ESL-TH-04-05-03

SIMULATION OF THERMAL PLANT OPTIMIZATION AND HYDRAULIC ASPECTS OF THERMAL DISTRIBUTION LOOPS FOR LARGE CAMPUSES

A Record of Study

by

QIANG CHEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF ENGINEERING

May 2004

Major Subject: Engineering
College of Engineering

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Approved as to style and content by:

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Jeff S. Haberl Member	Coordinator College of Engineering
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ABSTRACT

Simulation of Thermal Plant Optimization and Hydraulic Aspects of Thermal Distribution Loops for Large Campuses. (May 2004)

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Chair of Advisory Committee: Dr. David E. Claridge

Following an introduction, the author describes Texas A&M University and its utilities system. After that, the author presents how to construct simulation models for chilled water and heating hot water distribution systems. The simulation model was used in a $2.3 million Ross Street chilled water pipe replacement project at Texas A&M University. A second project conducted at the University of Texas at San Antonio was used as an example to demonstrate how to identify and design an optimal distribution system by using a simulation model. The author found that the minor losses of these closed loop thermal distribution systems are significantly higher than potable water distribution systems. In the second part of the report, the author presents the latest development of software called the Plant Optimization Program, which can simulate cogeneration plant operation, estimate its operation cost and provide optimized operation suggestions. The author also developed detailed simulation models for a gas turbine and heat recovery steam generator and identified significant potential savings. Finally, the author also used a steam turbine as an example to present a multi-regression method on constructing simulation models by using basic statistics and optimization algorithms.

This report presents a survey of the author’s working experience at the Energy Systems Laboratory (ESL) at Texas A&M University during the period of January 2002 through March 2004. The purpose of the above work was to allow the author to become familiar with the practice of engineering. The result is that the author knows how to complete a project from start to finish and understands how both technical and non-technical aspects of a project need to be considered in order to ensure a quality deliverable and bring a project to successful completion. This report concludes that the objectives of the internship were successfully accomplished and that the requirements for the degree of Degree of Engineering have been satisfied.

DEDICATION

To my wife Xiaohua Zheng

To my father Zhenghe Chen

To my mother Qin Xu

To my brother Guixi Chen

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my graduate advisor, Dr. David E. Claridge, for his great guidance, support and encouragement throughout the course of this work. I also wish to express my appreciation to my committee members, Dr. W. Dan Turner, Dr. Jeff S. Haberl, Dr. Warren M. Heffington, and Mr. Song Deng, for their careful reading and comments on the manuscript of this report. Portions of this report were extracted from project reports.

I am especially grateful to Mr. Song Deng. The projects and research reported in this study were directed under Mr. Deng's supervision and guidance. His advice and involvement played an indispensable role in this work. I would also like to thank Mr. Chen Xu for his dedicated support on my work. Finally, I would like to thank Mr. Joel Hugghins for helping me correct my report.

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CHAPTER I

INTRODUCTION

Background

In partial fulfillment of the requirements of the Doctor of Engineering (D. Eng.) at Texas A&M University (TAMU), the author is formally submitting this Record of Study based on the completion of his professional internship and his research work with the Energy Systems Laboratory, hereafter referred to as the ESL. The primary purpose of this report is to demonstrate that the objectives of the D. Eng. internship have been met.

The D. Eng. Program prepares individuals for a professional career in the field of engineering. The D. Eng. Program emphasizes engineering practice, public service and the development of leadership potential. Students are trained in the fields of business and communications to supplement their engineering skills and prepare them for a career that would encompass technical as well as non-technical fields. The D. Eng. Program is a practice-oriented, professional degree. Each student is required to spend a minimum of one year as an intern practicing under the supervision of a professional engineer in industry, business or government. The objective of the internship is to enable the student to demonstrate and enhance his or her abilities and to become familiar with the employer's approach to engineering design and analysis.

This Record of Study follows the style and format of *ASHRAE Transactions*.

This Record of Study addresses the field of Mechanical Engineering. The intern, who is the author of this report, started his internship on Jan. 15, 2002 and ended on Dec. 10, 2002 as a Research Technician under the direct supervision of the assistant director of the Energy Systems Laboratory, Mr. Song Deng, P.E. Afterwards, the author worked as a graduate assistant until his graduation. The reason that the author only worked as an intern for a year is because the author's visa status is F-1. According to regulations, the ISS (international student service) only authorized the author to work as a full time intern for a year to fulfill the author's curricular requirement.

Internship Site

The ESL is a division of the Texas Engineering Experiment Station (TEES), a part of the Texas A&M University System. The ESL is affiliated with the Energy Systems Group in the Department of Mechanical Engineering at TAMU. The focus of the ESL is energy conservation and improved efficiency in sizeable buildings and the thermal plants that serve them. The laboratory has one of the largest university-based research programs of its kind in the United States.

Presenting Final Objectives

The final internship objectives for the Doctor of Engineering Program at the ESL were approved by the office of Graduate Studies at TAMU and were as follows:

- Enhance mechanical engineering background and skills in the field of HVAC, cogeneration power plant, energy management and conservation technologies, hydraulic systems simulation, and metering related technologies by finishing assigned engineering projects.

- Improve individual behavior and technique in an engineering environment by working with ESL engineers and managers and also with clients. As part of a team, I will need to work with different people, such as my supervisor, colleagues and clients. I will play different roles under different situations, especially in an engineering environment. The goal is to train myself to work with others in a professional manner.
- Develop basic engineering managerial skills through working on multiple projects and leading a small team. I will use the experience of serving as a team leader on assigned projects to become oriented with the ESL project leadership and management model. I will use my role to practice basic engineering management techniques so that I can gain the project management capabilities and experience and also train and guide the graduate student assigned to my team.

Committee Selected

Committee members were selected to review the author's progress and to make recommendations for improvements. The committee consists of the following members:

- Dr. David E. Claridge, Committee Chairman

Dr. Claridge is a Professor of Mechanical Engineering and Associate Director of the Energy Systems Lab. He is a licensed Professional Engineer in Texas and has been with the Mechanical Engineering Department and the Energy Systems Lab for 17 years. Prior to coming to Texas A&M University, he taught at the University of Colorado and prior to that, he worked for NREL (National Renewable Energy Laboratory) and OTA (Office of Technology Assessment of the U.S. Congress). He is one of the originators of the Continuous Commissioning ® process.

- Dr. W. Dan Turner, Committee Member

Dr. Turner is a Professor of Mechanical Engineering and Director of the Energy Systems Lab. He is a licensed Professional Engineer in Texas and Arkansas and has 34 years of university-level experience in teaching, research, and administration. He is also one of the originators of the Continuous Commissioning ® process.

- Dr. Warren M. Heffington, Committee Member

Dr. Heffington is an Associate Professor of Mechanical Engineering and the head of the Texas A&M University Industrial Assessment Center (IAC). He is a licensed Professional Engineer in Texas. Dr. Heffington's area of interest is industrial energy use, energy auditing, energy efficiency and combustion. The Industrial Assessment Center Program is a national program sponsored by the Department of Energy and consists of centers at universities around the nation that provide services to industry.

- Dr. Jeff S. Haberl, Committee Member

Dr. Haberl is a Professor in the Department of Architecture and Associate Director of the Energy Systems Laboratory. Dr. Haberl's areas of interest are in HVAC design, energy conservation savings measurement techniques, metering and monitoring equipment, calibrated building energy simulations, building energy data visualization, on-line diagnostics for HVAC equipment, solar energy heating and cooling systems and solar energy measurements, and air pollution calibration associated with building energy use.

- Mr. Song Deng, Internship Supervisor

Song Deng is an Assistant Director of the Energy Systems Laboratory and Project Engineer/Manager for the Texas A&M University Continuous Commissioning ® project, a $5 million, eight-year program, with accumulated savings of over $20 million. He is a licensed Professional Engineer in Texas.

Engineering Modeling and Analysis

Simulation is one of the most powerful analysis tools available to those responsible for the design and operation of complex systems. In an increasingly competitive world, simulation has become a very powerful tool for the planning, design, and control of complex systems.

For the purpose of this report, simulation is defined "as the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various designs and/or strategies for the design or operation of the system." (Pedgen et al. 1995 page 3) Both model and system are key components of the definition of simulation. Model means a mathematical representation of a group of objects or ideas in some form other than the entity itself. A system means a group or collection of interrelated elements that cooperate to accomplish some stated objectives. Systems can be simulated, including those, which already exist and those that can be brought into existence, i.e., in the preliminary or planning stage of development.

Some systems are so complex that it is difficult to understand the operation of and interaction within the system without a dynamic computer model. Simulations are commonly performed when it is not practical for the real system to be directly subject to experimentation, or for the purpose of evaluating a system before it is actually built. The cost of modeling a new system is usually small in comparison to the capital investment involved in installing and construction of a new system. Simulation models are possibly the only method available for experimentation with systems that cannot be disturbed. Some systems are so critical or sensitive that it is not possible to make any types of operating changes to analyze the system. (Chung 2004)

The focus of this report will be on the simulations of combined cycle cogeneration plant and its thermal distribution loops.

Cogeneration Plant and Its Thermal Distribution Loops

For the purpose of this report, a district energy system is defined as a system, which produces steam, domestic hot water, heating hot water and/or chilled water at one or several central energy plants and then transmits and distributes this energy to residential, commercial and industrial consumers for domestic hot water, space heating, air-conditioning and other usage. Combined heat and power production is the process of producing both power and useful heat from a single energy source. The useful heat may be used for industrial process, used on site for space heating, or fed into a district-heating grid, i.e., thermal distribution loops.

A district energy system may consist of one or several subsystems, such as district heating system, district cooling system, domestic hot water system, and steam system. A district heating system could be a combination of heating-only plants, combined heat and power production plants, or waste heat recovery plants, a heat distribution loop, and the in-building installations for space heating. The district cooling system could be a combination of electrically driven or steam driven centrifugal chillers, and single/double absorption chillers using the waste heat in one or more energy plants, a chilled water distribution loop, and in-building installations for space cooling. The domestic hot water system consists of domestic hot water production equipment, a domestic hot water distribution loop and in-building installations. Similarly, the steam system consists of steam production equipment, distribution loop, and in-building installation for its usage.

The heat carrier in the heat distribution loop can be either hot water or steam. In the case of district cooling, hot water or steam may be fed through absorption chillers or chiller turbines to produce the desired cooling effect. Chilled water can be produced centrally and distributed through the chilled water distribution loop.

Commonly, all the utilities, i.e., chilled water, heating hot water for space heating and air-conditioning, domestic cold water, domestic hot water, steam, and electricity are produced from a single or several utility plants, usually a combined heat and power plant. Then, these utilities are delivered through designated distribution loops to the end users, which are the campus buildings.

There are two very important factors, which have directed the author in his work. One is that the capital investment for the distribution system is often the most expensive portion of a district heating and cooling system, usually constituting 50 to 70% of the total cost (ASHRAE 2000; NAP 1985). The chilled water production and heating hot water production represent 68.6% and 27.9% of the total thermal commodity production in the Central Utilities Plant at Texas A&M University in 2002. The Texas A&M University Ross Street chilled water pipe replacement project alone will cost $2.3 million. The focus of the author's work will be the simulation of chilled water and heating hot water distribution loops. The other factor is that supplying the utilities needs for a large university campus represents a tremendous recurring expenditure of university funds. The TAMU total energy cost was $25.7 million in 2002. How to minimize the operation cost and optimize the plant operation is a challenge.

The following chapters will be divided into three groups. The first group has one chapter. Since most of the author's work is related to Texas A&M University Utilities Plant and its thermal distribution system, this part is a description of the site. The second group describes hydraulic simulations and their application in solving engineering problems related to chilled water and heating hot water distribution loops. This part has five chapters. Chapter III introduces hydraulic network simulation by giving an overview of what it is and its applications, describing the simulation software currently in use, and outlining the basic steps in the modeling process. Chapter IV describes details on how to construct hydraulic simulation models by using the Texas A&M University Main Campus as an example. Chapter V presents details on how to use the constructed hydraulic simulation model to solve engineering design issues. The Ross Street 24-inch chilled water replacement project is used as an example. In chapter VI, the author gives details on how to identify optimal preliminary. One of the projects is the University of Texas at San Antonio 1604 campus chilled water loop expansion project. In chapter VII, the author conducted research on minor losses on various loops and developed a method to estimate minor losses. The third group is related to the simulation of the Texas A&M University cogeneration plant. There are three chapters in this part. Chapter VII describes the simulation software called the Energy Optimization Program, which is designed specifically for the Texas A&M University utilities system to simulate its operation, to perform thermo-economic cost analysis, and to suggest optimal operation alternatives. Chapter IX is about the simulation of a gas turbine and the heat recovery steam generator attached to it. While the author was working on upgrading the simulation models for the Energy Optimization Program, significant energy saving opportunity was identified. The potential savings from this finding could be as much as $577,000 per year. Chapter X is the last chapter, which details the model construction by using statistics and optimization.

CHAPTER II

TEXAS A&M UNIVERSITY UTILITIES SYSTEM DESCRIPTION

Overview

This chapter provides background information for the Texas A&M University and its utilities system. The utilities system includes six plants: the Central Utility Plant, South Satellite Plant #3, West Campus Plant #1, West Campus Plant #2, West Campus Plant #4 and the West Campus Switch Station. The size, types, and quantities of energy conversion equipment in each plant are detailed in this chapter after the utilities system overview. A thermodynamic analysis of the utilities system is presented by using year 2002 data. The Texas A&M University campus is divided into Main Campus and West Campus by a railroad. A brief introduction about chilled water and heating hot water distribution systems on both campuses is given. At last, the electricity and natural gas expenditures are presented to conclude the chapter.

Texas A&M University

Texas A&M University, the state's first public institution of higher education, was opened on Oct. 4, 1876 as the Agricultural and Mechanical College of Texas. In 1963, the name of the institution was changed to Texas A&M University to more accurately reflect its expanding role as a leader in teaching, research, and public service for the state, nation and world. While the initials "A" and "M" are a link to the university's past. They no longer represent any specific words as the school's curriculum has grown to include not only agriculture and engineering, but architecture, business, education, geosciences, liberal arts, medicine, science, and veterinary medicine.

Now, TAMU located in College Station, Texas, boasts a 5,200-acre campus - among one of the largest in the nation. It consists of Main Campus, West Campus, Riverside campus and others. With more than 140 buildings and 18.5 million square feet of gross building space, the value of the campus exceeds $1 billion. The university serves over 45,000 students, 2,400 faculties and more than 5,000 staff members (fall 2002 data). In addition to dormitories, academic and administrative buildings, the university also has the 286,100-square-foot university recreational center, one of the largest in the US.

Texas A&M University Utilities System

For a large campus like TAMU, there are needs for a variety of utilities, such as chilled water (CHW), heating hot water (HHW) for space heating and air-conditioning, domestic cold water (DCW), domestic hot water (DHW), steam, and electricity. In order to satisfy all these needs, a centralized system is a natural choice from an economic point of view. The advantages are that:

- The total capacity of a centralized plant is less than the sum of individual plants at the consumer’s premises because maximum requirements for different consumers are staggered: the diversity factor therefore operates in favor of the central plant. For example: the diversity factor for building block cooling loads is typically 0.85 for space total loads. (Bell 2000)

- Very large plants are more economical both in their initial cost and running expenses than smaller plants: the need to provide standby equipment can be reduced; there are also savings in the cost of supervising maintenance and a better grade of engineer can be employed.
- It is possible to use waste heat from combined heat and power plant turbines to be utilized to produce chilled and hot water.

It has been calculated that the operating costs of centralized plants can be as little as one third of those with individual plants. The best results are achieved when district heating and cooling are operated in conjunction with each other. (Diamant and Kut 1981)

The centralized utility system of TAMU started with a central utility plant originally built in 1917 with a single coal-fired boiler that provided building heating. As the university expanded over the decades, the plant has undergone a series of changes and has become a complex combined-cycle cogeneration system with boilers, gas turbine, steam turbines, chillers and heat exchangers. There are another four satellite plants built as part of the system. Today, it provides the campus with virtually all needed utilities – CHW, HHW for space heating and air-conditioning, DCW, DHW, steam, and a portion (about 50%) of the peak electricity to run the campus (Wei 1997). With the centralized utility system and the distribution system, TAMU has one of the largest campus type district energy systems in the US.

The TAMU utility system has grown to many times its original size over the years. Although the Central Utilities Plant (CUP) on the Main Campus has been in operation since 1917, other plants were built as the university expended. These additional plants include West Campus Plant #1 (WC1), West Campus Plant #2 (WC2), South Satellite Plant #3 (SS3) and West Campus Plant #4 (WC4).

Figure 1 is a diagram of the overall structure of the TAMU utilities system and its distribution systems. The utilities system uses purchased natural gas to produce CHW, HHW, DHW, steam and electricity. It can produce electricity on site to meet the base load. Extra electricity is purchased to meet the total peak load of the whole campus.

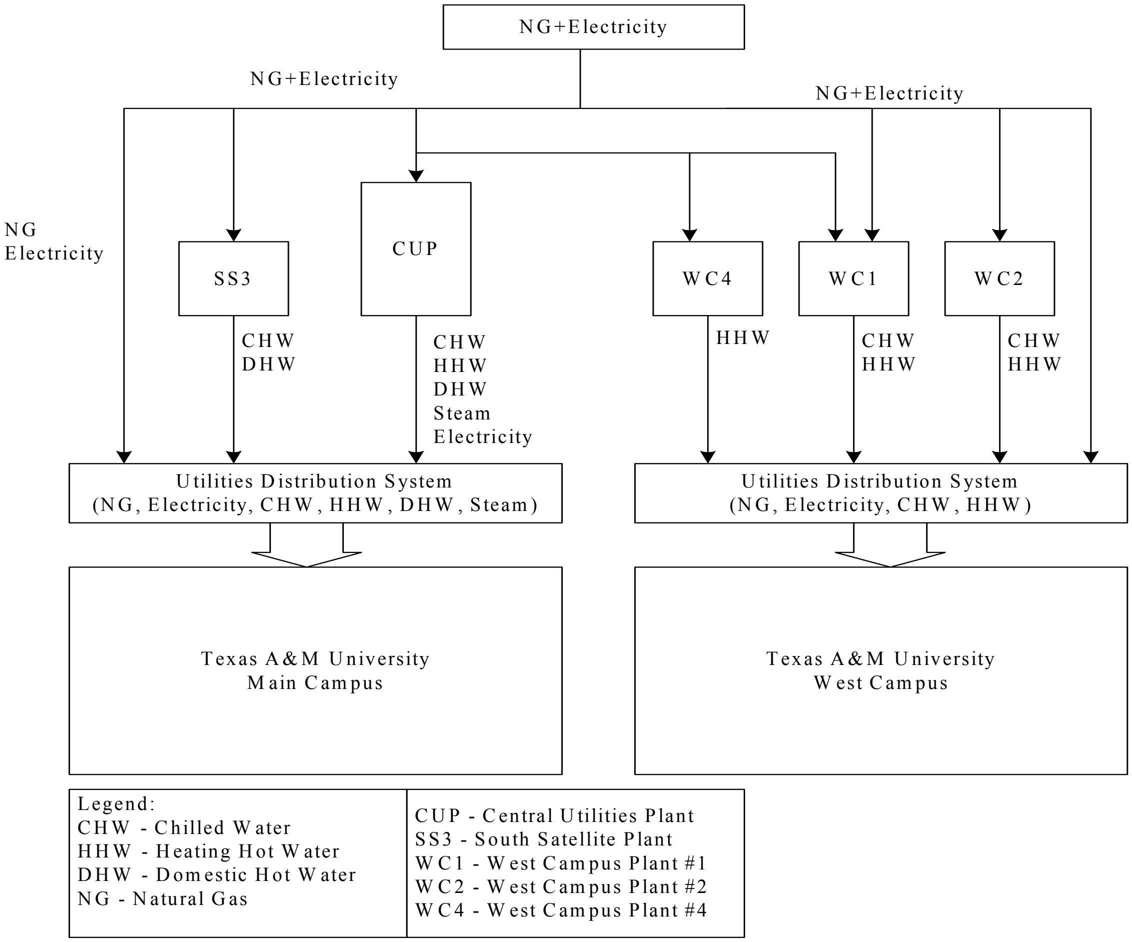


Figure 1 Overall structure of TAMU utilities system and its distribution systems.

The CUP provides CHW, HHW, DHW, steam and electricity to the Main Campus. SS3 provides CHW and DHW to Main Campus. Both plants are interconnected through complicated distribution systems. WC1 can produce CHW and HHW. WC2 mainly produces CHW. Though there is no boiler permanently installed at WC2, it can provide HHW to West Campus by using rental boilers. WC4 can only produce HHW.

There are distribution systems, which connect all the utilities plants and end users together. The CUP and SS3 are on Main Campus. Related distribution systems include the CHW distribution system, HHW distribution system, DHW distribution system, and the steam distribution system. Main Campus currently has 110 buildings with 12.5 million square feet of gross building space. WC1, WC2, and WC4 are on West Campus. Related distribution systems include the CHW distribution system and the HHW distribution system. There is no DHW distribution system or steam distribution system on West Campus. West Campus has 31 buildings with 4.3 million square feet of gross building space. The sizes, types, and quantities of energy conversion equipment in each plant are detailed in the following sections.

Central Utilities Plant

The CUP is a combined heat and power plant. It is the only plant on campus, which generates electricity and steam. The steam is produced at 600psig and 750ºF and is referred to as high-pressure steam. There are three gas-fired boilers (Boiler #9, #11 and #12) and one supplementary-firing heat recovery steam generator (HRSG, also known as boiler #10), which is coupled with a gas turbine generator. Boiler #9, #11 and

#12 are hereafter referred to as BL9, BL11 and BL12. Boiler #10 is hereafter referred to as HRSG or BL10. The design capacities of these boilers are 175,000 lbs/hr (BL9), 175,000 lbs/hr (BL10), 300,000 lbs/hr (BL11) and 200,000 lbs/hr (BL12) respectively. The total installed steam generation capacity is 850,000 pounds per hour. Each boiler has its own deaerator, which uses low pressure steam to heat and deoxygenate its feedwater. In 2002, the annual total steam production was 2,565 millions pounds and annual peak steam production was 431,000lbs/hr. Figure 2 shows the steam system of the CUP.

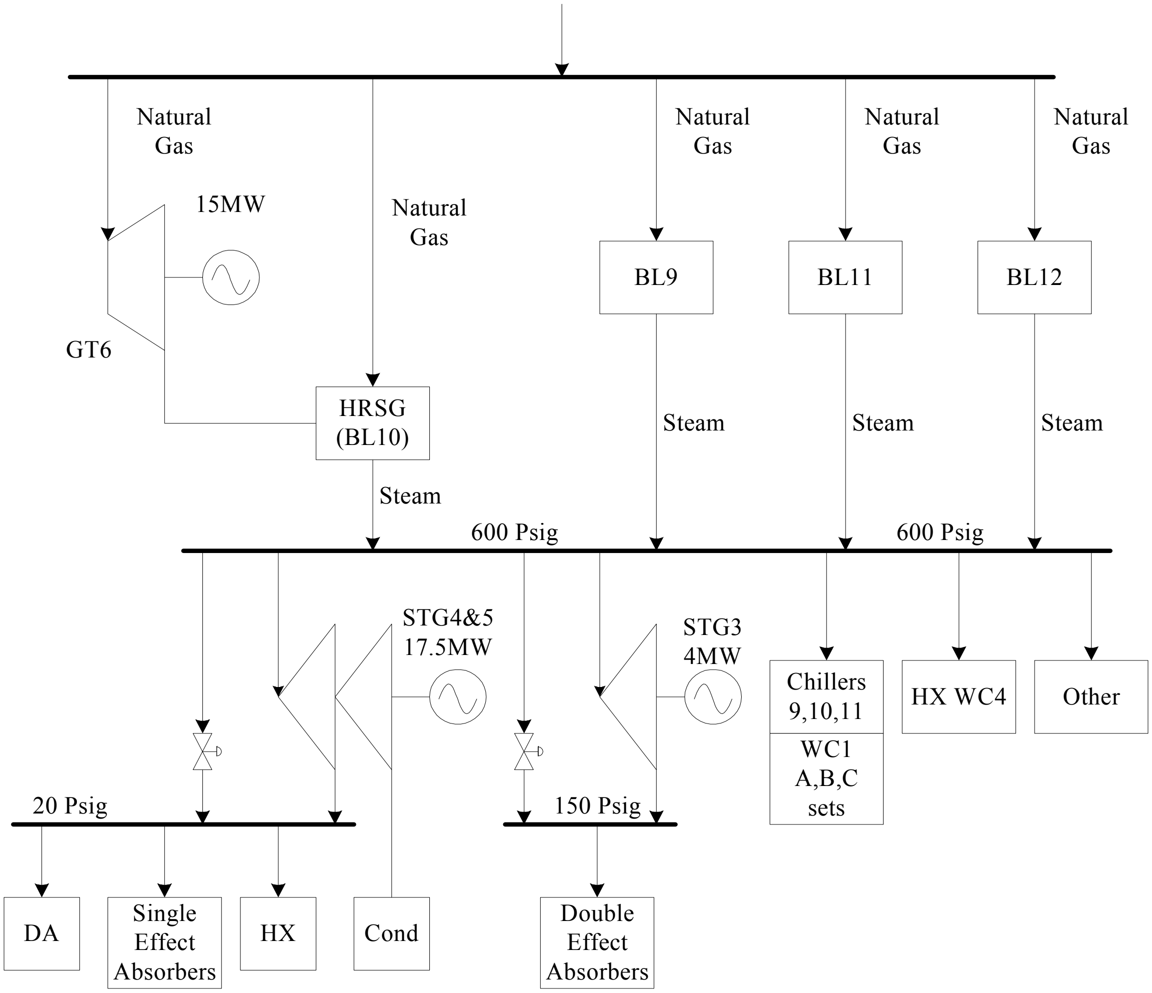


Figure 2 Central Utilities Plant steam system.

The CUP contains 38MW of continuous electricity generation capacity. The prime movers of the electricity production system include a 16.5MW GE G5211 gas turbine generator set (GT6); two extraction-condensing steam turbine generator sets (STG 4 and STG5) rated at 5MW and 12.5 MW, respectively, and a 4MW backpressure steam turbine generator set (STG3). The steam turbines all run on high-pressure steam; the extraction-condensing turbines provide extraction steam at 20psig (low pressure steam), whereas the backpressure steam turbine provides 150psig (medium pressure steam) exhaust steam. The plant was designed at base load. In other words, the university has to purchase some electricity from the local utility company. In 2002, TAMU had consumed a total of 402.8 million kWh. The peak load was 65.7MW in 2002. The CUP produced 189.6 million kWh and purchased 213.3 million kWh. The peak demand for purchased electricity was 52.97MW in 2002. The gas turbine produced 68.6 million kWh and steam turbines produced 121.0 million kWh of the electricity produced at the CUP. Figure 3 is a breakdown of CUP electricity production. As a rule of thumb for combined cycle gas turbine electric power plant, the steam turbine generates about 30% of the total electricity. TAMU was using boilers to produce the steam to generate a substantial portion of its electricity.

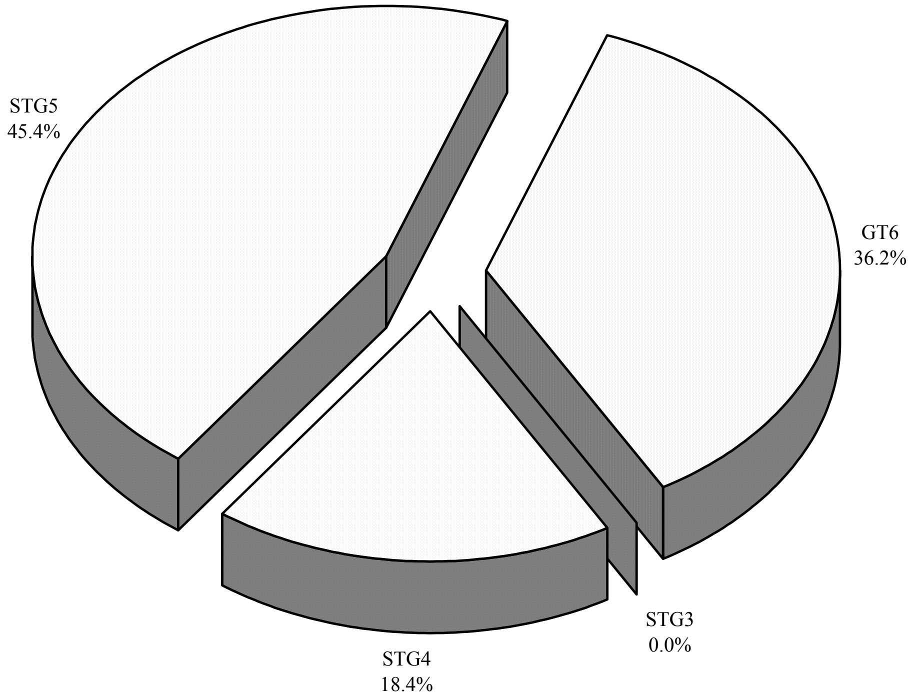


Figure 3 Breakdown of electricity production among prime movers.

The total installed chilling capacity of CUP is 21,056 tons. CHW is generated in the CUP using a mixture of chiller types including steam driven centrifugal, electric driven centrifugal, single effect absorption, and double effect absorption chillers. There are three identical 3,350-ton steam driven centrifugal chillers, one 3,350-ton electric chiller, two 1500-ton electric chillers, two 1,328-ton double effect absorption chillers and two single effect absorption chillers rated 900-ton and 1,100-ton respectively. In 2002, CUP produced 78.9 million ton-hours of chilled water. The peak-cooling load in 2002 was 14,460 tons.

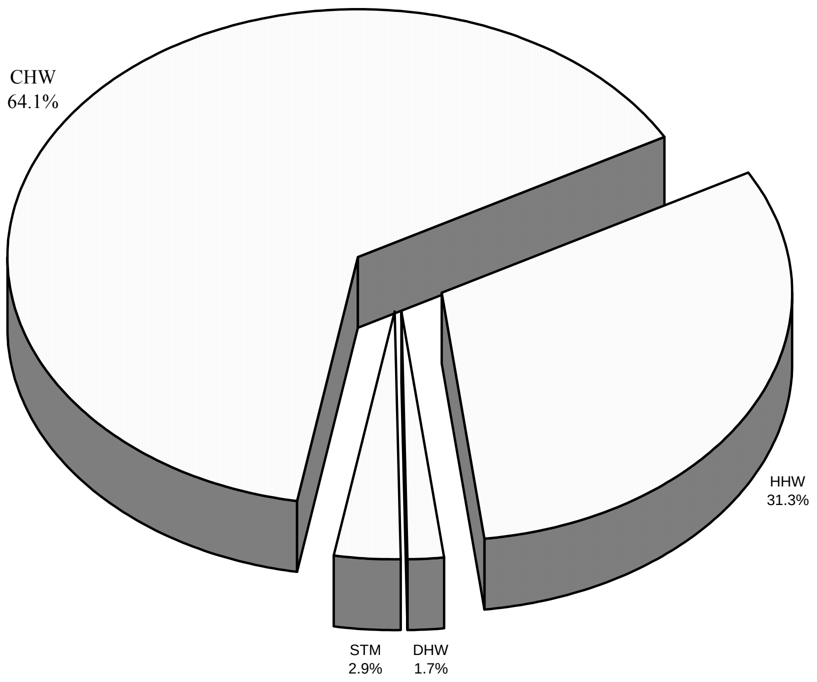


Figure 4 CUP thermal utilities production breakdown.

HHW and DHW are produced through six hot water heat exchangers and two domestic hot water heat exchangers. These heat exchangers are shell-and-tube surface contact type and use 20 psig steam that flows outside the tubes. The peak heating load in 2002 was 125.2 MMBTU/hr and the annual total production was 462.5 billion BTUs. The domestic hot water production was 24.8 billion BTUs. Figure 4 is a summary of CUP thermal utilities production by application.

West Campus Plant #1

The total installed cooling capacity of this plant is 10,000 tons. It uses electricity and steam to produce chilled water. There are three electrically driven centrifugal chillers. Two of them have 1,000-ton capacity and one has 2,000-ton capacity. There are also three pairs of centrifugal/absorption tandem sets. The steam driven centrifugal chillers each have 1100-ton capacity and the absorption chillers each have 900-ton capacity. In 2002, the WC1 produced 35.8 million ton-hours of chilled water. During the same period, the peak-cooling load reached 8,783 tons. For building heating, this plant has natural gas fired hot water boilers. These boilers are scheduled to be replaced in 2003. Figure 5 is a schematic of the WC1.

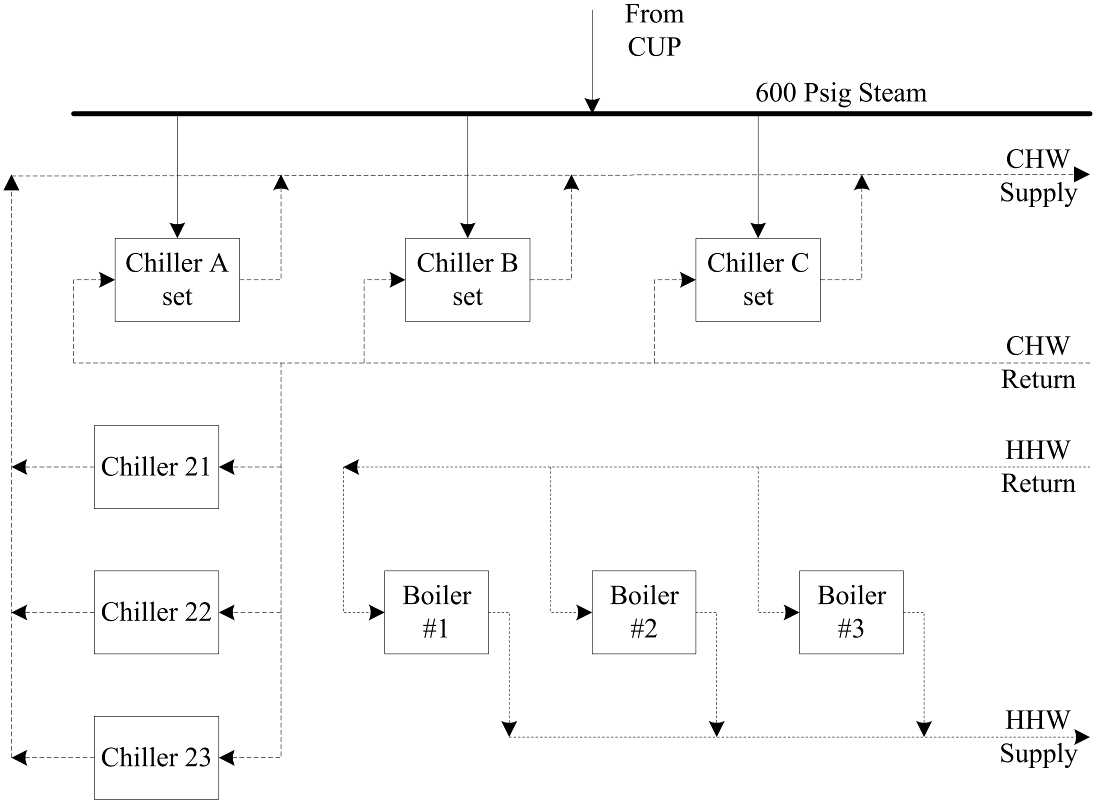


Figure 5 Schematic of WC1 steam system.

West Campus Plant #2

The total installed cooling capacity of this plant is 4,002 tons. This plant contains three identical electrically driven chillers with 1334-ton capacity each. There are three cooling towers. In 2002, the WC2 produced 9.89 million ton-hours of CHW for the West Campus. The peak-cooling load was as high as 3795.8 tons. For heating hot water production, rental boilers are often installed here temporarily.

South Satellite Plant #3

SS3 has three 1,100-ton electrically driven chillers and cooling towers for providing CHW to buildings. Two natural gas fired hot water generators produce DHW. In year 2002, the SS3 produced 16.0 million ton-hours of chilled water. The peak-cooling load in the same year was 3,300 tons. Though there is no HHW produced in SS3, there is a HHW circulation pump installed to relieve flow distribution problems at near by areas.

West Campus Plant #4

This plant receives a portion of the 600psi steam generated in the CUP to produce HHW for West Campus. This plant has a pressure-reducing valve to reduce the steam to 20psi and three heat exchangers working in parallel to condense the reduced pressure steam for HHW production. Figure 6 is a schematic of WC4.

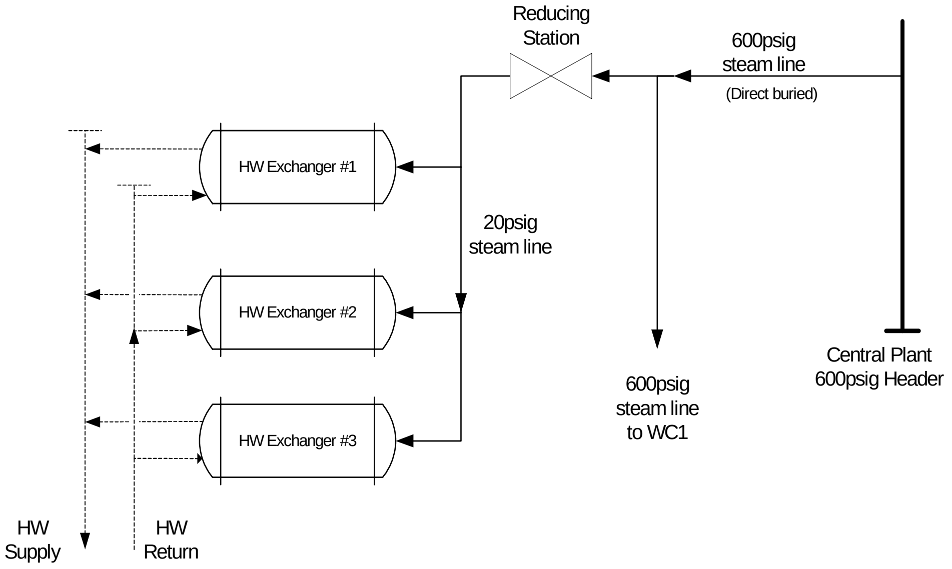


Figure 6 Schematic of WC4 steam system.

Energy Management and Control System

The existing energy management and control system (EMCS) in the TAMU utilities system was installed in 1995. The EMCS is the Westinghouse Distributed Processing Family (WDPF®) control and information system, which is a UNIX-based EMCS and provides modulating control, sequential control, and data acquisition for a wide variety of process applications. Since the upgrade of the WDPF Historian (a database) in 1998, most of the CUP and other satellite plants were integrated into the WDPF system. However, no matter how well such a system is instrumented or digitally controlled, it cannot maintain 100% instrumentation coverage or accuracy (Fleming 1997). For instance, there are not sufficient instruments in WC1 and WC2 to monitor their HHW production. Though WC4 is well instrumented, its sensors are tied to the APOGEE system, instead of the WDPF system. Reliability of data is another concern.

Wei (1997) discussed applying analytic redundancy (AR) to analyze conflicting measurement(s) and to correct the historical data. Based on monitored data, boiler efficiency of over 100% was observed. Obviously, there was significant instrument error (Wei 1997). One of the challenges of simulating this district energy system is to reduce the need for absolute instrumentation coverage by replying instead on basic thermodynamics.

West Campus Switching Station

The Main Campus at TAMU is separated from the West Campus by a railroad and a highway. As a result, the utilities systems for each side of campus are somewhat independent from each other. The electrical distribution systems were joined together in recent years at the West Campus Switching Station, through which all power from outside the university campus is routed.

The new switching station was built in late 2000 to replace the old switching station. There are six transformers, which connect the TAMU campus to the outside world. This new configuration enables the university to have two accesses to the outside electric system. The major benefits are increased system reliability and greater buying power in a deregulated power market. Unlike the old switch station, the electrical distribution systems of both campuses are integrated together, which makes it difficult to obtain the energy consumption for both campuses separately.

Thermodynamic Performance Analysis

TABLE 1 provides an annual overall summary of TAMU utilities system energy conversion performance for the year 2002.

TABLE 1

TAMU Utilities System Energy Consumption and Production in 2002

	CUP	**SS3**	**WC1**	**WC2**	**WC4**	**Overall**
Natural Gas Consumption	4,421,650	22,849	94,566	12,513		4,551,578
Electricity Production*	176,312,949[a]					176,312,949[a]
CHW	946,340	191,473	429,088	119,880		1,686,781
HHW	462,572		75,653[b]	10,010[b]	137,517[c]	685,752
DHW	24,819	18,279[b]				43,099
STM	43,575					43,575
Total Heat	1,477,306	209,752	504,741	129,890	137,517	2,459,206
Overall Efficiency						67.2%

a – Assumes 7% service station energy consumption. The annual gross production is 189,583,817kWh.

b – Assumes 80% boiler efficiency

c – Assumes the same CHW-to-HW ratio on Main Campus and West Campus

* – Electricity in kWh. All others are in MMBTU.

The overall thermodynamic efficiency of the overall utilities system is defined as

$$\eta_0 = (P + T)/F \tag{1}$$

where P represents the electricity, T represents the thermal or heat energy rate, and F represents the fuel input rate (all in consistent units).

Figure 7 illustrates the distribution of various thermal utilities among the total heat produced in TAMU utilities system. The CHW and HHW are the major thermal products of the utilities system. This fact also emphasizes the importance of cooling and heating requirements on the utilities system.

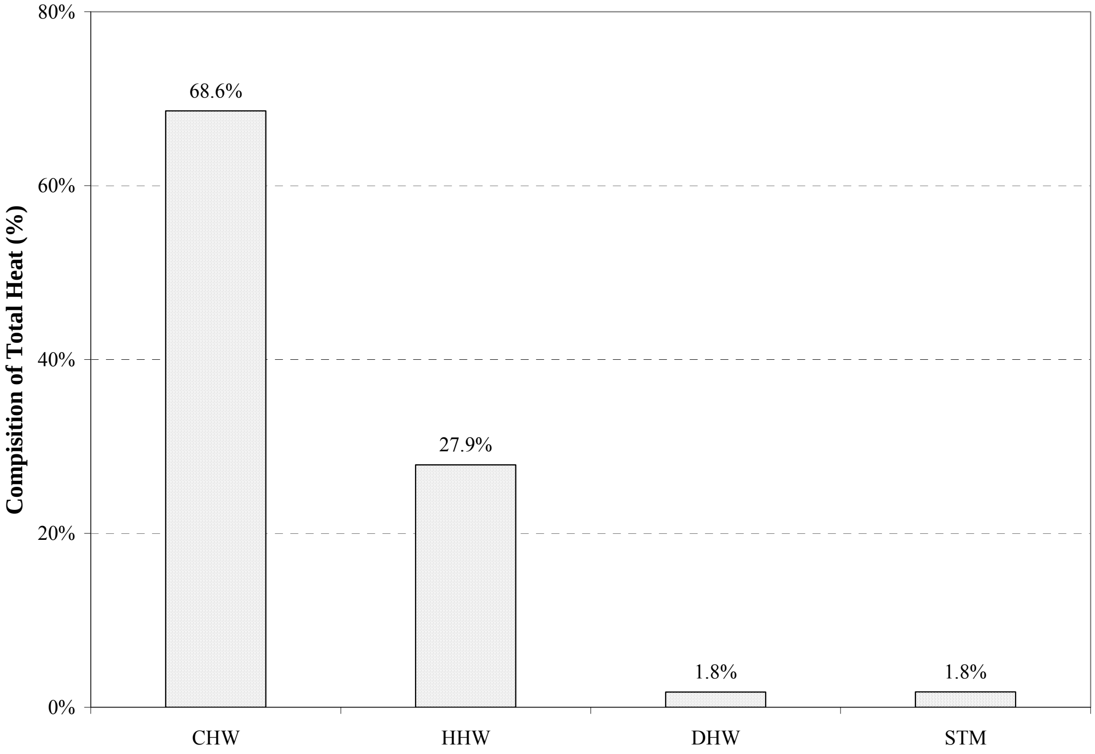


Figure 7 Composition of overall thermal production.

Figure 8 indicates that CUP and WC1 are the major plants on campus. These two plants service about 80% of the overall thermal load.

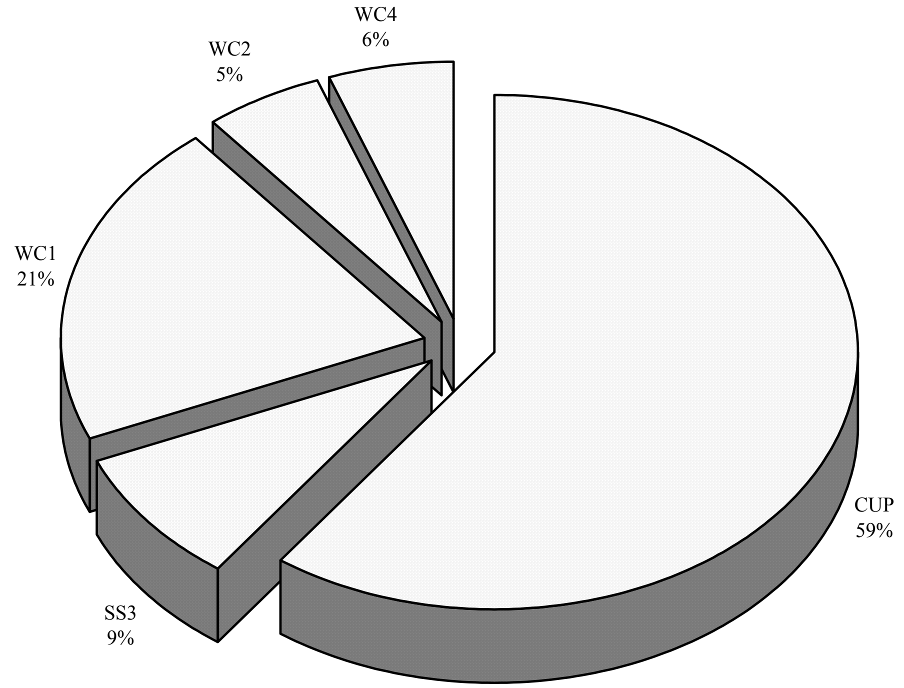


Figure 8 Overall utilities plants thermal production breakdown.

Main Campus Chilled Water and Heating Hot Water Distribution Loops

The TAMU Main Campus has very large and sophisticated CHW and HHW distribution loops. The existing distribution loop is also called a four-pipe system, which involves separate supply and return pipes for both space heating and air-conditioning. This piping system is widely used in the US. As the university expanded over the decades, the Main Campus alone has 12.5 million square feet of building space. These spaces are heated and air-conditioned by using chilled water and heating hot water. The

CHW and HHW distribution loops on Main Campus have 88,700 linear feet and 84,300 linear feet, respectively. In 2002, the CHW distribution loop circulated 18 billion gallons of water at an average rate of 34,300 GPM. Through this system, 107.5 million ton-hours of chilling were delivered. The average flow of the HHW distribution loop was more than 7,600 GPM in year 2002. It had circulated 4.0 billion gallons of water and delivered 462.5 billion BTUs of heating in that year. Figure 9 and Figure 10 are illustrations of CHW and HHW distribution loops on the TAMU Main Campus.

West Campus Chilled Water and Heating Hot Water Distribution Loops

The Texas A&M University West Campus has its own CHW and HHW distribution loops. The size of TAMU West Campus is approximately one third that of its Main Campus. The West Campus has about 4.3 million square feet of building space. These spaces are heated and air-conditioned by using chilled water and heating hot water. The CHW and HHW distribution loops on West Campus both have 55,990 linear feet. Through this system, 35.8 million ton-hours of chilling were delivered. Due to instrumentation problems, there is no available information about the amount of HHW delivered on West Campus.

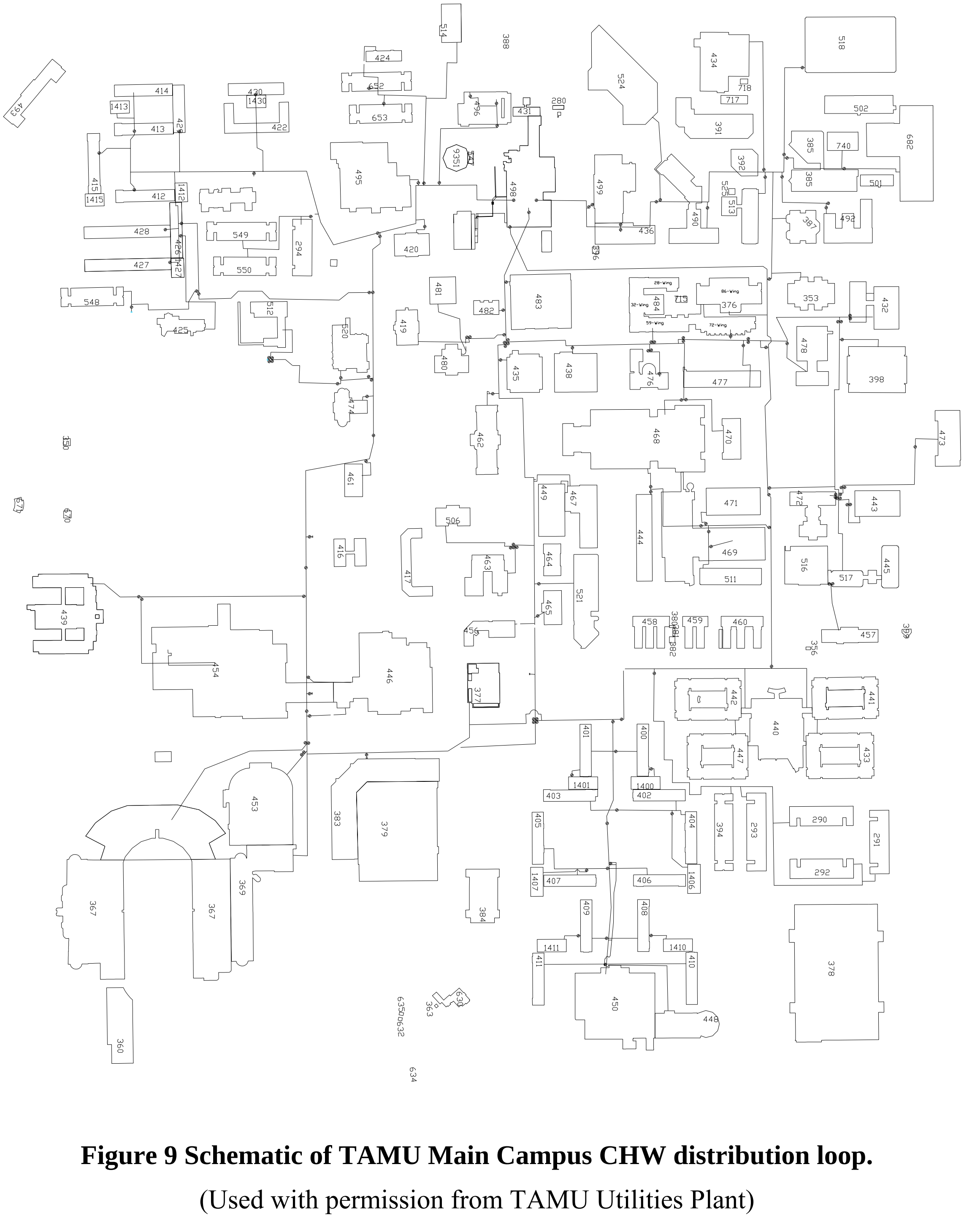


Figure 9 Schematic of TAMU Main Campus CHW distribution loop.

(Used with permission from TAMU Utilities Plant)

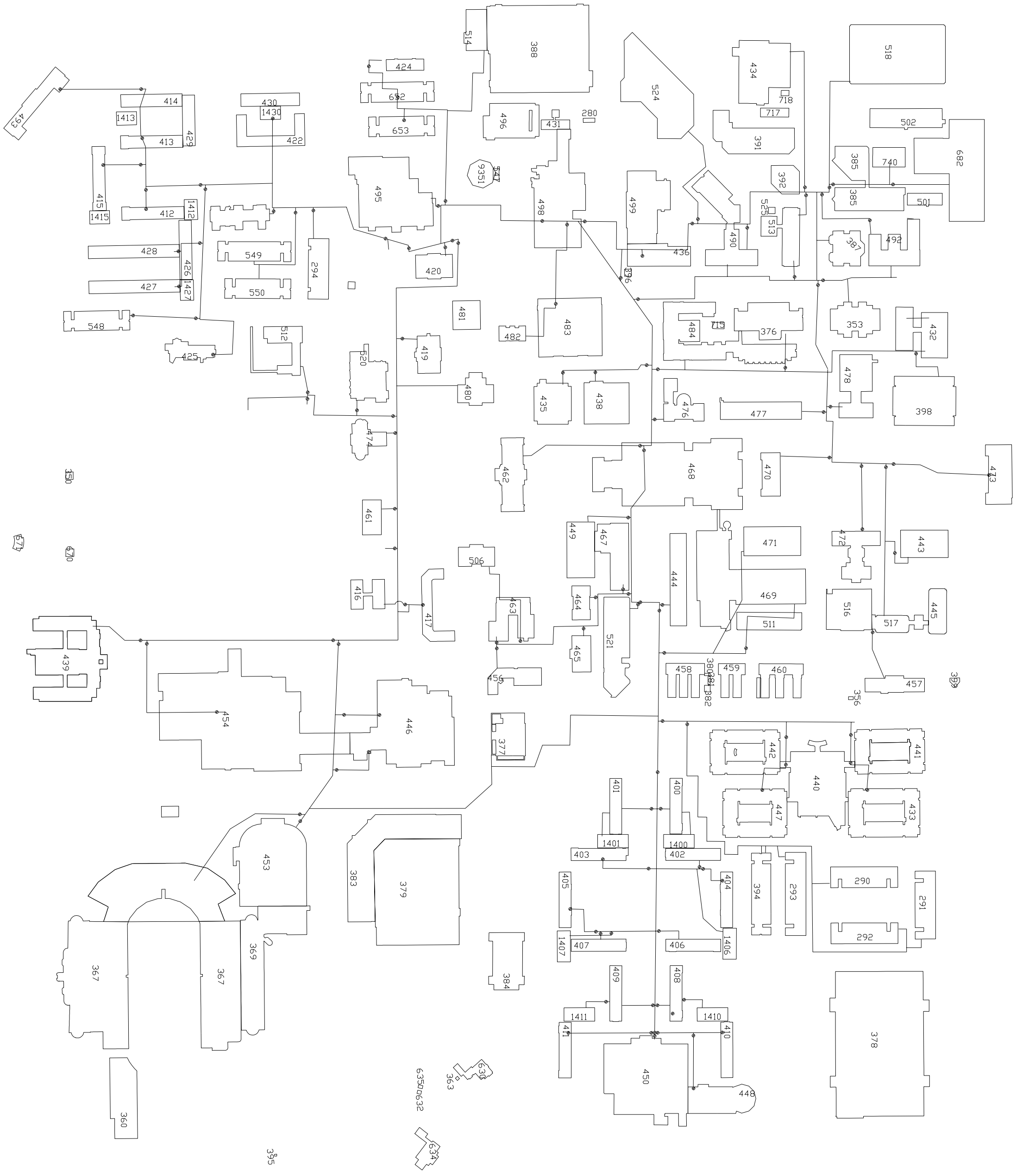


Figure 10 Schematic of TAMU Main Campus HHW distribution loop.

(Used with permission from TAMU Utilities Plant)

According to the university 30-year master plan, 12.6 million square feet of building space need to be added to the West Campus. The CHW and HHW distribution loops are expected to enlarge to several times their current size. A new thermal energy plant or even a cogeneration plant needs to be considered in the future. Figure 11 is an illustration of West Campus CHW and HHW distribution loops.

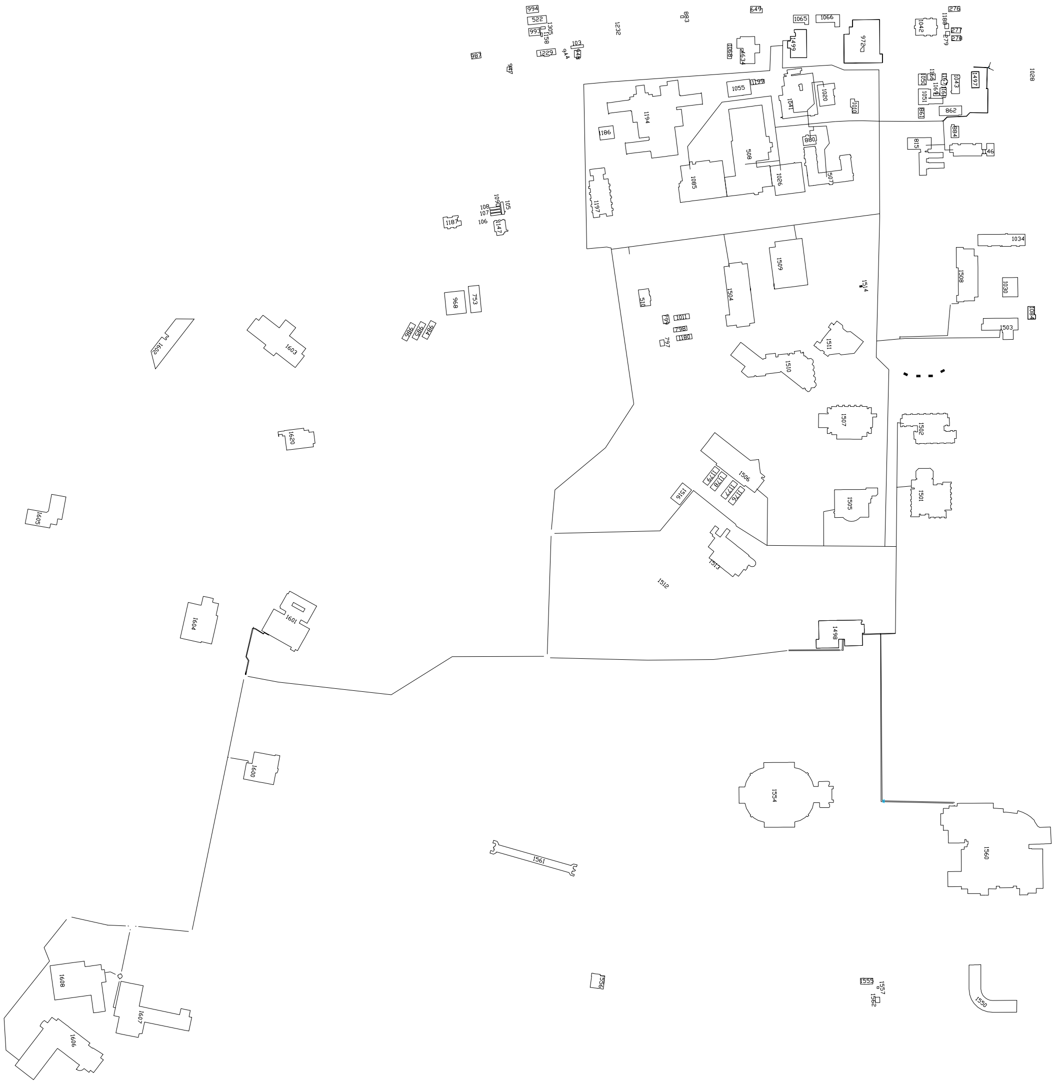


Figure 11 Schematic of TAMU West Campus CHW and HHW distribution loops.

(Used with permission from TAMU Utilities Plant)

Electricity and Natural Gas Expenditures

TAMU utilities system not only produces electricity on site, but also purchases electricity through the Brazos Electric Power Cooperative. TAMU receives very large bills on both natural gas and electricity purchasing every year. A summery of the electricity and natural gas purchased for the past is shown in TABLE 2.

TABLE 2

Electricity and Natural Gas Expenditures Summary

Fiscal Year	Natural Gas (MMBTU)	Electricity (kWh)	Natural Gas Cost ($)	Electricity Cost ($)	Natural Gas Price ($/MMBTU)	Purchased Electricity Price ($/kWh)
FY90	5,479,403	118,784,000	$15,299,297	$4,767,301	$2.79	$0.0401
FY91	5,517,516	116,626,400	$9,874,780	$4,486,213	$1.79	$0.0385
FY92	5,142,220	126,204,450	$9,839,308	$4,668,593	$1.91	$0.0370
FY93	5,233,029	127,042,600	$12,531,954	$5,276,747	$2.39	$0.0415
FY94	5,251,876	160,928,780	$12,343,785	$6,486,754	$2.35	$0.0403
FY95	5,435,942	164,322,516	$7,824,418	$6,651,822	$1.44	$0.0405
FY96	5,636,568	177,671,210	$11,740,860	$7,032,916	$2.08	$0.0396
FY97	5,911,204	123,157,367	$14,227,504	$5,643,387	$2.41	$0.0458
FY98	5,833,629	142,278,858	$14,838,601	$6,201,059	$2.54	$0.0436
FY99	5,581,616	155,874,726	$11,990,738	$7,289,348	$2.15	$0.0468
FY00	5,604,713	158,887,787	$17,207,537	$7,237,322	$3.07	$0.0455
FY01	5,169,500	186,148,710	$27,466,595	$9,645,563	$5.31	$0.0518
FY02	4,901,400	226,096,742	$19,380,377	$9,191,327	$3.95	$0.0407

CHAPTER III

HYDRAULIC NETWORK SIMULATION

Chapter Summary

This chapter introduces hydraulic network simulation by giving an overview of what it is and its applications, describing the simulation software currently in use, and outlining the basic steps in the modeling process. AFT Fathom (AFT 2000) is currently used to perform hydraulic analysis and simulation. The engineering assumptions, modeling capabilities, network solution methodology, components simulated, and the loss model are briefly discussed. The last section concludes this chapter by talking about model maintenance.

What is Hydraulic Network Simulation?

The term simulation generally refers to the process of imitating the behavior of one system through the functions of another. Hydraulic network models are commonly used for water distribution simulation. First of all, it is very expensive to manufacture and install piping network. This can represent about 70 percent of a project's capital costs (ASHRAE 2000). Secondly, it is usually not practical to directly conduct experimentation, or evaluate a hydraulic system before it is actually built. Under a lot of circumstances, simulations can be used to predict system response to events under a wide range of conditions without disrupting the actual system. Using simulations, problems can be anticipated in proposed or existing systems, and solutions can be evaluated before time, money, and materials are invested.

Application of Hydraulic Network Models

Simulation models of water distribution systems are very popular as a tool for analyzing water systems. They have been applied to a wide variety of problems including piping, pump, storage tank sizing, emergency operation, energy savings, reliability evaluation, and operator training. They are increasingly accepted as a reliable source of information in making engineering and operational decisions (Walski et al. 1990). Most water distribution models can be used to analyze a variety of pressure piping systems, such as industrial cooling systems, oil pipelines, or any network carrying an incompressible, single phase, Newtonian fluid in full pipes. In this report, the focus is the simulation and analysis of district heating and cooling water distribution systems. It is very common for a system to supply hundreds or thousands of people; thus the potential impact of a utility decision can be tremendous.

Models can simulate flows and pressure in water distribution systems. They are used for a variety of purpose (Methods et al. 2003; Walski et al. 1990):

- System Design

Alternative designs can be simulated with the simulation model and it is possible to recommend optimal piping layout and pipe sizes to design engineers. Simulating flows and pressures with alternative pumps in operation can be helpful in selecting new pumps or deciding which existing pumps to operate.

- Long-Range Master Planning and Preliminary Design

Planners carefully investigate all aspects of a water distribution system and try to determine which major capital improvements are necessary to ensure the quality of service for the future. One example would be the simulation of the University of Texas at San Antonio 1604 campus (Chapter VI).

- Renovation

As with all engineered systems, the wear and tear on a water distribution system may lead to the need to renovation portions of the system. An increasingly common problem is the renovation of an old existing system either for redevelopment or because of loss of carrying capacity and deterioration of the system (Walski 1995). Hydraulic simulations can be used to assess the impacts of such efforts, and to determine the most economical improvements. Ross Street chilled water pipes replacement project (Chapter V) is an example of such a renovation effort.

- Energy Management

Energy usage for pumping constitutes a significant portion of the operating expense of many utility plants. Hydraulic simulations can be utilized to study the usage of pumps, along with the behavior of the system. By developing and testing different pumping strategies, the effects on energy consumption can be evaluated and measures can be taken to save on energy costs.

- System Troubleshooting

When performance in an existing system is not up to standard in a thermal distribution loop, a model simulation can be used to identify probable causes. For example, a thermal distribution loop simulation study was carried out for the downtown campus of the University of Texas at San Antonio (Chen et al. 2002b). The simulation identified that one balancing valve in the condenser water loop probably was probably 75% shut and it was identified on a certain branch. A field crew was dispatched there and confirmed it. Opening that valve helped to avoid the cost of installing a new pump.

AFT Fathom

AFT Fathom is a visual platform for analyzing the hydraulic aspects of pipe flow networks. It was utilized to conduct hydraulic network simulations in this report. The following section will briefly introduce the engineering assumptions made in this software, its modeling capabilities, the methodology used in network solutions, the pipes and junctions, and the loss models employed.

Engineering assumptions in AFT Fathom (AFT 2000)

- Incompressible flow
- Steady-State conditions
- One dimensional flow
- Newtonian fluid model

Modeling capabilities

AFT Fathom can be used to model a wide variety of engineering systems, including (AFT 2000):

- Open or closed (recalculating) system

- Network systems that branch or loop
- Pressure fed and gravity fed systems
- Pumped system, including combination of pumps in series or in parallel
- Pumps with variable speed and controlled discharge pressure
- Systems with pressure and/or flow control valves
- Heat transfer analysis and system energy balance
- System with variable density and viscosity

Network solution methodology

This section discusses the numerical solution methodology utilized in AFT Fathom. It is based on the user manual, but includes additional derivation. The AFT Fathom makes use of standard matrix solution techniques (Jeppson 1976). The method is known as the H-Equation method, where H, the piezometric head, is solved for at each junction by forcing continuity of flow through each connecting pipe. Simultaneously, the head loss across each pipe is updated based on the flow balance information. The flow rate and head are solved in an inner-outer loop algorithm, where the flow is guessed, the head loss is calculated consistent with that guess, and the flow is updated according to the new pressure drop information. The Newton-Raphson method is employed to refine each successive solution, resulting in a sparse square matrix that is solved during each solution pass.

The concepts of pressure and hydraulic grade line (HGL, also called piezometric head) are related but use different frameworks for considering pipe system behavior. The

HGL includes both the static and elevational effects of pressure. The relationship between the two is given by equation (2):

$$HGL = \frac{P}{\rho g} + Z \tag{2}$$

where z is the elevation.

The solution technique makes use of the continuity and one-dimensional momentum equations. In the following discussion, subscripts denote values at junctions. Thus, Pi represents the pressure at junction i. Double subscripts denote values along pipes connecting two junctions, thus, $\dot{m}_{ij}$ represents the mass flow rate in the pipe connecting junctions i and j.

Application of the law of mass conservation to each junction yields:

$$\sum_{j=1}^{n} \dot{m}_{ij} = 0 \tag{3}$$

where n is the number of pipes connected to junction i. Equation (3) states that the net mass flow rate into each junction must sum to zero.

The basic equation for pipe pressure drop due to friction can be expressed with the Darcy-Weisbach equation:

$$\Delta P_f = f \frac{L}{D}\left(\frac{1}{2}\rho V^2\right) \tag{4}$$

where ΔP_f is the frictional pressure loss. The total pressure change between junctions is given by the momentum equation in the form of the Bernoulli equation:

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g Z_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g Z_2 + \Delta P_f \tag{5}$$

Solving for the frictional pressure drop for a constant area pipes yields:

$$\rho g\left(HGL_i - HGL_j\right) = \Delta P_f \tag{6}$$

where i and j denote upstream and downstream junction values.

The definition of mass flow rate is:

$$\dot{m} = \rho A V \tag{7}$$

Combining equation (4) and equation (6) and substituting for velocity, V, using equation (7) gives the mass flow for each pipe:

$$\left(\frac{HGL_i - HGL_j}{R_{ij}}\right)^{\frac{1}{2}} = \dot{m} \tag{8}$$

where R_{ij} is the effective flow resistance in the pipe and the subscript ij refers to the pipe connecting junctions i and j.

$$R_{ij} = \left(\frac{f_{ij} L_{ij}}{D_{ij}}\right)\frac{1}{2g\rho^2 A_{ij}^2} \tag{9}$$

Substituting equation (8) into equation (3) results in the equation to be applied to each junction i:

$$\sum_{i=1}^{n}\left(\frac{HGL_i - HGL_j}{R_{ij}}\right)^{\frac{1}{2}} = 0 \tag{10}$$

where n is the number of pipes connected to junction i.

To be completely general, equation (10) should be written for junction i:

$$\sum_{i=1}^{n}\left(\frac{HGL_i - HGL_j}{R_{ij}}\right)^{\frac{1}{2}} = \dot{m}_{i,boundary} \tag{11}$$

to allow for application of boundary condition flow rates to a boundary junction node.

Equation (11) as applied to each junction in the network represents the system of equations that need to be solved to determine the piezometric head at each junction. To solve this system, the Newton-Raphson method is employed. In the Newton-Raphson method, new values for each unknown are calculated based on the previous value and a correction that uses the first derivative of the function.

In this instance the function would be of the form:

$$F_i = \sum_{i=1}^{n}\left(\frac{HGL_i - HGL_j}{R_{ij}}\right)^{\frac{1}{2}} - \dot{m}_{i,boundary} \tag{12}$$

The method involves finding all the junction piezometric head, HGL_i, that cause all of the F_i to go to zero, thus satisfying equation (11) at all junctions. When applied to a system of equations, the Jacobian matrix contains all the required derivative information to employ the Newton-Raphson technique. The Jacobian, J_F, is given by:

$$J_F = \begin{bmatrix} \frac{\partial F_1}{\partial H_1} & \frac{\partial F_1}{\partial H_2} & \cdots & \frac{\partial F_1}{\partial H_n} \\ \frac{\partial F_2}{\partial H_1} & \frac{\partial F_2}{\partial H_2} & \cdots & \frac{\partial F_2}{\partial H_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial F_n}{\partial H_1} & \frac{\partial F_n}{\partial H_2} & \cdots & \frac{\partial F_n}{\partial H_n} \end{bmatrix} \tag{13}$$

The column matrix $\vec{H}$ contains the piezometric head at each junction, and column matrix $\vec{F}$ contains the F values at each junction. The updated solutions for $\vec{H}$ are obtained from the following Newton-Raphson equation:

$$\vec{H}_{new} = \vec{H}_{old} - J_F^{-1} \times \vec{F} \tag{14}$$

Modeling irrecoverable losses

AFT Fathom provides a flexible approach to selecting friction models for pipes and components (AFT 2000).

- Pipe Friction Loss Model

1. Absolute roughness – AFT Fathom's default method is to specify the roughness as an absolute average roughness height. Values of pipe roughness can be found in many pipe handbooks or from manufacturer's data. This uses the Darcy-Weisbach method.

2. Relative roughness – Some pipe roughness specifications are given as a relative roughness. In this case, the roughness height is divided by the pipe diameter. This uses the Darcy-Weisbach method.

3. Hazen-Williams – The Hazen-Williams method uses an empirical factor to relate the flow rate to the pressure drop in the pipe. This method is still in common use in the field of water distribution.

4. Explicit Friction factor – If the friction factor for the pipe is known, it can be entered explicitly.

5. Hydraulically smooth –A pipe can also be specified as hydraulically smooth. Modeling a pipe as hydraulically smooth implies that its roughness is negligible. However, having a small roughness is not the same as being frictionless. Rather, the pipe friction factor follows the hydraulically smooth curve in the turbulent region of a standard Moody diagram.

6. Frictionless – For modeling purposes, it is occasionally useful to model a pipe as having no friction.

7. MIT Equation – The MIT Equation is appropriate for crude oil.

8. Miller Turbulent – The Miller Turbulent method is appropriate for light hydrocarbons.

- Component Loss Model

AFT Fathom models component losses according to the following equation:

$$\Delta P_f = K\left(\frac{1}{2}\rho V^2\right) \tag{15}$$

where K is commonly referred to as the loss factor. Table 3 lists the sources for the loss models used in AFT Fathom. The losses implemented directly in the code.

Modeling process

The first step in undertaking any modeling project is to identify the need for the model and the purpose for which the model will be used.

Figure 12 shows that most of the work in modeling must be done before the model can be used to solve real problems. Therefore, it is important to budget sufficient time to develop the model before it has been developed and calibrated.

TABLE 3

Loss Model References

Junction Type	**References**
Bend	Crane 1998
Area Change	Crane 1998 and Idelchik 1994
Tee/Wye	Idelchik 1994 and Miller 1990
Valve	Crane 1998, Idelchik 1994 and Miller 1990
Orifice	Idelchik 1994
Screen	Idelchik 1994

Source: AFT 2000

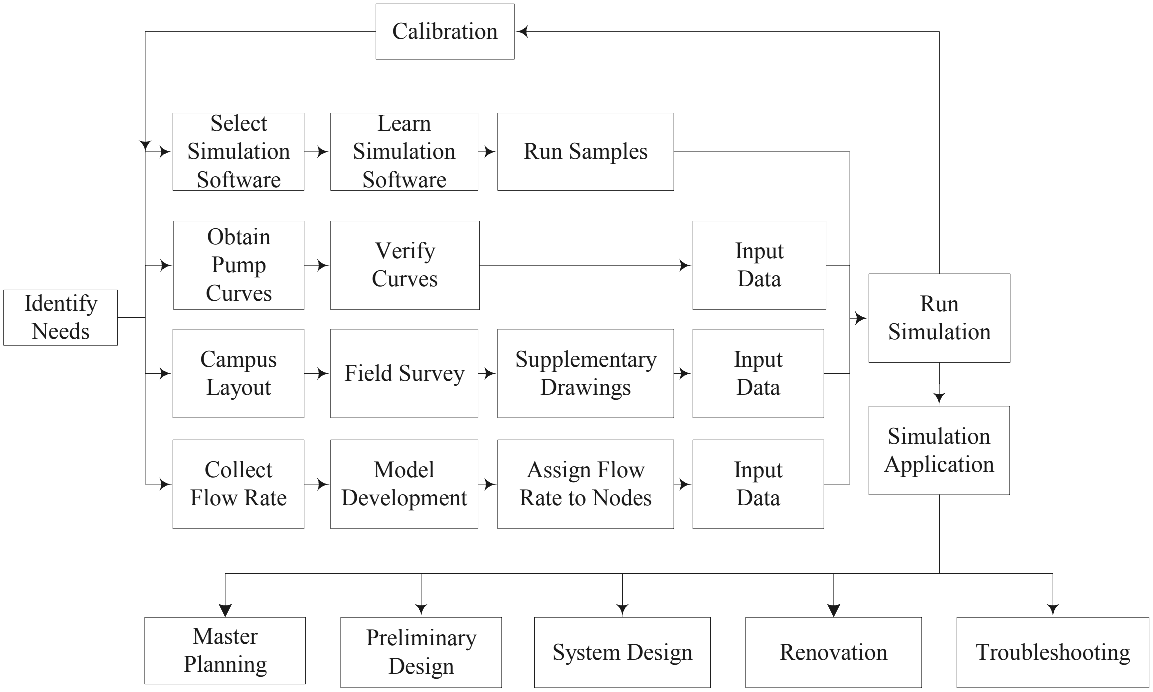


Figure 12 Modeling process of hydraulic system.

Assembling a model

A simulation model is a mathematical description of a real-world system. During the process of building a model, it is necessary to collect information describing the network. Some of the most commonly used resources include field measurements, system maps, as-built drawings, and electronic files. This information provides a wide variety of valuable system characteristics, such as:

- Pipe alignment, connectivity, material, diameter, length, etc.
- The locations of other system components, such as valves, bends, Tees, etc.
- Elevations
- Other utilities

Figure 13 illustrates the physical model of a hot water system.

Flow rate model

The consumption or use of water, also known as demand, is the driving force behind the hydraulic dynamics occurring in a system. The water flow rate can be obtained from metered historical data and the building design depending on the data availability and purposes. The designed flow rates were used in the simulation of the University of Texas at San Antonio 1604 campus (Chapter VI). For the simulation of the TAMU chilled water distribution system, the metered data were used in the model usage (Chapter IV), since the building CHW/HHW usage design information is hard to get. Figure 14 shows the output window of AFT Fathom.

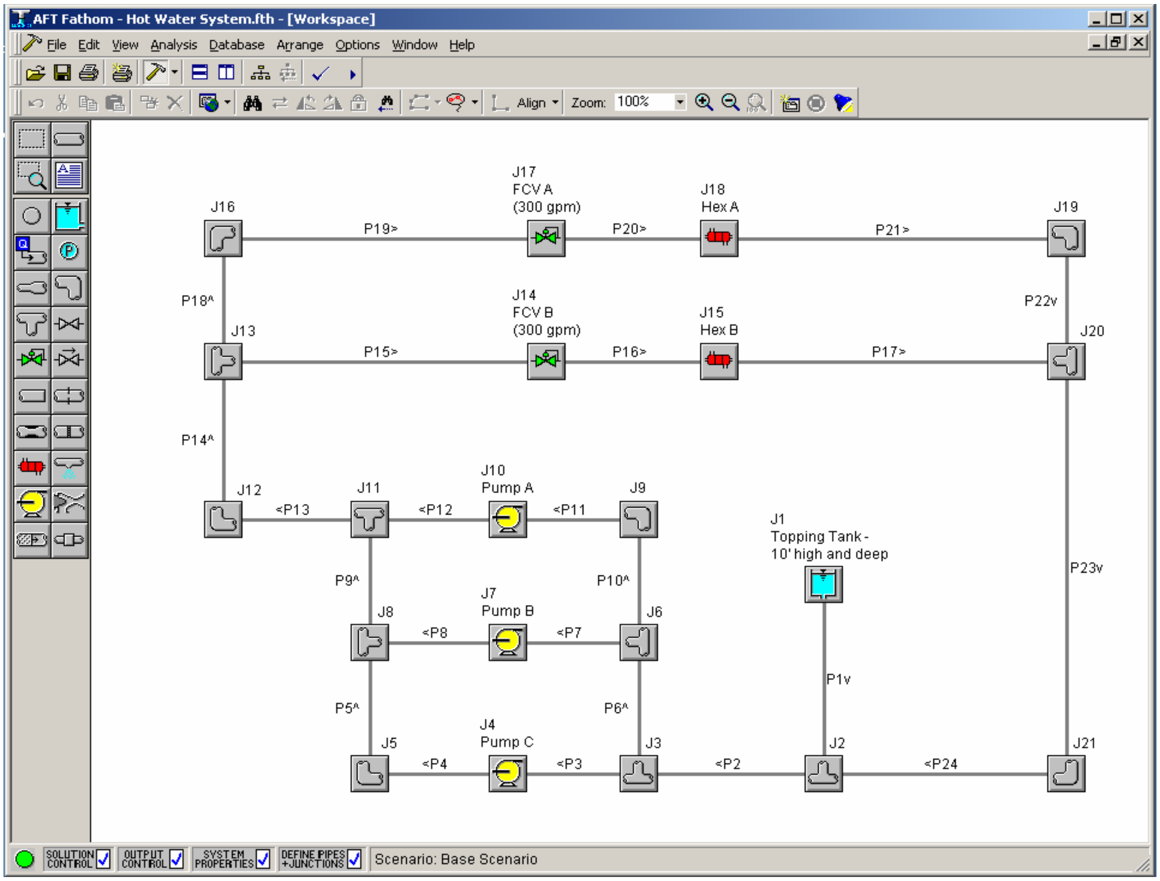
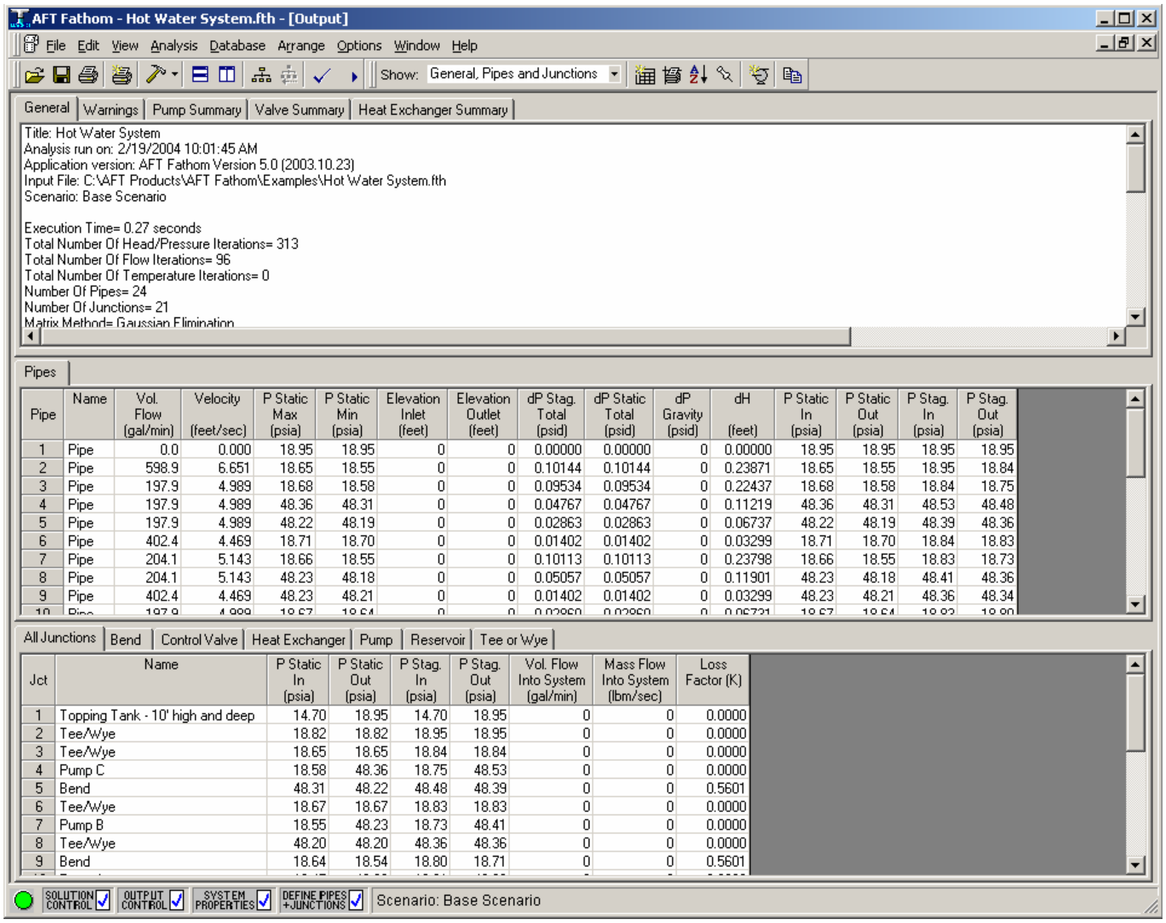


Figure 13 Graphical interface of AFT Fathom.

(AFT 2000)

Model Maintenance

Once a hydraulic simulation model is constructed and calibrated, it can be modified to simulate and predict system behavior under a range of conditions. The model represents a significant investment on the part of utility, and that investment should be maximized by carefully maintaining the model for use well into the future.



```
Title: Hot Water System
Analysis run on: 2/19/2004 10:01:45 AM
Application version: AFT Fathom Version 5.0 (2003.10.23)
Input File: C:\AFT Products\AFT Fathom\Examples\Hot Water System.fth
Scenario: Base Scenario

Execution Time= 0.27 seconds
Total Number Of Head/Pressure Iterations= 313
Total Number Of Flow Iterations= 96
Total Number Of Temperature Iterations= 0
Number Of Pipes= 24
Number Of Junctions= 21
Matrix Method= Gaussian Elimination
```

Pipe	Name	Vol. Flow (gal/min)	Velocity (feet/sec)	P Static Max (psia)	P Static Min (psia)	Elevation Inlet (feet)	Elevation Outlet (feet)	dP Stag. Total (psid)	dP Static Total (psid)	dP Gravity (psid)	dH (feet)	P Static In (psia)	P Static Out (psia)	P Stag. In (psia)	P Stag. Out (psia)
1	Pipe	0.0	0.000	18.95	18.95	0	0	0.00000	0.00000	0	0.00000	18.95	18.95	18.95	18.95
2	Pipe	598.9	6.651	18.65	18.55	0	0	0.10144	0.10144	0	0.23871	18.65	18.55	18.95	18.84
3	Pipe	197.9	4.989	18.68	18.58	0	0	0.09534	0.09534	0	0.22437	18.68	18.58	18.84	18.75
4	Pipe	197.9	4.989	48.36	48.31	0	0	0.04767	0.04767	0	0.11219	48.36	48.31	48.53	48.48
5	Pipe	197.9	4.989	48.22	48.19	0	0	0.02863	0.02863	0	0.06737	48.22	48.19	48.39	48.36
6	Pipe	402.4	4.469	18.71	18.70	0	0	0.01402	0.01402	0	0.03299	18.71	18.70	18.84	18.83
7	Pipe	204.1	5.143	18.66	18.55	0	0	0.10113	0.10113	0	0.23798	18.66	18.55	18.83	18.73
8	Pipe	204.1	5.143	48.23	48.18	0	0	0.05057	0.05057	0	0.11901	48.23	48.18	48.41	48.36
9	Pipe	402.4	4.469	48.23	48.21	0	0	0.01402	0.01402	0	0.03299	48.23	48.21	48.36	48.34

Jct	Name	P Static In (psia)	P Static Out (psia)	P Stag. In (psia)	P Stag. Out (psia)	Vol. Flow Into System (gal/min)	Mass Flow Into System (lbm/sec)	Loss Factor (K)
1	Topping Tank - 10' high and deep	14.70	18.95	14.70	18.95	0	0	0.0000
2	Tee/Wye	18.82	18.82	18.95	18.95	0	0	0.0000
3	Tee/Wye	18.65	18.65	18.84	18.84	0	0	0.0000
4	Pump C	18.58	48.36	18.75	48.53	0	0	0.0000
5	Bend	48.31	48.22	48.48	48.39	0	0	0.5601
6	Tee/Wye	18.67	18.67	18.83	18.83	0	0	0.0000
7	Pump B	18.55	48.23	18.73	48.41	0	0	0.0000
8	Tee/Wye	48.20	48.20	48.36	48.36	0	0	0.0000
9	Bend	18.64	18.54	18.80	18.71	0	0	0.5601

Scenario: Base Scenario

Figure 14 Output window of AFT Fathom.

(AFT 2000)

CHAPTER IV

HYDRAULIC SIMULATION OF TEXAS A&M UNIVERSITY MAIN CAMPUS

Chapter Summary

The Texas A&M University Main Campus has extensive and sophisticated chilled water and heating hot water distribution systems. As the university expanded over the decades, the Main Campus alone has grown to 12.5 million square feet of building space. The piping installation is often the most expensive portion of a district heating and cooling system. Manufacturing and installing pipes can represent about 70 percent of a project's capital costs. It is a challenge to properly design and operate such complex distribution networks. The primary objectives of this portion of the internship was to construct simulation models for TAMU Main Campus CHW and HHW distribution systems and to use both models for the planning, design and operation of these water distribution systems.

Detailed field surveys were conducted to collect accurate information of the existing CHW and HHW distribution systems. A new flow estimation method was developed to reduce simulation error. The CHW simulation model was then used to provide professional opinions on the TAMU 30-year Master Plan, the Central plant 24-inch chilled water pipe replacement project, the SS3 expansion, and the new chemical engineering building. Both simulation models have proven to be valuable assets to the TAMU.

Introduction

This chapter focuses primarily on the TAMU Main Campus. TAMU, located in College Station, Texas, has a 5,200-acre campus, which is among the largest in the nation. With more than 100 buildings and 18.5 million square feet of gross building space, the value of the campus exceeds $1 billion. There are two thermal energy plants on Main Campus, i.e. CUP and SS3. The CHW and HHW are distributed from the thermal energy plants to the buildings through underground piping systems to air-condition systems in the buildings. Over the years the university has become larger and larger and the centralized heating and cooling systems has become larger and more sophisticated as well. The TAMU Main Campus alone has 12.5 million gross square feet of building space and is still expanding every year. According to the university's 30-year master plan 5.9 million square feet of new building space is expected to be added and 0.9 million square feet of building space is scheduled to be demolished. The CHW and HHW distribution systems will need to be expanded and modified accordingly. Because the implementation cost is high, it is very important to design carefully. Take, for example, the complexity of the existing CHW and HHW distribution system. It is prudent to conduct thorough analysis for the planning, design and operation of such systems. Simulation is a powerful tool well suited for these purposes.

The objectives of this project are: (a) to construct models to simulate the existing CHW and HHW distribution systems, and (b) to use both models for the planning, design and operation of both water distribution systems.

A detailed field survey has been conducted over many months to collect accurate piping information for both distribution systems. Maps, drawings and related information were collected for reference as well. Figure 15 is a current map of the TAMU Main Campus. Figure 9 (page 27) and Figure 10 (page 28) are illustrations of the underground piping systems for CHW and HHW distribution. Flow rate data have been collected from the campus database.

The CHW simulation model was used to provide professional opinions on the TAMU 30-year Master Plan, the Ross Street 24-inch chilled water pipe replacement project, SS3 expansion, and the new Chemical Engineering building. After the installation of an inline pump and reconfiguration at SS3, the simulation results of the HHW simulation model were used to verify the accuracy of field data. They matched very well. Both simulation models were then proven to be valuable assets to the TAMU.

Construction of Simulation Models

There are three steps towards the construction of both models. The first step is to collect information to construct the physical layout of the underground piping systems in the computer. The second step is to obtain usage information for the buildings and plants. After the results of simulation are obtained, the third step is to verify the model. This section will talk about the first two steps.

Figure 15 TAMU Main Campus map.

(Used with permission from TAMU Utilities Plant)

Construct the physical layout of the piping systems

Usually, engineering drawings document every change to water distribution systems. This campus is an exception. First of all, this campus is expansive and it has been built over many years. Some buildings were built early in the last century. Over the years, the systems have been expanded, renovated, and reconstructed. A lot of information and many drawings were lost during the process. Even though there are frequently some drawings available, the reliability of the information is sometimes questionable. Accurate information about the distribution system is critical to the success of this project. Field surveys became extremely important for a campus like this. The campus map and both chilled water and heating hot water distribution systems drawings were obtained from the Space Science Laboratory (SSL) and are illustrated in Figure 15 (page 48), Figure 9 (page 27) and Figure 10 (page 28). Models were built to represent the actual building and piping layout. Figure 16 and Figure 17 are illustrations of the simulation models for the CHW and HHW distribution systems.

Some statistical data are presented in TABLE 4 below.

TABLE 4

Statistical Data about TAMU CHW/HHW Distribution Loops

Distribution System	**CHW Loop**	**HHW Loop**
Number of Pipes	1691	2220
Number of Junctions	1563	2094
Number of Models	114	117
Linear Length of Pipes (ft)	88,700	84,300
Gross Building Space (SQ.FT.)	>=11 million	>=11 million

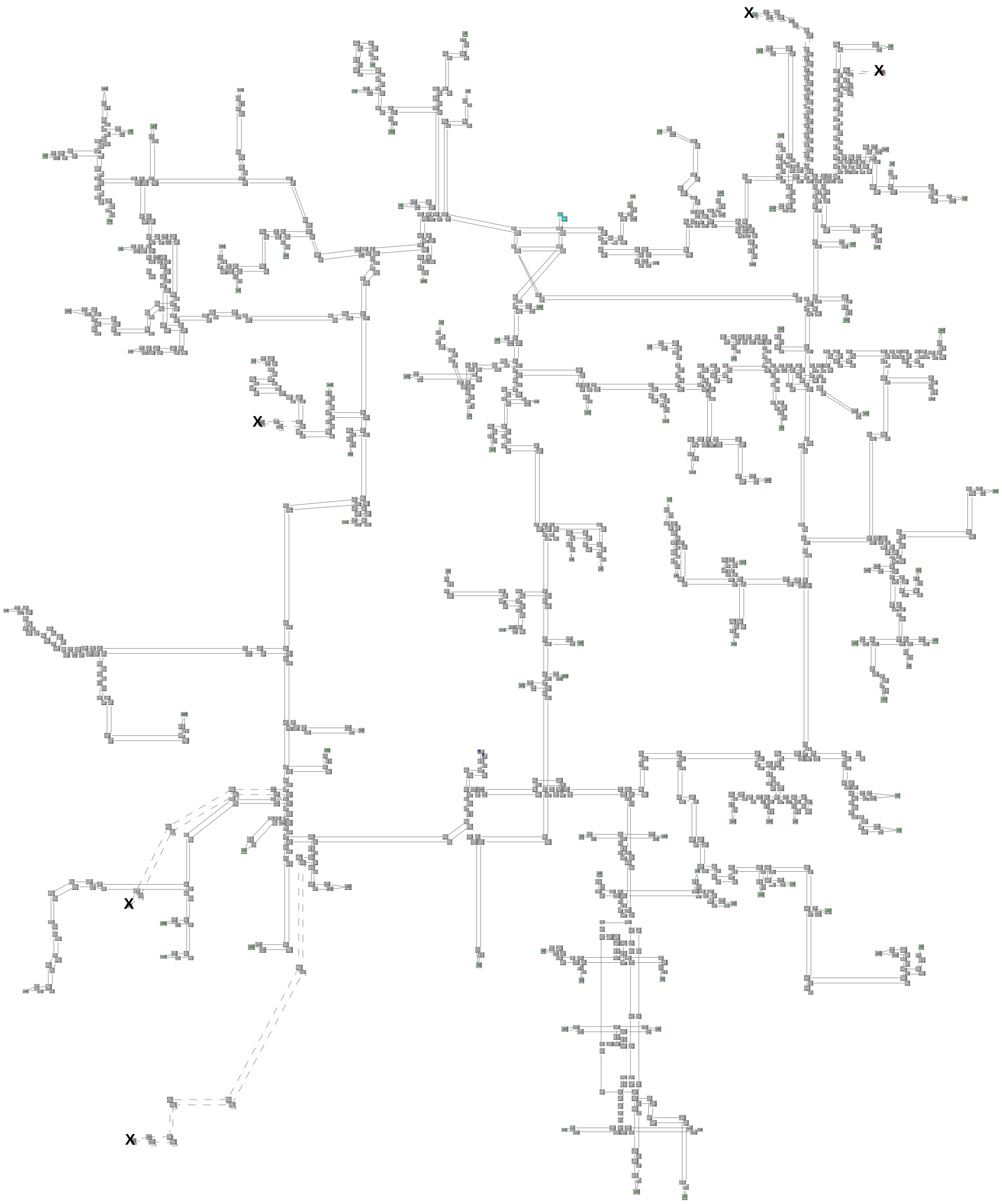


Figure 16 TAMU Main Campus CHW distribution loop simulation model.

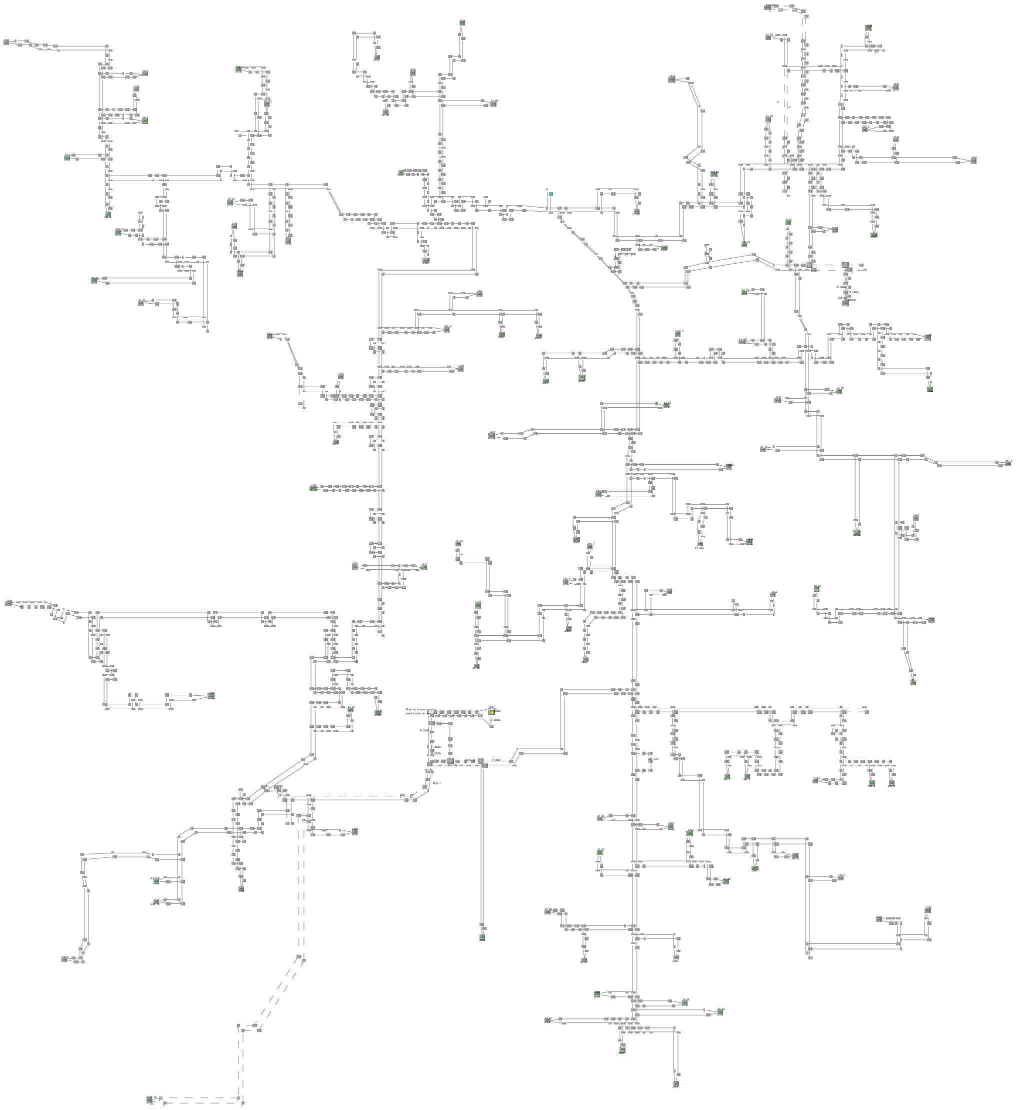


Figure 17 TAMU Main Campus HHW distribution loop simulation model.

Flow rate model development

Once the physical model was constructed, a flow rate has to be assigned to every building model on simulation model. Though there is a lot of buildings on campus have been metered, some of the buildings are not. For metered building, the building usage can simply use the metered value. For un-metered buildings, their water usages have to be estimated. In order to achieve the best results, the method developed made the following assumptions:

- Assume steady flow condition.
- Assume adherence to the law of mass conservation. The summation of estimated building water usage and monitored building water usage should be equal to the metered plants water supply.
- Assume same type of buildings have the same average flow per square foot.

Two spreadsheet programs, called model tuners, have been developed to estimate the usage for various buildings on campus, one for chilled water distribution system modeling, and another for heating hot water distribution system modeling.

Applications of Simulation Models

The CHW simulation model was used to provide professional opinions on the TAMU 30-year Master Plan, the Ross Street 24-inch chilled water pipe replacement project, the SS3 expansion, and the new chemical engineering building. After the installation of an inline pump and later reconfiguration of SS3, the simulation results of the TAMU Main Campus HHW simulation model were used to verify the field data. They match well. Both simulation models proved to be valuable asset to the TAMU.

CHAPTER V

ROSS STREET CHILLED WATER PIPES REPLACEMENT PROJECT

Introduction

The objective of this chapter is to demonstrate that water distribution models are very valuable assets to a facility through the application of a water distribution model to the Texas A&M University Ross Street 24-inch chilled water pipes replacement project. Two thermal utility plants provide all the chilled water for Main Campus air-conditioning systems. They are CUP and SS3. The plants have installed cooling capacity of 21,056 tons and 3,300 tons respectively. The CUP produces and delivers most of the chilled water on Main Campus through four pairs of 24-inch pipes. The chilled water pipes (also called the South Loop) are one of them, which need to be replaced. After many years of service the directly buried south loop began to deteriorate and leak water. Because of this, one side of the Ross Street has been closed for at least four years. Recently, the utility plant decided to build a tunnel under Ross Street and to replace the pipes of the south loop. However, they want to know if they need to replace them with the same size pipes or larger pipes. The simulation model of the TAMU CHW distribution system was used to study the impact of different pipe sizes on the existing system and the future campus. Simulations were conducted to support the utilities plant decision-making on this $2.3 million project. The simulation indicated that for the existing system and the future system, the pressure drops are 1.04 and 1.59ftWG/100ft for 24-inch pipes. The ASHRAE (2001) recommended general range of pipe friction loss used for design of hydraulic systems is 1 to 4 ftWG/100ft. In other words, replacing the current pipes with the same size pipes should be sufficient. The simulation results also indicated that if the existing pipes were replaced with larger pipes, such as 30-inch pipes, the building loop differential pressure would increase. However, the 30-inch pipe is not the final solution to negative loop end DP problems. The energy cost reduction $3,639/year by 30” piping is not enough to justify the increased first cost. The simulation also indicated that it is possible to replace these pipes without interrupting the continuous service to the Main Campus under low load conditions. Figure 18 illustrates the pipes, which are going to be replaced.

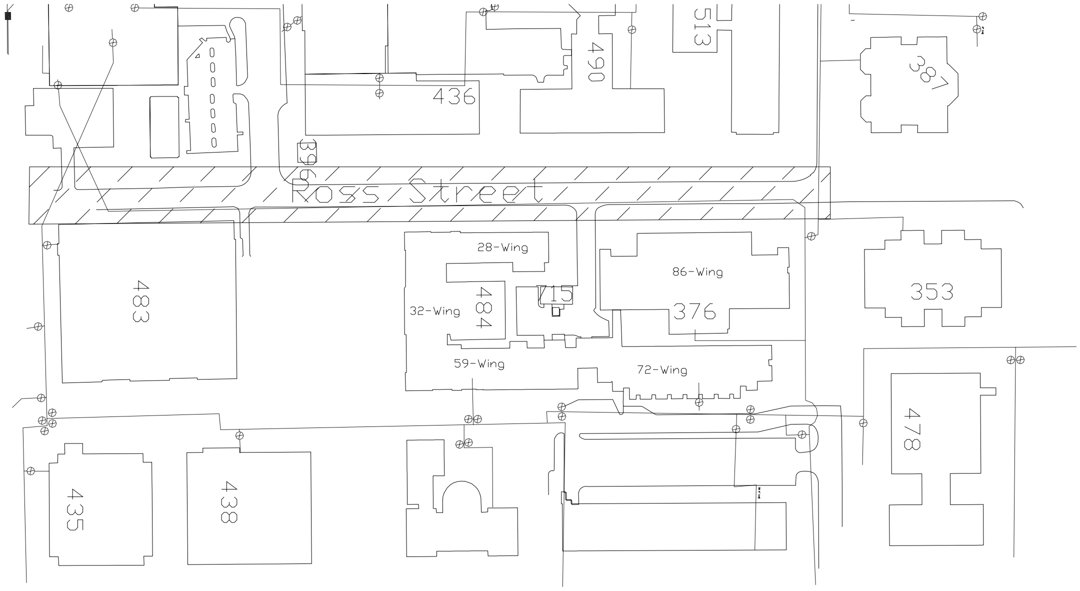


Figure 18 Ross Street CHW piping structure.

Impact of Different Pipe Sizes on Existing and Future Distribution Systems

Simulation assumptions

Existing system and Master Plan:

- Southside Satellite Plant flow 12,000 GPM.
- Central Utility Plant differential pressure: 14 psi.
- Existing system peak load is based on 94°F outside air temperature. The flow rate model is based on flow on Sep. 27th, 2002.

The proposed building flow model is based on university 30-year master plan data. Assume the new satellite plant is located besides Cater-Mattil Hall with a cooling capacity of 8,000 tons (16,000 GPM).

Simulation results

- For the existing system and for master plan, the simulation results indicate that the flow in the 24” pipe under the Ross Street is within its capacity.
- If the Ross Street 24” pipes were replaced with 30” pipes, the simulation results show improvement on building loop differential pressure for the main campus.
- Though using 30” pipe can improve the building loop DP on campus, Rudder Hall (bldg 291) and Adams Band Hall (448) area still suffer severe negative building loop DP. Replacing Ross Street CHW pipe with 30” pipe is not the final solution. Instead, there might be more effective solutions to this problem, such as increasing loop DP and CHW flow at SS3.

The simulation results are illustrated in TABLE 5.

TABLE 5

Effect of Ross Street CHW Pipe Size on CHW Distribution Loop

BLDG No.	BLDG Name	Building Loop DP (Psi)			
		Existing System		Master Plan	
		24" Ross	30" Ross	24" Ross	30" Ross
290	Wells Residence Hall	-12.25	-8.25	-23.59	-18.28
291	Rudder Residence Hall	-13.82	-9.82	-25.16	-19.85
415	Davis-Gary Residence Hall	-0.53	-0.19	6.73	7.11
439	Cain - Athletics Residence Hall	3.12	4.31	-5.66	-4.1
448	Adams (E.V.) Band Hall	-19.10	-15.28	-29.5	-24.25
517	Data Processing Addition	-3.39	1.10	-11.03	-4.61
473	Williams Administration Bldg	-2.14	2.35	-10.25	-3.83
518	Zachry Engineering Center	2.22	6.42	-6.08	-0.02
548	Clements Residence Hall	6.51	6.92	8.91	9.27
367	Kyle Field West Stand	2.73	4.27	-19.2	-15.75
420	Milner Hall	9.00	9.16	9.33	9.46
353	Bright HR CPSC/Aerospace Eng.	1.33	6.51	-4.24	3.32
456	Military Sciences Building	6.24	8.03	-7.71	-4.02
Pressure drop along Ross Street Pipe (Psi)		3.95	1.83	6.04	2.35
Pressure drop per 100ft (ftWG/100ft)		1.04	0.48	1.59	0.62
Flow through Ross Street Pipe (GPM)		12,395	16,246	16,612	20,857

Note: South loop is 872 feet long.
24” pipe capacity is 18,000 GPM (2ft/100ft design criteria)
30” pipe capacity is 35,000 GPM (2ft/100ft design criteria)

Pumping Power and Cost

The pipe friction losses can be expressed as:

$$h = KQ^2 \tag{16}$$

where

h = head loss due to friction (ft)
K = pipe resistance coefficient
Q = pipeline flow rate (GPM)

The pumping energy can be calculated by the equation below:

$$W = h \times Q / 5306.8 / \eta \tag{17}$$

where

W = total pumping energy (kW)
h = head loss (ft)
Q = flow rate (GPM)
η = pump efficiency

The annual average flow on South Loop is 8,275GPM. Head losses on the South Loop are 7.525 ft and 2.414 ft for 24” and 30” pipe respectively. Applying Equation 21, the estimated pumping energy difference is estimated to be 93,086 kWh per year, assume 75% pump efficiency. Assume the electricity cost is \$0.039/kWh, the pumping energy cost for the 30” pipe scenario will be \$3,630 less than 24” pipe scenario per year.

According to Bell (2000), the weight of 30” steel pipe is 25% more than 24” pipe. The increased pipe size will result in the larger fittings, support and tunnel size. In turn, the overall construction cost of the whole project will be more. Assume it will be 25% more. Because the project cost is \$2.3 million for 24” pipe replacement, the construction cost for 30” pipe scenario will be at least \$0.5 million more. The pumping energy cost reduction of 30” pipe scenario would not be able to justify its construction cost. From pumping energy and cost point of view, 24” pipe is better choice for Ross Street CHW pipe replacement project.

Impact of Shutting Down South Loop Under High Load Condition

The objective of this section is to evaluate the possibility of replacing the south loop under high load condition. If the south loop is going to be replaced in summer, the physical plant needs to evaluate the impact of shutting off the south loop from the rest of the chilled water distribution system.

Simulations were conducted to evaluate the potential impact. Imagine it is at 3:00PM on September 27, 2002 and the university is shutting down the south loop. The outside air temperature is 94^{o}F at that moment. Selected buildings are used to illustrate the impact of south loop shutdown. The results are in TABLE 6. Some of the buildings will suffer low loop differential pressure. This suggests that several areas of the campus will not have adequate cooling under these conditions. Therefore, it is not recommended to replace the south loop under high load condition.

TABLE 6

Impact of South Loop Shutdown When T_{oa} is 94^{o}F

BLDG #	BLDG Name	Building Loop DP (psi)	
		Normal Operation	Shutdown South Loop
290	Wells Residence Hall	-16.7	-38.4
291	Rudder Residence Hall	-18.5	-40.1
415	Davis-Gary Residence Hall	-3.9	-5.9
439	Cain - Athletics Residence Hall	-2.9	-10.5
448	Adams (E.V.) Band Hall	-24.1	-45.2
517	Data Processing Addition	-8.2	-32.3
473	Williams Administration Building	-4.5	-28.6
518	Zachry Engineering Center	2.6	-18.8
548	Clements Residence Hall	3.7	1.2
420	Milner Hall	7.9	7.0
353	Bright HR CPSC/AeroSpace Eng.	1.2	-24.3
456	Military Sciences Building	-2.0	-16.1

Impact of Shutting Down South Loop Under Low Load Condition

The objective of this section is to evaluate the possibility of replacing the south loop under low load condition. If the south loop is going to be replaced during spring or fall, the physical plant needs to evaluate the impact on the rest of the CHW distribution system as well. A simulation was conducted to evaluate the potential impact. Assume it is 4:00PM on January 6, 2002 and the university is shutting down the south loop. The outside air temperature was 60^{o}F at that time. The reason that such a day was selected is to check whether shutdown on a warm day in spring would jeopardize the overall university operation. Selected buildings are used to illustrate the impact of south loop shutdown. The results are shown in the TABLE 7.

The results indicate that even with the south loop being shutdown, the building loop differential pressures are still higher than normal operation in summer, which indicates sufficient flow for all the buildings on campus.

TABLE 7

Impact of South Loop Shutdown on Campus When T_{oa} is 60^oF

BLDG #	BLDG Name	Building Loop DP (psi)	
		Normal Operation	Shutdown South Loop
290	Wells Residence Hall	-1.38	-8.39
291	Rudder Residence Hall	-2.23	-9.25
415	Davis-Gary Residence Hall	11.48	10.87
439	Cain - Athletics Residence Hall	4.84	1.94
448	Adams (E.V.) Band Hall	4.94	-1.65
517	Data Processing Addition	1.14	-6.7
473	Williams Administration Building	7.45	-0.39
518	Zachry Engineering Center	10.17	2.88
548	Clements Residence Hall	10.93	10.27
420	Milner Hall	12.98	12.68
353	Bright HR CPSC/AeroSpace Eng.	7.00	-1.27
456	Military Sciences Building	9.22	5.23

Conclusions

- For the existing system and the master plan, the simulation results indicate that the flow in the 24” pipe under the Ross Street is within its capacity.
- If the Ross Street 24” pipes were replaced with 30” pipes, the simulation results show improvement on building loop differential pressure for the main campus. However, Rudder Hall (bldg 291) and Adams Band Hall (448) area still suffer severe negative building loop DP. Therefore, replacing Ross Street CHW pipe with 30” pipe is not the final solution.
- From pumping energy and cost point of view, the 24” pipe scenario is better than 30” pipe scenario. The estimated energy cost reduction of 30” pipe scenario would not be able to justify the construction cost increase over 24” pipe scenario.
- If the Ross Street 24” pipes were replaced in summer, a large area of campus may be forced to be shutdown due to inadequate cooling in the buildings.
- It is possible to shutdown the south loop and to replace it without disturbing the operation of the university in spring or fall.

CHAPTER VI

SIMULATION OF UNIVERSITY OF TEXAS AT SAN ANTONIO 1604 CAMPUS

Chapter Summary

The focus of this chapter is to demonstrate how the usage of the computerized simulation model can give the design engineer the ability to explore many more alternative designs and identify more cost-effective and robust designs. The University of Texas at San Antonio needs to expand their central chilled water distribution system as a result of planned additions to the campus. A simulation model was constructed and calibrated to its existing campus chilled water distribution system. It was used for master planning purposes. Six different alternatives have been designed and tested against each other by simulation. More detailed models were built for preliminary designs. Based on the simulation results, pipe sizes were selected for each design. Though there are many different scenarios, the optimal scenario is the one provides acceptable performance at the lowest cost. The simulation models are very useful in helping to find acceptable scenarios and to allow the engineer to compare the most optimal and cost-effective scenarios.

Introduction

Engineers designed distribution systems without using computerized simulations for many years. However, systems are increasingly complex now. As a result, calculating the flow rates and pressures in a piping network with branches, loops, valves, and heat exchangers can be very difficult without the aid of a computer. The objective of this chapter is to demonstrate through a case study that using simulation models properly can account for much more of the real-world systems than manual calculations are able to do. Engineers can use the models to explore many more alternative scenarios, resulting in more cost-effective designs.

In many circumstances, simulations can be used to predict system responses to events under a wide range of conditions without disrupting the actual system. Using simulations, problems can be anticipated in proposed or existing systems, and solutions can be evaluated before time, money, and materials are invested. Modern simulation software packages use a graphical user interface (GUI) that makes it easier to create models and visualize the results.

The basic method in this chapter is to build and calibrate a simulation model for an existing campus chilled water distribution system and to use this model to predict the differential pressure across the system by simulating many alternative designs. The optimized design will be the one that not only meets the design specifications, but also carries the lowest construction cost. Once the preliminary design was chosen, more detailed simulation can be conducted to further determine the optimal size of the pipes and locations of various fittings. A case study is presented to demonstrate how to build a simulation model for a given chilled water distribution loop, and how to use it to predict the system response for various designs, and to identify the optimal design for an actual site.

The University of Texas at San Antonio 1604 campus needs to expand its central chilled water distribution system as a result of planned additions to the campus. A simulation model was constructed for its current chilled water distribution system and calibrated by comparing it with other engineers' results. Six different scenarios were explored by using the models. The simulation results indicated that the best scenario is the one, which takes advantage of the crawl space beneath the Multidisciplinary Studies Building. Pipes are modeled to connect immediately before the reduction of the 24" pipes to the 20" pipes in the tunnel and the future Engineering Bioscience Building Phase III. Most of the pipe will parallel the existing pipes in the crawl space toward the current Engineering Biosciences Building.

Construction of Simulation Model

Site description

Figure 19 is an illustration of the University of Texas at San Antonio 1604 campus. Estimated gross area is 1.5 million square feet. The existing central chilled water distribution system is accessible though the underground tunnel and crawl spaces beneath the buildings.

Simulation software

The software used in the study is AFT Fathom 5.0, which is a product of Applied Flow Technology Corporation (AFT 2000).

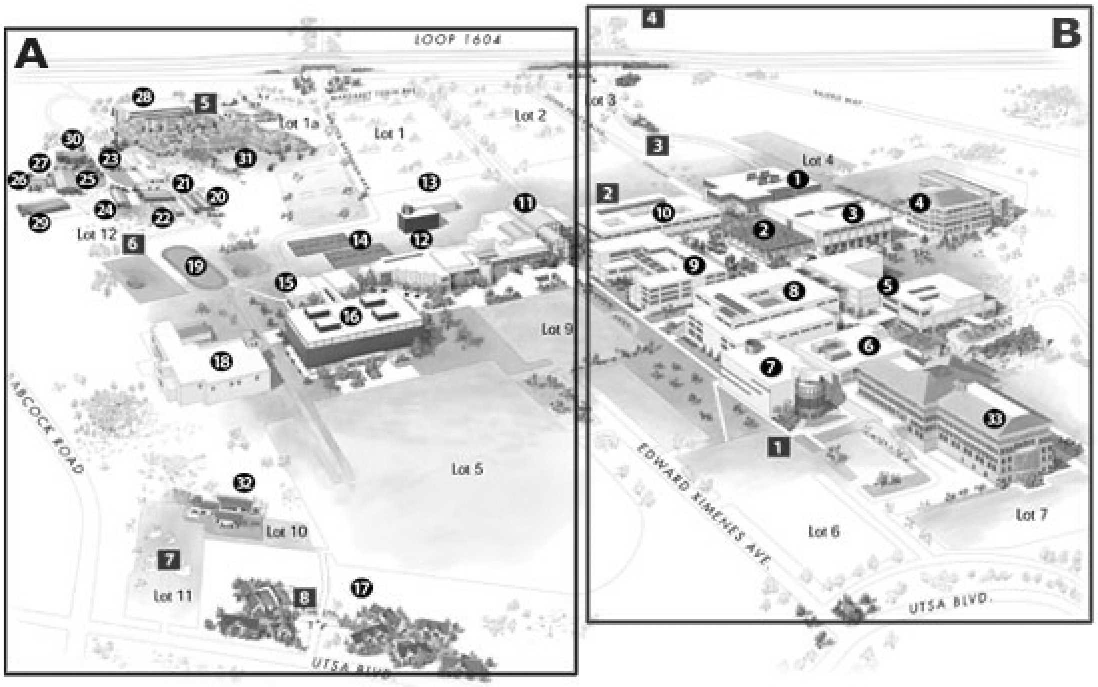


Figure 19 UTSA 1604 campus map.

LEGEND

1. Business Building/Visitor Center
2. Central Plaza and Sombrilla Plaza
3. John Peace Library
4. Academic Building III
5. Arts Building and Arts Addition
6. Engineering Building
7. Biosciences Building
8. Science Building
9. Multidisciplinary Studies Building
10. Humanities and Social Sciences
11. University Center
12. Physical Plant
13. Central Energy Plant
14. Tennis Courts
15. Physical Education.
16. Convocation Center
17. University Oaks Apartments
18. Health and Wellness Center
19. Track and Playing Fields
20. Power and Dynamics Lab
21. Science and Engineering Lab
22. Sculpture and Ceramics Studio
23. Science Labs
24. Business Services Annex
25. Center for Archaeological Research
26. Greenhouse
27. Soil and Concrete Lab
28. Chisholm Hall
29. Facilities Services Annex
30. Central Receiving/Purchasing
32. Child Development Center
33. Biotechnology, Sciences and Engr.

Source: University of Texas at San Antonio
http://www.utsa.edu/maps/
02/02/2004

Assembling of model

Song Deng had conducted an extensive field survey in November 2001. The physical structure of the simulation model is built upon field notes and draft reports. Chilled water consumption demand is based on a technical report by Shah Smith & Associates (SSA 1997). The newly built simulation was compared to an earlier report (Smith 1997) and it appeared to be reliable, consistent, and conservative (Chen et al. 2002a). The finished simulation model is illustrated in Figure 20.

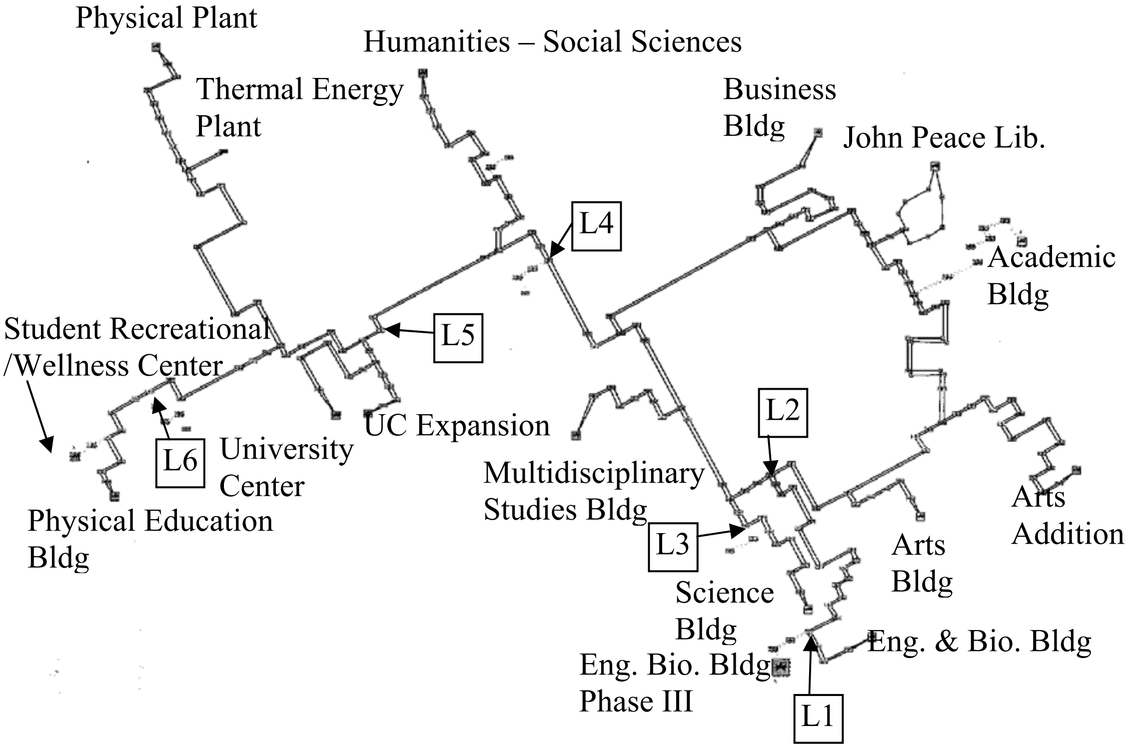


Figure 20 UTSA 1604 campus CHW distribution loop simulation model.

Building design flow and simulation results

This mode is called the base model. All the alternative scenarios are constructed based on this model by changing the existing or adding piping structures. The building flows and simulated building loop differential pressures are listed in TABLE 8 below.

TABLE 8

Building Design Flow and Simulation Results

BLDG No.	Building Name	Flow (GPM)	DP (psi)
520	Physical Plant	144	25.7
526	Humanities – Social Sciences	932	16.7
530	University Center	226	21.1
536	Business Building	921	12.9
542	John Peace Library	1163	10.9
548	Arts Addition	649	12.3
552	Engineering and Biosciences	1307	8.7
554	Science Building	955	10.3
556	Multidisciplinary Studies Building	813	12.5
570	Physical Education Building	584	22.0
583	University Center Expansion	513	20.9
585	Arts Building	100	13.1

Assume plant loop differential pressure is 26psi.

Model Verification

A similar study has been done earlier (Smith 1997). TABLE 9 illustrates the comparison between the new simulation results and previous calculations. With the same set of building model flows, the base model simulation results and the earlier calculation results are relatively close to each other.

The base model has sufficient accuracy to use in the simulation of other alternative design considerations. Based on this base model, other simulations can be conducted to predict possible future loop expansion designs and estimate pressure differences at various locations. This will help decision makers to evaluate their various options.

TABLE 9

Comparison between ESL Base Model and Smith's Study

BLDG #	BLDG Name	Flow (GPM)	Simulation DP (psi)	
			By ESL	By Smith
542	John Peace Library	1163	10.9	14.4
548	Arts Building (Arts Addition)	649	12.3	13.5
552	Engineering and Biosciences	1307	8.7	10.3
570	Physical Education Building	584	22.0	19.2

Identification of Preliminary Design

A model that has been assembled properly is an asset to the facility owner. After the model has been constructed and calibrated, it is ready to be used in design. To get the most benefit from the model, the designer should examine a broad range of alternatives. The objective of the simulation is to study the impact of the additional buildings on the existing central chilled water distribution system and to identify and recommend a preliminary design for future system expansion. The Student Recreational/Wellness

Center (Bldg 582) was scheduled to be built in 2002 on the UTSA 1604 campus. The Academic Building Phase 3 (Bldg 581) was scheduled to be built in 2003. The locations of these three buildings were previously decided upon as shown in Figure 19. The design of an optimal piping system for this will be the focus of this chapter. The estimated building chilled water flows are listed in the TABLE 10.

TABLE 10

Estimated Building Chilled Water Flows for Campus Expansion

Bldg	Bldg Name	Flow (GPM)
581	Academic Building Phase 3	1163
582	Student Recreational Center	557
584	Engineering Bioscience Bldg III	2038

Six potential tie-in points were chosen and are illustrated in Figure 20. Simulation models were built and are illustrated in the appendix in Figure 45 through Figure 50. The tie-in locations are chosen in a way that one location is further upstream than another. The facility owner specifies that the proposed preliminary design must provide positive building loop differential pressure for all buildings, which is one of the criteria for acceptable designs.

Scenario 1 simulates the system response if the future expansion is tied in at the nearest pipes. Scenario 2 and Scenario 3 were designed to investigate the effect of connecting the expansion to the loop structure. Scenario 3 is similar to Scenario 2, but further upstream. Scenario 4, 5 and 6 were designed to study the differential pressure distribution of moving the connecting point to the main pipe beyond the existing loop structure. Scenario 4 and 5 took advantage of the exiting crawlspace and underground tunnel. Smith (1997) proposed Scenario 6 for future campus expansions. This scenario requires digging up the parking lot on the south side of the campus. The simulation results are listed in TABLE 11.

TABLE 11

Simulation Results of Base Model and Campus Expansion Designs

Bldg	Bldg Name	Flow (GPM)	Differential Pressure (psi) for Various Scenarios						
			Base	1	2	3	4	5	6
520	Physical Plant	144	25.6	25.6	25.6	25.6	25.6	25.6	25.6
526	Humanities – Social Sciences	932	16.6	10.3	10.3	10.4	10.3	10.5	12.7
530	University Center	226	21.1	16.3	16.3	16.3	16.3	16.3	17.4
536	Business Building	921	12.8	-0.3	-0.3	0.2	4.1	5.7	7.3
542	John Peace Library	1163	10.9	-4.4	-4.4	-3.5	1.6	3.3	4.8
548	Arts Addition	649	12.2	-4.6	-4.6	-3.1	3.0	4.8	6.2
552	Engineering and Biosciences	1307	8.7	-22.1	-7.7	-5.7	1.7	4.1	4.6
554	Science Building	955	10.3	-4.4	-4.4	-5.8	1.9	3.6	5.0
556	Multidisciplinary Studies Bldg	813	12.5	-0.1	-0.1	-0.4	4.3	5.8	7.4
570	Physical Education Building	584	21.8	17.8	17.8	17.8	17.8	17.8	15.8
581	Academic Building Phase 3	1163	N/A	-5.1	-5.1	-3.8	1.9	3.7	5.0
582	Student Recreational Center	557	N/A	18.5	18.5	18.5	18.5	18.5	16.5
583	University Center Expansion	513	20.8	16.1	16.1	16.1	16.0	16.0	17.2
584	Engineering Bioscience Bldg III	2038	N/A	-22.8	-8.4	-5.5	2.0	4.0	4.5
585	Arts Building	100	13.0	-4.0	-4.1	-2.3	4.1	6.0	7.2

Based on the simulation results, the following conclusions can be made:

- According the simulation results of Scenario 1 and 2, running a branch to the new Engineering and Biosciences Building from near by loop will not result in acceptable designs.
- Scenario 3 further concludes that connecting the future Engineering Bioscience Building Phase III with nearby expansions such as from the Science Building is not a good design either. The loop should expand farther upstream.
- Scenario 4, 5 and 6 are all acceptable scenarios for preliminary design.
- Scenario 4 and Scenario 5 could take advantage of the crawl space and underground tunnel; therefore, construction cost and labor cost could be drastically reduced for these scenarios.

The Scenario 4 has the lowest estimated construction and labor cost and would also take advantage of the underground tunnel and crawlspace. It also has the benefit of having the minimum interference to the university and utility plant operation. It was therefore chosen as the preliminary design for the future campus expansions. It requires that a pair of chilled water supply and return pipes be built in parallel with the existing pipes in the tunnel. Once the preliminary design was determined, further detailed design was required.

Optimization of Preliminary Design

Additional more detailed simulation was conducted to investigate where to place the pipes and fittings and how to connect them to the existing central chilled water distribution system. After several rounds of simulation and discussion with the facility owner, the refined preliminary design was established (Figure 21). This design takes advantage of the crawlspace beneath the Multidisciplinary Studies Building. Pipes are modeled to connect immediately before the reduction of 24" pipe to 20" pipe in the tunnel. Most of the pipe goes along the existing pipes in the crawl space toward the current Engineering Biosciences Building. The first part is a 20" pipe, which connects locations A and B; it is about 790 feet long. The jumper at location B is 18" pipe. Then another 20" branch starts from location B and ties in to location C, which is about 290 feet long. The jumper pipe at location C is 14". Then another 18" pipe connects location D and the future Engineering Bioscience Building Phase III, which is about 430 feet long. Tees, valves, and area changes are modeled accordingly. Locations A, B, C and D are illustrated in Figure 21.

Assume that the future Engineering Bioscience Building Phase III (Bldg 584) uses 3900GPM chilled water.

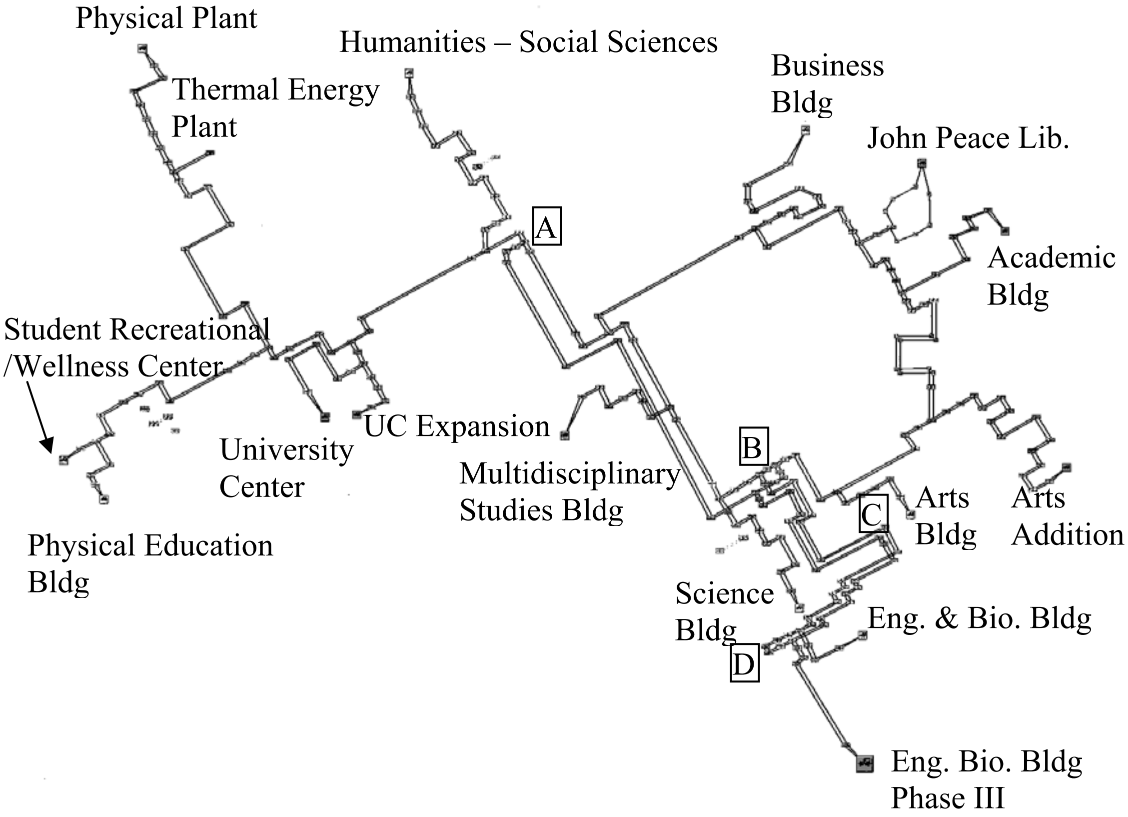


Figure 21 Optimal preliminary design.

This model is so detailed that the facility owner had been to the field and identified the locations of the valves, tees and pipes for the future expansion. Also with most of the information known, they could estimate the accurate material cost, construction cost and labor cost for the project. Since six different designs had been studied through simulation and all of the owner concerns have been taken into account, this design is considered to be the optimal design.

Conclusions

By presenting a case study, this chapter demonstrated how to use computerized simulation to construct and verify simulation models for an existing district cooling and heating system. With detailed field surveys and proper building load estimation, the advanced water distribution system simulation software can yield very accurate results. Based on the simulation model, the engineer can basically explore all possible designs, and by evaluating the simulation results, the best preliminary design can be identified. Once the preliminary design is accepted, further designs can be evaluated, optimizing each design by checking proper pipe size, locating tees and valves and so forth. The simulation model can be used to simulate the operation of a future central chilled water system by opening or closing valves. Using the simulation can result in more cost-effective and robust designs. This chapter presents a case study that identified and optimized designs for a district cooling and heating system in the hope that other design engineers can apply the same technique.

CHAPTER VII

IMPACT OF MINOR LOSSES ON DISTRIBUTION SYSTEM PIPING DESIGN

Chapter Summary

In the design of water distribution loops, many designers choose to ignore the minor losses, because minor losses are generally believed to be much smaller than the losses of pipe friction. Nevertheless, whether this is true for campus type district heating and cooling (DHC) systems still needs to be verified. The fact is that the piping is often the most expensive portion of a district heating and cooling system. Therefore, it is important to design it carefully. Simulations were conducted to study the minor losses on campus type DHC systems. The objectives of this chapter are to investigate losses caused by fittings on existing DHC systems and determine whether the minor losses are insignificant. Three actual systems were chosen for this study. They are University of Texas at San Antonio 1604 campus CHW distribution loop, and the Texas A&M University CHW and HHW distribution loops. They will be referring to as UTSA-CHW, TAMU-CHW and TAMU-HHW respectively. Field surveys have been conducted to collect the detailed information required. Simulation models were built to investigate the pipe friction losses and minor losses. The results indicated that the minor losses were 47.5%, 18.0% and 28.1% of total losses respectively. The conclusion is that the “minor” losses indeed constitute a significant portion of the total losses. In preliminary design and master plan, the minor losses should be reasonably estimated and generally should not be ignored. The simulation results a strong correlation between the "minor losses" and the number of fittings per 100ft pipes. A formula was proposed to estimate minor losses based on this finding. This could help the designers to build simulation models for preliminary design and master plan by changing the design factor in the pipe friction calculation to compensate for the minor losses.

Introduction

When designing a water distribution loop (open or closed loop) the minor losses, which are losses caused by various fittings, are generally believed to be much smaller than the head losses due to pipe friction. For this reason, many modelers choose to neglect minor losses (Methods et al. 2003). Another design guide states that when a chilled water distribution system has a minimum number of fittings, the added equivalent length for fittings in preliminary calculations can be ignored (IDEA 1983). However, it did not say what constitute a system with "minimum number" of fittings. The piping is often the most expensive portion of a DHC system. Manufacturing and installing pipes can represent about 70 percent of a project's capital costs (ASHRAE 2000; NAP 1985). Because the initial cost is high, it is very important to take extra precautions when designing district heating and cooling system to prevent undersized or oversized designs.

The objectives of this portion of the report are: (1) to find out what percent of losses are caused by fittings on existing DHC systems; (2) to determine whether the minor losses are insignificant in campus type DHC systems; and (3) to find a way to estimate the minor losses, if the minor losses are significant.

Method

When a liquid flows through a pipeline, there are energy losses due to the existence of friction and turbulence. These energy losses, also call head losses, are generally the result of two mechanisms: friction along the pipe walls and turbulence due to changes in streamlines through fittings and appurtenances (Methods et al. 2001). Head losses along the pipe wall are called friction losses or head losses due to friction, while losses due to turbulence within the bulk fluid are called minor losses.

The pipe friction losses can be expressed as:

$$h_L = K_P Q^2 \tag{18}$$

where

h_L = head loss due to friction (ft)
K_P = pipe resistance coefficient
Q = pipeline flow rate (GPM)

The minor losses can be expressed in similarly as:

$$h_M = K_M Q^2 \tag{19}$$

where

h_M = head loss due to minor losses (ft)
K_M = minor loss resistance coefficient

Q = flow rate (GPM)

For the case of a single pipeline between two points, the system head losses can be described in equation form as:

$$\Delta \mathrm{H} = \sum h_L + \sum h_M \tag{20}$$

Thus, the pipe friction losses and minor losses associated with each segment of pipe are summed along the total length of the pipeline. The relative contribution of minor losses to the total energy losses can be describes as:

$$\alpha = \frac{\sum h_M}{\sum h_L + \sum h_M} \tag{21}$$

When the system is more complex, the interdependencies of the hydraulic network make it impossible to describe the relative contribution of pipe friction losses and minor losses by head losses. In these cases, energy analysis using a hydraulic model may be needed. It is helpful to analyze the relative contribution of minor losses to the overall network.

In networks of interconnected hydraulic elements, there are different pipes and different fittings under different flow conditions. The total energy losses due to friction losses can be defined in equation form as:

$$W_P = \sum_{i=1}^{n} \left(h_{L,i} \times Q_{L,i} / 5306.8 \right) \tag{22}$$

where

W_P = total energy losses due to pipe friction (kW)

$h_{L,i}$ = head loss at pipe i (ft)

$Q_{L,i}$ = flow rate at pipe i (GPM)

The total energy losses due to minor losses can be defined in equation form as:

$$W_M = \sum_{i=1}^{n} \left(h_{M,i} \times Q_{M,i} / 5306.8 \right) \tag{23}$$

where

W_M = total energy losses due to minor losses (kW)

$h_{M,i}$ = head loss at fitting i (ft)

$Q_{M,i}$ = flow rate at pipe i (GPM)

Thus, the energy losses due to pipe friction losses and minor losses associated with each segment of pipe are summed over the water distribution network. Therefore, the relative contribution of minor losses to the total energy losses can be describes as:

$$\alpha = \frac{W_M}{W_P + W_M} \tag{24}$$

Results

Three simulation models were built for actual thermal distribution loops. They are UTSA 1604 campus CHW distribution loop, TAMU Main Campus CHW distribution loop and HHW distribution loop. They are described in previous chapters. The simulation results were listed in Table 12.

TABLE 12

UTSA-CHW, TAMU-CHW and TAMU-HHW Simulation Results

Items	TAMU-CHW	TAMU-HHW	UTSA-CHW
N	1424	1927	387
L	88,332	84,267	12,630
α	18.0%	28.1%	47.5%
ρ	16	23	31

where

N	Total Number of Fittings
L	Total Pipe Length (ft)
α	Relative Contribution of Minor losses to Total Energy Losses
ρ	Fitting Density. It is defined to be equal to $N/L \times 1000$

Conclusions

- Minor losses are a significant portion of the total piping network energy losses for all three water distribution loops.
- In preliminary design and master plan of a DHC system, the minor losses should be reasonably estimated and should not be ignored.
- The percentage of losses due to minor losses is related the fitting density. See Figure 22.
- Since if there is no fitting on the pipeline, α will be zero. A formula (25) was proposed to estimate the minor losses.

$$\alpha = 0.0302\rho^2 + 0.5811\rho \qquad (25)$$

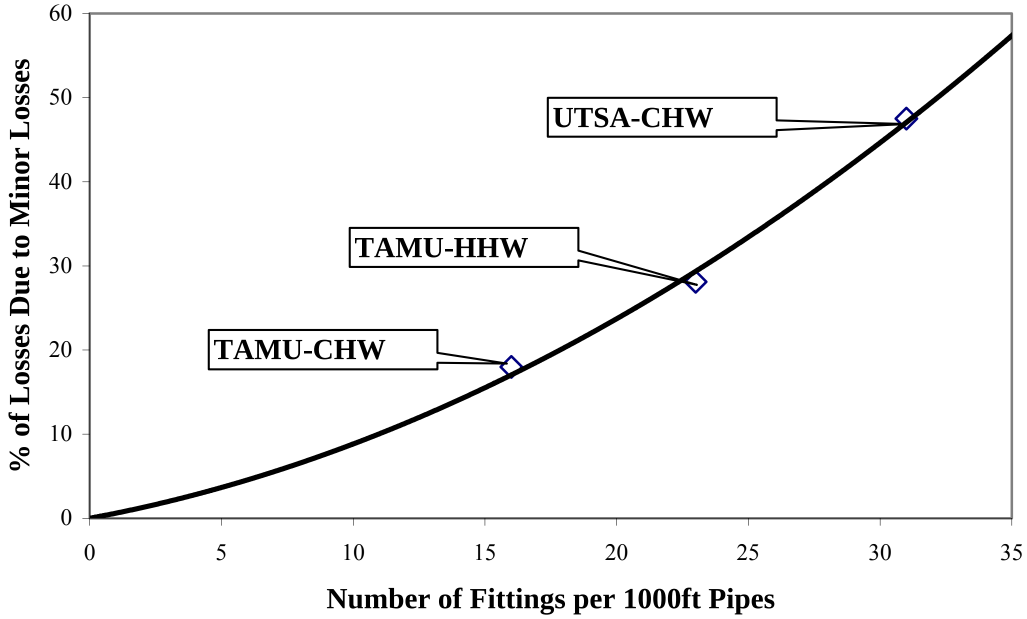


Figure 22 Relationship between minor losses and fitting density.

CHAPTER VIII

ENERGY OPTIMIZATION PROGRAM

Chapter Summary

Supplying the utilities needs for a large university campus represents a tremendous recurring expenditure of university funds, which often competes against faculty salaries and other expenses. The TAMU total energy cost was $25.7 million in 2002*. Coupled with the budget cut due to the weak economic situation in Texas and the US in recent years, pressure is mounting on the utilities administration to find ways to minimize operation cost of the utilities plants. The ESL is currently setting application and refining the Energy Optimization Program (EOP) to calculate plant production cost and to optimize its operation. The author's assignment is to refine and improve the EOP. Its performance had been greatly improved by replacing all of its equipment models and new databases have been added. It can access data and perform simulations for extended periods of time. It can perform energy balance and economic evaluation for extended period of time automatically. Further work still needs to be done to improve its economic evaluation model and to enhance optimization over an extended period of time.

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* - Data are from TAMU bills for the period between Jan. 2002 and Dec. 2002.

Objectives

The objectives of this chapter are: (a) to simulate the interconnected combined cycle cogeneration and district energy plants of Texas A&M University, (2) to perform thermo-economic cost allocation to calculate the production cost of various thermal commodities and electricity, and (3) to optimize operation in terms of low operational cost.

Introduction

Unlike most other commodities, electricity, steam, hot water and chilled water are very difficult to store in a practical manner on a large scale. For this reason, electricity, steam, hot water and chilled water must generally be produced when the customers need them. They must be transported by means of extensive transmission and distribution systems, which help to stabilize and equalize the load in the systems. Nevertheless, large fluctuations in demand during the day require quick reactions from plants in order to maintain the balance between supply and demand. A reliable supply of electricity, steam, hot water and chilled water was always and still is a major priority. In the past few years a new priority has been set by a global trend to deregulate the energy market. Deregulation has opened to competition a historically closed and protected industry. Deregulation and competition have brought about a need for flexibility, reliability, increased automation and cost minimization in generating plants. To stay competitive, power plants will need to run optimally all the time, requiring advanced control and optimization strategies. (Oluwande 2001)

The determination of the profitability and feasibility of proposed combined heat and power plants is generally the focus of the cogeneration literature. Optimization problems in combined systems, assessment of costs and economic effects of combined heat and power generation are not strange terms (e.g., Marecki 1988; Kehlhofer et al. 1999; Sarabchi 2001; Donne et al. 2001). However, many of these studies are directed towards design evaluation and optimization rather than cost analysis and operational optimization for existing systems. The operation of plant equipment is often radically different from the design assumptions and frequently changes. The dynamics of the energy markets, such as the changes and fluctuations of fuel price and electric cost and changes of load profiles, add more complexity to the determination of the operational cost of the facility.

Simulation of the Texas A&M University Utilities System

Despite the fact that supplying the utilities needs for a large university campus represents a tremendous recurring expenditure of university funds, the mechanical systems, which fulfill these needs, are seldom given attention until a sharp rise in fuel prices creates a crisis situation.

The response was to find ways to reduce consumption and increase efficiency. However, the solution to this problem is complicated for many reasons. One reason is that there are five interconnected utilities plants that serve the Texas A&M University campus. They produce utilities, such as chilled water, heating hot water, domestic hot water, steam and electricity, to meet the needs of the Main Campus, the West Campus and some remote loads. All of these utilities plants and the district energy networks are not working independently; rather they are working as one system. These utilities plants not only produce utilities for the campus, but also interact with each other through the district energy networks. A good example would be WC1 and WC2 working together to meet the cooling needs of the West Campus. The cooling load is dispatched based on the operation of chillers, primary pumps and secondary pumps in these plants. Another example would be found in WC4. Though there are separate CHW and HHW distribution systems on Main Campus and West Campus, the WC4 uses 600psig steam from the CUP to meet the heating load of West Campus. Similarly, the WC1 also uses 600psig steam from the CUP to produce chilled water for West Campus. Therefore, the CUP not only provides cooling for Main Campus; it also carries part of the cooling load on West Campus as well. The plants' interaction is also illustrated through the electricity distribution network throughout the whole campus, where the generating equipment in the CUP provides part of the electricity to all the satellite plants which use it to meet cooling needs. CUP and WC1 use both steam and electricity to produce chilled water. The steam driven equipment interacts with electrical driven equipment throughout the system.

Another complication in solving the problems of consumption reduction and efficiency increase was how one intelligently evaluates energy conservation opportunities? Fleming (1997) had proposed a simplified thermodynamic approach to cost allocation in a combined cycle cogeneration and district energy system. He concluded that it is possible to estimate production cost at the component level, the equipment level, the whole plant level and even the whole campus level.

History of Energy Optimization Program

SEGA Inc. (1985~1997)

This program was originated from 1985, when the utilities plant contracted the SEGA Inc. to perform an energy study. A small program was developed based on the SEGA's thermal analysis package, which named EndResult®. Until 1997, the program was converted to spreadsheet-based software, using the old version of Microsoft Excel. During this period of time, the progress was fairly slow. Only major equipments in the Central Utilities Plant and the three tandem-set chillers at the West I satellite plant were modeled. At that time, the program could not even result in a converged solution.

Energy Systems Laboratory (1997~2001)

In early 1997, ESL was requested by the utilities plant to work closely with SEGA to provide supports on the EOP project. After several month of intensive hard work by SEGA, ESL and the utilities plant personnel, the program could finally get converged. Since 1998, ESL was requested by the utilities plant to carry out the full responsibility to maintain and further develop this program. The ESL EOP team rewrote all the codes to replace the obsolete macro by the visual basic for application language (VBA), which is more powerful, compatible, and flexible. In the mean time, all the equipments in the central utilities plant and the satellite plants are modeled and included into the EOP (Zhou 2001). In 2001, although the program converged, it could only provide very rough and preliminary results.

Energy Systems Laboratory (2002~Pressent)

Since the beginning of the year 2002, ESL upgraded all the individual equipment models using actual metered historical data. Comparing to the old models, which regressed from manufacture design data or field test data, the upgraded models greatly increased the program’s accuracy. Now the EOP has grown into a much more applicable package of software based on the database technology. It can automatically simulate over a period of time, thus providing the opportunities to perform the annual thermal and economic analysis.

Methodology

This section provides information on how the EOP is integrated and works. It will cover the following aspects, including: assumptions made, data source, how the equipment model is constructed, how the system model is integrated, how the costs are allocated, what numerical solution scheme is used to achieve energy balancing, and at last how the database, the EOP spreadsheet and the post simulation process are integrated together. (Chen et al. 2004)

Engineering assumptions

- Steady-state conditions
- Steam header pressure and temperature are constant. Steam is well mixed on all the headers.

  - High pressure steam header: 600psig, 700F
  - Medium pressure steam header: 150psig, 492F
  - Low pressure steam header: 20psig, 258.77F
  - Condensate: 130F at atmosphere pressure
- No CHW, HHW, DHW, steam or condensate leakage on the pipe.
- 7.6% Boiler blowdown
- The RO unit on site makes all the condensate.
- Natural gas higher heating value (HHV) is equal to 1,020Btu/Scf
- 99% heat conversion efficiency of the heating hot water exchanger array
- 100% heat conversion efficiency of the DA and no steam losses.
- No heat loss on PRV and Desuperheater
- 1.5%O2 level in boiler #9/11 exhaust
- Feed water pump efficiency: 70%

System boundary

The EOP covers all the thermal and electric production in CUP, CHW and DHW production in SS3, WC1 and WC2, and HHW production in WC4. Because of inadequate instrumentation coverage, the EOP does not cover the DHW production at SS3, HHW production in both WC1 and WC2.

Data source

Data source includes Westinghouse database, Square-D database, natural gas bills, electricity bills, plant logbook and manufacturer provided field test data and curves.

Equipment modeling

The whole simulation model of the system was developed and tested in modules – boilers, gas turbine, HRSG, steam turbine generators, absorption chillers, electric chillers, pumps, heat exchangers, PRV and desuperheater. Each module was constructed based on the best available data. Most of the equipment models were constructed based on the metered hourly data for the year 2002. When there is inadequate metering coverage to certain equipment, field test data or manufacturer provided data were used. Equipment does not have data at all, such as PRV and desuperheater, law of mass and energy conservation are applied. The modeling technique is the multiple regression method (details see Chapter X).

System modeling

All the equipment models were linked together to form the system model. The general principles of the system modeling and simulation are the mass conservation, energy conservation and general economic principle.

Rules of cost assignment

The rules of cost assignment are listed as follows:

1. Cost passes down
2. First law (STG3/4/5)
3. Avoid cost (GT6 and HRSG)

Most of the equipments in the utilities plant are "single" output equipment. This equipment only produces one thermal commodity, such as chillers, boilers, heat exchangers, PRVs and so forth. For this kind of equipments, rule 1 applies. The STG

3/4/5 produce both thermal and electrical commodities. Rule 1 applies to these equipments. Avoid cost was used in gas turbine and HRSG combined set. They will be explained in further details.

Numerical solution schemes

Due to the fact that the energy measurement has error and conflict with each other throughout the system, implicit iteration method is applied to achieve energy balance. At first, the energy demands of all equipment are calculated based on the metered data. The energy supply will be adjusted when it is different from the demand. The program adjusts the equipment supply in small steps until the whole system reaches energy balance and mass balance.

System integration

All the input and output data are stored in a databases (MS Access ®). The program automatically pools the data, initializes the input, runs energy balancing and solves the converged solution, and then stores the results back to the database. The program can solve solution for every hour for extended period of time, e.g. FY02. Then post simulation process to combine the hourly data to monthly and annual cost allocation report. Figure 23 below illustrated the overall structure of EOP.

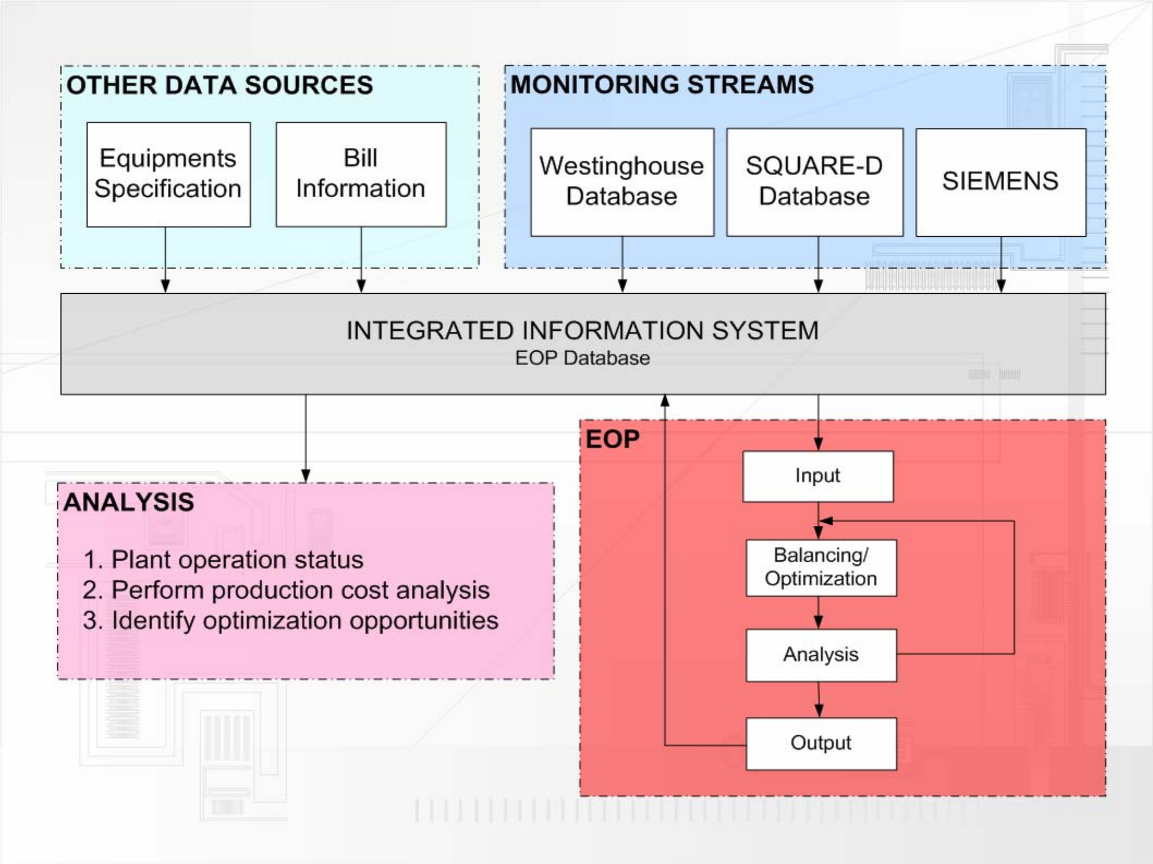
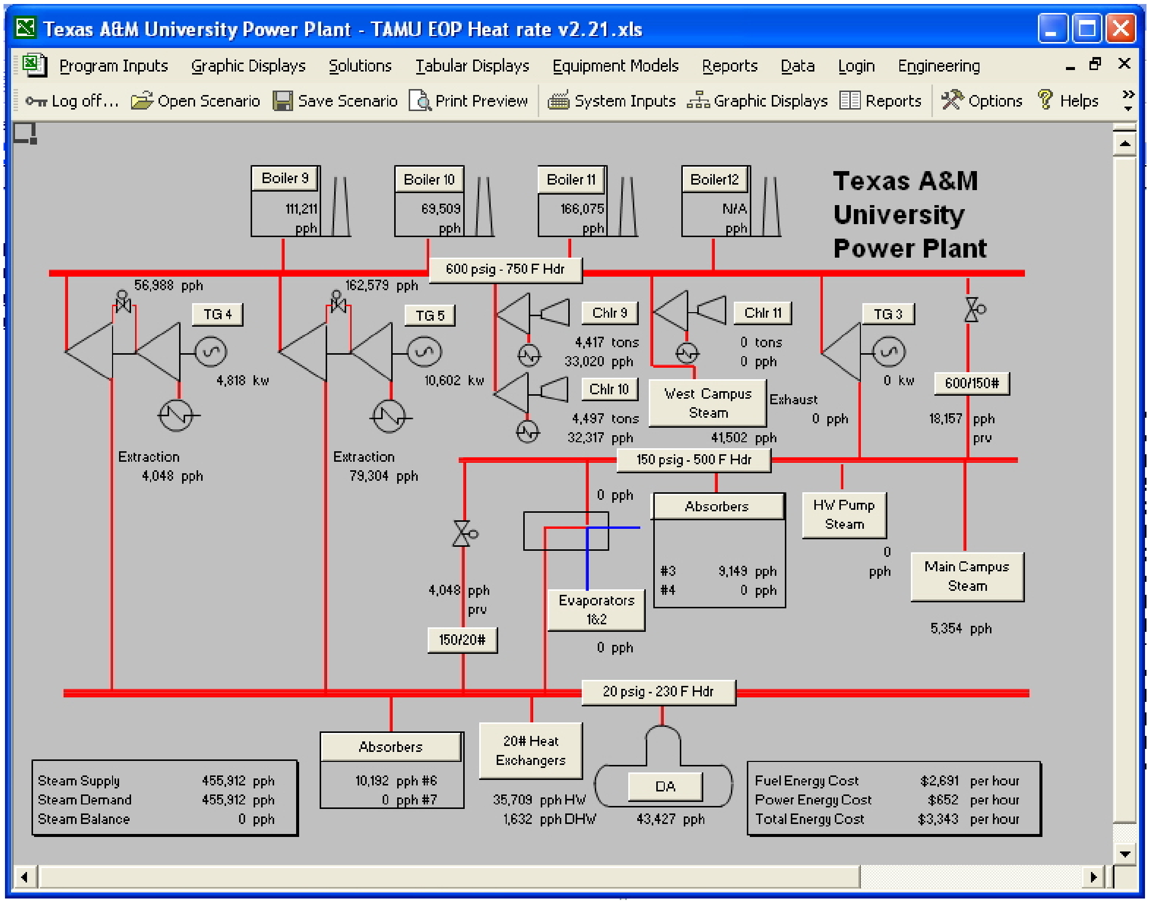


Figure 23 EOP system structure.

Graphical Interface of EOP

The EOP has a user-friendly graphical interface. Figure 24 illustrates the CUP system status.



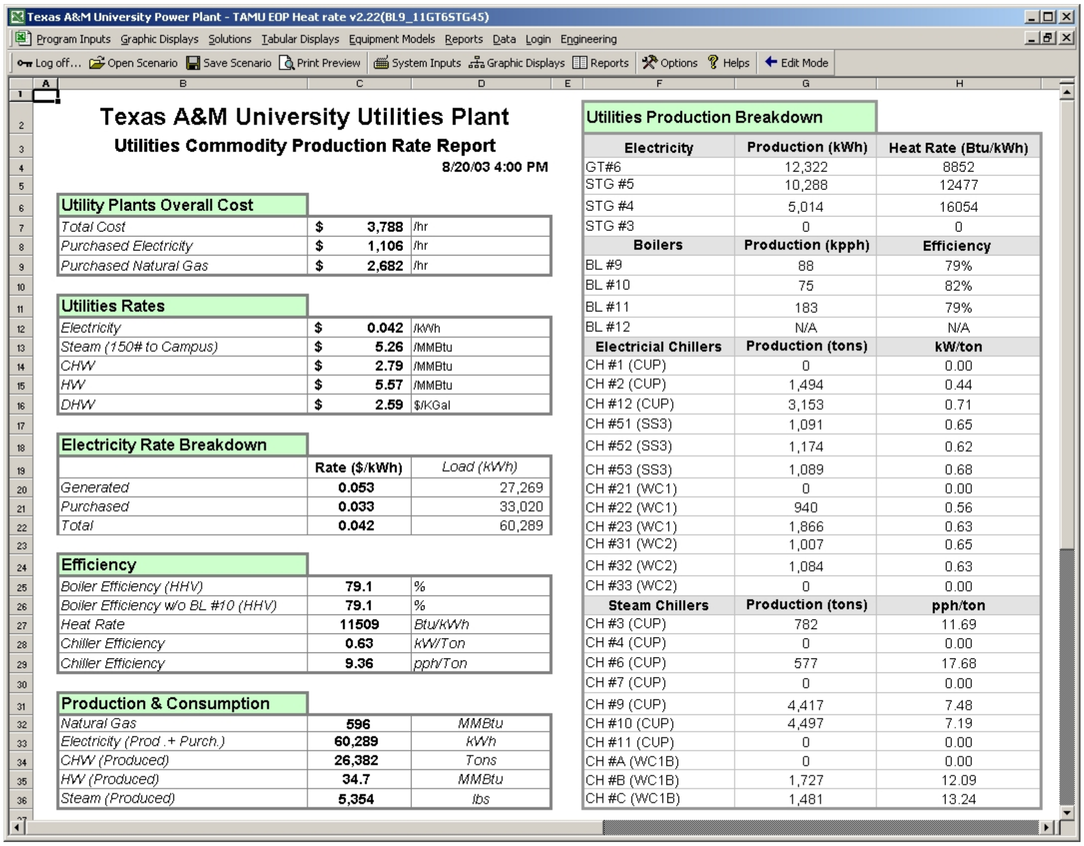
Steam Supply 455,912 pph
Steam Demand 455,912 pph
Steam Balance 0 pph

Fuel Energy Cost $2,691 per hour
Power Energy Cost $652 per hour
Total Energy Cost $3,343 per hour

Figure 24 Graphical interface of EOP.

The EOP is able to perform elaborate simulations for a given period of time. The user only needs to choose when to start and when to stop the simulation.

After the simulation is done, the EOP can report its analysis results. Figure 25 shows that total cost of operation for a given hour and production rates for the various commodities the TAMU utilities system produced. All of this is done automatically. The results are written back to a database, so that it can be further analyzed.



Texas A&M University Utilities Plant

Utilities Commodity Production Rate Report

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Utility Plants Overall Cost

Total Cost	$	**3,788**	/hr
Purchased Electricity	$	**1,106**	/hr
Purchased Natural Gas	$	**2,682**	/hr

Utilities Rates

Electricity	$	**0.042**	/kWh
Steam (150# to Campus)	$	**5.26**	/MMBtu
CHW	$	**2.79**	/MMBtu
HW	$	**5.57**	/MMBtu
DHW	$	**2.59**	$/KGal

Electricity Rate Breakdown

	Rate ($/kWh)	*Load (kWh)*
Generated	**0.053**	27,269
Purchased	**0.033**	33,020
Total	**0.042**	60,289

Efficiency

Boiler Efficiency (HHV)	**79.1**	%
Boiler Efficiency w/o BL #10 (HHV)	**79.1**	%
Heat Rate	**11509**	*Btu/kWh*
Chiller Efficiency	**0.63**	*kW/Ton*
Chiller Efficiency	**9.36**	*pph/Ton*

Production & Consumption

Natural Gas	**596**	*MMBtu*
Electricity (Prod .+ Purch.)	**60,289**	*kWh*
CHW (Produced)	**26,382**	*Tons*
HW (Produced)	**34.7**	*MMBtu*
Steam (Produced)	**5,354**	*lbs*

Utilities Production Breakdown

Electricity	Production (kWh)	Heat Rate (Btu/kWh)
GT#6	12,322	8852
STG #5	10,288	12477
STG #4	5,014	16054
STG #3	0	0
Boilers	**Production (kpph)**	**Efficiency**
BL #9	88	79%
BL #10	75	82%
BL #11	183	79%
BL #12	N/A	N/A
Electricial Chillers	**Production (tons)**	**kW/ton**
CH #1 (CUP)	0	0.00
CH #2 (CUP)	1,494	0.44
CH #12 (CUP)	3,153	0.71
CH #51 (SS3)	1,091	0.65
CH #52 (SS3)	1,174	0.62
CH #53 (SS3)	1,089	0.68
CH #21 (WC1)	0	0.00
CH #22 (WC1)	940	0.56
CH #23 (WC1)	1,866	0.63
CH #31 (WC2)	1,007	0.65
CH #32 (WC2)	1,084	0.63
CH #33 (WC2)	0	0.00
Steam Chillers	**Production (tons)**	**pph/ton**
CH #3 (CUP)	782	11.69
CH #4 (CUP)	0	0.00
CH #6 (CUP)	577	17.68
CH #7 (CUP)	0	0.00
CH #9 (CUP)	4,417	7.48
CH #10 (CUP)	4,497	7.19
CH #11 (CUP)	0	0.00
CH #A (WC1B)	0	0.00
CH #B (WC1B)	1,727	12.09
CH #C (WC1B)	1,481	13.24

Figure 25 EOP generated rate report.

Simulation Results

The following two figures are selected to illustrate some of the simulation results. Figure 26 is simulated hourly operating cost for the utilities system. Figure 27 shows an example of cost allocation for one specific hour. TAMU utilities plants annual energy cost allocation can be obtained by combining the annual EOP results and the annual natural gas bills of other satellite plants.

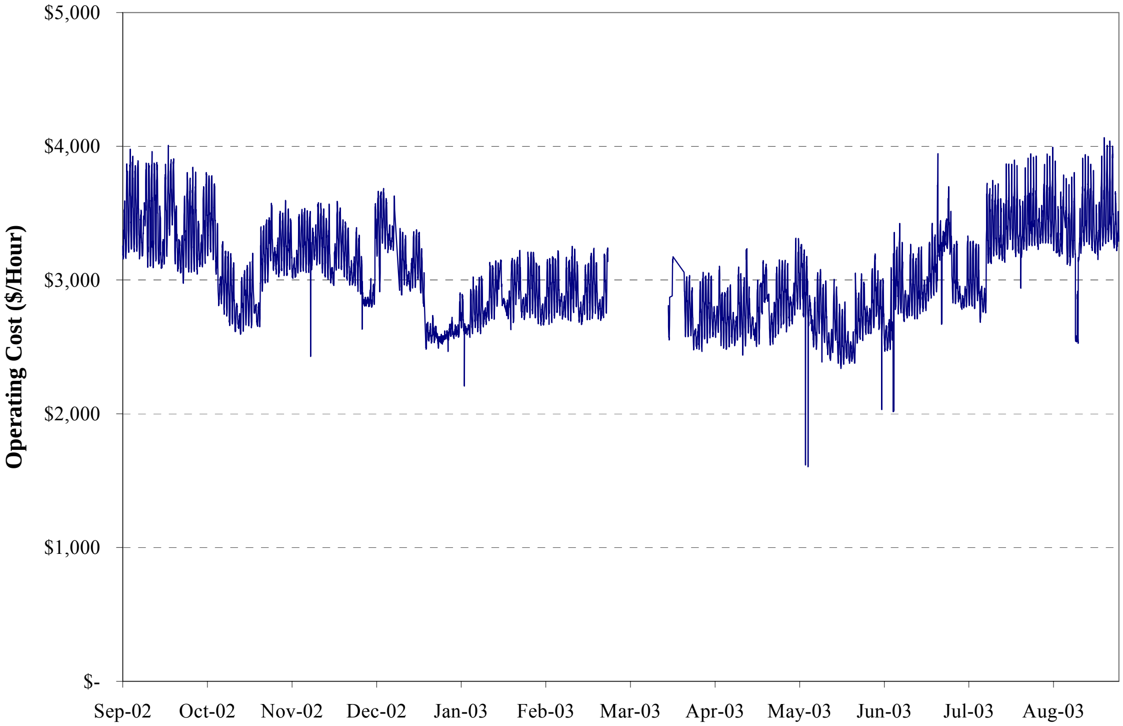
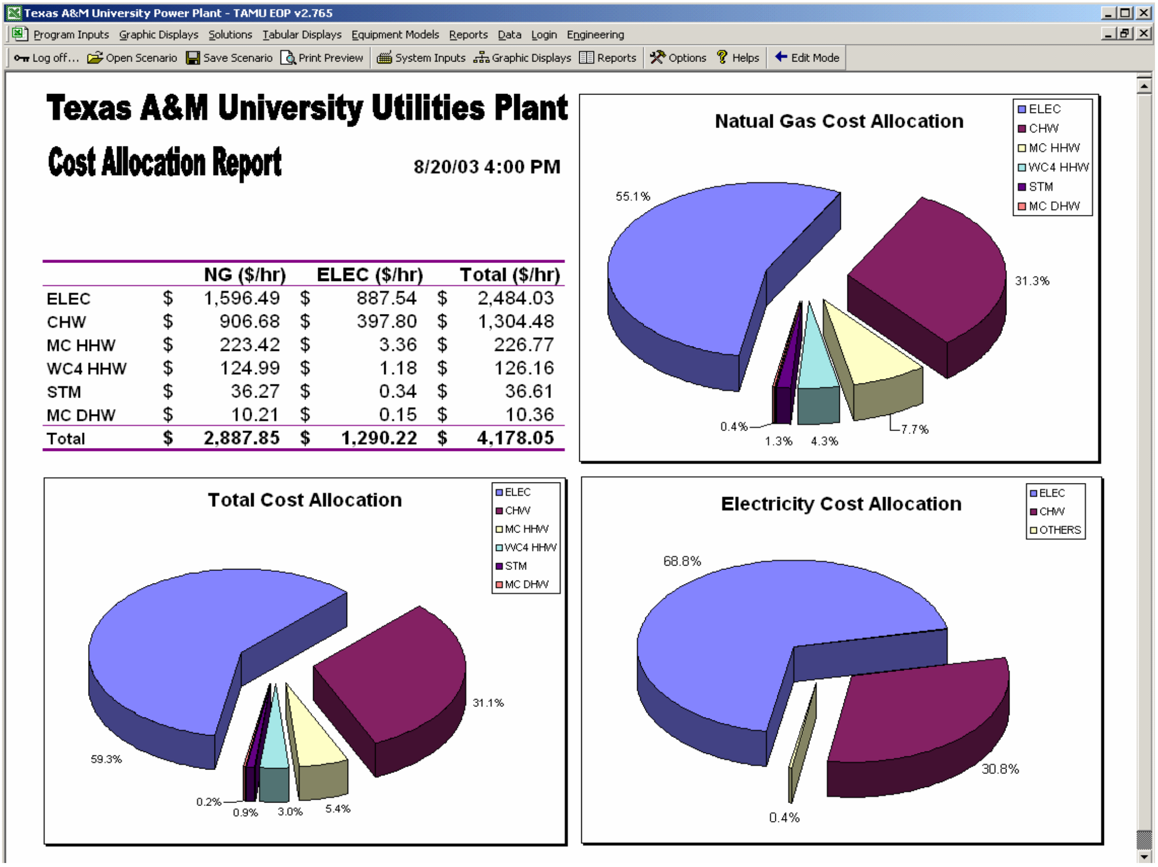


Figure 26 FY03 TAMU utilities system hourly operating cost.

Network Structure and System Integration for the Future EOP

Figure 28 is the network structure of the future EOP. The EOP will read data from the WDPF database, Square-D database and the EOP database. The simulation and optimization results can be written back to the EOP database. Other people can access data stored in the EOP database by using Crystal Report® or MS EXCEL®. Results can be published on the Internet for public access. For system security, all of the vital parts of the systems are protected by a firewall.



Texas A&M University Utilities Plant

Cost Allocation Report

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		NG ($/hr)		ELEC ($/hr)		Total ($/hr)
ELEC	$	1,596.49	$	887.54	$	2,484.03
CHW	$	906.68	$	397.80	$	1,304.48
MC HHW	$	223.42	$	3.36	$	226.77
WC4 HHW	$	124.99	$	1.18	$	126.16
STM	$	36.27	$	0.34	$	36.61
MC DHW	$	10.21	$	0.15	$	10.36
Total	**$**	**2,887.85**	**$**	**1,290.22**	**$**	**4,178.05**

Figure 27 EOP generated hourly cost allocation report.

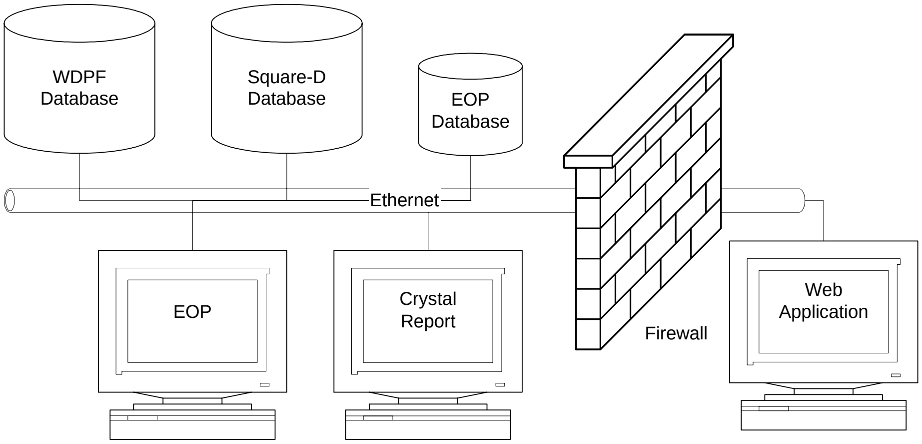


Figure 28 Future EOP network structure.

CHAPTER IX

GAS TURBINE AND HEAT RECOVERY STEAM GENERATOR ANALYSIS

Chapter Summary

The objectives of this chapter are: (1) to analyze the performance of the gas turbine generator set #6 (GT6) and heat recovery steam generator (HRSG or BL10) of the TAMU CUP, (2) to identify potential energy saving opportunities and (3) to recommend energy conservation measures. Literature about gas turbines and HRSG combined sets has been reviewed to investigate generally accepted practice in this industry. Field investigation has also been conducted. Data for the past one and a half years concerning BL9, BL11, GT6 and HRSG have been compiled from the Westinghouse database and analyzed. A simulation model was constructed and calibrated to accurately represent the behavior of the gas turbine and the HRSG combined set.

The findings indicate that: supplementary firing is an efficient way to increase the steam generation in the HRSG. Additional steam in the HRSG is generated at an efficiency of nearly 100% (Ganapathy 2003). The metered results of the HRSG on site also confirmed this with an efficiency of 95.8% on a higher heating value (HHV) basis. While at the same time, the average efficiency of the BL9 and BL11 is merely 80.94% on a HHV basis. Since the supplementary-firing is the most efficient way to produce additional steam on site, it is recommended to load the supplementary burner as high as possible, whenever, the gas turbine is in operation. Assume the gas turbine is operated 8000 hours per year, and the natural gas price is \$4.5/MMBtu. The estimated fuel saving could be as much as \$577,000 per year by fully loading the HRSG burner to 99MSCFH. Since the duct burner of the HRSG hasn't been operated above 75MSCFH before, it is also recommended that a test be conducted to determine the upper firing rate of the duct burner for continuous operation of the HRSG.

Introduction

The objectives of this investigation are: (1) to evaluate the performance of the GT6 and HRSG of the TAMU CUP, (2) to identify potential energy saving opportunities and (3) to implement energy conservation measures.

The data for the past one and a half years indicate that the HRSG was usually operated in recovery mode and supplementary-firing wasn't used very often. The steam production of the HRSG seldom exceeds 110 kpph (thousand pound per hour), while its design capacity is 175 kpph. This indicates great potential for fuel savings.

Literature Review

Supplementary-firing is the use of a burner or burners in the sides of the duct upstream of the HRSG to raise the temperature of the entering gas stream prior to combustion (Figure 29). This is most commonly applied in gas turbine applications where the oxygen-rich (15% to 18%) exhaust can provide efficient combustion. Today's cogeneration plants have both HRSGs and packaged steam generators. To generate a desired quantity of steam efficiently, the load vs. efficiency characteristics of both the HRSG and the steam generator should be known.

"Supplementary-firing is an efficient way to increase the steam generation in HRSG. Additional steam in the HRSG is generated at an efficiency of nearly 100%." (Ganapathy 2003) The HRSG system efficiency in gas turbine plants will improve with the addition of auxiliary fuel, which increases the gas temperature to the HRSG and hence increases its steam generation.

"The efficiency is increased with supplemental firing because almost every Btu of burner fuel is converted to useful thermal energy. This is because the mass flow and final temperature of the exhaust temperature remain almost constant during supplementary firing. The increased temperature difference across the HRSG results in more heat recovered per pound of exhaust gas." (Petchers 2003)

"The efficiency of the HRSG system improves with firing. The reason is that with the same oxygen content entering the burner, more fuel is being fired thus reducing the excess air leaving the stack; also with an increase in inlet gas temperature the exit gas temperature from a HRSG with an economizer usually deceases. This is due to the significantly larger ratio of water to gas flow in the fired mode compared to the ratio in the unfired mode. The gas flow remains nearly constant, while the steam production and the water flowing through the economizer increases, depending on the extent of firing. This fact is partly responsible for the improvement in efficiency." (Ganapathy 1991)

Equipment Description

Gas turbine and HRSG

The TAMU gas turbine was first installed in 1971 and recently upgraded to a rated capacity of 16.5MW. It is a single shaft open cycle turbine with a supplementary-fired heat recovery steam generator located behind it. It runs on natural gas, but it can fire no. #2 fuel oil. The exhaust gas leaves the gas turbine #6 at about 950^{o}F. Figure 29 shows the arrangement of the gas turbine and the supplementary-fired HRSG on site. The HRSG, which is also call Boiler #10 (BL10), has a rated capacity of 175 kpph. It has one electrically driven feedwater pump and one steam driven feedwater pump. Since the original diverter valve between the gas turbine and the HRSG was removed, the HRSG must be operated whenever the gas turbine is in operation. This HRSG is equipped with a duct burner and a runner burner. The runner burner can be switched on/off in the field manually. When it is on, the gas flow to the HRSG is about 20MSCFH. The duct burner can be controlled through the control room, but only after the runner burner is lit.

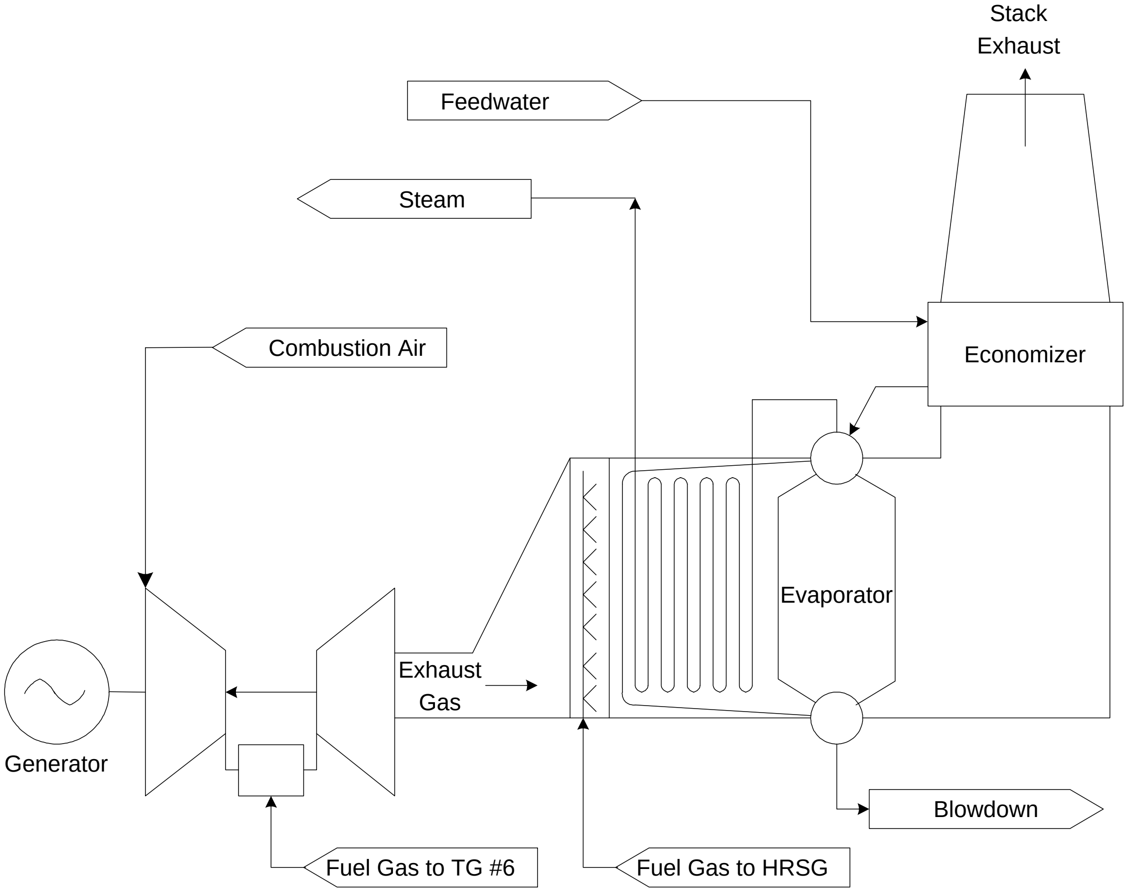


Figure 29 Schematic of the gas turbine and HRSG.

Original design specifications

- Gas Turbine Model

General Electric Model G5211, Capacity14.9MW Gas Turbine

- Design Specifications

The gas turbine generator #6 was originally rated at 14.9MW. After a major upgrade in late 2002, the capacity was increased to 16.5MW. Table 14 is the design specifications of the gas turbine generator #6 before and after the upgrade.

TABLE 13

Gas Turbine Generator #6 Design Specifications

		Pre-renovation	After-renovation
Design Output	MW	14.9	16.5
Design Heat Rate (LHV)	MMBTU/MW-HR	14.69	14.44
Design Fuel Consumption	MMBTU/HR	218.9	238.3
Ratio HHV/LHV		1.11	1.11
Design Air Flow	LB/HR	720,000	720,000
Design Shaft Speed	RPM	5,100	5100

Note: Compressor Inlet Temperature 80F Barometric Pressure 14.49 PSIA

- Design Performance Under Different Load and Ambient Temperature

TABLE 14 and TABLE 15 were derived from manufacturer provided curves.

TABLE 14

Effect of Gas Turbine Load on Its Performance

Gen. Output	% of Design Load Fuel Consumption	Gen. Output (MW)	Fuel Flow (MMBTU/HR)	Fuel Flow (MSCFH)	Heat Rate (MMBTU/MW-HR)	Eff.
10%	37.2%	1.7	88.6	96.5	53.7	6.4%
20%	43.5%	3.3	103.7	112.8	31.4	10.9%
30%	50.0%	5.0	119.2	129.7	24.1	14.2%
40%	56.5%	6.6	134.6	146.5	20.4	16.7%
50%	63.5%	8.3	151.3	164.7	18.3	18.6%
60%	71.0%	9.9	169.2	184.1	17.1	20.0%
70%	78.2%	11.6	186.4	202.8	16.1	21.1%
80%	85.5%	13.2	203.7	221.7	15.4	22.1%
90%	92.5%	14.9	220.4	239.9	14.8	23.0%
100%	100.0%	16.5	238.3	259.3	14.4	23.6%
110%	108.0%	18.2	257.4	280.1	14.2	24.1%
120%	117.5%	19.8	280.0	304.7	14.1	24.1%

Note: Heat Rate is based on LHV in the above table.

TABLE 15

Effect of Ambient Temperature on Gas Turbine Performance

Comp. Inlet Temp.	% of Design Output	% of Design Air Flow	% of Design Heat Rate	Design Output (MW)	Design Air Flow (LB/HR)	Design Heat Rate (MMBTU/MW-HR)
0	127.7%	115.9%	98.5%	21.1	834,480	14.2
20	121.5%	112.0%	98.4%	20.0	806,400	14.2
40	115.0%	108.0%	98.3%	19.0	777,600	14.2
60	107.8%	103.9%	98.8%	17.8	748,080	14.3
80	100.0%	100.0%	100.0%	16.5	720,000	14.4
100	91.2%	96.0%	102.3%	15.0	691,200	14.8
120	81.7%	92.0%	105.5%	13.5	662,400	15.2

- Gas Turbine Performance Evaluation

The actual performance of the gas turbine has been evaluated by comparing its metered data with its manufacturer provided curves (Figure 30). It seems that the performance of gas turbine #6 meets the design specifications whenever the power output is above 60% of rated output.

Simulation Model Construction and Verification

Simulation model specification

The simulation model was developed to use the gas turbine power production, the HRSG steam production and the outside air temperature as input. The simulation then predicts the gas turbine fuel consumption and indicates if HRSG is in recovery mode or supplementary-firing mode. If the HRSG is in supplementary-firing mode, the simulation model predicts the fuel consumption of the HRSG burner.

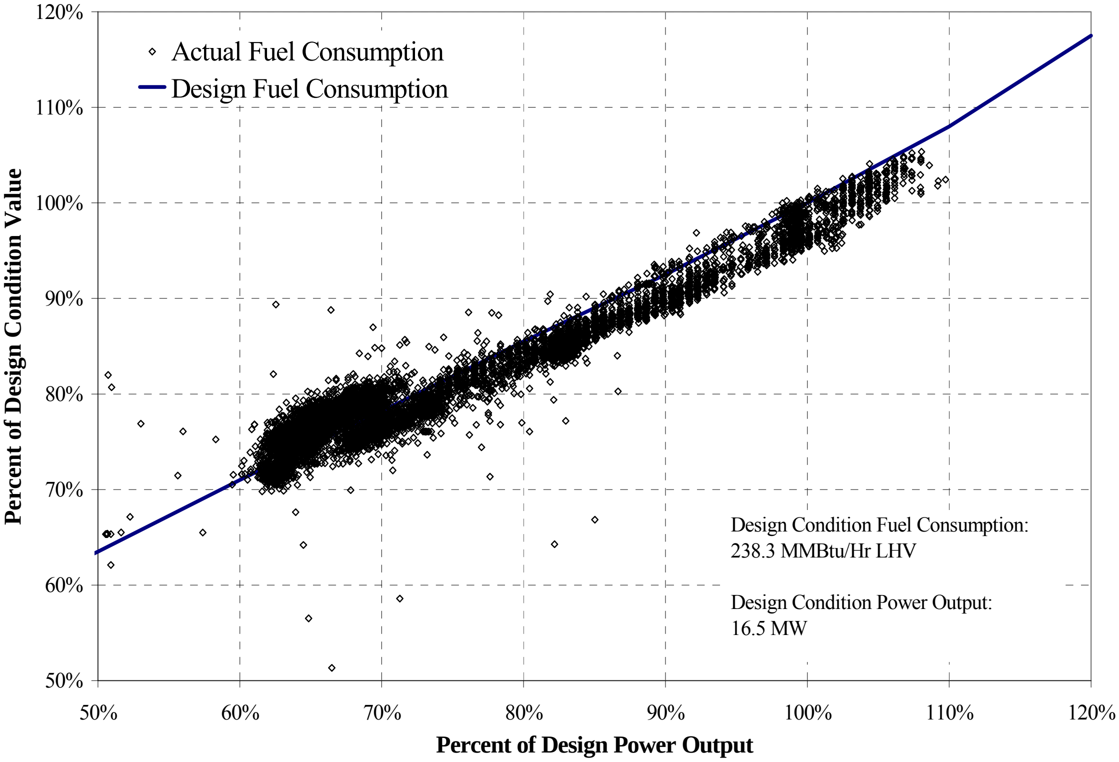


Figure 30 GT6 performance evaluation.

Simulation model

The simulation includes three parts. The first part is to simulate the total natural gas flow for gas turbine and HRSG combined set. The second part is to simulate the natural gas flow for gas turbine. The third part is to identify the HRSG operating mode by comparing the simulated gas turbine gas flow and the combined set gas flow. Assume higher heating value: HHV=1031Btu/scf. Data were pulled from the Westinghouse database from 1/1/2002 through 6/22/2003 on hourly basis.

- GT6 and HRSG combined set simulation model

Assume the total gas flow is function of GT6 power output, HRSG steam flow, and ambient temperature. Applying the method described in the next chapter. The GT6 and HRSG combined set model can be expressed as:

$$Q_1 = f\left(P, STM, T_{oa}\right) = \left(\sum_{i=1}^{8} A_i X_i^{\ *}\right) \times \sigma_{Q1} + \overline{Q_1} \tag{26}$$

The definitions of x_i and X_i^* are listed in TABLE 16. The values of $\overline{Q_1}$, σ_{Q1}, $\bar{x}_i$, σ_{xi} and A_i are provided in TABLE 17.

TABLE 16

Definitions of GT6 and HRSG Combined Set Simulation Model

$x_1 = STM^2$	$X_1^* = \frac{x_1 - \bar{x}_1}{\sigma_{x1}}$
$x_2 = P^2$	$X_2^* = \frac{x_2 - \bar{x}_2}{\sigma_{x2}}$
$x_3 = STM \times P$	$X_3^* = \frac{x_3 - \bar{x}_3}{\sigma_{x3}}$
$x_4 = STM \times T_{oa}$	$X_4^* = \frac{x_4 - \bar{x}_4}{\sigma_{x4}}$
$x_5 = P \times T_{oa}$	$X_5^* = \frac{x_5 - \bar{x}_5}{\sigma_{x5}}$
$x_6 = STM$	$X_6^* = \frac{x_6 - \bar{x}_6}{\sigma_{x6}}$
$x_7 = P$	$X_7^* = \frac{x_7 - \bar{x}_7}{\sigma_{x7}}$
$x_8 = T_{oa}$	$X_8^* = \frac{x_8 - \bar{x}_8}{\sigma_{x8}}$

TABLE 17

Coefficients of GT6 and HRSG Combined Set Simulation Model

$\overline{Q}_1 = 222.91$	$\sigma_{Q1} = 22.79$	
$\overline{x}_1 = 6{,}484.96$	$\sigma_{x1} = 2{,}279.05$	$A_1 = -0.0389$
$\overline{x}_2 = 157{,}999{,}929.55$	$\sigma_{x2} = 54{,}407{,}373.03$	$A_2 = 0.2031$
$\overline{x}_3 = 990{,}966.11$	$\sigma_{x3} = 278{,}839.44$	$A_3 = 0.1747$
$\overline{x}_4 = 5746.02$	$\sigma_{x4} = 1492.83$	$A_4 = -0.1611$
$\overline{x}_5 = 879{,}125.42$	$\sigma_{x5} = 149{,}659.37$	$A_5 = -0.3761$
$\overline{x}_6 = 79.32$	$\sigma_{x6} = 13.93$	$A_6 = 0.7058$
$\overline{x}_7 = 12{,}365.97$	$\sigma_{x7} = 2069.61$	$A_7 = 0.4277$
$\overline{x}_8 = 72.65$	$\sigma_{x8} = 14.76$	$A_8 = 0.4130$

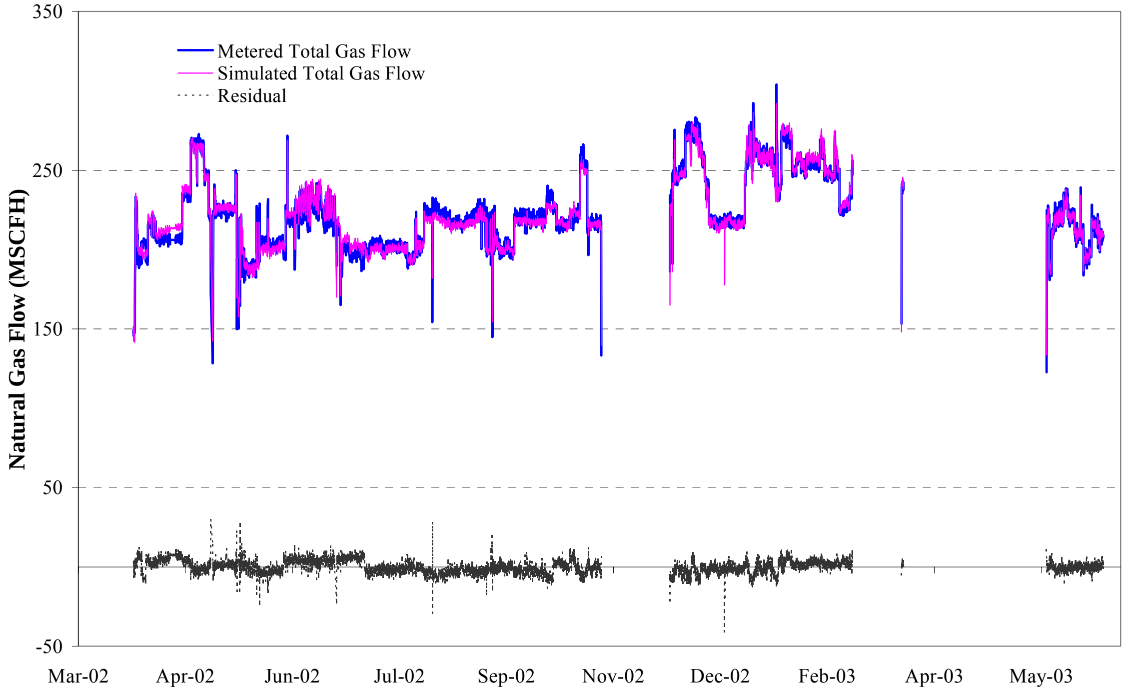


Figure 31 Comparison between metered and simulated GT6 and HRSG combined set natural gas flow.

The mean value and standard deviation of error are 0 and 4.19 respectively. The ratio between the RMSE of the error and the mean value is 1.9%. Figure 31 is a comparison between simulated and metered total gas flow.

- GT6 simulation model

Assume the gas flow is function of GT6 power output, and ambient temperature. Applying the method described in the next chapter. The GT6 model can be expressed as:

$$Q_2 = f\left(P, T_{oa}\right) = \left(\sum_{i=1}^{3} A_i X_i^{\ *}\right) \times \sigma_{Q2} + \overline{Q}_2 \tag{27}$$

The definitions of x_i and X_i^* are listed in TABLE 18. The values of $\overline{Q}_2$, σ_{Q2}, $\overline{x}_i$, σ_{xi} and A_i are provided in TABLE 19.

TABLE 18

Definitions of GT6 Simulation Model

$x_1 = P^2$	$X_1^* = \dfrac{x_1 - \overline{x}_1}{\sigma_{x1}}$
$x_2 = P$	$X_2^* = \dfrac{x_2 - \overline{x}_2}{\sigma_{x2}}$
$x_3 = T_{oa}$	$X_3^* = \dfrac{x_3 - \overline{x}_3}{\sigma_{x3}}$

TABLE 19

Coefficients of GT6 Simulation Model

$\overline{Q}_2 = 208.91$	$\sigma_{Q2} = 20.01$	
$\overline{x}_1 = 157{,}999{,}929.55$	$\sigma_{x1} = 54{,}407{,}373.03$	$A_1 = 1.1151$
$\overline{x}_2 = 12{,}365.97$	$\sigma_{x2} = 2069.61$	$A_2 = -0.0977$
$\overline{x}_3 = 72.65$	$\sigma_{x3} = 14.76$	$A_3 = 0.0749$

The mean value and standard deviation of error are 0 and 4.86 respectively. The ratio between the RMSE of the error and the mean value is 2.3%. Figure 32 is a comparison between simulated and metered gas turbine gas flow.

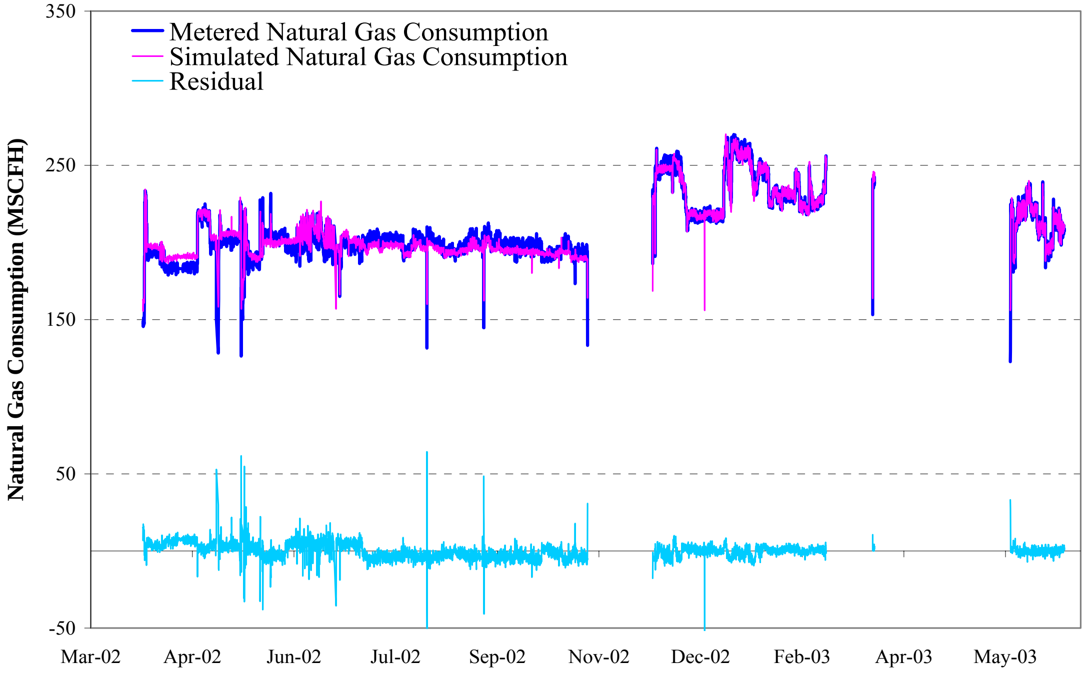


Figure 32 Comparison between metered and simulated GT6 natural gas consumption.

- Identifying of HRSG Operating Mode

Because the HRSG has a runner burner and a duct burner, whenever it is in supplementary-firing mode, its natural gas consumption will be at least 20 MSCFH. Therefore, the method to identify HRSG operating mode is to compare the simulated natural gas flow between the GT6 and the combined set. By try-and-error, it was found that when the difference between the simulated GT6 and combined set natural gas flow is less than 12 MSCFH, the HRSG is in recovery mode. Otherwise it is in supplementary mode. This can also be considered as the HRSG simulation model.

$$Q_{HRSG}=\begin{cases} 0 & \text{If } Q_1\text{-}Q_2 < 12 \text{ MSCFH. (Recovery mode)} \\ Q_1 - Q_2 & \text{If } Q_1\text{-}Q_2 >= 12 \text{ MSCFH. (Supplementary-firing mode)} \end{cases} \qquad (28)$$

When the HSRG is in supplementary-firing mode, by comparing the metered HRSG natural gas consumption and the simulated HRSG natural gas consumption, the mean value and standard deviation of error are found to be –0.19 and 2.28 respectively. The ratio between the RMSE of the error and the mean value of metered natural gas consumption is 16%. Figure 33 is a comparison between simulated and metered gas consumption for HRSG.

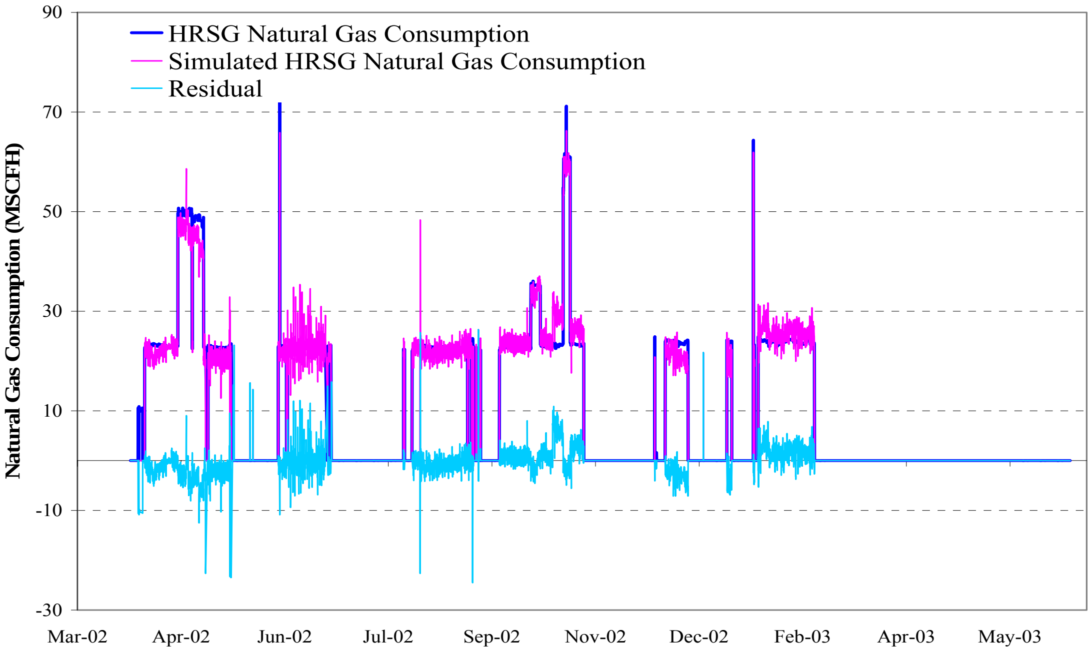


Figure 33 Comparison between metered and simulated HRSG natural gas consumption.

GT6 and HRSG simulation model verification

Figure 34 illustrates the comparison between GT6 metered and simulated gas consumption. From this diagram, the GT6 is mostly operated above 60% of its designed power output. Figure 35 is a scatter chart of HRSG steam production vs. GT #6 power output.

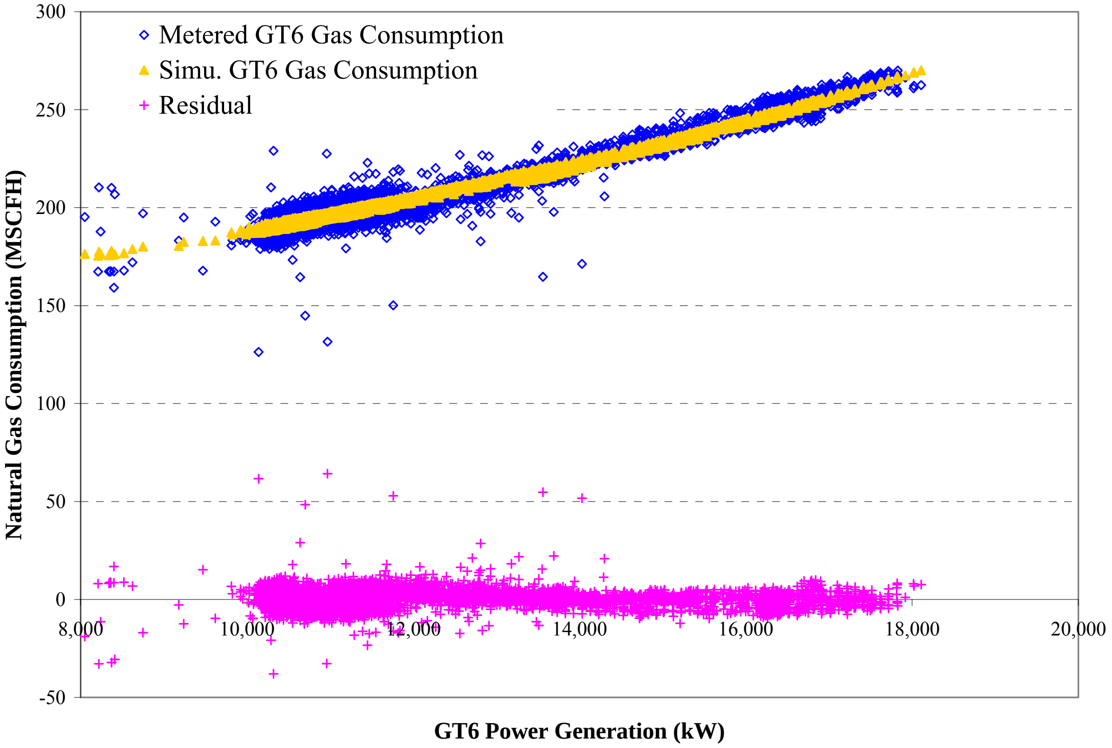


Figure 34 Relationship between gas consumption and power production of GT6.

Identification of Energy Saving Potentials

Because gas turbine combustor temperature is limited to about 2400-2500^{o}F for metallurgical reasons, a large amount of compressed air is used to cool the flame. In tern, not only increases the exhaust gas flow from the turbine, but also result in about 15-

18 vol% oxygen in the exhaust gas flow. The large amount of oxygen in the exhaust gas enables fuel to be fired without the addition of air. Supplementary-firing will raise the temperature of the entering gas stream prior to combustion.

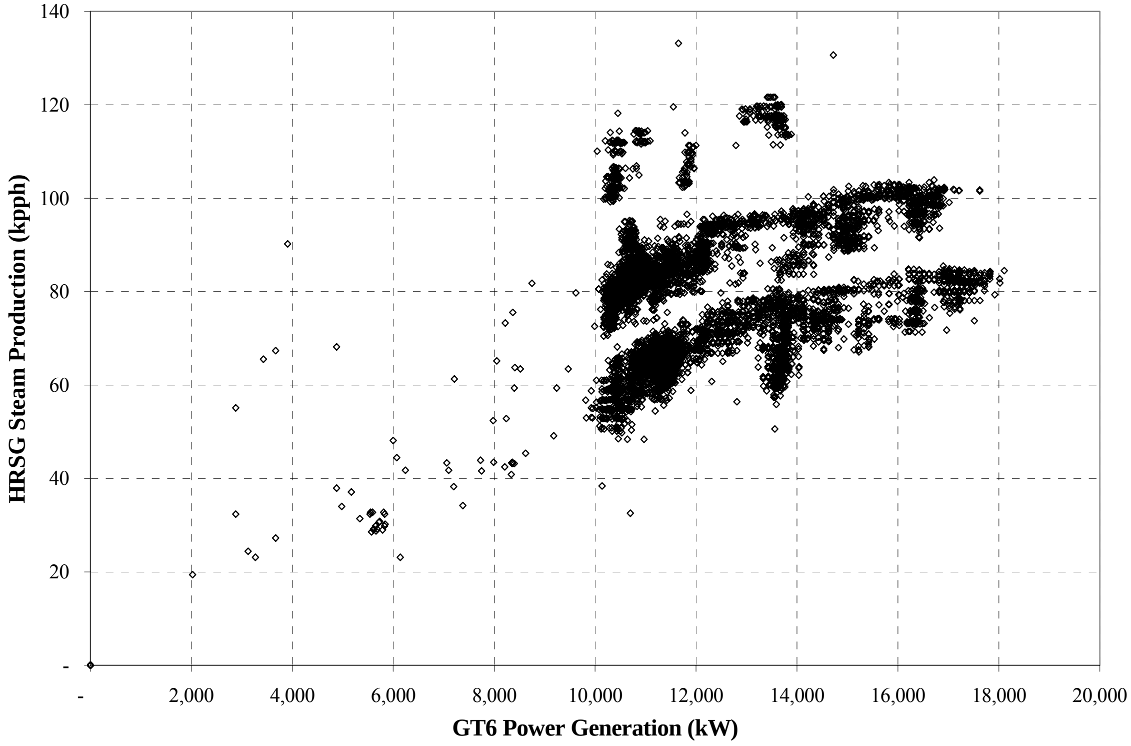


Figure 35 HRSG steam production vs. GT6 power generation.

The efficiency of the HRSG system improves with supplementary-firing. There are two reasons. The first reason is that the exhaust gas inlet temperature increases through supplementary-firing and it increases steam generation in HRSG as well. The addition of fuel reduces the effective excess air in the exhaust gases, because no air is added, only fuel. Hence, the exhaust gas loss in relation to the steam production is reduced. Another reason is that unlike conventional steam generator, the gas turbine exhaust gas flow does not vary much, the stack temperature of the HRSG decreases or remains constant, because of the increased flow of feed water in the economizer, which in turn offers a larger heat sink.

In this case, the highest furnace temperature of the HRSG is less than 1130°F (Figure 36). In fact, most of the time, the furnace temperature was less than 1000°F. According to the HRSG design, it can be operated continuously at a furnace temperature of 1400°F. There is energy saving potential here. Also, the maximum steam production of the HRSG in the past one and half years is about 133 kpph when it is fired at 76 MSCFH. Most of the time, the steam production is less than 100,000lb/hr (Figure 37). The design capacity of HRSG is 175 kpph. Therefore, there is plenty of capacity available for a higher firing rate.

Assume the CUP boilers' average efficiency is 80.94%, which is the average efficiency of BL9 and BL11 for the past one and half years. Assume the same power profile and outside air temperature profile. Assume the gas turbine works 8000 hours a year and the natural gas price is $4.50/MMBtu. Five different scenarios had been simulated. Each scenario assumes that the HRSG is operated in supplementary-firing mode for specified amount of natural gas. Because the total demand on 600# steam is the same in the plant, producing more steam by HRSG means that the BL9 and BL11 will produce less steam. The estimated average efficiency for supplementary-firing is 95.8% on a higher heating value basis. Using more efficient HRSG can result in less natural gas consumption, i.e. fuel savings.

TABLE 20 lists estimated fuel savings corresponding to the five operation scenarios.

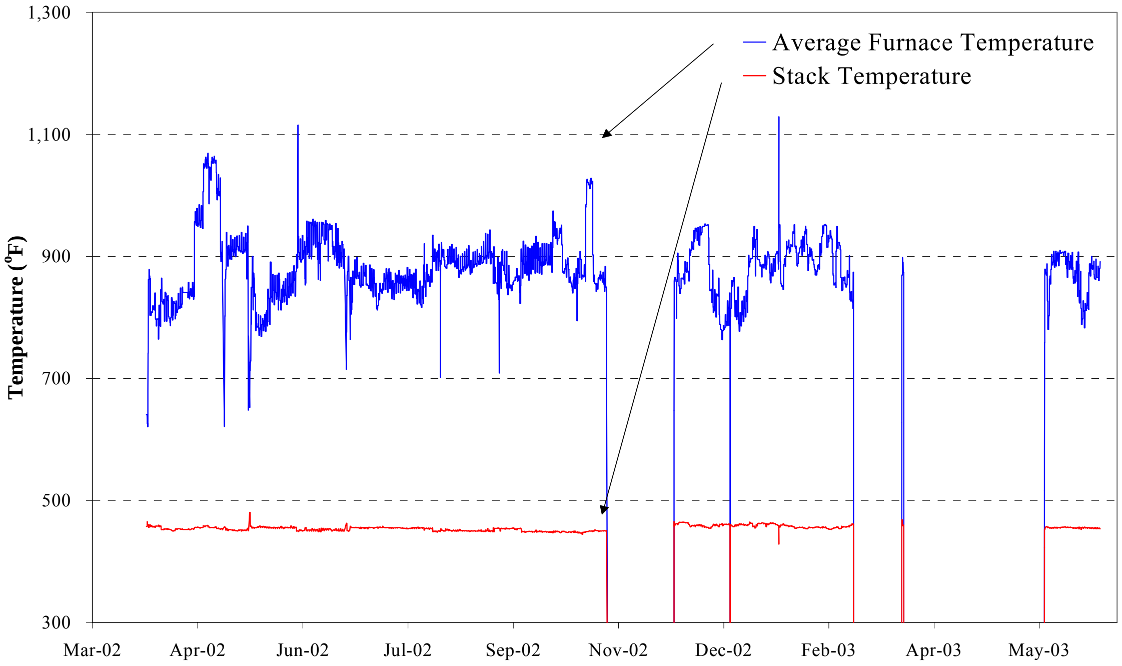


Figure 36 HRSG stack and average furnace temperature time series.

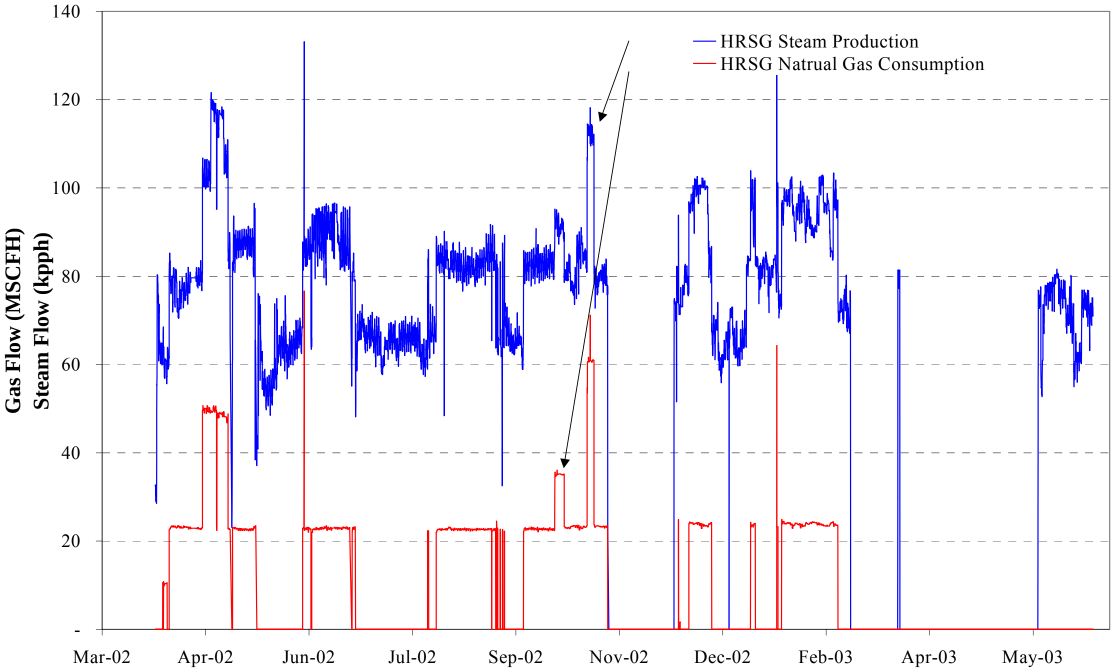


Figure 37 HRSG gas consumption and steam production time series.

TABLE 20

Estimated Fuel Savings for Various Operation Scenarios

Scenario	HRSG Natural Gas Consumption (MSCFH)	Annual HRSG Gas Consumption (MSCF)	Steam Production (klb)	Estimated Annual Savings ($)	Maximum Steam Flow (kpph)
1	60	480,000	962,139	$312,632	140
2	70	560,000	1,033,301	$380,596	149
3	80	640,000	1,104,450	$448,546	158
4	90	720,000	1,175,605	$516,503	167
5	99	792,000	1,239,645	$577,664	175

Conclusion and Recommendations

- Since supplementary-firing is the most efficient way to produce additional steam, it is recommended to load the supplementary burner as high as possible, whenever the gas turbine is in operation.
- For the TAMU gas turbine #6 and HRSG combined set, the estimated average efficiency for supplementary-firing is 95.8% on a higher heating value basis.
- The maximum fuel saving potential for the HRSG is estimated to be $577,000 per year, assuming GT6 operates 8000 hours a year and HRSG burner natural gas flow is 99MSCFH.
- It is recommended to conduct a test to determine the HRSG's upper firing limit, since it has never been operated beyond 75mscfh. It is necessary to know how much more capacity this HRSG has available.

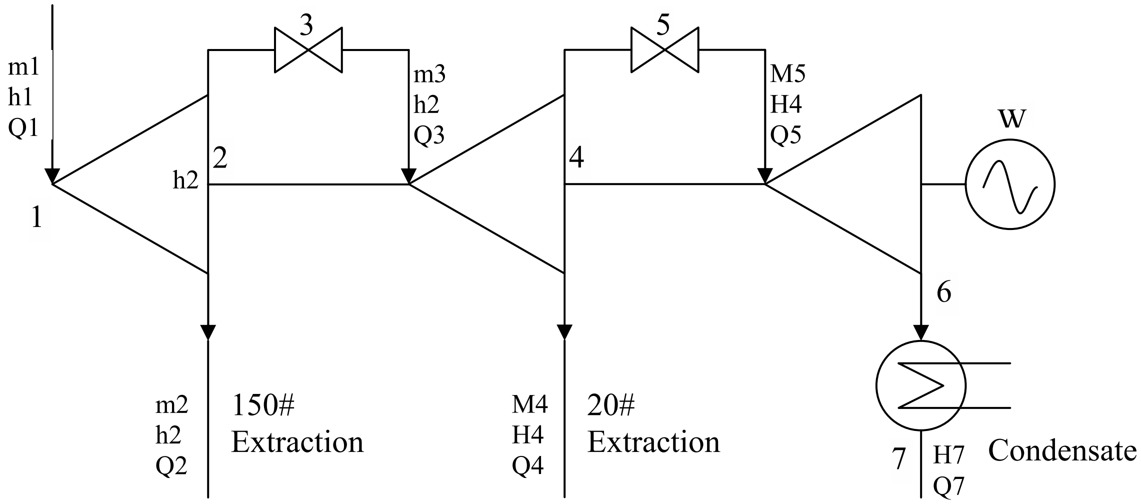
CHAPTER X

STEAM TURBINE SIMULATION MODEL CONSTRUCTION AND ANALYSIS

Chapter Summary

The objective of this chapter is to provide a multiple-regression method for constructing simulation models by using basic statistics and optimization algorithms. The least squares criterion is used as the object function to determine the optimized simulation model. The optimization code used is the Generalized Reduced Gradient (GRG2) nonlinear optimization, which is built into MS EXCEL®. Steam turbine generator #5 is used as an example to demonstrate the procedures for constructing an optimized simulation model. The simulation model identified has zero mean bias error and the RMSE is 4.64 and 2.9% of the mean value of the throttle steam flow. The metered throttle steam flow and simulated throttle steam flow match each other very closely. STG5 usually produces 7 to 13 MW of electric power over its operating range,. Its efficiency is about 25% to 35% with higher efficiency corresponding to higher rates of extraction steam flow. Comparison as of actual operating performance and design performance shows there are significant differences between the two. At a 12 MW load, the average throttle steam flow is 190 kpph, while the design curves suggest 160 kpph. Accordingly, the efficiency of metered operation is 30%, while the design performance indicates 40%. An engineer should be cautious about relying too heavily upon the design curves. The application of normalized variables can measure the relative contribution of each of the variables, thus providing a way to build a simpler simulation model.

Equipment Description



1: throttle steam (662F, 598psig)
2: 150# extraction steam (150psig)
3: to second stage turbine
4: 20# extraction steam (20psig)
5: to third stage turbine
6: exhaust steam
7: condenser outlet

Figure 38 STG5 structure diagram.

Steam turbine generator #5 in the CUP is a double-automatic-extraction condensing turbine generator. It utilizes steam as the working substance and has a power generation capacity of 12.5MW. Figure 38 shows a schematic of steam flow in STG5. The whole process is divided into three stages of expansion. The high pressure, high temperature steam (600 psig) enters the turbine (status 1) and expands in the first stage. At the end of the first stage turbine (status 2) part of the steam is extracted (at 150 psig) while the rest flows (status 3) into the second stage turbine for further expansion. At the end of the second stage turbine (status 4), part of the steam is extracted yet again (at 20 psig), and then the rest of the steam flows (status 5) through the last turbine into the condenser (status 6), and leaves the condenser as condensate (at status 7). The central issue of the turbine model is to estimate throttle steam flow based on the known power production and the extraction steam flow, m_4. Since the 150# steam extraction valve was shut for many years and there is no expectation it will be used in the future, steam generator #5 is equivalent to a two-stage turbine generator. For simplicity, the STG5 was considered a two stage turbine generator in the remainder part of this chapter, the first two stage turbines will be referred as the first stage turbine, and the last stage turbine of STG5 will be called the second stage turbine.

Procedures to Construct Simulation Model for Steam Turbine Generator

Zhou (1997) studied the original EOP model and proposed a method for the STG4. He suggested that the relationship between throttle steam flow, m_1 and turbine power production, W, is in the form of $m_1 = C_1 \times W + C_2 \times m_2$, where m_2 is extraction steam flow, C_1 and C_2 are constant coefficients. However, he did not mention how to obtain both C_1 and C_2 and what their values might be.

A different method and a different model are proposed here. STG5 is used as an example to demonstration how to use statistics and optimization algorithms to construct a simulation model. The procedures developed here could be used to study other equipment as well.

Assume the STG5 throttle steam flow, m_1, is a function of its power output, P, and extraction steam flow, m_4. Assume that the underlying relationship is at least “well behaved" to the extent that it has a Taylor series expansion and that the first few terms of this expansion will yield a fairly good approximation. Thus the data can be fit to a polynomial, that is, a prediction equation of the form shown below.

$$m_1 = a \times P^2 + b \times P \times m_4 + c \times m_4^2 + d \times P + e \times m_4 + f + \varepsilon \tag{29}$$

In order to apply the multiple-regression method (Miller and Freund 1977), equation (29) can be viewed as a linear equation with multiple variables in the form of equation (30) below.

$$m_1 = a \times x_1 + b \times x_2 + c \times x_3 + d \times x_4 + e \times x_5 + f + \varepsilon \tag{30}$$

Where

$$\begin{aligned} x_1 &= P^2 \\ x_2 &= P \times m_4 \\ x_3 &= m_4^2 \\ x_4 &= P \\ x_5 &= m_4 \end{aligned}$$

Though these variables are related to each other, for mathematical purposes, they are treated independently. From a statistical point of view, though there are enormous amounts of metered data, they must be considered to be nothing more than a group of sample data. Then the conception of normalization can be introduced here. We can define equation (31) to normalize all the variables:

$$X^* = \frac{x - \bar{x}}{\sigma_x} \tag{31}$$

where:

$\bar{x}$ - mean value of x

σ_x - standard deviation of x.

Then equation (30) can be rewritten as equation (32) and equation (33):

$$M_1^* = a \times X_1^* + b \times X_2^* + c \times X_3^* + d \times X_4^* + e \times X_5^* \tag{32}$$

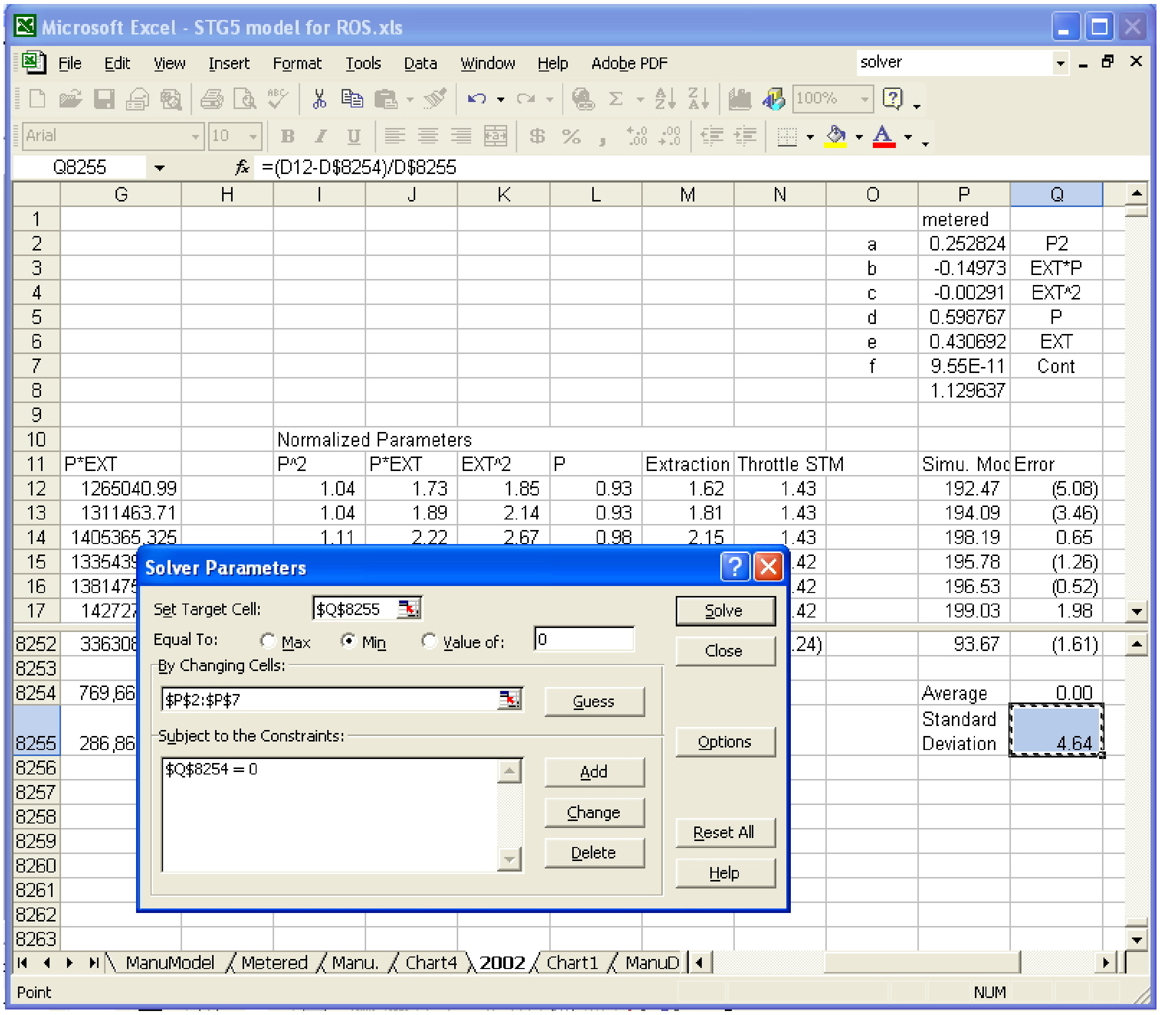
$$m_1 = M_1^* \times \sigma_{m1} + \overline{m}_1 + \varepsilon \tag{33}$$

Equation (32) is the normalized simulation model for STG5. Equation (33) is the final simulation model for STG5. It also carries an error, which has zero mean value. The benefit of normalization is that all the variables are dimensionless and on the same scale. Therefore, the estimators for a, b, c, d, and e will be able to indicate the relative contributions of each of the variables. This is very useful feature when it comes to determining what the simulation model will look like.

For n sets of observations (P_i , m_{4i} , m_{1i}), there are "n" corresponding sets of error ε_i . Since we cannot minimize each of the ε_i values individually, one approach we might try is to make the mean value of ε_i to zero and minimize the standard deviation of the ε_i. In other words, we shall choose a, b, c, d, and e so that the standard deviation of the errors, σ_ε, which is defined in equation (34) is minimum.

$$\begin{aligned}\sigma_\varepsilon &= \sqrt{\frac{\sum_{i=1}^{n} \varepsilon_i^2}{n-1}} \\ &= \sqrt{\frac{\sum_{i=1}^{n} \left[(m_{1i} - \overline{m}_1) - \left(a \times X_1^* + b \times X_2^* + c \times X_3^* + d \times X_4^* + e \times X_5^* \right) \times \sigma_{m1} \right]^2}{n-1}}\end{aligned} \tag{34}$$

This criterion is called the criterion of least squares. The Gauss-Markov theorem states that among all linear unbiased estimators for a, b, c, d, and e, the least squares estimators have the smallest variance. Instead of using complicated matrix calculation procedures, MS Solver® was used to find the least squares estimators, i.e. the optimized estimators.



Q8255 =(D12-D$8254)/D$8255

	G	H	I	J	K	L	M	N	O	P	Q
1										metered	
2									a	0.252824	P2
3									b	-0.14973	EXT*P
4									c	-0.00291	EXT^2
5									d	0.598767	P
6									e	0.430692	EXT
7									f	9.55E-11	Cont
8										1.129637	
9											
10			Normalized Parameters								
11	P*EXT		P^2	P*EXT	EXT^2	P	Extraction	Throttle STM		Simu. Moc	Error
12	1265040.99		1.04	1.73	1.85	0.93	1.62	1.43		192.47	(5.08)
13	1311463.71		1.04	1.89	2.14	0.93	1.81	1.43		194.09	(3.46)
14	1405365.325		1.11	2.22	2.67	0.98	2.15	1.43		198.19	0.65
15	1335439							.42		195.78	(1.26)
16	1381475							.42		196.53	(0.52)
17	142727							.42		199.03	1.98
8252	336308							.24)		93.67	(1.61)
8253											
8254	769,66									Average	0.00
8255	286,86									Standard Deviation	4.64

Set Target Cell: $Q$8255

Equal To: ○ Max ● Min ○ Value of: 0

By Changing Cells: $P$2:$P$7

Subject to the Constraints: $Q$8254 = 0

Figure 39 Using solver to find least-squares estimators in EXCEL.

Microsoft Excel Solver® uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code developed by Leon Lasdon of the University of Texas at Austin, and Allan Waren of Cleveland State University. Figure 39 is an illustration of the Solver's® interface. Lee (2002) noted that model optimization researchers have been using this tool in various fields, such as the process engineering, finance, mathematics, and so forth.

Identified STG5 Simulation Model

Applying the method described above, the STG5 model is found to be:

$$m_1 = f(P, m_4) = \left(a \times X_1^* + b \times X_2^* + c \times X_3^* + d \times X_4^* + e \times X_5^*\right) \times \sigma_{m1} + \overline{m}_1 \tag{35}$$

The definitions of x_i and X_i^* are listed in TABLE 21. The values of $\overline{m}_1$, σ_{m1}, $\overline{x}_i$, σ_{xi}, a, b, c, d and e are provided in TABLE 22.

TABLE 21

Definitions of STG5 Simulation Model

$x_1 = P^2$	$X_1^* = \frac{x_1 - \overline{x}_1}{\sigma_{x1}}$
$x_2 = P \times m_4$	$X_2^* = \frac{x_2 - \overline{x}_2}{\sigma_{x2}}$
$x_3 = m_4^2$	$X_3^* = \frac{x_3 - \overline{x}_3}{\sigma_{x3}}$
$x_4 = P$	$X_4^* = \frac{x_4 - \overline{x}_4}{\sigma_{x4}}$
$x_5 = m_4$	$X_5^* = \frac{x_5 - \overline{x}_5}{\sigma_{x5}}$

TABLE 22

Coefficients of STG5 Simulation Model

$\overline{m}_1 = 157.60$	$\sigma_{m1} = 27.83$	
$\overline{x}_1 = 112{,}069{,}165$	$\sigma_{x1} = 34{,}171{,}794$	a = 0.25282
$\overline{x}_2 = 769{,}664.42$	$\sigma_{x2} = 286{,}863.92$	b = -0.14973
$\overline{x}_3 = 5{,}593.76$	$\sigma_{x3} = 2{,}833.84$	c = -0.00291
$\overline{x}_4 = 10{,}421.69$	$\sigma_{x4} = 1{,}859.53$	d = 0.59877
$\overline{x}_5 = 72.13$	$\sigma_{x5} = 19.76$	e = 0.43069

The mean value and standard deviation of error are 0 and 4.64 respectively. Since the mean error is zero, the standard deviation and root mean square error (RMSE) are equivalent to each other. But this set of estimators is guaranteed to have minimal RMSE. The ratio between the RMSE of the error and the mean value of throttle steam is 2.9%. Figure 40 illustrates the simulated STG5 throttle steam flow under different power output and extraction flow. Figure 41 illustrates the metered STG5 throttle steam flow under the same power output and extraction flow. Note that the relative contribution of the square of steam extraction flow is only 0.3%. Hence the simulation model could be further simplified by removing the second order term of the steam extraction flow.

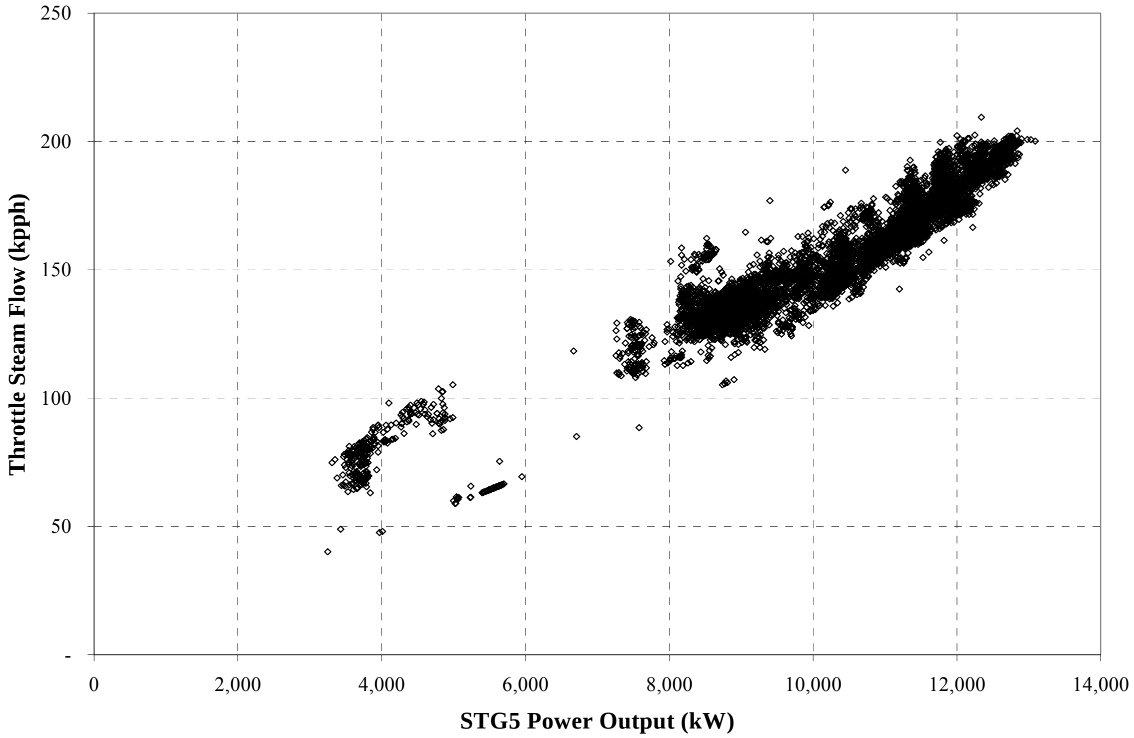


Figure 40 Simulated STG5 throttle steam flow vs. power output.

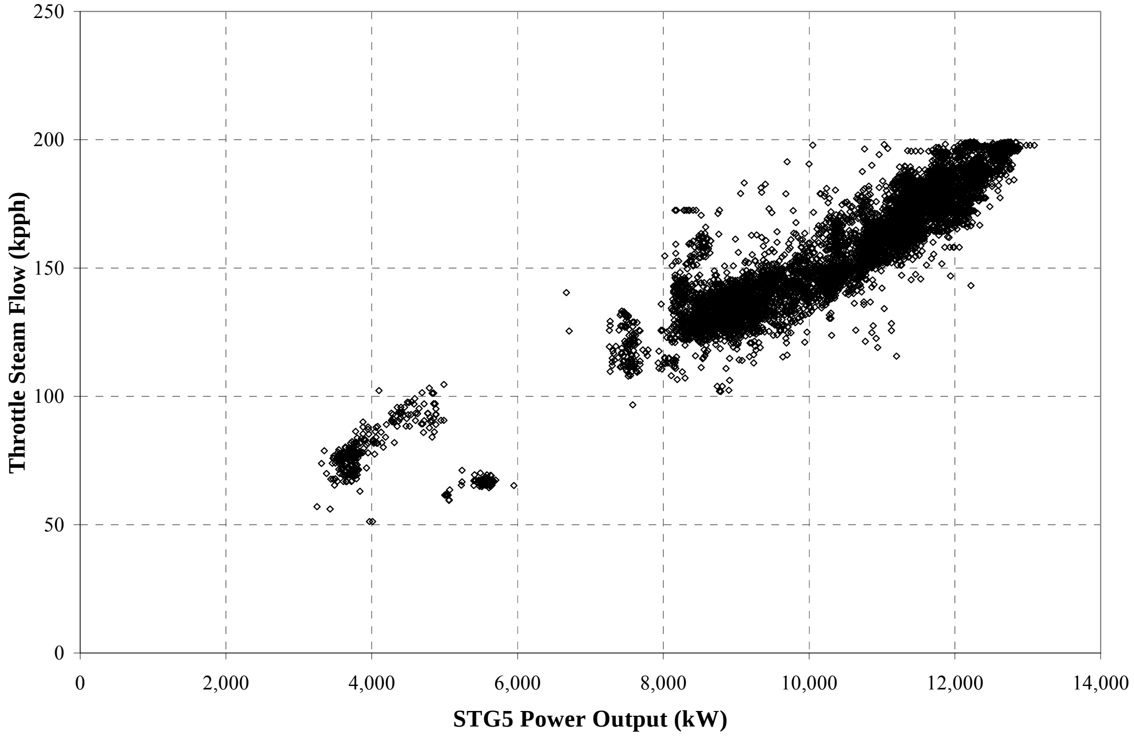


Figure 41 Metered STG5 throttle steam flow vs. power output.

Determination of Turbine Efficiency

Assume the overall efficiency of STG5 is η. The overall turbine efficiency can be calculated as:

$$\eta = \frac{P}{m_1 \times (H_1 - H_7) - m_4 \times \left(H_4 - H_7\right)} \tag{36}$$

Where P is power output, H_1 is the enthalpy of the throttle steam, H_4 is the enthalpy of extraction steam and H_7 is the enthalpy of condensate. Figure 42 illustrates the STG5 overall efficiency under different power output and extraction flow. The general operating range of STG5 is between 7 and 13 MW, though occasionally we see about 4 MW. The efficiency is between 20% and 50%.

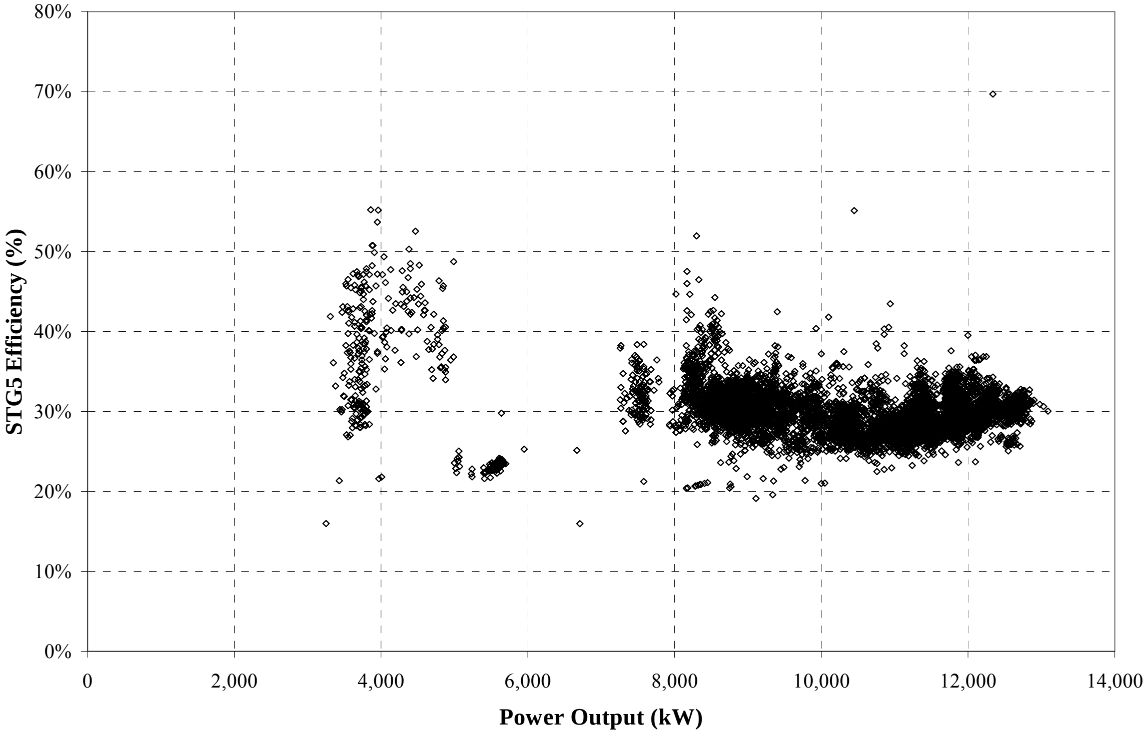


Figure 42 Metered STG5 power generation efficiency.

Figure 43 shows the relationship among efficiency, power output and extraction steam flow. When there is no extraction, the efficiency is about 19% and it does not change much with power. Under constant power output, increased extraction steam yields higher efficiency. Under constant extraction flow, higher power output results in lower steam turbine efficiency. Note: in operation, this steam turbine generator is usually operated with extraction. Therefore no significant operation at 20% efficiency is observed in Figure 42.

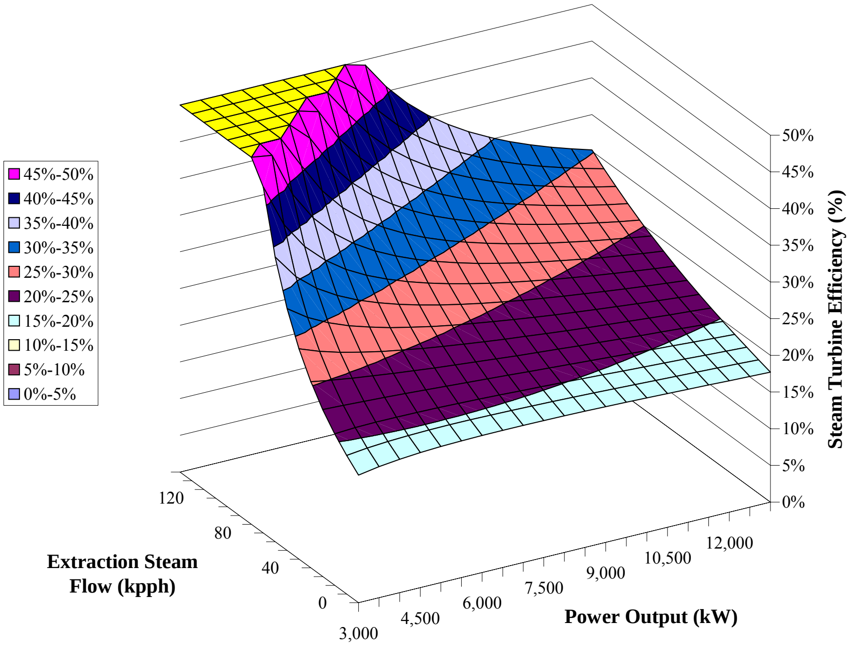


Figure 43 Impact of power and extraction on turbine efficiency.

Comparison between STG5 Design Performance and Metered Performance

Knowing the actual performance of every piece of equipment is critical to engineers and facility management. Using field test data for a single moment or writing down the numbers on a piece of paper for short periods of time would not tell much about potential differences. Most of the time, the engineers rely on their experience or manufacturer provided performance curves. But the question is how much an engineer can trust the performance curves. A simulation model based on design curves (Figure 53 on page 143) was constructed and used to make comparison with the actual operating performance.

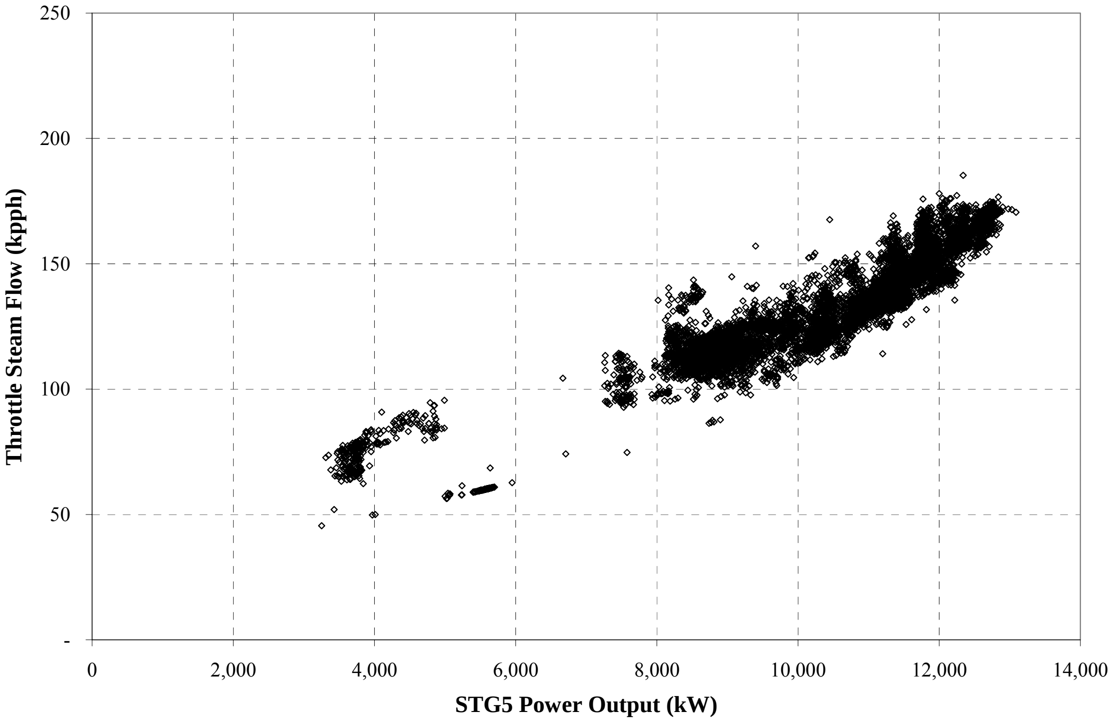


Figure 44 STG5 design throttle steam flow vs. power output.

Figure 41 and Figure 44 show that the difference between design performance and metered performance is quite significant for STG5. Under the same power output and extraction steam flow, the required throttle steam flow is much larger than design performance. This indicates lower than design steam turbine efficiency. When the STG5 power load is 12 MW, the average throttle steam is about 190 kpph, while the design performance suggests 160 kpph.

Conclusions

A method based on statistics and optimization has been presented. The basic assumption is that the underlying relationship is at least "well behaved" to the extent that it has a Taylor series expansion and that the first few terms of this expansion will yield a fairly good approximation. Steam turbine generator #5 is used as an example to demonstrate the procedure. The normalized variables make it possible to measure the relative contribution of each of the variables, enabling further reduction in the complexity of the simulation model without affecting the model performance.

Since the method applies the criterion of least squares, the final simulation model has the smallest variances for a given set of estimators. In other words, the simulation model has the smallest RMSE provided that the mean value of error is zero. Instead of a complicated matrix calculation, the Generalized Reduced Gradient (GRG2) nonlinear optimization code built into MS EXCEL Solver® was used as the optimization algorithm.

Based on 2002 data, the optimized STG5 simulation has zero mean error and the RMSE is 4.64, only 2.9% of average throttle steam flow. The simulated and metered results match very well. Over its operating range, STG5 usually produces 7 to 13 MW of electric power. Its efficiency is about 25% to 35%. Its efficiency increases, when its extraction steam flow increases.

The difference between design performance and metered performance was also studied. It was found that under the same power load and extraction steam flow, the metered throttle steam flow could be quite different from that indicated by the design curves. At 12 MW load, the average throttle steam flow is 190 kpph, while the design curves say 160 kpph. Additionally, the efficiency of metered operation is 30%, while the design performance indicates 40%. An engineer should be cautious about the design curves.

CHAPTER XI

SUMMARY

The selection of ESL was an excellent decision because it allowed the author to utilize his diversified knowledge base in real engineering applications. ESL offered the author an outstanding opportunity to experience the successful operation of a leading research and engineering organization in the country. Furthermore, the position also provided a continuous intellectual stimulus such that the author never experienced boredom. Each project and deliverables is different from each other and is a challenge. All the practices allowed the author to realize his limits and shortcomings, the author has the will and the determination to accomplish improvement by studying and practice. The author also realizes that after all the years of studying and training, he had obtained skills and knowledge to get things done.

Overall, the above experience contributed significantly to the objectives of the Doctor of Engineering program and provided the author with an opportunity to develop a wide range of knowledge, both technical and non-technical. The result is that the author knows how to complete a project from start to finish and understands how both technical and non-technical aspects of a project need to be considered in order to ensure a quality deliverable and bring a project to successful completion. All the projects cannot be done by one or two persons' efforts. It is the contribution from the whole team, from the line manager and other team member. During these projects, the author learned how to work in a team, how to do things properly and to manage time more efficiently, how to resolve conflicts and different opinions within the team and how to respect others' opinions.

This report concludes that the objectives of the Doctor of Engineering program were successfully accomplished and that the requirements for the degree of Degree of Engineering have been satisfied.

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APPENDIX

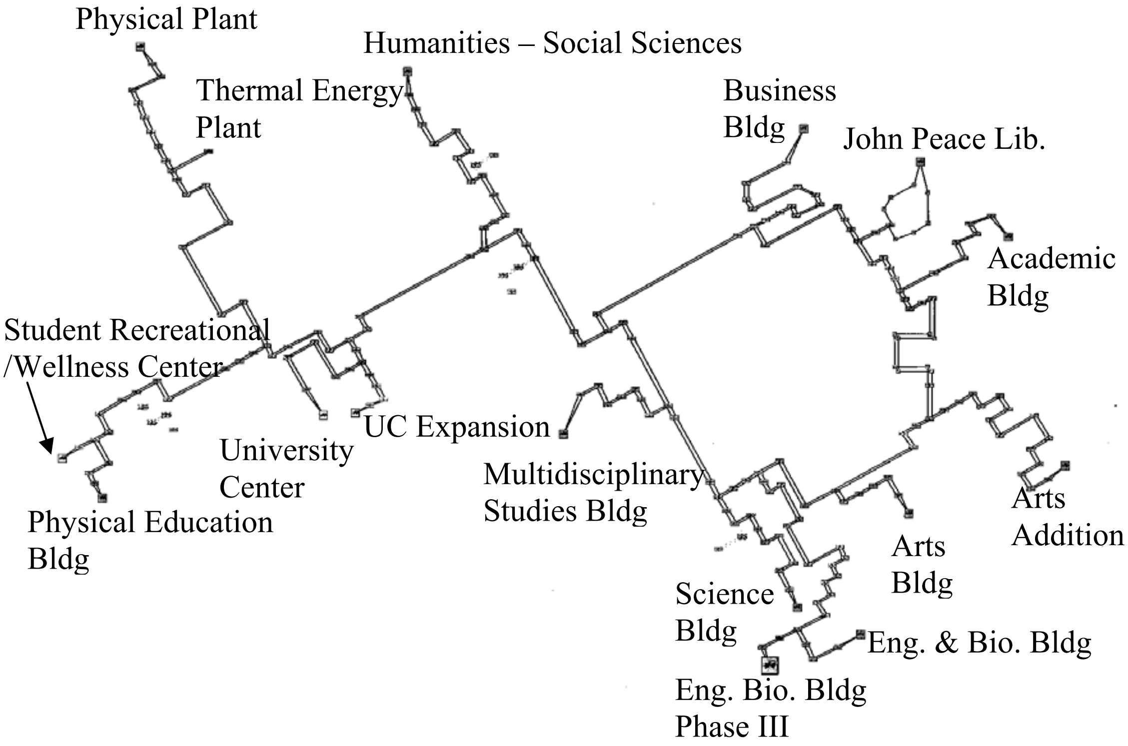


Figure 45 Scenario 1 for USTA 1604 campus CHW system expansion.

This scenario explores the possible pressure distribution if the piping system is simply extended from the current Engineering and Biosciences Building.

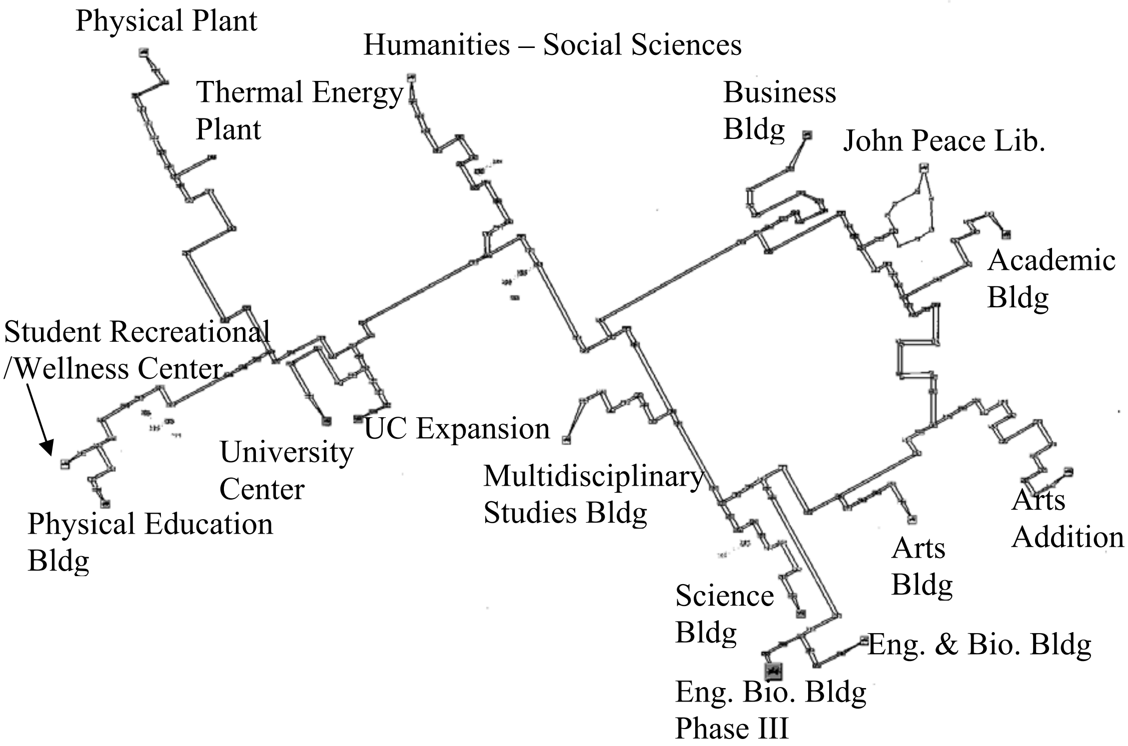


Figure 46 Scenario 2 for USTA 1604 campus CHW system expansion.

Since the combined flow of both the current Engineering and Biosciences Building and future Engineering Bioscience Building Phase III will be more than 3000 GPM, which is almost the capacity of the current 12” pipe which supplies chilled water to the current Engineering and Biosciences Building. There are also a lot of elbows on this branch. It is reasonable to study the outcome, if a larger pipe replaces that branch. In this scenario a 16” 180 feet long pipe is used to replace the current pipe.

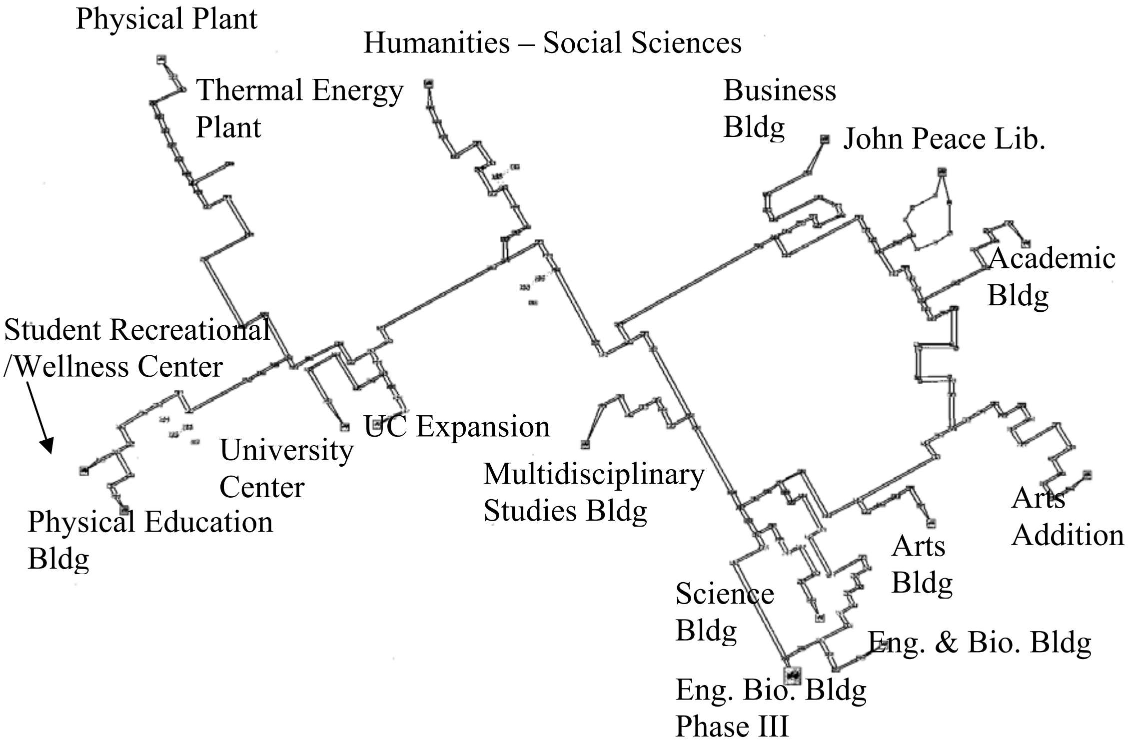


Figure 47 Scenario 3 for USTA 1604 campus CHW system expansion.

According to the field survey, there is a capped end of pipe beneath the Science Building. This design takes advantage of that capped end. A 12” pipe is designed to replace it and connect the future Engineering Bioscience Building Phase III. This newly added pipe would join the pipe extended from the current Engineering and Biosciences Building. This will result in a small circular pipe structure. This added pipe is estimated to be about 170 feet long.

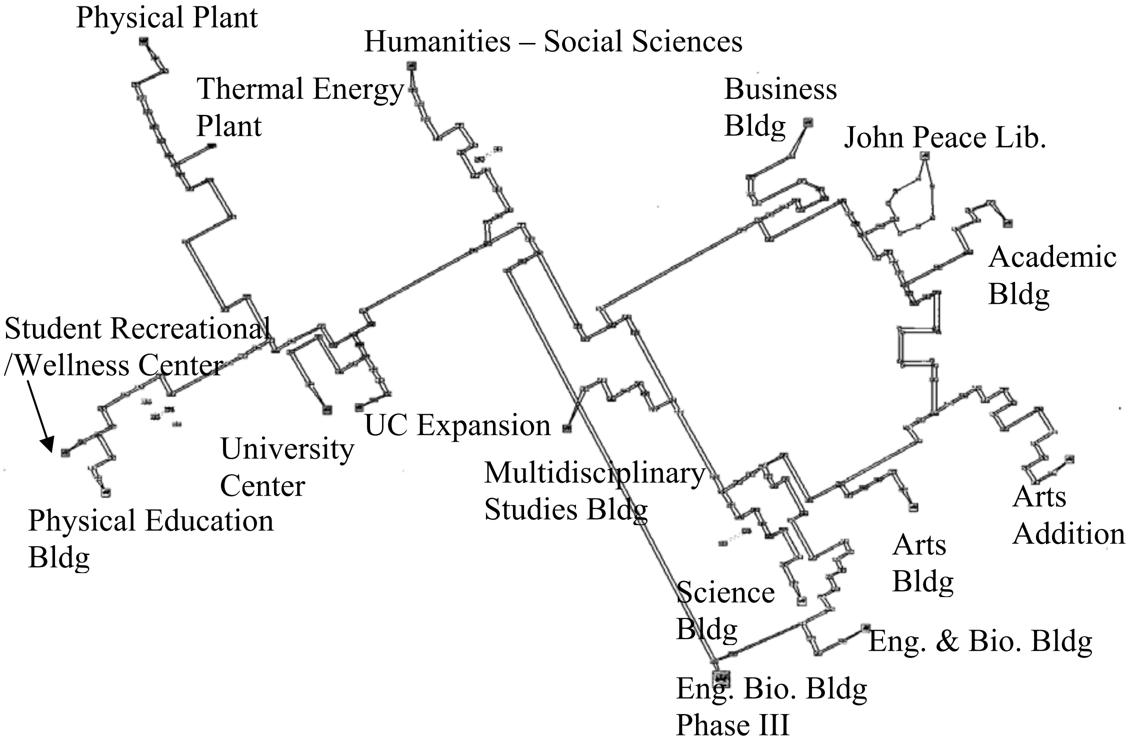


Figure 48 Scenario 4 for USTA 1604 campus CHW system expansion.

There is a capped pipe beneath the Humanities - Social Sciences Building. This scenario takes advantage of that capped end. A 12” pipe is designed to replace it and connect the future Engineering Bioscience Building Phase III. This pipe will go along with the underground tunnel and then join the pipe extended from the current Engineering and Biosciences Building. This will result in a circular structure as well. And the chilled water supply of the future Engineering and Biosciences Building will be from both places. This added pipe is estimated to be about 700 feet long.

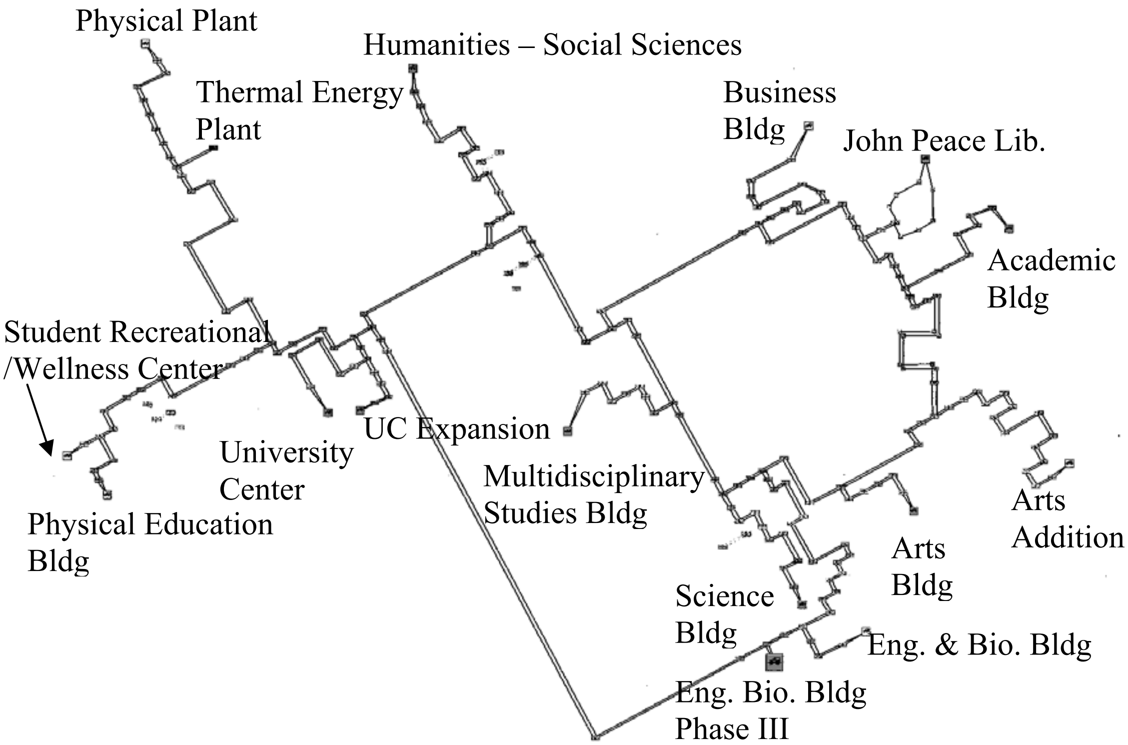


Figure 49 Scenario 5 for USTA 1604 campus CHW system expansion.

This design assumes that a 14" pipe connects the future Engineering Bioscience Building Phase III and the main pipe beneath the University Center Expansion. The underground pipe goes along the underground tunnel. The length of this pipe is estimated to be about 1000 feet.

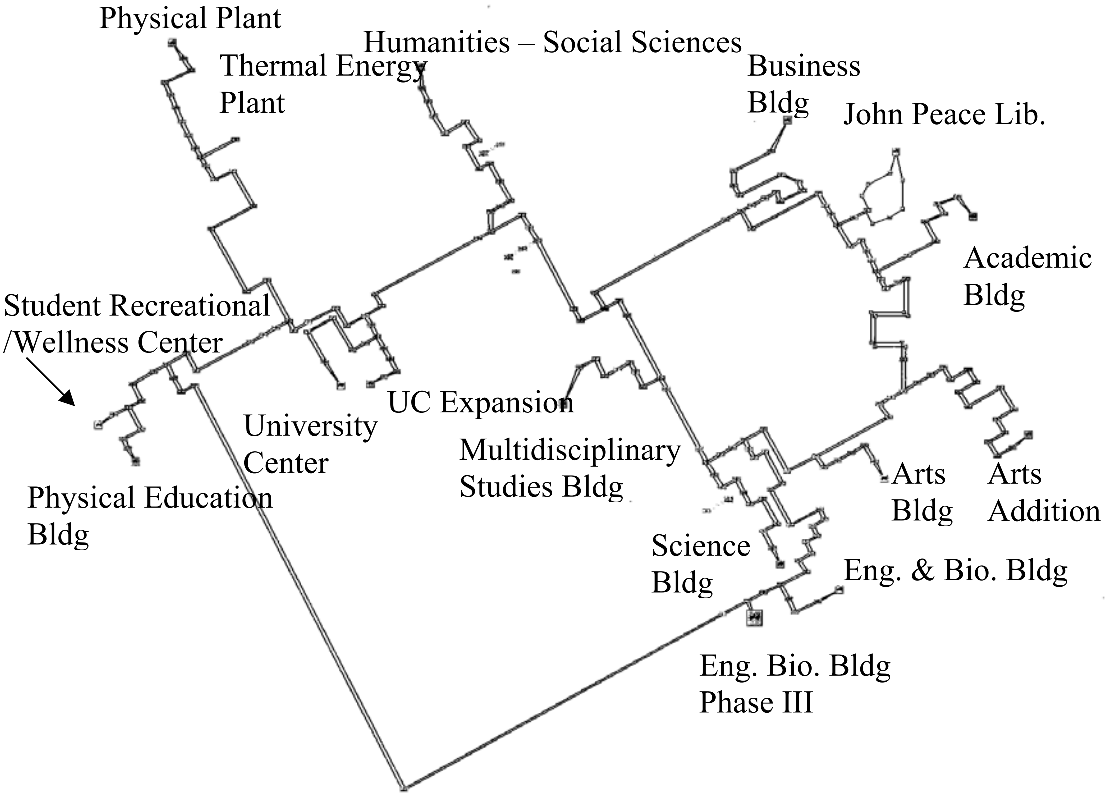
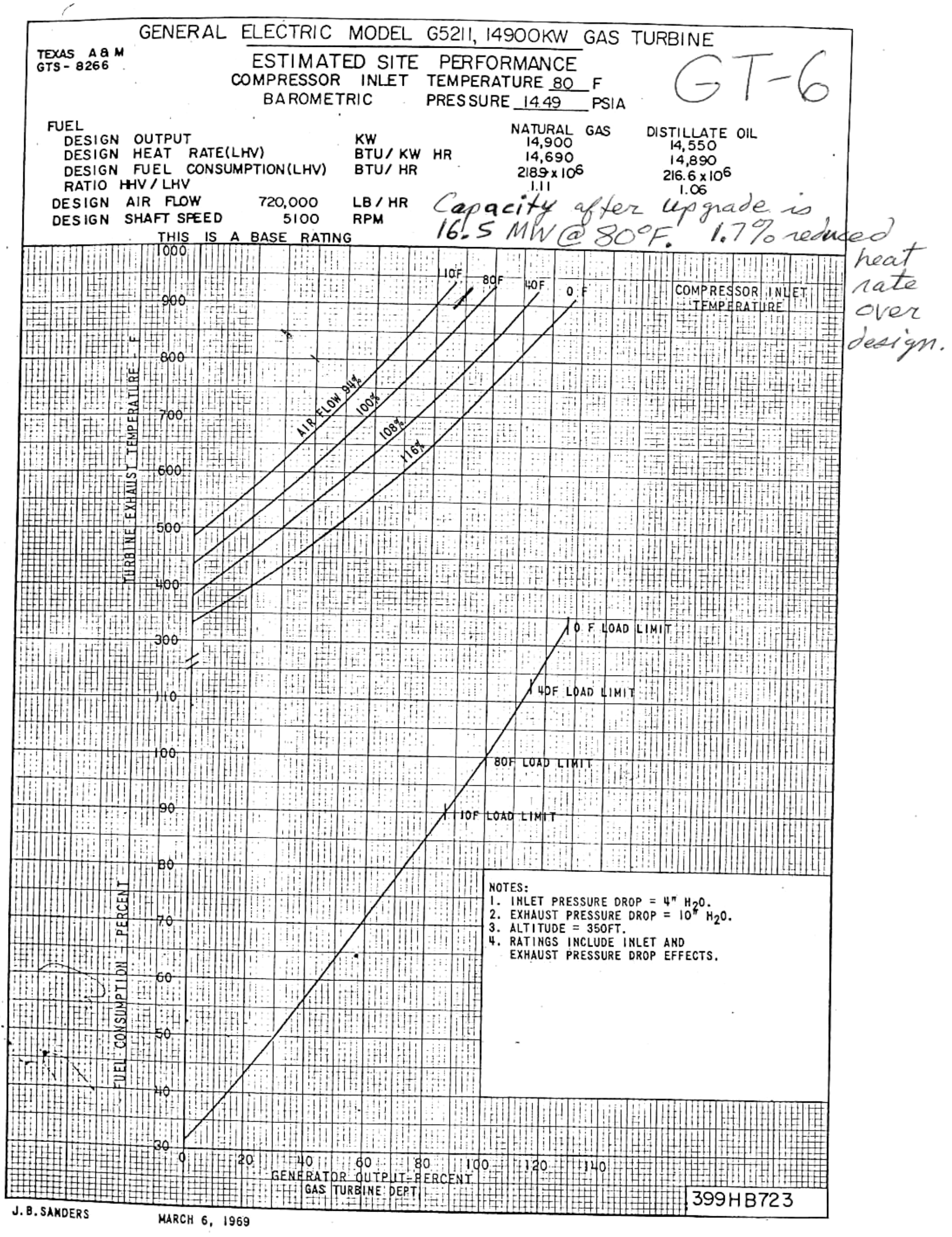


Figure 50 Scenario 6 for USTA 1604 campus CHW system expansion.

This scenario takes advantage of the underground tunnel between the Physical Education Building and the University Center. A 14” pipe is modeled to connect the future tunnel extension mentioned above and the future Engineering Bioscience Building Phase III. The underground pipe goes southeast first and turns northeast toward the future Engineering Bioscience Building Phase III. There are no buildings above the ground. The length of this pipe is estimated to be about 1500 feet.



GENERAL ELECTRIC MODEL G5211, 14900KW GAS TURBINE

TEXAS A & M
GTS - 8266

ESTIMATED SITE PERFORMANCE
COMPRESSOR INLET TEMPERATURE 80 F
BAROMETRIC PRESSURE 14.49 PSIA

GT-6

FUEL

		NATURAL GAS	DISTILLATE OIL
DESIGN OUTPUT	KW	14,900	14,550
DESIGN HEAT RATE(LHV)	BTU/KW HR	14,690	14,890
DESIGN FUEL CONSUMPTION(LHV)	BTU/HR	218.9 x 10^6	216.6 x 10^6
RATIO HHV/LHV		1.11	1.06

DESIGN AIR FLOW 720,000 LB/HR
DESIGN SHAFT SPEED 5100 RPM
THIS IS A BASE RATING

Capacity after upgrade is 16.5 MW @ 80°F. 1.7% reduced heat rate over design.

NOTES:
1. INLET PRESSURE DROP = 4" H_2O.
2. EXHAUST PRESSURE DROP = 10" H_2O.
3. ALTITUDE = 350FT.
4. RATINGS INCLUDE INLET AND EXHAUST PRESSURE DROP EFFECTS.

GAS TURBINE DEPT.
399HB723

J. B. SANDERS
MARCH 6, 1969

Figure 51 General Electric Model G5211 performance curves (I).

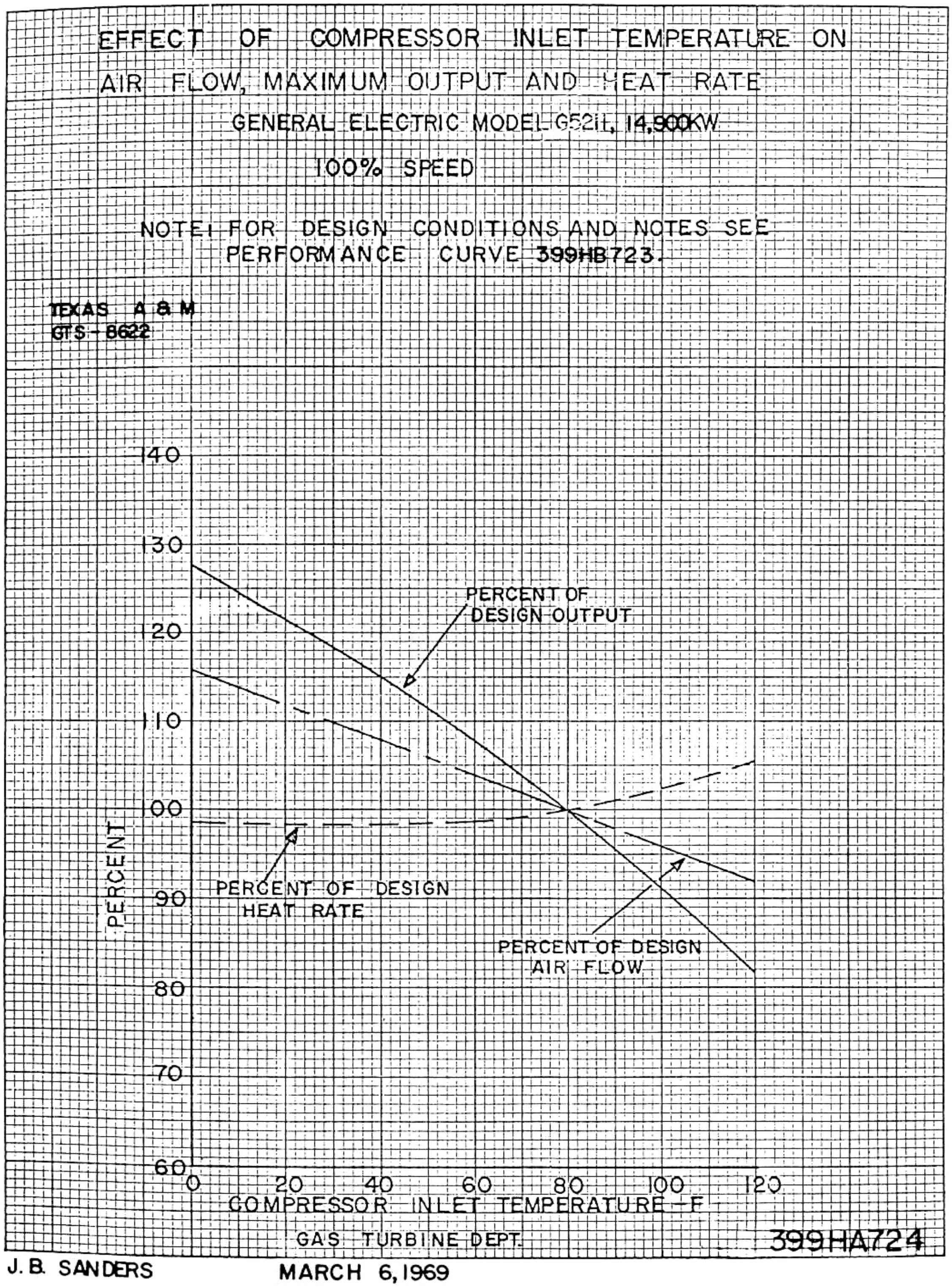


Figure 52 General Electric Model G5211 performance curves (II).

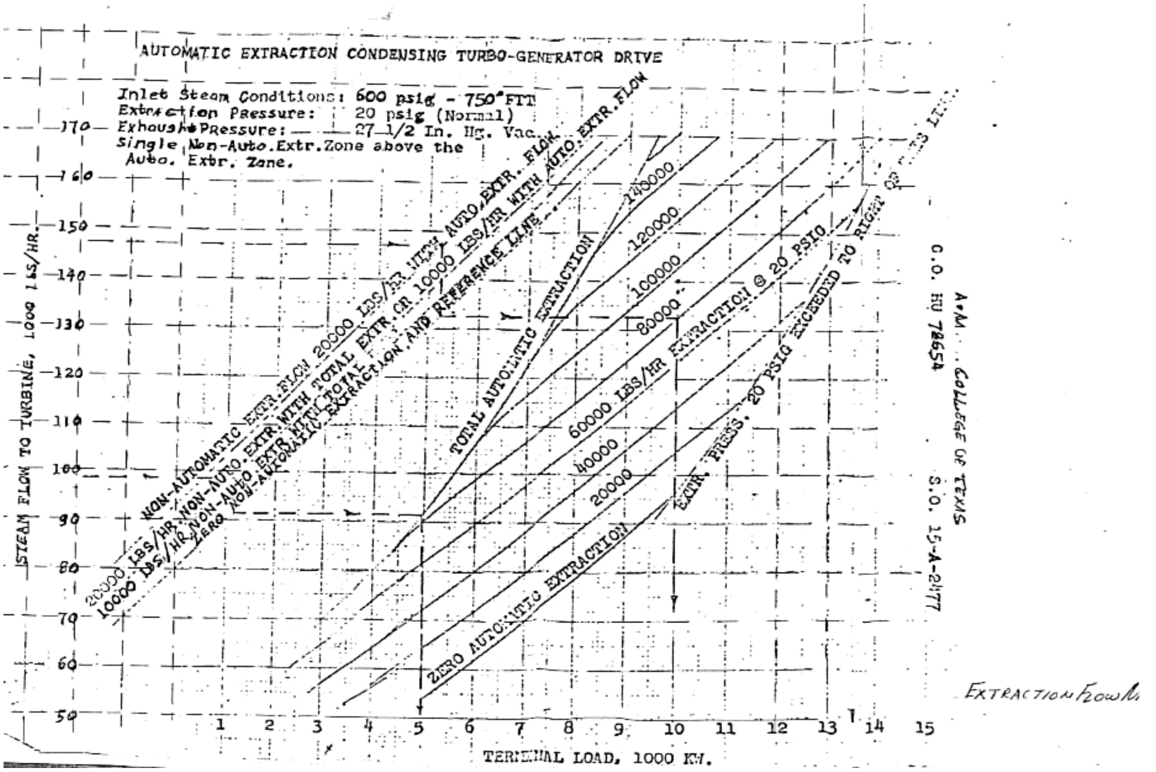


Figure 53 Westinghouse provided STG5 performance curves.

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