*Paper No: 07-IAGT-2.2*

# INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

# New Technique for Steam Injection (STIG) Using Once Through Steam Generator (GTI/OTSG) Heat Recovery to Improve Operational Flexibility and Cost Performance

**by**

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**Presented at the 17th Symposium on Industrial Application of Gas Turbines (IAGT)**
**Banff, Alberta, Canada – October 2007**

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# Abstract:

Utilities world wide are faced with issues of high energy cost, high capital costs and tightening environmental legislation. Steam injection (STIG) is a technique which can increase a plant's ability to generate extra power without burning extra fuel and requiring moderate capital investment. In this paper we present a new method of generating steam required by the Steam Injection Process (STIG), using a Once Through Steam Generator (OTSG). This approach is an improvement over the conventional method of steam injection because it utilizes waste heat from the exhaust of the gas turbine (GT) to produce low cost steam resulting in a lower cost and more flexible process. A high strength, thin walled, high temperature nickel alloy steam generator is used in the hot gas path to provide superheated steam suitable for use in the GT and at a low operational cost. The paper discusses current applications of this method on several gas turbines (frame and aero-derivative) which include the GE Frame 7FA and ABB GT11N1 gas turbines. Additionally the paper explores the unique capabilities of the OTSG that allow for dry running, simple operation and high operational availability.

## 1. Introduction:

Over the last two decades, the gas turbine has seen tremendous development and market expansion. Whereas gas turbines represented only twenty (20) percent of the power generation market twenty (20) years ago, they now claim approximately forty (40) percent of new capacity additions. Some forecasts predict that gas turbines may furnish more than eighty (80) percent of all new U.S. generation capacity in coming decades. Gas turbines have been long used by utilities for peaking capacity, however, with changes in the power industry, new environmental legislation and increased efficiency, the gas turbine is now being dispatched for base load power. Much of this growth can be accredited to large (>50 MW) combined cycle plants which exhibit low capital cost and high thermal efficiency. Manufacturers are offering new and larger capacity turbines with more advanced cycles that operate at higher efficiencies.

### The Brayton Cycle:

The thermodynamic cycle associated with the majority of gas turbines is the Brayton cycle, an open-cycle using atmospheric air as the working fluid. An open cycle means that the air is passed through the turbine only once. The thermodynamic steps of the Brayton cycle includes: 1) compression of atmospheric air, 2) introduction and ignition of fuel and 3) expansion of heated combustion gases through a turbine section. A stationary gas turbine consists of a compressor, combustor and a turbine, as shown in Figure 1. The compressor section provides pressurized air to the combustor where fuel is added and burned. Hot combustion gases leave the combustor and enter the turbine section where the gases are expanded across the turbine blades to rotate one or more shafts. These drive shafts spin and in turn simultaneously power the compressor section and the electric generator. The simple cycle thermal efficiency of a gas turbine can range from twenty-five (25) percent in small units to forty (40) percent or more in recuperated cycles, large high temperature units and some aero-derivative units. The thermal efficiency of the most advanced gas turbine combined cycle plants is approaching sixty (60) percent. The thermal efficiency of cogeneration applications can approach eighty (80) percent where a major portion of the waste heat in the turbine exhaust is recovered to produce useful steam.

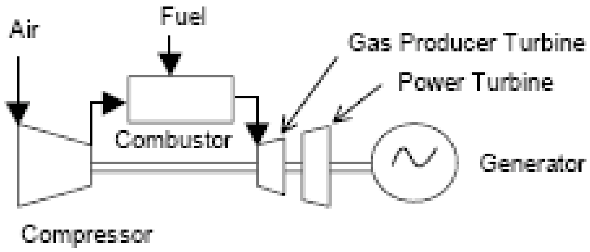


**Figure 1**: Gas Turbine Components

**Steam Injection Gas Turbine (STIG):**

Steam Injected Gas Turbine (STIG) systems operate as an enhancement to the Brayton cycle. High quality steam is used to increase the power output and improve operating efficiency of the basic Brayton cycle. Steam is typically produced by an auxiliary steam boiler, external steam source or external process source and then injected into the combustion chamber of the gas turbine. The site at which this steam is injected differs according to the design of the particular gas turbine, however, in principal high pressure steam is injected into the high-pressure sections of the GT via the combustor fuel nozzles and compressor discharge plenum. Most gas turbine vendors offer a standard kit that is suitable to convert their turbines to accept steam injection from an external source.

In its most basic form, steam injection works by increasing general mass flow through the GT's power turbine. The increased mass flow generates an increase in the rotational torque and power output. Normally, as mass flow through the power turbine increases so to does the mass flow through the compressor stages. While this power increase is beneficial, it is offset by an increase in parasitic load due to the compression of increased air coming into the GT. The beauty of the STIG process lies in its ability to increase the mass flow in the power turbine with out increasing the mass flow through the compressor stages. STIG uses high pressure dry steam compressed to greater than 500 psi and heated to over 700 F and injects this steam after the compressor. Thus it bypasses the compressor stage increasing the power generated in the turbine stages without increasing the resulting compression loads.

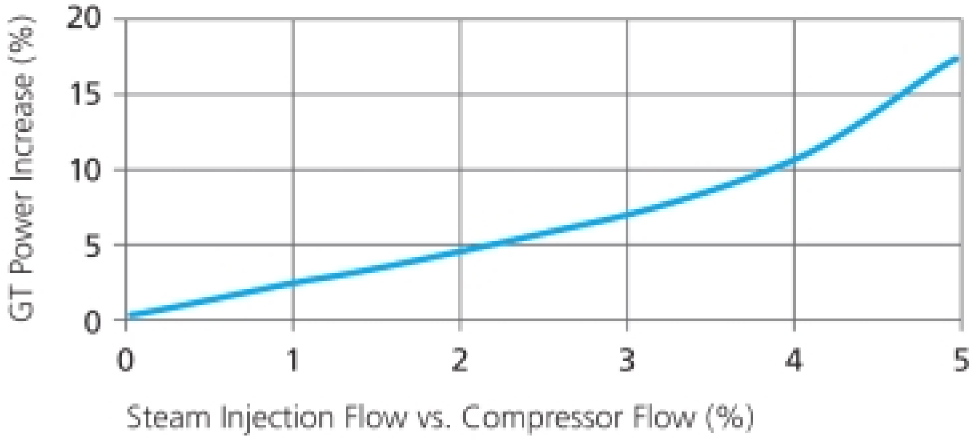


**Figure 2**: Power Increase due to STIG

### Benefits of Steam Injection (STIG):

Steam Injection (STIG) technology offers a clear improvement over the Brayton cycle while providing a fully flexible operating cycle. The amount of steam injected into the combustor can vary at a rate of between 2% and 10%. The main benefits of STIG are an increase in power output and a decrease in NOx emissions from the gas turbine. Table 1 compares the cost per installed KW and the heat rates for various gas turbine power applications. STIG / GTI is by far the cheapest method to augment the power capacity of an existing facility. Benefits of steam injection include:

- 5 to 25 % more power from the base gas turbine
- 2.5 – 15% reduction in base fuel consumption
- Reduction of NOx emission
- Injects maximum steam when electric prices are high
- Absorbs excess steam when process demand is low
- Flexible process (Steam injection 50% - 100% load)

| PLANT TYPE | INSTALLED COST ($/kW) | HEAT RATE (Btu/kWhr) |
|---|---|---|
| SIMPLE CYCLE | $400- | 9500 |
| COMBINED CYCLE | $600- | 6100 |
| COGENERATION | $680-$950 | 9500 |
| GTI | $227.50* | 400 |

**Table 1**: Installed Cost and Heat Rate for STIG/GTI

**Please note**: * GTi installed cost is based on our Gaffney South Carolina Project (2004).

## 2. The Steam Injection Process:

### Introduction:

Figure 3 illustrates the components required for a STIG process. The major components are: 1) the gas turbine and generator set, 2) water treatment plant, and 3) steam source. Each component must be engineered to best match the application and its particular needs.

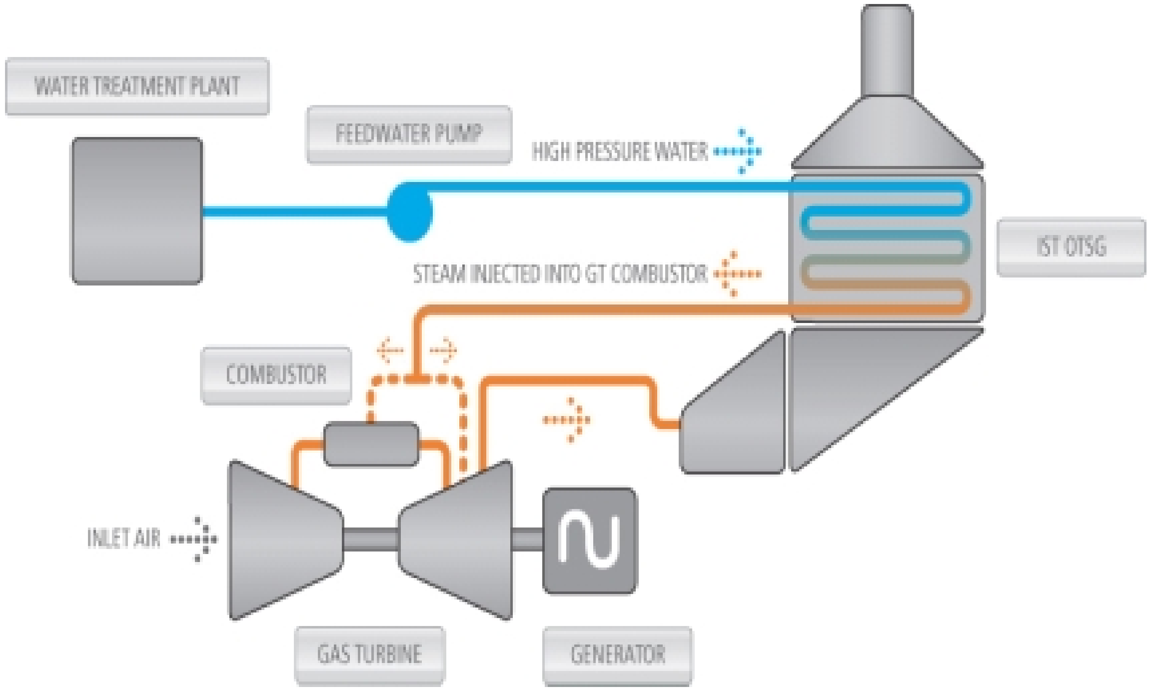


**Figure 3**: Steam Injection Process using GTI / OTSG as the Steam Source

### The Gas Turbine

The Gas Turbine is the core of the STIG process. In its simplest form, the gas turbine consists of a compressor, a combustor and a power turbine. The compressor stages, squeeze the incoming air from atmospheric pressure to the required combustion pressure for the combustor. The combustor mixes the compressed air, introduces fuel and ignites the fuel air mixture. The heated combustion gases expand through the power turbine stages producing power and heat. Gas turbines range in size from 30 kW (microturbines) to 250 MW (industrial frames).

## The Water Treatment Plant:

Increasingly water treatment is being required for all steam generation. Good water treatment extends the life of the pressure tubes, monitoring instruments and the associated steam plant. Likewise, water treatment is critical to the effectiveness and long term durability of the STIG process. Water quality in STIG is maintained using straightforward and conventional deionization and polishing exchange systems. These systems eliminate deposition of minerals and residue on the gas turbine components. De-ionized water treatment systems combined with condensate polishers are the simplest solution and are not unique to STIG. They are increasingly being used on traditional drum-type HRSGs and are favored for any installation where life-cycle costs, high reliability and high purity steam is desired.

## The Steam Source:

Gas turbine injection rates can vary from two (2) to ten (10) percent of the gas turbines mass flow. For example, a 5% steam injection rate, on a GE frame 7FA would require 176,559 lbs/hr of 500 psi and 700 F high quality dry steam. This process would require a steam facility capable of supplying this capacity of steam for each of their turbines. Traditionally, these steam requirements would be supplied by one of the following sources:

- auxiliary boilers,
- process steam
- or a modified HRSG specifically designed for this application

IST has been in the business of supplying Once Through Steam Generators (OTSG) for this application since 1996.

## 3. The GTI/OTSG Heat Exchanger as Steam Source:

### OTSG History:

The Once Through Steam Generator (OTSG) technology was developed as a joint venture between Solar Turbines and the U.S. Navy as part of the RACER (RAnkine Cycle Energy Recovery) program. The design goals for this project was to design a light weight, fast cycling, high power and modular heat recovery boiler to be used in the construction of the Navy's next generation of advanced war ship. IST has further invested over 300,000 man hours and 2,500,000 operational hours in the continuing development of the basic OTSG technology.

### GTI/OTSG Design:

The once-through steam generator (OTSG), in its simplest form, is a continuous tube heat exchanger in which preheating, evaporation, and superheating of the feed-water takes place consecutively, within one continuous circuit, as can be seen in Figure 4. Many tubes are mounted in parallel and are joined by headers thus providing a common inlet for feed-water and a common outlet for steam. Unlike a drum boiler where natural circulation is used, water is forced through the tubes by a boiler feed-water pump, entering the OTSG at the "cold" end and maintaining constant flow through the tube bundle. As the water flows through the heated bundle, it changes phase along the circuit as it extracts heat from the gas flow. Water then exits as superheated steam at the "hot" end of the unit. Gas flow is in the opposite direction to that of the water flow (counter current flow).

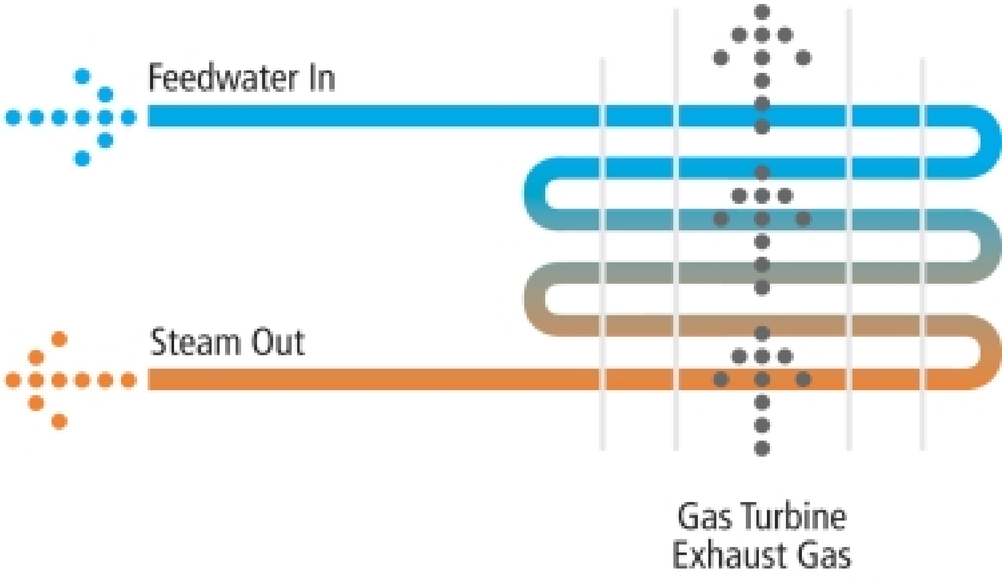


**Figure 4**: **OTSG Design (6 Row Bundle)**

Unlike conventional HRSGs, an OTSGs does not have defined economizer, evaporator or super-heater sections, thus providing it with a unique ability to adapt and adjust to its heat inputs. The region of the tube bundle where water is converted into steam, known as the steam-water interface, is free to move through the tube bundle. Depending on the available heat from the gas turbine, the feed-water pressure and the mass flow rate of feed-water, the steam-water interface will move forward or back in the bundle. In a 50 row bundle, this point can migrate up or down 4 rows.

The single point of control for the OTSG is the feed-water control valve; actuation depends on predefined operating conditions that are set through the distributed control system (DCS). The DCS is connected to a feed forward and feedback control loop, which monitor the heat input from the gas turbine, load changes and outlet steam conditions, respectively. If a load transient from the gas turbine is monitored, the feed forward control system will adjust the feed-water flow to a new predicted value based on the turbine exhaust temperature, thus producing steady state superheated steam conditions. The GTI-OTSG can be controlled using one of the following control schemes: 1) steam temperature control, 2) steam pressure control or 3) GT demand control. Please refer to figure 5 for illustration of steam temperature control, however pressure and load can also be used for control purposes.

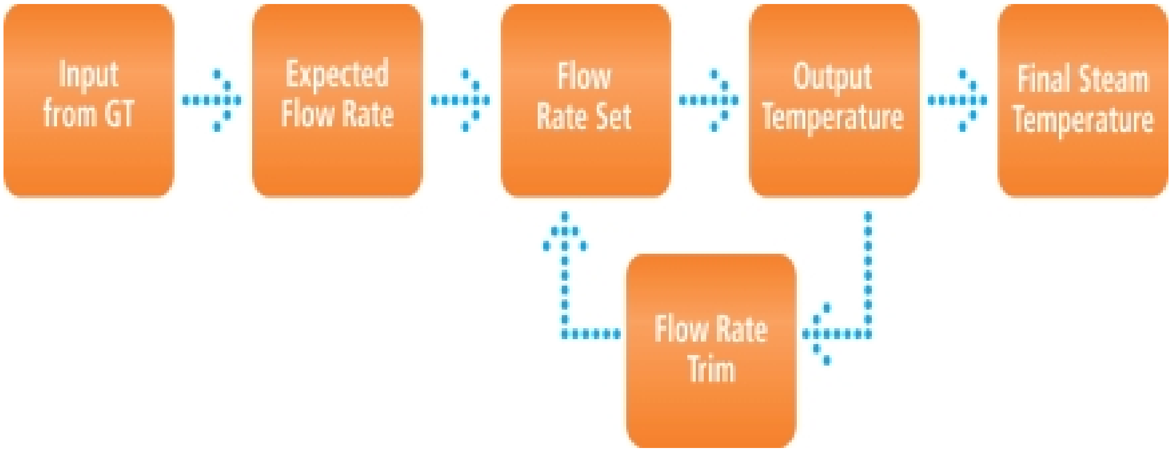


**Figure 5**: **OTSG Control**

**Small Compact Design:**

GTI/OTSG technology is ideally suited for locations where space is restricted as is true for a retro fit of an existing open cycle GT. The elimination of the bypass stack and diverter valve, together with the system's modular design, allows the design to be up to 50 % smaller, lighter and more compact than a comparable HRSG.

When configured for GTI/OTSG operation we typically arrange the system with horizontal gas flow and vertical heat extraction tubes as can be seen in Figure 6. The vertical tube configuration results in a smaller footprint, pushing the units vertically rather than horizontally and allowing for installation in an existing gas path.

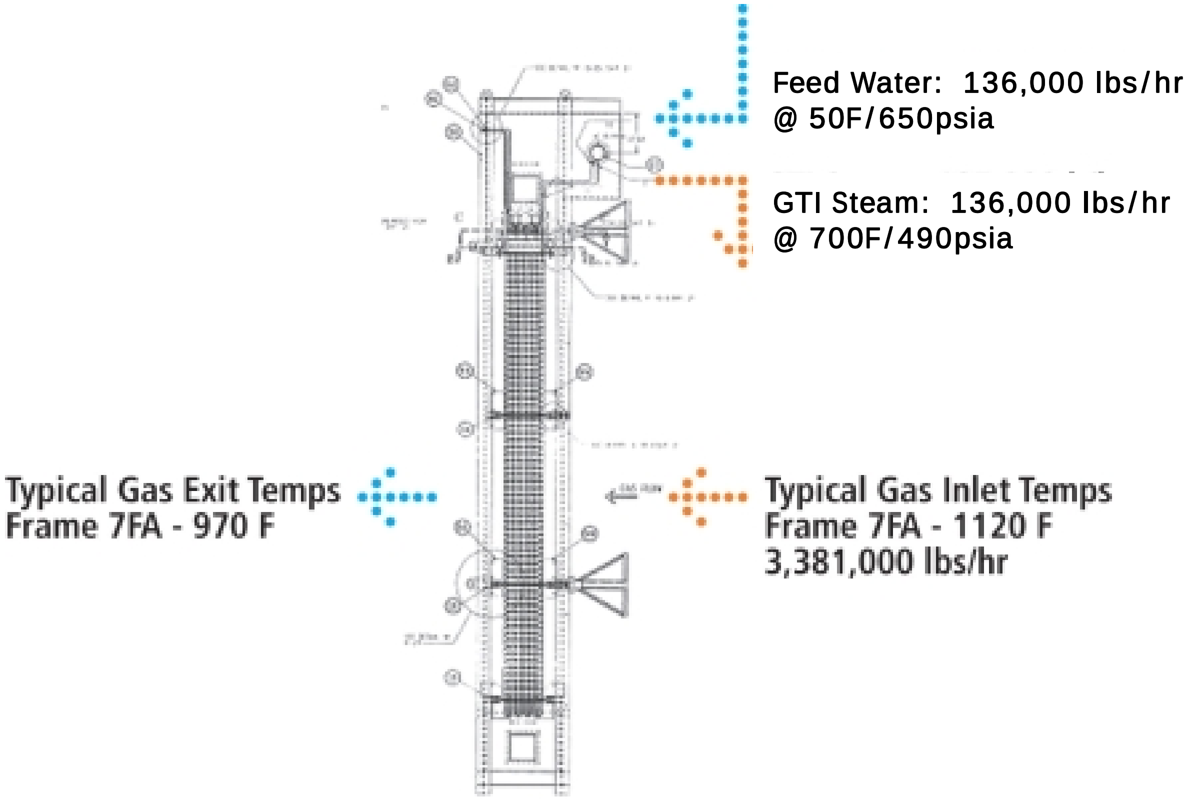


**Figure 6**: Standard Configuration of the GTI / OTSG

## Advanced Material Construction:

The GTI/OTSG uses specially developed and fabricated finned tubes matched to the operating temperature and requirements of the gas turbine. The main driver of tube selection is the dry running temperature of the Gas Turbine. Many frame based units will run as high as 1300 F and thus the GTI/OTSG unit must be designed to sustain these temperatures. The tubes are made of high alloy nickel material as seen in Table 3, and capable of exposure to high temperatures in accordance with Section I of the ASME Boiler Code. The proprietary finned tubing manufacturing process allows many different combinations of fin material to be bonded to the tubing. For most applications carbon steel fins are optimum due to their superior thermal properties, but stainless steel and alloy fins are possible when operation at high temperatures or installed in the cold economizer rows of the bundle so as to eliminate the effects of corrosion caused by water condensation.

Pressure parts are designed, manufactured and inspected in accordance with ASME Section I Boiler and Pressure Vessel Code as can be seen in Table 2.

| ***ASME Material*** |
|---|
| SB423 NO8825 |
| SB407 NO8800 |
| SB407 NO8810 |

**Table 2**: Material Selection

Table 3, lists the chemical composition of the two main alloys that we use for our pressure tubes.

| | Ni | Cr | Mo | Fe | Cu | C | Al | Ti |
|---|---|---|---|---|---|---|---|---|
| Incoloy 800 | 32.5 | 21 | - | 46 | 0.4 | 0.05 | 0.2 | 0.3 |
| Incoloy 825 | 42 | 21.5 | 3 | 28 | 2 | - | 0.2 | 0.9 |

**Table 3** - Nominal Chemical Compositions (% Weight)

Table 4, lists the DIN information for the materials we use to create our pressure bundle.

| ASME Material | SB407 NO8800 CW /Annealed | SB423 NO8825 CW /Annealed |
|---|---|---|
| Product Raw Form | Pipe and tube (seamless) | Pipe and tube (seamless) |
| DIN Material | X10NiCrAlTi3230 | NiCr21Mo |
| Werstoff Nr. | 1.4876 | 2.4858 |
| Condition | CW | CW |
| Heat Treatment | Soft Annealed | Soft Annealed |
| Material Standard | VdTUV 412 | VdTUV 432/2 |

**Table 4** - DIN data

**Designed to Dry Run:**

Conventional HRSGs use carbon steel as the tube material. Carbon steel loses strength at elevated temperatures, thus, making a bypass stack and diverter valves necessary to prevent the hot exhaust from damaging the tubes during dry running conditions. The GTI / OTSG uses high-nickel Incoloy 800 and 825 alloy tube material, which maintains a substantial fraction of its strength and corrosion resistance at high temperatures. Advanced material selection, permits full dry running up to a maximum temperature of 1500 F. Further, Incoloy 800 and 825 tube materials limits the OTSG’s oxygen sensitivity, avoiding the need for active chemical water treatment.

The alloy tube bundle is supported vertically by support hangers spaced along the unit’s length. The hangers are supported by beams and hung from module sidewalls. The flexible connection to the sidewall allows the beams to expand thermally towards the sidewalls and to move axially parallel to the sidewalls. This construction allows a high degree of thermal flexibility, which is ideal for dry run operation and cyclic duty applications.

**Modular Fabrication:**

Factory construction of the pressure module leads to high quality control and 100% inspection of all pressure welds by means of ultrasonic testing. The pressure module is commonly a single module with the entire ASME Section I boiler proper components factory welded and code inspected before leaving our fabrication plant. The GTI/OTSG can be shipped in sizes exceeding 181,436 kilograms/module (400,000 lbs/module) and heat transfer areas of about 27,870 square meters/module (300,000 square feet/module) to any location in the world. IST is proud of the fact that we have OTSG's operating in 13 countries and at 116 locations around the world. The modular approach minimizes erection and installation cost and time. This reduces the project's gestation period and makes the STIG application increasingly more attractive to developers and financiers

**System Maintenance:**

System maintenance for the GTI/OTSG is significantly reduced when compared to a traditional HRSG. The combination of reduced complexity, lower number of interconnecting piping, fewer valves, transducers, control connections, and instrumentation etc. greatly reduces the work required to keep the STIG system operating at its peak effectiveness. The GTI/OTSG, itself, does not have any moving parts, essentially it is a large heat exchanger. The ancillary equipment, such as safety valves, control valves, and attemperators, are drastically reduced when compared to a standard HRSG.

During a scheduled GT shutdown the internal tube bundle of the OTSG can be visually inspected for possible damage, leaks or other maintenance requirements. 100% of the welded parts, u-bends, jumper tubes and headers are located in maintenance cavities, which are fully accessible via maintenance doors, at the top and bottom of the unit.

Figure 7, illustrates the comparative availability of an OTSG boiler and a standard Drum HRSG as prepared by one of our customers with multiple OTSG and HRSG units in operation.

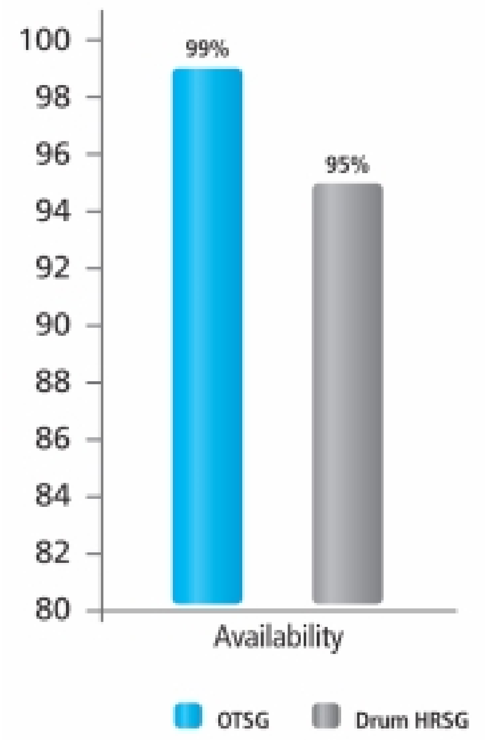


**Figure 7**: OTSG Availability

**Equipment Installation:**

The modular design of the GTI/OTSG minimizes time and cost associated with field installation. These savings reduce the project's gestation period making STIG augmentation projects increasingly attractive to developers and financiers as shown in Table 1. Installation costs are reduced because the OTSG is designed around one or two main modules. Each of these modules is shop fabricated and shop tested and can be delivered to the point of erection by road or by rail. The modular design and manufacturing facilitates rapid construction and minimizes both on site work-hours and crane time at the erection site.

**Figure 8a**: Installation Sequence for GTI/OTSG

**Figure 8b**:  Installation Sequence for GTI/OTSG

**Figure 8c**:  Installation Sequence for GTI/OTSG

**Figure 8d**: Installation Sequence for GTI/OTSG

Figures 8a to 8d illustrate the installation process. The first step involves the modification of the original open cycle plant ducting. The next step, involves the installation of a pad foundation required to support the GTI/OTSG. The GTI/OTSG is now ready to be set in position and often this operation can be performed within one day following the placement of the footings. The GTI is simply raised from the shipping vehicle to an upright position and lifted into the space created during the duct modification stage. The final step is to seal weld the unit. Additional time is required for completing the module expansion joints, construction of the feed water treatment system, external piping, connections to the gas turbine and commissioning. A typical 7FA installation with balance of plant equipment is illustrated in Figure 9.

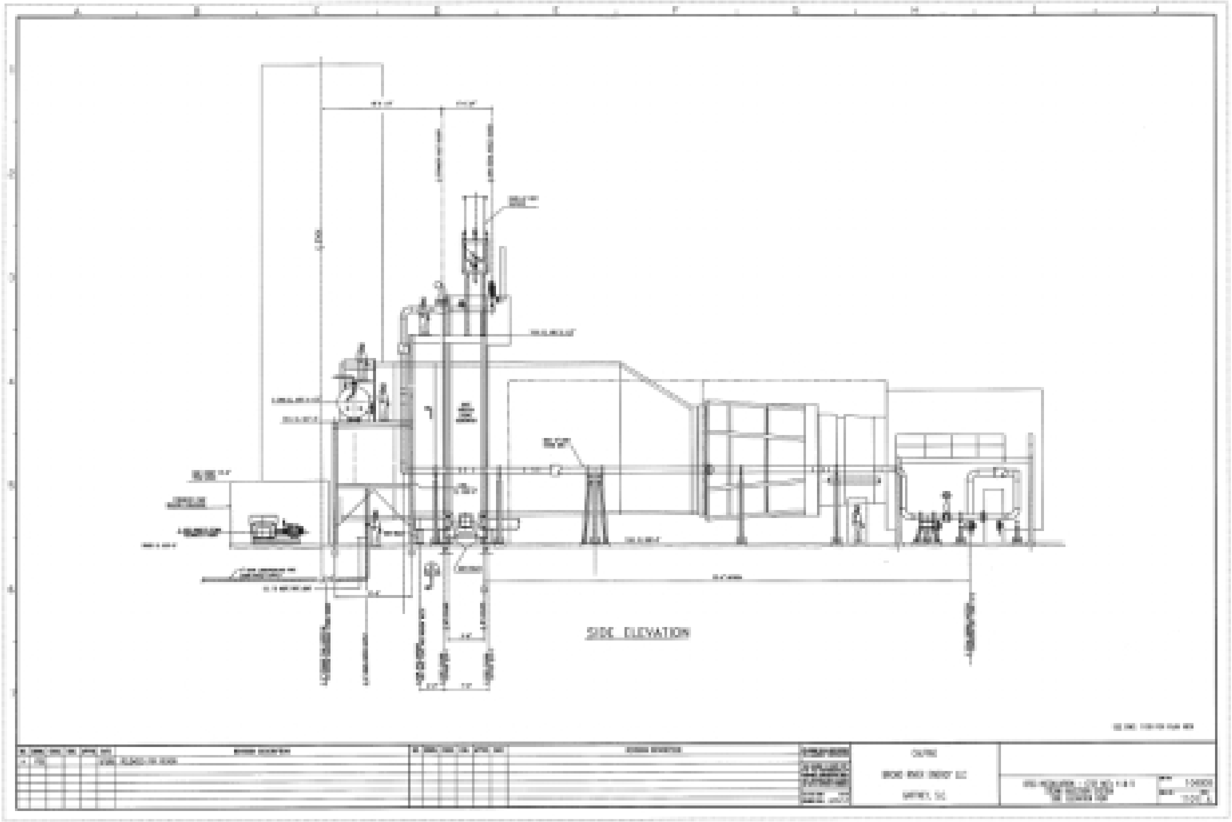


**Figure 9**:  Balance of Plant Equipment

The duration of this type of retrofit project (7FA sized) is approximately three to four weeks. The capital expense for the equipment is approximately U$2,000,000 for the GTI modules and approximately U$2,000,000 for the balance of plant equipment and installation services.

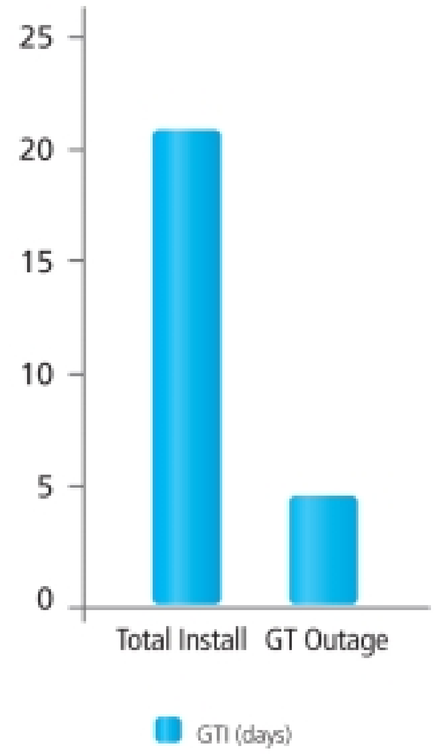


**Figure 10**:  Project Installation Time

## 4. Operational Performance:

### Startup Operation:

The GTI-OTSG heat recovery system can be started simultaneously with the start of the gas turbine or after the gas turbine is on line and fully loaded. Figure 11 illustrates the standard start-up sequence for a typical single pressure OTSG running in temperature control mode (pressure and demand control modes are also possible but are not discussed here). When the stack temperature of the OTSG reaches greater than 300 F, feed-water is admitted into the OTSG. For the first six minutes, feed-water is introduced slowly and in a controlled manner, so as to stabilize the flow in the feed-water header and avoid tube quenching.

From seven minutes to approximately fifteen minutes, the rate of feed-water introduction is increased reaching 20% of the design flow. At this point the OTSG will produce superheated steam at the same temperature as the gas turbine inlet temperature (an attemperator is used to control steam temperature to the desired temperature level). Standard practice is to hold the steam output constant at approximately 20% of the maximum flow level for several minutes. This is done to warm up the GT steam supply piping with the required length of time determined by the design of the supply piping and usually approximately ten minutes. Once the balance of plant piping is warm, the OTSG continues to ramp-up both steam pressure and feed-water flow rate.

After approximately thirty minutes of ramp time, the feed-water flow rate has reached 85% to 90% of the design flow rate. At this point the feed-water flow rate is brought into closed loop control based on the superheater steam temperature feedback signal. After a further five minutes, the temperature of the steam produced by the OTSG is in full temperature control. Full steam production is available after thirty-five minutes time.

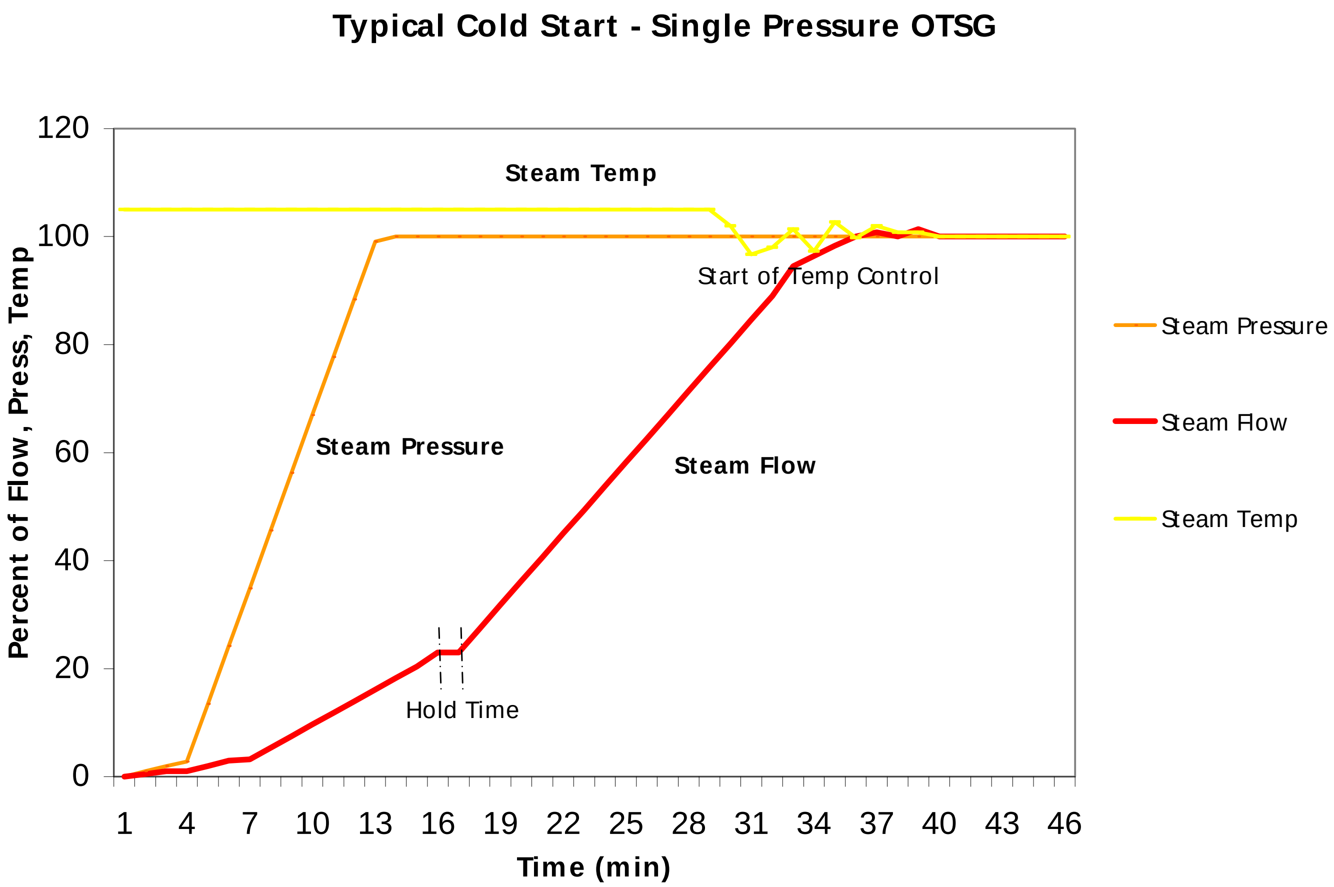


**Figure 11**: OTSG Start-up Curve for a Typical Gas Turbine

### Dry – Run Operation:

The GTI/OTSG unique ability to run dry provides the owner/developer with reduced operational risk and lower investment cost. Two stacks, extra bypass ducting and dampers are not required for the GTI/OTSG unit to run in by-pass mode. Consequently, the GTI can be cycled up and down very quickly as demand requires. When steam is not required for injection as during non-peak hours, the feed-water flow is simply turned off, and the OTSG is allowed to boil dry. Approximately, fifteen minutes later the OTSG boiler is dry and safe for dry-run operation without a fear of damage.

### Normal Operation and Control of the OTSG:

The OTSG is simple to operate and simple to control due to its single water/steam flow path and the elimination of many drum related components required for a typical HRSG. Single point control is all that is required with the feed-water flow rate being the only controlled variable. A feed-water control value driven by the plant’s DCS system is used to control the flow of feed-water entering the OTSG. Admission of feed-water into the boiler is regulated at a rate necessary to produce either the desired steam temperature, steam pressure or output load depending on the desired control protocol.

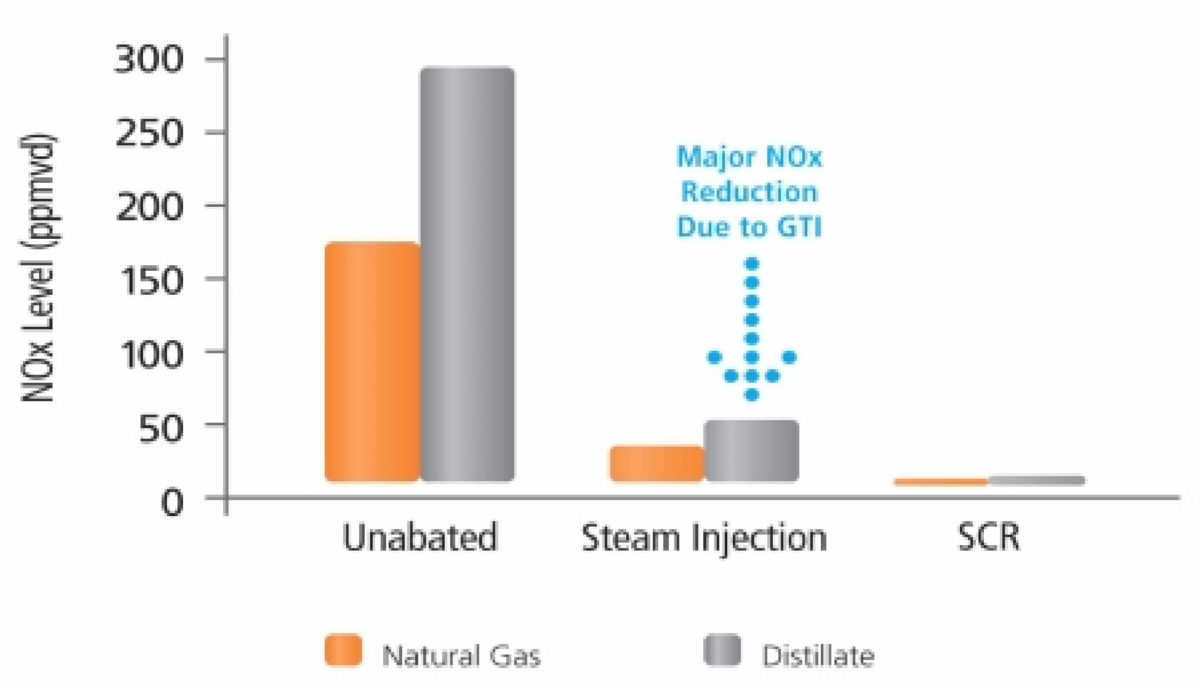
Under steady state conditions, the superheat temperature of the steam exiting the OTSG can be maintained at ± 5 degrees F of the set point. Transients are accommodated using a simple feed-forward control strategy that sets the feed-water flow to a predicted value based on turbine exhaust temperature and flow rate (please refer to figure 5). This control approach allows for precise and fast transient response across a wide range of operating conditions.

In general, increasing the feed-water flow rate will increase water mass flow and thus decrease outlet steam temperature.  Likewise, decreasing the feed-water flow rate will decrease water mass flow and thus increase the steam temperature exiting the OTSG.

Lastly, the OTSG is very flexible and can adjust to off-design points.  The superheat zone of the OTSG is free to move and can be found anywhere from the first few rows to the last outlet row. Consequently, a range of steam flows, pressures and temperatures can be accommodated to customize the performance during start-up, normal operation and for off design operation.

**NOx Control:**

Injection of steam into the gas turbine has the benefit of reducing the emissions of NOx. Figure 12, illustrates the effects of steam injection on the emissions of the gas turbine and compares it to other emission control methods. NOx emission control using steam injection can be a very cost effective method but there are limits to its control. In general, controlling NOx to the 50 ppmvd at 15% $O_2$ adjusted levels for distillate fuels and 25 ppmvd at 15% $O_2$ adjusted levels for natural gas fuels is well within its capability. If much lower levels are required then SCR and other technologies are required.



**<u>Figure 12</u>:** NOx Emission Control Methods

**Power Augmentation and Fuel Savings:**

The next major benefit that steam injection offers is its ability to deliver extra power from the owners existing install base.  Steam injection is a very flexible process which provides between five (5%) and twenty (20%) percent extra power output.  Figure 13, illustrates the relationship between the level of steam injection and the resulting power output of the gas turbine.  Shown as an example, a gas turbine with an injection rate of three point five (3.5%) percent of compressor flow, could increase its power output by an extra eight (8%) percent.  Additionally, the owner could elect to reduce fuel consumption and maintain the same nominal power output.

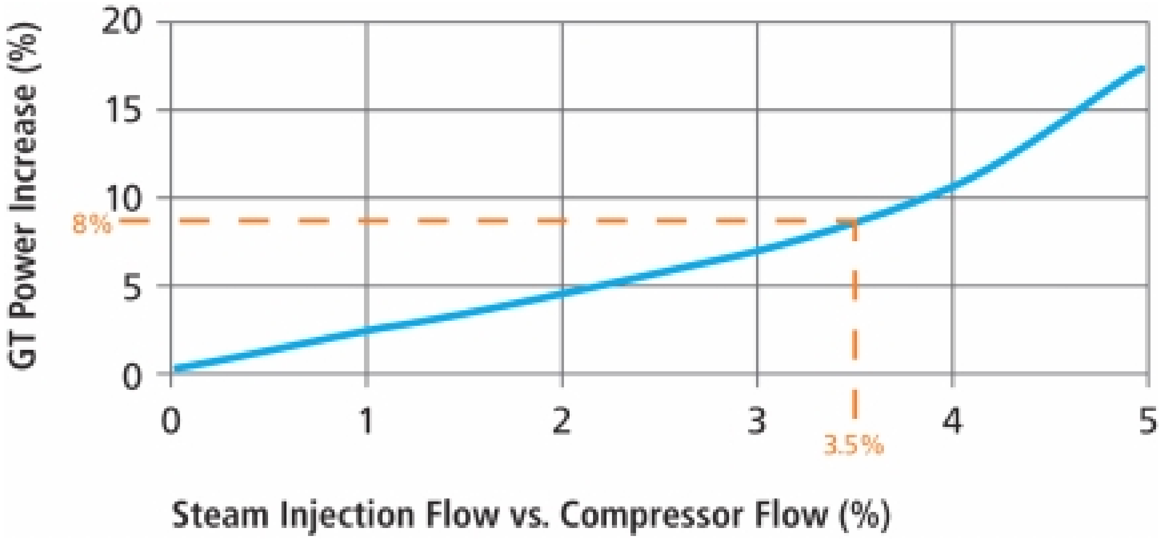


**Figure 13**:  Power Augmentation

## 5. GTI/OTSG Applications:

IST has installed GTI/OTSG heat recovery boilers on fifteen (15) gas turbines. Figure 14 illustrates the various gas turbines that GTI/OTSG units have been installed on. Our first three units were installed in Puerto Rico on three (3) ABB GT11N1 80 MW machines in 1996. These units increased the usable power from the GT11N1 by approximately 10%.

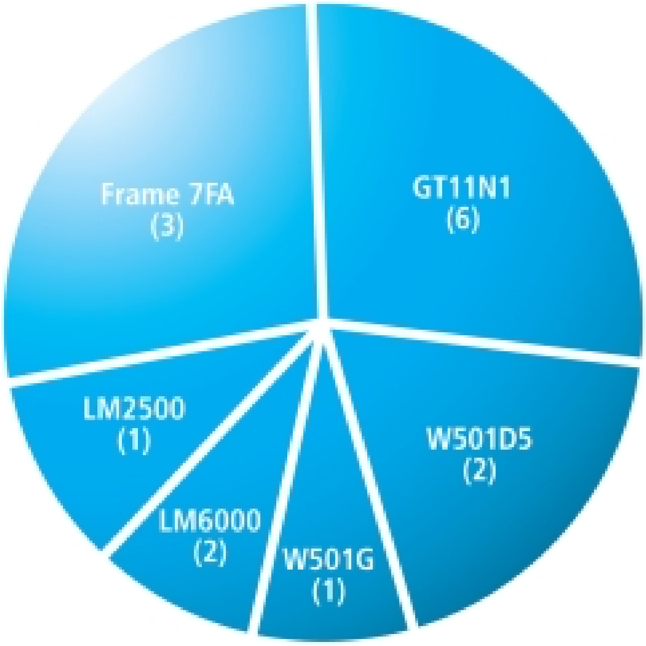


**Figure 14**: Gas Turbines with GTI/OTSG added.

In general, most frame or aero-derivative based gas turbines can be steam injected. In each case the manufacturer should be consulted. Often they have developed best methods to adapt their gas turbine to accept steam injection. Rarely are the required modifications extensive or cost prohibitive. Larger frame based units will notices better returns on the capital expenditure versus the kilowatt increase of the gas turbine ($ / KW).

## 6. Conclusion:

From the above paper, the reader can see how utilities world wide can utilize steam injection to address issues of high energy cost, high capital costs and tightening environmental legislation. Additionally, the reader has seen how steam injection can increase a plant's ability to generate extra power without burning additional fuel and doing this at a moderate capital investment.

Further the reader has seen how a Once Through Steam Generator (OTSG) can be used to provide the steam required for the STIG process. The high strength, thin walled, high temperature nickel alloy tube bundle of the GTI/OTSG steam generator is suitable for operation in the hot gas path and will provide high quality superheated steam suitable for use in their gas turbine. The GTI/OTSG has no moving parts and a minimum of instruments resulting in high uptime and low operational expenses. Additionally, operation of the GTI/OTSG was discussed, exploring the unique capabilities of the OTSG that allows for dry running, simple operation and high operational availability. Finally, the reader has seen how GTI is operationally flexible and can be used on both frame and aero-derivative gas turbines.

# 7. References:

1. **Major, B., and Powers, B**., Cost Analysis of NOx Control Alternatives for Stationary Gas Turbines. *Onsite Sycom Energy Corp Document*, May 2000.