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RAPID CYCLING OF OTSG POWER PLANTS

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The demand for power has been increasing ever since the harnessing of electricity. Effective and efficient methods of generating power has become a greater focus, as the appetites of a growing population has increased, thanks to the advancements in technology. Now more so than ever, the electricity requirements are ever increasing, as new products are developed every year in every field, and electrical consumers such as climate control, handheld devices, even transportation vehicles have led to larger draws for power plants to accommodate. With a greater emphasis on the environmental impacts of power production, renewable energy sources have grown in popularity. Due to the nature of renewable generation, it becomes critical to ensure the grid also has sufficient non-renewable sources to maintain a stable level of power production. As a result, the unpredictable generation from renewables is stabilized by other sources with fast starting and cycling capabilities.

Of the major sources of electricity, none have managed to become the “perfect” solution. Coal has been identified as a major source of pollution, and plants are being decommissioned around the globe. Nuclear power has disposal and safety issues, the latter being brought to the forefront of attention as a result of the disaster at the Fukushima Daiichi nuclear plant. Natural gas, while relatively clean, is still a combustion based source and leads to emissions of NO_x, CO and greenhouse gases. And renewables are clean but expensive to produce, and have major issues of reliability. One successful method for meeting the demands of the grid is a combination of renewables and natural gas, or more specifically wind turbines augmented with gas turbine back up.

Wind turbines operate on a fairly simple premise – the spinning of the turbine through a gearbox will use its rotational energy with a generator to produce electricity. The technological advancements applied to these turbines have produced units that can efficiently generate power without introducing pollutants to the environment. This “free” power does not require consuming of the earth’s resources, only to harness the environment that currently exists. Studies are performed to optimize locations of wind farms, both on land and offshore, while attempting to maintain a close distance to the major consumers of electricity. Full reliance on wind power is however not a realistic option. As a result of the inherent variability of wind gusts, the blades will see spikes and lulls in what can be harnessed. Electrical production can rapidly drop with little advance warning. To supplement this, natural gas powered generation has gained popularity. The new generation of gas turbines can begin producing power within 10 minutes. With this availability, sudden losses in wind generated power can be quickly compensated by "cycling" the amount of electricity being produced from gas based power plants.

While many gas turbines are operated as stand alone units, the efficiency of this configuration has a significant amount of wastage of the total available energy. Generally speaking, most modern turbines operate at around 40% efficiency, meaning a large amount of the fuel energy is not harnessed. One common method to improve this is by introducing a steam cycle. This can allow for efficiencies of around 60%. The former configuration is often referred to as "simple cycle", whereas when steam equipment is added the plant configuration now is called "combined cycle".

When operated in simple cycle, turbines will produce high temperature exhausts (which in turn possess high thermal energy) and can typically be from 400^{o}C to 600^{o}C. These exhaust gases will be released into the atmosphere, at the rate of millions of pounds an hour. In a combined cycle configuration, heat recovery is done on this exhaust, to harness some of the energy that would otherwise be wasted. Hence the terms "waste heat" or "heat recovery" is used when referring to combined cycle equipment.

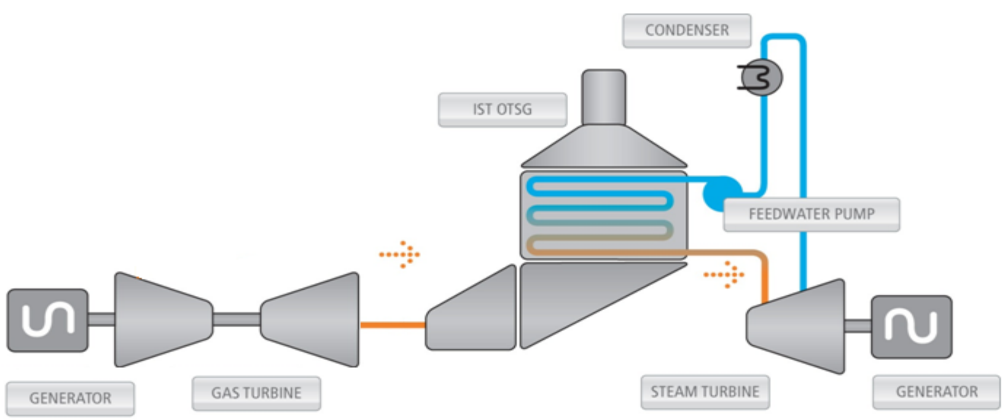

Figure 1: Schematic of a combined cycle plant.

A simple schematic of a combined cycle system is shown in Figure 1. The exhaust gases are collected and passed into a heat recovery steam generator or HRSG. Water is introduced into the boiler and it recovers the heat from the exhaust gases and then converts it to steam. This steam is then sent to a steam turbine which extracts the energy and converts it to electricity. Thus by having a secondary means of recovering energy, the overall system becomes more efficient, or in other words, more electricity is produced when using the same amount of natural gas. This improves the usage of a limited resource, and reduces the amount of pollutants produced per mass of fuel burned.

While combined cycle offers many benefits, there are reasons why it is not always the ideal solution. These can include:

- The upfront capital costs are significantly greater, and major equipment such as a steam turbine and condenser may be too expensive for the owner.
- The complexity of the plant increases with the additional equipment, which leads to more sophisticated controls and higher trained personnel
- Maintenance costs will go up, as there are more equipment and systems to monitor and maintain.
- The amount of land available for the plant may not allow for the extra equipment.
- The system can become slower and less responsive to the changes necessary for following the grid. One major reason for this is the HRSG.

HRSGs are large boilers designed to maximize the heat recovery. Cold feedwater enters the boiler through tubes, and the hot turbine exhaust gases pass over the outside surfaces, transferring the heat to the water until steam is produced. A specialized form of HRSG is called a Once Through Steam Generator, or OTSG. What makes the OTSG unique is the fact it does not use drums. Traditional HRSGs can have multiple drums and sections which include extractions and circulation of the water/ steam. In an OTSG, all feedwater entering the boiler will exit as steam.

The design of the OTSG leads itself to fast starts and transients. Whereas drum boilers can be very large and contain a great deal of thermal mass, the OTSG is compact and well suited to quick ramps. The following sections elaborate on some of the differences between an OTSG and drum boilers, and the specific reasons it is capable of improved cycling operation.

“Drumless” Design

The fundamental difference between a traditional HRSG and an OTSG is the absence of a drum. In an OTSG, the tubes are configured perpendicular to the gas turbine exhaust. Cold feedwater is introduced at the top and enters the module through tubes. These tubes will carry the water from one end to the other, then through a hairpin and back in the opposite direction. This forms a continuous serpentine pattern across the gas path area. Figure 2 depicts the water and exhaust flow pattern.

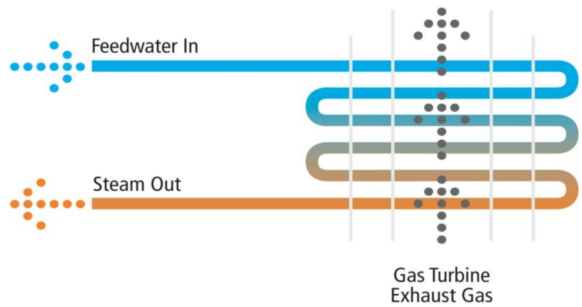

Figure 2: Heat transfer schematic

As the exhaust gases move through the boiler and across the outside of the tubes, heat is transferred to the water inside the tubes. To improve the heat transfer, extended surfaces are added as fins on the exterior of the tubes. These significantly increase the surface area, and by extension the amount of heat recovered is increased in a more compact module. One circuit is shown, in practice there would be a number of these circuits in parallel, connected to common feedwater and outlet headers. As more heat is collected the temperature of the water will increase, until steam is produced. The OTSG will be designed to remove as much heat as practical, and once past the pressure parts tubes they are exhausted through a stack at a much cooler temperature (generally between 100 – 120^{o}C). The end result is that many Megawatts (MW) of thermal energy have been recovered, which will then be converted to additional electricity via a steam turbine. The steam then travels to a condenser which returns the steam to liquid form, and is then sent back into the OTSG as feedwater. This forms a closed loop for the water cycle.

Steam production in a drum type HRSG is achieved by circulating water in the evaporator section and controlling the steam leaving the drum. This results in a large inventory of water within the boiler, which then causes the boiler to be slower to respond to changes. By having a lightweight pressure parts module with a smaller inventory of water, the OTSG can modify the steam production much quicker than a drum boiler. A traditional HRSG must allow the large volume of water in the drum to heat and evaporate prior to steam production. The OTSG on the other hand starts dry, with very no water inventory, and the thermal lag of steam production is much shorter, allowing for quicker start up periods.

<u>Superior Tube Materials</u>

The OTSG is designed using the high grade tube materials Incoloy 825 (SB423 NO8825) and Incoloy 800 (SB407 NO8800). These alloys have a high degree of strength at elevated temperatures, attributed to the large amount of nickel in the composition (~42% for 825 and ~35% for 800). The high strength allows for thinner walls while avoiding the concerns of stress and fatigue. Also, smaller diameter tubes can be used. What this translates into is a low thermal mass of metal, and a much lighter and compact tube bundle. Traditional HRSGs have large and heavy drums, and also lower grade pipe materials which necessitates thick walls and increased mass. This translates into longer times for the heat to penetrate the tube walls and be transferred to the water. The result is slow response to thermal output, which is not conducive to supplying electricity for grids with varying loads. Conversely, with less metal in the pressure parts bundle, an OTSG will transfer heat quickly from the exhaust gases to the water.

Flexibility and Ramping

The once through path also simplifies the operation of the boiler. When a drum is present, there are three general sections required: an economizer, evaporator and superheater. Each section operates within specific parameters, and to maintain temperatures and flow rates adds restrictions to rapid changes. Operating outside of the designated regimes could lead to damage of the equipment. The OTSG does not have designated sections, and allows the boiler sections to grow or reduce in size and as a result offers a great deal of flexibility in ramp rates. This again translates into faster response time.

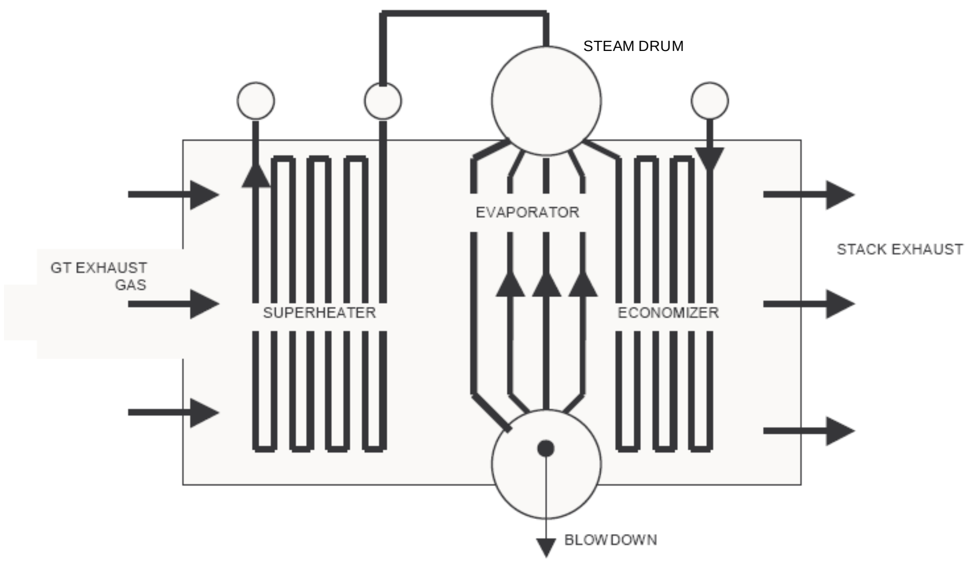

Figure 3: Typical Drum Type HRSG

Figure 3 shows a schematic of a typical drum type HRSG. It is essential that no steam is formed in the economizer section. Steam is produced in the evaporator via circulation with the drums.

A significant consideration for fast ramps are the thermal stresses as temperatures rapidly increase and decrease. In a peaking plant, the thermal output from the gas turbine can vary according to grid demand. For heat recovery boilers, of prime concern are welded connections between expanding pipes and static headers. Heating and cooling at these connection points can lead to stresses and ultimately failure. The OTSG counters this by allowing expansion to occur in a controlled manner.

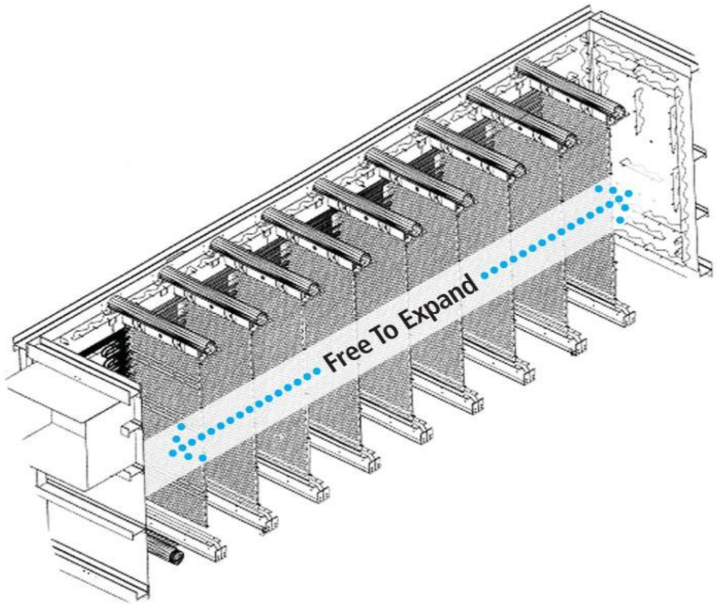

Figure 4: Cut away of pressure parts module.

The horizontal tubes are held in place by tubesheets, which are large plates with holes for the tubes to pass through (Figure 4). These tubesheets are located at specific intervals to support the tubes, and are top supported from the upper beams of the module. As hot turbine exhaust gases enter from the bottom, the hottest temperatures will be at this location. The gases cool as they transfer heat to the water inside the tubes, and this creates a temperature differential. The tubes at the bottom will expand more than the ones at the top, and to account for this the tubesheets are fixed only at the top. The bottoms of the tubesheets are allowed to bend and they do not confine the tubes. The tube materials of Inconnel 825 and 800 are resistant to the stresses of rapid expansion. At either end of the module, the hairpins or u-bends are located in the maintenance cavities, and out of the direct path of the hot gases. With the additional consideration of seamless tubes, all welds are located away from direct heat to avoid potential weak points. This design allows faster start ups than would be possible with a drum type of HRSG.

Another point that warrants mentioning is the ability for the OTSG to “turn down” steam production more so than a drum boiler. As previously discussed, there are no designated sections for economizer, evaporator or superheater. As a result, each of these sections are allowed to grow or contract. In the example where a reduced steam load is required, the amount of water in the system will be reduced, and steam may now be produced several rows earlier than at the location during normal operation. In this situation the superheater operates with more rows, or has grown in size. A desuperheater can be used to reduce the steam temperature downstream of the OTSG. This turndown operation can be key when modulating the electrical output of the plant. A drum HRSG can also operate in turndown, but not to the same extent, and not as quickly as a once through boiler.

Simple Control System

The control system for an OTSG is another factor allowing it to be conducive to fast ramps. Whereas in a drum type boiler there are many parameters to control within specified limits (level of water in drum, temperatures in economizer, evaporator, superheater sections, etc.), the OTSG focuses on a single point of control: the outlet steam temperature. The steam pressure is set by the equipment downstream of the OTSG, leaving only the temperature to control. A feedforward/ feedback loop is used to control outlet temperature (Figure 5).

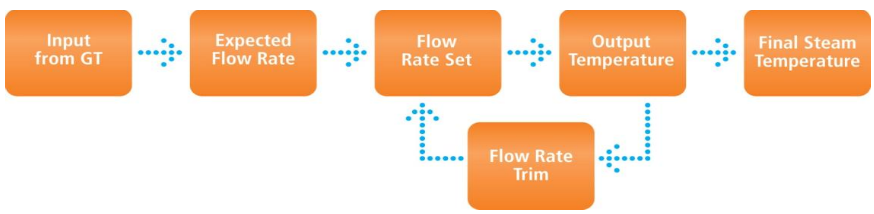

Figure 5: OTSG Control Scheme

The OTSG control system will initially determine the gas turbine exhaust parameters (mass flow and temperature). This is the feedforward portion. Using an algorithm, an Expected Flow Rate is sent to the feedwater control valve to set the amount of water flow. Next the outlet steam temperature is measured using thermocouples. If the system determines the steam to be too hot, a feedback signal is sent to the feedwater control valve to "trim" the position and open it further, allowing more water into the OTSG. With more inventory recovering more heat, the steam temperature drops. Conversely, if the steam temperature is too low, the trim signal will tell the valve to close and reduce the amount of steam produced. By this method of adjustment, the final steam temperature can be maintained.

The benefit of a simplified control system is that a) there are fewer constraints on the system and b) by focusing solely on the steam temperature, the system becomes more responsive to changes. This helps the OTSG ramp up quicker than a drum type HRSG.

Structural Considerations

Thermal expansion of the OTSG has already been mentioned in a previous section, however it also extends beyond the pressure parts module. When gas turbines are brought online, the temperature of the ducting can also increase from ambient to over 500°C in a matter of minutes. A fixed structure would suffer stresses in this type of operation.

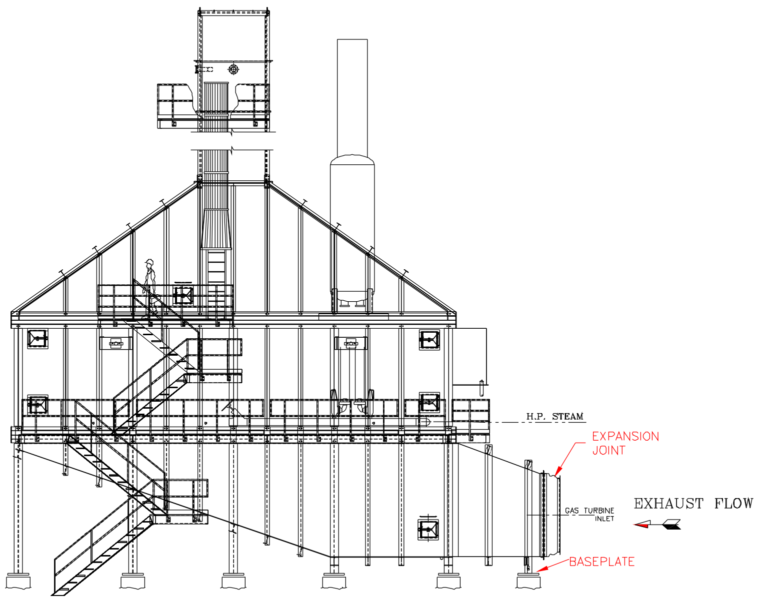

Figure 6 – General Arrangement

There are two items to note in the diagram in Figure 6. The first is an expansion joint, which allows for rapid changes to the ducting as a result of the casing growth close to the gas turbine. The second is the vertical stiffeners that extend from grade through to the top of the OTSG. At the bottom of each of the stiffeners, baseplates are installed which incorporate fabreeka pads. These pads allow for small movements as the OTSG grows horizontally. Of the many stiffeners, one will be held in place, allowing for controlled growth in the two dimensions along the ground.

Case Study: Entek OTSG Plant

The Entek plant in Izmit, Turkey was commissioned in 2009. The site consisted of 1 GE LM6000-PC gas turbine operated in combined cycle with an OTSG. Primary fuel was to be natural gas, and the plant Heat Balance required steam at the following conditions:

Table 1: Entek Steam Requirements

	High Pressure (HP)	Low Pressure (LP)
Steam Production (kg/hr)	43,450	14,652
Temperature (^oC)	420	227
Pressure (bar a)	44	7.0

Both HP and LP steam is sent to a steam turbine for additional production of electricity. Of particular importance during startup is the rapid availability of LP steam to be used for the steam turbine gland seals to prepare it for operation.

For standard dual pressure OTSGs, the startup sequence is to begin with the HP steam being brought online and in control, followed by LP steam. This is done to establish an exhaust temperature profile in the OTSG, with hotter exhaust at the bottom, gradually cooling as it continues through the boiler. The LP circuit is designed for operation within certain parameters, and as the OTSG is initially started dry (no water in the system), all tubes are exposed to full exhaust temperature, in this case 420^oC.

During startup, the introduction of cold feedwater into hot tubes will create a temperature differential and “shock” the tubes. If uncontrolled, this could cause the tubes to shrink and bend. To account for this, two methods are employed:

1) Flexible tubes connect the inlet header to the first row of tubes. These tubes are designed with bends, so when the tubes contract the forces are absorbed by the bends, relieving the stress (Figure 7).

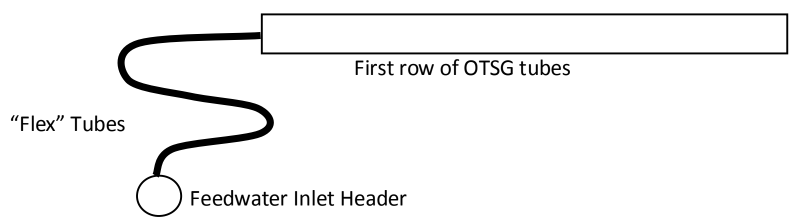

Figure 7: Flex Tubes and Inlet Row

2) The feedwater is slowly introduced into the OTSG according to a specific ramp. This controlled increase in the water entering the unit allows the tubes to gradually cool and reach a steady state where heat from outside the tubes is transferred through the tube walls and to the water inside. The ramp is also essential for developing steam pressure, which is also increased according to specific parameters.

As the water inventory increases within the unit, a temperature profile develops in the OTSG. A gradient forms where gases are hottest at the entrance to the module and coolest at the exit. The LP steam circuit is then started in a similar manner to HP, although flex tubes are not required as the exhaust temperatures in this section have been cooled as a result of the heat absorbed by the HP tubes. As a result, the temperature difference between feedwater and inlet tubes are much smaller and can be absorbed the the tubes themselves.

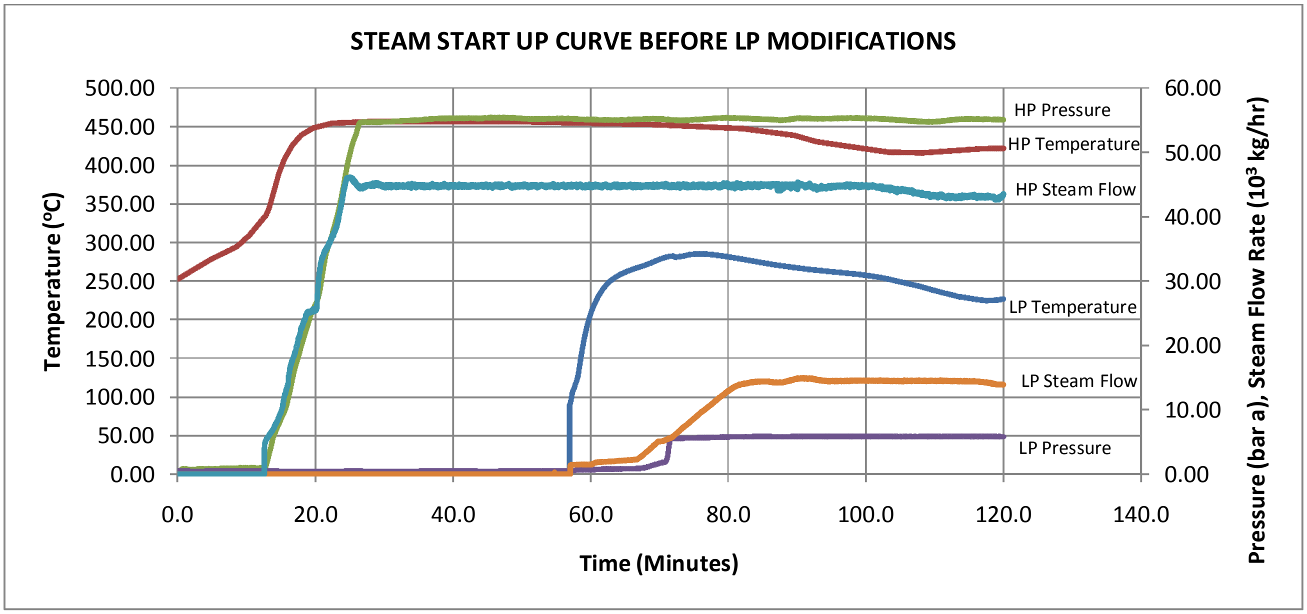

Figure 8: Initial Start up curves for Entek OTSG.

Figure 8 shows the start up results at plant commissioning. Feedwater was introduced to the HP circuit according to a ramp, starting at time "0". Steam production is seen at the outlet of the OTSG at approximately 12.5 minutes. The steam temperature quickly rises to the gas temperature, and pressure and flow are increased at controlled rates. The LP steam circuit is started at 57 minutes, and is in temperature control after 120 minutes.

The Entek plant approached IST in an effort to reduce the LP production time. A study was performed to determine the best solution while minimizing the modifications required. Options considered included a let down station of the HP steam (which would reduce the pressure), or retrofitting flex tubes for the LP section. Both options were deemed cost and time prohibitive. The optimal solution was a more aggressive ramp rate. Analysis of the operation was necessary to ensure the mechanical design of the OTSG would not be over-stressed and prevent damage to the equipment. A review of other OTSG plants was made, and it was determined that the exhaust gas temperature at the LP inlet rows should not exceed 300°C. As a result, the following modifications were recommended:

1) Increase the ramp rate of the HP section. As this circuit must be in operation prior to LP steam production, a reduction in the HP time would mean the LP sequence could commence earlier. When minimum turndown is achieved at the 16 minute mark (Figure 9), the feedwater flow rate was increased at 12% per minute (originally 6%) and the pressure increase was allowed at 345 kPa/minute (originally 175 kPa).
2) With the HP steam circuit operating quicker, the temperature profile in the OTSG was rapidly established. Instead of waiting for the HP circuit to achieve temperature control, The LP was started once the HP flow achieved 100%, followed by a 25 minute delay. This time would ensure the gas temperatures in the module are stable, and also that the 300^{o}C temperature permissive could be met prior to allowing feedwater into the LP circuit.

LP steam production now commenced at 50 minutes (formerly 57 minutes), with temperature control achieved at 105 minutes (formerly 113 minutes). An additional modification was made to the system to improve the situation:

3) An LP desuperheater was added downstream of the OTSG. When the minimum turndown of 2,198 kg/hr was achieved, the desuperheater would spray water to meet the required temperature for the gland seals. Thus conditioned steam was now available at the 59 minute mark.

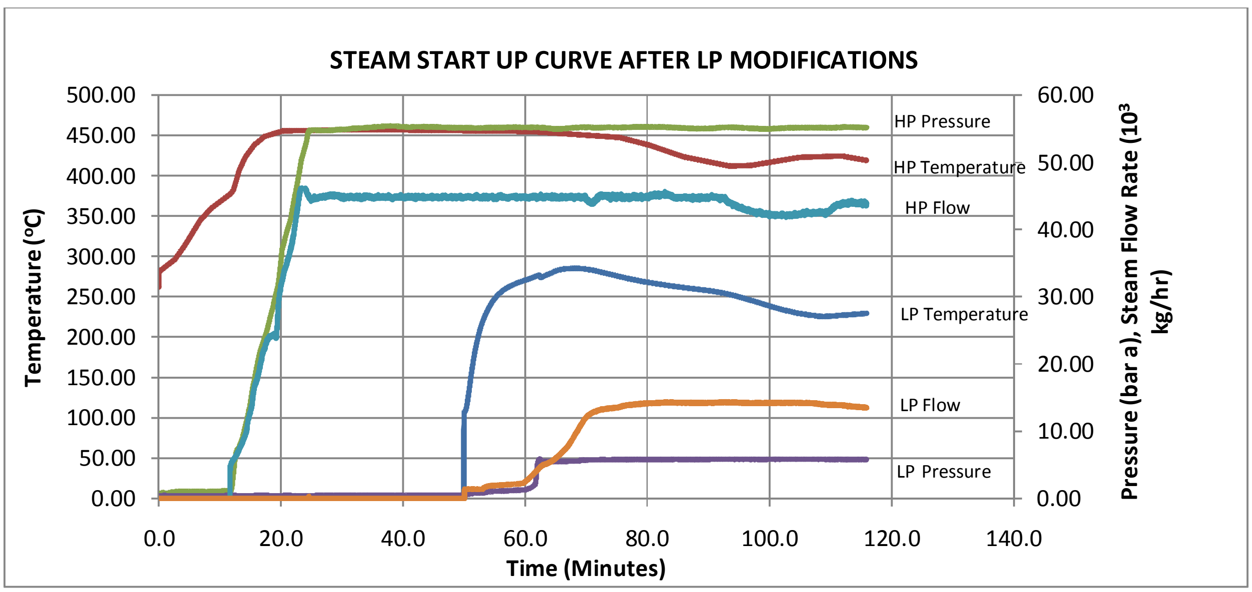

Figure 9: Start up curves after LP Modifications.

These modifications resulted in an advancement of the LP steam by 24 minutes. The client was happy with this solution, as minimal capital investment was required and they were able to produce the required power more quickly. As this is a cycling plant, the faster the electrical output is achieved, the more profitable the plant becomes.

Summary

A Once Through Steam Generator is inherently quicker at start up and load changes than a drum type HRSG. These boilers are operated in cycling operation, sometimes with start up/ shutdown sequences several times a day. In addition, the flexibility and turndown abilities make it ideal for electrical grids where power generation is variable. OTSGs represent a very important advancement power generation technology in the future.