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ADVANCED ABSORPTION CHILLER CONVERTS TURBINE EXHAUST TO AIR CONDITIONING

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ABSTRACT

The value of "waste heat" is demonstrated by a 2,500-ton absorption chiller that uses exhaust from a 4.5-MW turbine as its only source of fuel. By design, the full heat output of a natural-gas-powered Solar turbine closely matches the capacity of a Broad chiller. For the past year, this combined cooling and power system has provided chilled water for the Domain in Austin, Texas, a multi-use complex. Field data verify a fuel efficiency of 74% based on the higher heating value (HHV) of natural gas—as compared with the national average efficiency of 32% for central power plant electricity generation and transmission. System efficiency and chiller efficiency (coefficient of performance, or COP) correlate with an R^2 value of >0.9.

The U.S. Department of Energy's Distributed Energy Program [1] and Oak Ridge National Laboratory teamed with Austin Energy, a municipal utility, to develop this modular integrated energy system (IES). Burns & McDonnell developed, installed, and tested the system, the largest in the nation to use the approach of recycling waste heat to drive an absorption chiller. Capital cost comparisons document a 10–15% cost reduction because this skid-mounted, streamlined design supplies air conditioning with an exhaust-fired double-effect absorption chiller. The IES has a net present value (NPV) of over $12M.

KEYWORDS

Integrated energy system; combined heat and power; absorption chiller; turbine; waste heat; thermal energy

MODULAR INTEGRATED ENERGY SYSTEM (IES) DESCRIPTION

The modular integrated energy system (IES) is a highly efficient, modular, on-site energy system that was installed at the Domain in Austin, Texas, a multi-use complex that includes retail, residential, and industrial space. The IES combines a natural-gas-fired 4.5-MW combustion turbine generator with an advanced exhaust-fired 2,500-ton double-effect absorption chiller to produce cooling and power. This flexible system can be configured with a 4.3-MW Mercury 50 turbine coupled to a 1,000-ton absorption chiller (see Figure 1). Electricity generated by the natural-gas-fired turbine can be used on site and/or exported for use by the local utility or regional transmission authority. Under certain conditions (e.g., severe weather) the turbine can be operated with No. 2 fuel oil. The chiller unit can be configured as a chiller or as a chiller/heater (see Figure 2).

The 950°F turbine exhaust heat is exchanged to evaporate water from a natural absorbent, lithium bromide. As the vapor condenses, more than 2,500 tons of chilled water is produced at full capacity without any additional fuel. This advanced double-effect chiller uses two stages of heat exchange to improve efficiency and can be configured to produce hot and chilled water simultaneously (see Figure 2). A portion of the chilled water (200–300 tons) is used to cool the turbine inlet air, improving electric efficiency. The remaining chilled water output can be used to serve a site's cooling load by charging a thermal energy storage system (planned for future installation at the Domain) or by supplying a district chilled-water system.

Integrated Energy System Modular Components

- 4.5-MW Centaur 50 Solar Turbine combustion turbine with 12.47-kV generator
- Toromont natural gas compressor
- Diverter valve with bypass stack and duct to absorption chiller
- Broad USA 2500-ton exhaust-fired two-stage absorption chiller
- Chiller exhaust stack module
- Inlet air-cooling module with inlet air filter

Equipment

- Process controls integrated with condenser water pumps
- 12.47-kVA high-voltage switch for tie to utility substation
- Isolation transformer
- 480-V distribution switchgear

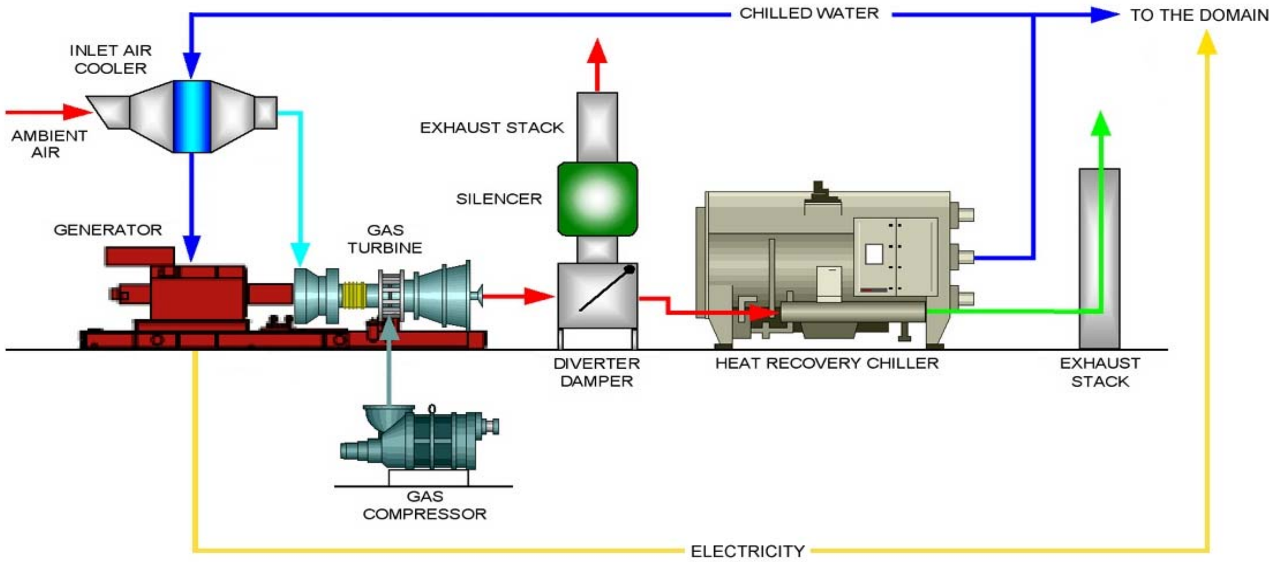

Figure 1. Modular integrated energy system. The system, installed in Austin, Texas, is composed of six modular components that are built and shipped separately.

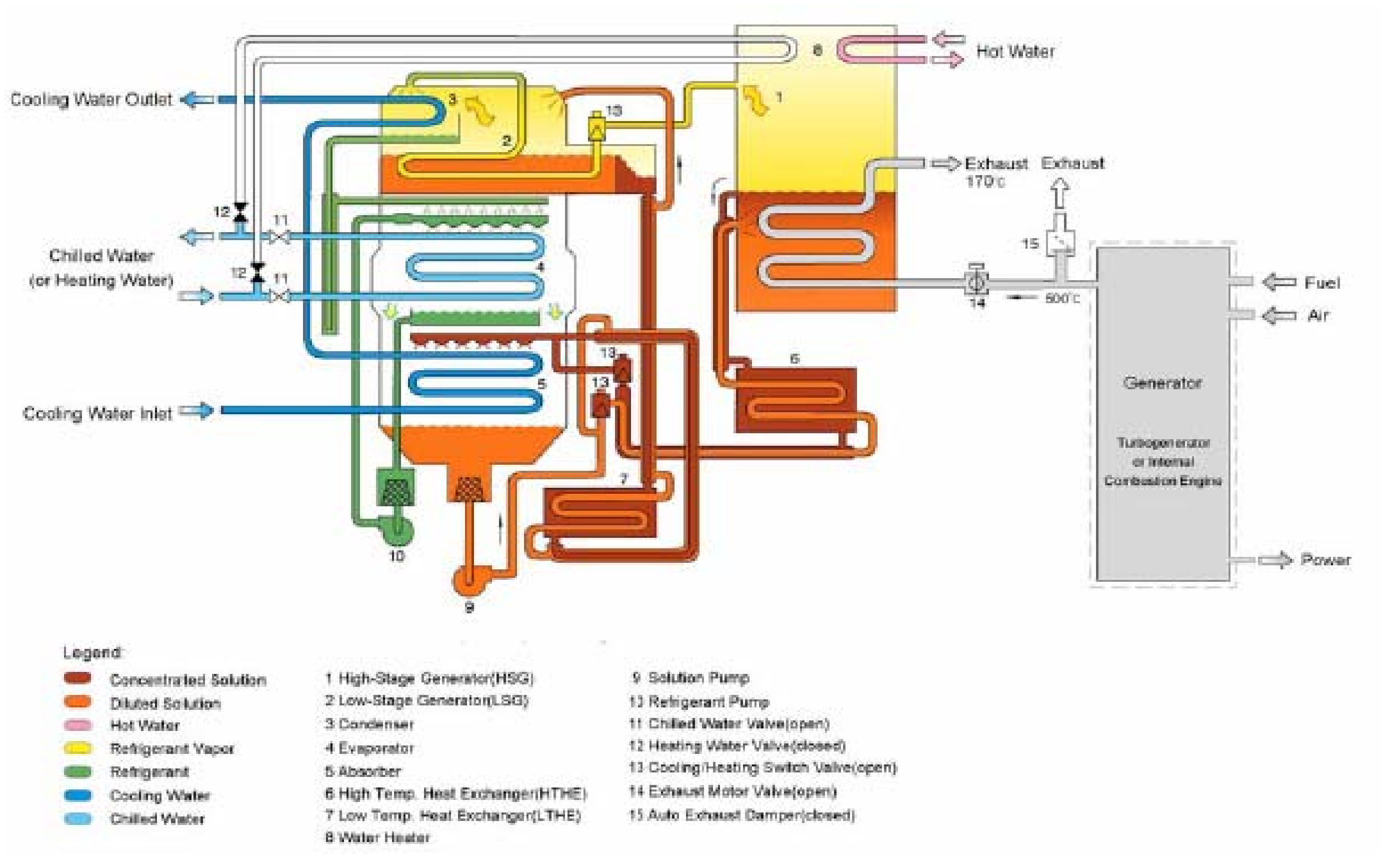

Figure 2. Double-effect absorption chiller uses heat from turbine exhaust to produce 2500 tons of chilled water. (*Note:* Hot water is not produced in the Domain application.)

A diverter valve and a stack are installed between the turbine and the chiller to modulate the flow of exhaust through the chiller, controlling the amount of chilled water (or hot water) produced by the system. The diverter valve may be completely shut, diverting all exhaust out through the stack during periods when the owner/operator desires to run the turbine only. The combined electrical and thermal efficiency of the system exceeds 80%, based on the higher heating value (HHV) of natural gas. The system design is modular, allowing for the six major components to be pre-manufactured and delivered to the site on skids [2].

PREDICTED ECONOMIC PERFORMANCE

A Microsoft Excel–based modeling tool was developed to use technical and economic factors to predict the system's economic performance (see Table 1) [3]. The model was refined by evaluating several sites to accommodate variations in commercial and technical constraints. Important variables were held constant regardless of equipment configuration:

- 2004 as the first year of operation,
- a 20-year length of analysis,
- a 5.5% discount rate,
- a 3.0% fuel cost and electricity cost/revenue escalation rate,
- a $0.1497/ ton-hr chilled water revenue,
- a 0.005 $/kWh prime mover operating and maintenance (O&M) cost,
- one week per year estimated system downtime due to maintenance,
- a 0.006 $/ton-hr heat recovery equipment O&M cost, and
- use of temperature bin data for Austin, Texas.

Comparisons between various equipment configurations were modeled to optimize economic performance. For example, the modular equipment configuration selected and installed at the Domain "drives" the absorption chiller with turbine exhaust, eliminating heat recovery steam generators (HRSGs). By eliminating the requirement to produce steam, capital costs are reduced by 10–15% compared to a custom-designed system that converts exhaust heat to steam to drive the chiller [4]. Capital and operating costs were used to establish a site-specific net present value (NPV) for proposed IES projects over the project life-cycle (see Table 2). The calculated NPV for the cost and revenue streams associated with the proposed IES system are compared to the NPV for the cost and revenue streams associated with a site's existing or planned conventional energy system. The results of this head-to-head economic comparison of a turbine-based IES system with conventional technologies such as boilers, HRSGs, electric centrifugal chillers, and grid power are shown in Figure 3. Factors that affect the economic success of an IES include

- full use of the thermal output from the prime mover
- the configuration and components of the heat recovery system
- payback of capital costs by long-term operating costs
- economics sensitive to natural gas and electricity prices
- economics sensitive to the revenue rate for chilled water and electricity produced by the system
- the annual operating hours of the system

The number of hours during which the system is thermally base-loaded is a key factor in the overall economics of the project. Although the combustion turbine can be operated

Table 1. Modeling Tool Inputs to IES Model

Model Input	Input Parameters[a] Integrated Energy System	Electric System
Cost/expected revenue		
Capital cost	$8M	$3M
Fuel cost, $/MMBtu	$4M	N/A
Electricity cost/revenue, $/kWh	$0.06/kWh usage and revenue	$0.06/kWh usage
Cost for system parasitic loads, $/ton	$0.25	$0.90
Loads and equipment capacity		
Prime mover electrical capacity, MW	4.5-MW Centaur 50 Combustion Turbine	N/A
Heat recovery equipment thermal capacity, tons	2,500-ton Broad absorption chiller	2 × 1,200 ton electric centrifugal chiller

[a] Values from IES and electric system in the Domain, Austin, Texas.

Table 2. Modeling Tool IES Output: Economic Performance

Model Output	Value
NPV of the project over the analysis term	$13M
Life cycle cost of the project	$16M (NPV)
Annual fuel usage and cost	$960,000
Annual O&M costs	$170,000
Number of years required to pay back project investment	7
Investment rate of return over the analysis term	19%
Anticipated system efficiency	79%
Annual thermal energy	11,250,000 Ton-hrs
Annual electric production	16.6M kWh
Annual thermal product	Chilled water: $1.7M
Annual electric revenues	Electricity: $990,000

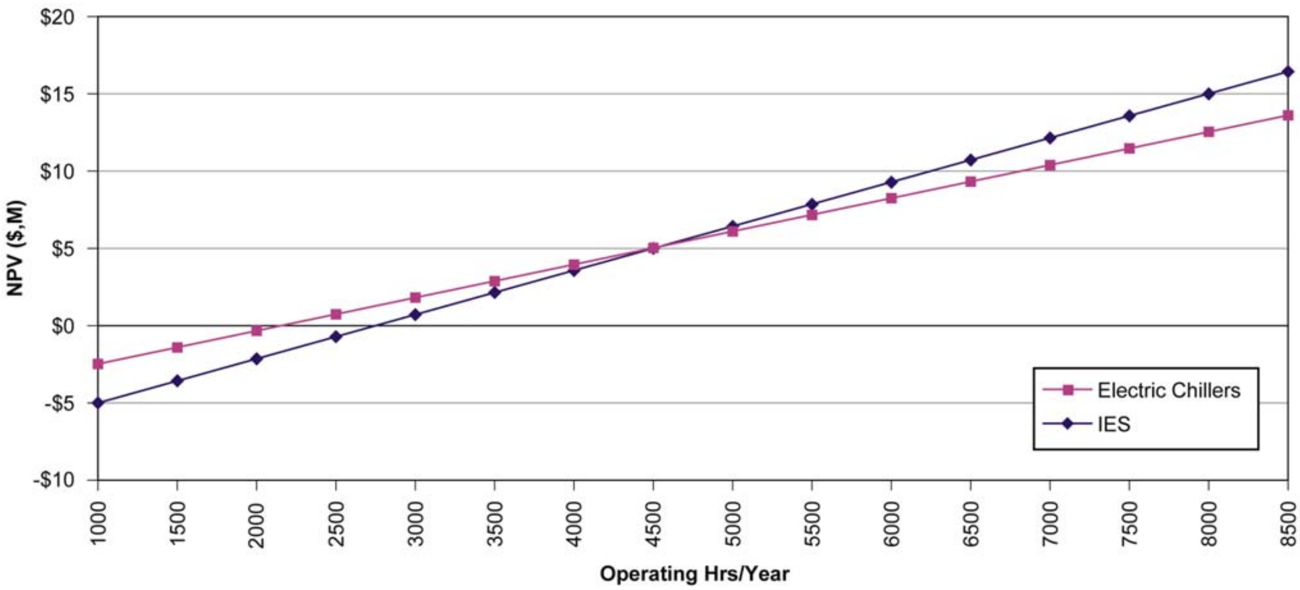

Figure 3. CHP System Is Base-Loaded To Recover Capital Costs.

independently with the absorption chiller shut down, this operating configuration has a detrimental impact on overall system efficiency, project economics, and system emissions (a reduction in NO_x emissions credits under output-based environmental standards). Also, IES equipment should be base-loaded to support constant thermal loads (24/7, year-round). IES projects will not be economically feasible, particularly in areas of inexpensive grid power, unless the owner can base-load the thermal component of the system at least 4,500 h/year to maximize either cost savings or revenue from the sale of chilled water and/or heating. This predictive modeling and simulation is being refined to help guide operations.

PRELIMINARY PERFORMANCE ASSESSMENT

The project's data collection objectives, location, and procedure; data validation; and data formatting requirements were originally defined and documented in a testing and rating procedures and standards report [5]. This data protocol is being revised to reflect the long-term monitoring protocol recently promulgated by the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) [6]. The gross efficiency of the IES (without ancillary loads; operating under part-load conditions) was calculated on the basis of data collected and plotted against both turbine and chiller output (see Figure 4). The equation used for IES gross efficiency was

$$E_{gross} = \frac{W_{el} + Q_{AC} \cdot C_1 \cdot C_2}{Q_{in} \cdot C_2} \cdot 100,\ \% \qquad (1)$$

where

W_{el} = net electric power generated by the gas turbine, kW

Q_{AC} = cooling capacity produced by absorption chiller, tons

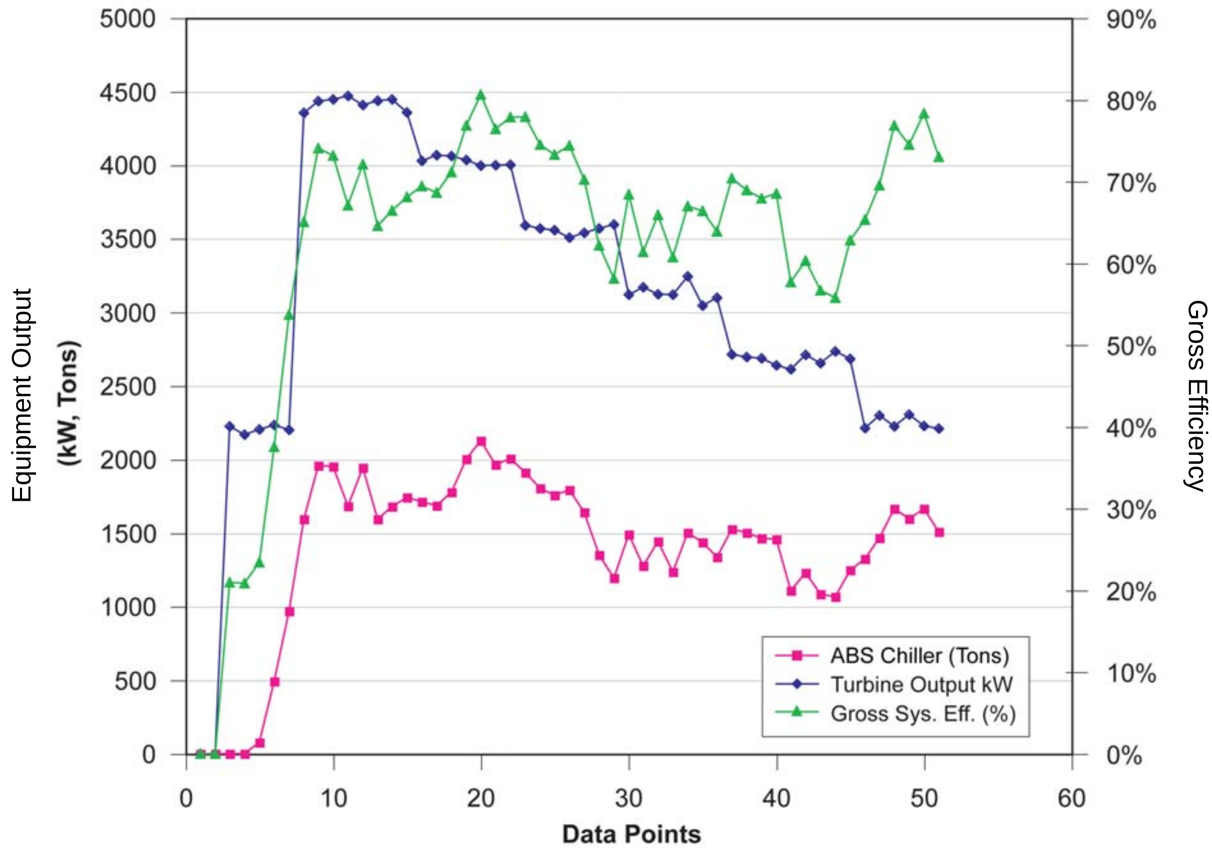

Figure 4. ABS Chiller and Turbine Output vs IES Gross Efficiency.

C_1 = Btu/h-to-ton conversion factor, 12,000 (Btu/h)/ton
C_2 = Btu/h to kW conversion factor, 2.9×10^{-4} kW/(Btu/h)
Q_{in} = HHV-based heat input to the turbine with natural gas, Btu/h

The mathematical correlation between electric and chiller output versus total system efficiency is represented by R^2 values, with a value of 1 being a perfect correlation. Gross IES efficiency correlates well with chilled water output (see Table 3).

Table 3. Correlation of IES Efficiency and Output

IES Output	Correlation with IES Efficiency (R^2)
Electricity	0.49
Cooling capacity	0.91

During full-load conditions, when the IES is producing chilled water near its rated capacity, overall system efficiency is in excess of 80%. As an example of how chiller output drives gross efficiency, data taken on March 23, 2005, at 4:36 p.m. was investigated. The energy content of the natural gas input and inlet cooling for the turbine was 54.5 MMBtu/h HHV, the turbine output was 4,342 kW, and the chiller output was 2,638 tons, resulting in a gross efficiency of 85.3% HHV (or 94.6% based on the lower heating value of natural gas).

An important aspect of field data acquisition is testing how well the absorption chiller is controlled based on the temperature of the cooling water leaving the absorption chiller. When the leaving temperature of the chiller increases, a signal is sent to the exhaust damper, which closes the damper. This closure decreases the mass flow of vented turbine exhaust and increases the mass flow and energy available to the chiller. Note that this control logic is effective in controlling the output of the absorption chiller (see Figure 5).

CONCLUSION

An advanced IES has been designed and installed at a multi-use complex, the Domain, in Austin, Texas. The modular components of the system are a 4.5-MW natural-gas-fired turbine and a turbine-exhaust fired double-effect 2,500-ton absorption chiller. Turbine exhaust is the only source of fuel for the absorption chiller. The project demonstrates innovation in both technology and design, with the equipment delivered on prefabricated skids to ease installation. The innovative design also uses the full heat output of a natural-gas-powered turbine to closely match the capacity of the chiller. This IES has operated for the past year, with data acquisition and analysis beginning during the fall of 2004. Preliminary field data verify

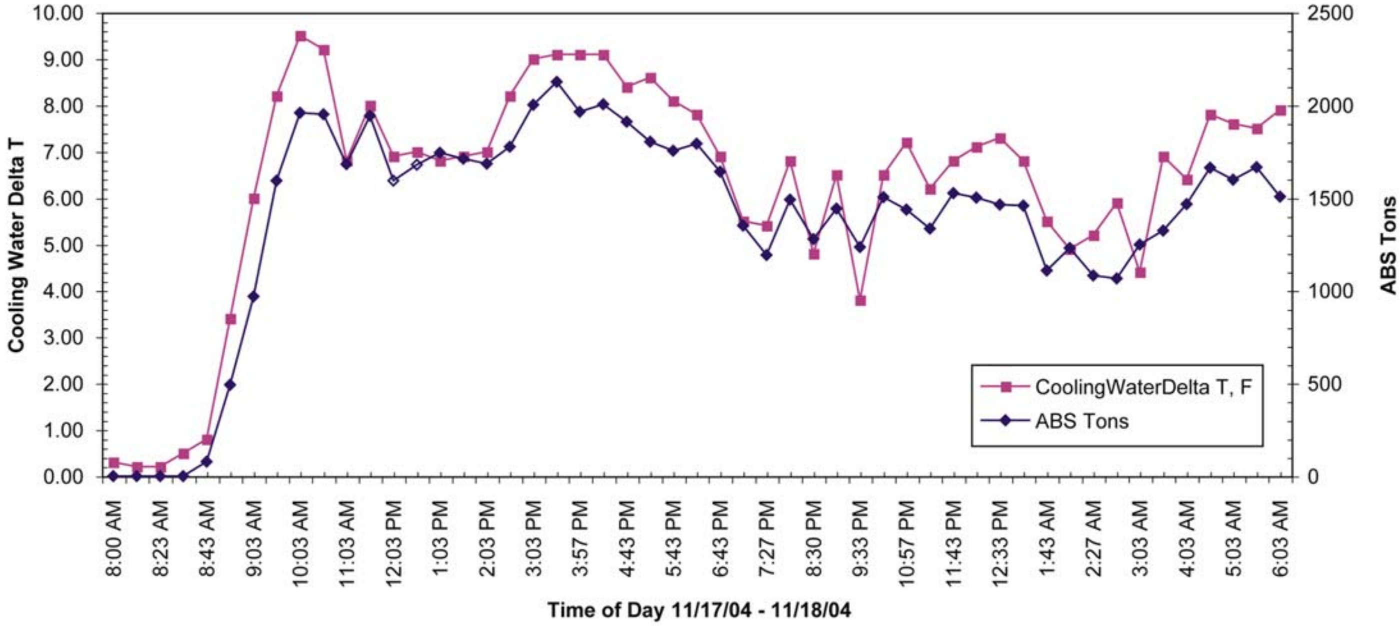

Figure 5. Cooling Water ∆T vs Tons.

a fuel efficiency of 74% based the HHV of natural gas, with the chiller performance dominating system efficiency. Control of the absorption chiller output has been verified through field tests.

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