DATA CENTER RENOVATION

DELAWARE

KRISTEN SHEHAB

SPRING 2005

MECHANICAL OPTION

FACULTY CONSULTANT: DR. FREIHAUT

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9.0 APPENDICES

1.0 EXECUTIVE SUMMARY

This is a case study of the feasibility of changing a data center renovation into a cogeneration facility. The 175,000 square foot building contains 80,000 square feet of high load density computer room space. The computer rooms contain critical equipment that is sensitive to power quality.

The intent of this thesis was to highlight the effects of switching the main source of power from the grid to natural gas driven turbine generators. A heat recovery system is added, and electric chillers are switched to absorption chillers to utilize the otherwise waste thermal energy. Since absorption chillers have a higher condenser water flow rate than electric chillers, condenser water side equipment including piping, pumps and cooling towers should be resized.

The new turbines are to be located outside and turbine performance is dependent upon inlet air conditions, decreasing as temperature increases. Inlet cooling from excess refrigeration produced from the oversized chillers is used to increase power output.

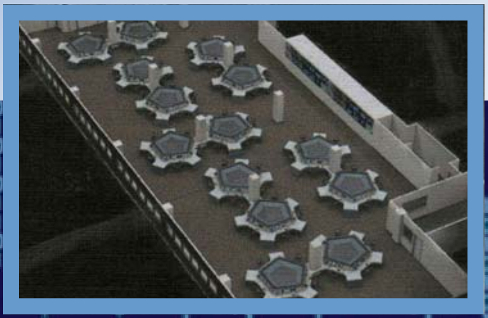
Cogeneration emissions and efficiency standards are controlled by government policies. The Department of Energy (DOE)'s Model Emissions Rule regulates the amount of emissions a generator is allowed to emit. The Public Utility Regulatory Policies Act (PURPA) states a cogeneration facility must recover and use a certain percentage of waste heat from the combustion process in order to be able to obtain benefits including the sell back of excess energy to the utility. The system is designed to adhere to both of these standards as well as statewide regulations.

The first cost of a cogeneration system is always significant and payback periods are difficult to quantify. In Delaware, natural gas is priced more than electricity. Considerations about the quality and uptime of electricity produced from the generators as opposed to the utility are significant because of the sensitive equipment contained in the data center.

DATA CENTER

DELAWARE

KRISTEN SHEHAB, MECHANICAL



PROJECT TEAM

- ♦GENERAL CONTRACTOR:NASON, WHITING-TURNER
- ♦MECHANICAL: I.D. GRIFFITH
- ♦ELECTRICAL: FURNESS ELECTRIC
- ♦ARCHITECTS/ENGINEERS: CCG FACILITIES INTEGRATION

ARCHITECTURE

- ♦175,000 SQUARE FEET
- ♦24,000 SQUARE FOOT EXPANSION OF RAISED FLOOR COMPUTER EQUIPMENT AREA
- ♦DEVELOPMENT OF NEW 16,000 SQUARE FOOT SYSTEM AND NETWORK COMMAND CENTER

MECHANICAL SYSTEM

- ♦REPLACEMENT OF EXISTING WATER-COOLED CHILLER PLANT WITH NEW 1,800 TON PLANT AND DISTRIBUTION SYSTEM
- ♦COMPUTER ROOMS COOLED WITH CRAC (COMPUTER ROOM AIR CONDITIONING) UNITS COOLING LOAD DENSITIES UP TO 80 W/SF
- ♦LOOPED PIPING FOR BIDIRECTIONAL FLOW

LIGHTING/ELECTRICAL SYSTEM

- ♦RECONFIGURATION OF ELECTRIC SERVICE AND NEW EMERGENCY POWER GENERATION ON-SITE WITH ULTIMATE EXPANSION TO 10.5 MW
- ♦REPLACEMENT OF EXISTING UPS SYSTEMS WITH THREE NEW MULTI-MODULE 2,400 KW SYSTEMS AND DISTRIBUTION

STRUCTURAL SYSTEM

- ♦STRUCTURAL STEEL FRAME WITH PRECAST CONCRETE FACADE.
- ♦STEEL FRAMED ROOF WITH ROOF CURBS FOR MECHANICAL EQUIPMENT

CONSTRUCTION MANAGEMENT

- ♦NO INTERRUPTION TO ONGOING PRODUCTION OPERATIONS

♦ENGINEERING FEES	$320,000
♦ELECTRICAL UPGRADES	$6,039,800
♦MECHANICAL UPGRADES	$9,699,911

2.2 Primary Project Team

Contractors

General: Nason, Whiting –Turner

Electrical: Furness Electric

Mechanical: I.D. Griffith

Architect: CCG Facilities Integration

Engineers

Mechanical: CCG Facilities Integration

Electrical: CCG Facilities Integration

Owner: Withheld

2.3 Building Statistics

General Project Data

Building Name: Withheld at Owner's Request

Location and Site: Delaware

Occupancy/ Function Type: Data Center, Industrial Occupancy

Size: 175,000 SF

Number of Stories: Three Stories Above Grade

Dates of Construction

Originally Built: 1983

Electrical Upgrades: Bidding/Construction: 9.15.00-5.15.01

Mechanical Upgrades: Bidding/Construction: 9.15.00-7.01.01

Actual Cost Information

Engineering Fees: $320,000

Electrical Upgrades: $6,039,800

Mechanical Upgrades: $9,699,911

Delivery Method: Design Bid Build

Architecture

Help Desk and Offices: 60,000 sf.

Data Center Space: 80,000 SF.

GMC (Global Management Center): Approx. 5300 sf on 27" raised floor on the second floor data center side.

Global Help Desk: floor on the second floor data center side.

IEMC (Integrated Enterprise Management Center): Approx.
16,000 sf. on slab on the second floor office side.

Zoning and Code:

Zoning: Industrial

Code: Boca

3.0 Existing Conditions

The Data center contains 3 levels covering approximately 175,000 square feet. Computer room space on the first and second floor are the concentration of this thesis.

3.1 Data Center Design Objectives

The most important factor taken into consideration with the data center upgrades is operational down time. The mechanical and electrical system upgrades are designed to maintain and improve reliability and availability.

It is critical to review the existing facility and support systems and general operating methods for elements of risk exposure to continuous technology systems operation, and to improve operations. Redundancy of critical mechanical equipment is designed to provide the total number of units required plus one as standby (N+1). This is classified as Tier III redundancy, meaning systems are served by a single active path, redundant components, and concurrently maintainable. Annual downtime for a Tier III system is 1.6 hours.

3.2 Air Side

The mechanical system for this data center is a combination fourteen separate air handling units, both constant volume and variable volume. Supplemental computer room air conditioning (CRAC) units (100% recirculated air) are added for additional cooling for high load densities. Two air handlers supply the service floor. Four air handlers supply the electrical unlimited power supply (UPS) rooms with transfer air to the battery rooms. Six air handler units are dedicated to the ventilation of the first and second floor computer rooms and UNIX rooms.

3.3 Water Side

A 2,400 ton chilled water plant services the cooling load. Five water cooled chillers are connected in parallel and operate at a constant volume around the clock. They operate on refrigerant 134a. Chilled water and cooling tower water pumps operate in parallel at constant volume to serve the non-designated volume flow.

Free cooling is provided on colder days by a plate type heat exchanger.

Selection of the primary and backup makeup water system (city or well) is provided by the Building Automation System (BAS). Upon sensing a critical low water level in any cooling tower water basin, the backup makeup water system is enabled.

3.4 Energy Sources and Rates for the Site

The data center is designed to run 24 hours a day its primary source of power is the electric utility, and emergency power provided by diesel generators.

The data center operates on an N+1 Redundant Uninterruptible Power Supply (UPS) system.

- Transmission service is provided by Conectiv. Three phase circuits carry a nominal voltage of 34,500 Volts.
- Three 17,500 kW diesel powered backup generators are supported by a 10,000 gallon fiberglass underground fuel oil storage tank.
- Battery backup is also provided as part of the UPS System and is used in the case of utility power outage and generator warm-up. In the event of a utility failure the generators are started within 8 seconds. The batteries produce DC power to the UPS system which is then converted to AC. They are designed to last 30 min at 600KW or 12-15 min at 750 kW.

3.5 Overview

Reliability, efficiency, and emissions are addressed in this thesis.

Currently the electric utility is the primary source of power and the data center’s reliability is dependent on the utility. Though efforts have been made in the right direction with backup batteries and diesel generators, utility downtime is still an issue.

Further, over 95% of the utility’s energy source is coal. This is a large source of emissions from SO2, NO2 and CO2 particulates. Since data centers consume so much energy that they are categorized as industrial processes, efforts must be made to use power wisely.

4.0 MECHANICAL EXISTING CONDITIONS

4.1 Outdoor and Indoor Design Conditions

Outdoor

Outdoor weather data was taken from the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) Fundamentals for Wilmington Delaware. This yielded cooling design at 1% conditions 89F drybulb and 74F wetbulb. Heating design at 99.6% conditions is 10F drybulb and 7.7F wetbulb.

Indoor

To maintain 72F computer room space temperatures with 50% relative humidity, the ventilation air must be cooled down to at least 52F so that sufficient moisture is removed. A 49F supply air temperature is required to maintain 45% relative humidity in the spaces. Fourteen Air Handling Units (AHU's) serve the renovation space. Two serve the service level at a 55F and 25850 cfm each. Four serve the UPS and battery rooms using 100% return air with 28000 cfm each. Two units serve the first and second floor unix and computer rooms with 0.1 cfm/ft^2 outdoor air. Humidifiers are added to these to provide a 72F setpoint. The Global management center and Global Help Desk are served by four penthouse mounted AHU's. Two direct expansion units serve a separate section of the building.

Computer Room Air Conditioning Units

Due to high load densities in the computer rooms, supplemental computer room air conditioning units are required. These units are 100% recirculated air and are located on the chilled water system. These all operate at N+1 Redundancy. Average Load densities for computer rooms are 65W/ft^2 with peak densities up to 80W/ft^2. When the loads reach 80 W/ft^2 capacity reduction is required in other spaces. Each unit is set to maintain interior space conditions of 72F and 45% RH. Unit capacities are either 252.1 MBH or 346.1 MBH. These units have no latent capacity.

4.2 WATERSIDE SYSTEMS

Chilled water and condenser systems water originate at 5 parallel chillers. These systems are described below and illustrated in Appendices A and B.

Chilled and Condenser Water

Four (plus one redundant) 600 Ton chillers serve the building cooling load. The chillers are connected in parallel with 1,200 gpm flowing through the evaporator and 1,800 gpm through the condenser. The chillers have unit mounted variable frequency drives. They operate on refrigerant 134a (1,1,1,2-Tetrafluoroethane) which is an ethane series halocarbon that conforms to international standards. Water is cooled from57F to 45F. They consume 330 kW each.

Chilled Water Pumps are set in parallel. Flow on the chilled water side is supported by five 75 hp, 1,200 gpm, constant speed pumps. Each pump has a 13.05 inch impeller. Design motor efficiency is 79.23%. Design Break horse power is 57.37 hp.

Cooling Tower Water Pumps are set in parallel. Flow on the cooling tower water side is supported by five 60 hp, 1,800 gpm, constant speed pumps. Each pump has a 10.66 inch impeller. Design motor efficiency is 79.88%. Design Break Horse Power is 51.21 hp.

Four (plus one redundant) Cooling towers are set up in parallel. They designed for1,800 gpm to cool water from 95F to 85F, a 10 degree range. Fans consume 30 hp for each unit. Basin heaters consume 24 kW each.

Free Cooling Operation

A plate type heat exchanger is used for free cooling. Chillers are deenergized when condenser water supply temperature is measured below 60F. Condenser water temperature set point is reset to 42F. The heat exchanger is sized for 14,400 MBH.

Makeup Water System

Well Makeup Water System: An alternate source of makeup water is provided from a hydropneumatic tank fed by three wells.

4.3 ANNUAL ENERGY CONSUMPTION

A brief summary of annual energy consumption for the data center renovation is listed as follows. Though there are 5 cooling tower water pumps, chilled water pumps, and chillers, due to N+1 redundancy, only four of each type of equipment are to be run at any given time. Also, only nine of the fourteen Air Handling Units run consecutively. Annual energy consumption by the mechanical system can be viewed in Table 1. The mechanical system utilizes approximately 21,000 MWh/year. This number may have a small error since the existing air handler energy utilization was approximated.

Table 1: Energy Consumption from Existing Mechanical Equipment

Equipment Name	Manufacturer	Capacity	kWh/ year	Quantity	Total kWh/year
Cooling Tower Water Pump	Armstrong	1,800 gpm	394,200	4	1,576,800
Chilled Water Pump	Armstrong	1,200 gpm	490,560	4	1,962,240
Cooling Tower	Marley	1,800 gpm	1,051,200	4	1,051,200
Chiller	Carrier	600 ton	2,890,800	4	11,563,200
Computer Room AC	Liebert	252.1 MBH	49,056	*45	2,207,520
Computer Room AC	Liebert	346.1 MBH	65,700	*25	1,642,500
AHU 1-14			175,200	9	1,576,800
Total kWh/year					21,580,260

*Approximately 80% of CRAC units in use at any given time.

** Values for AHU's are not supplied at this point, 20 kW will be assumed.

According to the Energy Information Administration, the 2003 average energy rate for the industrial sector is $14.89/MMBtu. The electric consumption for the building is 8,910 kW, 78,051,600 kW annually. The total yearly utility cost is $3,965,160.

5.0 INTRODUCTION TO REDESIGN

5.1 Alternative Solutions

Fuel Cells

There are many different fuel cell technologies that are under development, all are electrochemical devices that convert chemical energy into electrical energy without combustion. Fuel cells can operate using various fuels. When hydrogen and oxygen are used as the primary fuels for the chemical reaction, the byproducts of electrical production are pure water and heat. Fuel cells, which have no moving parts, produce direct current electricity that may be inverted to alternating current for buildings. Since hydrogen is rarely available in a pure state it must be extracted from other compounds such as carbon based fuels like natural gas. These fuels must be processed or reformed into a hydrogen-rich gas mixture. The reforming process produces carbon dioxide and trace amounts of carbon monoxide such as that found in the coal combustion process. Transmission losses can be neglected and the process has a higher efficiency than that from the utility

Pressurized Solid Oxide Fuel Cell with Gas Turbine Power System

Technologies will generate electricity and also use the heat and water produced in the cell to power steam turbines and generate even more electricity. When a Pressurized Solid Oxide fuel cell (SOFC) generator and a natural gas turbine (GT) are integrated, they are capable of converting natural gas fuel energy to electric power with high efficiencies.

5.2 Cogeneration with Turbine Generators

In this cogeneration topping-cycle system, electricity is produced for the building and the recovered heat is used to drive the absorption chillers.

Natural gas driven combustion turbine generators with lithium bromide / water absorption chillers is a practical way of achieving reliability, efficiency, and minimal emissions.

The goal is to remove the data center's electric dependency from the grid and use turbine generators to operate off of natural gas. Shifting power from the utility to synchronous turbine generators should improve reliability given proper redundancy and maintenance.

Because of emissions regulations, Selective Catalyst Reduction (SCR) systems may be required in order to reduce exhaust stream pollutants. The existing backup generators operate off of diesel fuel which also give off large quantities of emissions. Emissions should be measured for the natural gas driven engines. Since the diesel generators are designated for emergencies, emissions are held to different standards and will not be checked.

In order to optimize generator efficiency, heat recovery is important. Waste heat can be sent to absorption chillers. By making use of the waste, efficiency of the fuel increases. In a lithium bromide/water absorption cycle, heat drives water vapor out of a LiBr solution. Absorption chiller types are categorized on the number of effects. The higher number of effects, the more heat required to drive the cycle. This report will address single stage indirect fired chillers.

Electrical

Natural gas powered combustion turbine generators supplemented with heat recovery steam generators have been chosen for the plant. Four turbines have been selected (3+1). The units are rated for 59F and sea level. The capacity of these units at higher input air temperatures decreases slightly, which influences equipment selection.

When equipped with unfired heat recovery steam generator (HRSG), exhaust steam is used as input for the absorption chillers.

The generators are to be interconnected to the grid. In order to prevent problems synchronizers, relays and breakers are to be added.

Mechanical

Excess steam from the heat recovery system will be lead to the indirect fired absorption chillers. Single effect has been chosen. In single effect chillers using lithium bromide and water, the water evaporates in order to extract heat in the evaporator. Though the efficiency of these machines is lower than double effect, the excessive amount of low pressure steam produced by the generators makes single effect acceptable.

Absorption chillers use a higher flow rate on the condenser water side. Because of this, larger pumps and cooling towers are required. Larger pipes are also required.

Integration into building

Cogeneration with absorption chillers have strong effects on the mechanical and electrical side of the building. Cost analysis such as lifecycle costs and annual savings should be addressed. Fuel costs are especially important to this analysis. These should be obtained from the department of energy. Location of equipment is also important. It may be difficult to fit the larger equipment onto the site.

6.0 SYSTEM REDESIGN

6.1 COMBUSTION TURBINE GENERATORS

Combustion turbines consist of a compressor section, a combustion chamber (burner), and an expansion power turbine section. The compressor draws air in and boosts combustion air pressure. The combustion chamber mixes fuel and air for combustion. The turbine extracts energy from the combustion gases. The gas turbine is an internal combustion engine and employs a continuous combustion process. About two thirds of the shaft power produced by the turbine is used to run the compressor, with the remaining third running the generator which produces electrical power.

Thermodynamically, gas turbines operate on the (open cycle) Brayton cycle. It includes adiabatic compression (Points 1-2). Constant pressure heating (Points 2-3), is obtained when fuel is injected into the combustor with continuous ignition. Adiabatic expansion (Points 3-4) of the hot compressed air reduces the pressure and temperature while increasing its volume. This is represented as flow through the turbine to point 3 then flow through the power turbine to point 4. Power output is proportional to the absolute temperature of the gas temperature. The thermal efficiency of the Brayton cycle is a function of pressure ratio, ambient air temperature, and turbine inlet air temperature. Heat is then absorbed into the atmosphere. The greatest power output occurs when the turbine is operated at maximum temperature while operating inlet air at a minimum temperature. Components of a simple cycle gas turbine are shown in Figure 1. The thermodynamic process of the Brayton cycle is illustrated in Figure 2.

Figure 1: Simple Cycle Gas Turbine

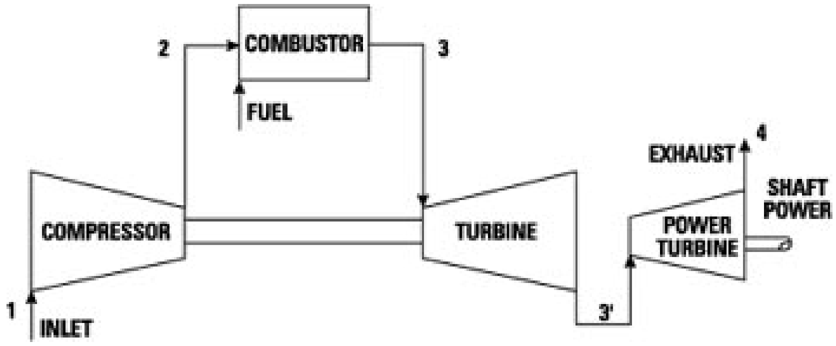
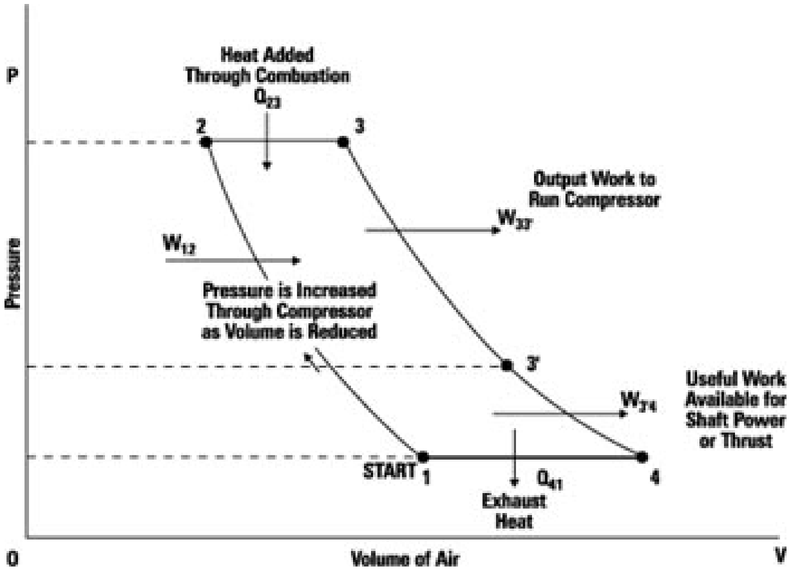


Figure 2: Brayton Cycle



The turbine chosen is single shaft, meaning the air compressor, gas producer turbine and power turbine are on the same shaft.

Generators work when a voltage inducted wire is moved through a magnetic field. The wire and the field move in alternating directions producing alternating power. Since the generator is producing 60 Hz, it operates at 1,800 rpm (a multiple of 60). The Centaur 40 turbine generator set is synchronous, meaning it provides its own source of reactive power and operates independently of external power sources (grid). Paralleling of dissimilar machines increases the likelihood of producing circulating currents. Dissimilar machines may produce slightly different waveforms. Even if the generators frequency, voltage, and waves are exactly matched, waves may not be coincident. This issue is mitigated by using only 4 Centaur 40s at once. If a larger number of smaller generators were used, or a combination of dissimilar generators was used, circulating currents become a bigger issue.

6.2 Turbine Selection

The Generator system chosen is the combination of three Solar Centaur 40 for the base load, with one redundant Centaur 40 unit running cold. The Centaur 40 turbines are rated at 3,515 kWe at 59F and sea level (ISO Standard conditions). Performance curves have been entered into Excel and matched up with hourly bin data from BinMaker Plus for Wilmington Delaware. Turbine performance data can be found in Appendix C. A brief summary is shown in Table 2.

Table 2: Centaur 40 Performance

	ISO (59F)	Average (54F)	Design Day (91F)
Quantity of Equipment	3 + 1	3 + 1	3+ 1
Electric Output kWe	10,545	10,728	9,222
Fuel (MMBtu/hr)	130	134	154

The generators were sized to meet the electrical requirements for the building. The electric load was determined as follows. The air side system supports 8,440 kW (2,400 tons of cooling). Since there is minimal envelope load induced on the building, for purposes of being conservative, we will assume it is zero. This means that the cooling capability of the building would be able to support 8,440 kW of electric load. Electric load for unconditioned spaces is also taken into account; this consists of the running cooling towers and rooftop air handling units, this is approximately 320 kW. Since the system is designed to support the whole building, the non-renovated space should also be taken into account. This space is being used as office space. Values for electric consumption were obtained from "Table C10 Electricity Consumption and Expenditure Intensities, 1999" Produced by the Energy Information Administration 1999 Commercial Buildings Energy Consumption Survey: Consumption and Expenditures Tables. It states that office spaces consume 18.7 kWh per square foot. This number was then multiplied by the floor space and divided by peak hours. This equates to 310 kW. The total electric load on the building is then computed as 9,089 kW.

Though the generators can support this entire load on the design day, because excess power is sold back to the grid, inlet cooling should be looked into. There is a 12.5% decrease in energy output when the temperature increases from 59F to design day conditions of 91F.

6.3 INLET COOLING

At high ambient temperatures, the power and efficiency of gas turbines decreases. Three approaches to air inlet cooling may be taken, including refrigeration, evaporative cooling, and thermal energy storage.

Evaporative cooling is an option. It has low capital costs. It sprays water directly into the inlet air stream. As the water evaporates, it cools the water, but is limited to wet bulb temperature. It consumes large quantities of water and is used more in larger turbines.

Thermal energy storage systems can be used to cool inlet air. The thermal energy storage for the data center, however, is only used for emergency cooling and is not designed for cooling under normal load leveling conditions.

Refrigeration cooling cools the inlet air through a heat exchanger, causing an additional pressure drop in the entering compressor air. This slightly lowers the cycle power and efficiency, but these losses are offset by the decrease in inlet air temperature. Refrigeration cooling with excess cooling produced by the chillers is shown as follows.

In order to determine the amount of cooling needed, it is important to know the inlet air flow rate. With three units at 40.5 [lb/sec] each and relative humidity of 60% at 59F, specific volume can be used to calculate the total flow rate is computed as 96,230 cfm. Calculations for inlet cooling are shown as follows:

Ideal Conditions:

Q [btu/hr] = 1.08 * cfm * Delta T

Q = 1.08 * 96,230 cfm * [91 F-59 F]

Q = 3,325,640 [btu/hr] * [ton/(12,000 btu/hr)]

Q = 277 Tons

Cooling using excess cooling from absorption chillers:

661*4 Tons (New Chillers)- 600*4 Tons (Existing Chillers) = 244 Tons

244 Tons = 2,928,000 Btu/hr

Q [btu/hr] = 1.08 * cfm * Delta T

2,928,000 [btu/hr] = 1.08 * {varies} [cfm] * Delta T

Solve for Delta T given varying inlet flow rate.

As specific volume decreases, delta T increases for the same mass flows. To be conservative, specific volume is set to follow the path when air at the design outdoor condition of 91F DB and 75F WB is sensibly cooled until saturation and then follows the saturation line. Inlet mass flows are consistent with the inlet temperature. Inlet Temperatures range from 63F to 44F when outdoor air ranges from 91F to 71F. Calculations for Inlet Air Cooling can be found in Appendix H. For outdoor temperatures below 71F, the cooling coil should be modulated.

At 63 F the turbine generator produces 3.45 MWe which is equivalent to a 1.8 % decrease in efficiency from ISO Conditions. Compared to a 12.5% decrease, inlet cooling becomes justifiable. Fuel inputs and electric outputs for the Centaur 40 given new inlet air conditions are shown in Table 3.

Table 3: Centaur 40 Performance with Inlet Cooling

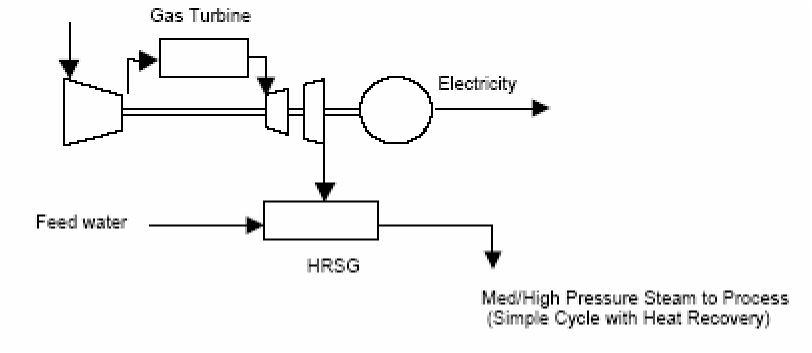
	ISO (59F)	Average Output	Design Day (91F)
Quantity of Equipment	3+1	3 + 1	3+1
Electric Output kWe	11,154	11,429	10,351
Fuel (MMBtu/hr)	136	139	128

Three coils should be selected at 33,000 cfm and 61 Tons each. The air velocity should be kept at or below 550 FPM. Face area is dependent upon the heat transfer coefficient of the coil which is dependent upon fin configuration. The coil should be custom designed by the manufacturer.

6.4 HEAT RECOVERY

Cogeneration operation uses a simple cycle gas turbine with a heat recovery heat exchanger to recover exhaust heat from the turbine and converts it to steam for useful thermal energy. In this case the recovered steam will be used to drive the absorption chillers. Gas turbines are ideally suited for cogeneration applications because their high-temperature exhaust for steam applications. An illustration of the turbine and recovery process is shown in Figure 3.

Figure 3: Turbine Generator System with HRSG



Solar engineers heat recovery steam generators (HRSG) to be integrated with their turbines. The basis of the unfired steam generator is 150 psig dry and saturated steam, however only 14.5 psig is necessary for the chillers so the HRSG should be designed based around 14.5 psig.

In order to find the mass flow of the steam, several other factors must be considered. First a combustion analysis of Natural Gas must be performed based on the mass flows of the turbine. Natural Gas is assumed to be Methane (CH_4). From this the humidity ratio of the exhaust air can be found to get the dew point. The temperature of the heat recovery stack should be higher than the dew point to prevent condensation. The minimum HRSG temperature is 275 F, which is well above the dew point of the exhaust. It is then necessary to find the exhaust power [btu/h]. This is then divided by the heat of vaporization of water to obtain the mass flow of steam [lb/h]. The average steam mass flow for four units is 81,365 lbm/h. The total required stream for all four absorption chillers is 41,000 lbm/h.

Supplementary firing increases steam production in the HRSG relative to an unfired unit. It operates on the principal that the combustion process consumes less than the available oxygen in the turbine air flow. This allows supplementary fuel firing. It raises the exhaust gas temperature entering the HRSG up to 2,800 F. This, however is not necessary, since the amount of steam produced by an unfired unit is sufficient for the selected absorption chillers. Performance data can be found in Appendix D. Calculations for the heat recovery steam generator are shown in Appendix J.

6.5 New Power

The existing transformers are stepping down 35 kV from the utility. New transformers should be sized to replace the existing ones. The Centaur 40 generator may be specified with a voltage ranging from 3,300 to 13,800 V. A transformer would be sized to step down from the new voltage to 480 V.

Busses should also be resized to contain the new amperage.

6.6 Energy Sell Back

Since it is important to run a redundant generator for reliability purposes, energy sell back becomes an important issue. Concerns with interconnection arise from both the utility and the power producer. Power quality is an issue because the quality of power available from the site generator exceeds the quality available from the grid. This is typically caused by other end users connected to the grid. Utilities are concerned with power safety. If personnel are working on a deenergized utility and an interconnected generator is energized, safety hazards occur for the personnel. This is prevented if the utility installs an external disconnect switch accessible by utility personnel. Dispatchability is also a concern for the utilities. It is required the cogenerator be isolated from the utility grid during periods of emergency for grid safety. Grid operation is very intricate, and the addition of more power sources increases this complexity.

Circuit breakers isolate problems at the load and to protect the remainder of the network. Circuit breakers and fuses are devices that are designed to open or break a circuit. This happens automatically when currents exceed a preset limit for a preset period of time. A circuit breaker may be triggered directly or as the result of a signal from a relay. Relays monitor, voltage, power, current, frequency, phase imbalances, and the direction of power flow in a circuit. They signal circuit breakers to open if tolerances are exceeded.

The Centaur 40 is equipped with auto synchronizing. Synchronization must be used when multiple generators are linked with each other and the grid. An anticipatory synchronizer monitors both the bus and generator in order to parallel the generator to the bus. It initiates closure when the generator is matched to that bus. It corrects for speed and voltage by providing signals to the generator for synchronization. Overrides are also included to allow the generator to feed into a dead bus is may be necessary for emergency or black-start operations. An anticipatory synchronizer causes closure at a minimum phase difference.

Upon startup of the engine generator, it must be brought up to speed unloaded. Startup should be controlled both manually and automatically. Automatic startup may be triggered by a load condition or a comparison of on-line capacity and loads. Since, however, the system is to be run at full capacity 24/7 the system should remain online unless there is machine failure or maintenance. The startup signal initiates the cranking of the engine, opens the fuel supply, lubricates the engine and activates the system heat rejection, along with activation of the synchronizer. The Centaur 40 is equipped with startup controls.

Since multiple generators are connected in parallel, additional controls are necessary to balance and regulate both the real and reactive loads among generators. If reactive loads are not balanced circulating currents may occur. These currents result in generator overheating, degraded performance, and a shortened lifespan. Generator loop control can reduce the risk of this happening. Load control is important for the control of the fuel or steam being delivered to each prime mover. It should be based on power being delivered by the engine, not a current measurement. Unbalanced loads result in failure to use available capacity.

Paralleling should be based on "Random access" meaning generators are paralleled to the bus in the order in which they are available. Synchronizers must be equipped for each generator in order for this to work. Since each Centaur 40 is equipped with synchronizers, this is the best option.

PURPA requires that any qualifying cogeneration facility with a capacity less than 80 megawatts be able to sell back power to the utility. Conectiv classifies this facility as Rider "EP", meaning it is a qualifying facility with generating capacity of grater than 1,000 kW. This category purchases power under special contracts, rather than a set tariff. The utility is required to pay the cogenerator the avoided cost, meaning it is required to pay the amount it would cost to produce the electricity in real time.

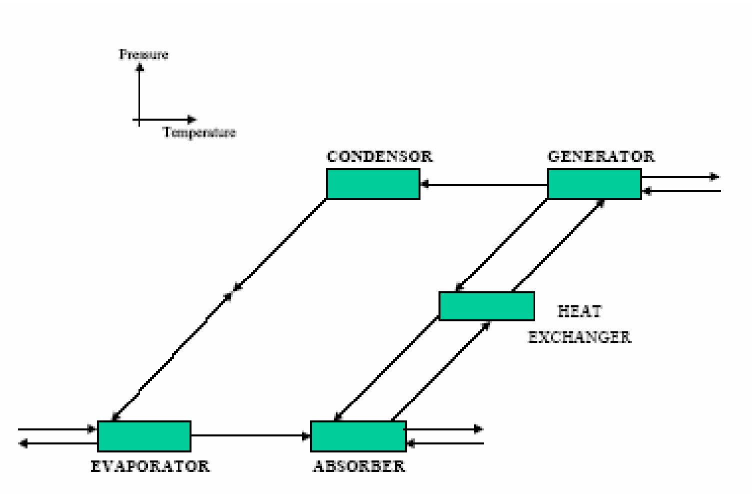
For simplicity it is assumed the utility pays out half the industrial charged rate ($7.45/MMBtu). While the four generators produce approximately 3,515 kW each at rated conditions (59F, 60% RH), the building only consumes 9,089 kW. The annual excess energy produced by the generators is 18,823,042 kWh. The total revenue from the utility is $478,122 per year. Calculations for energy sell back along with utility costs are shown in Appendix K.

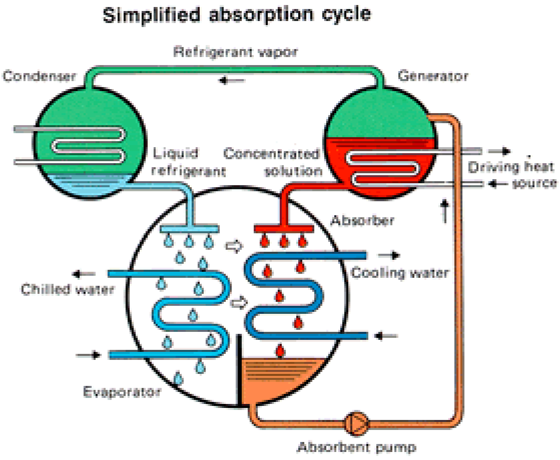
6.7 Absorption Chillers

The use of absorption chillers eliminates the high incremental cost of electric cooling. Absorption chillers may be run off of natural gas or recovered steam. Utilizing waste heat from a generator that would otherwise be exhausted increases system the cost-effectiveness, compared to consuming gas directly. Emissions are reduced because CFC and HCFC refrigerants are not used in the absorption cycle. Other benefits include vibration-free operation, lower pressure systems with no large rotating components, high reliability, and low maintenance.

The single-effect cycle consists of an evaporator, absorber, generator and condenser. Figure XX shows in the Pressure-Temperature diagram in Figure 4. Figure 5 shows a generic diagram of the absorption cycle.

Figure 4: Pressure Temperature Diagram, Figure 5: Single Effect Absorption Refrigeration Cycle





The single stage absorption cycle employs an absorbate (refrigerant), and an absorbent. In this case water is used as the refrigerant and lithium bromide as the absorbent. These fluids are separated and recombined in the absorption cycle. The cycle works as follows:

- The LiBr releases heat when low –pressure water vapor is absorbed.
- The liquid solution is pumped to a high pressure generator. This process uses significantly less electricity the compression process of the electric chiller.
- Heat is added at the generator from recovered steam.

- Water is desorbed from the LiBr and vaporized.
- The vapor proceeds to the condenser, where heat is rejected and condensed to a high pressure liquid.
    - The remaining liquid LiBr in the generator passes through a pressure reducing valve. Low-pressure water vapors returning from the evaporator mix with the LiBr so the cycle can be repeated.
- An expansion valve is used to throttle the high pressure liquid.
- The liquid moves to the evaporator where it absorbs heat and evaporates.

Though the new equipment may be different, the waterside systems are set up the same as the existing system. Schematics can be found in Appendices A and B. Since the new system is designed to support the same load as the existing facility its cooling capacity is 24,000 tons. Chillers selected are four Board single stage absorption chillers (model BDS 200), plus one redundant. Each chiller has a 661 ton cooling capacity. Of this, 24,000 tons will be used for the building thermal load while the remaining 244 tons will be used to support inlet cooling for the turbines. Chiller data can be seen in Table 4. Performance data can be found in Appendix E.

Table 4: Absorption Chiller Data.

	Board Single – Stage Chiller	
	Condenser	Evaporator
Quantity	4 + 1	4 + 1
Flow rate (gpm)	2,869	1,257
Temperature (F)	85 – 97.5	56.7 – 44
Pressure Drop (Ft. H2O)	22	7.6
Input: Electric (kW)	8.4	
Input: Steam (lb/h)	10,243	
Output (Tons)	661	
Rated COP	0.78	

Chiller staging will follow the same sequence of operations as the existing system, however adjustments should be made to account for turbine inlet cooling loads due to outdoor conditions. When no inlet cooling is required, one chiller shall be run at part load.

6.8 COOLING TOWER

The existing cooling towers would need to be replaced with larger ones to compensate for the higher condenser water flow rate required for absorption chillers as opposed to a standard electric chiller. Cooling tower selection is based on flow rate and range. The new flow rate for the condenser water side is 2,869 gpm per chiller. The cooling tower will be needed to decrease the condenser water temperature from 97.5 F to 85 F. This corresponds to a range of 12.5 F. One cooling tower is chosen for each chiller, these are set up in parallel and also non-dedicated. The cooling towers chosen are Marley NC8312N1. Data can be found in Table 5. Performance data can be found in Appendix F.

Table 5: Cooling Tower Data

	Marley Cooling Tower
Model	NC8312N1
Quantity	4 + 1
Flow rate (gpm)	2,869
Temperature (F)	97.5 – 85
Wet Bulb (F)	79
Range (F)	12.5
RPM	1,800
Fan Motor Output BHP	100

6.9 Condenser Water Pumps and piping

Cooling towers are not the only equipment effected by the higher condenser water flow rate. Pumps are also re-designed to handle the higher flow. Though the flow on the chilled water side increases, the existing pipes can support the new flow.

Condenser water pumps will be set up the same as in the existing conditions, however the size changes. New Bell and Gossett pumps are selected for 2,869 gpm. Pump data is shown in Table 6. Performance data is given in Appendix G.

Table 6: Pump Data

	Condenser	Chilled Water
Quantity	4 + 1	4 + 1
Flow rate (gpm)	2,869	1,257
Head (ft)	100	150
Motor (BHP)	88	75
Size	8G	8x6x13
Series	1510	4030
RPM	1770	1800
Brand	B&G	Armstrong

The existing condenser water piping is insufficient for supporting the new flow. Table 7 illustrates how pipe size must be changed to support new flow rates. All 10 inch pipe shall be removed and replaced with 12 inch pipe. All 18 inch pipe shall be replaced with 24 inch pipe.

Table 7: Condenser Water Piping

	Flow (gpm)	Diameter (in)	Head Loss (ft/100 ft)
Old	1800	10	1.543
Old	1800	12	0.628
Old	7200	18	1.425
New	2869	12	1.518
New	11476	24	0.778

7.0 System Redesign Analysis

7.1 Emissions

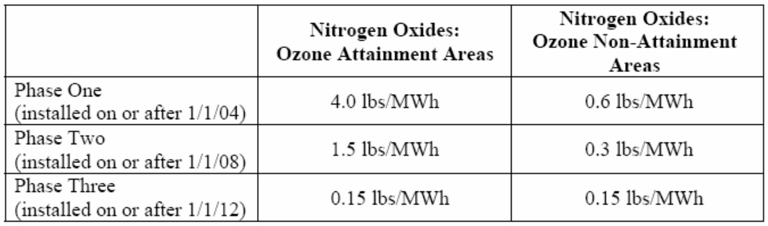
Natural gas is a clean burning fossil fuel. It consists of a mixture of hydrocarbon gases, primarily Methane (CH_4). In analyzing the combustion process, it is evident the amount of carbon dioxide (CO_2) produced from the combustion of hydrocarbon fuels is directly proportional to the amount of carbon in the fuel. Methane contains less carbon than coal and oil. Because gas contains fewer impurities and is easier to purify than coal and oil, it is cleaner burning. Exhaust consists mainly of water and CO_2, with very little Carbon Monoxide (CO) or Nitrogen oxide (NO_x). Emissions for natural gas, oil, and coal are shown in Table 8.

Table 8: Fossil Fuel Emissions

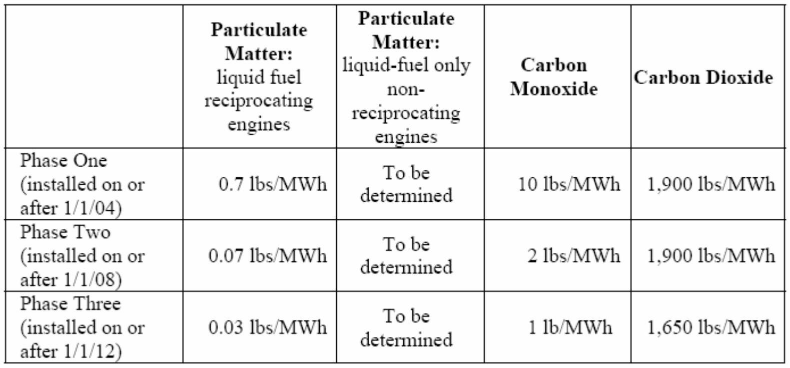
Fossil Fuel Emission Levels - Pounds per Billion Btu of Energy Input			
Pollutant	**Natural Gas**	**Oil**	**Coal**
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016
Source: EIA – Natural Gas Issues and Trends 1998			

Emissions are a concern on the national level. The national model rule for regulation of emissions from distributed generation is sponsored by the US DOE’s National Renewable Energy Lab and coordinated by the Regulatory Assistance Project (RAP). The Model Emissions Rule addresses emissions standards for Non-Emergency Generators as shown in Table 9.

Table 9: NO_x, CO and CO_2 Regulations



	Nitrogen Oxides: Ozone Attainment Areas	**Nitrogen Oxides: Ozone Non-Attainment Areas**
Phase One (installed on or after 1/1/04)	4.0 lbs/MWh	0.6 lbs/MWh
Phase Two (installed on or after 1/1/08)	1.5 lbs/MWh	0.3 lbs/MWh
Phase Three (installed on or after 1/1/12)	0.15 lbs/MWh	0.15 lbs/MWh



	Particulate Matter: liquid fuel reciprocating engines	**Particulate Matter:** liquid-fuel only non-reciprocating engines	**Carbon Monoxide**	**Carbon Dioxide**
Phase One (installed on or after 1/1/04)	0.7 lbs/MWh	To be determined	10 lbs/MWh	1,900 lbs/MWh
Phase Two (installed on or after 1/1/08)	0.07 lbs/MWh	To be determined	2 lbs/MWh	1,900 lbs/MWh
Phase Three (installed on or after 1/1/12)	0.03 lbs/MWh	To be determined	1 lb/MWh	1,650 lbs/MWh

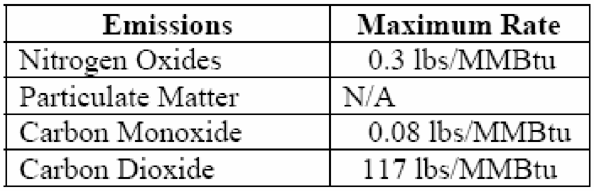
The building is located in a non-attainment area and should therefore follow more stringent NO_x standards. The installation is to be between 1/1/04 and 1/1/08 which puts it in the phase one category.

Since the turbine is connected to a heat recovery steam generator, credit for emissions based on the emissions that would have been created by a conventional separate system to generate the same thermal output can be subtracted. The credit will be subtracted from the actual emission rate of the CHP unit to produce the emission rate used for compliance purposes.

$$\text{Credit lbs/Mwh}_{\text{emissions}} = [(\text{boiler limit lbs/MMBtu})/(\text{boiler efficiency})] * [3.412/(\text{power to heat ratio})]$$

- The emission rates for the displaced thermal system (*e.g.*, boiler) are shown in Table 10.

  Table 10: Typical Boiler Emissions



Emissions	Maximum Rate
Nitrogen Oxides	0.3 lbs/MMBtu
Particulate Matter	N/A
Carbon Monoxide	0.08 lbs/MMBtu
Carbon Dioxide	117 lbs/MMBtu

- The efficiency of the avoided thermal system is assumed to be 80%.

Delaware emissions requirements for plants listed in tons per year are shown in Table 11.

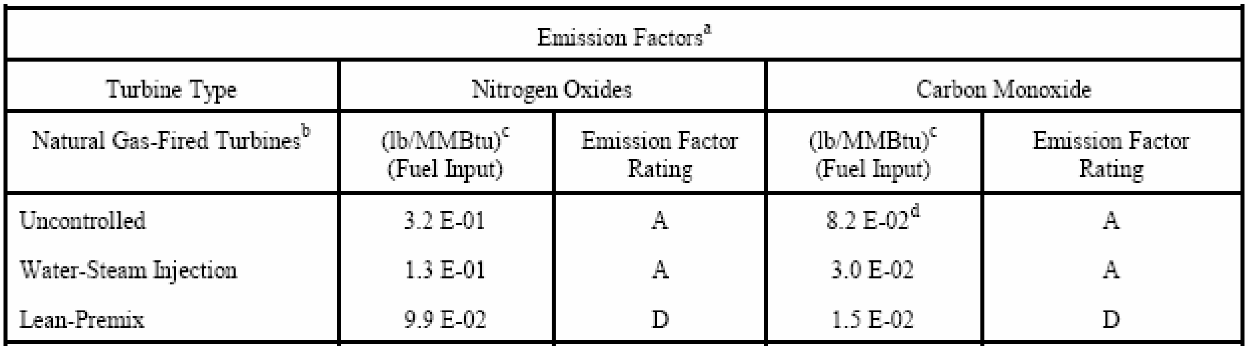
Table 11: Delaware Emissions Requirements

Delaware [tpy]	
NO_x	40
VOC	40
CO	100
CO_2	-
SO_2	40
PM	25
Lead	0.6
* NO_x	25
*VOC	25
* For Non-attainment areas	

The Centaur 40 has optional emission controls including Lean-Premix, Dry, Low Emission (SoLoNox) and Water injection. In order to determine whether either of these are required the uncontrolled unit should be analyzed.

The following data is provided by *AP 42, Fifth Edition, Volume I – Chapter 3: Stationary Internal Combustion Sources* for stationary gas turbines. Table 12 shows NO_x and CO emission factors for natural gas-fired turbines based on a higher heating value (HHV) of 1020 Btu/scf, average heating value should be accounted for in analyzing annual emissions.

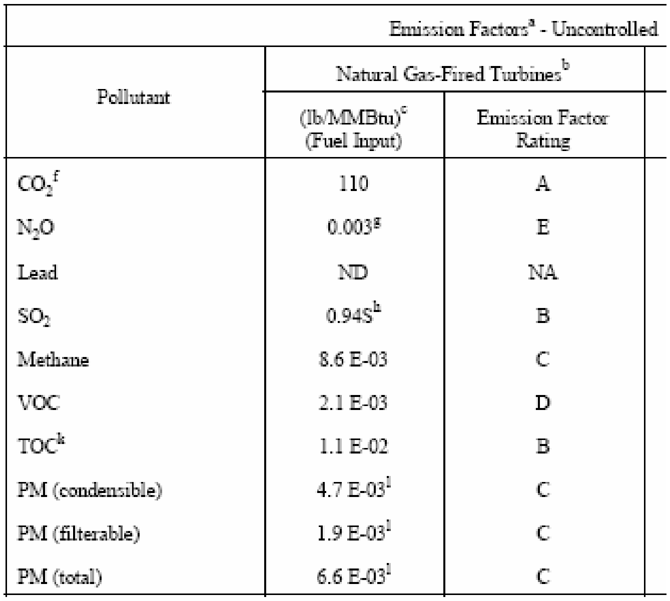
Table 12: Gas Turbine NO_x , CO Emissions



Emission Factors[a]				
Turbine Type	Nitrogen Oxides		Carbon Monoxide	
Natural Gas-Fired Turbines[b]	(lb/MMBtu)[c] (Fuel Input)	Emission Factor Rating	(lb/MMBtu)[c] (Fuel Input)	Emission Factor Rating
Uncontrolled	3.2 E-01	A	8.2 E-02[d]	A
Water-Steam Injection	1.3 E-01	A	3.0 E-02	A
Lean-Premix	9.9 E-02	D	1.5 E-02	D

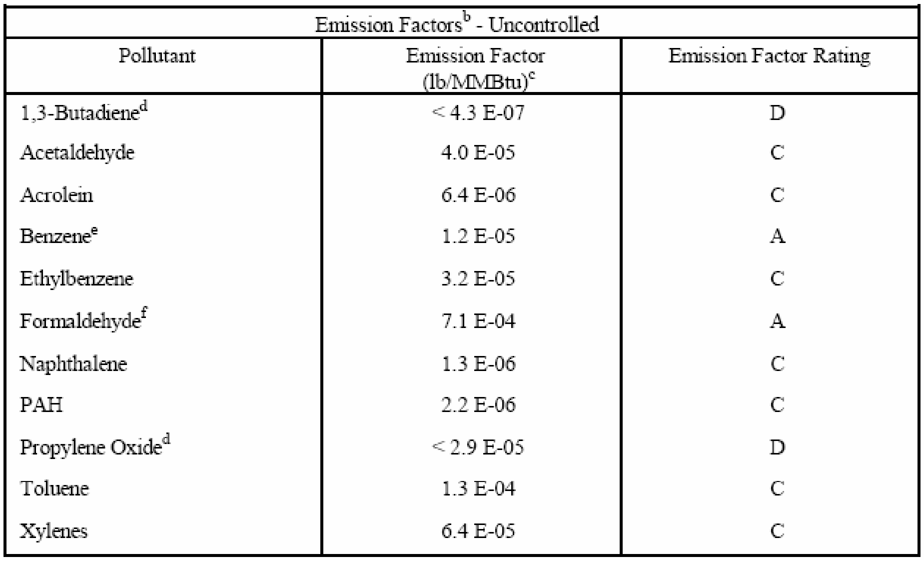
Table 13 shows emission factors for natural gas turbines including Carbon Dioxide (CO2), lead, Sulfur Dioxide (SO2), Volatile Organic Compounds (VOCs), and Partiaculate Matter (PM). No data was obtained for lead. Emission factors for particulate matter are based on combustion turbines using water-steam injection. Emission factors for other hazardous air pollutants (as stated in the *Clean Air Act*) are shown in Table 14.

Table 13: Gas Turbine Emissions



Pollutant	Emission Factors[a] - Uncontrolled	
	Natural Gas-Fired Turbines[b]	
	(lb/MMBtu)[c] (Fuel Input)	Emission Factor Rating
CO_2[f]	110	A
N_2O	0.003[g]	E
Lead	ND	NA
SO_2	0.94S[h]	B
Methane	8.6 E-03	C
VOC	2.1 E-03	D
TOC[k]	1.1 E-02	B
PM (condensible)	4.7 E-03[l]	C
PM (filterable)	1.9 E-03[l]	C
PM (total)	6.6 E-03[l]	C

Table 14: Gas Turbine Emissions



Emission Factors[b] - Uncontrolled		
Pollutant	Emission Factor (lb/MMBtu)[c]	Emission Factor Rating
1,3-Butadiene[d]	< 4.3 E-07	D
Acetaldehyde	4.0 E-05	C
Acrolein	6.4 E-06	C
Benzene[e]	1.2 E-05	A
Ethylbenzene	3.2 E-05	C
Formaldehyde[f]	7.1 E-04	A
Naphthalene	1.3 E-06	C
PAH	2.2 E-06	C
Propylene Oxide[d]	< 2.9 E-05	D
Toluene	1.3 E-04	C
Xylenes	6.4 E-05	C

Emissions factors in tons per year for the Centaur 40 are shown in Table 15.

Table 15: Centaur 40 Emissions

Emissions Factors [Tons/year] – 3.515 MW			
	Uncontrolled	Water Steam Injection	Lean-Premix
NO_x	4.93	2.00	1.52
CO	1.26	0.46	0.23
CO_2	20804.12	-	-
Lead	-	-	-
SO_2	0.60	-	-
VOC	0.40	-	-
PM – Condensible	-	0.89	-
PM – Filterable	-	0.36	-
PM – Total	-	1.25	-
* For 3.515 MW unit consuming 43.17 MMBtu/hr (rated conditions)			

Emissions factors in tons per year for the Centaur 40 with HRSG are shown in Table 16.

Table 16: Centaur 40 Emissions with HRSG Credit

Emissions Factors With HRSG Credit [Tons/year] – 3.515 MW			
	Uncontrolled	Water Steam Injection	Lean-Premix
NO_x	2.76	-0.17	-0.64
CO	0.68	-0.12	-0.35
CO_2	19958.20	-	-
Lead	-	-	-
SO_2	0.60	-	-
VOC	0.40	-	-
PM – Condensible	-	0.89	-
PM – Filterable	-	0.36	-
PM – Total	-	1.25	-
* For 3.515 MW unit consuming 43.17 MMBtu/hr (rated conditions)			

Tables 15 and 16 show that the Centaur 40 running uncontrolled complies to national and state emissions standards. It is not necessary to add water steam injection or lean-premix.

7.2 SYSTEM EFFICIENCIES

System efficiencies for combined heat and power are looked at in terms of total efficiency, power/steam ratio, net heat rate, and effective electrical efficiency. Combined heat and power efficiencies are shown in Table 17.

- Total efficiency = (electric generated + net steam produced) / (fuel input)
- Power/Steam Ratio = electric power output (Btu)/ useful steam output (Btu)
- Net Heat Rate = (fuel input – fuel for steam if no HRSG)/ electric output (kW).
    - If no heat recovery is used the fuel would be needed to support a boiler, assume 80% efficiency.
- Effective Electrical Efficiency = (electric power output) / (Total fuel– total heat recovered/.8)
    - Equivalent to 3412 Btu/kWh/Net Heat Rate.

Table 17: Cogeneration Efficiencies

Total CHP Efficiency (%), HHV	0.78
Power/Heat Ratio	0.56
Net Heat Rate (Btu/kWh)	4577
.Effective Electrical Efficiency (%), HHV	0.75
FERC Efficiency	0.53

Since the steam produced only goes to the absorption chillers which only require 10,243 lb/hr each, the excess steam would be wasted. New efficiencies are shown in Table 18.

Table 18: System Efficiencies

Total CHP Efficiency (%), HHV	0.62
Power/Heat Ratio	0.84
Net Heat Rate (Btu/kWh)	7072
Effective Electrical Efficiency (%), HHV	0.48
FERC Efficiency	0.45

Not all non-utility generators (NUG) can be classified as qualified facilities (QF). According to the Public Utility Regulatory Policies Act (PURPA), along with operating and ownership criteria it must follow efficiency requirements established by the Federal Energy Regulatory Commission (FERC). The ownership standard states that no more than 50% of a facility be owned by electric utilities. The operating standard required that a minimum of 5% of the useful output be in the form of useful thermal energy. The efficiency standard states that the efficiency be at least 45% for topping cycles. If the amount of useful thermal energy exceeds 15%, then the efficiency threshold decreases to 42.5%.

- FERC Efficiency = Power output + .5 * useful thermal output / energy input
    - Energy input measured at lower heating value (LHV).

The FERC efficiency is 45% making it a qualifying facility. If there was one redundant generator running hot and one running cold, the FERC efficiency would only be 41% because there is no use for the recovered steam from that extra unit. The system would not be able to obtain status as a QF. If the facility does not have QF status, the utility is not required to purchase excess power produced by the cogenerator.

7.3 First Cost

According to Conectiv's natural gas tariff, the customer is responsible for making the necessary arrangements for delivering gas to the company's interconnection with the delivering pipeline supplier. Also, interconnection fees between the generators and electric grid are to be paid by the customer.

Equipment costs are also included in first cost. Equipment costs for the new system are shown in Table 19, while costs for the equipment the new system replaces are listed in Table 20. Though renovation costs for the existing system have been quantified, they were not for the same equipment so these values cannot be compared directly. Table 20 shows only the equipment that would be effected by the new redesign. It is evident that the first cost of the new system is much greater. Payback will depend on energy costs and avoided costs due to improved reliability.

Table 19: New Equipment First Cost

Equipment	Quantity	Unit Price	Total Cost	Source
Cooling Tower Pumps	5	8,000	40,000	B&G
Absorption Chillers	5	256,000	1,280,000	Broad
Centaur 40 Turbine/Generator	4	970/kW	13,638,200	Solar
Cooling Tower	2,400 Ton	333,500	333,500	Marley
Inlet Cooling Coil	1	4,000	12,000	Trane
Piping 12"	350 LF	128/LF	44,800	Means
Piping 24"	850 LF	247/LF	209,950	Means
			$15,558,450	

Table 20: Existing Equipment First Cost

Equipment	Quantity	Unit Price	Total Cost	Source
Cooling Tower Pumps	5	7,490	37,450	Means
Centrifugal Chillers	5	142,722	713,610	Carrier
Cooling Tower	5	37,900/ 600ton	189,500	Means
Piping 12"	350 LF	128/LF	44,800	Means
Piping 18"	850 LF	177/LF	150,450	Means
			$1,135,810	

7.4 ENERGY COST DATA

According to the Energy Information Administration's Annual Energy Outlook (AEO) 2005, the cost of natural gas and electricity for an industrial end use is as follows:

Table 21: AEO for Natural Gas and Electricity

	Natural Gas ($/MCF)	Electricity (Cent/kWh)
2003	5.72	5.10
2015	4.96	5.00
2025	5.63	5.40

Energy rates for both electricity and natural gas, though not equal, appear to follow the same trends through 2025. It does not appear natural gas will become cheaper than electricity, so there is no payback apparent in the next 25 years due to utility savings.

7.5 MAINTENANCE

Operation and maintenance costs include routine inspections, scheduled overhauls. Routine maintenance practices are in included in Table 22.

Table 22: Centaur 40 O&M

On-line running maintenance
Predictive Maintenance
Plotting Trends
Performance Testing
Fuel Consumption
Heat Rate
Vibration Analysis
Preventive Maintenance

In addition to daily maintenance by visual inspection of filters and site conditions, more intensive inspections should be provided every 4,000 hours. These shall ensure the turbines don't have damage due to worn bearings, rotors, and damaged blade tips causing excessive vibration. The combustion path is also inspected for wear and cleanliness Restoration overhauls should be performed every 25,000 to 50,000 hours. Operating the turbine over the rated capacity for significant periods of time dramatically increases the number of hot path inspections and overhauls. Centaur 40 costs appear in Table 23. According to Solar the expected maintenance cost for a system rated for 10MW is approximately $0.0055/kWh. The yearly O & M cost of this system is $550,601.

Table 23: Centaur 40 O&M Costs

Electric Capacity, kW	10,000
Variable (service contract), $/kWh	0.0045
Variable (Consumables), $/kWh	0.0001
Fixed, $/kW-yr	7.5
Fixed, $/kWh @ 8000 hrs/year	0.0009
Total O&M Costs, $/kWh	0.0055

7.6 RELIABILITY

Reliability can be looked at on a couple different levels, it can be expressed as a function of outages, and more specifically power quality. Reliability issues arise from equipment downtime as well as from the grid. When analyzing cogeneration versus utility power different issues arise.

The equivalent availability factor (EAF) measures duration as well as extent of outages. It is useful for multi-engine systems where an outage of one or more engines could occur. Combustion turbine based systems where capacity may be limited by high ambient temps and systems where full or partial failure of ancillary subsystems or equipment limits the output of the cogeneration system.

EAF = (1-POR)*(1-EFOR)

- POR is the planned outage factor which is the ratio of planned outage ours to total hours.
- EFOR is the equivalent forced outage rate which considers partial outages.
    - EFOR = (forced outage hours + equivalent forced derated hours) / (forced outage hours + total service hours)

Power quality is also an issue because fluctuations can be detrimental to sensitive computer equipment. It can be expressed as voltage sags, transient voltages, harmonics, and frequency variations. Sags, and swells, are the most common and are brief reductions, or increases, in voltage ranging from one cycle to a second or so. They are typically caused within the building, but may also arrive from the utility. Transient over-voltages are high-frequency increases in voltage on AC mains. Low frequency transients are caused by capacitor switching, while high frequency transients are typically caused by inductive loads and lightning. Harmonics are caused when waveforms are not sinusoidal current distorted. Frequency variations from the utility grids associated with catastrophic collapses are also a concern.

Reliability numbers are difficult to quantify, but because power quality issues are very common, the reliability of a cogeneration plant is much greater than that of a building served by the grid.

8.1 CONCLUSION

When converting a building to cogeneration there are several benefits as well as drawbacks. Benefits include increased reliability, and lower emissions from the production of energy. The biggest engineering concerns when designing a data center with sensitive equipment are reliability and redundancy. This system takes care of both concerns. Though it may not be a concern of the owner, the lower emissions from the cogenerator as opposed to using electricity from the grid is also a benefit. The main drawback is first cost. In order to build a building using cogeneration, the owner must have a sufficient capital. Though some states give incentives for cogeneration, there are none for the state of Delaware for a facility of this size. Payback periods may not be evident given the larger cost of natural gas compared with electricity. Savings in reliability, however, do provide a significant payback though quantifying the specific uptime/ power quality is beyond the scope of this case study.

Though Cogeneration facilities have a significant first cost and payback may not be readily evident, the reliability of the system may be attractive enough for the owner to make the initial investment.

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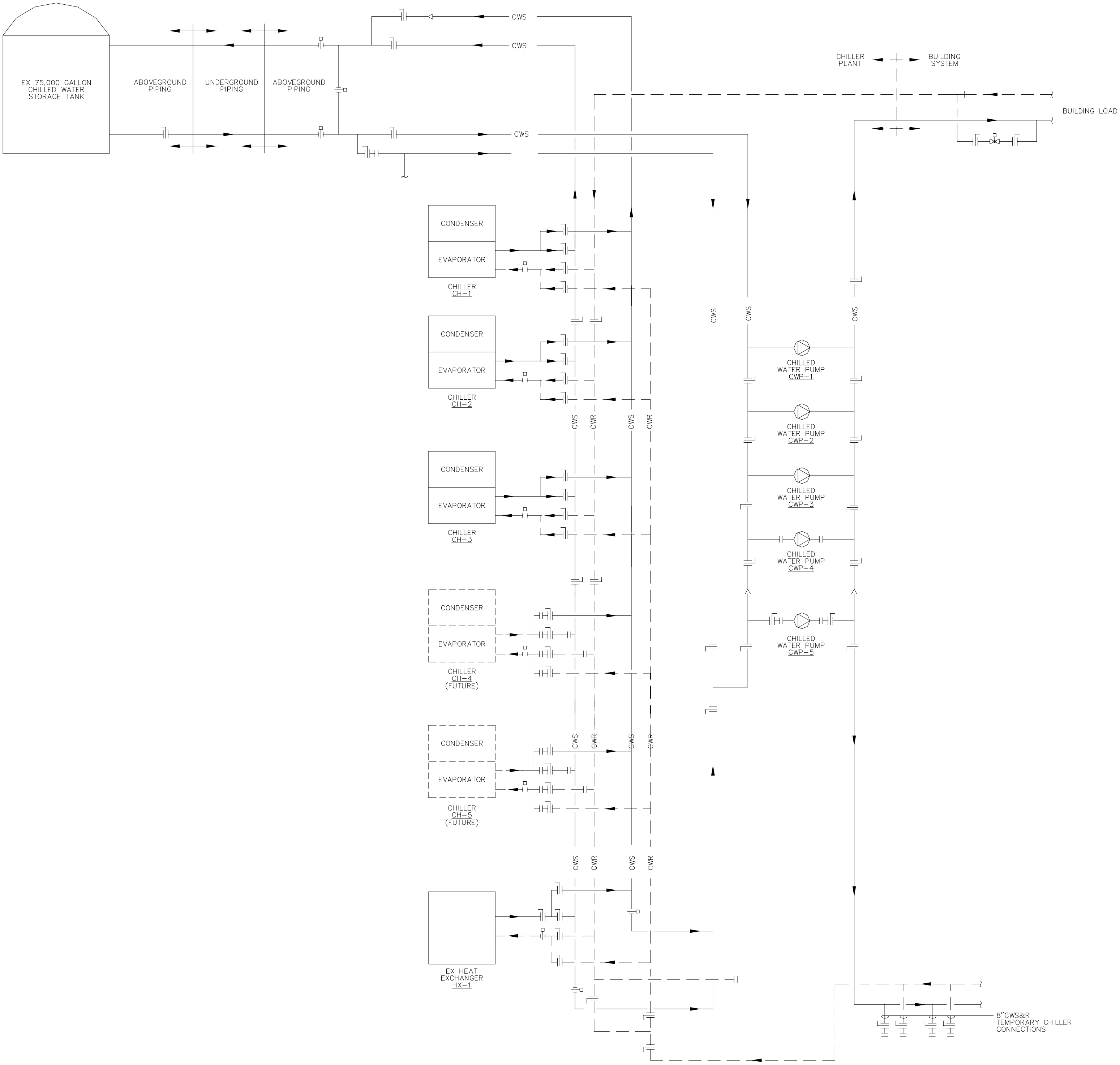
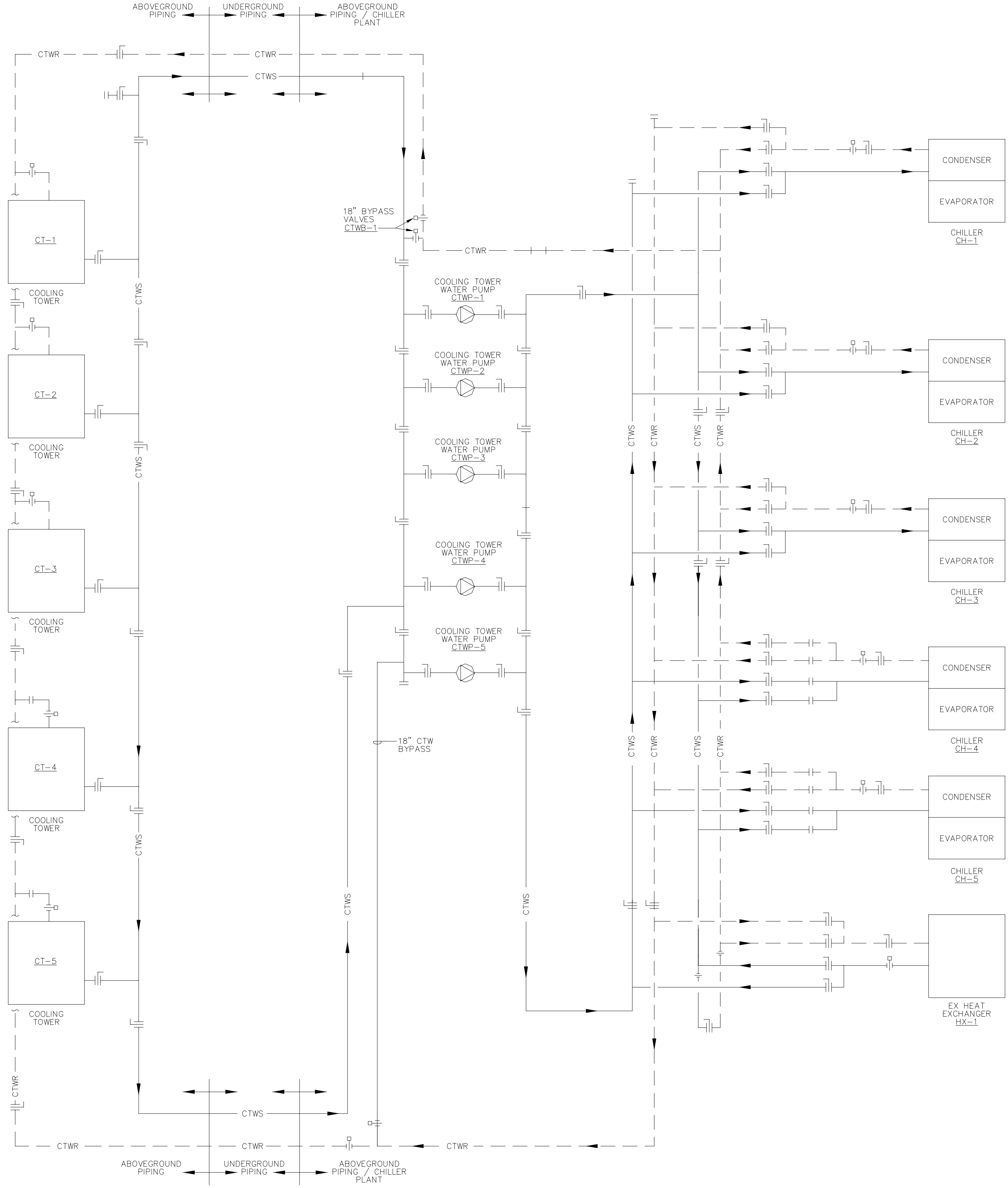
Appendix A: Chilled Water Schematic



Appendix B: Condenser Water Schematic



Solar® Turbines
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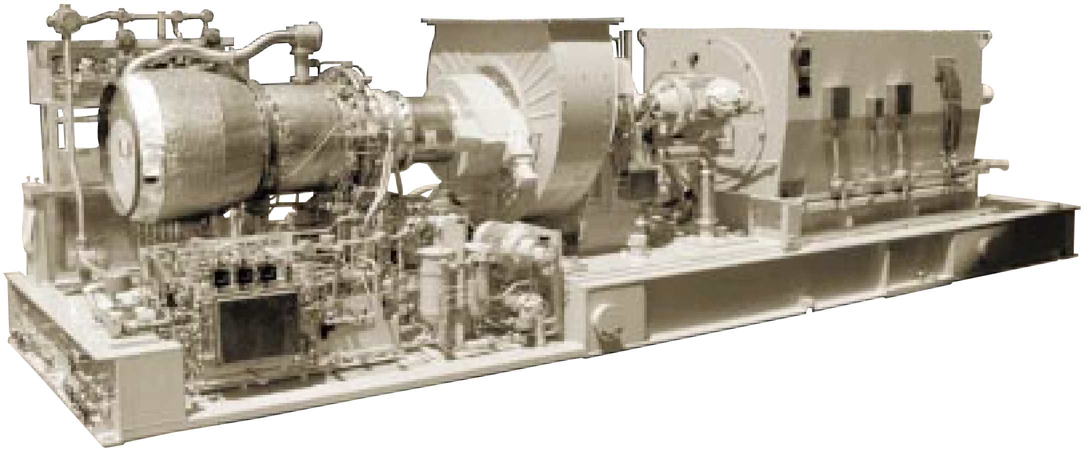
CENTAUR 40

Gas Turbine Generator Set



General Specifications

Centaur® 40 Gas Turbine

- Industrial, Single-Shaft
- Axial Compressor
  - – 11-Stage
  - – Variable Inlet Guide Vanes
  - – Compression Ratio: 9.7:1
  - – Inlet Airflow: 18.4 kg/sec (40.5 lb/sec)
  - – Max. Speed: 14,944 rpm (50 Hz) 14,951 rpm (60 Hz)
- Combustion Chamber
  - – Annular-Type
  - – Optional: Lean-Premix, Dry, Low Emission (*SoLoNO*$_x$™) or Water Injection
  - – 10 Fuel Injectors
  - – Torch Ignitor System
- Turbine
  - – 3-Stage, Reaction
- Bearings
  - – Journal: Tilting-Pad
  - – Thrust: Fixed Tapered Land
- Coatings
  - – Compressor: Inorganic Aluminum
  - – Turbine and Nozzle Blades: Precious Metal Diffusion Aluminide
- Vibration Transducer Type
  - – Velocity

Main Reduction Drive

- Epicyclic Type
- 1500 or 1800 rpm

Generator

- Type: Salient Pole, 3 Phase, 6 Wire, Wye Connected, Synchronous, with Brushless Exciter
- Construction Options
  - – Open Drip Proof
  - – Weather Protected II (WPII)
  - – Totally Enclosed Water/Air Cooled
- Sleeve Bearings
- Voltage Regulation
  - – Solid-State Regulation with Permanent Magnet Generator
- Insulation/Rise Options
  - – NEMA Class F with F Rise
  - – NEMA Class F with B Rise
- Voltages: 3300 to 13,800 Volt
- Frequency: 50 or 60 Hz

Key Package Features

- Base Frame with Drip Pans
- 316L Stainless Steel Piping
- Compression-Type Tube Fittings
- Fluid Gauge Panel
- Electrical System Options
  - – NEC, Class I, Group D, Div 2
  - – IEC, Zone 2
- *Turbotronic™* Microprocessor Control System
  - – Free-Standing Control Console
  - – Color Video Display
  - – Vibration Monitoring
- Control Options
  - – 24-Vdc Control Battery/Charger
  - – Gas Turbine and Package Temperature Monitoring
  - – Serial Link Supervisory Interface
  - – Turbine Performance Map
  - – Historical Displays
  - – Printer/Logger
  - – Predictive Emissions Monitoring
  - – Field Programming
- Start Systems
  - – Pneumatic
  - – Direct Drive AC
- Fuel Systems
  - – Natural Gas
  - – Liquid
  - – Dual (Gas/Liquid)
  - – Alternate Fuels
- Integrated Lube Oil System
  - – Turbine-Driven Accessories
- Oil System Options
  - – Oil Cooler
  - – Oil Heater
  - – Tank Vent Separator
  - – Flame Trap
- Axial Compressor Cleaning Systems
  - – On-Crank
  - – On-Crank/On-Line
  - – Stationary Cleaning Tank
  - – Portable Cleaning Tank
- Air Inlet and Exhaust System Options
- Enclosure and Associated Options
- Factory Testing of Turbine and Package
- Documentation
  - – Drawings
  - – Quality Control Data Book
  - – Inspection and Test Plan
  - – Test Reports

Solar Turbines
A Caterpillar Company

CENTAUR 40
Gas Turbine Generator Set

Performance

No Inlet/Exhaust Losses,
Relative Humidity 60%,
Natural Gas Fuel with
LHV = 31.5 to 43.3 MJ/nm^3
(800 to 1100 Btu/scf)

Nominal Rating – ISO
At 15°C (59°F), Sea Level

Output Power
Continuous Duty
3515 kW_e

Heat Rate
12 912 kJ/kW_e-hr
(12,240 Btu/kW_e-hr)

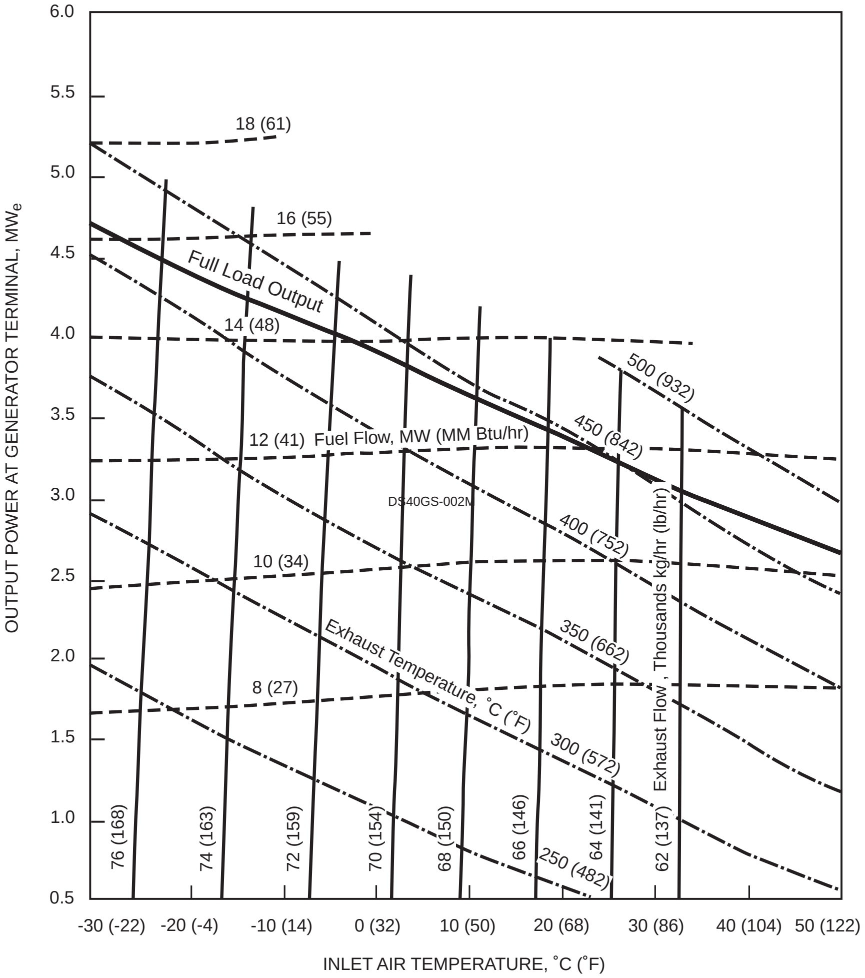
Exhaust Flow
67 004 kg/hr
(147,718 lb/hr)

Exhaust Temp
437°C (819°F)

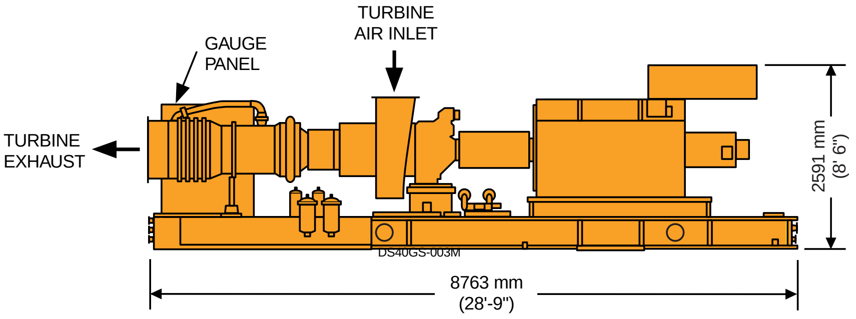
Nominal/Expected Power
Not Guaranteed

°C = (°F - 32) 5/9; 0.7457 kW = 1 hp;
1.055 kJ/kW_e-hr = 1 Btu/kW_e-hr;
0.4536 kg = 1 lb
STANDBY RATINGS AVAILABLE

Available Power



Package Dimensions



Typical Package Weight = 26 015 kg (57,350 lb)
Width = 2.44 m (8' 0")

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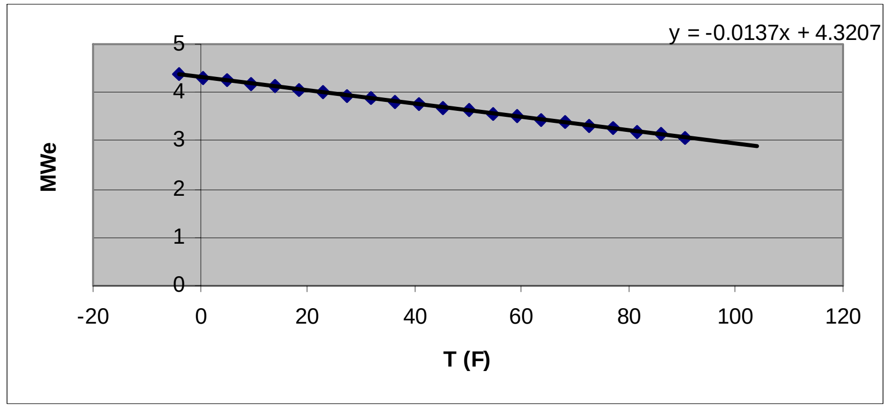
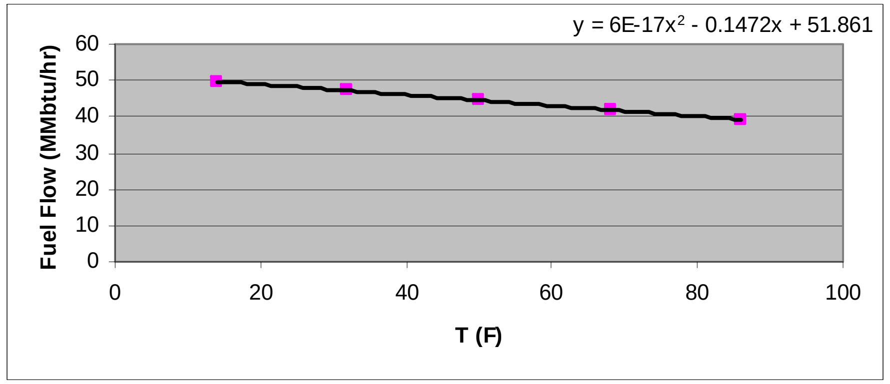
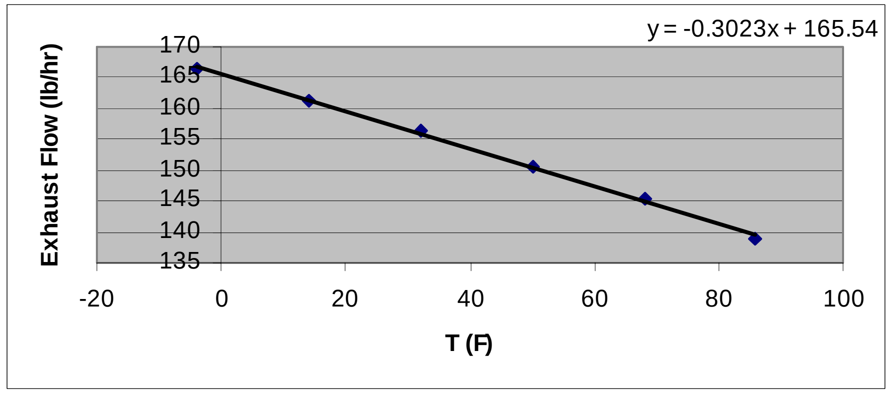
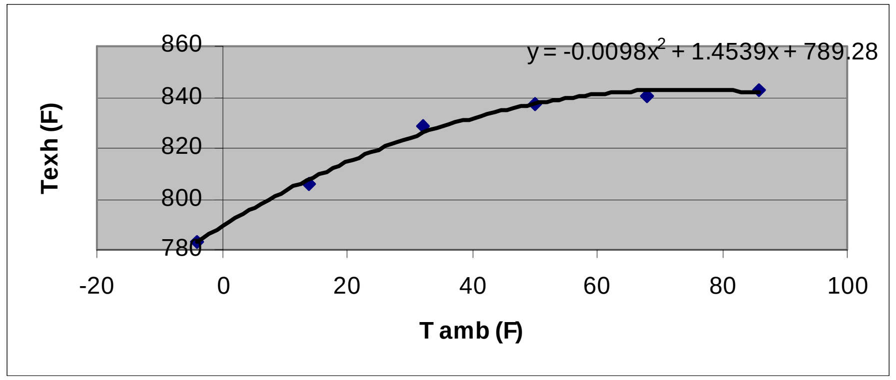
APPENDIX C: CENTAUR 40 PERFORMANCE DATA

Mid points	Hours		Mwe	MWH	Fuel Flow (MMBtu/hr)	Fuel Flow (MMBtu)	Fuel Flow (lb/hr)	Exhaust flow (Lb/hr)	Inlet Flow (lb/hr)	Exhaust Temp (F)
91	30	2730	3.074	92.220	38.47	1153.97	1611.13	138030.70	136419.57	840.43
89	57	5073	3.101	176.780	38.76	2209.33	1623.46	138635.30	137011.84	841.05
87	108	9396	3.129	337.910	39.05	4217.90	1635.79	139239.90	137604.11	841.59
85	145	12325	3.156	457.649	39.35	5705.61	1648.13	139844.50	138196.37	842.06
83	155	12865	3.184	493.458	39.64	6144.73	1660.46	140449.10	138788.64	842.44
81	198	16038	3.211	635.778	39.94	7907.68	1672.79	141053.70	139380.91	842.75
79	204	16116	3.238	660.634	40.23	8207.37	1685.12	141658.30	139973.18	842.98
77	177	13629	3.266	578.047	40.53	7173.21	1697.45	142262.90	140565.45	843.13
75	301	22575	3.293	991.253	40.82	12287.12	1709.78	142867.50	141157.72	843.20
73	495	36135	3.321	1643.697	41.12	20352.12	1722.11	143472.10	141749.99	843.19
71	392	27832	3.348	1312.416	41.41	16232.64	1734.44	144076.70	142342.26	843.11
69	355	24495	3.375	1198.267	41.70	14804.99	1746.77	144681.30	142934.53	842.94
67	339	22713	3.403	1153.549	42.00	14237.53	1759.10	145285.90	143526.80	842.70
65	302	19630	3.430	1035.920	42.29	12772.49	1771.43	145890.50	144119.07	842.38
63	247	15561	3.458	854.027	42.59	10519.09	1783.77	146495.10	144711.33	841.98
61	244	14884	3.485	850.340	42.88	10463.16	1796.10	147099.70	145303.60	841.50
59	157	9263	3.512	551.447	43.18	6778.66	1808.43	147704.30	145895.87	840.95
57	227	12939	3.540	803.535	43.47	9867.83	1820.76	148308.90	146488.14	840.31
55	300	16500	3.567	1070.160	43.77	13129.50	1833.09	148913.50	147080.41	839.60
53	224	11872	3.595	805.190	44.06	9869.31	1845.42	149518.10	147672.68	838.81
51	224	11424	3.622	811.328	44.35	9935.25	1857.75	150122.70	148264.95	837.94
49	267	13083	3.649	974.390	44.65	11921.07	1870.08	150727.30	148857.22	836.99
47	344	16168	3.677	1264.819	44.94	15460.25	1882.41	151331.90	149449.49	835.97
45	309	13905	3.704	1144.598	45.24	13978.23	1894.74	151936.50	150041.76	834.86
43	337	14491	3.732	1257.549	45.53	15344.08	1907.07	152541.10	150634.03	833.68
41	223	9143	3.759	838.257	45.83	10219.15	1919.41	153145.70	151226.29	832.42
39	326	12714	3.786	1234.366	46.12	15035.19	1931.74	153750.30	151818.56	831.08
37	509	18833	3.814	1941.224	46.41	23625.03	1944.07	154354.90	152410.83	829.66
35	312	10920	3.841	1198.454	46.71	14573.21	1956.40	154959.50	153003.10	828.16
33	285	9405	3.869	1102.551	47.00	13395.97	1968.73	155564.10	153595.37	826.59
31	207	6417	3.896	806.472	47.30	9790.64	1981.06	156168.70	154187.64	824.93
29	152	4408	3.923	596.357	47.59	7234.01	1993.39	156773.30	154779.91	823.20
27	107	2889	3.951	422.736	47.89	5123.87	2005.72	157377.90	155372.18	821.39
25	110	2750	3.978	437.602	48.18	5299.91	2018.05	157982.50	155964.45	819.50
23	65	1495	4.006	260.364	48.48	3150.90	2030.38	158587.10	156556.72	817.54
21	80	1680	4.033	322.640	48.77	3901.58	2042.71	159191.70	157148.99	815.49
19	85	1615	4.060	345.134	49.06	4170.46	2055.05	159796.30	157741.25	813.37
17	54	918	4.088	220.741	49.36	2665.36	2067.38	160400.90	158333.52	811.16
15	47	705	4.115	193.414	49.65	2333.69	2079.71	161005.50	158925.79	808.88
13	29	377	4.143	120.135	49.95	1448.47	2092.04	161610.10	159518.06	806.52
11	15	165	4.170	62.550	50.24	753.63	2104.37	162214.70	160110.33	804.09
9	8	72	4.197	33.579	50.54	404.29	2116.70	162819.30	160702.60	801.57
7	4	28	4.225	16.899	50.83	203.32	2129.03	163423.90	161294.87	798.98
5	4	20	4.252	17.009	51.13	204.50	2141.36	164028.50	161887.14	796.30









Solar® Turbines
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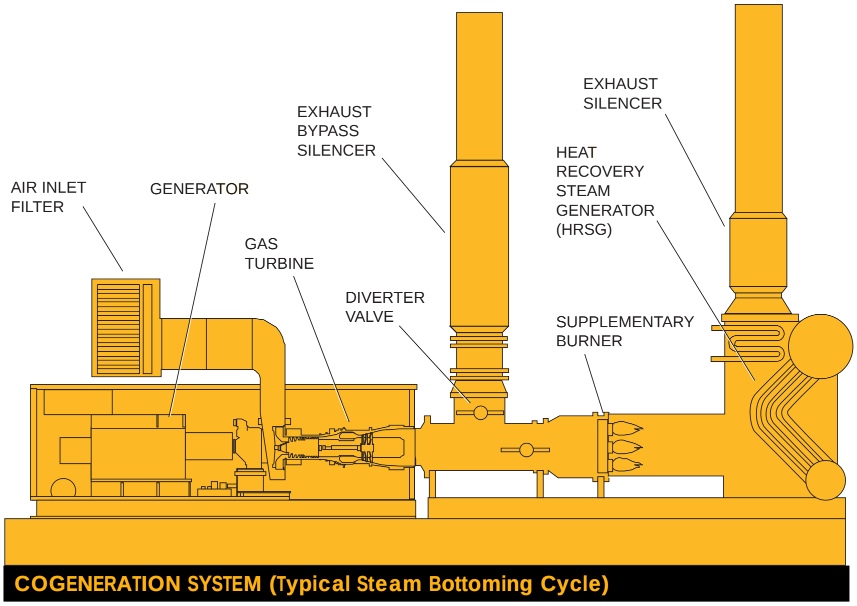
Heat Recovery Typical Performance

ASSUMPTIONS	Metric	English
Site Conditions		
Elevation	0 m	0 ft
Temperature	15°C	59°F
Fuel	Natural Gas	
Load	100%	
Inlet Pressure Loss, H_2O	75 mm	3 in.
Exhaust Pressure Loss, H_2O	175 mm	7 in.
HRSG / Steam Data		
Steam Pressure	8.6 bar gauge	125 psig
Steam Conditions	Dry and Saturated	
Pinch Temperature	17C°	30F°
Condensate Return	49°C	120°F
Boiler Inlet	110°C	230°F
Economizer Approach	22C°	40F°



COGENERATION SYSTEM (Typical Steam Bottoming Cycle)

	Saturn 20	Centaur 40	Centaur 50	Mercury 50	Taurus 60	Taurus 70	Mars 90	Mars 100	Titan 130
SPECIFIC SITE PERFORMANCE									
Electrical Output, kWe	1174	3419	4483	4072	5071	7352	9216	10 439	13 197
Exhaust Temperature, °C	511	441	513	351	489	489	468	491	493
°F	952	826	956	663	912	913	875	915	920
Turbine Fuel Input, GJ/hr	17.8	45.1	56.0	37.5	61.3	79.5	106.0	117.7	145.0
MMBtu/hr	16.8	42.7	53.1	35.5	58.1	75.4	100.5	111.5	137.4
Exhaust Mass Flow, thousand kg/hr	23.4	66.5	68.2	60.6	78.9	96.3	143.5	149.3	178.3
thousand lb/hr	51.5	146.6	150.3	133.6	173.9	212.3	(316.4	329.1	393.0
EXHAUST HEAT AVAILABLE									
Heat Credit, GJ/hr	12.4	30.3	36.3	21.7	39.9	48.8	69.5	75.8	91.0
MMBtu/hr	11.7	28.7	34.4	20.6	37.8	46.2	65.8	71.8	86.3
Net System Efficiency, %	94	95	94	97	95	95	97	96	96
PROCESS STEAM PRODUCTION (UNFIRED)									
Steam Output, tonnes/hr	3.7	8.1	10.9	4.6	11.6	14.2	19.6	22.1	26.6
thousand lb/hr	8.2	17.9	24.0	10.2	25.5	31.2	43.1	48.6	58.6
Net System Efficiency, %	72	69	74	68	73	75	74	75	75
PROCESS STEAM PRODUCTION WITH SUPPLEMENTAL FIRING, 760°C (1400°F)									
Steam Output, tonnes/hr	6.9	19.6	20.0	17.9	23.2	28.3	42.2	43.9	52.4
thousand lb/hr	15.1	43.1	44.1	39.4	51.1	62.4	93.0	96.7	115.4
Additional Fuel to Burner, GJ/hr	6.8	24.6	19.7	28.5	24.9	30.4	48.7	46.9	55.5
MMBtu/hr	6.4	23.3	18.6	27.0	23.6	28.8	46.2	44.5	52.6
Net System Efficiency, %	82	83	83	85	83	84	85	85	84
PROCESS STEAM PRODUCTION WITH SUPPLEMENTAL FIRING, 1538°C (2800°F)									
Steam Output, tonnes/hr	16.8	48.0	49.1	43.9	56.9	69.4	103.6	107.7	128.5
thousand lb/hr	37.1	105.9	108.3	96.7	125.4	153.1	228.3	237.3	283.4
Additional Fuel to Burner, GJ/hr	29.0	88.4	84.5	87.2	100.2	122.2	186.0	189.3	225.5
MMBtu/hr	27.5	83.8	80.1	82.7	94.9	115.9	176.2	179.4	213.7
Net System Efficiency, %	92	92	92	93	93	93	93	93	93

NOTES:
1. Alternative steam pressures and temperatures available upon request.
2. Minimum stack temperature with:
   Gas fuel = 135°C (275°F)
   Liquid fuel = 163°C (325°F)

CONVERSION FACTORS FOR CHILLING APPLICATIONS:

Older Mechanical Chiller: 0.8 kW/hr = 1 Ton of Refrigeration
Newer Mechanical Chiller: 0.6 kW/hr = 1 Ton of Refrigeration
Single-Effect Absorption Chiller: 18.7 lb/hr of Steam = 1 Ton of Refrigeration
Double-Effect Absorption Chiller: 9.9 lb/hr of Steam = 1 Ton of Refrigeration

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DSHR-TP2800/1000/4M

Appendix E: Chiller Performance Curves

Model	**BDS**	**175**	**200**	**250**
cooling capacity				
	Tons	579	661	827
	kW	2035	2326	2908
	10^4kcal/h	175	200	250
chilled water 44°F/56.7°F low flow(B)				
flowrate	GPM	1100	1257	1571
pressure drop	Ft.H_2O	7.6	7.6	12.5
cooling water 97.5°F/85°F				
flowrate	GPM	2510	2869	3586
pressure drop	Ft.H_2O	22	22	28
max.steam consumption	lb/h	8962	10243	12803
power	kW	8.4	8.4	8.7
solution weight	klbs	11.5	13.2	15.2
unit ship.weight	Klbs	41.0	47.4	53.7
operation weight	klbs	48.0	55.1	63.0

General Conditions:

1. Rated saturated steam pressure:14.5psig
2. Rated condensate temperature:203°F
3. Rated chilled W.outlet/inlet temp.:(A)44°F/54°F (B)44°F/56.7°F
4. Rated cooling W.outlet/inlet temp.:97.5°F/85°F
5. Lowest permitted outlet temp.for chilled water:41°F
   (except special order)
6. Lowest permitted inlet temp.for cooling water:50°F
   Lowest inlet temp.in operating:65°F (no limit if 3-way valve is equipped)
7. Pressure limit for chilled/cooling water:116psig
   (except special order)
8. Fouling factor for chilled water:0.0001hr ft^2°F/Btu
   for cooling water:0.00025hr ft^2°F/Btu
9. LiBr solution concentration:50%
10. Machine room temperature:41~109°F, humidity≤85%
11. Adjustable chilled water flowarate:50~120%
    (according to flowrate A)
12. Adjustable cooling water flowarate:30~140%

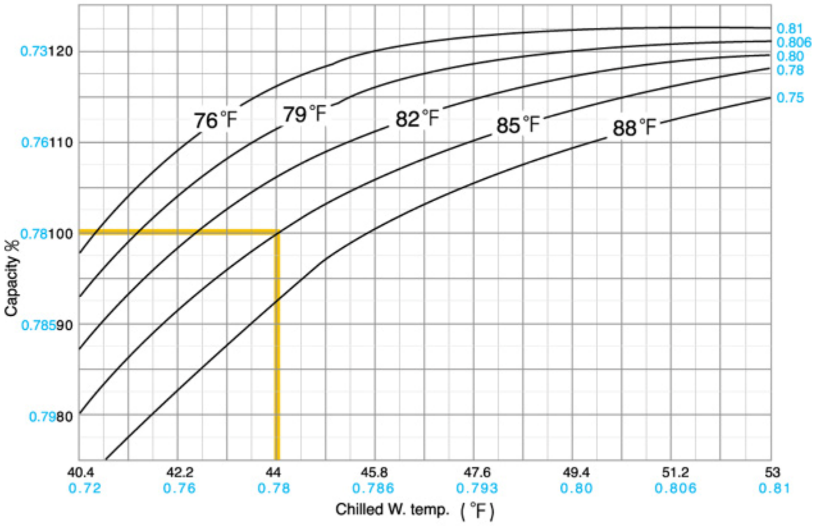
Adjustable load:5~115% Rated COP:0.78

Note:

①Technical specification is based upon ARI 560 Stantard "Absorption Water Chilling and Water Heating Packages".

Appendix E: Chiller Performance Curves

Chilled W./cooling W./Capacity/COP (model selection)



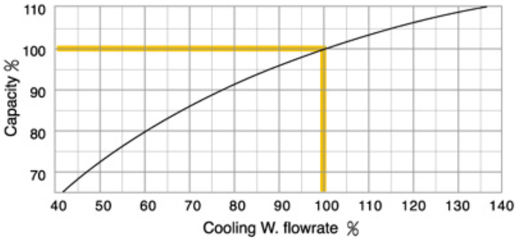
Note: The figure in blue is COP. In calculation, 3 of them will be added and then divided by 3. Example:

① Known: cooling capacity is 100%, cooling W. temp. 82°F;
check out chilled W. temp. is 42.6°F, COP is 0.782, i.e. (0.78+0.8+0.765)/3=0.782

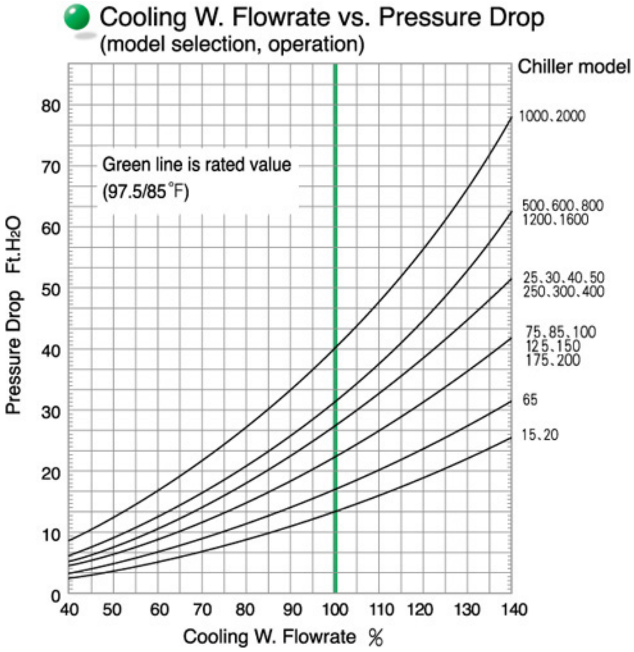
② Known: chilled W. temp. 49.4°F.cooling W. temp. 85°F;
check out cooling capacity is 113%, COP=0.777

③ Known: cooling capacity is 110%, chilled water 44°F;
check out cooling water temperature is 80.2°F, COP =0.781

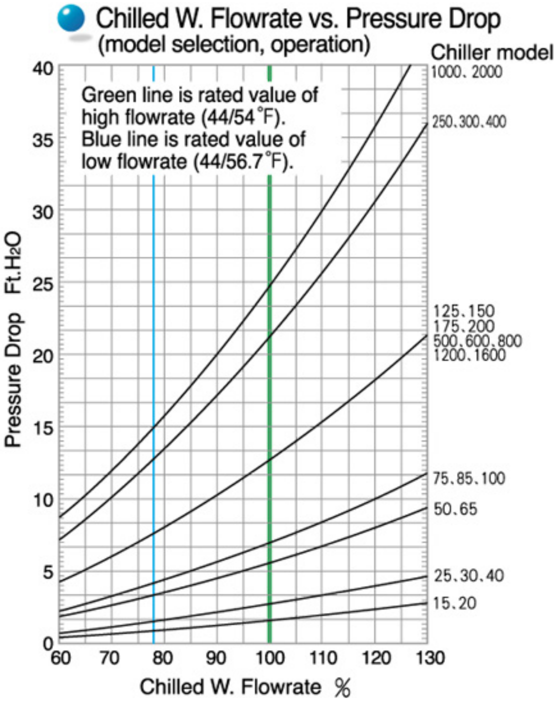
Cooling W. flowrate vs. Capacity (model selection, operation)



APPENDIX E: CHILLER PERFORMANCE CURVES

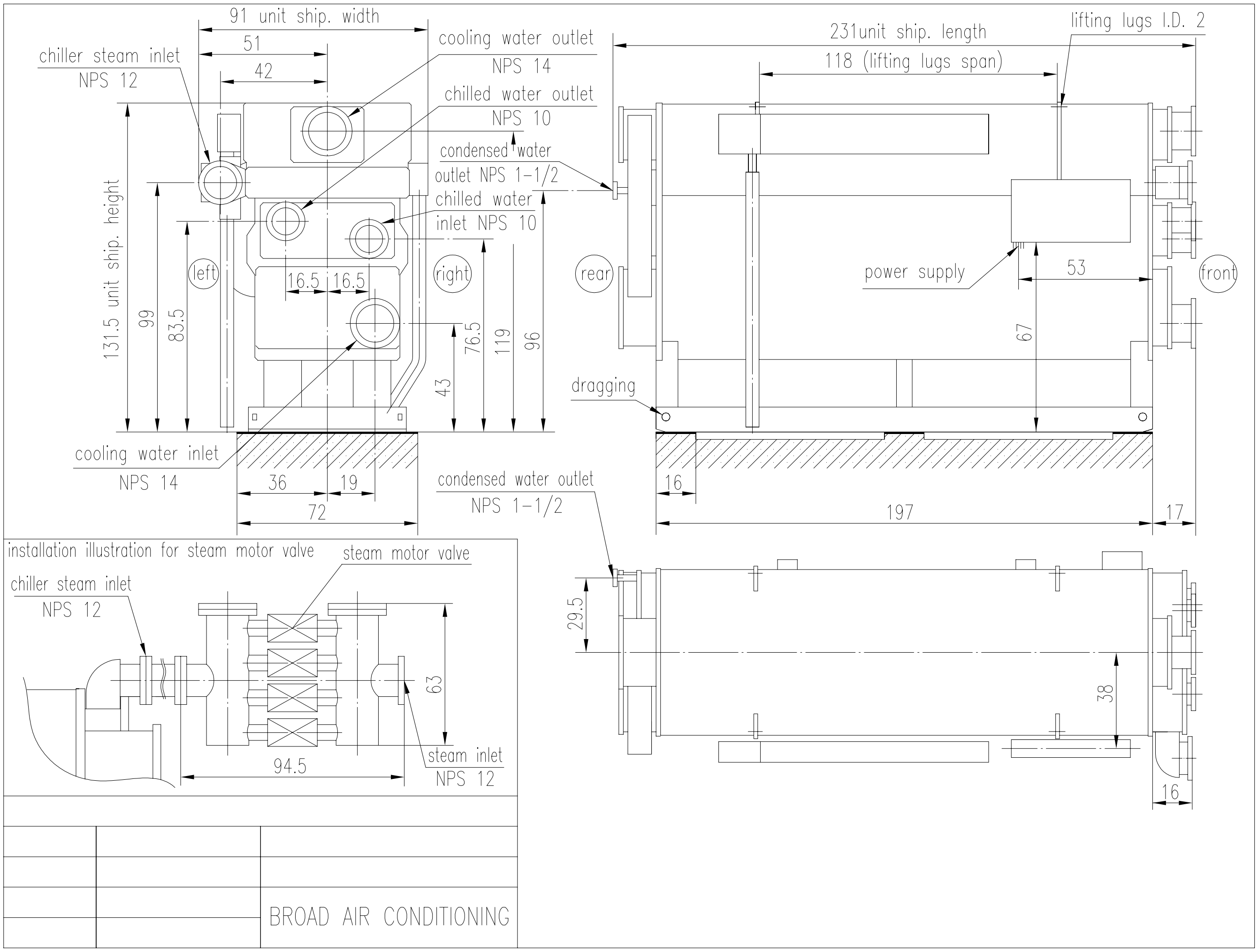

Cooling W. Flowrate vs. Pressure Drop
(model selection, operation)

Green line is rated value (97.5/85°F)

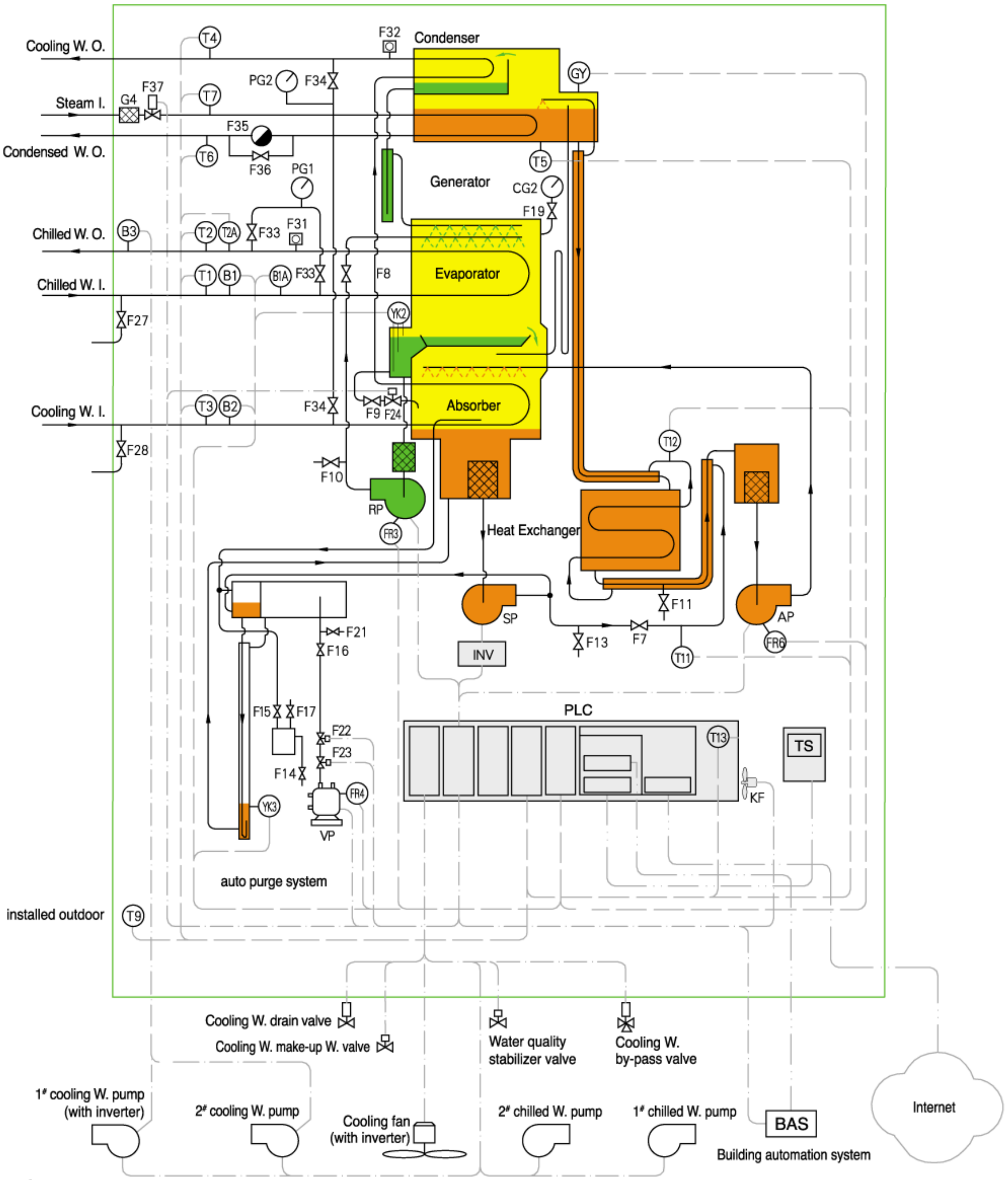

Chilled W. Flowrate vs. Pressure Drop
(model selection, operation)

Green line is rated value of high flowrate (44/54°F). Blue line is rated value of low flowrate (44/56.7°F).

Appendix E: Chiller Dimensional Data



APPENDIX E: CHILLER SCHEMATIC



Code:

T1	chilled W. inlet temp. sensor	B3	chilled W. flow switch	CG2	compound gauge	F19	main shell pressure valve
T2	chilled W. outlet temp. sensor	GY	pressure control	PG1	pressure gauge	F21	nitrogen charging valve
T2A	chilled W. calibrating temp. sensor	YK2	refrigerant level probe	PG2	pressure gauge	F22	purge solenoid valve
T3	cooling W. inlet temp. sensor	YK3	non-condensable probe	G4	steam filter	F23	purge solenoid valve
T4	cooling W. outlet temp. sensor	FR3	refrigerant pump thermal relay	F7	concentration regulating valve	F24	refrigerant solenoid valve
T5	generator temp. sensor	FR4	vacuum pump thermal relay	F8	refrigerant regulating valve	F27	chilled W. drain valve
T6	condensed W. outlet temp. sensor	FR6	absorber pump thermal relay	F9	refrigerant by-pass valve	F28	cooling W. drain valve
T7	steam intlet temp. sensor	INV	solution pump inverter	F10	refrigerant sampling valve	F31	chilled W. vent valve
T9	ambient temp. sensor	TS	touch screen	F11	concentrated solution sampling valve	F32	cooling W. vent valve
T11	exchanger diluted solution inlet temp. sensor	PLC	programmable logic controller	F13	diluted solution sampling valve	F33	chilled W. pressure valve
T12	generator crystallization sensor	KF	control casing draft fan	F14	main purge valve	F34	cooling W. pressure valve
T13	control casing temp. sensor	RP	refrigerant pump	F15	direct purge valve	F35	steam trap
B1	chilled W. flow switch	SP	solution pump	F16	air cannister valve	F36	condensed w. by-pass valve
B1A	chilled W. flow switch	VP	vacuum pump	F17	sampling purge valve	F37	steam motor valve
B2	cooling W. flow switch	AP	absorber pump				

Notes: 1. ▭ BROAD supply scope

2. All the components are installed and commissioned in the factory before shipment except T9.

3. Wire type:

— · — · — actuator signal output
— — — sensor signal input
— · · — communication signal

Marley UPDATE™ Version 4.3.2
Product Data: 2/2/2005

3/11/2005 3:48:50 PM

Job Information

Data Center

Delaware

Selected By

Penn State
104 Engineering Unit A
University Park, PA
wpb5@psu.edu

PSUAE
Tel 814-863-2076

Marley Contact

H & H Associates, Inc.
4510 Westport Drive
Mechanicsburg, PA 17055
frank@hhassociates.com

Tel 717-796-2401
Fax 717-796-9717

Cooling Tower Definition

Manufacturer	Marley Cooling Technologies	Fan Motor Speed	1800 rpm
Product	NC Class	Fan Motor Capacity per cell	100.0 BHp
Model	NC8312N1	Fan Motor Output per cell	100.0 BHp
Cells	1	Fan Motor Output total	100.0 BHp
CTI Certified	Yes	Air Flow per cell	320200 cfm
Fan	12.00 ft, 7 Blades	Air Flow total	320200 cfm
Fan Speed	289 rpm, 10895 fpm	ASHRAE 90.1 Performance	43.2 gpm/Hp
Fans per cell	1		

Sound Pressure Level 84 dBA/Cell, 5.00 ft from Air Inlet Face. See sound report for details.

Conditions

Tower Water Flow	2869 gpm	Air Density In	0.07076 lb/ft³
Hot Water Temperature	97.50 °F	Air Density Out	0.07075 lb/ft³
Range	12.50 °F	Humidity Ratio In	0.01779
Cold Water Temperature	85.00 °F	Humidity Ratio Out	0.03180
Approach	6.00 °F	Wet-Bulb Temp. Out	90.60 °F
Wet-Bulb Temperature	79.00 °F	Estimated Evaporation	37 gpm
Relative Humidity	50 %		

- This selection meets your design conditions.

Weights & Dimensions

	Per Cell	Total
Shipping Weight	21790 lb	21790 lb
Max Operating Weight	44430 lb	44430 lb
Width	22.42 ft	22.42 ft
Length	13.90 ft	13.90 ft
Height	23.33 ft	
Static Lift	19.21 ft	

Minimum Enclosure Clearance

Clearance required on air inlet sides of tower without altering performance. Assumes no air from below tower.

Solid Wall	10.69 ft
50 % Open Wall	8.24 ft

Weights and dimensions do not include options; refer to sales drawings. For CAD layouts refer to file NC8312K.dxf

Cold Weather Operation

Heater Sizing (Minimum ambient temperature to maintain collection basin water at 40 °F)

Heater kW/Cell	30.0	24.0	18.0	15.0	12.0	9.0	7.5
Ambient Temperature °F	-20.40	-7.45	5.50	11.98	18.45	24.93	28.17

Marley UPDATE™ Version 4.3.2
Product Data: 2/2/2005

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Job Information

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Tel 717-796-2401
Fax 717-796-9717

Cooling Tower Definition

Manufacturer	Marley Cooling Technologies	Fan Motor Speed	1800 rpm	Design Range	12.50 °F
Product	NC Class	Fan Motor Output per cell	100.0 BHp	Design Wet-Bulb	79.00 °F
Model	NC8312N1	Fan Motor Efficiency	90.0 %	Cold Water Set Point	85.00 °F
Cells	1	Tower Water Flow	2869 gpm	Average Wet-Bulb	79.00 °F
Fan	12.00 ft, 7 Blades	Static Lift	19.21 ft	Range at Avg. Wet-Bulb	12.50 °F
Fans per cell	1	Pump Efficiency	70.0 %	Maximum Wet-Bulb	79.00 °F
Wet-Bulb Profile	Linear				

Interval Information					Single-Speed Fan			Two-Speed Fan				Variable-Speed Fan		Pump
Wet-Bulb Interval °F		Cold Water °F	Range °F	Hours	Hours Full	Hours Off	Energy kWh	Hours Full	Hours Half	Hours Off	Energy kWh	Motor Output BHp	Energy kWh	Energy kWh
79.00	79.00	85.00	12.50	2000.0	1984.5	15.5	164430.4	1847.6	152.4	0.0	154890.7	82.0	135854.9	29690.0
		Totals		2000.0	1984.5	15.5	164430.4	1847.6	152.4	0.0	154890.7		135854.9	29690.0

Marley UPDATE™ Version 4.3.2
Product Data: 2/2/2005

3/11/2005 4:12:46 PM

Job Information

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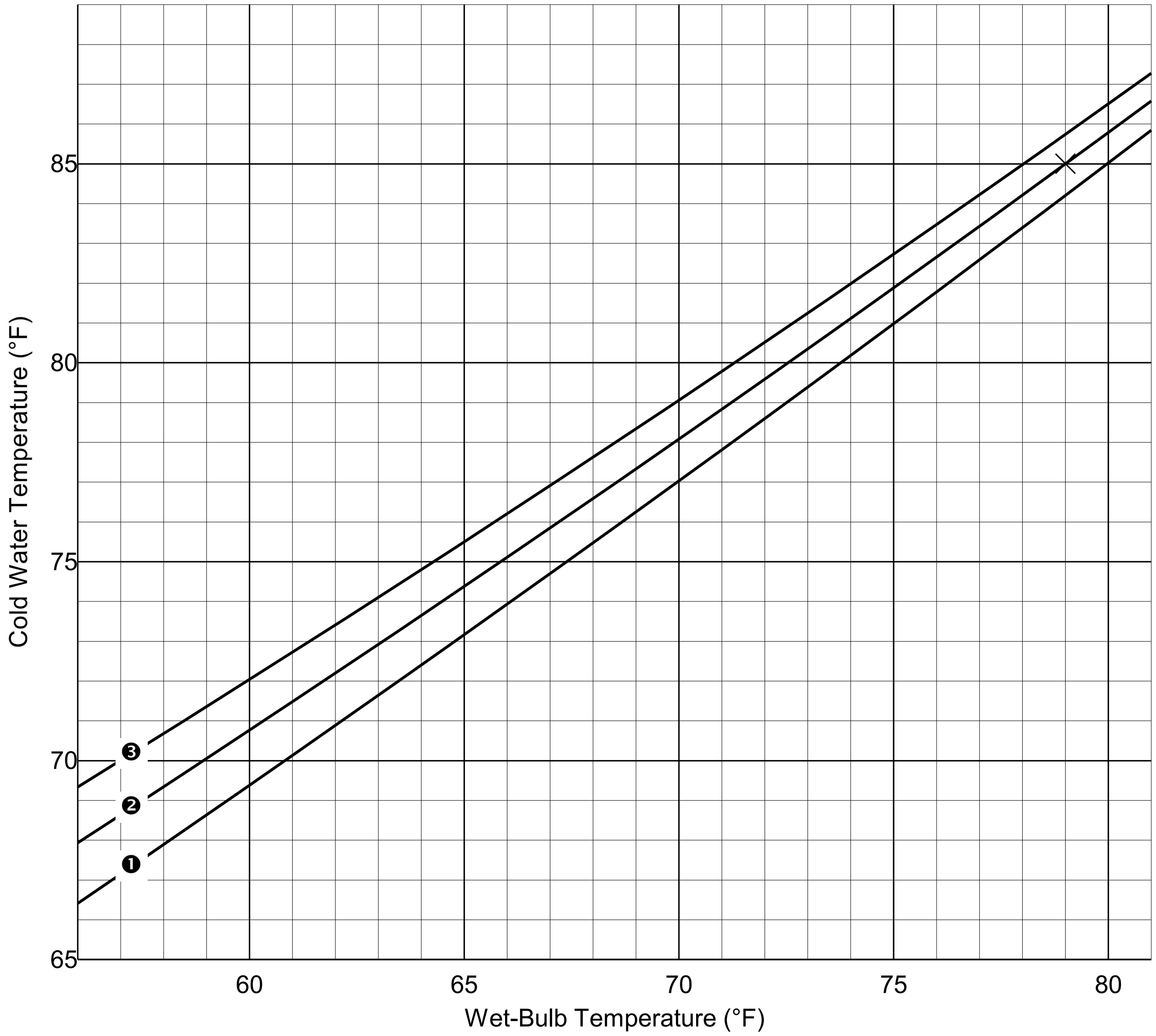
Cooling Tower Definition

Manufacturer	Marley Cooling Technologies
Product	NC Class
Model	NC8312N1
Cells	1
Fan	12.00 ft, 7 Blades
Fans per cell	1
Fan Motor Capacity per cell	100.0 BHp



Design Conditions

Tower Water Flow	2869 gpm
Hot Water Temperature	97.50 °F
Cold Water Temperature	85.00 °F
Wet-Bulb Temperature	79.00 °F

Curve Conditions

Tower Water Flow (100.0 %)	2869 gpm
Fan Speed (100.0 %)	289 rpm
Fan Motor Speed (100.0 %)	1800 rpm
Fan Motor Output per cell	100.0 BHp
Fan Motor Output total	100.0 BHp

Legend

❶	10.5 °F Range
❷	12.5 °F Range
❸	14.5 °F Range
×	Design Point

APPENDIX G: PUMP DATA

Bell and Gossett

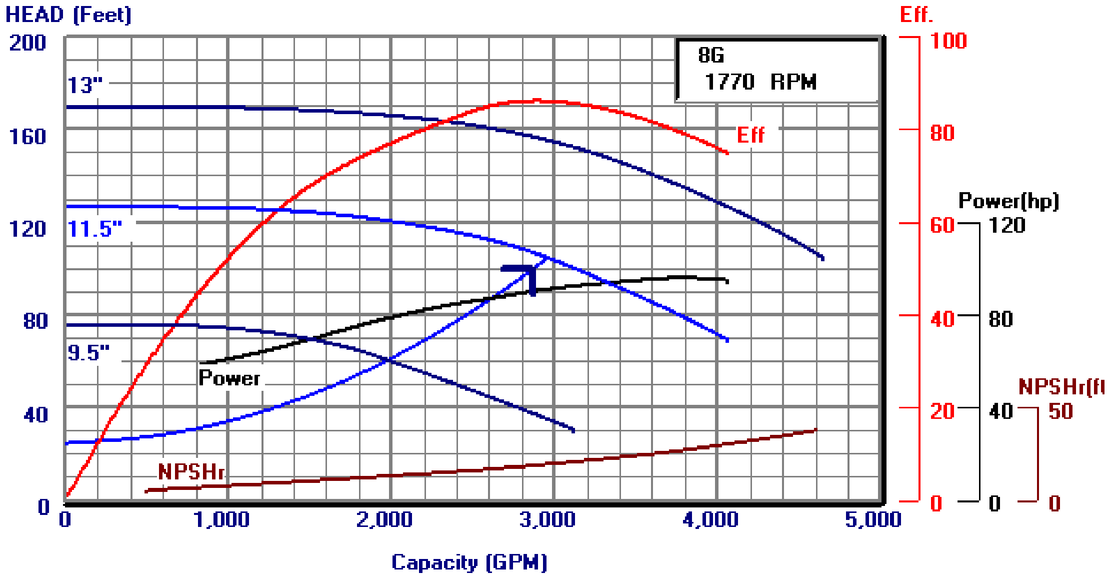
SUMMARY

System Capacity = 2869 GPM					Total Developed Head = 100 Feet				
Pump Series	Model	Speed (RPM)	Pump Efficiency	Duty Point (BHP)	Motor Size (HP)	Impeller Size(in)	Weight (lbs)	Cost Index	Quote Request
1510	8G	1770	85.78	84.68	100	11.5	1700	100%	

PUMP DETAILS

1510 8G			
Flow Rate (GPM)	2869	Pump Head (Feet)	100
Speed (RPM)	1770	NPSHr (Feet)	18.7
Weight (lbs)	1700	Cost Index	100%
Suction Size (in.)	10	Suction Velocity (fps)	11.7
Discharge Size (in.)	8	Discharge Velocity (fps)	18.4
Impeller Size (in.)	11.5	Pump Efficiency (%)	85.78
Max. Flow (GPM)	4041	Duty Flow/Max Flow (%)	71.0
Flow @ BEP (GPM)	2775	Min. Rec. Flow (GPM)	693.8
Selected Motor Size (HP)	100	Selected Motor Size (kw)	74.57
Duty-Point Power (BHP)	84.68	Duty-Point Power (kw)	63.15
Maximum Power (BHP)	88.10	Maximum Power (kw)	65.70
Motor Manufacturer	US Prem Eff	Full Load Amps	112.00
Manufacturer Catalog Number	R322	Full Load Efficiency (%)	96.1
Frame Size	404TS	Full Load Power Factor (%)	86.5

APPENDIX G: PUMP CURVES



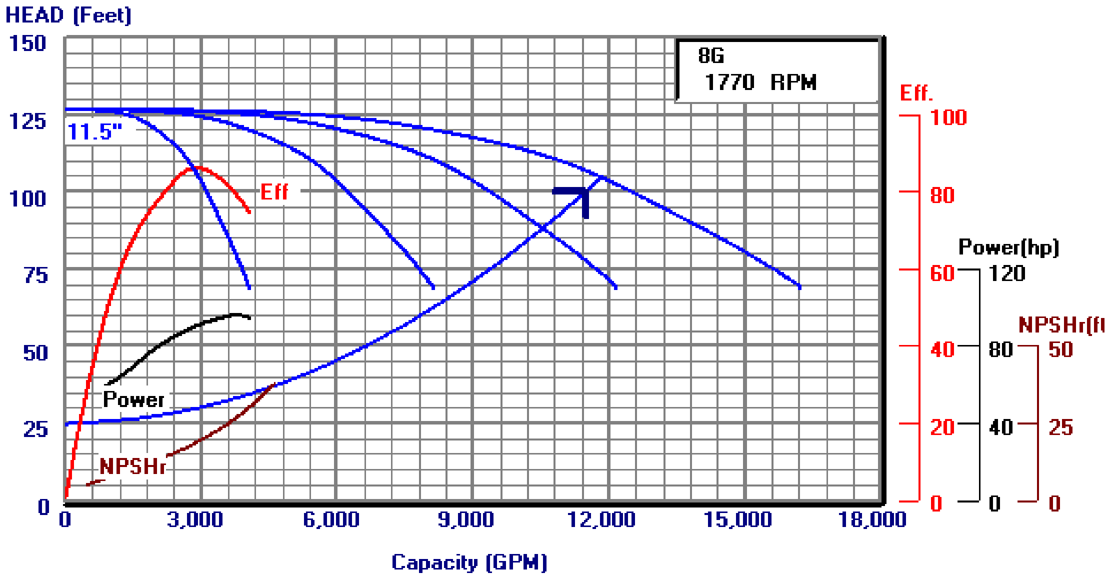
Pump Series: 1510
Suction Size = 10 "
Discharge Size = 8 "

Min Imp Dia = 9.5 "
Max Imp Dia = 13 "
Cut Dia = 11.5 "

Design Capacity =2869.0
Design Head =100.0
Motor Size =100 HP

ITT Bell & Gossett
8200 N. Austin
Morton Grove, Il 60053

The Power and Eff. curves shown are for the cut dia. impeller.



Pump Series: 1510
Suction Size = 10 "
Discharge Size = 8 "

Min Imp Dia = 9.5 "
Max Imp Dia = 13 "
Cut Dia = 11.5 "

Design Capacity =11476.0
Design Head =100.0
Motor Size =100 HP

ITT Bell & Gossett
8200 N. Austin
Morton Grove, Il 60053

The Power and Eff. curves shown are only for single pump operation.

Appendix H: Inlet Cooling

$$\text{Inlet}_{\text{cfm}} = \frac{\text{inlet}_{\text{mass}}}{60} \cdot \text{specific}_{\text{vol}}$$

$$2.928 \times 10^{6} = 1.08 \cdot \text{Inlet}_{\text{cfm}} \cdot \delta_{T}$$

$$\text{Inlet}_{\text{Temp}} = \text{To} - \delta_{T}$$

Parametric Table: Inlet Temps

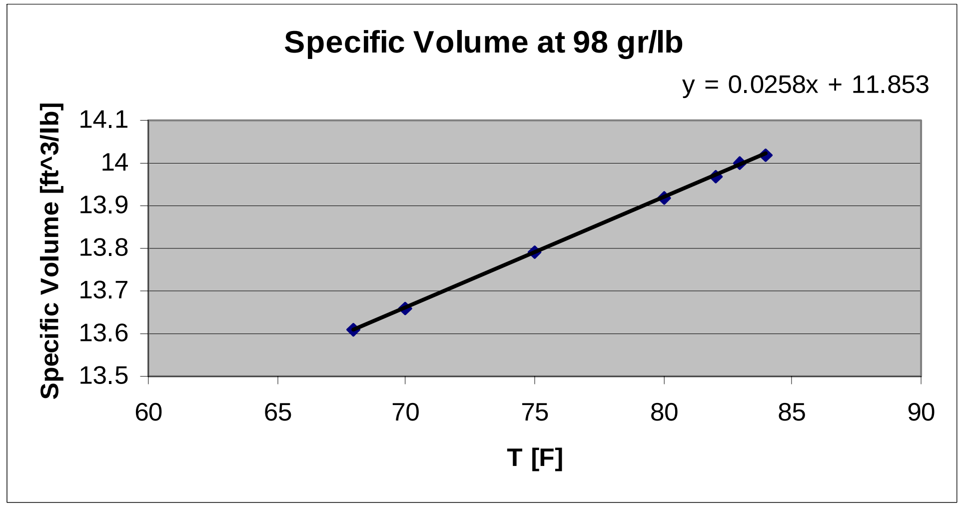
	To	**$\text{inlet}_{\text{mass}}$**	**$\text{specific}_{\text{vol}}$**	**$\text{Inlet}_{\text{Temp}}$**	**δ_T**	**$\text{Inlet}_{\text{cfm}}$**
Run 1	91	414092	13.48	*61.86*	*29.14*	*93033*
Run 2	89	415906	13.43	*59.88*	*29.12*	*93094*
Run 3	87	417720	13.38	*57.9*	*29.1*	*93151*
Run 4	85	419534	13.33	*55.91*	*29.09*	*93206*
Run 5	83	421347	13.29	*53.95*	*29.05*	*93328*
Run 6	81	423161	13.24	*51.97*	*29.03*	*93378*
Run 7	79	424975	13.19	*49.98*	*29.02*	*93424*
Run 8	77	426789	13.14	*47.99*	*29.01*	*93467*
Run 9	75	428603	12.86	*45.49*	*29.51*	*91864*
Run 10	73	430416	12.81	*43.5*	*29.5*	*91894*
Run 11	71	432230	12.76	*41.51*	*29.49*	*91921*

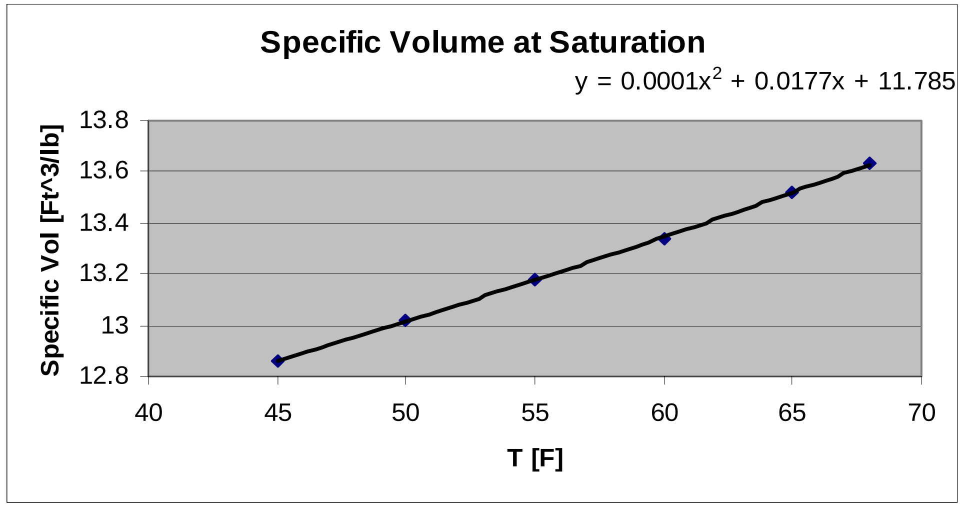
Parametric Table: Inlet Temps for Adjusted Flows

	To	**$\text{inlet}_{\text{mass}}$**	**$\text{specific}_{\text{vol}}$**	**$\text{Inlet}_{\text{Temp}}$**	**δ_T**	**$\text{Inlet}_{\text{cfm}}$**
Run 1	91	439485	13.48	*63.54*	*27.46*	*98738*
Run 2	89	441299	13.45	*61.59*	*27.41*	*98925*
Run 3	87	443113	13.4	*59.6*	*27.4*	*98962*
Run 4	85	444927	13.35	*57.61*	*27.39*	*98996*
Run 5	83	446741	13.3	*55.62*	*27.38*	*99027*
Run 6	81	448554	13.24	*53.61*	*27.39*	*98981*
Run 7	79	450368	13.19	*51.62*	*27.38*	*99006*
Run 8	77	452182	13.14	*49.62*	*27.38*	*99028*
Run 9	75	453996	13.09	*47.63*	*27.37*	*99047*
Run 10	73	455810	13.03	*45.61*	*27.39*	*98987*
Run 11	71	457623	12.98	*43.61*	*27.39*	*98999*

APPENDIX H: INLET COOLING CALCULATIONS

Mid points	Inlet Temp	Specific Volume [ft^3/lb]	Hours	New Mwe	New MWH	New Fuel Flow (MMBtu/hr)	New Fuel Flow (MMBtu)	New Exhaust flow (Lb/hr)	New Exhaust Temp (F)
91	64	13.49	30	3.450	103.506	42.51	2700.95	146331.86	842.09
89	62	13.44	57	3.477	198.184	42.79	2635.74	146921.34	841.65
87	60	13.39	108	3.504	378.451	43.09	2568.04	147522.92	841.12
85	58	13.34	145	3.531	512.059	43.38	2499.17	148124.50	840.51
83	56	13.29	155	3.559	551.599	43.67	2429.13	148726.07	839.83
81	54	13.24	198	3.586	710.076	43.97	2357.21	149333.70	839.06
79	52	13.18	204	3.614	737.155	44.26	2284.83	149935.27	838.22
77	50	13.13	177	3.641	644.440	44.56	2210.92	150539.87	837.29
75	48	12.85	301	3.668	1104.119	44.85	2136.20	151141.45	836.30
73	46	12.80	495	3.696	1829.442	45.15	2059.16	151752.10	835.21
71	44	12.75	392	3.723	1459.511	45.44	1981.71	152356.70	834.05
69	44	12.76	355	3.718	1319.855	45.38	1996.90	152238.80	834.28
67	44	12.76	339	3.718	1260.368	45.38	1996.90	152238.80	834.28
65	44	12.76	302	3.718	1122.806	45.38	1996.90	152238.80	834.28
63	44	12.76	247	3.718	918.321	45.38	1996.90	152238.80	834.28
61	44	12.76	244	3.718	907.168	45.38	1996.90	152238.80	834.28
59	44	12.76	157	3.718	583.710	45.38	1996.90	152238.80	834.28
57	44	12.76	227	3.718	843.963	45.38	1996.90	152238.80	834.28
55	44	12.76	300	3.718	1115.370	45.38	1996.90	152238.80	834.28
53	44	12.76	224	3.718	832.810	45.38	1996.90	152238.80	834.28
51	44	12.76	224	3.718	832.810	45.38	1996.90	152238.80	834.28
49	44	12.76	267	3.718	992.679	45.38	1996.90	152238.80	834.28
47	44	12.76	344	3.718	1278.958	45.38	1996.90	152238.80	834.28
45	44	12.76	309	3.718	1148.831	45.38	1996.90	152238.80	834.28
43	43	12.73	337	3.732	1257.549	45.53	1957.85	152541.10	833.68
41	41	12.68	223	3.759	838.257	45.83	1878.86	153145.70	832.42
39	39	12.63	326	3.786	1234.366	46.12	1798.69	153750.30	831.08
37	37	12.58	509	3.814	1941.224	46.41	1717.34	154354.90	829.66
35	35	12.53	312	3.841	1198.454	46.71	1634.82	154959.50	828.16
33	33	12.48	285	3.869	1102.551	47.00	1551.11	155564.10	826.59
31	31	12.43	207	3.896	806.472	47.30	1466.23	156168.70	824.93
29	29	12.38	152	3.923	596.357	47.59	1380.17	156773.30	823.20
27	27	12.34	107	3.951	422.736	47.89	1292.94	157377.90	821.39
25	25	12.29	110	3.978	437.602	48.18	1204.53	157982.50	819.50
23	23	12.25	65	4.006	260.364	48.48	1114.93	158587.10	817.54
21	21	12.20	80	4.033	322.640	48.77	1024.17	159191.70	815.49
19	19	12.16	85	4.060	345.134	49.06	932.22	159796.30	813.37
17	17	12.11	54	4.088	220.741	49.36	839.10	160400.90	811.16
15	15	12.07	47	4.115	193.414	49.65	744.80	161005.50	808.88
13	13	12.03	29	4.143	120.135	49.95	649.32	161610.10	806.52
11	11	11.99	15	4.170	62.550	50.24	552.66	162214.70	804.09
9	9	11.95	8	4.197	33.579	50.54	454.83	162819.30	801.57
7	7	11.91	4	4.225	16.899	50.83	355.81	163423.90	798.98
5	5	11.88	4	4.252	17.009	51.13	255.63	164028.50	796.30





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"Appendix J: Heat Recovery Steam Generator"

"Heat recovery given inlet cooling for turbine"

"****************************************************************************************************"
"Combustion of Natural Gas"
"Humidity ratio consistant with worst case humidity ratio of 70 and saturated W = .016lb/lb"
{beta*CH4 + alpha*((2*O2 + 7.52*N2)+.0015*H2O) = beta*CO2 + beta*2*H2O + .0015*alpha*H2O + 2*(alpha - beta)*O2 + alpha * 7.52*N2}

"Molecular Weights[lbm/mole]"
CH4 = 16.04246*convert(g,lbm)
CO2 = 44.0095*convert(g,lbm)
H2O = 33.00674*convert(g,lbm)
O2 = 31.9988*convert(g,lbm)
N2 = 28.01348*convert(g,lbm)

{Mdot_fuel + Mdot_in = Mdot_exhaust}

Beta*CH4 = Mdot_Fuel
alpha*(2*O2 + 7.52*N2 + .0015*H2O) = Mdot_in
{(beta*CO2 + beta*2*H2O + .0015*alpha*H2O + 2*(alpha - beta)*O2 + alpha * 7.52*N2) = Mdot_exhaust}

Fuel_AIR = Mdot_in/Mdot_Fuel
W = ( beta*2*H2O + .0015*alpha*H2O)/(beta*CO2 + 2*(alpha - beta)*O2 + alpha * 7.52*N2)

P_part_h2o= (( beta*2*H2O + .0015*alpha*H2O)/(beta*CO2 + 2*(alpha - beta)*O2 + alpha * 7.52*N2))*Po#

DPT = T_SAT(water,P = P_part_h2o)


H_1 = Enthalpy(steam, p=29.2,x=0)
H_2 = Enthalpy(steam,p=29.2,x=1)

Hvap = H_2 - H_1



"****************************************************************************************************"
{CP1_CO2 = SPECHEAT(CO2,T = Texh)
CP1_H2O = SPECHEAT(CO2,T = Texh)
CP1_O2  = SPECHEAT(CO2,T = Texh)
CP1_N2 = SPECHEAT(CO2,T = Texh)

CP2_CO2 = SPECHEAT(CO2,T = 275)
CP2_H2O = SPECHEAT(CO2,T = 275)
CP2_O2  = SPECHEAT(CO2,T = 275)
CP2_N2 = SPECHEAT(CO2,T = 275)


Q_CO2 =(beta* CO2)*((CP1_CO2*Texh)-(CP2_CO2*280))
Q_H2O = (beta*2*H2O + .0015*alpha*H2O)*((CP1_H2O*Texh)-(CP2_H2O*280))
Q_O2 =  (2*(alpha - beta)*O2)*((CP1_O2*Texh)-(CP2_O2*280))
Q_N2 = (alpha * 7.52*N2)*((CP1_N2*Texh)-(CP2_N2*280))

"****************************************************************************************************"
Qg = (Q_CO2 + Q_H2O + Q_O2 + Q_N2)

"Losses do to radiation (2%), blowdown (5%), diverter valve (2%)"

Qs = Qg*(1-.02)*(1-.05)*(1-.02)

hs = enthalpy(steam, p = 29.2,x=1)
hf = enthalpy(water, p = 29.2, T =60)
```

```
Msteam = Qs/(hs - hf)}
"****************************************************************************************************************"
"Masses"
{Mass_CO2 =(beta* CO2)
Mass_H2O = (beta*2*H2O + .0015*alpha*H2O)
Mass_O2 =  (2*(alpha - beta)*O2)
Mass_N2 = (7.52*alpha* N2)
Mdot_fuel = 1739
Mdot_in = 142570}

"**************************************************************************************************************"
```

Parametric Table: DP, Alpha, Beta

	β	α	DPT [F]	Hvap	W	$Fuel_{Air}$	$Mdot_{fuel}$	$Mdot_{in}$
Run 1	50332	238639	92.66	946.4	0.05167	81.19	1780	144551
Run 2	50672	239592	92.75	946.4	0.05181	80.97	1792	145129
Run 3	51019	240565	92.84	946.4	0.05195	80.74	1805	145718
Run 4	51366	241538	92.93	946.4	0.0521	80.52	1817	146307
Run 5	51713	242511	93.02	946.4	0.05224	80.3	1829	146897
Run 6	52063	243494	93.11	946.4	0.05239	80.09	1842	147492
Run 7	52410	244467	93.2	946.4	0.05253	79.87	1854	148081
Run 8	52758	245444	93.28	946.4	0.05267	79.66	1866	148674
Run 9	53105	246417	93.37	946.4	0.05281	79.46	1879	149263
Run 10	53457	247405	93.45	946.4	0.05295	79.25	1891	149861
Run 11	53806	248383	93.54	946.4	0.05308	79.05	1903	150453
Run 12	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 13	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 14	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 15	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 16	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 17	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 18	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 19	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 20	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 21	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 22	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 23	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 24	53738	248192	93.52	946.4	0.05306	79.09	1901	150338
Run 25	53912	248681	93.56	946.4	0.05312	78.99	1907	150634
Run 26	54261	249659	93.65	946.4	0.05326	78.79	1919	151226
Run 27	54610	250636	93.73	946.4	0.05339	78.59	1932	151819
Run 28	54958	251614	93.81	946.4	0.05353	78.4	1944	152411
Run 29	55307	252592	93.89	946.4	0.05366	78.21	1956	153003
Run 30	55655	253570	93.97	946.4	0.05379	78.02	1969	153595
Run 31	56004	254548	94.05	946.4	0.05392	77.83	1981	154188
Run 32	56352	255525	94.13	946.4	0.05405	77.65	1993	154780
Run 33	56701	256503	94.2	946.4	0.05418	77.46	2006	155372
Run 34	57050	257481	94.28	946.4	0.05431	77.28	2018	155964
Run 35	57398	258459	94.35	946.4	0.05444	77.11	2030	156557
Run 36	57747	259436	94.43	946.4	0.05456	76.93	2043	157149
Run 37	58095	260414	94.5	946.4	0.05469	76.76	2055	157741
Run 38	58444	261392	94.58	946.4	0.05481	76.59	2067	158334
Run 39	58793	262370	94.65	946.4	0.05493	76.42	2080	158926
Run 40	59141	263348	94.72	946.4	0.05506	76.25	2092	159518
Run 41	59490	264325	94.79	946.4	0.05518	76.08	2104	160110
Run 42	59838	265303	94.86	946.4	0.0553	75.92	2117	160703
Run 43	60187	266281	94.93	946.4	0.05542	75.76	2129	161295
Run 44	60536	267259	95	946.4	0.05554	75.6	2141	161887

Parametric Table: Q, M Steam

	Msteam	Qs	Qg	Texh	Mdot$_{fuel}$	Mdot$_{in}$
Run 1	*19850*	*2.254E+07*	*2.471E+07*	842.1	1780	144551
Run 2	*19914*	*2.261E+07*	*2.479E+07*	841.7	1792	145129
Run 3	*19976*	*2.268E+07*	*2.486E+07*	841.1	1805	145718
Run 4	*20035*	*2.275E+07*	*2.494E+07*	840.5	1817	146307
Run 5	*20091*	*2.282E+07*	*2.501E+07*	839.8	1829	146897
Run 6	*20144*	*2.288E+07*	*2.507E+07*	839.1	1842	147492
Run 7	*20193*	*2.293E+07*	*2.513E+07*	838.2	1854	148081
Run 8	*20239*	*2.298E+07*	*2.519E+07*	837.3	1866	148674
Run 9	*20282*	*2.303E+07*	*2.524E+07*	836.3	1879	149263
Run 10	*20322*	*2.308E+07*	*2.529E+07*	835.2	1891	149861
Run 11	*20357*	*2.312E+07*	*2.534E+07*	834	1903	150453
Run 12	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 13	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 14	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 15	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 16	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 17	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 18	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 19	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 20	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 21	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 22	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 23	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 24	*20351*	*2.311E+07*	*2.533E+07*	834.3	1901	150338
Run 25	*20367*	*2.313E+07*	*2.535E+07*	833.7	1907	150634
Run 26	*20399*	*2.316E+07*	*2.539E+07*	832.4	1919	151226
Run 27	*20426*	*2.320E+07*	*2.542E+07*	831.1	1932	151819
Run 28	*20450*	*2.322E+07*	*2.545E+07*	829.7	1944	152411
Run 29	*20471*	*2.325E+07*	*2.548E+07*	828.2	1956	153003
Run 30	*20488*	*2.327E+07*	*2.550E+07*	826.6	1969	153595
Run 31	*20500*	*2.328E+07*	*2.552E+07*	824.9	1981	154188
Run 32	*20510*	*2.329E+07*	*2.553E+07*	823.2	1993	154780
Run 33	*20515*	*2.330E+07*	*2.553E+07*	821.4	2006	155372
Run 34	*20517*	*2.330E+07*	*2.554E+07*	819.5	2018	155964
Run 35	*20515*	*2.330E+07*	*2.553E+07*	817.5	2030	156557
Run 36	*20509*	*2.329E+07*	*2.553E+07*	815.5	2043	157149
Run 37	*20499*	*2.328E+07*	*2.551E+07*	813.4	2055	157741
Run 38	*20485*	*2.326E+07*	*2.550E+07*	811.2	2067	158334
Run 39	*20468*	*2.324E+07*	*2.548E+07*	808.9	2080	158926
Run 40	*20446*	*2.322E+07*	*2.545E+07*	806.5	2092	159518
Run 41	*20420*	*2.319E+07*	*2.542E+07*	804.1	2104	160110
Run 42	*20391*	*2.316E+07*	*2.538E+07*	801.6	2117	160703
Run 43	*20357*	*2.312E+07*	*2.534E+07*	799	2129	161295
Run 44	*20319*	*2.307E+07*	*2.529E+07*	796.3	2141	161887

APPENDIX J: HEAT RECOVERY STEAM GENERATION

Mid points Drybulb (F)	Inlet Temp	Total Msteam [lbm/h]	Total Steam Required	Excess Steam	% Excess Steam
91	64	79400	40972	38428	48
89	62	79656	40972	38684	49
87	60	79904	40972	38932	49
85	58	80140	40972	39168	49
83	56	80364	40972	39392	49
81	54	80576	40972	39604	49
79	52	80772	40972	39800	49
77	50	80956	40972	39984	49
75	48	81128	40972	40156	49
73	46	81288	40972	40316	50
71	44	81428	40972	40456	50
69	44	81404	40972	40432	50
67	44	81404	40972	40432	50
65	44	81404	40972	40432	50
63	44	81404	40972	40432	50
61	44	81404	40972	40432	50
59	44	81404	40972	40432	50
57	44	81404	40972	40432	50
55	44	81404	40972	40432	50
53	44	81404	40972	40432	50
51	44	81404	40972	40432	50
49	44	81404	40972	40432	50
47	44	81404	40972	40432	50
45	44	81404	40972	40432	50
43	43	81468	40972	40496	50
41	41	81596	40972	40624	50
39	39	81704	40972	40732	50
37	37	81800	40972	40828	50
35	35	81884	40972	40912	50
33	33	81952	40972	40980	50
31	31	82000	40972	41028	50
29	29	82040	40972	41068	50
27	27	82060	40972	41088	50
25	25	82068	40972	41096	50
23	23	82060	40972	41088	50
21	21	82036	40972	41064	50
19	19	81996	40972	41024	50
17	17	81940	40972	40968	50
15	15	81872	40972	40900	50
13	13	81784	40972	40812	50
11	11	81680	40972	40708	50
9	9	81564	40972	40592	50
7	7	81428	40972	40456	50
5	5	81276	40972	40304	50

Appendix K: Energy Sell back, Utility Costs

Mid points Drybulb	Inlet Temp	Hours	New Mwe	New MWH	Gas Cost ($/h)	Total gas cost ($)	Energy Required (kW)	Excess Energy (kw)	Annual Sell Back (kWh)
91	64	30	3.450	103.506	902.58	27077.54	9089	1261.61	37848.18
89	62	57	3.477	198.184	908.68	51794.73	9089	1341.75	76479.81
87	60	108	3.504	378.451	914.90	98809.13	9089	1423.54	153742.32
85	58	145	3.531	512.059	921.12	133562.28	9089	1505.33	218272.71
83	56	155	3.559	551.599	927.34	143737.54	9089	1587.12	246003.29
81	54	198	3.586	710.076	933.62	184857.03	9089	1669.73	330606.34
79	52	204	3.614	737.155	939.84	191727.60	9089	1751.52	357309.67
77	50	177	3.641	644.440	946.09	167458.33	9089	1833.72	324568.09
75	48	301	3.668	1104.119	952.31	286645.95	9089	1915.51	576567.61
73	46	495	3.696	1829.442	958.63	474519.73	9089	1998.53	989271.86
71	44	392	3.723	1459.511	964.88	378231.71	9089	2080.73	815645.77
69	44	355	3.718	1319.855	963.66	342098.54	9089	2064.70	732968.50
67	44	339	3.718	1260.368	963.66	326680.01	9089	2064.70	699933.30
65	44	302	3.718	1122.806	963.66	291024.67	9089	2064.70	623539.40
63	44	247	3.718	918.321	963.66	238023.49	9089	2064.70	509980.90
61	44	244	3.718	907.168	963.66	235132.51	9089	2064.70	503786.80
59	44	157	3.718	583.710	963.66	151294.28	9089	2064.70	324157.90
57	44	227	3.718	843.963	963.66	218750.33	9089	2064.70	468686.90
55	44	300	3.718	1115.370	963.66	289097.35	9089	2064.70	619410.00
53	44	224	3.718	832.810	963.66	215859.36	9089	2064.70	462492.80
51	44	224	3.718	832.810	963.66	215859.36	9089	2064.70	462492.80
49	44	267	3.718	992.679	963.66	257296.65	9089	2064.70	551274.90
47	44	344	3.718	1278.958	963.66	331498.30	9089	2064.70	710256.80
45	44	309	3.718	1148.831	963.66	297770.27	9089	2064.70	637992.30
43	43	337	3.732	1257.549	966.78	325806.00	9089	2105.80	709654.60
41	41	223	3.759	838.257	973.03	216986.69	9089	2188.00	487924.00
39	39	326	3.786	1234.366	979.29	319247.10	9089	2270.20	740085.20
37	37	509	3.814	1941.224	985.54	501638.17	9089	2352.40	1197371.60
35	35	312	3.841	1198.454	991.79	309437.78	9089	2434.60	759595.20
33	33	285	3.869	1102.551	998.04	284441.08	9089	2516.80	717288.00
31	31	207	3.896	806.472	1004.29	207888.02	9089	2599.00	537993.00
29	29	152	3.923	596.357	1010.54	153602.24	9089	2681.20	407542.40
27	27	107	3.951	422.736	1016.79	108796.76	9089	2763.40	295683.80
25	25	110	3.978	437.602	1023.04	112534.76	9089	2845.60	313016.00
23	23	65	4.006	260.364	1029.29	66904.13	9089	2927.80	190307.00
21	21	80	4.033	322.640	1035.55	82843.63	9089	3010.00	240800.00
19	19	85	4.060	345.134	1041.80	88552.70	9089	3092.20	262837.00
17	17	54	4.088	220.741	1048.05	56594.57	9089	3174.40	171417.60
15	15	47	4.115	193.414	1054.30	49552.04	9089	3256.60	153060.20
13	13	29	4.143	120.135	1060.55	30755.94	9089	3338.80	96825.20
11	11	15	4.170	62.550	1066.80	16002.01	9089	3421.00	51315.00
9	9	8	4.197	33.579	1073.05	8584.42	9089	3503.20	28025.60
7	7	4	4.225	16.899	1079.30	4317.21	9089	3585.40	14341.60
5	5	4	4.252	17.009	1085.55	4342.22	9089	3667.60	14670.40
					Total Gas:	**8497634.15**			**18823042.33**
								Sell back:	**$478,122**

Appendix L:Efficiencies

Cogeneration System												
Mid points Drybulb (F)	Inlet Temp	Hours	Mwe	MW (MMBtu/h)	Fuel Flow (MMBtu/hr)	Qsteam [MMbtu/h]	Msteam [lbm/h]	Total efficiency	Power/Steam Ratio	Net Heat Rate (Btu/kWh)	Effective Electrical Efficiency	FERC efficiency
91	64	30	10.35061	35.32	127.52	68	59550.00	0.81	0.52	4154.22	0.82	0.54
89	62	57	10.43075	35.59	128.38	68	59742.00	0.81	0.52	4179.69	0.82	0.54
87	60	108	10.51254	35.87	129.26	68	59928.00	0.80	0.53	4205.80	0.81	0.54
85	58	145	10.59433	36.15	130.14	68	60105.00	0.80	0.53	4231.50	0.81	0.54
83	56	155	10.67612	36.43	131.02	68	60273.00	0.80	0.53	4256.81	0.80	0.54
81	54	198	10.75873	36.71	131.91	69	60432.00	0.80	0.53	4285.71	0.80	0.54
79	52	204	10.84052	36.99	132.79	69	60579.00	0.80	0.54	4317.15	0.79	0.54
77	50	177	10.92272	37.27	133.67	69	60717.00	0.79	0.54	4348.35	0.78	0.54
75	48	301	11.00451	37.55	134.55	69	60846.00	0.79	0.54	4378.85	0.78	0.54
73	46	495	11.08753	37.83	135.44	69	60966.00	0.79	0.55	4409.61	0.77	0.53
71	44	392	11.16973	38.11	136.32	69	61071.00	0.79	0.55	4442.80	0.77	0.53
69	44	355	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
67	44	339	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
65	44	302	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
63	44	247	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
61	44	244	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
59	44	157	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
57	44	227	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
55	44	300	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
53	44	224	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
51	44	224	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
49	44	267	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
47	44	344	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
45	44	309	11.1537	38.06	136.15	69	61053.00	0.79	0.55	4437.10	0.77	0.53
43	43	337	11.1948	38.20	136.59	69	61101.00	0.79	0.55	4453.56	0.77	0.53
41	41	223	11.277	38.48	137.48	69	61197.00	0.79	0.55	4489.44	0.76	0.53
39	39	326	11.3592	38.76	138.36	70	61278.00	0.78	0.56	4521.50	0.75	0.53
37	37	509	11.4414	39.04	139.24	70	61350.00	0.78	0.56	4559.65	0.75	0.53
35	35	312	11.5236	39.32	140.13	70	61413.00	0.78	0.56	4594.01	0.74	0.53
33	33	285	11.6058	39.60	141.01	70	61464.00	0.78	0.57	4631.11	0.74	0.53
31	31	207	11.688	39.88	141.89	70	61500.00	0.77	0.57	4670.89	0.73	0.53
29	29	152	11.7702	40.16	142.78	70	61530.00	0.77	0.57	4710.12	0.72	0.53
27	27	107	11.8524	40.44	143.66	70	61545.00	0.77	0.58	4748.81	0.72	0.52
25	25	110	11.9346	40.72	144.54	70	61551.00	0.77	0.58	4790.11	0.71	0.52
23	23	65	12.0168	41.00	145.43	70	61545.00	0.76	0.59	4830.84	0.71	0.52
21	21	80	12.099	41.28	146.31	70	61527.00	0.76	0.59	4874.11	0.70	0.52
19	19	85	12.1812	41.56	147.19	70	61497.00	0.76	0.60	4916.81	0.69	0.52
17	17	54	12.2634	41.84	148.08	70	61455.00	0.75	0.60	4961.98	0.69	0.52
15	15	47	12.3456	42.12	148.96	70	61404.00	0.75	0.60	5006.56	0.68	0.52
13	13	29	12.4278	42.40	149.84	70	61338.00	0.75	0.61	5050.55	0.68	0.52
11	11	15	12.51	42.68	150.73	70	61260.00	0.74	0.61	5096.95	0.67	0.51
9	9	8	12.5922	42.96	151.61	69	61173.00	0.74	0.62	5142.76	0.66	0.51
7	7	4	12.6744	43.25	152.49	69	61071.00	0.74	0.62	5190.92	0.66	0.51
5	5	4	12.7566	43.53	153.38	69	60957.00	0.74	0.63	5241.40	0.65	0.51
								0.78	**0.56**	**4576.70**	**0.75**	**0.53**

System Using Only Enough Steam to Fuel Chillers						
Qsteam [MMbtu/h]	Msteam [lbm/h]	Total efficiency	Power/Steam Ratio	Net Heat Rate (Btu/kWh)	Effective Electrical Efficiency	FERC efficiency
47	40972.00	0.64	0.76	6701.86	0.51	0.46
47	40972.00	0.64	0.77	6733.58	0.51	0.46
47	40972.00	0.64	0.77	6764.88	0.50	0.46
47	40972.00	0.64	0.78	6794.87	0.50	0.46
47	40972.00	0.63	0.78	6823.60	0.50	0.46
47	40972.00	0.63	0.79	6853.76	0.50	0.45
47	40972.00	0.63	0.80	6884.43	0.50	0.45
47	40972.00	0.63	0.80	6914.00	0.49	0.45
47	40972.00	0.62	0.81	6942.20	0.49	0.45
47	40972.00	0.62	0.81	6969.63	0.49	0.45
47	40972.00	0.62	0.82	6997.35	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	6992.69	0.49	0.45
47	40972.00	0.62	0.82	7006.05	0.49	0.45
47	40972.00	0.62	0.83	7034.71	0.49	0.45
47	40972.00	0.62	0.83	7059.50	0.48	0.45
47	40972.00	0.61	0.84	7087.56	0.48	0.45
47	40972.00	0.61	0.84	7112.31	0.48	0.45
47	40972.00	0.61	0.85	7137.89	0.48	0.45
47	40972.00	0.61	0.86	7164.03	0.48	0.45
47	40972.00	0.61	0.86	7189.32	0.47	0.44
47	40972.00	0.61	0.87	7213.07	0.47	0.44
47	40972.00	0.60	0.88	7237.86	0.47	0.44
47	40972.00	0.60	0.88	7261.38	0.47	0.44
47	40972.00	0.60	0.89	7285.70	0.47	0.44
47	40972.00	0.60	0.89	7308.76	0.47	0.44
47	40972.00	0.60	0.90	7332.63	0.47	0.44
47	40972.00	0.60	0.91	7355.49	0.46	0.44
47	40972.00	0.59	0.91	7376.90	0.46	0.44
47	40972.00	0.59	0.92	7399.12	0.46	0.44
47	40972.00	0.59	0.92	7420.38	0.46	0.44
47	40972.00	0.59	0.93	7442.21	0.46	0.44
47	40972.00	0.59	0.94	7464.84	0.46	0.44
		0.62	**0.84**	**7072.15**	**0.48**	**0.45**

Total CHP Efficiency (%), HHV	0.62
Power/Heat Ratio	0.84
Net Heat Rate (Btu/kWh)	7072.15
Effective Electrical Efficiency (%), HHV	0.48
FERC Efficiency	0.45

Total CHP Efficiency (%), HHV	0.78
Power/Heat Ratio	0.56
Net Heat Rate (Btu/kWh)	4576.70
Effective Electrical Efficiency (%), HHV	0.75
FERC Efficiency	0.53