The Future of Gas Turbine Technology
7th International Gas Turbine Conference
14-15 October 2014, Brussels, Belgium

Paper ID Number (*14*)

REVIEW OF HRSG CAPABILITIES FOR FLEXIBLE OPERATION

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ABSTRACT

In Europe, Combined Cycle operators are faced with increased cycling and less operation hours. To meet these challenges, the HRSG must be capable of rapid load transients, operation at low loads to provide spinning reserve, long periods of standstill and frequent start/stop cycles. Although many HRSG suppliers take these considerations into account for new HRSGs, they were not always considered in the past.

This paper will summarize the main HRSG related challenges that need to be considered for this type of operation. The paper will then demonstrate how these aspects are taken into account for the design of new units. Finally, the paper will go into detail on how existing HRSGs can be reviewed and improved in the context of these new market requirements. The main risks for different existing designs will be highlighted and different mitigation measures will be listed. This will be illustrated with some case studies where improvements were implemented on actual plants.

INTRODUCTION

In Europe and around the world, Combined Cycle operators need to adapt their units to deal with increased cyclic operation and a reduced number of operation hours. This trend is driven by a combination of factors related to gas and electricity prices as well as by the increased volatility in the power production caused by the large amount of renewable generating capacity that is coming on line.

To meet these challenges, the requirement to the HRSG can be very different and depend very much on the local situation and the market design. Examples of such requirements are the capability of rapid load transients, operation at low loads to provide spinning reserve, long periods of standstill and frequent start/stop cycles. Depending on the type of flexible operation that is required, the degradation modes and the requirements to the HRSG can be very different.

NOMENCLATURE

FAC	Flow accelerated corrosion
GT	Gas turbine
HCF	High cycle fatigue
HP	High pressure
HRH	Hot reheater
IP	Intermediate pressure
LCF	Low cycle fatigue
LP	Low pressure
RAM	Reliability, availability, maintainability
ST	Steam turbine

FAILURE MODES

By now, most plant operators are aware that cycling an HRSG can lead to significant problems. In order to determine the main risks related to flexible operation, it is important to have a good understanding of what can go wrong and why. This section provides an overview of failure modes that are either accelerated or caused by the different flexible operation modes.

Creep:

This is the gradual and time-dependent material deformation behavior under steady loading at high temperatures. It is a well-known failure mechanism for components that are exposed for long periods of time to high temperatures, such as HP superheater and reheater tubes, outlet headers, manifolds, tubes and piping. Although this failure mode is typically associated with base load operation, it can also occur when operating the gas turbine at the lowest possible load that is within emissions compliance. This could result in higher gas turbine exhaust temperatures and lower exhaust gas flows. Even if the HRSG inlet temperature does not increase, the lower mass flow causes a change in the balance of heat pickup. Often, this results in a bias toward higher heat pickup in the finishing superheater, leading to higher steam temperatures.

Low Cycle Fatigue (LCF):

Fatigue is damage caused by cyclic load. In the case of thermal fatigue, the cyclic loading is caused by temperature differences during load gradients. They can result from the following:

a. Through-wall temperature differences:
   It takes time to completely heat up thick walled components in high temperature areas, such as the HP drum and outlet headers and manifolds of the HP superheater and reheater. The portion which already sees a higher temperature will expand more than the portion which is still at a lower temperature, leading to thermal stresses.
b. Junctions between thick and thin walled sections.
   Components with different wall thicknesses will heat up and expand at different rates, leading to thermal stresses.
c. Junctions between dissimilar materials:
   Dissimilar metals (stainless and ferritic) have different thermal expansion coefficients leading to thermal stresses.
d. Economizer start-up:
   In the initial phase of the start-up, no feedwater is required. The stagnant feedwater in the economizer will heat up and when the feedwater requirement starts, colder feedwater will be added, leading to a sudden temperature change, causing through-wall temperature differences as well as temperature differences between the colder upstream part and the warmer downstream part.

Thermal shock caused by quenching:

Quench is a tensile overload caused by a sudden, unanticipated rapid local cool down. This can occur because of:

a. Condensation of steam during the purge cycle in a hot or warm start. If the condensate is not evacuated by an effective drain system, it can cause thermal stress and deformation (bending) in lower headers and manifolds, caused by top to bottom temperature differences. In case the condensate is still not removed when the steam starts flowing, condensate migration can cause thermal stress at superheater outlet headers and can also cool down individual superheater tubes. Cooling down individual tubes may lead to plastic deformation (stretching) resulting in bowed tubes when the tubes return back to their normal temperature.
b. Insufficient evaporation of desuperheater spray. This can be caused by a bad spray nozzle, too much spray water or insufficient downstream straight pipe length. This will lead to impingement or thermal deformation of downstream piping. In case of an interstage desuperheater, it can cause tube bowing and deformation of lower headers and/or manifolds in downstream superheater or reheater modules.

Water side corrosion

In a cycling unit, it is more difficult to control the water steam chemistry. Reasons include: time delay in sampling because of sample line length, fluctuations in analyzers measurements due to frequent changes in pressure/flow, oxygen and CO2 ingress during standstill periods and rapid fluctuation of chemical dosing requirements during load changes. These conditions can more easily mask the ingress of contaminants as well as promote the generation of oxides and subsequent deposition on heat transfer surfaces. This can lead to:

a. Flow accelerated corrosion (FAC):
   The protective oxide layer as well as base metal on carbon steel dissolves in a stream of flowing water (single phase) or wet steam (two phase), accelerated by the mass transport of soluble iron away from the surface by flow/turbulence. FAC generally take place in the temperature range of 50ºC-250ºC (Caravaggio, 2014), with peak rates at about 150ºC.
   The risk for FAC is further increased in the case of low pH values and insufficient oxidizing power, e.g. in cases where oxygen scavengers are used (Gabrielli, 2004). Single phase FAC can happen in economizers, FW heaters, deaerators or in the desuperheater water supply. Two phase FAC is usually limited to the LP evaporator. In

certain cases, especially in cases where the load (and temperature) is reduced, it can also occur on the IP evaporator.

Figure 1: Hole caused by FAC on connection of LP evaporator outlet header

b. Corrosion fatigue:
With this failure mode, the effects of corrosion and fatigue are combined. When the inner magnetite layer is damaged at locations with high stress concentration (e.g. tube restraint, tube to header connection), the metal will be exposed to the corrosive medium.

c. Standstill corrosion:
During longer periods of standstill, with insufficient preservation, oxygen ingress can lead to general corrosion and pitting on the water side of the tubes.

d. Under deposit corrosion:
Oxides as well as hardness salts transported by feedwater will lead to deposits in the evaporator. Soluble contaminants entering the system (cooling water leaks, make-up water, etc.) can concentrate under these deposits. Depending on the type of contaminant, this can lead to hydrogen damage, caustic corrosion (wastage), etc.

Flue gas side corrosion or damage:

a. In case of insufficient flue gas side preservation during longer standstill periods, condensate can form on the tube surfaces, leading to corrosion. The corrosive effect is worse in case the tubes already have sulfur based deposits, e.g. downstream of an SCR. In addition to the damage caused by the corrosion, thermodynamic performance suffers due to corrosion deposits restricting gas flow, increasing backpressure for the gas turbine and reducing heat absorption.

b. Condensation and deposition of water and sulfur compounds can also occur in operation, when the metal surface temperature is cooled down below the respective dew points.

Figure 2: Flue gas side deposits

c. Duct burner:
   i. Operation at lower loads can lead to longer flames, increasing the risk of flame impingement on downstream tubes.
   ii. Fast duct burner ramp-up can cause overheating of the tubes since it takes some time for the steam flow to increase and cool down the tubes.
   iii. At lower loads, burners are often not in operation. In case individual runners are not isolated, flue gas circulation can lead to condensation, which causes corrosion and possibly thermal deformation of the runners. The corrosion products can result in burner nozzle blockage, which could lead to overheating of other nozzles, or downstream tube damage.

Structure:

a. Valves:
   i. Use on low-load conditions (throttling) increases wear rate.
   ii. More frequent loading of valves (e.g. vents, drains) accelerates lifetime consumption.
   iii. Control accuracy of control valves such as feedwater control, decreases in low flow situations. This can lead to drum level issues, especially if combined with item "i", above.
   iv. Increased loading on valve glands can lead to leaks, possibly also causing consequential damage to valve stems and related parts.
   v. Increased production of iron oxides can lead to valve erosion and potential clogging issues.

b. Cyclic loading also increases lifetime consumption of expansion bellows and expansion joints.

c. Casing (especially hot casing) can suffer from fatigue cracking. Subsequent flue gas leaks can damage equipment such as instruments or can heat up structural parts.

d. HCF fatigue damage of liner retention studs can lead to casing hot spots.

e. Desuperheater:
   Increased usage leads to accelerated lifetime consumption.

NEW EQUIPMENT DESIGN

From the previous section, it is clear that cyclic operation can lead to new degradation modes, or it can accelerate others. Over the past decade, there has been an increased focus on issues related to cycling. This section will show an overview of the most important design features that can be used to enhance the cyclic capability of HRSGs (Bauver et al, 2003).

Flexibility and Stepped Component Thickness

Small diameter headers in conjunction with step changes in pressure part thickness lead to minimum tube-to-header temperature differences at the weld joint. The use of a single row harp eliminates the bend in the tube near the header, and permits more rapid rates of temperature change than more conventional thick-walled headers used with multi-row harps (see Figure 3).

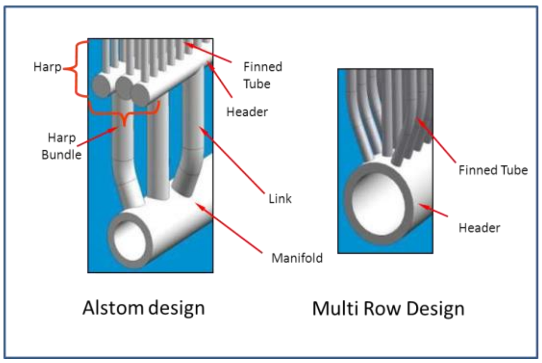

Figure 3: Pressure part design

Superheater and reheater condensate drain systems that are designed with the drain manifold separate from the lower harp headers can rapidly drain accumulating condensate away from the harp tube inlets in the lower harp header and into a large manifold located below the harp headers. This functions as a generous sluice-way for receiving condensate during a hot restart. This arrangement precludes the possibility of water backing up into individual tubes, preventing damage from condensate flooding.

Because it is sometimes challenging to maintain ideal water/steam chemistry conditions in a cycling plant, an additional assurance is to use material with some chromium content, such as grade 11 (1¼% Cr) steel, for the most critical components subject to FAC in the LP evaporator, such as the risers, the outlet manifolds and the links.

Superheater and reheater desuperheater design is also an area that requires sufficient attention. The straight section upstream of the desuperheater should be sufficient to allow for a good flow distribution and the straight section downstream must be enough to allow for complete evaporation of the injected water before reaching a bend. The control logic should protect against overspray, prevent water injection at low or no steam flow operation and should also have sufficient accuracy to deal with fluctuating loads.

If it is anticipated that the unit will have longer shutdown periods, it is important to plan a nitrogen blanketing system for the water side protection, and a stack damper and in some cases a dehumidification system for the flue gas side.

Other measures may include a cold casing design, a feedwater control valve for the start-up, an economizer recirculation line or an improved SCR control concept.

REVIEW OF EXISTING HRSGS FOR FLEXIBLE OPERATION

For an existing unit without all these design features, it is usually commercially not viable to implement all possible changes. The most appropriate approach is to assess the current design and identify areas that are prone to accelerated damage as a result of flexible operation. Alstom has developed an initial review at a high level to accomplish this. It starts with a documentation review followed by a one day on-site assessment executed by an integrated team of operators and Alstom engineers. The results of this assessment provide the required inputs to prioritize additional detailed analysis needs and/or actual improvement measures. The output of this assessment is the foundation for a roadmap to reliable and profitable flexible operation.

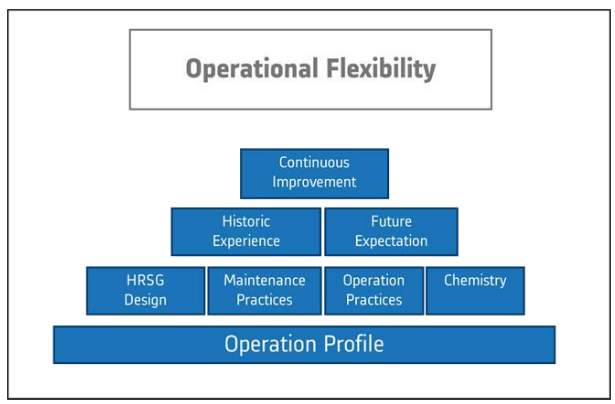

Figure 4: Assessment levels

The on-site assessment focuses on different levels (see Figure 4):

1. Level 1: Operation profile:
   Operational flexibility can have different dimensions. Each dimension drives different failure mechanisms. The following dimensions were considered:

- High number of start/stop cycles.
- A lot of low part load operation.
- Prolonged periods of standstill.
- Frequent and fast load fluctuations.

2. Level 2: How well is the plant set-up to deal with flexibility?
    - Does the design cover the required flexibility needs?
    - Are pro-active maintenance practices in place to reduce the risk exposure?
    - Are adequate operation practices in place and does the operations team monitor the plant to reduce operational flexibility related risk exposure?
    - Are adequate and robust water chemistry procedures and practices in place to reduce the risk by flexible operation?
3. Level 3:
    - What have been the experiences so far? Do they confirm the expectations from level 2?
    - What does the planning for the future look like?
4. Level 4: continuous improvement
    - Are processes in place to use lessons of the past to reduce future risk exposure?

A questionnaire that systematically covers all the risks in these different chapters has been developed. Every possible sub risk is evaluated on a scale of 1 to 5 (see Figure 5).

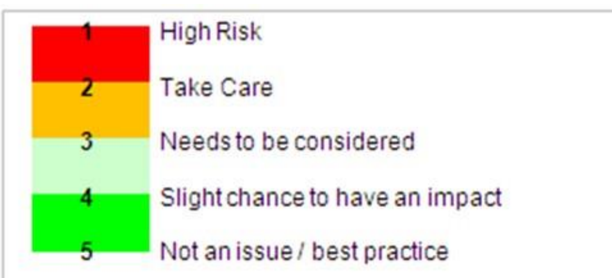

Figure 5: Scoring.

The results are then averaged into a high level overview (see Figure 6).

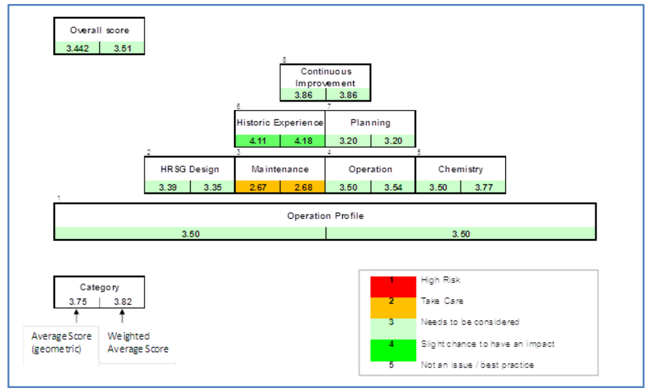

Figure 6: Overview of the result.

The score includes an average and a weighted average. The weighting gives more weight to those items that have a higher risk (frequency and / or impact). The report includes a drill down and a discussion on what is actually causing the average number to go down. For the highest risks, recommendations will be made. Typical recommendations include:

- Perform a cyclic life or corrosion assessment in order to better quantify risks as well as the remaining cyclic lifetime. The results will help to prioritize inspection areas and is a good input for an investment planning.
- Installation of additional surface thermocouples on steam pipes, HRSG tubes or headers and a monitoring software. This will help to detect flooding of lower headers or manifolds, desuperheater overspray, economizer stagnation or local overheating of tubes.
- Replacement of the desuperheater with a design that is better suited for cyclic operation, and/or improvement of the control logic. For cases such as operation at lower loads, where additional capacity is needed, it might be required to modify the piping or to install an additional desuperheater.
- Review the drainage system: increase the diameter, lay-out (slope of drain lines, location of blow down tank) or control logic to avoid flooding of lower headers or manifolds.
- Install an additional start-up control valve to improve the start-up reliability.
- Review water/steam chemistry control practices.
- Add additional sampling equipment or improve sampling methods. One example is the installation of a degassed cation conductivity monitor.
- CO catalyst for improved turn down.
- Plant specific concept changes, such as a steam by-pass for faster warm up of certain steam pipes, can reduce the start-up time, minimizing pressure part distress.
- Installation of standstill preservation systems and/or a stack damper.

- Large scale modifications like upgrading pressure parts with more flexible designs (e.g. grade 11 material in LP evaporator, upgrade superheater to single row harps). This type of improvement is only economically justified in cases where chronic issues are dramatically affecting the RAM or thermodynamic performance of the plant.

CASE STUDY 1

The current power generation market in Italy requires daily start/stop operation. This capability is a key factor for all utilities to gain commercial advantage among other competitors. In this case study, the gas turbine was changed out on an existing non-Alstom HRSG and the intention was to use it in a daily start/stop mode.

Figure 7: HRSG unit in Italy

Because the gas turbine was replaced, a verification of the HRSG for the new gas turbine flue gas condition was required. In order to achieve the cyclic load requirements, the following modifications were implemented:

- A lifetime assessment, including a finite element analysis (FEM) (see Figure 8) was performed to calculate the already consumed lifetime and to predict the future lifetime consumption, based the new cyclic load conditions. Results of the assessment showed that critical components, such as the HP drum and the HP superheater, can be operated in cyclic load condition for the entire expected HRSG lifetime;

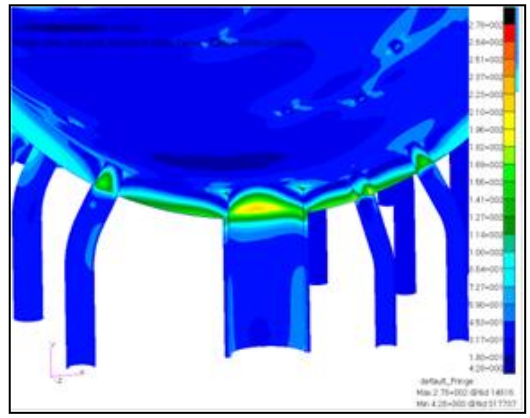

Figure 8: FEM to detect maximum HP drum gradient during hot start

- A desuperheater was added to the HP main steam line. The desuperheater controls the steam temperature during start up and allows the loading of the GT to 100%, without constraint while awaiting the warm-up of the ST. The steam temperature at the ST inlet is controlled by the desuperheater set-point based on ST status (hot, cold or warm start). This allows a fast ramp of the GT and the HRSG up to the minimum technical load, allowing for the gradual warming-up of the ST;
- A new drain system was installed. The new drain valves allow the condensate removal over a wide pressure range during the GT purge cycle. This avoids the need to reduce the HRSG pressure in case of a hot start-up. The new valves are controlled by an automatic start-up sequence, opening 3 minutes before GT «flame-ON» and closing in a timed sequence. The timing is set based on a calculation of the condensate production and removal rate. Particular care is required for the design of the drain system and for the control valve selection, since high pressure condensate flashes and could reach sonic velocities in the drain pipes to the atmospheric pressure blow-down tank;
- New HP and IP start-up vents were installed to improve flexibility. Both vents were equipped with silencers, in order to meet the noise emission limits according to the Italian law;
- The drum level control valves were replaced to deal with the reduced steam production caused by the new GT exhaust conditions.

Figure 9: Detail of modified drain system

After these modifications, the HRSG was able to operate with the new GT conditions in a daily start/stop mode instead of base load.

CASE STUDY 2

For another case in Italy, the market demanded a start-up time of less than one hour. This plant is equipped with two HRSGs linked to a common ST. The bottlenecks in the start-up rate were the HRH steam lines, which needed a warm-up time of more than two hours. In order to reduce this warm-up time for the HRH lines of both the HRSGs, new warm-up lines were designed and installed. The project included:

- Development of a transient thermal model of the HRH steam lines, in order to determine the required size of the new warm-up lines to heat HRH lines from 300 °C to 450 °C in 30 minutes over the entire length (see Figure 10);
- Basic and detail engineering of the new warm-up lines, starting from the new nozzles on the existing HRH lines, before the HRH stop valves, up to the new common expansion vessel and relevant vent line and silencer. Each warm-up line is equipped with one zero leakage motorized control valve and 2 manual stop valves. Particular care was taken during the design of the new warm-up lines and in the valve selection, due to the high steam velocities inside the pipes;
- Due to the high steam velocity inside the warm-up lines, a noise study was performed to correctly design the silencer, the expansion vessel and the thermal / acoustic insulation and meet the noise emission limits of the Italian law;

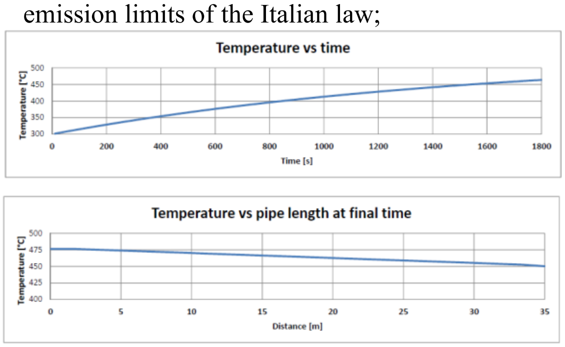

Figure 10: thermal transient calculation of one HRH line

- Design, manufacturing and installation of new steel structures, supporting the new warm-up lines, according to the Italian law;
- Manufacturing , installation and commissioning of the new warm-up lines and relevant equipment (valves, silencers, etc), according to PED (see Figure 11);

Figure 11: New warm-up HRH steam heating lines

- PED assessment, including lifetime assessment and certification of the modification, according to the Italian law;
- Tuning of the system.

After installation and commissioning, a successful performance test was performed:

- HRH lines heating time was reduced from more than 2 hours to 30 minutes (tests were performed heating from 280 °C up to 430 °C, see Figure 12);
- Noise emissions are kept under 85 dBA.

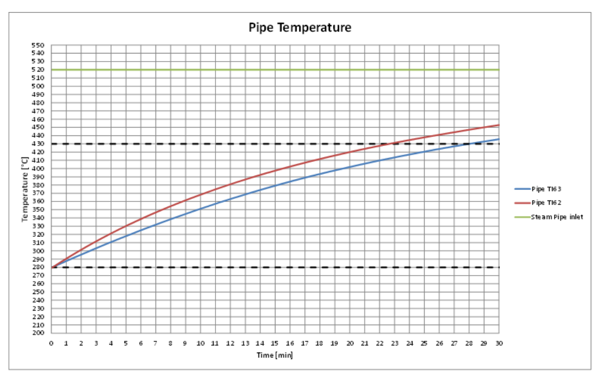

Figure 12: Performance test results

The reduced fuel consumption associated to this modification lead to a project payback time of about one year.

CONCLUSION

An effective modification of HRSG assets for flexible operation has to be based on the actual market needs and the expected drivers of asset degradation or damage. This needs to be derived from the component design as well as on past, current and anticipated future experience and operation profile. Once an engineering review has identified the areas with the highest criticality, this analysis can then be used to determine where it makes the most sense to implement improvement measures in order to obtain an optimized HRSG for cyclic operation. Because of the importance of such a review, it pays off to get external support to jointly perform such an analysis.

REFERENCES

Bauver, W. / Perrin, I. / Mastronarde, T.:
"Fast Startup and Design for Cycling of Large HRSGs", Power-Gen International, Las Vegas (NV, USA), December 2003.

Caravaggio, Michael
"Latest EPRI Chemistry guidelines for Combined Cycle / Heat Recovery Steam Generators", European HRSG Forum, May 2014.

Gabrielli, Frank:
"Flow Assisted Corrosion: failures / water chemistry aspects", EPRI International Conference on Boiler and HRSG Tube Failures and Inspections, San Diego (CA, USA), November 2004.