Combined Cycle/TES Plant Can Save $1,244,474 per Year

Proposed Cogen System for a 1,100,000-ft^2 Medical Complex Has a Payback Period of 2.6 Years

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ABSTRACT

This article presents a comparative analysis between an innovative "proposed," combined heating/cooling cogeneration power plant and a "base" plant for an approximately 1.1 million ft^2 hospital/office complex to be located in Toledo, Ohio. The complex consists of three buildings: a six-story hospital and two identical 12-story office towers: While each of the buildings in the base plant has its own central plant, the proposed Modular Hybrid Combined Cycle Cogeneration/TES plant is designed to serve the entire complex.

The comparative analysis between the two plants has shown substantial cost savings for the proposed plant because of reduction in utility and maintenance costs and, therefore, the total annual operating costs of the overall plant. This reduction in operating costs is mainly due to the fact that approximately 95% of the total required annual electrical power is produced on-site by cogeneration, and therefore only 5% of its annual estimated power needs are needed to be purchased from a utility.

Reduction in the number of plant operators for the proposed plant has also made sizable contribution to the annual operating cost savings. Although the installed first cost of the proposed plant was higher in comparison, the total operating cost savings of $1,244,474 per year has resulted in a cost-effective simple payback period of 2.6 years for

the proposed plant.

Additionally, the design of the proposed plant has resulted in a substantially compact central plant (an approximately 29% decrease in physical size) in comparison to the base plant having three separate central plants. The fully dedicated proposed plant contributes to reduced demand charges associated with the time-of-use electrical rates, better operation and maintenance, efficient energy management, higher overall system efficiency, and reduced levels of emissions and noise.

With the anticipated nationwide deregulation of the electric utility industry (already underway in 40 states), the proposed plant can offer viable solutions to electric, steam, heating and cooling generation needs for large multi-building complexes.

INTRODUCTION

In the last 10 years, gas cooling technologies have improved greatly and gained popularity. Although research and development currently continue in improving gas-cooling systems, transfer of technology has been slow. In implementing the wide use of these systems, manufacturers, researchers, and heating, ventilating and air conditioning (HVAC) design professionals must properly analyze, select and specify systems and associated equipment applicable to a site-specific situation. Some of the governing factors affecting the implementation of gas cooling systems are operating characteristics, space requirements, system integration, installed first and operating costs (including continuous maintenance), and life-cycle cost.

The cooling/heating central plants can also be combined with thermal energy storage (TES) systems. The major operating cost of a cooling/heating central plant and the buildings it serves is the electrical power that must be purchased from a utility. The operating costs of a building are reduced considerably when lower cost, off-peak electricity is used to produce and store energy for future cooling in TES systems. These systems also help electric utilities save energy and reduce harmful emissions. TES shifts energy consumption from peak afternoon electricity rates to low nighttime periods when utilities generally operate only their most efficient plants, which results in saving significant amounts of source energy and rate reduction to building owners. In this way, the building also avoids high peak-demand charges associated with the energy used during summer daytime periods. Time-of-day rates during the evening hours can be much less than those of daytime rates. In Chicago, for example, large office buildings may have an effective summertime energy cost of 15.4 cents per kWh in comparison to 2.8 cents per kWh at night.[1]

Even with reduced rates, the continuous demand for and cost of electricity to satisfy all building needs including the operation of the central plant are still extremely high. Based on a population increase from 5.3 billion to 8.1 billion, world demand for electrical power is expected to double by the year 2020. According to current data, North America with about 949 MW of installed capacity serves 377 million people at an annual rate of 2.52 kW per capita. On the other hand, 1.2 billion people in China have 181 MW installed capacity at a rate of 0.15 kW per capita, while south Asia and sub-Saharan Africa are the lowest consumers at 0.09 kW per person.[2]

Long-term supplies of natural gas and deregulation concerns seem to be the major driving forces behind the recent changes in our electrical power industry. California's electrical industry deregulation bill (AB 1890) was recently approved. The passage of the bill makes California one of the 40 states now in the process of deregulating their electric power industries. This measure would provide a free market that over time would allow consumers and businesses to make their own deals with the lowest-cost providers of power. Beginning in 1998, the state's power market would be phased in over five years.[3]

To reduce the dependence on purchased electrical power and, therefore extremely high annual operating costs, electrical power may be produced efficiently on-site by means of cogeneration. Cogeneration has for a long time been considered to be the most effective and least costly way of generating electrical power from waste heat. Although cogeneration has been in practice since the early 1900s, it was abandoned due to continuing decline in the price of electricity through the 1930s and 1940s. Most manufacturing plants believed that it would be more beneficial to them to purchase a fairly constant and reliable supply of electricity from a utility than to produce it on-site.

The energy crisis of the early 1970s forced the industry in a desperate effort to reduce the ever-increasing energy costs and made it turn to various types of cogeneration for viable solutions. In the early 1980s,[4] however, the lack of basic knowledge of cogeneration systems on the part of most maintenance engineers and inexperienced operating personnel of central power plants limited the wide implementation of cogeneration systems.[5] As a result, cogeneration was not received well. Additionally, the attitude of the electric utilities toward this revitalized process was less than positive because they felt that the industry was moving toward abandoning the generating capacity of the utilities to supply industry's ever-increasing electrical power needs. On the other hand, some utilities, faced with a drastic shortage of electricity, began to promote cogeneration as part of an overall demand-side management/integrated resource planning campaign.[5]

The trend toward the use of cogeneration in recent years,[6,7] however, has changed considerably and there is a renewed interest. At the recent World Congress of Chemical Engineering conference, the U.S. Department of Energy (DOE) Morgantown Energy Technology Center reported increased use of direct-fired gas turbines designed for power generation (aside from the aircraft engine technology).[8] Gas-turbines are fast coming on line as production units as well as for peak handling, offering lower emission levels, utilization rates exceeding 90% uptimes, and improved efficiencies. Gas-turbine packages and deregulation of power production already underway in 40 states are pointing toward widely distributed generation grids with current utilities eventually providing transmission, maintenance and billing services.[8]

This article presents a comparative analysis between an innovative, combined heating/cooling cogeneration power plant ("proposed") and a "base" plant for an approximately 1.1 million ft^2 hospital/office complex to be located in Toledo, Ohio. The hospital/office complex consists of three buildings: a six-story hospital and two identical 12-story office towers. In the base plant while the hospital building is served by a plant containing a TES system with electrical centrifugal chillers system, each of the office towers is served by a separate plant that has its own electrical chillers system. The electric and natural gas services in the Toledo, Ohio site was to be provided by the Toledo Edison Company and Columbia Gas of Ohio, respectively. Their current service rates are specified in Section 5: Comparative Economic Analysis of Base and Proposed Plants, of this article.

Our firm, *DESIGN BUILD SYSTEMS,* was asked by one of our clients (a developer of multibuildings in the Midwest) to evaluate the above-mentioned complex containing three separate plants (base plant). This evaluation was based on the initial schematics, preliminary plans, and other programmatic information developed by our client's architectural and engineering team. Due to the size of the project and adjacencies of buildings within the hospital/office complex for the Toledo, Ohio, site, *DESIGN BUILD SYSTEMS* decided to conduct a comparative analysis between constructing separate conventionally designed central plants within each of the buildings and constructing a combined heating/cooling central cogeneration plant based on its prior work with modular hybrid combined-cycle cogeneration/TES central plant design that was developed for cogeneration plants in the range of 3 MW to 20 MW. The proposed plant would then serve all three buildings within the hospital/office complex at an available location reasonably close, however, visually concealed by attractive landscaping from the complex by taking full advantage of the contours of the selected site.

The comparison between the two would be contrasted with three conventionally designed stand-alone central heating/cooling plant concepts, was made on the basis of their combined physical size; efficient production of on-site power, and useful thermal energy to satisfy all electrical and cooling/heating demands. The resulting reduction in purchased electrical power from utilities and associated demand charges; efficient energy management of the overall heating/cooling power plant; installed first cost; operation & maintenance (O&M) costs; simple payback period; and the environmental issues such as low exhaust emission[9] and noise levels were then factored in.

A HOSPITAL/OFFICE COMPLEX

As mentioned above the hospital/office complex consists of three buildings: a hospital and two identical office towers. The complex was to be located in Toledo, Ohio. The following is a description of each building in the complex.

Description of Hospital Building

The hospital building is a six-story, rectangular building with a gross floor area Of 450,000 ft^2 (75,000 ft^2/floor) of which 18,000 ft^2 (3000 ft^2/floor) or approximately 4% is unconditioned floor area, and the remaining 432,000 ft^2 (72,000 ft^2/floor) or approximately 96% is conditioned floor area. All floors are 13 ft floor-to-floor and 9 ft floor-to-ceiling. The long sides of the building face north and south.

The typical floor plans for Floor 1 and Floors 2 through 6 in Figure 1 show how the patient and food service areas are subdivided, and common function areas on different floors are grouped together to form nine thermal zones for modeling purposes. The building is divided into five types of functions representative of hospitals of this size. The assignment of the floor space on a given floor to one or more of the five functions is arbitrary, but the relative size of the total floor space assigned to each function is based on the results of a survey of several hospitals. Similarly, the internal loads and the profiles for the operation of the loads are selected to produce overall annual load factors that are consistent with those of hospitals in the Midwest. Design criteria for the building, HVAC systems, and mechanical plant equipment are selected to satisfy the criteria of *ASHRAE Standard 90.1-1989: Energy Efficient Design of New Buildings Except New Low-Rise Residential Buildings.*

The five types of functions used are as follows:

PAT: Patient areas, nursing stations, and hallways (Floors 2 through 6);
ADM: Administrative, business office, cashier, classrooms, records, pharmacy, etc. (Floors 1 through 6);
SUR: Surgery, recovery, treatment, therapy, out-patient, laboratories, etc. (Floors 1 through 6);
FOO: Food service areas (cafeteria, kitchens, food supplies, lounges, vending, etc.) (Floor 1 only); and
LAU: Laundry, housekeeping, supplies, storage, maintenance, engineering, etc. (Floors 1 through 6).

The vision glass area is 31% of the gross exterior wall area (45% of the floor-to-ceiling wall area). The glass characteristics includes a shading coefficient of 0.55, an overall U-value of 0.59 Btu/hr-ft^2-°F, and visible light transmittance of 0.67. The opaque wall is of concrete panel and brick or stone with an overall U-value of 0.085 Btu/hr-ft^2-°F. The roof is medium construction with an overall U-value of 0.053 Btu/hr-ft^2-°F.

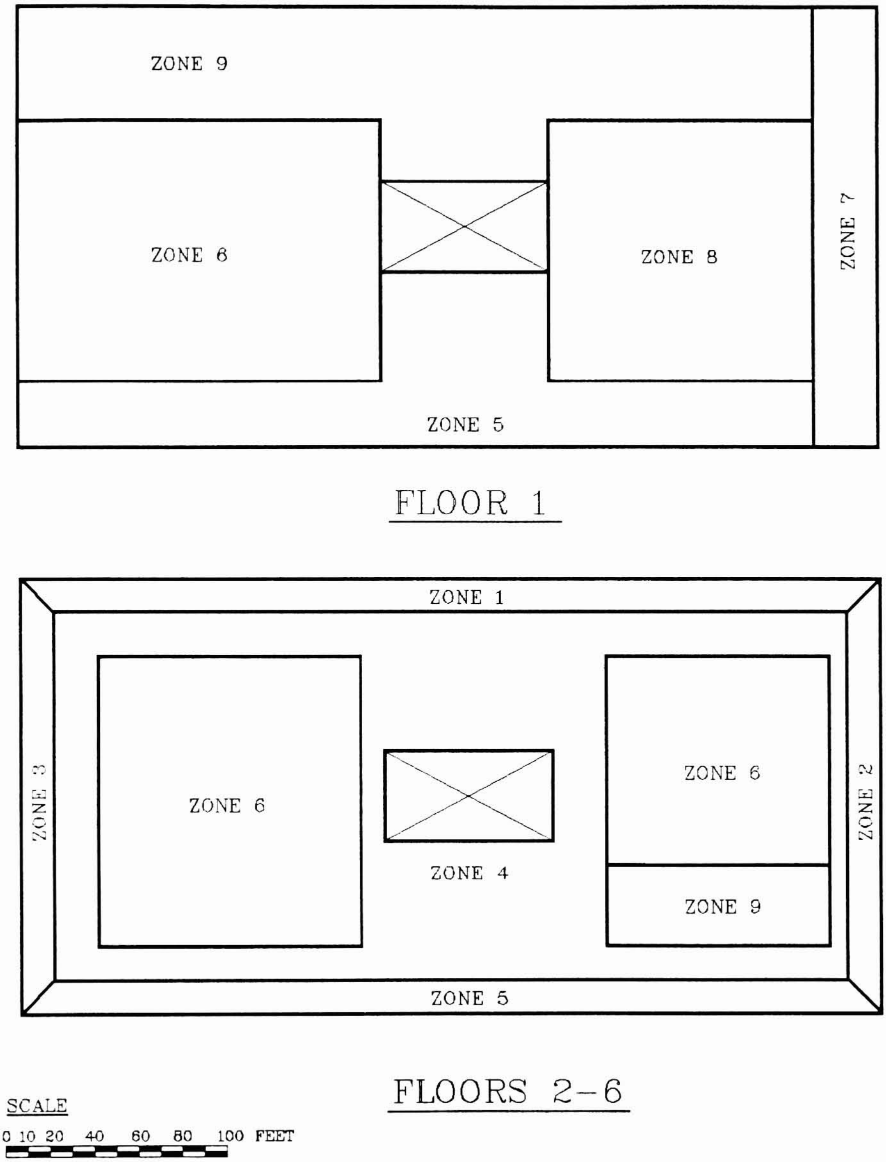

Figure 1. Typical Floor Plans for Floors 1 and 2 through 6 for Hospital Building

The lighting is provided by recessed fluorescents with varying design lighting (1.4 W/ft^2 to 2.5 W/ft^2) for different types of functions. The design receptacle load is also variable by type of function (0.5 W/ft^2 to 1.0 W/ft^2). Design occupancy is varied from 100 ft^2/person to 400 ft^2/ person.

The hospital has its own laundry. The laundry when combined with the food service area contributes to a rather large service water heating load and direct process gas load. Hourly profiles of lighting, receptacle, occupancy, thermostat, fan operation, and service water heating are varied extensively between various types of functions. Except for the administrative area, all areas are assumed to have a continuous (8760 hours) fan operation.

The building is heated and cooled by variable-air-volume (VAV) distribution systems with reheat boxes activated at the minimum primary air damper setting (0.25 cfm/ft^2 to 0.40 cfm/ft^2 for different function areas). Nine separate VAV distribution systems (zones) distinguished by exposure and space function are identified as follows for energy analysis purposes:

Zone 1: North patient perimeter (Floors 2 through 6)
Zone 2: East patient perimeter (Floors 2 through 6)
Zone 3: West patient perimeter (Floors 2 through 6)
Zone 4: Patient interior (Floors 2 through 6)
Zone 5: Administration (Floors 1 through 6)
Zone 6: Surgery (Floors 1 through 6)
Zone 7: Food service perimeter (Floor 1)
Zone 8: Food service interior (Floor 1)
Zone 9: Laundry (Floors 1 through 6)

A slightly tighter room temperature control band is assumed for the hospital than normally listed in office buildings. The heating thermostat is set at 72°F and the cooling thermostat at 74°F with deadband control (float) between these temperatures. The ventilating air requirement is modeled as a constant percentage (20% to 80%) of the supply airflow at any given hour for various function areas. In actual practice, many of the areas would use 100 percent outside air, and other areas would be designed for constant minimum outside air rather than constant percentage of supply air. However, an evaluation of actual hospital operating practices indicates that the outside airflow assumptions will produce a reasonable representation of the actual outside air load. All VAV systems have both economizer and fan inlet vane damper control.

Description of Office Towers

The hospital/office complex also contains two identical office towers. Each office tower is a 12-story, rectangular building with a gross floor area of 323,208 ft^2 (26,934 ft^2/floor) of which 308,808 ft^2 (25,734 ft^2/floor) or approximately 95% is conditioned floor area, and 14 400 ft^2 (1200 ft^2/floor) or approximately 5% is unconditioned floor area. All floors are 13 ft floor-to-floor and 10 ft floor-to-ceiling. The long sides of the tower face north and south. Figure 2 shows a typical floor plan for one of the two office towers.

The office tower walls are constructed from glass spandrel with an overall U-value of 0.082 Btu/hr-ft^2-°F. The facade of a typical floor is 31% vision glass on all exposures with a shading coefficient of 0.55,

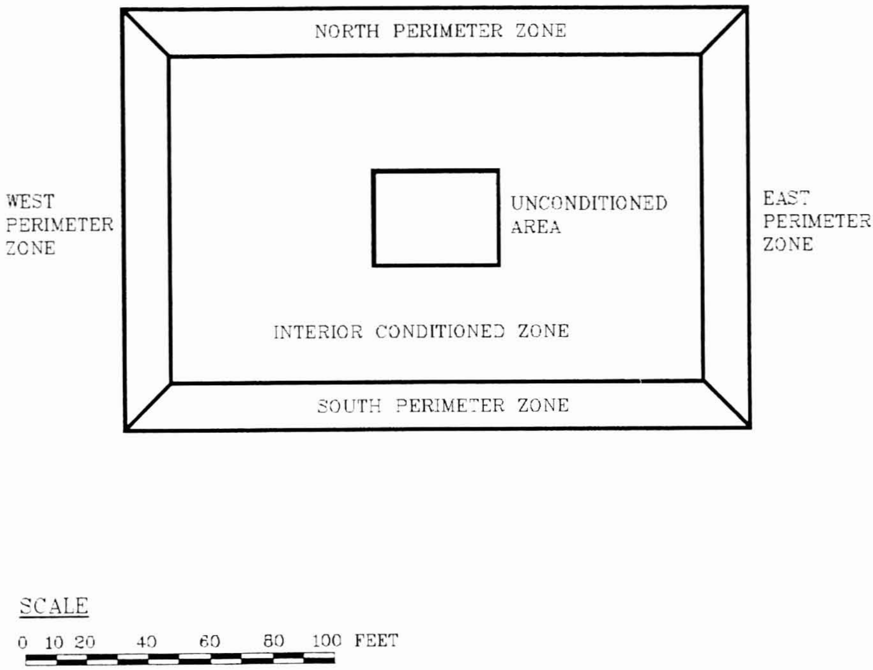

Figure 2. A Typical Floor Plan for Office Tower.

without interior or exterior shading, and a glass visible light transmittance of 0.67. The overall U-value for windows is 0.57 Btu/hr-ft^2-°F. The roof construction has an overall U-value of 0.053 Btu/hr-ft^2-°F.

Lighting is provided by recessed fluorescent fixtures with a design lighting load of 2.00 W/ft^2 for all task areas which include 100% of the perimeter zones and 67% of the interior conditioned area. Non-task areas (33% of the interior conditioned area) have a lighting load of 1.00 W/ft^2. The unconditioned areas have a lighting load of 0.20 W/ft^2 Design receptacle load is 1.0 W/ft^2 of the conditioned floor area.

The office tower is heated and cooled by VAV distribution systems. Separate VAV systems (one per exposure) serve each of the perimeter zones and one VAV system serves the interior zone of the office tower for all floors. Primary air supply temperature is set at 55°F at design conditions, but each zone can independently use demand reset up to a maximum of 60°F.

During the heating season, thermostats are set at 70°F, and during the cooling season at 75°F. Dead-band thermostat control exists when the space temperature is above 70°F and below 75°F. During this time, the VAV supply air boxes are at minimum position without reheat. The minimum VAV damper setting is 0.3 cfm/ft^2 for all zones. The minimum ventilation air quantity is 0.15 cfm/ft^2 of the conditioned floor area during occupied hours. All VAV systems have both economizer and fan inlet vane damper control.

CENTRAL PLANT CONFIGURATIONS

Base Plant

In the base plant while the hospital building is served by a plant containing a TES system with electrical centrifugal chillers, each of the office towers is served by a separate plant that has an electric centrifugal chillers system.

TES Plant with Electrical Centrifugal Chillers for Hospital Building

As shown in Figure 3, the TES plant is served by a base-load electric centrifugal chiller, and a TES system consisting of an ice chiller, a TES tank, a heat-exchanger, and associated piping. Please note that all plant configurations (including the proposed plant) are drawn to same scale for the purposes of easy physical size comparison with respect to each other. Figure 4 shows the mechanical room section for the hospital. The 750-ton base load chiller is rated at 0.58 kW/ton and at part-load. The ice chiller (ice builder) is rated at 0.901 kW/ton and produces a maximum of 520 tons when making ice. The ice chiller operates at full-load most of the time, but for those hours when it is "topping off" the TES system, uses the same part-load profile as the conventional electric chiller. The TES tank (comprising of nine separate ice banks) has a total capacity of 6240 ton-hr. The TES tank consists of a multiple-tube serpentine coil submerged in an insulated tank of water. Both the coil and tank are constructed from hot-dip galvanized steel for corrosion protection. The TES system, however, operates only May through September. During these months, the base-load chiller satisfies the load up to its full capacity of 750 tons between 8 am and 8 pm every day of the week. Any cooling requirement during those hours in excess of 750 tons is satisfied by the TES system.

During the other 12 hours of the day (recharge period of 8 pm to 8 am), the base-load chiller satisfies the natural load of the building, and the ice chiller recharges the TES tank. After the TES tank is fully charged, the ice chiller will not come on to top off the TES tank until the losses from the TES tank equal at least 5% of the rated capacity of the ice chiller (26 tons). Since a full tank would have standby losses of 5.2 tons per hour, the ice chiller would cycle about every 5 hours when the TES tank is full and not in use.

When sizing a TES plant, trade-offs must be considered. One of the two ways to operate the hospital TES plant is to serve the base-cooling load with one chiller and use the TES system to satisfy the peak load. Another approach would be to serve the base-cooling load with the TES system and use the chiller to satisfy the peak load. Although first option is chosen here the second option is perfectly acceptable. A third option involves the installation of a complete TES system to satisfy 100 percent of the peak-cooling load and recharging the TES tank during off-peak hours. Since the hospital building in this case has a fairly high continuous cooling load, a full TES system was not believed to be warranted.

In sizing a TES system, the trade-off of operating costs vs. installed equipment costs must be examined. For example, the larger the TES tank the greater the operating cost savings will be due to the larger avoided peak charges, but the higher the installed cost will be due to the larger TES tank and larger ice chiller. A good starting point

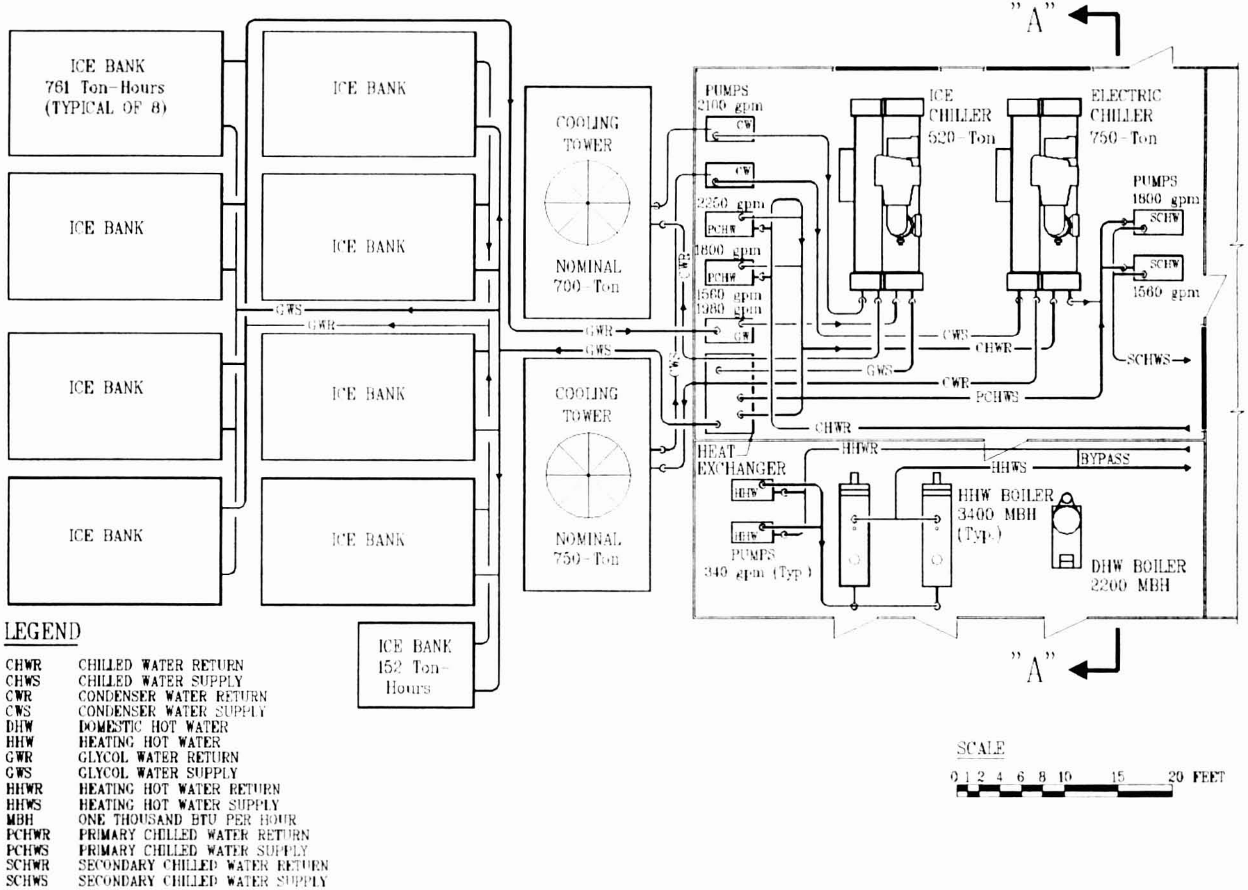

Figure 3. Base Plant: TES Plant with Electrical Centrifugal Chillers for Hospital Building

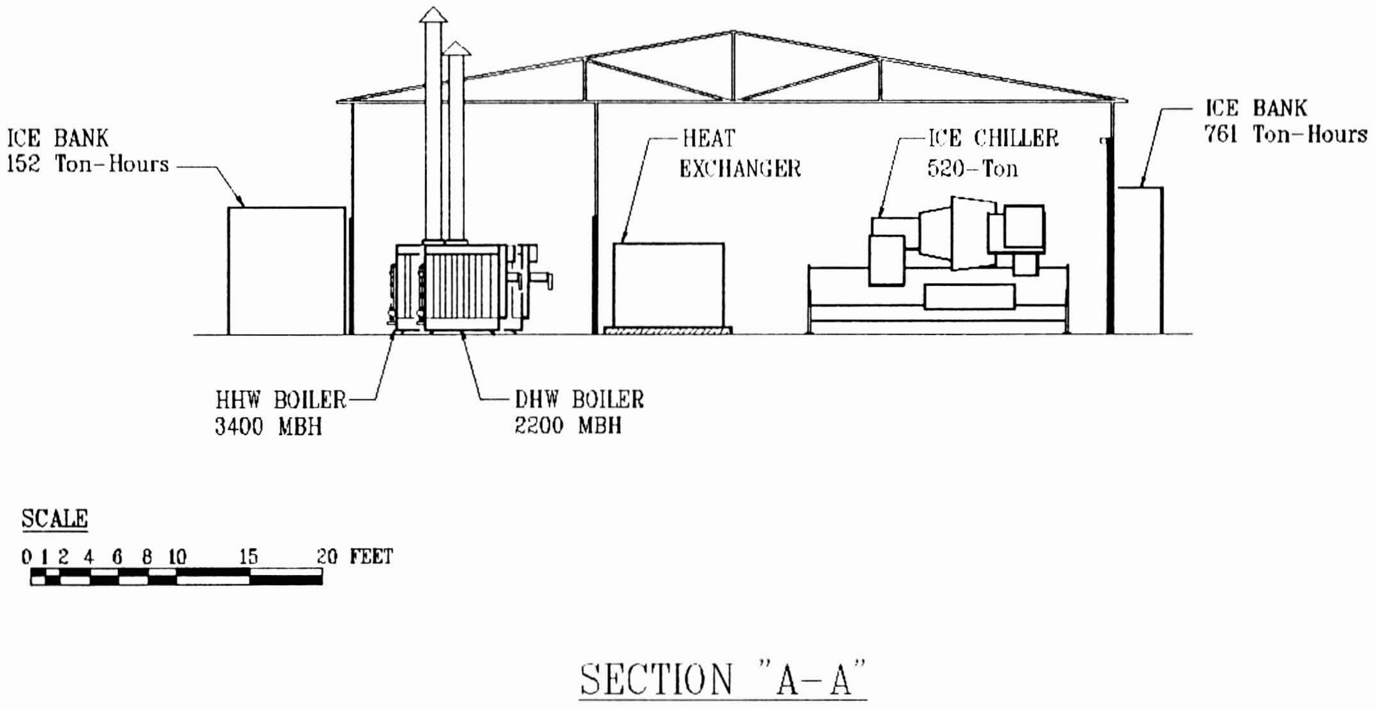

Figure 4. Base Plant: Mechanical Room Section for Hospital Building

is to assume a base-load that is 50% of the design cooling load (or 700 tons, in this case). Evaluation of operating and purchase costs of a 700-ton, a 750-ton, and an 800-ton base load chiller has yielded the 750-ton base load chiller as the most suitable one. The peak-cooling load day for the hospital building is shown in Figure 5.

For the hospital, the most constraining aspect is the long on-peak demand time (12 hours). That means the TES system will have to shave peak for at least 12 hours out of the day, leaving the remaining 12 hours to recharge the TES tank. This rather long demand period results in a large TES system and a large ice chiller.

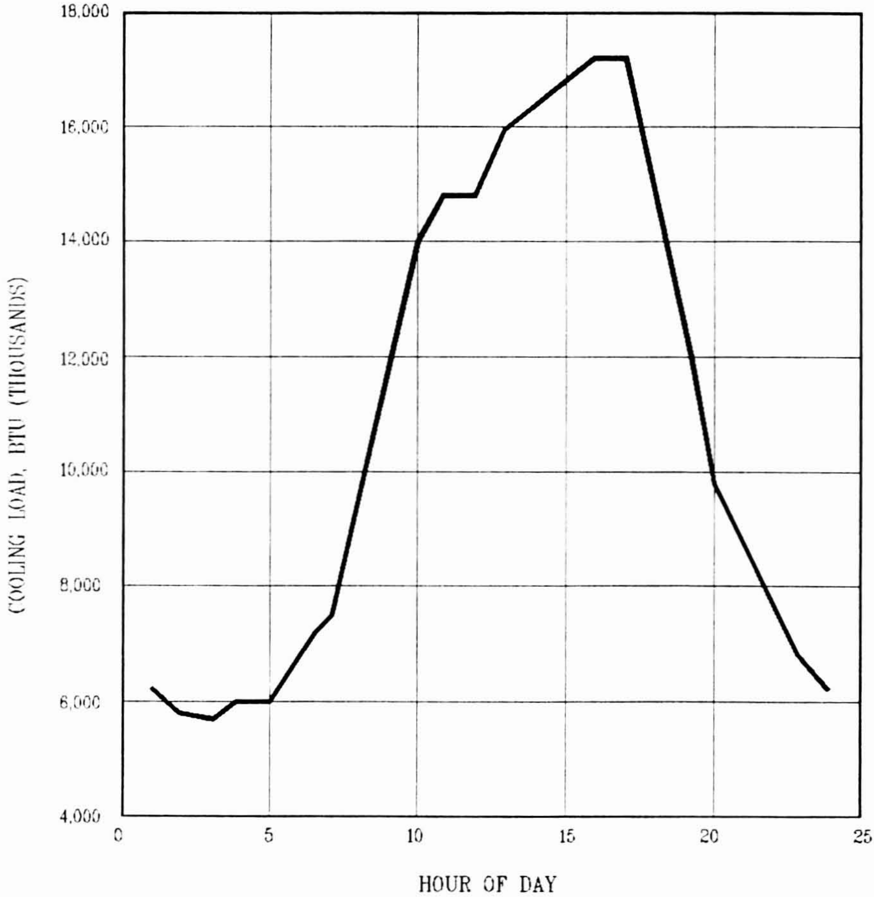

Figure 5. Peak Cooling Load Day for Hospital Building

For the selected base-load chiller of 750 tons, additional cooling must be supplied by the TES system when the hospital cooling load is greater than 9,000,000 Btu (750 tons × 12,000 Btu/ton). The peak day analysis performed indicates that the TES system must be sized to supply 5660 ton-hr of cooling. With only 12 hours of regeneration time, the size of the ice chiller must be 472 tons. However, the TES tank and the ice chiller should be designed with some reserve capacity. Although a rather modest design (i.e., contingency) factor of 10% was chosen for the hospital, designers usually have the option to choose a more conservative factor of 15% to 20% in the event of a large load. Using a 10% design factor leads to a total capacity of 6226 ton-hr for the TES tank and 519 tons for the ice chiller. For this analysis, the TES tank capacity is rounded to 6240 ton-hr and the ice chiller capacity to 520 tons at ice building conditions.

Typically, a chiller is rated at a condition where it is required to produce supply water at 44°F. Under ice building conditions, however, a chiller must chill a glycol solution at around 22°F. To produce a glycol solution at 22°F, the chiller's capacity is derated by approximately 25%, which implies that it can only operate at 75% of its rated capacity when providing a glycol solution at 22°F. Therefore, an ice chiller with a rated capacity of approximately 700 tons (520 tons/0.75) is required for the hospital building here. Both the lower fluid temperature and the transport properties of the cool glycol solution contribute to increased power use of the chiller. For example, a chiller with a rated input of 0.60 kW/ton will have an energy input of approximately 0.90 kW/ton at ice building conditions.

This plant is designed to operate as a primary/secondary chilled-water-distribution system with primary chilled-water pumps delivering a constant flow of chilled-water through the chillers. The secondary chilled-water pumps are equipped with variable-speed drives to vary the flow of chilled-water in direct proportion to the cooling load. The secondary chilled-water-distribution system operates at typical design temperatures of 44°F (leaving-water temperature) and 54°F (return-water temperature). The condenser-water-piping system for the chillers operates at typical design temperatures of 85°F (leaving-water temperature) and 95°F (return-water temperature). The heat-rejection equipment consists of a 700-ton and a 750-ton cooling tower. The cooling towers are equipped with two-speed axial type fans for energy conservation and accurate temperature control through multiple stages of capacity.

Electrical Centrifugal Chillers System Plant for Office Tower

Each office tower plant contains two 400-ton electric centrifugal chillers connected in parallel with condenser-water design temperature difference of 10°F and with minimum entering condenser-water temperature of 65°F (refer to Figure 6). Figure 7 shows the mechanical room section for one of the office towers. The plant also has two 3400 Mbh, gas-fired hot water boilers for space-heating service, and one 230 Mbh gas-fired hot water heater for domestic hot water service. The plant is designed to operate as a primary/secondary chilled-water-distribution system with primary chilled-water pumps delivering a constant flow of chilled-water through the chillers. The temperature across the chiller is proportional to the load when below design conditions. The secondary chilled-water pumps are equipped with variable-speed drives to vary the flow of chilled-water in direct proportion to the cooling load.

The secondary chilled-water-distribution system operates at typical design temperatures of 44°F (leaving-water temperature) and 54°F (return-water temperature). The condenser-waterpiping system for the chillers operates at typical design temperatures of 85°F (leaving-water temperature) and 95°F (return-water temperature). The heat-rejection equipment consists of two 400-ton cooling towers. The cooling towers are equipped with two-speed axial type fans for energy conservation and accurate temperature control through multiple stages of capacity.

Proposed Plant

Modular Hybrid Combined-Cycle

Cogeneration / TES Plant for Hospital / Office Complex

This innovative hybrid plant[10] combines gas-cooling, TES and cogeneration (to produce on-site electrical power from waste heat) to serve the three-building hospital/office complex as opposed to the base plant having three separate plants as described earlier.

System Description

The proposed central plant (shown in Figure 8) serving the three-building complex described above consists of a gas-turbine/centrifugal chiller, a gas-turbine cogeneration unit with a heat-recovery steam generator (HRSG), a condensing steam-turbine generator unit, a deaerator, TES system (cold and hot), and cooling towers. A control

LEGEND

CHWR	CHILLED WATER RETURN
CHWS	CHILLED WATER SUPPLY
CWR	CONDENSER WATER RETURN
CWS	CONDENSER WATER SUPPLY
DHW	DOMESTIC HOT WATER
HHW	HEATING HOT WATER
GWR	GLYCOL WATER RETURN
GWS	GLYCOL WATER SUPPLY
HHWR	HEATING HOT WATER RETURN
HHWS	HEATING HOT WATER SUPPLY
MBH	ONE THOUSAND BTU PER HOUR
PCHWR	PRIMARY CHILLED WATER RETURN
PCHWS	PRIMARY CHILLED WATER SUPPLY
SCHWR	SECONDARY CHILLED WATER RETURN
SCHWS	SECONDARY CHILLED WATER SUPPLY

SCALE

0 1 2 4 6 8 10 15 20 FEET

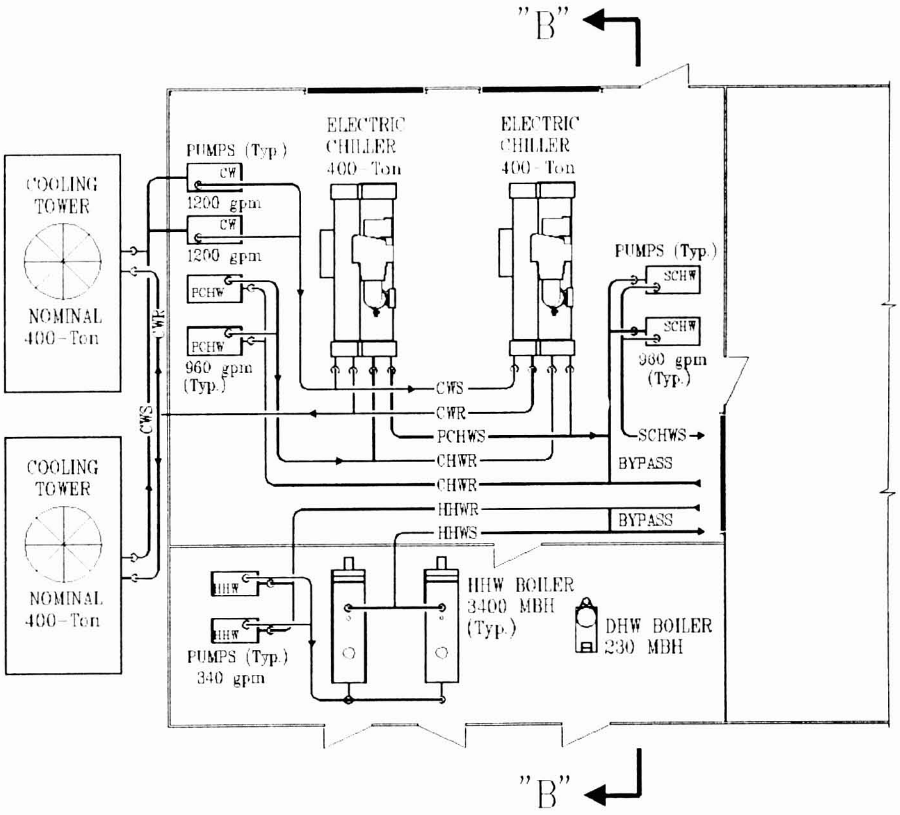

Figure 6. Base Plant: Electrical Centrifugal Chillers System Plant for Office Tower

room built in the plant contains the turbine control system panel, a boiler and auxiliary equipment control, and a monitoring system. The plant also has two 6000 Mbh gas-fired hot water boilers and one 1015-Mbh hot water converter with one hot-water storage tank for space heating service, and one 2660-Mbh hot water heater for domestic hot-water service. The plant will be located above the ground and adjacent to the hospital/office complex (refer to Figure 9 for the gas/steam turbine boiler room section). The plant provides the required heating, steam, chilled-water for cooling, and a peak electrical power of 3787 kW for the entire hospital/office complex. Pertinent technical data for each unit within the plant are shown in Table 1.

As shown in Table 2, the York Gas-Turbine/Centrifugal Chiller is a nominal 2000-ton centrifugal chiller driven by a gas-turbine which produces 1560 hp at an inlet air temperature of 59°F. The centrifugal chiller is designed to operate with a standard 10°F temperature-differential across the evaporator and condenser. A nominal 2000-ton cooling tower is used to remove the waste-heat from the condenser. The gas-turbine produces less power when the inlet air temperature exceeds 59°F.[11] A cooling coil with a 44°F entering chilled-water temperature is provided in the air inlet to maintain a 59°F inlet air temperature. While this takes some cooling tonnage, there is a net gain in energy cost that varies depending on the inlet air humidity. The available exhaust-heat energy is ducted to the HRSG of the Kawasaki Gas-Turbine Cogeneration Unit to generate steam. The steam then drives a condensing steam-turbine with a power output of 2325 kW.

The Kawasaki Gas-Turbine Cogeneration Unit consists of a gas-turbine, a generator, a turbine exhaust system, an HRSG, and a control system (refer to Table 3). The nominal 1.5-MW cogeneration unit integrates with the available exhaust-heat energy of the York Gas Turbine/Centrifugal Chiller. At the International Organization for Standardization (ISO) conditions (59°F, sea level), the cogeneration unit will provide 16,900 pph unfired (turbine-only) and 29,500 pph (fully-fired) superheated steam without steam injection to feed the condensing steam-turbine (refer to Figure 10). The efficiency of the gas-turbine varies with the inlet air temperature. With an inlet air temperature of 104°F, the capacity of the gas-turbine is derated to 1119 kW without steam injection. A cooling coil with a 44°F entering chilled-water temperature is provided in the air inlet to maintain a 59°F inlet air temperature. The power outputs of the gas turbine at an

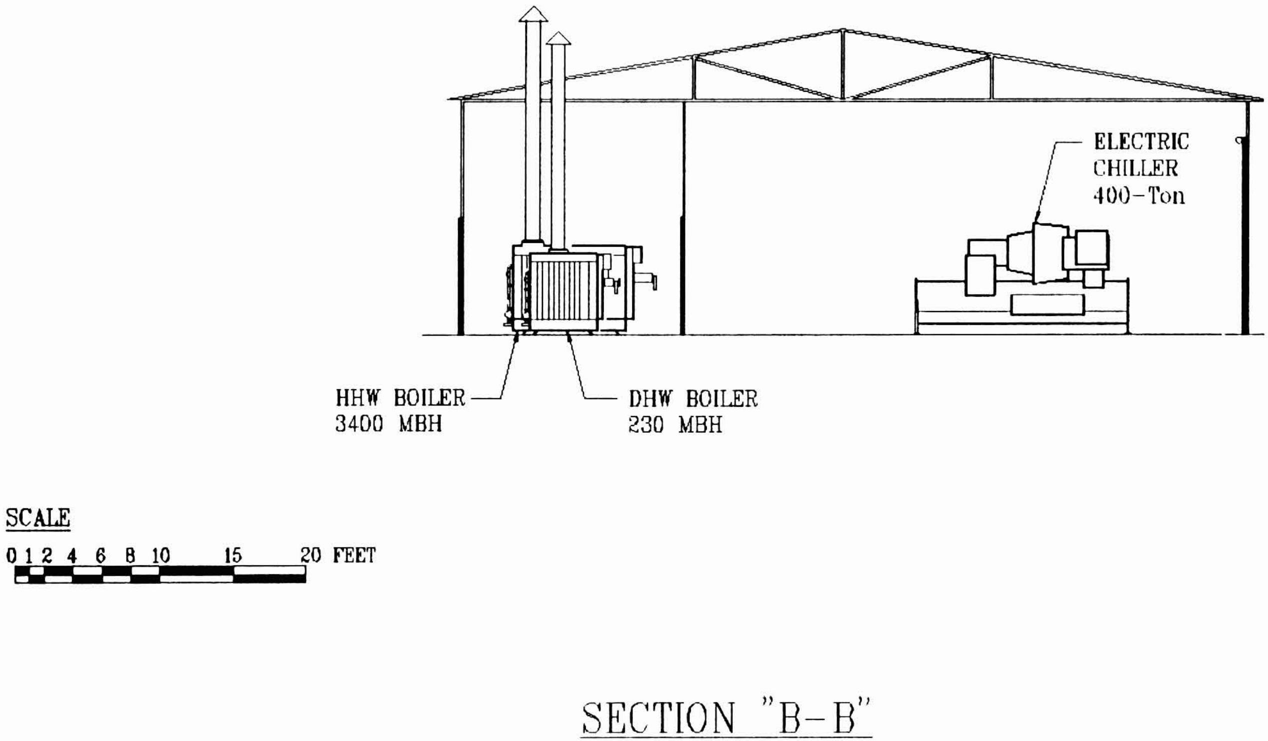

Figure 7. Base Plant: Mechanical Room Section for Office Tower

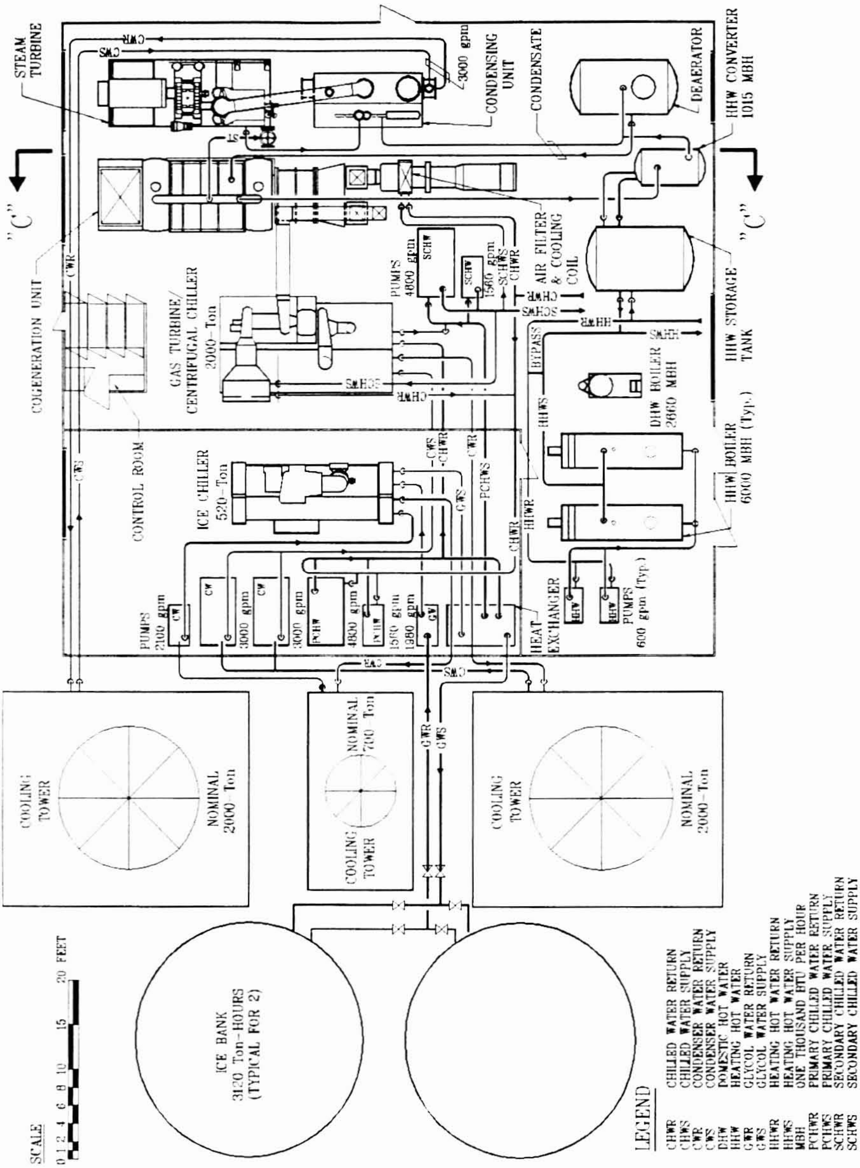

Figure 8. Proposed Plant: Modular Hybrid Combined-Cycle Cogeneration/TES Plant for Hospital/Office Complex

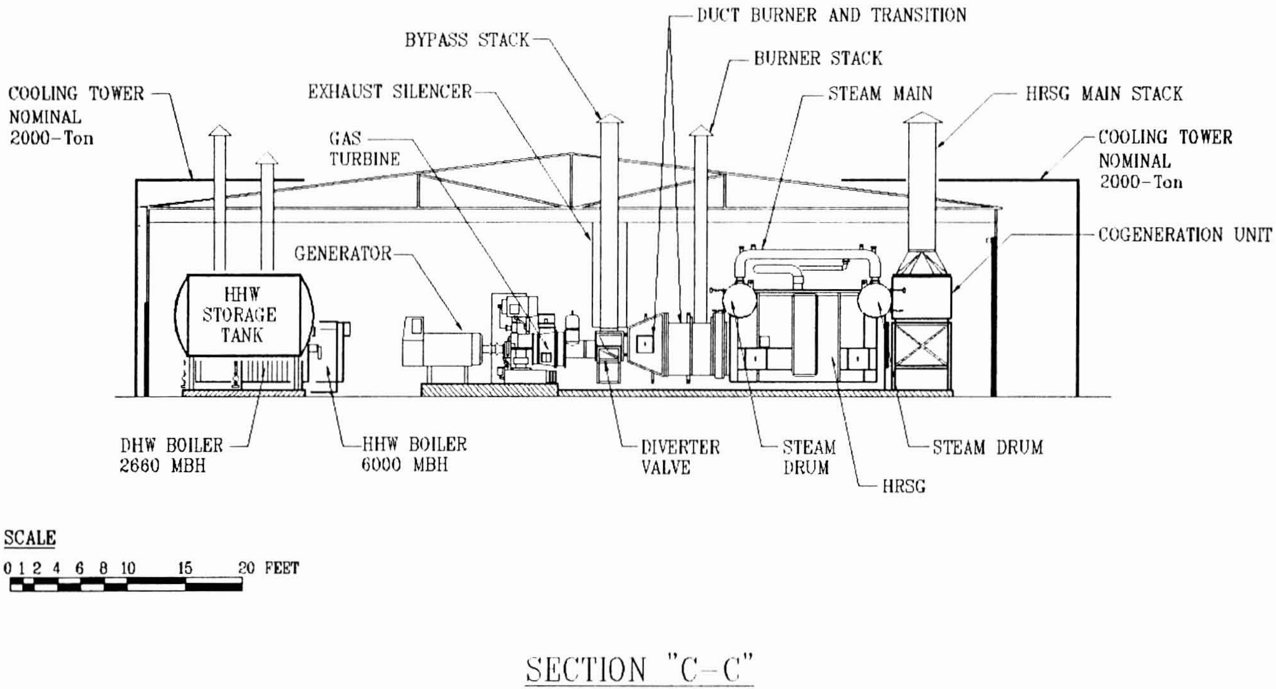

Figure 9. Gas/Steam Turbine Boiler Room Section for Proposed Plant

Table 1 Technical Data for Each Unit within Proposed Plant

Description	*Kawasaki Gas Turbine Cogeneration Unit*	*York Gas Turbine/Chiller*	*Condensing Steam Turbine Generator Unit*	*Centrifugal Chiller/Ice Chiller*
Fuel	Natural gas	Natural gas	Steam	Electric
Rated Output	1462 kW at 59°F DBT	2000 tons at 59°F DBT	2325 kW at 85°F CWT	700/520 at 85°F CWT
Rated Input	20,660 Mbh	15,921 Mbh	30,690 Mbh	435/469 kW
Rated Heat Recovery	9596 Mbh (without duct-firing)	9596 Mbh (without duct-firing)		
Rated Airflow	14,000 cfm	13,500 cfm		
Duct-Firing Output	6445 Mbh	6445 Mbh		
Duct-Firing Input	7860 Mbh	7860 Mbh		

Table 2.
Specifications for York Gas-Turbine/Centrifugal Chiller

COMPONENT	*SPECIFICATION*
CHILLER	
Capacity (ton)	2000
Power (BHP)	1560
Full load chiller performance (Btu/ton-hr)	9185
Unit COP (HHV)	1.31
ENGINE	
Turbine model	T-1600
Maximum engine power (hp)	1605
Full load turbine performance (Btu/BHP-hr)	11,775
Fuel flow (SCFH)	18,098
Inlet air flow (lb-hr)	56,500
Exhaust flow (lb-hr)	57,200
Exhaust temperature (°F)	940
EVAPORATOR	
Flow rate (gpm)	4800
Passes	2
Entering temperature (°F)	54
Leaving temperature (°F)	44
Pressure-drop (ft)	20.5
CONDENSER	
Flow rate (gpm)	6000
Passes	2
Entering temperature (°F)	85
Leaving temperature (°F)	95
Pressure-drop (ft)	15.6

inlet air temperature of 59°F are 1584 kW with steam injection and 1462 kW without steam injection. The power output remains the same as inlet air temperature drops below 59°F (refer to Table 4 for the power output of the Kawasaki Gas-Turbine Cogeneration Unit). The turbine exhaust system includes two flow diverter valves and two duct burners and is located upstream of the HRSG.

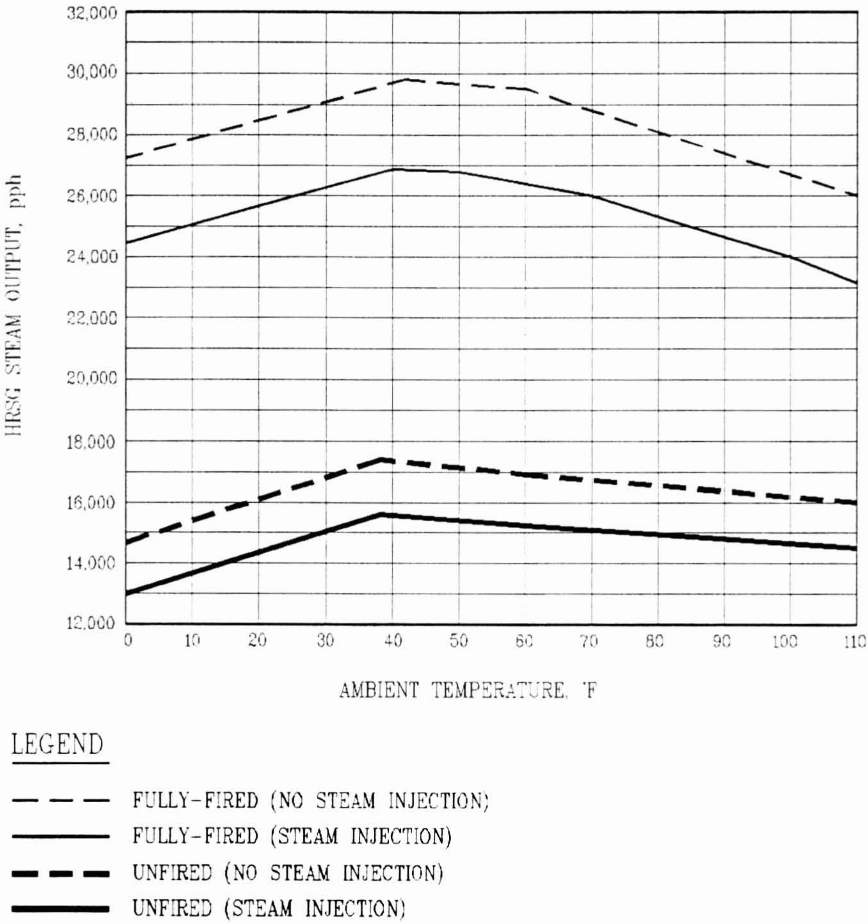

Figure 10. Steam Output of Kawasaki Gas-Turbine Cogeneration Unit

Table 3.
Specifications for Kawasaki Gas-Turbine Cogeneration Unit

OPERATIONAL MODE	
Turbine (1) in cogeneration mode with or without duct-firing	
CONFIGURATION (PRIMARY COMPONENTS)	(Power-only mode)
Gas Turbine (1)	Natural gas or #2 diesel fuel
Primary fuel type	
Gas Turbine ISO Performance:	
Turbine inlet temperature (°F)	1814
Mass flow (lb/s)	17.8
Pressure ratio	9 4:1
Exhaust gas temperature (°F)	964
Generator (1)	
Synchronous AC generator	3-phase, 60 Hz 1800 rpm 1500 kW at 4160 VAC 1875 KVA, 0 8 power factor
Turbine Exhaust System	
Flow diverter valve	Bypass flow is silenced
Duct burner	Natural gas 14.0 MMBtu/hr (maximum)
Heat Recovery Steam Generator	
Economizer	227°F entering BFW
Boiler	29,500 pph (250 psig to 420 psig saturated or superheated)

(Continued)

Table 3. (*Concluded*)

Special features	Removable superheater section Removable boiler section for maintenance Removable economizer section for maintenance
Control System	General Electric FANUC
GT	1 PLC microprocessor for turbine
HRSG	1 PLC microprocessor for the HRSG and auxiliaries (Total of 2 microprocessors)
Operator Interface	GE CIMPLICITY (graphics software)
COGENERATION UNIT OPERATIONAL DATA	
Ambient Conditions	
Minimum temperature (°F)	0
Maximum temperature (°F)	110
Maximum altitude (ft)	8200 above mean sea level
Deliverables with Duct-Firing and Steam Injection (ISO Conditions)	
Electrical output	1584 kW at 59°F inlet air temperature
Fuel input	28.2 MMBtu/hr (LHV)
Heat rate (fuel chargeable to power)	3391 Btu/kWh (LHV)
Steam output	Saturated—29,000 pph (33,000 without steam injection) (250 psig, 406°F to 420 psig, 452°F) Superheated—26,700 pph (29,500 without steam injection) (250 psig, 565°F to 420 psig, 599°F)
Parasitic loads	18 kW to 150 kW
Other Data	
Overall sound pressure level	85 dBA (3 ft horizontal and 5 ft vertical from unit)
Four-zone fire protection system	

Table 4.
Turbine Fuel Consumption and Generator Output of Kawasaki Gas-Turbine Cogeneration Unit.

Ambient Temperature (°F)	Ambient Temperature (°C)	Generator Output (kW) (with steam inj.)	Generator Output (kW) (without steam inj.)	Fuel Consumption (MMBtu/hr) (with steam inj.)	Fuel Consumption (MMBtu/hr (without steam inj.)
0	–17.8	1584	1584	21.899	22.40
10	–12.2	1584	1584	—	22.18
14	–10.0	1584	1584	21.493	—
20	–6.7	1584	1584	—	22.03
30	–1.1	1584	1584	—	21.94
32	0.0	1584	1584	21.241	—
40	4.4	1584	1453	—	21.91
42	3.3	1584	1584	21.210	21.90
50	10.0	1584	1526	21.200	21.30
59	15.0	1584	1462	21.244	20.66
60	15.5	1584	1453	—	20.58
63	17.1	1584	1433	21.282	—
68	20.0	1542	1395	20.883	—
70	21.1	—	1380	—	19.88
80	26.7	—	1304	—	19.19
86	30.0	1394	1258	19.552	—
90	32.2	—	1227	—	18.51
100	37.8	—	1149	—	17.85
104	40.0	1244	1119	18.286	—
110	43.3	1195	1073	17.876	17.21

The Steam-Turbine Generator Unit (STGU) is a multistage condensing type and consists of a steam-turbine and a condensing unit. The superheated steam produced at 29,500 pph in the HRSG of the Kawasaki Gas-Turbine Cogeneration Unit is piped to the STGU which generates a power output of 2325 kW (refer to Table 1). The condensing unit is equipped with two condensate pumps and two cooling-water pumps. A 3000-gpm of cooling water at 85°F is provided via a nominal 2000-ton cooling tower to carry off the waste-heat from the condensing unit with a cooling water temperature-rise of 20°F. The temperature of the cooling-water affects the efficiency of the condensing unit. The lower the temperature is, the higher the efficiency that can be attained. A lower temperature makes it possible to obtain a lower pressure in the condenser, producing a greater useful enthalpy-drop in the steam-turbine. A deaerator is used to remove oxygen and carbon dioxide from make-up water and condensate, and hence to reduce corrosion in the HRSG and the system.

The TES system of the base plant originally designed to operate with a total capacity of 6240 ton-hr is utilized for the proposed plant, except for the type of TES tanks (refer to Figure 8). The TES system of the proposed plant consists of a 520-ton low temperature ice chiller, a plate-and-frame heat exchanger, and two TES tanks containing plastic balls encapsulating deionized water.

Supporting equipment of the system includes an ice inventory control system, a 700-ton cooling tower, a chilled-water pump, a glycol pump, and a condenser pump. The ice chiller is designed to operate with a 10°F temperature-differential across the evaporator and condenser. The two TES vertical tanks are 26.5 ft in diameter and 16 ft in height with a nominal volume of 64,266 gallons each. The total foot print of both tanks is 1102 ft^2 and is 44% less than the total foot print of the TES tank used in the base plant. The TES tanks are filled with "ice balls." The ice balls manufactured by Cryogel headquartered in San Diego, California, are approximately 4 inches in diameter plastic spheres filled with water and a freeze-point enhancing nucleating agent. During the nighttime, the ice chiller cools a glycol/water solution to 23°F for the TES tanks. The water within the ice balls freezes and, therefore stores cooling energy for use during the nighttime.

During the daytime, the glycol solution is warmed by the chilled-water returning from the buildings through a plate-and-frame heat exchanger and passed over the ice balls in the TES tanks. The warm solution melts the ice, cooling the glycol for use in cooling the buildings. The ice chiller continues to operate during the daytime and acts as a conventional chiller during the cooling period.

The system is designed to operate as a primary/secondary chilled-water-distribution system with primary chilled-water pumps delivering a constant flow of chilled-water through the chillers. The secondary chilled-water pumps are equipped with variable-speed drives to vary the flow of chilled-water in direct proportion to the cooling load. The secondary chilled-water-distribution system operates at typical design temperatures of 44°F (leaving-water temperature) and 54°F (return-water temperature). The condenser-water-piping system for the chillers operates at typical design temperatures of 85°F (leaving-water temperature) and 95°F (return-water temperature).

System Operation

When the load is below 1462 kW, only the Kawasaki Gas-Turbine Cogeneration Unit is in operation. The steam generated from the HRSG of the Kawasaki Gas-Turbine Cogeneration Unit is piped to the hot-water converter to produce hot water. The hot water then goes into the hot-water storage tank up to 60,000 Mbh for space heating. If the storage tank is full, the steam is dissipated.

When the load is above 1462 kW (e.g., 1700 kW, more than the power output of the Kawasaki Gas-Turbine Cogeneration Unit), the STGU is brought on-line. The STGU now uses the unfired heat-recovery from the Kawasaki Gas-Turbine Cogeneration Unit to try to drive it. If the heat is not enough to produce the steam in order to produce the additional 238 kW which it needs out of the STGU, the duct burner of the Kawasaki Gas-Turbine Cogeneration Unit fires and supplements the required heat to produce the 238 kW off the STGU. The duct burner will not fire unless there is an inadequate amount of steam from the unfired HRSG associated with the amount of heat. If the unfired heat-recovery is more than the need of STGU (i.e., when the heat recovery is available from the York Gas-Turbine/Centrifugal Chiller at this time), then there is some excess of steam. The excess steam is piped to the hot-water converter to produce hot water. The hot water then goes into the hot-water storage tank up to 60,000 Mbh. If the storage tank is full, the steam is dissipated.

A diverter valve is located in the exhaust-gas ductwork between the gas-turbine and the duct burner in the Kawasaki Gas-Turbine

Cogeneration Unit. The diverter valve is equipped with an exhaust silencer and has its own bypass stack The diverter valve serves as a bypass for the exhaust gases of the gas-turbine engine when HRSG requires maintenance. The exhaust gases are diverted to the atmosphere through the bypass stack during HRSG maintenance, which allows the turbine/generator to remain in service. The diverter valve is also used to modulate the exhaust gases into the HRSG to match steam generation with power demand.

The STGU is designed to produce 2325 kW at 30,000 lb of heated steam input. In the summertime, the STGU uses the heat-recovery from both the York Gas-Turbine/Centrifugal Chiller and the Kawasaki Gas-Turbine Cogeneration Unit to produce the full power output of 2325 kW. In the wintertime when the cooling load does not exist (and, therefore the York Gas Turbine/Centrifugal Chiller is not in operation), the STGU can produce only 50% of its rated output. Therefore, in the wintertime when the load is 3300 kW, part of that power will have to be purchased because the STGU cannot produce the entire 3300 kW without the York Gas Turbine/Centrifugal Chiller operating.

FIRST INSTALLED COST COMPARISONS FOR BASE AND PROPOSED PLANTS

The installed first costs of the base and proposed plants are estimated based on the specific equipment associated with the heating and cooling systems (refer to Table 5). The base plant equipment includes chillers, cooling towers, TES tanks, heating hot-water boilers, and piping and associated pumping equipment. The equipment for the proposed plant includes a cogeneration unit, a gas-turbine/chiller unit, a steam-turbine/condensing unit, a dearator, cooling towers, heating hot-water (HHW) boilers, an HHW converter, an HHW storage-tank, TES tanks, control room air-conditioning, and piping and associated pumping equipment. Cost items such as electrical, gas piping, and flue stacks are also included in the costs of chillers, cogeneration unit, and gas-turbine/chiller. The electrical costs for chillers include a transformer, a switchgear and a power feeder. The cost figures are the designer's estimates based on equipment cost data obtained from the manufacturers of the major equipment specified herein as well as the *Means 1995 Cost Data*.

Table 5. Comparative Installed First Costs of Base and Proposed Plants

Equipment	Base Plant Cost for Individual Buildings ($)		Total Base Plant Cost ($)	Total Proposed Plant Cost ($)
	Hospital Building	Office Towers		
Chillers	280,720	578,920	859,640	—
Cogeneration Unit	—	—	—	2,179,150
Gas Turbine/Chiller Unit	—	—	—	1,000,000
Steam Turbine/Condensing Unit	—	—	—	940,000
Separation Wall	—	—	—	6,400
Dearator	—	—	—	30,700
Cooling Towers	77,400	104,400	181,800	277,230
HHW Boilers	78,890	157,780	236,670	110,900
HHW Converter	—	—	—	1,500
HHW Storage Tank	—	—	—	3,500
TES System	581,790	—	581,790	590,370
Pumps	81,150	102,400	183,550	129,350
Piping	97,650	87,660	185,310	204,100
Control Room A/C	—	—	—	4,000
Sub-Total	1,197,600	1,031,160	2,228,760	5,477,200
Overhead & Profit	239,520	206,230	445,750	477,568
TOTAL	1,437,120	1,237,390	2,674,510	5,954,768

HHW: Hot heating water
TES: Cost of thermal energy storage system includes an ice chiller, ice banks, and a heat-exchanger.
A/C: Air conditioning.

COMPARATIVE ECONOMIC ANALYSIS OF BASE AND PROPOSED PLANTS

An economic analysis for the individual three-building base and the proposed plants has been conducted. Table 6 summarizes the comparative results of this economic analysis for these two plants. We will now discuss briefly the factors used in conducting this economic analysis. An economic analysis is performed using annual energy costs, annual cooling tower water costs, annual maintenance costs, and installed first costs. The electric and gas consumption costs are simulated by one of the most commonly-used energy analysis programs: *Energy System Analysis Series* (ESAS). The ESAS is a group of sophisticated computer programs. It is used to evaluate the design and operating characteristics, energy demand and consumption, energy costs, and life-cycle cost on an hourly, full-year basis for building energy systems and the mechanical plants that serve them. The analysis is usually performed for a typical weather year, but specific periods of actual weather data can be used to compare actual building performance to potential building performance for the period.

The ESAS contains three basic program groups. The first program group is the Building & Distribution System Program (ERE). This program group calculates the thermal and electrical loads hourly for the building (or a section of the building), and simulates the operation of the air-distribution system in satisfying these loads for a full year. Additionally, one can observe the effect of changes in various other operating parameters.

The second program group is the Building Section Summation & Cooling Storage Program (TCR) that sums the hourly, full-year loads from multiple ERE computer runs described above of various building sections to find total diversified system loads that must be satisfied by a given mechanical plant configuration. The program group is also used to model cooling (or heating) storage systems, with recharge rates, tank sizes, and operating strategy as variables. One can also modify selected loads for selected periods in the hourly data file, permitting the load profile to be "tuned" to specific requirements. Up to nine ERE computer outputs can be summed and/or modified in each TCR computer run, and those summations can be combined in subsequent TCR computer runs, thereby permitting an infinite number of building sections to be merged before being imposed on a mechanical plant configuration.

Table 6.
Comparative Economic Analysis of Base and Proposed Plants

COST	*BASE PLANT*	*PROPOSED PLANT*
ANNUAL ENERGY COST		
Electricity	$1,916,329	$276,305
Gas	$124,813	$1,049,725
Total	$2,041,142	$1,326,030
ANNUAL COOLING TOWER WATER COSTS		
Water	$2,975	$3,856
Sewer	$7,328	$9,499
Chemicals	$4,699	$6,091
Total	$15,002	$19,446
ANNUAL MAINTENANCE COST		
Chillers	$125,706	$110,376
Boilers	$226,708	$58,692
Gas & Steam Turbines	—	$262,800
Plant Operator(s)	$919,860	$306,600
Total	$1,272,274	$738,468
TOTAL OPERATING COST	$3,328,418	$2,083,944
SAVINGS VS. BASE PLANT	—	$1,244,474
INSTALLED FIRST COST (refer to Table 5)	$2,674,510	$5,954,768
COST PREMIUM VS. BASE PLANT	—	$3,280,258
PAYBACK PERIOD		
Simple Payback Period without Rebate (yr)		2.6
Columbia Gas Rebate Available		0
Simple Payback Period with Rebate (yr)		2.6

The third program group, Mechanical Plant Analysis Program (EEC), simulates the operation of the various pieces of mechanical plant equipment on an hourly, full-year basis as they respond to loads imposed by the building's air-side system (and cooling storage system, if used) to find monthly and annual energy demand and consumption for various systems under evaluation. The program group also permits the monthly utility demand and consumption data to be grouped into various time-of-day brackets. Up to six plant configurations can be simulated in each EEC computer run with up to four different sets of hourly load requirements used in each EEC computer run.

Electric and natural gas services in the Toledo, Ohio area are provided by the Toledo Edison Company and Columbia Gas of Ohio, respectively. Both utilities are contacted to obtain information on the current electric and gas rates that are applicable to the size of buildings. One of the two electric rates used is the Schedule GS-12 *(Large General Service Rate)* for buildings using greater than or equal to 150 KVA demand. Another electric rate used is the Schedule PV44 *(Large Power Rate)* for buildings with greater than or equal to 650 KVA demand at 4160 VAC or more. The gas rate utilized is the Schedule LGS *(Large General Service)* for buildings using greater than 18,000 MCF/per year. As can be seen in Table 6, there is an increase in gas cost for the proposed plant ($124,813 to $1,049,725). However, the real savings for the proposed plant results from the reduced electricity cost. The electricity cost decreased from $1,916,329 to $276,3051 resulting in a total annual energy cost savings (gas and electricity) of $715,112. The electric and gas consumptions of the proposed plant are summarized in Table 7.

In estimating annual cooling tower water costs including water consumption, sewer charges, and chemical treatment requirements for both the base and proposed plants, the *ESAS* energy analysis program in conjunction with the *ASHRAE 1992 Systems and Equipment Handbook* and the Marley Cooling Tower company publication, entitled: *Cooling Tower Fundamentals,* are utilized. Water rates for the Toledo, Ohio area are obtained from the City of Toledo, Department of Public Utilities. The current water rate of $4.96 per 1000 ft^3 for a monthly consumption of 160,000 ft^3 to 1,160,000 ft^3 is adequate for the hospital/ office complex. Sewer utility costs based on current rates are also obtained from the City of Toledo, Department of Public Utilities. For a non-industrial building located within the city limits, the volume

Table 7. Electric and Gas Consumptions of Proposed Plant.

MONTH	GAS USE (MCF)	PEAK DAY GAS USE (MCF)	ELECTRIC USE (kWh)	PEAK ELECTRIC DEMAND kW (60 MIN)
January	21,803.0	864.6	1,350,614	2624
February	20,234.8	887.0	1,254,270	3035
March	21,526.1	918.2	1,416,170	3787
April	21,981.3	966.3	1,487,010	3787
May	24,718.6	1096.0	1,655,023	3787
June	28,657.6	1108.1	1,839,100	3787
July	30,047.6	1128.3	1,901,475	3787
August	30,011.0	1096.1	1,910,862	3787
September	26,123.7	1082.0	1,725,251	3787
October	22,807.5	983.9	1,548,190	3787
November	20,248.8	855.0	1,369,681	3445
December	21,865.5	831.7	1,373,704	2624
ANNUAL:	290,025.7	1128.3	18,831,350	3787

charge is \$12.22 per 1000 ft^3. As can be seen in Table 6, the annual cooling tower water costs are \$15,002 for the base plant and \$19,446 for the proposed plant.

In estimating maintenance and repair costs for both the base and proposed plants, manufacturers of respective equipment are consulted. These costs include major chillers and boiler overhaul over the life span of the equipment. Accordingly, the average maintenance and repair costs for the chillers and boilers are assumed to be \$43.80/ton/year and \$4.38/MBtu/year, respectively. The maintenance and repair costs for the gas- and steam-turbines for the proposed plant are estimated to be \$262,800/year. The plant operator cost is estimated based on one person, 24 hr/day, 365 days/year at \$35/hr fully loaded per plant. Table 6 shows that the proposed plant saves \$1,244,474 a year in total operating costs. The lower portion of Table 6 presents the operating cost savings and installed cost premium for the proposed plant. The ratio of these two quantities gives the simple payback period as 2.6 years for the proposed plant.

CONCLUSIONS

This study introduced an innovative central cogeneration plant concept. Study results also show the proposed Modular Hybrid Combined-Cycle Cogeneration/TES plant effectively serves the entire hospital/office complex when compared with the base plant in which each of the three buildings is served by its own heating/cooling plant. A detailed evaluation of the proposed plant has shown substantial cost savings by effectively reducing the utility and maintenance costs and, therefore the total annual operating costs of the overall plant. This substantial reduction in operating costs is mainly due to the fact that approximately 95% of the total required annual electrical power is produced on-site by cogeneration, and therefore only 5% of its annual estimated power needs are needed to be purchased from a utility. The electrical power to be purchased from a utility, although small in comparison to the electricity generated by cogeneration (5% vs. 95%, in this case), is still quite expensive. It averages over 22 cents/kWh a year and reaches as high as 58 cents/kWh in the summertime. Meanwhile, the electricity generated on-site by cogeneration is estimated to cost approximately 3.8 cents/kWh. Although the waste exhaust heat from the York Gas-Turbine/Centrifugal Chiller and the Kawasaki Gas-Turbine Cogeneration Unit is available to produce excess steam at the HRSG, the economic analysis did not optimize the capacity of the HHW converter and HHW storage-tank nor the utilization of the STGU.

Although cost of the natural gas consumption for the proposed plant in comparison to the base plant has increased (\$124,813 to \$1,049,725 as shown in Table 6), the substantial savings (\$1,640,024) on the overall electrical power consumption was sufficient enough to offset this increase. Another category of cost savings that played a very important role in reducing the total yearly operating costs of the proposed plant is the maintenance cost. In this category, the cost of maintaining a number of plant operators for the base plant (with three separate plants) is the governing factor. Reducing the number of plant operators for the proposed plant resulted in a substantial reduction in operator cost from $919,860/year to $306,600/year. Holding the annual cooling tower water costs for the base and proposed plants fairly constant in comparison, the proposed plant has realized a substantial total operating cost savings of $1,244,474 per year. Although the installed first cost of the proposed plant was higher in comparison ($5,954,768 vs. $2,674,510), the above total operating cost savings of $1,244,474 per year was able to bring the simple payback period for the proposed plant to a very reasonable and cost-effective period of 2.6 years (refer to Table 6).

The design of the proposed plant has resulted in a substantially compact central plant (7,599 ft^2 vs. 10,684 ft^2, an approximately 29% decrease in physical size) in comparison to the base plant having three separate plants. Additionally, the proposed (fully-dedicated) Modular Hybrid Combined-Cycle Cogeneration/TES plant contributes to reduced demand charges associated with the time-of-use electrical rates, better operation and maintenance, efficient energy management, higher overall system efficiency, and reduced levels of emissions and noise.

In the light of on-going deregulation of electrical power industry, the cost of producing electrical power should continue to go down once stranded costs are amortized. The current and proposed deregulation measures would allow consumers and businesses to make their own decisions in purchasing electrical power from the lowest-cost providers. With the anticipated nationwide deregulation of the electric utility industry (already underway in 40 states including California), the proposed Modular Hybrid Combined-Cycle Cogeneration/TES plant can offer viable solutions to electric, steam, heating and cooling generation needs for large multi-building complexes.

Acknowledgment

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