In the past decade Once Through Heat Recovery Steam Generators (OTSGs) have evolved into a cost competitive and technologically advanced Heat Recovery Steam Generator (HRSG). This is the first new technology to be introduced into the heat recovery field since the wide scale introduction of combined cycles. Over two million operating hours have been accumulated on the units now in service. However, many power plant designers and developers are not aware of the OTSG's superior technology and the many cost, operating and performance advantages that may be obtained when compared with drum boilers. Drum-type HRSGs have many components such as drums, downcomers, separate economizers, generating tubes, separate superheaters, circulation systems and blowdown systems that are unnecessary ancillary components not essential to produce steam efficiently. Water tube drum units were developed to prevent scaling, corrosion and allow control of the steam generating process. With modern materials, control systems, design technology, and water treatment systems these traditional boiler components are costly and not required in a modern combined cycle plant.

OTSG/HRSG DESCRIPTION

The once-through steam generator (OTSG), in its simplest form, is a continuous tube heat exchanger in which preheating, evaporation, and superheating of the feedwater takes place consecutively, see Figure 1. 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 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).

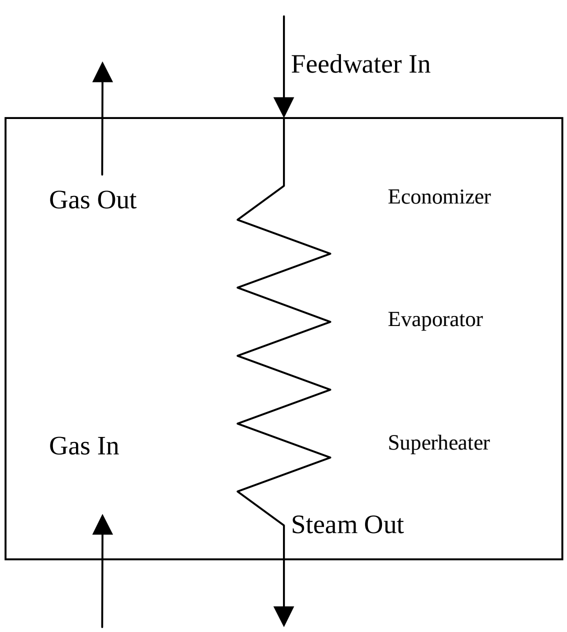


Figure 1. Once Through Steam Generator

Unlike conventional heat recovery steam generators (HRSGs), OTSGs do not have defined economizer, evaporator or superheater sections. The point at which the steam-water interface exists is free to move through the horizontal tube bank depending on the heat input and mass flow rate and pressure of the water. The single point of control for the OTSG is the feedwater control valve; actuation depends on predefined operating conditions that are set through the distributed control system (DCS). The DCS is connected to a feedforward and feedback control loop, which monitor the transients in gas turbine load and outlet steam conditions, respectively. If a transient in gas turbine load is monitored, the feedforward control sets the feedwater flow to a predicted value based on the turbine exhaust temperature, producing steady state superheated steam conditions. Please refer to the Flowsheet (figure 6) for illustration.

Also unlike conventional HRSGs (Figure #2.), OTSGs do not have steam drums, mud drums or blowdown systems. Water volume is typically one-eight to one-tenth that of a conventional drum-type HRSG. The absence of a blowdown system limits the steam generators thermal losses and lowers the makeup requirements to less than 0.1 percent of the total cycle flow rate, thereby permitting a smaller makeup treatment plant.

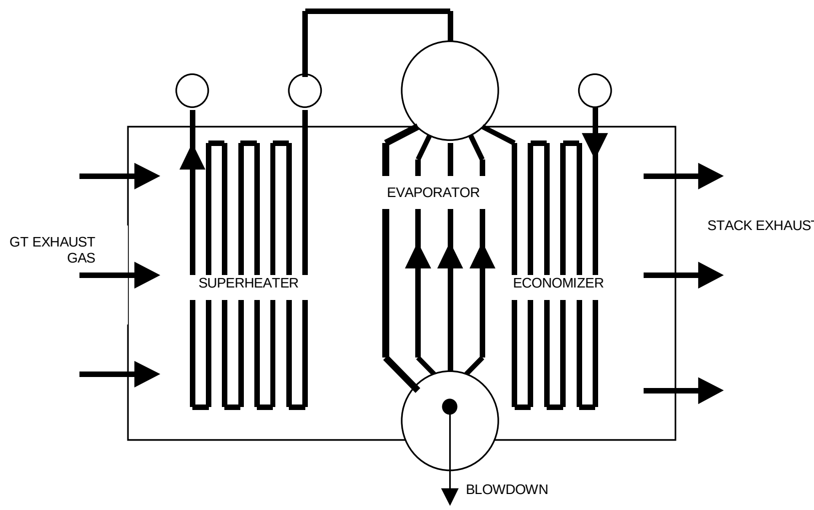


Figure 2. Drum-Type HRSG

Water quality is maintained using conventional deionization and polishing exchange systems, which eliminate deposition into the tube bundle and carryover to the steam turbine. Deionized water treatment systems and condensate polishers are not unique to OTSGs; they are being used with increased frequency on traditional drum-type HRSGs and are favoured for any installation where low life-cycle costs, high reliability, and/or high purity steam is desired.

OTSGs configured for combined cycle or cogeneration operation are typically arranged as vertical flow/horizontal tube systems. The horizontal tube configuration results in a smaller footprint, pushing the units vertically rather than horizontally. The addition of an SCR or CO catalyst system does not add to the boiler footprint because it only it requires the addition of extra modules, only increasing the boiler height (See Figure 3).

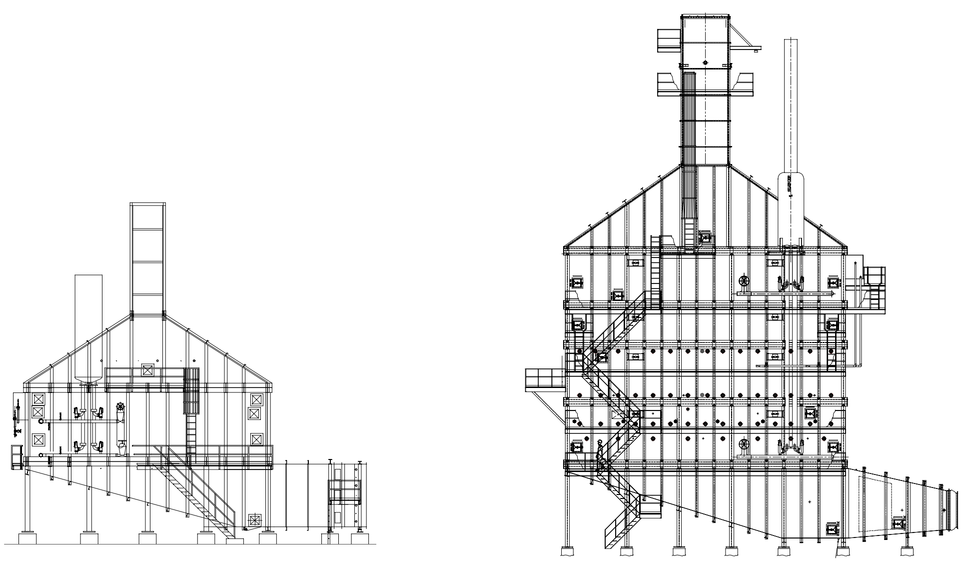


Figure 3: Single module boiler vs. multiple module boiler (with SCR)

Conventional HRSGs use carbon steel as the tube material. Carbon steel loses strength at elevated temperatures, however, making bypass stacks and diverter valves necessary to prevent the hot exhaust from damaging the tubes during dry running conditions. The use of high-nickel Incoloy 800 and 825 alloy tube material, which maintains a substantial fraction of its strength and corrosion resistance at high temperatures, permits full dry running without the need for a bypass stack or diverter valve. Incoloy tube material also limits the OTSG's oxygen sensitivity, avoiding the need for active chemical water treatment. The elimination of the bypass stack and diverter valve, together with the system's modular design, causes the OTSG to be up to 60 percent smaller and lighter than a comparable HRSG, making the OTSG suitable for projects that have size and weight restrictions.

Figure 4. shows a typical OTSG steam/water flow path. Feedwater is metered into the first rows of tubes on the OTSG's exhaust gas outlet end. Water and steam are directed by U-bends at each row to the hot inlet gas in a counter flow path until it reaches the desired superheat temperature and is collected in a header and directed to the steam turbine. Water is heated, evaporated and superheated in one continuous flow path within each of the many parallel circuits. Any orientation can be configured, since gravity forces are not used in the design. Water flow can be down with exhaust gases vertically upwards, or it can be horizontal gas flow with vertical. All of these configurations have been extensively tested and installed.

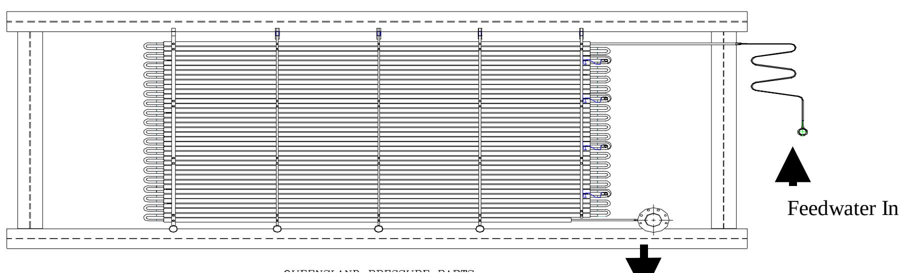


Figure 4. OTSG Pressure Parts

MECHANICAL DESIGN CHARACTERISTICS OF THE OTSG SYSTEM

The OTSG uses specially developed and fabricated finned tubes matched to the operating requirements of the OTSG. Most of the 85 OTSG units in operation to date have a requirement for dry operation at full gas turbine power. As discussed, the tubes are made of high nickel alloy capable of exposure to high temperatures as per Section I of the ASME Boiler Code. Dry operation with most current gas turbines allows the use of carbon steel fins, which are currently installed on many OTSGs for the most cost-effective heat transfer surfaces; stainless steel fins are employed when the ambient conditions are severe. The high nickel stainless steel tubes permits the use of passive water treatment (PWT) with the OTSG. The proprietary finned tubing manufacturing process allows many different combinations of fin material to be bonded to the high nickel seamless/welded tubes. This bonding process allows operation of the tubes to temperatures over 1500ºF if stainless steel fins are used. For most applications carbon steel fins are optimum but stainless steel fins have been operated to high temperatures or installed in cold economizer rows without feedheating to improve performance while minimizing corrosion caused by water condensation.

HRSGs are susceptible to the cold end problems in the preheater rows of the boilers. These problems include corrosion or stress corrosion cracking of the carbon steel or stainless steel heat exchanger tubes and corrosion of the carbon steel fins due to operations below the acid dew point. In order to avoid these types of cold end problems, HRSGs are designed to accommodate slightly higher stack temperatures and higher feedwater temperatures, which, in turn, can reduces the overall plant efficiency. OTSG systems employ alloy 825 and stainless steel fins in the inlet rows (economizer) of all the pressure levels and a preheater is not required. These materials minimize the effects of corrosion; therefore the OTSG systems accommodate lower feedwater (as low as 60°F) and therefore lower stack temperatures.

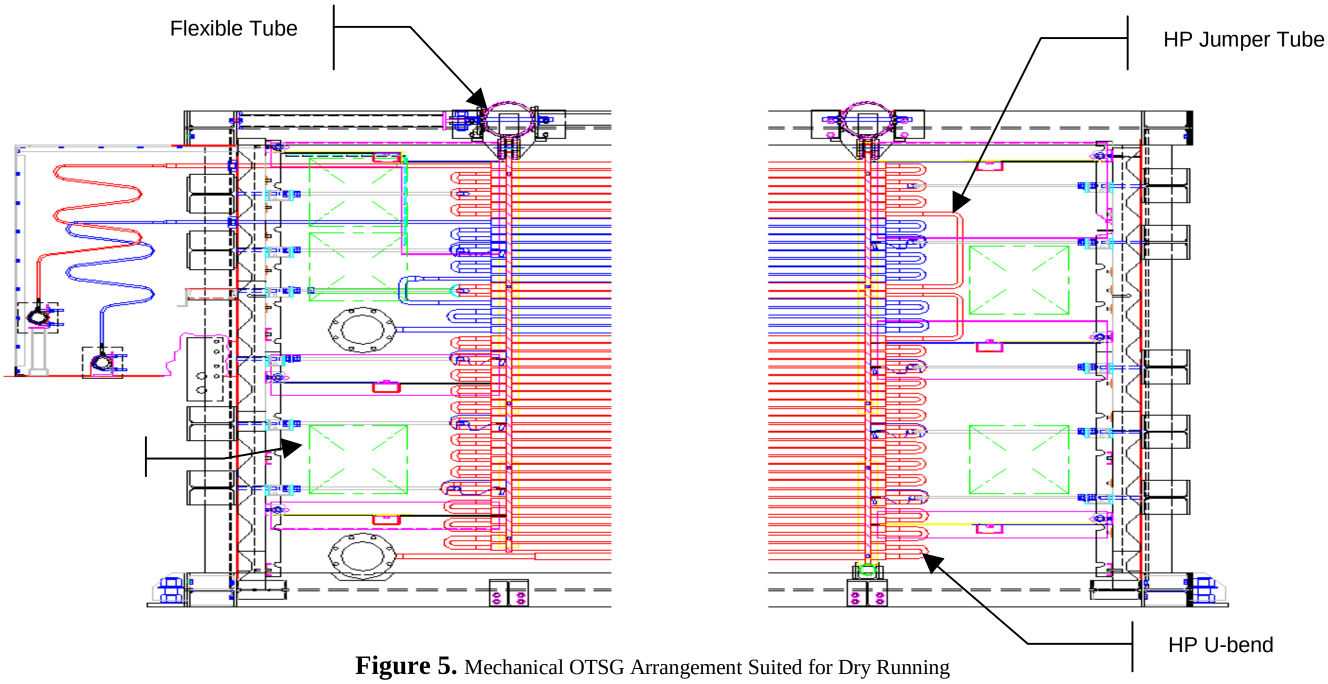


Figure 5. Mechanical OTSG Arrangement Suited for Dry Running

The majority of the OTSG units installed accommodate exhaust gas that flows vertically upward and the water flow enters at the top and flows downward through the serpentine tube bundle to exit at the bottom as superheated steam. Every few feet flexible tube sheets support the bundle. The tube sheets are hung from the top by cross beams mounted on side pads that compensate the structure for differential thermal growth (Figure 5). A thermally matched spreader system adjusts the support beam position to allow compensation for thermal expansion. The tubes are free to slide within the tube sheets, and the tube sheets can flex with the entire bundle. This construction allows a high degree of thermal flexibility and is needed for dry operating capabilities and cyclic duty applications.

Multiple pressure units are configured by the use of longer u-bends or jumper tubes that allow different pressure level sections of the OTSG to be located in the optimum gas temperature zone for best performance. Figure 5. illustrates a typical arrangement of u-bends and jumper tubes. Since drums and the large amount of interconnecting piping needed on multiple pressure units are not required, the OTSG becomes more cost efficient as the number of pressure levels increase.

OTSGs installed to date are fully modularized. The OTSG is usually in a single module with the entire ASME Section I boiler proper components factory welded and code inspected before leaving the factory. A single module OTSG can be shipped in sizes up to about 30,000 square meters (300,000 square feet) to many locations. The single module approach minimizes erection and installation time and cost. This reduces the project's gestation period and causes the combined cycles to become increasingly more attractive to developers and financiers.

SCR AND CO CATALYST SYSTEMS

As environmental regulations dictate equipment selection for power plants, SCR and CO catalysts are being integrated into HRSGs. The OTSG can be easily outfitted with an SCR or CO catalyst by simply adding extra module space for the catalyst, ammonia injection grid or mixing space (See figure 3). 9 of IST's 85 boilers sold to date have required SCR installations.

The catalysts have a defined temperature zone where the they operate at peak efficiency. Because the OTSG has no fixed sections, the tube bundle can be split at any location and the SCR inserted. This allows the SCR to see the optimal temperature much more easily in an OTSG.

WATER CHEMISTRY REQUIREMENTS

The high nickel stainless steel tubing is of small diameter and thin walls. Water solids are removed externally and not in the steam generator, and no chemicals are needed for the OTSG. Oxygen removal is also unnecessary and typical control of feedwater chemistry and drum chemistry is not used in operating OTSGs. Only a simple conductivity transducer is used to monitor the OTSG's feedwater total dissolved solids (TDS) levels of less than 50ppb or less than a cation conductivity of 0.25 micro-mhos/cm. In a power plant application (no steam loss to process) a 0.1% or less makeup is commonly experienced (no blowdown required as with drum – type HRSGs) and exchange D.I. beds for make-up and full flow polishing is often the most cost effective solution. For cogeneration where makeup can be higher, some systems use reverse osmosis and exchange beds or regenerative D.I. systems. HRSGs traditionally have make up rates of 2.5% or higher in combined cycle applications. The 2.5% percent makeup is due to blowdown and steam losses through the system. The blowdown must be disposed of, and in some cases blowdown treatment is a requirement. Therefore, additional disposal equipment would be required, and the plant would have a thermal loss due to the blowdown.

Consistent management of water and steam side chemistry is essential for long term reliability and durability of the HRSG. High pressure boilers are very unforgiving of even isolated major chemistry excursions. The thin wall tubes used in both HRSGs and OTSGs leave no practical corrosion margin for even occasional chemistry excursions.

Post construction chemical cleaning of water side components and steam purge of steam pipes is extremely important to long term durability of HRSGs. Many HRSGs, which were not thoroughly cleaned, have suffered corrosion from failure to completely drain while shutdown due to clogging of maintenance drains. This problem is not experienced with OTSGs systems. As explained above, the OTSG has polished feedwater entering the unit and in turn clean steam leaving the unit. The OTSG does not contain or add any impurities to the system and the unit arrives with 100% of the pressure parts completed and sealed in a clean state. In addition, any water that is contained within the tube bundle during a shutdown scenario will completely boil dry due to the residual heat contained within the fully insulated unit. This feature will increase the plant's operability and reduce the maintenance requirements that would have otherwise been encountered if an HRSGs were used.

HRSG systems require elevated thermal deaerators to reduce the dissolved oxygen in the water/steam. This is a requirement because of the carbon steel tubes and drums in the unit. The alloy 800 and alloy 825 tube material commonly used in OTSG systems are not oxygen sensitive, therefore the OTSG does not require deaeration to the same extent as the HRSG steam plants.

Often there is carbon steel piping within the steam plants of combined cycles featuring OTSGs as the heat recovery boiler. Therefore, it is advisable that deaeration be used, and a vacuum deaerator may be the most practical alternative. A vacuum deaerator's physical size is smaller and the cost is often less. The vacuum deaerator also uses less steam than a tradition pressurized deaerator which could otherwise be contributed to the plant balance and improve the cycle efficiency. Vacuum deaerators cause lower feedwater temperatures, however low feedwater and stack temperatures do not promote corrosion problems for OTSGs in the cold economizer end.

OTSG vs. HRSG OPERATION

The OTSG's have no steam or water drums or blowdown systems. All feedwater entering the OTSG is converted to steam. During start-up, steam production will begin shortly after admission of feedwater into the OTSG. By starting steam production as soon as the temperature of the exhaust gas exiting the OTSG has reached a minimum required value, the thermal shock factor is reduced and the life of the OTSG will be maximized.

As water is first admitted to the OTSG, the steam being produced will be very near the exhaust gas temperature at the inlet to the OTSG. The steam temperature can only be controlled when the steam production has reached unfired full load unless a downstream attemperator is used. 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.

During start-up, the steam temperature may be higher than permitted to the inlet of the steam process (depending on steam process and gas turbine design). Therefore, the steam plant must be designed to allow the steam produced from the OTSG to be temperature regulated before admission to the plant steam piping system.

There are constraints on the ramp rates for the start of steam production on the OTSG's. In addition, there are constraints on the steam output pressure transients. In particular, rapid pressure transients must be avoided. Rapid pressure reductions can cause the water in the OTSG tubes to swell in sections where the water has not been fully evaporated. This may result in water being swept along into downstream tubing in the higher temperature zones creating a risk of tube failure. The ramp rates for OTSG systems are considerably faster than drum-type HRSG systems, typically in the order of magnitude of 1/3 the time. The OTSG contains significantly

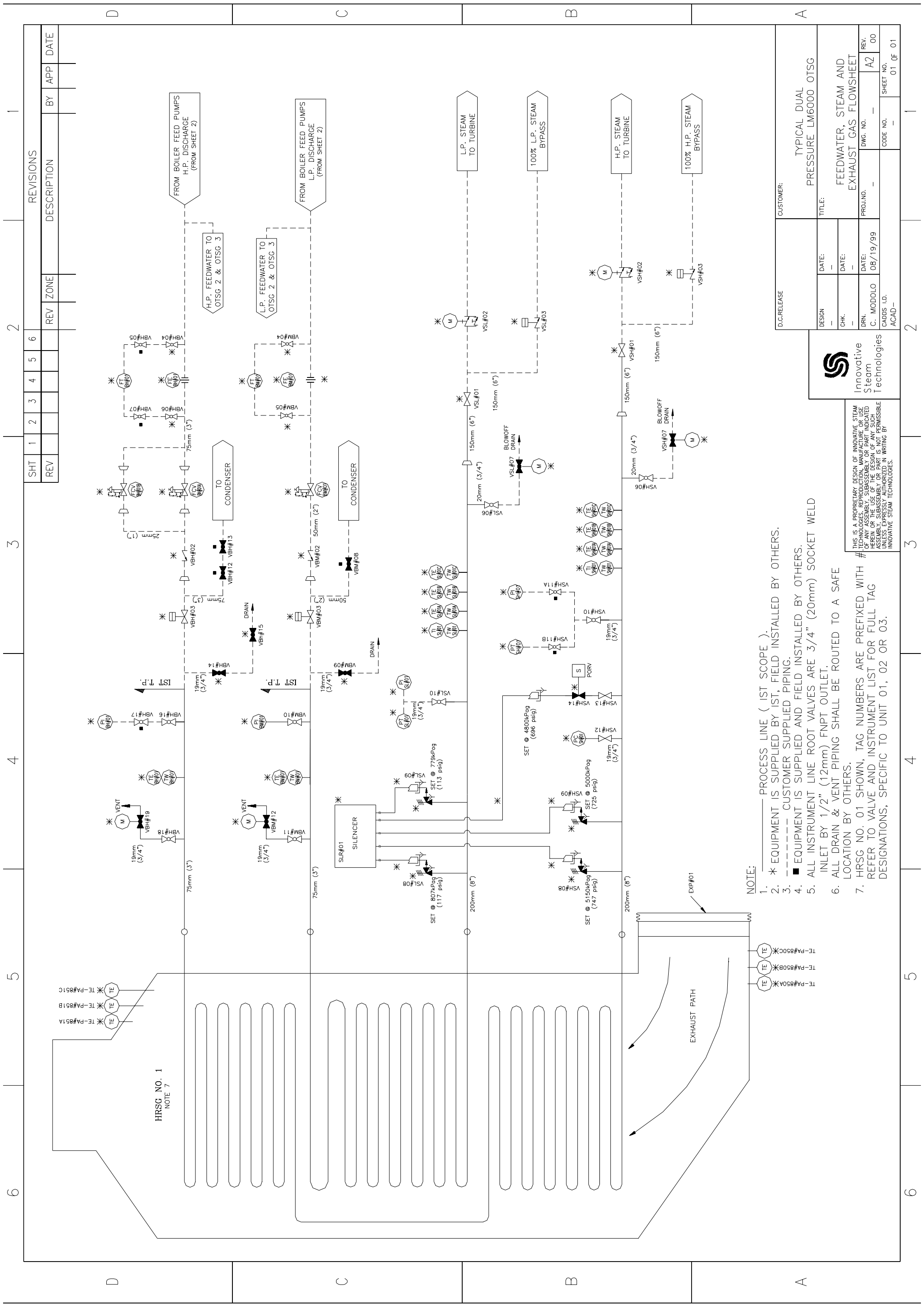


Figure 6: Typical Steam and Feedwater Flowsheet

less water than a drum type unit and in fact the OTSG is started dry, therefore the unit does not have to wait until the large volumes of water contained within drum units heats and begins to evaporate. This causes the OTSG to be ideally suited for combined cycle applications where cycling or daily start-up and shutdowns are required. The cyclic load does not mechanically effect the OTSG since all the tubes and headers are relatively thin walled which means that the material is geometrically stronger than HRSGs under these loading scenarios. Figure 7. contains a typical start-up curve for a dual pressure OTSG system coupled to a 40MW LM6000 gas turbine.

Since all feedwater entering the OTSG is converted to steam, the feedwater must be of the highest quality to ensure that no scaling occurs inside the tubing and that the purity of the steam output is suitable for the process. To minimise the risk of problems with the OTSG, pH and conductivity must be continuously controlled and monitored to confirm that the water quality is always within the specification.

It is important that steam de-superheating stations are operating properly. Failure to maintain proper downstream conditions could result in equipment damage if required operating conditions are exceeded. As a point for operating consideration, excessive venting of steam from the OTSG will require high make-up rates, placing greater demand on the demineralization and chemistry control equipment. These combined effects will result in reduced plant efficiency, increased chemical consumption and accelerated exhaustion of demineralization units.

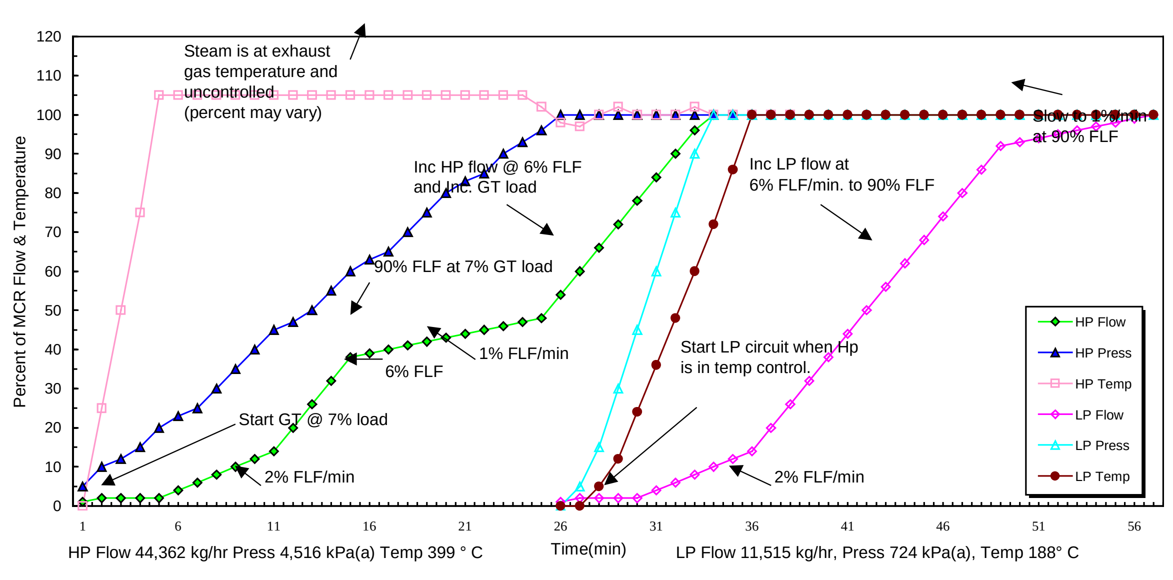
The OTSG does not have the steam accumulation ability to the same extent as a drum-type HRSG system. When the steam side of a drum plant is trip, the drums contain residue steam for a longer period than the small diameter tubes of the OTSG. Though the small diameter tubes and low water content do contribute to the boiler’s response time and performance, the small diameter tubes create a large water side pressure drop which must be accounted for in the project evaluation. Essentially, the feedwater pumps are sized larger than drum units and the auxiliary power consumption increases. This marginal increase in capital and operational cost can easily be offset by the elimination of the bypass stack.

OTSG DESCRIPTION - CONTROLS

The OTSG has a simple control system due to simplification of the water/steam flow path and elimination of many components required for a typical HRSG. A single point of control is all that is needed. Feedwater flow rate is the only control variable. Feedwater is regulated at the rate necessary to produce the desired steam temperature. Since the water level can be anywhere from the first row to the outlet row, a wide range of steam flows, pressures and temperatures can be accommodated for start-up, normal operation and design optimization. The traditional drum-type HRSG has a fixed geometry superheater that cannot accommodate wide operational changes without multiple desuperheaters being employed. The OTSG allows off-design operation because in effect, it has a variable length superheater.

At the operator’s preference, the OTSG can be started simultaneously with the start of the gas turbine, or, after the gas turbine is fully loaded and on-line. The OTSG is normally started hot and dry once the gas turbine has started. This is to ensure the tubes are hot. At an exhaust temperature of about 300ºF (leaving the OTSG) the feedwater flow rate is ramped up as the gas turbine is loaded (similar to the fuel acceleration control for the gas turbine). When hot starts are used and water flow is below approximately 93% of design flow, the OTSG will produce superheated steam at the same temperature as the inlet gas from the gas turbine. When loaded, and the water flow is at 85% to 90% of the rated set point for gas turbine operating conditions, the feedwater will go to closed loop control on superheater temperature feedback (refer to Figure 7). At steady state conditions, superheat temperature can normally be maintained at ±5ºF of a set point or an approach temperature. Transients are accommodated with a feed-forward control strategy that sets the feedwater flow to a predicted value based on turbine exhaust temperature and flow rate. The patented approach to controls and the use of microprocessors provides precise and fast transient response across a wide range of operating conditions. The OTSG has demonstrated reliable operation without difficulty, with the most demanding transients that can be required of gas turbines.

Figure 7. Typical Start-up Curve for an Dual Pressure OTSG Coupled to a 40MW LM6000 GT
Innovative Steam Technologies
Contract # CXXXXX
Start-up Curve From Cold - In Percent of MCR Guarantee



This “self operating” feature is a critical benefit for the OTSG. Combined cycle plants using OTSGs usually require 50% less operator engineers and maintenance technicians than a comparable drum-type HRSG plant. This is due to the OTSGs ability to operate itself, via the feedforward and feedback control loop. Some combined cycle plants installed in Canada and Australia operate unattended in the evening shift or remotely from distance control stations.

HEAT RECOVERY BOILER MAINTENANCE REQUIREMENTS

HRSG system maintenance is significant due to the complexity of the interconnecting piping, valves, transducers, control connections, etc. OTSG maintenance is typically performed during scheduled GT shutdowns. The maintenance requirements are very limited due to the inherent design benefits of the OTSG system. Figure 6 illustrates the simplicity of the flowsheet and instrumentation required to control and operate the unit. The amount of instrumentation is significantly less compared to a drum-type HRSG, which translates to significant maintenance savings. The 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 have scheduled maintenance requirements as dictated by the equipment vendor, but again, the amount of equipment is reduced with an OTSG system.

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 u-bends, jumper tubes and headers are located in maintenance cavities, which have access via maintenance doors, at both ends of the unit (Figure 5). If a tube leak is present, the single circuit can be taken out of service within a few hours and the tube repair could be completed when the schedule permits. The majority of OTSGs have approximately 50 circuits of tubes in each module, therefore, if one circuit is lost in the unlikely event of a tube rupture or weld failure, the circuit would be manually blanked off and the performance would be degraded by less than 1%.

ERECTION BENEFITS

There is a significant potential saving if the installation cost of the heat recovery boilers can be lowered. Most OTSGs are designed in five modules: inlet duct, plenum, steam generator module, hood and stack (refer to figure 3). Each of the five modules is shop fabricated and can be delivered to the point of erection by rail, road or ocean vessel. The modular design and manufacturing facilitates rapid construction and minimizes crane and work-hour requirements at the erection sites. The OTSGs can be set in position within one day following the placement of the plenum. Once the plenum is set, the steam generator module, hood and stack are simply placed on top of each other and then seal welded. Additional time is required for completing the module joints and for external piping and commissioning.

The erection cost and duration of many combined cycles is often under estimated making the initial project evaluation in valid. The installation cost is a significant portion of the overall project cost; therefore it is essential that combined cycles be evaluated on an installed basis. The installation savings of an OTSG are the single most beneficial cost savings within a project. The duration of a typical LM6000 sized OTSG takes approximately 3 weeks to complete, and is approximately 25% the cost of a drum type HRSG. Therefore, these costs must be equated in to the evaluation, and the potential cost savings would offset the cost of the polishing system and alloy material.