IPRO 320   Summer 2006
Sustainable Planning for IIT Buildings

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1. Introduction

1.1 The Problem

Building systems must be designed, constructed, commissioned, operated and maintained to provide the building occupants with a functional, comfortable, safe, flexible, properly illuminated, durable and reliable environment to perform the functions for which the different spaces are intended.

Even with the aforementioned requirements in mind, the design, operation and maintenance of building systems are imperfect processes. The level of performance of building systems is greatly affected by the skill, training, craftsmanship and performance of various people which are actively involved in the different stages of design and implementation processes. In addition, since most building's systems operate and respond to continually changing conditions which are dictated by the system's utilization and other conditions, there is a definite need to verify, document and adjust the performance of building's systems to meet the operational needs within the capabilities of the design. In other words, building's systems must be commissioned since this is the process that provides the right procedures, and methods of documenting achieving and verifying that the building's systems conform to the design and meet user's needs.

In this project, we have concentrated on the first stage of the commissioning process of the heating ventilation and air conditioning (HVAC) of various buildings located in the Illinois Institute of Technology main campus.

1.2 Project Goals

The main objective of this project is to justify the development of an initial commissioning plan for the future commissioning process of the HVAC system of some buildings' systems on campus. Since the commissioning process is a very complicated and extensive process which must include all building's systems as well as the building as a single system in order to meet the user's needs, the different teams were assigned to the initial stage of the commissioning process which is to evaluate the need for commissioning. The team based its conclusions based on thermal comfort conditions of the buildings on campus. Mainly, the team's goals were reduced to field inspections, review of existing drawings and data, review of building equipment and operation, and evaluation of operation and maintenance procedures. In order to achieve these objectives we gathered Heating Ventilation and Air Conditioning performance data (Temperature, Humidity) of some buildings on campus and analyzed it to suggest the need for future commissioning. Our team will deliver systems descriptions and documentation requirements, for future commissioning processes as well as it will theoretically justify the need for the aforementioned. The evaluation of the systems' performance might provide some feasible solutions to some of the problems that are found.

2. Team Structure and Assignments

This project lacked personnel which limited the quantity of teams and the increased the work load of the different teams. Finally, we divided into two teams the field data analysis team and the research team. The teams' structure and responsibilities are discussed below.

The Research Team

The research team was assigned the tasks of reviewing building's systems, equipment and operations and the evaluation of the systems to justify the initial commissioning plan development. The research must deliver the systems description, and the required documentation for the development of the commissioning plan. In addition, this team should provide possible solutions for the problems that are found.

The Field and Data Analysis Team

This team was assigned the tasks of field inspections, evaluation of existing drawings and data, collection of recent performance data throughout all campus buildings as well as map out all collected data to properly depict possible areas where commissioning issues are present. Through this process, the field data analysis team will ensure that all performance data is clear and concise.

3.0 Setting work into Motion

Heating Ventilation and Air Conditioning System

3.1 Field Inspections

The air conditioning systems analyzed throughout these buildings are classified as unitary systems since they are factory assembled, balanced, and tested air conditioning units. These units are installed in nearby mechanical rooms from which the air is ducted to the space which is to be conditioned. Even though this type of system is classified as a unitary system, the system is built up by using a central source of cooling from which chilled water is pumped to fan coil units which exchange energy and distribute air to the different zones through ducts. [1]

Other than this limited information, we can provide some machines' equipment manufacturers because of available data. Additionally, during the visual inspections, all equipment seemed to be functioning. This conclusion is based on room conditions as well as inspection of supply and return ducts.

3.2 Review of existing drawings and data

We had all building architectural drawings which made the development of an inspection plan possible. However, we did not have any mechanical plans which limited the analysis of the results as well as their significance. Moreover, the available data was provided to us by a third party. This data is limited only to the main air handling unit's performance. This performance data is comprised of air handling unit manufacturer information and

[1] Wang Shank K. *Handbook of Air Conditioning and Refrigeration* McGraw Hill, Inc, 1993

actual status of the components such as the unit's capacity, volume handled, fan's rpms, and air quality. However, this data is not helpful unless, we have building design parameters or data of room's performance. In addition, all the data must be analyzed in accordance to equipment manufacturer characteristics curves to provide meaningful analysis.

3.3 Review building systems

At this point, it is important to note that the analyzed buildings we have limited availability of the required documentation. Since elevation plans are not available, reviewing these systems is limited to visual inspections. However, some factors that might be important for the process of air conditioning can be specified.

HUB, MTCC and Crown Hall buildings

The McCormick Tribune Campus Center's walls as well as Crown Hall's and the HUB's are made of glass which plays an important role when analyzing radiation effects on building performance.

Glass in wall and windows transmit large amounts of energy into buildings which is converted into sensible heat when absorbed by the objects in the spaces. This fact greatly increases summer loads and might possibly affect specific zones during specific times of the day. In addition, glass traps heat as well. This condition is very desirable during the winter but very undesirable during the summer.

All other buildings are made of solid bricks which from a radiation point of view; they reflect much of the energy. However, they bring heat conduction into play since they are not really good insulators. This in turn might affect performance analysis of gathered data for the zones are at variable load conditions at different times of the day.

Moreover, most buildings on campus have changed their design use. Therefore, load calculations must be made in accordance to actual space use having into consideration new load peak times. Differences in actual occupancy and internal sources of load have changed thus the system requires redesigning with new internal sensible load, internal latent load which might change the total load of different zones within the buildings.

3.4 Review building equipment

Most buildings have reduced their cooling loads since their occupancy has rather decreased. Assuming an initially well designed system, most of the equipments should be oversized for their actual load. The work is to be done in the air handling units as well as individual spaces. The air diffusers in different spaces are making some appreciable noise which could be due to possible reduction in pressure loses of the system if the duct work was redesigned and the system was not balanced or possible dampers failures or in need of adjustment.

3.5 Review building operation and performance

Our work in this part of the project was limited to reviewing actual comfort conditions in occupied rooms in all buildings as opposed to machine performance parameters analysis.

Building thermal Comfort

The main purpose of a Heating Ventilation and Air conditioning System is to provide comfort. Therefore, it is important to analyze present conditions and performance of the HVAC system.

Thermal comfort is defined as the state of mind in which one acknowledges satisfaction with regard to the thermal environment.[2] The American Society of Heating Ventilation and Air conditioning Engineers (ASHRAE) has done extensive research based on previous works by other institutions and developed charts with comfort zones. The ANSI/ASHRAE standard 55-1981 specifies winter and summer comfort zones to provide with parameters for analyzing thermal comfort in different environments[3]. There are a wide variety of comfort charts with different variables plotted vs. operating temperature at different humidity percentages. These comforts charts attempt to relate the factors of temperature, humidity and air movement to human comfort. Even though, we are presenting a wide variety of chart, for the analysis of our collected data, we are to use the Wet-Bulb Temperature vs. Dry-Bulb Temperature chart at 15-25 ft/min air speed which is considered one of the most useful charts available for office space activities[4].

It is important to note that these charts are subjective judgments made by people and how they personally felt for different combinations of temperature humidity and air movement. Therefore the comfort zones are not absolute and are based on percentage of surveyed people. The comfort zone was developed by showing the zones in which more than 50% of the people reported being comfortable. In addition, even though comfort charts are helpful for analyzing data; they are to be used with care. Some local experience may dictate different values than what these charts say. In addition radiation effects were considered negligible in the development of these charts and they can be considerable in different conditions.

It is imperative at this point to emphasize that we have used this charts to analyze our collected data since no design parameters were available to us. Some occupied space might have been designed to perform the way it is performing due to conditions that were required at the time of design.

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[2] Wang Shank K. *Handbook of Air Conditioning and Refrigeration* McGraw Hill, Inc, 1993

[3] ASHRAE Handbook http://www.ashrae.org/template/EducationLinkLanding/category/1553;jsessionid=aaaeUIIcz91dJx retrieved July 23 2006

[4] Harris Norman C. Modern Air Conditioning Practice. McGraw Hill Book Company Gregg Division 1983

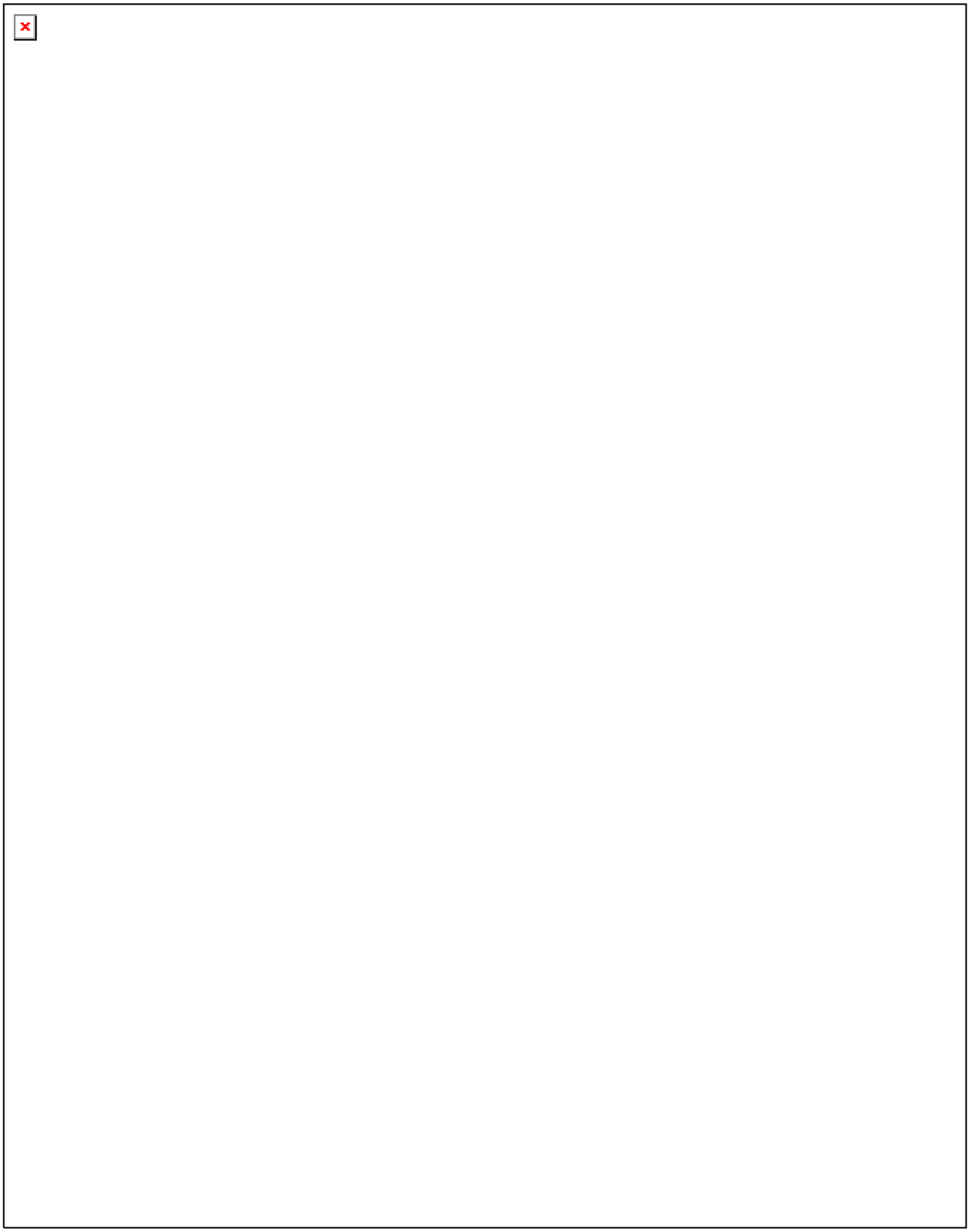

Figure 3.1 Fanger’s Comfort Charts[5]

[5] Wang Shank K. *Handbook of Air Conditioning and Refrigeration* McGraw Hill, Inc, 1993

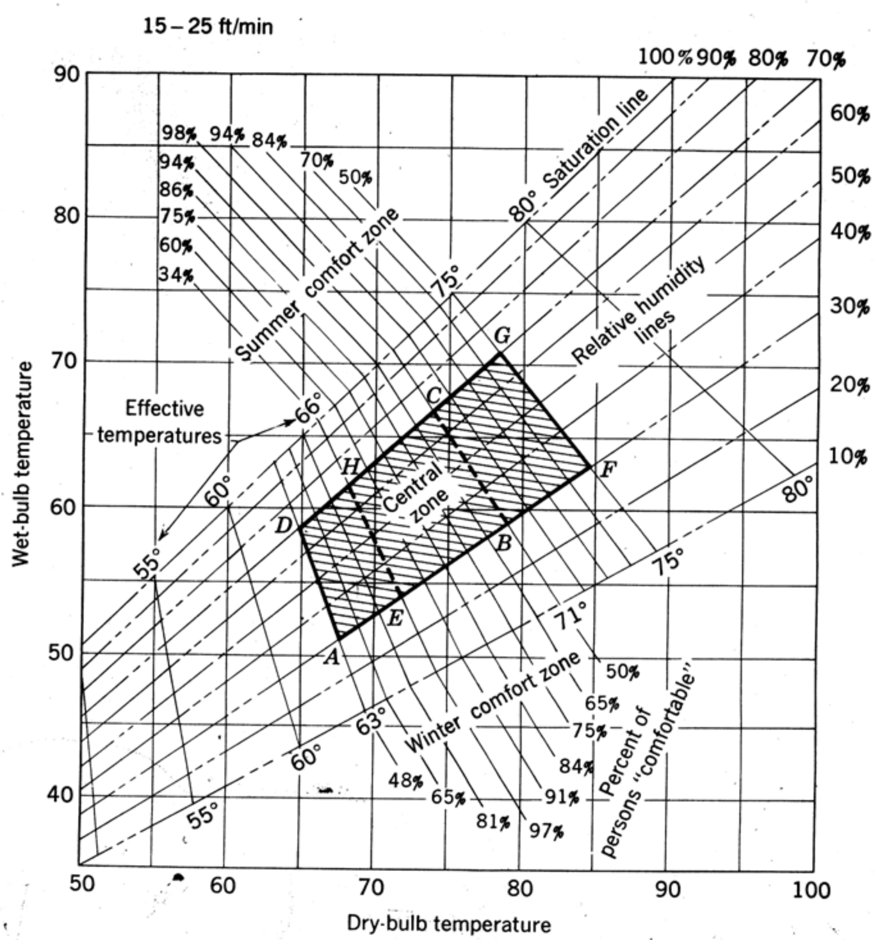

Figure 3.2 The comfort chart[6]

This chart is based on an activity level of 1.2 and the clothing insulation is specified to be 0.5 clo which is light slacks and short-sleeve shirts or comparable with an air velocity of less than 50 ft/min and around 15-25 ft/min for optimal conditions. The ASHRAE standard 55-1981 recommends and optimal effective temperature of 76 Fahrenheit with boundaries of 73-79 Fahrenheit. The chart is interpreted as it is and should be shifted by 1 Fahrenheit for every 0.1 clo in clothing insulation.

Bellow, we present the results of the measurements of temperature and humidity for different buildings in the Illinois Institute of Technology main campus during the summer of 2006.

We have represented every room as a point in the comfort chart in every building. The Comfort chart utilized in the Wet-Bulb temperature vs. Dry-Bulb Temperature with standard conditions of 15-25 ft/min of air speed and light clothing.

[6] Harris Norman C. Modern Air Conditioning Practice. McGraw Hill Book Company Gregg Division 1983

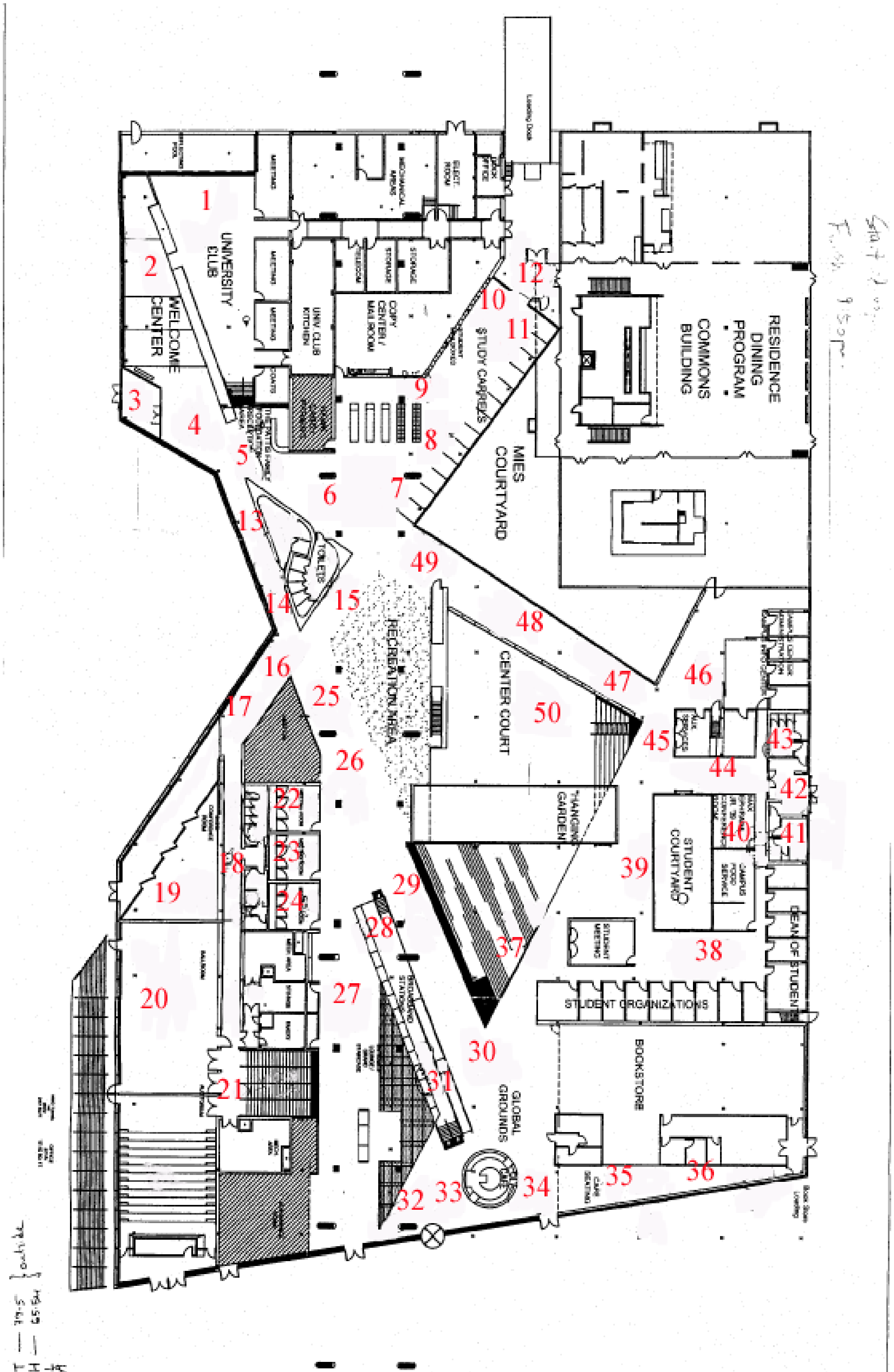
UNIVERSITY CLUB
WELCOME CENTER
UNIV CLUB KITCHEN
COPY CENTER/ MAILROOM
STUDY CARRELS
MIES COURTYARD
RESIDENCE DINING PROGRAM
COMMONS BUILDING
TOILETS
RECREATION AREA
CENTER COURT
"HANGING" GARDEN
STUDENT COURTYARD
CAMPUS FOOD SERVICE
STUDENT MEETING
STUDENT ORGANIZATIONS
DEAN OF STUDENTS
BOOKSTORE
GLOBAL GROUNDS
Loading Dock
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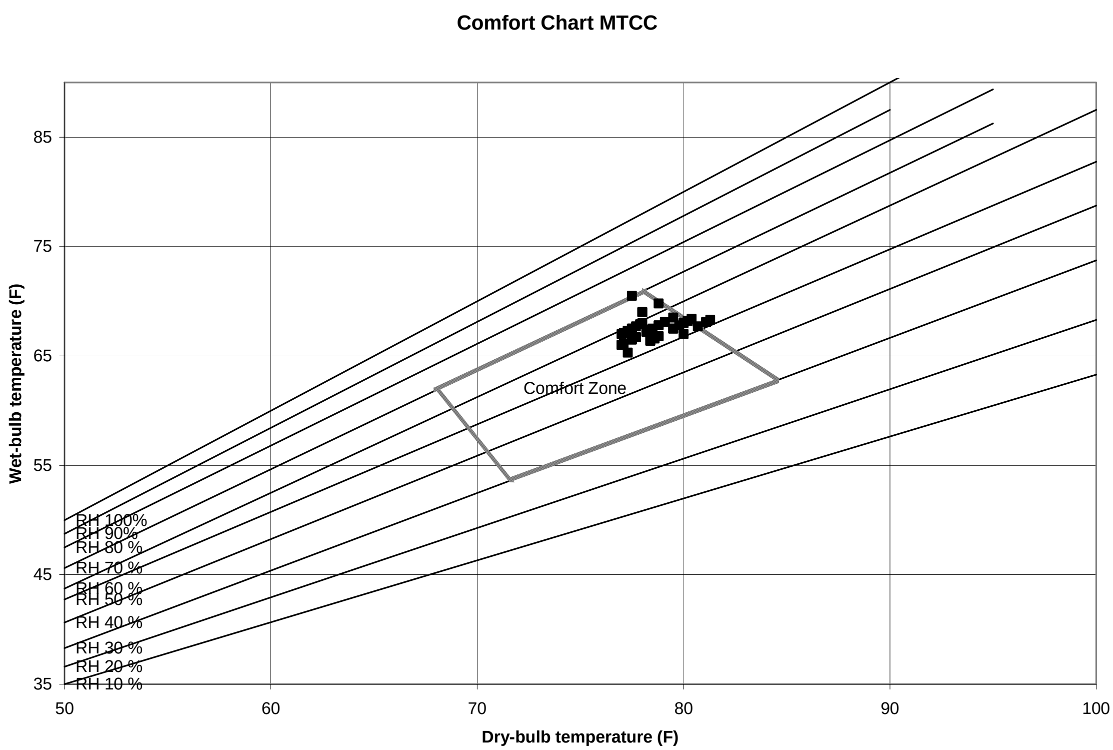
Figure 1: MTCC floor plans

MTTC Building					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
Outside	79.5	65.54	12	YES	71.5
1	79.1	54.2	12	NO	68.1
2	78.5	54	12	NO	67.5
3	78.8	60	12	NO	69.8
4	78.2	53.7	12	NO	67.2
5	79.5	52.2	12	NO	68.5
6	79.5	52	12	NO	67.5
7	81.1	49.4	13	YES	68.1
8	80.2	51.3	13	NO	68.2
9	79.8	51.4	12	NO	67.8
10	80	52.5	13	NO	68
11	80.4	52.4	13	YES	68.4
12	80	54	13	NO	68
13	78.8	55	12	NO	67.8
14	78.8	53.5	12	NO	67.8
15	78	57	12	NO	68
16	78.4	53	12	NO	67.4
17	78.6	51	12	NO	66.6
18	78.8	51	12	NO	66.8
19	78.8	49.1	12	NO	66.8
20	77.3	50.2	12	NO	65.3
21	77.5	52.5	12	NO	66.5
22	78.4	51.5	12	NO	66.4
23	78.4	50.5	12	NO	66.4
24	77.9	57.6	12	NO	67.9
25	77.1	55.3	12	NO	67.1
26	77.5	53	12	NO	66.5
27	80	51.3	13	NO	68
28	77.1	55	12	NO	66.1
29	77	54.4	12	NO	66
30	77	54.5	12	NO	66
31	77	55	12	NO	66
32	77	56	12	NO	67
33	77.7	55	12	NO	66.7
34	77	57	12	NO	67
35	77.5	58.3	12	NO	67.5
36	77.7	59	12	NO	67.7
37	77.7	53.4	12	NO	66.7
38	77.5	54.5	12	NO	66.5
39	77.3	55.5	12	NO	67.3
40	77.5	55.38	12	NO	67.5
41	78	62	12	NO	69

42	77.5	68	12	YES	70.5
43	78	62	12	NO	69
44	77.3	55.4	12	NO	67.3
45	80	50.8	13	NO	67
46	79.5	50.8	12	NO	67.5
47	81.1	50	13	YES	68.1
48	80.7	50	13	YES	67.7
49	81.3	48.5	13	YES	68.3
50	77.7	54.8	12	NO	66.7



Every point represents the different zones and their location in the comfort chart.

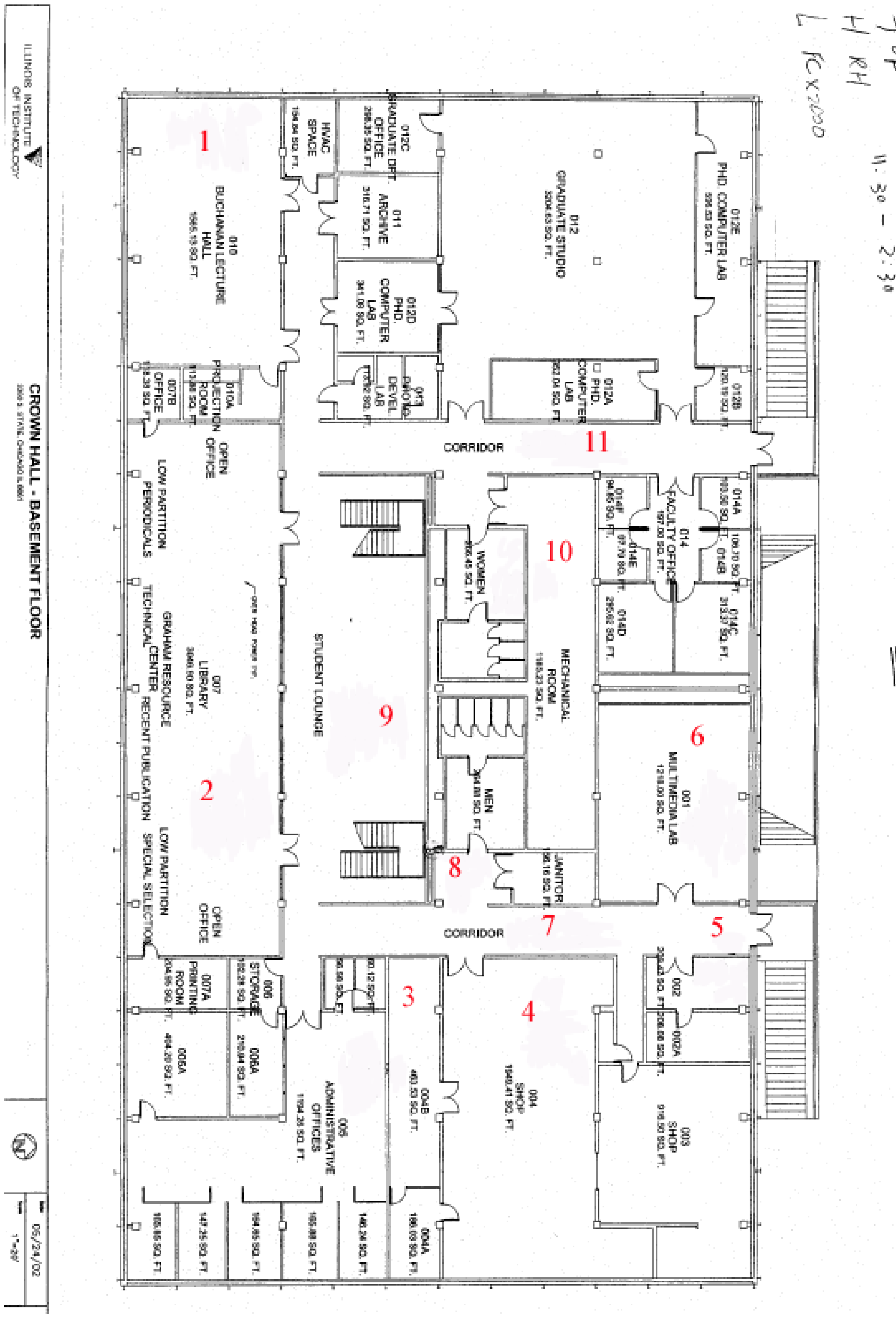
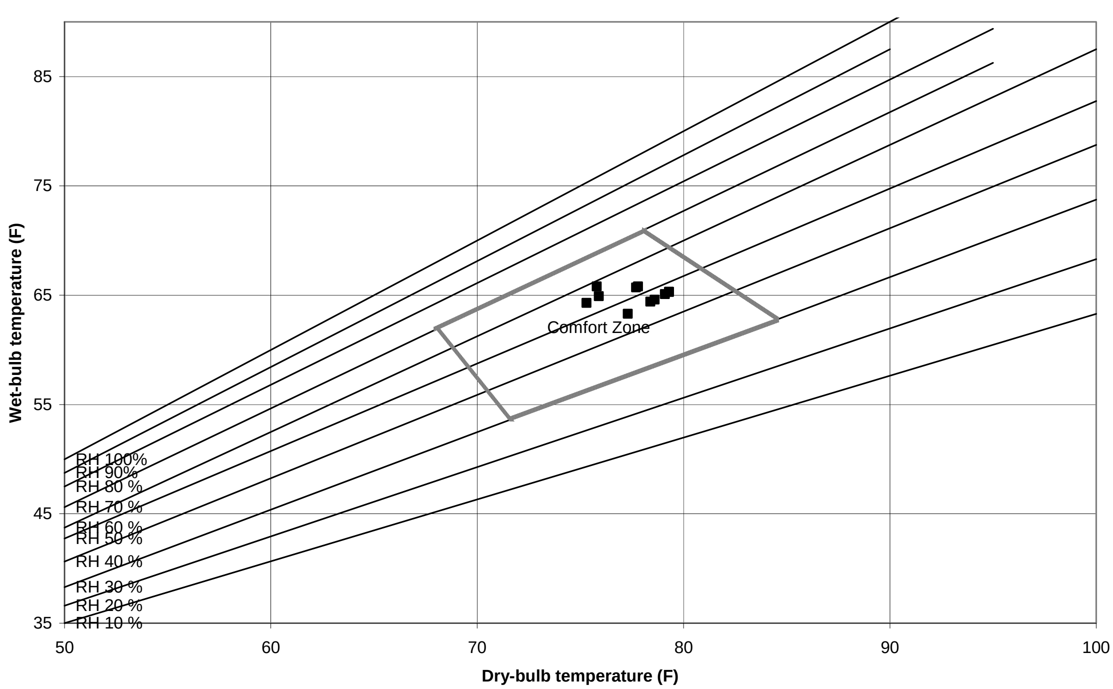


Figure 2 Crown Hall Basement

Crown Hall Building Basement					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	75.3	52.1	11	NO	64.3
2	77.3	42.6	12	NO	63.3
3	77.8	48.1	12	NO	65.8
4	78.4	43.6	12	NO	64.4
5	79.3	42.1	12	NO	65.3
6	79.3	43.9	12	NO	65.3
7	79.1	42.1	12	NO	65.1
8	78.6	44.5	12	NO	64.6
9	77.7	49.7	12	NO	65.7
10	75.9	52.1	11	NO	64.9
11	75.8	55	11	NO	65.8

Comfort Chart Crown Hall Basement



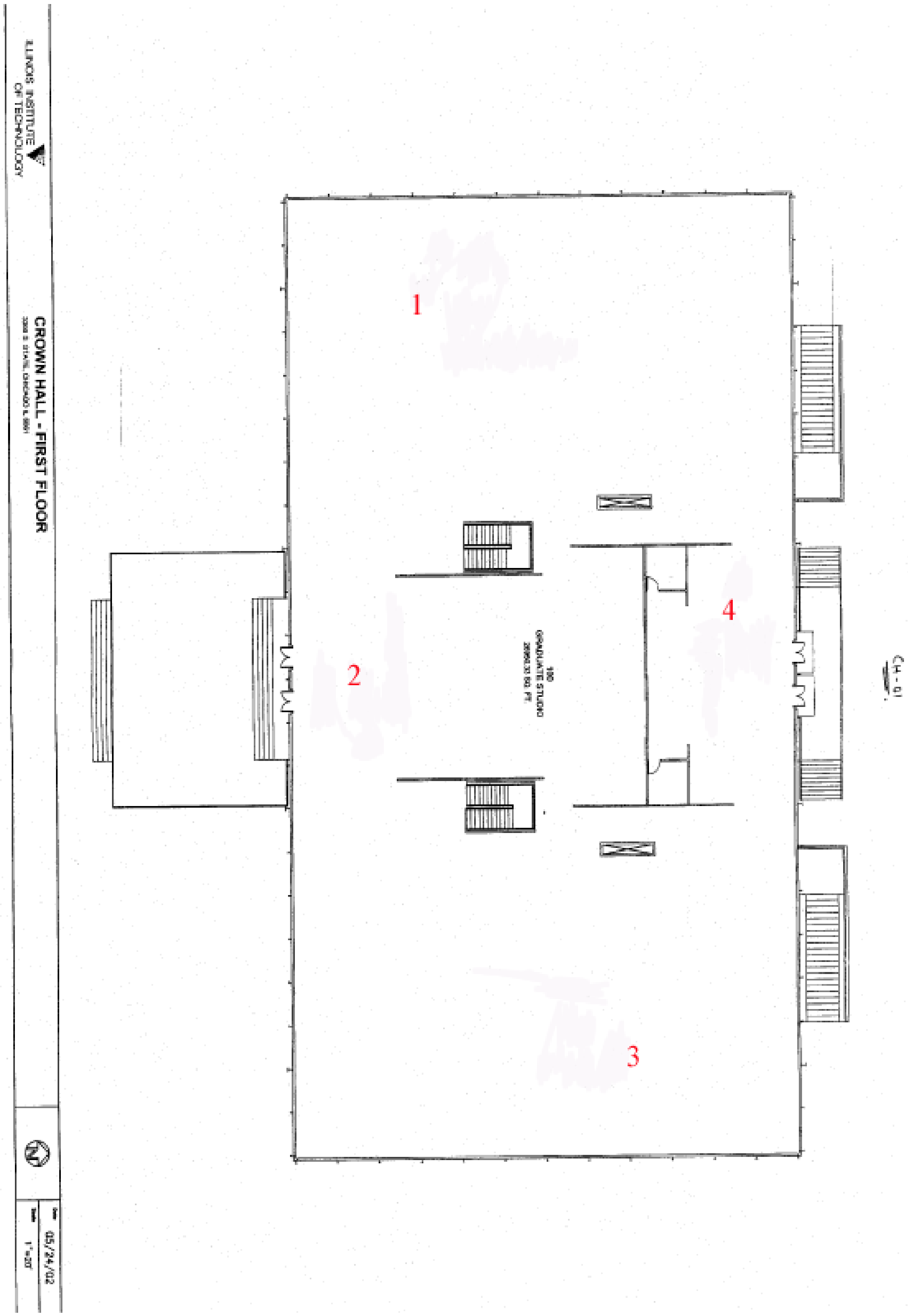
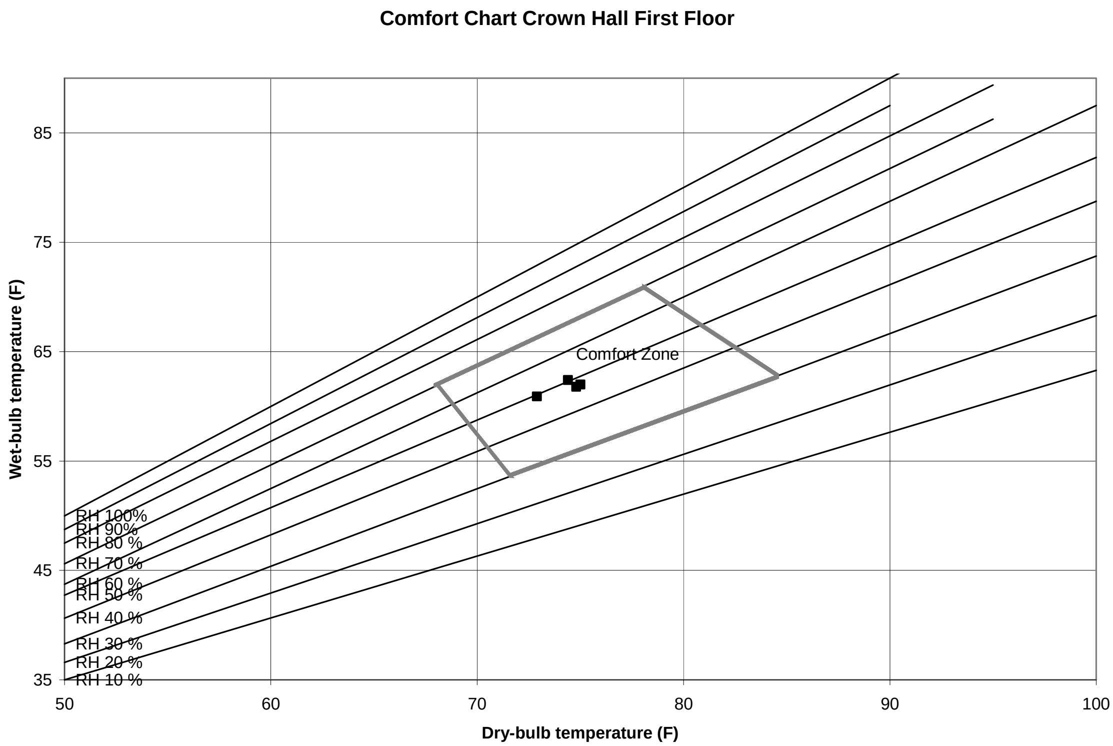


Figure 3 Crown Hall first floor

Crown Hall Building First Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	75	45	11	NO	62
2	72.9	47.5	11	NO	60.9
3	74.4	48.1	11	NO	62.4
4	74.8	45.6	11	NO	61.8



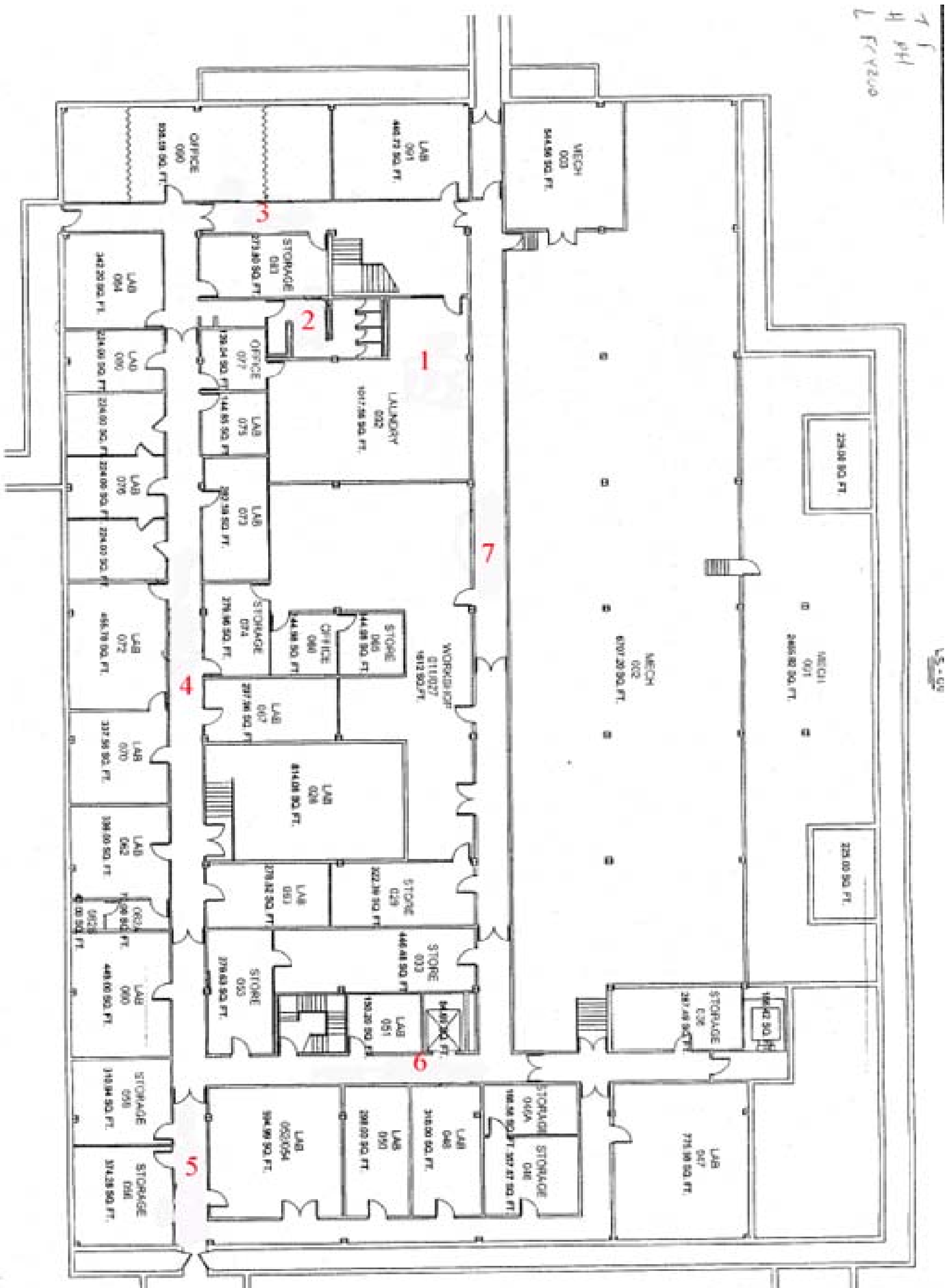
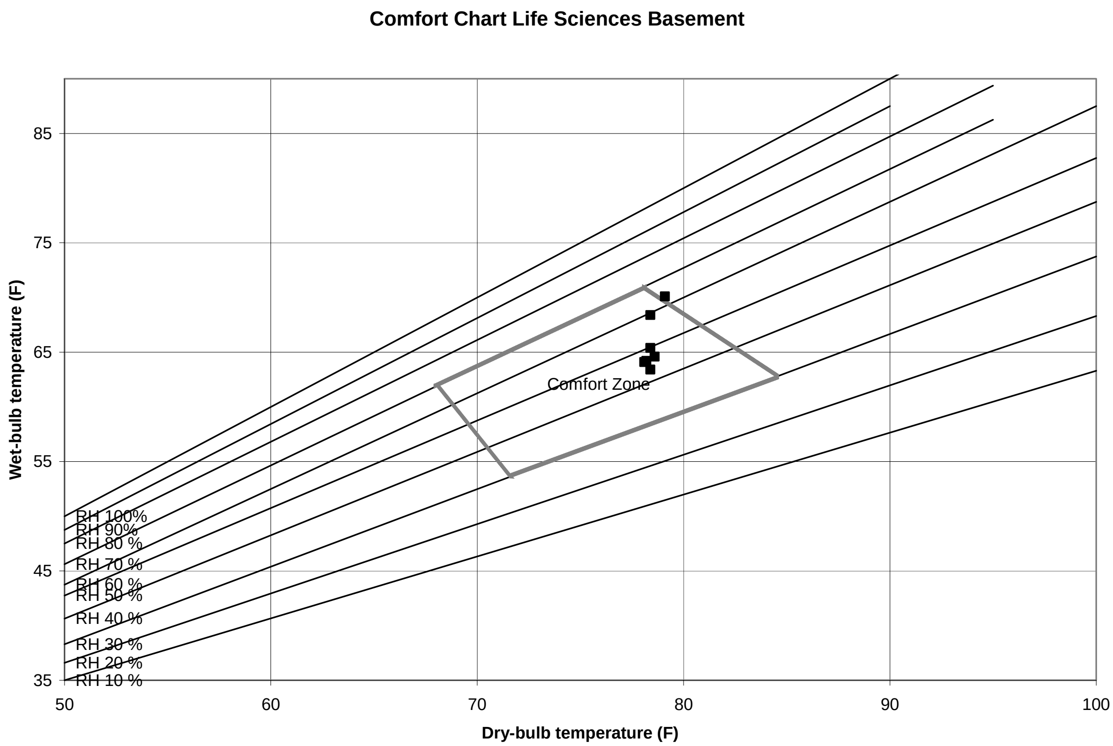


Figure 4 Life Sciences basement

Life Sciences Building Basement					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	78.2	43.1	12	NO	64.2
2	78.4	45.9	12	NO	65.4
3	78.6	43	12	NO	64.6
4	78.1	42.3	12	NO	64.1
5	78.4	41.8	12	NO	63.4
6	78.4	57.2	12	NO	68.4
7	79.1	61.4	12	YES	70.1



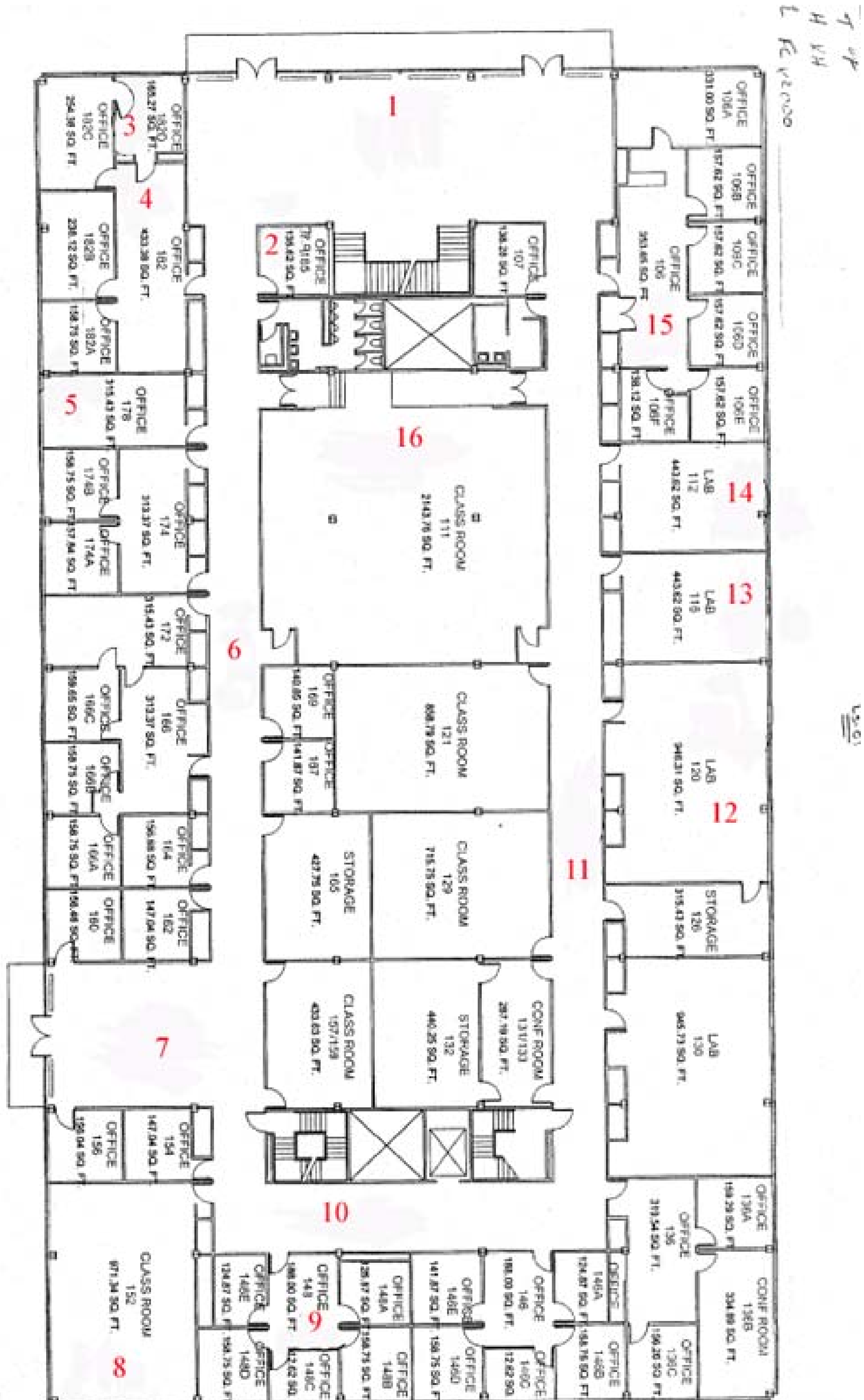
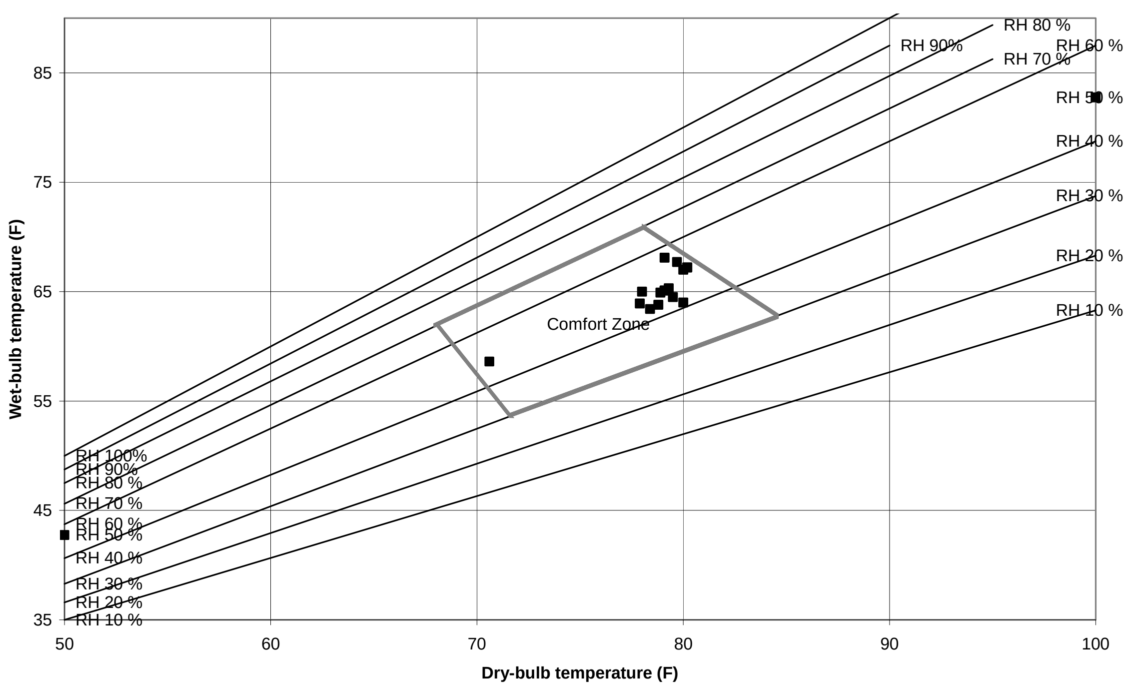


Figure 5 Life Sciences first floor

Life Sciences Building First Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	79.3	42.8	12	NO	65.3
2	78.9	44.2	12	NO	64.9
3	79.1	44.2	12	NO	65.1
4	79.1	53.4	12	NO	68.1
5	78.0	46.5	12	NO	65
6	70.6	45.0	10	NO	58.6
7	78.8	41.8	12	NO	63.8
8	79.1	42.2	12	NO	65.1
9	79.7	52.0	12	NO	67.7
10	80.0	48.6	13	NO	67
11	80.2	47.2	13	NO	67.2
12	80.2	48.4	13	NO	67.2
13	80.0	39.7	13	NO	64
14	79.5	40.2	12	NO	64.5
15	78.4	41.2	12	NO	63.4
16	77.9	42.5	12	NO	63.9

Comfort Chart Life Sciences First Floor



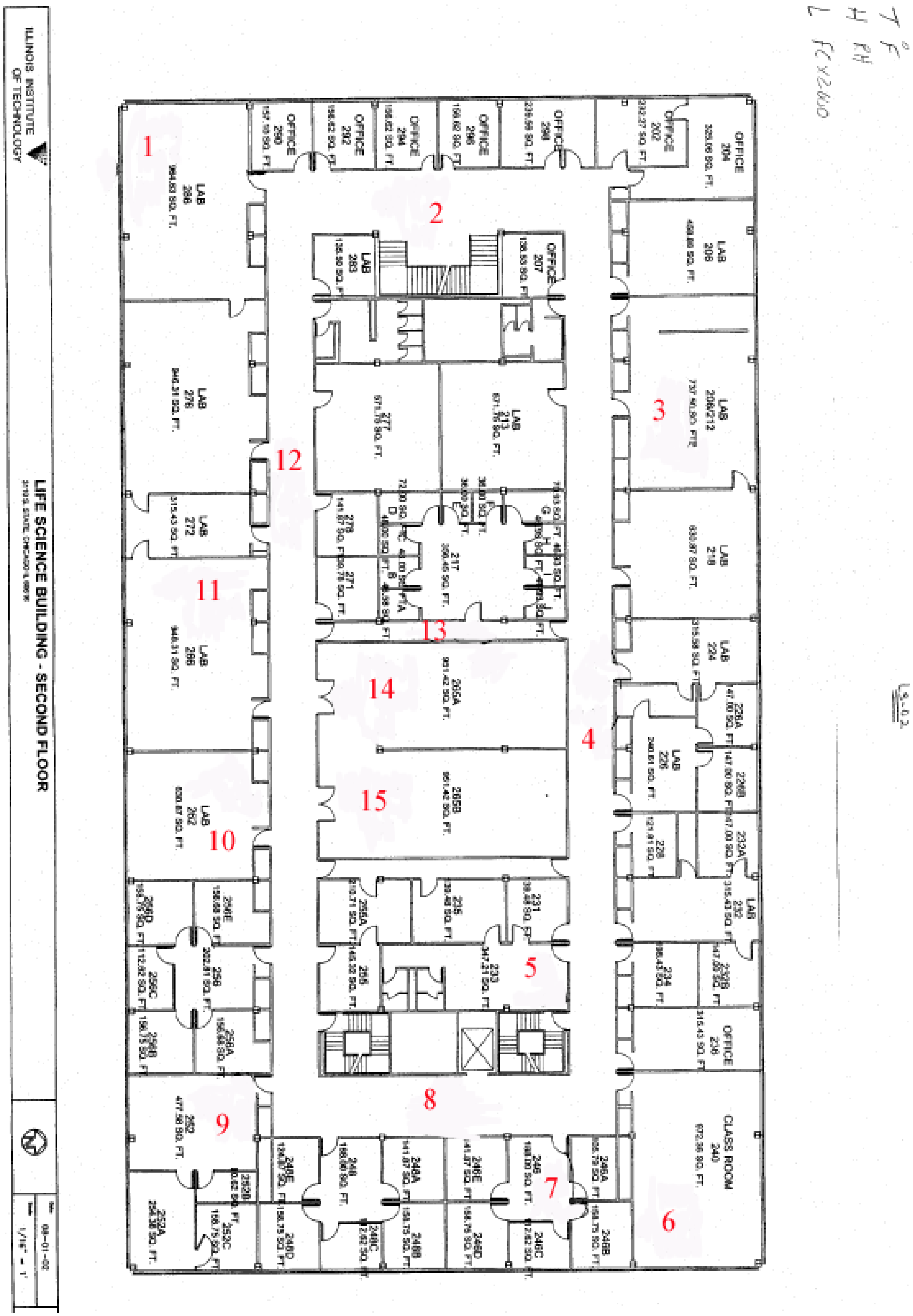
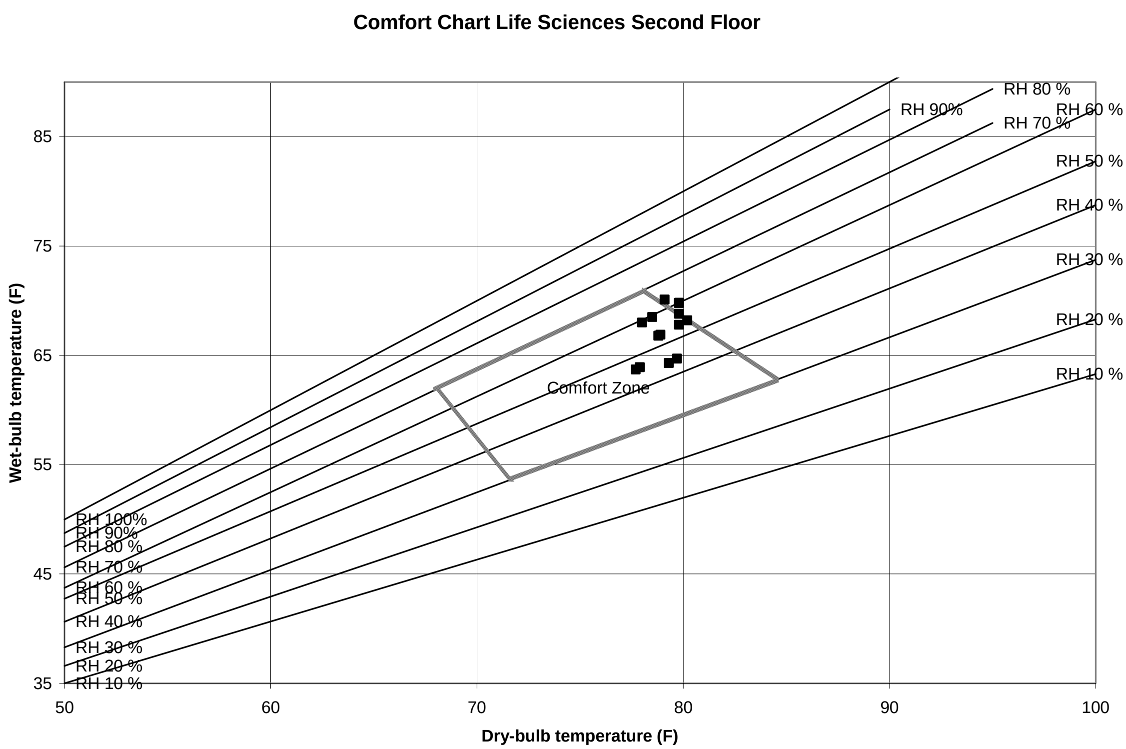


Figure 6 Life Sciences second floor

Life Sciences Building Second Floor					
Room Number	**Dry-Bulb Temperature (F)**	**Relative Humidity (%)**	**Psychometric Table Column**	**Comfort Problem**	**Wet-Bulb Temperature (F)**
1	77.9	44.7	12	NO	63.9
2	77.7	43.0	12	NO	63.7
3	79.7	42.0	12	NO	64.7
4	80.2	53.3	13	NO	68.2
5	79.3	41.0	12	NO	64.3
6	79.8	58.0	12	YES	69.8
7	79.8	50.9	12	NO	67.8
8	79.8	54.0	12	NO	68.8
9	79.8	56.2	12	YES	69.8
10	78.9	50.3	12	NO	66.9
11	78.5	57.2	12	NO	68.5
12	78.0	58.7	12	NO	68
13	79.8	58.5	12	YES	69.8
14	79.1	59.2	12	YES	70.1
15	78.8	50.3	12	NO	66.8



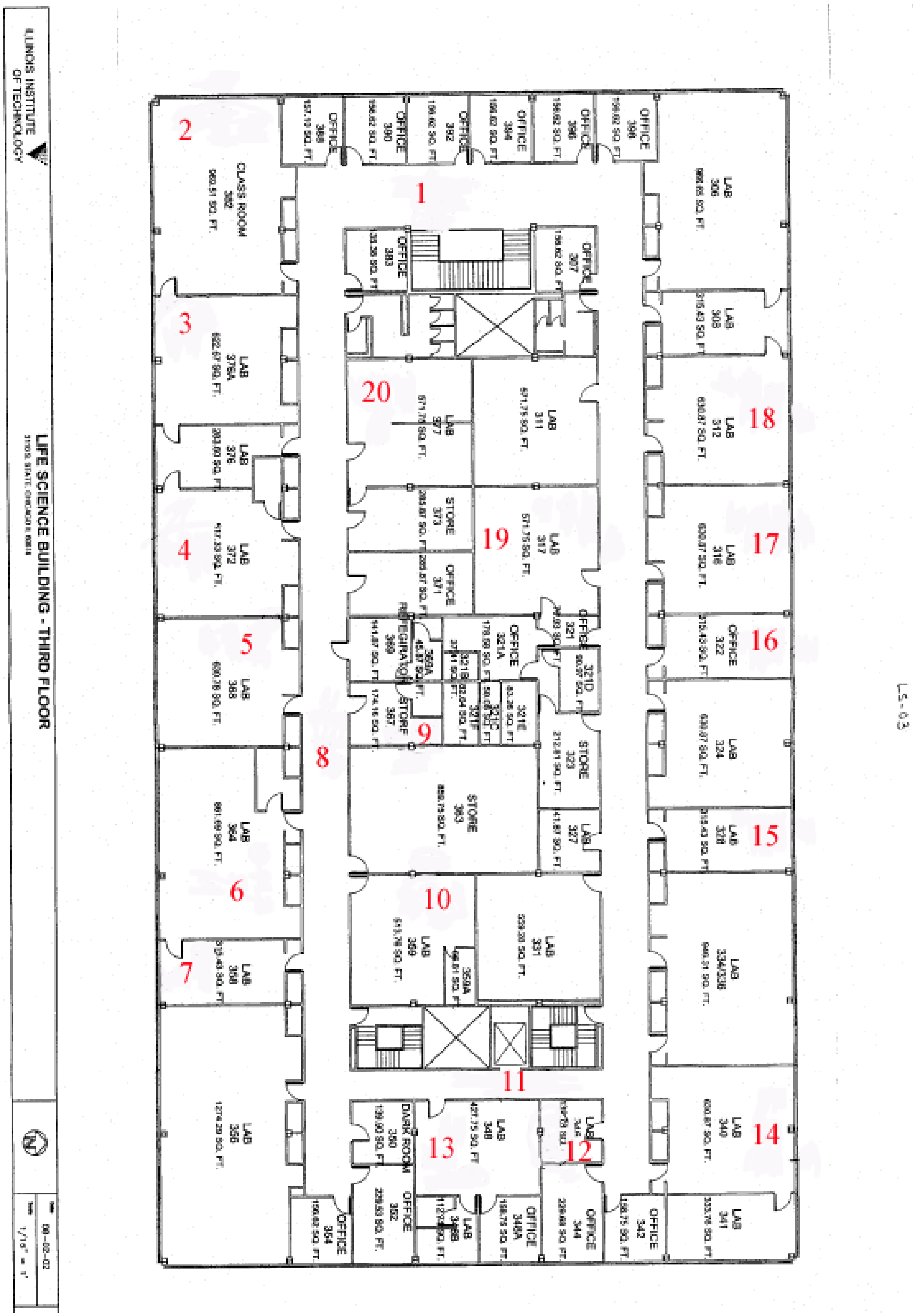
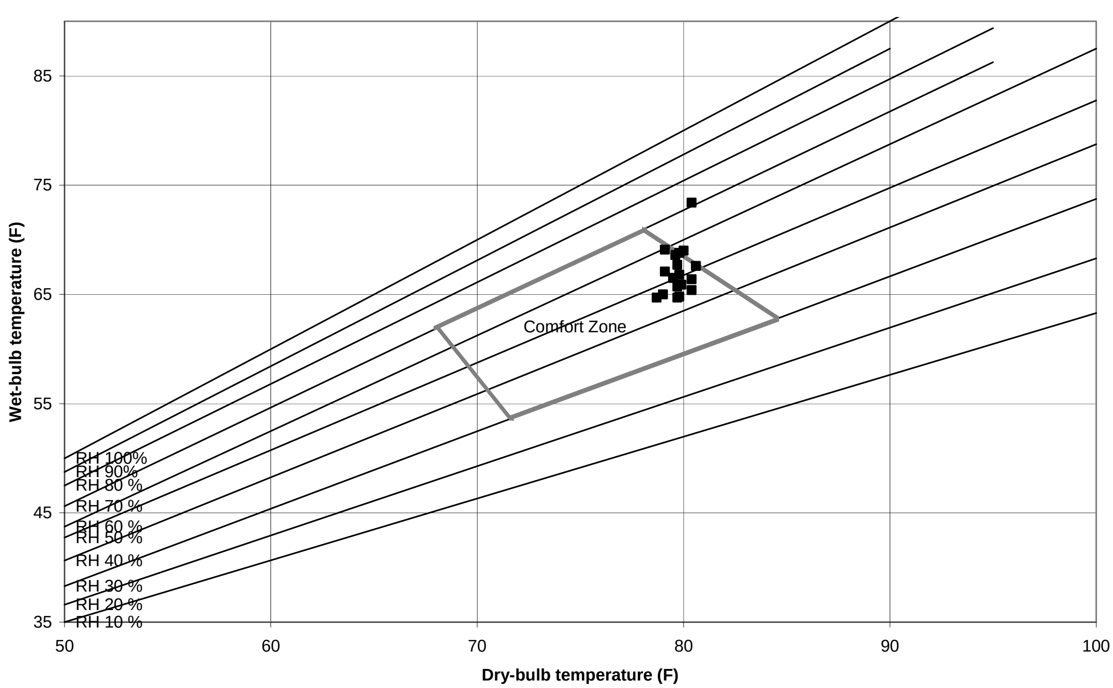


Figure 7 Life Sciences third floor

Life Sciences Building Third Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	79.1	51.7	12	NO	67.1
2	79.0	42.8	12	NO	65
3	79.9	43.9	12	NO	65.9
4	79.5	45.4	12	NO	66.5
5	79.5	45.5	12	NO	66.5
6	79.7	50.0	12	NO	67.7
7	79.8	42.0	12	NO	64.8
8	79.8	54.6	12	NO	68.8
9	78.7	44.2	12	NO	64.7
10	79.7	43.6	12	NO	65.7
11	80.0	54.2	13	YES	69
12	79.6	52.2	12	NO	68.6
13	79.8	46.4	12	NO	66.8
14	79.7	42.0	12	NO	64.7
15	79.8	54.4	12	NO	68.8
16	80.4	69.3	13	YES	73.4
17	80.6	48.9	13	NO	67.6
18	80.4	46.5	13	NO	66.4
19	80.4	42.3	13	NO	65.4
20	79.1	56.6	12	NO	69.1

Comfort Chart Life Sciences Third Floor



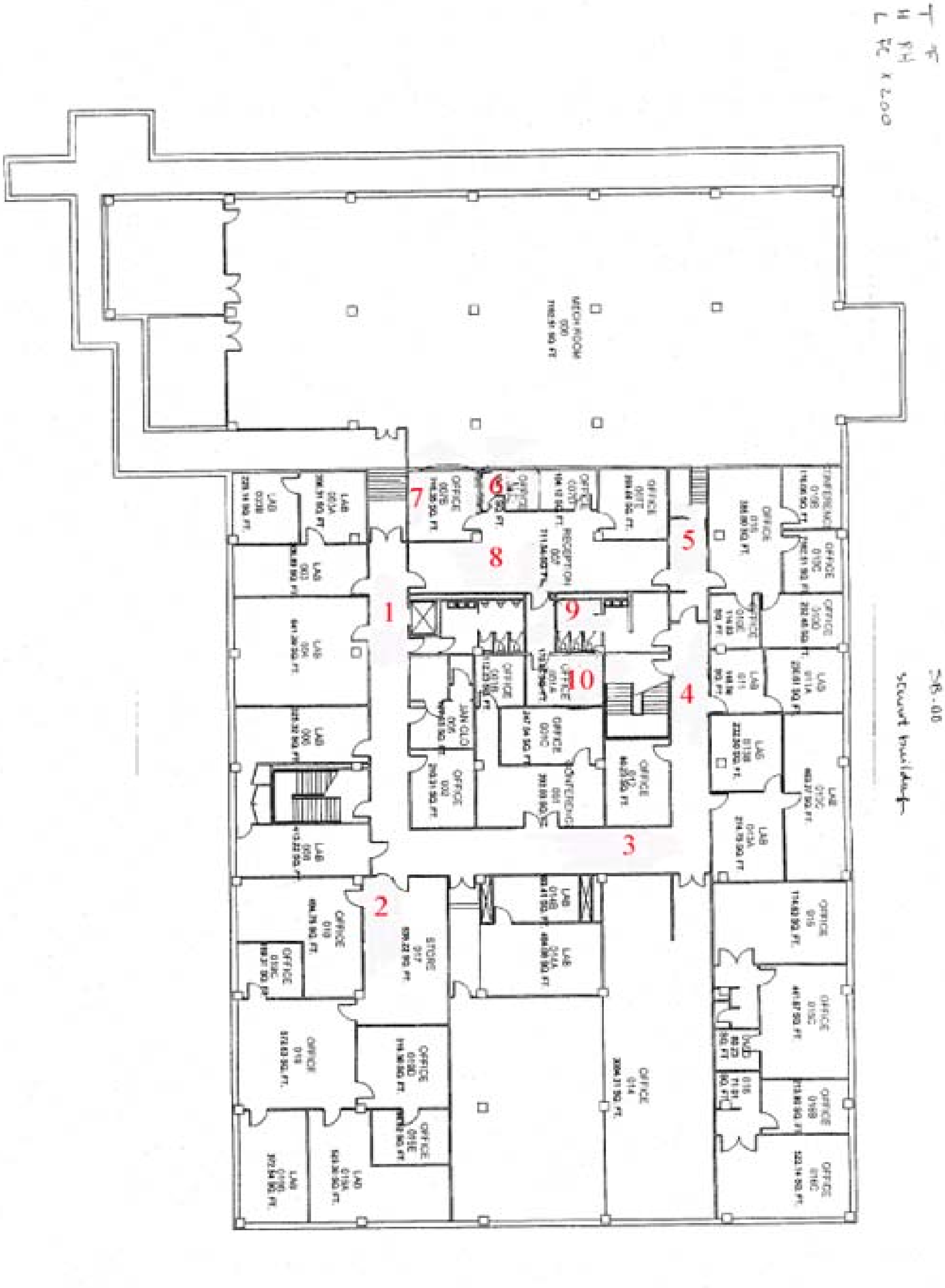
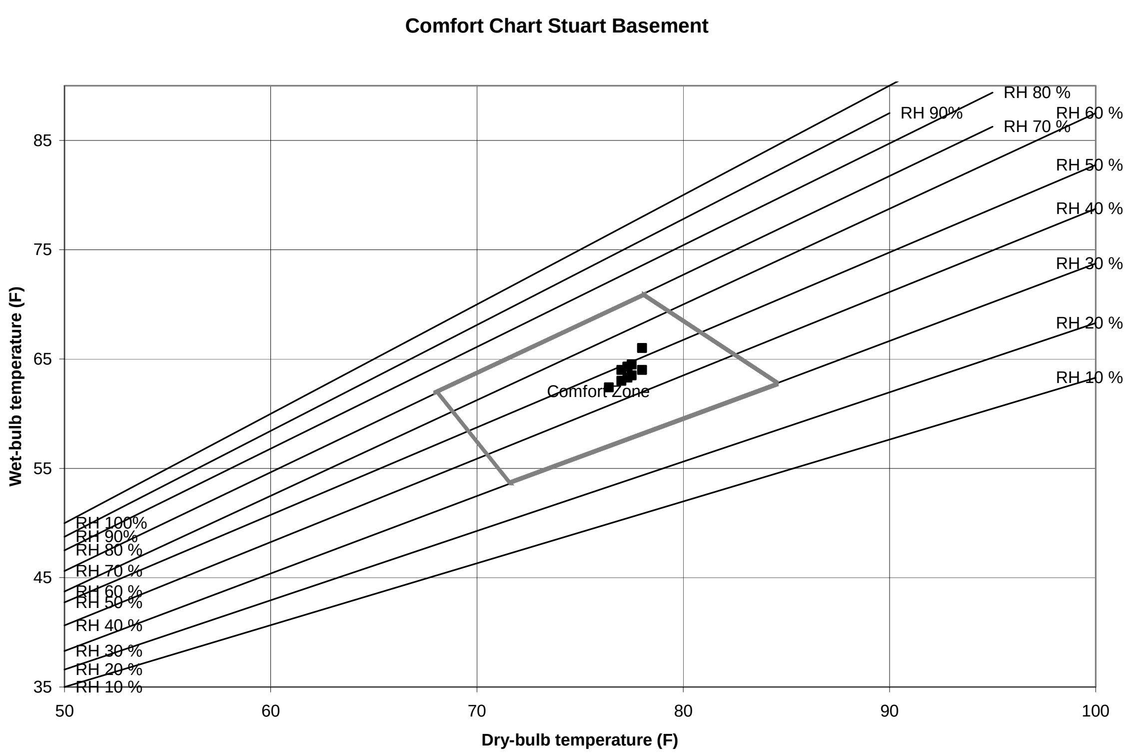


Figure 8 Stuart basement

Stuart Building Basement					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	77.0	47.1	12	NO	64
2	77.3	47.6	12	NO	64.3
3	77.5	45.9	12	NO	64.5
4	78.0	50.3	12	NO	66
5	76.4	44.9	12	NO	62.4
6	77.0	45.0	12	NO	63
7	77.3	43.0	12	NO	63.3
8	77.5	44.3	12	NO	63.5
9	78.0	42.7	12	NO	64
10	77.3	45.5	12	NO	64.3



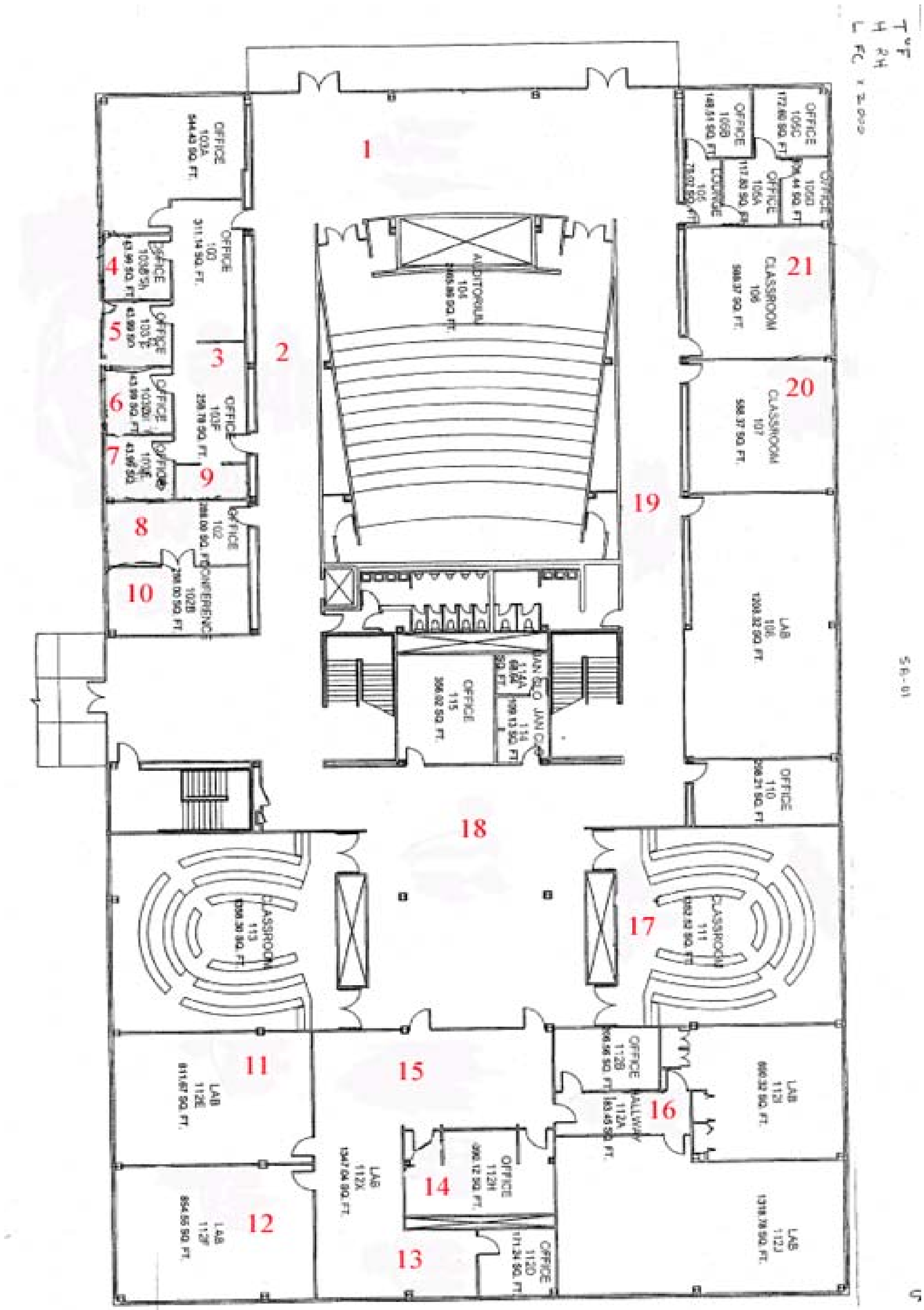
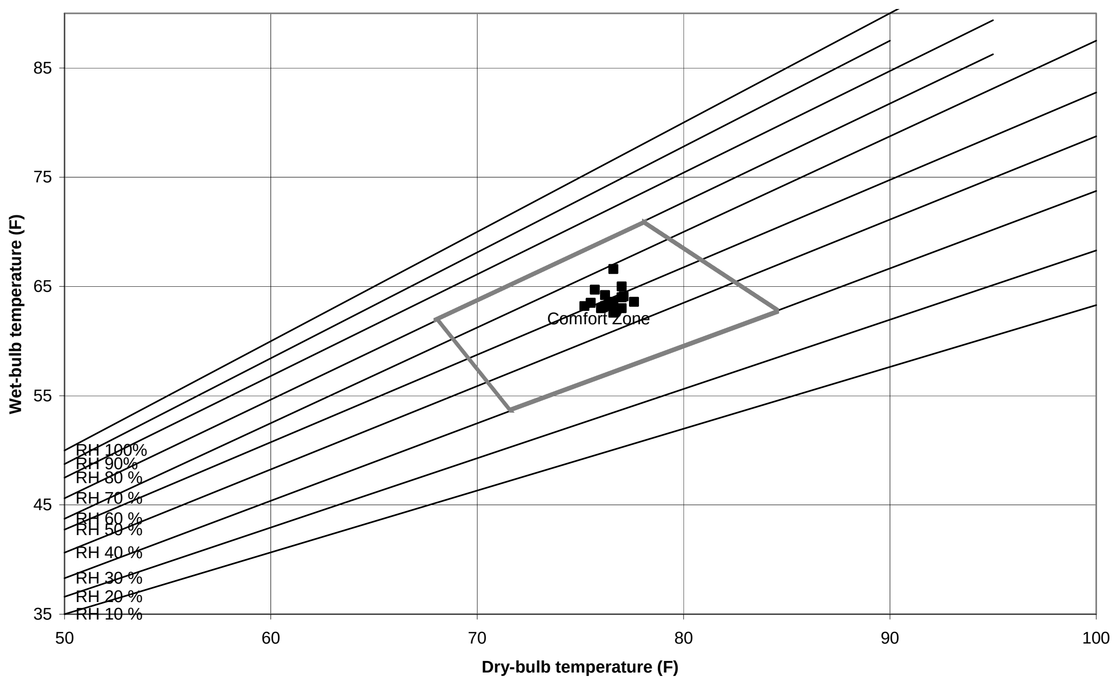


Figure 9 Stuart First Floor

Stuart Building First Floor					
Room Number	**Dry-Bulb Temperature (F)**	**Relative Humidity (%)**	**Psychometric Table Column**	**Comfort Problem**	**Wet-Bulb Temperature (F)**
1	75.5	47.0	11	NO	63.5
2	75.2	46.6	11	NO	63.2
3	75.7	49.3	11	NO	64.7
4	75.5	48.8	11	NO	63.5
5	76.0	46.7	12	NO	63
6	76.1	46.0	12	NO	63.1
7	76.2	50.0	12	NO	64.2
8	77.0	52.0	12	NO	65
9	76.6	56.6	12	NO	66.6
10	77.1	47.8	12	NO	64.1
11	76.5	46.2	12	NO	63.5
12	77.0	46.3	12	NO	64
13	77.0	45.1	12	NO	64
14	76.2	46.3	12	NO	63.2
15	76.6	44.9	12	NO	62.6
16	76.4	45.4	12	NO	63.4
17	76.7	44.5	12	NO	62.7
18	77.0	44.0	12	NO	63
19	77.6	45.0	12	NO	63.6
20	76.6	45.6	12	NO	63.6
21	76.2	45.4	12	NO	63.2

Comfort Chart StuartFirst Floor



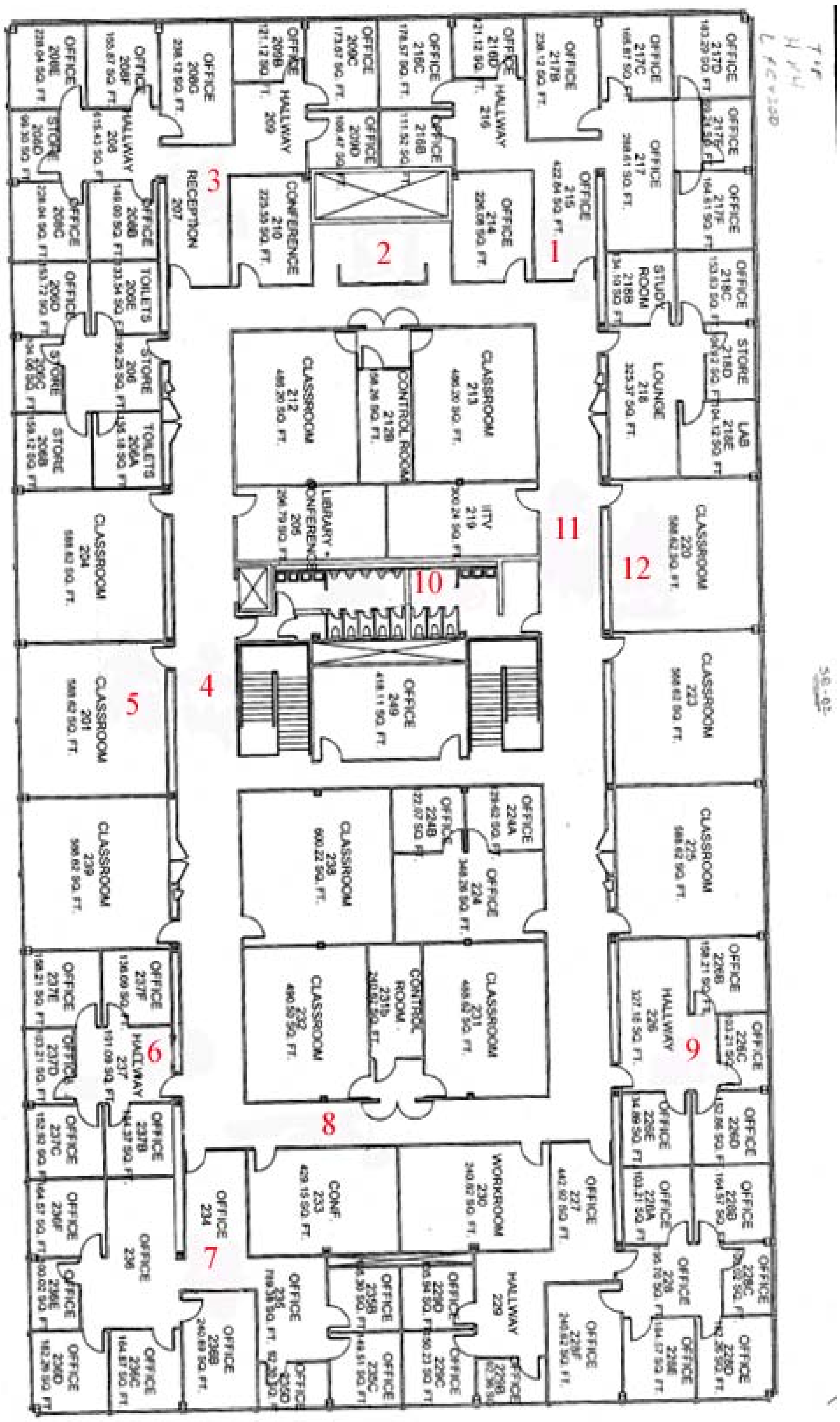
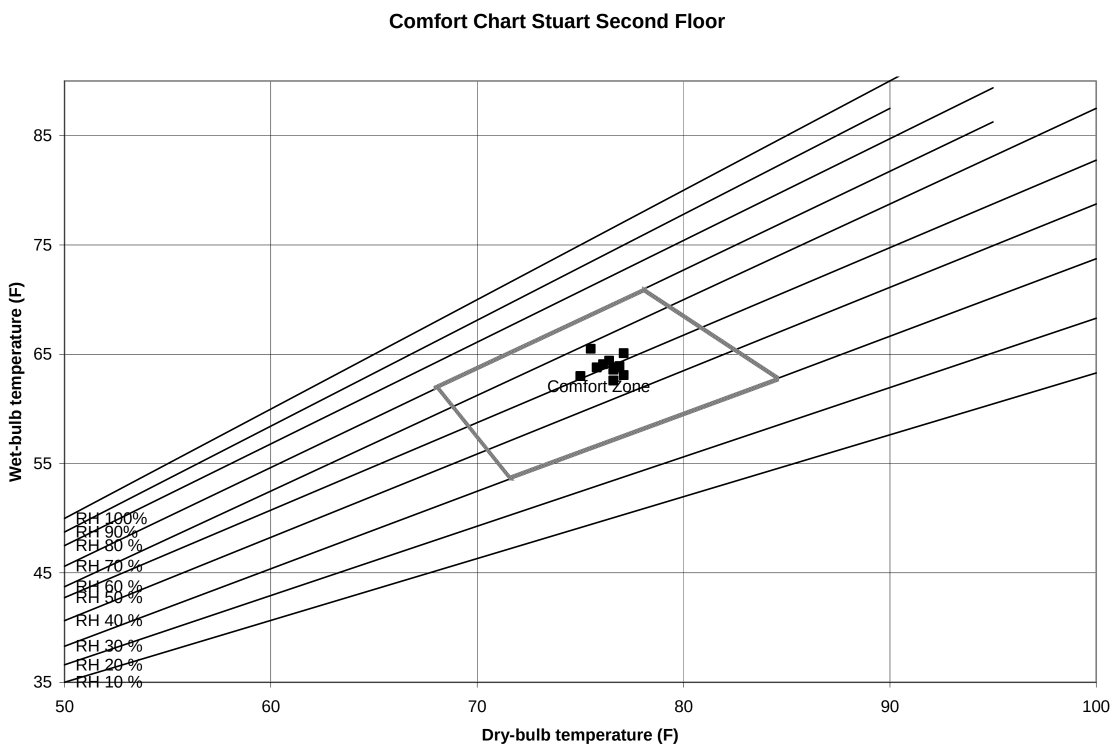


Figure 10 Stuart second Floor

Stuart Building Second Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	75.5	55.5	11	NO	65.5
2	75.8	47.3	11	NO	63.8
3	76.1	50.2	12	NO	64.1
4	77.1	49.0	12	NO	65.1
5	77.1	44.9	12	NO	63.1
6	76.9	47.9	12	NO	63.9
7	76.6	45.4	12	NO	63.6
8	76.8	45.9	12	NO	63.8
9	76.8	45.7	12	NO	63.8
10	75.0	47.0	11	NO	63
11	76.6	44.6	12	NO	62.6
12	76.4	48.6	12	NO	64.4



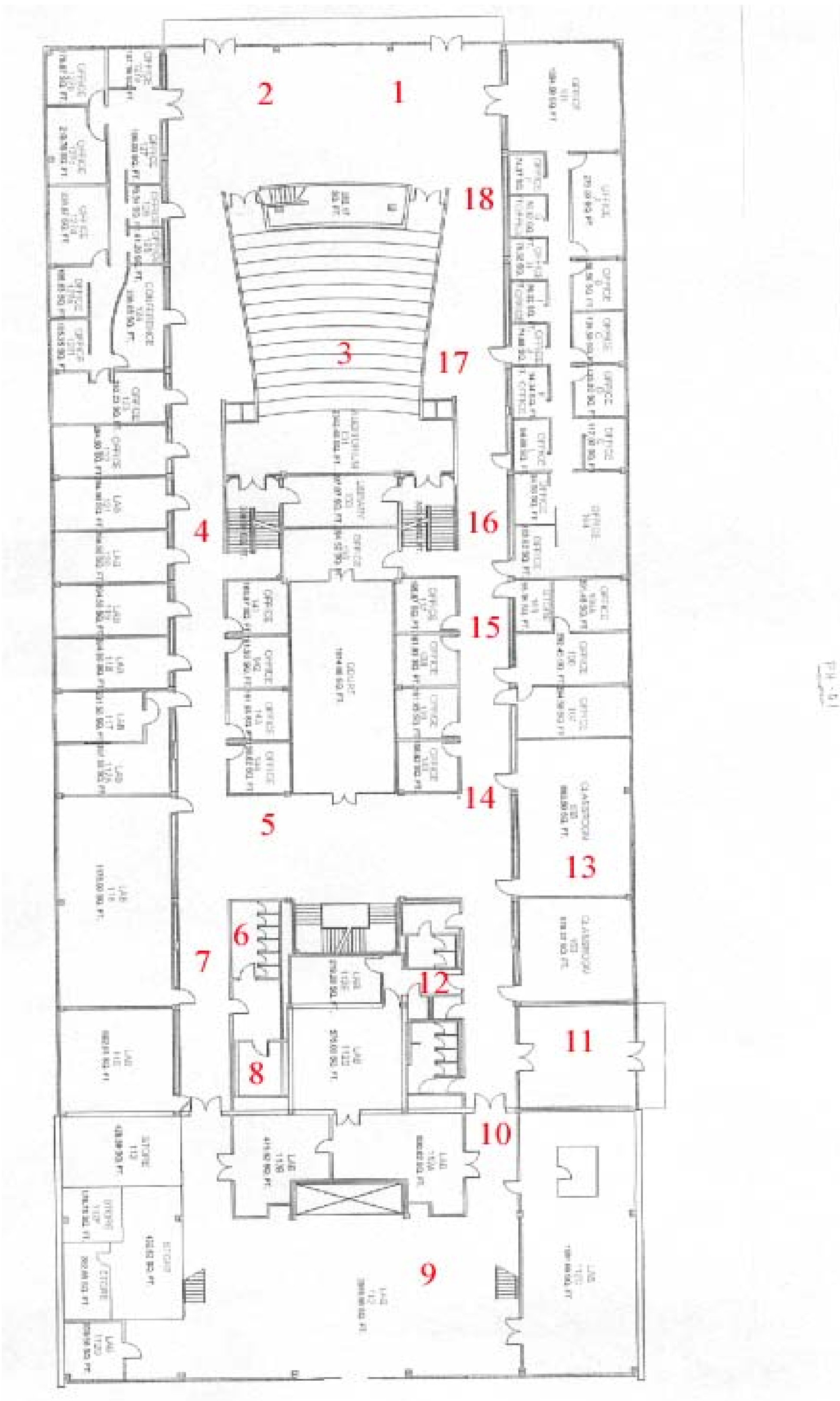
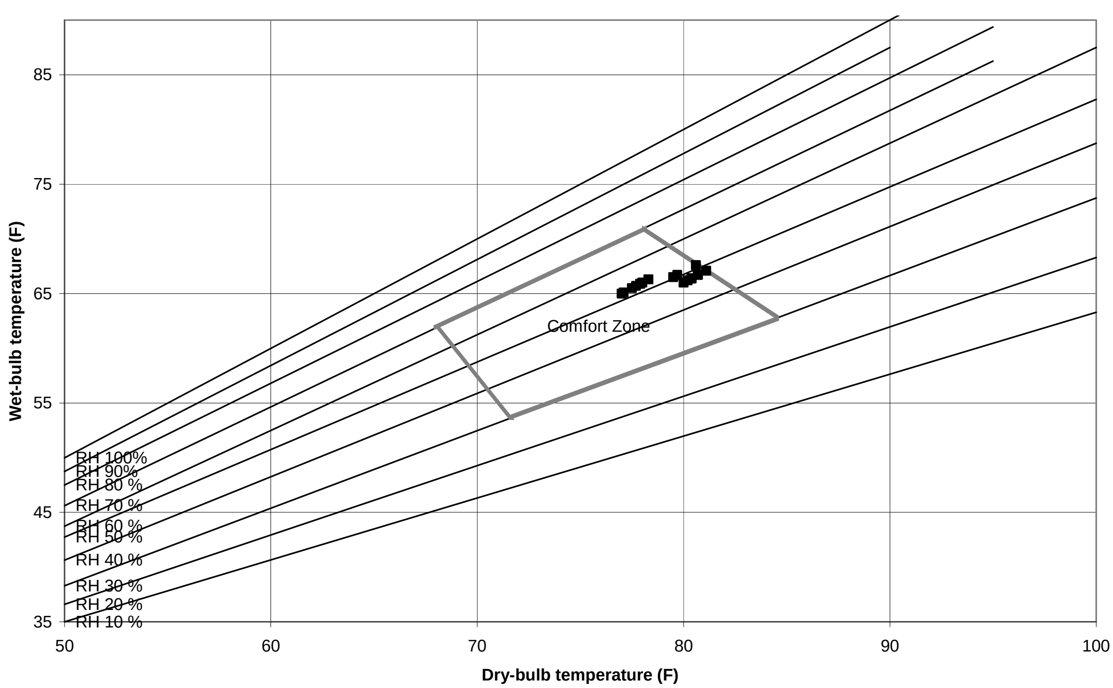


Figure 11 Perlstein Hall first floor

Perlstein Hall Building First Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	77.1	51.4	12	NO	65.1
2	77.0	52.0	12	NO	65
3	80.4	46.1	13	NO	66.4
4	80.7	44.1	13	NO	66.7
5	80.6	48.9	13	NO	67.6
6	80.4	46.7	13	NO	66.4
7	80.7	46.0	13	NO	66.7
8	81.1	46.9	13	NO	67.1
9	80.4	46.6	13	NO	66.4
10	80.2	46.5	13	NO	66.2
11	80.0	45.0	13	NO	66
12	79.7	45.9	12	NO	66.7
13	79.5	47.9	12	NO	66.5
14	78.3	48.1	12	NO	66.3
15	78.0	49.3	12	NO	66
16	77.9	49.6	12	NO	65.9
17	77.7	49.9	12	NO	65.7
18	77.5	51.4	12	NO	65.5

Comfort Chart Perlstein Hall First Floor



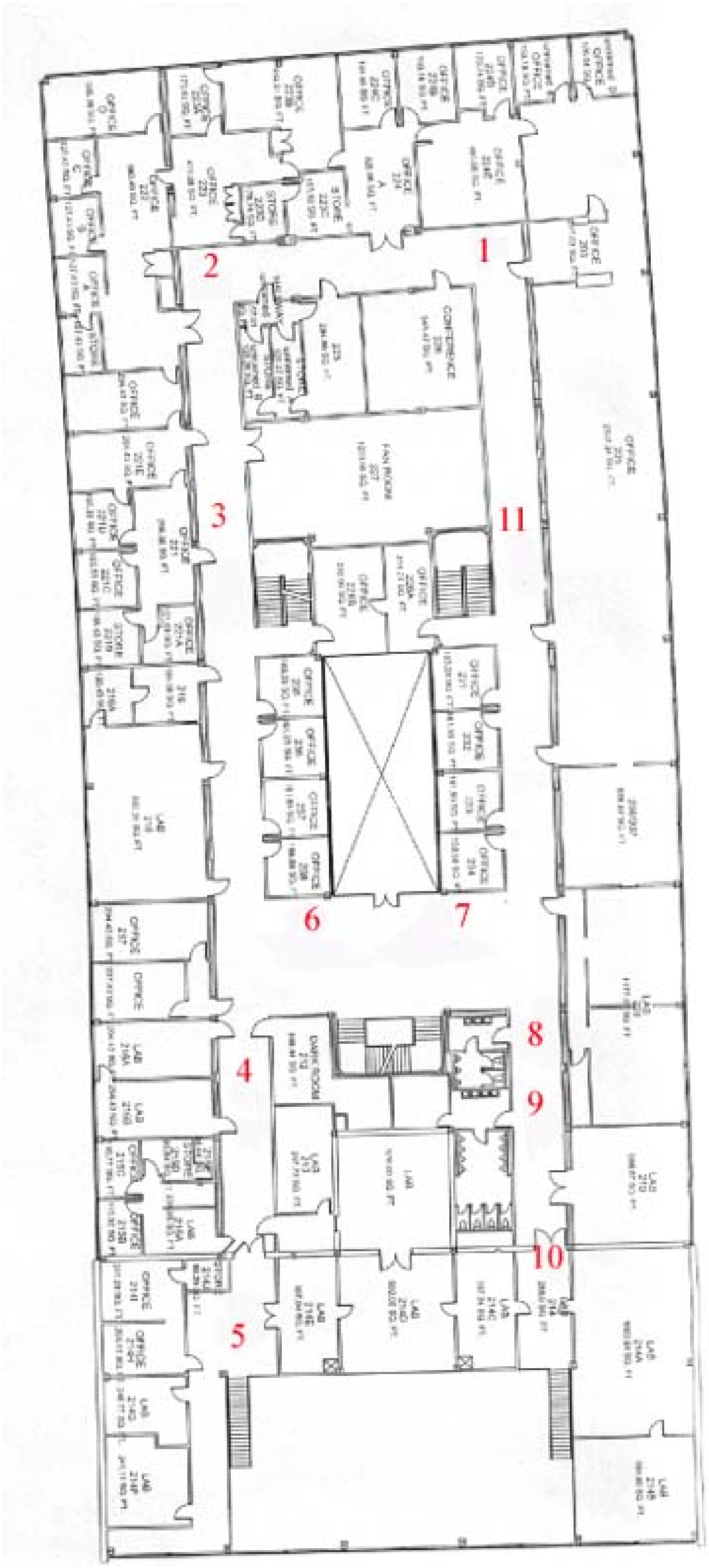
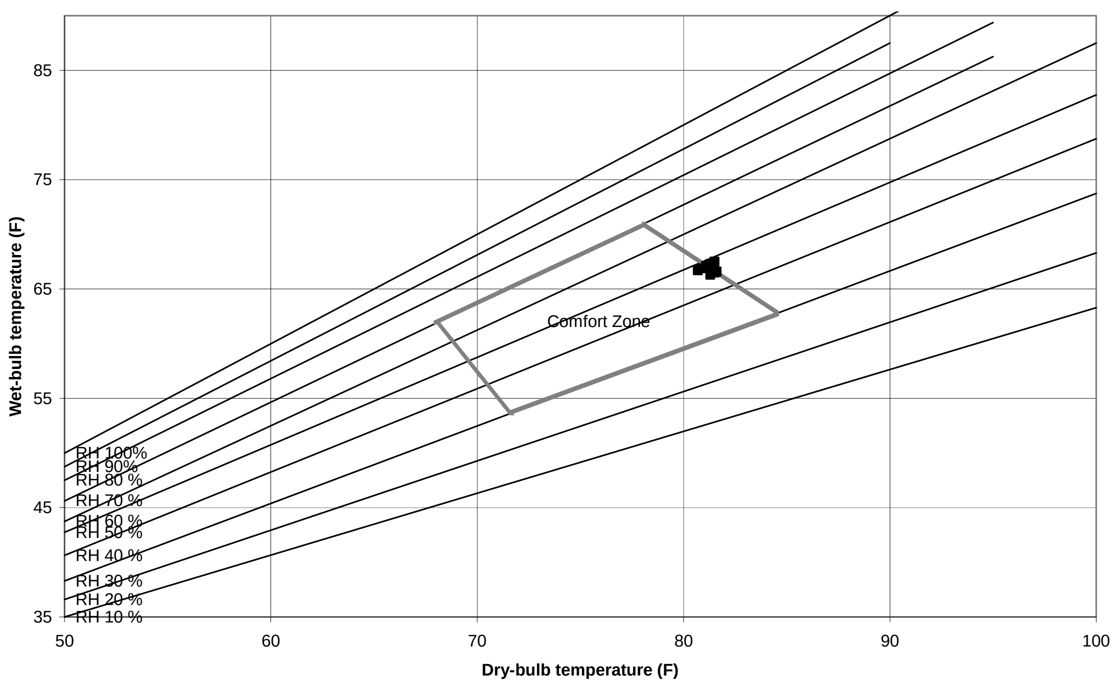


Figure 12 Perlstein Hall second floor

Perlstein Hall Building Second Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	81.5	42.3	13	NO	66.5
2	81.5	42.2	13	NO	66.5
3	80.7	44.9	13	NO	66.7
4	81.5	43.2	13	NO	66.5
5	81.6	43.8	13	YES	66.6
6	80.9	44.2	13	NO	66.9
7	81.1	44.9	13	NO	67.1
8	81.5	44.6	13	YES	67.5
9	81.3	44.0	13	NO	66.3
10	81.3	45.2	13	YES	67.3
11	81.6	42.8	13	YES	66.6

Comfort Chart Perlstein Hall Second Floor



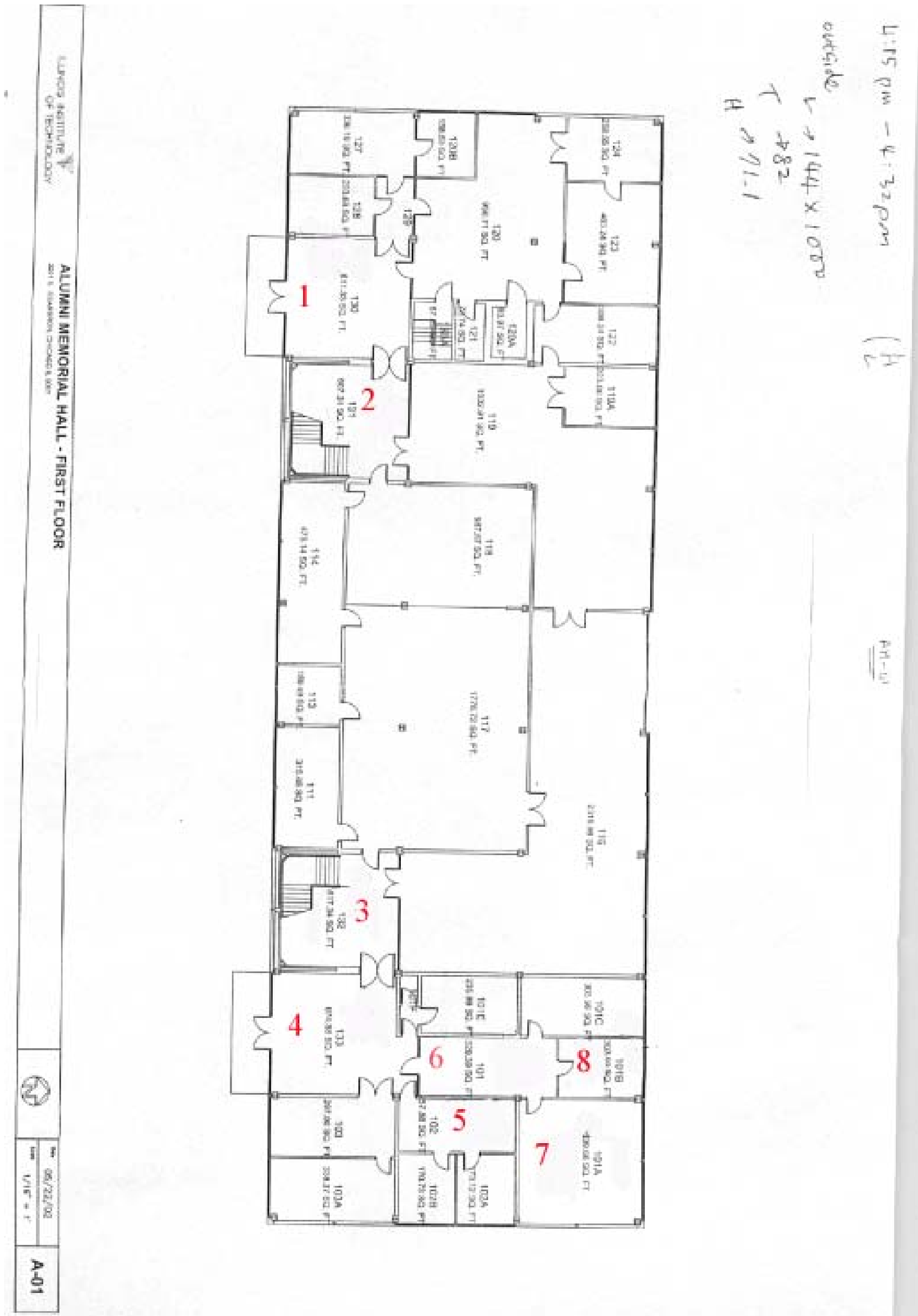
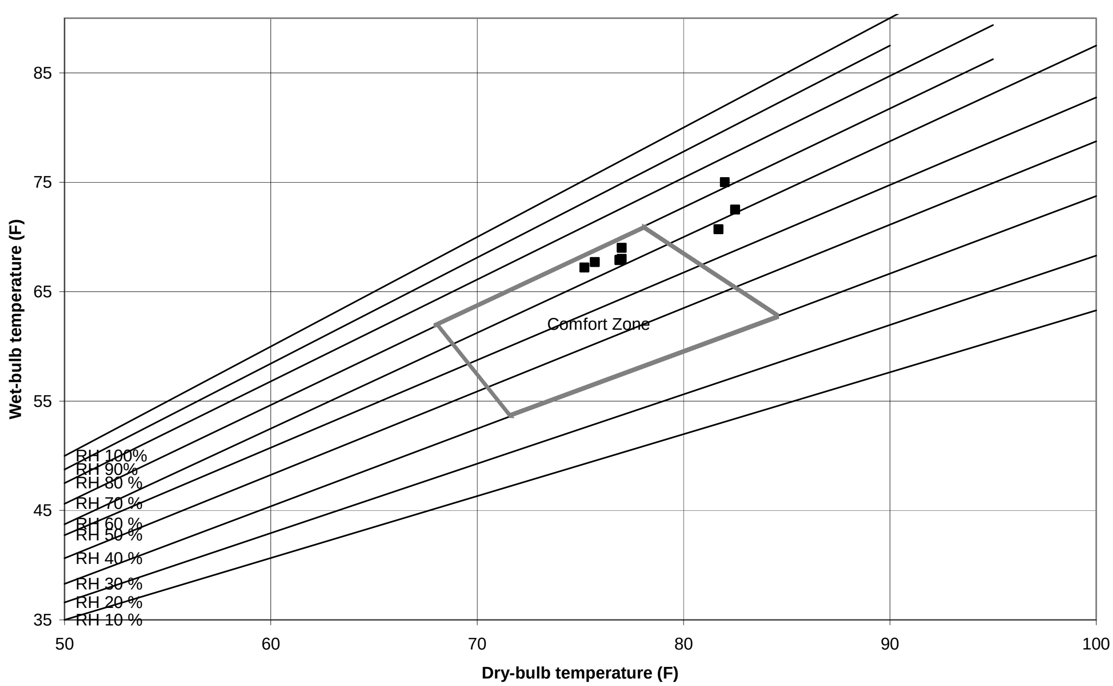


Figure 13 Alumni Memorial Hall first floor

Alumni Memorial Hall Building First Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	82.0	71.1	13	YES	75
2	82.5	57.2	13	YES	72.5
3	81.7	54.2	13	YES	70.7
4	75.2	64.4	11	NO	67.2
5	75.7	64.7	11	NO	67.7
6	77.0	63.0	12	NO	68
7	76.9	59.3	12	NO	67.9
8	76.9	59.5	12	NO	67.9
9	77.0	64.4	12	NO	69

Comfort Chart Alumni Memorial Hall First Floor



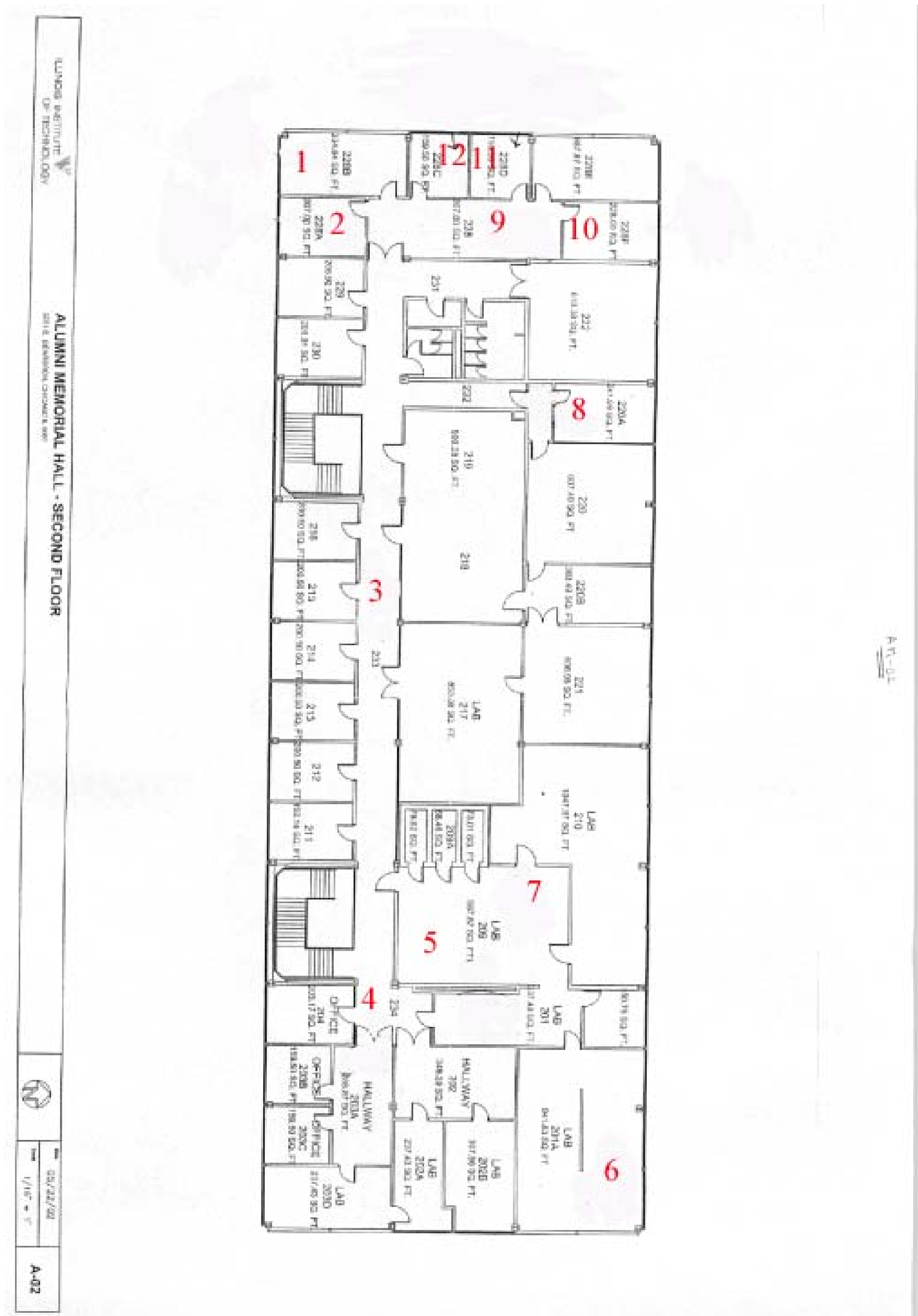
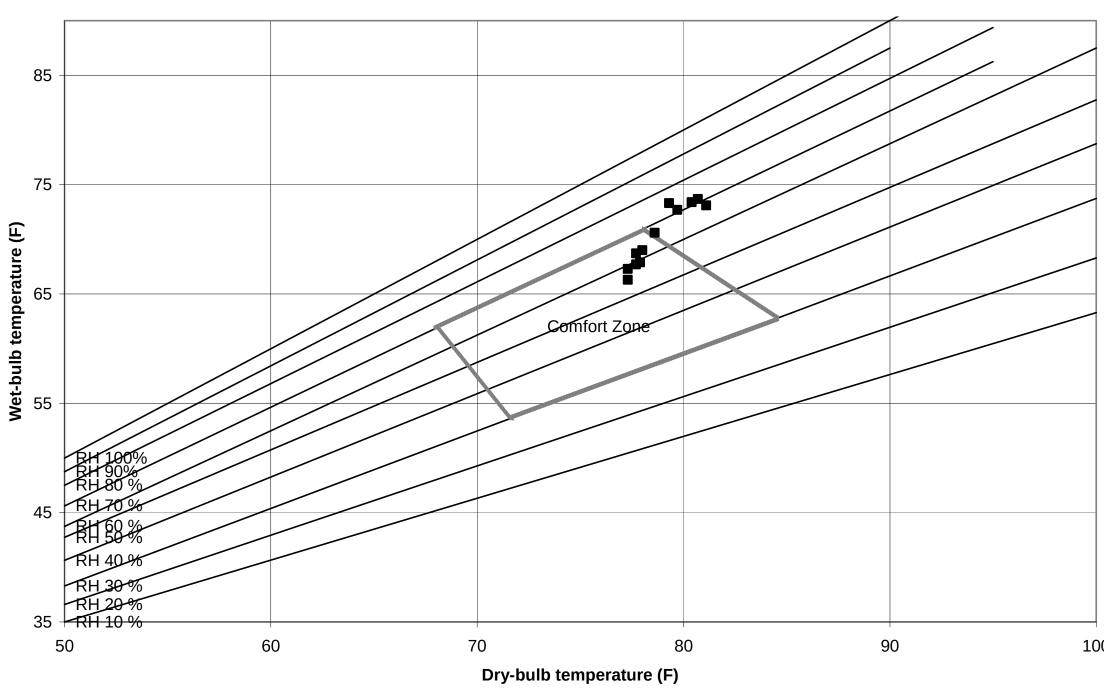


Figure 14 Alumni Memorial Hall second floor

Alumni Memorial Hall Building Second Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	79.7	68.1	12	YES	72.7
2	79.3	72.0	12	YES	73.3
3	77.3	58.0	12	NO	67.3
4	77.7	62.2	12	NO	68.7
5	77.9	58.2	12	NO	67.9
6	77.7	57.7	12	NO	67.7
7	77.3	53.2	12	NO	66.3
8	78.0	60.3	12	NO	69
9	78.6	64.2	12	YES	70.6
10	81.1	65.0	13	YES	73.1
11	80.7	68.2	13	YES	73.7
12	80.4	69.1	13	YES	73.4

Comfort Chart Alumni Memorial Hall Second Floor



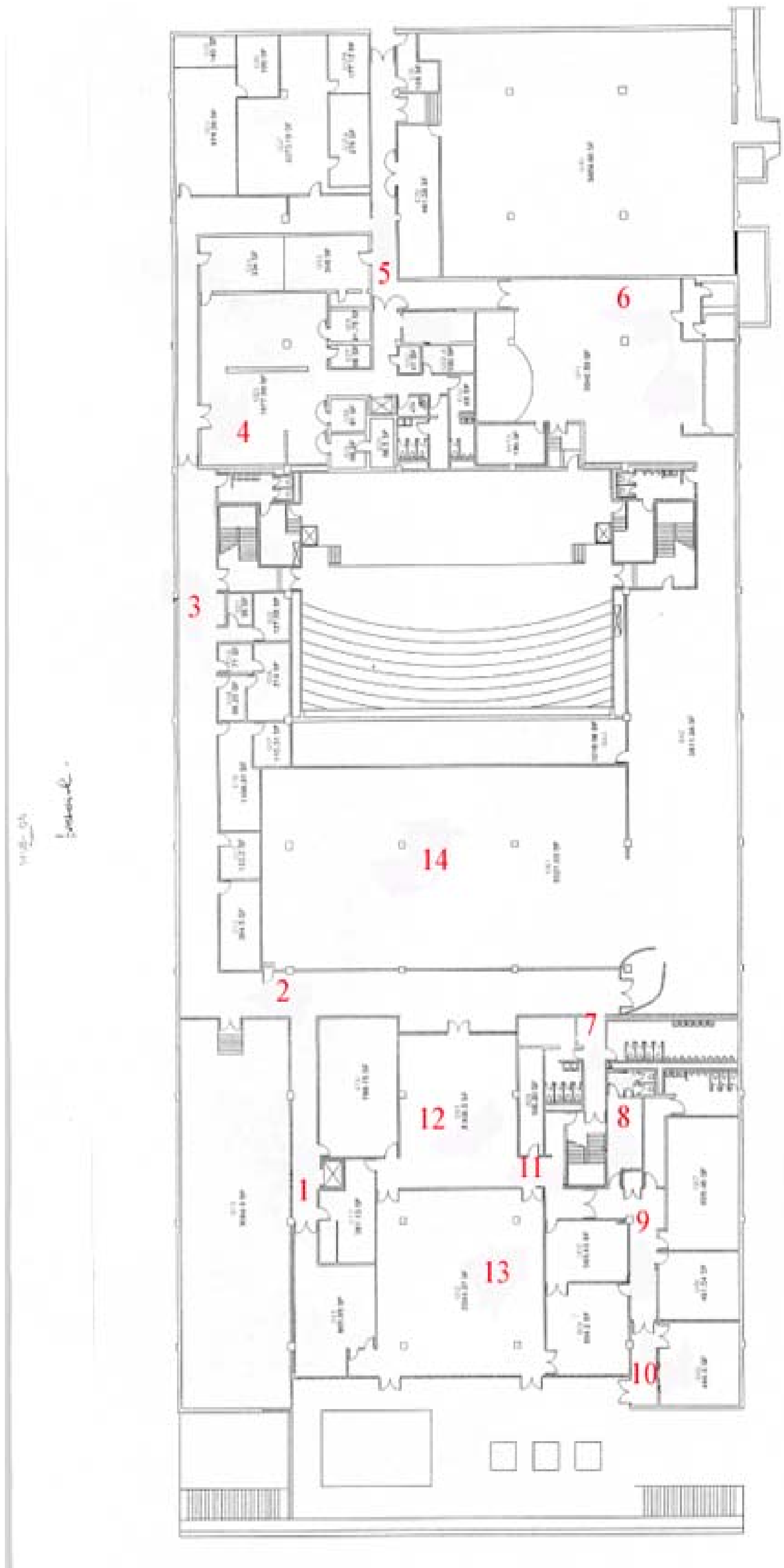
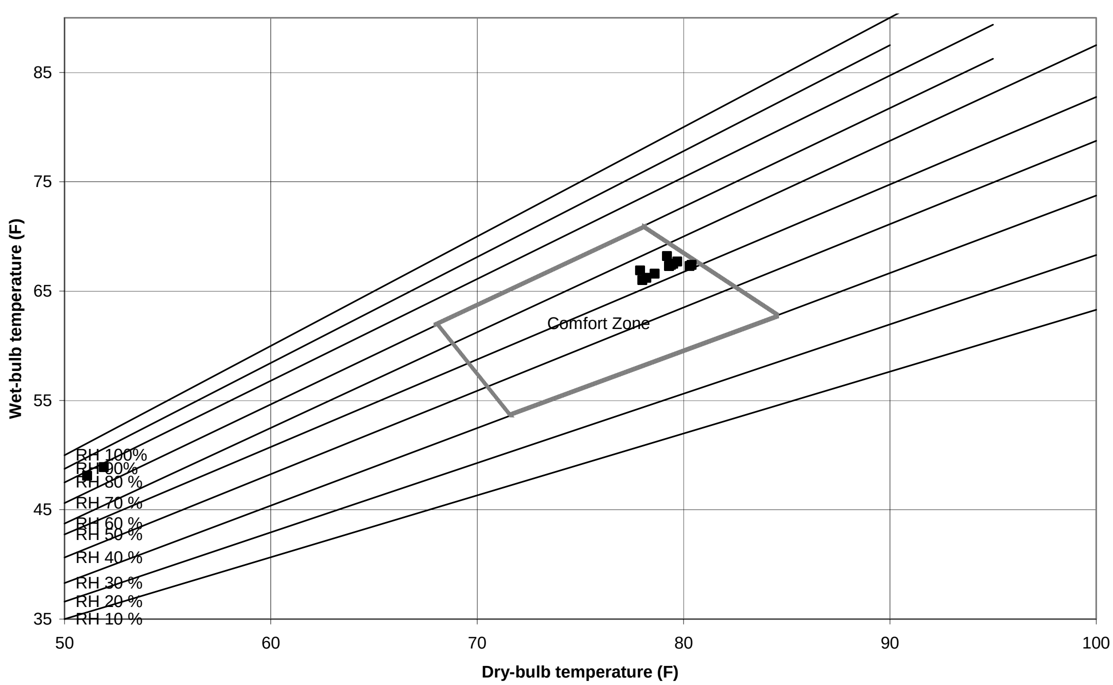


Figure 15 Hub basement

HUB Building Basement					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	79.4	51.8	12	NO	67.4
2	79.3	51.4	12	NO	67.3
3	79.7	50.2	12	NO	67.7
4	79.2	53.0	12	NO	68.2
5	80.4	50.3	13	NO	67.4
6	80.3	50.1	13	NO	67.3
7	78.2	51.9	12	NO	66.2
8	78.0	51.6	12	NO	66
9	51.9	79.9	5	YES	48.9
10	78.6	51.7	12	NO	66.6
11	77.9	53.4	12	NO	66.9
12	79.3	51.5	12	NO	67.3
13	51.1	79.9	5	YES	48.1
14	79.5	50.2	12	NO	67.5

Comfort Chart HUB Basement



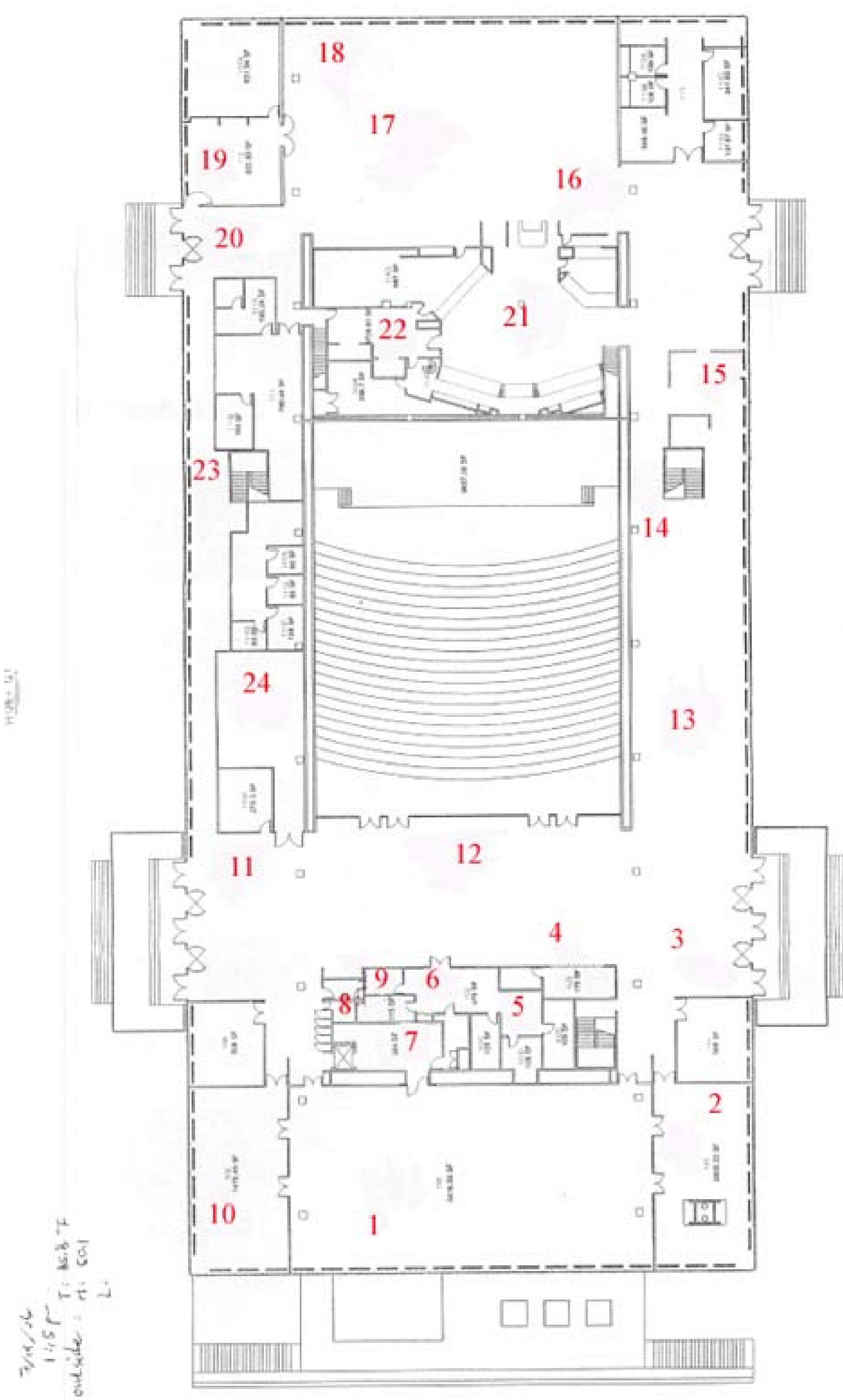
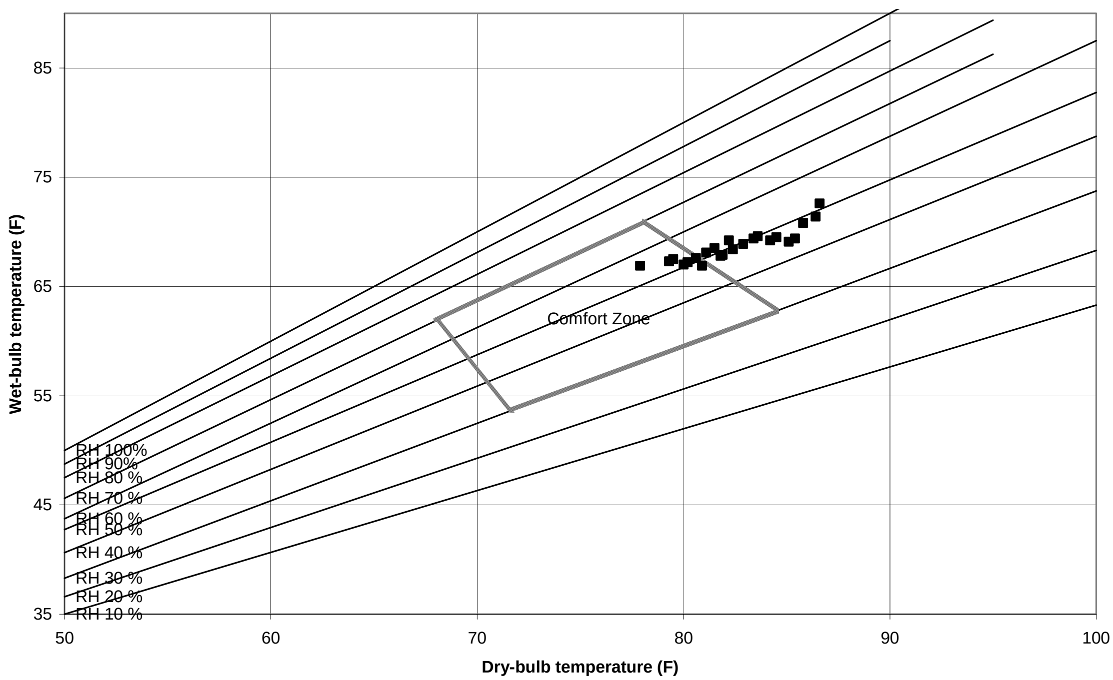


Figure 16 Hub first floor

HUB Building First Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.9	46.8	13	NO	66.9
2	80.6	47.4	13	NO	67.6
3	80.0	50.3	13	NO	67
4	86.6	47.3	14	YES	72.6
5	81.8	46.8	13	YES	67.8
6	82.4	46.8	13	YES	68.4
7	81.5	47.2	13	YES	68.5
8	81.9	44.8	13	YES	67.9
9	82.2	47.4	13	YES	69.2
10	81.1	48.5	13	YES	68.1
11	83.6	45.9	13	YES	69.6
12	82.9	46.4	13	YES	68.9
13	80.2	49.5	13	NO	67.2
14	80.2	49.6	13	NO	67.2
15	86.4	44.1	14	YES	71.4
16	85.8	44.4	14	YES	70.8
17	85.4	43.9	14	YES	69.4
18	85.1	43.3	14	YES	69.1
19	77.9	53.0	12	NO	66.9
20	84.5	45.9	14	YES	69.5
21	79.3	50.3	12	NO	67.3
22	79.5	49.6	12	NO	67.5
23	84.2	45.2	14	YES	69.2
24	83.4	45.9	13	YES	69.4

Comfort Chart HUB First Floor



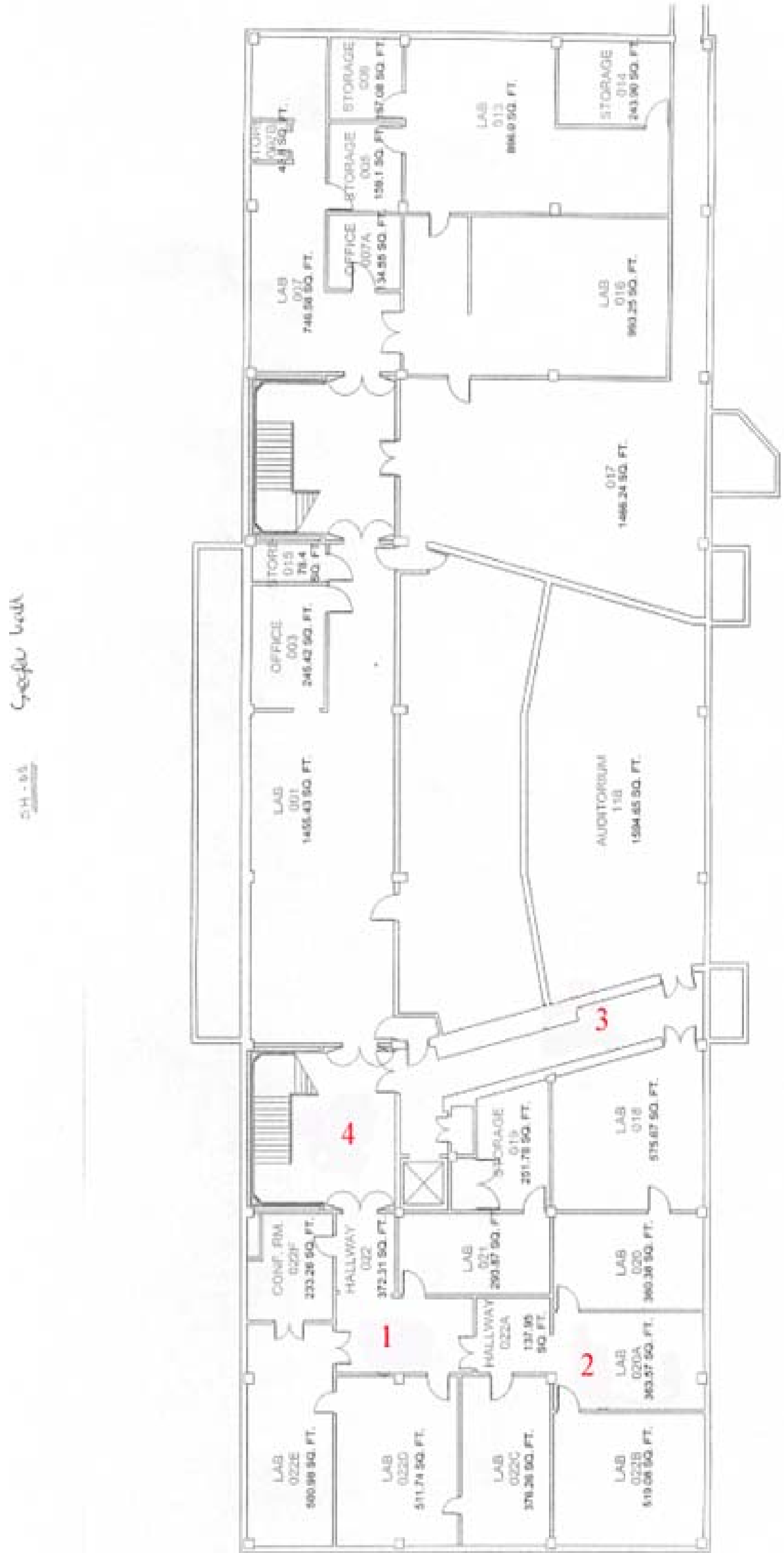
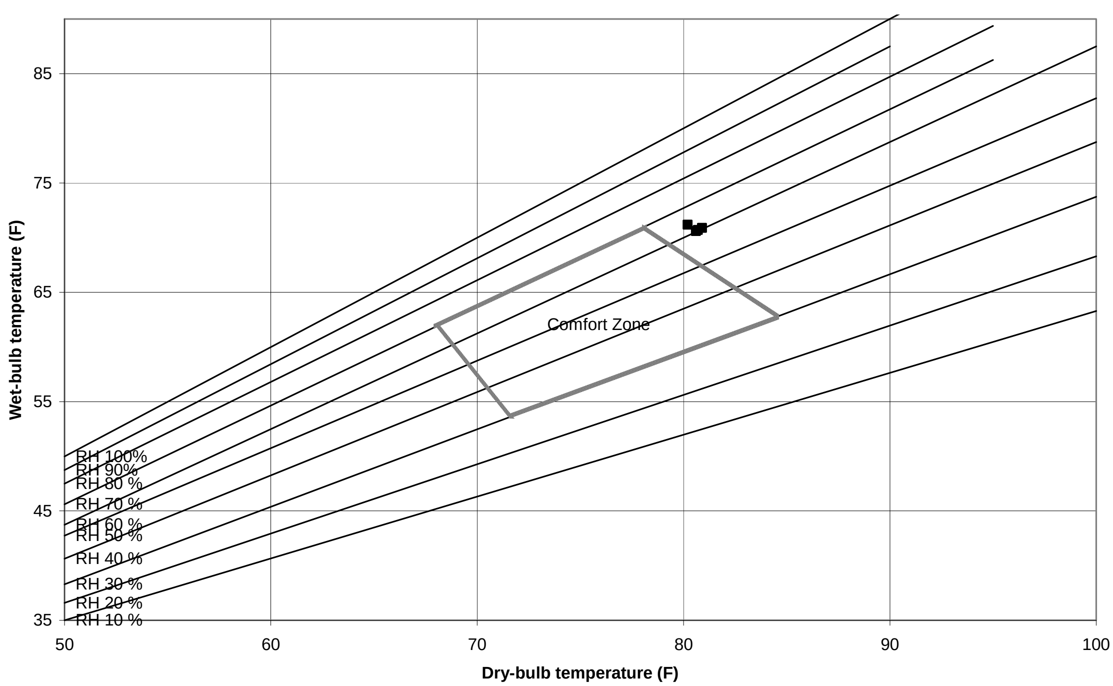


Figure 17 Siegel Hall basement

Siegel Hall Building Basement

Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.7	58.2	13	YES	70.7
2	80.9	57.1	13	YES	70.9
3	80.6	60.0	13	YES	70.6
4	80.2	62.5	13	YES	71.2

Comfort Chart Seigel Hall Basement



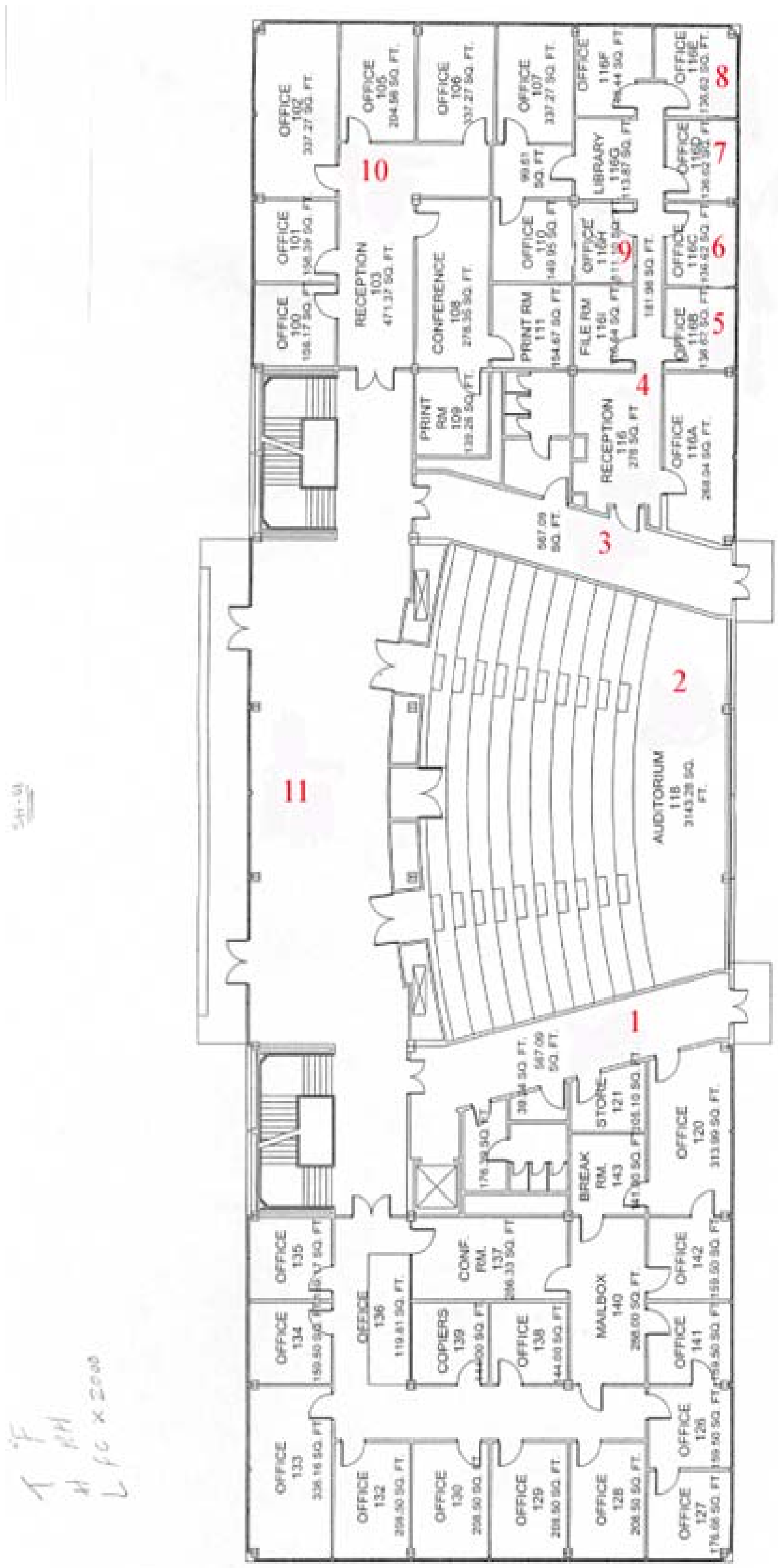
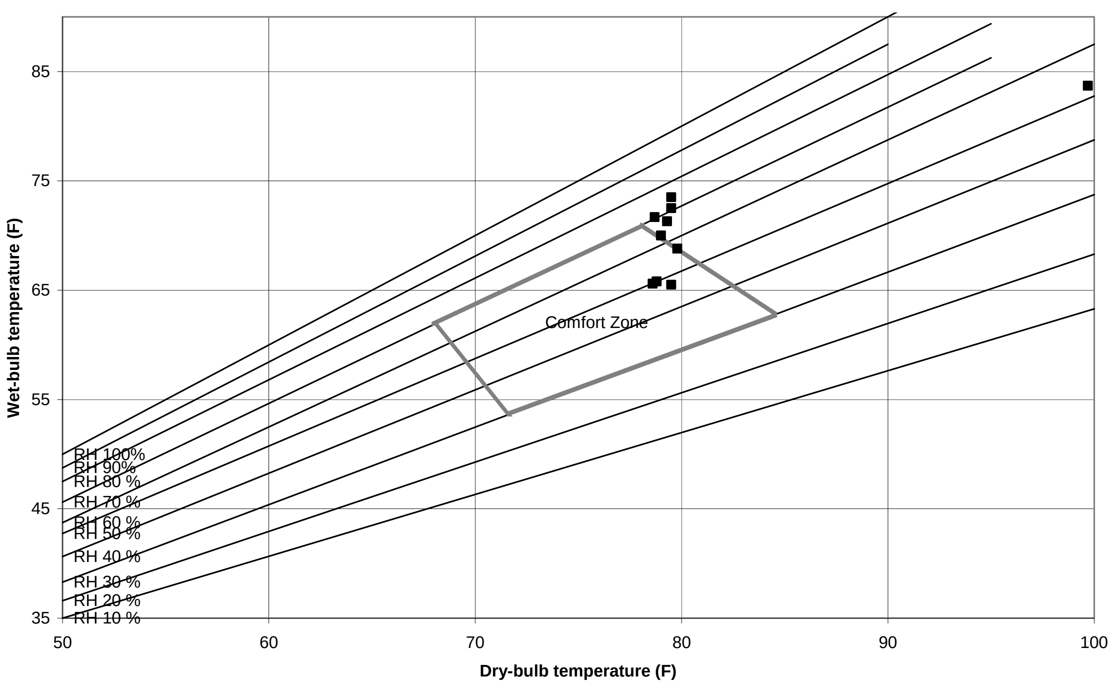


Figure 18 Siegel Hall first floor

Siegel Hall Building First Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	79.5	74.0	12	YES	73.5
2	79.3	64.2	12	YES	71.3
3	79.5	69.2	12	YES	72.5
4	78.6	48.0	12	NO	65.6
5	78.8	46.3	12	NO	65.8
6	79.8	53.5	12	NO	68.8
7			#N/A	#N/A	#N/A
8	79.5	44.5	12	NO	65.5
9	99.7	48.4	17	YES	83.7
10	79.0	61.7	12	YES	70
11	78.7	67.7	12	YES	71.7

Comfort Chart Seigel Hall First Floor



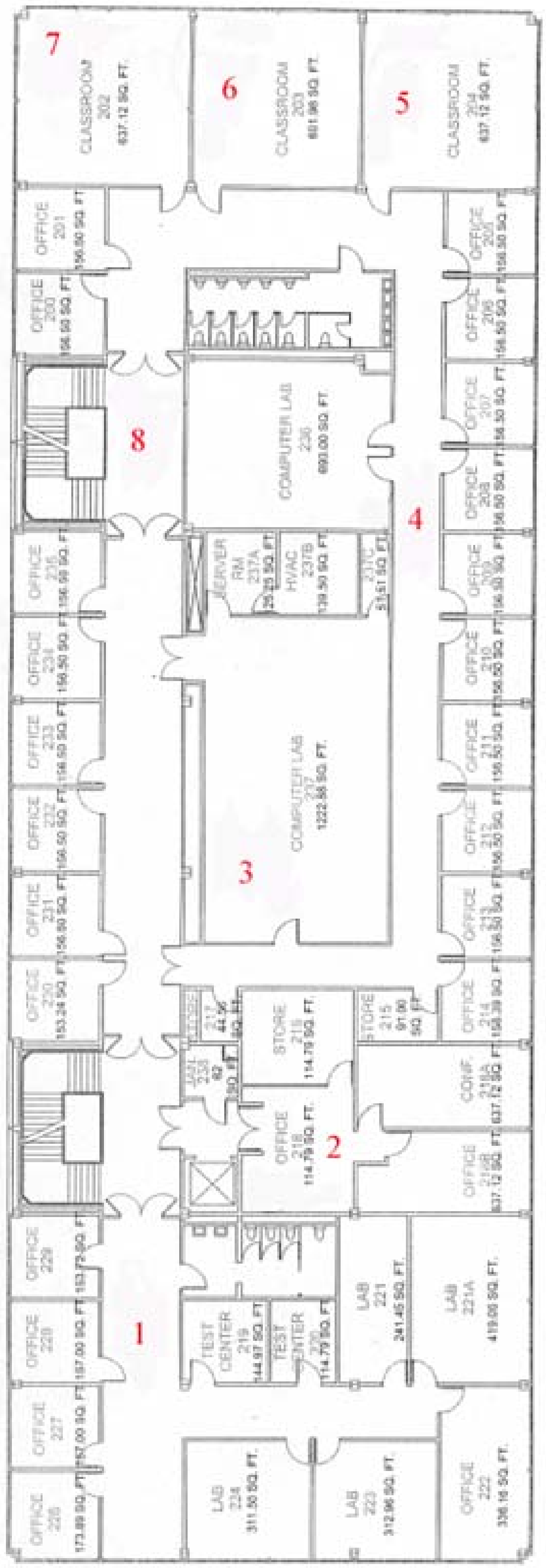
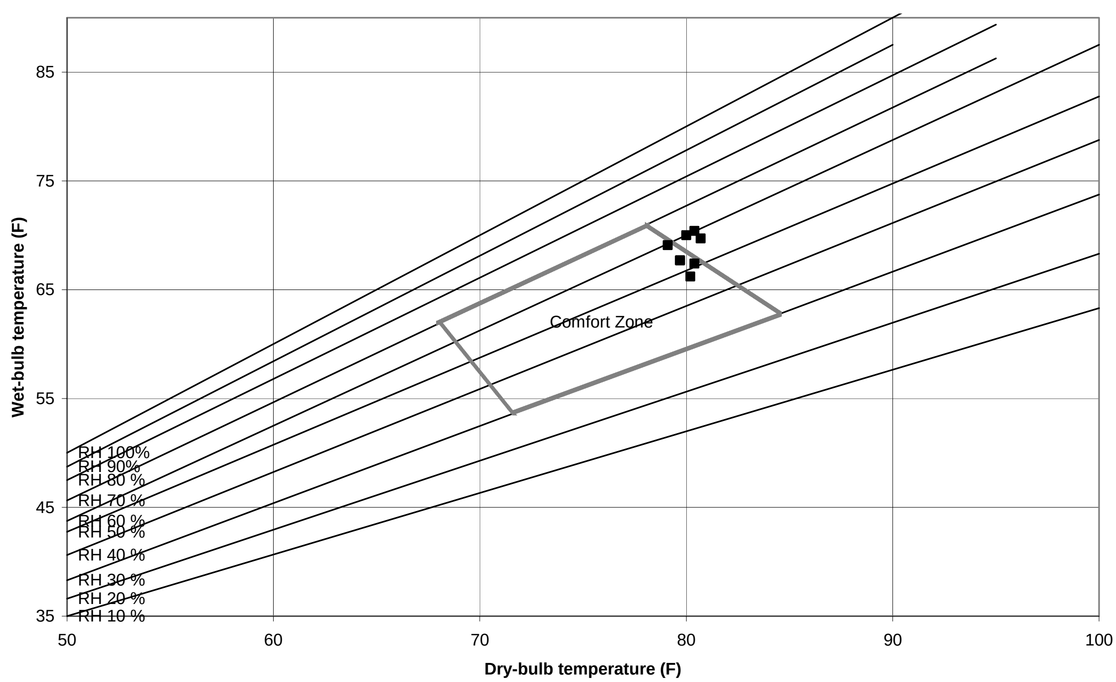


Figure 19 Siegel Hall second floor

Siegel Hall Building Second Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.7	56.1	13	YES	69.7
2	79.7	50.7	12	NO	67.7
3	80.2	47.0	13	NO	66.2
4	79.1	58.4	12	NO	69.1
5	79.7	49.0	12	NO	67.7
6	80.4	48.3	13	NO	67.4
7	80.4	57.8	13	YES	70.4
8	80.0	60.9	13	YES	70

Comfort Chart Seigel Hall Second Floor



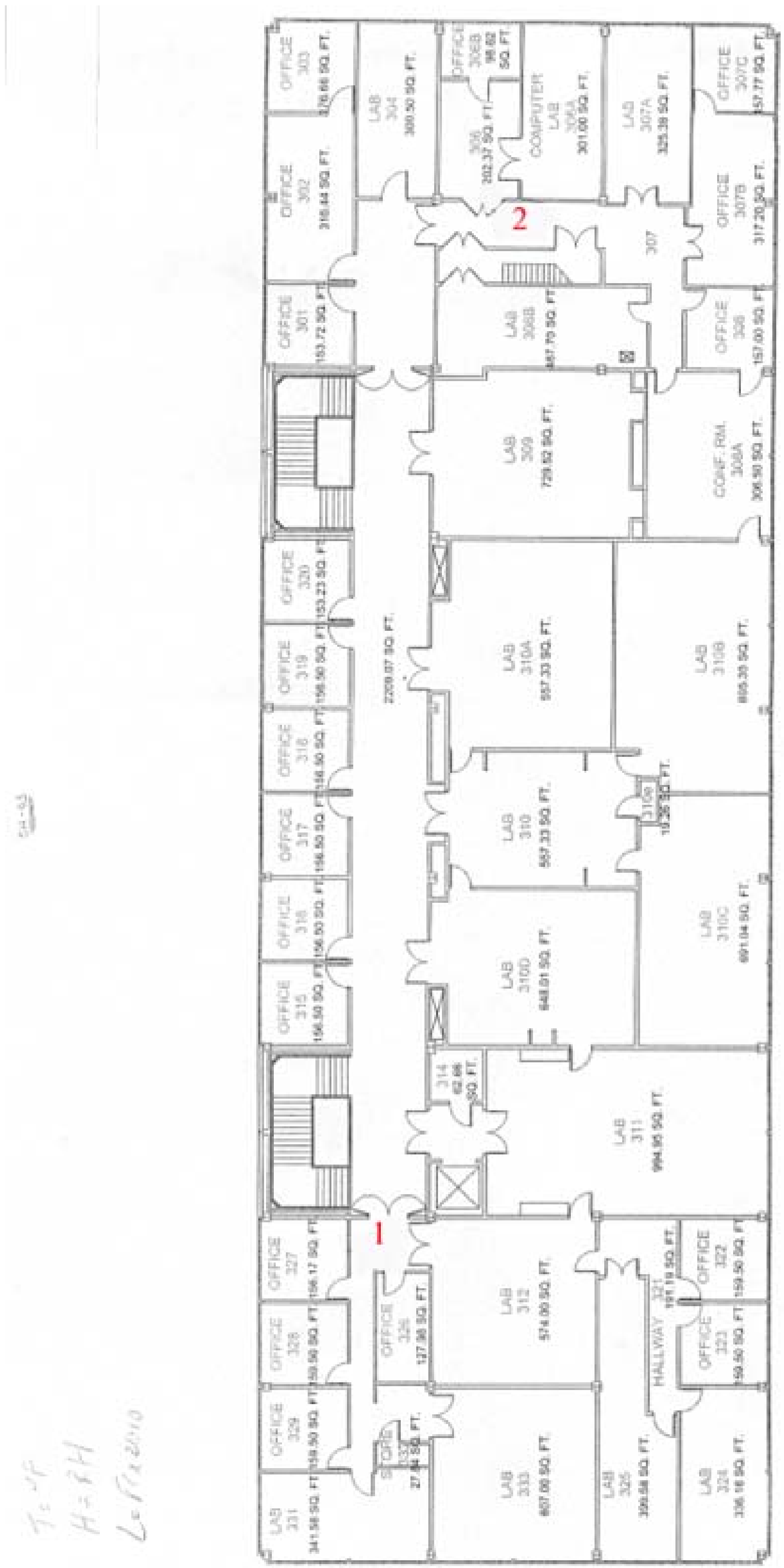
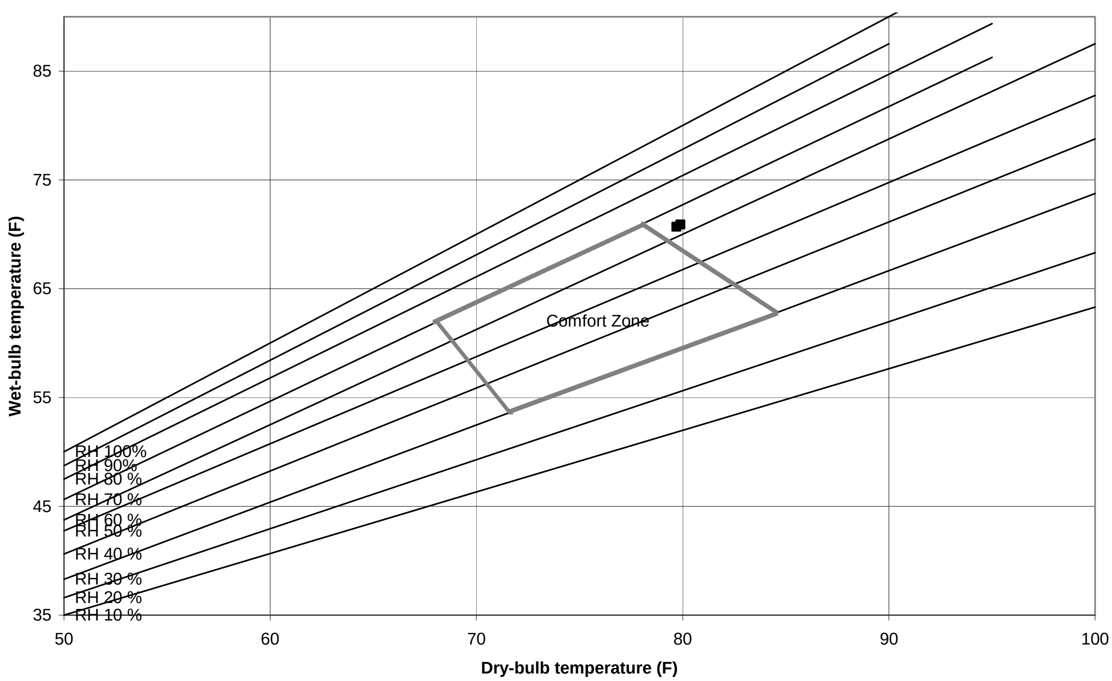


Figure 20 Siegel Hall third floor

Siegel Hall Building Third Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	79.7	59.2	12	YES	70.7
2	79.9	62.9	12	YES	70.9

Comfort Chart Seigel Hall Third Floor



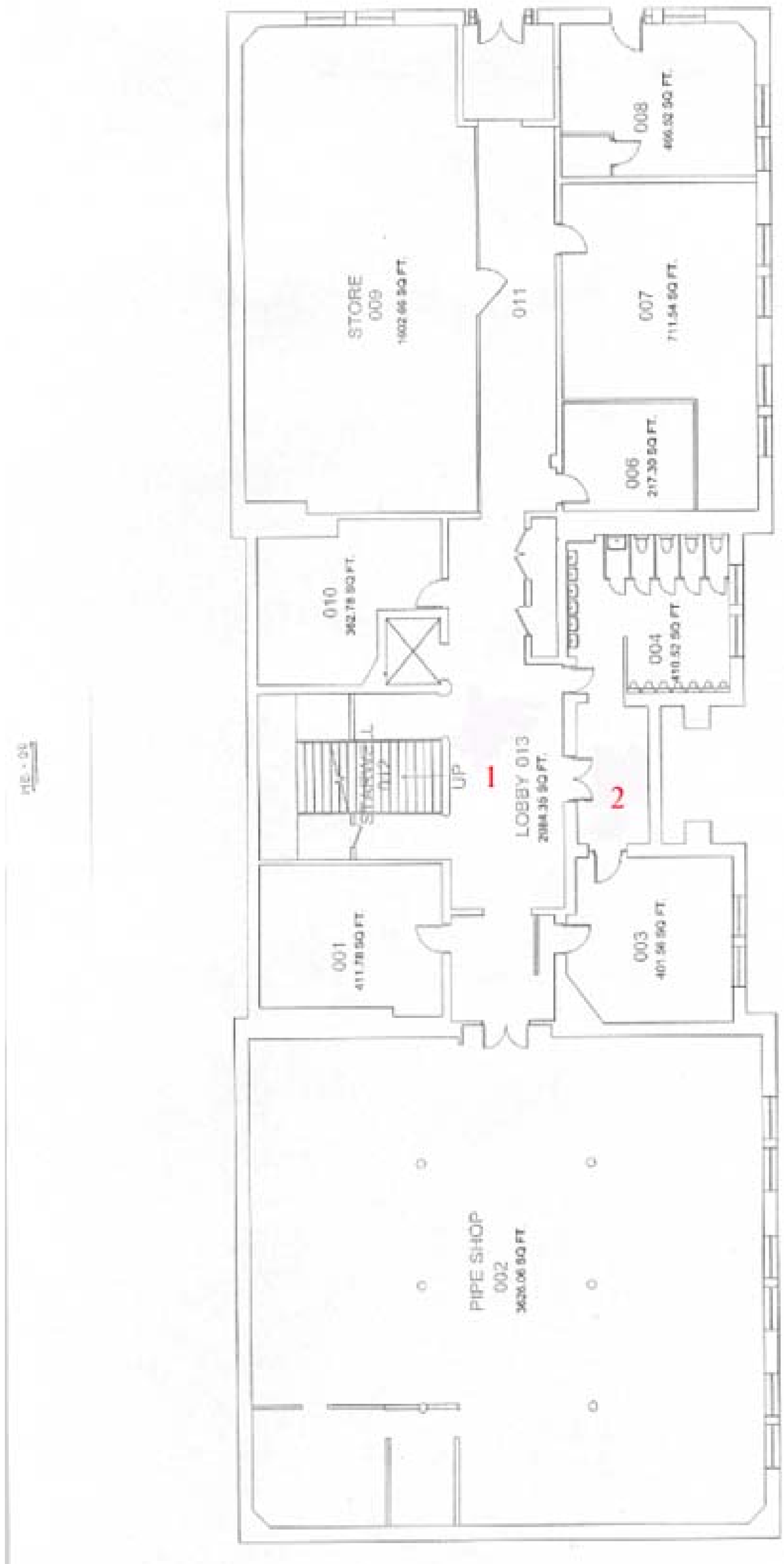
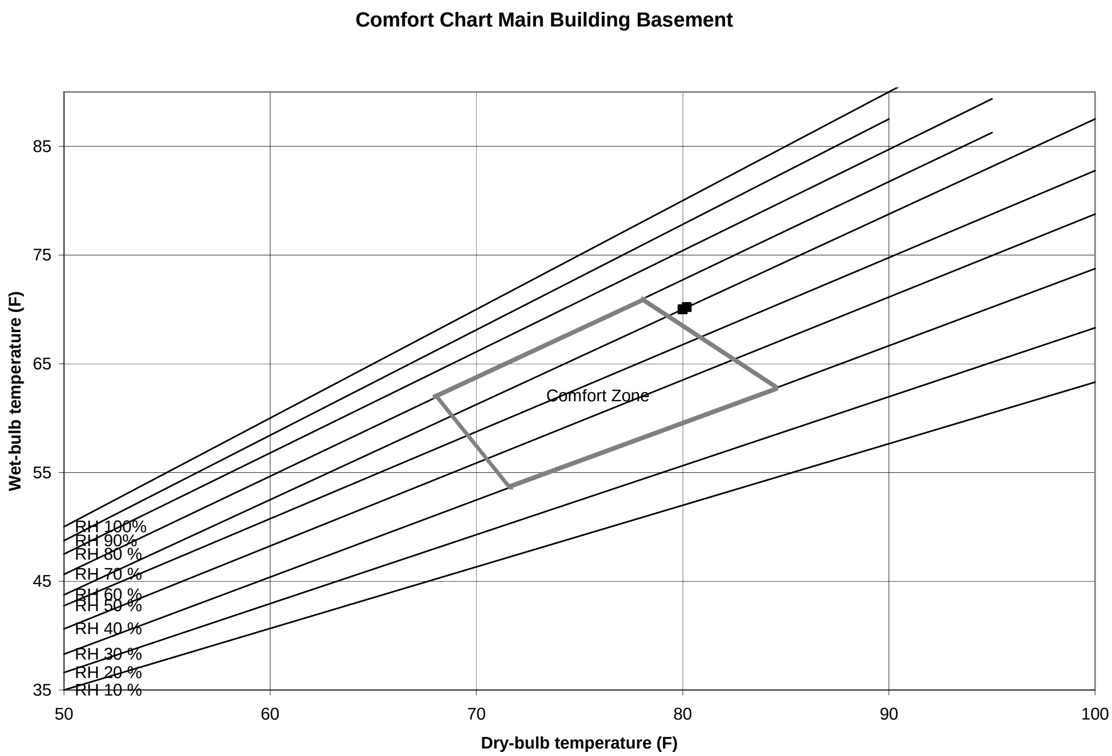


Figure 21 Main basement

Main Building Basement					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.0	59.0	13	YES	70
2	80.2	60.5	13	YES	70.2



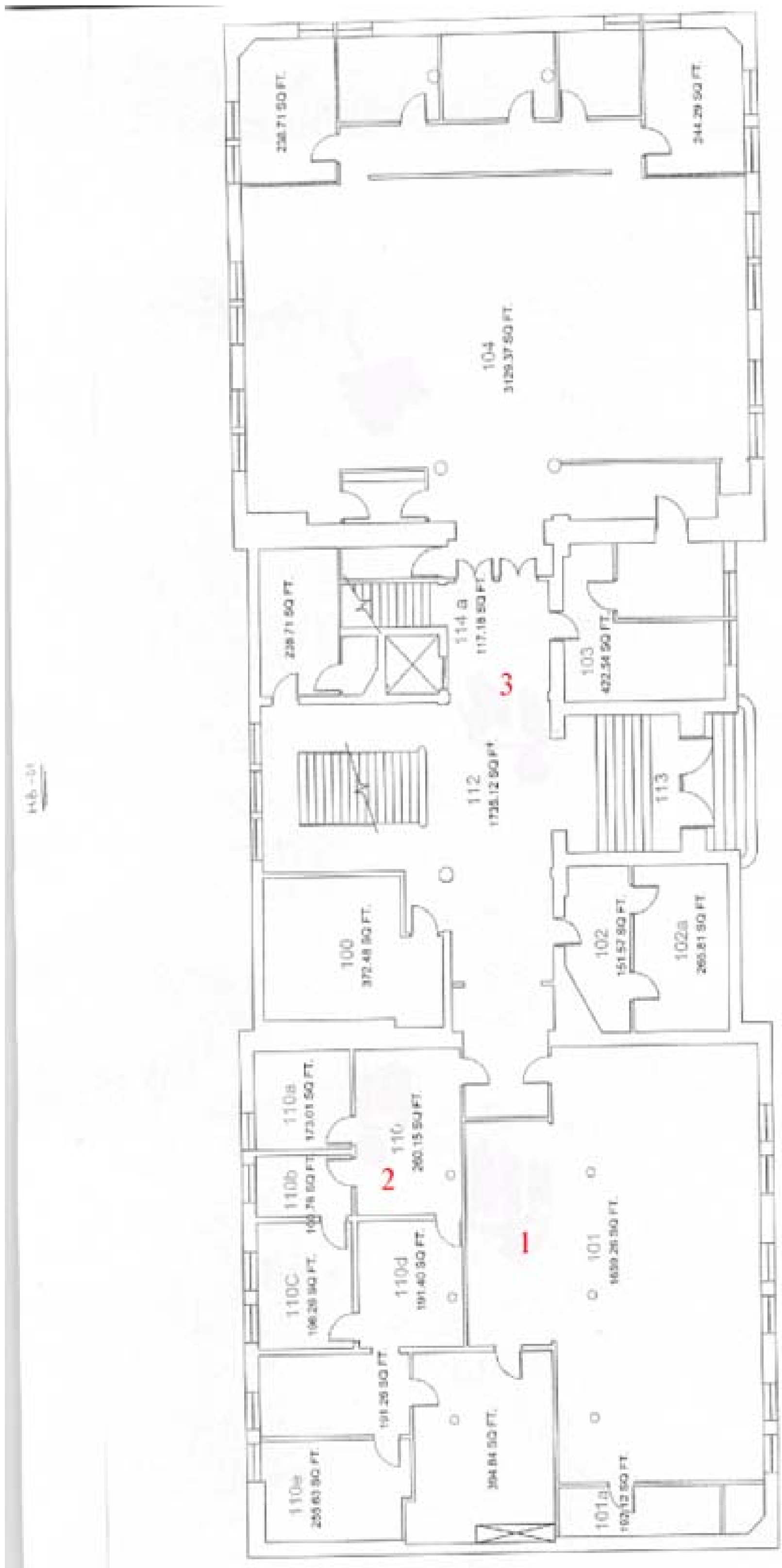
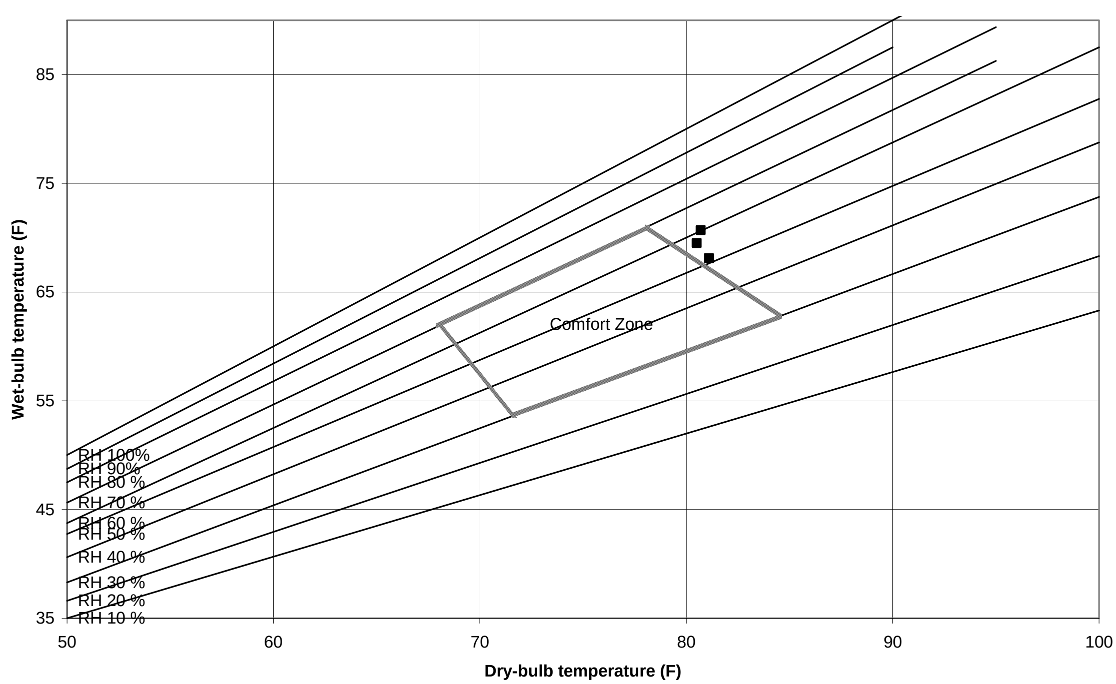


Figure 22 Main first floor

Main Building First Floor					
Room Number	**Dry-Bulb Temperature (F)**	**Relative Humidity (%)**	**Psychometric Table Column**	**Comfort Problem**	**Wet-Bulb Temperature (F)**
1	81.1	50.8	13	YES	68.1
2	80.5	56.2	13	YES	69.5
3	80.7	60.0	13	YES	70.7

Comfort Chart Main First Floor



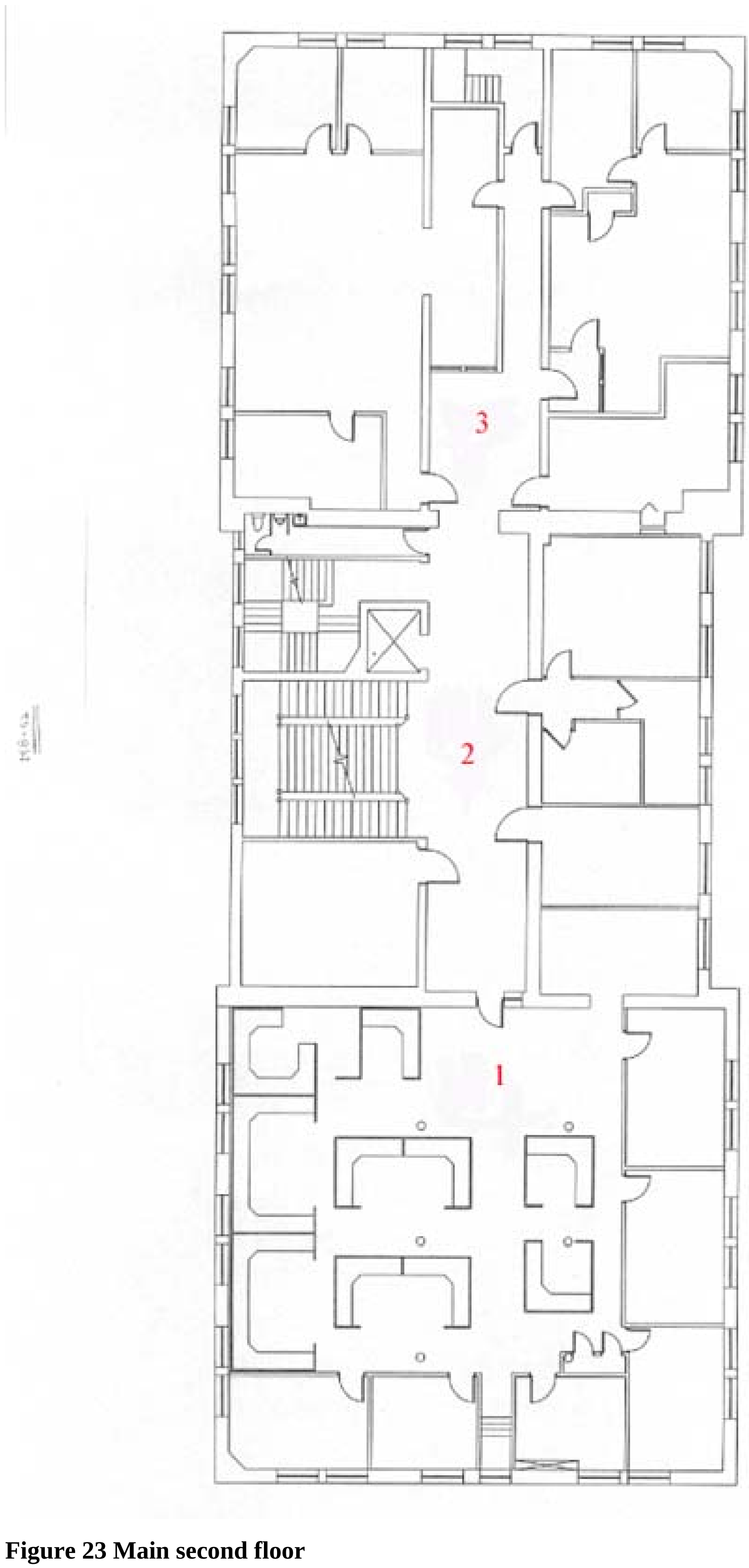
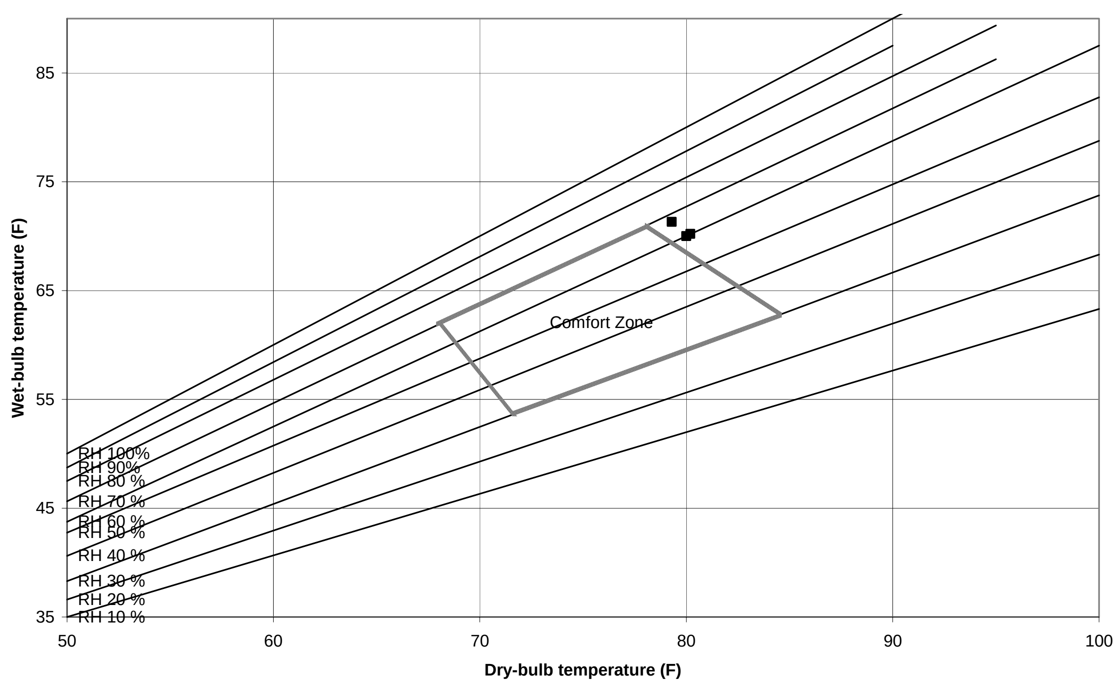


Figure 23 Main second floor

Main Building Second Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.0	60.6	13	YES	70
2	80.2	60.4	13	YES	70.2
3	79.3	64.0	12	YES	71.3

Comfort Chart Main Second Floor



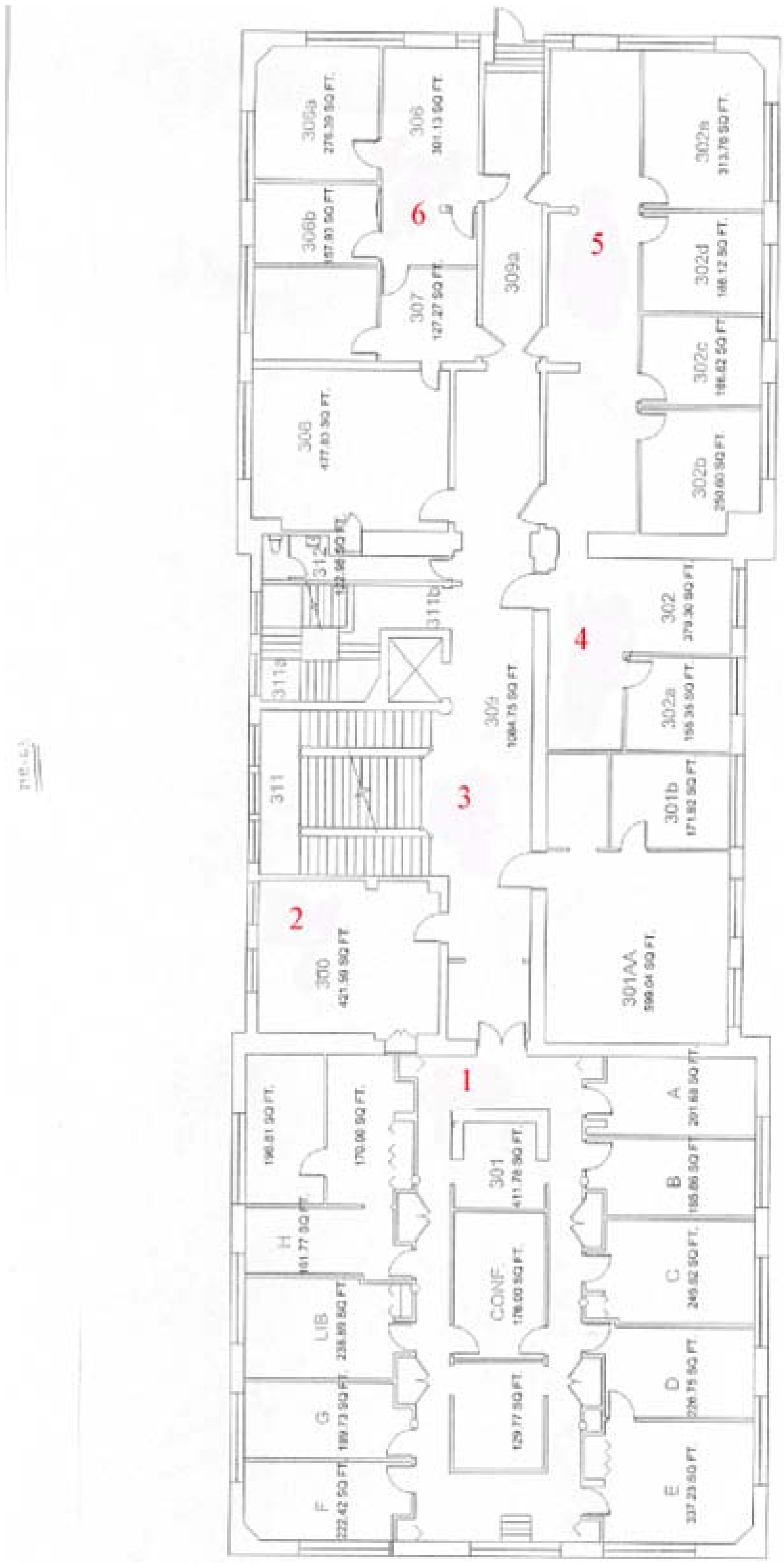


Figure 24 Main third floor

Main Building Third Floor

Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.2	52.9	13	NO	68.2
2	80.4	60.2	13	YES	70.4
3	81.1	57.6	13	YES	71.1
4	80.2	50.7	13	NO	67.2
5	80.4	52.6	13	YES	68.4
6	80.7	42.2	13	NO	65.7

Comfort Chart Main Third Floor

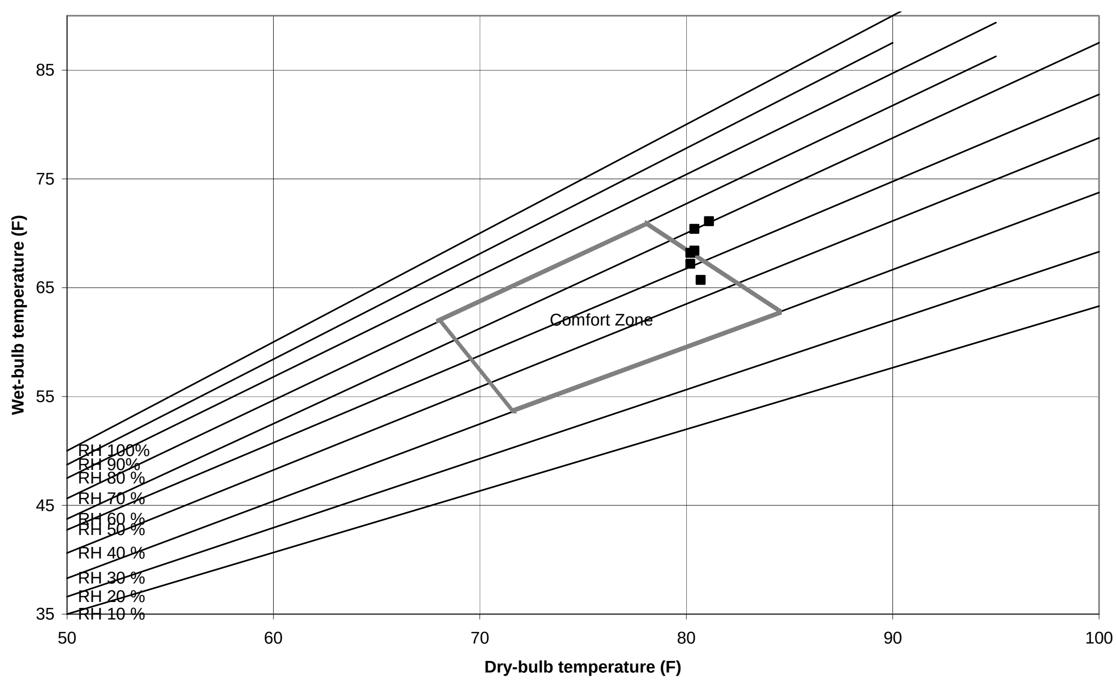
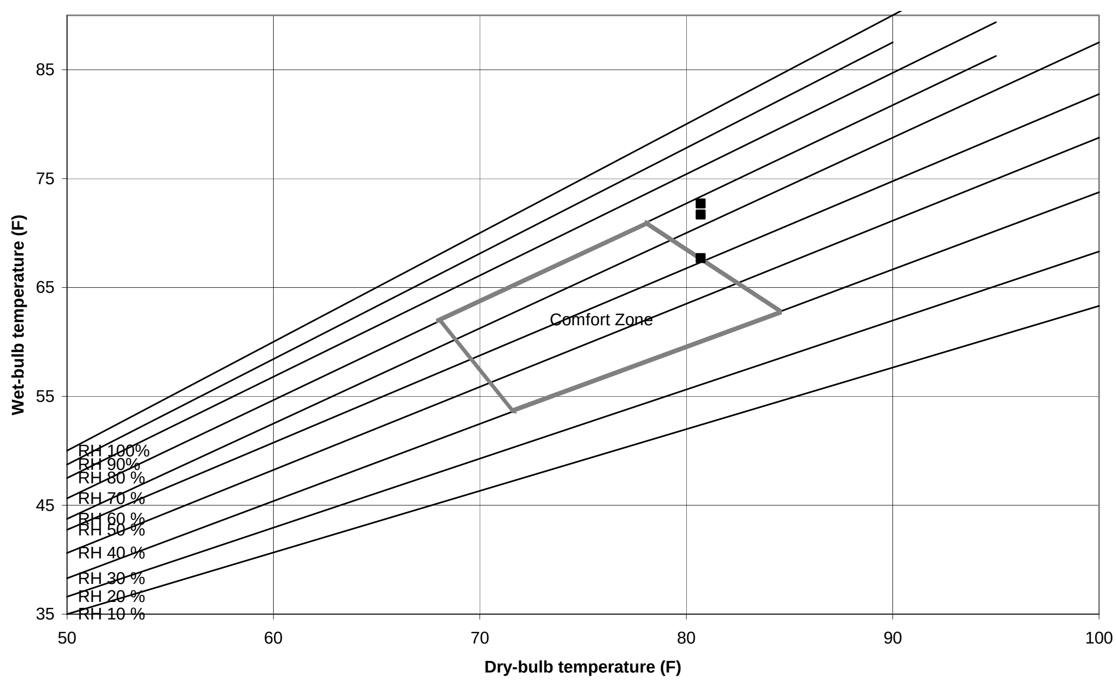


Figure 25 Main fourth floor

Main Building Fourth Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.7	65.0	13	YES	72.7
2	80.7	50.4	13	YES	67.7
3	80.7	63.5	13	YES	71.7

Comfort Chart Main Fourth Floor



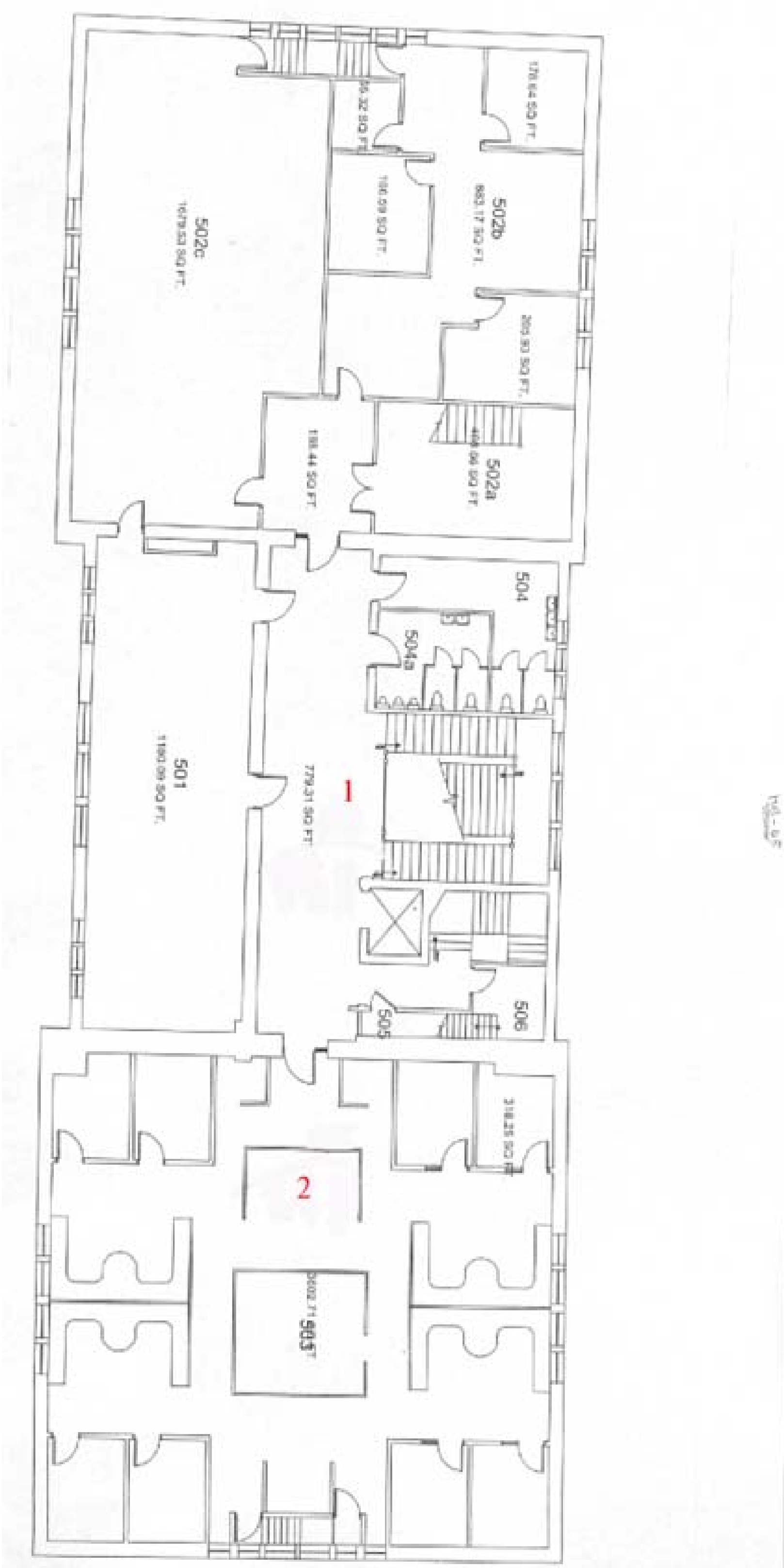
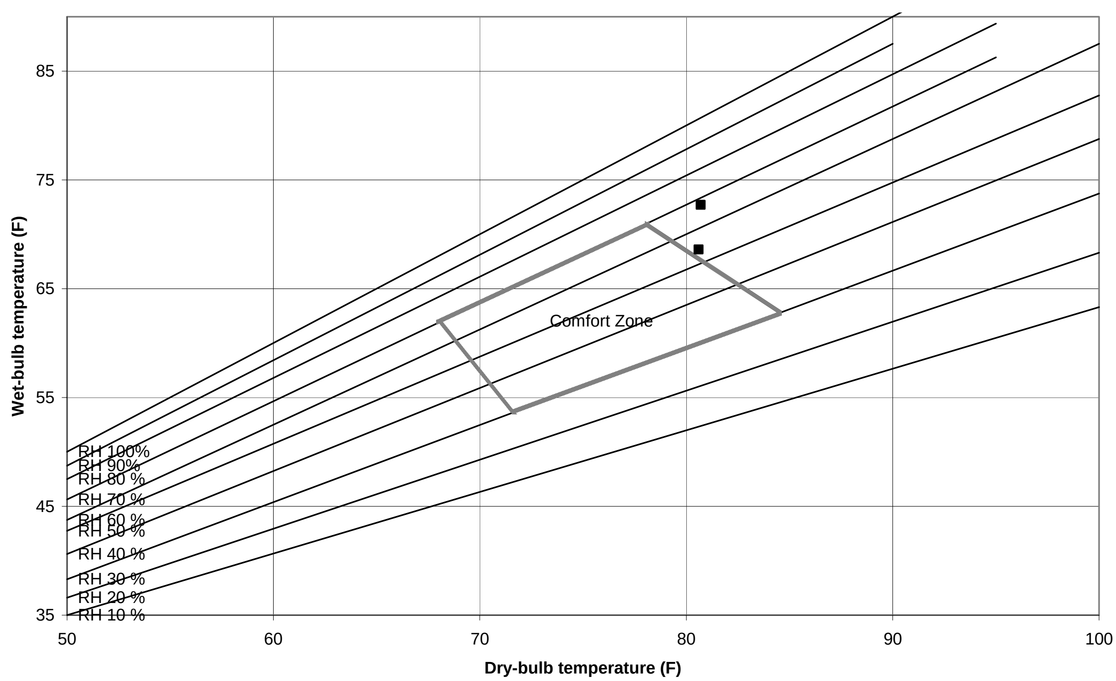


Figure 26 Main fifth floor

Main Building Fifth Floor					
Room Number	Dry-Bulb Temperature (F)	Relative Humidity (%)	Psychometric Table Column	Comfort Problem	Wet-Bulb Temperature (F)
1	80.7	64.8	13	YES	72.7
2	80.6	52.3	13	YES	68.6

Comfort Chart Main Fifth Floor



4. Conclusion

4.1 System description

General Observations

All general observations are based on visual inspections and are not detailed to each building.

Some buildings, specially the Life Sciences building are under conditions of extreme negative pressure. This situation might be due lack of renewal air with a lot of outside venting. This situation promotes infiltration at different locations and limits exhaust venting.

In addition, According to Hill Mechanical Services, and outside contractor, the sequence of operations for the control system of some of the buildings is not up to date or not operating properly.

Most buildings main air side design consists of main air handling units located in the mechanical room serving constant volume air to the rooms on different floors. Each air handling unit has a cooling coil and steam coil for cooling/heating. Most buildings' designs include cooling towers on the roof, chilled water pumps, condenser water pumps and electric chillers located in the mechanical room.

Some buildings are equipped many exhaust fans with potentially more installed due to space use changes.

The control systems are mostly pneumatic, DOS based manufactured by SIEMENS with some possible user interface in the mechanical rooms. This system is very outdated and probably has outlived its useful life.

4.2 Required Documentation

For the development of the commission plan the following documentation is required

1. Detailed mechanical plans of all facilities.
2. Detailed OEM machine performance curves of air handling units and exhaust fans.
3. Fan Curves.
4. Descriptive memory plans.
5. Load calculation sheet for all facilities if available.

4.3 Basis for future commissioning

The justification of a need for the development of a commissioning plan, in this project, is based on thermal comfort performance data collected for each of the building on campus.

The comfort chart use to analyze the data in all buildings on campus is believed to be the basis for thermal environmental conditions for human occupancy. However, it is important to understand that optimum conditions usually require a compromise with finances. In addition, departures from optimum conditions sometimes are justified by situations such as, short occupancy spaces and change in use of the space.

McCormick Tribune Campus Center

The McCormick Tribune Campus Center should be commissioned based on comfort problems. Most rooms are in borderline areas of the comfort chart where only 50 % of people might feel comfortable. In addition, the radiation effects that a person might experience due to the glass walls increases the effective temperature. The rooms that are exposed to radiation effects have much more load than others and the air supply to those rooms should be modulated to account for the varying loads during the day. Moreover, the more affected spaces are underneath the CTA Line acoustic insulator which are spaces dedicated to physical activities which require a much lower effective temperature.

Even though the comfort chart identifies some problems, there are other factors to take into account. The MTCC is short occupancy building during the summer which might affect the decision to commission the building.

Crown Hall

Crown Hall ultimately provides perfect comfort for about 94-98 % of the people according to the comfort chart. In addition, radiation effects are less critical in this building since the walls are covered and effective temperature becomes less of a problem. Moreover, even with convection effects taken into account, the building still provides great comfort for the summer. Note that this building is fairly unoccupied during the summer. Therefore, this building should not be commissioned on the basis of thermal comfort.

Life Sciences Building

The Life Sciences building should be commissioned base on comfort. According to the comfort chart, several rooms have extreme comfort problems even when the building is unoccupied and without taking radiation effects into account. About 12 % of the rooms surveyed provide severe comfort conditions. Moreover, the building has an extreme negative pressure which makes it very humid for infiltration effects of non treated air.

Stuart Building

The Stuart Building should not be commissioned based on comfort problems. The building provides optimal comfort for about 86-94 % of the people according to the comfort chart.

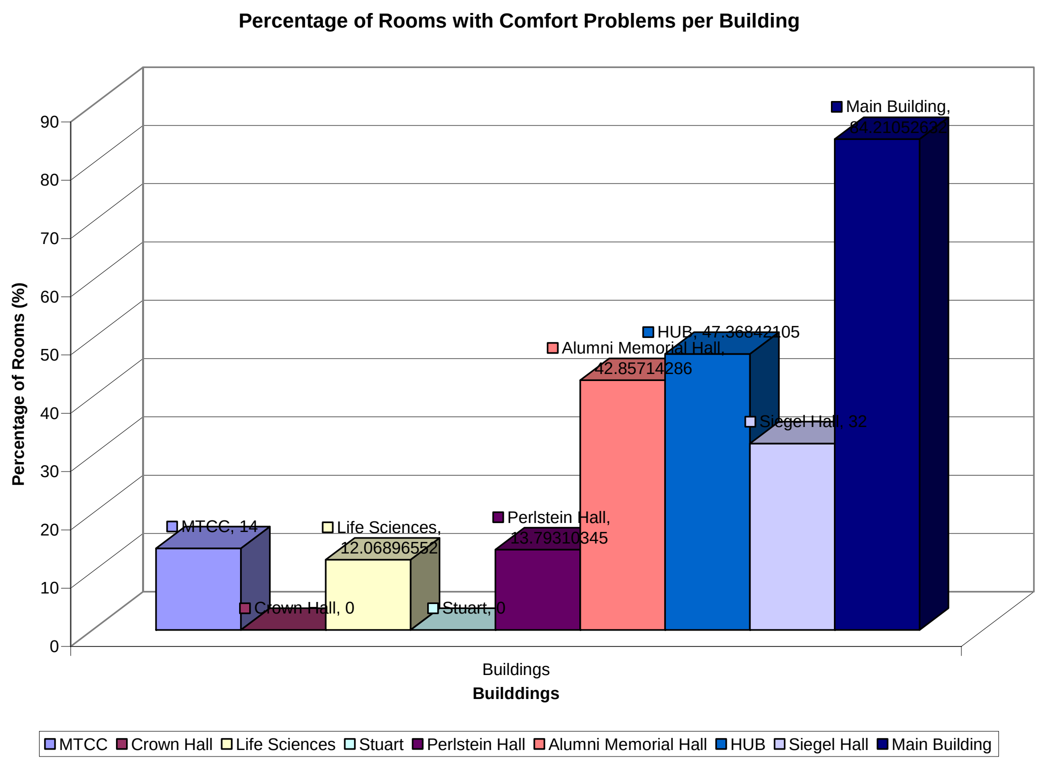
Perlstein Hall

Perlstein Hall should be commissioned based on comfort problems. About 13 % of surveyed rooms manifest extreme comfort problems mostly on the second floor. The rest of the rooms are borderline which provide discomfort for about 50 % of the occupants. However, the first floor of the building provides optimal conditions.

Alumni Memorial Hall, HUB, Siegel Hall and Main Building

These buildings experience extreme values of effective temperature. According to the comfort chart, these buildings would provide comfort for less than 50 % in all rooms surveyed. The extremes humidity and temperature values are very discomforting in these buildings. 42%, 47%, 32% 80%, respectively of the surveyed rooms in these buildings exhibit extreme cases of temperature and humidity combinations which translate into a very high effective temperature.

Bellow there is a summary chart of the percentage of rooms with problems in each building



5. Recommendations for Future IPROs

5.1 Load Calculations for Each Building

1. Obtain design conditions specification for the buildings.
    a. Inside design
    b. Outside design
    c. Location
    d. Ventilation
    e. Escalators
    f. Door Traffic
2. Perform a load calculation procedure
    a. Determine transmission leakage through windows, doors, walls and ceiling
    b. Determine internal sensible heat gains
        i. Lights
        ii. People according to activity
        iii. Appliances

iv. Motors
3. Compare to design specifications.
    a. Determine if oversized or undersized according to modern regulations

5.2 Perform Balance Testing

1. Obtain main air handling units design specifications
2. Obtain main air handling unit's performance data. See appendix 1
3. Perform room by room measurements of air volume. See appendix 2
    a. Prototypes of measurement devices were developed during summer 2006
4. Calculate performance coefficients
    a. $\frac{BTU}{ft^2}$
    b. $\frac{cfm}{ft^2}$
5. Evaluate results on a room by room basis
    a. What room is being over or under ventilated.

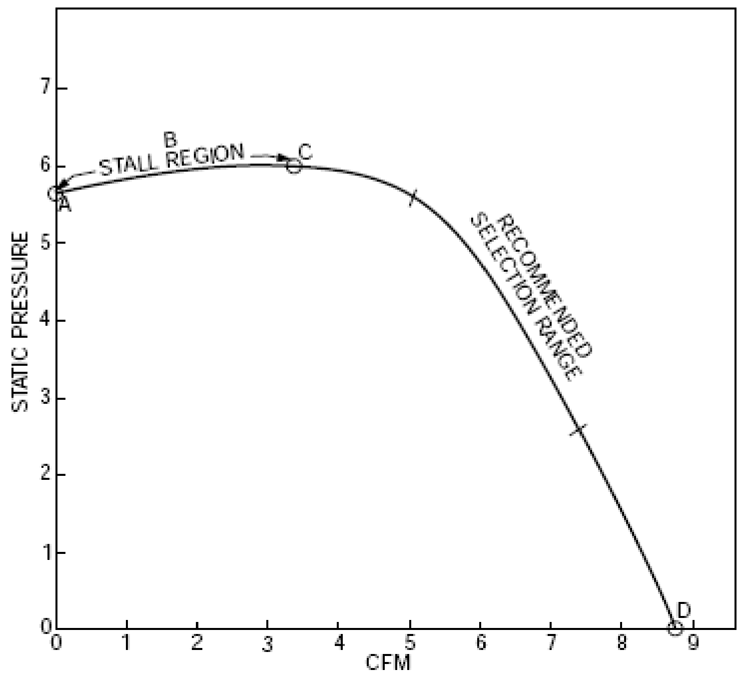
Appendix 1

Understanding fan curves

Pressure vs. Volume Curves

The most important characteristic curve for a fan is the Pressure vs. Volume curve. This type of curve is generally provided by the fan or blower manufacturer in a family of curves at different revolutions per minute.
This type of family of curves is normally expressed in total pressure or static pressure vs. volume handled by the fan. Since usually the air speed in the system could be variable the most commonly available curve is the static pressure vs. volume curve.

This graph represents an example of a single curve for a hypothetical fan.



[7]

Point A represents the point of zero airflow on the static pressure curve. Point B depicts the stall region of the static pressure curve. The system must be designed to operate outside of that region since the fan could generate excessive noise and vibration. Point D is the point of maximum airflow, which is the fan operating in an open volume. Curve segment CD is the stable portion of the fan curve and where the system should operate. The rest of the curves are fairly similar changing in the extremes cases for very high or low rpms.
As a common method for identifying unstable operating points, one analyzes that for a system static pressure the fan could handle two or more air volumes.

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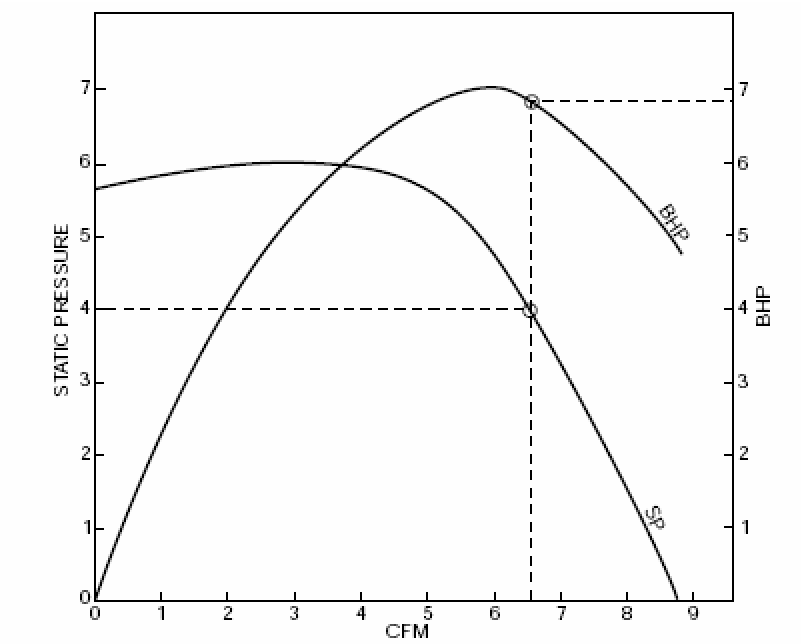
7 http://www.tcf.com/TCFAdmin/EN/CLA/pdfs/ED2000.pdf#search='static%20pressure%20for%20variable%20shapes'

Horsepower Curve

The horsepower curve is usually also superimposed onto the static pressure curve to show the operating point and fan consumption



[8]

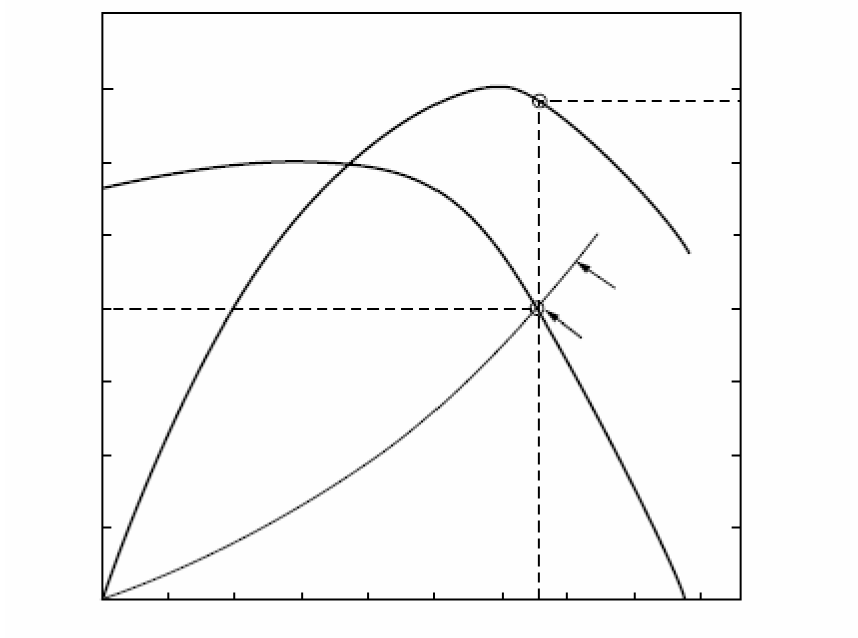
To determine BHP simply extend vertically the CFM point for the desired operating point until it intersects the BHP curve. This value is the power that would be consumed by the fan motor.

Operating Point

The operating point is defined as the fan pressure rise and volumetric flow rate condition where the fan and system are in a stable equilibrium. This corresponds to the condition at which the fan static pressure vs. volume characteristic intersects the system pressure loss.

The following graph shows the operating point for the whole system. It illustrates the static pressure characteristic of the fan and the system and their point of intersection which is the stable state.

8 http://www.tcf.com/TCFAdmin/EN/CLA/pdfs/ED2000.pdf#search='static%20pressure%20for%20variable%20shapes'



[9]

As long as the system does not contain automatic dampers, the system will perform according to the laws of fan. Those are as follows:

1) $\frac{CFM}{rpm} = cons\tan t$
2) $\frac{SP}{rpm^2} = cons\tan t$
3) $\frac{HP}{rpm^3} = cons\tan t$

Interpreting the graphs

The fan must operate along the system line.

The fan unit provides insights into what is happening in an air conditioning system.

For example, the systems was designed and tested and was delivering a certain volume at some rpms. If current data from the main air handling unit specifies less volume and less static pressure for the fan, then one could conclude that the fan is either not operating at the design rpms or the belts are defective or some have failed. Moreover, from a static pressure point of view, the system once designed can not change the pressure losses. Thus any change in static pressure of the fan immediately indicates some problems with the duct work.

[9] http://www.tcf.com/TCFAdmin/EN/CLA/pdfs/ED2000.pdf#search='static%20pressure%20for%20variable%20shapes'

AIR FLOW CAPTURE HOOD

One method of making a building more comfortable and energy efficient is to calibrate the HVAC system that services the building. A part of this activity involves air balancing where some kind of air capture hood is used on diffusers to determine the actual amount of air flow moving through the ducts and comparing the data with what is required. If required, valves on the diffusers, VAV boxes, or the main fans can be adjusted to best suit the spaces in the building.

Commercial air flow capture hoods are commonly used for this task, which consists of a collapsable hood on top and a pressure differential meter at the bottom which gives an air flow reading when the hood is pressed against a diffuser. However, commercial hoods can cost several thousand dollars and usually requires the user to step on a ladder to reach the diffuser, although these hoods may provide fairly accurate readings and usually come with convenient attachments for different sized diffusers.

We decided to try to build some prototype capture hoods ourselves with low cost materials in order to perform the task without having to spend thousands of dollars on equipment. Instead of using a pressure differential meter, we purchased an affordable 4 in 1 meter that has an air velocity function, which we used to measure the velocity of the air at the bottom opening of the prototypes. We then used that number and multiplied it by the square area of the opening to get the volume of air flow, or CFM.

The 1st prototype was constructed out off a durable plastic tarp wrapped around two pieces of electrical metal conduit bent into squares. The top was 27" sq and the bottom was 16" sq. When put in place, it hung 6 ft from the ceiling to allow a person to measure the air flow without having to step up. Another person would use the pivoting handle bar which also allows the hood to be placed over diffusers on virtical walls. However, it was decided that the tarp was too flexible and bulky to be conveniently and accurately used.

The 2nd prototype was created from 1/2" extruded polystyrene foam for the top half, and 1/2" foam core board for the bottom half in order to provide a rigid construction. We believe that this would create less air resistance and provide more accurate readings, and would be easier for users to handle. The material is very lightweight and easy to carry. The two halves are detachable for ease of storage and transportation and connected with metal flashing through friction and sealed with weather stripping. Large handles are provided at the bottom of the hood, 5 ft from the top. The top expands to 27" sq and the bottom narrows down to 12" sq, which was calculated to be the minium acceptable reduction in opening size to prevent large loss of air flow.

The 3rd prototype was created in consideration for large diffusers. The top expands to 37" sq and the bottom narrows down to 14" sq. The materials are also lightweight. However, this hood is very large and sometimes difficult to transport and handle. It may not fit through small doors.

The most usable capture hood would most likely be the 2nd prototype. It has reliable seals and its ability to disassemble allows it to be mobile. It is possible to create a low cost hood for only $40 for use with an air velocity meter, which can be purchased for under $100, instead of purchasing extremely expensive commerical hoods, while maintaining accurate readings.

Commercial Hood ~ $2000

1st Prototype ~ $20

4 IN 1 METER
W/ AIR VELOCITY
used with prototype hoods
~ $150

2nd Prototype ~ $40

3rd Prototype ~ $30

Preliminary Testing for Prototype 2

Prototype 2 was tested on an a supply and return diffuser, and compared with professionally taken measurements.

Supply

Proto2	Professional	Error
340 CFM	380 CFM	10.5%

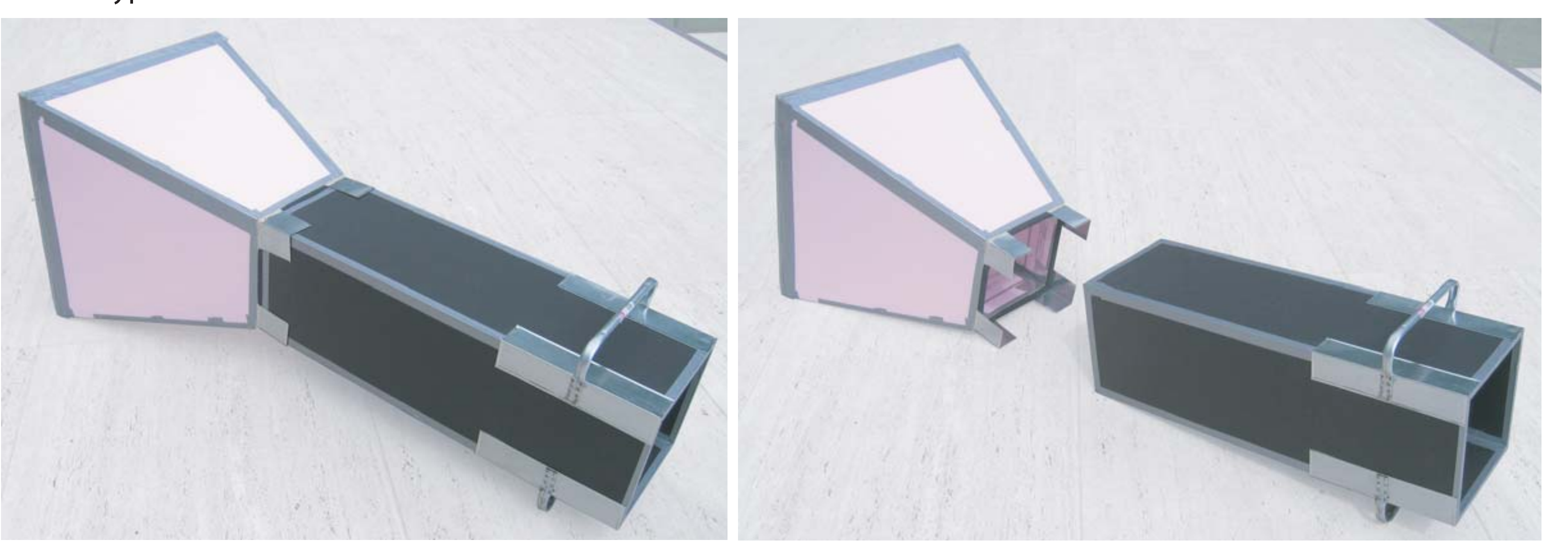
Return

Proto2	Professional	Error
65 CFM	100 CFM	35%

This prototype is fairly accurate at higher air flows, but less accurate at low flows. It would probably be possible to formulate a correction factor in proportion to air flow to achieve accurate measurements using a low cost, self-made hood.

Prototype 3

Prototype 2



AIR FLOW CAPTURE HOOD

7.1 Case Study

Background

By definition, commissioning is the process of ensuring that the complex array of equipment that provides lighting, heating, cooling, ventilation and other amenities in facilities works together effectively and efficiently [4]. Commissioning typically begins during the facility's conceptual design phase and ideally continues throughout the life of the facility.

Most buildings that were built in the early to middle twentieth century served a growing industrial nation. Today, those same buildings are typically used as office spaces without any change to the building's lighting or mechanical system. Unknowingly to most owners, this difference in space usage will result in higher electrical and mechanical cost for the building. In order to combat this issue, many owners contact energy engineers to perform a building energy audit to see what can be done to reduce cost and increase efficiency for the building. Retro-commissioning and energy auditing have the same meaning when dealing with post-constructed buildings.

As mentioned above, energy auditing is performed by energy service companies to improve the energy efficiency of buildings. Since the oil embargo of 1973, significant improvements have been made in the energy efficiency of new buildings. However, the majority of the existing stock of buildings are more than a decade old and do not meet current energy efficiency construction standards. Investing to improve the energy efficiency of buildings provides an immediate and relatively predictable positive cash flow resulting from lower energy bills. Typically, an energy services company assumes all the risks for a retrofit project by performing the engineering analysis and obtaining the initial capital to purchase and install equipment needed for energy efficiency improvements [5]. Energy auditing, i.e. retro-commissioning, is an important step used by energy service companies to insure the success of their performance contracting projects.

Energy auditing of buildings can range from short walk-through of the facility to a detailed analysis with hourly computer simulation. Generally, four types of energy audits can be distinguished by the following:

1.) Walk-Through Audit – This audit consists of a short on-site visit of the facility to identify areas where simple and inexpensive actions can provide immediate energy use and/or operating cost savings.

2.) Utility Cost Analysis – The main purpose of this type of audit is to carefully analyze the operating costs of the facility. Typically, the utility data over several years are evaluated to identify the patterns of energy use, peak demand, weather effects, and potential energy savings.

3.) Standard Energy Audit – The standard audit provides a comprehensive energy analysis for the energy systems of the facility. This audit includes the development of a baseline for the energy use of the facility and the evaluation of the energy savings and the cost effectiveness of selected energy conservation measures. Typically, simplified tools are used in the standard energy audit to develop baseline energy models and to predict the energy savings of energy conservation measures.

4.) Detailed Energy Audit – This audit is the most comprehensive but also time-consuming energy audit type. Specifically, the detailed energy audit includes the use of instruments to measure energy use for the whole building and/or for some energy systems within the building. In addition, sophisticated computer simulation programs are considered for detailed energy audits to evaluate and recommend energy retrofits for the facility.

The techniques available to perform measurements for an energy audit are diverse. During an on-site visit, hand-held and clamp-on instruments can be used to determine the variation of some building parameters such as the indoor air temperature, the luminance level, and the electrical energy use. When long-term measurements are needed, sensors are used and connected to a data-acquisition system so measured data can be stored and be remotely accessible.

To perform an energy audit, several tasks are carried out depending on the type of the audit and the size and function of the audited building. The steps are described here:

1.) Building & Utility Data Analysis – The main purpose of this step is to evaluate the characteristics of the energy systems and the patterns of energy use for the building. The building characteristics can be collected from the architectural/mechanical/electrical drawings and/or from discussions with building operators. The energy use patterns can be obtained from a compilation of utility bills over several years. The analysis of the variation of utility bills allows the auditor to determine if there are any seasonal and weather effects on the building energy use.

2.) Walk-through Survey – Potential energy savings measures should be identified with this step. The results are important since they determine if the building warrants any further energy auditing work. Some of the steps involved include identifying the customer concerns and needs, checking the current operating and maintenance procedures, and determining the existing operating conditions of major energy use equipment.

3.) Baseline for Building Energy Use – The main purpose of this step is to develop a base-case model that represents the existing energy use and operating conditions for the building. This model is to be used as a reference to estimate the energy savings incurred from appropriately selected energy conservation measures.

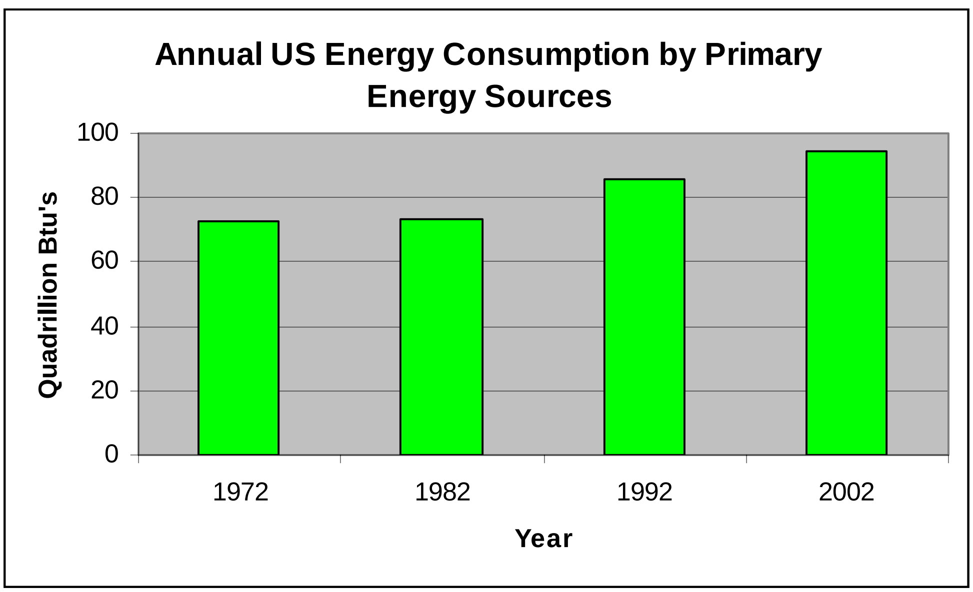
4.) Evaluation of Energy Savings Measures – A list of cost-effective energy conservation measures is determined using both energy savings and economic analysis. The following items are recommended for this step: prepare a list of energy conservation measures; determine the energy savings due to the various energy conservation measures important to the building using the baseline energy use simulation model; estimate the initial costs required to implement the conservation measures; evaluate the cost-effectiveness of each energy conservation measure using an economic analysis method.

Energy Sources

The energy cost is an important part of the economic viability of several energy conservation measures. The sources of energy used in the US include: coal, natural gas, petroleum products, and electricity. The electricity can be generated from either power plants fueled from primary sources or from nuclear power plants or renewable energy sources. In the US, the energy consumption has fluctuated in response to significant changes in oil prices, economic growth rates, and environmental concerns. The US energy consumption increased from 66 quadrillion British thermal units (Btu) in 1970 to 94 quadrillion Btu in 2002 [6]. The table & graph below shows the changes in US energy consumption by source from 1972 to 2002 [7].

Table 1 - Annual US Energy Consumption by Primary Energy Sources [7]

Primary Energy Source	**1972**	**1982**	**1992**	**2002**
Coal	12.077	15.322	19.158	21.620
Natural Gas	22.469	18.505	20.131	21.840
Petroleum Products	32.947	30.232	33.527	36.537
Nuclear Power	0.584	3.131	6.607	7.157
Renewable Energy	4.478	6.293	6.308	7.073
Total	72.758	73.442	85.495	94.231
	(Units in Quadrillion Btu)			



From the data above, it is evident that the consumption of coal has increased from 12 quadrillion Btu in 1972 to 21.6 quadrillion Btu in 2002. However, the US consumption of natural gas actually declined from 22.5 quadrillion Btu in 1972 to 18.5 quadrillion in

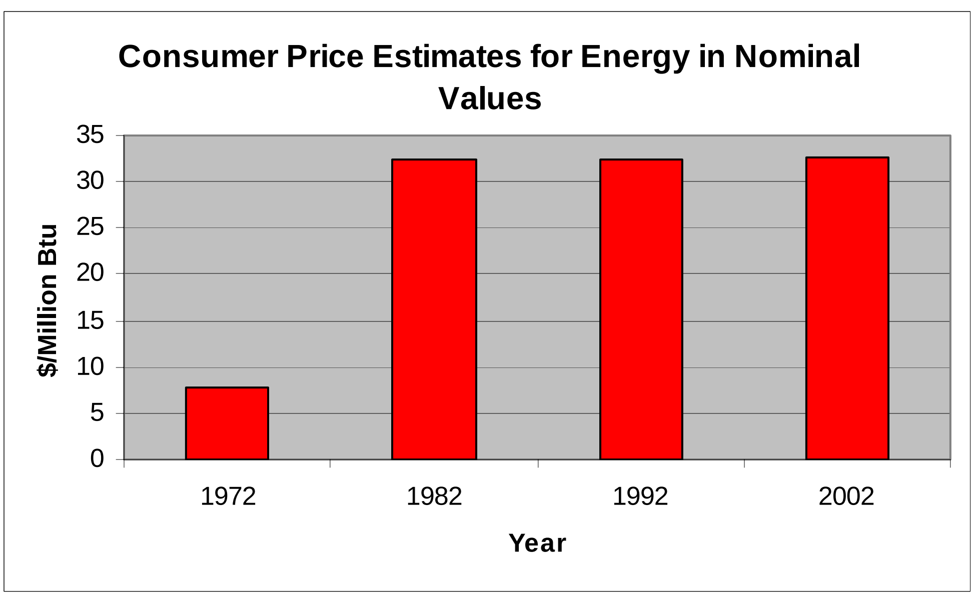
1982 before increasing slightly to 21.8 quadrillion Btu in 2002. Between 1972 & 2002, consumption of other energy sources have generally increased. The increase is from 33.0 quadrillion Btu to 33.5 quadrillion Btu for petroleum products, from 0.6 quadrillion Btu to 7.2 quadrillion Btu for nuclear power, and from 4.5 quadrillion Btu to 7.1 quadrillion Btu for renewable energy which consists of hydroelectric power.

The table below depicts the average energy prices for each primary fuel type.

Table 2 - Consumer Price Estimates for Energy in Nominal Values [7]

Primary Energy Source	**1972**	**1982**	**1992**	**2002**
Coal	0.45	1.73	1.46	1.37
Natural Gas	-	4.23	3.89	3.81
Petroleum Products	1.78	8.35	7.04	7.23
Electricity	5.54	18.16	20.07	20.30
Total	7.77	32.47	32.46	32.71
	(Units in $/Million Btu)			

Over the years, coal remains the cheapest energy source. The graph below illustrates the price increase in total energy consumption over the past thirty-years.



As seen, the prices of all energy sources have increased significantly after the energy crisis of 1973.

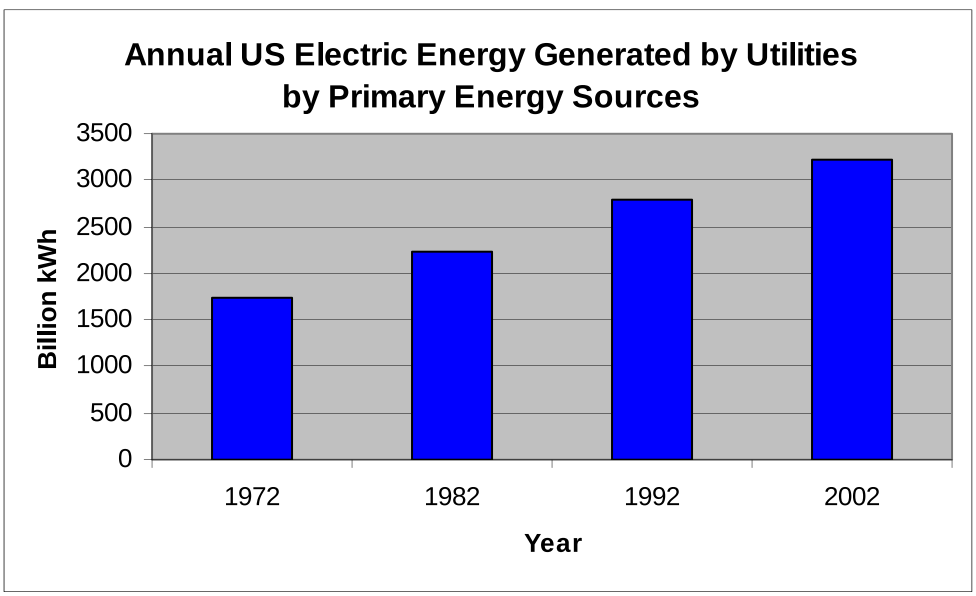
A. Electricity

In the US, coal is the fuel of choice for most existing electrical power plants as shown in the table below.

Table 3 - Annual US Electric Energy Generated by Utilities by Primary Energy Sources [7]

Primary Energy Source	1972	1982	1992	2002
Coal	771	1192	1576	1807
Natural Gas	376	305	264	309
Petroleum Products	274	147	89	110
Nuclear Power	54	283	619	674
Renewable Energy	274	314	254	316
Total	1749	2241	2802	3216
	(Units in Billion kWh)			

The graph below shows the increase in the annual US electric energy generated by utilities over the last thirty-years.



Gas-fired power plants are expected to be more common in the future due to more efficient and reliable combustion turbines.

The electricity sold by US utilities has increased steadily for all end-use sectors as shown in the table below.

Table 4 - Annual US Electric Energy Sold by Utilities Sector [7]

End-Use Sector	1972	1982	1992	2002
Residential	539	730	936	1124
Commercial	359	526	761	949
Industrial	641	745	973	1047
	(Units in Billion kWh)			

The increase in electricity consumption could be even higher without the various energy conservation programs implemented by the Federal or State governments and utilities. For instance, it is estimated that the demand-side-management programs provided by utilities have saved about 35 billion kWh in electrical energy use during 1992 and over 56 billion kWh in 2001 [6].

The prices of electricity for all end-use sectors have actually decreased since 1982 after a recovery period from the 1973 energy crisis as shown in the table below.

Table 5 - Average Retail Prices of Electric Energy Sold [7]

End-Use Sector	1972	1982	1992	2002
Residential	7.2	9.8	8.2	7.4
Commercial	6.9	9.8	7.7	6.6
Industrial	3.6	7.1	4.8	4.0
	(Units in cents per kWh)			

As shown, industrial customers enjoyed the lowest electricity price over the years while the highest cost was for residential customers.

Currently, the electricity market is in the midst of a restructuring period and is becoming very competitive. A number of technologies have emerged in the last decade that allow generation of electricity with reduced waste, cost, and environmental impact. It is expected that these emerging technologies will improve the future deregulated market.

i. Motors

In the US, there were 125 million operating motors in the range of 1 to 120 horsepower in 1999. These motors consumed approximately 55% of the electricity generated in the US [6]. In large industrial facilities, motors can account for as much as 90% of the total electrical energy use. In commercial buildings, motors can account for more than 50% of the building electrical load.

Motors convert electrical energy to mechanical energy and are typically to drive machines. The driven machines can serve a myriad of purposes in the building including moving air (supply and exhaust fans), compressing gases and producing materials. To select the type of motor to be used for a particular application, several factors have to be considered including:

- The form of the electrical energy that can be delivered to the motor: direct current or alternating current, single or three phase.
- The requirements of the driven machine such as motor speed and load cycles.
- The environment in which the motor is to operate.

Based on their efficiency, motors can be classified into two categories: standard-efficiency motors, and high or premium-efficiency (energy-efficient) motors. The energy-efficient motors are 2 to 10 percentage points more efficient than standard-efficiency motors depending on the size. The table below summarizes the differences.

Table 6 - Typical Motor Efficiencies [8]		
Motor Mechanical Power Output KW (HP)	**Average Nominal Efficiency For Standard-Efficiency Motor**	**Average Nominal Efficiency For Premium-Efficiency Motor**
0.75 (1.0)	0.730	0.830
1.12 (1.5)	0.750	0.830
1.50 (2.0)	0.770	0.830
2.25 (3.0)	0.800	0.865
3.73 (5.0)	0.820	0.876
5.60 (7.5)	0.840	0.885
7.46 (10)	0.850	0.896
11.20 (15)	0.860	0.910
14.92 (20)	0.875	0.916
18.65 (25)	0.880	0.926
22.38 (30)	0.885	0.928
29.84 (40)	0.895	0.930
37.30 (50)	0.900	0.932
44.76 (60)	0.905	0.933
55.95 (75)	0.910	0.935
74.60 (100)	0.915	0.940
93.25 (125)	0.920	0.942
111.9 (150)	0.925	0.946
149.2 (200)	0.930	0.953

ii. Lighting

Lighting accounts for a significant portion of the energy use in commercial buildings. For instance, in office buildings, 30% to 50% of the electricity consumption is used to provide lighting. In addition, heat generated by lighting contributes to additional thermal loads that need to be removed by the cooling equipment. Typically, energy retrofits of lighting equipment are very cost-effective with payback periods of less than 2 years in most applications.

In the US, lighting energy efficiency features are the most often considered strategies to reduce the energy costs in commercial buildings as shown in the following table.

Table 7 - Level of Participation in Lighting Conservation Programs by US Commercial Buildings [9]

Lighting Retrofit	**Percent Participation In Number Of Buildings**	**Percent Participation In Floor Area Of Spaces**
Energy Efficient Lamps and Ballasts	31	49
Specular Reflectors	18	32
Time Clock	10	23
Manual Dimmer Switches	10	23
Natural Lighting Control Sensors	7	13
Occupancy Sensors	5	11

There are typically three options to reduce the energy use attributed to lighting systems as briefly described below:

- Reduce the wattage rating for the luminaries including both the lighting sources (lamps) and the power transformation devices (ballasts).
- Reduce the time of use of the lighting systems through lighting controls. Automatic controls have been developed to decrease the use of a lighting system so illumination is provided only during times when it is actually needed. Energy-efficient lighting controls include the occupancy sensing systems and light dimming controls through the use of daylighting.
- Reduce the number of luminaries. This goal can be achieved only in cases where delamping is possible due to over-illumination.

Improvements in the energy-efficiency of lighting systems have provided several opportunities to reduce electrical energy use in buildings. Typically, three factors determine the proper level of light for a particular space. These factors include the age of the occupants, speed and accuracy requirements, and background contrast. It is a common misconception to consider that overlighting a space provided higher visual quality. It has been shown that overlighting can actually reduce the illuminance quality and the visual comfort level within a space in addition to wasting energy. That being said, it is important when upgrading a lighting system to determine and maintain the adequate illuminance level as recommended by the building codes. The table below depicts the recommended lighting levels in the US.

Table 8 - Recommended Lighting Levels for Various Applications [9]

Application	**Lighting Levels (Lux)**
Offices	
General	200-500
Reading Tasks	200-500
Drafting	1000-2000
Classrooms	
General	200-500
Chalkboards	500-1000
Retail Stores	
General	200-500
Task Areas	200-500
Hospitals	
Patient Rooms	100-200
Manufacturing	
Fine Knitting	1000-2000
Electronics	1000-2000

B. Natural Gas

As illustrated below, the total US consumption of natural gas has actually declined between 1972 & 2002.

Table 9 - Annual US Consumption of Natural Gas by Sector [7]

End-Use Sector	1972	1982	1992	2002
Residential	5.13	4.63	4.69	4.51
Commercial	2.61	2.61	2.80	3.09
Industrial	9.62	6.94	8.70	9.71
	(Units in Trillion cubic feet)			

The industrial sector experienced the highest reduction in natural gas use in the 1980's. The main reason for the decline in natural gas use is attributed to the restructuring and the deregulation of several segments of the gas industry during most of the 1970's. However, with the ever-increasing cost of oil, natural gas is expected to increase in use and price (see table below). Many engineers believe the future for natural gas as a primary energy source for electricity generation to be very promising. Gas-fired power plants are competitive because of their high efficiencies (approaching 50%) and are environmentally attractive since they produce significantly lower carbon and sulfur emissions than plants powered by coal or oil [6].

Table 10 - Average Retail Prices of Natural Gas by Sector [7]

End-Use Sector	1972	1982	1992	2002
Residential	3.62	7.36	5.89	6.05
Commercial	2.63	6.87	4.88	4.84
Industrial	1.35	5.51	2.84	2.72
	(Units in dollars per 1000 cubic feet)			

C. Petroleum Products

Overall, the US consumption of fuel oil and other petroleum products has remained almost the same between 1972 & 2002, as shown in the table below.

Table 11 - US Consumption of Petroleum Products by Sector [7]

End-Use Sector	1972	1982	1992	2002
Residential/Commercial	2.25	1.24	1.12	1.13
Industrial	4.19	4.06	4.55	4.81
Transportation	8.57	9.31	10.95	12.22
Electric Utilities	1.36	0.69	0.42	0.52
Total	16.37	15.30	17.04	18.68
	(Units in Million barrels per day)			

However, the oil price has fluctuated significantly over the past decades with prices currently topping out around $75 per barrel.

D. Coal

Coal is primarily used as an energy source for power generation by electric utilities in the US (see table below).

Table 12 - US Consumption of Coal by Sector [7]

End-Use Sector	1972	1982	1992	2002
Residential/Commercial	11.7	8.2	6.2	6.3
Industrial	160.1	103.0	106.4	97.9
Electric Utilities	351.8	593.7	795.1	933.4
Total	523.6	704.9	907.7	1037.6
	(Units in Millions of short tons)			

The total US consumption of coal has actually increased between 1972 & 2002 due primarily to the growth in coal use by electric utilities. In all other sectors, the coal consumption has generally decreased. Although coal has maintained a low cost over the past decades ($20/short ton), the price of coal is expected to rise slowly due to reserve depletion and slow growth in labor productivity [6]. This coupled with environmental concerns may cause a future decline of coal consumption in the US.

Energy Rates [5]

A. Electricity Rates

To generate electricity, utilities have to consider several operating costs to determine their rates. Typically, an electrical utility is faced with the following cost items: generation plant, transmission/distribution systems, fuel costs, administrative costs. Other factors that affect the cost of electricity include the generating capacity of the utility, and the demand/supply condition at a given time.

Utilities can tailor their rates to the customer needs for electricity using several methods. Some of the common rate structures used by US utilities are block pricing rates, seasonal pricing rates, and innovative rates.

i.) Common Features of Utility Rates

There are several utility rate features and concepts that the auditor should be familiar with to be able to interpret and correctly analyze the utility billing procedure.

1.) Billing Demand

The billing demand is the demand that is billed by the utility. The billing demand is often determined from the peak demand obtained for one month or billing cycle. The peak demand, also known as the actual demand, is defined as the maximum demand or maximum average measured demand in any fifteen-minute period in the billing cycle.

2.) Power Factor Clause

The power factor is defined as the ratio of actual power used by the consumer to the total power supplied by the utility. The idea behind this is defined as follows: For the same actual power consumed by two customers but with different power factor values, the utility has to supply higher total power to the customer with the lower power factor. To penalize for low power factors, some utilities use a power factor clause to change the billing demand or to impose new charges according to the value of the power factor.

3.) Ratchet Clause

Typically, the utility charges are billed monthly. The demand charges are based on monthly peak demand. However, when peak demand charges for one month is significantly higher than for the other months (such as the case for buildings with high cooling loads in the summer months), the utility has to supply the required peak demand and thus operate additional generators for only one or two months. For the rest of the year, the utility will have to maintain these additional generators. To recover some of this maintenance cost and to encourage demand shaving, some utilities use a ratchet clause in the determination of the billed demand.

4.) Fuel Cost Adjustment

Most utilities have to purchase primary energy sources to generate electricity. Since the cost of these commodities changes over time, the utilities impose an adjustment to their energy charges to account for any cost variation of their primary energy sources. Generally, utilities provide in the description of their rate structure a formula that they use to calculate the fuel cost adjustment.

5.) Service Level

Utilities typically offer several rate structures for a given customer depending on the type of service. For instance, utilities may have different rates depending on the voltage level provided to the customers. The higher the delivery voltage level, the cheaper is the energy rate. In particular, utilities offer reduced rates for demand and/or energy charges to customers that own their service transformers.

ii.) Block Pricing Rates

In block pricing rates, the energy price depends on the rate of electricity consumption using either inverted blocks or descending blocks. An inverted block pricing rate structure increases the energy price as the consumption increases. A descending block rate structure reduces the price as the energy consumption increases. The rate is referred to as a "flat" rate when the energy price does not vary with the consumption level. Block pricing rate structures are commonly used as the existing rate structure in the US. For residential customers, a combination of descending, flat, and inverted rate structures is used throughout the US. For industrial and commercial customers, descending energy rate structures are used almost exclusively.

iii.) Seasonal Pricing Rates

Some electric utilities offer seasonal rate structures to reflect the monthly variations in their generation capacity and energy cost differences. Generally, the utilities that provide seasonal rate structures use different energy and/or demand charges during winter and summer months. The summer charges are typically higher than winter charges for most electric utilities due to higher energy consumption attributed to cooling of buildings.

Based on a survey conducted throughout the US, over 55% of US electric utilities offer seasonal pricing rates for residential customers. Only 5% of electric utilities had residential rates where the winter rate is actually higher than the summer rate. These utilities are located in the Northeast and the West regions of the US. The same survey reveals that over 42% of US utilities use seasonal pricing rates for commercial and industrial customers. Only 7% of utilities surveyed offer rates with higher winter prices for their commercial and industrial customers.

iv.) Innovative Rates

Innovate rates have the main objective to profitably meet the customer needs. Some utilities have new technologies through the use of innovate rates to retain their customers. Several categories of rates can be considered to be innovative rates. In the US, innovative rates can be classified into seven categories:

1.) Time-of-Use (TOU) Rates

The time-of-use (TOU) rates are time-differentiated rates with the cost of electricity varying during specific times of the day and/or the year. The TOU rates, which first appeared in the 1940's, set "on-peak" and "off-peak" periods with different energy and/or demand charges. Generally, the on-peak periods occur during daytime hours and have higher costs of energy and demand than the off-peak periods, which occur during night-time.

2.) Real-Time Pricing (RTP) Rates

Real-time-pricing rates are time-differentiated rates but the cost of electricity varies on an hourly basis. Usually the utilities inform their customers of the hourly electricity prices only a few hours before they take effect, which can be a potential inconvenience for customers.

3.) The End-Use Rates

To encourage customers to install and operate specific energy-consuming equipment, some US utilities offer end-use rates. With these rates, the utilities can impose operation periods and/or efficiency standards for selected and predefined equipment. For example, the air-conditioning rate allows electric utilities to interrupt service or cycle off the air conditioning equipment during specific times. Usually, the end-use rates require separate metering of the equipment.

4.) Specialty Rates

The specialty rates are provided by utilities for specific purposes such as energy conservation and dispatchable customer generation. Energy conservation rates are offered by a limited number of US utilities to foster the use of energy efficient equipment and/or high standards of building materials. Dispatchable customer generation rates are provided to customers that have standby generators on their premises. In exchange for a reduced rate or credit, the customers are requested to operate the generators whenever the utility needs additional generating capacity.

5.) Financial Incentive Rates

Financial incentive rates encompass economic development rates, displacement rates, and surplus power rates. The economic development rates are typically offered to encourage new customers to locate in specific areas that need to be economically revitalized. The displacement rates are offered to customers that are capable of generating electricity to entice them to use utility-provided electricity. The surplus power rates are highly reduced energy rates that are offered to large commercial and industrial customers when the utility has an excess of electric capacity.

6.) Non-Firm Rates

The non-firm rates include interruptible rates, stand-by rates, and load management rates. Interruptible rates are offered to customers that can reduce or even eliminate (interrupt) their electricity needs from the utility. The electricity pricing rates depend on several factors such as the capacity that can be interrupted, the length of interruption, and the notification before interruption. Stand-by rates are intended for customers that require utility-provided electricity on an intermittent basis since they are capable of generating most of their electricity needs. Load management rates are offered by utilities to control the usage of specific equipment such as space conditioning systems during peak periods.

7.) Energy Purchase Rates

The energy purchase rates, also known as buy-back rates, are offered by utilities that want to purchase specific levels of energy or generating capacity from customers. The customers are non-utility electricity generators that qualify under the requirements of Public Utility Regulatory Policies Act (PURPA) such as cogeneration facilities, and independent power producers.

B. Natural Gas Rates

The rate structures for natural gas are similar to those described for electricity. Natural gas utilities rarely charge for peak demands. However, energy shares using block rates or seasonal rates are commonly offered. The price of natural gas is determined based on the interruptible priority class selected by the customer. A customer with a low priority has a cheaper rate but can by curtailed whenever a shortage in the gas supply is experienced by the utility. However, some small quantities of gas are generally supplied to prevent the pipes from freezing and to keep the pilot lights burning.

C. Utility Rates for Other Energy Sources

The utility structures for energy sources other than electricity and natural gas are generally based on a flat rate. The crude oil is typically charged per gallon while coal is priced on a per ton basis. The prices of oil products and coal are set by market conditions but may vary within a geographical area depending on local surcharge and tax rates. Moreover, fuel oil or coal can be classified in a number of grades. The grades of fuel oil depend on the distillation process. The grades of coal depend on the sulfur content and percentage of moisture.

In some applications, it may be possible and desirable to purchase steam or chilled water to condition buildings rather than using primary fuel to operate boilers and chillers. Steam can be available from large cogeneration plants. Chilled water and steam may also be produced based on the economics of scale in district heating/cooling systems. Generally, steam and chilled water are both charged based on either a flat rate or a block rate structure for both energy and demand. The steam is charged based on pound per hour (for demand charges) or thousand of pounds (for energy charges). Meanwhile, the chilled water is charged on the basis of tons (for demand charges) or ton-hours (for energy charges).

Economics

There are several economic parameters that affect a decision between various investment alternatives. To perform a sound economic analysis for energy retrofits, it is important that the auditor by familiar with the most important economic parameters and be aware of the basic economic concepts. The parameters and concepts that significantly affect the economic decision-making include:

- The time value of money and interest rates including simple and compounded interest.
- Inflation and composite interest rate.
- Taxes including sales, local, state, and federal tax charges.
- Depreciation rate and salvage value.

A. Life-Cycle Cost Analysis

The Life-Cycle Cost (LCC) analysis method is the most commonly accepted method used to assess the economic benefits of energy conservation projects over their lifetime. The method is used to evaluate at least two alternative of a given project. Only one alternative will be selected for implementation based on the economic analysis.

B. General Procedure for an Economic Evaluation

It is important to remember that the recommendations for energy conservation projects that stem from an energy audit should be based on an economically sound analysis. The auditor should ask several questions before making the final recommendations such as:

- Will project savings exceed costs?
- Which design solution will be most cost-effective?
- What project size will minimize overall building costs?
- Which combination of interrelated projects will maximize net savings?

- What priority should projects be given if the owner has limited investment capacity?

In any economic evaluation, the following systematic approach should be used:

1.) Define the problem that the proposed retrofit project is attempting to address and state the main objective of the project.
2.) Identify the constraints related to the implementation of the project.
3.) Identify technically sound strategies and alternative to meet the objective of the project.
4.) Select a method of economic evaluation.
5.) Compile data and establish assumptions.
6.) Calculate indicators of economic performance.
7.) Evaluate the alternatives.
8.) Perform sensitivity analyses.
9.) Take into account unqualified effects.
10.) Make recommendations.

Once the project for energy retrofit is selected based on an economic analysis, it is important to decide on the financing options to actually carry out the project and implement the measures that allows a reduction in energy cost of operating the facility.

There are several alternatives that the owner or the facility manager can use to finance an energy retrofit project. These alternative can be found under three main categories:

- Direct Purchasing
- Leasing

- Performance Contracting

Estimating Energy Savings

After an energy audit of a facility, a set of energy conservation measures (ECMs) are typically recommended. However, several of the ECMs that are cost-effective are often not implemented due to a number of factors. The most common reason for not implementing ECMs is the lack of internal funding sources. Energy projects have to compete for limited funds against other projects that are perceived to have more visible impacts, such as improvements in productivity within the facility.

Over the last decade, a new mechanism for funding energy projects has been proposed to improve energy efficiency of existing buildings. This mechanism is called performance contracting. An important feature of performance contracting is the need for a proven protocol for measuring and verifying energy cost savings. This measurement protocol has to be accepted by all the parties involved in the performance contracting project.

The predicted energy savings for energy projects based on an energy audit analysis are generally different from the actual savings measured after implementation of the energy conservation retrofits. Direct measurements of energy savings from energy efficiency retrofits or operational changes are almost impossible to perform since several factors can affect energy use such as weather conditions, levels of occupancy, and HVAC operating procedures. For instance, during abnormally cold and warm weather years, energy consumption for a commercial building can be respectively 28% higher and 26% lower than the average weather year energy use.

Summary & Case Study Example

In summary, the benefits of retrocommissioning (energy auditing) are numerous. The following lists the benefits:

- Identifies system operating, control, and maintenance problems.
- Aids in long-term planning and major maintenance budgeting.
- Helps ensure a healthy, comfortable, and productive working environment for occupants.
- Reduces energy waste and ensures that energy-using equipment operates efficiently.
- Provides energy cost savings that often pay back investment.
- Reduces maintenance costs; reduces premature equipment failure.

- Provides complete and accurate building documentation; expedites troubleshooting.
- Provides appropriate training to operating staff to increase skill levels; increases staff effectiveness in serving customers or tenants.
- Reduces risk and increases the asset value of the building.

A 1996 study of the cost-effectiveness of retrocommissioning in 44 existing buildings revealed attractive paybacks, even when estimates were based solely on energy costs savings. Table 4 summarizes the 44 buildings that were retrocommissioned. Retrocommissioning proved to have modest project costs of between \$10,000 and \$52,000, resulting in whole-building energy savings of 5–15%. Based on energy savings alone, for an investment of 5 to 43 cents per square foot, commissioning existing buildings delivered simple paybacks that rarely exceeded 4 years—and were often 2 years or less. [1]

The study showed that retrocommissioning costs vary according to the complexity of the systems, the number of pieces of equipment, and the objectives or scope of the retrocommissioning project rather than by building type. Retrocommissioning costs for only 10 of the buildings exceeded 28 cents per square foot. Yet, 9 of these 10 had simple paybacks of 2 years or less. The buildings ranged from medical facilities and schools to office buildings. The actual project cost for these 10 buildings ranged from \$14,000 to \$52,000, but for the majority (8 buildings) project costs were about \$24,000. The higher cost per square foot for these buildings was mostly a function of their *smaller size*. Only two of them were over 100,000 ft^2. The rest were between 44,000 and 77,000 ft^2. In comparison, the largest building in the study (623,000 ft^2) cost the most to commission—

$80,000—but the cost per square foot was only 13 cents. Simple payback for this building was only 6 months.

Although little research has been completed to document the link between comfort and productivity, common sense tells us that comfortable employees are more productive. The few studies that have been conducted on this topic agree. One estimate of productivity losses in a typical office building where occupants complained of discomfort was stated in the following terms [2]: Presentation to National Electric Light and Power Association, 1989, by Cedric Trueman, Sr., technical advisor for British Columbia Buildings Corp.

Payroll costs	$150/ft^2/year
Productivity lost to complaint time	$0.10/ft^2/year

This example assumes that this typical building has one occupant per 200 ft^2 of space and an annual payroll cost of $30,000/person or $150/ft^2 of office space. If one out of every five employees spends only 30 minutes a month compensating for or complaining about the lighting or the temperature or both, the employer loses $0.10/ft^2 in annual productivity. For a 100,000-ft^2 building, this amounts to $10,000 per year. Because uncomfortable employees probably spend more than just half an hour each month addressing building comfort issues, the actual losses may be higher.

If comfort problems are severe enough to make employees ill, business owners can sustain additional productivity losses and increased liability risks. Building operation costs also increase, as operators respond to more complaints.

These problems concern not only building owners who occupy their buildings: they affect owners who rent building space as well. Tenants who are experiencing comfort and productivity problems may not remain tenants for long. Based on the estimated costs shown in the table below [3], losing a tenant in Class A office space can be expensive.

Cost of losing a tenant

Five-year lease value	$262,500
Rent loss due to vacancy	$26,250
Improvements for new tenant	$52,500–70,000
Leasing commission	$13,125
Total cost of losing tenant	$91,875–109,375

Assuming an average office size of 3,500 ft^2, rented at $15/$ft^2$ a year, a typical five-year lease has a value of $262,500. If a tenant leaves, this space will remain vacant an average of 6 months, for a total rent loss of $26,250. Improvements and build-outs to satisfy a new tenant usually run $15–$20/ft^2, or $52,500–$70,000 in this case. On top of all this, the building owner often pays a leasing commission of 5% of the 5-year lease value, or $13,125. Thus, the total cost of losing one tenant could range from $91,875 to $109,375, or 35 to 42% of the 5-year lease value. If a building develops a reputation for being uncomfortable and unproductive, the vacancy period could last longer. Word of uncomfortable building conditions is likely to spread among business peers; market research shows that dissatisfied customers—in this case, tenants—are likely to complain to 7 to 10 of their peers.

References

[1] J. Gregerson, “Cost Effectiveness of Commissioning 44 Existing Buildings,” in *Proceedings of the National Conference on Building Commissioning* (Huntington Beach, Calif., April 28–30, 1997).

[2] Presentation to National Electric Light and Power Association, 1989, by Cedric Trueman, Sr., technical advisor for British Columbia Buildings Corp.

[3] ASHRAE presentation by David Zier of Melvin Mark Company. The Melvin Mark Company owns, manages, and develops real estate. Available at www.cbs.state.or.us/ external/ooe/cons/commsave.htm.

[4] Bloomfield, D.P. and Fisk, D.J., *The Optimization of Intermittent Heating, Building and Environment*, 12, 43, 1977.

[5] Azebergi, R., Hunsberger R., Zhou, N., *A Residential Building Energy Audit*, University of Colorado, 2000.

[6] EIA, Energy Information Agency, Energy Facts, 2000, DOE/EIA-0469, Washington, DC, 2004.

[7] EIA, Energy Information Agency, Annual Review of Energy, DOE, EIA, Washington, DC, 2004.

[8] Czarkowski, D., and A. Domigan, "Performance of Electric Power Meters and Analyzers in Adjustable Speed Drive Applications", ASHRAE Transactions, 103(1), 1997.

[9] Herron, D.J., *Energy Engineering*, 1999.