Innovative Steam Technologies

# OPERATIONAL EXPERIENCE WITH ONCE THROUGH STEAM GENERATORS IN GAS TURBINE COMBINED CYCLE APPLICATIONS

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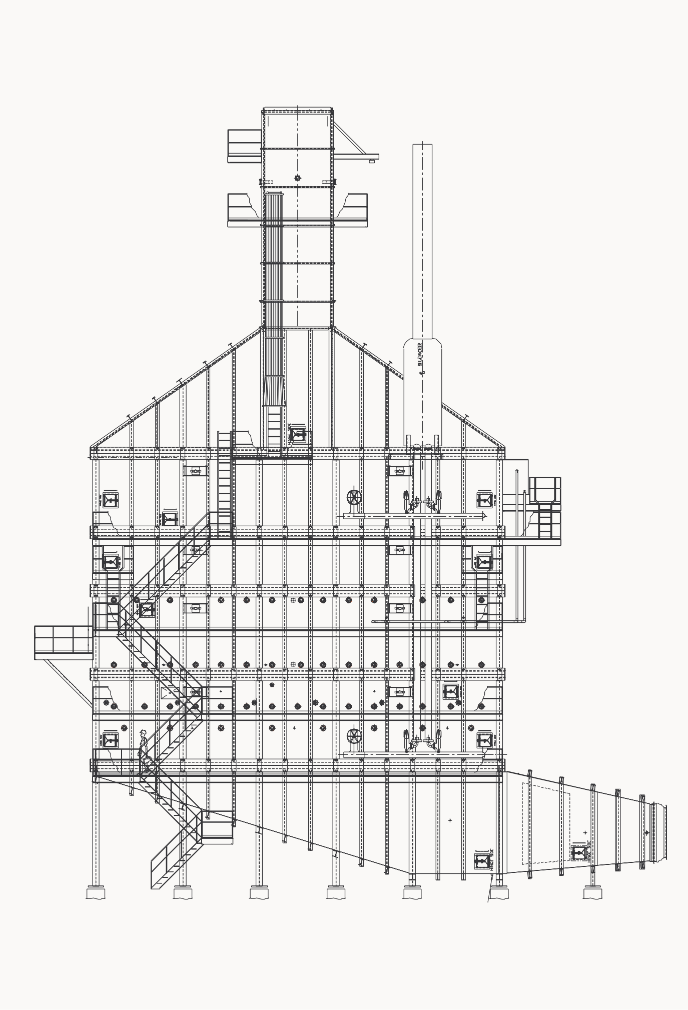

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# OPERATIONAL EXPERIENCE WITH ONCE THROUGH STEAM GENERATORS IN GAS TURBINE COMBINED CYCLE APPLICATIONS

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## ABSTRACT

Once Through Steam Generators (OTSG) have been used successfully in gas turbine combined cycle applications for all gas turbine sizes and steam cycles. Significant operational experience has been gained in the areas of all-volatile feedwater treatment, cold feedwater operation, corrosive duty applications, dry running, daily start/stop operation, transient operation and turndown.

The once-through steam generator, in its simplest form, is a continuous tube in which preheating, evaporation, and superheating of the working fluid takes place consecutively. Unlike traditional drum type HRSG's, the OTSG does not have a steam drum. Water enters at one end of the OTSG through the inlet header and exits the other end of the OTSG as superheated steam through the outlet header. Elimination of steam and mud drums (and associated water inventory) has vastly improved the fast start capabilities.

The once-through steam generator achieves dissolved and suspended solids separation external to the steam generator by pre-treatment of the OTSG feedwater. Any solids remaining in the feedwater, either suspended or dissolved, can form deposits on the OTSG tubing and/or be carried over to the steam turbine or gas turbine. Dissolved oxygen control is not a critical issue for the IST OTSG, which is made of high nickel alloy tubing. In some instances feedwater has been directly admitted into the cycle without any oxygen treatment. OTSGs have also been designed for low feedwater applications as dictated by plant design. In some applications water has been admitted to the OTSG at water temperatures as low as 59 F (15 C). Use of the high nickel tubing has also eliminated the risk of iron carryover and flow assisted erosion/corrosion associated with carbon steel or low alloy tubing.

The OTSG can be designed for dry running. Dry running refers to operation of the OTSG without any water/steam flow inside the tubing allowing tremendous operational flexibility. Should steam not be required, the OTSG can be run dry without a gas bypass stack and damper. Tube material selection and operational guidelines depend on the maximum gas temperature expected during dry running. A series of dry running tests have been conducted on OTSGs behind gas turbines operating on liquid fuel. Following soot fouling tests in which soot was accumulated on the cold section of the OTSG, cleaning tests were completed. The cleaning tests involved running the OTSG at elevated gas temperatures without feedwater flowing through the OTSG. Heat transfer performance was fully recovered by performing a dry boiler burnoff at 900 F for 100 minutes. Similar tests have been completed in an attempt to remove the corrosive products associated with SCR operation. Dry running at gas temperatures approaching 900 F followed by compressed air blasting is also successful at removing the deposits associated with SCR operation.

## CHARACTERISTICS OF ONCE THROUGH STEAM GENERATORS

The once-through steam generator, in its simplest form, is a continuous tube in which preheating, evaporation, and superheating of the working fluid takes place consecutively as indicated in Figure #1.

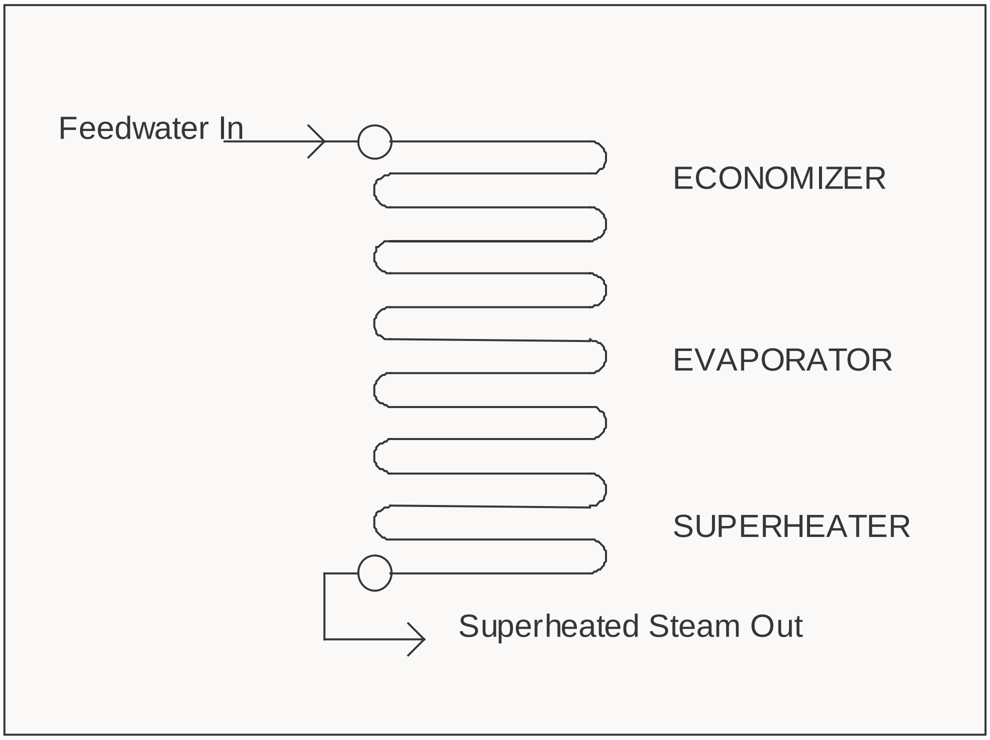


Figure #1 – Once through steam generator (OTSG)

In practice, of course, many tubes are mounted in parallel and are joined by headers thus providing a common inlet for feedwater and a common outlet for steam.  Water is forced through the tubes by a boiler feedwater pump, entering the OTSG at the "cold" end.  The water changes phase to steam midway along the circuit and exits as superheated steam at the "hot" or bottom of the unit.  Gas flow is in the opposite direction to that of the water flow (counter current flow).  The highest temperature gas comes into contact with water that has already been turned to steam.  This makes it possible to provide superheated steam.

The advantages inherent in the once-through concept can be summarised as follows:

1. Minimum volume, weight, and complexity.
2. Inherently safe as the water volume is minimized by using only small diameter tubing.
3. Temperature or pressure control are easily achieved with only feedwater flow rate regulation.
4. Complete elimination of all by-pass stack and diverter valve requirements while still allowing full dry run capability.
5. Complete modular design with inherently lower installation time and cost.
6. Operational benefits such as improved off design (turn down) efficiency

The once-through steam generator achieves dissolved and suspended solids separation external to the steam generator by pre-treatment of the OTSG feedwater.  Any solids remaining in the feedwater, either suspended or dissolved, can form deposits on the OTSG tubing and/or be carried over to the gas turbine.  Dissolved oxygen control is not a critical issue for the IST OTSG, which is made of alloy tubing.

OTSG’s can be supplied in both horizontal tube/vertical gas flow arrangements (Figure #2 and #3) as well as vertical tube/horizontal gas flow arrangements (Figure #4 and #5) to match customer requirements.

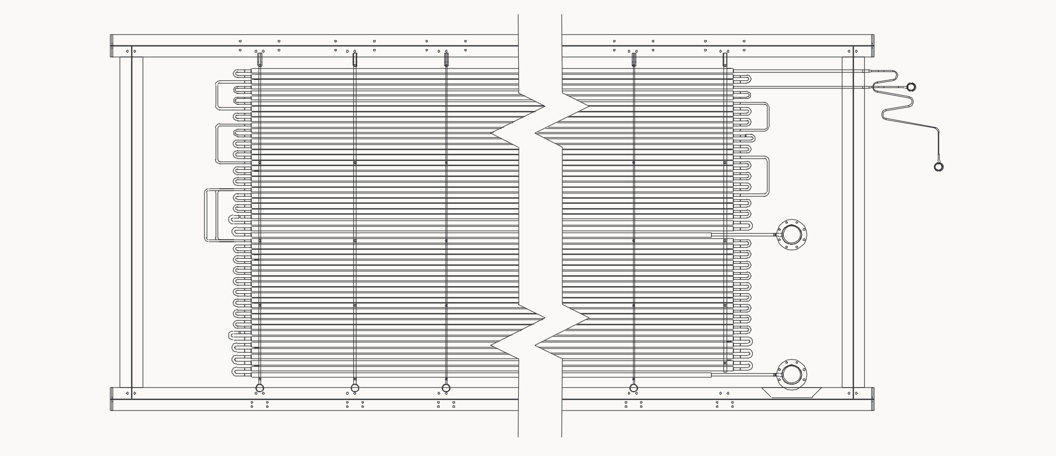


Figure #2 – Horizontal Tube / Vertical Gas Flow Arrangement

Figure #3 – Horizontal Tube / Vertical Gas Flow Arrangement
LM6000 Gas Turbine

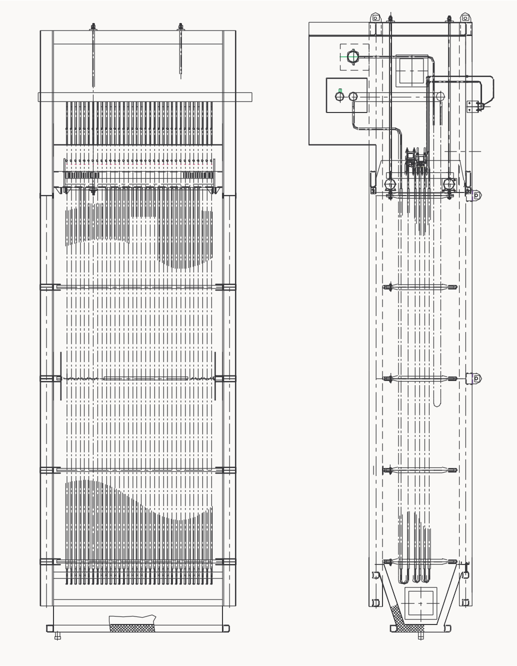


Figure #4 – Vertical Tube/Horizontal Gas Flow Arrangement

Figure #5 – Vertical Tube/Horizontal Gas Flow Arrangement
Frame 7FA Gas Turbine

Innovative Steam Technologies's OTSG's have been used for combined cycle, cogeneration and gas turbine steam injection applications. With over 85 units supplied to date internationally, a great deal of experience has been gained in the application of the OTSG to combined cycle gas turbine applications.

Specific experience regarding the following areas will be discussed in detail:

a) All Volatile Feedwater Treatment
b) Cold Feedwater Operation
c) Corrosive Duty Applications
d) Dry Running
e) Daily Start/Stop Operation
f) Transient Operation
g) Turndown

## ALL VOLATILE FEEDWATER TREATMENT

In once-through boilers, there are two available options for water treatment, all volatile treatment (AVT) and oxygenated treatment (OT). Both treatments are feedwater treatments.

All-Volatile Treatment (AVT) is used to minimize corrosion and erosion corrosion in the pre-boiler system by using deaerated high purity water with an elevated pH. The pH elevation is achieved by the addition of ammonia. The target range for pH depends upon the metallurgy of the pre-boiler system (all-ferrous or Fe-Cu mixed). The oxygen concentration in the feedwater is reduced using an oxygen scavenger, such as hydrazine or carbohydrazide. The result of AVT treatment is a layer of magnetite ($Fe_3O_4$) on all steel surfaces which protects the metal from corrosion. All of IST's OTSG's to date have used all-volatile treatment.

Oxygenated Treatment (OT) uses oxygenated high purity water to minimize corrosion and erosion-corrosion in the pre-boiler system. Oxygen, hydrogen peroxide, or air is injected into the feedwater to achieve an oxidizing environment. The pH is adjusted using ammonia, but the target pH range is lower than in AVT. The result of OT is a layer of hematite on steel surfaces which is more adherent than magnetite.

The OTSG requires demineralized and polished feedwater to eliminate solids in the feedwater, dissolved or suspended, which could be deposited in the dry-out zone or be carried over to the steam turbine /gas turbine (if steam injected). Therefore the demineralized and polished feedwater must be very low in both suspended and dissolved solids, in the area of 40 to 50 ppb (parts per billion) corresponding to a cation conductivity of 0.25 uS/cm. In combined cycle applications (no steam loss to process) a 0.1% or less makeup is commonly experienced. A system designed for 0.5% to 1.0% makeup rate provides a 5 to 10 safety factor. Application of the OTSG and air-cooled condensers can reduce the plant's needs and cost of water to a minimum.

The production of good quality feedwater is usually a function of a makeup demineralizer and a condensate polisher, although depending on system requirements, one of these items can sometimes be eliminated. Where demineralizer or polisher requirements are minimal, replacement resin bottles can minimize system capital and operating costs. This can eliminate the need for onsite acid and caustic facilities used for regeneration.

Conductivity measurement is recommended for monitoring because there is a direct correlation between dissolved solids and conductivity. For systems using ammonia/amines for pH control, it will be necessary to use cation conductivity rather than specific conductivity to monitor the steam/water quality. The purpose of the cation conductivity measurement is to remove the masking effect of the ammonia and its derivatives, in the water.

## COLD FEEDWATER APPLICATION

The thermal efficiency of steam generators is increased as the exhaust stack temperature is lowered. Using a lower feedwater temperature will result in a lower stack exhaust temperature, but admitting cold feedwater into HRSG's presents various complications such as dewpoint corrosion. During the combustion of fossil fuels containing sulfur, sulfur dioxide and sulfur trioxide are present. The sulfur trioxide combines with water vapor in the flue gas to form sulfuric acid, which will condense on components operating at temperatures below the acid dew point.

Two options exist to prevent dewpoint corrosion, preheat the incoming water above the dewpoint temperature or use corrosion resistant materials. The use of carbon and conventional stainless steel tubing limits the temperature range in which the boiler can safely and reliably operate. High nickel alloys have superior properties in respect to general corrosion and stress-corrosion cracking, which are the main limiting factors in HRSG cold end design and material selection. ASME approved SB423 NO8825 (commercially known as Incoloy 825) offers unsurpassed properties and allows the acceptance of cold feedwater in the economizer section of an HRSG. The last decade has allowed IST to generate an impressive operational record in plants where this material has been used and confirms all advanced properties claimed by their manufacturers. The composition of Incoloy 825 is as follows:

| **Incoloy 825** | **Percentage (%)** |
|---|---|
| Nickel | 38.0 – 46.0 |
| Iron | 22.0 min. |
| Chromium | 19.5 – 23.5 |
| Molybdenum | 2.5 – 3.5 |
| Copper | 1.5 – 3.0 |
| Titanium | 0.6 – 1.2 |
| Carbon | 0.05 max. |
| Manganese | 1.0 max. |
| Sulfur | 0.03 max. |
| Silicon | 0.5 max. |
| Aluminum | 0.2 max. |

Typical feedwater inlet temperatures into the steam generators are below 100 F (38 C) with some applications as low as 59 F (15 C). Due to the cold feedwater applicability of the OTSG, vacuum dearators are commonly used to achieve the required oxygen levels. Vacuum deaeration offers the following benefits:

- Reduced amount of steam (energy) required for deaeration
- Utilizes heat (steam) that would be otherwise wasted
- Located in the condenser's vicinity, the vacuum deaerator reduces and eliminates a considerable amount of piping
- Positively impacts overall plant efficiency
- Adds to the plant design flexibility (equipment layout)

## CORROSIVE DUTY APPLICATIONS

Today's HRSG's are forced to operate in increasingly severe environments. These environments may be due to oil firing, SCR integration and/or marine environments. Testing has been completed by IST to simulate some of these corrosive environments. Operating experience has confirmed these material choices.

IST's standard fin tube connection is a brazed joint as shown in Figure #6. This brazing process is used to attach either carbon steel or stainless steel fins to the tubing.

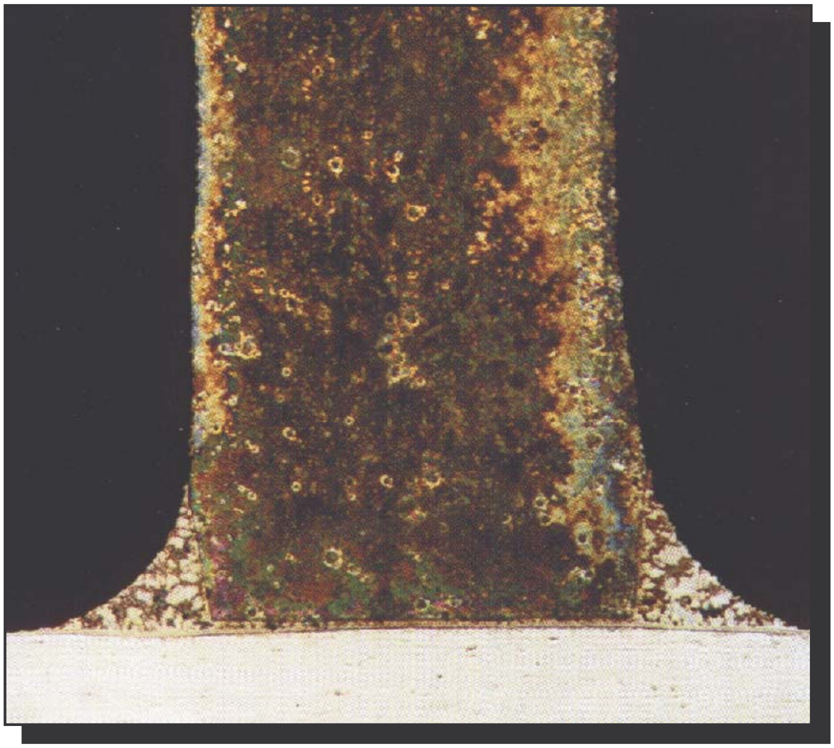


Figure #6 - Fin Tube Braze Connection

Accelerated corrosion test have been completed by IST to ensure appropriate materials are used for the pressure parts (fin, tube and braze material). An example is accelerated corrosion testing in ASTM G28-97, Method B Solution consisting of 23% $H_2SO_4$, 1.2% HCl, 1% $FeCl_3$ and 1% $CuCl_2$. Various fin/tube material combinations were used to verify applicability.

Figure # 7 - ASTM G28-97 Mixture

Figure #8 -
409SS fins / SB423 NO8825 after 48 hours

Figure # 9 -
316 SS / SB423 NO8825 after 7 days

## DRY RUNNING

Dry running refers to operation without any water/steam flowing through the inside of the tubing. The tubing used in the OTSG is not susceptible to exfoliation, which occurs with carbon steel tubes operating in a high temperature range exceeding 900 F (482 C).

During periods of no steam demand or steam system maintenance the OTSG can be run dry. This dry run capability eliminates the need for costly gas bypass dampers and exhaust stacks, which frequently contribute to increased maintenance and loss of performance. In some climates the ability to start dry allows the exhaust of the gas turbine to warm the tubes above freezing before introducing water. Loss of feedwater or any other problems with the steam system do not require shutdown of the steam turbine. Dry operation is particularly useful in the following types of power plants:

- Utilization of “waste” heat from compressor drive turbines or in a situation where the prime movers reliability cannot be compromised by the addition of a waste heat system.
- Where cogeneration systems are on the grid and have contracts to supply power as dispatched. In case of a steam system problem the gas turbine can still supply approximately 65% of the combined cycle power.
- Peaking and intermediate duty steam injected gas turbines where the gas turbine can still provide 80% to 90% of the plant capacity.

Dry running can also be used to “clean” the OTSG pressure parts by oxidizing liquid fuel soot deposits while continuing the gas turbine operation. When operated “dry”, the OTSG cleans itself in a fashion similar to a domestic self-cleaning oven by oxidizing any soot deposits that may be present. This eliminates the need for sootblowers and their steam loss, operating and maintenance costs.

The advantages of dry running have been proven in liquid fired gas turbine applications such as diesel oil. A series of tests were conducted on OTSG’s in the early 1980’s. Following soot fouling tests in which soot was accumulated on the cold section of the OTSG, cleaning tests were completed. The cleaning tests involved running the OTSG at elevated gas temperatures without feedwater flowing through the OTSG. Dry running tests were run at 840 F for 60 minutes and 900 F for 60 minutes and 100 minutes. Heat transfer performance was fully recovered by performing a dry boiler burnoff at 900 F for 100 minutes. IST currently has a number of OTSG’s operating successfully behind liquid fuel fired gas turbines.

Similar tests have been completed in an attempt to remove the corrosive products associated with SCR operation. While gas temperatures of 800 F to 1000 F were used in the testing, current limitations of medium temperature SCR catalysts are in the range of 870 F to 900 F.

Finned tubes were manually covered in mixtures of ammonium sulphate. The tubes were photographed before exposure, after exposure and after blowing with compressed air to remove loose deposits. Compressed air is used in lieu of water washing to eliminate the concern of corrosive mixtures depositing on the surfaces below the SCR housing.

Figure #10 shows photographs of tubes coated with ammonium sulphate before exposure for four hours at 900 F, after exposure and after blowing with compressed air.

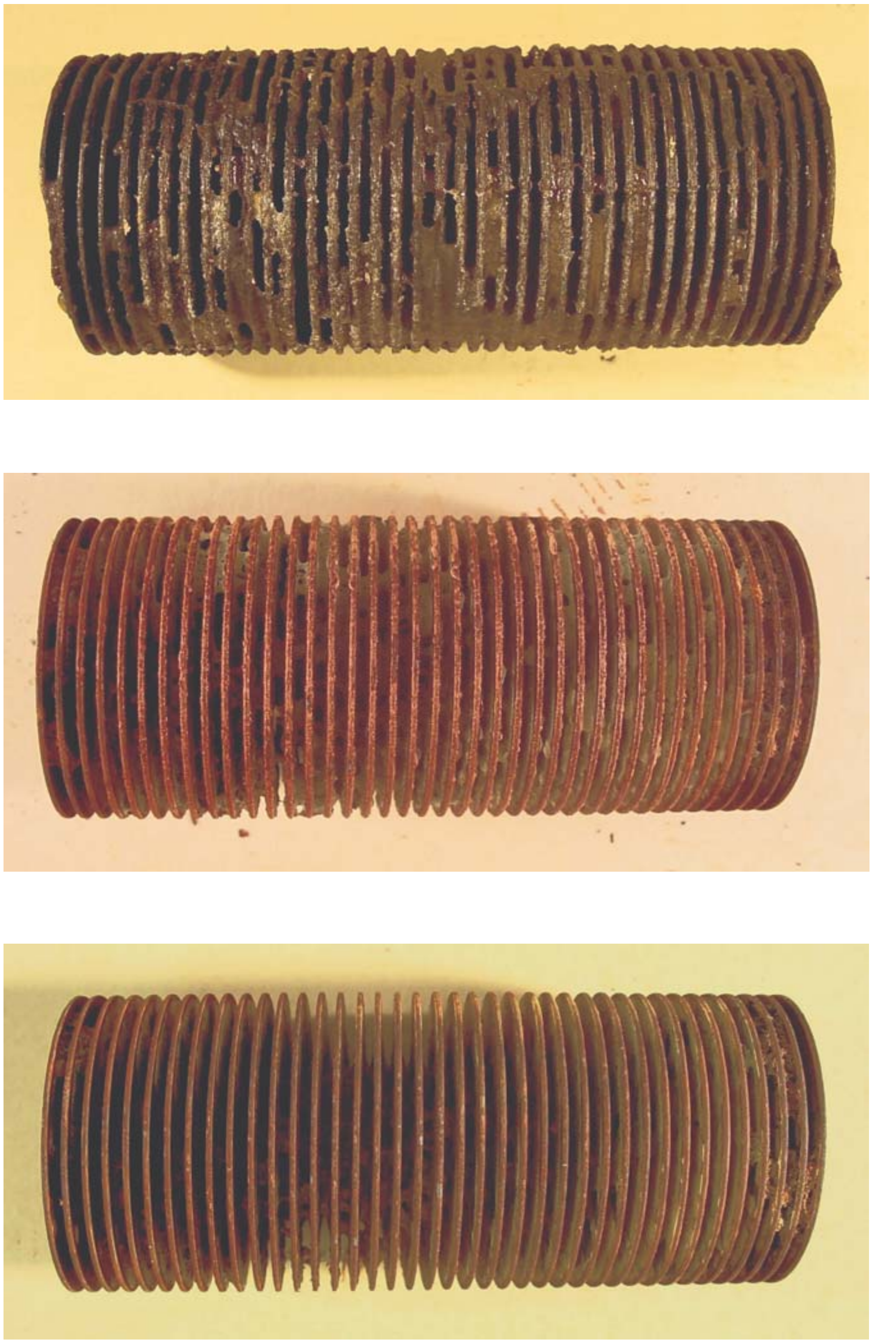


Figure #10 - Tube coated with ammonium sulphate, after heating at 900 F for four hours and after blowing with compressed air.

Heating the tubes to 900 F for a period of up to four hours followed by blowing with compressed air appears capable of removing the bulk of the ammonium sulphate deposits.

Below is a photograph of an exhaust stack from a unit during a dry cleaning run. This specific OTSG system is a liquid fuel fired gas turbine with an SCR and a feedwater inlet temperature of approximately 70 F. The plume of smoke can be seen escaping from the exhaust stack.

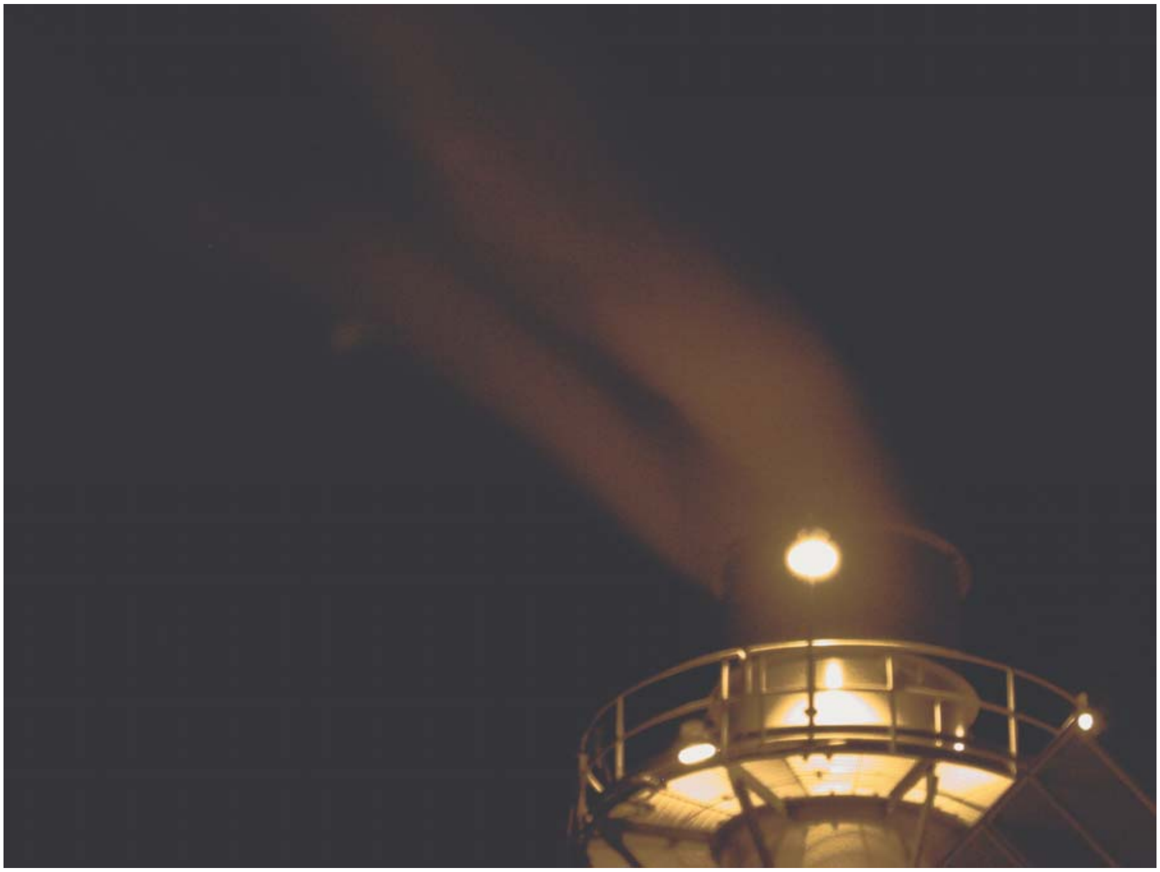


Figure #11 – Exhaust Stack of an OTSG During Soot Cleaning

## DAILY START / STOP OPERATION

Traditional drum type HRSG’s rely on circulating water in the evaporator section to produce steam. Circulation ratios (ratio of water mass flow entering the evaporator circuit to steam mass flow leaving) vary between natural circulation and forced circulation units. In forced circulation units, the circulation ratio is kept to a minimum to reduce circulating pump power losses while still maintaining adequate water velocity in the tubing. In the OTSG, there is no water circulation and the water inventory is much less than either the forced circulation or natural circulation units. Water volume is typically one-eighth to one-tenth that of a conventional drum-type HRSG.

As a result of this water inventory, traditional HRSG’s respond slower to transients. The OTSG contains significantly less water than a drum type unit during operation. In fact the OTSG is started dry, therefore the unit does not have to wait until the large volumes of water contained within the drum heats and begins to evaporate as in traditional HRSG’s. This gives the OTSG the ability to achieve very fast startups.

Unlike conventional HRSG’s, OTSG's do not have steam drums, mud drums or interconnecting piping. The elimination of these components reduces the heat accumulation of the OTSG and the thermal lag associated with them. The tubing used in the OTSG is made of high nickel alloy tubing capable of exposure to high temperatures as per Section I of the ASME Boiler Code. The increased strength allows the small diameter tubing 0.75-inch to 1.25-inch diameter tubes (19 mm to 32 mm diameter) to be supplied in wall thicknesses generally ranging from 0.049 inch to 0.065 inches thick (1.2 mm to 1.7 mm). The OTSG’s small diameter tubing, lack of drums and interconnecting piping results in the OTSG being approximately 60 percent of the weight of traditional HRSG’s.

Dual pressure OTSG’s can be brought on-line to controlled steam conditions in less than 60 minutes for either cold start or hot start applications. For daily cycling applications with SCR’s, the SCR and associated ammonia system can be brought on-line in less than 10 minutes.

A typical cold start-up curve is provided in Figure #12.

To minimize the thermal shock to the OTSG during start-up, the feedwater flow should be initiated as soon as the recommended minimum gas temperature is sensed in the OTSG and before the gas turbine has stabilized at full power. Typically, a threshold temperature is established for the exhaust gas exiting the OTSG. When this temperature is attained, the main steam line drain valves are opened, and the HP low flow feedwater control valve is ramped open slowly.

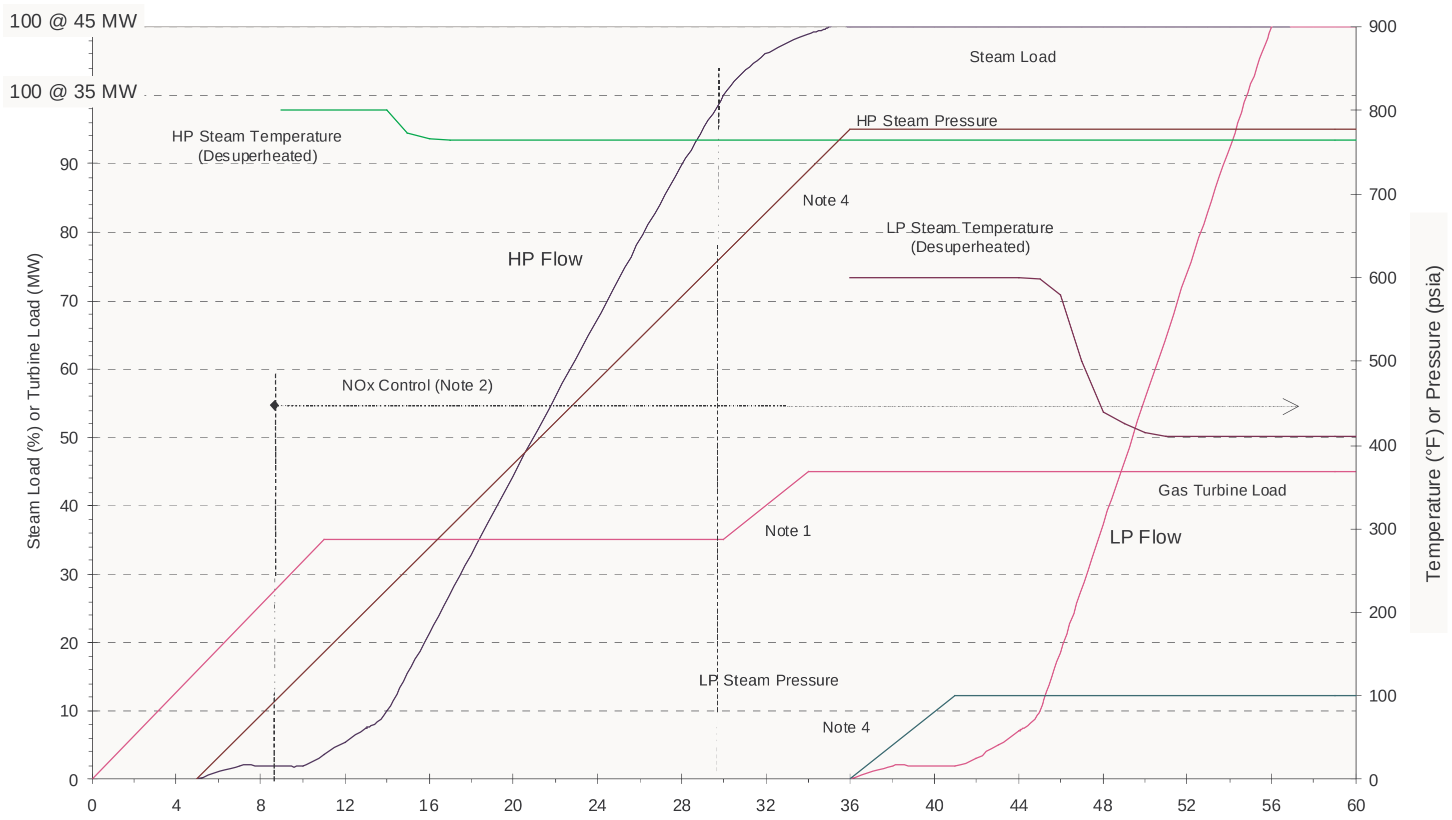
Certain permissive conditions must be met prior to starting the OTSG. These permissives ensure there is sufficient heat in the OTSG for steam generation.

- Confirm that the OTSG gas inlet temperature > 500 F (260 C)
- Confirm OTSG stack temperature > 350 F (180 C)

As water is first admitted to the OTSG, the steam being produced will be very near the turbine exhaust gas temperature at the inlet plenum of the OTSG. In the absence of an outlet attemperator, the steam temperature can only be controlled when the steam production has reached near full steaming capacity. Once this point is reached, varying the feedwater flow rate into the OTSG controls steam temperature. Increasing feedwater flow will decrease outlet temperature and vice versa.

Full controlled steam flow for both the HP and LP sections can be attained within approximately 60 minutes from initiation of the gas turbine ramp. With the use of an outlet attemperator, controlled steam can be provided to the plant after attaining approximately 10% of the full, unfired steam flow. This occurs around ten minutes into the startup.

**Typical Start Up (Hot or Cold Start)**



Notes:
1. GT Ramp will be based on maintaining a pre-determined gas temperature into SCR. OTSG water flow is ramped as GT load increases (Maximum ramp rate is 6% / minute).
2. Ammonia can be injected once gas temperature entering SCR exeeds 500°F.
3. Time 0 is GT ramp start
4. HP & LP steam pressure rise at a rate of 25 psi / minute max

Figure #12 – Typical Dual Pressure OTSG Startup Curve

## TRANSIENT OPERATION

The success of IST's OTSG during transient operation is based on overall system simplicity. This carries over into the control system as well. For a typical dual pressure OTSG, there is a single controlled analog output to the feedwater flow control valve, which modulates feedwater flow rate to obtain the desired superheated steam outlet temperature or outlet pressure. Normal operation will be at a steam outlet temperature or steam pressure set point.

The goal of the control system is to generate as much energy from the gas turbine exhaust heat as possible, while limiting the maximum steam temperature to a value, which can be tolerated by the steam process. To provide both rapid response to gas turbine load transients and accurate control of steam temperature, a dual element control is recommended. The two elements consist of a predictive, or feed forward element, and a trim, or feedback portion. The two command signals are summed to obtain the total feedwater flow command signal.

During steady state gas turbine operation, feedwater flow rates are adjusted via feedback control loops, which maintain the superheated steam temperatures at the desired set point. This set point may be constant or a function of incoming gas temperature.

Algorithms are provided for the feedforward element. During load transients (load swings), the predictive element is used to keep the feedwater flow rate properly matched to the heat input from the gas turbine exhaust gas. By measuring the temperature of the exhaust gas entering the OTSG, predicting the stack gas temperature (by algorithm), and using the supplied exhaust gas mass flow rate (provided by the gas turbine manufacturer), the quantity of heat available in the engine exhaust is calculated. A heat balance is then performed on the OTSG to determine the predicted steam production at the new gas turbine operating condition. The feed forward term sets the amount of feedwater to be admitted to the OTSG.

The feed forward control substantially reduces excursions in steam temperature that would otherwise occur during gas turbine load transients.

The steam temperature feedback control discussed above has proportional plus integral control with a low proportional gain to reduce the influence of the temperature error signal during transients and to provide accurate steam temperature control during steady state operation. The feedback command signal is generated by the error signal between the measured steam outlet temperature and the steam temperature set point.

The feed forward and feedback commands are summed in an integral controller, which generates the feedwater valve position command signal. This valve position command signal is typically a 4-to-20-milliamp signal to the feedwater valve. The measured flow rate is fed back for comparison to the feedwater flow command signal.

A typical flowsheet for a dual pressure, unfired OTSG is shown in Figure #13.

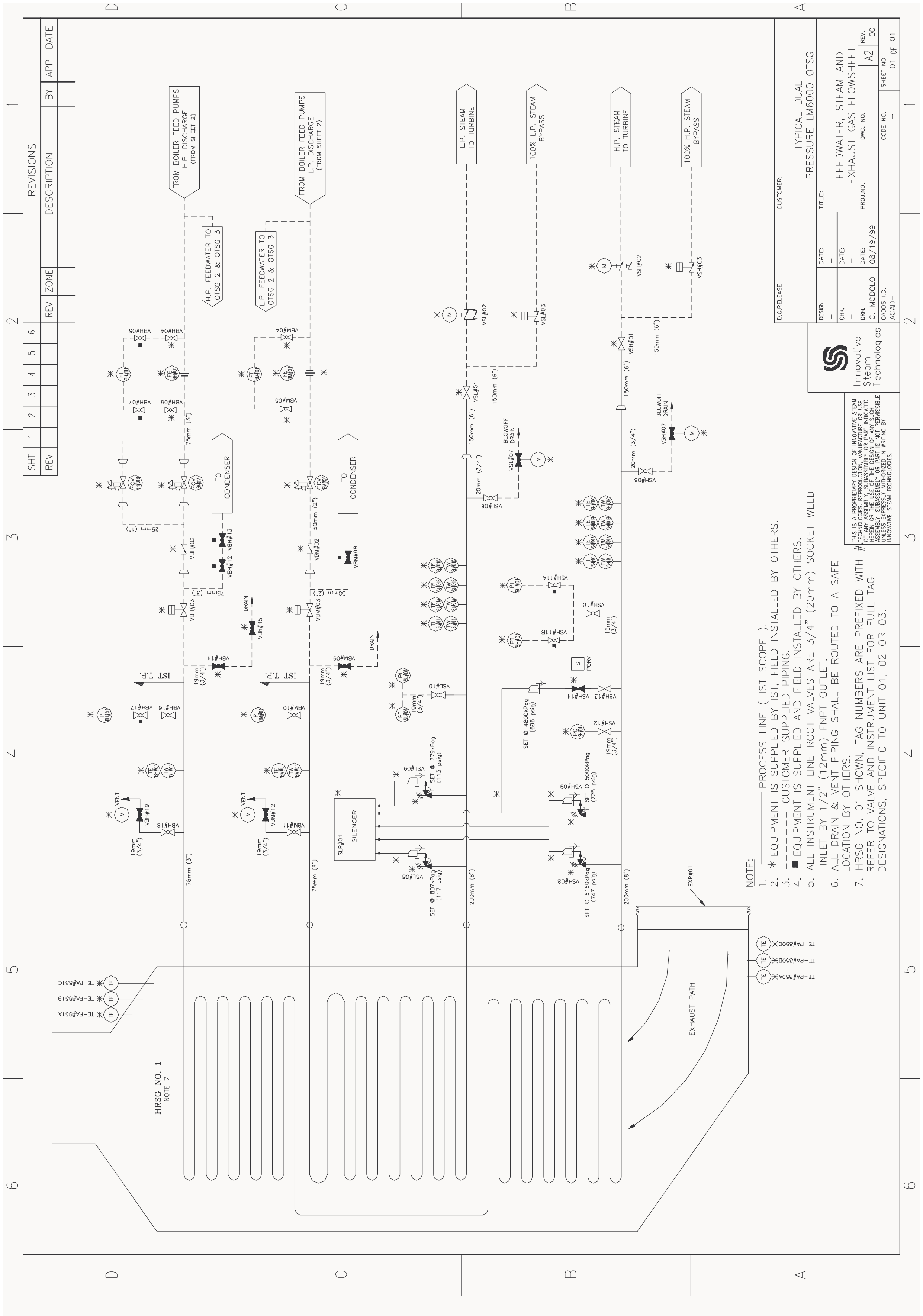


Figure #13 – OTSG Flowsheet

## PART LOAD OPERATION

Unlike traditional natural circulation or forced circulation HRSG's, the OTSG does not have a steam drum. Water enters at one end of the OTSG through the inlet header and exits the other end of the OTSG as superheated steam through the outlet header. The evaporator section is free to move throughout the bundle depending on the operational load. In traditional natural circulation (Figure #14) or forced circulation HRSG's, the steam drum forms a distinct boundary between the economizer, evaporator and superheater.

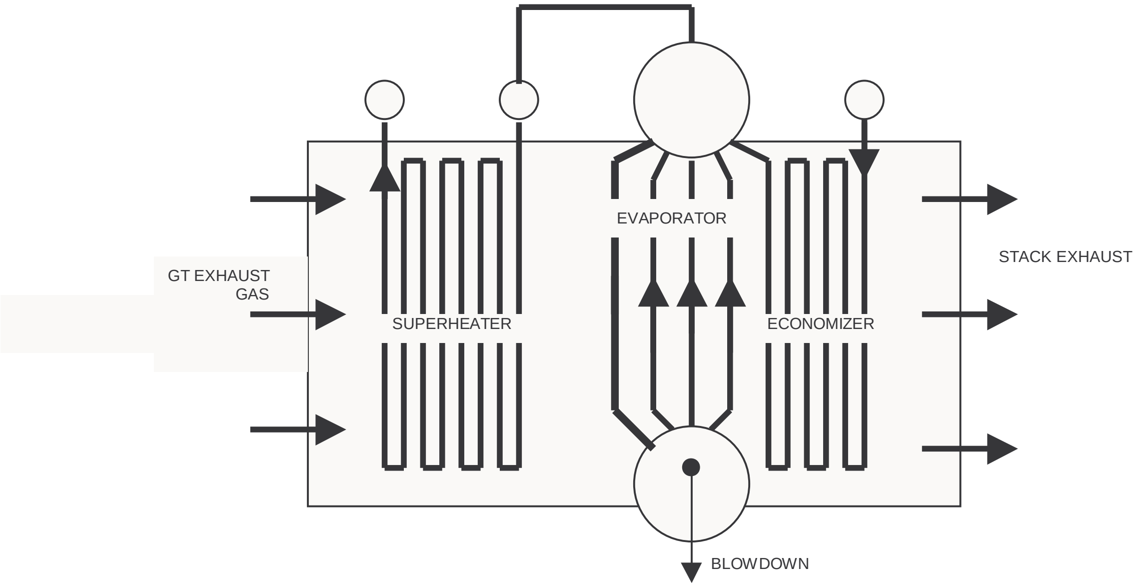


Figure #14 Drum -Type HRSG

Without a boundary for the steam generator, there is ultimate flexibility in steam production levels. This allows the OTSG to vary water/steam flow to maintain the required gas temperature entering the SCR catalyst section at off load cases.

This flexibility is indicated with the table below. Table #1 illustrates the ability of the gas temperature at a section of the OTSG to be controlled by modulating feedwater flow. This table specifically looks at the case of maintaining a constant gas inlet temperature at the face of an SCR in a single pressure OTSG.

|  | Fired Full Load | Unfired Full Load | Unfired Part Load |
|---|---|---|---|
| Exhaust Gas Flow (lb/hr) | 1,112,400 | 1,112,400 | 1,112,400 |
| Gas Temperature (F) | 839 | 839 | 839 |
| Duct Firing Temperature (F) | 1022 | N/A | N/A |
| Stack Temperature (F) | 316 | 332 | 346 |
| Steam Flow (lb/hr) | 200,409 | 139,750 | 119,000 |
| Steam Outlet Temperature (F) | 475 | 475 | 759 |
|  |  |  |  |
| Gas Temp Into SCR (F) | 690 | 613 | 694 |
|  | See Figure #15 | See Figure #16 | See Figure #17 |

Table #1 – Load Comparison for OTSG

For a fixed gas turbine load the OTSG can operate at part load conditions without the requirement for gas or steam bypassing. By throttling back the feedwater flow to the OTSG and desuperheating at the outlet header, the OTSG can adapt to wide load swings.

Assume the SCR is located in the OTSG bundle based upon the full load fired point of operation. The SCR would be located at a gas temperature of approximately 690 F where the SCR will operate at maximum efficiency (Figure #15).

During unfired full load operation, the SCR will now be located in a gas temperature zone of approximately 613 F (Figure #16), which is not at the maximum efficiency of the SCR. By reducing water flow to the OTSG, the gas temperature at the SCR can be increased to the maximum efficiency temperature of approximately 694 F (Figure #17).

The capability to modulate the feedwater flow and the ability of the evaporator to float throughout the tube bundle allows the OTSG to adapt to a variety of part load conditions without a requirement for a gas turbine bypass or steam bypass.

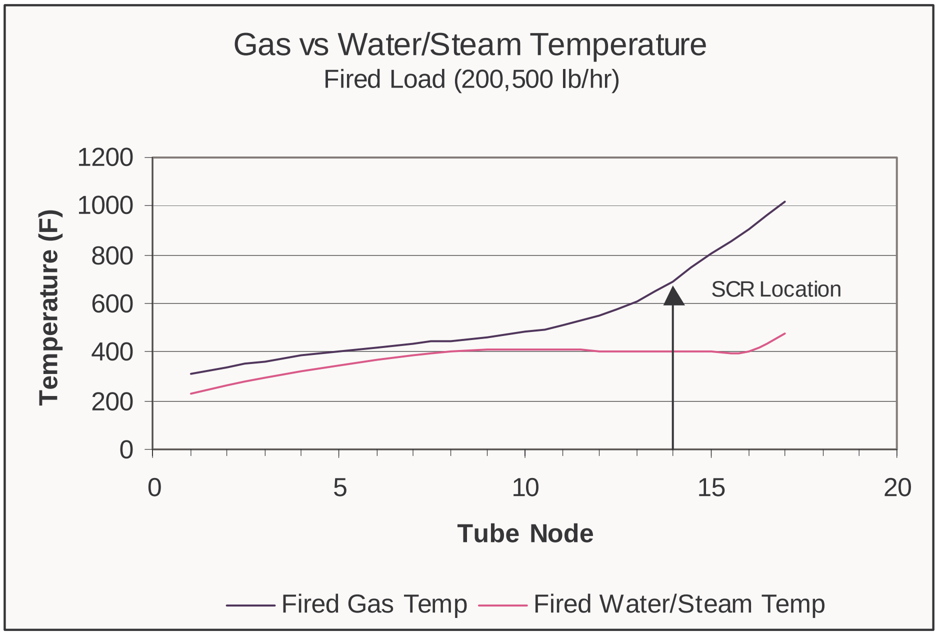


Figure #15 – Fired Full Load Operation

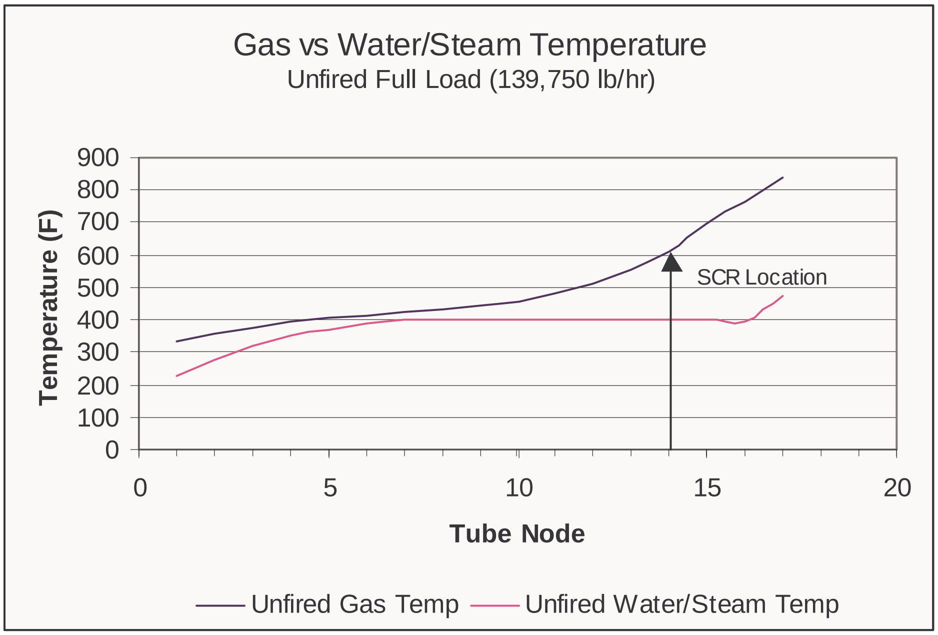


Figure #16 – Unfired Full Load Operation

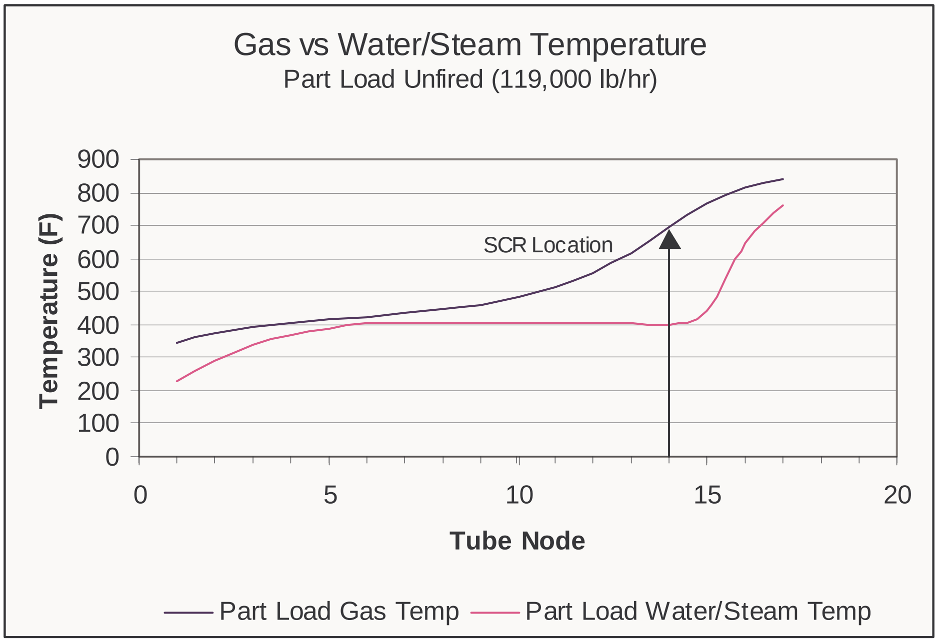


Figure #17 – Unfired Part Load Operation

## SUMMARY

The OTSG has successfully been applied to gas turbine combined cycle power plants. The many advantages inherent in the OTSG design are currently being leveraged at more than 85 installations internationally. Significant operational experience has been gained in the areas of all-volatile feedwater treatment, cold feedwater operation, corrosive duty applications, dry running, daily start/stop operation, transient operation and turndown.