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GAS TURBINE INLET AIR TREATMENT: A NEW TECHNOLOGY

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ABSTRACT

This paper describes the development, application, and performance verification of a new patented technology for cleaning and cooling combustion air to a gas turbine. A two-year in-depth research program at Dow Chemical Company in Freeport, Texas resulted in the development of this technology. At the conclusion of the research and development program, full-scale application of the hardware was made on a 100 MW combined cycle gas turbine, and its performance monitored for two years. Application of the new technology resulted in increased power output, higher reliability, NOx emission reduction, reduced maintenance costs, and higher total system efficiency. Since the new technology has produced very large cost savings, Dow is using the new technology on three new combined cycle machines currently being installed, and further is exploring conversion of existing combined cycle gas turbines to this new technology.

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I. HISTORICAL EXPERIENCE

The Dow Chemical Company's experience with the installation, operation, maintenance, and performance monitoring of industrial gas turbines utilized for power generation began in 1965 with the start-up of a Westinghouse model 301 gas turbine at a chemical research and manufacturing facility in Freeport, Texas. At the time, this was one of the largest operating gas turbines in the world, capable of generating approximately 33 megawatts (MW) under base load conditions. Three years later, a Westinghouse model 501A gas turbine was also placed in service and was one of the largest operating gas turbines in the world at 43 MW. As these units and others proved the benefit of gas turbines with heat recovery units in the industrial cogeneration arena, several new generations of industrial and aero-derivative gas turbines were installed in Freeport and other Dow sites throughout the U.S., Canada, Europe, and South America. In Freeport, this progression led to today's current fleet of fourteen operating gas turbines, which includes several GE Frame 7E and Westinghouse 501D5 gas turbines, and will continue with the operation of a new cogeneration facility, built by Destec Engineering, Inc., which will include three new GE Frame 7EA units.

One significant challenge to operating these base loaded units on the Texas Gulf Coast has always been to find methods of effectively combating the effects of high humidity, heat, salt and other airborne contaminants of gas turbine performance and on the various air and gas path components in the gas turbines. As gas turbine operating experience has been gained, so has experience with various techniques of conditioning the air entering the gas turbine compressors. This includes experience with inlet air conditioning and compressor cleaning systems which involve one or more techniques such as mechanical separators, demisters, water wash columns, wetted media evaporative coolers, low and high efficiency filtration media, on- and off-line compressor cleaning (water, detergents, pecan hulls, etc.) and the most recently developed inlet air cleaning technology.

The corrected(*) data in Figure (1) shows the typical degradation experienced on three, basically identical, 100 MW gas turbine units in 1987 using "old technology" or what is considered today to be a relatively standard high efficiency filtration system and routine on-line and off-line cleanings. The basic trend is a total output loss of between 1 and 3% per month between off-line cleanings due to reduced compressor and turbine performance, and the recovery of only a portion of the lost output following the off-line cleanings. With this data in hand, the significant opportunity to increase profits by reducing performance losses, down time, and maintenance losses associated with gas turbine air contaminant ingestion was recognized. This led to the research, development, and 1990 full scale implementation of a new inlet air cleaning system on one of these 100 MW units.

(*) Data is for base load operation only and has been corrected to compensate for the effects of variation in ambient temperature, barometric pressure, and steam injection rates. The %MW factor on the Y-axis is the % of output of the turbine compared to a base period output. The base period data was accumulated 1 to 2 years after startup at times immediately after an off-line wash.

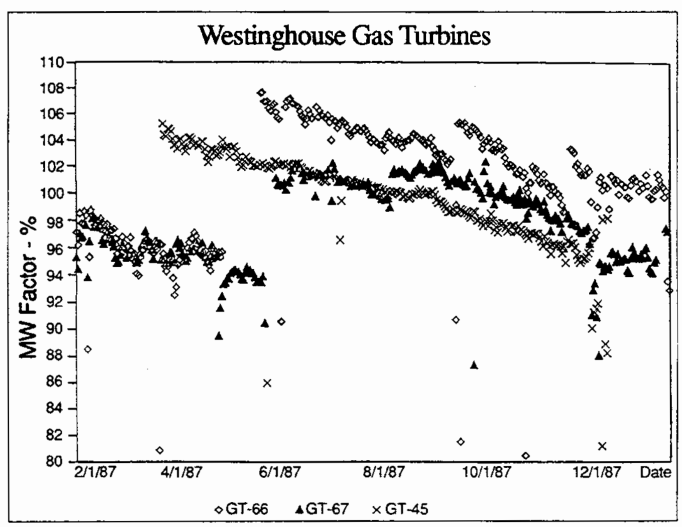

Figure 1

II. TECHNOLOGY DEVELOPMENT

Due to the history of performance degradation of Dow's gas turbine fleet and its economic impact, Dow assembled a project team and launched a research project in early 1988. A pilot plant facility was built with three major objectives:

1. Using both artificial fog from spray nozzles and actual ambient fog when available, evaluate a range of fog removal techniques.

2. Using laser beam particle counting technology, evaluate all major filter designs and efficiencies on the market at that time.

3. Build, instrument, and operate a high intensity water scrubber system to determine the optimum operating and design parameters and effectiveness to humidify and clean the air leaving a filter system.

The pilot plant was constructed and installed adjacent to one of Dow's large gas turbine inlets so that the quality of air entering the pilot plant would be essentially the same as that entering the gas turbine. A drawing of the pilot plant is shown on Figure (2). Major components included from left to right a fog nozzle spray system, a 6' by 6' frame to hold a range of fog removal devices, a frame system to hold nine 2' x 2' high efficiency filter elements, and a stainless steel scrubber module consisting of air straightening blades, 2 stages of high intensity spray nozzles, a disengagement section, a coalescing pad section, and blade moisture separators. A water tank and pump system was used to circulate water through the nozzles to absorb contaminants. Downstream of the scrubber module was flow tube and blower driven by a variable speed motor so that a range of air flows could be simulated. All components were designed to facilitate direct scale-up to a gas turbine inlet system. The plant was fully instrumented with both commercially available instruments and some specially developed instruments to measure all relevant process variables and air and water quality at each stage in the process. A process computer controller was used to control the plant and monitor and store the data.

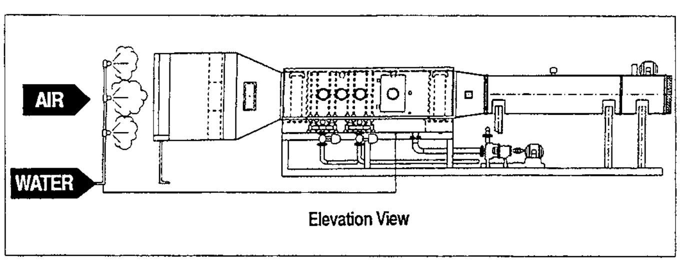

Figure 2

FOG REMOVAL

Fog removal is desired due to the impact of heavy fogs on turbine output. During a heavy and long lasting fog, the inlet filters to the turbine become saturated with moisture. Once this happens, the soluble component of dirt in the filter is dissolved, re-enters the air stream and is deposited on the compressor blades. One brand of a blade style fog removal system and several brands of a mesh pad style fog removal system were evaluated. The ability of the two types of systems to remove fog was similar; however, the pad system had lower pressure drop. Within the pad style system, performance was related to the density and mesh size of the pad.

However, neither system would completely eliminate moisture entering the filter section. If a fog is dense enough and last long enough, the filters will get wet and eventually unload their dirt—but the higher the efficiency of the pad, the less severe the problem.

HIGH EFFICIENCY FILTERS

A laser beam particle counter was used to measure filter performance. The standard efficiency of filters in the industry is about 90% on an average ASHRAE rating system. Filter performances cited herein refer to test procedures as defined in the ASHRAE Equipment Handbook, 1983 Chapter 10. As Dow was using a filter of this rating and having turbine performance loss, it was decided that the research effort would concentrate on higher efficiency filters. It was quickly learned that the smallest particle size range of our analyzer, 0.19 to 0.3 microns was the best range to differentiate filter performance. The 90% ASHRAE filter does very little to remove particles in this range, see Figure (3). Eight different filters with efficiencies from 90%

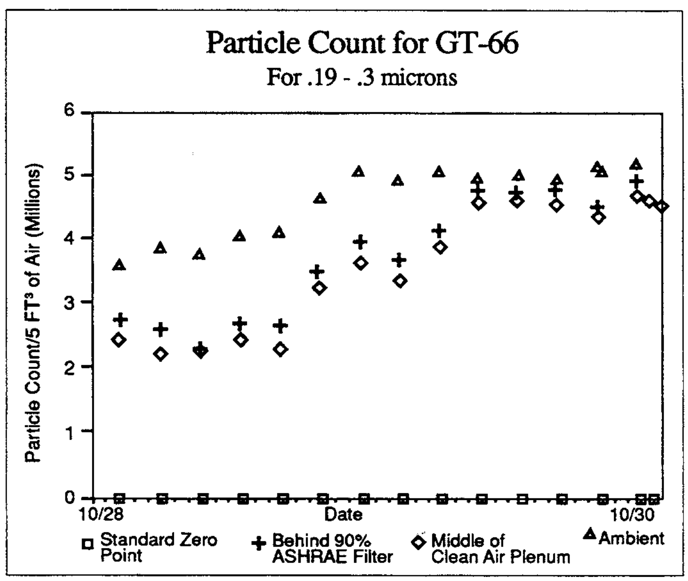

Figure 3

ASHRAE up to 99.97% DOP were studied. Figure (4) shows a particle count penetration comparison of five of these filters. As shown, the 99.97% DOP filter essentially removed all particles as shown on the standard zero line. As the efficiency dropped, the penetration increased within the 90% ASHRAE filter allowing over 2.5 million particles penetration in five cubic feet of air. The 95% DOP filters were quite good in comparison, allowing about 0.5 million particles penetration. Pressure drop tests showed the best filter, the 99.97% DOP to be excessive at about 1.2 inches of water, or about twice that of the 95% DOP element. More extensive tests of this filter and two brands of 95% DOP filters showed several differences.

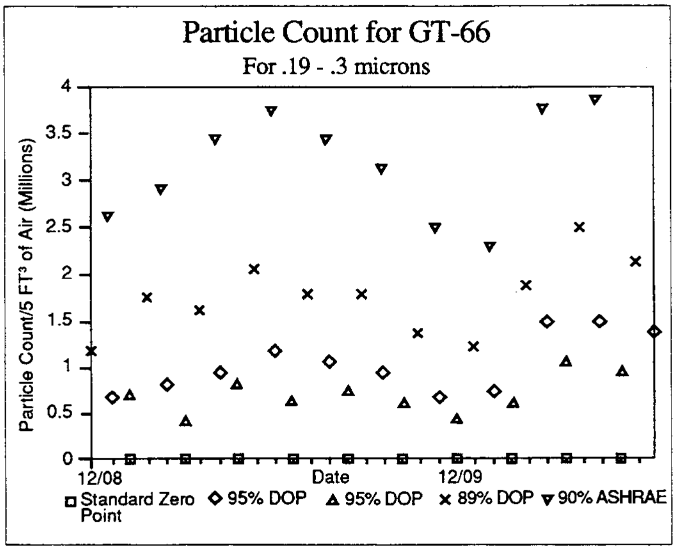

Figure 4

First, even though a filter may be rated for a certain removal percent, such as 95%, the actual efficiency depends on the specifications the filter vendor puts on the manufacturer of the media. One of our filter element vendors had specified 94% media, where the other vendor specified 97% media. Needless to say, penetration tests with the particle counter located directly behind the center of the element showed better results from the 97% media element.

Second, the sealing system for the edges of the media in the filter element frame were different. Placing the particle counter nearer the edges of the elements showed differences in performance. Filters which were "potted" with a urethane foam material had zero leakage. Elements which were sealed with just a compression seal of fiberglass showed edge leakage. The bottom line is that all 95% DOP rated filter elements are not created equal. Their performance is affected by the media specification and the edge sealing system.

Third, the square footage of media in the 2' x 2' x 1' thick frame affects the pressure drop and the dirt collection capacity and life of the element. Media surface areas of over 300 square feet are possible.

And fourth is the gasket system to seal the element to the mounting frame in the filter house. If the gasket is not thick enough and not made from a rubber which is soft and also has good recoverability, leakage may occur. In addition, the adhesive system used to attach the gasket to the filter element is very import ant. In some cases, the gasket comes off completely, allowing it to go through the combustion turbine.

Finally, the element holding devices must also be positively sealed to prevent bypass of contaminated air.

WATER SCRUBBING

The effectiveness of the water scrubbing section of the pilot plant was determined by several different techniques. A special analytical instrumentation system was developed which measured the conductivity of the air; the cleaner the air, the lower the conductivity. Figure (5) shows the impact on ambient air for a 95% DOP filter and the water scrubber system. As shown, the filter cuts the conductivity in about half. However, the scrubber cuts the conductivity in about half again. The scrubber is picking up particulate and ionics which penetrate the filter element. Figure (6) shows on two different runs what happens to the water basin during the same period of time. As the air is being cleaned up, the water is absorbing the contaminants and the conductivity in the water increases. Figure (7) shows seven runs of data in which the sodium levels in the basin were measured. Sodium levels after a 24 hour run were elevated by as much as 20 times the initial levels before the run. Sulfates and chlorides were also absorbed in the scrubbing water. Figure (8) shows on two different 24 hour runs very significant increases in these components in the basin water.

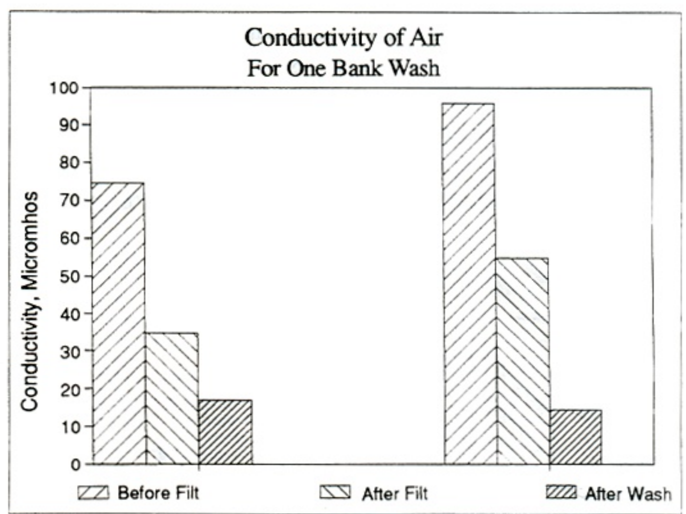

Figure 5

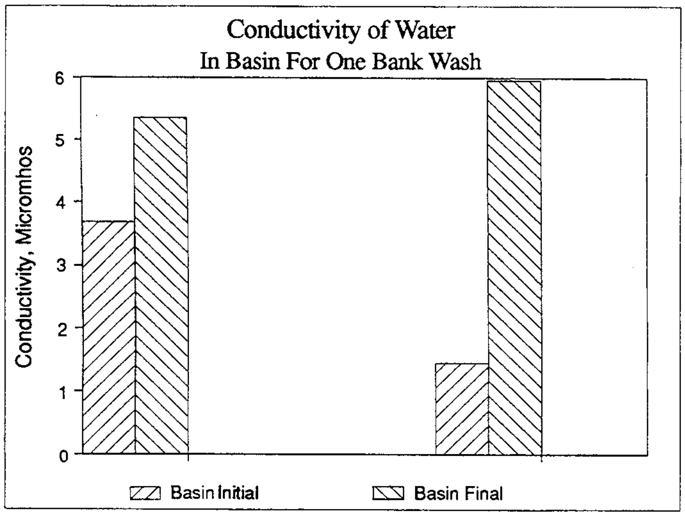

Figure 6

100 MEGAWATT TURBINE SCALE UP PROJECT

The positive results of this research project were shown to Dow management and an authorization request was made to fund a full scale project to take all the information learned in the pilot plant and implement it on a 100 MW combustion turbine. A pad type fog removal system, a two stage filtration system, and a water scrubbing system were designed, built, and retrofitted to an existing operating turbine unit during a scheduled maintenance outage. Figure (9) shows a plan view sketch of the system. This "New Technology" inlet air cleaning system was operational in January 1990. After three months of debugging and optimizing of all operating variables, performance testing began. The results of this test will be described later, but it has been so successful that Dow is looking at retrofitting this technology to at least four other large turbine units in its Freeport facility.

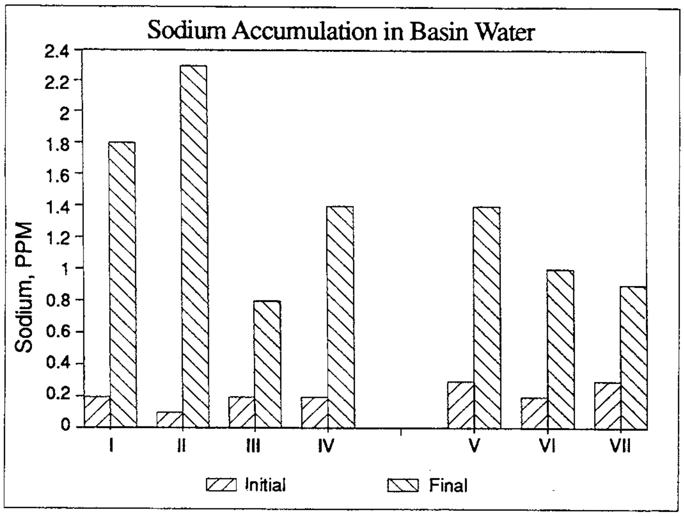

Figure 7

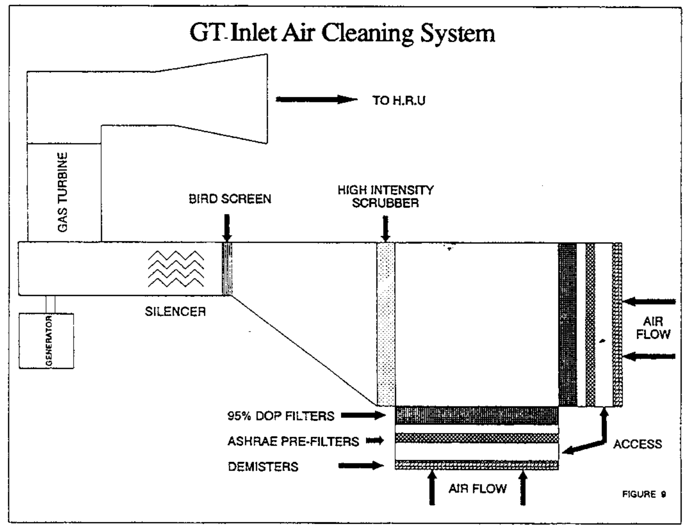

Figure 9

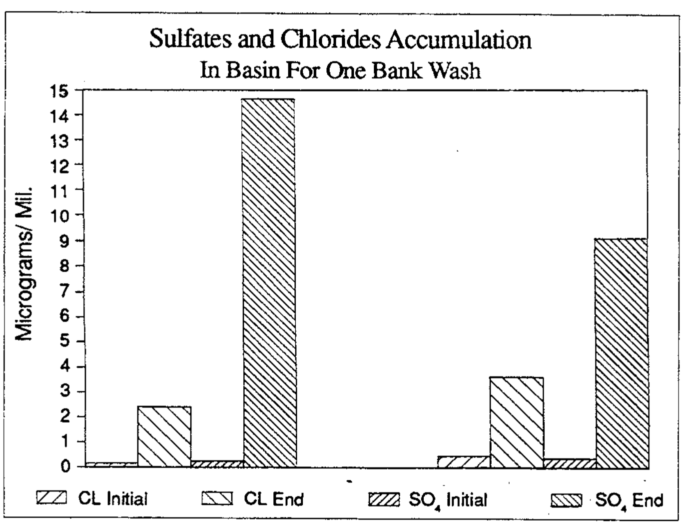

Figure 8

III. TECHNOLOGY AND HARDWARE DESCRIPTION OF 100 MEGAWATT GAS TURBINE INLET SYSTEM

FOG/RAIN REMOVAL

Since the location of the gas turbine is coastal Texas, it is of prime importance to ensure that no free moisture is drawn into the inlet system and conveyed to the turbine compressor inlet. The Texas coastal area experiences high annual rainfall and is also accustomed to fogs which manifest themselves primarily in the early morning hours. Therefore, the application of full scale hardware designed to eliminate free moisture from these fogs was deemed important. A series of free moisture elimination devices and techniques were used. First, a low velocity weather hood was utilized to deny ingress of larger water droplets, primarily rain.

Then following the hoods are a set of low velocity demister/coalescer pads to remove the smaller droplet sizes, primarily fog. These pads are synthetic material and are mounted in the inlet system complete with holding frames, drain troughs and downspouts so that any coalesced or separated free moisture is conveyed immediately to the exterior of the inlet system.

PARTICULATE FILTERS

Of critical importance to the operation of the gas turbine is the particulate removal capability which, in this "New Technology" system, consists of a high-efficiency barrier air filter element. The filter element has a 95% DOP efficiency rating and thus represents a dramatic departure from current industry particulate filter selection. The features mentioned in Section II were specified, thus making these elements a unique filter for gas turbine intake systems. With the final filter element in the 95% DOP efficiency range it became necessary, of course, to utilize a prefilter to extend the life of the more costly high-efficiency element and for this task a disposable prefilter element was selected. The prefilter was chosen after several tests to provide an optimum balance of three criteria, i.e. efficiency, dust holding capacity, and minimal pressure drop.

SCRUBBER

Contained in the atmosphere around Freeport are various other gaseous contaminants including chlorides, sulphates, and sodium. These aerosols being both sub-micron particulates and ionic vapors cannot be totally removed by particulate air filters. A proprietary scrubber system, complete with tanks, pumps, and instrumentation to monitor water quality, flowrate, etc. was included to remove the majority of these contaminants.

A second benefit of the scrubber system is the ability to provide an 80% humidifying efficiency and thus on hot days allows the increase of output from the gas turbine itself. The benefits of evaporative cooling have been amply demonstrated in the gas turbine industry.

The overall packaging of the above system components was accomplished in utilizing corrosion resistant materials to ensure a long life of the air filter housing as well as permanent internal structures and components.

IV. BENEFITS/RESULTS OF A 100 MW GAS TURBINE APPLICATION

Once the full scale "New Technology" inlet air conditioning system had been installed and atwo year performance study completed, the benefits of the new system were verified in several areas, including increased performance, reduced maintenance requirements, reduced NOx emissions, and higher total system efficiency and reliability.

The increased performance is characterized by reduced degradation of power output, reduced increases in heatrate, and increased overall output due to evaporative cooling effects. Figure (10) shows a typical degradation in output with the "New Technology" system of approximately 0.25%/month, which should be compared to the 1.0% to 3.0%/month shown of the "old technology" rates in Figure (1). As this data includes degradation due to compressor wear which may not be completely removed with a better inlet cleaning system, this non-recoverable component of the data must be subtracted out to perform a true comparison of the technologies. Figure (15) shows the total and non-recoverable component of the "new technology" power degradation for the first year after a major overhaul. The distance between the plots is the recoverable degradation of 0.05% per month. This is the component which can be recovered during an off-line wash of the compressor. Utilizing "old technology's" heat rate data and applying the reduced output data to expected heatrate degradation relationships, calculations were done to

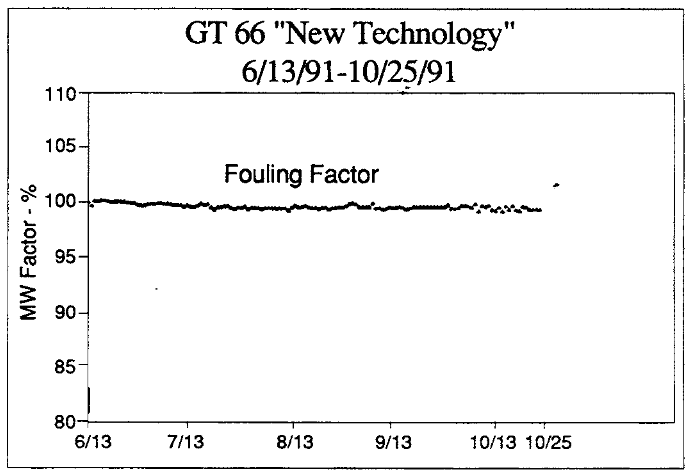

Figure 10

predict that the "old technology" inlet air systems create recoverable heatrate increases of approximately 0.080%/month, while the "New Technology" system reduces that amount to approximately 0.004%/month. Finally, this new system has displayed an 80% evaporative cooling effectiveness to provide even more gas turbine output, especially during hot and/or dry weather conditions. Figures (1a) and (11b) show the ambient wet bulb/dry bulb temperatures and relative humidity profiles, respectively, for a typical July day in Freeport, Texas, while Figure (11c) compares the compressor inlet temperature (CIT) associated with the two technologies. Due to these ambient conditions and typical local power demands, the increased power output associated with the "new technology's" CIT reduction (which is a result of increased mass flow through the gas turbine compressor) peaks during the time of year and the time of day when power demands are highest and pricing is usually the most attractive.

A reduction in overall maintenance costs is also expected with the application of the new inlet air cleaning technology. This is due to the virtual elimination of the need to shut down specifically for off-line washes, and through the reduced corrosion and erosion effects associated with removing contaminants from the air before it enters the compressor. Comparison of visual inspections of the turbine and compressor sections one and two years after installation of the new system to past visual inspections and photographs of the same and other Dow Freeport gas turbines, revealed the cleanest and least eroded compressor and turbine components ever experienced in more than two decades of gas turbine maintenance activities.

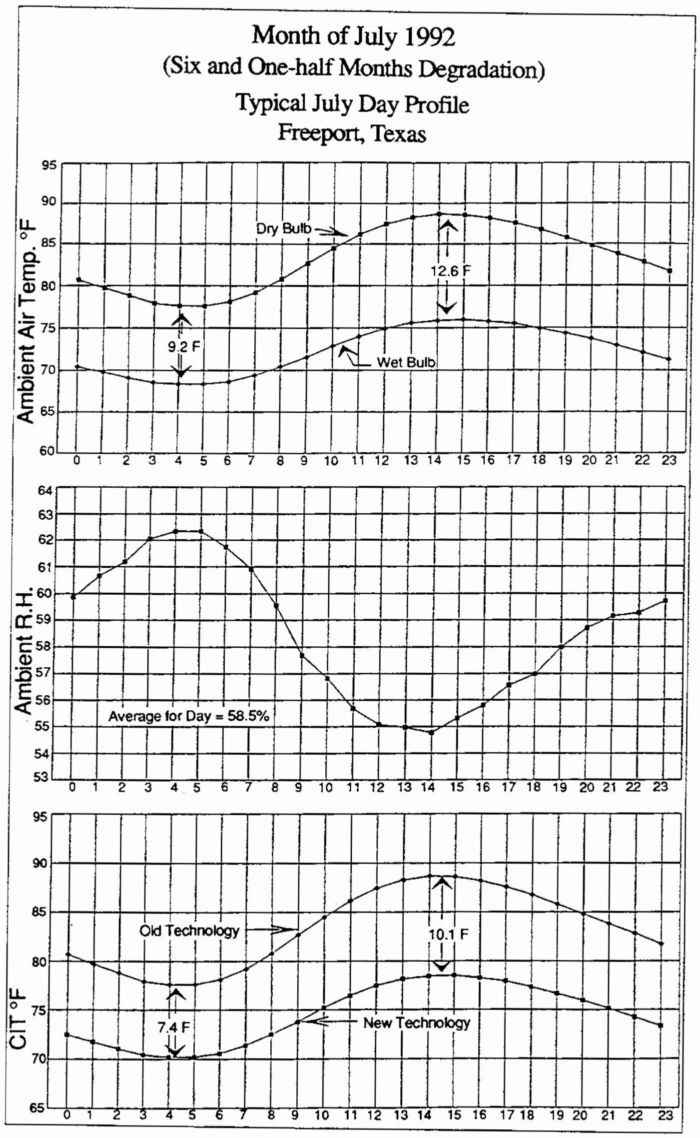

Figure 11 a, b, and c

Though it was not a driving force in the original development of the new inlet air cleaning technology, an additional benefit gained during operation of the new system was a net annual reduction in the gas turbine's overall NOx production calculated to be approximately 8%. This reduction is primarily a result of increasing the relative humidity of the air entering the compressor, which ultimately reduces the flame temperature in the combustion zone. Calculations are based on measured NOx emission data at various relative humidities.

Finally, a higher total system efficiency and reliability of the gas turbine, heat recovery unit, and associated processes using the steam and power they produce can be expected with the new system. This is supported by the increased gas turbine output, which also results in additional steam production in the heat recovery unit; the reduced need for off-line washes and associated maintenance outages, which reduces thermal cycling and extends part life; and the reduced fouling, corrosion and erosion effects, which help to minimize the possibility of unstable operation or rotating blade and other component failures.

V. ECONOMICS

To accurately calculate the dollar savings from the "New Technology", a rather complex computer model was developed. A somewhat "generic" power plant was modeled consisting of a 100 MW gas turbine with a three drum HRU, and a 1250 psig throttle condensing steam turbine. As the gas turbine output changes due to ambient conditions or compressor fouling, the HRU output and steam turbine power generation also change. Figure (12) provides a comparison of output degradation plotting old technology versus "New Technology" over a five year period. The actual data from Figures (1) and (10) were used to plot Figure (12) and the program subtracts the same non-recoverable curve of Figure (15) from both sets of data. The plant is always in the power purchase mode from the utility, so that decreases in generation result in higher purchases and vice versa. The model is calculated every hour of the day for a five year maintenance cycle which is repeated two times for an assumed project life of 15 years. The "old technology" plant gas turbine shuts down every six months for an off-line wash, where in the "new technology" cycle this is unnecessary. Otherwise, regular manufacturer's recommended maintenance intervals are assumed.

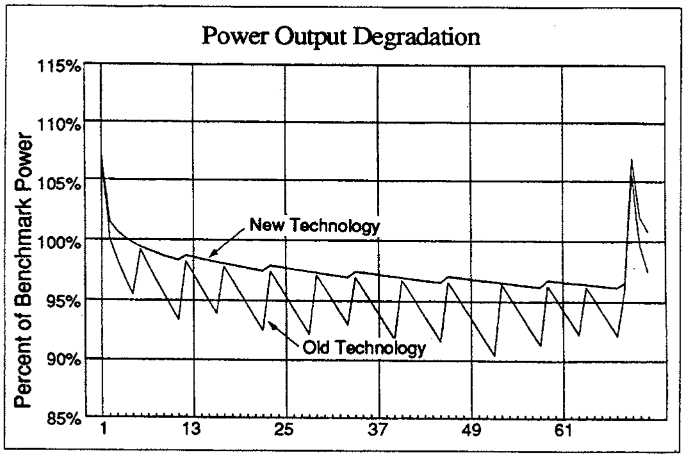

Figure 12

SPECIFIC BASES

1. Purchased power price for energy averages $30.00 per MWH in 1992, but varies with time of day per Figure (13).

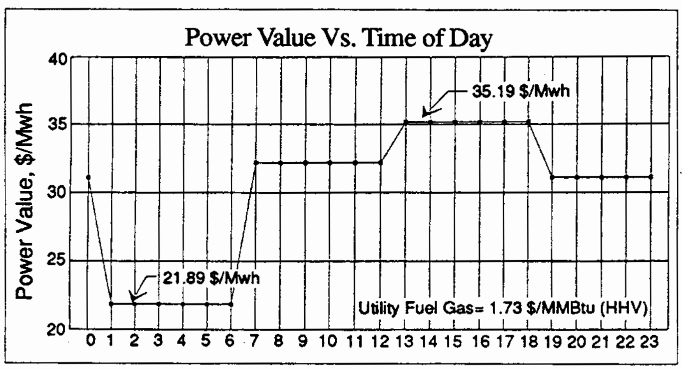

Figure 13

2. An assumed 1992 fuel gas price of $1.70 per MMBTU was used for these economics.

3. Ambient relative humidity varies each hour per actual data for the Texas Gulf Coast, normalized to an average of 60 percent for the base case.

4. "Old Technology" recoverable power degradation rate is 1% per month, and the "New Technology" rate is .05% per month.

6. Evaporative cooling effectiveness of "New Technology" is 80%.

Besides the base case described above, three sensitivities were run, one with a relative humidity of 50%, one with a fuel price of $2.00 per MMBTU, and one with a power price of $35.00 per MWH. The results of these runs are shown on Figure (14). As shown, the project midlife savings in 1992 dollars for the base case is $856,013, with the sensitivities showing savings from $627, 043 to $1,248,877 per year. These economics are for illustrative purposes only. The actual savings for a user of this technology would have to be calculated by the prospective user based on their actual cycle configuration and existing degradation rates, power purchase contract, fuel price, maintenance history, relative humidity, etc.

Results of Economic Evaluation for New Technology Gas Turbine Inlet Air System

		Sensitivities		
	Base Case	Relative Humidity	Fuel Price	Power Price
Fuel gas unit price (1992 starting value)	1.70	1.70	12.00	1.70
Average power value (1992 starting value)	30.00	30.00	30.00	35.00
Annual average relative humidity	60	50	60	60
Old Technology power degradation rate*	1.00%	1.00%	1.00%	1.00%
New Technology power degradation rate*	0.05%	0.05%	0.05%	0.05%
Old Technology heat rate degradation rate*	0.080%	0.080%	0.080%	0.080%
New Technology heat rate degradation rate*	0.004%	0.004%	0.004%	0.004%
Old Technology evaporative cooler effectiveness	0.0%	0.0%	0.0%	0.0%
New Technology evaporative cooler effectiveness	80.0%	80.0%	80.0%	80.0%
Annual savings, mid-life, in 1992$	856,013	1,008,713	627,043	1,248,877
**Recoverable* component, %/month				

Figure 14

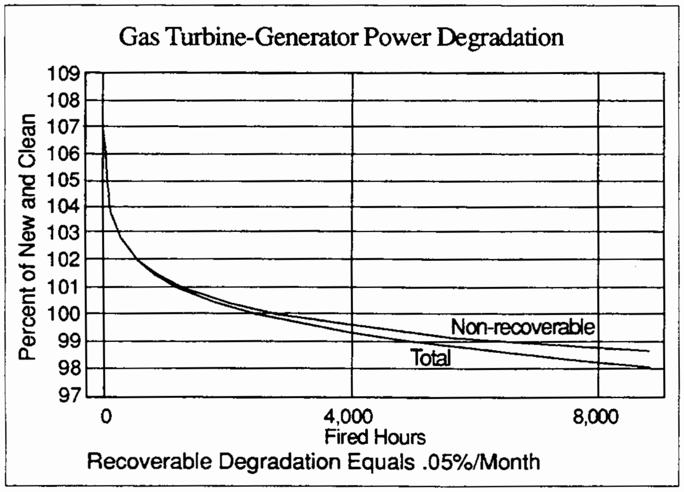

Figure 15

ACKNOWLEDGEMENTS

L.L. Melton - A Process Associate with The Dow Chemical Co., and was responsible for the pilot plant research and development program for the "New Technology".

John A. Bajer - A Senior Research Technician with The Dow Chemical Co. in the Hydrocarbons and Energy Research Department, and was responsible for the operation and data collection for the pilot plant.

Debbie Lind - With Destec Energy Inc., formerly a Research Engineer with The Dow Chemical Co., was responsible for the computer analysis of the data from the pilot plant and the full scale installation.