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RELIABILITY AND AVAILABILITY EVALUATION FOR DRUM-TYPE AND ONCE THROUGH HEAT RECOVERY STEAM GENERATORS

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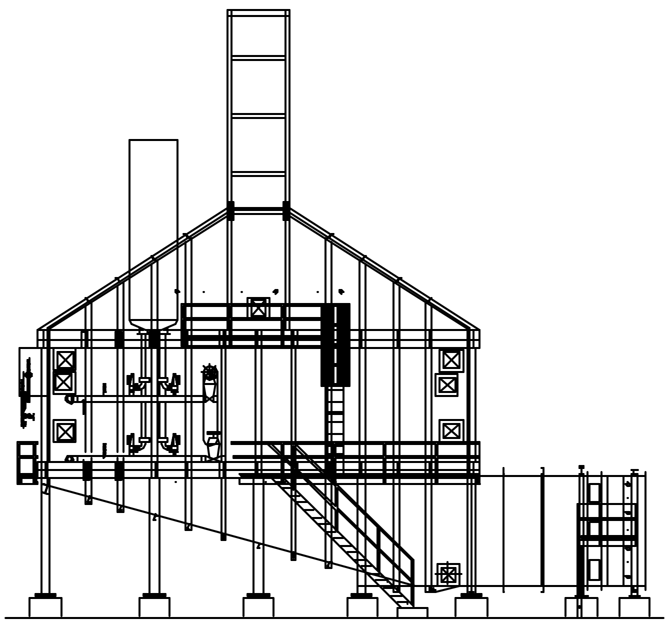

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RELIABILITY AND AVAILABILITY EVALUATION FOR DRUM-TYPE AND ONCE THROUGH HEAT RECOVERY STEAM GENERATORS

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ABSTRACT

Reliability and availability are critical issues for owners and operators of today's modern power plants. Heat Recovery Steam Generators (HRSGs) often play a significant role in the overall availability of combined cycle and cogeneration plants. By understanding the most common causes of unscheduled outages in HRSGs and following proper maintenance programs, plant returns can be improved.

Using EPRI published data on criticality rankings for HRSGs, the major factors causing boiler downtime for both drum-type and once through steam generators are evaluated. By using modern boiler design and materials, many of the troublesome components specified by EPRI can either be eliminated or have their reliability improved.

Power plant owners can use this information for both the specification of new HRSGs as well as for the development of maintenance programs for existing plants.

Introduction

Combined cycle power plants are based on combining two different thermodynamic cycles; the Brayton cycle, in the form of a gas turbine, and the Rankine cycle, in the form of a steam cycle. The waste heat from the gas turbine engine is recovered and used to generate steam in a heat recovery steam generator (figure 1). By joining these two cycles together, both the plant's efficiency and the power output can be increased. By adding a steam cycle, when comparing to the base simple cycle gas turbine plant, the energy efficiency can be up to 20% higher and total plant power output can increase by 40%.

The benefits of a steam system do have a cost. By adding the steam cycle, the complexity of the plant is greatly increased. A heat recovery boiler, steam turbine, water treatment system, piping and extra controls are now required for the power plant operation. Each component will have costs associated with both maintenance and efficiency that must be evaluated to ensure the proper equipment selection. Costs can either be grouped as a capital cost (initial investment) or a life-cycle cost (the ongoing cost of operating the equipment). When costs are estimated for the entire life span of a power plant, the importance of life-cycle costs is observed.

One of the major factors that affect a plant's bottom line is availability. Availability is defined as the percentage of time that a component will be available for service if required. The two main factors that availability accounts for are reliability, the time between failures, and maintainability, the ease of repair. Availability does not take into account time spent on repairs during scheduled maintenance shutdowns, only unscheduled repairs or equipment malfunctions. Any unscheduled repairs that must be made on the component affect availability numbers greatly.

Each component of a combined cycle plant has a degree of maintenance and reliability that must be factored into their selection. It is imperative that equipment is selected that is simple and inexpensive to maintain and repair, as well as reliable. Unscheduled outages are a major concern to plant owners because they can take a much longer time to resolve and the repairs are usually costlier than routine maintenance because of a potential lack of equipment and labor.

Many systems in a plant, feedwater pumps for example, are designed with redundant systems to eliminate unscheduled maintenance. By adding a back-up, the availability can be increased for small components. A heat recovery boiler is a major piece of equipment and back-up systems can not be justified. It is therefore crucial for an HRSG to have high availability.

Any outages to the HRSG will cost the owner money, and this becomes very costly when looked at on a net present value basis. According to the assumptions made in table 3, a 1% lower availability can create a yearly loss of $31,500 USD on power sales alone for a 20 MW steam cycle. This equates to a net present value of $445,000 USD over the life of a plant. This value does not include the labor and equipment cost of repair, which can be an even greater amount, especially if specialized equipment is required or if the site is either remote, or difficult to access.

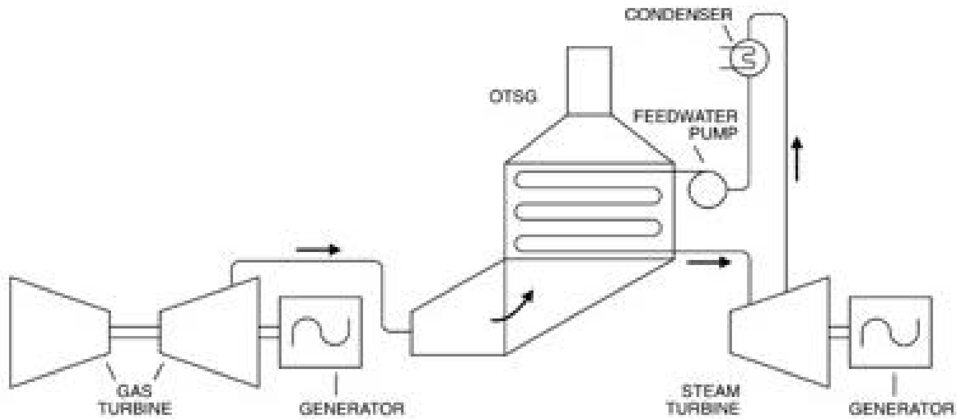

Figure 1; A schematic of a combined cycle power plant.

Availability in Once Through and Drum-Type Heat Recovery Steam Generators

The drum-type Heat Recovery Steam Generator (HRSG) design has been used for decades in combined cycle plants. The design has evolved very little during its life span. Plant designers have accepted the operating and availability issues associated with this type of boiler because of the length of time that they were available on the market with no alternative technologies.

Most of the unscheduled outages for drum-type HRSGs can be attributed to the following:

- Tube or weld failures caused by corrosion or defects
- Instrumentation or control system malfunction
- Piping failures
- Valve malfunction
- Ductwork failures
- Drum level and water quality control issues
- Exhaust bypass system malfunction

The Once Through Steam Generator (OTSG) was developed in the 1980's by Solar Turbines, the United States Navy and the United States' Department of Energy. The design criteria behind the project was to create a simplified boiler that was light, compact and could operate more reliably than a conventional drum-type boiler. The technology has been further developed by Innovative Steam Technologies (IST).

The result of this research was the development of a continuous flow heat exchanger, with a serpentine, incoloy tube bundle (Figure 2). The once through design eliminates the need for drums. Feedwater enters a header and is evenly distributed into a sufficient number of finned-tube circuits. The economizer, evaporator and superheater have no distinct sections within the OTSG – the evaporation point is free to move up and down within the tube bundle to accommodate the instantaneous operating conditions, in effect creating a variable length superheater.

When the design of the HRSG was being evaluated in the initial OTSG development stage, boiler components were evaluated. There were many components that were not used for heat transfer (the main role of the boiler) and only decreased the boiler's availability. The following items were eliminated with the OTSG's development:

- Steam drums
- Drum level controls
- Blowdown systems
- Bypass stack and diverter damper
- Soot blowers
- Chemical injection systems
- Steam conditioning (Attemperator)

The OTSG is best described as a heat exchanger, because there is nothing complex about its operation. The boiler has a simple control logic and has no moving parts. The boiler itself requires no spare parts, and is designed around a 25 year life span.

The OTSG requires a minimal amount of operator supervision. In fact, one plant that Innovative Steam Technologies supplied boilers to operates unattended. In this case, the high availability of the OTSG is crucial to this plant's operation.

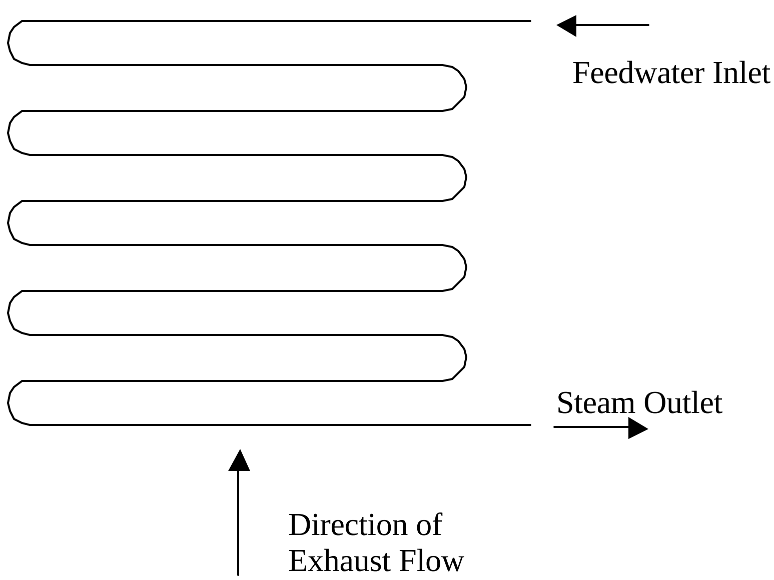

Figure 2; Simplified Schematic of the Once Through Steam Generator Tube Bundle

Design Features of the OTSG that apply to Availability

Incoloy Tubes

The OTSG uses only thin-walled Incoloy 800 and 825 tubing. These high nickle content materials are very resistant to corrosion and are not sensitive to oxygen or pH levels in the feedwater, while still maintaining its superior mechanical properties.

Incoloy 825 (ASTM Grade SB423 NO8825), because of its greater resistance to acid attack and stress corrosion cracking than Incoloy 800 (and much greater than carbon steel tubing), is used in the cold end of the boiler, where the water temperature inside the tubes is lower than the acid-dew point of the exhaust gas. This can cause acid to condense on the outer tube surface. With the use of Incoloy 825, OTSGs can see very low feedwater temperatures, resulting in lower stack temperatures, without corrosion concerns that are present with carbon steel tubing.

Unlike carbon steel tubes, Incoloy 800 and 825 tubes maintain high strength at elevated temperatures (up to 1000°F). This allows for dry-run operation (no steam being produced) for most gas turbines on the market up to 50MW in size. Because of the dry-run ability, the requirement for a gas bypass system is eliminated. Soot blowers are also eliminated because any deposits on the fins or tubes will quickly be removed when exposed to temperatures in the range of 900°F. In effect, the OTSG operates like a self-cleaning oven (Figure 3).

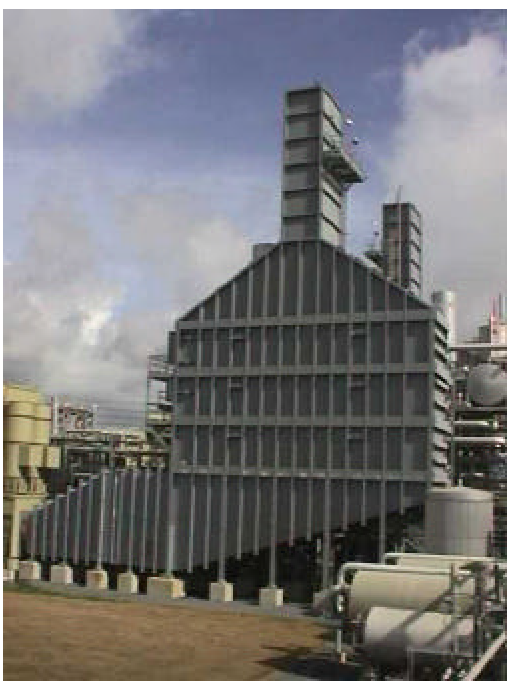

Figure 3; OTSGs are coupled directly to the gas turbine and do not require gas bypass systems

The dry-run ability also helps in boilers that are equipped with SCR systems. One major issue is the formation of ammonium sulfates between the fins, reducing the heat transfer efficiency. Dry-running followed by blowing with compressed air can remove the ammonium sulfate deposits.

In dry-run operation, there is a potential for an oxidation layer to occur on the surface of tubes and fins. To form a layer 0.005" thick would require approximately 1 ½ years of dry-run operation. This problem is limited to carbon steel fins, and would only degrade the boiler performance slightly, and would not actually affect the boiler's availability.

The tubing material is very resistant to water-side erosion, especially since steam velocities are limited to 100 ft/s in the boiler. After millions of operating hours, Innovative Steam Technologies has never seen any evidence of tube erosion in either U-bends or straight sections in incoloy 800 or 825 tubing.

The fact that the OTSG uses only thin-walled tubes means that there is a much lower risk of developing problems associated with thermal cycling of the pressure parts. Drums must be heated slowly and evenly to ensure that no cycling takes place. On plants that have regular starts and stops of the steam system, the life of the drums can become significantly reduced.

Typical sizes of tubing used in OTSGs range in diameters from ½" to 1 ¼" and thicknesses from 0.049" to 0.092". 0.049" is the minimum tube thickness that IST uses due to handling requirements, even if the code calculations allow for a thinner tube.

The fact that the OTSG has no fixed geometry means that the superheater is of variable length. On a drum-type boiler, carry-over of water from the drum to the superheater is a major concern and can either cause scaling from deposits in the water or damage the superheater tubes by quenching them. Drum levels must be closely monitored to ensure this does not happen.

Finning Process

The OTSG uses a proprietary finning process that has a minimal impact on the integrity of the tubes. Instead of the standard industry practice of attaching fins using continuous electrical welding, the fins in the OTSG are attached using a brazing procedure. The braze does not affect the surface of the tubes, eliminating the risk of developing areas of stress concentration on the tubes (Figure 4).

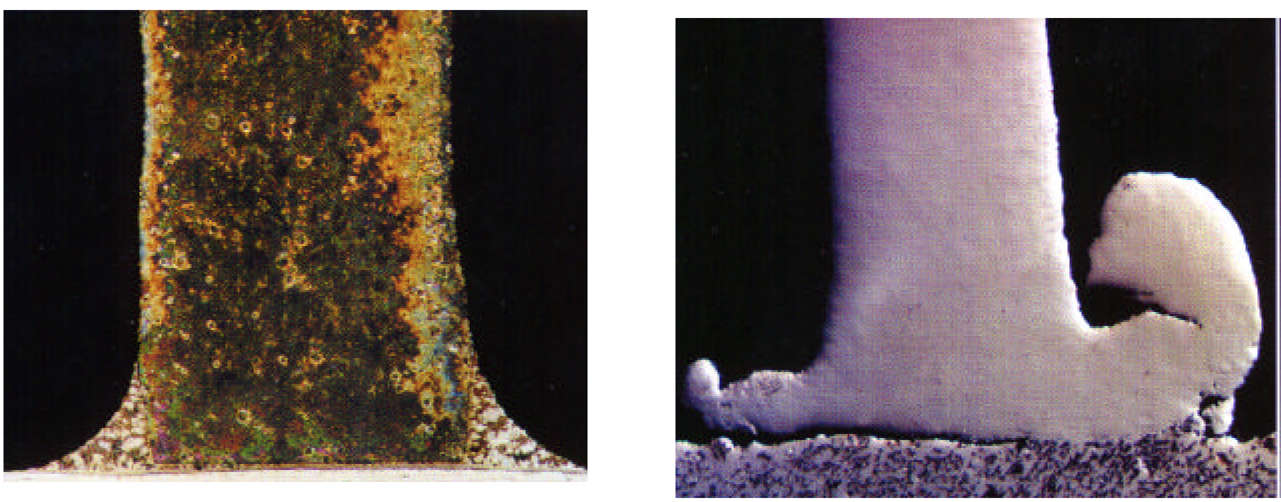

Figure 4; The braze finning process (left) creates a very effective heat transfer surface, while minimizing the impact on the tube integrity.

Tube Welding Process

IST uses an orbital TIG (Tungsten-Inert Gas) welding process that has been specially designed for the OTSG tubing. The welding process is an automated, single pass weld that uses no filler material and creates very consistent weld quality. (Figure 5)

Figure 5; Orbital welding the u-bends to the boiler's tube bundle.

Valves and Instrumentation

The OTSG is based on a simple control system. There is a single point of control – the boiler only needs to control the feedwater flow rate. The control logic does a simple heat balance on the boiler to determine the how much heat is being transferred from the gas turbine exhaust to the water/steam. This information is gathered from the turbine operating data, as well as thermocouples in the boiler (3 at the inlet duct). Triple redundancy is used for the thermocouples to ensure that any calibration errors or malfunction can be detected quickly. There is a final trim done using a feed back loop based on the final steam temperature (measured using 3 more thermocouples). In comparison, a drum boiler requires a larger quantity and many more types of instruments as well as several control valves to maintain drum levels. Every instrument and valve used is a reliability concern. By eliminating a large number of extra controls, availability will increase. (See figures 6 & 7)

Water Quality

The OTSG, because it has no blowdown system, relies on water to be purified before entering the tube bundle. Because the water is treated and the conductivity is tested before being admitted to the boiler, the chance of scaling the inner surface of the tubes is minimized.

By controlling the water quality external to the boiler, the water treatment equipment can be more easily serviced and controlled.

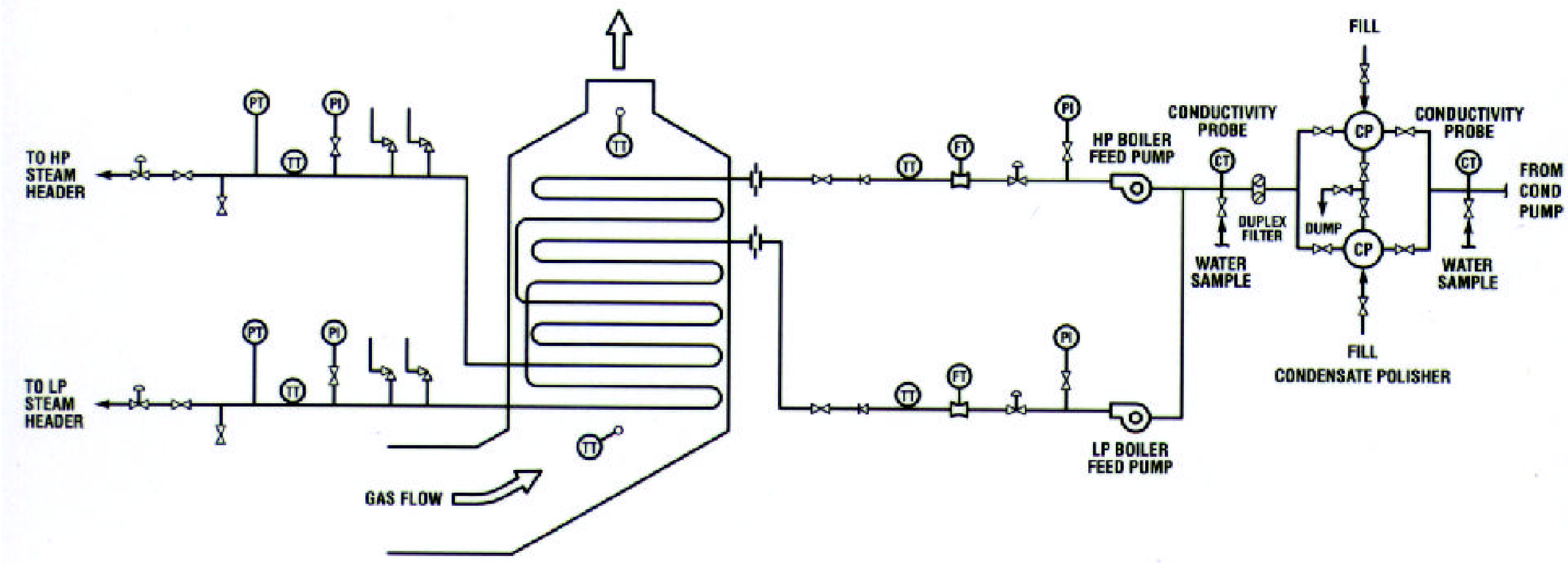

Figure 6; Typical flowsheet for an OTSG boiler

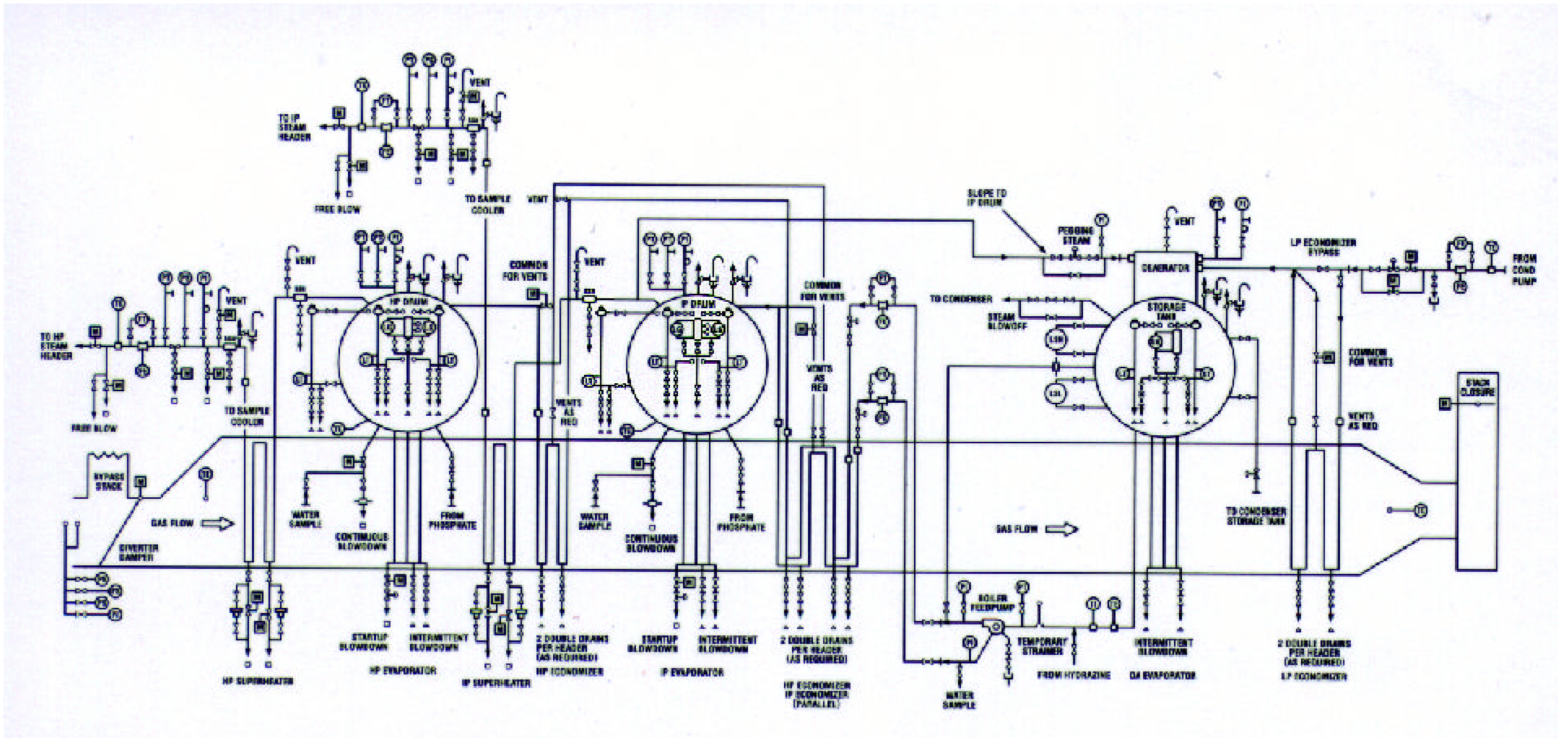

Figure 7; Typical P & ID for a dual pressure drum-type boiler

OTSG Layout

The OTSG has a horizontal tube arrangement with a vertical gas flow path. The tube matrix is supported by Chrome-Molybdenum and Stainless Steel tubesheets. Each of the tube circuits are joined together with u-bends. An OTSG would typically have about 2000 tubes and u-bends.

Every u-bend and tube weld is accessible from maintenance cavities on either end of the boiler (Figure 8). This allows for easy access and simplified repairs to the tube bundle. If there is a problem with one particular tube circuit, the ends can be easily capped, allowing the boiler be back in operation after a few hours – with a small amount of efficiency loss. The u-bend, weld or tube repair can be made during the next scheduled shut-down. A loss of 2.5% of the boiler's surface area only results in less than a 1% loss in steam production.

Because of the tube layout, if any water is left in the boiler when it is shut down, it will naturally drain out of the bottom of the tube matrix due to gravity. There is no chance of water pooling in the boiler. The pooling can be an availability risk in cold climates where the water in the tubes could freeze, expand and crack the tubes. There is also little risk that any water left in the boiler during a shut down will cause corrosion because of the tube quality.

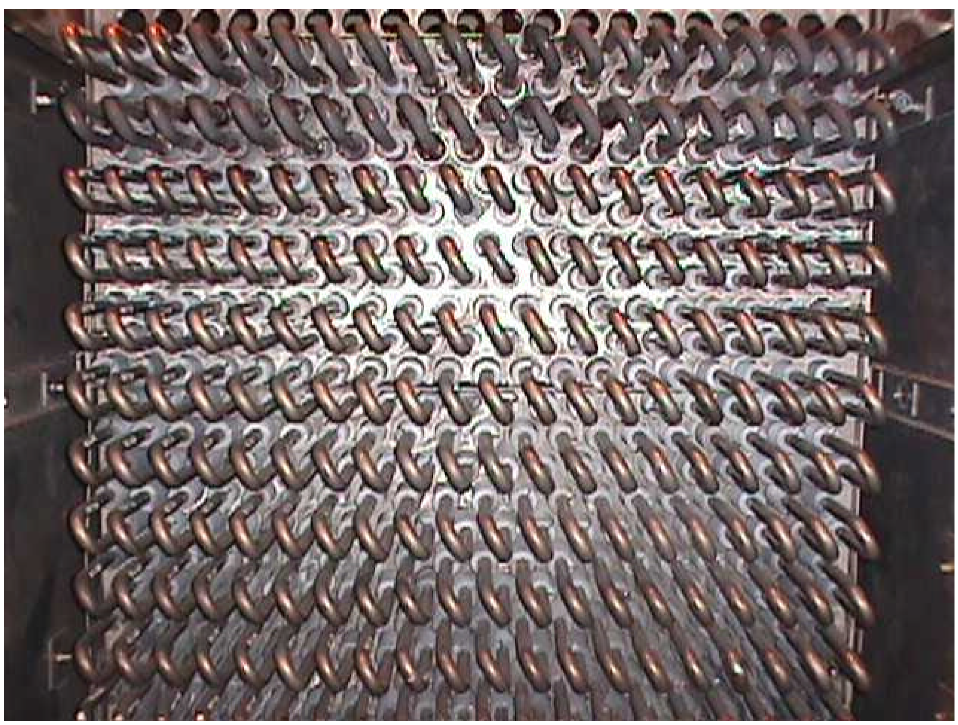

Figure 8; All u-bends and welds are accessible from the maintenance cavities on both ends of the OTSG. In the event of a tube, weld or u-bend failure, a circuit can either be brought out of service with a minimal impact on performance or repaired without causing damage to other tubes.

Comparision of Theoretical Availability for OTSGs Vs. Drum-Type HRSGs

According to published data on boiler failure mechanisms, there are several components in a boiler that contribute significantly to the overall availability. Table 1 shows a listing of these components, the mean time between failures (MTBF) and the mean down time (MDT) required for repair. The components that apply to OTSGs or drum-type boilers are designated.

This information was collected from data on 28 HRSGs in the Electric Power Research Institute's (EPRI) Reliability Assessment System (ERAS) database. The 28 drum-type boilers had a total of 416, 617 cumulative operating hours.

Feedwater System	MTBF (h)	MDT (h)	OTSG	Drum-Type
Boiler Feed Pumps	4,480	17.1	X	X
H.P. Control Valves	16,665	16.8	X	X
L.P. Control Valves	16,665	16.8	X	X
Deaerator	13,887	4.0		X
D.A. Steam Supply Heater	36,215	6.5		X
Polishers	138,872	4.0	X	
Boiler				
Economizer Section	6,944	22.8		X
Evaporator Section	26,039	35.4		X
H.P. Steam Drum	59,517	9.6		X
L.P. Steam Drum	59,517	9.6		X
Superheater Section	416,617	6.3		X
Once-Through Boiler Tubing			X	
HRSG Instrumentation and Controls				
Inst. and Controls -- General	9,920	5.0	X	X
Drum Level Controls -- General	83,323	5.8		X
Superheat Controls -- General	83,323	5.8	X	
High/Low Drum Level	7,575	1.2		X
Feedwater flow Measurement	104,154	11.6	X	
Flow Measurement	104,154	11.6		X
Drum Level Measurement	33,329	4.6		X
Setam Temp Measurement	104,154	4.0	X	
Inlet Gas Temp Measurement	104,154	4.0	X	
HRSG Piping, Valves and Ductwork				
Piping	52,077	6.3		X
Safety Valves	9,469	8.6	X	X
Blowdown System Valves	13,887	5.9		X
Ductwork	83,323	87.6	X	X

Table 1; The main systems that contribute to reduced HRSG availability

For this evaluation, assumptions were made about the OTSG incoloy tubing. Values of 40,000 hours for MTBF and 24 hours for MDT were used for tubing as a conservative estimate. Data was not available for the incoloy tubing at the time the study was done.

After an evaluation was done on the components using the MTBF and MDT values, a theoretical availability number can be determined for both boiler types. The results are listed in Table 2. It can be noted that the OTSG has minor improvements in the availability of the feedwater, instrumentation and controls and the piping, valves and ductwork subsystems. There is a major increase with the boiler subsection. The design of the OTSG tube bundle theoretically has a much higher availability than a drum-type boiler.

SYSTEM AVAILABILITIES	Drum-Type HRSG Model	OTSG
Feedwater System	99.37	99.42
Boiler	99.50	99.94
HRSG Instrumentation and Controls	99.88	99.94
HRSG Piping, Valves, and Ductwork	99.75	99.80
HRSG SYSTEM DESIGN COMPARISON		
Total HRSG System Availability	98.52	99.10
Difference Between Drum Type and Once-Through Design	- -	0.58

Table 2; Predicted availability of once through and drum-type HRSGs.
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Figure 9 compares the relative effect of each boiler's components on availability. It should be noted that the OTSG has either an equivalent availability or improves on the availability of each boiler component. The OTSG also has many fewer components that factor into the availability calculation.

Availability can be vary greatly with the amount of preventative maintenance that is performed. It is up to the plant manager to optimize the amount of maintenance that is performed to balance preventative and repair costs.

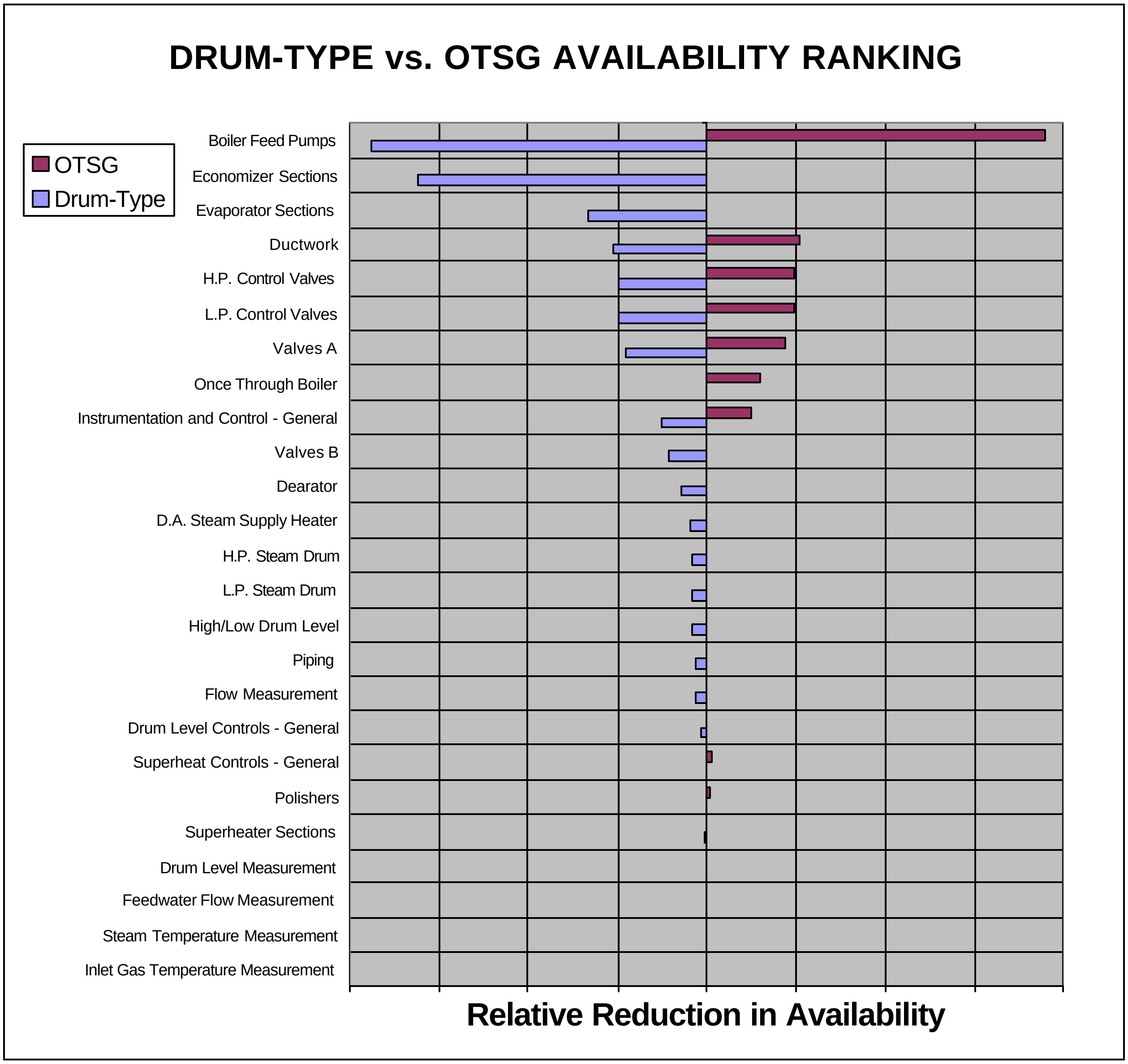

Figure 9; Components that cause reductions in availability for drum-type and once through steam generators.

Discussion of the Test Procedure

The testing procedure done by EPRI has three omissions that should be noted:

1. Gas bypass system was not included in the criticality rankings and would lead to a lower drum-type boiler availability.
2. The study does not factor in equipment such as SCR systems that are now included with boiler designs. SCR systems can cause extensive damage to the boiler components and have a large effect on the boiler's availability.
3. The evaluation of the OTSG and drum-type HRSG assumes that tube corrosion and erosion are the only factors involved in the availability of the drum-type and OTSG tube bundle. The study does not account for tube restraint systems, flow distribution problems or other causes of tube damage.

HRSG Availability Cost Implications

Availability can affect a plant's costs in two ways: loss of revenue from power production and increased costs for maintenance and repairs. Table 3 shows the costs associated with each factor. The important thing to consider is the amount of money that is saved over the life-span of a plant can be quite significant.

Profit from Power Generation (Assumed)	$ 0.02	/kwhr
Total Power Loss	20	MW
Number of Hours of Plant Operation (per year)	7884	hr
1% Loss of Operation due to Availability	78.84	hr
Total Power Sales Loss during one (1) year	$ 31,536.00	USD
Cost of labour for repairs (Assumed)	$ 75.00	/hr
Total Labour Cost	$ 5,913.00	USD
Total Yearly cost due to Availability	$ 37,449.00	USD
Number of Years	25	yrs
Interest Rate	5%	
Net Present Value	**$527,804.13**	USD

Table 3; Sample cost evaluation for plant availbility and maintenance cost factors.