

DESIGN AND MODIFICATION OF HEAT RECOVERY STEAM GENERATORS FOR CYCLING OPERATIONS

**Akber Pasha and Robert Allen
Vogt-NEM inc.
Louisville, Ky.**

ABSTRACT

Today's Heat Recovery Steam Generators, which form a part of Combined Cycle plant, are exposed to more severe operation than just running at a base load. The deregulation of electric generation industry has resulted in merchant plants. These plants are required to supply electrical power to the grid as needed and when needed. This means that these plants will be coming on line with minimal notice and will be shut down in the same way. This puts a strain on the HRSG and unless properly designed and operated to withstand the quick start-ups and shut downs, the integrity of the HRSGs will be compromised. Oftentimes a simple delay of 5 minutes in start-up may prolong the life of the boiler by months.

The paper describes various mechanisms which affect the integrity of the boilers. These include the damage mechanisms, their effect on various parts and how to control them. The causes and the end results of these damage mechanisms are not the same for various components of the boiler. So classification of the component and from there to the critical component, its potential for failure and the method to avoid the failure or delay the failure form an essential part of this paper. A set of design considerations are given, so that the user can ascertain that these were followed in designing the unit. The operating requirements form an essential part of managing boiler life. This paper includes considerable discussion on these monitoring requirements to keep the boiler from developing forced shutdowns.

A methodology to refurbish the existing HRSGs designed for base load operations forms the second part of the paper. This is provided so that the remaining life of existing units can be estimated and suitable programs and modifications can be installed to extend the life under cyclic operations.

INTRODUCTION

Today's Combined Cycle power plants (CCPP) using Gas Turbines have become a very popular power production option. Heat Recovery Steam Generators (HRSG), along with the Steam Turbines are essential parts of a Combined Cycle System. Almost every utility in and out of the country is using CCPP's to satisfy every day power demands. Because of this, the CCPP's, and consequently the HRSG's, are exposed to fast changing operating conditions. These conditions put extra strain on the components and affect the life of the



Fig.1 : A Three Pressure Level HRSG

components. The following paragraphs identifies some of the many mechanisms which can affect the life of a boiler component, how cycling enhances the effect and how to design and operate the new HRSGs to counteract these effects.

The existing HRSGs, which are already in service pose another problem. Most of these were designed for base load operation. Now they may be cycled to satisfy the new demand requirements. It is possible to modify them for cycling operation or at least put a monitoring program to gage the effect of cycling. A program detailing how to modify or monitor the existing units is also described.

TYPICAL COMBINED CYCLE HRSG

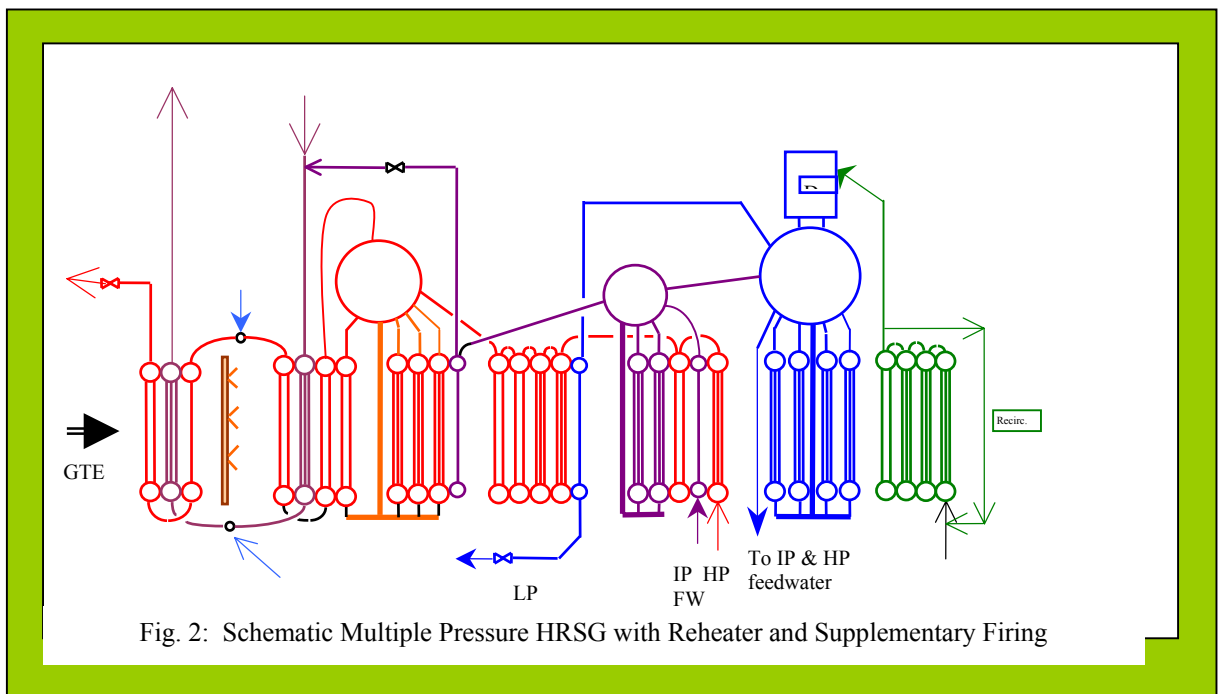
A typical Combined Cycle HRSG produces steam at three pressure levels plus steam reheat. The auxiliary firing through a duct burner is most often used to increase the steam production. There is also a feed water heater to increase the heat recovery and reduce the deaerating load of the integral deaerator. The heat transfer sections are located in series along the gas path to optimize the heat recovery. It is not uncommon to have 15 to 20 heat transfer sections such as Superheaters, Reheaters, Evaporators and Economizers at various locations along the gas flow. The emission

control regulations may require addition of Selective Catalytic Reduction system (SCR) and Carbon Monoxide Converters (CO). Some units may have gas bypass damper, though it has not found wide usage in US. All of these components are exposed to different temperatures and pressures at different times while the HRSG is started and operated. How well the components adopt or react to the transient and base load conditions determines the integrity of the whole HRSG.

MECHANISMS WHICH IMPACT THE HRSG LIFE:

The basic mechanisms which affect the life of an HRSG are listed below. These mechanisms and the interaction of these mechanisms affect the performance and integrity of the HRSG components.

- Low Cycle Fatigue : Damage occurs at low cycles when the strain is high. LCF or Low Cycle Fatigue is the most predominant mechanism in HRSGs.
- Creep : Damage due to material being at high temperature and stress for considerable amount of time.
- Thermal Shock: Impingement of cold water or Steam on hot surfaces can damage the material
- Oxidation: oxidation and exfoliation due to



- high temperatures
- Differential Expansion: If adjacent tubes or pipes are at different temperature, uneven expansion can stress both the tubes. Piping supports also play a part in this
- Corrosion Fatigue : The crack initiation happens due to corrosion and damage is caused by fatigue and corrosion. Typically occurs 300 - 500 F
- Corrosion in tubes : Due to improper water chemistry
- Flow Accelerated Corrosion (FAC): Corrosion Accelerated due to chemistry & Flow
- Corrosion Product Migration: Migration of corrosion products may cause further corrosion or other damage
- Deposits: Temperature or water chemistry fluctuations may result in deposits
- Erosion: Transient high velocities may initiate or perpetuate erosion

CRITICAL HRSG COMPONENTS

All components in an HRSG are affected by the life affecting mechanisms shown above.

However some components may be more vulnerable because of their location, construction or exposure. These need to be designed and monitored more closely for any kind of life affecting conditions. The critical components in an HRSG generally consist of :

- Superheater and Reheater Outlets
- Tube to header joints in Hot sections
- Drum to Down comer nozzle in HP drum
- Bent portion of the heat transfer tubes
- Attemperators
- Bypass Valves

HOW CYCLING HAPPENS

Basically cycling is defined as the reversal of stresses in a component and can happen by the imposition and relaxation of loads and because of reversal of temperatures. When a component is exposed to a rapidly changing high temperature fluid, all parts of the component may not heat up uniformly. Consequently the differential expansion creates high differential stresses and stress reversals.

Cycling can happen due to various reasons. The main reason being the change of plant load requirements and emergencies. Plant load

changes include short notice start-ups, GT load changes, part load operations and varying auxiliary burner inputs. The way a boiler is shut down and laid up can also affect the boiler integrity. In an emergency such as a steam turbine trip, the boiler has to shut down very rapidly causing undue or reversing stresses. Sometime with a very narrow working window, a boiler may be force cooled to make some repairs. This force cooling can also create temperature differentials. Failure or abnormal operation of other equipment such as pumps and valves etc. may impose cycling conditions on the HRSG.

HOW CYCLING IMPACTS THE LIFE AFFECTING MECHANISMS

Most of the time Cycling either creates or enhances the effect of mechanisms which affect the life of the component.

Creep damage by definition is caused by a prolonged exposure to high temperature and stress. Creep may be the only mechanism which is not caused or enhanced by cycling.

Fatigue and Fatigue damage are the most prevalent mechanisms affecting the boiler life and are a direct consequence of cycling.

Water chemistry upsets which result in corrosion may be due to cycling or because of failure of water chemistry controls.

For example for a rapidly starting HRSG, the Superheater is exposed to high temperature on the outside of the tube and headers whereas inside may still be cool. This creates high thermal stress. Some typical examples of how cycling creates or enhances the damaging mechanisms are given below.

Superheaters and Reheaters:

- Fatigue : The impingement of hot gasses on cold surfaces at start-up or of cold gasses on hot surfaces at shut down creates thermal gradients. Similarly the condensed steam in the tubes after shutdown impinge on hot surfaces if the condensate remains in the tubes. The high pressure components are more vulnerable to fatigue effects due to higher thicknesses.
- Thermal Shock : Condensate in Superheater or cold reheat in hot and dry Reheater would

result in thermal shock to the inner surfaces of the tubes and headers.

- Creep: Only the high temperature component are prone to creep damage. High Temperature transients and continuous high temperature operation may increase the creep rate. However if the creep is coupled with fatigue due to cycling, the damage will be much higher than that which can occur if the same fatigue or creep is working alone.
- Oxidation: Exposure of the metal to higher temperature than what it was designed for particularly during initial start-ups can result in Oxidation.. Oxidation and exfoliation can

happen inside and outside due to gasses and steam. Dry Reheater designs are particularly vulnerable.

- Differential Expansion : Uneven heating of tubes due to flow mal-distribution and due to temperature mal-distribution can cause adjacent tubes to expand differently. Both compressive and tensile loads are imposed.
- Depositions : Uneven or excessively fast ramp rates may result in liquid in the Superheaters and formation of deposits.

Damage Mechanism	Low Cycle Fatigue	Creep	Thermal Shock	Differential Expansion	Corrosion Fatigue	Oxidation / Exfoliation	Chemical Corrosion	Flow Acc. Corrosion	Corr. Product Migration and
HRSB Component	1	2	3	4	5	6	7	8	9
Superheaters	√	√	√	√		√	√		
Attemperators	√	√	√	√			√	√	√
Reheaters	√		√	√	√	√	√		√
Evaporators	√			√	√	√		√	√
Economizers	√			√	√	√		√	√
Drums	√	√			√	√			√
Piping	√	√	√	√	√	√			√
Valves		√	√		√	√			√
Fins & Tubes	√	√	√	√	√	√	√		
Liners, Casing etc.	√	√	√	√		√			
Ducts	√	√		√		√			
Dampers	√	√		√		√			
Structurals						√			
Stacks					√	√			

Table 1: Showing the HRSB Components and their vulnerability to damaging Mechanisms

Evaporators:

- Low Cycle Fatigue: LCF occurs in natural circulation evaporators during startup because circulation has not been fully established..
- Differential Expansion : Uneven heating of tubes due to flow distribution and / or temperature distribution may cause adjacent tubes to expand differently. Both compressive and tensile loads can be imposed.
- Depositions : Uneven heating or heat flux anomalies may result in local dry-outs and deposition of salts in evaporator tubes. These depositions result in further distorting the flow and heat flux distribution.
- Flow Accelerated Corrosion: Two phase flows result in FAC, particularly in low pressure systems.
- Corrosion Product Migration : The corrosion products formed at one location may migrate to another place and under right condition may form deposits there. These deposits then result in uneven heat fluxes causing problems.
- Erosion : Solids in the water and water in the two phase flow systems can cause erosion at higher velocities

Economizers and Feed water heaters:

- Low Cycle fatigue: The impingement of cold water on hot surfaces particularly at a very quick shutdown and restart sets up LCF.
- Differential Expansion : Uneven heating of tubes due to flow distribution and / or temperature distribution can cause adjacent tubes to expand differently. Both compressive and tensile loads are imposed.
- Depositions : Uneven or excessively fast ramp rates can result in solids precipitation and deposition causing uneven heating
- Flow Accelerated Corrosion : Single Phase FAC in economizers is being recognized as one cause of failures. Often it occurs because, during start-ups and at transition time, the water chemistry may be out of control.
- Corrosion Fatigue : Chemical imbalances can create corrosion and the cycling loading can enhance the effect due to fatigue.
- Erosion : Solids in the water can cause erosion at higher velocities

DESIGN CONSIDERATIONS FOR CYCLING

In the design phase the most important requirement is to make sure that all the factors which affect the life of HRSG have been accounted for. This means that either the design features must be modified to mitigate the effect of damaging factor or the damaging factor must be eliminated. The most common way to ensure this is to do a Life Cycle Analysis. A typical life cycle analysis consists of the following steps:

- Define basic operating conditions
- Establish Lifetime operating details
- Determine most critical components
- Dynamic Analysis of the critical components. This is perhaps the most critical factor in the life cycle analysis. There are various programs available which indicate the dynamic behavior of a component. However these programs need to be custom fitted to a given HRSG and to do this the model has to be very well defined. In addition the operating conditions such as pressure and temperature ramps that cause the changes in the components need to be defined very thoroughly. Most of the life cycle analyses do not give good results because of conservatism employed in the model. This happens because oftentimes the details of the component or the operating conditions are not worked out completely and the model is not refined.
- Calculate the Cumulative Damage Factor (CDF): There are various methods available to calculate the CDF and include the methods suggested by ASME, TRD and British Standards etc. One important factor in calculating the CDF is to use a consistent method rather than indiscriminately mixing various methods with different assumptions and data used in deriving the formulas.
- Revise the Design and / or Operating conditions if the CDF is higher than allowable

Some of the items which would help in minimizing and monitoring the damage due to cycling may consist of the following:

- Smaller diameter, tubes, headers and Drums
- Automated Vents And Drains
- HP SHTR bypass to RHTR
- Wet Reheaters

- On Line water chemistry monitors
- Stack Dampers
- Leak Proof Valves
- Metal Thermocouples
- Avoidance of Bends
- Flexible Connections
- Motorized Blowdowns
- Economizer Recirculation
- No Cascading Blowdowns
- External Kettle Boilers
- Ability to Clean
- Spray Coatings
- Higher Grade Metal Alloys
- Bypass Dampers
- Multiple Attemperators
- Good steam/water side flow distribution at all loads

It may be noted that it is possible to design an HRSG without these features and still maintain the integrity of the boiler over the intended life of the boiler. The key is to do a life cycle analysis. If the life cycle requirements are met with only some or none of these features, then the design should be acceptable.

OPERATING CONSIDERATIONS FOR CYCLING

Start-ups: How the boiler is started-up is one key item affecting the boiler life. Rapid starting results in enhanced fatigue and if not avoidable entirely, it should be minimized. One way to do is to plan the start-ups and shutdowns and slowdown where possible. The manufacturer supplied start-up and shut down procedure may have some contingency built in. These may be analyzed and removed. However this is possible only if all the operating conditions including the condition of the HRSG when starting are well defined.

Ramping to Load : Generally after a soak period wherein the HRSG components have minimized temperature differences, the ramping can be done very fast. Again a planned ramping is much better. Oftentimes ramping a running boiler is much faster than starting a new boiler. So it is advisable to ramp up the running unit and ramp down as the cold unit comes on line.

Load Changes: Similar to Ramping, the load changes, if done gradually should result in minimizing the cycling effects. Oftentimes the

manufacturers suggest load changes in steps rather than continuously. For example instead of a continuous 10% change, the load may be changed in five 2% load changes with a dwell after each change.

Shutdowns: Shutdowns by themselves may not be a bigger problem, unless the purge requirements cause cold air to blow into the HRSG. Limitation on air flow should help in minimizing its effect.

Lay-ups: The chemistry upsets and oxygen intrusion during lay-ups effect the boiler conditions. When the boiler is put on line, the heat will increase the damage.

MODIFYING EXISTING UNITS FOR CYCLING

Today many HRSGs which were designed for base load conditions are required to run as cyclic units. Obviously the plant owners are interested in knowing what will be the impact and how to improve the life expectancy. To do this a vendor, preferably an HRSG manufacturer, is selected to make a study, suggest modifications and implement and monitor the operations. The basic program consists of the following :

Condition Assessment

- Critical Component identification and determination of their condition
- Checking of Instrumentation and controls
- Review of Operational History
- Establishing of a baseline benchmark

Develop required modifications for Cyclic Operations:

- Definition of the proposed operations by the owner
- Review of the proposed Cycling operations
- Development of complete Life Cycle Analysis of the critical components
- Determination of the Hardware modifications required

Physical Modifications

The physical modifications are done to the extent possible and permissible. Sometimes a modification may be feasible and cost effective but may not be permitted because of code requirements.

Monitoring program.

After the modification, a monitoring program should be developed and installed. The program should monitor the following variables:

- Temperatures, gas, water and steam
- Drum Levels
- Attenuator flows
- Steam and water flows and velocities
- Water Chemistry
- Steam Purity and Constituents
- GT & Burner Fuel
- Exhaust Gas Conditions

Review and analysis of data

Once the monitoring program data is available it is reviewed and checked against the assumptions. If there are any changes between the actual and initially specified operating conditions these are noted and their effect on the life expectancy is assessed. Based on this assessment some further adjustments are made.

Final inspection and review:

After at least a year the unit condition is checked. This includes checking of thicknesses, corrosion and deposits etc. and would involve non destructive and destructive testing of some suspected components. The values thus obtained are checked against the

baseline benchmark. Based on this data, further modifications are suggested or the operating conditions are changed.

CONCLUSIONS

Designing and operating the HRSGs for cyclic operation requires detailed definition of the operating conditions and close co-operation between the designer and the operator. The monitoring system should be such that it should give a very thorough picture of the mechanisms affecting the life and integrity of the boiler. Periodic review of the data is necessary to compare the actual conditions with the expected conditions. For the existing units long term cooperation between the operators and the designers and free exchange of data is very essential. Generally the boilers designed for base load can run with cyclic loads with minor hardware changes. Sometime a very minor adjustment in the operating condition may preclude the necessity of a major modification. For this reason, if for nothing else, thorough understanding of the operations by the designer and good understanding of the design and its impact on the unit by the Operators is essential.

1. Abstract Type: Manuscript Presentation
2. This paper has not been previously presented or published anywhere.

3. Topic: 1. **Power Plant Technology**
 ➤ Boilers/HRSGs
 2. **Operation & Maintenance**
 ➤ Life Extension
4. Contact: **Akber Pasha** (Primary Contact)

Technical Director
Vogt-Nem Inc.
4000 Dupont Circle
Louisville, Ky. 40207-4811
Phone : 502-899-4618
Fax: 502-899-4667
e-mail: apasha@vogt-nem.com

Robert Allen (Co-author)
Senior Engineer
Vogt-Nem Inc.
4000 Dupont Circle
Louisville, Ky. 40207-4811
Phone : 502-899-1920
Fax: 502-899-4667
e-mail: rallen@vogt-nem.com