Innovative Steam Technologies

Heat Recovery for Steam Injected Gas Turbine Applications

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SUMMARY

An innovative heat recovery steam generator now allows a cost-effective approach to gas turbine steam injection, even for peaking applications. Technologies of waste heat recovery by use of a once through steam generator (OTSG) and simplified water treatment have been successfully demonstrated in combined cycle applications. Over one million hours of operation in the field with combined cycle OTSGs have shown the characteristics that make this technology ideally matched to steam injection. Passive water treatment, elimination of deaeration systems and drums, fast transient response, dry operation capabilities, and simplicity of controls are well matched to all steam injection applications. The first OTSGs, specifically matched to a peaking application have been delivered for three 80 MW gas turbines.

INTRODUCTION

Steam injection into a gas turbine increases power, reduces heat rate and NOX. Steam injection has been used for over forty years in some gas turbines to increase power. In recent years steam injection has been more extensively used for NOX control, and to provide flexibility in cogeneration service. The next generation of many turbines is planning to use steam cooling. All of these applications need a source of very clean dry steam at pressures, generally greater than 300 psig. In a combined cycle, or when installed at an existing steam plant, superheated injection steam is available as extraction from the steam turbine or from a low pressure section of the HRSG. In installations where a process steam HRSG is used for cogeneration, water injection is often used since the steam is not sufficiently clean, the pressure is too low for injection, or the steam for process requirements has a high economic value. The development of a new type of steam generator now gives systems design engineers the flexibility to cost-effectively use steam injection for peaking and intermediate duty applications. In applications that can not economically justify combined cycles but can reduce the installed cost per KW and reduce operating costs through steam injection, the development of the OTSG now allows steam injection to be considered economically practical for many peaking machines. With thousands of peaking gas turbines already installed, the OTSG development now permits repowering to be considered for increased power and reduced emission. When the turbo generator design has sufficient mechanical and electric power margins, 10% or more peaking power can be gained at competitive cost by repowering existing machines. By this type of peak power addition permitting problems can be minimized.

The use of supplementary firing the heat recovery steam generators to produce extra steam for injection into the gas turbine can also be a peaking option. The high degree of flexibility inherent in an OTSG without the need for fixed boundaries between superheater and evaporation heat transfer sections, is a key consideration for this type of peaking system.

Waste heat recovery, using an OTSG for injection steam, eliminates drums, many valves, boiler water chemicals, boiler blow-down and the need for an exhaust by-pass valve and stack. By elimination of drums, transient peaking and spinning reserve applications become practical with OTSG technology. Lower water treatment costs can also result with the OTSG. Typically, both drum boilers and the OTSG require D.I. feedwater in this application, but the OTSG eliminates the need for costly blow-down of boiler chemicals.

OTSG Design and System Simplification

The OTSG is the simplest design possible to recover waste heat from a gas turbine. It is configured as a serpentine tube bundle with parallel circuits. Water enters at one end and exits as superheated steam. Figures 1 and 2 illustrate the simplicity of this design when compared with traditional drum designs.

A photograph of a circuit (Figure 3) shows that actual hardware is as simple as the schematic. Drums, level controls, blow-down, chemical injection, numerous valves ßand other components are eliminated with the OTSG design. A high nickel stainless steel, used in the tubes, allows operation without the need of any chemical additions or the need to deaerate the boiler feedwater. The tube material also

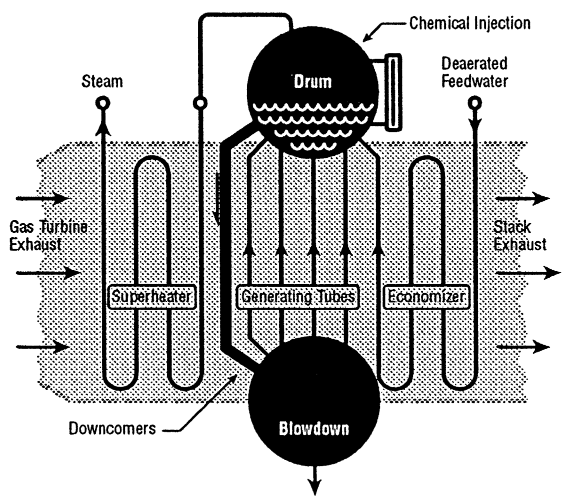


Figure 1 Typical drum-type HRSG (horizontal gas flow without recirculation pump).

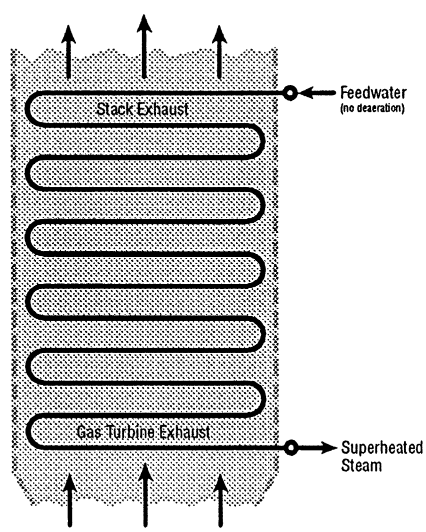


Figure 2 Typical OTSG (vertical or horizontal gas flow).

permits dry operation at full power. Thus, an exhaust bypass valve and an auxiliary exhaust stack are not needed to operate the gas turbine if the steam is not available.

Twenty one OTSGs are in operation, with more than one million accumulated hours. Two units have operated over two hundred thousand hours without the need of waterside cleaning. Most OTSGs use passive water treatment, that is, neutral D.I. water polished to less than fifty parts per billion total dissolved solids. Oxygen control is not required and several OTSGs have been operating without a system deaeration for over one hundred thousand hours each. Figure 4 is an overview of these high time units installed in Okarche, Ok. in a natural gas processing plant. No additional personnel were added to the operating staff for these two combined cycles. Simplicity of the OTSG resulted in reduced complexity of the steam plant, and allowed fully automated operation of both combined cycles for the last fourteen years. Passive - neutral treatment of feedwater and boiler water also contributed to the full automation at the Okarche, OK. gas process plant with only a minimum attention by operators.

A graphic comparison of the system's advantages of the OTSG technologies, compared with natural or forced circulation drum boilers is shown in Figure 5.

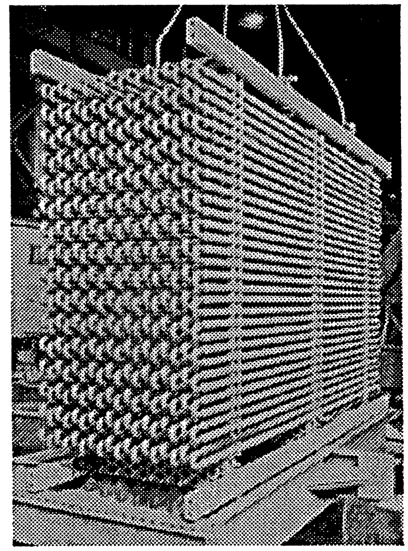


Figure 3 OTSG with feedwater in at top left and superheated steam out at bottom left.

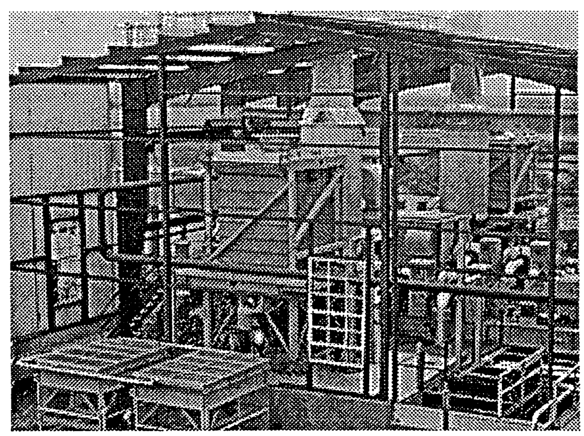
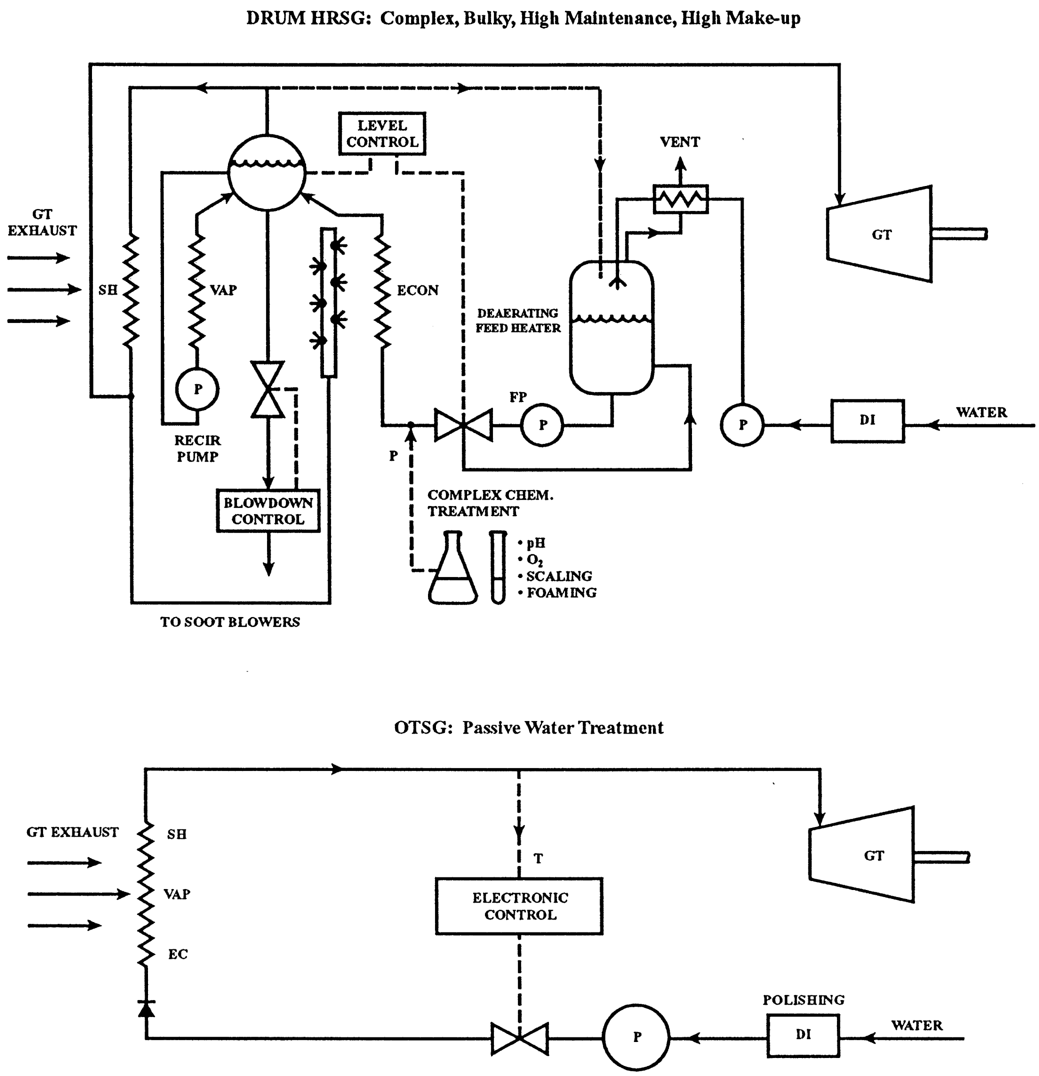


Figure 4 GPM Corporation combined cycles with two OTSG's and exchange resin systems.



RELIABILITY GAINS:

- **Dramatic Recuction in Component Count**
- **Simplified Controls**
- **Passive Water Treat**
- **Dissolved Solids Control Only**
- **No Soot Blowers – Self Cleaning**
- **No Blow Down**
- **Dramatic Reduction in Joints, Gaskets, and Glands**

***Figure 5** Steam injected Gas Turbine (GT) schematic comparison between OTSG and drum HRSG.*

A total of nine OTSGs, selected for simplicity, are now installed on the TransCanada Pipeline. An exemption from the strict requirements for licensed operating engineers has been granted to all OTSGs in Ontario, Canada. It was authorized because of the inherent safety in the all tubular design configuration with the small mass of water and steam all contained in small diameter tubes, and the capability to operate safely without feedwater.

Figure 6 shows two of the five operating units in Ontario on the pipeline. This power plant is planned to be operated remotely without operators for most of the time. This plant produces about thirty eight MWs. Three new additional pipeline OTSGs were commissioned in 1994 in another Ontario location, and four additional units have been delivered for startup in late 1996 on the same pipeline. All nine OTSGs on this pipeline are outdoor installations with air-cooled condensers.

Mechanical Configuration

Since the OTSG uses forced circulation, it can be installed with horizontal or vertical gas flow paths to best match the site or economic evaluation of the project. Figures 7 and 8 illustrate both of these configurations using fully modular steam generators. For minimum plant height a horizontal flow, using horizontal tubes, can also be arranged. As a result of the design simplicity and the use of small diameter thin wall tubing, a single module steam generator of several hundred thousand square feet can be delivered to most sites. A dual pressure unit of about two hundred thousand square feet is shown being installed at a remote site in Figures 9, 10 and 11. Two units, as shown in Figure 6, took about four hours to erect in position as complete steam generators. To complete the installation of mechanical equipment only the inlet feedwater and outlet superheater lines need to be connected and the ducting seal welded.

The OTSG is inherently rugged and can be readily designed for rapid transients, high-pressure and high-temperature operations. Figure 8 is a vertical tube configuration operated at inlet gas temperature of 2500 degrees F with outlet steam at 1500 degrees F. This unit is being developed for the US DOE to improve cogeneration in exhaust fired combined cycles.

The three OTSGs, designed for steam injection on ABB 11N1 peaking gas turbines, have a horizontal flow path and vertical tube arrangement, as shown in Figure 8. In this arrangement only a few inches extra length in the power plant's plot plan is needed since the OTSG's length in the flow direction is only about 12 inches. Total length of the exhaust ducting is greater, since diffusion takes physical length or space for flow distribution components.

Injection Steam Requirements

The high metal temperatures and high velocity gases in the hot section of the turbine coupled with small passages requires that the injection steam must be extremely

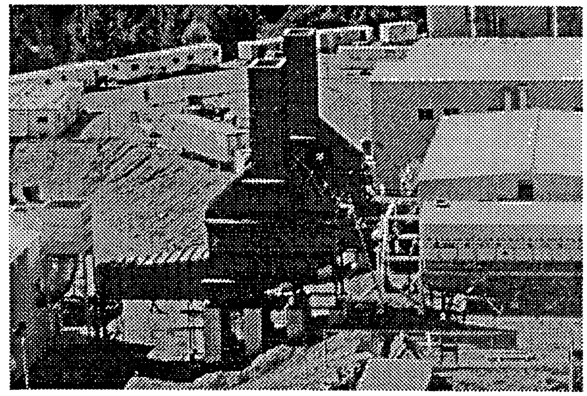


***Figure 6** Two OTSG's installed on a hillside site at TransCanada Pipeline's Nipigon plant.*

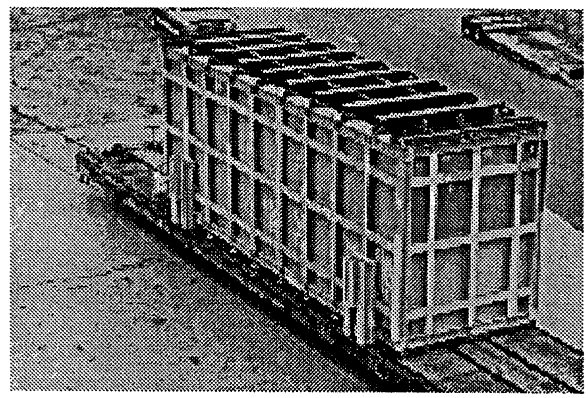


***Figure 7** The tube bundle is suspended from thermally-balanced, sliding beams to accommodate thermal growth in any operating mode.*

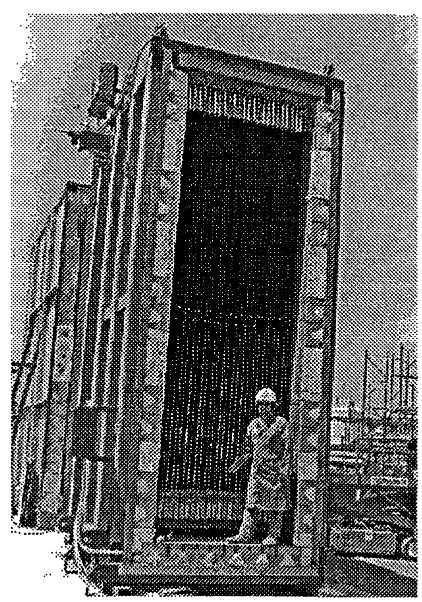
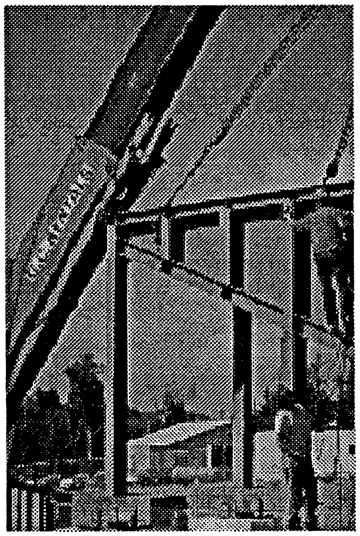
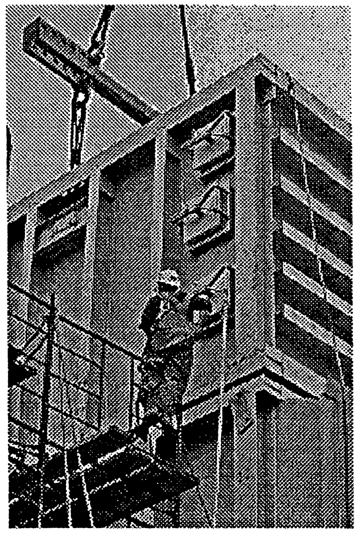
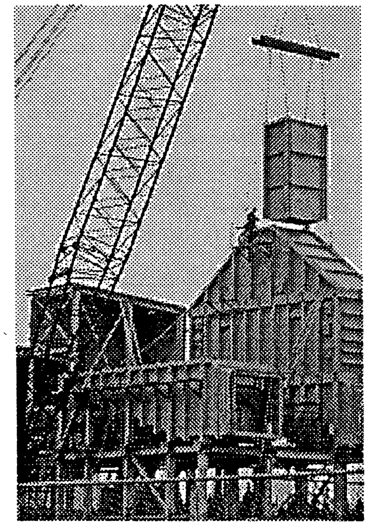


***Figure 8** OTSG with vertical tubes for horizontal gas flow.*

Figures 9, 10, & 11 ***OTSG installation sequence. OTSG's are easy to install. ASME Code welds inside the Section 1 pressure boundary are not required.***

low in entrained solids and moisture. Chemical corrodents, such as alkali metal compounds, must be maintained well below one part per million, to prevent rapid corrosion of hot section components. Moisture can result in thermal stresses, fatigue, and erosion. Thus, a minimum amount of superheat is needed. Performance of the gas turbine is normally improved through the injection of the highest amount of superheat economically feasible. For steam cooled turbines, high-pressure steam at intermediate superheat temperatures may be optimum, but very low entrained solids are necessary, probably less than a few ppb.

Each engine may have a different set of criteria, but they will all require very clean and dry steam. The maximum contaminant allowed is different for each engine. The following is one engine manufacturer's requirements for steam injection for added power, efficiency, and NOX reduction:

- Conductivity	< 0.5 micromhos
- SiO_2	< 50 ppb
- Na + K	< 10 ppb
- iron	as low as possible
- undissolved solids	none

It should be noted, the above is only for a given diesel fuel fired engine with about 10% mass flow of steam related to engine air mass flow. It is also dependent on a limit placed on fuel and inlet air contamination, which is also maintained at low levels. In the above "none" is not possible, but shows the sensitivity of engine manufacturers to contamination introduced into the turbine. Drum HRSG design issues of level upsets, carryover of chemicals, crud, rust and exfoliation of superheater tubes cause extra concern in steam injection systems, since chemicals and particulates can cause more damage in gas turbines than in steam turbines.

Operation Requirements

The OTSG is well matched to the demanding operational requirements of steam injection. In addition to steam purity criteria, steam injection is often applied to systems with challenging operational requirements, such as peaking and cyclic cogeneration service. Many applications will require frequent and rapid starts. Peaking and dispatched intermediate duty will also require fast load changes. In peaking duty most of the time will be in cold stand-by waiting to be rapidly dispatched. This type of operation can be the most damaging and difficult for carbon steel drum boilers. For many cogeneration applications steam injection would also be cycled between demand peaks for process steam and electricity.

Low cycle fatigue, transient drum level control, boiler water chemistry, oxygen scavenging, standby, and prevention of chemical carry-over are some of the more critical problems for cycling duty drum boilers. For heat recovery to produce only enough steam for injection, or steam cooling, the surface area is a small fraction of a combined cycle heat recovery steam generator (HRSG). Thus, the complexity and large number of extra components plus operating costs may make drum HRSGs uneconomical in many peaking and some intermediate duty applications.

NOX reduction steam injection turbines, capable of large power gains by steam injection, and the use of steam cooling requires a new approach to steam generation to be economical on simple cycle installations.

OTSG Advantages in Steam Injection

The simple configuration integrated with high nickel stainless steel and passive water treatment, should prove to be ideal for steam injection service. For peaking duty, the OTSG may be the only economically viable solution for many sites.

Advantages of the OTSG include:

- a - gas turbine corrosion and erosion protection
- b - rapid start and cyclic operation capabilities
- c - elimination of feedwater heating and deaeration equipment
- d - elimination of boiler chemicals for pH, oxygen, and scale control
- e - dry operation capabilities to prevent damage when mistakes occur, or in the case of emergency operation of the gas turbine without the requirement for by-pass exhaust system
- f - dry standby or lay-up without the need of nitrogen blanketing to prevent water-side corrosion when unit is on cold standby
- g - moisture carryover protection
- h - low water treatment costs by elimination of blowdown and loss of chemicals
- i - unattended, or reduced number of operators
- j - it is a single, complete heat recovery unit, providing rapid erection and commissioning
- k - compact, light weight with vertical or horizontal gas path for maximum siting flexibility
- l - inherent freeze protection (eliminates need of heated building)
- m - low cost

In the following section an explanation of each of the above advantages is given in more detail. In general, the comments are applicable for new installations and repowering existing simple cycle peaking gas turbines with steam injection for NOx reduction and increased power. These advantages take on even greater significance for future steam cooled gas turbines for peaking and baseload applications.

A - GAS TURBINE CORROSION AND EROSION PROTECTION

The most critical issue in steam injection of gas turbines is to maintain the high steam purity listed above. Any deviation from stringent turbine manufacturer's requirements could result in damaging corrosion, erosion, and deposition. Drum water treatment to control pH normally requires phosphates that have high sodium levels. Carryover and upsets in chemistry, swell during transient operations, and level control malfunctions are major causes of drum water ingestion and chemical carryover into steam turbines. The consequences for carryover into the gas turbine hot section parts are more damaging than for steam turbines. Standard specifications for drum unit solid entrainment in the steam is to maintain them at less than 1.0 ppm. For some gas turbines total solids carryover is specified below 50 ppb. To keep solids less than 50 ppb takes special drum internal or external separation equipment. In addition, very low solids must be maintained in the drum by using D.I. feedwater and extensive use of volatile boiler water chemicals. Cyclic duty can result in upsets that further challenge the maintenance of high-purity steam.

In an OTSG system the feedwater and consequently the steam is maintained at less than 50 ppb TDS through the use of a full-flow mixed bed polishing system. This type system has proved highly effective and reliable in OTSG combined cycle installations that have been operating over 10 years. Although the operating experience on combined cycles does not include 100% makeup, as in steam injected engines, one system using six OTSGs has been designed for 100% makeup (Figure 12). This system was designed for 180,000 pounds per hour, but generally operated at less than 50,000 pounds per hour of makeup feedwater. Feedwater in this system has a typical measured conductivity of less than 0.1 micromho and on periodic analytical measurements has shown TDS levels less than 10 ppb in feedwater. It should also be pointed out that hundreds of gas turbines have been using the same water treatment recommended for the OTSG feedwater for NOx water injection with good results for over twenty years.

In an all stainless OTSG the purity of the feedwater determines the steam purity. The steam purity is better than the engine feedwater total dissolved and suspended solids on a steady state basis Controlling water conductivity entering the OTSG is relatively simple and reliable when compared to controlling the solids carryover from a drum unit. Simple conductivity transducers that continually monitor the water's conductivity, have high response and can reliably alarm or shutdown the system at any level of dissolved solids deemed dangerous to the turbine before the contaminated water is

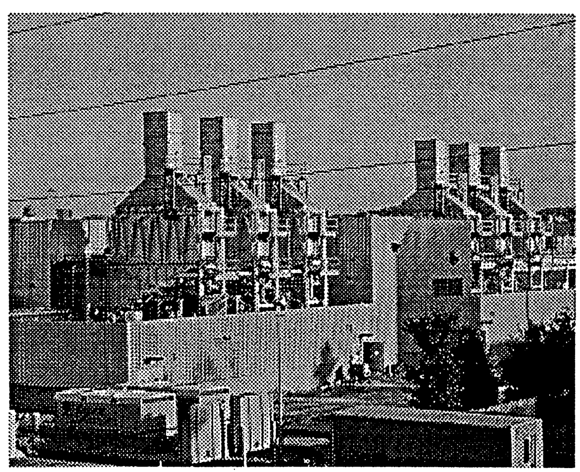


Figure 12 Six single-pressure OTSGs installed at York, Pennsylvania.

evaporated. Suspended solids in the feedwater can also be filtered effectively in the cold liquid state much more efficiently and cost-effectively when compared to filtering steam at the outlet.

Exfoliation of superheater scale and corrosion products have been a serious problem in causing erosion of steam turbines resulting in efficiency degradation and replacement of blades in steam turbines. Filters in high temperature and pressure lines to the turbine have been considered, but have cost and pressure loss issues. The use of Alloy 800 series material in the OTSG eliminates exfoliation caused damage. No evidence of scale buildup or exfoliation has ever been observed, even with OTSGs that have operated dry for thousands of hours in gas turbine exhausts, up to 5000 hours at 1100 degrees F. Testing of other superheater tubes of higher alloy content shows no exfoliation to 1600 degrees F.

B - RAPID START AND CYCLIC OPERATION

Mechanical design and construction of OTSG is optimum to minimize stresses during rapid starts and cyclic operation that many steam injection engines are applied. By elimination of drums and large diameter interconnecting pipes a basic cause of high cyclic stresses is minimized and largely eliminated. The elimination of thick wall drum sections and hundreds of thick to thin wall transitions, commonly required in natural circulation, or forced circulation drum units, minimizes cyclic stresses. High nickel stainless steel with high-strength small diameter seamless tubing allows thin wall construction throughout the entire unit. The use of machine produced butt orthogonous welds throughout the construction further improves the transient performance. The thin wall construction, in addition to minimizing transient thermal stresses, also reduces mass and thermal inertia, thereby allowing fast thermal response for rapid load transients. For very rapid on load requirements the superheater outlet manifold and piping to turbine will become the limiting factors. Special header design and high-temperature electric heaters can be useful in these applications to allow the maximum rate of steam production to closely follow the maximum rate of turbine loading.

C - ELIMINATION OF FEEDWATER HEATING AND DEAERATION EQUIPMENT

High nickel alloys used on all water wetted and steam side components do not require deaeration or pH control. In addition, by using stainless steel fins on the feedwater preheating section feedwater temperatures as low as 40 degrees F can be considered for natural gas and DF#2. Visible plume from exhaust is generally more of a limit than condensation and corrosion with materials used in the OTSG construction. Fouling from DF#2 soot can also build up below the dew point.

The OTSG's unique ability to operate dry allows soot deposits to be rapidly removed by it's self-cleaning feature of cooking off soot when the temperature of the preheater is raised above 830 degree F by dry operation.

The OTSG reduces system complexity and cost through the elimination of deaeration and feed heating components and controls. In addition, upsets in either feed heating or deaeration with carbon steel drum units can result in system shutdowns (or corrosion), reducing the power plant's availability.

D - ELIMINATION OF BOILER CHEMICALS FOR pH, OXYGEN, AND SCALE CONTROL

The OTSG uses passive control of feedwater. Contaminants are removed from the water, but nothing is added. Solids are removed from the water by R.O. and or D.I. and polished to less than 50 ppb by a mixed bed D.I. No chemicals are added or required for the OTSG. It only requires a conductivity measurement to ensure that the TDS levels are acceptable. High blowdown rates for 100% makeup on drum units for steam injection are eliminated. The addition of chemicals to prevent scaling, provide pH control, eliminate oxygen and prevent priming are not required with the OTSG. With drum units on AVT adequate control of chemistry results in 100% loss of all chemicals fed into the system resulting in high operating cost for chemicals for oxygen and pH control, plus the need to D.I. and polish the feedwater for a drum unit to prevent scaling.

E - DRY OPERATION

An OTSG can be designed to operate dry at gas turbine exhaust temperatures. This will allow the gas turbine to operate in emergency peaking situations. It also provides insurance against damaging equipment in case of failure, or error in equipment or personnel. Since steam injection may often be used in peaking units that have minimum or no operators, this feature may be especially valuable in this type of application. If an exhaust by-pass valve and stack are used for this function in a drum unit, their initial costs are large in proportion to the HRSG's cost, since the steam injection HRSGs normally require much less surface area when compared to combined cycle units. In addition, the diverting valve will generally occupy more site area then the entire OTSG typically used for steam injection.

F - NON OPERATING CORROSION PROTECTION

OTSG shutdowns are normally dry. The feedwater is shut off few minutes before the gas turbine, resulting in the unit being dried out as the water is evaporated. Dry starts are normal. No other shutdown corrosion prevention is necessary. Nitrogen blanketing or filling with treated water are not necessary. In vertical tube units an emergency trip of the gas turbine may cause some water to remain in the bottom of the tubes. This will dry out to small pockets of water at the bottom of preheated U-bends. Using Alloy 800 series material presents neither a corrosion nor a freezing problem. If the gas turbine can be restarted, this small amount of water can be dried out in a few minutes at no load. Hydrostatic tests of vertical tube OTSGs should be generally performed when the turbine is operational, since it provides a quick means of rapidly drying out a unit full of water if ambient temperatures drop to freezing levels. Other methods of dewatering OTSGs have also been demonstrated in tests.

G - MOISTURE CARRYOVER PROTECTION

Traditional drum boilers under cyclic conditions expected in many steam injection applications can be prone to drum level upsets. Rapid startups, step load changes can change steaming rates and pressure and corresponding drum levels dramatically. The dry start of the OTSG allows superheated steam at low pressure to exit the steam generator as water is added to the already warm preheater sections (a couple of minutes after the turbine reaches no load conditions). Water rate would be increased until the superheater temperature approaches the set point from the safe, or hot, side. In this process the superheater temperature will be at the turbine exhaust temperature until it approaches the set point, and a feedback control brings it down to the set point. Drum shrink and swell transient controls are replaced by providing a long superheater length during rapid on load transients. In off load transients the superheater length can also be rapidly reduced by shutting off feedwater, or reverse flow to rapidly increase the length of superheater to maintain adequate superheat and minimize superheat temperature reductions as the exhaust temperature of the turbine rapidly reduces. The outlet temperature of the superheater will, at the best conditions, closely follow the exhaust gas temperature of the turbine, once it has reduced to the full power steam temperature set point. A variable superheater length is the key to providing the maximum superheater temperature control, and prevention of moisture carry over in transients causing swell.

H - LOW WATER TREATMENT COSTS BY ELIMINATION OF BLOWDOWNS

The primary cost of water treatment for both OTSG and drum units is to obtain D.I. feedwater. A drum unit would not, typically, use a mixed bed polisher in the feedwater system, as required by the OTSG. However, without a polishing system a high rate of blowdown will be required since 100% makeup is required. If phosphates and other solids are used to prevent scaling, control pH, and oxygen control they will be lost in the blowdown discharge, causing a cost and disposal problem. Use of volatile chemical treatment will cause loss of all the chemicals as they are carried- over and injected into the turbine. In an OTSG with no chemical additions, chemical loss and blowdown are zero. Cost for the mixed bed polishing function for an OTSG is, generally, expected to be less then the chemicals used and lost in a 100% makeup system for a drum unit. In addition, chemicals or crud concentrating in the drum are a corrodent to gas turbines, if carried-over in even small amounts during transients or normal operation.

I - UNATTENDED OR REDUCED OPERATING PERSONNEL

An OTSG's simplicity, capability of dry operation, and inherent freedom from boiler explosion potential allows unattended operation. In the first government agency approached to eliminate operators, the OTSG was exempt from requirements of the Province to have licensed engineers operating boilers. In Ontario, Canada they revised their codes to allow remotely monitored and dispatched operation of OTSG combined cycles. Although it is not certain other agencies would follow, the opportunity exists to eliminate a major cost issue, particularly for peaking systems.

J - SINGLE COMPLETE STEAM GENERATOR PROVIDING A SINGLE-LIFT MODULE

All 21 OTSGs currently operating with surface areas of up to 200,000 square feet are s single-lift unit with only the feedwater inlet and the superheater steam outlet required to be connected in the field. This reduces time span and cost of erection, particularly important in repowering of existing simple cycle machines. In a number of pipeline gas turbines, the steam generator was installed in the ducting in a few days, and then run dry until the rest of the steam equipment was ready, minimizing down time for the pipeline turbine driven compressor.

K - COMPACT, LIGHT WEIGHT, WITH VERTICAL OR HORIZONTAL GAS PATH FOR MAXIMUM SITING FLEXIBILITY

A typical OTSG for a steam injected 80 MW engine is shown in Figure 13 ready for shipment. It is for a horizontal gas flow path with vertical tube installation. Since the OTSG is generally designed with one inch diameter tubes and has no drums, downcomers or recirculation pumps, it is inherently the most compact arrangement when compared to drum units. It can be installed in a number of different flow arrangements, such as directly over the engine, with vertical gas flow in the existing silencer for minimum footprint. For minimum height, horizontal tubes mounted at the turbine engine's centerline, is another one of many alternatives.

L - INHERENT FREEZE PROTECTION WITHOUT HEATED ENCLOSURE BUILDINGS

Horizontal tube OTSGs with vertical gas flow are self-draining with the inlet water at the top and superheated steam header at the bottom. Horizontal tube units with horizontal gas flow will also drain but it will take longer. Vertical tube units do not drain automatically, and would normally be dried out during normal shutdown by turning feedwater off shortly before engine is stopped. No load engine operation for a few minutes will dry all configurations for fast freeze protection without heat tracing or internal heater. On a cold start operating the engine at no load for a few minutes will allow the OTSG to heat up to above freezing conditions before water is introduced. Feedwater lines and some types of gage lines will require heat tracing. Considerable cost can be saved in cold climates by elimination of heated building enclosures. Figure 14 is a typical outdoor installation in -40 degree conditions. For climates in very low temperatures a cold start is safe without concerns of tube cracking from notch sensitivity using Alloy 800 series tubes, even at minus 60 degrees below zero.

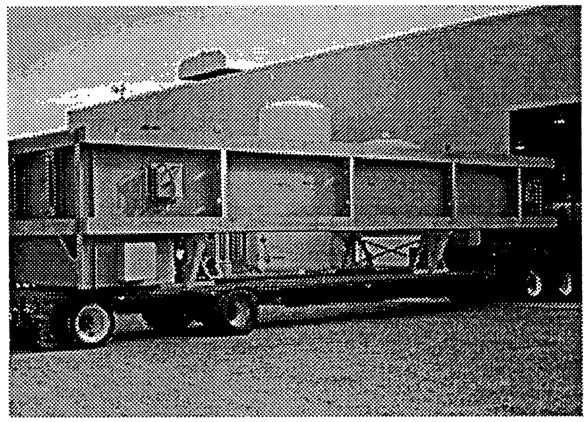


Figure 13 ***An OTSG uniquely designed for steam injection in 80 MW peaking gas turbines. This is one of three units currently being installed in Puerto Rico.***

M - LOW COST

Current OTSGs are cost competitive with carbon steel drum units for full surface area combined cycle heat recovery steam generators. Simplicity of systems, elimination of many system's components, fast erection times and short commissioning time spans contribute to competitive position. In a steam injection gas turbine system the surface area of the heat exchanger is relatively smaller and the relative costs saved in the systems, component elimination and commissioning will be proportionally larger. In addition, operating costs are expected to be significantly lower, as a result of passive water treatment and reduced operating personnel costs.

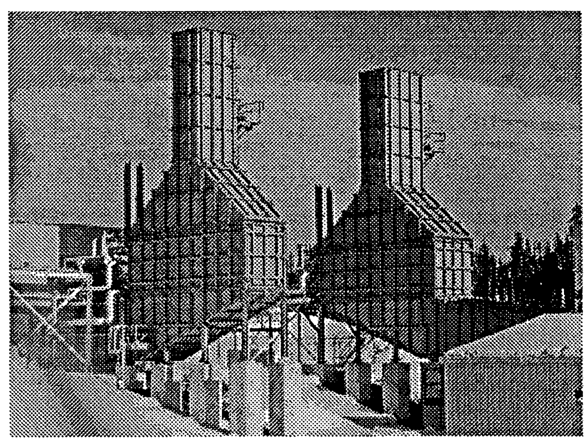


Figure 14 ***Two OTSGs installed outdoors in a severe winter environment.***

SUMMARY

The OTSG provides an innovative component that can reduce costs for steam injected gas turbine projects. For some projects the availability of the OTSG for steam injection or cooling may make the project cost-effective when a combined cycle or single cycle project is unattractive due to capital or operating cost evaluation criteria.