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EXHAUST-DRIVEN ABSORPTION CHILLER-HEATER AND REFERENCE DESIGNS ADVANCE THE USE OF IES TECHNOLOGY

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ABSTRACT

An absorption chiller employing an advanced exhaust-driven design is the key element in a new integrated energy system (IES) recently installed at a major military installation. This 1,000-ton absorption chiller recovers heat directly from the exhaust stream produced by a large gas turbine generator. This new technology can also be delivered in the form of a chiller-heater to provide heating or cooling from the same piece of heat recovery equipment. This equipment arrangement simplifies the construction of IES systems. The project team has also developed a set of reference designs to aid building owners and design engineers in applying this integrated energy system configuration (gas turbine and exhaust-driven absorption chiller-heater). These reference designs simplify the IES design process with standard designs, which is expected to result in reduced installed cost and increased use of integrated energy systems in building applications. This paper describes the exhaust-driven absorption technology and its application at the field site, as well as the development and use of the reference designs.

Keywords: Absorption chiller-heater; cooling, heating, and power systems; distributed energy; reference designs

INTRODUCTION

A key strategy in the effort to increase the use of IES, also known as cooling-heating-and-power (CHP) systems, is the development of technologies that reduce installed cost and offer improved operating economics. A project has been formed to develop an advanced exhaust-driven absorption chiller-heater technology and apply it in a series of pre-engineered “reference designs.” The focus of the project is on systems in the 1- to 5-MW size range, with 900 to 3000 tons of cooling, intended for central plant and district energy applications serving multiple buildings. The major equipment consists of a turbine-generator and an absorption chiller-heater. Systems of this size are too large for the major equipment to be fabricated into one complete assembly, due to shipping limitations. But these systems can be thought of as being packaged as a set of modules, each corresponding to a piece of major equipment. Typically, the turbine-generator and the absorption chiller-heater would make up the two major modules in a packaged system. The reference design concept is built around these two key equipment modules.

ABSORPTION TECHNOLOGY

Absorption technology has been in commercial use since the 1890s. Recent innovations in the fields of metallurgy, instrumentation, and controls have resulted in absorption technology having a unique position in commercial and industrial applications.

Absorbers have been used in heat recovery projects and IES applications for many years. IES systems were typically used either in large commercial sectors or industrial plants. Recent changes in the field of power generation and its application to smaller sectors have radically changed the IES industry, its products, and its applications. Distributed generation, promoting on-site generation with smaller capacity power plants, is considered more appropriate. With this change, the applications for such IES products have also changed quite rapidly. The commercial sector and general HVAC applications have great potential for distributed generation with IES products and technologies. Such applications target businesses with power generation and HVAC with the use of waste heat to provide heating in the winter and cooling in the summer.

Development

Although the prime mover is much smaller in capacity than the typical power plant application, the demand for heat recovery and its use does not diminish. These “miniature” power plants still demand an overall system efficiency in excess of 70% to justify the complete heat recovery and energy-efficient system operation. All of this has to be achieved with an economically viable solution.

A closer look at the application reveals that the end product from the IES system is in the form of chilled water or hot water, since most of the commercial buildings use hydronic systems for HVAC.

Traditionally, absorbers were used only to produce chilled water as chiller equipment for building cooling or refrigeration use. Recent advances in absorption technology allow them to be used also as heating equipment, replacing the boiler typically needed for building HVAC. These units are chiller-heaters and provide chilled water for summer air-conditioning applications as well as hot water for winter heating.

Commercially, absorption chillers or chiller-heaters use steam, hot water, or fossil fuel (natural gas or fuel oil) as their primary source of energy. Hence, IES plants using absorption chillers typically have a heat recovery steam generator (HRSG) or heat recovery hot water heater to produce hot water or steam as the primary heat source. Additionally, this equipment is used in the winter to provide hot water or heating water for building HVAC applications.

This effort is focused on developing a product that can use the waste heat directly to provide the building with chilled water for summer HVAC applications and hot water for winter heating without the intermediate phases of producing steam or hot water. This approach is illustrated in Figure 1. The design not only eliminates the use of a traditional HRSG and the associated accessories, but also simplifies the system configuration, in turn providing a commercially viable solution.

Product Description

Absorption chillers and chiller-heaters use heat in any convenient form to produce chilled water or hot water. The majority of a gas turbine's waste energy is in the form of exhaust gases. Typical exhaust gases from the turbine have a temperature range of ~850-1,000ºF and large exhaust flow. These temperature ranges justify using a double-effect absorption chiller or chiller-heater.

The exhaust gases from the turbine pass directly through the high-stage generator (HSG) section of the absorber. The heat absorbed in this generator is used to regenerate the weak solution of lithium bromide (LiBr). The refrigerant (water) is used in the evaporator section to produce chilled water or in the high-stage generator to produce hot water, independently or simultaneously. This design is shown schematically in Figure 2.

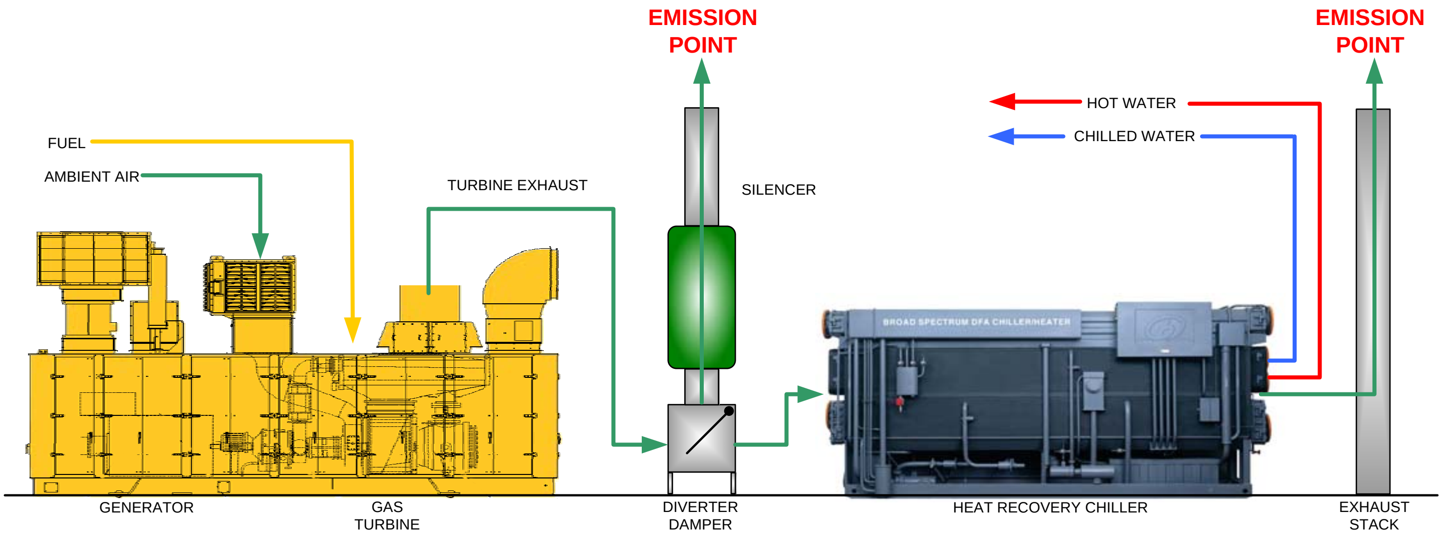


Figure 1. Integrated Energy System with Absorption Chiller-Heater

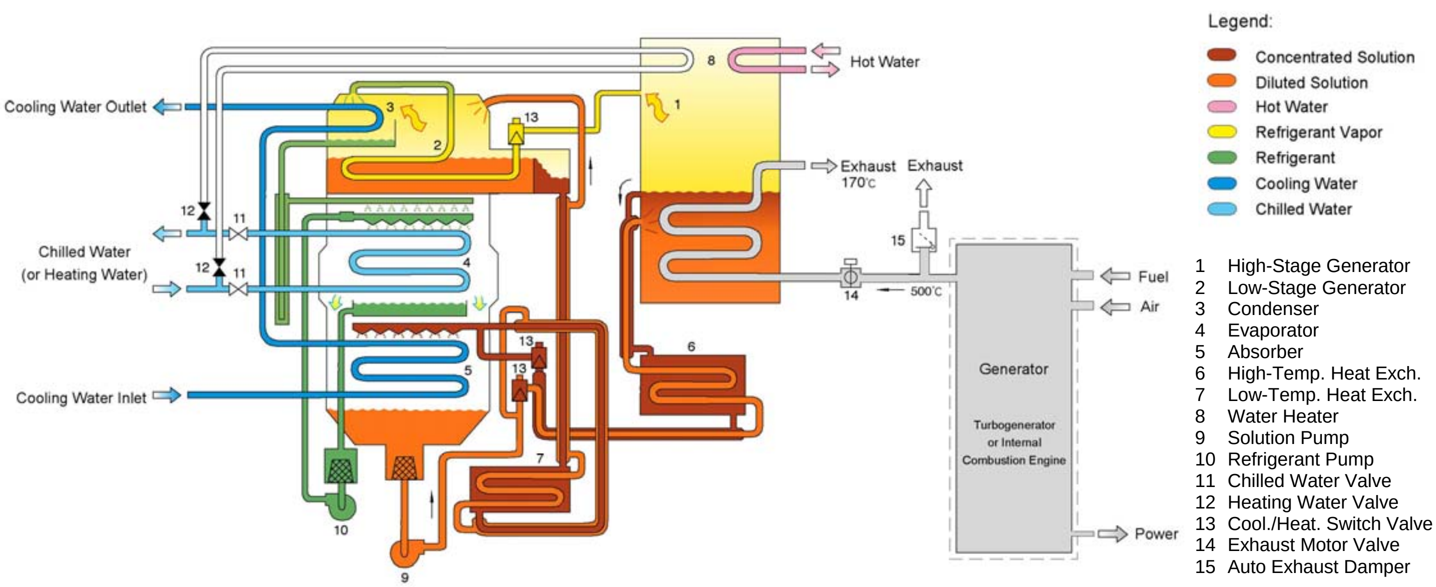


Figure 2. Absorption Chiller-Heater Schematic Diagram

The uniqueness of this design is the use of exhaust gases directly into the absorber as a primary heat source for producing heating hot water or chilled water. Based on the chilled water or hot water requirement, the heat input is controlled to the absorber. Typically, a three-way modulating damper or an induced-draft fan is used to accomplish this task.

Performance

This development consisted of using a standard direct-fired 1,000 refrigeration tons (RT) absorption chiller-heater design with a modified high-stage generator that was suitable for taking 900-950ºF exhaust gases of the requisite quantity. Typically, the design considers ~330-340ºF as the exhaust exit temperature from the absorber after heat recovery in the cooling mode (or 290-300ºF in the heating mode). The performance specifications are shown in Table 1.

The waste-heat-fired absorption chiller-heater requires 9,250 MBH of heat to produce 1,000 RT of chilled water at 44ºF. Table 1 shows the performance of the 1,000 RT absorber with 8,560 MBH of heating capacity at a 180ºF hot water temperature.

Table 1. Performance Specifications

		Specifications
Unit		
Cooling capacity	RT	1,000
Cooling capacity	kW	3,520
Heating capacity	MBH	8,560
Chilled Water Circuit		
Outlet temperature	ºF	44
Inlet temperature	ºF	54
Chilled water flow	GPM	2,397
Cooling Water Circuit		
Outlet temperature	ºF	95
Inlet temperature	ºF	85
Flowrate	GPM	4,085
Heating Water Circuit		
Outlet temperature	ºF	180
Inlet temperature	ºF	160
Flowrate	GPM	855
Exhaust Gases (Heat Input)		
Inlet temperature	ºF	932
Heat input	MBH	9,250
Electrical Requirement		
Power supply	V/Ph/Hz	460/3/60
Electric consumption	kW	8.8

Design Challenges

Typical exhaust conditions are of high volume and low temperature as compared to a direct natural-gas-fired unit. The design of the high-stage generator had to accommodate for this high volume of turbine exhaust while maintaining the backpressure requirement of the turbine. Hence, the standard turbulators in the high-stage generator had to be modified to accommodate the pressure drop requirement.

Although the design had to be liberal enough to effect good heat recovery, manufacturing cost was also considered in the design of the HSG. Lithium bromide is an expensive material. Liberal designs increase the LiBr quantities required in the high-stage generator, leading to higher product cost. The designs had to be compact with enough surface area to effect considerable heat recovery.

Compared to a standard natural-gas-fired high-stage generator, the amount of liquid in the machine is fairly large. This can create liquid stagnation and make the solution ineffective. For this reason, the flows of liquids in the machine were modified to obtain optimum heat and mass transfer.

The exhaust-gas-fired machines have to be designed to handle a large volume of flue gas effectively. To attain a degree of evenness in the flow of exhaust gases, the area provided on the exhaust gas inlet box was increased to create a plenum effect. Also, the turbulator design was modified to affect the flow of exhaust gases and achieve evenness in the flue gas path. Some changes were also made in the design of the control logic. Since the medium to be controlled now is exhaust gases, the rate of change of flow with respect to load was slowed to avoid any sudden changes in the system. The control reaction time to changes in conditions was also increased to provide control actions that are less aggressive than in the case of direct natural-gas-fired machines.

Applications

Traditionally, the IES concept involved a complex and expensive system with several equipments and accessories. With “miniaturization” of IES systems, the applications now target the commercial sector of the market. Generally, in such applications, the waste heat is used to provide the building with heating and cooling for HVAC purposes. Since a single piece of equipment tagged onto the prime mover provides heating and cooling, the overall system becomes much simpler and more cost-effective. The system can now be used year around with good energy efficiency. This opens several applications in the commercial sector, from supermarkets to commercial complexes to shopping malls. Systems typically from 50 kW to a few megawatts can effectively convert waste heat to a more useful form of energy. Hospitals, hotels, and residential complexes can use an efficient and cost-effective IES system for air conditioning and domestic hot water use.

A system recently installed at a major military installation incorporated an exhaust-gas-driven chiller. A photo of the unit is shown in Figure 3. This IES system offsets a portion of the grid electric power and results in an energy-efficient system.

Although the applications for such IES systems are numerous, providing an integrated approach to meet the energy needs in terms of its power, heating, and cooling requirements should always be considered.

REFERENCE DESIGNS

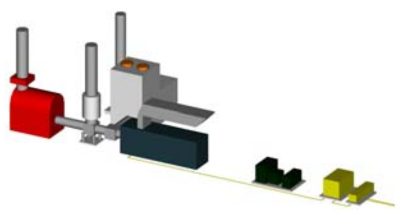
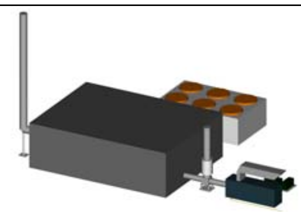
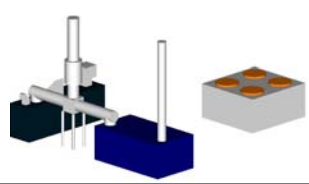
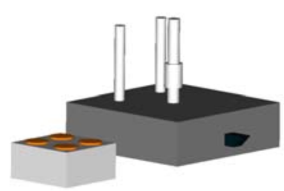
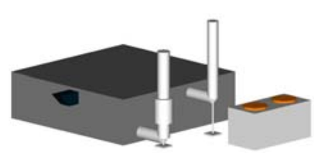
Five reference design packages have been developed that focus on IES modular systems in the 1- to 5-MW size range, with 900 to 3,000 tons of cooling, intended for central plant and district energy applications serving multiple buildings.

Figure 3. Absorption Chiller

Development of standardized packaged IES modular systems with sophisticated controls will provide lower life-cycle costs and will also speed the acceptance of this technology in the marketplace. Streamlining the up-front design process, together with on-line optimization of system operation, is needed to produce the greatest benefit from IES technology.

The reference design configurations were selected to cover a variety of siting conditions. A number of example applications are shown in Table 2. Some have new plant buildings constructed to house the IES equipment, some have complete outdoor installations, while some detail the modification of an existing plant or mechanical space. Site conditions and interface issues are unique to every project; however, the reference designs present a common example that can be applied to a typical IES solution for a facility.

Table 2. Reference Design Examples

	5.3-MW Turbine, 1,200-Ton Chiller-Heater, Outdoor Installation with Inlet Air Cooler, New Chiller Building, Existing Plant Expansion
	5.3-MW Turbine, 3,000-Ton Chiller-Heater, New Stand-alone Plant Building
	4.5-MW Turbine, 1,300-Ton Chiller-Heater, Complete Outdoor Installation, Auxiliaries Installed in Existing Space
	3.4-MW Turbine, 2,000-Ton Chiller-Heater, New Stand-alone Plant Building, Dual Chiller-Heaters
	1.2-MW Turbine, 900-Ton Chiller-Heater, Existing Plant Expansion, All Contained in Existing Space

Because IES installation scenarios vary widely, packaging is dependent on modularity; namely, the ability to construct a system by choosing from a selection of compatible components with standardized interfaces. This is especially important for larger IES systems, where the physical size of the equipment prohibits the manufacture and shipment of the entire system in one enclosure. Packaging these systems into a number of component modules, with each corresponding to a piece of major equipment (i.e., gas turbine-generator and absorption chiller-heater), simplifies the design and installation process by reducing the amount of site-specific engineering and site preparation required.

Developing a set of reference design packages reduces the amount of custom design work required for a given site application. The reference designs are not intended to replace responsible detailed engineering, but will help engineers, developers, and facility managers evaluate the ability of IES technology to meet their energy needs. Readily available reference designs can serve to shorten the time required to perform the upfront analysis needed to quantify the economic and other benefits offered in each individual application. This will help speed the process of evaluating candidate IES applications.

Figure 4 depicts a typical outdoor installation of a gas turbine and absorption chiller-heater. Both the turbine and chiller-heater are contained within weatherproof enclosures. An exhaust "diverter" is placed in the exhaust steam between the turbine and the chiller-heater, which can route the exhaust away from the chiller-heater during start-up, maintenance, or to satisfy periods of low chiller-heater demand.

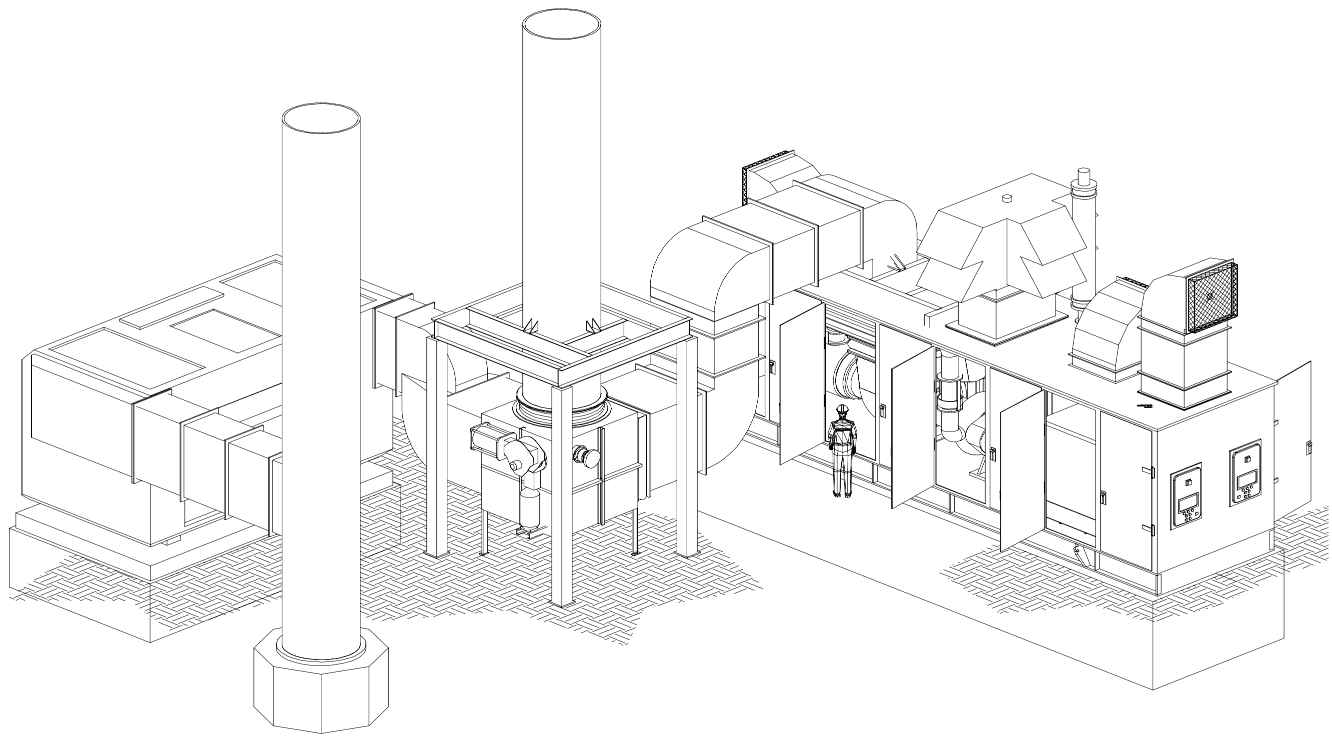


Figure 4. Gas Turbine and Absorption Chiller-Heater Installation

Reference Design Contents

The modular design packages will provide IES systems that are more cost-competitive through a reduction in installed cost and optimal matching of equipment to the energy loads. These improved economics can serve to validate applications that may have otherwise been difficult to justify (from a purely economic standpoint). For these borderline applications, the other benefits provided by IES technology (e.g., reduced emissions, improved indoor air quality (IAQ) when used with desiccant technologies, and increased energy efficiency) are thus made available to the central plant/building owner and occupants.

The reference designs show the module configurations (equipment types, physical arrangements, and performance ratings) of the available packaged IES system designs. These pre-engineered designs will help speed the design process through reuse of the design data. Along with equipment selections and performance data, the reference design packages contain schematics and block diagrams, high- level piping and instrumentation diagrams (PIDs), and CAD drawings showing an example of how the equipment could be arranged and interconnected (covering mechanical, electrical, and general construction elements). The designs also include key specifications and performance data at the module and system levels, as well as templates for simulating system performance (packaged IES system types, equipment data, and a database for utility cost schedules and load profiles that can be tailored to a particular site).

Excerpts from example turbine/exhaust and chiller-heater PIDs are shown in Figures 5 and 6. The designs include sizing, flow, connection, and instrumentation data. A database of performance and sizing information is included that references

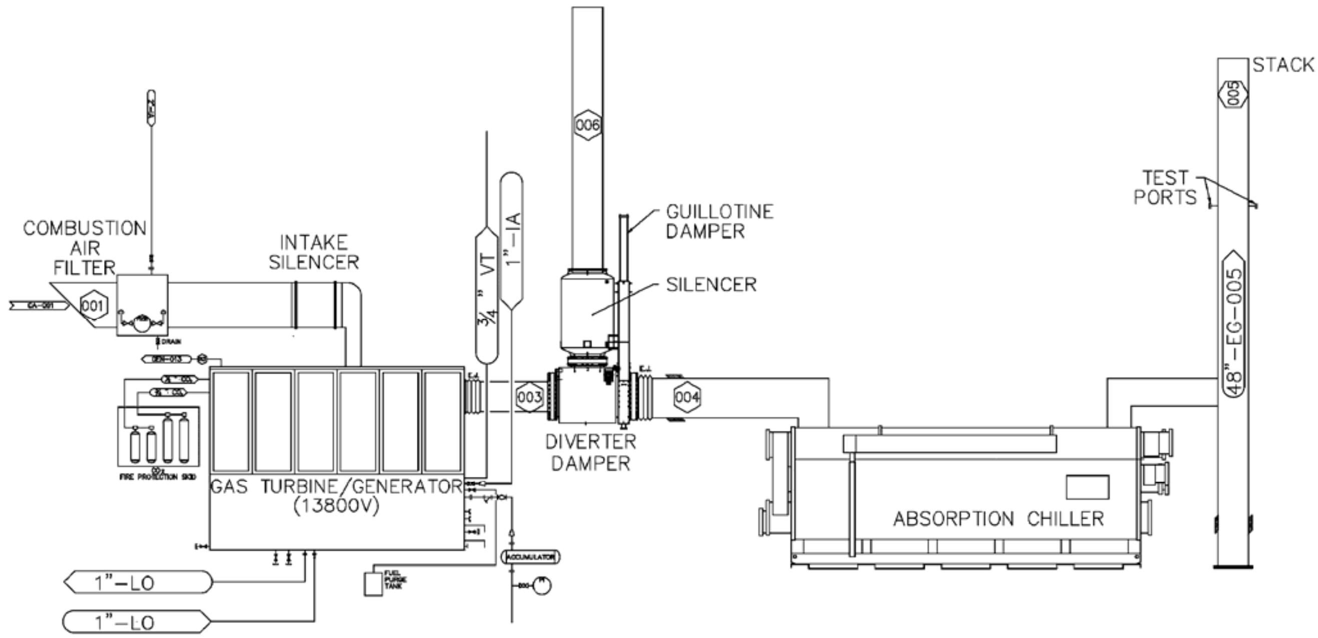


Figure 5. Turbine/Exhaust PID

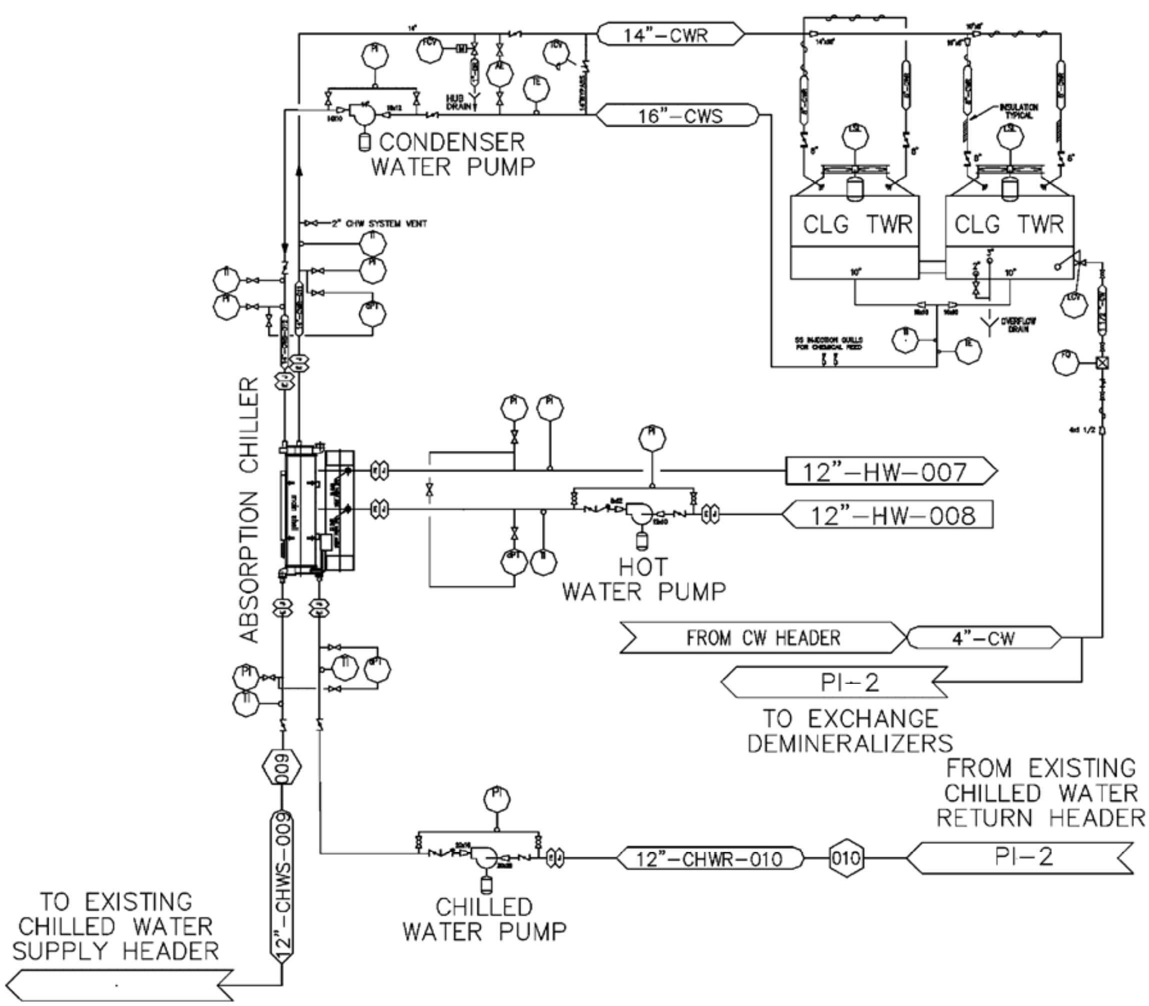


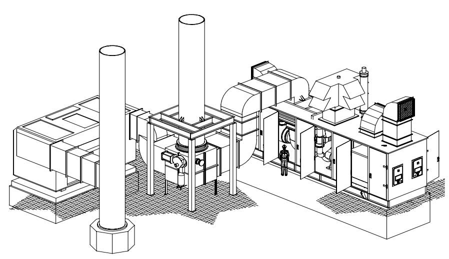
Figure 6. Absorption Chiller-Heater PID

the PIDs. Facility personnel will be able to extract footprint, weight/structural concerns, and a simple bill of materials for cost estimating. Calculations included in the reference design packages are conservative and are appropriate for use in preliminary analyses. Responsible project engineers will use this information as an evaluation tool and a basis for a final design, and will then expand these reference designs to include site-specific calculations and the other elements of a final detailed design.

Example Performance Criteria

An absorption chiller-heater provides an excellent heat sink for waste heat during the cooling months. Although the chiller-heater has the capability to operate in heating and cooling modes simultaneously, this example will assume that the unit is operating in 100% cooling mode only. Performance data shown in Table 3 are from the 90°F operating bin, which is generally a worst-case operating point for the gas turbine.

Table 3. Reference Design Examples

4.5-MW/1,300 Ton Design Performance Summary		90°F Design Point	% Efficiency
	Turbine Fuel Consumption	32,088 MBH	--
	Power Generation	12,802 MBH	39.9%
	Chiller Heat Recovery	13,147 MBH	41.0%
	Chilled Water Generation	15,780 MBH	COP 1.2
	Fuel Efficiency:		80.9%

This particular design produces 3,752 kW and 1,315 tons (for 44°F chilled water) at a 90°F operating point. Fuel consumption is for natural gas based on the lower heating value (LHV), and the power generated figure is a typical kilowatt to Btu/hr conversion. The chiller heat recovery term shows the total heat extracted from the turbine exhaust stream by the chiller-heater. Depending on the site conditions, a chiller-heater and its exhaust ductwork are typically assumed to have approximately 3% to 4% in radiant and convective heat losses, which are not reflected in these performance numbers. The total efficiency number shown depicts the total fuel efficiency/thermal heart recovery and performance of the IES system and does not account for chilled water generation efficiencies. The chilled water generation term assumes a chiller-heater coefficient of performance (COP) of 1.2 for these calculations. These performance projections have been prepared in accordance with a recently proposed industry standard [1].

An exhaust-heat-driven (indirect-fired) absorption chiller-heater has a distinct advantage with respect to overall system efficiency. No interim heating medium is used outside of the chiller-heater package. For example, energy losses when generating steam or hot water to drive a conventional absorption chiller are eliminated, increasing the system efficiency.

INSTALLATION SITE APPLICATION

The absorption technology, elements of the reference design concept, and a new control optimization technology have been installed in a field site at the 82nd Central Heating Plant at Ft. Bragg, NC. This project is part of a larger study of the benefits of IES systems that could apply to other large federal facilities [2].

This facility is one of 14 central plants on the post. This IES system is an important element of the Army's strategy to improve energy efficiency and reduce operating costs on the post. Due to the specific needs of this site, the absorption technology was applied in the form of a chiller-only unit. At the time of installation, the hot water load was much less than a chiller-heater could have provided (most of the heat load was required in the form of steam). For this reason, the absorption chiller is integrated into the system, in parallel with a heat recovery steam generator, in the turbine's exhaust path.

The 82nd Plant provides district heating and cooling to serve a large number of barracks and other buildings with 125-psig steam for heating, 170ºF hot water (converted from steam), and 44ºF chilled water for cooling. The plant originally contained five large water tube steam boilers. Four of these boilers performed poorly and were unreliable and in need of replacement. This condition provided an excellent application for installing a cooling, heating, and power system.

The IES system's major equipment consists of a 5-MW gas turbine generator, a heat recovery steam generator, and the 1,000-ton exhaust-driven absorption chiller. The IES equipment is fired with natural gas and can also be fired with fuel oil as a backup fuel source. The plant also includes an auxiliary steam boiler and an auxiliary electric centrifugal chiller for backup or to provide additional capacity when required. The IES system has an electrical generating capacity of 5,250 kW and a heating capacity of 28,700 lb per hour of steam at nominal ambient conditions (60ºF). The plant serves a year-around heating load for domestic hot water and food service needs. Space heating loads are served during the fall and winter months. Cooling is provided during the spring, summer, and early fall.

The IES system operates in a base load condition, essentially offsetting some of the electric demand on the post. The balance of the electric load is purchased from the local electric utility. During periods of low heating load, the heating demand is less than the maximum thermal output of the IES system. During periods of high heating load, the auxiliary duct burner is employed to increase the output of the HRSG. At present, all of the cooling load for the buildings served can be satisfied by the 1,000-ton absorption chiller.

The IES system is operated in a number of different load-following strategies, based on achieving the best economic performance. The appropriate operating strategy is determined by an on-line optimization function that is resident in the plant's supervisory control system. The control optimization function developed on this project considers the electric load, heating and cooling loads, utility rates (grid electricity, fuel prices), equipment characteristics, and weather data to determine how to best meet these loads using the IES equipment, electric grid power, and the non-IES heating and cooling equipment. The optimizer guides the plant operator by recommending the optimal setpoints for electric power generation, heating, and cooling equipment. The economic performance (cost savings) provided by the IES optimizer software is a function of the energy prices, energy loads, and equipment characteristics of the site. Simulations of this software have shown an estimated annual energy cost savings of approximately 5% over the typical user-specified operating strategy. In practice, the actual annual performance will vary as energy prices and energy loads fluctuate. This optimizer software should translate into further improvements in energy efficiency and reduced emissions for this IES system.

By converting fuel into both electrical and thermal energy, this IES system improves the overall energy efficiency of the 82nd Plant. The electricity produced displaces some of the power that was previously purchased from the local electric utility, generated in part at coal-fired power plants. The related transmission and distribution losses are avoided through the use of on-site generation. This project is also a key contributor to the post's energy security initiative. The on-site generation capacity of this IES system is a valuable asset that can be used to mitigate the effects of utility plant outages and other disruptions on the electrical grid.

Due to the installation of this IES system, emissions are effectively decreased by reducing the need for utility-provided power from coal-fired central plants. In addition, this IES system reduces emissions by replacing the poorly performing steam boilers at the 82nd Plant. The turbine generator employs state-of-the-art low-NOx burners that offer excellent emissions performance, with NOx emissions measured at less than 25 ppm under steady-state operating conditions. This emissions performance provides a significant reduction over the approximate 290-ppm NOx emissions produced by the existing steam boilers that the new IES system replaces.

ACKNOWLEDGMENTS

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