A NOVEL CONCEPT FOR REDUCING WATER USAGE AND INCREASING EFFICIENCY IN POWER GENERATION

FINAL REPORT

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Principal Authors: Shiao-Hung Chiang
Guy Weismantel

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Submitting Organizations:

University Of Pittsburgh
Chemical & Petroleum Engineering Dept
Pittsburgh, PA 15261

Weismantel International
1826 Spruce Knob Court
Kingwood, TX 77339

ABSTRACT

The objective of the project is to apply a unique ice thermal storage (ITS) technology to cooling the intake air to gas turbines used for power generation. In Phase I, the work includes theoretical analysis, computer simulation, engineering design and cost evaluation of this novel ITS technology.

The study includes two typical gas turbines (an industrial and an aeroderivative type gas turbine) operated at two different geographic locations: Phoenix, AZ and Houston, TX. Simulation runs are performed to generate data for both power output (KW) and heat rate (Btu/KWh) as well as water recovery (acre ft/yr) in terms of intake air temperature and humidity based on weather data and turbine performance curves. Preliminary engineering design of a typical equipment arrangement for turbine inlet air-cooling operation using the ITS system is presented. A cost analysis has been performed to demonstrate the market viability of the ITS technology.

When the ITS technology is applied to gas turbines, a net power gain up to 40% and a heat rate reduction as much as 7% can be achieved. In addition, a significant amount of water can be recovered (up to 200 acre-ft of water per year for a 50 MW turbine). The total cost saving is estimated to be $500,000/yr for a 50 MW gas turbine generator. These results have clearly demonstrated that the use of ITS technology to cool the intake-air to gas turbines is an efficient and cost effective means to improve the overall performance of its power generation capacity with an important added benefit of water recovery in power plant operation. Thus, further development of ITS technology for commercial applications in power generation, particularly in coal-based IGCC power plants is warranted.

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Theoretical Analysis: A methodology has been developed to calculate the power output and heat rate of gas turbines as well as the quantity of recoverable water from air in terms of intake air temperature and humidity based on weather data and turbine performance curves.

Computer Simulation: Based on the results of theoretical analysis, computer simulation has been carried out for an industrial and an aeroderivative gas turbine operated at two different geographic locations: Phoenix, AZ and Houston, TX. Simulation runs are performed to generate data for both power output (KW) and heat rate (Btu/KWh) as well as water recovery (acre ft/yr) when the ITS system is used.

Engineering Design and Cost Analysis: Preliminary engineering design of a typical equipment arrangement for turbine inlet air-cooling operation using the ITS system is presented. A cost analysis has been performed to demonstrate the market viability of the ITS technology.

Conclusions: When the ITS technology is applied to gas turbines, a net power gain up to 40% and a heat rate reduction as much as 7% can be achieved. In addition, a significant amount of water can be recovered (up to 200 acre-ft of water per year for a 50 MW turbine). The total cost saving is estimated to be $500,000/yr for a 50 MW gas turbine generator. These results have clearly demonstrated that the use of ITS technology to cool the intake-air to gas turbines is an efficient and cost effective means to improve the overall performance of its power generation capacity with critically important added benefit of water recovery in power plant operation.

2.0 TECHNICAL

In this section, an introduction, the technical background and the objectives of the project are presented separately below.

2.1 INTRODUCTION

In recent years, gas turbines play an increasingly important role in electric power generation for the utility industry to meet the peak demand of power in the summer time. This trend will continue as newly developed coal-based integrated combine cycle (IGCC) power plants come on stream. Unlike most other components, commercial gas turbines are available in discrete sizes, which provide optimum performance only at or near their ISO-design temperature of 59 ^{0}F (15 ^{0}C). They are not readily adaptable to intermediate rating and lose efficiency when operated away from the design point. Additionally, gas turbine efficiency is highly affected by the mass flow rate of inlet-air, which in turn depends on the ambient temperatures. Therefore, power output from a gas turbine decreases significantly during hot summer months just when more power is needed.

Recent studies by Electric Power Research Institute and The American Society of Mechanical Engineers [1-11] have shown that cooling the gas turbine generator inlet-air to increase its density during period of high ambient temperatures is a cost effective means of increasing the power output of the generator while also reducing the heat rate of the gas turbine. Engineers consider thermal storage because: (1) the technology is basically sound, (2) the economics offer reasonable payback and Return on Investment (ROI). Specifically, a technology based on ice thermal storage (ITS) can offer cost effective intake-air cooling to optimize the power output of a gas turbine. In addition, it recovers condensate from the air. The water recovered can be used in other parts of the power plant, particularly in the coal-fired section of an IGCC power plant, or for external commercial or residential use.

2.2 BACKGROUND

The gas turbine generators currently manufactured by U.S. manufacturers have significantly different performance characteristics. The two principal characteristics that will be addressed here are: (1) the capacity of the equipment, or KW output, and (2) the heat rate, or Btu's of gas energy consumed per KWh.

By comparison to other steam-turbine electric generators, the capacity of gas turbine generator power plants is severely degraded by summer peak temperatures. This is true of both simple cycle and combined cycle plants. Both KW output and heat rate vary with the inlet air temperature. As mentioned above, the KW output varies very significantly and it degrades the greatest at the hottest summer temperatures. Both variables can be best understood by examining at the manufacturer's performance curves, which are prepared to show the percentage change in heat rate and KW output from the 100% performance level that exists at the ISO-design point of 59°F (or 15°C). Using data from REC Associates, typical power output and heat rate curves for two GE gas turbines are shown in Figure 1[12, 13]. As one might observe, the way to achieve improved gas-turbine KW output is simply to chill the inlet air during warm weather, and in so doing, one can achieve the desired performance levels possible at whatever temperature the chilling plant is capable of producing. A gas turbine can lose as much as 36% in KW output capacity during the same 105 °F peak summer day in comparison to the basic (ISO) design rating at 59 °F. When this machine is operating at 64% of design, it will require an improvement of 56% to recover the lost capacity (1.56x64%= 100%).

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* **Remarks:** *For convenience of the reader, all data presented in this report are expressed in conventional English units used by the power industry. A list of conversion factors for converting these English units to International Systems (SI) units is given on page 22.*

It is easy to recover ISO 100% capacity when one chills the gas turbine inlet air to the 59 °F air temperature on the warmest days. In fact, it is practical to chill the 105 °F air further to a temperature of about 40 °F and achieve more than 60% improvement in degraded power output on these turbines. This radical improvement in capacity is very important when one considers the fact that the value of the capacity is at its highest on the hottest summer days when the customer's air conditioning and refrigeration equipment is causing the greatest demand for electric power. It is also true that a given gas turbine in a very warm summer 120 °F location can achieve even more KW output. An 85% improvement is possible on certain gas turbines in Phoenix. But in all cases, the improvement possible with inlet air chilling is very significant, especially in regions where air temperatures rise to the level of 95 °F and above.

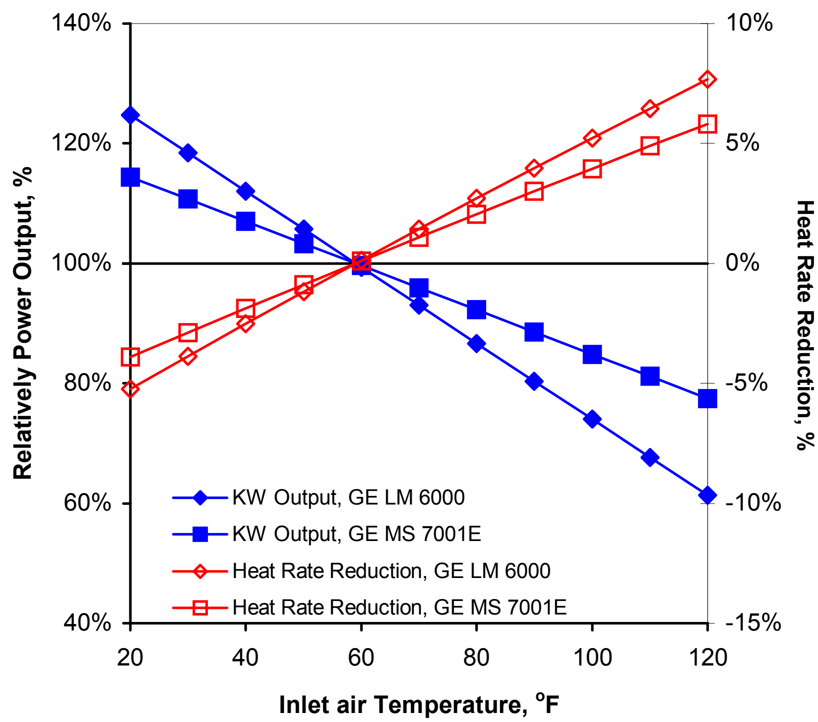

Figure 1 Influence of inlet air temperature on power output and heat rate[12,13]

2.2.1 Intake Air Cooling Overview

Selecting the correct cooling technology should be based on overall economics to include an ROI analysis. This suggests a closer look at operations and maintenance costs, cooling methodology, and the effect of the cooling technology on the turbine. The pros and cons of the various air cooling technologies are listed in Table 1 [14]. As shown in this table, the ice thermal cooling techniques, the TriConditoner unit (an ITS system), show high net power increase and flexible operations, which are important to current power generation systems.

Table 1 Comparing Intake air cooling technologies

Features	Evaporative cooler	On-line refrigeration	Cold water thermal storage	IceShucker thermal storage	IceOnCoil thermal storage	TriConditioner (IEC, ICC, Rht)	TriConditioner (ICC)
Cost/KW on peak day	Low	Medium	Medium	High	Medium	Medium	Medium
Net KW increase on peak day	0-15%	10-25%	20-50%	20-50%	20-50%	20-50%	20-50%
Storage space requirement	None	None	High	Medium/High	Medium	Medium	Medium
Condensate recovery possible	No	Yes	Yes	Yes	Yes	Yes	Yes
Evaporated water droplets to gas turbine inlet	High	No	No	No	No	Optional	Optional
Mist evaporation	No	No	No	No	No	Yes	No
Flexible operations	No	No	No	No	No	Yes	Partial
Sub-grade storage possible	NA	NA	No	No	Optional	Optional	Optional
Freeze-protected water system possible	No	Yes	No	No	Optional	Optional	Yes

In a typical equipment arrangement for ice thermal cooling, as shown in Figure 2, hot ambient air enters an indirect evaporative cooler where it is cooled from ambient temperature to approximately 79 ºF by water supplied from a cooling tower. The air then enters a direction contact chiller where ice water from the ice thermal storage unit cools and dehumidifies the air to approximately 40 ºF and 100% relative humidity. Other ancillary hardware, such as reheat coil, can be part of the system to modify or control temperature and relative humidity. In such thermal storage cooling systems, water vapor in the air will condense as the air is dehumidified during the chilling phase of the air conditioning process. This water can be an important by-product, which is available for gas turbine NO_X emission control or can be utilized elsewhere, such as in boiler feed water heaters. This would significantly reduce water treatment costs in the coal-fired section of a combined cycle power plant.

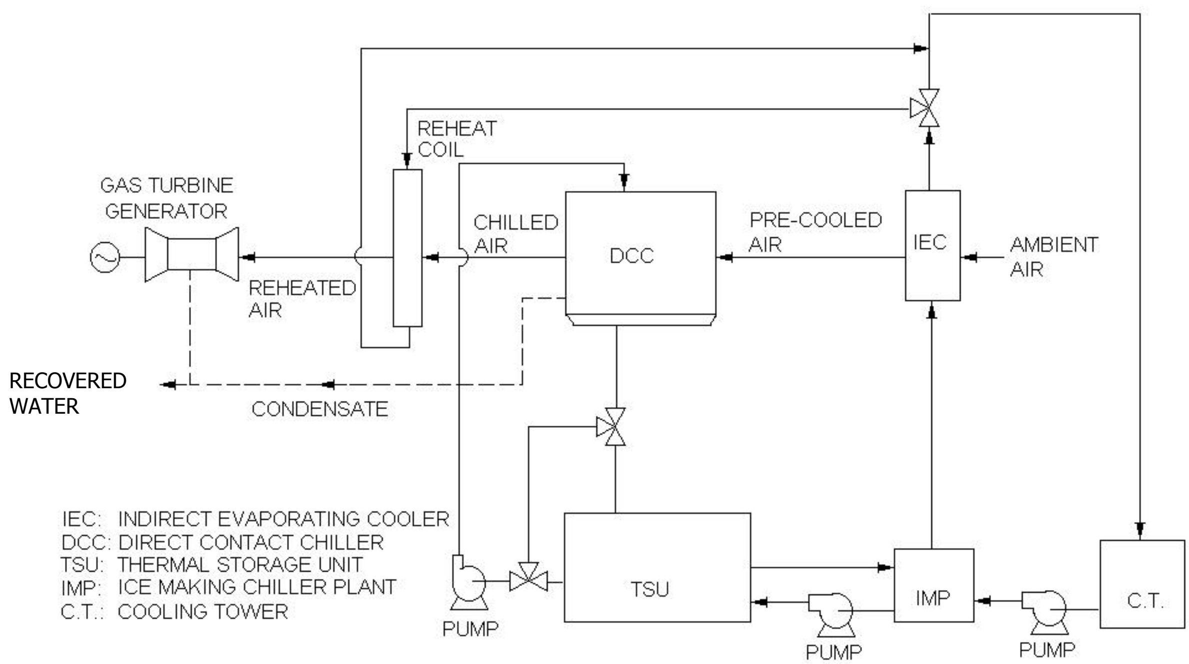

Figure 2 Ice thermal storage system for intake air cooling to gas turbine generator

2.2.2 Economic Justification

Thermal storage applied to inlet of gas turbines can usually be installed on an existing site for a fraction of the cost to install new generator capacity and can easily cost less than the incentive utilities pay customers for off-peak-load shifting. To put the value of this technology in perspective, a typical 44 MW unit may average only 29 MW of output in hot summer day, as shown in Table 2, which was an actual case at an East Texas facility, done by REC Associates. On a turbine that acts as a prime mover in a process plant or gas pipeline, this loss of power driving a compressor translates into loss of throughput and a corresponding loss of production or flow. In the case of a turbine used for power generation, the 15 MW loss in power is equivalent to more than $500,000 per year loss in power sales. Therefore, the energy savings is particularly important in hot climates. The air-cooling technology being offered restores the turbine to its design condition at a cost of $200 per KW or less. This compares to a cost of up to $1,000 or more per KW for a replacement turbine to make up for the loss of power without intake air-cooling. (Both these numbers change depending upon the design configuration used in the system). In addition, large amount of condensed water can save the net water purchase and water treatment. For example, producing pure water can be a significant factor in a coal-based IGCC power plant.

Table 2 Economic Evaluation Of Triconditioner (An ITS Unit) With GE LM6000 Plant[12]

Assumptions: 800/KW Plant, Investment, Fuel & Typical 200/KW Installed Ice Thermal Storage (ITS) System for Cooling Gas Turbine Intake Air		
PLANT CONCEPT	**LM6**	**LM6+ITS**
KW Output @ 59 ^{0}F Ambient	43500	43500
KW Output @ 102 ^{0}F Ambient	28666	43269.5
Plant INV., $/KW @ 59 ^{0}F Design	800	1000
Investment, Dollars	34800000	37766800
Investment, $/KW @ 102 ^{0}F	1214	873
Loan Payback @ 12% annual = $/yr	4176000	4532016
KWh/YR Generated for Houston	351000000	381000000
Income @ 5c/KWh x KWh/YR (Note: Does not credit ITS with more peak value)	17550000	19050000
Fuel $/yr @ 8500 Btu/hr @ $2.50/Mcuft (Note Does not charge ITS for ice-making fuel)	7458750	8096250
Net Income for Operators	5915250	6421734
Income Differential Per Year (Net Saving)		506484
Income Differential for 20 Yr Loan		10129680

As shown in Table 2 above, the improvement in chilled air performance can more than offset the costs of chilling equipment, especially in view of the fact that nearly all generation companies charge a much higher price for electric power supplied during warmer weather, and that is when conventional units start reducing capability, while inlet chilled air units can produce much more, up to 50 to 70% greater KW output during the hottest weather in comparison to the un-cooled inlet air gas turbines. Indeed, if all the gas turbines producing power for California at whatever location, in or out of state, had this full ice thermal cooling equipment, there may not have been a failure of the deregulation system or summer peak blackouts. This is apparently true of the California system now, especially with all the gas turbines, which have recently been brought online. In fact, the needed chilling equipment can easily be justified when one considers that adding more gas turbines will cost up to 4 times as much. Another way of looking at it is to consider that inlet-air-chilled systems are clearly the least-cost-suppliers of electricity during those peak periods of greatest demand. This should give impetus to utilities and Independent Power Producers (IPP) to add this technology to their existing and new gas turbine/combined cycle plants to best compete in the free market in this era of de-regulation and competitive power production.

2.3 OBJECTIVE

The objective of this project is to apply the ice thermal storage technology to intake-air cooling to gas turbines used in power plants (including combined cycle plants) in order to increase overall power output, improve efficiency or reduce heat rate, and have additional benefit of reducing the water usage in power generation systems by recovering condensate from humid air. To achieve the objective, work has been conducted in the following three areas:

(1) Theoretical Analysis: A methodology is developed to calculate the power output and heat rate of gas turbines, as well as the quantity of recoverable water from air in terms of intake air temperature and humidity based on weather data and turbine performance curves.

(2) Computer Simulation: Based on the results of theoretical analysis, simulation runs are carried out for an industrial and an aeroderivative gas turbine operated at two different geographic locations: Phoenix, AZ and Houston, TX. Calculations are performed to generate data for both power output (KW) and heat rate (Btu/KWh) as well as water recovery (acre feet/yr) when the ITS system is used.

(3) Engineering Design and Cost Analysis: Preliminary engineering design of a typical equipment arrangement for turbine inlet air-cooling operation using the ITS system is presented. A cost analysis is performed to demonstrate the market viability of the ITS technology (see Table 2 on page 7).

3.0 RESULTS AND DISCUSSION

In this section, the analytic approach and computational results for the application of an ice thermal storage system to improve the performance of gas turbines operation will be discussed.

3.1 TASK 1: THEORETICAL ANALYSIS

To properly evaluate the benefits of ice thermal storage (ITS) technology for intake air-cooling to gas turbine used in power plants, an analysis of turbine performance and water recovery potential as a function of intake air temperature has been performed. The analytical work consists of: (1) establishing the baseline performance curves (see Figure 1 on page 4) for an industrial-grade (GE MS7001E) and an aeroderivative-type (GE LM6000) gas turbine; (2) assembling an annual record of "Engineering Weather Data," which include dry/wet bulb temperatures, for two selected sites: Phoenix, AZ and Houston, TX; and (3) developing a methodology to calculate the power output and heat rate of gas turbines, as well as the quantity of recoverable water from air cooling as a function of intake-air temperature and humidity based on weather data and specified operating conditions.

3.2 TASK 2: COMPUTER SIMULATION

To define turbine performance, a "computer simulation" based on spreadsheet calculation is performed. A set of manufacturer's turbine performance curves, local weather data and gas turbine specifications are applied in the spreadsheet calculations. The spreadsheet consists of three parts: input data, technical calculations, and economic calculations. The input data includes information about the type of the gas turbine, customer's location, and on-peak/off-peak day periods. The technical calculations encompass the gas turbine performance data, thermodynamic properties of the air, and parameters of the major components, including heat exchangers, refrigeration plant, and thermal storage unit. The economic calculations are the program's actual output, which contains information regarding gained output, materials' costs, and over-all cost of the ITS system. The economical analyses are based on manufacturers' and "Means" cost data.

3.2.1 Power Output Gains and Heat Rate Reductions

For this section of the report, discussion will be limited to hot weather peaking for electric power production and more specifically to the use of ITS system as a means of load shifting (i.e. providing peaking power capacity while shifting the parasitic energy consumption of the ice making equipment to non-peak periods).

In practice, thermal energy storage (TES) systems featuring ice or chilled water are increasingly used for HVAC Applications as well as for turbine inlet air chilling applications. Both ice and water based TES Systems are proven in service. However, the ice-based system (i.e., the ice thermal storage, ITS system) is chosen here because of two key advantages:

1. ***Less restriction on system operation*** - As air is chilled, humidity increases to 100% as the dew point temperature is reached. For most locations during hot weather, the dew point is reached somewhere between 50 and 75ºF. Because of the acceleration chilling effect, most turbine manufacturers recommend 40ºF ± as the minimum temperature for humid inlet air in order to avoid ice formation at the compressor inlet. Both ice and water based TES systems are adaptable to chilling turbine inlet air to 40ºF. However, for turbine inlet air temperatures below about 45ºF, the water based TES System requires adjustments, which may affect load shifting or system arrangement. Thus, the use of ice-based system is preferred.

2**.** ***Less Space Requirements*** - For a given duration peaking cycle, the ice based TES System requires less space (tank size) than does the water based TES System when applied to gas turbine operations. Since economics for water and ice based TES Systems are relatively comparable, reduced space requirements favors ice based systems.

The detailed results obtained by computer simulation are presented in the Appendix. A comparison of the performance of two selected gas turbines operated at two different geographic locations (Houston, TX and Phoenix, AZ) is summarized in the table below.

Table 3 Comparison of power output gains and heat rate reductions for two gas turbines at two cities

Types of gas Turbines		GE LM 6000 (Aeroderivative)	GE MS 7001E (Industrial)	GE LM 6000 (Aeroderivative)	GE MS 7001E (Industrial)
Power Output @ISO, KW		39970	77300	39970	77300
Locations		Houston, TX	Houston, TX	Phoenix, AZ	Phoenix, AZ
Specified Ambient Air (SAA)	db (IN), ^{0}F	97	97	107	107
	wb (IN), ^{0}F	78	78	73	73
Specified Cold Air (SCA)	db (OUT), ^{0}F	40	40	55	40
	wb (OUT), ^{0}F	40	40	55	40
Net Output Gain, KW		14749	15417	15887	18469
Increased Output, %		36.9	19.9	39.7	23.9
Heat Rate Reduction, %		7.19	5.45	6.58	6.38

In Table 3, the data show that the increases in power output for the both turbines are very large, ranging from 20 to 40%. The greatest increase occurs when the turbine is located at a hot desert site, such as Phoenix, AZ. In addition, there is also a significant reduction in heat rate (or an increase in turbine efficiency) for all cases. An improvement in efficiency will translate into savings in fuel (or gas consumption in this case) and lowering the overall operating cost for power generation.

3.2.2 Water Recovery Rates

Water recover rates are related to airflow, temperature and pressure (elevation) and relative humidity. The standard psychrometric chart (see Figure A-4 in the Appendix) can be used to calculate the weight of water (condensate) per one pound of dry air at various temperatures. If one assumes all of the water drops out during thermal cooling, literally, many acre feet of water become available for reuse, even when the gas turbine is operated at a desert location, such as Phoenix, AZ (see Table 4 below). Also, the computer simulation shows that nearly 200 acre ft/yr of water can be recovered when a 50MW gas turbine (GE LM6000) is installed with an ITS system and operated in Houston, TX.

Table 4 Comparison of water recovery for two gas turbines at two cities

Types of gas Turbines		GE LM 6000 (Aeroderivative)	GE MS 7001E (Industrial)	GE LM 6000 (Aeroderivative)	GE MS 7001E (Industrial)
Locations		Houston, TX	Houston, TX	Phoenix, AZ	Phoenix, AZ
Air mass flow at ISO, lb/hr		982,300	2,200,000	982,300	2,200,000
Specified Ambient Air (SAA)	db (IN), ^{0}F	97	97	107	107
	wb (IN), ^{0}F	78	78	73	73
Specified Cold Air (SCA)	db (OUT), ^{0}F	40	40	55	40
	wb (OUT), ^{0}F	40	40	55	40
Water Recovered Rate, m^3/Yr		108996	244112	8605	115632
Water Recovered Rate,acre-ft/Yr		88.40	197.98	6.98	93.78

3.3 **TASK 3: ENGINEERING DESIGN AND COST EVALUATION**

The key is to design and size the inlet-air cooling system based on specific project economics and the incremental payback rates for each time-of-use period. In most cases, sizing the system based on a maximum cooling day is not going to be the most cost-effective option.

In considering thermal storage unit, the total project cost must be compared to the increased revenue expected. Some general "rules of thumb," which define first costs and energy requirements of the various sub-systems, can be used for quick estimates and to screen technologies for greater scrutiny. But site-specific factors – particularly the climate in which the turbine will operate – dictate much of the economics. The factors, including, installed increase cooling system cost ($/ton); natural gas prices at the plant site; parasitic load to drive the cooling system and ancillary equipment; projected costs of operation and maintenance; Time-Of-Use (TOU) electric rates in the area; and Water recovery; have been considered into the selection equation.

3.3.1 Weather Information

Weather data is available from "The Army, Navy and Air Force Guide for Weather Data". Sample weather data for July in Phoenix, AZ, are given in Table 3. It shows specific periods of the day over July when various wet and dry bulb temperatures occur. This will give the variations in a plant to compare operations and economics with or without inlet cooling.

Table 5 Sample Engineering Weather Data
Phoenix, AZ (Latitude 33 33 N Longitude 112 22 W Elevation 1101 feet)

Temperature Range, db, ^{o}F	Total Obsn	wb, ^{o}F
105/109	69	72
100/104	117	71
95/99	119	71
90/94	135	70
85/89	139	66
80/84	96	67
75/79	42	66
70/74	7	60
65/69	1	54
<64	NA	NA

3.3.2 Specific Plant Information

When thermal storage is integrated as part of a gas turbines intake air system, which is part of a combined cycle power plant, there is some base data available. This is because some "on-purpose" thermal storage already exists in large heating ventilation and air conditioning (HVAC) systems (for example, Chicago, IL, New Orleans, LA) and in certain power plants. The first large power plant installation using the ITS system was in Fayetteville, NC. It consisted of eight gas turbines (combined cycle) retrofitted with weekly cycle ice thermal storage for inlet air chilling to enhance power output on peak summer days. The following are typical system details:

- System design ambient air temperature ....102 ^{0}F (77 ^{0}F wet bulb)
- Air cooling coils design temperature ....92 ^{0}F (80 ^{0}F wet bulb)
- Chilled turbine inlet air temperature ....40 ^{0}F
- KW output increase at design ....53 MW (28%)
  estimated savings = $3,000,000 per year = less than 5 yr payback based on purchase of less summer peaking electricity.
- Installed costs.. $280/kW
- Gas turbines ....8 – GE MS5001P, 6 in combined cycle
- Operating hours..250 hrs from June '93 to November 1, '93
- Design peak loads ....4 hrs/day x 5 days/wk x 3 weeks =60 hrs
- Design cooling system operating hours ....80 hrs/yr
- Actual operating hours..Highly variable, choosing startup of incremental turbine or use of ice on operating units
- Air cooling load @ system design ambient ....221 MBtu/hr
  includes 2.1% for generator and auxiliary cooing plus an estimated 1 to 2% more for insulation and pump heat losses
- Gas turbine air mass flow rate .... 928,000 lb/hr (each of 8)

3.3.2.1 Ice Production System

Four 1250 hp ton Vogt rotary screw compressors with evaporative condensers and eight 325-ton turbo ice sheet harvesting evaporators with NH_3 refrigerant. Liquid NH_3 overfeed system sized for weekly cycle. Ice shucking by hot-gas bypass when sheets become 3/8" thick.

3.3.2.2 Ice Storage Tanks

An ice capacity of 173,300 ton-hours in two round insulated pre-stressed concrete tanks on piles. Tanks are domed to 50' center height, 40' sidewalls of 100' diameter.

3.3.2.3 Piping

For chilled water, carbon steel with 10 ft/sec max velocity.

3.3.2.4 Pumps

For chilled water, 36,000 gpm total. Five pumps of 9,000 gpm. Each capable of handling two gas turbines.

3.3.2.5 Coils

For ice water are Heatcraft 112 coils used, eighty planned, with each being 61 sq ft face area, with 10 rows of .035" thick wall stainless steel tubes (ammonia is not compatible with copper), with seven aluminum plate fins per inch of .016 thickness, 46.63 F leaving water temperature, 6.33 ft/sec tube velocity, 345 ft/min air face velocity, 0.55" H_2O air pressure drop and coils arranged in a 3-sided box-array. Each coil weights about 4,000 pounds.

3.3.3 Turbine Performance

From a size point of view, the actual size of a thermal storage unit does require an adequate footprint, however ice storage boxes can be stacked one on top of the other to save land space. This technique is done quite frequently in HVAC systems.

The ducting and airflow devices are quite large in a gas turbine; consequently, the air cooling interface with ice must match up with the piping without creating a ΔP (head loss) across the filter-cooling system. Some resizing of the air movement equipment may be necessary.

Overall, however, once the ice unit is in place and operating, one can expect performance increases consistent with turbine efficiency and heat rate curves. Once the unit (intake air) reaches (i.e. air is cooled) ISO conditions, performance corrections, such as those shown in Figure 3 below, can be documented.

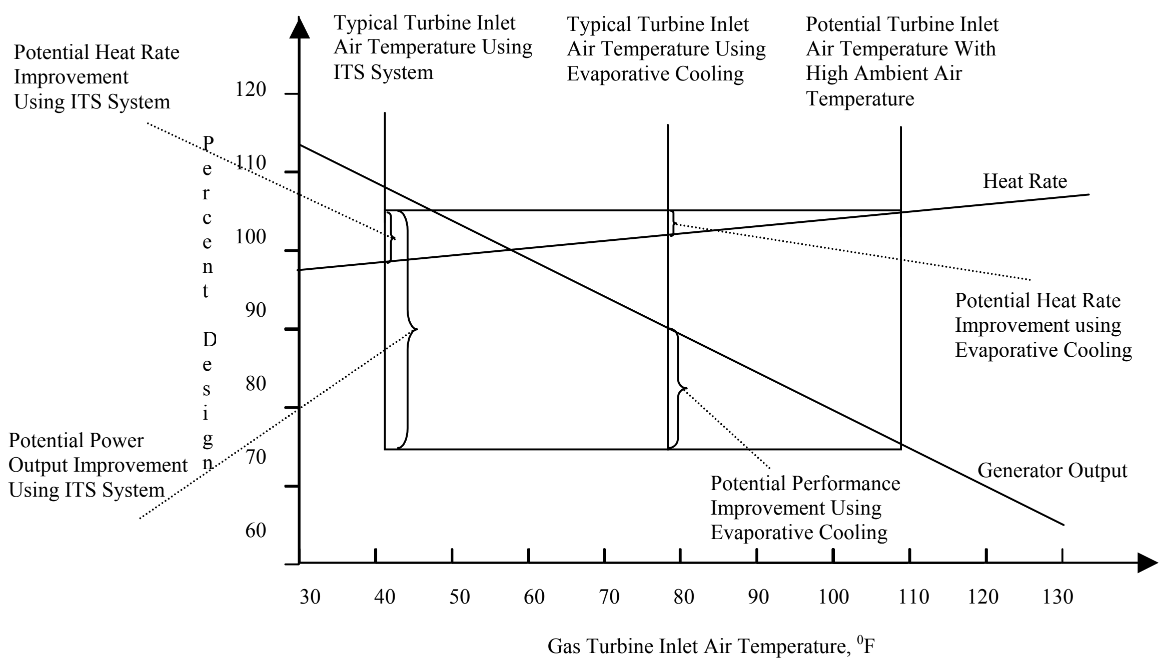

Figure 3. Typical Turbine Generator Performance Correction

3.3.4 Cost Analysis

An evaluation of the cost for producing additional power (KW) to meeting summer peak demand by using ITS system has been performed for two gas turbines (GE LM600 and GE MS7001E) operated in Houston, TX and Phoenix, AZ. The detailed results are presented in Figure A-2 (page A-5) in the Appendix. The data show that a significant savings in cost for a unit increase in power output can be achieved. In fact the cost for each KW gain in generating capacity ranges from $52 to $200, which is much lower than the typical installed cost for a new turbine generator system. Such cost advantage coupled with improvement in overall performance (as discussed in previous sections) clearly indicates that further development of the ice thermal storage technology for cooling intake air to gas turbines used in power plants, particularly in newly developed coal-based IGCC plants, is warranted.

4.0 CONCLUSIONS

Utilities that require additional capacity during high ambient temperatures must either add new turbine generators or improve the performance of existing equipment. Such decisions are based on actual costs as well as regulatory and specific site conditions.

With the increasing use of gas turbines for power generation during peak load period to meet the electricity demand in the U.S., all efforts to improve and maintain efficiency of gas turbine generator should be considered. The technical and economic aspects of gas turbine inlet air-cooling systems as a means of improving capacities and heat rates of gas turbines that experience high ambient air temperatures have been evaluated in this study. The focus is to examine the efficacies of ITS technology as a means to cool intake-air to gas turbines operating at high ambient temperatures.

Two different cases have been examined: one under hot and arid ambient conditions (Phoenix, AZ), and the other under hot and humid conditions (Huston, TX). An aeroderivative and an industrial gas turbine have been considered. Calculated results show that significant improvement in both power output (KW) and heat rate (or efficiency) can be achieved by using the ITS system. The technology works best in hot desert conditions but also shows advantages in hot, humid coastal regions. The quantity of water that can be recovered from an ITS system for cooling intake-air is also found to be very significant. In addition, a cost analysis shows that the total cost saving can be as much as $500,000/yr for a 50 MW gas turbine generator.

These results have clearly demonstrated that the use of ITS technology for cooling the intake-air to gas turbines is an efficient and cost effective means to improve the overall performance of its power generation capacity with added benefit of water recovery for power plant operation. Further development of this technology for power plant applications should be explored.

5.0 FUTURE WORK

The results of Phase I study has clearly shown that the application of the ice thermal storage (ITS) technology provides a significant improvement in overall electric power output (KW) and energy efficiency (reduction in heat rate) while afford the critically important benefit of reducing water usage in power generation systems by recovering condensate from humid air. Phase II study will examine the potential application of ITS technology to integrated gasification combined cycle (IGCC) power plants.

A process flow diagram will be prepared for analyzing an integrated ITS system for conditioning the intake-air with water recovery capability for gas turbine-generator operations. Based on the results of process analysis and computer simulation, a laboratory test program will be formulated to collect experimental data for the integrated system operating under simulated ambient air temperature and humidity conditions. Based on laboratory test results, a detailed engineering/cost analysis will be performed to evaluate the commercial viability of the use of ITS technology for IGCC power plant operations.

Finally, it is anticipated that an action plan for future commercial scale testing of the ITS system in a selected coal-based IGCC power plant will be proposed for implementation in the Phase III of the project.

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LIST OF ABREVIATIONS AND ACRONYMS

acre ft.	Acre Feet
BAC	Baltimore Air Coil
Btu	British thermal unit
C.T.	Cooling Tower
cu ft	Cubic feet
db	Dry Bulb
DCC	Direct Contact Chilling
DDC	Direct Digital Control
DEC	Direct Evaporative Cooling
DOE	US Department of Energy
ft	Feet
GE	General Electric Company
gpm	Gallons per minute
G-T	Gas Turbine (Natural Gas Fired Turbine)
Grains	1/7000 of a Pound (or one pound = 7000 grains)
HR	Heat Rate
hr	Hour
HVAC	Heating, Ventilating and Air Conditioning
IAC	Intake Air Cooling
ICC	Indirect Contact Chilling
IEC	Indirect Evaporative Cooling
IGCC	Integrated Gasification Combine Cycle
IL	Illinois
IMP	Ice Making Plants
in	Inches
ISO	International Standards Organization
ITS	Ice Thermal Storage
KW	Kilowatt (1,000 watts)
KWh	Kilowatthour (1,000 watthours)
lbs	Pounds
lbs/hr	Pounds per hour
m (M)	Meter or million
Mcuft	Thousand cubic feet

MWh	Megawatthour (1,000 KWH)
NOx	Nitrogen Oxides
O&M	Operation and Maintenance
Obsn	Number of Observations
REC	R. E. Cates Associates
RH	Relative Humidity
ROI	Return on Investment
SAA	Specified Ambient Air
SCA	Specified Cold Air
SCFM	Standard Cubic Feet per minute
SOx	Sulfur Oxides
TES	Thermal Energy Storage
wb	Wet Bulb

LIST OF CONVERSION FACTORS

To convert from	**To**	**Multiply by**
acre ft	m^3	1233
Btu/hr	KW	0.0002929
cu. Ft,	m^3	0.0283
^0F	K (degree Kelvin)	0.5555 (Then add 255.37)
Ft	m	0.3408
KWh	Watt-sec	3.6
lb	Kg	0.4536
lb/hr	Kg/s	0.000126

APPENDIX SAMPLE CALCULATIONS FOR GAS TURBINE PERFORMANCE

To properly evaluate the benefits of ice thermal storage system, and intake air-cooling for a specific gas turbine application, the following information is necessary:

- The manufacturer's performance curves and the Psychrometric Chart
- The climatic data for the location of the gas turbine generator being evaluated
- The air mass flow rate of the gas turbine compressor
- The desired turbine inlet air dry bulb and wet bulb temperatures
- The number of days the gas turbine generator will operate annually
- The number of off-peak hours each day that are available to build ice
- The number of hours each day when the gas turbine generator's performance is to be augmented

The Calculation of The Increase In Turbine Power Output:

1. Read the KW output at ISO condition at sea level, output curve coefficients and degradation factor from the gas turbine manufacturer's performance curves
2. Read the air inlet temperature, or at specified ambient air (SAA) temperature and specified cold air (SCA) temperature
3. Apply all parameters in Equation (1) to calculate the net increase in KW output

$$\Delta N = N\left[\left(A \times (T_{SAA} - T_{SCA})\right)\right]\left(1 - f\right) \qquad (1)$$

where:

ΔN = net increase in power output, KW
N = G-T KW output at ISO condition at sea level, KW
A = output curve coefficient
T_{SAA} = Specified ambient air (SAA) temperature, ^oF
T_{SCA} = Specified cold air (SCA) temperature, ^oF
***f** = G-T Degradation Factor, if new, **f** = 0.*

The Calculation of Heat Rate Reduction:

1. Read the heat rate reduction coefficients from the gas turbine manufacturer's performance curves
2. Read the air inlet temperature, or at specified ambient air (SAA) temperature and specified cold air (SCA) temperature
3. Apply all parameters in Equation (2) to calculate the Heat Rate Reduction (%)

$$HR = 1 - \exp\left(\frac{T_{SCA} - T_{SAA}}{100} \times B\right) \qquad (2)$$

where:

HR = Heat rate reduction, %
B = Heat rate reduction coefficient

The Calculation of Cost for Net Incremental Unit Power Output Gain :

The total Install Price for ITS includes:

1. Total Indirect Contact Chilling Coil Cost
2. Current materials budget price (2002)
3. Refrigerant plant

The output gain price equals total install price/net output gain

The Calculation of Water Recover Rate:

1. Read the air flow rate at SAA temperature from the gas turbine manufacturer's performance curves;
2. Read the peak load period (in this calculation is 4-hr/day and 5 days/week)
3. Read the difference of humidity ratio between the wet bulb temperatures at the SAA temperature and the SCA temperature from the Psychrometric Chart;
4. Calculate the water recovery rate by multiplying the values of air flow rate, peak load period and the humidity ratio difference.

The operating condition, performance parameters of gas turbines and the calculated results are summarized in Tables A-1 and A-2 below. In addition, results are also shown in Fig. A1-A5.

Table A-1 Operating conditions and performance parameters of gas turbines at two cities

Type of gas Turbine		GE LM 6000 (Houston, TX)	GE MS 7001E (Houston, TX)	GE LM 6000 (Phoenix, AZ)	GE MS 7001E (Phoenix, AZ)
Output, KW at ISO condition		39970	773000	39970	773000
Air mass flow at ISO, Lb/hr		982,300	2,200,000	982,300	2,200,000
Performance Parameter A		0.002500	0.003692	0.002500	0.003692
Performance Parameter B		0.1139	0.098338	0.1139	0.098338
Specified Ambient Air (SAA)	db (IN), ^{0}F	97	97	107	107
	wb (IN), ^{0}F	78	78	73	73
Specified Cold Air (SCA)	db (OUT), ^{0}F	40	40	55	40
	wb (OUT), ^{0}F	40	40	55	40

Table A-2 Calculated power out gains, heat rate reductions and water recovery for two gas turbines at two cities based on operating conditions shown in Table A-1

Type of gas Turbine	LM 6000 (Houston, TX)	GE MS 7001E (Houston, TX)	LM 6000 (Phoenix, AZ)	GE MS 7001E (Phoenix, AZ)
Net Output Gain, KW	14749	15417	15887	18469
Increased Output, %	36.9	19.9	39.7	23.9
Heat Rate Reduction, %	7.19	5.45	6.58	6.38
Water Recovered Rate, m^3/Yr	108996	244,112	8605	115632
Water Recovered Rate, acre-ft/Yr	88.40	197.98	6.98	93.78

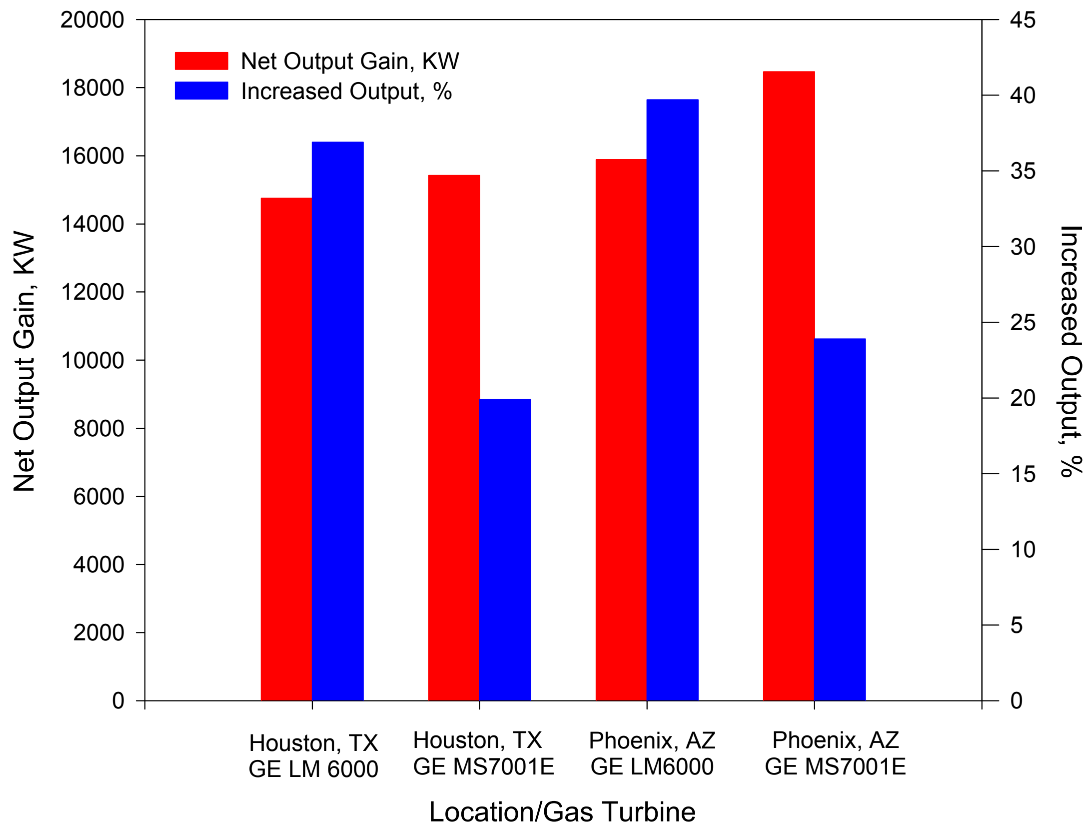

Figure A-1 Output gain for different turbines and locations

(SCA temperature for GE LM 6000 at Phoenix, AZ is 55 °F, instead of 40 °F in the other cases)

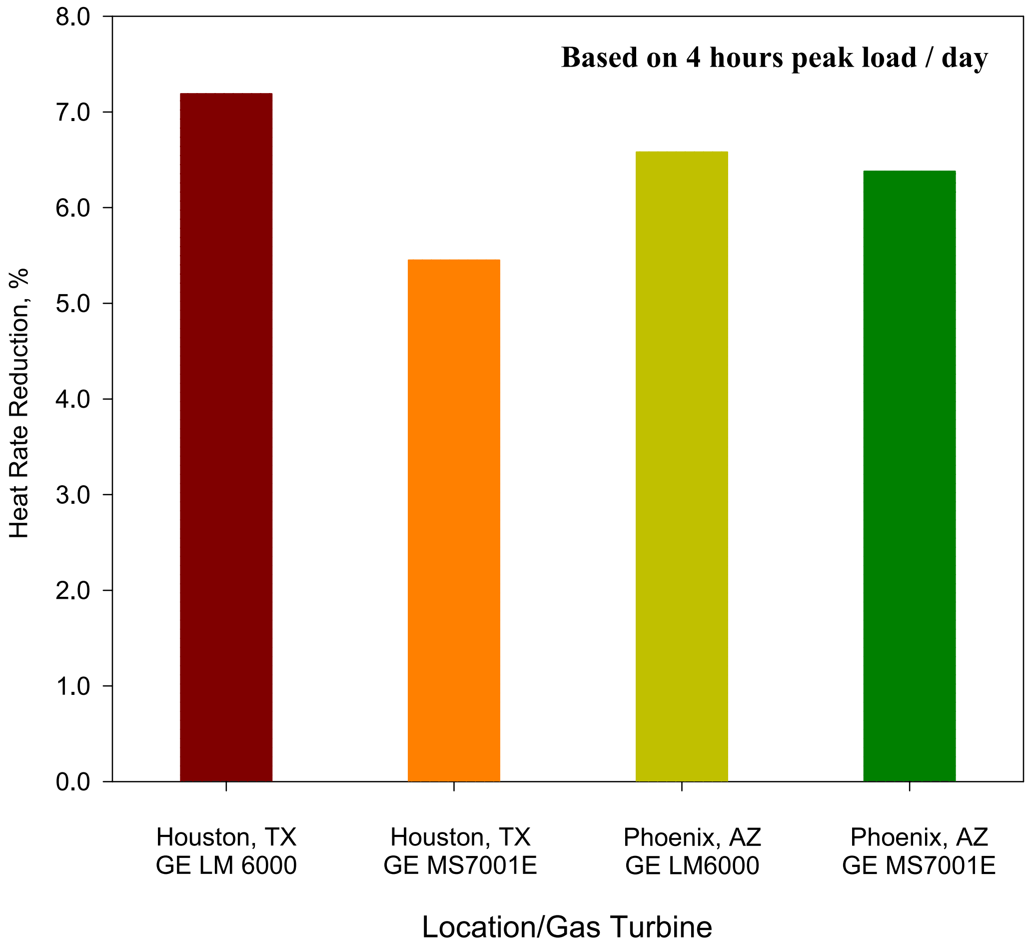

Figure A-2 Heat rate reduction for different turbines and locations

(SCA temperature for GE LM 6000 at Phoenix, AZ is 55 ^{o}F, instead of 40 ^{o}F in the other cases)

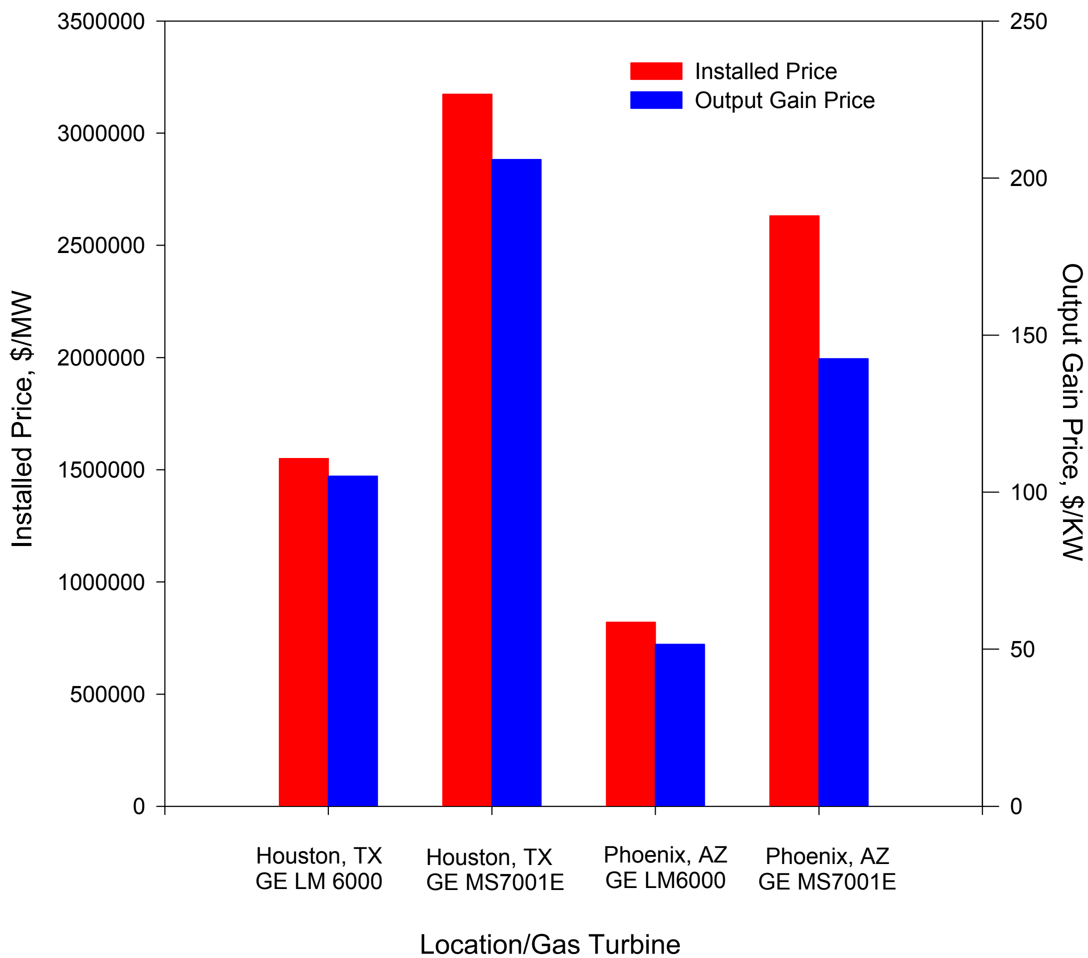

Figure A-3 Cost estimates for different turbines and locations

(SCA temperature for GE LM 6000 at Phoenix, AZ is 55 ^{o}F, instead of 40 ^{o}F in the other cases)

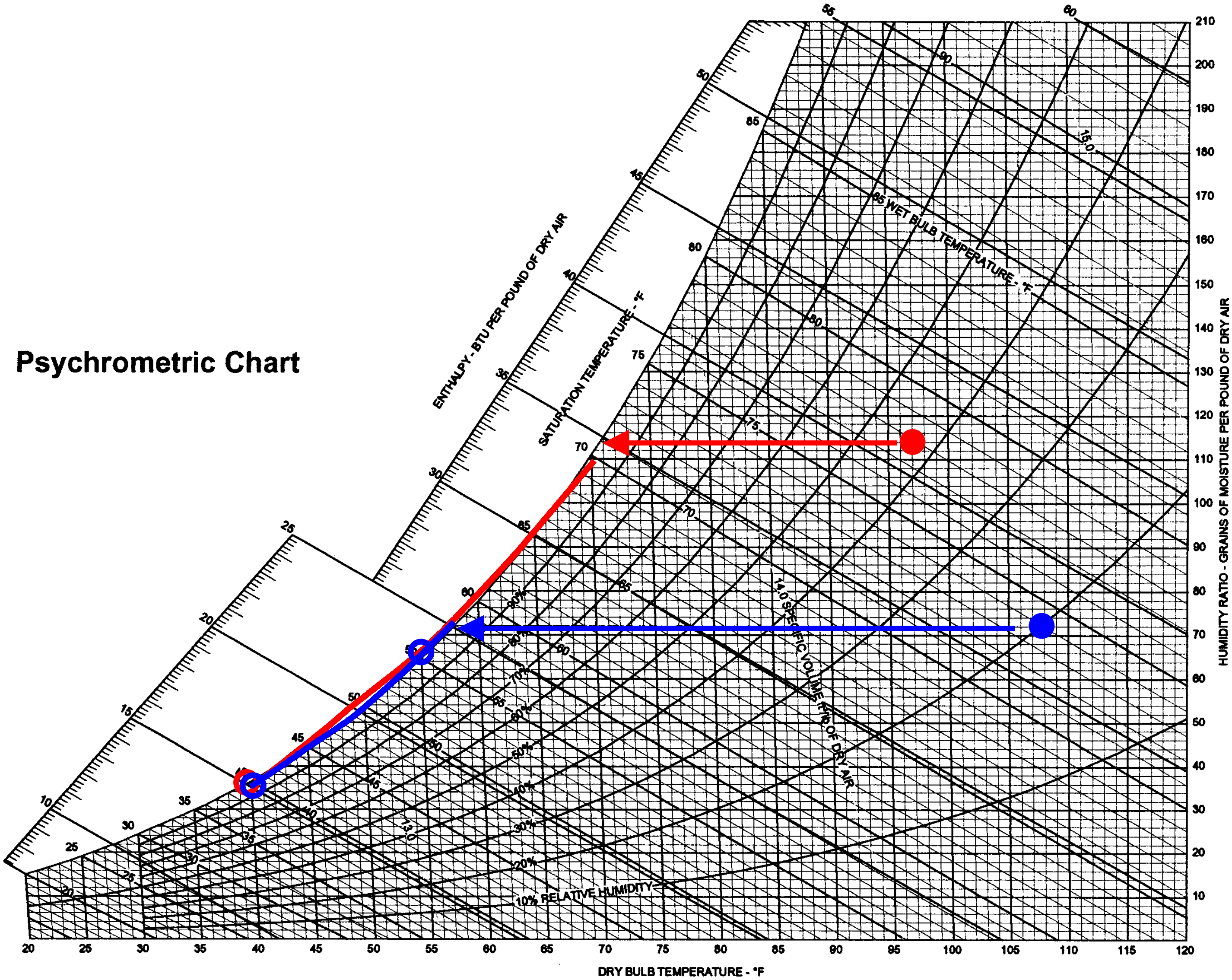

Figure A-4 Psychrometric Chart

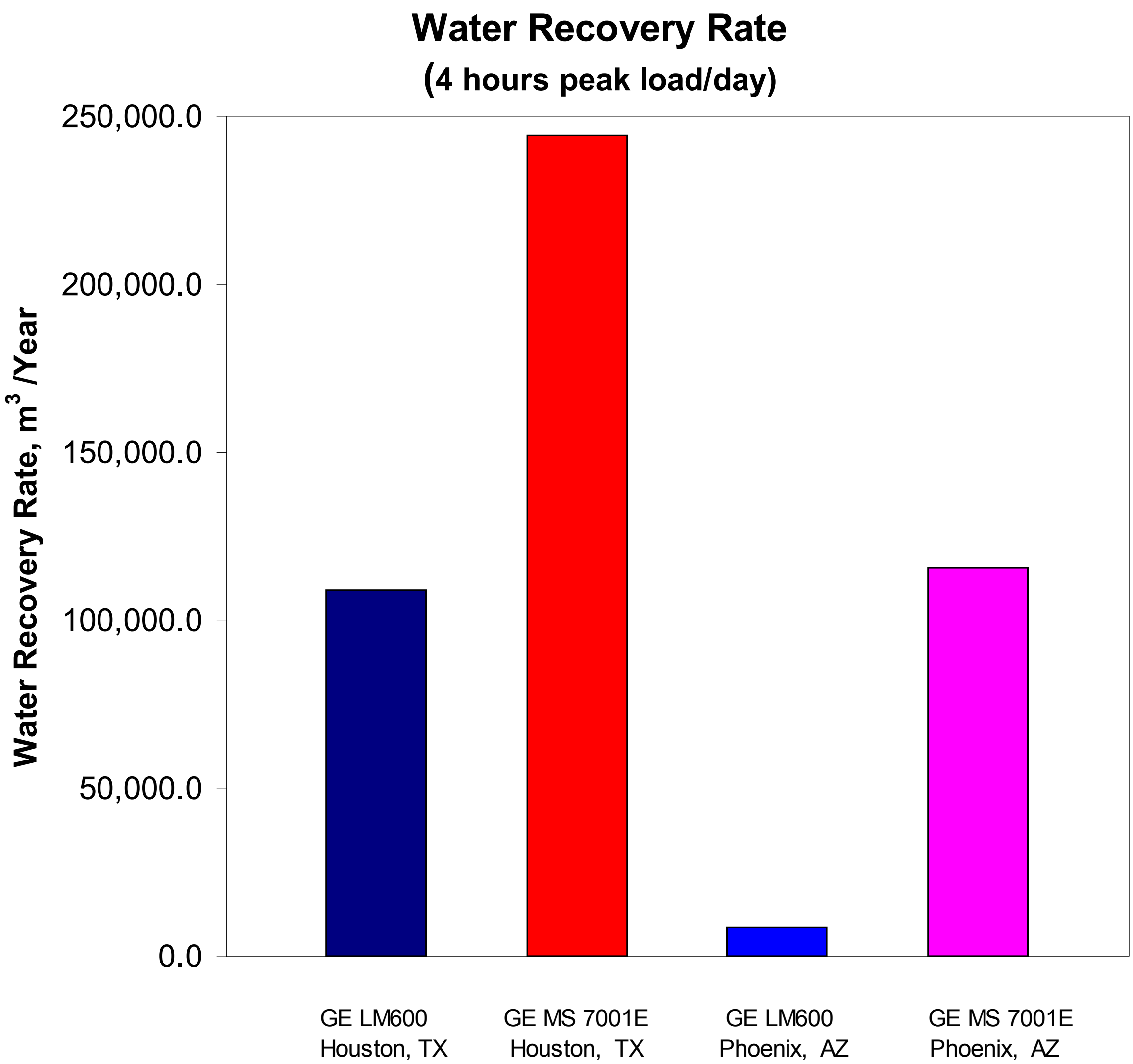

Figure A-5(a) Water recovery rates (m^3/yr) for different turbines and locations

(SCA temperature for GE LM 6000 at Phoenix, AZ is 55 ^oF, instead of 40 ^oF in the other cases)

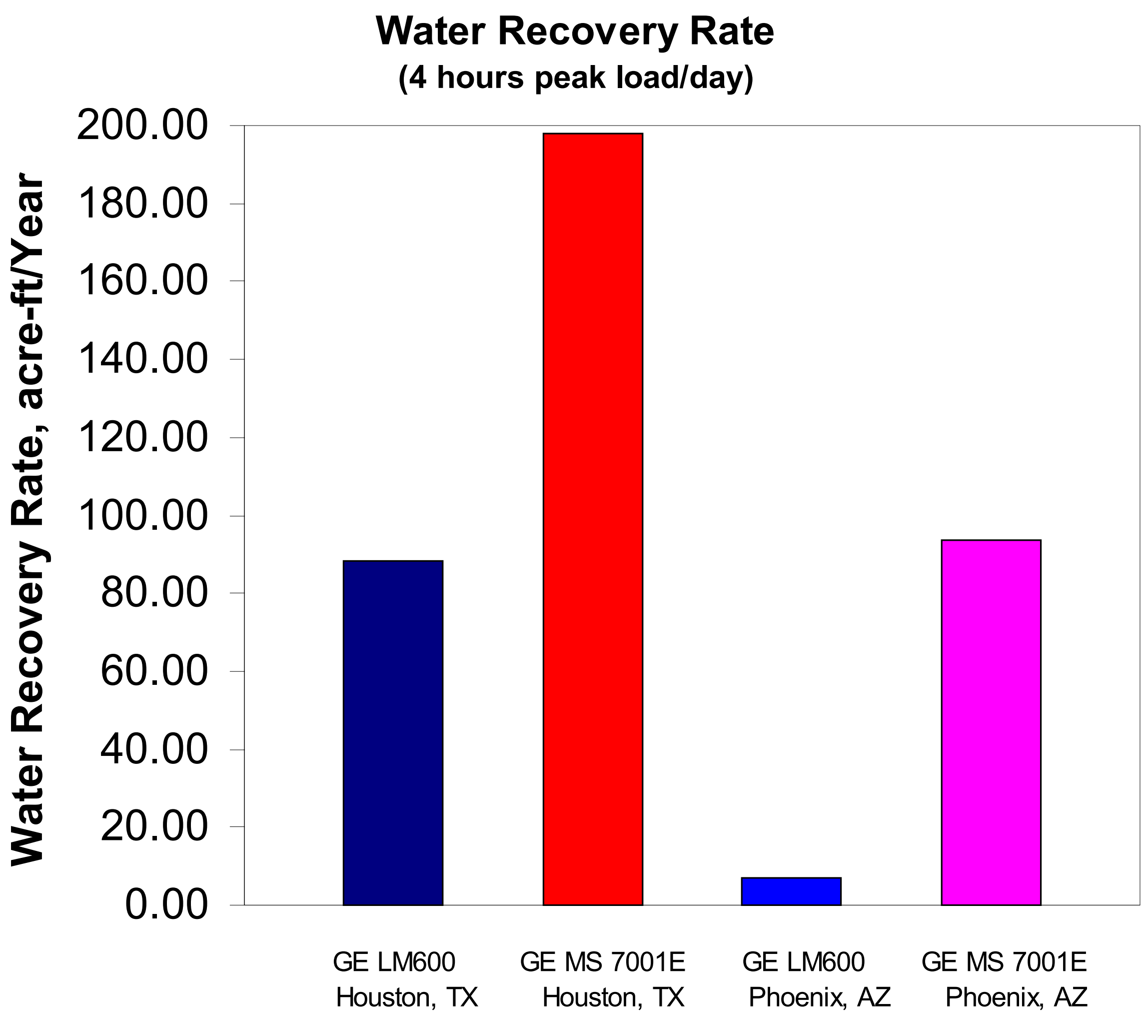

Figure A-5(b) Water recovery rates (acre-ft/yr) for different turbines and locations

(SCA temperature for GE LM 6000 at Phoenix, AZ is 55 °F, instead of 40 °F in the other cases)