Innovative Steam Technologies

TRANSIENT BEHAVIOUR OF ONCE THROUGH HEAT RECOVERY STEAM GENERATORS

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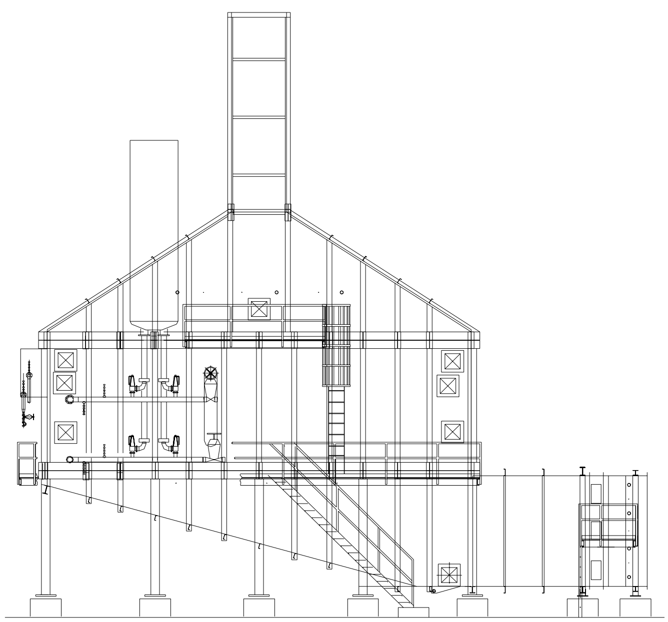

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ABSTRACT

Once through heat recovery steam generators (OTSG's) are being used in many applications worldwide, which require quick response times, such as those encountered in daily start/stop operation or gas turbine steam injection.

The ability of a steam generator to respond to transient loads depends on three criteria:
a) The position of the boundaries of the steam generator sections.
b) The filling mass, or water/steam inventory, of the steam generator.
c) The capacity of heat accumulation of the steam generator.

a) Boundaries

In natural or forced circulation HRSG's there are definite boundaries for the economizer, evaporator and superheater sections as dictated by the steam drum. As the boundaries (dimensions and surface area) are fixed, the flexibility of the steam generator is set and the steam temperature and/or pressure will fluctuate during the transient.

In OTSG's, there are no distinct boundaries. During the transient, the economizer, evaporator and superheater are free to move throughout the steam generator allowing stable steam outlet temperatures through a wide range of loads.

b) Filling Mass

The filling mass (mass of water and steam contained in the steam generator) for a natural or forced circulation HRSG boiler is much greater than the OTSG. Steam drums, interconnecting piping and large diameter tubes hold a considerable mass of water, which must be heated or cooled.

The OTSG does not have steam drums and uses smaller diameter tubes resulting in a reduced water/steam volume. This reduced volume allows for faster startup and improved response to thermal transients.

c) Heat Accumulation

In natural or forced circulation HRSG's, the majority of the heat accumulation is in the thick walled drums, tubing and interconnecting piping. This makes natural and forced circulation HRSG's thermally sluggish.

The OTSG does not have a steam drum or interconnecting piping and is fabricated from thin wall tubing, minimizing the residual heat in the steam generator.

OTSG Controls

The OTSG is unique in that it is controlled with a patented combination of feedforward and feedback controls. While the feedback controller is modulating the feedwater flow to maintain the steam temperature (or pressure) set point, the feedforward is constantly calculating the incoming gas energy to predict stable steam flows. This feedforward signal adjusts the feedwater flow rate at the instant a change in gas flow or temperature is sensed.

Innovative Steam Technologies has monitored the transient behavior of several OTSG's in the field during start up, shut down and other transient conditions associated with combined cycle and gas turbine injection applications. The transient response of the OTSG will be detailed using field data accumulated through years of successful operation.

NOMENCLATURE

OTSG - Once through steam generator
HRSG - Heat recovery steam generator
Economizer – gas to single-phase water heat exchanger
Evaporator – gas to two-phase water/steam heat exchanger
Superheater – gas to single-phase steam heat exchanger
SCR – Selective Catalytic Reduction
NOx – Nitrous oxides
DCS – Distributed Control System
Attemperator – Apparatus for reducing and controlling the temperature of a superheated fluid passing through it. This is accomplished by spraying high purity water into a steam pipe.

INTRODUCTION

Due to recent trends in the power generation industry such as deregulation, HRSG's are being required to operate differently to meet the owner's needs. Operation modes such as daily start/stop, peaking or load following are commonplace today to meet dispatching requirements. The transient response and cycling capability of steam generators must be considered for successful long-term operation of modern power stations.

Two types of HRSG's are most commonly used in the world today– vertical tube/horizontal gas flow/natural circulation and horizontal tube/vertical gas flow/forced circulation HRSG's. Both of these types of HRSG's are limited in their transient response characteristic by the defined boundaries for the economizer, evaporator and superheater sections, the amount of water/steam inventory and the thick walled components such as the steam drum. The OTSG is unique in that it produces steam without the use of a drum. While reducing the water inventory, the lack of a drum also allows the boiling section of the OTSG to move freely throughout the tube bundle as dictated by the operating condition.

The OTSG may be the only option for long-term reliability when quick transient responses are required.

CALCULATION OF TRANSIENT RESPONSE

The laws of the conservation of mass and energy dictate the transient response of steam generators. Simplified equations are provided below.

$W_s – S_d = d/dt\,(W_{in})$ ………. (1)
$Q_s – Q_d = d/dt\,(Q_{in})$ ……….. (2)

where:
W_s – quantity of water supplied to the steam generator
Q_s - quantity of heat supplied to the steam generator
S_d – quantity of steam delivered from the steam generator
Q_d – quantity of heat delivered from the steam generator
W_{in} – quantity of water in the steam generator
Q_{in} – quantity of heat in the steam generator

$Q_{in} = (M_m c_m t_m + M_w c_w t_w + M_s C_s t_s)$
M - mass
C – specific heat
m – metal
w – water
s – steam

Response time is dependant on the water/steam inventory and quantity of heat in the steam generator.

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.

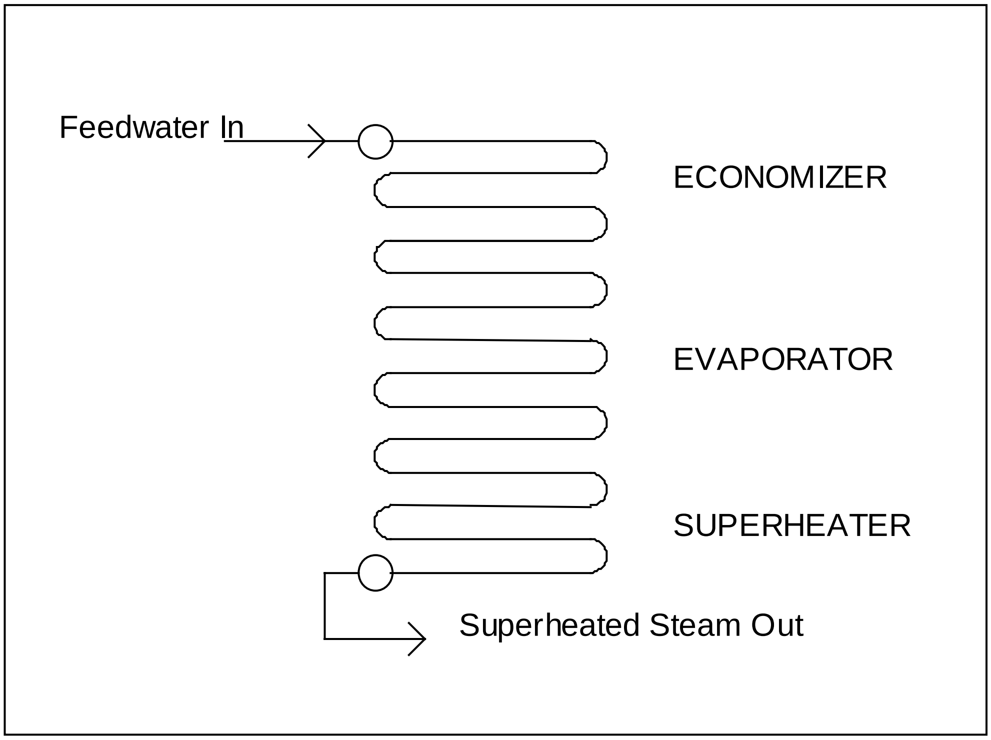

Figure #1 – Once through steam generator (OTSG)

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.

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 process. Dissolved oxygen control is not a critical issue for the IST OTSG, which is made of alloy tubing.

OTSG's have been supplied in both horizontal tube/vertical gas flow arrangements (Figure #2) as well as vertical tube/horizontal gas flow arrangements (Figure #3) to match customer requirements.

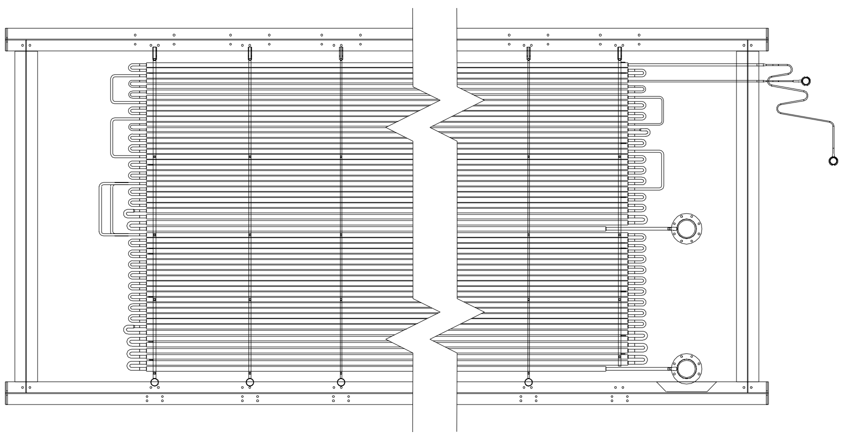

Figure #2 – Horizontal Tube/Vertical Gas Flow Arrangement

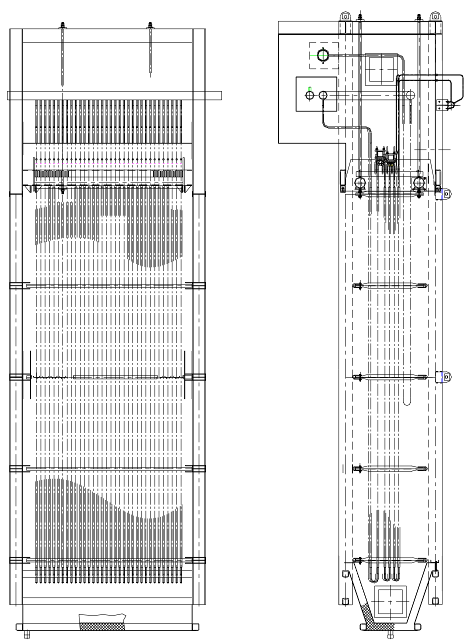

Figure #3 – Vertical Tube/Horizontal Gas Flow Arrangement

BOUNDARIES

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 #4) or forced circulation HRSG's, the steam drum forms a distinct boundary between the economizer, evaporator and superheater. This limits the flexibility of load following for the steam generator.

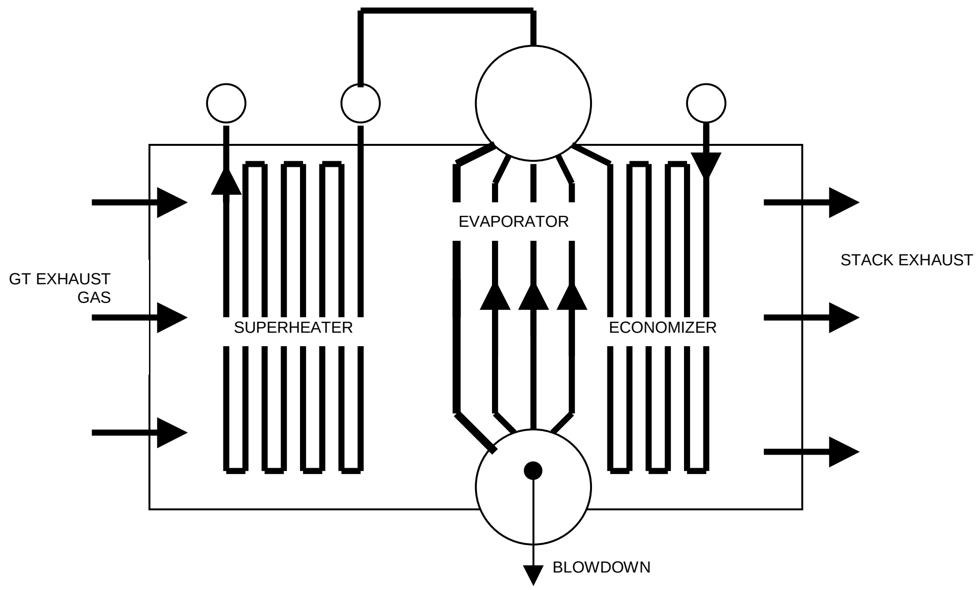

Figure #4 Drum -Type HRSG

Without a boundary for the steam generator, there is no concern of producing steam in unwanted sections as is the case with drum type HRSG's. At different loads the economizer outlet temperature can approach the drum saturation temperature. If this occurs, the economizer is referred to as "steaming". Economizer steaming can lead to water hammer or steam blanketing. Steam blanketing of an economizer can lead to corrosion failure, expansion problems or performance degradation. Other problems associated with part load operation can be reduced steam temperature that can adversely affect operations of the steam turbine.

Alternatively, the OTSG provides maximum flexibility for load swings. The evaporator section is allowed to float through the steam generator depending on steam demand. Table #1 illustrates the ability of the evaporator section of a single pressure OTSG to float through unfired, fired and part load conditions.

	Unfired Full Load	Unfired Part Load	Fired Full 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)	N/A	N/A	1200
Stack Temperature (F)	332	544	309
Steam Flow (lb/hr)	139,750	70,000	255,000
Steam Outlet Temperature (F)	475	839	475
Total number of tube rows	32	32	32
Number of economizer rows	10	2	14
Number of evaporator rows	18	2	16
Number of superheater rows	4	28	2
	See Figure #5	See Figure #6	See Figure #7

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. From full-unfired load to part load, the evaporator rows are reduced from 18 rows to 2 rows. As the OTSG transitions to full fired load the evaporator section again increases. If fixed economizer, evaporator and superheater sections were provided; these wide swings in load would not be possible. The unfired full load, unfired part load and fired full load conditions are also illustrated in Figure #5, Figure #6 and Figure #7 respectively.

It can be seen that the evaporator section is freely allowed to float. With an outlet attemperator the final steam temperature of 475 F can be maintained at all loads.

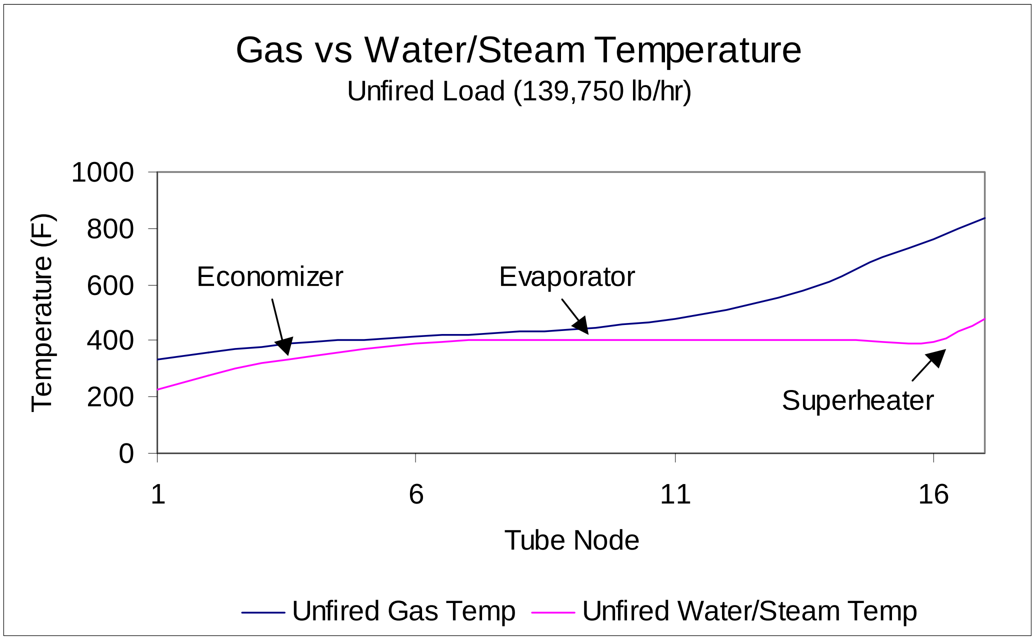

Figure #5 – Unfired Full Load

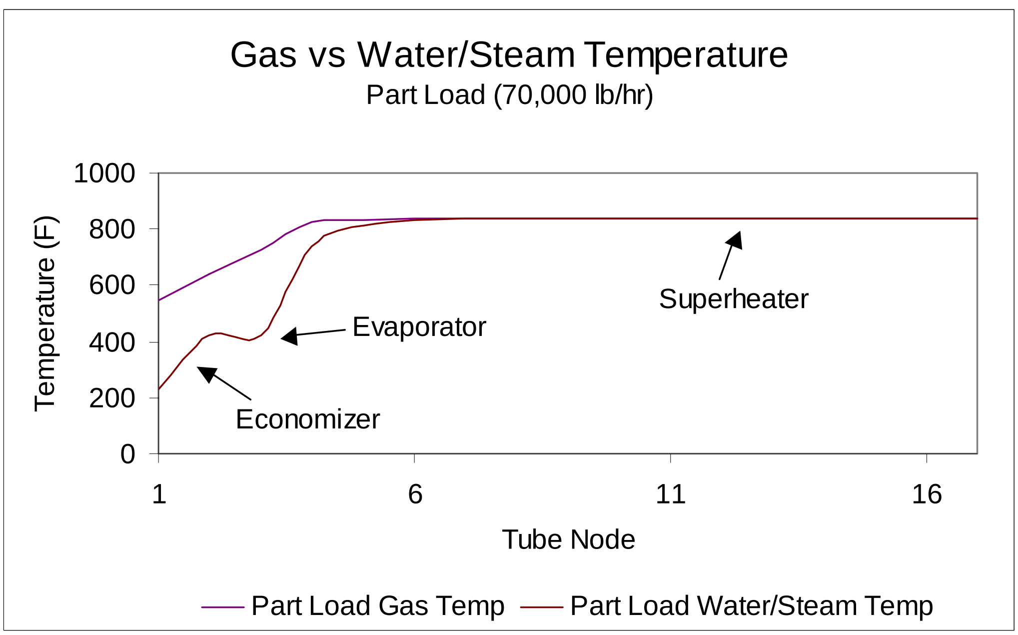

Figure #6 – Unfired Part Load

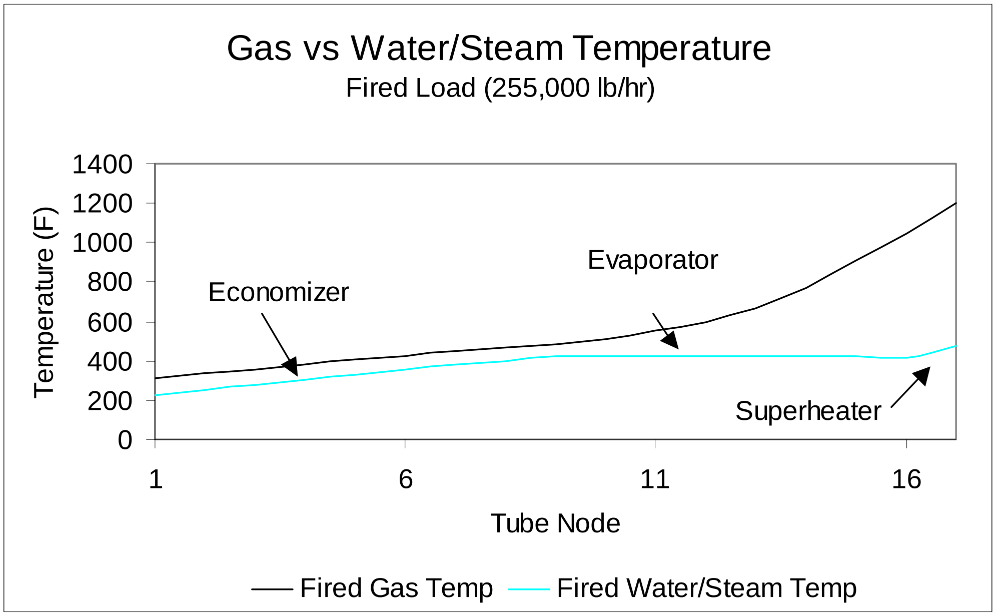

Figure #7 – Fired Full Load

FILLING MASS

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. This circulation ratio can range from 2 to 25 depending on the operating pressure of the evaporator. In natural circulation units, the circulation ratio ranges from 6 to 30 depending on evaporator pressure. 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.

HEAT ACCUMULATION

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 SB423 NO8825 and SB407 NO8800 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.

CONTROL OF ONCE THROUGH STEAM GENERATORS

The elimination of drums also simplifies the control of OTSG's. Traditional problems of drum level shrink or swell with potential for scaling and carryover are eliminated in fast startup transients.

The success of IST's OTSG and steam system 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 analogue 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. This is shown schematically in Figure #8. 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.

Algorithms with constants to fit curves which reflect the OTSG's performance are generated by IST. Some of the factors and terms of the algorithms are measured and others are calculated by the DCS as sub-algorithms. Measured parameters include; steam temperature, steam pressure, turbine exhaust gas temperature, feedwater temperature, and feedwater flow rate. Calculated values include: predicted stack temperature, gas specific heat, steam temperature set point and steam enthalpy. Gas mass flow calculation or measured parameter is provided by the gas turbine manufacturer.

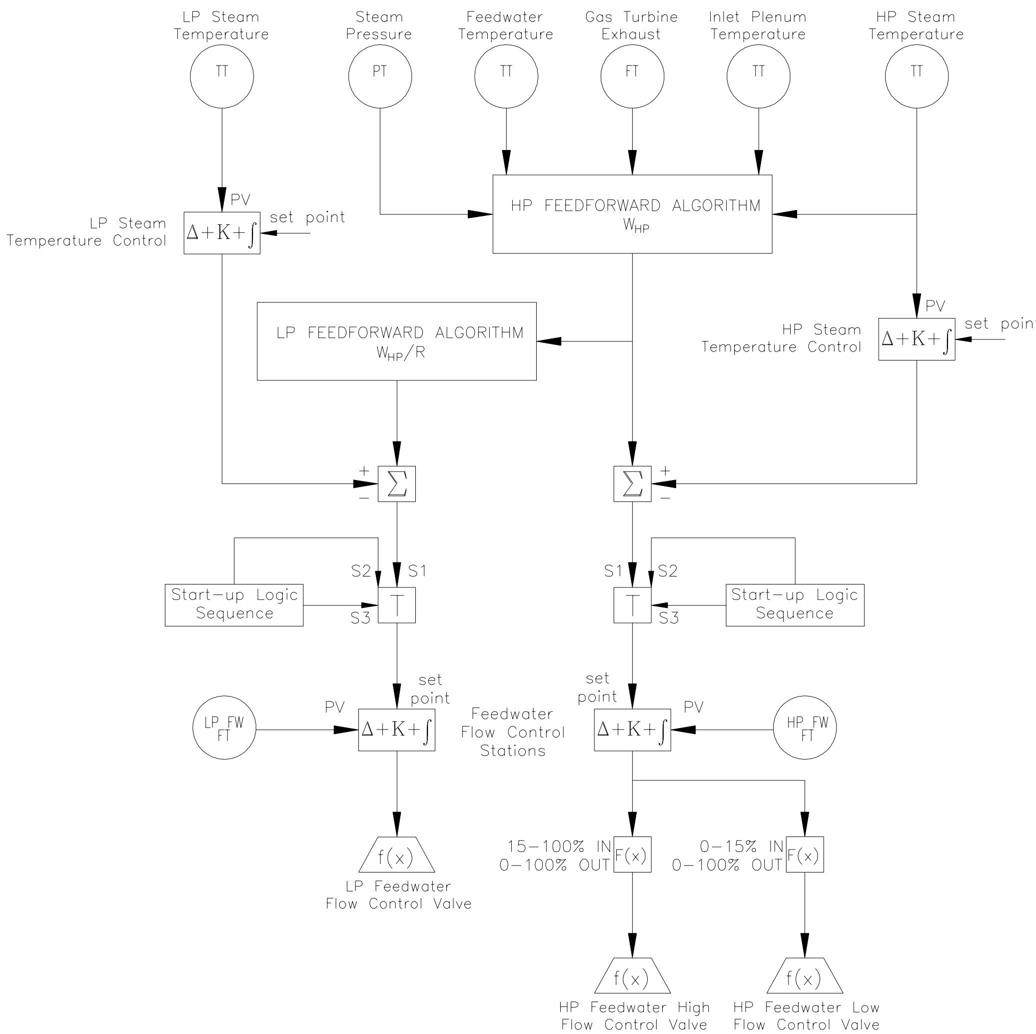

Figure #8 – Control Diagram for Dual Pressure OTSG

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.

The typical valves and instrumentation associated with a dual pressure, unfired OTSG are shown in Figure #9.

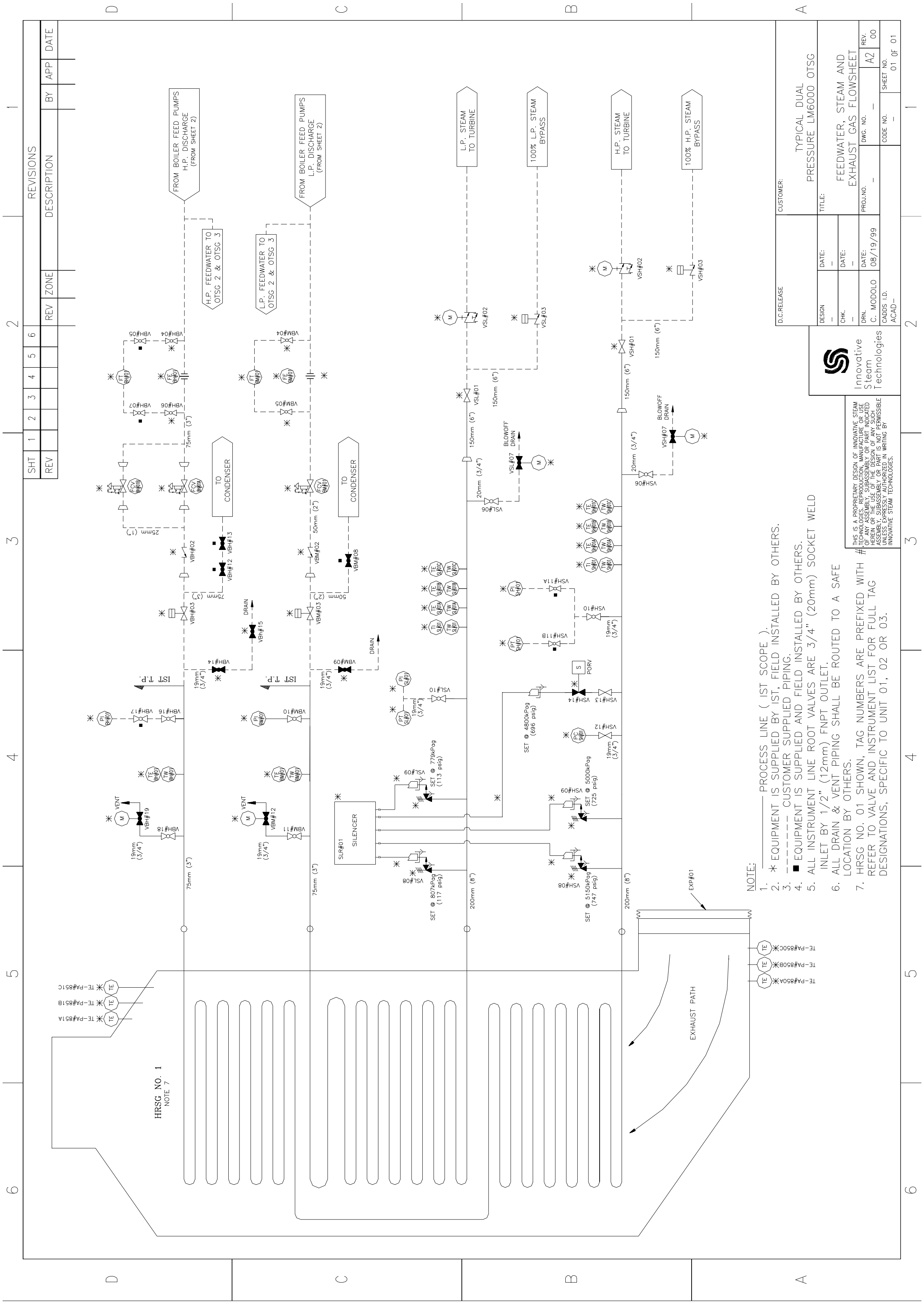

Figure #9 – OTSG Flowsheet

TRANSIENT EVENTS

During the past few years IST has been documenting the transient response of the OTSG on operating units. Tube metal thermocouples are placed throughout the steam generator in the economizer, evaporator and superheater sections to measure tube temperatures as the gas turbine is brought on/off line and as the OTSG is cycled as per demand requirements. Transient events such as start up, base load transient and shut down are shown below.

<u>Start up (Cold Start)</u>

A cold start occurs when the OTSG is not at operating pressure. The initial conditions of the OTSG are at ambient conditions and atmospheric pressure in the steam headers.

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, if possible. 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. A typical startup curve for a dual pressure OTSG is provided in Figure #10.

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 five minutes into the startup.

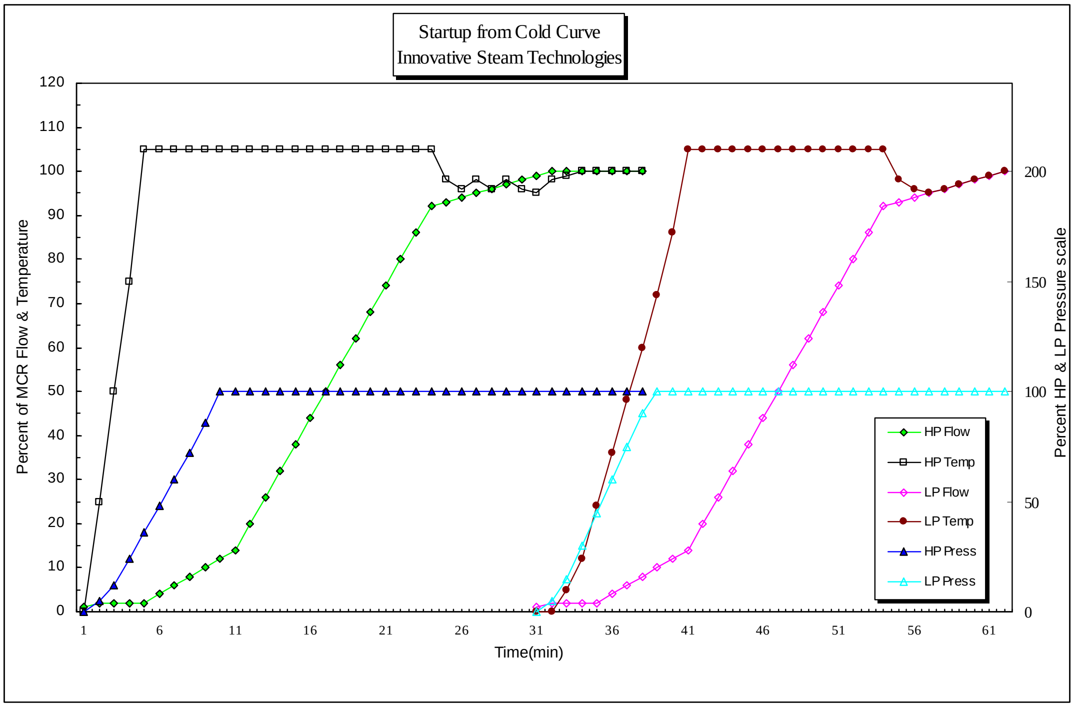

Figure #10 – Typical Dual Pressure OTSG Startup Curve

Actual field measurements (Figure #11 and Figure #12) are provided from a dual pressure OTSG operating in a combined cycle power plant. The gas turbine is ramped to a part load condition and held. During this specific start up, the operator held the gas turbine at load for approximately 7 hours before ramping the gas turbine to full load and initiating the steam flow to the OTSG. This is not required for the OTSG startup but indicates the flexibility of running the OTSG dry to suit the plant requirements (warming up steam lines or preparing the steam turbine). Figure #11 indicates the response of the HP section when starting from cold conditions (- 4 F or –20 C).

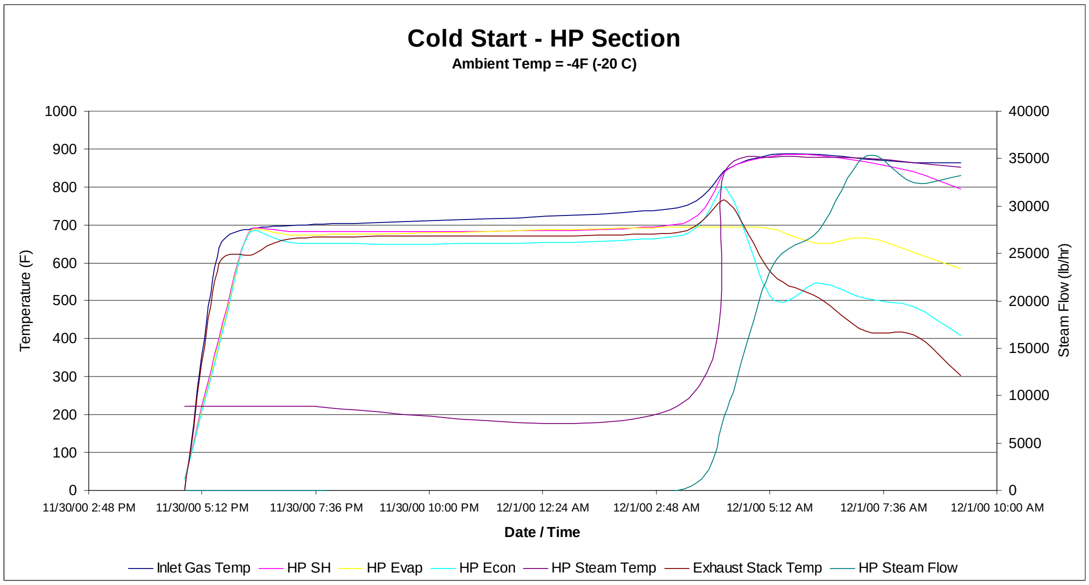

Figure #11 – Cold Start – HP Section

The OTSG, when operating dry, closely follows the gas turbine exhaust temperature. When first water is admitted to the OTSG at approximately 2:30 AM, the steam temperature rapidly rises to gas temperature. As the feedwater flow is increased, the economizer, evaporator and superheater sections begin to stabilize. It will take approximately 95% of full load HP flow to begin to see the outlet steam temperature diverge from the incoming gas temperature. An outlet attemperator can be used during the startup ramp to provide controlled steam temperatures for use in other areas of the plant. Unlike traditional HRSG's, there is no water inventory to heat up to provide useful steam, the initial steam out of the OTSG is of high temperature.

The LP section is started after the HP section has stabilized. As shown in Figure #12, the LP startup is similar to the HP section. Initial steam is supplied at local gas temperatures, which is approximately 550 F (288 C) during this ramp.

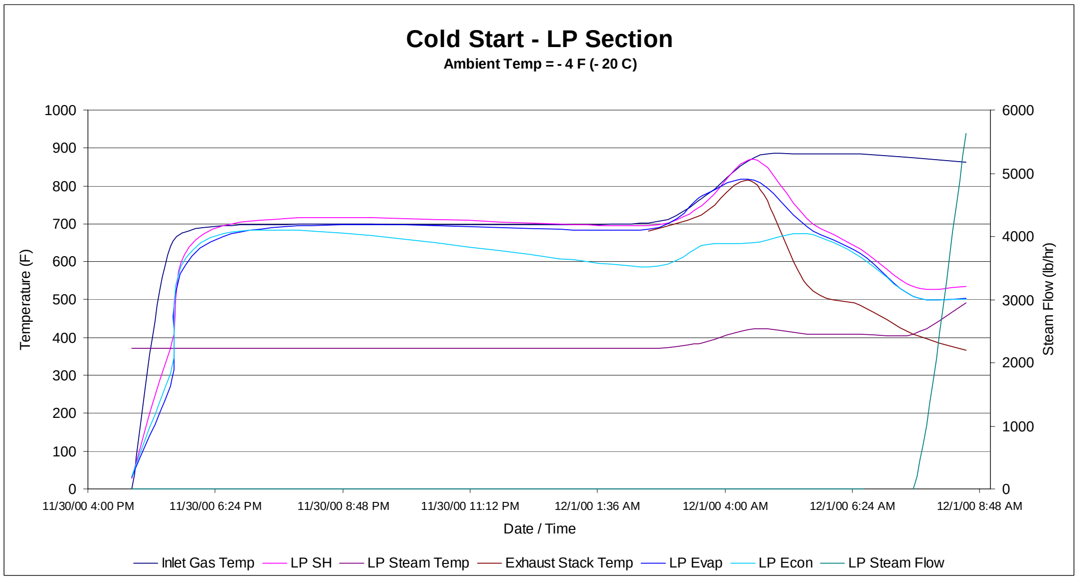

Figure #12 – Cold Start – LP Section

Base Load

Once the OTSG has reached full load conditions, transients can occur as dictated by demand swings or changes in gas turbine load. These types of transients are critical for gas turbine injection applications where steam is provided for power augmentation, NOx control or cooling applications. Figure #13 was obtained from an OTSG providing steam for gas turbine cooling.

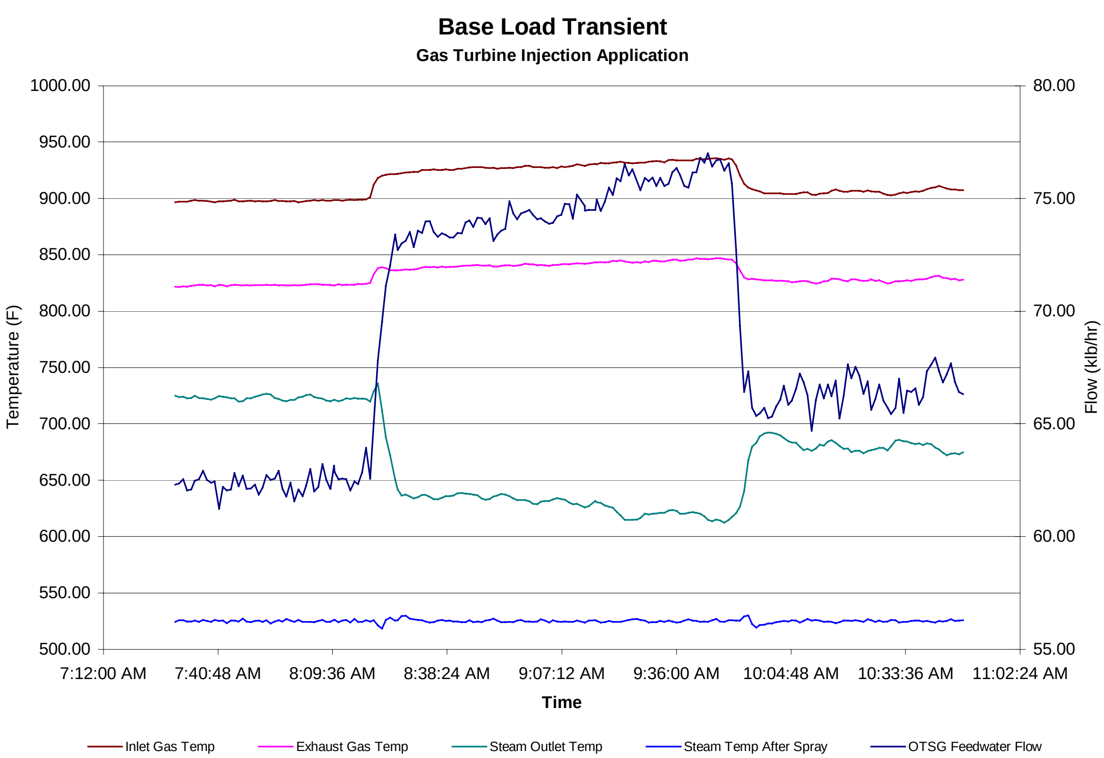

Figure #13 – Base Load Transient

When the transient occurs at approximately 8:15 am, the exhaust temperature of the gas turbine increases and the control system requests an increase in feedwater flow. Instantaneously the OTSG steam outlet temperature responds to the feedwater increase. It is evident that there is no thermal lag associated with the OTSG. Once again, an outlet attemperator is used to maintain controlled steam temperature to the gas turbine injection nozzles. The controlled steam temperature (after spray) is maintained throughout the transient.

Shut down

Normally the OTSG is shutdown prior to shutting down the gas turbine. This allows all the water to be boiled out of the OTSG in preparation for a restart, thereby allowing the operator to restart the OTSG using normal start-up procedures. Otherwise additional time for restart will be required in order to boil the unit dry. Figure #14 illustrates the shutdown characteristics of a dual pressure OTSG operating in a combined cycle power plant. The gas turbine follows it's normal run down and is taken off line at approximately 1:30 AM. The OTSG cools rather slowly until the access doors are opened. Even with a draft passing through the OTSG at –4 F (-20 C) ambient temperatures, the OTSG remains at approximately 200 F (93 C) after an eight-hour shutdown. In daily cycling applications, stack dampers can be provided to retain energy overnight. During the subsequent ramping of the gas turbine during the start up, OTSG permissives can quickly be achieved.

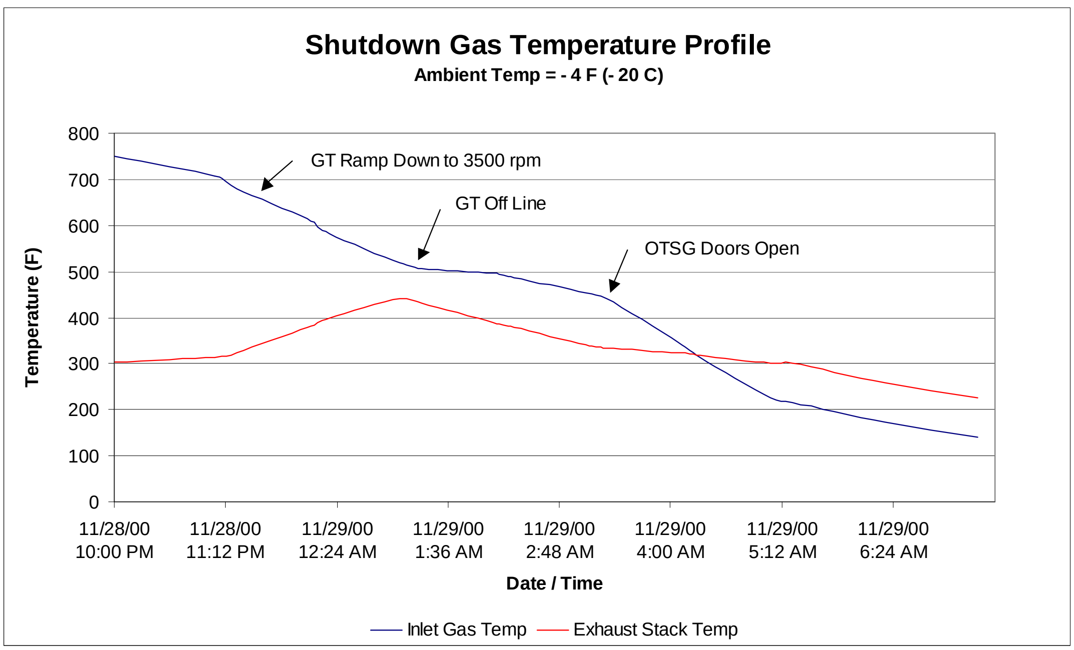

Figure #14 – Gas Temperatures during Shutdown

Further cool down profiles of the HP and LP sections are provided in Figure #15 and Figure #16 respectively.

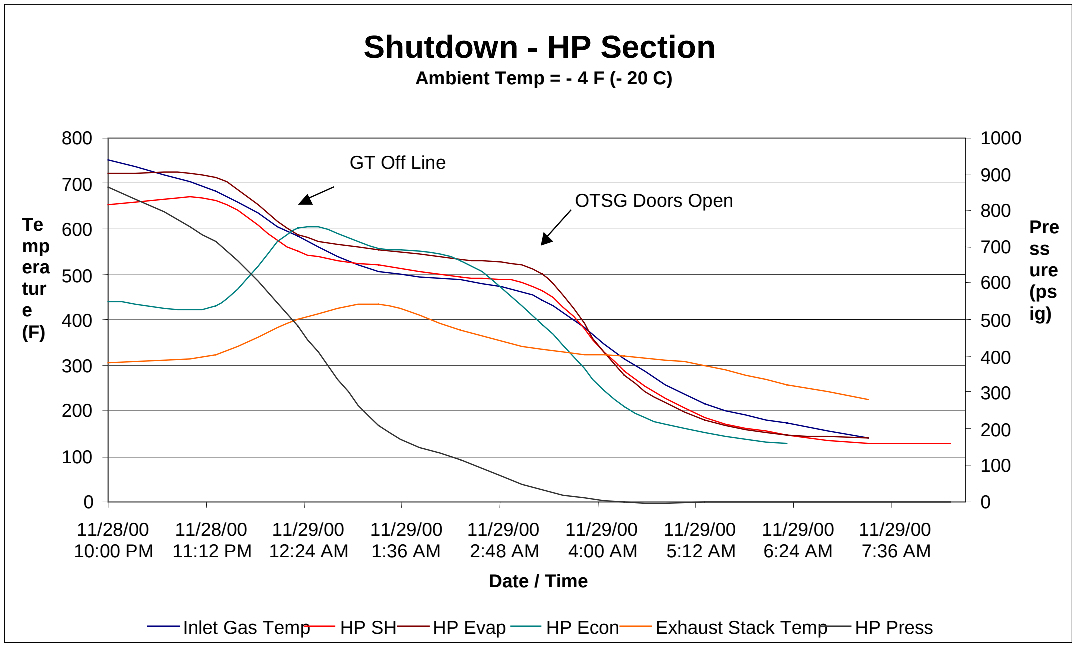

Figure #15 – HP Temperatures during Shutdown

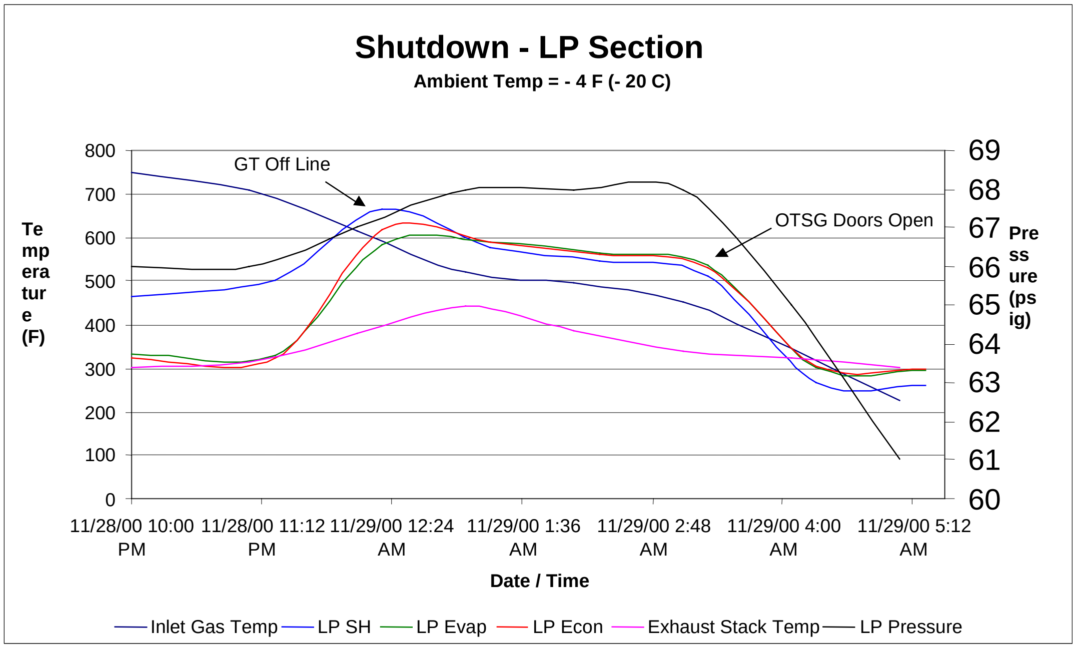

Figure #16 – LP Temperatures during Shutdown

APPLICATIONS

Daily Cycling with SCR Operation

Today's stringent emission restrictions on power plants require SCR systems to come on-line as fast as possible in order to minimize harmful NOx emissions. In order to initiate ammonia injection and NOx removal, minimum gas temperatures must be achieved at the face of the SCR catalyst. The fast startup characteristic of the OTSG allows the required gas temperatures at the face of the SCR to be met quicker than in traditional HRSG's.

The first step is to ramp the gas turbine to a predefined load to initiate SCR operation. The gas turbine is ramped up until the gas temperature reaches approximately 800°F. The suggested GT/SCR start up procedure is as follows:

a) Ramp gas turbine to 800°F
b) Monitor the gas temperature into the SCR. When the gas temperature reaches the minimum allowed, ammonia is injected for NOx control. The time to reach the required SCR inlet gas temperature is estimated at 5 minutes from when the gas turbine is started for a typical 40 MW gas turbine.
c) Once the SCR is operational, the next step will be to start the OTSG steam production.

The OTSG water ramp sequence can be started once the inlet plenum and stack permissives of 500°F and 350°F, have been reached respectively. The time to reach these permissives is estimated to be approximately 15 minutes from turbine start for a typical 40 MW gas turbine. Figure #17 is a typical startup curve for a dual pressure OTSG complete with an SCR.

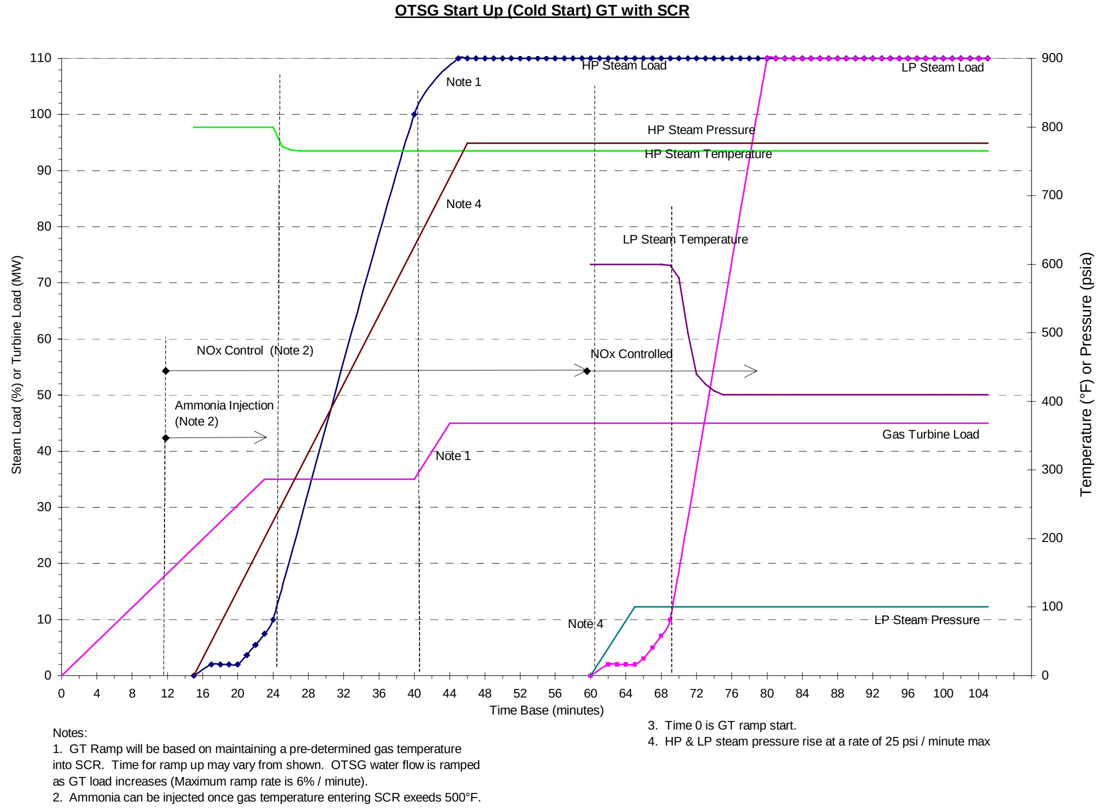

Figure #17 – Start up curve - Dual pressure OTSG with SCR

Gas Turbine Steam Injection

The OTSG is uniquely matched to the demanding operational requirements of gas turbine steam injection applications. Gas turbines are injected with steam for NOx control, power augmentation and/or cooling. Steam injection is most often applied to plants requiring peaking and cyclic service. These applications require fast start capabilities and response to quick load changes. In peaking duty, most of the time the OTSG is in cold standby waiting to be dispatched. This type of operation can be very challenging for traditional drum type HRSG's.

OTSG's Coupled to Compressor Drives

Gas turbines are quite often used as compressor drives on natural gas pipelines. The load of the gas turbine is dictated by the needs of the pipelines. The load following capabilities of the OTSG are required to supply a reliable source of steam during the daily swings caused by natural gas demands.

CONCLUSION

Traditional drum type HRSG's are limited in their fast response and transient capability by the steam drums and associated water inventory and mass of metal. Using an OTSG and eliminating the drums and interconnecting piping, the fast start and transient capabilities are vastly improved. The high degree of flexibility inherent in an OTSG without the need for fixed boundaries between the superheater, evaporator and economizer sections makes the OTSG the best choice for any system requiring fast transients.