Design aspects of once through systems for heat recovery steam generators for base load and cyclic operation

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The paper describes a once-through approach to the design of heat recovery steam generators, thereby eliminating boiler drums, and many other items of equipment. Two pressure operation is possible. To enable the steam generator to start up from dry, high creep strength Incoloy type materials are used for all of the tubing. This also enables the system to cope with fluctuations in the water-to-steam transition point. Such a design is therefore highly suitable for cyclic operation. One of the features of this particular design is the ability to operate dry, that is with no water flow through the tubing, even though the gas turbine is at full output. Materials specifications for operation with dirty fuels, particularly in a corrosive marine environment, are discussed. Some details of water treatments needed and typical start up schedules are given. The paper also comments briefly on some of the limitations of conventional HRSGs.

Keywords: once-through systems, heat recovery steam generators

1. INTRODUCTION

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 cycle plant. Over two million operating hours have been accumulated on the units now in service.

The design and concept of OTSG units makes them highly suitable for units which load cycle or two shift, since many of the components which cause difficulties with HRSG units of a conventional design have been eliminated. These include steam drums, downcomers, separate economizers, generating tubes, separate superheaters, circulation systems and blowdown systems. This equipment was needed to prevent scaling, corrosion and allow control of the steam generating process. Such an approach was necessary due to the limitations of carbon steel tubing and the difficulties with older style water treatment methods. With modern high alloy stainless materials, which have excellent high temperature strength and corrosion resistance, plus water treatment systems of the zero solids type, a much simpler system has emerged. This permits faster startup times, more flexible operation, and reduced maintenance.

2. ONCE THROUGH STEAM GENERATOR DESCRIPTION

The once-through steam generator (OTSG), in its simplest form, is a continuous tube heat exchanger in which the preheating, evaporation, and superheating of the feedwater takes place. Tubes are mounted in parallel and are joined by headers, so providing a common inlet for the feedwater and a common outlet for the 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 end or bottom of the unit. Gas flow is in the opposite direction to that of the water flow (counter current flow). As with more conventional systems, the OTSG can supply superheated steam at two different pressures.

Accordingly, 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 tube bank, this depending on the heat input, flow rate and pressure of the water. The single point of control for the OTSG is the feedwater control valve. The actuation of this 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

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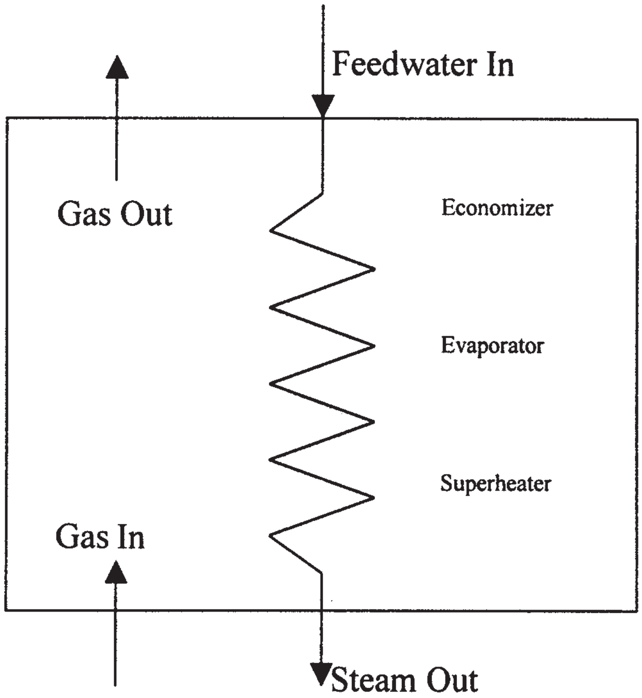

Figure 1 Once through steam generator.

turbine load and outlet steam conditions, respectively. If a change in the gas turbine output should occur, the feed-forward control sets the feedwater flow to a predicted value based on the turbine exhaust temperature, producing steady state superheated steam conditions.

As indicated above, OTSGs do not have steam drums, mud drums or blowdown systems. Water volume is typically one-eighth 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 water treatment plant, which is a bonus for cyclic operation.

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. However, it is the use of a 'zero solids' approach to water treatment that is an essential feature in the success of the OTSG. The other key development is the use of Incoloy type materials to give both good high temperature creep and fatigue strength, plus good resistance to stress corrosion

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. Footprint is an important factor to consider where ground space is at a premium. In Figure 3 is given a comparison between the overall size of an LM6000 40MW OTSG to that of a comparable LM6000 40MW HRSG. The footprint of the OTSG, in the foreground, is significantly smaller than that of the HRSG in the background.

Conventional HRSGs use carbon steel as the tube material. Carbon steel loses strength at elevated tempera-

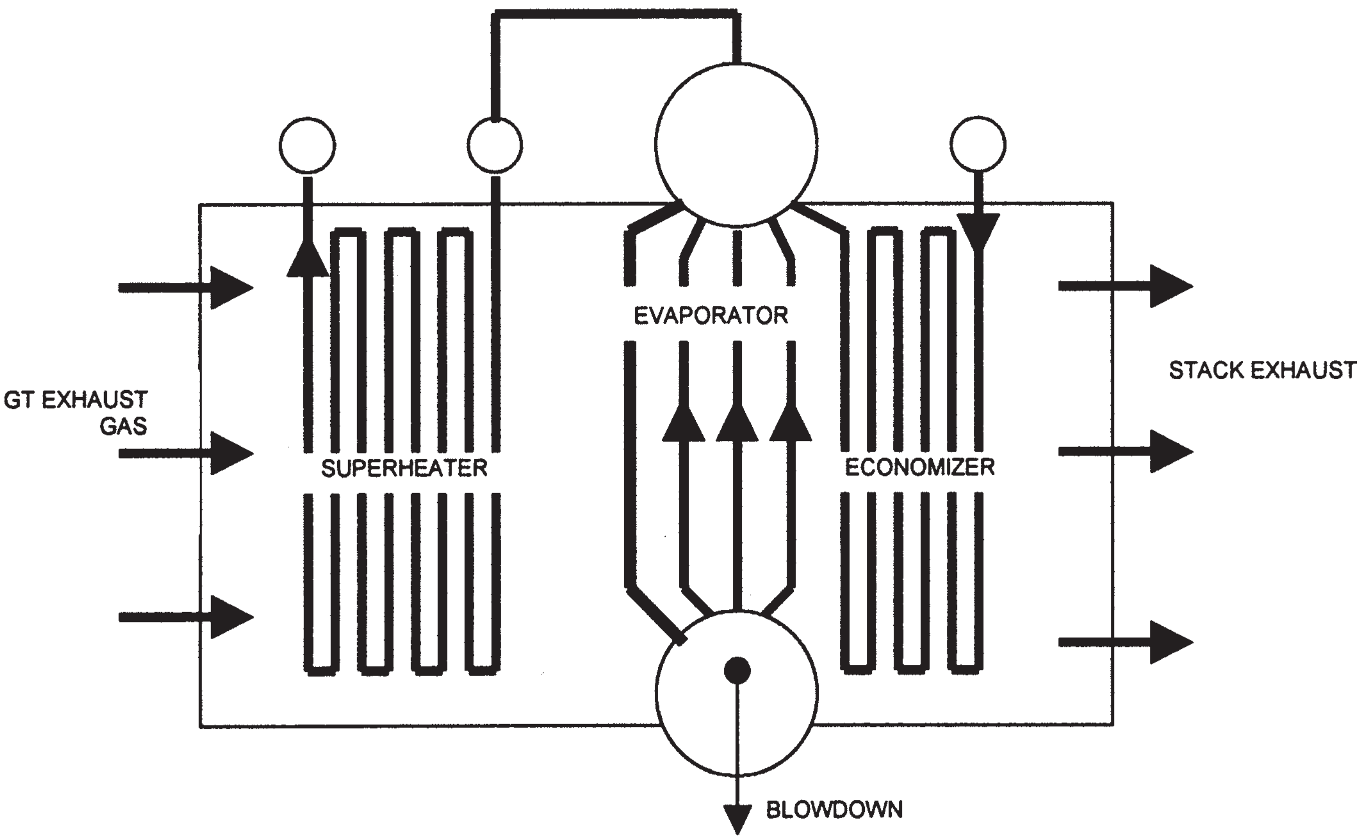

Figure 2 Drum-type HRSG.

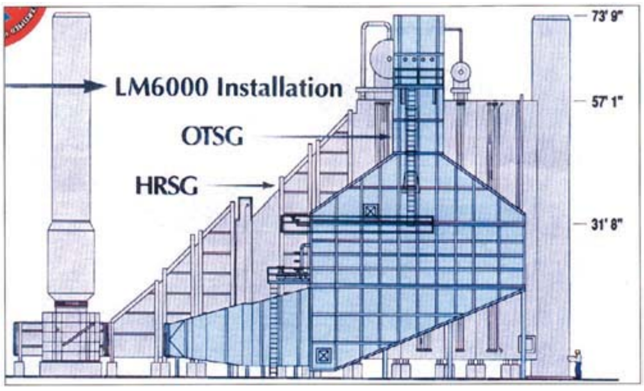

Figure 3 Plan view and footprint comparison of a LM6000 40 MW OTSG to a LM6000 40 MW drum-type HRSG. Both units are approximately 5 m at their widest point.

tures, however, making gas turbine 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 maintain a substantial fraction of their 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.

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, where the steam 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. That is, the flow through the tubes is dictated by the overall design, plus the flow rate from the pump . Water flow can be downwards with exhaust gases vertically upwards, or it can be horizontal gas flow with vertical tubes, or horizontal gas flow with horizontal tubes. All of these configurations have been extensively tested and installed.

The ductwork for an OTSG system can also be arranged to allow the OTSG units to be located directly above the gas turbines, particularly for gas turbines that exhaust vertically.

3. 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 50 OTSG units in operation to date have a requirement for dry operation, that is with no water flow through the tubing, 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 (815°C) if stainless steel fins are used. For most applications carbon steel fins are optimum. Stainless steel fins will be specified where there is a need for strength and oxidation resistance in superheater sections. However they can also be installed in the back end section of the OTSG, to minimize condensation type corrosion.

In contrast, conventional 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 operation below the acid dew point. These problems are amplified when the turbine fuel contains a high sulfur content, which is a primary fuel in developing countries. In order to avoid these types of cold end problems, HRSGs, when using this type of fuel, need to run at relatively high stack and feedwater temperatures, which, in turn, will reduce the overall plant

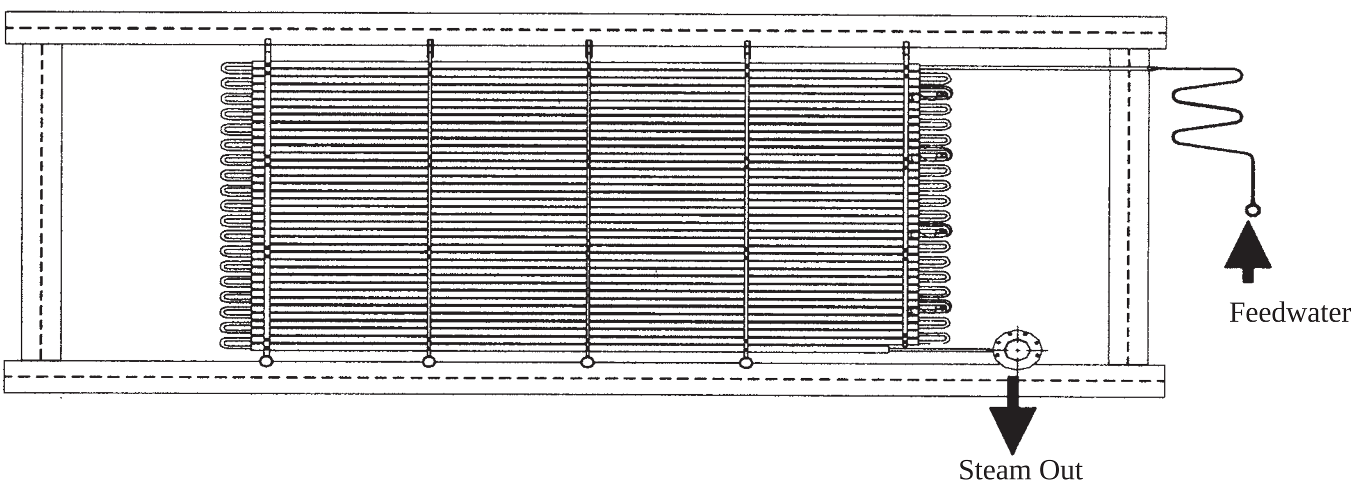

Figure 4 OTSG pressure parts.

efficiency. The use of corrosion resistant finning and tubing, in the low temperature sections of the OTSG enables it to run with feedwater temperatures lower than 60ºF (15°C).

The majority of the OTSG units installed accommodate exhaust gas that flows vertically upward, so that the water flow enters at the top and flows downward through a 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. 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 for the high degree of thermal flexibility that 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. These are 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 to many locations. The single module approach minimizes erection and installation time and cost.

4. DESIGN FOR CORROSION UNDER MARINE AND COASTAL CONDITIONS

The are numerous environmental factors that must be considered when designing OTSGs/HRSGs for marine applications, as when equipment is located in coastal areas or mounted on barges. These factors have a direct impact on the plant performance, maintainability and the cost of the equipment.

The main design concern in a marine environment is airborne salts that can be deposited on the heat transfer surfaces, heat exchanger tubes and the liner plates of the interior of the heat recovery boilers. The salts are chlorides, which in contact with certain metals can cause significant and rapid corrosion. This is especially true if a conventional carbon steel type HRSG is by-passed or not in service. Under a ‘by-pass’ or ‘out of service scenario’, the drum-type HRSG has the potential of having moisture build up on the tubes and the potential for accelerated corrosion of the heat exchanger tubes. Materials such as, carbon steel, low alloy, and COR-TEN are susceptible to corrosion failures in these environments; and these corrosion effects are amplified when the exhaust gas contains high sulphur content.

OTSGs employ alloy 825 as the heat exchanger tubes throughout the entire tube bundle. This material is more costly, due to the high nickel content, than carbon steel or a T22, however this material is well suited and more resistant to these corrosion effects. The alloy 825 has a high resistance to acids such as: sulphuric, phosphoric, hydrochloric, organic, and a suitability for a sea water environment.

In addition, the heat transfer finning material in OTSGs is stainless steel which is better suited for conditions where sodium chloride attack or stress corrosion cracking may be present. The use of 409SS or 316SS

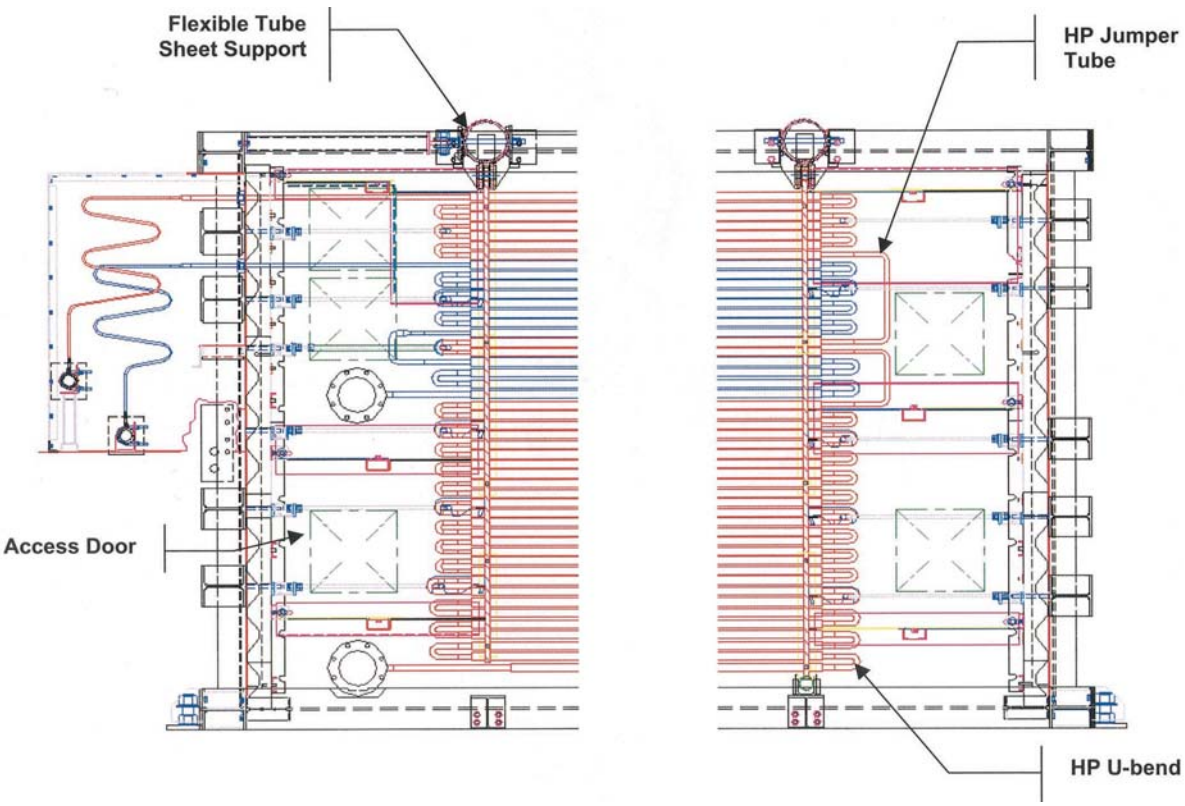

Figure 5 Mechanical OTSG arrangement suited for dry running.

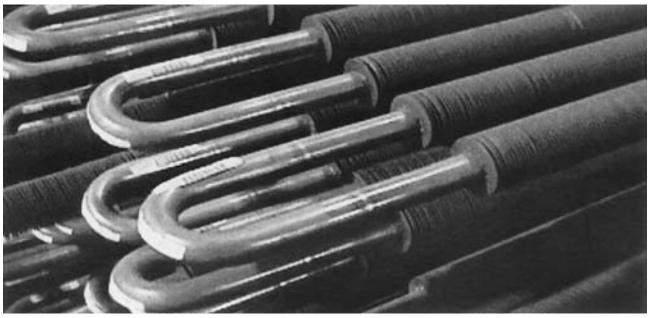

Figure 6 OTSG alloy 825 heat exchanger tubes and stainless steel finns.

liner plates to a through out also reduces the susceptibility to corrosion.

5. WATER CHEMISTRY REQUIREMENTS

The Incoloy tubing is of small diameter and thin walls. Water solids are removed in the treatment plant, so that blow down requirements are minimal. Because of the use of Incoloy, rather than carbon steel, the need to reduce oxygen to very low levels is also unnecessary. Only a simple conductivity transducer is used to monitor the OTSG's feedwater total dissolved solids. Typical TDS requirements are less than 50ppb or a cation conductivity of under 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). 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. OTSGs with the highest operating time have full flow feedwater polishing exchange beds. These last about 3 years before replacement is required, which can be an added benefit for reducing maintenance requirements. Here it should be noted that HRSGs traditionally have make-up rates of 2.5% or higher in cyclic operation. The 2.5% percent make-up 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.

6. 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 turbine and system pipework. 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 increasing this by a factor of three. The OTSG contains significantly less water than a drum type unit. In fact the OTSG is started dry 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. This 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.

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.

It is clear that an OTSG does not have the reserve of steam as that of a drum-type HRSG system. When the steam side of a drum plant is tripped, the drums contain residual steam and water for a longer period than the

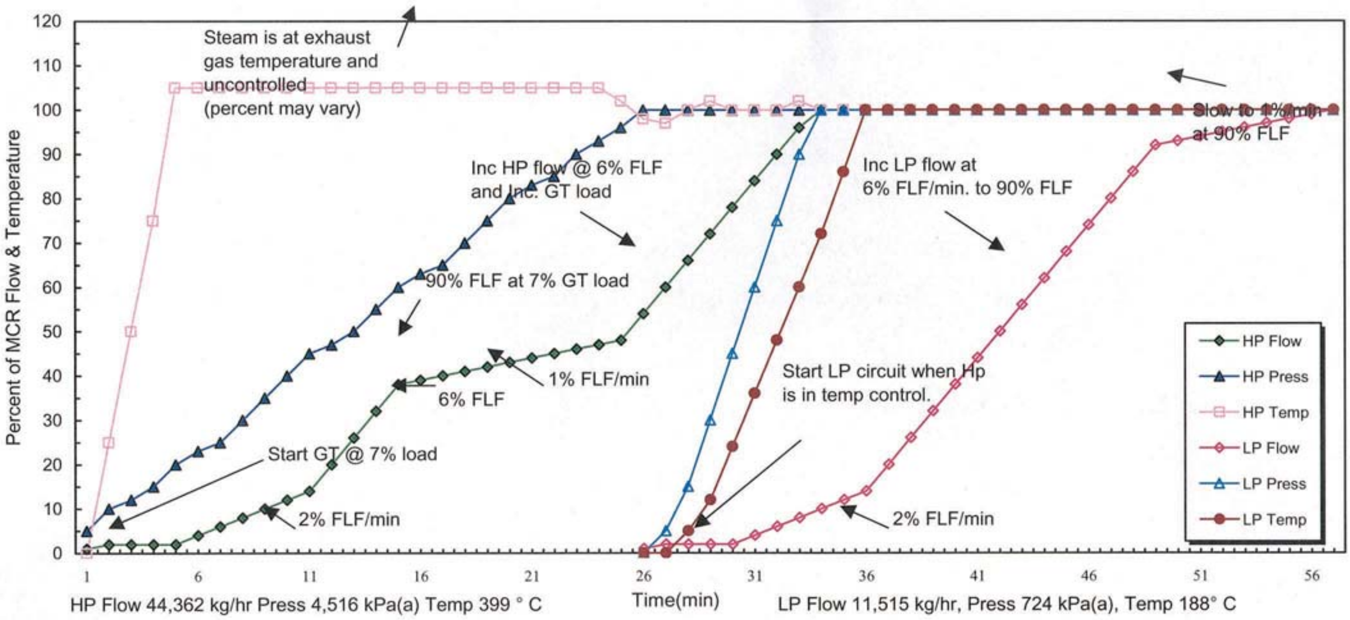

Figure 7 Typical start-up curve for an Dual Pressure OTSG coupled to a 40 MW LM6000 GT innovative steam technologies. Contrast # CXXXXX. Start-up curve from cold – in percent of MCR guarantee.

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. This needs to be accounted for in the project evaluation. Essentially, feedwater pumps need to be bigger than those for drum units. This marginal increase in capital and operating costs will be offset by the elimination of the bypass stack.

7. 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 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 (175°C), 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(2.5°C) 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.

8. 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. 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.

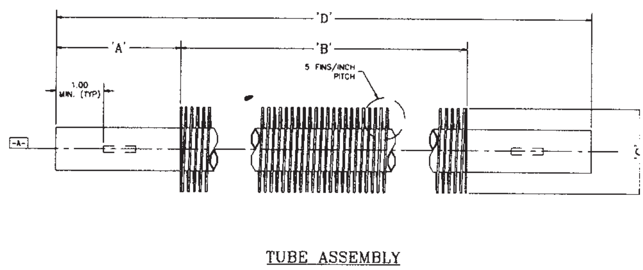

Figure 8 Fin pitch illustration.

The OTSG system does not require soot blowers, even with liquid fuels. Design considerations would be made if Naphtha or a #2 Oil were to be used as the primary fuel for the gas turbine or supplementary firing system. The fin pitch for natural gas units is typically 8–9 fins/in, however when the primary fuel is a liquid fuel the fin pitch would decrease to 5–6 fins/in (Figure 8). This design consideration prevents clogging of the fin spaces and promotes the prolonged efficiency of the unit. In addition, any carbon based constituents that deposit on the fins or heat exchanger tubes can be “baked off” during a dry running scenario. Many HRSG systems that are designed for heavier fuels have no alternative but to soot blow the tube bundle. This reduces the availability of the unit and makes for a cumbersome maintenance requirement, which must be avoided on barge applications.

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%.

9.CONCLUSIONS

This description of a commercial OTSG system has shown that through a combination of high alloy materials and a zero solids water treatment system, this design of heat recovery steam generator offers the following:

- Good performance under load following and two shift operation
- Fast start up
- Ability to operate under dry running conditions
- Reduced feedwater and maintenance demands

REFERENCES

M.Pearson, R. Anderson, Reliability and Durability from Large HRSGs GTCC Design Forges Ahead, *Power Engineering International*, September 1998

M. Brady, Once Through Steam Generators Power Remote Sites, *Power Engineering*, June 1998

T. Duffy, Once Through Heat Recovery Steam Generators Evaluation Criteria for Combined