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Assessment of Inlet Cooling to Enhance Output of a Fleet of Gas Turbines

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ABSTRACT

An analysis was made to assess the potential enhancement of a fleet of 14 small gas turbines' power output by employing an inlet air cooling scheme at a gas process plant. Various gas turbine (GT) inlet air cooling schemes were reviewed. The inlet fogging scheme was selected for detailed studies due to its low installation capital costs. The results indicate a potential of 10% enhancement in power output on a warm, dry day, a 5% enhancement in a typical summer day, but only a 1% enhancement in a hot humid day. It is shown that the relative humidity is the most important factor that affects the impact of inlet fogging. Therefore, the inlet fogging can enhance GT power output not only in the hot summer, but also in other dry days during the year. An annual analysis was also conducted based on New Orleans's annual weather conditions. The results indicate a potential of increased power of 2.34% with inlet fogging to saturated state and additional 5% increased power with 0.5%(wt.) overspray. The total potential power increase for the gas turbine fleet is 7.39% at $265/HP. Since the gas turbine fleet consists of small units, the installation cost is much higher than a typical cost of $34~60/HP for installing an inlet fogging system on a gas turbine larger than 300MW. However, this installation capital cost is 57% cheaper than buying a new gas turbine, which will cost about $608/HP.

NOMENCLATURE

GT	Gas turbine
RH	Relative humidity
TIC	Turbine inlet cooling
TIT	Turbine inlet temperature

INTRODUCTION

In an effort to improve operational performance at a natural gas process plant in Louisiana, the plant personnel wanted to identify opportunities to improve plant energy efficiency, increase product throughput, and generally improve the plant's per-unit production costs. It has been known that the power output and efficiency of gas turbines are reduced significantly during the summer because the air becomes less dense (which results in less mass flow rate), and the compressor's work increases with increased ambient temperature. It has been estimated that every 1°F rise of ambient air temperature reduces the gas turbine output by approximately 0.3 to 0.5% [1]. Therefore, one of the focused efforts for improving product yield is to assess the options to increase power availability and/or product throughput of the plant's 15 small, gas fired combustion turbines. Furthermore, emphasis is directed at lower risk (both economic and technical) enhancement opportunities. While there exists numerous options to improve the performance of gas turbine systems, many involve elaborate technology and/or extensive modifications to the engine systems. In addition, the smaller size of the GTs (all systems rated under 4,000 hp) would not allow for an economic modification using most of the technologies due to the lack of the "economy of scale" typically seen on larger, utility grade projects (i.e. engines rated >25,000 hp).

Some of the generic gas turbine power enhancement options as displayed in Table 1. While these options apply to larger engines, the results are deemed appropriate to place options in perspective, even for this study's smaller machines.

Inlet cooling power augmentation is probably the most widely utilized gas turbine power upgrade option around the globe. Including both evaporative technologies and fogging systems, hundreds of installations have been successfully completed and are currently operating. Typically, low initial first cost, ease of installation, limited downtime, and rather simple operational control have made inlet cooling a cost effective power upgrade options for most engines operating in climates that peak above ISO standard conditions (59^{o}F, 60% relative humidity). This paper will therefore examine TIC options as applicable at the plant site.

Table 1 Performance enhancements for 50 – 100 MW combustion turbines in a simple cycle plant

Method	Δ Capacity	Δ Heat Rate	$ Per KW
Water Injection to Combustor or Inter-Stage	+10%	+4%	< $50[1]
Inlet Fogging and Evaporative Cooling[7]	+5% - +15%	-2.5%	~ $50[1,7]
Fogger with 1% Inlet Over-Spray	+10% to +20%	-5%	$75 to $100[1]
Conventional Steam Injection to Combustor or CDP Air	+10% to +15%	-5% to -7%	$ $200[2]
Conventional Steam Injection with Supplemental Firing	+10% to +15%	+2% to 0%	~ $250[3]
Inlet Chilling - Refrigeration or Thermal (Ice) Storage[7]	+22.5%	-5%	$200 to $400[7]
Supercharging	+15% to +20%	-4%	~ $200
"Power-Cool" Supercharging with Inlet Fogging	+ 15% to +30%	-5% to -6%	~ $250[1]
Compressor Coatings and Enhanced Wash Systems	+0.5% to +3%	-0.5% to -3%	< $60
Thermal Barrier Coatings	+5% to +15%	-0.5% to -1%	< $50
High-Flow Inlet Guide Vanes	+4.5%	-1%	$20 to $100
Compressor Aerodynamic Upgrades	+10% to +20%	-1.5% to -5%	$150 to $250
Turbine Hot-Parts Upgrades	+5% to + 10%	-2% to –5%	$150 to $250
Wet Compression	+10% to +20%	-1.5%	~$100[4]
Cheng-Boost Steam Injection[5]	+15% to +30%	-5% to -8%	$149 to $349[2]
Advanced Cheng System Steam Injection[5,8]	+21% to +68%	-20% to –29%	$310 to $548[6]

(Source EPRI CPC 107 – December 2001 for all but Cheng Technologies[8])

TABLE NOTES:

(All water use technologies assume a viable source of suitable, fresh water is available)

1. Add approximately $30 per kW if treated water system is not already available.
2. Assumes that suitable steam source is available.
3. Assumes that HRSG is already installed, but includes duct-burner installation.
4. Approximate cost including treated water system; current market prices are targeted at $200 per kW or more.
5. Cheng data at 85^o F, 60% R.H. and Standard Pressure with natural gas;
6. Assumes "new" plant installation with used and rebuilt combustion turbine; performance improvements are as compared to underlying simple-cycle engine performance; cost per kW is for total plant output and includes new HRSG and balance of plant improvements.
7. See additional performance and cost data specific to inlet cooling & chilling technologies within this report.
8. For the ACS, the cost per kW is calculated on the total output of a retrofitted plant, not just on the incremental output over that of the simple-cycle engine, because the cost and complexity of the ACS retrofit and the resulting performance improvements are so great that it would not be undertaken unless there was a requirement for an entire plant's worth of capacity with the attendant performance characteristics.

GAS TURBINE INLET COOLING REVIEW

Overview of Inlet Cooling

Gas turbine inlet cooling is extremely effective in counteracting the decreasing GT performance during hot and humid summer when the power demand reaches maximum. South Louisiana's summer is especially hot and humid, inlet cooling is an option that must be evaluated. The capital cost for an inlet-cooling device is cheaper than installing a stand-by unit only for peak-load needs.

There are a number of technologies which can be deployed to accomplish the lowering of the inlet air temperature into the compressor inlet, which in turn, increases the density of that air and the corresponding mass flow through the GT, allowing increased power output during warm or hot ambient conditions.

The options to improve GT performance/output through inlet cooling are numerous including both indirect evaporative "pre-cooling" systems, active "chiller" refrigeration based systems (both electrically driven and thermally driven), desiccant cooling systems, and a number of water spray/fogging options. Caution needs to be taken to avoid frosting when the static pressure reduces during flow's acceleration through the inlet converging duct. This inlet cooling option will be evaluated by both investment economics as well as viability of this generation enhancement to the anticipated load profile of the GT plant in question.

Evaporative cooling and refrigeration are two common methods for providing inlet cooling. Evaporative cooling can be achieved either by mixed or non-mixed method. In the mixed evaporation, water will be evaporated and mixed with air before enter the compressor. Small water droplets (mist) less than 5μm can be injected into the GT inlet to reach cooling effect as well as increase the mass flow rate. Selections of appropriate cooling technologies depend on site environment and load characteristics.

Turbine inlet cooling (TIC) technology increases the mass-flow through the combustion turbine by cooling the inlet air. Cooler air is denser, and since combustion turbines are constant volume flow machines, denser air equates to greater mass flow. Gas turbine output is a strong function of ambient temperature and typically lose between 0.3% and 0.5% of their ISO rated power for every 1ºF rise in inlet temperature (see Fig. 1). Conversely a 1ºF drop in temperature by evaporative cooling of the inlet raises the gas turbine power output between 0.3% and 0.5%. Once the specific megawatt-per-degree-cooling number for the turbine in question has been determined (which is available from the OEM's turbine performance versus ambient temperature charts), this number can then be multiplied by the annual operational hours of effective cooling to arrive at the total annual MW-hr power boost that can be expected from inlet cooling for that turbine at that site.

The chart in Fig. 2 provides a generic evaluation of evaporative inlet cooling for a 'typical' gas turbine power plant. Obviously, coincident wet bulb temperatures (associated with relative humidity, RH-%) will directly dictate the value of evaporative systems, although even in hot and humid climates, summer peaking conditions in the afternoons tend to have somewhat lower humidity levels than are design case. This would result in a rather valuable power augmentation when needed most, during peak times.

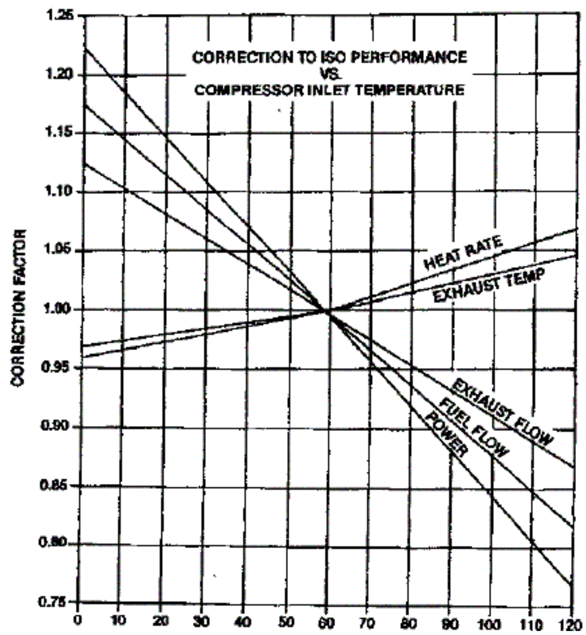

Figure 1 Siemens 501D5A performance vs. GT inlet temperature

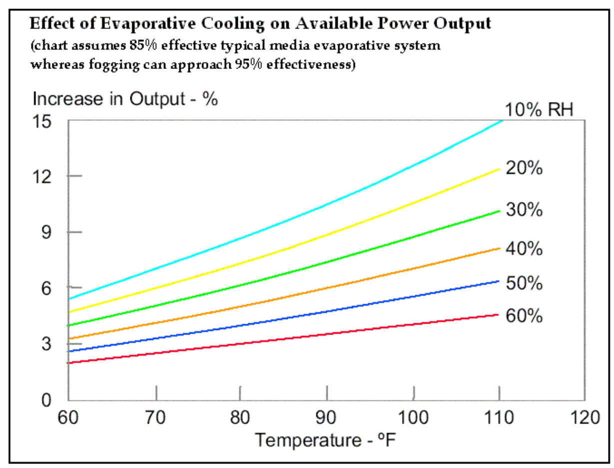

Figure 2: Evaporative cooling vs. GT power

Inlet Cooling Technologies

Inlet cooling technologies can fall into a number of different specific applications. The two main distinctions will be whether or not active refrigeration or "chilling" is utilized, as is the case with electric or absorption driven chillers. In either case, the cooling is accomplished by either evaporation – whether through fogging, evaporative cooling pads or spray injection – or through active / mechanical refrigeration.

Active refrigeration systems can chill inlet air to just about any temperature that does not result in ice buildup on the cooling coils from the ambient relative humidity. For optimization and practical reasons, systems are usually designed to operate above 48 ºF. Refrigeration, whether by direct chilling or ice storage, is relatively costly requiring considerable maintenance, has a fairly high parasitic load, and requires a fairly large area to accommodate the refrigeration equipment. The basic difference between direct chilling and ice storage is that direct chilling has a sustained and relatively constant parasitic load while the combustion turbine is operating, whereas ice storage has a high parasitic load that is used to make ice during off-peak hours that is then melted to provide refrigeration during peak hours. The required installation space for ice storage is also considerably larger than the space required for direct chilling and can often eliminate the viability of that option.

Typically, active chilling will be applied around 5 primary systems:

1. Electric driven, compressor based refrigeration chillers.
2. Heat driven, absorption refrigeration based chillers.
3. A thermal storage system where low temperature ice or solution is made through active chilling using power and/or heat available during off-peak times so that this low temperature storage can be used during on-peak times to increase gas turbine power output without significant parasitic power used by refrigeration equipment.
4. A ‘combination’ system that may include both electric and absorption chilling as well as partial thermal storage.
5. Indirect chilling systems where inlet air passes over a cooling coil containing a fluid that is being circulated to a separate cooling source which could include a heat exchange system using a cool primary source such as a river or well water.

Evaporative systems do not utilize any active refrigeration equipment. Instead, the system deployed acts more of a “cooling” process where inlet temperatures can be reduced to approach the coincident wet bulb temperature. These evaporative systems generally fall into three categories:

1. Direct “wet” systems which use water sprayed onto air steam or onto a media in the main inlet air stream.
2. Fogging systems where water is carefully atomized so as to achieve full evaporation either before entering the compressor section or to provide some degree of compressor intercooling by completing the vaporization within the initial sections of the compressor.
3. Indirect "dry" systems ---similar to the indirect chilling system except that the separated primary source is provided by evaporative cooling.

Evaporation cooling has an advantage in that the mass of the water used for cooling also contributes to the turbines performance (i.e. increases mass flow through the turbine). The major disadvantage of evaporation is that its effects diminish with rising wet bulb temperatures, associated with hot and humid days when power (electricity) is usually most valuable, and that it is rarely possible to cool the inlet air below about 42^o F, which provides a limit on the potential performance improvement.

Evaporation also uses a considerable amount of water and can lead to compressor section and turbine section maintenance problems, if operating parameters are not carefully observed. While evaporation can be relatively inexpensive to install, maintenance costs can be high and performance can suffer if water of required quality is not used, which is an area where operators often try to reduce costs. For applications in which water will be ingested into the gas turbine compressor such as sprays and fogging technologies, the best approach is to utilize high quality, demineralized water.

Bhargava and Meher-Homji [2] presented the results of a comprehensive parametric analysis on the effect of inlet fogging on a wide range of existing gas turbines. Both evaporative and overspray fogging conditions were analyzed. It shows that the performance parameters indicative of inlet fogging effects have definitive correlation with the key gas turbine design parameters. In addition, they indicated that aero-derivative gas turbines, in comparison to the industrial machines, have higher performance improvement from inlet fogging.

Chaker et. al. [3-5] presented the results of extensive experimental and theoretical studies conducted over several years and coupled with practical aspects learned in the implementation of nearly 500 inlet fogging systems on gas turbines ranging from 5 to 250 MW. Their studies covered the underlying theory of droplet thermodynamics and heat transfer and provided practical points relating to the implementation and application of inlet fogging to gas turbine engines. They also described the different measurement techniques available to design nozzles. Their papers collectively provided experimental data on different nozzles and recommended a standardized nozzle testing method for gas turbine inlet air fogging. The complex behavior of fog droplets in the inlet duct was addressed and experimental results from several wind tunnel studies were documented.

Khan and Wang [6] developed a wet compression thermodynamic model for a gas turbine system (FogGT) with inlet fog cooling specifically for burning low calorific value (LCV) fuels. When LCV fuels are burned, saturated fogging can achieve a net output power increases approximately 1-2%, while 2% overspray can achieve 20% net output enhancement. As the ambient temperature or relative humidity increases, the net output power decreases. For LCV fuels, the thermal efficiency is approximately 10~16% (3~5 percentage points) lower than using natural gas. Fog/overspray could either slightly increase or decrease the thermal efficiency depending on the ambient conditions.

Yap and Wang [7] compared the performance of power enhancement of inlet fogging and steam injection in 5MW power plants burning producer gases derived from gasifying biomass wastes to produce power. The result of 5MWe inlet fog cooling increases GT output power from 4.76 % to 0.5% with negligible GT efficiency changes. Inlet fog cooling provides lower power augmentation for the combined cycle than for a simple GT cycle, raging from 3.7% ~ 0.39%, and adversely affects the combined cycle efficiency ranging from -0.1% ~ -1%. The reduced benefit of inlet fog cooling for a combined cycle could be explained by the heavily loaded compressor condition, attributed to using the LCV fuels. An additional burden from the fog cooling with the increased mass flow rate results in an undesirable compressor performance and reduced TIT, both factors contribute to a marginal GT power augmentation and an adverse impact to total plant efficiency when LCV fuels are used. Comparison between inlet fog cooling and steam injection using the same amount of water mass flow indicates that steam injection is doing worse than inlet fog cooling in augmenting power output when LCV fuels are used.

Of course other technologies are available and any combination of the above examples can be used to maximize the value of an inlet cooling systems. For instance, an indirect evaporative system could be used ahead of active chilling and/or ice storage systems to maximize inlet cooling with minimal power use (see Fig. 3 detail of “hybrid system”).

The major concerns of installing these inlet cooling systems is their cost effectiveness as well as their impacts on operational integrity of the power plant. Inlet coils and systems can increase pressure drops in the system while equipment malfunctions and down time can negatively affect the entire power system. Some of the systems available are customized directly for gas turbine power plants and can be easily installed with minimal system modifications or downtime.

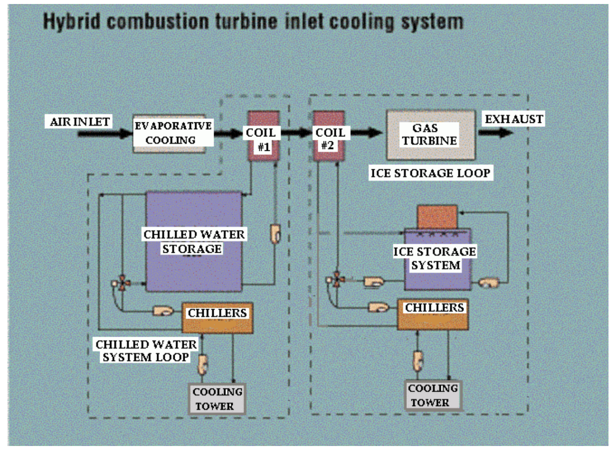

Figure 3: “Hybrid” inlet cooling system (with ice thermal storage)

Inlet Cooling Project Criteria

Installed cost evaluations are only a part of the criteria for determining optimized system applications. The system’s operational costs and the annual value of the additional power supplied are just as important as are installed costs considerations.

Turbine inlet cooling is a viable and potentially cost effective power upgrade option applicable for both simple and combined cycle plants. The technology offers a straightforward equipment application, which provides for cost effective increases in power output while minimally impacting standard operating conditions. The technologies typically offer the best $/kW option with the least risk associated with operational complications or economic criteria risks. Determining the value of a particular system depends on numerous specific project criteria. Specific consideration issues include the following items:

1. Determine whether peak turbine power is required during the hot periods of the year. Afternoon, summer peaking utility supplies would be best candidates for TIC.

2. Short peaks will favor thermal storage systems, while longer peaks or unknown peaks will favor on-line chilling systems.

3. If parasitic power a critical issue during peak periods, then what is the difference in energy

costs between on-peak and off-peak periods. Thermal storage systems must have off-peak power to operate while no-storage chilling systems do not.

4. Hot, dry climates are the best of all inlet cooling/chilling candidates, although this type climate is not a necessity to utilize TIC. Generally, the southern Louisiana climate initially appears to favor TIC technology options.

5. Is there a good fresh water supply available for use as cooling tower makeup or to supply a treatment plant for evaporative or fogging applications? If so, then it would be best to use water-cooled equipment and evaporative/fogging technologies are an option. If not, then air-cooled mechanical chillers may be required. The dynamics of operation of air-cooled applications will tend to favor thermal storage systems even more than water-cooled applications.

6. Different gas turbine engines will obtain better results from active inlet chilling. Turbines with outputs which are more susceptible to temperature vs. airflow rate are the best inlet chilling candidates. Examples are the Frame 7FA, 501F, GT24 and LM6000. The Frame 7EA is a less ideal candidate and the Frame 6 still less so, although all of these can be good candidates if the climatic conditions at the job location are right (i.e. hot and dry). An LM2500 STIG 50 is an example of a bad candidate for TIC regardless of climate. For example, the turbines in Table 3 are ranked in order of best incremental $/kW to worst $/kW gained with TIC, assuming a Los Angeles-area climate of 95F db/70.8 wb, and using on-line chilling to 50F.

7. An alternate water supply option for salt water source would be to utilize this water for condensing on water cooled chillers, especially for power plants which are located in coastal areas.

8. Depending on what energy source is available at the lowest cost; low pressure steam (15 psig), medium pressure steam (115 psig), or parasitic electric power will impact the decision on what TIC technology is most applicable. Water-cooled centrifugal chilling systems require approx 0.72 kW/ton of parasitic power. Single-stage absorber systems require about 0.19 kW/ton of parasitic power and 19 lbs/ton-hr of 15 psig steam. Two-stage absorption systems require approx 0.143 kW/ton of parasitic power and 10 lbs/ton-hr of 115 psig steam. The system with the lowest energy operating cost is generally the best option as the total installed capital cost differences between the systems is not too great.

The major concerns of installing these inlet cooling systems include their cost effectiveness as well as their impact on operational integrity of the power plant. Inlet coils and systems can increase pressure drops in the system while equipment malfunctions and down time can negatively affect the entire power system. Some of the systems available are customized directly for gas turbine power plants and can be easily installed with minimal system modifications or downtime. Inlet fogging systems tend to be rather simple with almost negligible pressure drops and are generally inexpensive to install compared with other options. Precision control systems customized for the specific location and project are required to ensure proper operation without adverse problems being created.

Table 3 Ranking of GT candidates for employing inlet cooling

Ranking	Brand	Model	$/KW
1	Alstom	GT24	173 (Best)
2	GE	LM6000	180
3	Siemens	Trent	212
4	Siemens	W501G	218
5	GE	LM5000	237
6	GE	7FA	242
7	Siemens	W501FA	247
8	GE	7EC	264
9	Alstom	11N2	286
10	Siemens	W501D5	308
11	Siemens	W501DA	311
12	GE	9E	312
13	GE	7EA	312
14	GE	LM2500	320
15	Siemens	W251B11	352
16	GE	Frame 6	417
17	GE	LM1600	440
18	Alstom	11N1	449
19	GE	LM2500 STIG 40	472
20	GE	Frame 5	670
21	GE	LM2500 STIG 80	N/A (Worst)

STUDIED CASES

The information of the studied fleet of 15 gas turbines is shown in Table 4.

Table 4 Studied Gas Turbine Fleet

Delta Gathering Station
- Group 1:
  - #3 Solar Saturn T1001S-236, 1200 HP
  - #4 Solar Saturn T1001S-236A, 1100 HP
  - #5 Solar Saturn T1001S-268, 1100 HP
  - #6 Solar Saturn T1001S-268A, 1100 HP
  - #7 Solar Saturn T1001S-192*, 1100 HP
  - (*100 ft away from above four units)
- Group 2:
  - #8 Solar Centaur CS400, 3830HP
  - #9 Solar Centaur CS400, 3830HP
- Group 3: (100 feet from Group 2)
  - #10 Solar Centaur CS400, 3830HP
  - #11 Solar Saturn T1001S-186, 1100HP
- Stabilized Plant
  - #1 Solar Saturn CSS-1200, 1200 HP
  - #2 Solar Saturn CSS-1200, 1200 HP
  - #3 Solar Saturn CSS-1200, 1200 HP
- Cryogenic Plant
  - Cogen GE model

Given the background review presented earlier, this study focuses its power augmentation consideration on inlet air cooling technologies. Obviously, not all systems are cost effective for any gas turbine plant. Careful consideration to system parameters and investment criteria must be examined. Installed costs for inlet cooling systems vary drastically. On larger, industrial and utility gas turbine systems, fogging systems have been installed to increase power outputs at minimal costs in the $25-$50/kW range while active chilling systems can exceed $500/kW installed costs. A project optimization analysis needs to be performed to determine what are the objectives of such a project and which technology(s) best meet those objectives. If a quick return is desired and investment capital is limited, then evaporative systems will likely work best. However, if maximum power output is desired to meet summer peaking conditions then active chilling will likely be the solution.

This study's approach is to maximize the benefits with minimal costs and/or operational risks. While an active chilling (refrigeration) scheme to lower turbine inlet air would prove beneficial, the first costs of installing multiple chillers at the various gas turbine sites appeares to involve much more costs than some of the self-contained evaporative options. Even installing a central plant chilling system with chilled water distribution to each of the gas turbine plants would likely be much more expensive than the evaporative options. In addition, annual operational costs (O&M as well as parasitic power requirements) of these refrigeration systems would be much greater than the anticipated evaporative options, particularly the fogging technology option.

One key opportunity that has not been fully explored as yet is to evaluate the potential to utilize any excess refrigeration capacity that may be available in the plant's cryogenic operations. If the capacity exists and can be satisfactorily interconnected to a chilled water production system, there could be significant potential to deploy inlet air refrigerated coils to the turbine inlets. Details of this interconnection and the operational impacts on the plant's cryogenic systems is not performed as part of this phase of study, but may be an opportunity for future focus.

In evaluating the benefits of power output enhancements at the studied plant, it is realized that economic evaluations could take a number of different approaches. While the net result is increased horsepower, the actual product throughput of the facility is what really matters. Because of the number of engines at different plant locations, the concept of comparing increased power output against a new engine seemed to make the most sense. It should be noted however, that because of the infrastructure associated with the 15 operating engines, simply installing another engine (or two) in the plant would not actually benefit all process streams equally. By contrast, increasing power incrementally at each engine maximizes existing infrastructure (piping systems, compressors, controls, etc.) value with minimal impacts or modifications.

Evaporative Fogging Evaluation

While researching inlet fogging considerations and application examples, the authors contacted MEE Industries, a global leader in this technology with fogging systems installed and operational on hundreds of gas turbine engines.

In recent years, confidence has grown in fog cooling technology as a reliable and cost-efficient method of power augmentation. Installations are now considered "options" as opposed to experimental. Most of all major turbine manufacturers offer some form of fogging power options for their systems. As a result, larger facilities are employing it more and more. Tennessee Valley Authority's (TVA) chose

MEE Industries for an eight million dollar contract to install high-pressure fog cooling systems on 48 of their utility peaking gas turbines. One of the single largest inlet air fogging projects in history, TVA decided to install high-pressure fog in order to gain additional output, especially during the hot summer months in their service areas. These fog systems were installed on peaking turbines at four different plant sites and were designed to provide 20°F of fog cooling and an additional 6°F of intercooling.

Research indicated that fogging offered considerable benefits with minimal risks for most gas turbine applications (although some engines demonstrate much better characteristics of power increases than others). An example list of benefits suggested by Fog technology inlet cooling are as follows:

- Increases output by up to 20%
- Improves heat rate up to 5%
- Reduces NOx emissions
- Field tested and proven technology with hundreds of system installations
- Lowest capital, installation, and O&M costs compared to other cooling technologies (typically)
- ~100% evaporation efficiency with low inlet pressure drop
- Easy retrofit, typically 1-3 days outage
- Optional fog compressor inter-cooling for additional power boost (see below)

In most situations, evaporative / fogging options will tend to offer the best and quickest return for the invested dollar assuming a fresh water source is not a 'fatal' issue (as previously mentioned, fogging and overspray systems should consider utilizing a high quality, demineralized water supply source). These systems may be deployed economically with minimum installation modifications and minimal inlet pressure drops. In addition, they still allow other power augmentation technologies to be effectively installed for even greater value.

Inlet fogging systems are rather simple (see Figure 7) with almost negligible pressure drops and very inexpensive to install. The provided precision control systems customized for the specific location and project ensure proper operation without adverse problems being created.

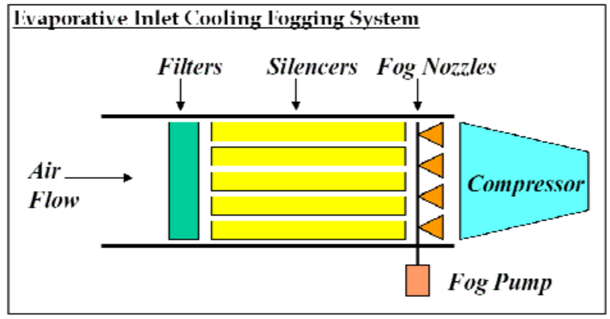

Figure 7 Simple GT fogging component diagram

Specific Reference Conditions for Studied Cases

The commercial software, GateCycle, was used to simulate the performance of Solar Saturn and Solar Centaur gas turbines employing the inlet fogging scheme. Based on the actual plant site weather data in summer, four cases representing four snap shots of weather during the day were considered. For each case, the lowest GT inlet temperature that can be achieved by employing fogging scheme is assumed to be the saturated temperature that maintains a constant enthalpy (or adiabatic cooling) for air-water mixture. These four representative cases are:

(Ambient air) (Saturated state after fogging)
Case 1: 77°F, 30% RH → 58°F, 100RH
(in a dry and warm day)
Case 2: 76°F, 95%RH → 73.5°F, 100 %RH
(in a summer morning)
Case 3: 88°F, 77%RH → 77°F, 100%RH
(in a summer afternoon)
Case 4: 90°F, 70%RH → 82°F, 100%RH
(near early afternoon)

The results for Solar Saturn gas turbines are shown in Table 5. Cases 1 and 2 clearly indicate that the output enhancement closely related to the relative humidity (RH) in the ambient air. Case 1 and Case 2 have a similar static temperature at about 77°F, but Case 2 has a higher RH at 95%. Inlet fogging can reduce the temperature of Case 1 down to 58°F, whereas Case 2 quickly reaches saturation and its temperature can only be reduced to 73.5°F. The impact of this difference in RH is significant. The output in Case 1 is enhanced 9.14% and efficiency is increased 3.3%, whereas the performance of Case 2 is only minimally improved with 1% enhancement in power and 0.44% increase in efficiency, respectively.

Table 5 Simulation of Solar Saturn gas turbine power and efficiency enhancements using inlet fogging for the ISO condition and four reference cases

Design Information:		Solar Saturn 1993, power generation type.				
	TIT = 1630 F	Fuel: Natural gas, 75 F, 250psig				
Temp, F	Rel Hum	Power, MW	Heat Rate, BTU/kWh	Efficiency	Power Increase, %	Efficiency Increase, %
60	0.60	1.089	14715	0.2319	0.000	0.000
77	0.30	1.011	15163	0.2250	-7.209	-2.975
76	0.95	1.029	15122	0.2256	-5.562	-2.717
88	0.67	0.977	15448	0.2209	-10.285	-4.743
90	0.70	0.971	15501	0.2201	-10.855	-5.088
58	1.00	1.103	14695	0.2324	1.278	0.216
73.5	1.00	1.039	15055	0.2266	-4.589	-2.285
77	1.00	1.026	15146	0.2253	-5.808	-2.846
82	1.00	1.008	15277	0.2233	-7.475	-3.708
Comparisons						
Ambient condition	Saturated condition	Heat Rate Reduction, %	Power Increase, %	Efficiency Increase, %		
77F, 30% →	58F,100%	3.09	9.147	3.289		
76F,95% →	73.5F,100%	0.44	1.031	0.443		
88F,67% →	77F,100%	1.95	4.990	1.992		
90F,70% →	82F,100%	1.45	3.791	1.454		

Table 6 Simulation of Solar Centaur gas turbine power and efficiency enhancements using inlet fogging for four reference cases

Simulation Information		Solar Centaur 1993, power generation type.				
	TIT=1945.6 F	Fuel: Natural gas, 75 F, 250psig				
Temp, F	Rel Hum	Power, MW	Heat Rate	Efficiency	Power Increase, %	Efficiency Increase, %
60	0.60	4.309	12281	0.2778	0.000	0.000
77	0.30	4.032	12555	0.2718	-6.417	-2.160
76	0.95	4.098	12546	0.2720	-4.881	-2.088
88	0.67	3.918	12743	0.2678	-9.065	-3.600
90	0.70	3.897	12778	0.2670	-9.559	-3.888
58	1.00	4.357	12254	0.2784	1.121	0.216
73.5	1.00	4.135	12505	0.2729	-4.022	-1.764
77	1.00	4.089	12563	0.2716	-5.089	-2.232
82	1.00	4.026	12647	0.2698	-6.549	-2.880
Comparisons						
Ambient condition	Saturated condition	Heat Rate Reduction, %	Power Increase, %	Efficiency Increase, %		
77F, 30% →	58F,100%	2.397	8.056	2.428		
76F,95% →	73.5F,100%	0.327	0.903	0.331		
88F,67% →	77F,100%	1.413	4.372	1.419		
90F,70% →	82F,100%	1.025	3.328	1.049		

Cases 3 and 4 represent conditions in the late and early afternoon respectively. Usually when the temperature becomes highest in the early afternoon, the RH drops from 95% in the morning to around 70%. Both Cases 3 and 4 indicate moderate enhancements in power output (3.7% ~ 5%) and efficiency (1.5% ~2.0%). Among these four representative cases, it can be seen that the RH humidity is the most important factor that affects the impact of inlet fogging. Case 1 represents a warm, dry day that can frequently occur in the spring and fall . Therefore, the inlet fogging can enhance GT power output not only in the hot summer, but also in other dry days during the year; for example, during the recent warm days between Christmas and New Year in Louisiana.

The results for Solar Centaur gas turbines (see Table 6) are similar. Although the enhancements for Centaur are a bit lower than those for Saturn, the capital costs and O&M costs per HP will be about 15% lower than those for smaller Saturn engines.

Analysis for Annual Conditions

After analyzing specific reference conditions, MEE Industries provided its analysis for the specific SOLAR gas turbines deployed at the studied plant site (Saturn-20 and Centaur-40 engines) utilizing New Orleans's annual weather data. In view of the small power enhancement by employing inlet fogging, MEE's analysis combined inlet fogging with a ~0.5%(mass) of total water/fog overspray at the compressor inlet (designed to further increase mass flow and provide additional inter-cooling during compression in the compressor). The results of MEE's annual analysis indicated some minimal power increases with inlet fogging alone and reasonable benefits with 0.5% water (fog) overspray.

Based on the weather conditions with ambient wet bulb temperatures above 45^o F (approximately 7,686 hr./year), the analysis indicates the potential of increasing power 2.34% with inlet fogging to saturated state and additional 5% of increased power with 0.5%(wt.) overspray. The total potential power increase for the studied gas turbine fleet is 7.39% or 1,900HP. It should be noted that the extremely high humidity conditions prevailing at the plant site are believed to have diminished some of the anticipated power increase. Tables 7 and 8 show the potential power enhancements of each month based on the annual weather condition in New Orleans. It can be seen that the highest power enhancement occurs between April and June of each year.

Table 7 Monthly simulation of Solar Saturn gas turbine power enhancements using inlet fogging (courtesy of Mee Industries)

	Solar Saturn New Orleans Weather					
Min WBT	: 45F	ECDH	hours over	Avg increase	Avg increase	Tot Avg
Month	Days	(hr.F)	Min WBT	cool to sat	overspray	output increase
Jan	31	1972	421	1.41%	3.27%	4.67%
Feb	28	2456	461	1.94%	3.96%	5.90%
Mar	31	3755	657	2.68%	5.10%	7.77%
Apr	30	4322	708	3.18%	5.67%	8.85%
May	31	4526	744	3.22%	5.77%	8.99%
Jun	30	4357	720	3.21%	5.77%	8.98%
Jul	31	4114	745	2.93%	5.77%	8.70%
Aug	31	4138	695	2.95%	5.39%	8.34%
Sep	30	4145	689	3.05%	5.52%	8.58%
Oct	31	4265	738	3.04%	5.72%	8.76%
Nov	30	3082	612	2.27%	4.90%	7.17%
Dec	31	2303	497	1.64%	3.85%	5.49%
Tot	365	43435	7686	2.63%	5.06%	7.69%

Table 8 Monthly simulation of Solar Centaur gas turbine power enhancements using inlet fogging (Courtesy of Mee Industries)

Solar Centaur New Orleans Weather						
Min WBT	: 45F	ECDH	hours over	Avg increase	Avg increase	Tot Avg
Month	Days	(hr.F)	Min WBT	cool to sat	overspray	output increase
Jan	31	1972	421	1.25%	3.25%	4.51%
Feb	28	2456	461	1.73%	3.95%	5.67%
Mar	31	3755	657	2.38%	5.08%	7.46%
Apr	30	4322	708	2.83%	5.65%	8.49%
May	31	4526	744	2.87%	5.75%	8.62%
Jun	30	4357	720	2.86%	5.75%	8.60%
Jul	31	4114	745	2.61%	5.75%	8.36%
Aug	31	4138	695	2.63%	5.37%	7.99%
Sep	30	4145	689	2.72%	5.51%	8.22%
Oct	31	4265	738	2.71%	5.70%	8.41%
Nov	30	3082	612	2.02%	4.89%	6.91%
Dec	31	2303	497	1.46%	3.84%	5.30%
Tot	365	43435	7686	2.34%	5.05%	7.39%

Using installed costs estimates provided by MEE for the specific location and engine types, the estimated installed project cost would be ~$510,000, not including costs for water treatment facilities that may be required. As previously stated, by increasing the power incrementally on each individual engine, the existing infrastructure (compressors, piping, controls, etc.) do not need modification and the facility can reap the full benefits of increased product throughput with minimal disruption to operations. By comparison, installing even a single Saturn-20, would only provide an additional 1,590 hp at 1 process unit site and would cost an estimated $966,000 installed.

Using a power unit cost approach to the fogging application project would indicate an approximate $265/HP (average of the 15 engines) compared to a $608/HP estimate for a single Saturn-20 or $506/HP for a single Centaur-40 (4,700 HP at and installed cost of ~$2,380,000) engine addition. Even with this approach, the fogging option would provide power at about half the cost of additional engines not to mention the fact that multiple engines would likely need to be deployed to achieve the same distributed results with all the associated infrastructure, and the associated space requirements and impacts to operations during interconnection.

The detailed results of the annual analysis are included in Table 9. The results of this annual analysis indicate that fogging should be further evaluated for a viable and cost effective option to incrementally increase the power (product throughput) of the studied gas turbine systems. A specific site analysis by a reputable supplier(s) of such systems should serve to better document both the opportunity and costs associated with these systems including the treated water supply issues and anticipated O&M (current O&M estimates from MEE indicates that with systems running a full year, consumables would run approximately $2,000/yr with associated manpower at 16 hrs/yr - not including water supply or treatment).

It needs to be pointed out that there have been some concerns over the potential erosion and corrosion in the compressor caused by overspraying water mist, although there are no clear indications to prove or disprove these concerns. Khan and Wang [8] specifically investigated the erosion issue by conducting a computational simulation of wet compression in a single rotor-stator compressor stage using the commercial code, Fluent. A sliding mesh scheme was used to simulate the stator-rotor interaction in a rotating frame. The results showed that the most eroded area occurs in fore-body of the rotor suction side, corresponding to a droplet attack angle of 30°. The largest erosion rate is predicted as 6.15×10^{-8} (kg/m^2-s) or 1.93 (kg/m^2-yr), which is approximately equivalent to a loss of 200 μm thickness of metal layer per year. Their model was preliminary and further investigations are needed.

Table 9 Inlet fogging analysis based on annual weather condition at New Orleans

Sub-Plant ID	GT Driver Application	Rated HP	MEE Analysis Solar GTs - New Orleans Weather Annual Days	ECDH (hr.F)	hours over Min WBT	Avg increase cool to sat	Avg increase overspray	Min WBT: 45° Tot Avg output increase	Increased Gross Power-HP	Installed Cost Estimate (sub-Plant)	Indicated $/HP
Group 1:	#3 Solar Saturn T1001S-236,	1,200	365	43,435	7,686	2.63%	5.06%	7.69%	92.3		
	#4 Solar Saturn T1001S-236A,	1,100	365	43,435	7,686	2.63%	5.06%	7.69%	84.6		
	#5 Solar Saturn T1001S-268,	1,100	365	43,435	7,686	2.63%	5.06%	7.69%	84.6		
	#6 Solar Saturn T1001S-268A,	1,100	365	43,435	7,686	2.63%	5.06%	7.69%	84.6		
	#7 Solar Saturn T1001S-192,	1,100	365	43,435	7,686	2.63%	5.06%	7.69%	84.6		
Group Sub-Total									430.7	$ 126,500	$ 294
Group 2:	#8 Solar Centaur CS400	3,830	365	43,435	7,686	2.34%	5.05%	7.39%	282.9		
	#9 Solar Centaur CS400	3,830	365	43,435	7,686	2.34%	5.05%	7.39%	282.9		
Group Sub-Total									565.7	$ 103,500	$ 183
Group 3:	#10 Solar Centaur CS400	3,830	365	43,435	7,686	2.34%	5.05%	7.39%	282.9		
	#11 Solar Saturn T1001S-186	1,100	365	43,435	7,686	2.63%	5.06%	7.69%	84.6		
Group Sub-Total									367.5	$ 96,600	$ 263
Stabilized	#1 Solar Saturn CSS-1200,	1,200	365	43,435	7,686	2.63%	5.06%	7.69%	92.3		
	#2 Solar Saturn CSS-1200,	1,200	365	43,435	7,686	2.63%	5.06%	7.69%	92.3		
	#3 Solar Saturn CSS-1200,	1,200	365	43,435	7,686	2.63%	5.06%	7.69%	92.3		
Group Sub-Total									276.9	$ 105,800	$ 382
Cryogenic	Co-gen Solar Centaur	3,830	365	43,435	7,686	2.34%	5.05%	7.39%	282.9	$ 77,050	$ 272
Total Plant Assessment									1,924	$ 509,450	$ 265
[*NOTE: Installed costs include 15% for foundation skid, site interface, and project engineering & overhead BUT does NOT include demin water supply equipment)											
Comparative Industry Default - New GTs ONLY		ISO HP					Engine $	Basic Install $			
	SOLAR Saturn 20*	1,590					$ 690,000	$ 276,000		$ 966,000 *	$ 608
	SOLAR Centaur 40*	4,700					$ 1,700,000	$ 680,000		$ 2,380,000 *	$ 506
[*NOTE: Installed costs include 40% for compressor/pump, site interface, and project engineering & overhead)											

CONCLUSIONS

A preliminary analysis was made to assess the potential enhancement of gas turbines' power output by employing inlet air fogging scheme at a gas process plant in Louisiana. Various gas turbine inlet air-cooling schemes were briefly reviewed. Inlet fogging scheme was selected for detailed studies due to its low installation capital costs.

Computational simulation was conducted using the commercial code, GateCycle, for four references cases which are representatives of four snap shots of summer weather at site including the conditions in a dry warm day, in a hot-humid morning, in the hottest time in the earlier afternoon, and in the later afternoon. The results indicate a potential of 10% enhancement in power output on a warm, dry day, 5% enhancement on a typical summer day, but only 1% enhancement on a hot humid day. It is shown that the relative humidity is the most important factor that affects the impact of inlet fogging. Therefore, the inlet fogging can enhance GT power output not only in the hot summer, but also in other dry days during the year.

The MEE Industries provided an annual analysis based on New Orleans's annual weather conditions with ambient wet-bulb temperatures above 45^{o}F (approximately 7,686 hr/year). The results indicate a potential of increased power of 2.34% with inlet fogging to saturated state and additional 5% increased power with 0.5%(wt.) overspray. The total potential power increase for the studied gas turbine fleet is 7.39% or 1,900HP. The concern for the potential erosion and corrosion in the compressor caused by overspray should be further investigated.

The total installed cost is estimated to be $509,450 at $265/HP. Since the studied GT consists of small gas turbine units, the installation cost is much higher than a typical cost of $34~60/HP for installing a inlet fogging system on a gas turbine larger than 300MW. However, this installation capital cost is 57% cheaper than buying a new Solar Saturn gas turbine, which will cost about $608/HP. Current O&M estimates from MEE indicated that with the systems running a full year, consumables would run approximately $2,000/yr with associated manpower at 16 hrs/yr - not including water supply or treatment.

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