ENERGY ANALYSIS OF BOK BUILDING

By

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1993

Submitted to the Faculty of the Graduate College of the
Oklahoma State University in Partial Fulfilment of
The Requirements for the Degree of
MASTER OF SCIENCE
December, 1999

ENERGY ANALYSIS OF BOK BUILDING

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ACKNOWLEDGEMENTS

At first, I would like to express my deepest appreciation to Dr. J. D. Spitler who has shown so much guidance and patience to me in the past two years. His professional knowledge and wisdom contributed much to this project. I could not ask for a better advisor, mentor and friend.

Also, my sincere appreciation extends to Dr. Dan Fisher and Dr. S. J. Rees. Their technical insights have shed light during some of the darkest moments in my research.

I would like to thank Williams Headquarters Building Company for funding this project. I want to express special thanks to Mr. G. D. Shahadi, without his consistent help, this project would not be done.

I also thank Dr. R. D. Delahoussaye and Dr. R. L. Dougherty for their time and invaluable advice while serving in my committee.

Moreover, I want to express my gratitude to my parents, Ming-chao Feng and Yu-e Zhang for their unconditional love in my life. Without their sacrifice and support, my dream to be educated in U. S. will never come true.

At last, but not the least, I would like to thank my dear husband Ning So whom I have met and "used" much during the study because just so happened that he works in the BOK building. Thanks forever for your love and support.

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CHAPTER 1 INTRODUCTION

1.1 Introduction

Heating, ventilation, and air conditioning (HVAC) systems can be the largest energy consumers in buildings. In addition to facilitating employee productivity, a properly designed, installed, and maintained HVAC system can greatly reduce energy consumption and large operating costs of a building.

The Bank of Oklahoma Tower (BOK), owned and operated by Williams Headquarters Building Company (WHBC), is a 52-story multipurpose building located in downtown area of Tulsa, Oklahoma. It measures about 160 feet by 160 feet and is about 1361 feet in height. As the tallest building in the State of Oklahoma, the BOK houses about 1500 employees in nearly 1,200,000 gross square feet. The BOK receives steam and chilled water from a nearby-centralized district heating and cooling system, which is owned by Trigen-Oklahoma District Energy Corporation.

The goal of this project is to investigate retrofits or system modifications that would be economically feasible and result in minimum energy costs for the BOK. The building was surveyed at first to get information about its physical properties and operation. It was then simulated with a detailed energy analysis program, the Building Loads Analysis and System Thermodynamics (BLAST) program. At the same time, actual energy consumption data was collected for several different time periods by using the building energy management system. Weather data for these same periods was obtained from a nearby weather station.

Using the weather data and the building model, a comparison between the calculated energy consumption and the measured energy consumption was made. The building model was then calibrated (i.e., various input parameters were adjusted to match the measured data.). Finally, by using the calibrated model, a number of potential retrofits were analysed.

This energy research project is funded by the Williams Headquarters Building Company.

A brief overview of the procedure and tools used in this project is given in this chapter. A more detailed discussion of the building and the model is given in Chapter 2. The weather data collection and processing are described in Chapter 3. Details of the calibration procedure are given in Chapter 4. The in-depth retrofit analysis is provided in Chapter 5, and in Chapter 6 we make conclusions and recommendations.

1.2 Background

1.2.1 BLAST

We choose BLAST as the main tool of this energy analysis project for the following reasons:

1. The BLAST program uses extremely rigorous and detailed algorithms to compute zone loads, to simulate fan systems, and to simulate boiler and chiller plants.

2. The BLAST program has a very powerful and user friendly interface, The Heat Balance Loads Calculator (HBLC). HBLC is accompanied by a library that contains the properties of all materials and wall, roof, and floor section listed in ASHRAE Handbook of Fundamentals.

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3. The program execution time is brief enough to allow many alternatives to be studied economically.

1.2.1.1 Heat Balance Method

The Building Loads Analysis and System Thermodynamics (BLAST) program is a comprehensive program for investigating energy consumption and energy system performance in new or retrofit buildings. In addition to performing design day calculations necessary for mechanical equipment design, BLAST also estimates the annual energy performance of the facility, which is essential for determining compliance with design energy budgets.

The heat balance method is used in BLAST for cooling load and heating load calculation. Three different heat balances are performed in the BLAST loads calculations: the outside surface heat balance, the inside surface heat balance, and the zone heat balance. Each of these heat balances is performed separately on all of the zones and surfaces within a given building description.

The goal of the outside surface heat balance is to determine the outside surface temperature ("Outside" means "outside the zone" and does not necessarily mean outdoors). The inside surface temperature, heat storage in the surface, solar radiation, thermal radiation, and convection affect the outside surface temperature.

The goal of the inside surface heat balance is to determine the inside surface temperature ("Inside" means the side that is exposed to the zone). The inside surface temperature is affected by factors which include the outside surface temperature, heat

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storage in the surface, radiant transfer with other surfaces in the zone, solar radiation entering the zone, radiant energy produced by internal heat gains, and the zone air temperature.

The goal of the zone heat balance is to determine the zone air temperature. The zone air temperature is affected by zone surface temperatures, convective energy produced by internal heat gains, infiltration, and heating or cooling energy produced by the system.

Figure 1-1 shows three heat balances performed simultaneously in a zone load calculation. For a given hour of a simulation, BLAST performs the outside surface heat balances, the inside surface heat balances, the zone heat balances, and then repeats the process. Each heat balance adjusts the surface temperatures and the zone temperatures so that the next heat balance sees slightly different conditions. The iterations continue until the solution converges and the conditions are no longer changing. At this point the simulation for one hour is complete.

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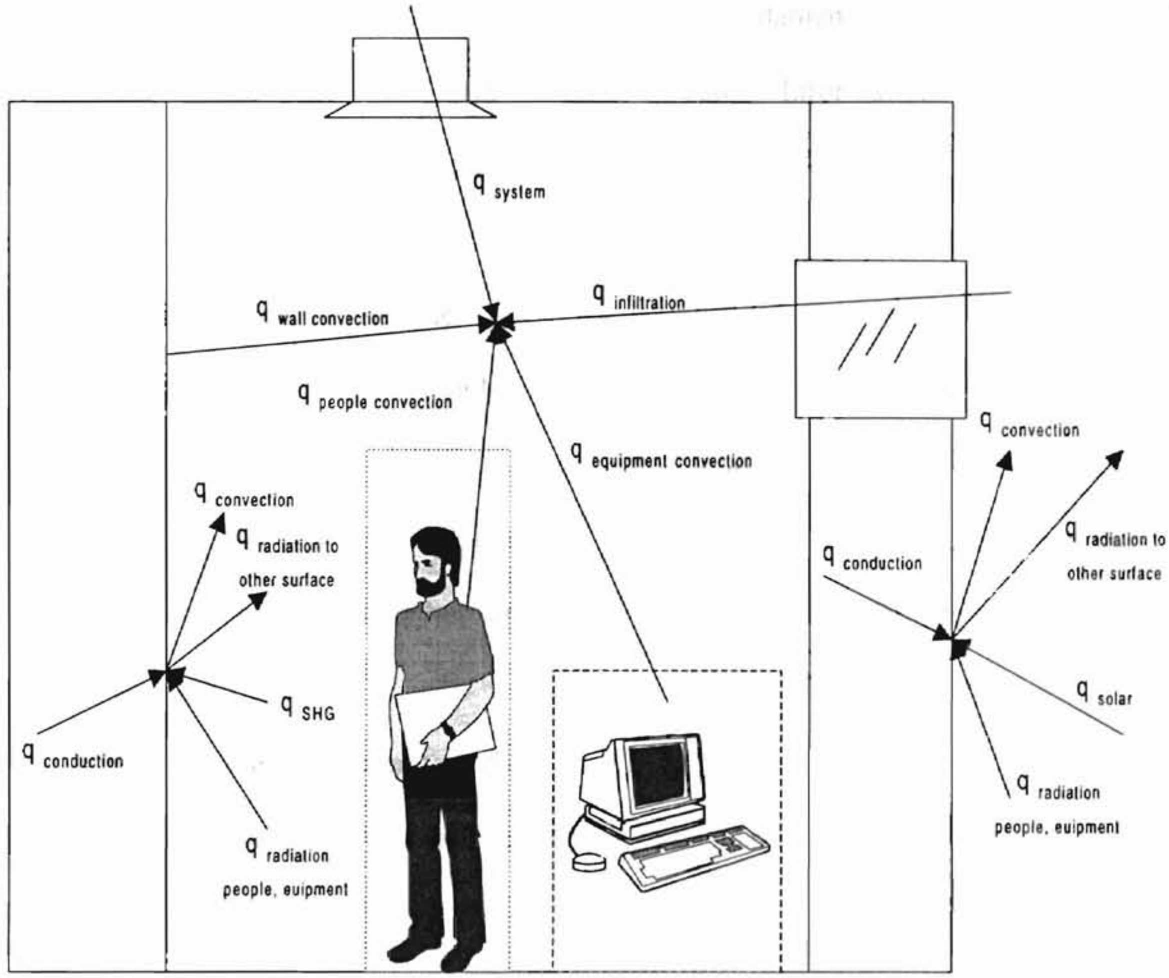

Figure 1-1 Heat Balances in a Zone

1.2.1.2 Main Programs

BLAST comes with auxiliary programs, two of which, HBLC and WIFE are utilised in this project and described below.

The HBLC program provides a powerful and user-friendly Windows interface to enter the input and calculate heating and cooling loads, allowing the user to access complex heat-balance algorithms quickly and easily by a graphical approach. Hourly heating and cooling loads is computed and can be graphically displayed. Also, the HBLC

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program is accompanied by a library that contains the properties of all materials and wall, roof, and floor sections listed in ASHRAE Handbook of Fundamentals.

Weather data is processed in the WIFE (Weather Information File Encoder) program of BLAST. The WIFE program has three functions: to create processed weather files for running BLAST, to modify existing weather files, and to report the status of the data contained in the raw weather file.

When creating a BLAST readable weather data, a user written input file is required, which contains general command and information for running WIFE, such as run periods, site of weather data, tape type, etc. Raw weather tapes may be different due to the difference of sources. Weather tapes such as TRY, TMY, SOLMET, ASCII are acceptable in WIFE program.

Two output files are generated after running Wife program: one is a user readable output file and the other is a processed weather file to be read by BLAST.

1.2.1.3 Main Structure

The BOK building description is reflected in the BLAST input file, which is a text file generated through HBLC and read as input by the BLAST program. It consists of four major sections: lead input section, building description section, fan system description section and central plant description.

The lead input defines the overall simulation parameters, which are stored in BLAST libraries. All the commonly used information is stored in the library under convenient names and may be specified by the user in the input language. The library is

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divided into smaller sections, such as the schedule library (occupancy, equipment usage, infiltration, etc), the locations library (latitude, longitude, and time zones for named locations), the design days library (weather data for design day), the controls library (space temperature control strategies), the materials library (the thermodynamic properties of typical building materials), the walls library, floor library, etc. Materials, as well as wall, roof, and floor sections found in the BLAST library are from the ASHRAE Handbook of Fundamentals. The BLAST program language also provides the user with the capability to define additional entries in any of the library's subsets or to print the contents of the entire library.

Figure 1-2 shows the structure of BLAST described above and the relation among zone simulation, fan system simulation and plant simulation. All of them are generated from the input file, and their simulation results are included in the BLAST output file. The weather data is applied to these three simulation steps, citing the environment of the whole simulation.

The building simulation begins by performing the zone simulation at first, giving information about zone loads, zone temperature, etc. Fan system simulation is then performed on the base of the zone simulation results, and as a result, it provides the information on system demands including electric power, gas, steam, hot water, and chilled water. The central plant simulation is performed next, using the fan system simulation results and then generating the corresponding plant demands. It contains information about the demands of electric power, gas, fuel, and purchased heating and cooling.

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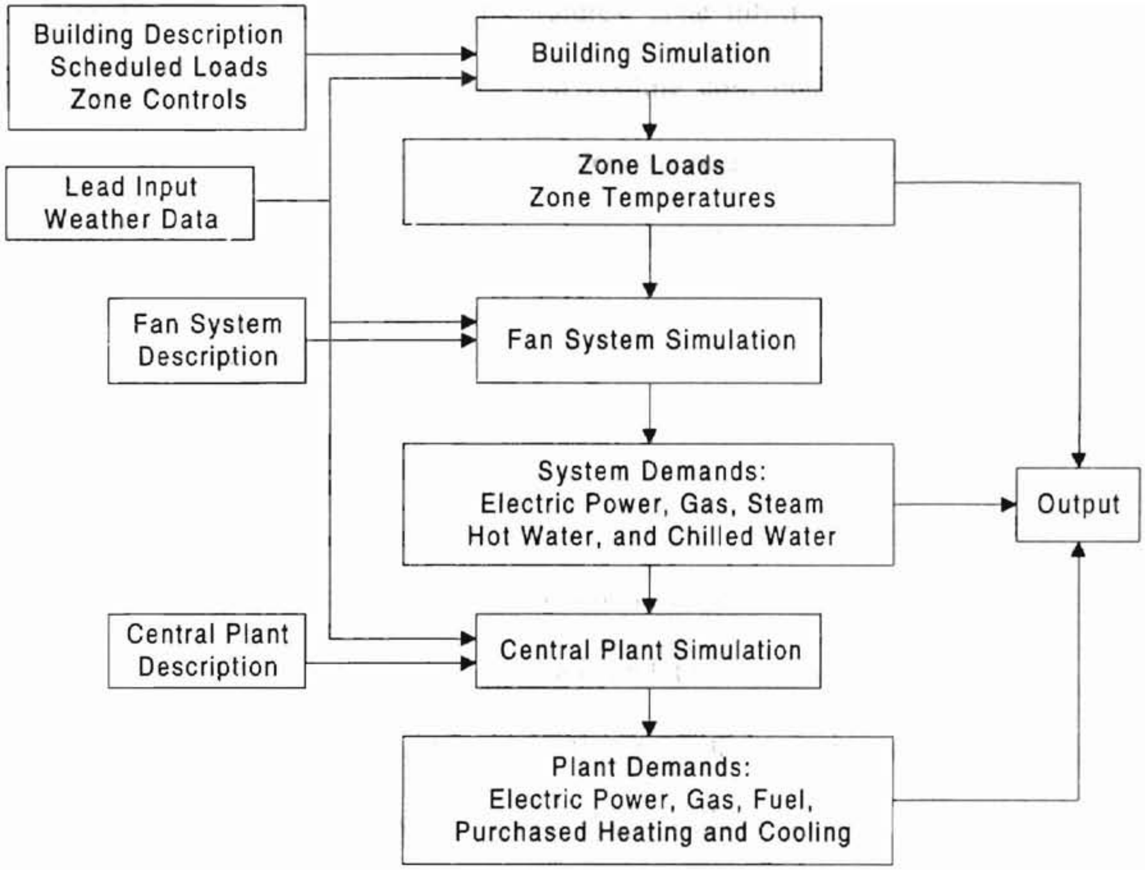

Figure 1-2 BLAST Structure

Simulation results can be reported in two ways. After each run of simulation, an output file is generated automatically, and it includes default reports and user specified reports, giving monthly information on building, fan system and central plant simulation. Errors and warning information can also be found in the output file after the program crashes, which is very helpful for user to debug and modify the program. The second type of output utilizes the Report Writer capabilities of BLAST, and they trace the specified variables hour by hour for time period requested by the user. Four kinds of variables are available in Report Writer. Zone variables contain hourly reports of number of occupants,

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electric demand for lights, zone temperatures, zone infiltration, etc. System variables describe hourly load on heating coil and cooling coil, hourly return air temperature, system electric load, etc. Plant variables reflect the hourly simulation results of heat and cooling demand from all fan systems, hourly total electric demand, etc.

1.2.2 Calibration Tools

1.2.2.1 Haberl

Many studies have shown that calibrations at the hourly level offer the best alignment between the simulation program and the measured data. However, it is a significant problem to quickly and efficiently search through thousands of hourly output data to see the comparison between measured data and simulated output.

Haberl [1993] developed a graphical tool kit, a three-dimensional comparative plot routine that allows one to efficiently compare (and thus calibrate) computer predicted data to measured data from an existing building. The case study building is a four-story, multipurpose building located at university campus near Houston, and its actual hourly electrical consumption was collected at first. To demonstrate the effectiveness of this procedure, three different types of day-typing routines in DOE-2 were used, and correspondingly three different types of electrical consumption output were viewed through 3-D plots. It is straightforward to see hourly differences among three different types of day typing from those figures. Haberl then concluded that the availability of comparative three-dimensional surface plots significantly improved the ability to view small differences between the simulated and measured data.

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1.2.2.2 Graphical Tools

Two-dimensional graphs are used in this project to perform comparisons during the calibration. Both the actual and simulated data are processed and placed into the columns in the spreadsheet of Microsoft Excel, and the two-dimensional graph is generated from them. This is a quick and easy way to compare the small difference between the measured and simulated data.

1.2.3 Mesonet

Mesonet is the Oklahoma's automated weather station network. Operated since early 1994, Mesonet consists of 111 sites scattered throughout Oklahoma and separated by an average distance of 19 miles. Each site measures at least the following parameters: air temperature, humidity, barometric station pressure, winds speed and direction, rainfall and snowfall, solar radiation, and soil temperature. Every 15 minutes, data collected at 5 minutes intervals are relayed through a telecommunication network to a central base-station computer located at the Oklahoma Climatological Survey in Norman, where the data are tested, archived and distributed to various customers. Thus, not only past weather conditions, but also the near real time (generally within 15 minutes) weather data across the state are available through Mesonet.

1.2.4 Equipment Heat Gain

The actual equipment loads of commercial buildings has always been an uncertain factor for HVAC designers and energy analysts. It is difficult to know exactly how many

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and what kinds of office equipment are in use at a specific time. 1993 ASHRAE Handbook-Fundamentals gives "In offices having computer display terminal at most desks, heat gains range up to 15 BTU/h.ft^2 (4.4 W/ft^2)", but does not provide a detailed guidance for assumption in actual needs.

Komor [1997] made an extensive study of measured equipment load data drawn from 44 typical commercial buildings covering 1.3 million ft^2. He reported that the mean equipment loads for these buildings was 0.83 W/ft^2, far below the typical assumption of 2-5 W/ft^2. Based on these data, he pointed out that the overestimation of office equipment heat gains is typical. He verifies his point by calculating the power consumption of office equipment in a typical commercial building, and the equipment load was 1.02 W/ft^2, which was consistent with the measured data.

Additionally, he analyzed the general trend of office equipment using in the next decade. Noticing the contribution of manufacturers to increase the energy efficiency of office equipment and the declining rate of growth of equipment density, he concluded that office equipment load should not be greater than 1.25 W/ft^2 except for some compelling reasons.

1.2.5 Tulsa Weather Condition

Tulsa lies in the North-East part of the state of Oklahoma at an elevation of 700 feet above sea level.

The climate of Tulsa is essentially continental in character. Temperatures occasionally fall below zero in winter but only last a very short time. Temperatures of 100 degrees or higher are often experienced from late July to early September, but are

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usually accompanied by low relative humidity and southerly breeze. Spring has an abundance of rain and the fall season is long with a great number of sunny days and cool nights. The greatest amounts of snow are received from January to early March. The snow is usually light and only remains on the ground for brief periods. Table 1-1 gives an overview of Tulsa weather condition.

Annual Heating	Annual Cooling	Winter design conditions		Summer design conditions		Annual
Design Days	Design Days	99%	97.5%	Dry Bulb 0.5%	Wet Bulb 0.5%	Precipitation
3877	1802	8 ° F	13 ° F	96 ° F	74 ° F	39.9 In.

Table 1-1 General Tulsa Weather Condition

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CHAPTER 2 DESCRIPTION OF BOK BUILDING

2.1 The Building and the Model

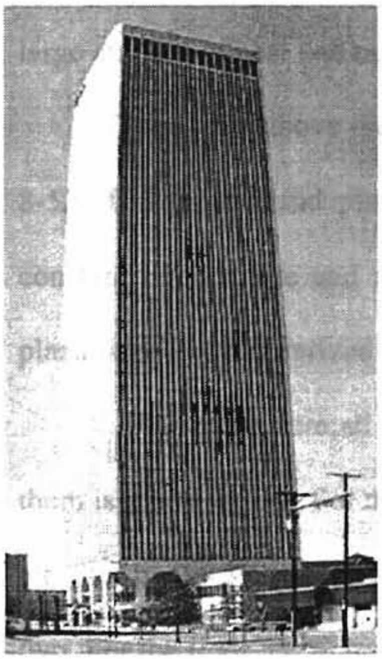

Figure 2-1. Photo of the BOK Building

2.1.1 The Building

The BOK building is a 52-story multipurpose office building located in downtown area of Tulsa. It measures about 160 feet by 160 feet and is about 1360 feet in height. The BOK is oriented in a 20° Northeast to North direction and is not shaded by any other structures. The building has a large area of glazing. About 60-70% of the exterior envelope is glazed, and this consists of about 247,000 ft^2 double-pane windows

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(floors 8-49) and 17,600 ft^2 single-pane windows (plaza and floors 50-52) without set back. All the glazing is coated with film.

There are two underground floors in the BOK – the service floor and the garage floor. The service floor includes a large data center, in which the equipment generates large amount of heat and needs 24-hour air conditioning throughout the year.

The floors above the ground consist of the ground floor, the plaza floor and floors 8-52. The ground and plaza floors are multi-functional floors, both of which require constant temperature and moisture for 24 hours throughout the year. Additionally, the plaza floor is characterized as great height and large area of glazing.

Floors 8-52 are all similar to each other and the floor-to-floor height for most of them is 12.08 inches. For the floors 8-24 (type 1), the core of each floor consists of three elevator banks. For the floors 25-38 (type 2), the elevator banks on each floor decrease to two. For the floor 39-50 (type 3), there is only one elevator bank in the core of each floor. There is no elevator in the floor 51 and 52. Table 2-1 lists the heights for each floor, and Figure 2-2 gives the information about changes of core plans and the relevant heights.

No.	Floor	Height
1	Garage	14 ft.
2	Service	16 ft.
3	Ground	20 ft.
4	Plaza	20 – 36 ft.
5	Floor 8-9	14.8
6	Floor 10-46	12.8 ft
7	Floor 47-48	16.8 ft
8	Floor 49-50	17.5 ft
9	Floor 51	12 ft
10	Floor 52	11.1 ft

Table 2-1 Height of Each Floor

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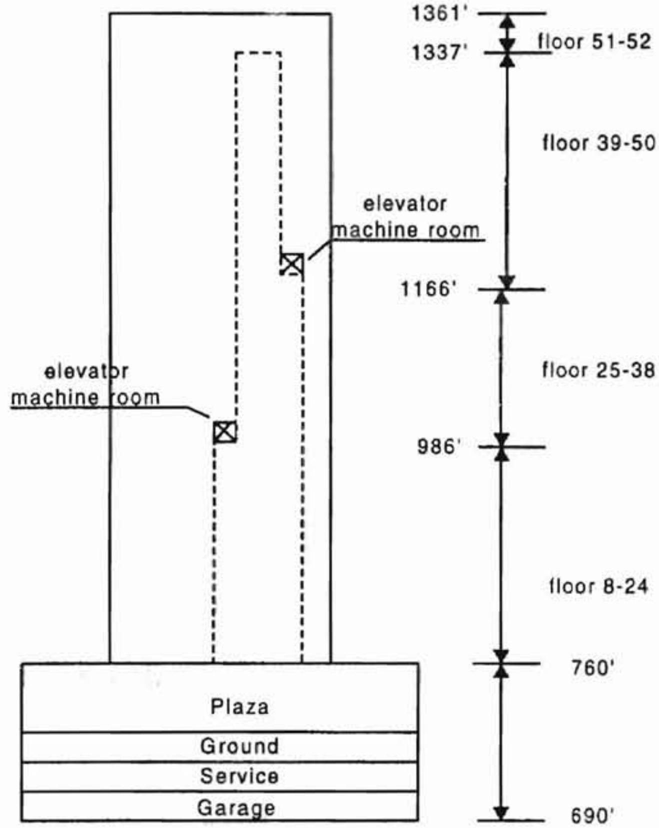

Figure 2- 2 The BOK Cross Sectional View

2.1.2 Building Model

2.1.2.1 Division of Floors

According to the different core plans, different HVAC systems and different operations, we divided the whole building into 9 kinds of typical floors as the first step to build a model. That is:

1. Garage
2. Service
3. Ground
4. Plaza
5. Floor 8^{th} – 24^{th}

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6. Floor 25^{th} - 38^{th}
7. Floor 39^{th} – 48^{th}
8. Floor 49-51^{st}
9. Floor 52^{nd}

2.1.2.2 Building Elements

We collected the information on the building elements by on-site surveys, reviewing plans and interviewing operation engineers. Based on the information obtained a number of material and building elements have been defined in BLAST input files. This includes exterior and interior walls, ceilings, floors, roofs, slab on grade floor, basement wall and window. The following set of tables and figures show the composition of the building elements and the relevant thermal properties.

Tables 2-2, 3, 4, 5, 6 and 7 and figures 2-3, 4, 5, 6, 7, and 8 are about external wall, partition, ceiling, floor, roof, and slab on grade floor as well as their thermal properties. There are two kinds of floors and ceilings. Floor type1 and ceiling type1 apply to floors 8-24 & 38-46 & 48-49, while floor type2 and ceiling type2 are used in floor 25-37 & 47. We describe windows by defining the thermal resistance and shading coefficient of glass in BLAST. Two kinds of windows, single-pane for plaza and floors 51-52 and double-panes for floors 8-50 are created. Figure 2-9 shows compositions of both kinds of windows, and Table 2-8 contains detailed information about optical properties.

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Layer	Thickness	D	C_P	K
Material	Inch	lbm / ft^3	Btu / (lbm-F)	Btu / (hr-ft-F)
alumwall1				
Aluminum1	1 / 8	171.00	0.214	128.00
Board Installation (IN81)	R = 1.01 $(hr\text{-}ft^2\text{-}F)$ / Btu			
MV Hollow CBLK (IN82)	8	53.00	0.20	0.3876
Standard Batt Insulation (IN82)	R = 1.01 $(hr\text{-}ft^2\text{-}F)$ / Btu			
GYP Sheathing Board (E6)	1 / 2	49.00	0.20	0.0926

Table 2-2 External Wall Specification

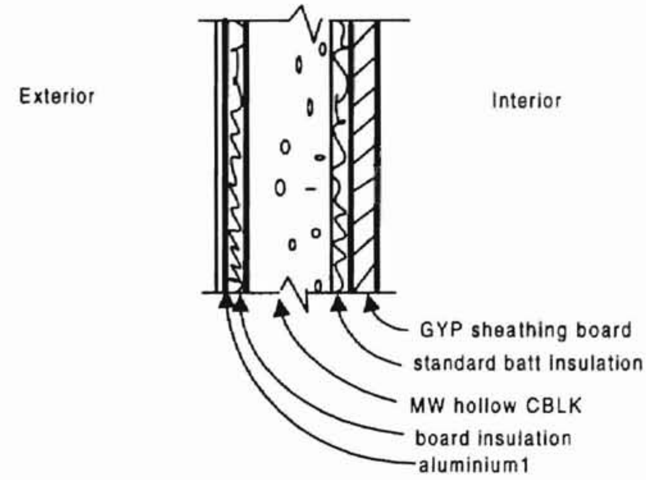

Figure 2-3. External Wall

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Layer Material	Thickness Inch	D lbm / ft³	C_P Btu / (lbm-F)	K Btu / (hr-ft-F)
Type 1: partition 02				
Plaster (E1)	3 / 4	100.00	0.20	0.42
LW Concrete Block (C2)	4	38	0.20	0.22
Plaster (E1)	3 / 4	100.00	0.20	0.42
Type 2: partition 23				
Plaster (E1)	3 / 4	100.00	0.20	0.42
Airspace Resistance (B1)	$R = 0.910$ (hr-ft²-F) / Btu			
Plaster (E1)	3 / 4	100.00	0.20	0.42

Table 2-3 Partition Type 1 & 2

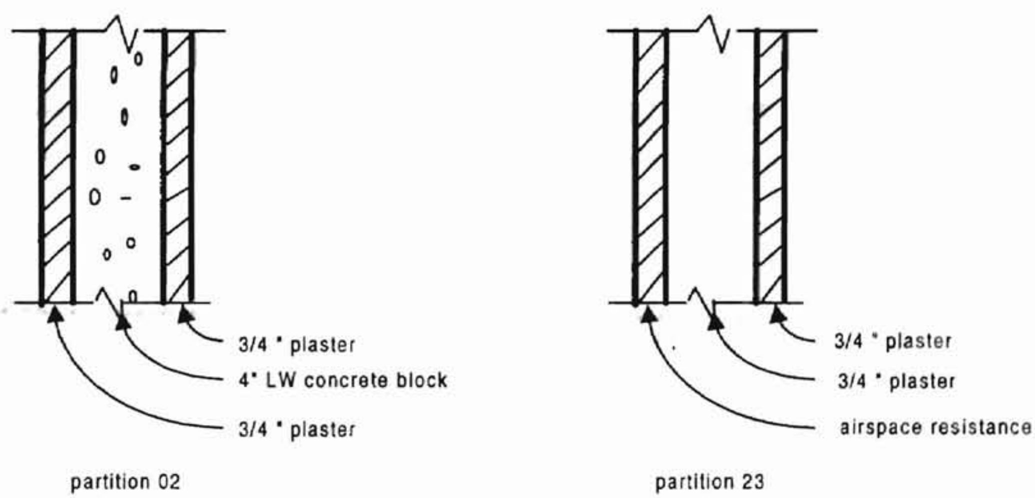

Figure 2-4. Partition Type 1 & 2

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Layer	Thickness	D	C_P	K
Material	Inch	lbm / ft^3	Btu / (lbm-F)	Btu / (hr-ft-F)
Type 1: cceil1				
Carpet Fibrous Pad	R = 2.0803 (hr-ft^2-F) / Btu			
Concrete1	3.5	61.00	0.20	0.47
Airspace-ceiling	R = 0.9998 (hr-ft^2-F) / Btu			
GYP Board (E8)	5 / 8	49.00	0.20	0.0926
Type 2: cceil2				
Carpet Fibrous Pad	R = 2.0803 (hr-ft^2-F) / Btu			
Concrete1	3.5	61.00	0.20	0.47
Airspace-ceiling	R = 0.9998 (hr-ft^2-F) / Btu			
Acoustic Tile (E5)	3 / 4	30.00	0.20	0.035

Table 2-4 Ceiling Type 1 & 2

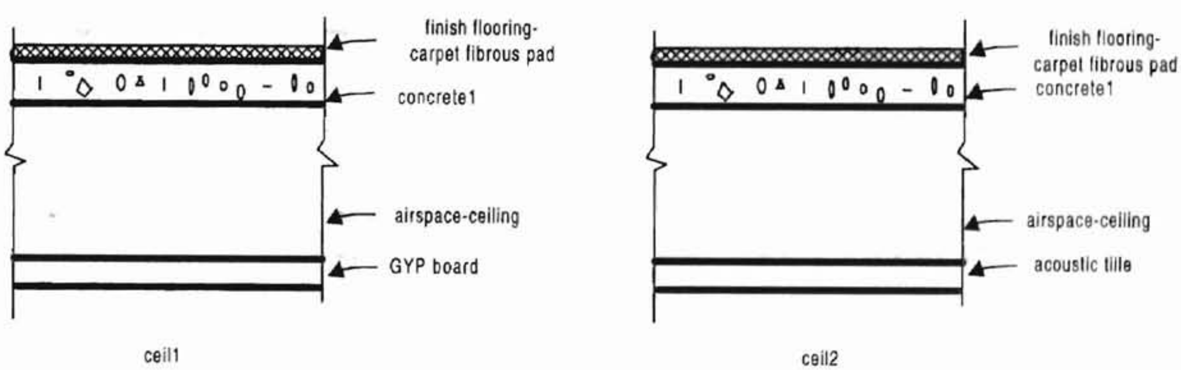

Figure 2-5. Ceiling Type 1 & 2

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Layer Material	Thickness Inch	D lbm / ft^3	C_P Btu / (lbm-F)	K Btu / (hr-ft-F)
Type 1: cfloor1				
GYP Board (E8)	5 / 8	49.00	0.20	0.0926
Airspace-ceiling	$R = 0.9998$ (hr-ft^2-F) / Btu			
Concrete1	3.5	61.00	0.20	0.47
Carpet Fibrous Pad	$R = 2.0803$ (hr-ft^2-F) / Btu			
Type 2: cfloor2				
Acoustic Tile (E5)	3 / 4	30.00	0.20	0.035
Airspace-ceiling	$R = 0.9998$ (hr-ft^2-F) / Btu			
Concrete1	3.5	61.00	0.20	0.47
Carpet Fibrous Pad	$R = 2.0803$ (hr-ft^2-F) / Btu			

Table 2-5 Floor Type 1 & 2

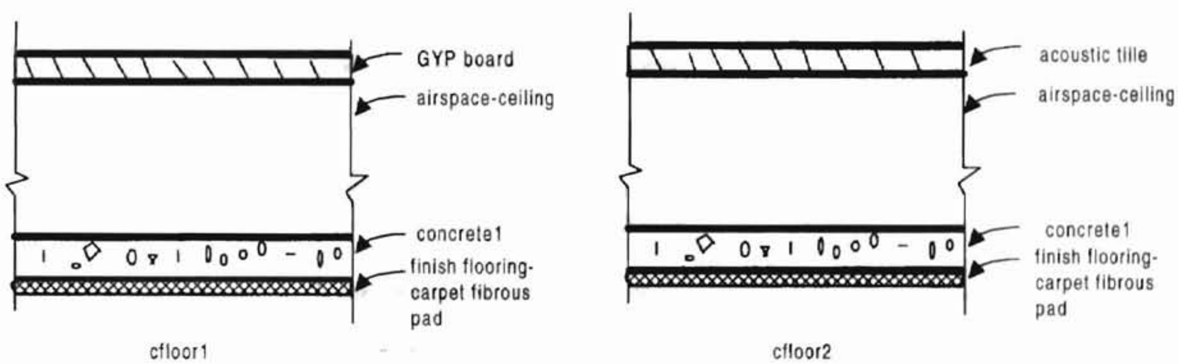

Figure 2-6. Floor Type 1 & 2

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Layer Material	Thickness Inch	D lbm / ft^3	C_P Btu / (lbm-F)	K Btu / (hr-ft-F)
Roof 01				
HW Concrete (C12)	2	140.00	0.20	1.00
Airspace Resistance (B1)	R = 0.91 (hr-ft^2-F) / Btu			
Dense Insulation (B6)	2	5.70	0.20	0.025
Slag or Stone (E2)	1 / 2	55.00	0.40	0.83
Felt and Memberane (E3)	3 / 8	70.00	0.40	0.11
HW Concrete (C5)	4	140.00	0.20	1.00
Ceiling Airspace (E4)	R = 1.00 (hr-ft^2-F) / Btu			
Acoustic Tile (E5)	3 / 4	30.00	0.20	0.035

Table 2-6 Roof Type

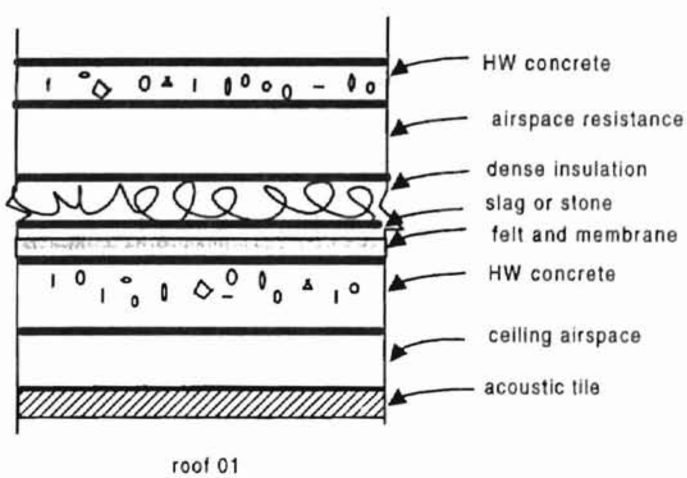

Figure 2-7. Roof Type

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Layer	Thickness	D	C_P	K
Material	Inch	lbm / ft^3	Btu / (lbm-F)	Btu / (hr-ft-F)
Floor Slab 8 IN				
Dirt	12	65.00	0.20	0.10
HW Concrete (C10)	8	61.0	0.20	0.60

Table 2-7 Slab on Grade Floor

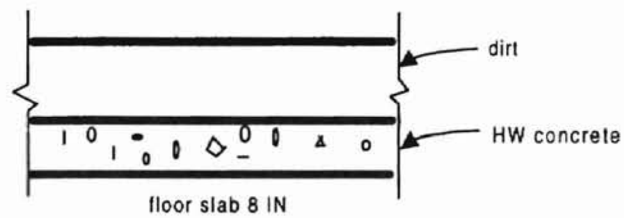

Figure 2-8. Slab on Grade Floor

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Type: wind1		
Double glazed, tinted, aluminum framed with thermal break		
Layer Material	Thickness (In.)	Coating
Bronze Glass	1 / 4	Yes
Air Space	1 / 2	No
Clear Glass	1 / 4	Yes
R = 0.980 (hr-ft^2-F) / Btu, SC = 0.57		
Type 2: wind2		
Single pane bronze, polished, tempered glass, aluminum frame		
Layer Material	Thickness (In.)	Coating
Bronze Glass	1 / 2	Yes
R = 0.070 (hr-ft^2-F) / Btu, SC = 0.71		

Table 2-8 Window Type 1 & 2

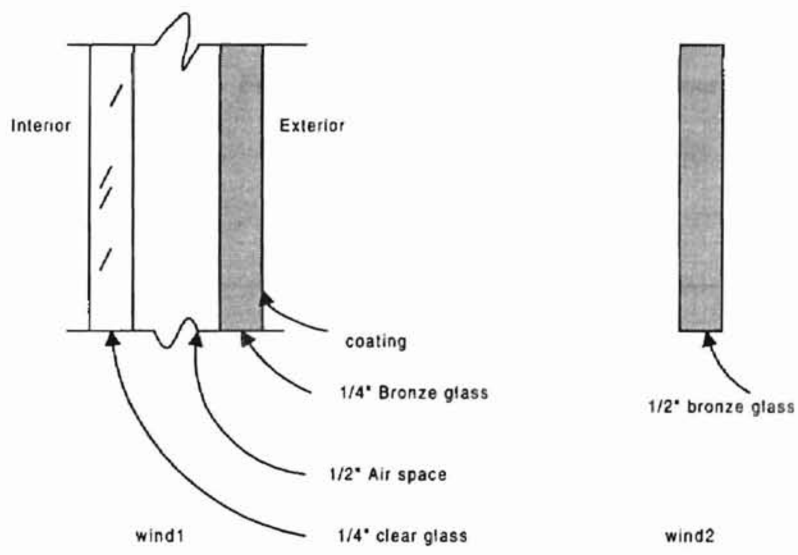

Figure 2-9. Window Type 1& 2

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2.1.2.3 Layout of the Zone

The zone layouts for each kind of typical floor are shown in the following figures. In Figures 2-15 and 2-16, the numbers in parentheses represent zone numbers. These zones are on different floors from other zones but laid out in the same way. Floors where these zones site are included in the parentheses in the figure name correspondingly.

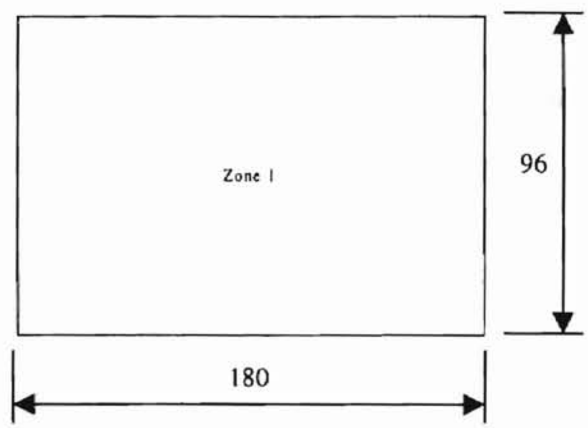

Figure 2-10. Zone Layout for Garage Floor

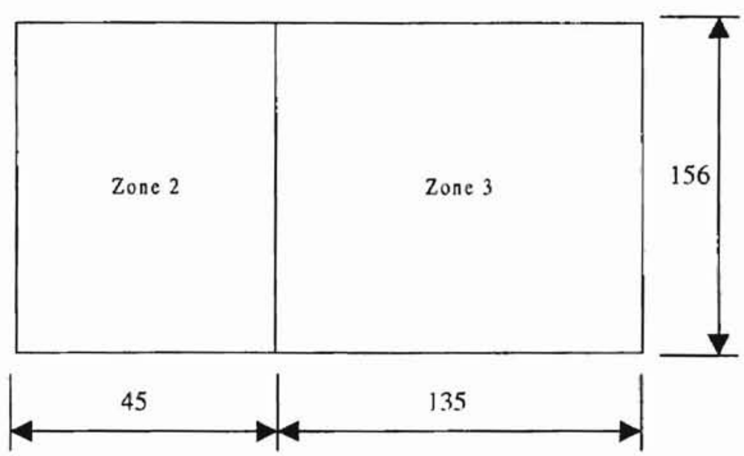

Figure 2-11. Zone Layout for Service Floor

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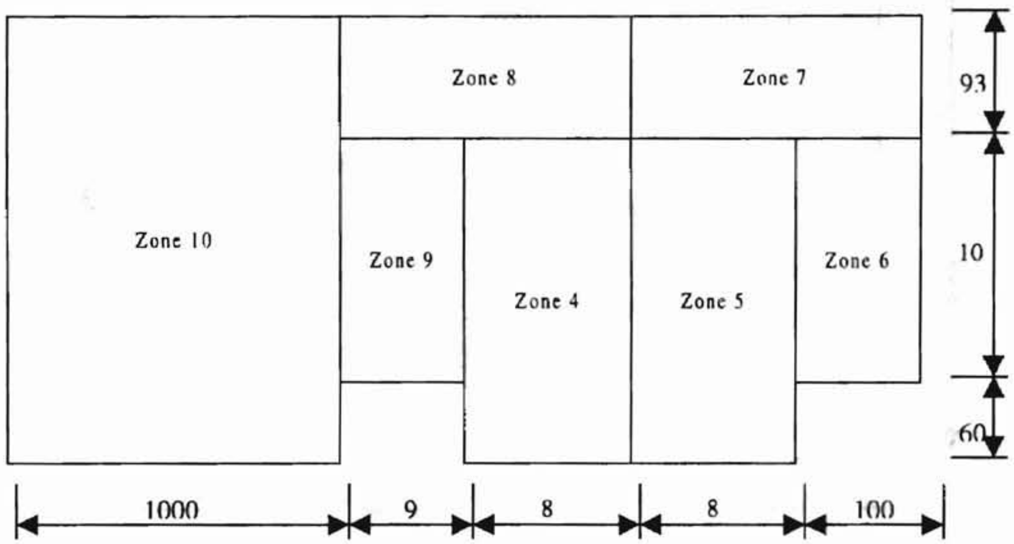

Figure 2-12. Zone Layout for Ground Floor

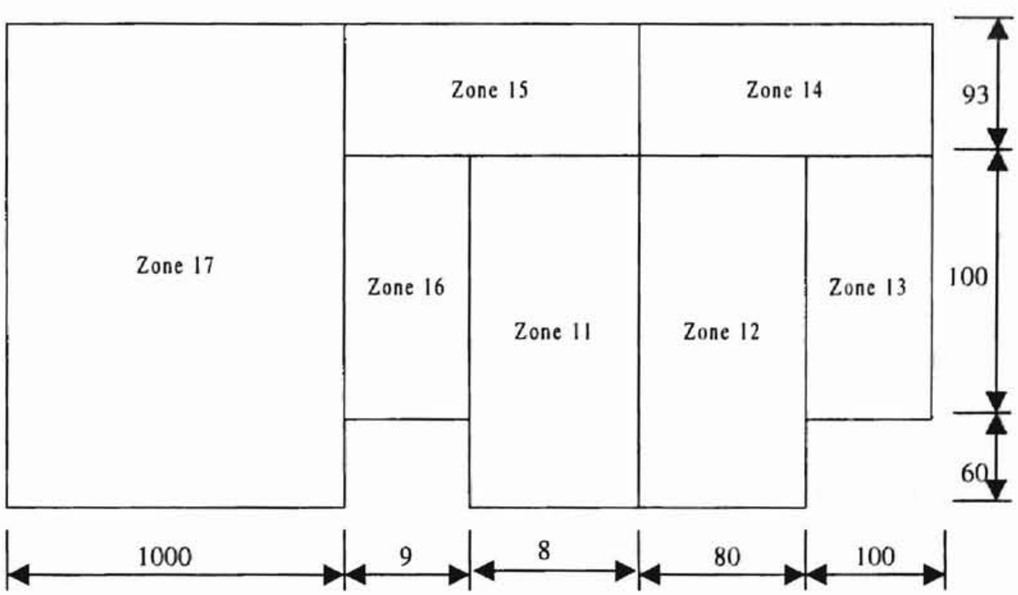

Figure 2-13. Zone Layout for Plaza Floor

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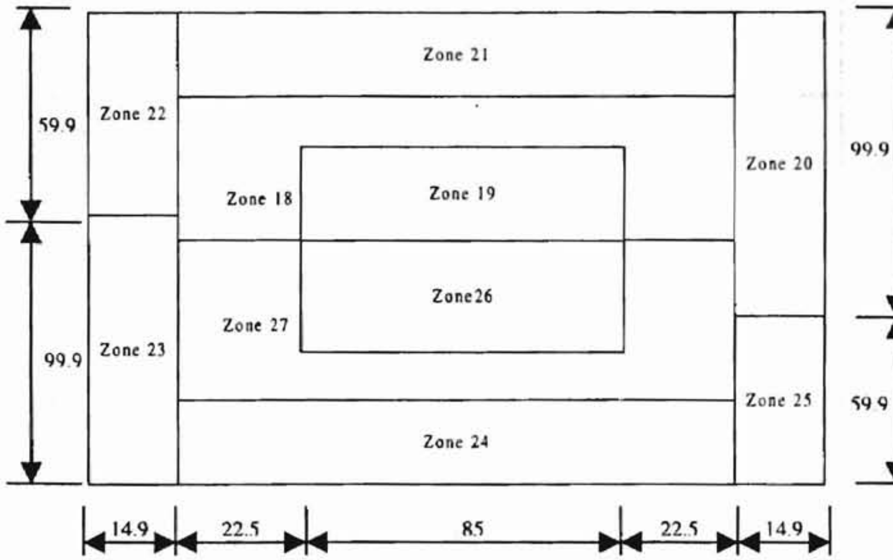

Figure 2-14. Zone Layout for Floors 8 –24

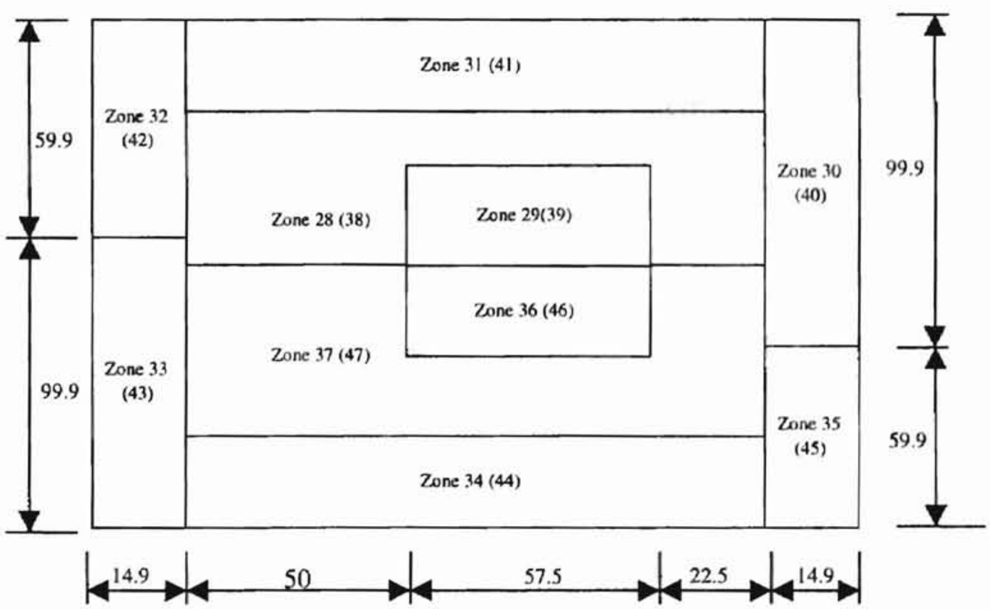

Figure 2-15. Zone Layout for Floors 25 – 38

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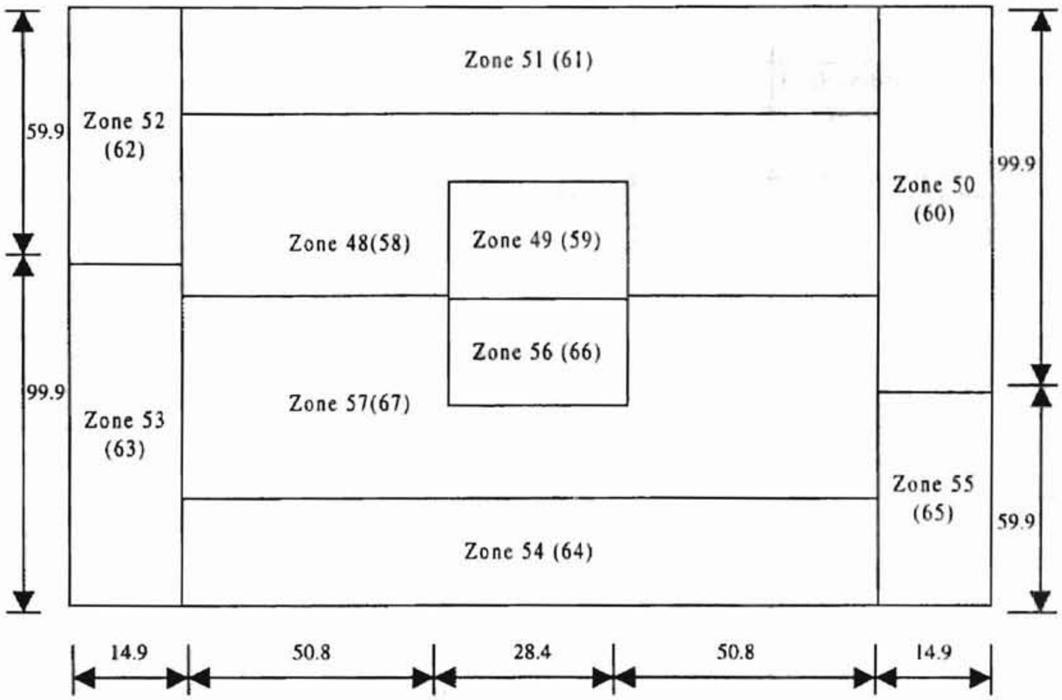

Figure 2-16. Zone Layout for Floors 39 – 51 (52)

Table 2-9a and Table 2-9b give information on internal heat gains of each zone. The equipment heat gain at peak time is 0.8 W/ft^2. Each person has approximately an office area of 120 ft^2. The lighting information is provided by WHBC.

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Zone	Area	People		Lights		Electricity	
	Ft^2	Peak	Schedule	Peak (KBtu)	Schedule	Peak (KBtu)	Schedule
1	17280	250	people	44.8	lights	47.2	equipment
2	7171	50	people	41.2	lights	215	equipment
3	21216	150	people	124	lights	57.2	equipment
4	12803	160	people	12.1	lights	349	equipment
5	12792	160	people	12.1	lights	34.9	equipment
6	10000	100	people	9.1	lights	27.3	equipment
7	16368	150	people	9.1	lights	44.7	equipment
8	16350	150	people	9.1	lights	44.7	equipment
9	9200	100	people	9.1	lights	25.1	equipment
10	253100	200	people	112	lights	345	equipment
11	12803	160	people	12.1	lights	34.9	equipment
12	12792	160	people	12.1	lights	34.9	equipment
13	10000	100	people	9.1	lights	27.3	equipment
14	16368	150	people	9.1	lights	44.7	equipment
15	16350	150	people	9.1	lights	44.7	equipment
16	9200	100	people	9.1	lights	25.1	equipment
17	253100	200	people	112	lights	345	equipment
18	1734	15	people	6.7	lights	4.8	equipment
19	8436	65	people	32.3	lights	23	equipment
20	1489	10	people	5.7	lights	4.1	equipment
21	637	5	people	2.5	lights	1.7	equipment
22	891	5	people	3.4	lights	2.4	equipment
23	1489	10	people	5.7	lights	4.1	equipment
24	637	5	people	2.5	lights	1.7	equipment
25	893	6	people	3.4	lights	2.4	equipment
26	1742	12	people	6.7	lights	4.8	equipment
27	7543	60	people	32.3	lights	23	equipment
28	1173	15	people	6.7	lights	4.8	equipment
29	8997	65	people	32.3	lights	23	equipment
30	1489	10	people	5.7	lights	4.1	equipment
31	637	5	people	2.5	lights	1.7	equipment
32	891	5	people	3.4	lights	2.4	equipment
33	1489	10	people	5.7	lights	4.1	equipment
34	637	5	people	2.5	lights	1.7	equipment
35	893	6	people	3.4	lights	2.4	equipment
36	1173	12	people	6.7	lights	4.8	equipment
37	8163	60	people	32.3	lights	23	equipment
38	579	15	people	6.7	lights	72	equipment
39	9584	65	people	32.3	lights	345	equipment

Table 2-9a. Heat gains (Zones1-39)

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40	1489	10	people	5.7	lights	61.5	equipment
41	637	5	people	2.5	lights	25.5	equipment
42	893	5	people	3.4	lights	36	equipment
43	1489	10	people	5.7	lights	61.5	equipment
44	639	5	people	2.5	lights	25.5	equipment
45	893	6	people	3.4	lights	36	equipment
46	579	12	people	6.7	lights	42	equipment
47	8780	60	people	32.3	lights	345	equipment
48	579	15	people	6.7	lights	4.8	equipment
49	9584	65	people	32.3	lights	23	equipment
50	1489	10	people	5.7	lights	4.1	equipment
51	637	5	people	2.5	lights	1.7	equipment
52	893	5	people	3.4	lights	2.4	equipment
53	1489	10	people	5.7	lights	4.1	equipment
54	637	5	people	2.5	lights	1.7	equipment
55	893	6	people	3.4	lights	2.4	equipment
56	579	12	people	6.7	lights	4.8	equipment
57	8780	60	people	32.3	lights	23	equipment
58	579	15	people	6.7	lights	4.8	equipment
59	9584	65	people	32.3	lights	23	equipment
60	1489	10	people	5.7	lights	4.1	equipment
61	637	5	people	2.5	lights	1.7	equipment
62	893	5	people	3.4	lights	2.4	equipment
63	1489	10	people	5.7	lights	4.1	equipment
64	639	5	people	2.5	lights	1.7	equipment
65	893	6	people	3.4	lights	2.4	equipment
66	579	12	people	6.7	lights	4.8	equipment
67	8780	60	people	32.3	lights	23	equipment

Table 2-9b. Heat Gains (Zones 40 - 67)

2.2 HVAC Systems Modeling

2.2.1 HVAC Systems

The HVAC systems for the garage, service, ground and plaza floors are mainly multizone systems, in which the requirements of the different zones of the building are met by mixing cold air and warm air through dampers at the central air handler in response to zone thermostats. The mixed conditioned air is distributed throughout the

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building by a system of single-zone ducts. Figure 2-17 shows the typical multizone unit for these floors.

Floors 50-52 have dual duct systems, which are similar with the multizone systems. In the dual duct system, all the air is conditioned in a central apparatus and distributed to the conditioned zones through two parallel ducts. One duct carries cold air and the other warm air, providing air sources for both heating and cooling at all times. In each conditioned zone, a mixing valve responsive to a room thermostat mixes the warm and cold air in proper proportions to satisfy the prevailing heating or cooling load of the space.

The multizone system in BLAST is shown in Figure 2-18, and it represents the multizone and dual duct systems above, both of which simultaneously consume both chilled water and hot water although it only calls for the cooling air or heating air at one specific period. The only difference between the multizone and dual duct system is that the cold air and hot air are mixed in different locations - the former is insider the central air handler and the latter is outside the central air handler.

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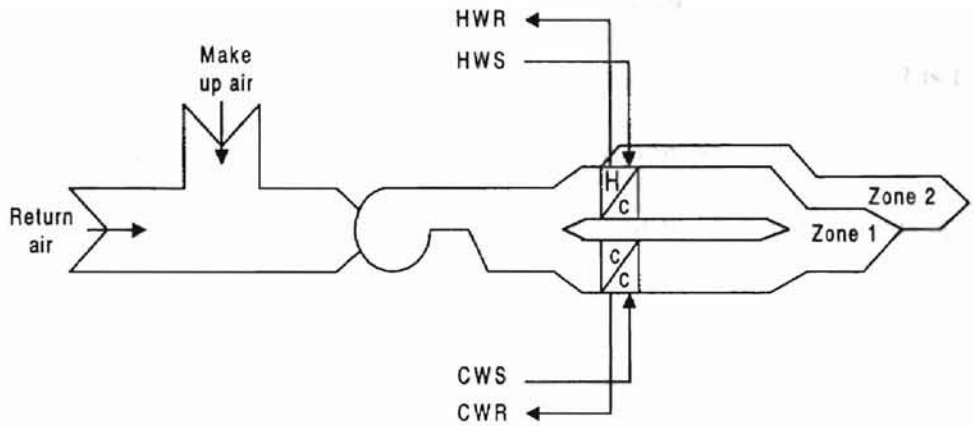

Figure 2-17. Typical Multizone (dual duct) Unit for Podium Floors & Floors 50-52

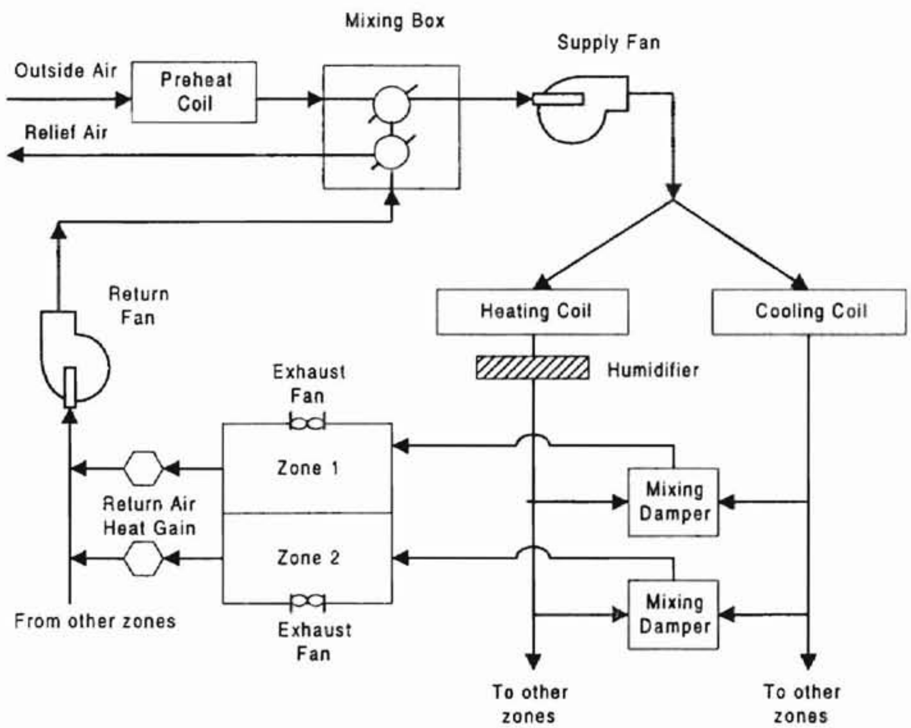

Figure 2-18 Multizone System in BLAST

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The multizone units applied in floors 8-49 have one bypass deck, which is different from those for podium floors. The unit shown in Figure 2-19 is typical for both north and south fan systems of each floor. The unit provides the conditioned air to the perimeter and internal zones at the same time, and the perimeter zones apply the heating coil while the internal zones have no heating coil.

In summer, when both the perimeter and internal zones call for cooling air, the make up air (outside air) mixes with the return air at first, and then the mixed air is distributed into the cooling duct and bypass duct at appropriate ratio according to the thermostat output. Then the cooled air and the mixed air mix with each other before they are conveyed to the internal zones and perimeter zones.

In winter, the internal zones still have cooling loads for their high internal loads, so fan systems operate in the same way as in the summer. The heating coil is applied for the perimeter zone in the winter, and the cooling water valve is closed when the heating water valve for the heating coil begins to open. The reverse is the same. That is, the hot water valve is closed whenever the cooling water valve is open. The cooling coil and the heating coil are never open at the same time, which is the major difference from the multizone system of podium floors described before.

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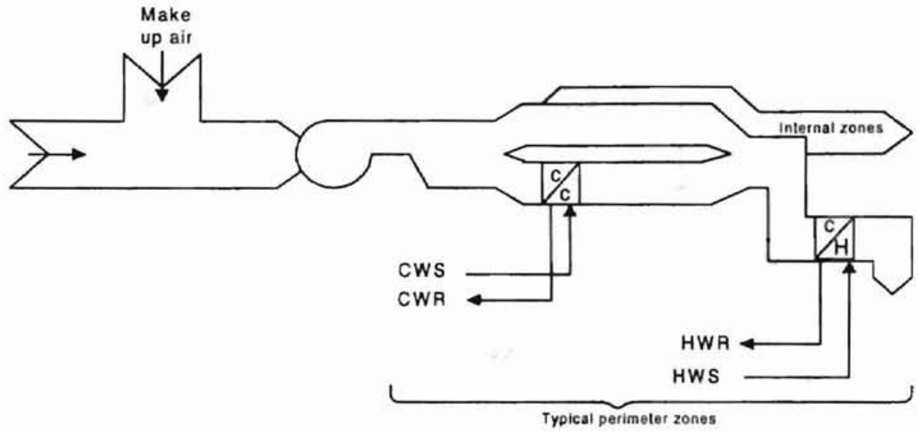

Figure 2-19 Typical Multizone Unit for Floors 8-49

The fan mixing box is applied at the end of system for the heating of the perimeter zone. The fan has two speeds and it varies corresponding to different zone temperatures. The thermostat senses the temperature of the zone with the highest cooling load and then modulates the actuator to satisfy the heating demand.

The three-deck multizone system is used in the BLAST input file to describe the multizone system on floors 8-49. Figure 2-20 is the scheme of the three-deck multizone system in the BLAST. The system conditions all the air in a central apparatus and distributes it to the conditioned spaces through three parallel ducts. One duct carries cold air, one carries unconditioned mixed air and the other warm air, providing air sources for both heating and cooling at all times. The zone thermostat can call, in sequence, for full hot air, hot air and bypass mix, full bypass, cold air and bypass mix, and full cold air. The bypass multizone saves energy by avoiding simultaneously heating and cooling the supply air to the zones.

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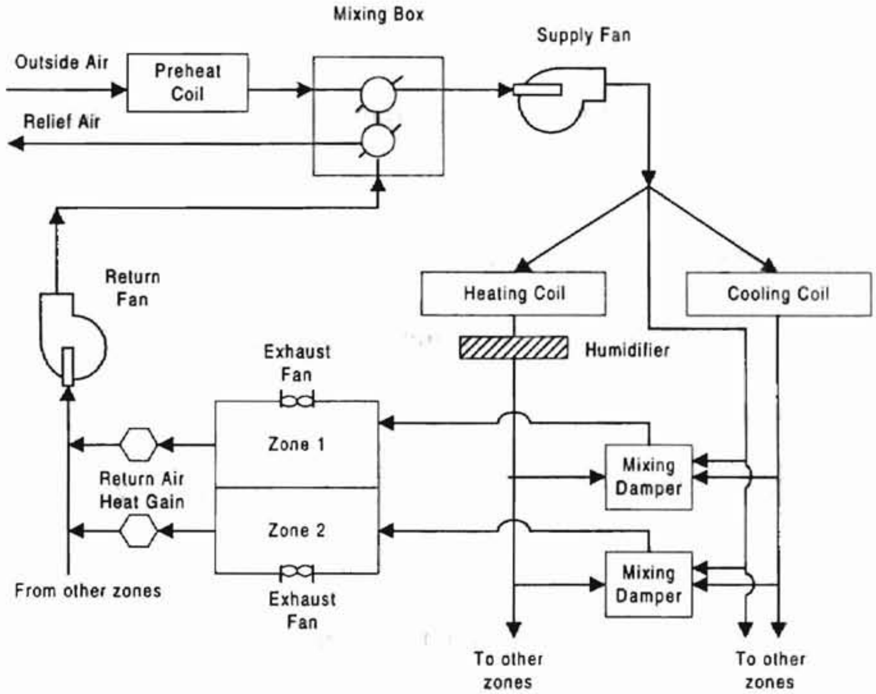

Figure 2-20 Three-deck Multizone System in BLAST

We choose the three-deck multizone system to represent actual multizone systems on floors 8-49 on the basis of the similarity of their control sequence and operation. The three-deck multizone system works in a way close to the actual multizone system. At full heating load the heater is turned on and the mixture of the return and outside air is heated. As the zone temperature rises, with the zone thermostat satisfied, the heater is turned off and the cooling coil is fully closed. When the zone temperature rises, the cooling coil modulates toward open. At the same time the bypass damper modulate toward closed. At full cooling load, the cooling coil damper is fully open and the bypass damper is fully closed. Cold deck air and hot deck air are never mixed with each other.

The limitation of the three-deck multizone model is that we assume the supply air fan speed is constant in the BLAST input file, while in the actual powered mixing box the

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two-speed fan is applied and varies its speed corresponding to different zone temperatures.

This limitation of the model may be one of reasons that there is some discrepancy between the simulated and actual steam consumption (for the heating) after the calibration in Chapter 4. However, the overall calibration results shown in Chapter 4 prove that the three-deck multizone system works very closely to the actual system, and it is reasonable to describe the actual system by using three-deck multizone system model.

Different types of auxiliary units are also used for some floors. There are about 15 auxiliary units on the service floor, such as Leibert units, Carrier, Airflow, and heat pump, to meet the high cooling loads in the data center area. Both floor 14 and 18 have large equipment load, and many Magic Aire auxiliary units are used to ensure the required indoor environment.

For typical floors, cooling control will be cold deck reset from the area thermostat with the highest cooling demand though signal selector, and the heating control will be hot deck reset from the area thermostat with the largest heating demand through signal selector. Space control will be the room thermostat modulating its zone damper to maintain area temperature.

The unit fan will be started and stopped by the FMS system. Smoke detector will stop the unit fan when an abnormal condition exists. The hot deck and cold deck controls will be enabled when the fan is on and disabled when the fan is off.

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2.2.2 HVAC System Model

Table 2-10 provides detailed information on each kind of floors, which is the base of the BOK model in BLAST.

Floor	Zones	Systems
Garage	1	Multizone system 1
Service	3	Multizone system 2
	2	Multizone system 13
Ground	4,9	Multizone system 6
	5,6	Multizone system 3
	7	Multizone system 4
	8	Multizone system 5
	10	Multizone system 7
Plaza	11,16	Three deck multizone system 11
	12,13	Multizone system 8
	14	Multizone system 9
	15	Multizone system 10
	17	Multizone system 12
8-24	18,19,20,21,22	Three deck multizone system 14
	23,24,25,26,27	Three deck multizone system 15
25-38	28,29,30,31,32	Three deck multizone system 16
	33,34,35,36,37	Three deck multizone system 17
39-48	38,39,40,41,42	Four pipe fan coil system 18
	43,44,45,46,47	Four pipe fan coil system 19
49-51	48,49,50,51,52	Multizone system 20
	53,54,55,56,57	Multizone system 21
52	58,59,60,61,62	Multizone system 22
	63,64,65,66,67	Multizone system 23

Table 2-10 Summary of System Locations

2.2.3 Schedules and Model

The occupancy and lighting profiles for the BOK building are characterised by a weekday schedule of 8 a.m. to 7 p.m. Significant evening use of the building occurs on weekdays between 7 p.m. and 11 p.m. Weekend use is moderate.

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Six temporary schedules are defined in the BOK model to represent schedules of occupancy, lighting and equipment. Figure 2-21 represents the occupancy schedule for weekdays. The occupancy schedule at weekends (also holidays) is defined zero initially. Figures 2-22 and 2-23 represent the lighting schedules for weekdays and weekends (also holidays). Figures 2-24 and 2-25 represent the equipment schedule for weekdays and weekends (also holidays).

These schedules are modified as part of the calibration procedure described in Chapter 4.

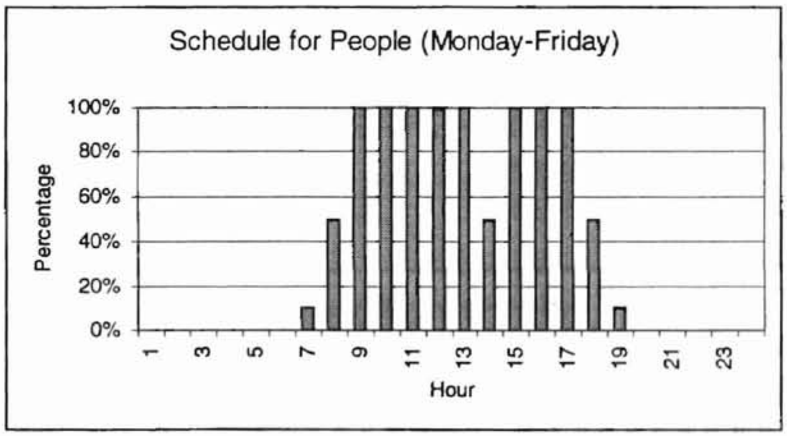

Figure 2-21 Occupancy Schedule (Monday-Friday)

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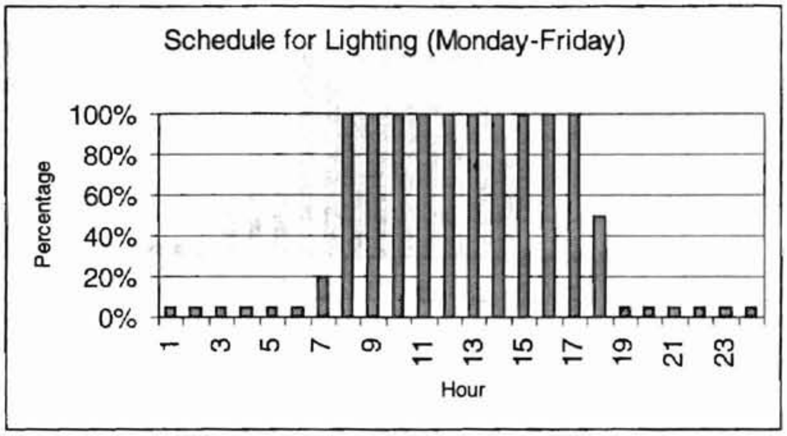

Figure 2-22 Lighting Schedule (Monday-Friday)

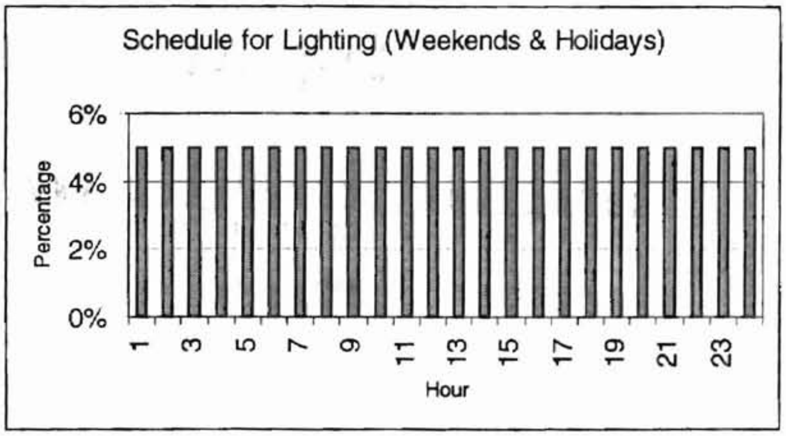

Figure 2-23 Lighting Schedule (Weekends and Holidays)

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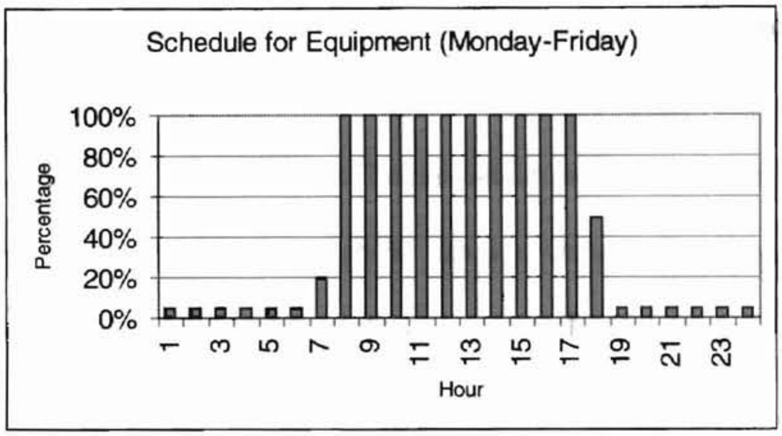

Figure 2-24 Equipment Schedule (Monday-Friday)

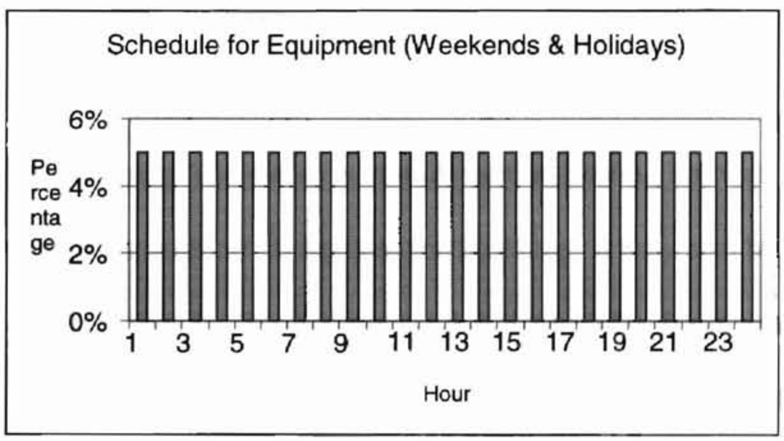

Figure 2-25 Equipment Schedule (Weekends and Holidays)

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2.3 Plant Modeling

Based on the ten-year contract with Trigen-Oklahoma District Energy Corporation, the BOK has purchased chilled water and steam from Trigen since 1991. The chilled water is supplied from Trigen which is located four blocks west of the building. The water is pumped through 30" lines at first and then is reduced to an 18" line before entering the BOK building with approximately 150 psig. The only thing that is supplied before the pumps are the Data Center located on service level for the Leibert units. The remaining water is sent through the pump and then distributed into two ways: one is used to feed all fan units - Garage through Plaza, and the second path is the high rise system which supplies Plaza intermediate through the 51st floor. The water from different system will mix before returning to the Trigen. The BOK is billed for the gallons and the temperature difference of the chilled water.

The steam is supplied from Trigen through an 8" line that enters the building at approximately 150 psig. The steam is mainly used in heating hot water, which in turn is used to heat the parameter air throughout the building. It may also be used to heat the domestic water for sinks in the restrooms and direct heat for fresh air fans.

The central plant simulation in BLAST uses weather data, results of air distribution system simulations, and user input describing the central plant to simulate boilers, chillers, on site power generating equipment, and computes monthly and annual fuel and electrical power consumption.

The central plant simulation of BLAST can simulate any thermodynamically feasible system consisting of the central plant components, such as boilers, centrifugal or reciprocating chillers, absorption chillers, cooling towers, and purchased heating or

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cooling. In the BOK model, we define the central plant as purchased cooling and heating, and the cooling/heating coil loads are met by purchasing chilled water and steam from outside source. In Chapter 5, retrofits are considered by replacing the purchased cooling and heating with boiler and chiller in the BLAST input file.

Once the hot water, chilled water, steam, gas, and electric power demands of the building fan system are known, the central plant must be simulated to determine the building's final purchased electric power, gas, steam and fuel consumption.

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CHAPTER 3 WEATHER DATA

3.1 Mesonet Weather Data

The actual weather data in Tulsa are obtained by using an automated weather station network, the Mesonet (Mesoscale Network). The Mesonet consists of 111 sites scattered throughout Oklahoma and separated by an average distance of 19 miles. The Bixby site is chosen in this project for that it is the closest to BOK, about 16 miles from Tulsa downtown area and thus the weather conditions of Bixby can reflect those of BOK fairly well. Thousands of Mesonet weather files are downloaded through the Internet, in which the information about the air temperature, relative humidity, wind speed, wind direction, atmospheric pressure, rainfall, and solar radiation is obtained in five minutes segments. Table 3-1 is a list of the 5-minute weather observations that are used.

Variable	Description	Period of Observation	Units
RELH	Relative Humidity	5 minutes	Percent
TAIR	Air temperature at 1.5 m	5 minutes	Degrees Celsius
WSPD	Average Wind Speed at 10 m	5 minutes	Meters/Second
WDIR	Wind Direction at 10 m	5 minutes	Degrees
RAIN	Rainfall since 0000 GMT	5 minutes	Millimeters
PRES	Station Pressure	5 minutes	Millibars
SRAD	Solar Radiation Flux	5 minutes	Watts/Meter^2

Table 3-1 Mesonet Weather Data

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A Fortran program is written to process the Mesonet weather data into a tape with BLAST ASCII format. The raw weather data tape is then further processed by BLAST WIFE program to create the weather file with a form suitable for use with the BLAST program. At the same time, user readable output reports can be produced to give weather information such as dry bulb temperature, web bulb temperature, wind speed, and solar radiation on an hourly basis, as well as calendar information showing special days and holidays. Figure 3-1 is a flow chart of the weather data process.

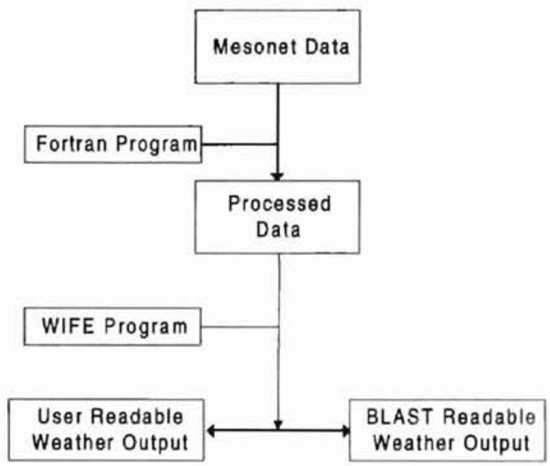

Figure 3-1 Flow Chart of Weather Data Process

In this project, we created two BLAST readable weather output files. One contains the weather data in 1997 (from Sept.01- Dec.31), and another contains the weather data in 1998 (from Jan.01- Jun.01). Both of the files are used for the BOK model to predict the energy consumption (chilled water and steam) in the corresponding two periods.

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3.2 Empirical Splitting Procedure

The hourly total solar radiation is obtained from the Mesonet, and then we split it into beam and diffuse radiation with Fortran program. The correlation provided by Reindl, [1990] is used in the splitting procedure, which is based on a data set with 22,000 hourly measurements from five European and North American. In this correlation, the hourly diffuse fraction is influenced by the climatic and geometric variables, including the clearness index, solar altitude, ambient temperature, and relative humidity. That is:

Interval: $0 < K_t < 0.3$; Constraint: $I_d / I < 1.0$

$$I_d / I = 1.000 - 0.232\ K_t + 0.0239 \sin(a) - 0.000682\ T_a + 0.0195\ \Phi \quad (3\text{-}1)$$

Interval: $0.3 < K_t < 0.78$; Constraint: $I_d / I < 0.97$ and $I_d / I > 0.1$

$$I_d / I = 1.329 - 1.716\ K_t + 0.267 \sin(a) - 0.00357\ T_a + 0.106\ \Phi \quad (3\text{-}2)$$

Interval: $0.78 < K_t$; Constraint: $I_d / I > 0.1$

$$I_d / I = 0.426\ K_t - 0.256 \sin(a) + 0.00349\ T_a + 0.0734\ \Phi \quad (3\text{-}3)$$

Where

a = altitude angle

I_d = hourly diffuse radiation on a horizontal surface, W / m^2

I = hourly total radiation on a horizontal surface, W / m^2

K_t = clearness index

T_a = dry bulb air temperature, ° C

Φ = solar altitude

K_t is the ratio of hourly total radiation on horizontal to hourly extraterrestrial radiation on horizontal, and it is found by following the procedure below:

At first, we calculate the declination degree by:

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$$D = 23.45 \sin (360/365 * (284 + n)) \quad (3\text{-}4)$$

Secondly, the coefficient "b" is given by the equation (3-5):

$$b = (n - 1)*360/365 \quad (3\text{-}5)$$

Then we get the equation of time by using the coefficient "b":

$$E = 229.2\,(0.000075 + 0.001868 \cos (b) - 0.032077 \sin (b) - 0.014615 \cos (2b) - 0.04089 \sin (2b)) \quad (3\text{-}6)$$

Then the solar altitude is found by using the equation below:

$$Alti = \cos^{-1} [\cos (l) \cos (h) \cos (d) + \sin (l) \sin (d)] \quad (3\text{-}7)$$

We calculate the extraterrestrial radiation on horizontal:

$$G_{sc,\ Horizontal} = G_{sc}\,(0.033 \cos (360n / 365)) \cos (Alti) \quad (3\text{-}8)$$

Thus the hourly clearness index is found by using the definition:

$$K_t = I / G_{sc,\ Horizontal} \quad (3\text{-}9)$$

Where

Alti = solar altitude angle, degrees

b = coefficient

D = declination, degrees

E = equation of time, min.

G_{sc} = extraterrestrial radiation, measured on the plane normal to the radiation on the n^{th} day of the year, and $G_{sc} = 1367\ W/m^2$

$G_{sc,\ Horizontal}$ = extraterrestrial radiation on horizontal, W/m^2

h = hour angle, degrees

l = local solar time

n = n^{th} day of the year

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3.3 Program Algorithms

The wet bulb temperature is calculated with known dry bulb temperature, pressure and relative humidity [ASHRAE Handbook 1997]. Newton Raphson method is applied to solve non-linear equations to find the saturation humidity ratio, the water vapor saturation pressure, and the wet bulb temperature.

The saturation pressure over liquid water for the temperature range of 32 ° F to 392 ° F is given by the following formula:

$$Ln\ (P_{ws}) = (C_1/T_r + C_2 + C_3{*}T_r + C_4{*}T_r^2 + C_5{*}T_r^3 + C_6{*}\ Ln\ (T_r)) \qquad (3\text{-}10)$$

Where

C1 = -1.0440397 E+04

C2 = -1.1294650 E+01

C3 = -2.7022355 E-02

C4 = 1.2890360 E-2

C5 = -2.4780681 E-09

C6 = 6.5459673 E+00

T_r = absolute temperature, ° R

The humidity ratio of the saturated moist air relates to the saturation pressure of water vapor in the absence of air at the given temperature and the total pressure. The formula is given below:

$$W_s = 0.62198\ P_{ws}/\ (P - P_{ws}) \qquad (3\text{-}11)$$

The humidity ratio at the specific temperature and pressure is given by:

$$H_r = [(1093 - 0.556T{*})\ W_s - 0.240\ (T_f\text{-}T{*})]\ /\ (1093 + 0.444T_f - T{*}) \qquad (3\text{-}12)$$

Both T_r and T^* are wet bulb temperatures, and they can be converted by following the formula:

$$T_r = T^* + 459.67 \qquad (3\text{-}13)$$

Where

H_r = humidity ratio, lb. (water) / lb. (dry air)

W_s = humidity ratio at saturation, lb. (water) / lb. (dry air)

P_{ws} = saturation pressure, Psia

P = total mixture temperature of dry air and water vapor, Psia

T_f = dry bulb temperature, ° F

T^* = wet bulb temperature, ° F.

3.4 BLAST WIFE Program

The Weather Information File Encoder (WIFE) program processes weather data tapes to produce files containing surface and solar data in the form used by the BLAST program. It has three basic functions: to create processed weather files for running BLAST, to modify existing weather files, and to report the status of the data contained on the raw weather file.

When creating a processed weather file, two input files are required, which include user written input file and raw weather data. The former contains the minimum amount of information necessary, such as name and position of weather file site, run period, tape type, etc, and the latter is the processed weather data from Mesonet. Two output files are created by WIFE - one is user readable output file, and another is readable by BLAST.

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The raw weather data from Mesonet is processed into an ASCII format which is readable by WIFE, in which header information describing file attributes come first. Following the header information, twenty-four (24) lines of weather information are shown for each day of the year. The format of each one-hour block is shown below:

Format	Description
Format (A40,1X,2F11.3)	Weather title, latitude,longitude
Format (F6.0,2X,I6,2X,I4,2X,I4)	Time Zone, Weather Station number, Number of Days, Version Number Where: 1. Time Zone – 0 is GMT, 6 is Central, etc. 2. Version Number – not really Used for this application
Format (I4,2I2,1X,48I1)	Year, Month, Day of Month, Rain (for each hour), Snow (for each hour) Where: 1. Year – 4 digit year 2. Month – (1=Jan,…,12=Dec) 3. Day of Month – (1,…,31, must be valid for Month) 4. Rain, Snow (0 is none, 1 is yes)
Format (3(8F10.6,/))	Dry Bulb Temperature for each hour (Degrees C)
Format (3(8F10.6,/))	Wet Bulb Temperature for each hour (Degrees C)
Format (4(6F12.5,/))	Barometric Pressure for each hour (Newton/Meters^2)
Format (2(12F6.4,/))	Humidity Ratio for each hour
Format (3(8F10.5,/))	Wind Speed for each hour (Meters/Second)
Format (2(12F6.2,/))	Wind Direction for each hour (Degrees, 0=North, 90=East, 180=South, 270=West)
Format (3(8F10.5,/))	Beam for each hour (Watts/Meters^2)
Format (2(8F10.5,/),8F10.5)	Diffuse for each hour (Watts/Meters^2)

Table 3-2 ASCII Format in BLAST

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CHAPTER 4 CALIBRATION

4.1 Purpose of Calibration

The initial model we developed in Chapter 3 incorporates information from the as-built drawings, construction inspection notes, and operation and maintenance (O&M) audit. However, as usually occurs in the real engineering world, the model unavoidably involves numerous assumptions and is only an approximate description of the building.

It is the purpose of calibration to increase the model's ability to reasonably estimate the building's energy use and the energy savings benefits of efficiency improvements. The calibration process involves iterative tuning, testing and validating the model and is a very important step to develop an accurate model. The calibrated model is then used to evaluate the feasibility of possible alternatives in Chapter 5.

4.2 Calibration Methodology

Generally, two methods exist for the calibration, both of which need actual energy consumption information. The first adjusts the model to match the monthly actual energy consumption data, and the second relies on hourly actual energy consumption data for a long time period. Studies of Kaplan [1990] show that the calibrations at the hourly level seem to offer the best alignment between the simulation program and the measured data.

The method of calibration at hourly level has been primarily used in this project, and at the end of this calibration process, the monthly measured energy consumption data has been used to check the hourly calibration process. As a result, it shows that the

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monthly energy consumption predicted by the hourly- calibrated model matches the actual monthly end-use energy consumption data very well.

4.3 Calibration Procedure

4.3.1 Source Data

We made the first survey to BOK on Oct. 28th 1997. Two data sets of utility bills are provided by WHBC. As shown in Table 4-1, one containing the actual building chilled water consumption for Sept 04 - Oct. 23, 1997, Nov. 04 - Dec. 31, 1997, Jan.04 - Jun. 03, 1998, and the other containing the actual building steam consumption for Jan.04 – Jun.03, 1998. Both of the data are provided in fifteen-minute packets. We write a simple Fortran program to extract the hourly data of chilled water consumption and steam consumption. Correspondingly two files are generated, as the base of our later calibration.

Utility Bills	Period		
Chilled Water	Sept.04 - Oct.23	Nov.04 - Dec.31	Jan.01- Jun.04
Steam	——	——	Jan.04 - Jun.04

Table 4-1 Utility Bill Periods

The second kind of data set is about the monthly or seasonal end-use of chilled water and steam consumption for floors and for the whole buildings. These data are useful to give us an idea about the distribution of the chilled water and steam

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consumption for some parts of the building, by which we can check and adjust our model during the calibration process.

Figure 4-1 is given as an example, showing information about the chilled water consumption allocation, from which we can see that the chilled water consumption for the garage floors accounts much more than typical floors.

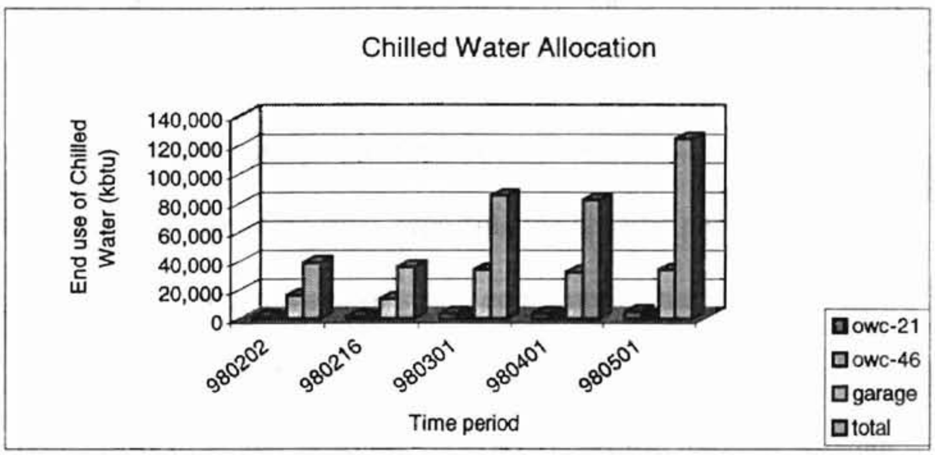

Figure 4-1 Chilled Water Allocation for Specific Floors

4.3.2 BOK Calibration Procedure

Figure 4-2 is a flow chart of the overall calibration procedure. Our primary source of information includes as-built drawings, on- site survey, and the actual energy consumption data in 15-minute segment as well as Mesonet weather data in 5-minute packages.

As described in Chapter 3, Fortran program is written to process the Mesonet weather data into a tape with BLAST ASCII format. The raw weather data tape is then

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further processed by the BLAST WIFE program to create the weather file with a form suitable for use with the BLAST program. Another Fortran program is written to extract hourly actual chilled water consumption and steam consumption data from 15-minute segment. Two output files are created at this step: one contains hourly chilled water (or steam) consumption data and another is the weather file with the format that is readable for the BLAST.

A BLAST input file ("bin" file) is produced for the BOK and then is used to run the simulation. A default output file is created automatically, which contains information about the monthly energy consumption and other information. The specified hourly report is also produced at the same time, reporting the specific parameter hour by hour. The hourly output about chilled water or steam consumption are translated into a contiguous columnar format and then merged with measured data for the same period.

Two-dimensional graphs in Excel are used to perform the comparisons. This process was then repeated each time an adjustment was made in the BLAST input file until that the disagreement between the measured and simulated fell within an acceptable range. Generally, the modification will be considered acceptable only when it results in better matches for both chilled water and steam simulation and makes physical sense at the same time.

The tuning process is iterative and attempts to minimize the disagreement between the simulated and actual data. It is very possible that for each tuning step, large amount of hourly outputs is generated, and the disagreements occurred in every hour are different. How to define the "minimal" and when should we stop are two important questions. Two criteria are used: one is the direct comparison of the actual and simulated

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data by graphics created from Excel or Look3D, another is root-mean-square method to compare results from different inputs during a time period. There are no absolute criteria to tell us when we should stop. Good engineering sense and reasonable analysis are necessary in telling if the disagreements are in tolerance and "minimal".

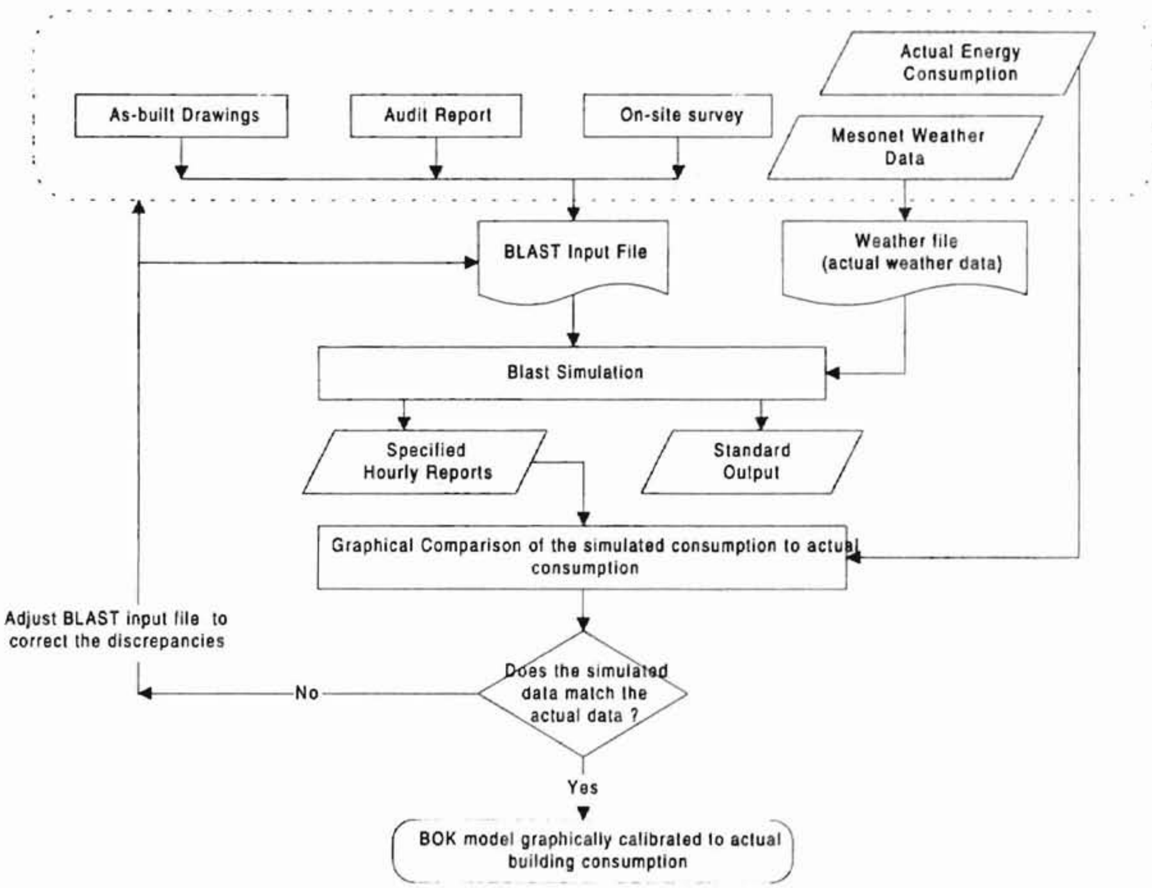

Figure 4-2 Flow Diagram for the Calibration Procedure

4.3.3 Adjusted Parameters

The heating and cooling energy consumption in large commercial building is a complex function of climatic conditions (e.g., outdoor dry-bulb and wet-bulb

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temperatures, solar radiation, relative humidity, wind speed and direction), building characteristics (e.g., physical properties of the envelop of the building), building use (e.g., occupancy schedule, lighting schedule, equipment schedule), system characteristics (e.g., hot and cold deck temperature, economizer cycle), system operation (e.g., control profile, fan system schedule), etc.

It is not possible to obtain all the information about the building operations. For example, it is difficult to know exactly how many people there are in the building, how much equipment is in use and what kind of equipment, etc., at any time. Actual lighting usage is also somewhat uncertain, especially during weekend or holiday. Assumptions are made when necessary, and they may be replaced or modified in the calibration process.

All the descriptions of the building are reflected in a BLAST input file, which can mainly be divided into three blocks: zone description, fan system description, and plant description. Hundred of parameters in the input file, and in the calibration process, we pay attentions on the factors with uncertainties.

The sensitivity study of the parameters is the foundation of calibration. HVAC system operation profiles and the building schedule have great effects on the simulation results. The building schedule includes schedules for people, electrical equipment, lighting, and infiltration, etc. The first adjustments to the model are to correct obvious disagreements. We begin the calibration process by modifying these parameters at first. Other uncertainties in the input file, such as the thermal properties of the envelope will then be considered next.

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4.3.3.1 Adjustment of Zone Description

Table 4-2 gives a summary of the adjusted zone parameters in the BLAST input file, and they mainly include physical properties, people, electrical equipment, lighting, infiltration, control, internal mass, ventilation, all of which have uncertainties. The major adjustment process are introduced and discussed in the following.

Items	Parameters
People	Peak, Schedule, Activity level, Percent Radiant
Electrical Equipment	Peak, Schedule, Percent radiant, latent, and lost
Lighting	Peak, Schedule, Percent return air, radiant, visible, replaceable
Infiltration	Peak, Schedule, Relevant Coefficient
Control	Profile, Schedule
Cross Mixing	Peak, Schedule

Table 4-2 Adjusted Zone Variables

The BOK building is a characterised as having high internal heat gains, which mainly consist of people, electrical equipment and lighting. After on-site survey and interview with building operators, we got information about the maximum number of people and peak lighting level. We assume the use of electrical equipment in the BOK is as in the typical office building.

For typical floors of the BOK building, the average office area for per person is 105 ft^2, including the public space such as elevators, hallway and meeting rooms. Considering the people activity in the typical office building is "seated, very light work",

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we define the peak activity level for the people is 0.45 KBtu/hr for average. The percent radiant from people is 60%.

The fixture for the typical floors are 2XL1 recessed fluorescent fixtures with two bulbs. There are about 360 light fixture for each typical floor. We assume the power consumption for each bulb is 40 Watts, and thus calculate out that the average power consumption of lighting per square feet is 1.0 W/ft^2 for each typical floor.

The peak power consumption for electrical equipment is assumed as 0.8 W/ft^2 by referring to Paul Komor (1997).

The cross-mixing statement is used to describe zones that have a large opening between them. By referring to Faye McQuiston (1994), we assume the average air velocity is 20 ft/min, and then determine the amount of air being exchanged by multiply the area of the cross section between two zones. The equal amounts of air (ft^3/s) between two different zones are specified in the input file and therefore BLAST calculates the appropriate energy balances for both zones. The schedule is constant for all hours.

In order to demonstrate the calibration process and results, in the following we give an example of the adjustment of operation schedules for people, lighting and electrical equipment.

The initial operation schedules for people, lighting and electrical equipment is shown in Figures 2-19 to 2-24 in Chapter 2. They affect the steam and chilled water consumption directly and are adjusted many times during the calibration.

Figures 4-3 and 4-4 show differences between default and adjusted people schedules for weekdays and weekends & holidays. It is apparent that during weekend & holidays, the hourly profile percentages are higher than default values. Also, from 7:00

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PM to 7:00 AM in every weekday, hourly profile percentages increase after the adjustment. The first change means that there would be more heat gains during the weekends and holidays. In the same way, the second change will result to the increase of heat gains at night (from 7:00 PM to 7:00 AM).

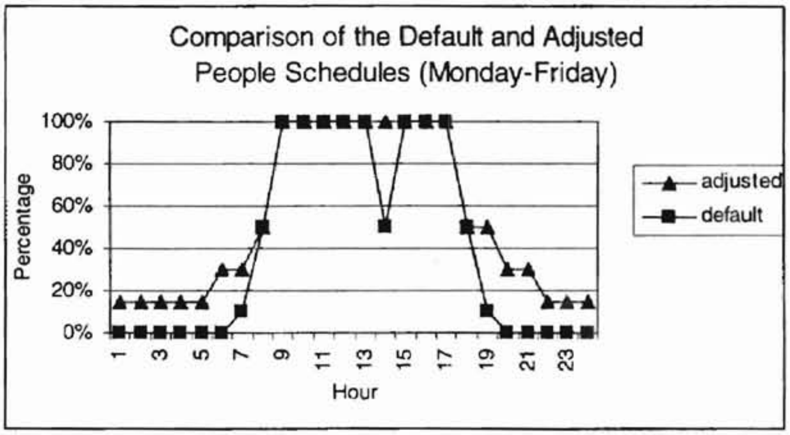

Figure 4-3 Comparison of the Default and Adjusted People Schedules (Monday-Friday)

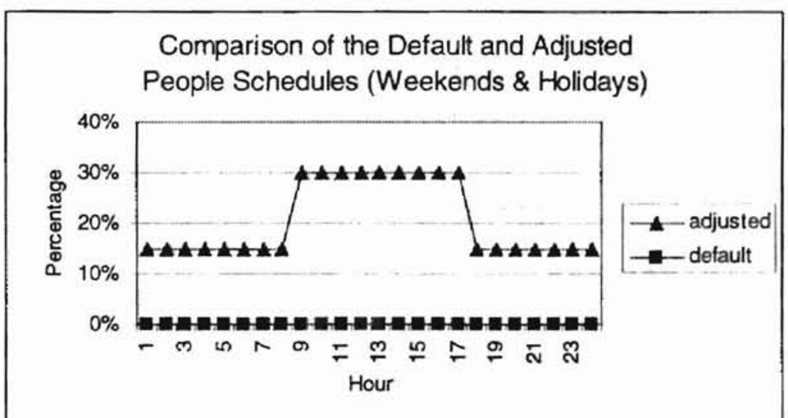

Figure 4-4 Comparison of the Default and Adjusted People Schedules (Weekends & Holidays)

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Figures 4-5 and 4-6 demonstrate differences between default and adjusted lighting schedules during weekdays and weekends & holidays. These differences are similar with those of the people schedule. Hourly profile percentages during the weekends and holidays become higher after the adjustment. Also, hourly percentages are higher than default values from 7:00 PM to 7:00 AM each weekday.

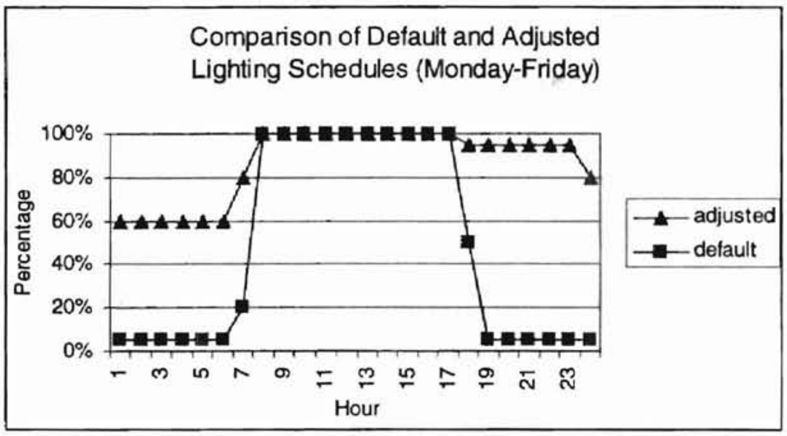

Figure 4-5 Comparison of the Default and Adjusted Lighting Schedules (Monday-Friday)

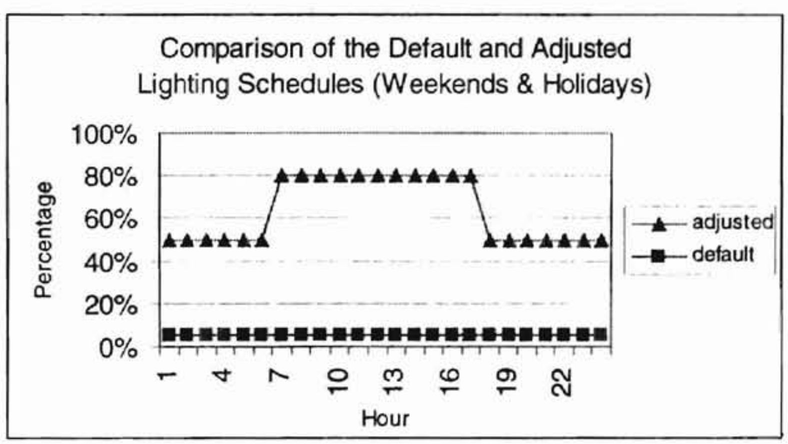

Figure 4-6 Comparison of the Default and Adjusted Lighting Schedules (Weekends & Holidays)

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Figures 4-7 and 4-8 show that after the adjustment hourly percentages of equipment schedule change in the same way of those of people and lighting schedules.

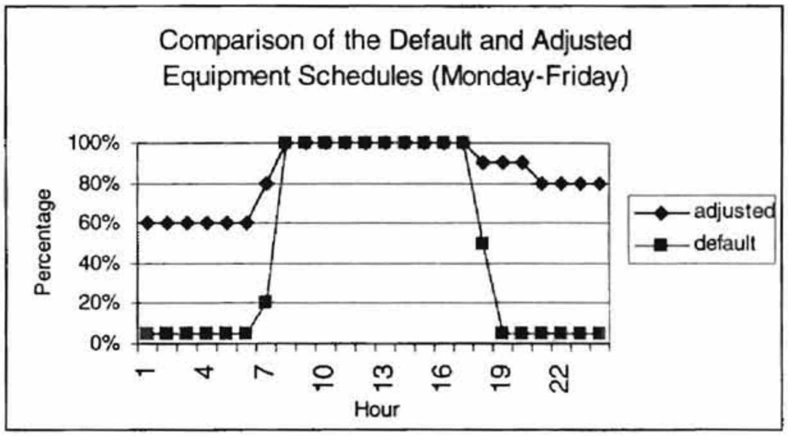

Figure 4-7 Comparison of the Default and Adjusted Equipment Schedules (Monday-Friday)

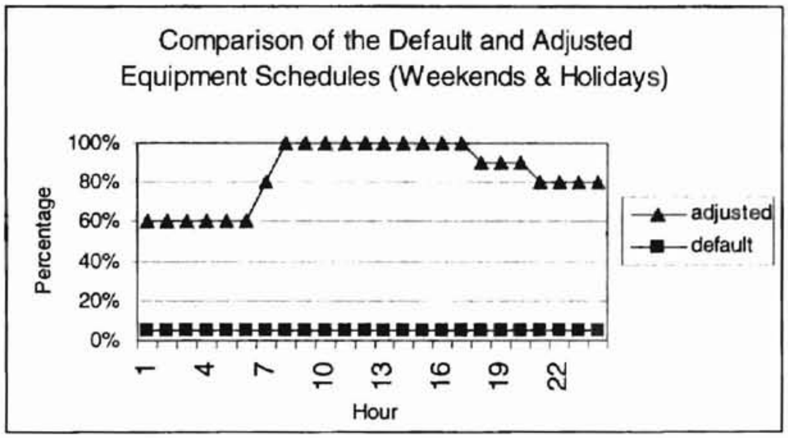

Figure 4-8 Comparison of the Default and Adjusted Equipment Schedules (Weekends & Holidays)

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The hourly chilled water consumption is obtained after we run the simulation by using the BLAST default schedule for people, lighting and equipment. These data are then compared to the actual chilled water consumption hour by hour and the comparison result for a specific period (Feb.01 – Feb.12) is shown in Figure 4-9. It is clear that the predicted chilled water consumption is lower than the actual chilled water consumption at night and weekend.

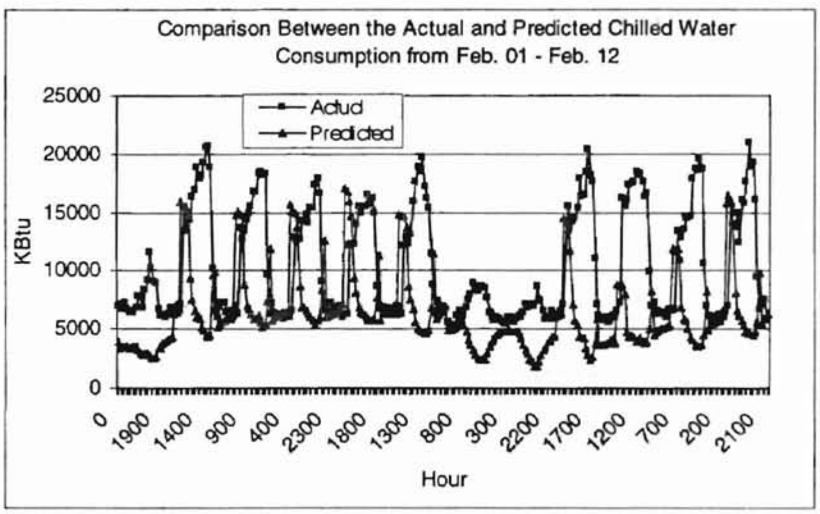

Figure 4-9 Comparison between the Actual and Predicted Chilled Water Consumption from Feb.01 – Feb.12 (BLAST Default Schedule)

The chilled water consumption with calibrated schedules of people, equipment and lighting is shown in Figure 4-10. It shows that there is an apparent increase in the simulated chilled water consumption at night and weekend, and they match the actual data very well.

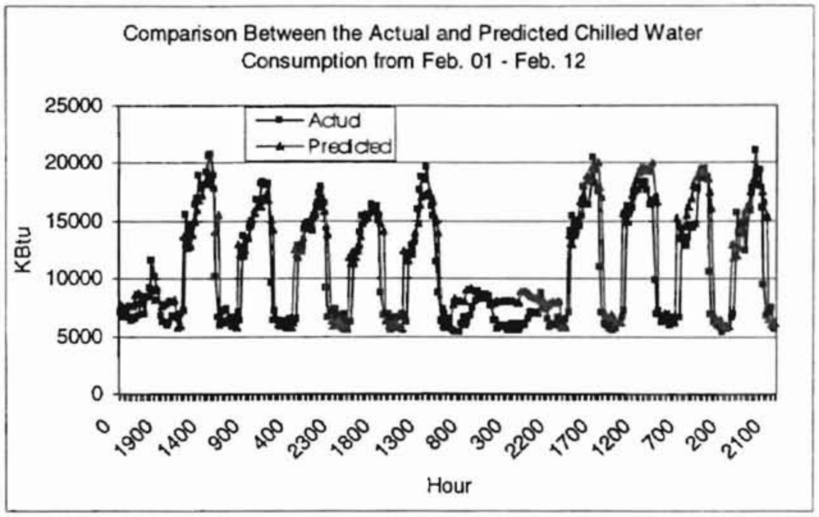

Figure 4-10 Comparison between the Actual and Predicted Chilled Water Consumption from Feb. 01 – Feb. 12 (Adjusted Schedule)

4.3.3.2 Adjustment of Fan System

4.3.3.2.1 Cold Deck and Hot Deck Control

The direct digital control is applied in the HVAC systems of the BOK building. For fan systems, the cold deck strategy is ZONE CONTROLLED, that is, the zone requiring the coldest air is used to establish the cold deck set point. It is defined as the following in the BLAST input file:

"COLD DECK CONTROL = ZONE CONTROLLED;

COLD DECK CONTROL SCHEDULE = (45 AT 55, 65 AT 65);"

If the zone requiring the coldest air must be supplied with air at a temperature of 55 ° F (this air temperature is calculated by BLAST for each hour of the simulation), the cold deck set point is 45 ° F. If the zone requiring the coldest air needs air at a temperature of 65 ° F, then the cold deck set point is 65 ° F. For any temperatures between 55 ° F and 65 ° F, linear interpolation is performed to establish the cold deck set point, as shown in Figure 4-11.

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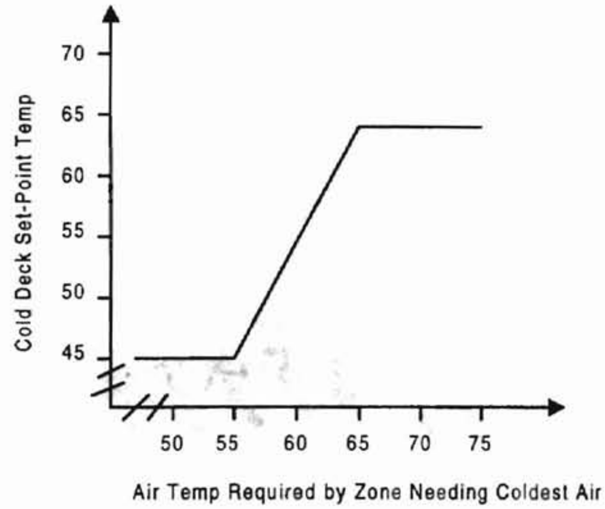

Figure 4-11 Cold Deck Control Schedule

There is a discrepancy for the hot water temperature control modes from the information provided by WHBC. It is described as the ZONE CONTROLLED and OUTSIDE AIR CONTROLLED in two different places. In the calibration process, we defined it as "ZONE CONTROLLED" and then "OUTSIDE AIR CONTROLLED". The hourly steam consumption for both hot deck controls are reported and we make the comparison.

Figure 4-12 shows the comparison between the actual and predicted steam consumption from Feb.07 – Feb.18 when the hot water temperature is zone controlled. We can see that the simulation dramatically overestimates the steam consumption at night and weekends.

Figure 4-13 shows the steam consumption from Feb.07 - Feb.18 when the hot water temperature is outside air controlled. There is a general decrease of steam consumption at night and weekends, and the predicted data can roughly trace the change tendency of the actual steam consumption. We know that the OUTSIDE AIR

CONTROLLED is much closer to the actual hot deck mode than ZONE

CONTROLLED.

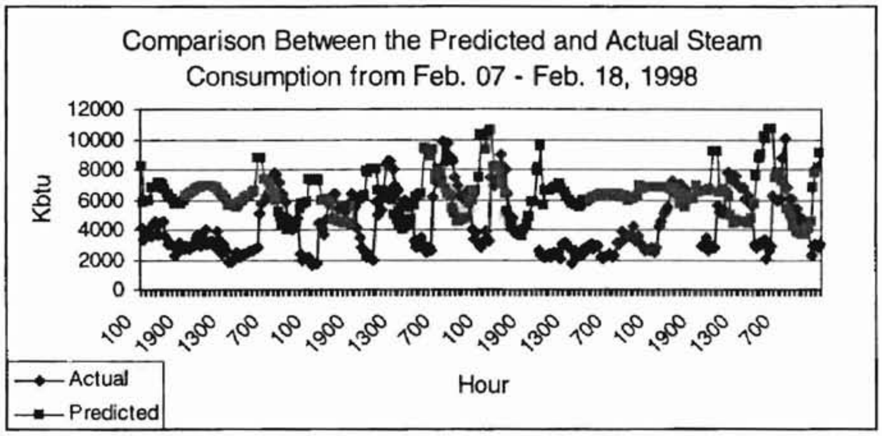

Figure 4-12 Comparison between the Predicted and Actual Steam Consumption from Feb.07 – Feb.18 (Zone Controlled)

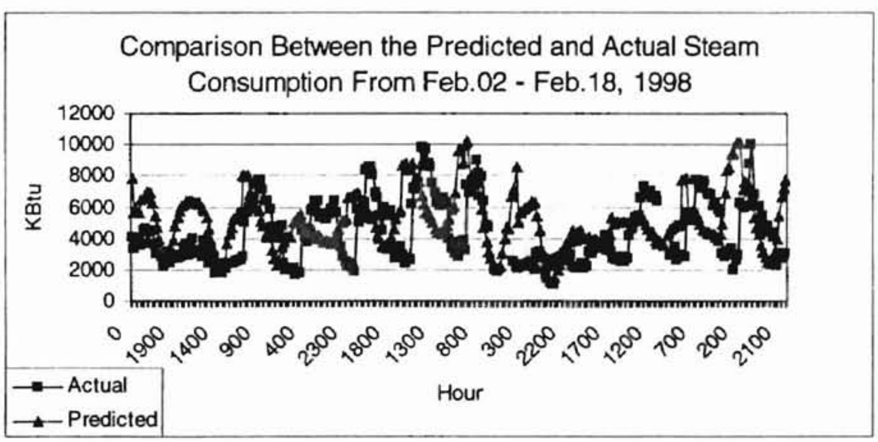

Figure 4-13 Comparison between the Predicted and Actual Steam Consumption from Feb.07 – Feb.18 (Outside Air Controlled)

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The hot deck control schedule is also calibrated, and the set temperature of the hot deck is adjusted. We finally define the hot deck control as the following after the calibration:

"HOT DECK CONTROL = OUTSIDE AIR CONTROLED;

HOT DECK CONTROL SCHEDULE = (120 at 0, 68 at 68);"

Figure 4-14 shows the linear interpolations of the hot deck control. If the temperature is 68 ° F outside, the hot deck temperature will be 68 ° F. As the outside temperature drops, the hot deck temperature will rise. When it is 0 ° F outside, the hot deck temperature will be 120 ° F. At this point, a signal limiter will take over and will not let the water temperature rise above 180 ° F even as the outside temperature falls.

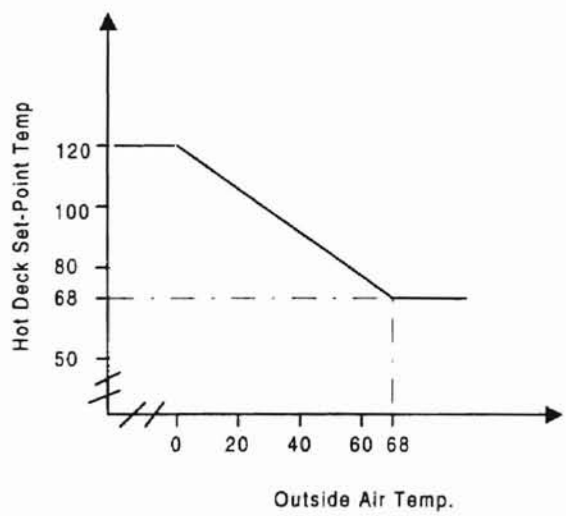

Figure 4-14 Hot Deck Control Schedule

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4.3.3.2.2 Fan System Selection

The type of fan system affects the energy consumption greatly. At first, the fan systems of the BOK building are defined as multizone system in the BLAST input file. Then we change them into three-deck multizone system. After the comparison and the iterative tuning process, we finally applied both multizone and three deck multizone systems BLAST input file. At this time, it shows that the hourly BLAST predicted energy consumption matches the actual data very well. Also, by investigating and reviewing plans, we notice that for the podium floors, the most fan systems are multizone systems, and for the other typical floors, the operation of the fan system is close to the three deck multizone systems. We define the operation of the Liebert units as fan coil system.

Figures 4-15, 4-16 and 4-17 show the different simulation results by applying the multizone system, three-deck multizone system, and the combination of them. For simplification, we call the three-deck multizone system "BLAST 1", the multizone system "BLAST 2", and the combination of them "BLAST3".

In Figure 4-15, the three-deck multizone system underestimates the chilled water consumption in January. On the contrary, in Figure 4-16, the multizone system overestimates the chilled water consumption in January. It demonstrates that the three-deck multizone system is more energy saving compared to the multizone system. The three-deck multizone system turns off the cold deck damper when it opens the hot deck damper in the cold weather, while the multizone system simultaneously supplies the hot and cold air to a perimeter zone in the cold weather.

In Figure 4-17, the combination of three-deck multizone system and multizone system predicts the chilled water consumption very well. After the survey to the BOK

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building, we know that the BOK building contains both multizone systems and three-deck multizone systems and therefore the simulation result physically makes sense.

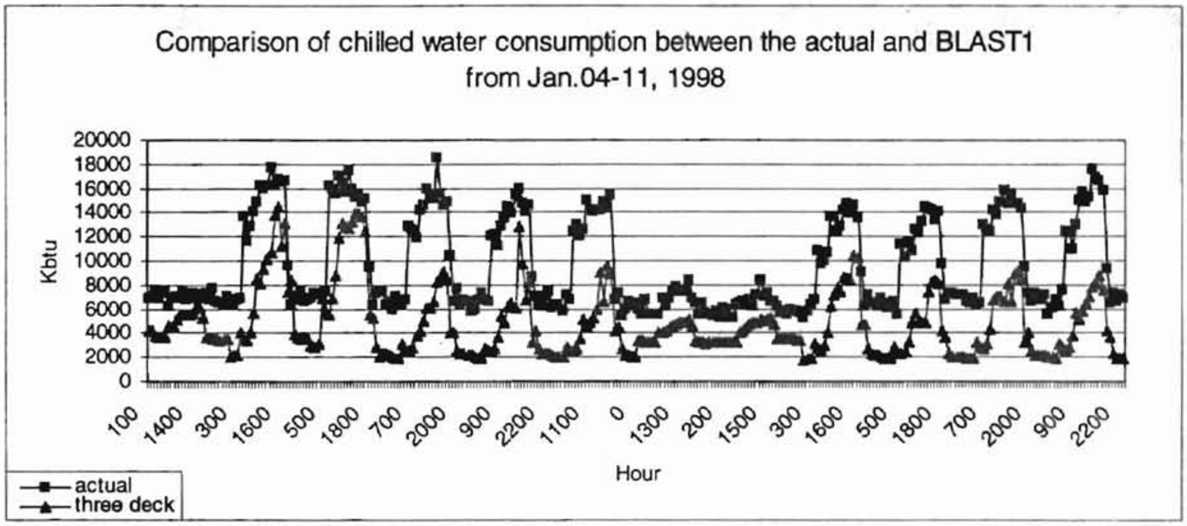

Figure 4-15 Comparison between the Actual and BLAST1 Simulated Chilled Water Consumption from Jan. 04 – Jan. 11, 1998

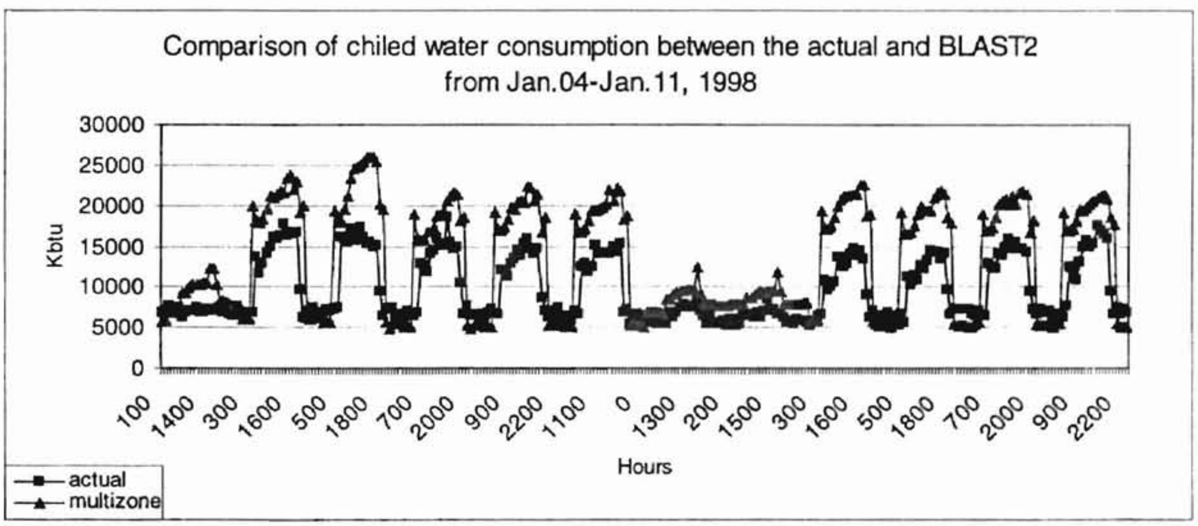

Figure 4-16 Comparison between the Actual and BLAST2 Simulated Chilled Water Consumption from Jan. 04- Jan.11, 1998

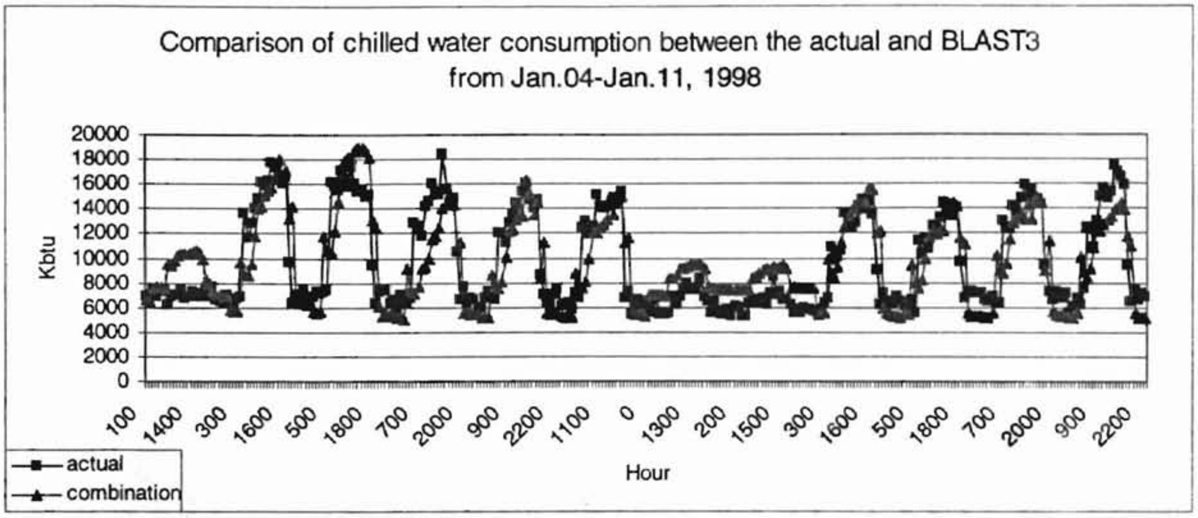

Figure 4-17 Comparison between the Actual and BLAST3 Simulated Chilled Water Consumption from Jan. 04 – Jan 11, 1998

4.4 Calibration Results

The final calibration results are shown in figures 4-18 to 4-26. We choose five time periods to represent the typical seasons throughout 1997 and 1998. The five periods are shown in the table below.

Period 1	Period 2	Period 3	Period 4	Period 5
Sept.04 – Sept.19, 1997	Dec.01- Dec.15, 1997	Jan.13- Jan.27, 1998	Mar.01 - Mar.15, 1998	May 15- May 31, 1998

Table 4-3 Periods of Calibration Results

Figures 4-18 to 4-23 illustrate the comparison results for the chilled water consumption from Sept. 1997 throughout May 1998. The hourly predicted chilled water consumption matches the actual data very well throughout ten months. Figures 4-24 to 4-26 demonstrate the comparison of steam consumption from Jan. 1998 to May 1998. They reflect the change tendency of steam correctly although there is some mismatch, which

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mainly due to the limitation of the fan system model. Refer to Chapter 2 for detailed analysis of the limitation.

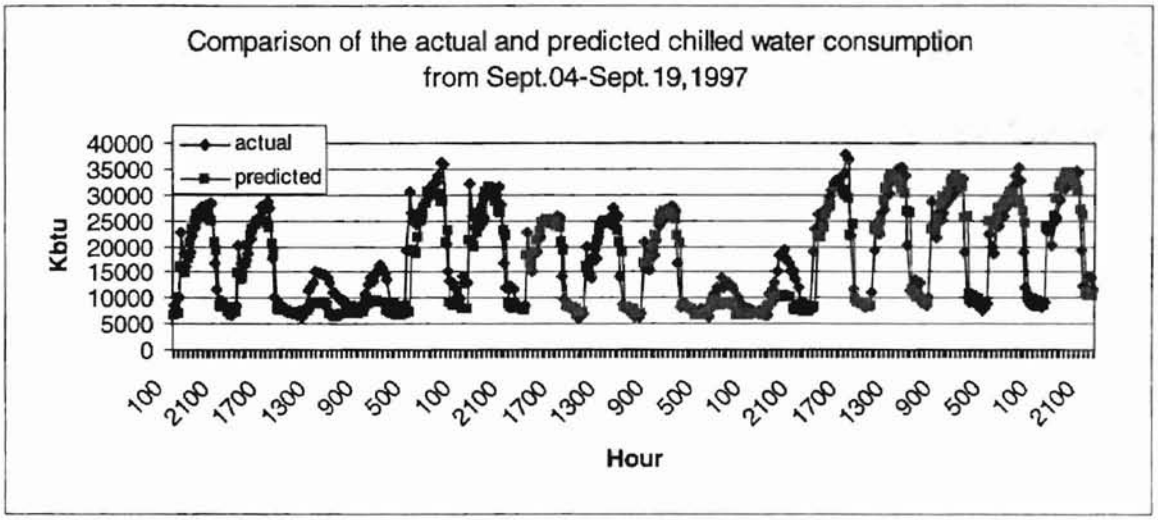

Figure 4-18 Comparison between the Actual and Predicted Chilled Water Consumption From Sept. 04 – Sept. 19, 1997

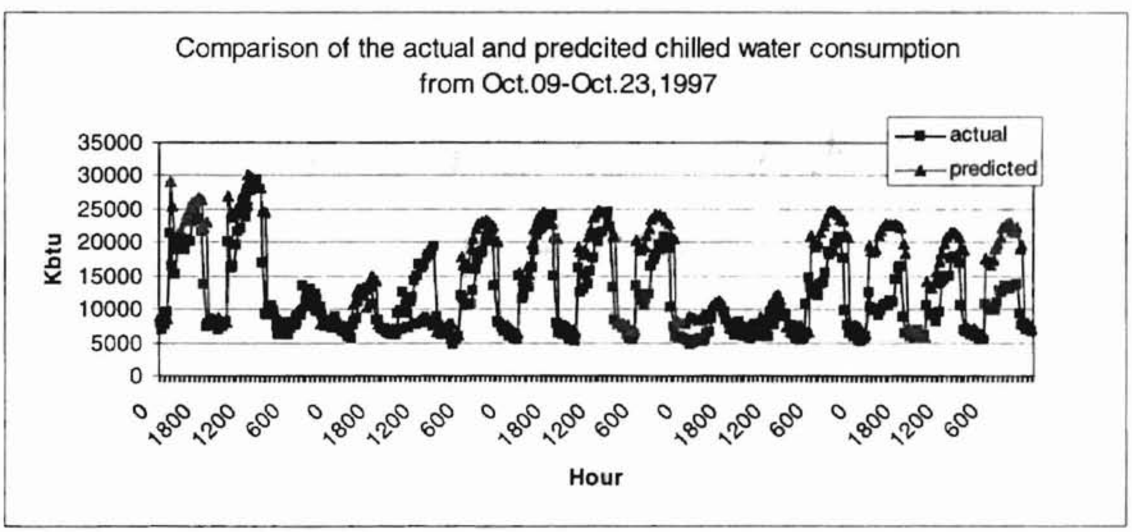

Figure 4-19 Comparison between the Actual and Predicted Chilled Water Consumption From Oct. 09 – Oct. 23, 1997

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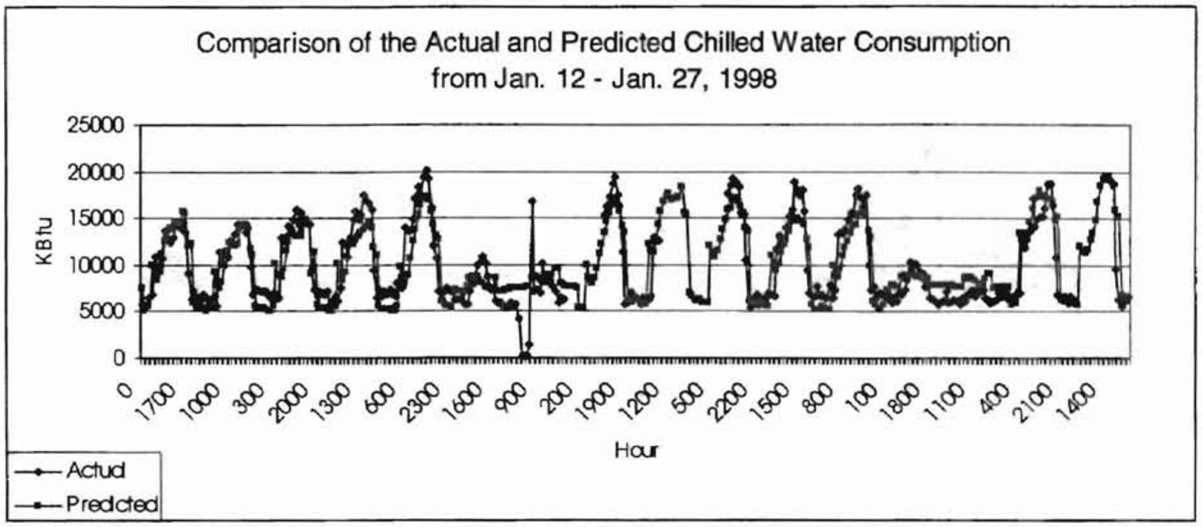

Figure 4-20 Comparison of the Actual and Predicted Chilled Water Consumption
From Jan.12 – Jan.27, 1998

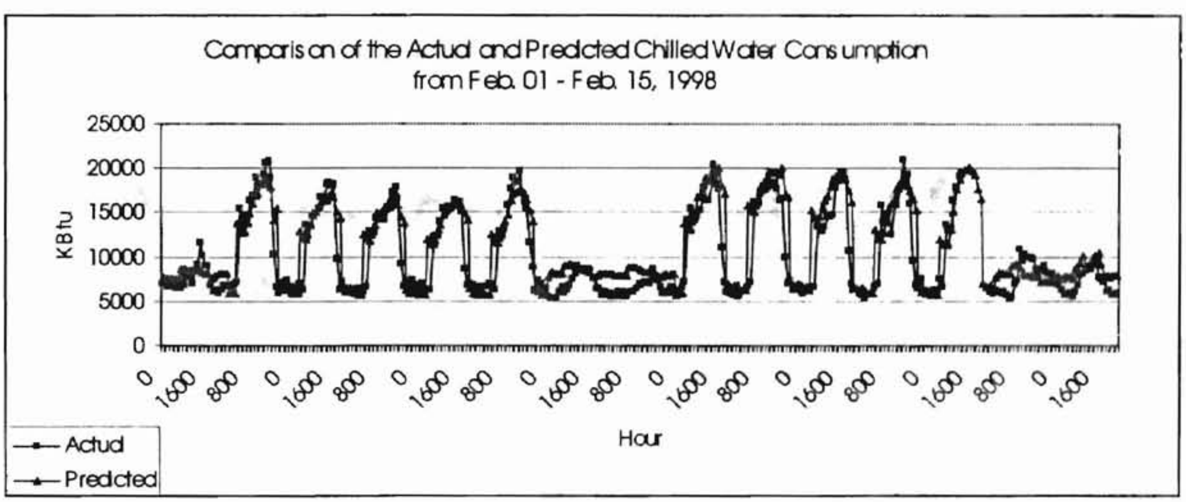

Figure 4-21 Comparison of the Actual and Predicted Chilled Water Consumption
From Feb. 01 – Feb. 15, 1998

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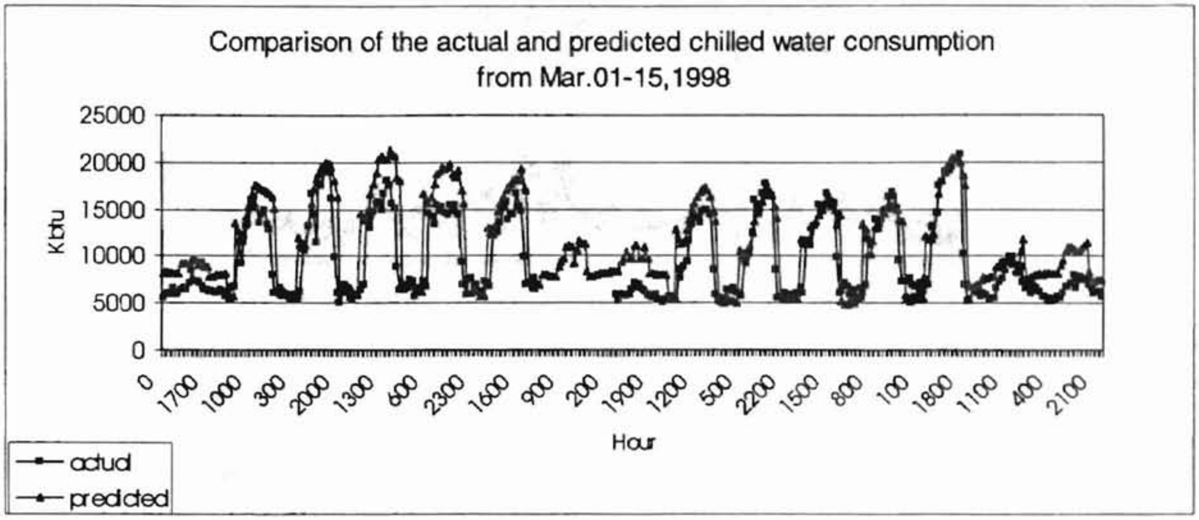

Figure 4-22 Comparison of the Actual and Predicted Chilled Water Consumption
From Mar. 01 – Mar. 15, 1998

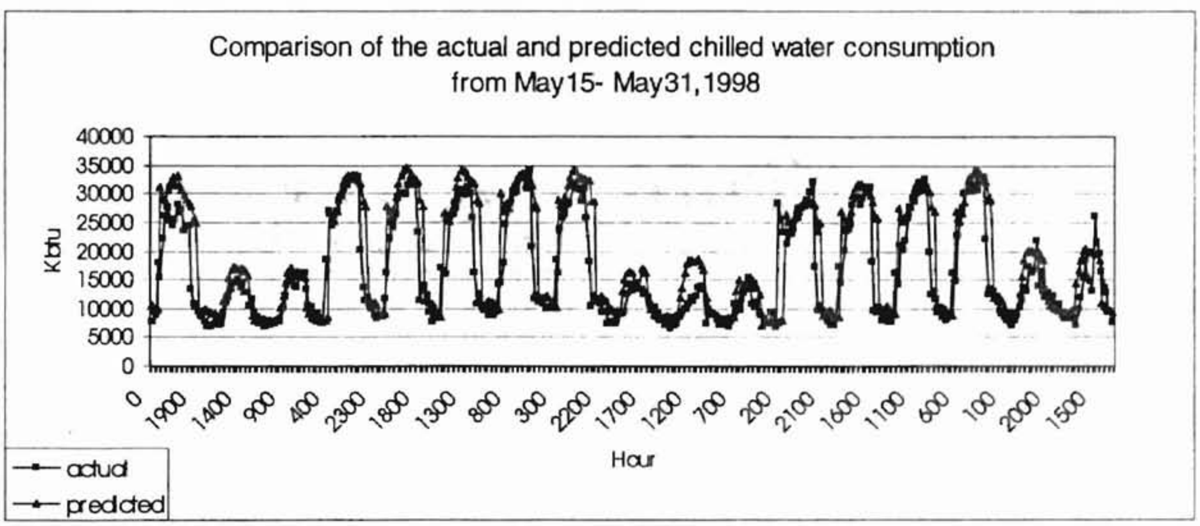

Figure 4-23 Comparison of the Actual and Predicted Chilled Water Consumption
From May 15 – May 31, 1998

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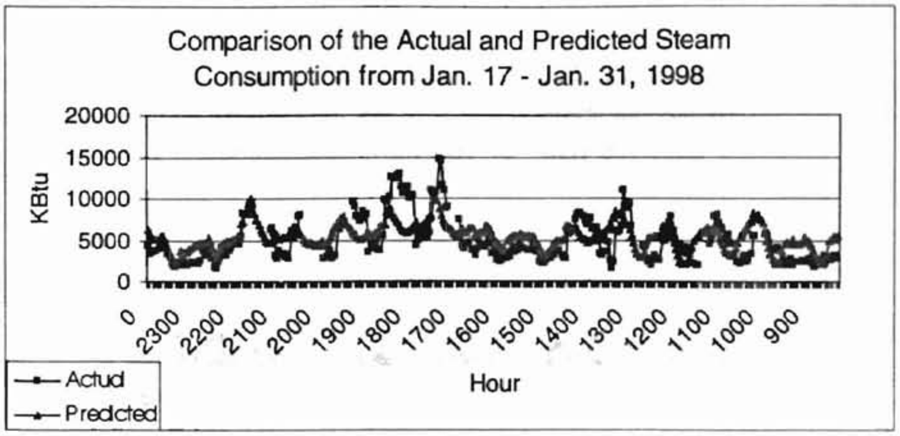

Figure 4-24 Comparison of the Actual and Predicted Steam Consumption From Jan. 17 – Jan. 31, 1998

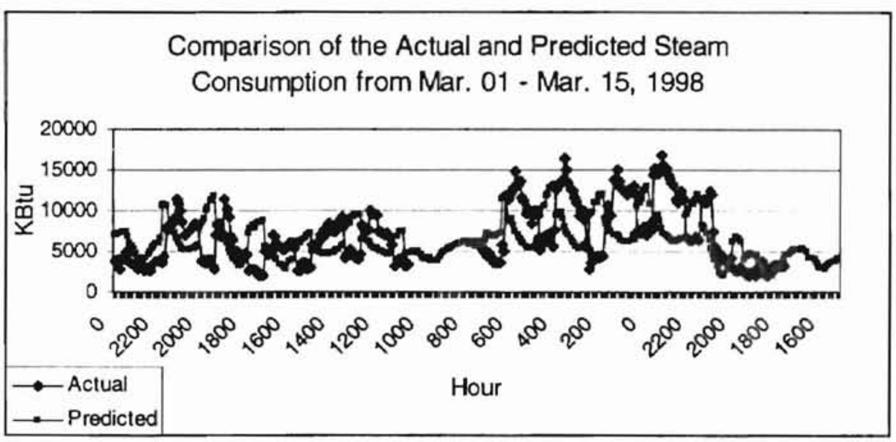

Figure 4-25 Comparison of the Actual and Predicted Steam Consumption From Mar. 01 – Mar. 15, 1998

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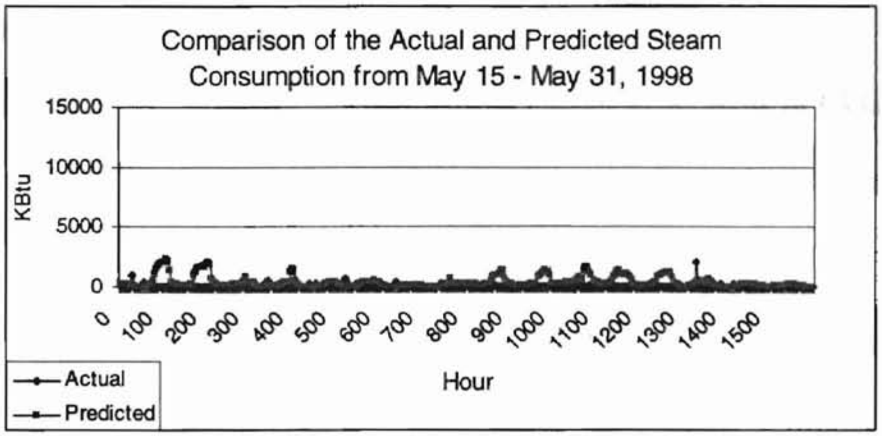

Figure 4-26 Comparison of the Actual and Predicted Steam Consumption From May 15 – May 31, 1998

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CHAPTER 5 RETROFIT ANALYSIS

5.1 Purpose of the Retrofit Analysis

WHBC owns and operates office buildings known as the Bank of Oklahoma Tower, Williams Center Tower I and II, Williams Forum, and the Westin Hotel located in Tulsa, Oklahoma. Based on the ten-year contract with Trigen-Oklahoma District Energy Corporation, WHBC has purchased cooling water and steam from Trigen for the above buildings since Jan. 01, 1991. These buildings are large and consume great heating and cooling energy. For example, in 1998, approximately 2 million dollars have been spent on the steam and chilled water purchasing from Trigen.

In order to reduce the annual energy cost in these buildings, a variety of retrofits and system modification have been investigated in this project. Based on the calibrated model of the BOK building, we concentrate on the retrofit analysis of the BOK building. We investigate the feasibility of constructing a central energy plant and its general functionary attributes at first. Other retrofits such as applying free cooling using cooling towers during cold weather and improving HVAC systems are also introduced and analyzed in this chapter.

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5.2 Present Cost Introduction and Analysis

5.2.1 Present Cost

Trigen-Oklahoma operates and maintains a privately owned district heating and cooling system in the City of Tulsa, Oklahoma, and sells thermal energy in the form of steam and chilled water to various customers.

Based on the agreement dated as of Jan.1, 1991, by and between Trigen-Oklahoma and WHBC, WHBC purchases the chilled water and steam from Trigen for buildings including the Bank of Oklahoma Tower, Williams Center Tower I and II, William Forum, Westin Hotel in Tulsa, Oklahoma. The contract is in effect for a period of ten years from the starting date, Jan.1, 1991.

According to the contract, Trigen will provide at WHBC's Point of Delivery a primary supply of steam at a minimum pressure of 100 psig, a maximum pressure of 175 psig and a maximum temperature of 420° F. WHBC should return the condensate from such steam to Trigen at the Point of Return at a minimum temperature of 110° F and at sufficient pressure to enter Trigen condensate return system and return the condensate to the central plant, but in no event shall WHBC be required to return condensate at a pressure exceeding 50 psig.

WHBC will received the chilled water at its point of delivery at 40-42° F or less and at pressures ranging from a minimum of 100 psig to a maximum of 150 psig and will use its best reasonable efforts to maintain at least a 20 psig pressure differential.

Both the steam and chilled water are paid monthly by WHBC at rates and related provisions specified in Thermal Energy Service Agreement, with certain rate adjustments. The rates for both steam and chilled water services are introduced in the following section.

Rates for steam:

The monthly steam charge is based on the following factors:

1. A monthly usage charge for each one thousand pounds (Mlb) of steam consumed of $4.60 per Mlb, and it is adjusted by the formula:

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Adjusted Usage Charge = Usage Charge * F_1/F_0

Where: F_1 = Trigen's weighted average cost of gas and or oil per million British thermal units (MMBTU), lower heating value consumed during the month prior to the billing period.

F_0 = Trigen's base cost of fuel of 2.55 per MMBTU.

2. An annual capacity charge covering the portion of Trigen's fixed costs of operating the system, the fixed amount of thermal losses, and the capital recovery and system restoration relative to the Customer's requested capacity. It is \$167,266.00 per year, and shall be increased by \$1,000.00 for each Mlb of excess usage. The charge is paid monthly by dividing the annual capacity charge of the previous year by twelve, and is adjusted by a general inflation (deflation) factor, as expressed in the following formula:

   Adjusted monthly capacity charge = Charge per above * [0.25 + (0.75 * $(CPI_1/CPI_0))]$

   Where: CPI_1 = The National Consumers Price Index For All Urban Consumers of the Bureau of Labor Statistics, U.S. Dept. of Labor, U.S. City Average for the most recent quarter for which such index has been published.

   CPI_0 = The said CPI-U for the base period (126.1) as of Dec. 31, 1989.

3. A meter charge. Trigen generally installs one meter per building, and a \$50.00 per month is charge for the service.

4. A lost condensate charge. All customers who return as condensate less than 96% of the steam volume delivered each month shall be subject to a lost condensate charge.

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Rates for chilled water:

The monthly chilled water charge is based on the following factors:

1. A monthly usage charge for each ton hour of chilled water consumed of $0.061 per ton hour, and it is adjusted by the formula:

   Adjusted Usage Charge = Usage Charge * F_1/F_0

   Where: F_1 = Trigen's weighted average cost of gas and or oil per million British thermal units (MMBTU), lower heating value consumed during the month prior to the billing period.

   F_0 = Trigen's base cost of fuel of 2.55 per MMBTU.

2. A pumping charge per thousand gallons. It is $0.10 per thousand gallons of chilled water taken by the customer in the billing period which shall be adjusted each month by the following formula:

   Adjusted Pumping Charge = Charge per above * F_1/F_0

   Where: F_1 and F_0 have the same meaning as above.

3. An annual capacity charge. It is $623,939.00 per year and will increase by $75 for each ton of excess usage. The charge is paid monthly by dividing the annual capacity charge of the previous year by twelve, and is adjusted by a general inflation (deflation) factor, as expressed in the following formula:

   Adjusted monthly capacity charge = Charge per above * $[0.25 + (0.75 * (CPI_1/CPI_0))]$

   Where: CPI_1 = The National Consumers Price Index For All Urban Consumers of the Bureau of Labor Statistics, U.S. Dept. of Labor, U.S. City Average for the most recent quarter for which such index has been published.

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CPI_0 = The said CPI-U for the base period (126.1) as of Dec. 31, 1989.

4. A meter charge. There is a $50.00 per month meter charge per building separately served by Trigen.
5. Lost water charge. All customers who return less than 100% of the volume of chilled water delivered each month shall be subject to a lost water charge.

An apparent billing discrepancy has been found - WHBC is charged "Right of Way Fee" for both thermal and cooling services, about 3% of the total billing each month, which is not shown in the contract. Some further inquiry maybe needed for a good explanation of the discrepancy.

Charts 5-1 and 5-2 are actual steam cost and chilled water cost paid to Trigen in July 1998. It shows that for the chilled water, the energy charge is more than half of the total charge for the chilled water, and for the steam, the capacity charge is much more than other items for the steam.

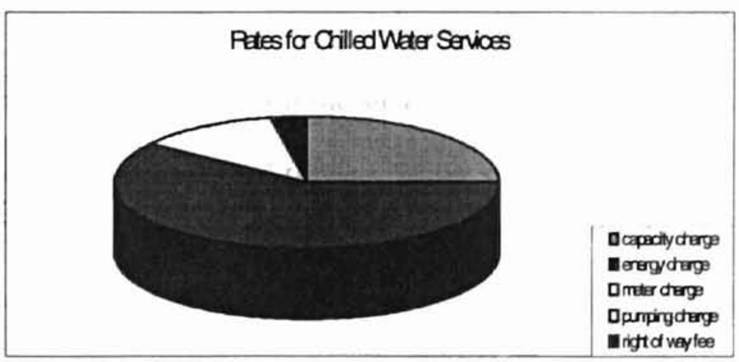

Figure 5-1. Rates for Chilled Water Services (July, 1998)

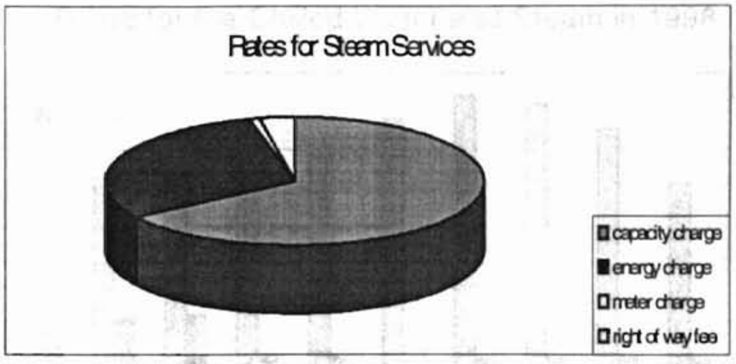

Figure 5-2. Rates for Steam Services (July, 1998)

There is the tax adjustment for both the chilled water and steam bills, a surcharge equal to the proportionate part of any license, occupation, or other similar fee or tax applicable to chilled water and steam service by Trigen to the WHBC.

The detailed information on billings of the BOK building is provided by WHBC, which includes chilled water and steam monthly billings from January to October in 1998. Figure 5-3 shows the comparison between actual monthly billings of the chilled water and steam during Jan. to Oct. in 1998. It is clear that the monthly billing for the chilled water is much more than that for the steam. In these ten months of 1998, the total costs for the chilled water is about 6.5 time as for the steam.

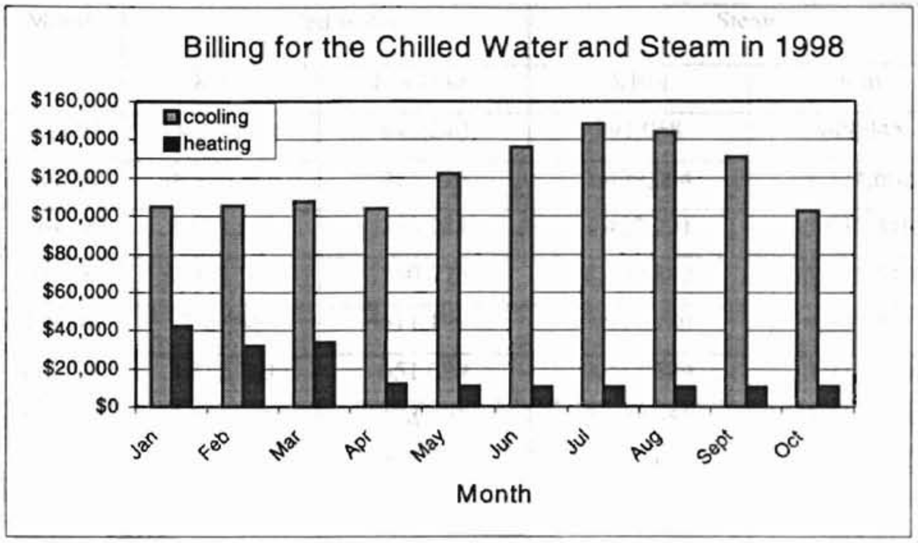

Figure 5-3 Billings for the chilled water and steam during Jan-Oct 1998

5.2.2 Comparison of the Predicted and Actual Energy Costs

The calibrated BOK model is applied to estimate the monthly chilled water and steam costs, and the accuracy of the model is verified by the comparison between simulated and actual costs. The 1997 and 1998 weather files are utilized to predict the energy consumption during 1997 and 1998. The hourly chilled water and steam consumption are obtained from the Report Writer of the BLAST, and then the hourly energy consumption is summed for every month so that we get the monthly energy consumption.

Table 5-1 shows the monthly chilled water and steam consumption during Sept. 1997 to May 1998 based on the simulation results of the BOK model.

Month	Chilled water		Steam	
	KBtu	Ton hours	KBtu	lbm
Sept 97	11,282,874	940,240	391,068	449,945
Oct. 97	10,984,757	915,396	1,499,054	1,724,662
Nov. 97	8,559,368	713,281	3,422,291	3,937,346
Dec. 97	9,008,706	750,726	4,542,842	5,226,540
Jan. 98	733,288	611,107	3,917,789	4,507,417
Feb. 98	7,812,709	651,059	3,417,589	3,931,936
Mar. 98	9,291,628	774,302	3,322,653	3,822,713
Apr. 98	10,386,002	865,500	1,694,553	1,949,583
May 98	13,150,746	1,095,895	308,540	354,975

Table 5-1 Simulated Monthly Chilled Water and Steam Consumption during Sept. 1997 – May 1998

On the basis of the monthly chilled water and steam consumption from the BLAST simulation, we calculate the monthly chilled water and steam costs by applying the actual billing contract. The calculations of each billing item are listed in Table 5-2 and Table 5-3. The "right of way" fee is not considered because it is not mentioned in the rating list of the contract.

Month	Cooling Energy		Cooling Capacity			Pumping		Meter	Subtotal	Taxed
	Cost	Adjusted	Cost	%	Adjusted	Cost	Adjusted	Cost		
Sept.97	$57,357	$66,531	$51,995	67.92	$43,049	$14,038	$16,284	$50	$125,914	$135,883
Oct.97	$55,839	$64,773	$51,995	67.92	$43,049	$13,667	$15,854	$50	$123,726	$133,521
Nov.97	$43,510	$50,472	$51,995	67.92	$43,049	$10,649	$12,353	$50	$105,924	$114,310
Dec.97	$45,794	$53,121	$51,995	67.92	$43,049	$11,208	$13,002	$50	$109,222	$117,869
Jan.98	$37,278	$43,242	$51,995	67.92	$43,049	$9,124	$10,584	$50	$96,925	$104,598
Feb.98	$39,715	$46,069	$51,995	67.92	$43,049	$9,720	$11,276	$50	$100,443	$108,396
Mar.98	$47,232	$54,790	$51,995	67.92	$43,049	$11,560	$13,410	$50	$111,299	$120,110
Apr.98	$52,796	$61,243	$51,995	67.85	$43,005	$12,922	$14,989	$50	$119,287	$128,731
May98	$66,850	$77,546	$51,995	67.03	$42,485	$18,980	$18,980	$50	$139,060	$150,069
Total										$1,113,487

Table 5-2 Simulated Chilled Water Charge during Sept. 1997-May 1998

Month	Heat Energy		Heat Capacity			Meter	Subtotal	Taxed
	Cost	Adjusted	Cost	%	Adjusted	Cost		
Sept.97	$2,072	$2,401	$13,939	53.12	$9,026	$50	$11,476	$12,385
Oct.97	$7,933	$9,203	$13,939	53.12	$9,026	$50	$18,279	$19,726
Nov.97	$18,112	$21,010	$13,939	53.12	$9,026	$50	$30,086	$32,467
Dec.97	$24,042	$27,889	$13,939	53.12	$9,026	$50	$36,945	$39,891
Jan.98	$20,734	$24,052	$13,939	53.12	$9,026	$50	$33,127	$35,750
Feb.98	$18,087	$20,981	$13,939	52.19	$8,868	$50	$29,899	$32,266
Mar.98	$17,585	$20,398	$13,939	51.82	$8,805	$50	$29,252	$31,569
Apr.98	$8,968	$10,402	$13,939	51.82	$8,805	$50	$19,258	$20,783
May98	$1,632	$1,894	$13,939	51.82	$8,805	$50	$10,749	$11,600
Total								$236,437

Table 5-3 Simulated Steam Charge during Sept. 1997-May 1998

The actual billings for chilled water and steam for the BOK building from Jan. to May in 1998 are provided by WHBC. In order to estimate actual billings from Sept. to Dec. 97, we make use of the actual monthly meter readings for the chilled water and steam, which are also provided by WHBC. The actual energy costs are calculated based on the billing contract between the WHBC and Trigen. The assumption was made that the energy consumption allocation among those buildings in last four months in 1997 is the same as those in Jan. 1998.

Table 5-4 is the summary of the monthly chilled water and steam cost comparison between the actual and predicted data. From Sept. 97 to Dec. 97, the "Actual" is an estimation of the actual cost by applying the actual cooling and heating loads.

Month	Actual			Predicted			Relative
	Cooling	Heating	Total	Cooling	Heating	Total	error
Sept. 97	$139,245	$9,053	$148,298	$135,883	$12,686	$148,569	0
Oct. 97	$136,892	$12,111	$149,003	$133,521	$19,726	$153,247	-3%
Nov. 97	$117,749	$36,210	$153,959	$114,310	$32,467	$146,777	5%
Dec. 97	$121,295	$39,573	$160,869	$117,869	$39,891	$157,760	2%
Jan. 98	$116,545	$47,107	$163,651	$104,598	$35,750	$140,348	14%
Feb. 98	$117,187	$35,551	$152,738	$108,396	$32,266	$140,662	8%
Mar. 98	$119,811	$37,426	$157,237	$120,110	$31,569	$151,679	4%
Apr. 98	$115,410	$13,503	$128,912	$128,731	$20,783	$149,514	-16%
May 98	$135,701	$11,885	$147,596	$150,069	$11,600	$161,669	-10%
Total			$1,362,253			$1,350,225	1%

Table 5-4 Actual and Predicted Chilled Water & Steam Costs (Sept. 1997 – May 1998)

Figure 5-4 shows the comparison of the actual and simulated total costs of the chilled water and steam for each month from Sept. 97 – May 98.

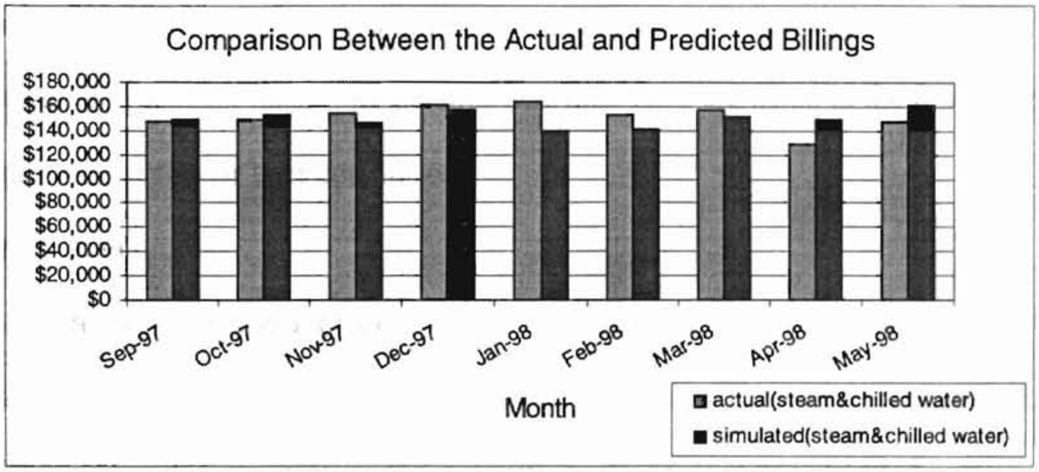

Figure 5-4 Comparison between the Actual and Predicted Billings

From Table 5-4 and Figure 5-4 above, we see that the BLAST model reasonably estimates the BOK energy cost. Simulated monthly energy billings are very close to the actual billings, and the average error is within 5%. Also, the error of the total energy estimation is within 5% as well.

5.2.3 Methodology for the Economic Analysis

5.2.3.1 Payback Method

The payback method is utilized in the economic analysis of possible retrofit options. The initial cost is estimated at first, and the total equipment costs and installation costs are the bottom line of the initial investment. We assume that the material and installation cost for the equipment is the number of units times the cost per unit. At the second step, we anticipate the annual energy savings per year using the BLAST simulation results. Then the initial cost is divided by the annual saving and we get the payback, based on which we draw conclusions and make recommendations.

Some factors are not considered in the financial analysis in this project, but they should be taken into account for further detailed analysis. They are listed in the following and to set the context for our later conclusions.

1) Cost of the land

The position of the central plant is very important, for it has great impact on the initial costs as well as affecting the energy consumption directly. The chillers and large pumps may cause significant vibration and noise, so the building is usually sited separately or in the underground. At the same time, for the economy and effects of energy delivery, the building is located as near as possible to the central of the heating load or cooling loads. The cooling towers may sit on the top of surrounding buildings.

The BOK building is located in the crowded downtown area of Tulsa, and the cost for building a separate plant may be much more expensive than the average due to the costs of renting or purchasing the land. The cost of the land is not considered in our retrofit analysis in this project.

2) Cost of salary and relevant facility

The salary paid to employees who operate and maintain the physical plant is not considered. Other incidental costs for the relevant facility including computer, printer, microwave, and copy machine are not included, either.

3) Cost of maintenance

The maintenance cost mainly includes the cost for regular checking and repairing equipment, such as chillers, boilers, and cooling towers, etc, and the cost for water treatment needed by the boiler and cooling tower. It is not considered at this step.

5.2.3.2 Baseline Operating Costs

One of the difficulties in our financial analysis is how to choose the weather file in order to estimate the baseline operating costs. The energy consumption depends greatly on the future weather condition, while obviously it is an uncertain factor.

TMY (NOAA Test Meteorological Year) weather tape in Tulsa is used for the financial analysis. They were prepared using weather data from the years between 1954 and 1972 and can represent the typical weather condition in Tulsa. One year worth of data is weighted using nine key indices: total horizontal radiation, maximum, minimum, and mean of dry bulb and dew point, and the maximum and mean of the wind speed. Twelve typical months were then chosen based on their closeness to the long-term cumulative distribution functions. Discontinuities between months were machine smoothed.

The calibrated BOK model is used to estimate the annual chilled water and steam costs. The TMY weather tape is applied to get the energy consumption for a typical year. The hourly chilled water and steam consumption is gained from the Report Writer of the BLAST. The following tables 5-5 and 5-6 give the information about the monthly chilled water consumption and steam consumption respectively, which are summations of the hourly chilled water and steam during a specific month period.

Month	Chilled Water (KBtu)	Chilled Water (Ton-hours)
January	7,005,319	583,777
February	7,296,408	608,034
March	10,000,454	833,371
April	10,297,198	858,100
May	12,621,390	1,051,783
June	14,949,824	1,245,819
July	17,323,574	1,443,631
August	17,108,065	1,425,672
September	13,618,148	1,134,846
October	12,716,527	1,059,711
November	9,812,761	817,730
December	8,596,193	716,349

Table 5-5 Monthly Chilled Water Consumption for TMY 1973

Month	Steam (KBtu)	Steam (lbm)
January	4,739,674	5,452,995
February	4,106,966	4,725,064
March	2,310,707	2,658,469
April	1,719,132	1,977,862
May	607,069	698,433
June	67,170	77,279
July	2,211	2,544
August	46,921	53,983
September	265,066	304,959
October	923,218	1,062,162
November	2,058,450	2,483,296
December	4,506,072	5,184,236

Table 5-6 Monthly Steam Consumption for TMY 1973

On the basis of the monthly chilled water and steam consumption, we calculate the monthly chilled water, steam costs by applying the actual billing contract. The calculations for each billing item are listed in Table 5-7 and Table 5-8. They set baseline operating costs for our later financial analysis. In these tables "Adjusted" means the base costs are adjusted by the inflation factor (CPI), as specified by the contract.

Month	Cooling Energy		Cooling Capacity		Pumping		Meter	Subtotal	Taxed
	Cost	Adjusted	Cost	Adjusted	Cost	Adjusted	Cost		
Jan.	$35,610	$41,308	$51,775	$63,382	$8,716	$10,110	50	$114,850	$123,943
Feb.	$37,090	$43,025	$51,775	$63,382	$9,078	$10,530	50	$116,987	$126,249
Mar.	$508,356	$58,969	$51,775	$63,382	$12,442	$14,433	50	$136,834	$147,667
Apr.	$52,344	$60,719	$51,775	$63,382	$12,811	$14,861	50	$139,012	$150,018
May	$64,159	$74,424	$51,775	$63,382	$15,703	$18,216	50	$156,070	$168,428
Jun.	$75,995	$88,154	$51,775	$63,382	$18,600	$21,576	50	$173,162	$186,871
Jul.	$88,062	$102,151	$51,775	$63,382	$21,553	$25,002	50	$190,585	$205,671
Aug.	$86,966	$100,881	$51,775	$63,382	$21,285	$24,691	50	$189,003	$203,967
Sept.	$69,226	$80,302	$51,775	$63,382	$16,943	$19,654	50	$163,388	$176,323
Oct.	$64,642	$74,985	$51,775	$63,382	$15,822	$18,353	50	$156,770	$169,181
Nov.	$49,882	$57,863	$51,775	$63,382	$12,209	$14,162	50	$135,457	$146,181
Dec.	$43,697	$50,689	$51,775	$63,382	$10,695	$12,406	50	$126,527	$136,544
Total									$1,941,045

Table 5-7 Simulated Chilled Water Charge for a Typical Year (Purchased Cooling)

Month	Heat Energy		Heat Capacity		Meter	Subtotal	Taxed
	Cost	Adjusted	Cost	Adjusted	Cost		
Jan.	$25,084	$29,097	$13,939	$16,991	$50	$46,139	$49,791
Feb.	$21,735	$25,213	$13,939	$16,991	$50	$42,254	$45,600
Mar.	$12,229	$14,186	$13,939	$16,991	$50	$31,227	$33,699
Apr.	$9,098	$10,554	$13,939	$16,991	$50	$27,595	$29,780
May	$3,213	$3,727	$13,939	$16,991	$50	$20,768	$22,412
Jun.	$355	$412	$13,939	$16,991	$50	$17,454	$18,836
Jul.	$12	$14	$13,939	$16,991	$50	$17,055	$18,405
Aug.	$248	$288	$13,939	$16,991	$50	$17,329	$18,701
Sept.	$1,403	$1,627	$13,939	$16,991	$50	$18,669	$20,147
Oct.	$4,886	$5,668	$13,939	$16,991	$50	$22,709	$24,507
Nov.	$11,423	$13,251	$13,939	$16,991	$50	$30,292	$32,691
Dec.	$23,847	$27,663	$13,939	$16,991	$50	$44,704	$48,244
Total							$362,813

Table 5-8 Simulated Steam Charge for a Typical Year (Purchased Heating)

5.3 Organization of the Retrofit Analysis

Based on the calibrated BOK model, a variety of possible retrofit options are examined to determine their predicted energy consumption and economic feasibility. This mainly includes the analysis of following items:

1. The feasibility of constructing a central energy plant and its general functionary attributes;
2. The feasibility of applying free cooling from cooling towers instead of purchasing the chilled water in the cold weather;

3. The feasibility of applying a central energy plant with free cooling from cooling towers;
4. HVAC improvements with purchased cooling ;
5. HVAC improvements with central plant;

Two additional factors are kept in mind throughout the retrofit analysis: minimal operation and maintenance costs and ease of implementation. Both of the financial benefit and the convenience of realization are required for the retrofit to be considered feasible.

5.3.1 BOK Model With Central Energy Plant

The heating and cooling sources are two critical elements in overall system energy efficiency. At this step, we consider the possibility of building a central energy plant, providing chilled water and steam to the BOK building instead of purchasing them from Trigen. The feasibility of the alternative will mainly depend on the financial feasibility. In the following we describe the physical plant at first, which includes choosing appropriate sizes of main equipment and making a rough design of the physical plant. Then we make the financial analysis using the methodology introduced in 5.2.3.

5.3.1.1 Design of Central Energy Plant

The calibrated BOK model is the basis of the alternative. The input file remains unchanged except the purchase cooling and heating are replaced by water-cooled chillers and natural gas boilers in the plant definition at the end of the input file. In other words, the heating and cooling are assumed to be generated in a central energy plant housed in a separate building, while other HVAC systems of the BOK building, such as distribution of the ductwork and delivery devices remain unchanged in the retrofit process.

We run the calibrated BOK model for the design day in BLAST to get the peak cooling and heating loads. Both chiller and boiler are sized for peaking cooling loads and heating loads respectively. Information on monthly and annual electric power, gas, steam, and fuel consumption is obtained in BLAST output file. It is reported in the BLAST output file that the total floor area of the BOK is 834604 ft^2, and we get the peak load per ft^2 by dividing the peak load by the total floor area. Table 5-9 gives the plant summary for the design day.

Equipment	Natural Gas Boiler	Elec. Chiller	Hot water Pump	Chilled Water Pump
Peak load	15,000 KBtu/hr	32,000 KBtu/hr	497 KBtu/hr	795 KBtu/hr
Time	Jan. 21, 5:00 AM	Jul. 21, 16:00 PM	Jan. 21, 24:00 AM	Jul. 21, 16:00 PM
Peak load	17.9 Btu/hr. ft^2	38.3 Btu/hr. ft^2	——	——

Table 5-9 Plant Summary for the Design Day

Based on the information above, we choose four boilers with four hot water pumps, four centrifugal chillers with four chilled water pumps, as well as four cooling towers serving four chillers. Their sizes are listed in Table 5-10.

Equipment	Natural gas Boiler	Elec. Chiller	Cooling Tower	Hot Water Pump	Chilled Water Pump
Number	4	4	4	4	4
Capacity	4650 KBtu/hr	10000 KBtu/hr	10000 KBtu/hr	50 HP	100 HP
				1200 gpm	3000 gpm

Table 5-10 Main Equipment Summary

The model of a boiler is simulated as a standard natural gas fired boiler. The performance of the boiler is based on the air to fuel ratio, natural gas heating value, boiler stack temperature and ambient air temperature.

The model of a chiller is simulated as a standard vapor compression refrigeration cycle with a water-cooled condenser and a centrifugal compressor. The cooling tower cools water by contacting it with air through a closed loop heat exchanger. In this alternative, the cooling tower serves chillers and one or more propeller or centrifugal fans move air vertically up or horizontally through the tower.

Figure 5-5 is a schematic diagram of our design, which includes all- air HVAC systems with separate air handlers, cooling towers, boilers and chillers.

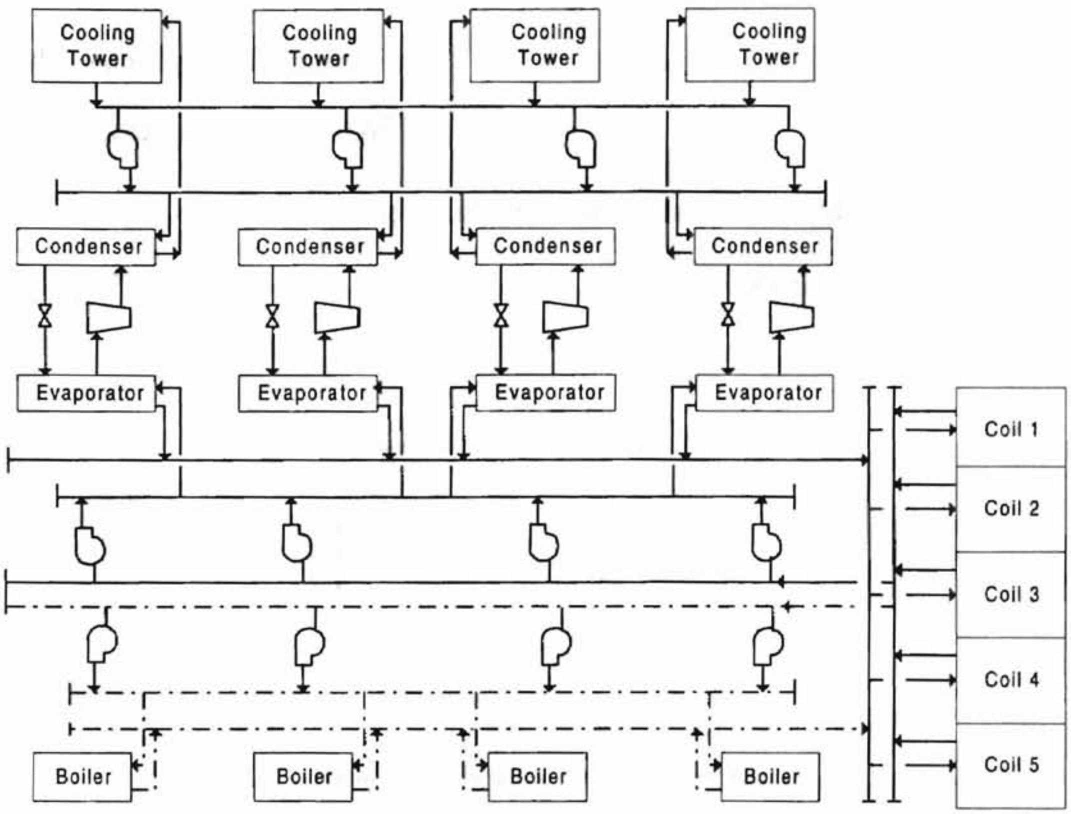

Figure 5-5 HVAC System with Boilers and Chillers

All the equipment may be placed in one building, or the boilers and chillers may be placed in separate buildings. There is no difference for the financial analysis. We assume that there are two separate buildings to be designed and built. One is for chillers and chilled water pumps and another is for boilers and hot water pumps. The Square Foot Estimating Method is applied to estimate the initial construction cost for two buildings.

We design the area of the building for chillers and cooling water pumps by referring to Li [1994], and the following two rules-of-thumb are used:

1. The physical plant area is 3.25 ft^2 for per ton cooling load.
2. The physical plant area is 0.6 – 1.0 % of the total building area.

Then the area for building a chiller plant by using the first rule is:

$$12000 \text{ KBtu/hr} * 4 * 3.25 / 12 = 13{,}000 \text{ ft}^2. \quad (5\text{-}1)$$

By using the second rule, we have:

$$1.0 \% * 834604.19 = 8{,}400 \text{ ft}^2. \quad (5\text{-}2)$$

We choose the smaller area (applying the second rule) because of the large size of the BOK building. The height of it is 23 Ft. Figure 5-6 is the plan view for it.

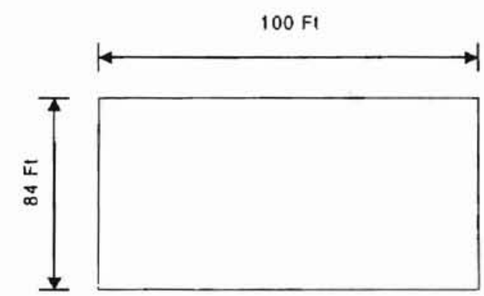

Figure 5-6 Plan View for the Chiller Plant

Similarly, we estimate the area of the building for boilers and hot water pumps by assuming that it is about 2.2% of the total building area. That is:

$$834604.19 * 2.2\% = 18{,}000 \text{ ft}^2. \quad (5\text{-}3)$$

Figure 5-7 is a plan view for the boiler plant. The height of it is 23 Ft.

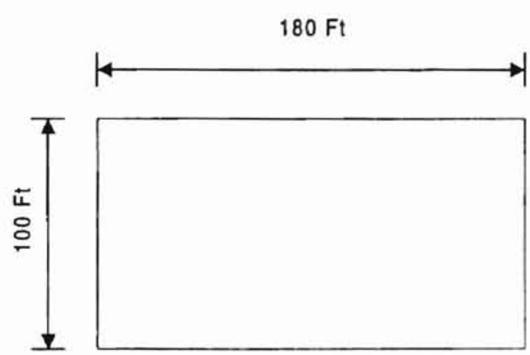

Figure 5-7 Plan View for the Boiler Plant

5.3.1.2 Financial Analysis

5.3.1.2.1 Initial Costs

We calculate the major equipment costs by referring to R.S. Means Co. [1999], which includes anticipating the material and installation cost for chillers, boilers, cooling towers, hot water pumps, and chilled water pumps. Calculation for each of them is introduced in the following respectively.

1) Cooling Tower:

We choose the galvanized draw - through cooling tower with capacity of 1000 tons. We assume the tower will shipped from the factory direct to the job site, and the job coordinator will then have a crane meet the truck and set the tower members at the erection site, whose costs are included in the installation costs.

Table 5-11 is based on standard rooftop installation with sleepers properly sized to distribute 29 lb./ft^2, properly flashed pitch pans, and steel guys to withstand 120-mile-per hour wind velocity. These costs do not include crane service, special rigging, water makeup and drain, wiring, pumps and starters, piping and controls.

Type	Galvanized Draw Through
Capacity	1,000 tons
Shipping weight	35,000 lb.
Operating weight	53,000 lb.
Base area	500 ft^2
Tower cost	$61,500
Installation	$22,500
Total	$84,000

Table 5-11 Cooling Tower Initial Costs

2.) Boiler:

Table 5-12 indicates material and installation costs for a larger cast-iron, oil-fired boiler with standard controls and a flame retention burner.

Type	Cast Iron, Gas, steam
Capacity	4650 MBH
Material Cost	$61,500
Installation Cost	$23,600
Total	$85,100

Table 5-12 Boiler Initial Costs

3.) Chiller:

Prices for a centrifugal chiller unit are shown in Table 5-13.

Type	Centrifugal, water cooled
Capacity,	1,000 Ton
Equipment Cost	$394,000
Installation Cost	$39,800
Total	$433,800

Table 5-13 Chiller Initial Costs

4.) Other Mechanical Costs:

Other initial investment includes the cost for purchasing and installing chilled water and hot water pumps, the plumbing, as well as the control equipment. By referring to Mauck (1999), we estimate the cost for purchasing and installing chilled water or hot water pumps is $50 / ton, for the plumbing of heating system or cooling system is $100 / ton, and for the control system for the heating or cooling is $ 50 / ton.

Table 5-14 gives a summary of initial costs of main equipment. The cooling system capacity is the capacity of chillers, and it is 4000 tons. Similarly, the heating system capacity is the capacity of boilers, each of which is 4650 KBtu / hr, that is, 388 tons.

	Equipment	Cost Each	Number	Cost
Cooling	Chiller	$433,800	4	$1,735,200
	Cooling tower	$84,000	4	$336,000
	Chilled Water Pumps	$ 50 / ton	4 * 1000 tons	$ 200,000
	Piping	$ 100 / ton	4 * 1000 tons	$ 400,000
	Controls	$ 50 / ton	4 * 1000 tons	$ 200,000
	Subtotal			$ 2,871,200
Heating	Boiler	$85,100	4	$340,400
	Hot Water Pumps	$ 50 / ton	4 * 388 tons	$ 77,600
	Piping	$ 100 / ton	4 * 388 tons	$ 155,200
	Controls	$ 50 / ton	4 * 388 tons	$ 77,600
	Subtotal			$ 650,800
Total cost		$ 3,522,000		

Table 5-14 Main Mechanical Costs

5.) Structure of the central plant

The Square Foot Estimating Method is utilized to anticipate costs of building physical plants. The structure of the plant is broken down into several components in order to developing an assembly estimate. They are:

1. Foundations including excavation and slab on grade;
2. Substructures including excavation and slab on grade;
3. Exterior closure, which is the building envelope including walls, windows, and doors.
4. Roofing including the related moisture protection and insulation;

5. Interior construction including partitions (fixed and movable), floors, ceilings, and decorating.

Table 5-15 provides an outline of how we get costs of each sections and total structure.

	Chiller Plant			Boiler Plant		
Component	Ft^2	$\$/Ft^2$	Cost	Ft^2	$\$/Ft^2$	Cost
Foundation	8,400	1.18	$9,912	18,000	1.18	$21,240
Substructure	8,400	1.05	$8,820	18,000	1.05	$18,900
Exterior closure	8464	7.63	$64,580	12,880	7.63	$98,274
Interior Construction	2300	8.54	$19,642	4140	8.54	$35,356
Roofing	8,400	1.13	$9,492	18,000	1.13	$20,340
Subtotal			$112,446			$194,110
Total	$306,556					

Table 5-15 Initial Cost for the Structure of Central Plant

6.) Electrical cost of the plant

The electrical cost includes the lighting, the main building transformer, metering arrangement, switch board, power and lighting panel, and fire alarm, etc. By referring Mauck (1999), we estimate the electrical cost in table 5-16 for the cooling systems, and minor electrical costs for boilers are neglected.

	Cooling System		
Items	$ / ton	Total Tons	Total Cost
Electrical	$ 120 / ton	4 * 1000	$480,000

Table 5-16 Initial Cost for the Electricity of Central Pla t

7.) **Total Cost**

The total initial cost would be the sum of the main HVAC equipment initial costs, the cost for the structure of physical plants, and the cost for the electricity of physical plants, and the design fee. By referring to R.S. Means Co. [1999], we calculated the fee for designing plants as 4% of the total initial cost of the plant. Table 5-17 puts together a budget estimate for building physical plants.

Item	Cost
Mechanical	$3,522,000
Structure	$306,556
Electrical	$480,000
Subtotal	$4,308,556
Design Fee	$172,342
Total Initial Cost	$4,480,898

Table 5-17 Total Initial Cost for Physical Plants

5.3.1.2.2 Annual Savings

Once the separate physical plants are built, the BOK building will consume natural gas and electricity instead of purchasing the chilled water and steam from Trigen. The annual saving is expressed in equation (5-4):

Annual savings = costs for purchasing the chilled water and steam – (electricity cost for physical plant – electricity cost for purchasing energy) – costs for natural gas.

(5-4)

Where, the difference of electrical costs between the purchasing energy and separate plants is mainly due to the electricity consumption by the chillers, cooling towers, hot and chilled water pumps, etc. Electrical power consumption by fans, lighting, electrical equipment, etc. is assumed to be the same for purchased energy and separate plant.

The price schedule of electricity is issued by Public Service Company of Oklahoma in Tulsa, which is the basis of our electricity cost estimate. The ratings are listed and explained in the following:

1. Base Service Charge: $22.80

If the customer has demand requirements of 500 kW or greater, the premise may require time differentiated metering including a communication link that meets the Company's requirements for meter reading. If the Company installs the phone line for its own use or if the customer installs the phone line, the customer's Base Service Charge will be $22.80 per month. We assume that WHBC installs the phone line.

2. Electricity Charge:

2a) On-Peak Season:

6.22 Cents	Per kWh for all kWh up to a maximum level equal to 150 multiplied by the current month maximum kilowatt (kW).
5.59 Cents	Per kWh for the next block of kWh up to a maximum level equal to 150 multiplied by the current month maximum kW.
3.58 Cents	Per kWh for all additional kWh used.

2b) Off-peak Season:

4.03 Cents	Per kWh for all kWh up to a maximum level equal to 150 multiplied by the current month maximum kilowatt (kW).
3.67 Cents	Per kWh for the next block of kWh up to a maximum level equal to 150 multiplied by the current month maximum kW.
3.03 Cents	Per kWh for all additional kWh used.

The On-Peak season is the Company's billing months of June through October inclusive. The Off-peak season is the Company's billing months of November through May inclusive.

The hourly total electricity consumption of the BOK building is gained from the output of the Report Writer. Based on the price schedule above, we then calculate the monthly electrical cost for both cases (purchasing the energy and building separate plants) throughout a typical year.

Tables 5-18a and 5-18b show each step to estimate the electrical cost for purchasing the energy, and in the same way Tables 5-19a and 5-19b indicate how to anticipate the electrical cost for applying separate plants. The bold and italic font is to distinguish the On-Peak season from Off-Peak season.

From Tables 5-18a and 5-18b, we get the total simulated electrical charge for a typical year when the purchased cooling and heating is applied:

Total Elec. Charge = \$ 586,161+ \$ 698,249= \$1,284,410 (5-5)

Similarly, from Tables 5-19a and 5-19b, we obtained the total simulated electrical charge for a typical year when the separate physical plant is used:

Total Elec. Charge = \$756,623 + \$ 958,852 = \$ 1,715,475 (5-6)

	Jan-73	Feb-73	Mar-73	Apr-73	May-73	*Jun-73*
Block1 (maximum, Kw)	3,982	3,982	3,982	3,982	3,982	*3,982*
Block1 ($)	24,070	24,070	24,070	24,070	24,070	*37,150*
Block2 (maximum, Kw)	3,982	3,982	3,982	3,982	3,982	*3,982*
Block2 ($)	21,920	21,920	21,920	21,920	21,920	*33,387*
block3 (Sum, Kwh)	1,320,723	1,115,804	1,376,852	1,290,038	1,376,833	*1,290,075*
Block3 ($)	40,018	33,809	41,719	39,088	41,718	*46,185*
Service ($)	23	23	23	23	23	*23*
Subtotal ($)	86,030	79,821	87,731	85,101	87,730	*116,745*
taxed ($)	92,841	86,141	94,677	91,838	94,676	*125,988*
Total (Jan.-Jun.)	$ 586,161					

Table 5-18a Simulated Elec. Charge for a Typical Year (Jan. – Jun.)
(Purchased Cooling and Heating)

	Jul-73	*Aug-73*	*Sep-73*	*Oct-73*	Nov-73	Dec-73
Block1 (maximum, Kw)	*3,982*	*3,982*	*3,982*	*3,982*	3,982	3,982
Block1 ($)	*37,150*	*37,150*	*37,150*	*37,150*	24,070	24,070
Block2 (maximum, Kw)	*3,982*	*3,982*	*3,982*	*3,982*	3,982	3,982
Block2 ($)	*33,387*	*33,387*	*33,387*	*33,387*	21,920	21,920
block3 (Sum, Kwh)	*1,364,175*	*1,390,572*	*1,263,641*	*1,376,888*	1,276,849	1,350,481
Block3 ($)	*48,837*	*49,782*	*45,238*	*49,293*	38,689	40,920
Service ($)	*23*	*23*	*23*	*23*	23	23
Subtotal ($)	*119,398*	*120,343*	*115,799*	*119,853*	84,701	86,932
taxed ($)	*128,850*	*129,870*	*124,966*	*129,342*	91,407	93,814
Total (Jul.-Dec.)	$ 698,249					

Table 5-18b Simulated Elec. Charge for a Typical Year (Jul. – Dec.)
(Purchased cooling and Heating)

	Jan-73	Feb-73	Mar-73	Apr-73	May-73	*Jun-73*
Block1 (maximum, Kw)	5,074	5,103	5,424	5,788	6,095	*6,548*
Block1 ($)	30,674	30,849	32,790	34,990	36,844	*61,094*
Block2 (maximum, Kw)	5,074	5,103	5,424	5,788	6,095	*6,548*
Block2 ($)	27,934	28,093	29,860	31,864	33,553	*54,906*
block3 (Sum, Kwh)	1,476,769	1,257,790	1,371,760	1,369,528	1,352,540	*1,426,623*
Block3 ($)	44,746	38,111	41,564	41,497	40,982	*51,073*
Service ($)	23	23	23	23	23	*23*
Subtotal ($)	103,376	97,076	104,237	108,373	111,401	*167,095*
taxed ($)	111,560	104,762	112,490	116,953	120,221	*180,324*
Total (Jan.-Jun.)	$756,623					

Table 5-19a Simulated Elec. Charge for a Typical Year (Jan.-Jun.)
(Separate Physical Plant)

	Jul-73	*Aug-73*	*Sep-73*	*Oct-73*	Nov-73	Dec-73
Block1 (maximum, Kw)	*6,634*	*6,522*	*6,203*	*6,188*	5,480	5,292
Block1 ($)	*61,894*	*60,846*	*57,877*	*57,735*	33,125	31,992
Block2 (maximum, Kw)	*6,634*	*6,522*	*6,203*	*6,188*	5,480	5,292
Block2 ($)	*55,625*	*54,683*	*52,014*	*51,887*	30,166	29,134
block3 (Sum, Kwh)	*1,648,319*	*1,667,644*	*1,429,790*	*1,467,908*	1,426,978	1,508,551
Block3 ($)	*59,010*	*59,702*	*51,186*	*52,551*	43,237	45,709
Service ($)	*23*	*23*	*23*	*23*	23	23
Subtotal ($)	*176,551*	*175,254*	*161,100*	*162,195*	106,551	106,858
taxed ($)	*190,528*	*189,128*	*173,855*	*175,036*	114,987	115,318
Total (Jul.-Dec.)	$ 958,852					

Table 5-19b Simulated Elec. Charge for a Typical Year (Jul.-Dec.)
(Separate Physical Plant)

We run the BOK model with separate physical plant and gained the hourly gas consumption from the output file of the Report Writer. The annual total gas consumption is the sum of the hourly consumption throughout the year, and it is 30,699,957 KBtu. We assume the natural gas combustion value is 1081 Btu per ft^3. Also, we get the information that the charge for natural gas delivery to the BOK building is 33.5 cents per ccf (100 ft^3) from the web site of public service company of Oklahoma - "http://www.ong.com/commercialrates.htm". Then the money charged for the natural gas would be:

$$(30{,}699{,}957 / 108.1) * 0.335 = \$95{,}139 \quad (5\text{-}7)$$

We apply the equation (5-4), and the annual saving would be:

$$\text{Annual saving} = 362{,}813 + 1{,}941{,}045 - (1{,}715{,}475 - 1{,}284{,}410) - 95{,}139$$

$$= \$1{,}777{,}654 \quad (5\text{-}8)$$

The summary of the financial analysis is listed in Table 5-20:

First Cost	$4,480,898
Annual savings	$1,777,654
Payback	2.5 year

Table 5-20 Central Plant Investment Analysis

The payback is quite short, which indicates that this would be an excellent investment. It should be noted that due to some costs not included in the analysis (such as the cost of purchasing or renting the land, cost of salary and relevant facility, cost of maintenance, etc.), the actual payback period will be longer than 2.5 years.

5.3.2 Free Cooling Tower with Purchased Energy

Airside economizer cycles and waterside free cooling are two basic approaches to achievement of energy savings. The airside economizers are fairly simple and can result in considerable energy and operational cost savings. In the BOK building, the airside economizers have been applied in some underground floors. However, because of its architectural constraints, the BOK lacks the potential for 100% outside air for most of floors, and it is hard to add more airside economizer cycles or airflow.

Waterside free cooling is another means to generate significant energy savings. The water from the cooling tower is used to cool the water directly when the ambient temperature is low enough, thus reducing or eliminating the need for refrigeration or purchased chilled water. In the following sections, we introduce the application of the free cooling tower to the BOK building, assuming the building remains on the Trigen system.

5.3.2.1 BOK Model with Free Cooling Tower

The goal of free cooling is to make the cooling tower act as the source of chilled water under suitable conditions of weather and cooling load. As a result, the greatest possible energy savings would accrue from turning off the chiller or stopping purchasing chilled water.

A basic loop utilizing a free cooling tower is illustrated in Figure 5-8. The principal components include the open cooling tower and the plate-and-frame heat exchanger. The use of heat exchanger is mainly to make complete isolation of two chilled water loops during the free cooling.

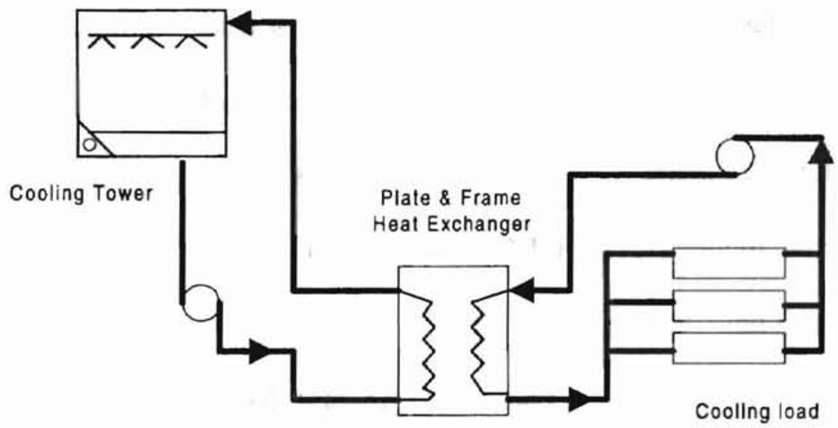

Figure 5-8 Free Cooling System

When the outside air temperature falls low enough, the cooling tower is turned on and the purchased chilled water circulates in a closed loop without flowing back to the Trigen. The chilled water is provided by the cooling tower instead of purchasing from Trigen, and thus large amount of cooling costs would be saved.

Based on the previous calibrated BOK model, we define four cooling towers with heat exchanger in place of the purchased cooling in the BLAST input file. Then the modified model is used to simulate the hourly cooling load contribution from cooling towers for a typical year. The financial analysis is made to find the balance between the chilled water savings and the increased initial costs. The initial costs for valves and pumps are neglected in this research.

For most installations, both operating efficiency and control of tower freezing dictate that the flow rate over the cooling tower should be constant at all times.

According to the formula above, reduction in heat load translate directly to reduce cooling range. In the BLAST program, we set the entering water temperature be 50 ° F. When the outside air wet bulb temperature falls below 42 ° F, the free cooling is turned on. We make the assumption that when the wet bulb temperature of the outside air is higher than 42 ° F, the free cooling is turned off.

Based on the weather data for a typical year in Tulsa, we count the total hours when outside air wet bulb temperature is lower than 42° F for every month, which is shown in Table 5-21. It shows that during most of December, January and February, the outside wet bulb temperature is lower than 42° F, and the free cooling can be applied in these three months.

Month	Jan.	Feb.	Mar	Apr.	May	Jun	Jul.	Aug.	Sept.	Oct.	Nov	Dec
Hours	526	509	80	107	5	0	0	0	0	18	140	587

Note: hours = total hours when $T_{outside\ wetbulb} < 42^{\circ}$ F

Table 5-21 Free Cooling Opportunity

5.3.2.2 Financial Analysis

Assuming the Trigen provides the BOK building the chilled water all the time except in January, February, and December, we run the simulation for three months including January, February and December. There may be some small additional savings in Nov., Mar., and April. According to the report writer, we obtain the hourly electricity consumption for the free cooling, the hourly water temperature leaving and entering the cooling tower, as well as the hourly water flow rate through the cooling tower. We set the flow rate as constant in the BLAST input file, and from the report writer, we read the flow rate is constant as 9990.56 gpm (total flow rate for four cooling towers).

The initial cost for free cooling is considered to be the cost of buying and installing major equipment including four cooling towers and four pumps. While the free cooling saves the money for purchasing chilled water from Trigen, it consumes more electricity than the purchased cooling due to the operation of cooling tower fans and pumps. Thus the annual savings would be the cost for purchasing the chilled water from Trigen minus the difference of electricity costs between the free cooling and the purchased cooling.

Table 5-22 is a summary of the cost for major equipment including four cooling towers and four pumps, and the total cost is $385,600, which is also the anticipation of the initial cost for applying free cooling.

Equipment	**Cost Each**	**Number**	**Cost**
Cooling Tower	$84,000	4	$336,000
Chilled Water Pumps	$ 50 / ton	4 * 1000 tons	$ 200,000
Total	$536,000		

Table 5-22 Major Equipment Cost

The electricity costs for the purchased cooling and the free cooling are listed in Table 5-23 for comparison. More electricity is used for free cooling than for purchased cooling because of the electricity consumption from cooling towers and pumps.

Electricity	Purchased Cooling	Free Cooling
January	$92,841	$102,365
February	$86,141	$92,256
December	$93,814	$101,000
Total	$ 272,796	$ 295,621

Table 5-23 Electricity Costs for Both the Purchased Cooling & Free Cooling

In order to calculate the saving cooling energy by the free cooling tower, we run the simulation and obtain the hourly cooling tower entering water temperature, the cooling tower leaving water temperature, and the cooling tower water flow rate from December to February. Then the hourly cooling energy savings are calculated by the Equation (5-9):

Cooling Savings = (Cooling tower leaving water temp. – Cooling tower entering water temp.) * Cooling tower flow rate * C_p

(5-9)

Where C_p is the specific heat of the water.

The energy saving in December, January and February are then summed respectively, and those hours when the free cooling tower is off are not concluded. We then calculate the money saved by the free cooling tower, and all items are listed in Table 5-24. The saving is also considered as the annual saving from the free cooling application.

	December	January	February
Saving Energy	4,143,875 KBtu	3,497,910 KBtu	3,655,908 KBtu
energy $	$21,065	$17,781	$18,584
adjusted $	$24,435	$20,626	$21,558
pumping	$5,156	$4,352	$4,549
adjusted $	$5,981	$5,048	$5,276
subtotal	$30,416	$25,674	$26,834
taxed	$32,824	$27,707	$28,958
Total	$89,489		

Table 5-24 Energy Saving

The total initial cost is $536,000 from Table 5-22. The annual saving comes from three months, and the formula is:

(Cooling Savings + electricity cost for purchased chilled water) – (electricity cost for free cooling) (5-10)

That is:

Annual saving = (89,489 + 272,796) – 295,621 = $ 66,664 (5-11)

We calculate the pay back period, that is:

536,000 / 66,664 = 8.0 (year)

The paybacks for using free cooling tower with purchasing the chilled water and steam from Trigen is about eight years. The initial investment is not high, but due to the weather condition in Tulsa, the free cooling tower can not be turned on and utilized all the time in January, February, and February, which makes the cooling savings not high enough and the initial investment can not be paid back within a short time.

We assume that the price for purchasing the chilled water from the Trige: from March to November is the same as in the current contract. Also, we assume that in

January, February and December the BOK building does not purchase the chilled water from Trigen any more and the free cooling is utilized.

However, two problems may exist in the actual situation and need our further consideration. The first is – the current contract would not allow this option. The second is how to ensure the indoor environment if the cooling tower can not satisfy the total cooling demand at some specific hours.

There may be some small additional savings in Nov., Mar., and April, which is not considered in the above financial analysis. Also, it is very possible that after consulting with the cooling tower manufacturer, the control and some parameters of the cooling tower are adjusted so that more cooling savings are obtained. Thus the payback may be less than eight years.

5.3.3 Free Cooling Chiller with Cooling Tower

5.3.3.1 The BOK Model with a Separate Central Plant and Free Cooling - Cooling Tower

The BOK Model with Free Cooling Chiller is actually a combination of the models described in 5.3.1 and 5.3.2. We assume that the separate plants for boilers and chillers are built. Different from the model in 5.3.1, this time the chiller with the free cooling - cooling tower is utilized. Figure 5-9 illustrates how the system works.

The chiller is by far the most energy-intensive component of the system. Logically, therefore, the greatest possible energy savings would accrue from being able turn it off. This, then, is the goal of free cooling – to avoid the energy costs associated with operating the chiller. Under suitable conditions of weather and heat load, the cooling tower can act as the source of chilled water.

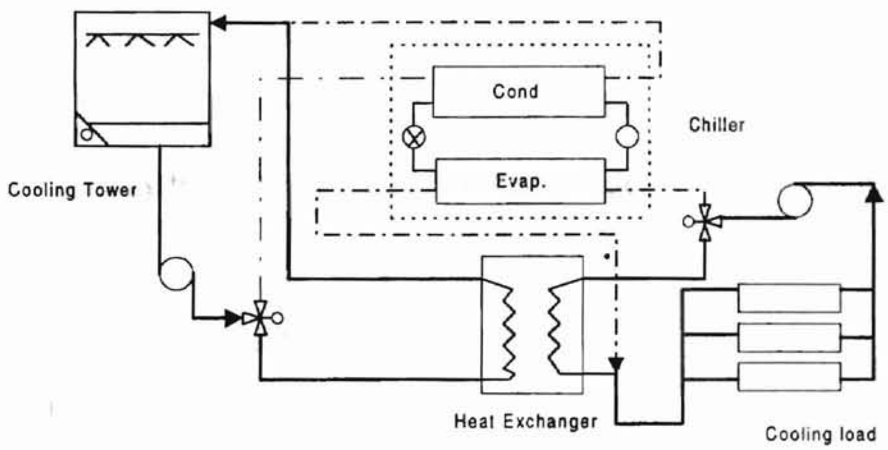

Figure 5-9 Chiller with the Free Cooling - Cooling Tower

When the outside wet-bulb temperature falls below 42° F, the cold water temperature produced by the cooling tower will be low enough to satisfy the requirements of the process or air-conditioning systems without assistance from the chiller. At that time, with a properly equipped and arranged piping system, the cooling tower water can service the load directly, avoiding the expense of compressor operation.

The Blast model of a free cooling chiller is simulated as a standard vapor compression refrigeration cycle with a water cooled condenser and a open centrifugal compressor which may obtain cooling with the compressor shut off when the condenser water temperature drops low enough by operating a small refrigerant pump as well as the chilled water and condenser pumps.

When changing from chiller to free-cooling operation, the following functions are mainly performed:

1.) Turn on cooling tower fans or increase speed.

2.) Increase the cooling tower water flow.

3.) Throttle the chilled-water flow through the evaporator.

4.) Shut down the chiller.

When changing from free cooling to chiller operation, the following functions are mainly performed:

1.) Turn off the cooling tower fans or decrease speed.

2.) Reduce tower water flow.

3.) Increase chilled-water flow through evaporator.

4.) Start chiller when tower water reaches 60 ° F.

In the BOK building, the chilled water can be produced by simultaneous operation of the free cooling system and the compressor-operated chiller. This requires isolation of the towers so that different cooling water temperature can be provided for each system.

5.3.3.2 Financial Analysis

We run the simulation for the free cooling chiller model and then calculated the electricity cost in the same way as the before. Tables 5-25a and 5-25b are summaries of the electricity cost, which is considered from the energy consumers as follows:

1) Power to run the chiller (compressor), when it is required.

2) Power to run the cooling tower fans.

3) Power to supply the pump head across the cooling tower.

Table 5-25a & 5-25b may be compared directly to Table 5-19a & 5-19b for the separate plant without free cooling.

	Jan-73	Feb-73	Mar-73	Apr-73	May-73	Jun-73
Block1 (maximum, Kw)	4,232	4,232	5,424	5,788	6,095	6,549
Block1 ($)	25,582	25,582	32,790	34,990	36,846	61,099
Block2 (maximum, Kw)	4,232	4,232	5,424	5,788	6,095	6,549
Block2 ($)	23,297	23,297	29,860	31,864	33,555	54,910
block3 (Sum, Kwh)	1,430,387	1,278,843	1,371,760	1,369,528	1,469,842	1,426,543
Block3 ($)	43,341	38,749	41,564	41,497	44,536	51,070
Service ($)	23	23	23	23	23	23
Subtotal ($)	92,242	87,651	104,237	108,373	114,961	167,102
taxed ($)	99,545	94,590	112,490	116,953	124,062	180,332
Total (Jan.-Jun.)	$ 727,972					

Table 5-25a Electric Cost for the Separate Central Plant and Free Cooling – cooling Tower (Jan. – Jun)

	Jul-73	Aug-73	Sep-73	Oct-73	Nov-73	Dec-73
Block1 (maximum, Kw)	6,634	6,522	6,204	6,188	5,480	4,232
Block1 ($)	61,899	60,851	57,881	57,739	33,125	25,582
Block2 (maximum, Kw)	6,634	6,522	6,204	6,188	5,480	4,232
Block2 ($)	55,630	54,688	52,018	51,891	30,166	23,297
block3 (Sum, Kwh)	1,648,334	1,667,639	1,426,602	1,448,656	1,426,978	1,456,926
Block3 ($)	59,010	59,701	51,069	51,862	43,237	44,145
Service ($)	23	23	23	23	23	23
Subtotal ($)	176,562	175,263	160,990	161,514	106,551	93,047
taxed ($)	190,540	189,139	173,736	174,301	114,987	100,413
Total (Jul.-Dec.)	$ 934,116					

Table 5-25b Electric Cost for the Separate Central Plant and Free Cooling – cooling Tower (Jul. – Dec)

The annual electrical cost for the separate plant with free cooling-cooling tower is:

Annual Electrical Costs = $ 727,972 + $ 934,116 = $ 1,662,088 (5-12)

We run the BOK model with separate physical plant and free cooling tower, and obtained the hourly gas consumption from the output file of the Report Write. The annual total gas consumption is the sum of the hourly consumption throughout the year, and it is 30,699,957 KBtu. We assume the natural gas combustion value is 1081 Btu per ft^3. Also, we get the information that the charge for natural gas delivery to the BOK building is 33.5 cents per ccf (100 ft^3). That is, the money charged for the natural gas would be:

30,699,957 /108.1 * 0.335 = $95,139 (5-13)

Referring to the Eq. (5-4), the annual saving is:

Annual savings = costs for purchasing the chilled water and steam – (electricity cost for physical plant – electricity cost for purchasing energy) – costs for natural gas

That is:

Annual savings = 362,813+1,941,045- (1,662,088-1,284,410) – 95139

= $1,831,041 (5-14)

The payback is obtained by dividing the initial cost by the annual savings, and the initial cost is obtained by referring to Table 5-17. Then we have:

Payback = 4,480,898 / 1,831,041 = 2.4 (year) (5-15)

The payback for the physical plant with free cooling tower is quite short. It is slightly better than building the physical plant without applying the free cooling tower in 5.3.1. Both of them have similar initial investment, while applying the free cooling tower will save some operation cost by making use the cooling of the outside air in winter.

5.3.4 HVAC Improvement with Purchased Cooling and Heating

At this stage, we notice that podium floors account more than half of the energy consumption, which include two underground floors- garage floor and service floor, and ground floor as well as plaza floor. All of them have great internal loads. Especially for the garage floor and service floor, both of them also have great cooling load in the winter.

From the drawings of the HVAC systems, we notice that the podium floors mainly apply the multizone fan systems, and the hot and the chilled water are provided simultaneously. Compared to the standard multizone, the bypass multizone can achieve energy savings by avoiding the use of the hot and chilled water at the same time. Considering the specific situations of the BOK, the converting can be accomplished by valving off the flow of hot water through the hot deck.

We then make the modification in the BLAST input file. We replace all the multizone systems of the underground floors with three deck multizone systems, as an approximation of the bypass multizone system. After running the simulation, we notice from the BLAST output file that the water consumption for those systems decreases. Also, the steam consumption for those bypass multizone systems is decreased to 0 throughout the year.

Table 5-26a and 5-26b is the total chilled water consumption and charge for the multizone systems of underground floors.

	Jan-73	Feb-73	Mar-73	Apr-73	May-73	Jun-73
ton-hours	164,000	154,000	185,000	179,000	195,000	210,000
energy	$ 10,004	$ 9,394	$ 11,285	$ 10,919	$ 11,895	$ 12,810
adjusted	$ 11,605	$ 10,897	$ 13,091	$ 12,666	$ 13,798	$ 14,860
Pumping	$ 24,485	$ 22,992	$ 27,621	$ 26,725	$ 29,114	$ 31,353
adjusted	$ 28,403	$ 26,671	$ 32,040	$ 31,001	$ 33,772	$ 36,369
subtotal	$ 40,007	$ 37,568	$ 45,130	$ 43,667	$ 47,570	$ 51,229
taxed	$ 43,175	$ 40,542	$ 48,703	$ 47,124	$ 51,336	$ 55,285
Total	$286,165					

Table 5-26a Chilled Water Consumption and Cost for Fan Systems of Underground Floor Before Improvement (Jan. – Jun.)

	Jul-73	Aug-73	Sep-73	Oct-73	Nov-73	Dec-73
ton-hours	231,000	225,000	205,000	197,000	178,000	170,000
energy	$14,091	$13,725	$12,505	$12,017	$10,858	$10,370
adjusted	$16,346	$15,921	$14,506	$13,940	$12,595	$12,029
Pumping	$34,488	$33,593	$30,607	$29,412	$26,575	$25,381
adjusted	$40,006	$38,967	$35,504	$34,118	$30,827	$29,442
subtotal	$56,352	$54,888	$50,009	$48,058	$43,423	$41,471
taxed	$60,813	$59,234	$53,969	$51,862	$46,861	$44,754
Total	$ 317,493					

Table 5-26b Chilled Water Consumption and Cost for Fan Systems of Underground Floor Before Improvement (Jul. – Dec.)

The total chilled water cost for fan systems of underground floors before the improvement is:

$$\text{Total chilled water cost of underground floors} = \$\,286{,}165 + \$\,317{,}493$$

$$= \$\,603{,}658 \qquad (5\text{-}16)$$

Tables 5-27a and 5-27b show the total steam consumption and charge before the improvement. The steam consumption and cost for fan systems of underground floor after improving them into bypass multizone systems is 0.

	Jan-73	Feb-73	Mar-73	Apr-73	May-73	Jun-73
pound	633,000	509,000	348,000	264,000	113,000	13,700
energy	$2,912	$2,341	$1,601	$1,214	$520	$63
adjusted	$3,378	$2,716	$1,857	$1,409	$603	$73
taxed	$3,645	$2,931	$2,004	$1,520	$651	$79
Total	$10,830					

Table 5-27a Steam Consumption and Cost for Fan Systems of Underground Floor Before Improvement (Jan.-Jun.)

	Jul-73	Aug-73	Sep-73	Oct-73	Nov-73	Dec-73
pound	525	10,700	52,700	171,000	333,000	563,000
energy	$2	$49	$242	$787	$1,532	$2,590
adjusted	$3	$57	$281	$912	$1,777	$3,004
taxed	$3	$62	$303	$985	$1,918	$3,242
Total	$ 6,512					

Table 5-27b Steam Consumption and Cost for Fan Systems of Underground Floor Before Improvement (Jul.-Dec.)

The total steam cost for fan systems of underground floor before the improvement is:

$$\text{Steam cost} = \$\ 10{,}830 + \$\ 6{,}512 = \$17{,}342 \tag{5-17}$$

The chilled water consumption and cost for fan systems of underground floors after the multizone systems are modified to bypass multizone systems are listed in following Tables 5-28a and 5-28b.

	Jan-73	Feb-73	Mar-73	Apr-73	May-73	Jun-73
ton-hours	115,000	115,000	157,000	158,000	186,000	209,000
energy	$7,015	$7,015	$9,577	$9,638	$11,346	$12,749
adjusted	$8,137	$8,137	$11,109	$11,180	$13,161	$14,789
Pumping	$17,170	$17,170	$23,440	$23,589	$27,770	$31,204
adjusted	$19,917	$19,917	$27,191	$27,364	$32,213	$36,196
subtotal	$28,054	$28,054	$38,300	$38,544	$45,374	$50,985
taxed	$30,275	$30,275	$41,332	$41,595	$48,967	$55,022
Total	$247,466					

Table 5-28a Chilled Water Consumption and Cost for Fan Systems of Underground Floor After Improvement (Jan. – Jun.)

	Jul-73	Aug-73	Sep-73	Oct-73	Nov-73	Dec-73
ton-hours	231,000	224,000	201,000	184,000	152,000	127,000
energy	$14,091	$13,664	$12,261	$11,224	$9,272	$7,747
adjusted	$16,346	$15,850	$14,223	$13,020	$10,756	$8,987
Pumping	$34,488	$33,443	$30,009	$27,471	$22,694	$18,961
adjusted	$40,006	$38,794	$34,811	$31,867	$26,325	$21,995
subtotal	$56,352	$54,644	$49,034	$44,886	$37,080	$30,981
taxed	$60,813	$58,971	$52,916	$48,440	$40,016	$33,434
Total	$ 294,589					

Table 5-28b Chilled Water Consumption and Cost for Fan Systems of Underground Floor After Improvement (Jul. – Dec.)

The annual chilled water cost after the improvement is:

$$\$247,466 + \$ 294,589 = \$ 542,055 \quad (5\text{-}18)$$

As described above, valving off the flow of hot water through the hot deck does not require any retrofit or investment cost. Thus the annual saving for this modification is:

Annual savings = (chilled water cost before improvement + steam cost before improvement) - chilled water cost after improvement (5-19)

That is:

$$\text{Annual savings} = (\$603,658 + \$17,342) - \$542,055 = \$ 78,945 \quad (5\text{-}20)$$

According to the unmet report in the output file, we know that the modified system can satisfy the cooling demand throughout the year. The bypass multizone system is an excellent alternative to reduce both the chilled water and steam consumption in the cold weather.

5.3.5 HVAC Improvement with Central Plant

In this part we change fan systems of underground floors from multizone systems to three-deck multizone systems, and at the same time, we apply the separate physical plant, which is actually the combination of alternatives introduced in 5.3.1 and 5.3.4.

We run the input file, in which the separate plant and bypass multizone in underground floors are defined. The hourly electricity and gas consumption are obtained. We then estimate the electricity cost for the separate plant with HVAC improvement, and it is \$ 1,711,404. The annual natural gas consumption is 27,177,939 KBtu, and it costs about \$ 84,224. Based on the Eq. (5-4), the annual savings for the combination is then written as:

Annual savings = (costs for purchasing the chilled water and steam + electricity Cost for purchasing energy) - (electricity cost for the separate plant with HVAC improvement + natural gas cost for the separate plant with HVAC improvement) (5-21)

That is:

Annual savings = (1,941,045 +362,813 + 1,284,410) – (1,711,404 + 84,224)

= \$ 1,792,640 (5-22)

Table 5-29 is the calculation of each item for the payback.

Initial Cost	\$4,480,898
Annual Savings	\$1,792,640
Payback	2.5 year

Table 5-29 Payback for HVAC Improvement with Central Plant

5.4 *Summary*

In above sections, five different retrofits are illustrated and their financial feasibility is analyzed. Each one has some advantages and disadvantages, in respect to the payback, ease of realization, initial investment, and annual savings. Generally the payback method is used to evaluate the economic efficiency of each alternative. Due to the restriction of the information and the actual situation, some assumptions are necessarily made during the payback calculation, and the payback may be changed after more detailed factors are taken into account in the future.

Table 5-30 makes comparisons among these alternatives. It lists different initial investment and operation costs and savings of each alternative for a typical year.

No.	Item	Initial Cost	Operation Cost	Annual Savings	Payback
Baseline	– Trigen	———	$3,588,268	———	———
A	Central Plant	$4,480,898	$1,810,614	$1,777,654	2.5 Year
B	Trigen with Waterside Economizer	$536,000	$ 3,521,604	$66,664	8.0 Year
C	Central Plant with Waterside Economizer	$4,480,898	$ 1,757,227	$1,831,041	2.4 Year
D	Trigen with HVAC Improvement	0	$3,509,323	$78,945	———
E	Central Plant with HVAC Improvement	$4,480,898	$1,795,628	$1,792,640	2.5 Year

Table 5-30 Cost and Savings for Different Alternatives

Figure 5-10 was drawn based on Table 5-30 to show cost comparisons among different alternatives. It is obvious that alternative "D" (Trigen with HVAC improvement) is financially feasibly for it does not need any initial costs.

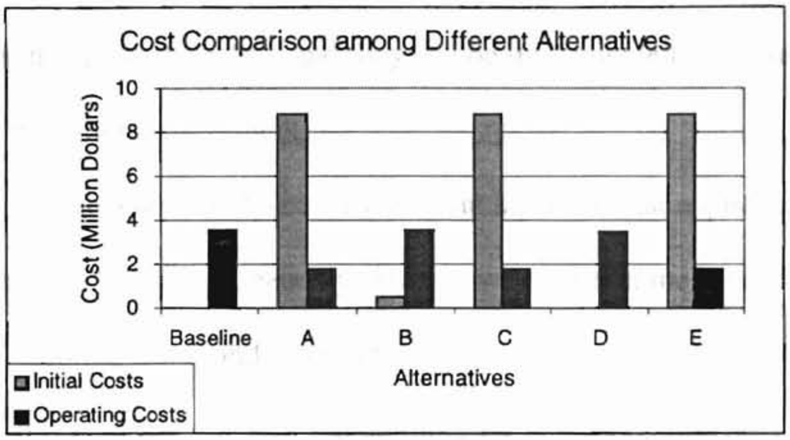

Figure 5-10 Cost Comparison among Different Alternatives

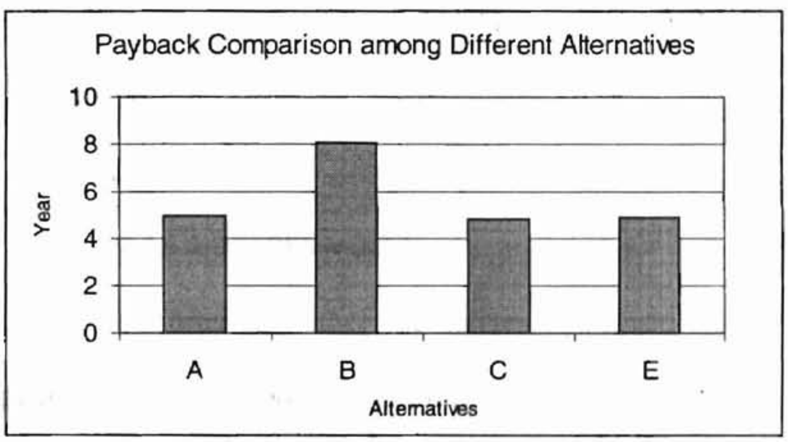

Figure 5-11 Payback Comparison among Different Alternatives

Figure 5-11 is also drawn based on Table 5-30. From it we can see that the alternative "B" has much longer payback period than alternative "A", "B", "C", thus it is less desirable from the business point of view. Alternatives "A", "C" and "E" are all based on building a new central plant, and the latter two are based on alternative "A". Alternative "C" implies the free cooling tower with the central plant and alternative "E" makes the HVAC improvement with the central plant. As they have almost the same initial costs as the alternative "A", and they can be implemented at the same time to get the best energy saving achievement.

Based on the above analysis, we create an input file that applies the alternative "C" and alternative "E" simultaneously. That is, we construct the central plant with the free cooling – cooling tower and modify the multizone systems in underground floors into bypass multizone systems at the same time. The hourly reports for the electricity and gas consumption are obtained. Using the same billing model as before, we calculate the electricity and gas costs. The electricity cost is \$ 1,658,017 and the gas cost is \$ 84,224. Thus according to the equation (5-4), we get the annual savings as:

Annual savings = (1,941,045 + 362,813 + 1,284,410) – (1,658,017 + 84,224)

= \$ 1,909,986 (5-23)

The payback is calculated by:

Payback = \$ 4,480,898 / \$ 1,909,986 = 2.3 year (5-24)

The payback is shorter than other alternatives, and it verifies that the option to run the separate plant with the free cooling – cooling tower and modify the multizone systems in underground floors into bypass multizone system would be an excellent alternative.

5.5 Additional Adjustment

As we mentioned in ***5.2.3.1***, due to the limitation of our information, we neglected the factors such as the cost of land where to build plant, the cost of salary of relevant facility, and the cost of maintenance in the financial analysis. However, these factors, especially the cost of the land, may have great effect on the evaluation of the financial feasibility, and it is very necessary to take them into account for further detailed analysis.

In the following we will make very rough estimates of the cost of land, the cost of salary and relevant facility, and the cost of maintenance, which will change the operating cost of alternatives we discussed before.

Based on the information we obtained, we assume that the physical plant is built in the area of the parking lot, which is owned by WHBC now. After the survey to the parking lot, the parking position for each car is measured 8 feet by 16.5 feet. The width between each parking lane is 20 feet. Thus we calculated the total area of each parking position:

$$A = 8 * (16.5 + 10) = 212 \text{ ft}^2 \tag{5-25}$$

The parking fee for each car per day is \$6, and is free for non-work day.

The total area of the physical plant is estimated in ***5.3.1.2,*** and it is about 26400 Ft^2. Thus, we calculated the total parking fee in this area per year.

$$\text{Parking fee} = (26,400 / 212) * 6 * 25 * 12 * 1.1 = \$\ 246,566 \tag{5-26}$$

We assume that two addition technicians are needed for maintain of the plant, and each one is paid by \$ 30,000 per year and the benefit is 25% of their salary. Thus the cost of them is:

$$\text{Salary} = 2 * 30,000 * (1 + 25\%) = \$\ 75,000 \tag{5-27}$$

The operating cost for each alternative would be increased by:

$$\text{Addition cost} = \$\ 246,566 + \$\ 75,000 = \$\ 321,566 \tag{5-28}$$

Table 5-31 gives a summary the initial cost and operating cost after the additional adjustment.

No.	Item	Initial Cost	Operation Cost	Annual Savings	Payback
Baseline	– Trigen	———	$3,588,268	———	———
A	Central Plant	$4,480,898	$2,132,180	$1,456,088	3.1 Year
B	Trigen with Waterside Economizer	$536,000	$3,521,604	$66,664	8.0 Year
C	Central Plant with Waterside Economizer	$4,480,898	$2,078,793	$1,509,475	3.0 Year
D	Trigen with HVAC Improvement	0	$3,521,604	$78,945	———
E	Central Plant with HVAC Improvement	$4,480,898	$2,117,194	$1,471,074	3.0 Year
Combination	Central Plant with Waterside Economizer & HVAC Improvement	$4,480,898	$ 1,999,848	$ 1,588,420	2.8 Year

Table 5-31 Cost and Savings for Different Alternatives after Adjustment

CHAPTER 6 CONCLUSIONS

Several conclusions may be drawn regarding various alternatives on the basis of the previous analysis.

The payback for constructing a separate plant is quite short, which indicates that this would be an excellent investment. It should be noted that some costs are only roughly estimated (such as the cost of purchasing or renting the land, cost of salary and relevant facility, cost of maintenance, etc) and the cost estimates may be further refined.

The option to use the free-cooling cooling tower with the purchased energy is less desirable. The payback is quite long, and it needs further consideration to find an operating strategy to allow it to run more hours without adversely impacting the indoor environment at some specific hours.

It is a viable option to construct a separate plant and at the same time apply the free-cooling cooling tower. The weather conditions in Tulsa provide a great opportunity to obtain savings by using the free cooling-cooling tower, especially in December, January and February. The payback is slightly better than that of using the separate plant without the free cooling. However, it is still recommended because there is no major equipment added for the free cooling and it can be implemented without difficulty.

The bypass multizone system is an excellent alternative for underground floors to reduce both the chilled water and steam consumption without any significant initial costs, and at the same time it can satisfy the cooling demand throughout the year.

Finally it is recommended that the separate plant with the free cooling-cooling tower and bypass multizone systems in the underground floors be implemented.

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