28,675**	**241**	**130**	**660**	**464,535**	**6,025**	**97,605**	**366,930**	**48,200**	**58,322**	**-**	**204,473**	**204**

[1] Room Temperature (70˚F) - Supply Air Temperature (55˚F)

[2] Formula for Calculating Total Sensible Design Load = 1.08 x Total CFM x Delta-T

[3] Formula for Calculating Ventilation Air Based on ASHRAE 62.1-2007 = Population x 25 CFM/Person

[4] Formula for Calculationg Sensible Cooling Capacity of Primary Air = 1.08 x Vent Air (CFM) x Delta-T

[5] Formula for Calculating Sensible Cooling Load to be Done by the Chilled Beam = Total Sensible Load - Sensible Capacity

[6] Formula for Calculating Total Latent Load = 200 BTU/hr x Population

[7] Formula for Calculating Latent Cooling Capacity of Primary Supply Air = 4840 x Vent Air (CFM) x (0.009 - 0.007)

[8] Check to Make Sure Latent Capacity is Greater Than Latent Load

[9] Formula for Calculating Average Sensible Load for the Chilled Beam per Room = Sensible Load by Beams / # of Rooms.

[10] Formula for Calculating the Chilled Beam Size per Room = Sensible Load/Room / 1000 BTU/hr/ft

Calculations		
Percent Reduction in Primary Air = 1 - (Vent Air/Total Supply Air)		**79%**
Average Chilled Beam Size per Room = (Total Chilled Beam Size/Room) / (Total # of Rooms)		**5**
Total Cost of VAV for Given Area = $342.68 x Total # of VAVs	$	**15,078**
Cost of VAV per SF = Total Cost of VAV for Given Area / 14,248 SF	$	**0.61**
Total Cost of Chilled Beams for Given Area = Total ft of Chilled Beam x $280/ft	$	**102,760**
Cost of Chilled Beams per SF = Total Cost of Chilled Beams for Given Area / 14,248 SF	$	**4.16**
Percent Increase of Chilled Beams Units over VAV Boxes		**682%**

Patient Rooms

Level 8 was analyzed as the typical floor for patient rooms. The entire floor functions as patient rooms and nursing stations. Each VAV box serves a certain zone that ranges from 1- 5 rooms. The following assumptions were used for the calculation.

- The supply CFM shown on the drawings for each corresponding VAV box represents the design loads for that zone.
- Each room that is a part of the zone has similar loads.
- By examining the entire floor (including the north, south, east, west and inside rooms) it will provide representative load conditions.
- The number of seats or area to a room was used to estimate the number of people that would occupy the room at maximum load.
- Sizing is based on cooling load, not heating load
    - Heating will only be required on perimeter spaces and can be accomplished by adding heating coils in the beams.

The following calculation is an example of how the chilled beams and primary air supply were sized.

VAV Box S8C-33

- Total Supply for this VAV = 900 CFM
- 12 people are expected to occupy the zone at maximum capacity
- 4 rooms are served by this VAV
- Room temperature design = 70˚F
- Supply primary air temperature = 55˚F

1. Total Sensible Design Load = 1.08 x Total Supply CFM x (Room Temp – Supply Temp)
= 1.08 x 900 CFM x (70˚F - 55˚F)
= 14,580 BTU/hr

2. Ventilation air required per ASHRAE 62.1 – 2007 is 25 CFM/person for patient rooms.

3. Ventilation Air Required = 25 CFM/person x 12 persons = 300 CFM

4. Assume that ventilation air governs primary air supply right now and then check to see if it is greater than the latent load air requirement later.

5. Sensible Cooling Capacity of Primary Air = 1.08 x Vent. Air CFM x (Room Temp – Supply Temp)
= 1.08 x 300 CFM x (70˚F - 55˚F)
= 4,860 BTU/hr

6. Sensible Cooling by Chilled Beam = Total Sensible Load – Sensible Capacity of Primary Air
= 14,580 BTU/hr – 4,860 BTU/hr
= 9,720 BTU/hr

7. Latent load in the room can be approximated by the general rule of thumb that each person gives off 200 BTU/hr of latent load.

8. Latent Load = 200 BTU/hr/person x 12 person = 2,400 BTU/hr

9. Latent Cooling Capacity of Primary Air = 4,840 x Vent. Air CFM x (W_{Room} – $W_{Primary}$)
= 4,840 x 300 CFM (0.009 – 0.007)
= 2,904 BTU/hr

10. The latent cooling capacity of primary air is greater than the latent load. Therefore, the ventilation air is adequate in supporting the latent load for the zone.

11. Sensible Load on Chilled Beam per Room = 9,720 BTU/hr ÷ 4 = 2,430 BTU/hr

12. On average, a chilled beam can produce 1,000 BTU/hr/ft of sensible cooling capacity.

13. Chilled Beam Size per Room= 2,430 BTU/hr ÷ 1,000 BTU/hr/ft = 2.43 ft ≈ 3 ft Chilled Beam

13. Primary Air Reduction = 1 – (Primary Air CFM ÷ Total Current Supply CFM)
= 1- (300 CFM ÷ 900 CFM)
= 67%

Table 6 on the following page shows all of the calculations for the typical patient rooms. Below is a summary of the findings:

- Percent Reduction in Primary Air = 74%
- Average Chilled Beam Size per Room = 6 ft
- Total Cost of VAVs for Typical Area = $6,854 = $0.48/SF
- Total Cost of Chilled Beams for Typical Area = $49,280 = $3.46/SF
- Percent Increase of Chilled Beams over VAV Boxes = 719%

Table 6: Chilled Beam Load Calculations for Patient Rooms

Chilled Beam Design Calculations

Typical Patient Room/Non-invasive Space (14,248 SF)

VAV Box	Total Supply CFM/VAV	Population/VAV	# of Rooms/VAV	Delta-T[1]	Sensible Load (BTU/hr)[2]	Vent Air (cfm)[3]	Sensible Capacity(BTU/hr)[4]	Sensible Load by Beams(BTU/hr)[5]	Latent Load(BTU/hr)[6]	Latent Capacity(BTU/hr)[7]	Latent OK?[8]	Sensible Load/Room[9]	Chilled Beam Size/Room[10]
S8C-33	900	12	4	15	14,580	300	4,860.00	9,720.00	2,400	2904	Yes	2,430.00	2.43
S8C-34	150	3	1	15	2,430	75	1,215.00	1,215.00	600	726	Yes	1,215.00	1.22
S8C-30	1,000	15	5	15	16,200	375	6,075.00	10,125.00	3,000	3630	Yes	2,025.00	2.03
S8C-28	350	3	1	15	5,670	75	1,215.00	4,455.00	600	726	Yes	4,455.00	4.46
S8C-25	350	3	1	15	5,670	75	1,215.00	4,455.00	600	726	Yes	4,455.00	4.46
S8C-26	1,200	6	1	15	19,440	150	2,430.00	17,010.00	1,200	1452	Yes	17,010.00	17.01
S8C-24	650	5	2	15	10,530	125	2,025.00	8,505.00	1,000	1210	Yes	4,252.50	4.25
S8C-16	800	12	4	15	12,960	300	4,860.00	8,100.00	2,400	2904	Yes	2,025.00	2.03
S8C-17	1,200	6	1	15	19,440	150	2,430.00	17,010.00	1,200	1452	Yes	17,010.00	17.01
S8C-19	800	4	1	15	12,960	100	1,620.00	11,340.00	800	968	Yes	11,340.00	11.34
S8C-18	800	12	4	15	12,960	300	4,860.00	8,100.00	2,400	2904	Yes	2,025.00	2.03
S8C-20	150	2	1	15	2,430	50	810.00	1,620.00	400	484	Yes	1,620.00	1.62
S8C-21	1,100	10	4	15	17,820	250	4,050.00	13,770.00	2,000	2420	Yes	3,442.50	3.44
S8C-22	225	3	1	15	3,645	75	1,215.00	2,430.00	600	726	Yes	2,430.00	2.43
S8C-23	300	3	1	15	4,860	75	1,215.00	3,645.00	600	726	Yes	3,645.00	3.65
S8C-11	800	12	4	15	12,960	300	4,860.00	8,100.00	2,400	2904	Yes	2,025.00	2.03
S8C-12	1,000	8	1	15	16,200	200	3,240.00	12,960.00	1,600	1936	Yes	12,960.00	12.96
S8C-13	600	9	3	15	9,720	225	3,645.00	6,075.00	1,800	2178	Yes	2,025.00	2.03
S8C-14	1,850	18	1	15	29,970	450	7,290.00	22,680.00	3,600	4356	Yes	22,680.00	22.68
S8C-15	400	4	2	15	6,480	100	1,620.00	4,860.00	800	968	Yes	2,430.00	2.43
Total 20	**14,625**	**150**	**43**	**300**	**236,925**	**3,750**	**60,750**	**176,175**	**30,000**	**36,300**	**-**	**121,500**	**122**

[1] Room Temperature (70°F) - Supply Air Temperature (55°F)

[2] Formula for Calculating Total Sensible Design Load = 1.08 x Total CFM x Delta-T

[3] Formula for Calculating Ventilation Air Based on ASHRAE 62.1-2007 = Population x 25 CFM/Person

[4] Formula for Calculationg Sensible Cooling Capacity of Primary Air = 1.08 x Vent Air (CFM) x Delta-T

[5] Formula for Calculating Sensible Cooling Load to be Done by the Chilled Beam = Total Sensible Load - Sensible Capacity

[6] Formula for Calculating Total Latent Load = 200 BTU/hr x Population

[7] Formula for Calculating Latent Cooling Capacity of Primary Supply Air = 4840 x Vent Air (CFM) x (0.009 - 0.007)

[8] Check to Make Sure Latent Capacity is Greater Than Latent Load

[9] Formula for Calculating Average Sensible Load for the Chilled Beam per Room = Sensible Load by Beams / # of Rooms.

[10] Formula for Calculating the Chilled Beam Size per Room = Sensible Load/Room / 1000 BTU/hr/ft

NOTES

Typical Patient Room Size: 12' x 15' w/10' Ceiling = 1,800 ft^3

AIA Requires Patient Rooms to Have 2 ACH-1 of Outdoor Air

Ventilation Air Required = 1,800 ft^3 x 2/hr x 1hr/60min = 60 CFM

Average Ventilation per Patient Room = 87 CFM -> OK

Calculations		
Percent Reduction in Primary Air = 1 - (Vent Air/Total Supply Air)		74%
Average Chilled Beam Size per Room = (Total Chilled Beam Size/Room) / (Total # of Rooms)		6
Total Cost of VAV for Given Area = $342.68 x Total # of VAVs	$	6,854
Cost of VAV per SF = Total Cost of VAV for Given Area / 14,248 SF	$	0.48
Total Cost of Chilled Beams for Given Area = Total ft of Chilled Beam x $280/ft	$	49,280
Cost of Chilled Beams per SF = Total Cost of Chilled Beams for Given Area / 14,248 SF	$	3.46
Percent Increase of Chilled Beams Units over VAV Boxes		719%

Cost Impact

An add-deduct cost analysis will be used to determine the initial cost impact of using chilled beams in place of a VAV system. Then a life-cycle cost analysis will be used to determine the payback period, if any.

Table 7 below is a summary of the current HVAC system costs for the entire building. Each line item will be reviewed to determine if there will be a cost change. The cost is broken down into material and labor cost. This is because savings in material costs will not be equal to savings in labor costs. Therefore, each will need to be addressed separately.

Table 7: Summary of Current HVAC Costs for Entire Building

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 6 figures reflect the total area of the building. As mentioned, the chilled beams will only be used in the non-invasive spaces. The project architect and owner's representative was contacted to get a space program. The following square footages were determined:

- Total building size = 1,600,000 SF
- Total circulation space including hallways, lobbies, waiting rooms, etc. = 48% of building size
- Total invasive space including operating rooms, emergency rooms, trauma, etc. = 35% of building size
- Total non-invasive space including offices, patient rooms, etc. = 17% of building size

Based on these SF's an assumption must be made on what percentage of the HVAC costs are impacted by the chilled beams. The circulation and non-invasive spaces can use chilled beams. However, some hallways or lobbies may be right next to operating rooms or any other type of invasive space. It would not make sense to use chilled beams in these areas. Therefore, it can be assumed that 5% of the circulation space is not applicable to chilled beams. The result is 60% of the total space is applicable to chilled beams.

In order to analyze the costs associated with the current VAV system in the 60% of the total building space, the design must be understood. A typical operating room has approximately 25% more HVAC loads than the non-invasive spaces, which is directly proportional to 25% more HVAC costs. Therefore, it can be assumed that the invasive spaces represent 50% of the total HVAC costs (40% x 1.25 = 50%).

Table 8 below represents the current HVAC costs associated with the non-invasive spaces.

Table 8: Summary of Current HVAC Costs for Non-invasive Spaces

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Chilled Beam Initial Cost Analysis

The following calculations are based on the non-invasive areas and costs.

Ductwork

The sizing of the chilled beams and primary air calculations yielded a 74–79% reduction in air. A 75% reduction will be used to be on the conservative side. From this we can assume the following:

- The cross sectional area of the ductwork can be reduced by 75%
- The ceiling plenum space can be reduced
    - Therefore, the floor-floor height can be reduced
- AHUs, fans, etc. can be reduced by 75% capacity

Ductwork material cost is determined by the weight of sheet metal. The surface area is directly related to weight. Therefore we can calculate the material savings based on a 75% reduction in cross sectional area.

Assume a 10" x 10" duct.

Surface Area (Perimeter) = 10" + 10" + 10" = 10" = 40"

Cross sectional area = 10" x 10" = 100 in^2

Reduced Cross Sectional Area = 100 in^2 x 0.25 = 25 in^2

Reduced Size = (25 in^2) ^1/2 = 5 " -> 5" x 5"

Reduced Surface Area (Perimeter) = 5" + 5" + 5" +5" = 20 in^2

See Figure 21 below for an illustration of this calculation.

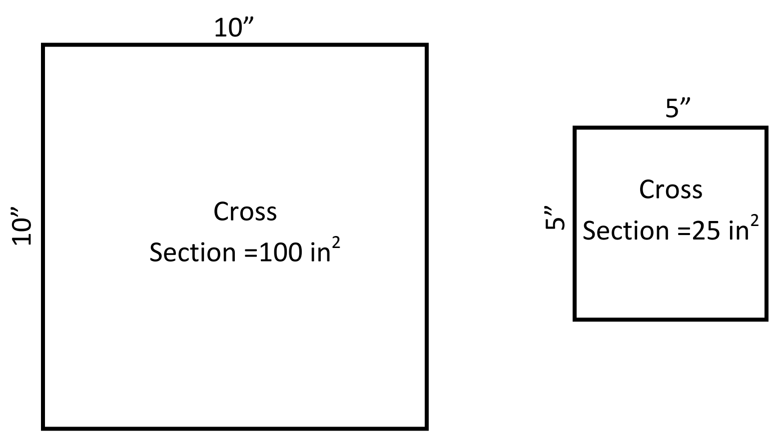


Figure 21: Illustration of Ductwork Reduction by 75%

From this calculation, we can conclude that there will be a 50% savings in ductwork material cost. However, this does not tell us anything about the labor savings. The labor costs to hang a duct that is 50% lighter and 75% smaller in cross section is not reduced by 50% because the craft still has to follow the same procedure. There will be some savings with handling and lifting the duct because it is lighter and smaller. Mike Topper, Project Manager for United Sheet Metal estimated a labor savings of 30% using the smaller duct.

[redacted]

Total Ductwork Cost = $11,910,761

AHUs, Fans, and Variable Frequency Drives

The AHUs and Fans can be downsized by 75% because they only have to provide 25% of their design CFMs. The cost savings for material and labor were estimated by the mechanical subcontractor, Poole and Kent. Donald Campbell, Vice President estimated a savings of 60% for material and 40% for labor for the AHUs, Fans, and VFDs.

[redacted]

Total AHU Cost = $1,642,800

[redacted]

Total Fans Cost = $129,436

[redacted]

Total VFD Cost = $254,313

Chilled Water Piping

As discussed in the chilled beam background, most of the cooling load will be delivered by chilled water pipes. The current VAV design has reheat coils in each VAV box which requires a hot water loop to be supplied to each floor. Based on the quantity and cost information for that, the chilled water pipe for the chilled beams can be estimated.

There is 160,000 linear feet of hot water piping at a cost of $11,483,700 with the current design. Therefore, the unit cost for material and labor is approximately $71.77/ft. For this estimate the cost of different size pipe will be ignored because it can be assumed that this unit cost is a representative average of the chilled water pipe sizes.

To estimate the quantity of chilled water piping for the chilled beam design, the typical spaces can be analyzed to get a quantity per square foot. The typical floor for the patient rooms has 14,248 SF of space. The typical patient room is 15'x12' with 12' corridors. The following assumptions can be made:

- At least 1 chilled beam will be in a room
- The chilled water loop will run through the center of each room in the ceiling plenum
- Branches from the main loop will run to the hallways
- A 20% allowance will be used for supply lines from the pumps to the loop and for branches
- 5% for waste
- The typical space can be approximated by a rectangle area 114'x126' = 14,364 SF

Figure 22 below is a drawing of a simplified typical floor. The red lines indicate the chilled/hot water pipe loops serving each chilled beam.

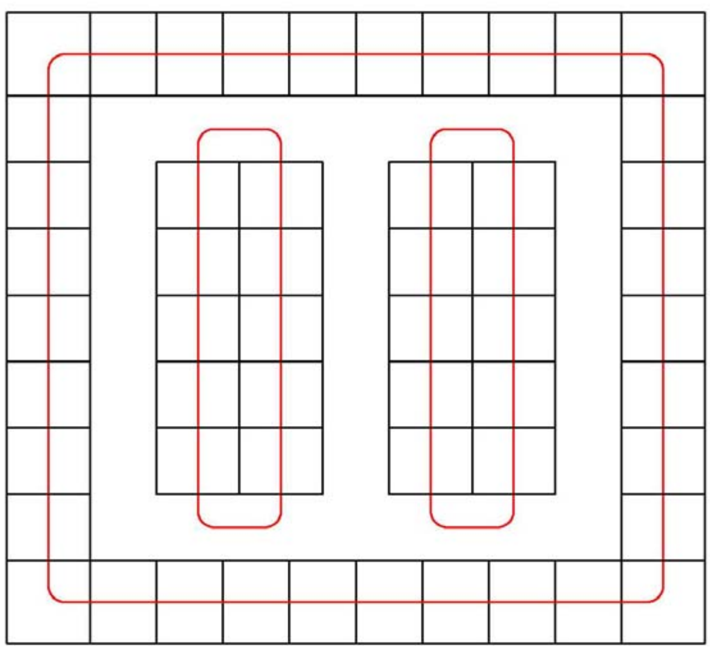


Figure 22: Simplified Typical Floor Piping Loop

From the assumptions on the previous page, the following calculations can be made:

Perimeter Loop = (2 x 99’) + (2 x 111’) = 420 lf

Interior Loops = (2 x 15’) + (2 x 72’) = 174 lf each

The perimeter loop will require a 4-pipe system for supply/return of hot and chilled water. This is because heating coils will be required for the perimeter spaces. The interior loops will only require a 2-pipe system for supply/return of chilled water.

Total Pipe = {(4 x 420’) + (2 x 2 x 174’)} x 1.05 x 1.2 = 2,994 lf

Total Pipe per Area = 2,994 lf ÷ 14,364 SF = 0.21 lf/SF

Non-invasive Area = 1.6M SF x 60% = 960,000 SF

Cost of Chilled Water Pipe to Chilled Beam = 960,000 SF x 0.21 lf/SF x $71.77/lf = $14,468,832

The chilled water piping line item includes pipe from the central utility plant to the AHUs. The cost for this pipe will not change because the same amount of chilled water will be needed (the building loads have not changed).This cost can be included with the chilled water pipe for the chilled beams.

Total Cost of Chilled Water Piping = $14,468,832 + $2,628,911 = $17,097,743

Pumps

The increased quantity of pipe will require the pumps to be upsized for the increase in volumetric flow. The increase cost for pumps should be directly proportional to the increase cost of piping.

Percent Increase in Piping = [redacted] = 252%

Total Cost of Pumps = [redacted] = **$308,669**

VAV Boxes/Chilled Beams

Table 9 below summarizes the findings in the Sizing the Chilled Beams section.

Table 9: Cost Comparison of Chilled Beams vs. VAV Boxes

	Office Rooms	Patient Rooms	Average
VAV Boxes	$0.61/SF	$0.48/SF	$0.55/SF
Chilled Beams	$4.16/SF	$3.46/SF	$3.81/SF
% Increase	682%	721%	693%

The cost data presented in Table 23 was based on the following figures:

- VAV Box Unit Cost = $1,028,033 ÷ 3,000 units = $342.68 (includes diffusers)
- Average Cost of Chilled Beam = $140/ft (Source: Pierces Associates)
- Average Cost of Installing Chilled Beam = $140/ft (Source: Pierces Associates)

Note that the cost per SF is lower for patient rooms than the offices. This is because the number of people occupying each room at maximum load is much lower. The average unit costs will be used for this analysis to provide an accurate representation.

The estimate can be verified by checking the estimated unit cost of the VAV boxes against the actual budget amount.

Estimated VAV Box Cost = 960,000 SF x $0.55/SF = $528,000

Actual VAV Box Cost = $514,017

The estimate proves to be very accurate by a margin of error of 3%.

The cost of VAV boxes will be replaced by the cost of Chilled Beams. The following calculation is used to estimate the cost.

Total Cost of Chilled Beams = 960,000 SF x $3.81/SF = $3,657,600

Controls

The control system for chilled beams are very simple compared to VAV systems. Each VAV box must be wired with low voltage to thermostats in each zone. Chilled beams regulate room temperature with a flow controller on the chilled water piping. The flow controller is entirely self contained and requires no power or control wiring. It measures the incoming room air temperature and adjusts to meet user's setting. Figure 23 below is a TROX VFL Flow Controller that could be used for this purpose.

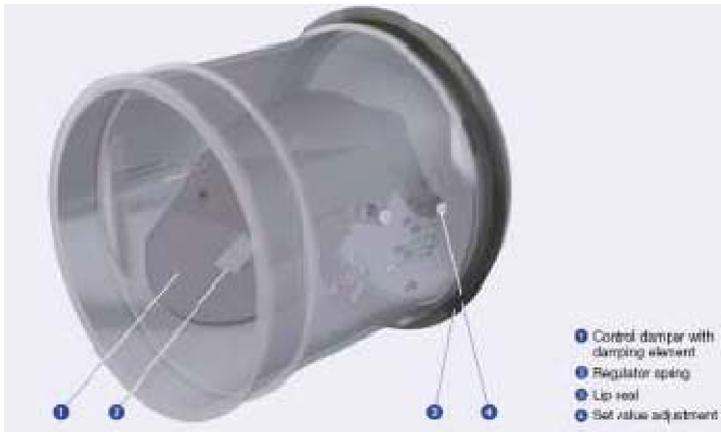


Figure 23: TROX VFL Flow Controller

This type of control system would come installed from the factory and is included in the chilled beam cost. Therefore the control line item will be zero for this analysis.

Total Cost of Controls = $0

Mechanical Insulation

The price for mechanical insulation is for the ductwork and hot water piping for the reheat coils. Poole and Kent believes that the chilled beam system will result in no difference in cost because the extra pipe insulation will be offset by the less amount of ductwork insulation.

[redacted]

Test & Balance

While consulting with Poole and Kent, it was determined that the cost for test & balance would not change. Even though, the chilled beams are supposed to be easier to commission, the mechanical construction industry is not familiar with the system at this time. They would likely carry some contingency in their bid for unforeseen problems with installing the system.

[redacted]

Other Components

The following HVAC components will be unaffected by the change to a chilled beam system. These line items are for operating rooms, medical gas, and humidity control that are not a part of the chilled beam system. Therefore, their cost will remain unchanged.

[redacted]

Chilled Beam HVAC System Initial Cost

To finalize the cost impact on the HVAC system, the cost of the VAV must be added to the chilled beams cost. Table 10 on the following page outlines the cost associated with each system. The chilled beam HVAC costs are compared to the original VAV budget to evaluate the savings. The following observations can be made:

- A total savings in HVAC cost = $572,832
- Most of the savings came from labor
- Significant savings in Ductwork = $7,300,143
- Savings was offset by increased cost of piping, water pumps and chilled beams

Building Façade Cost Impact

Floor-to-floor height for the NCB is on average 15'. The acoustical tile ceiling is to be located 8'-10' above finish floor, depending on which area of the building it is in. On average, the thickness of the decks is 8".

That means that the ceiling plenum ranges from 6'-4" to 4'-4". The limiting factor to how small you can make the ceiling plenum is the space under the steel girders. The typical girder on this project is a W21x57. That means that the clear space under the girder ranges from 4'-7" to 2'-7". To be on the conservative side, 2'-7" will be used for this analysis.

The mechanical overhead size is usually restricted by ductwork since it is the largest component. The 2'-7" between the ceiling and the girder is necessary to allow the ductwork to pass. Since a Chilled Beam system allows the ductwork to be downsized by 50% in length/width, the space between the ceiling and girder can also be downsized by 50%. This results in a 1'-4" space savings.

By reducing the ceiling plenum by 1'-4", the floor-to-floor height can also be reduced by the same amount. This will result in savings of precast and curtain wall. The following data is used to calculate the savings:

- Typical floor perimeter = 2,515 ft.
- Number of floors = 15
- Precast cost = $45.77/SF (see Project Background)
- Curtain Wall cost = $102.18/SF (see Project Background)
- Precast accounts for 43% of façade
- Curtain Wall accounts for 57% of façade

Only 60% of the façade SF can be reduced because the chilled beams are only used in non-invasive spaces. This assumes that the chilled beams will be used throughout an entire floor space.

Total amount of façade SF reduced = 1'-4"/floor x 15 floors x 2,515' x 0.6 = 30,180 SF

Total amount of Precast SF reduced = 30,180 SF x 0.43 = 12,977 SF

Total amount of Curtain Wall SF reduced = 30,180 SF x 0.57 = 17,203 SF

Total Savings in Precast = 12,977 SF x $45.77/SF = $593,957

Total Savings in Curtain Wall = 17,203 SF x $102.18/SF = $1,757,803

Structural Steel Cost Impact

The structural steel package scope can be reduced due to reducing the floor-to-floor height by 1'-4". A manual takeoff indicates that a typical floor has 219 columns with an average weight of 91.6 lbs/ft. In the Project Background section of this thesis, it was found that the structural steel cost was $2,352/ton. The following calculation can be used to calculate the savings, which accounts for 60% of the building area:

Total Reduction in Steel Scope = 219 columns x 91.6 lbs/ft/column x 1'-4"/floor x 15 floors x 0.6
= 120.3 tons

Total Savings in Structural Steel = 120.3 tons x $2,352/ton = $283,092

Chilled Beam Life Cycle Cost Analysis

Energy Savings

JHH estimates that the HVAC energy cost will be $2.35/SF annually. This equates to an annual energy bill of $3,760,000. As was determined in the previous section, 50% of the load will be used for the non-invasive spaces. Therefore, only half of the estimated annual energy bill will be affected by this analysis.

In order to project the energy savings accurately, it would require a detail energy model to predict the efficiency of the chilled beam system over the current VAV design. However, an energy model is outside the scope of this thesis analysis. Therefore, it was necessary to reach out to industry experts to get an estimate. There was over-whelming consensus that chilled beams would provide at least 20-35% in HVAC energy cost savings. The only similar project in the same geographical area that could be found for comparison was Constitution Center in Washington, D.C. This project was located in the same climate zone with a similar chilled beam design and building enclosure. SmithGroup, the A/E for that project estimated that they saved 23.8% in energy consumption by using the chilled beams in place of a VAV system.

Since, the actual energy efficiency of the system is not known; a life-cycle analysis will be conducted using 3 scenarios – 15%, 25%, and 35%. The life-cycle savings in energy cost for the chilled beam system is summarized on the following pages in Table 11, 12, and 13 for 15%, 25%, and 35% energy savings, respectively. A 3% rate of inflation is used for the calculation.

The following is a summary of the findings:

- 5 Year Savings for 15% Efficiency = $1,497,176
- 5 Year Savings for 25% Efficiency = $2,495,294
- 5 Year Savings for 35% Efficiency = $3,493,411

- 10 Year Savings for 15% Efficiency = $3,232,814
- 10 Year Savings for 25% Efficiency = $5,388,023
- 10 Year Savings for 35% Efficiency = $7,543,233

- 20 Year Savings for 15% Efficiency = $7,577,446
- 20 Year Savings for 25% Efficiency = $12,629,076
- 20 Year Savings for 35% Efficiency = $17,680,706

- 30 Year Savings for 15% Efficiency = $13,416,267
- 30 Year Savings for 25% Efficiency = $22,360,445
- 30 Year Savings for 35% Efficiency = $31,304,624

Table 11: HVAC Energy Life-Cycle Cost Analysis with 15% Efficiency

	Annual Energy Cost		Estimated Savings	
	Original VAV	**Chilled Beam - 15% Efficient**	**Yearly**	**Accumulated**
Year 1	$ 3,760,000	$ 3,478,000	$ 282,000	**$ 282,000**
Year 2	$ 3,872,800	$ 3,582,340	$ 290,460	**$ 572,460**
Year 3	$ 3,988,984	$ 3,689,810	$ 299,174	**$ 871,634**
Year 4	$ 4,108,654	$ 3,800,505	$ 308,149	**$ 1,179,783**
Year 5	$ 4,231,913	$ 3,914,520	$ 317,393	**$ 1,497,176**
Year 6	$ 4,358,871	$ 4,031,955	$ 326,915	**$ 1,824,092**
Year 7	$ 4,489,637	$ 4,152,914	$ 336,723	**$ 2,160,814**
Year 8	$ 4,624,326	$ 4,277,501	$ 346,824	**$ 2,507,639**
Year 9	$ 4,763,056	$ 4,405,826	$ 357,229	**$ 2,864,868**
Year 10	$ 4,905,947	$ 4,538,001	$ 367,946	**$ 3,232,814**
Year 11	$ 5,053,126	$ 4,674,141	$ 378,984	**$ 3,611,798**
Year 12	$ 5,204,719	$ 4,814,365	$ 390,354	**$ 4,002,152**
Year 13	$ 5,360,861	$ 4,958,796	$ 402,065	**$ 4,404,217**
Year 14	$ 5,521,687	$ 5,107,560	$ 414,127	**$ 4,818,343**
Year 15	$ 5,687,337	$ 5,260,787	$ 426,550	**$ 5,244,894**
Year 16	$ 5,857,957	$ 5,418,611	$ 439,347	**$ 5,684,241**
Year 17	$ 6,033,696	$ 5,581,169	$ 452,527	**$ 6,136,768**
Year 18	$ 6,214,707	$ 5,748,604	$ 466,103	**$ 6,602,871**
Year 19	$ 6,401,148	$ 5,921,062	$ 480,086	**$ 7,082,957**
Year 20	$ 6,593,183	$ 6,098,694	$ 494,489	**$ 7,577,446**
Year 21	$ 6,790,978	$ 6,281,655	$ 509,323	**$ 8,086,769**
Year 22	$ 6,994,708	$ 6,470,105	$ 524,603	**$ 8,611,372**
Year 23	$ 7,204,549	$ 6,664,208	$ 540,341	**$ 9,151,713**
Year 24	$ 7,420,685	$ 6,864,134	$ 556,551	**$ 9,708,265**
Year 25	$ 7,643,306	$ 7,070,058	$ 573,248	**$ 10,281,513**
Year 26	$ 7,872,605	$ 7,282,160	$ 590,445	**$ 10,871,958**
Year 27	$ 8,108,783	$ 7,500,624	$ 608,159	**$ 11,480,117**
Year 28	$ 8,352,047	$ 7,725,643	$ 626,403	**$ 12,106,520**
Year 29	$ 8,602,608	$ 7,957,412	$ 645,196	**$ 12,751,716**
Year 30	$ 8,860,686	$ 8,196,135	$ 664,551	**$ 13,416,267**
Year 31	$ 9,126,507	$ 8,442,019	$ 684,488	**$ 14,100,755**
Year 32	$ 9,400,302	$ 8,695,279	$ 705,023	**$ 14,805,778**
Year 33	$ 9,682,311	$ 8,956,138	$ 726,173	**$ 15,531,951**
Year 34	$ 9,972,780	$ 9,224,822	$ 747,959	**$ 16,279,910**
Year 35	$10,271,964	$ 9,501,567	$ 770,397	**$ 17,050,307**

Table 12: HVAC Energy Life-Cycle Cost Analysis with 25% Efficiency

	Annual Energy Cost		Estimated Savings	
	VAV	Chilled Beam - 25% Efficient	Yearly	Accumulated
Year 1	$ 3,760,000	$ 3,290,000	$ 470,000	**$ 470,000**
Year 2	$ 3,872,800	$ 3,388,700	$ 484,100	**$ 954,100**
Year 3	$ 3,988,984	$ 3,490,361	$ 498,623	**$ 1,452,723**
Year 4	$ 4,108,654	$ 3,595,072	$ 513,582	**$ 1,966,305**
Year 5	$ 4,231,913	$ 3,702,924	$ 528,989	**$ 2,495,294**
Year 6	$ 4,358,871	$ 3,814,012	$ 544,859	**$ 3,040,153**
Year 7	$ 4,489,637	$ 3,928,432	$ 561,205	**$ 3,601,357**
Year 8	$ 4,624,326	$ 4,046,285	$ 578,041	**$ 4,179,398**
Year 9	$ 4,763,056	$ 4,167,674	$ 595,382	**$ 4,774,780**
Year 10	$ 4,905,947	$ 4,292,704	$ 613,243	**$ 5,388,023**
Year 11	$ 5,053,126	$ 4,421,485	$ 631,641	**$ 6,019,664**
Year 12	$ 5,204,719	$ 4,554,129	$ 650,590	**$ 6,670,254**
Year 13	$ 5,360,861	$ 4,690,753	$ 670,108	**$ 7,340,362**
Year 14	$ 5,521,687	$ 4,831,476	$ 690,211	**$ 8,030,572**
Year 15	$ 5,687,337	$ 4,976,420	$ 710,917	**$ 8,741,490**
Year 16	$ 5,857,957	$ 5,125,713	$ 732,245	**$ 9,473,734**
Year 17	$ 6,033,696	$ 5,279,484	$ 754,212	**$ 10,227,946**
Year 18	$ 6,214,707	$ 5,437,869	$ 776,838	**$ 11,004,785**
Year 19	$ 6,401,148	$ 5,601,005	$ 800,144	**$ 11,804,928**
Year 20	$ 6,593,183	$ 5,769,035	$ 824,148	**$ 12,629,076**
Year 21	$ 6,790,978	$ 5,942,106	$ 848,872	**$ 13,477,948**
Year 22	$ 6,994,708	$ 6,120,369	$ 874,338	**$ 14,352,287**
Year 23	$ 7,204,549	$ 6,303,980	$ 900,569	**$ 15,252,855**
Year 24	$ 7,420,685	$ 6,493,100	$ 927,586	**$ 16,180,441**
Year 25	$ 7,643,306	$ 6,687,893	$ 955,413	**$ 17,135,854**
Year 26	$ 7,872,605	$ 6,888,529	$ 984,076	**$ 18,119,930**
Year 27	$ 8,108,783	$ 7,095,185	$ 1,013,598	**$ 19,133,528**
Year 28	$ 8,352,047	$ 7,308,041	$ 1,044,006	**$ 20,177,534**
Year 29	$ 8,602,608	$ 7,527,282	$ 1,075,326	**$ 21,252,860**
Year 30	$ 8,860,686	$ 7,753,101	$ 1,107,586	**$ 22,360,445**
Year 31	$ 9,126,507	$ 7,985,694	$ 1,140,813	**$ 23,501,259**
Year 32	$ 9,400,302	$ 8,225,264	$ 1,175,038	**$ 24,676,297**
Year 33	$ 9,682,311	$ 8,472,022	$ 1,210,289	**$ 25,886,585**
Year 34	$ 9,972,780	$ 8,726,183	$ 1,246,598	**$ 27,133,183**
Year 35	$10,271,964	$ 8,987,968	$ 1,283,995	**$ 28,417,178**

Table 13: HVAC Energy Life-Cycle Cost Analysis with 35% Efficiency

	Annual Energy Cost		Estimated Savings	
	VAV	**Chilled Beam - 35% Efficient**	**Yearly**	**Accumulated**
Year 1	$ 3,760,000	$3,102,000	$ 658,000	**$ 658,000**
Year 2	$ 3,872,800	$3,195,060	$ 677,740	**$ 1,335,740**
Year 3	$ 3,988,984	$3,290,911	$ 698,072	**$ 2,033,812**
Year 4	$ 4,108,654	$3,389,639	$ 719,014	**$ 2,752,827**
Year 5	$ 4,231,913	$3,491,328	$ 740,585	**$ 3,493,411**
Year 6	$ 4,358,871	$3,596,068	$ 762,802	**$ 4,256,214**
Year 7	$ 4,489,637	$3,703,950	$ 785,686	**$ 5,041,900**
Year 8	$ 4,624,326	$3,815,068	$ 809,257	**$ 5,851,157**
Year 9	$ 4,763,056	$3,929,520	$ 833,535	**$ 6,684,692**
Year 10	$ 4,905,947	$4,047,406	$ 858,541	**$ 7,543,233**
Year 11	$ 5,053,126	$4,168,828	$ 884,297	**$ 8,427,530**
Year 12	$ 5,204,719	$4,293,893	$ 910,826	**$ 9,338,355**
Year 13	$ 5,360,861	$4,422,710	$ 938,151	**$ 10,276,506**
Year 14	$ 5,521,687	$4,555,391	$ 966,295	**$ 11,242,801**
Year 15	$ 5,687,337	$4,692,053	$ 995,284	**$ 12,238,085**
Year 16	$ 5,857,957	$4,832,814	$ 1,025,143	**$ 13,263,228**
Year 17	$ 6,033,696	$4,977,799	$ 1,055,897	**$ 14,319,125**
Year 18	$ 6,214,707	$5,127,133	$ 1,087,574	**$ 15,406,698**
Year 19	$ 6,401,148	$5,280,947	$ 1,120,201	**$ 16,526,899**
Year 20	$ 6,593,183	$5,439,375	$ 1,153,807	**$ 17,680,706**
Year 21	$ 6,790,978	$5,602,557	$ 1,188,421	**$ 18,869,128**
Year 22	$ 6,994,708	$5,770,633	$ 1,224,074	**$ 20,093,201**
Year 23	$ 7,204,549	$5,943,752	$ 1,260,796	**$ 21,353,997**
Year 24	$ 7,420,685	$6,122,065	$ 1,298,620	**$ 22,652,617**
Year 25	$ 7,643,306	$6,305,727	$ 1,337,579	**$ 23,990,196**
Year 26	$ 7,872,605	$6,494,899	$ 1,377,706	**$ 25,367,902**
Year 27	$ 8,108,783	$6,689,746	$ 1,419,037	**$ 26,786,939**
Year 28	$ 8,352,047	$6,890,438	$ 1,461,608	**$ 28,248,547**
Year 29	$ 8,602,608	$7,097,151	$ 1,505,456	**$ 29,754,003**
Year 30	$ 8,860,686	$7,310,066	$ 1,550,620	**$ 31,304,624**
Year 31	$ 9,126,507	$7,529,368	$ 1,597,139	**$ 32,901,762**
Year 32	$ 9,400,302	$7,755,249	$ 1,645,053	**$ 34,546,815**
Year 33	$ 9,682,311	$7,987,906	$ 1,694,404	**$ 36,241,220**
Year 34	$ 9,972,780	$8,227,543	$ 1,745,237	**$ 37,986,456**
Year 35	$10,271,964	$8,474,370	$ 1,797,594	**$ 39,784,050**

Space Savings

There are 9 - 8'x26' mechanical shafts on each floor that can be reduced by 50% in size because the ductwork is going to decrease in size. Also, the mechanical room can be reduced in size because the AHU will either be smaller or some may be deleted. The savings in space in the mechanical room will be approximately 25%.

JHH has indicated that any space savings would be used as additional space to generate revenue. A square foot of space in the NCB will generate approximately [redacted] Using this information, the following calculation can be used to determine the additional revenue generated by this extra space.

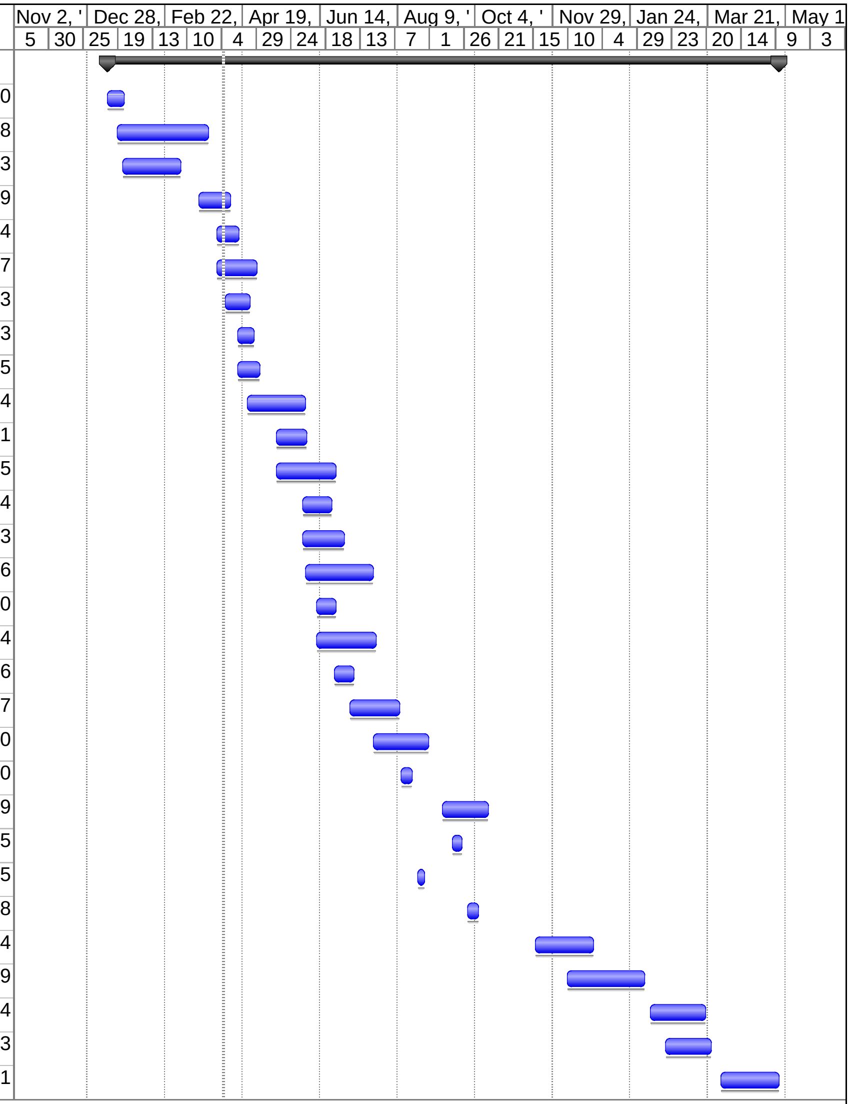
[redacted]

Schedule Impact

The original baseline schedule was acquired from the mechanical contractor (see the following page). A typical floor overhead schedule was analyzed to find the schedule impact of switching to a chilled beam system. The only activities that required changes to the duration are listed below. The affect to each is noted next to them and was determined in the previous section of this analysis. Note the float on each activity on the baseline schedule.

1. Install Duct Risers in Shafts – Decrease by 30%
2. Install Duct Mains – Decrease by 30%
3. Install HVAC Equipment – Decrease by 40%
4. Install Duct Branches – Decrease by 30%
5. Install OH CHW/RHHW/Steam Mains - Delete Reheat Hot Water (RHHW) and add 275%
6. Install OH CHW/RHHW/Steam Run Outs – Delete Reheat Hot Water (RHHW) and add 275%
7. Install OH CHW/RHHW/Steam Connections - Delete Reheat Hot Water (RHHW) and add 275%
8. Install Grilles, Registers & Diffusers – Delete and add Install Chilled Beams

ID		Task Name	Duration	Start	Finish	Float
1		**Typ. Floor Mech. Overhead**	**347 days**	**Mon 1/12/09**	**Tue 5/11/10**	
2		Overhead Dwg. Posting	10 days	Mon 1/12/09	Fri 1/23/09	0
3		Coordinate Drawings	48 days	Mon 1/19/09	Wed 3/25/09	78
4		Fab Branches	30 days	Fri 1/23/09	Thu 3/5/09	83
5		Install Sanitary/Sorm and Vent Riser	17 days	Thu 3/19/09	Fri 4/10/09	-29
6		Install Carriers	12 days	Wed 4/1/09	Thu 4/16/09	84
7		Install Sanitary/Storm and Vent Piping	21 days	Wed 4/1/09	Wed 4/29/09	-37
8		Install Duct Risers in Shafts	14 days	Tue 4/7/09	Fri 4/24/09	63
9		Complete Test Sanitary/Storm	8 days	Thu 4/16/09	Mon 4/27/09	193
10		Install Showers	12 days	Thu 4/16/09	Fri 5/1/09	55
11		Install Duct Mains	30 days	Thu 4/23/09	Wed 6/3/09	-104
12		Install Rack Piping (OH Domestic HW)	16 days	Thu 5/14/09	Thu 6/4/09	-51
13		Install HVAC Equipment	31 days	Thu 5/14/09	Thu 6/25/09	-105
14		Install Medical Gas Risers/Mains OH	15 days	Tue 6/2/09	Mon 6/22/09	84
15		Install Water Run Outs	22 days	Tue 6/2/09	Wed 7/1/09	143
16		Install Duct Branchees	35 days	Thu 6/4/09	Wed 7/22/09	-106
17		Install Gas Run Outs	10 days	Fri 6/12/09	Thu 6/25/09	80
18		Install OH CHW/RHHW/Steam Mains	31 days	Fri 6/12/09	Fri 7/24/09	134
19		Complete Duct Testing	10 days	Thu 6/25/09	Wed 7/8/09	116
20		Install OH CHW/RHHW/Steam Run Outs	26 days	Mon 7/6/09	Mon 8/10/09	77
21		Install OH CHW/RHHW/Steam Connections	28 days	Thu 7/23/09	Mon 8/31/09	70
22		Complete Test CHW and RH/HW	6 days	Wed 8/12/09	Wed 8/19/09	70
23		Install In-Wall Plumbing	23 days	Fri 9/11/09	Tue 10/13/09	-49
24		Public/Staff Toilet RI	5 days	Fri 9/18/09	Thu 9/24/09	85
25		Complete Test Gas	5 days	Mon 8/24/09	Fri 8/28/09	5
26		Complete Test Water	6 days	Tue 9/29/09	Tue 10/6/09	78
27		Insulate Piping	30 days	Tue 11/17/09	Mon 12/28/09	34
28		Insulate Ductwork	40 days	Thu 12/10/09	Wed 2/3/10	29
29		Identify & Tag	30 days	Mon 2/8/10	Fri 3/19/10	24
30		Install Plumbing Fixtures and Trim	23 days	Fri 2/19/10	Tue 3/23/10	53
31		Install Grilles, Registers & Diffusers	30 days	Wed 3/31/10	Tue 5/11/10	61



Project: JHH New Clinical Building
Schedule: Baseline Typ. Floor Mech. Overhead
Date: 4/7/09

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External Milestone | Deadline

The Install Grilles, Registers & Diffusers can be deleted because this will not be necessary with the chilled beams. The VAV boxes are included in the duration for Install Duct Branches. A new line item for Install Chilled Beams must be added. The following calculation can be used to determine the duration.

Typical Floor Area = 113,805 SF

Chilled Beam Cost per Floor = 113,805 SF x $3.81/SF = $433,597

Chilled Beams Cost per Foot = $280/lf

Total Amount of Linear Foot of Chilled Beams per Floor = $433,597 ÷ $280/lf = 1,549 lf

Typical Beam is 6ft

Quantity of Beams per Floor = 1,549 lf ÷ 6 ft/beam = 258 beams

Pierce Associates estimates that a crew can install 5 beams/day

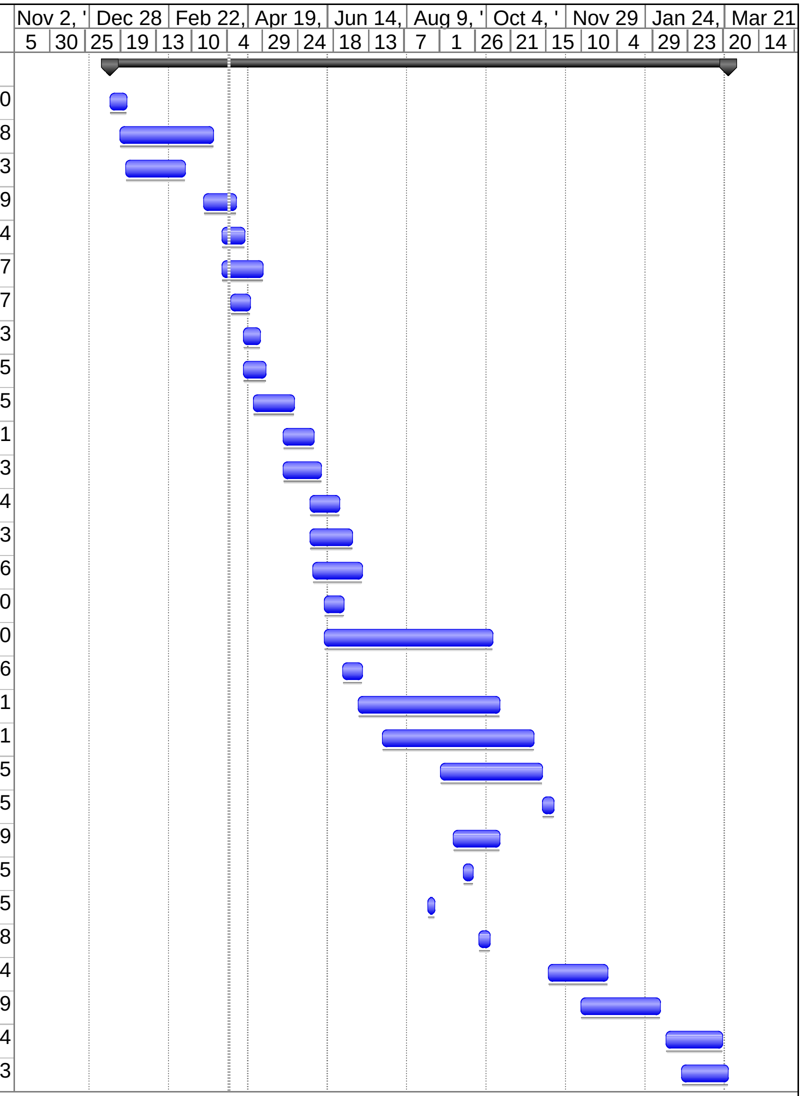
Total Duration per Floor = 258 beams ÷ 5 beams/day = 52 days

With this information, the baseline can be adjusted to reflect the new durations. The Install Chilled Beams activity will follow the Install Overhead Chilled Water/Steam (OH CHW/Steam) Connections. This will push the Complete Test CHW activity back. However, there is enough float in that activity to absorb the extended duration.

After reevaluating the schedule, it was found that the activities that are accelerated (Ductwork and HVAC Equipment) are on the critical path while the activities that are extended have a great deal of float. The result is that the critical path is accelerated 31 working days while the extra time for piping reduces the float but still does not hit the critical path.

The following page shows the new chilled beam overhead schedule. Note the changes in float as compared to the original baseline schedule. The changes in durations are reflected in the days of float.

ID		Task Name	Duration	Start	Finish	Float
1		**Typ. Floor Mech. Overhead**	**312 days**	**Mon 1/12/09**	**Tue 3/23/10**	
2		Overhead Dwg. Posting	10 days	Mon 1/12/09	Fri 1/23/09	0
3		Coordinate Drawings	48 days	Mon 1/19/09	Wed 3/25/09	78
4		Fab Branches	30 days	Fri 1/23/09	Thu 3/5/09	83
5		Install Sanitary/Sorm and Vent Riser	17 days	Thu 3/19/09	Fri 4/10/09	-29
6		Install Carriers	12 days	Wed 4/1/09	Thu 4/16/09	84
7		Install Sanitary/Storm and Vent Piping	21 days	Wed 4/1/09	Wed 4/29/09	-37
8		Install Duct Risers in Shafts	10 days	Tue 4/7/09	Mon 4/20/09	67
9		Complete Test Sanitary/Storm	8 days	Thu 4/16/09	Mon 4/27/09	193
10		Install Showers	12 days	Thu 4/16/09	Fri 5/1/09	55
11		Install Duct Mains	21 days	Thu 4/23/09	Thu 5/21/09	-95
12		Install Rack Piping (OH Domestic HW)	16 days	Thu 5/14/09	Thu 6/4/09	-51
13		Install HVAC Equipment	19 days	Thu 5/14/09	Tue 6/9/09	-93
14		Install Medical Gas Risers/Mains OH	15 days	Tue 6/2/09	Mon 6/22/09	84
15		Install Water Run Outs	22 days	Tue 6/2/09	Wed 7/1/09	143
16		Install Duct Branchees	25 days	Thu 6/4/09	Wed 7/8/09	-96
17		Install Gas Run Outs	10 days	Fri 6/12/09	Thu 6/25/09	80
18		Install OH CHW/Steam Mains	85 days	Fri 6/12/09	Thu 10/8/09	80
19		Complete Duct Testing	10 days	Thu 6/25/09	Wed 7/8/09	116
20		Install OH CHW/Steam Run Outs	72 days	Mon 7/6/09	Tue 10/13/09	31
21		Install OH CHW/Steam Connections	77 days	Thu 7/23/09	Fri 11/6/09	21
22		Install Chilled Beams	52 days	Wed 9/2/09	Thu 11/12/09	5
23		Complete Test CHW	6 days	Fri 11/13/09	Fri 11/20/09	5
24		Install In-Wall Plumbing	23 days	Fri 9/11/09	Tue 10/13/09	-49
25		Public/Staff Toilet RI	5 days	Fri 9/18/09	Thu 9/24/09	85
26		Complete Test Gas	5 days	Mon 8/24/09	Fri 8/28/09	5
27		Complete Test Water	6 days	Tue 9/29/09	Tue 10/6/09	78
28		Insulate Piping	30 days	Tue 11/17/09	Mon 12/28/09	34
29		Insulate Ductwork	40 days	Thu 12/10/09	Wed 2/3/10	29
30		Identify & Tag	30 days	Mon 2/8/10	Fri 3/19/10	24
31		Install Plumbing Fixtures and Trim	23 days	Fri 2/19/10	Tue 3/23/10	53



Project: JHH New Clinical Building
Schedule: Chilled Beam Typ. Floor Mech. Overhead
Date: 4/7/09

Task		Milestone		External Tasks	
Split		Summary		External Milestone	
Progress		Project Summary		Deadline	

Accelerating the typical floor overhead mechanical installation by 31 working days is significant. This equates to 9 floors (60% of the building) that save 31 working days each. Assuming that every floor had the same schedule (it does not, but assume this for calculation purposes) the entire overhead can be accelerated by 279 working days, or almost 13 months. In order to accurately determine the schedule impact, the entire building schedule must be analyzed. However, this is beyond the scope of this thesis.

What can be determined from this analysis is that the mechanical overhead installation would be taken off the critical path of the project if chilled beams are used. Another activity, like interior finishes would then be pushed to the critical path. This could potentially pick up a few days in the overall building schedule.

The most important part of this finding is that the affect of the mechanical system changes can be reduced. Using a chilled beam system could have reduced the delay because the system can be installed much faster.

6.6 Conclusion

A Chilled Beam HVAC system proves to be a viable alternative to a VAV system for this project. The analysis proved there was significant savings in first cost as well as life-cycle cost. The schedule impact of the new system showed that the mechanical overhead could be taken off the critical path if this system was used.

Ultimately, the owner's two main goals – to deliver this project on/under budget and on time has the most potential to be met with the chilled beam system. Although it is too late to use this system on this project, it does show that if this system would have been analyzed in preconstruction, it could have been selected as the primary system for the non-invasive spaces.

Although, many assumptions were made in this analysis, they were made in cooperation with industry experts and are appropriately accurate for an analysis of this level of detail. If this would have been done in the preconstruction phase, it would have determined the system is a viable alternative and would have required more research and calculations by industry experts.

During preliminary research for chilled beams, it was found that industry experts thought the initial cost of chilled beams would be 8-12% more than a conventional VAV system. However, this project was much different than a typical building which made chilled beams cheaper initially. The NCB had access to a central utility plant where the resources of chilled water and steam were assumed to be adequate. For this reason, the HVAC costs did not include chillers, boilers, cooling towers, etc. The NCB's ductwork costs accounted for 48% of the total budget, which is the area that saw the most cost savings. While, most of the savings were offset by increases in piping, the savings in floor-to-floor height yielded the largest initial cost savings.

The energy savings associated with the more efficient chilled beams proves to be the biggest savings to the owner. Assuming a very conservative 15% savings in energy cost demonstrated a substantial savings even in the first few years.

Possibly the most important part of the findings is the schedule savings. While more time was required to complete a typical floor because of the increase in piping (as seen in the increase cost of labor for piping), the critical activities were taken off the critical path. The result is the mechanical overhead is taken off the critical path of the entire project.

The changes in the mechanical system that have caused a 7 month delay in the project schedule would likely be absorbed in the savings in installation time with the chilled beams. Although, no detail analysis of the change orders and how they would directly affect the chilled beam system was conducted, the mechanical contractor felt it would provide significant savings.

This analysis concludes that chilled beams will likely become more popular in the U.S. marketplace. Further research on cost and schedule data is needed to accurately estimate the impact of a chilled beam system because the industry is relatively unfamiliar with the system.