Arab Fertilizer Association

Since 1975

QAFCO

QATAR FERTILISER COMPANY

# AFA WORKSHOP ON

# Process Waste Heat Boilers Integrity and Reliability

**Hotel Sharq Village & SPA**

**Qatar: 01 - 03 December 2014**

# Papers

# Program

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# Process Waste Heat Boilers Integrity and Reliability

## Hotel Sharq Village & SPA
Qatar: 01 - 03 December 2014

# Program

## DAY 1 – Monday: December 01, 2014

08:30 – 09:30 Registration

09:30 – 10:00 Welcome Address

10:00 – 11:15 KBR's Improved Design for Waste Heat Boilers in Ammonia Plant
**Umesh Jain,**
Chief Technical Advisor,
KBR Inc., USA

**11:15 – 11:45 Networking Coffee / Tea**

11:45 – 12:30 Failure of the New RG Waste Heat Boiler of Ammonia 5 at Qafco
**Marco van Graefschepe,**
Head of Ammonia 5,
QAFCO, Qatar

12:30 – 13:15 Lessons Learned from FERTIL-1: Waste Heat Boiler Operation
**Ali AL Hosani,**
Ammonia-1 Process Engineer,
FERTIL, UAE

13:15 - 14:00 Technical Assessment of SAFCO-4 Synthesis Loop Waste Heat Boiler-II Leakage

**Ekambaram Manavalan,**
Inspection Manager
**Abdulrahman Al Johani,**
Inspection Engineer,
SAFCO, Saudi Arabia

**14:00 Networking Lunch**

## DAY 2 – Tuesday: December 02, 2014

09:30 – 10:30 Technical and Economic Feasibility Assessment for a CHP System with ORC Technology
**David Alonso,**
CEO, DVA Global Energy Services, Spain

10:30 – 11:15 Ammonia Synloop Waste Heat Boiler Failure in Ammonia Plant III.
**Hossam Naiem**
**Abu-Qir Fertilizer Co.**, Egypt

**11:15 – 11:30 Networking Coffee / Tea**

11:30 – 13:15 Primary Waste Heat Boiler Failure Analysis Repair Methodology and Replacement
**Ahmed Al-Mulhim,**
Process Engineer,
ALBAYRONI, Saudi Arabia

13:15 – 14:00 Summary of History of Waste Heat Boiler in Ammonia IV (E 3205)- PIC
**Mohammad Folad,**
Planning Engineer, PIC, Kuwait

**14:00 Networking Lunch**

## DAY 3 – Wednesday: December 03, 2014

09:30 - 10:15 Waste heat recovery in fertilizer industry: OCP case study
**Hamid Mazouz,** Researcher
**Abdelaaziz ben el bou,**
Production Manager,
OCP SA, Morocco

10:15 - 11:00 Replacing of Waste Heat Boiler in Sulphuric Acid Plant
**Ibrahim Makhamreh,**
Plant Manager, JPMC, Jordan

**11:00 - 11:30 Networking Coffee / Tea**

11:30 - 12:15 Gas side corrosion of stack gas heat recovery economizer in oil-fired high pressure steam boiler
**Osama Khalil,**
Chemical Supervisor,
APC - Jordan

12:15 **Closing**

**13:00 Networking Lunch**

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# DAY 1 Monday: December 01, 2014

Int'l. Organization
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Process Waste Heat Boilers
Integrity and Reliability
Qatar : 01-03 December 2014

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# KBR's Improved Design for Waste Heat Boilers in Ammonia Plant

Umesh Jain
Chief Technical Advisor
KBR Inc.
USA

# ***KBR's Improved Design for Waste Heat Boilers in Ammonia Plant***

*Umesh Jain, KBR, Inc.*



## 1.0 Introduction

More than 150 ammonia plants worldwide use reformed gas waste heat boilers featuring bayonet style tube bundles. Legacy Kellogg (KBR) plants built from the 1960s to the 1980s typically have three shells numbered as 101-CA, 101-CB & 102-C. 101-CA and CB are bayonet, water tube boilers and 102-C is a fixed tube sheet, fire-tube boiler. Although the bayonet technology was highly successful and credible in that timeline, it has become obsolete. KBR has been offering single shell one pass floating head technology since the mid-1980s, which has been highly successful in numerous ammonia plants.

A review of on-stream factors of plants having bayonet boilers reveals that such aging boilers may contribute significantly to loss of production. Severe process conditions and inevitable transient operations lead to failure of these boilers. Smooth and reliable performance of these boilers is a pre-requisite for profitable operation of ammonia plants. Mechanical failures prevent optimum operations and require excessive maintenance.

KBR's water tube boiler with a floating head provides an opportunity to replace multiple existing exchangers with a single shell. This provides reliable, sustained operation proven in numerous grass-roots KBR plants built since the mid-1980's. Ammonia plants built prior to that time need to compete with the newer ones, and upgrading their boiler technology will enhance plant on-stream factor significantly. KBR has developed a cost effective execution solution, and plants with bayonet boilers are either implementing or considering this solution.

Modern natural gas-based, efficient ammonia plants produce high flows of high pressure steam using innovative heat integration. Such integration requires supplying boiler feed water and collecting of steam from the frontend and Ammonia Synthesis loop located far from each other. A simple, robust, low-cost and user friendly system for generating steam from waste heat is needed in the Synthesis loop to ensure profitable ammonia operations.

The unique KBR steam system provides a simple, user friendly and low-cost arrangement. The KBR ammonia synthesis loop uses two shell & tube exchangers in this demanding steam generation service. This is preferred compared to other complex mechanical designs including those with integral drums. The common steam drum approach is proven to be very user friendly as there are no routine operation and maintenance needs associated with each steam drum, e.g. level control, drum water analysis, chemical dosing and individual drum blow-down requirements. This system, proven in numerous KBR plants, is also very user friendly during operational transients as the operator has fewer things to manage such as only one drum level .

The paper discusses reliability issues associated with Reformed gas boilers and Synthesis loop boilers, compares different technologies and describes the retrofit execution.

## 2.0 Front End Waste Heat Boilers

Many legacy Kellogg (KBR) plants built prior to 1990s are producing 30% – 80% more than the nameplate ammonia production capacity. In every case no upgrade has been done to the existing waste heat boilers, 101-CA/CB. Operating at increased capacity increases the heat flux across exchanger tubes, increases the vaporization rate, and reduces the residence time in the steam drum, which leads to increased rate of tube failure.

Refer to Figure 1: The Secondary Reformer, 103-D effluent gas enters the shell through a distributor pipe with perforations for uniform distribution of gas. The gas at around 1,000ºC flows upwards heating water in tubes, and the cooled process gas then goes to the Secondary Waste Heat Boiler, 102-C, for further HP Steam Generation.

Boiler Feed Water (BFW) from the elevated Steam Drum, 101-F, flows through one down-comer into the water chamber where it enters the top of the inner tubes of 101-CA/CB and flows down. At the bottom of the inner tubes water flows up into the annular space between outer and inner tubes. High Pressure steam and BFW at ~105 bar (g) rise in the annular space to the steam chamber and then to the steam drum through two risers.

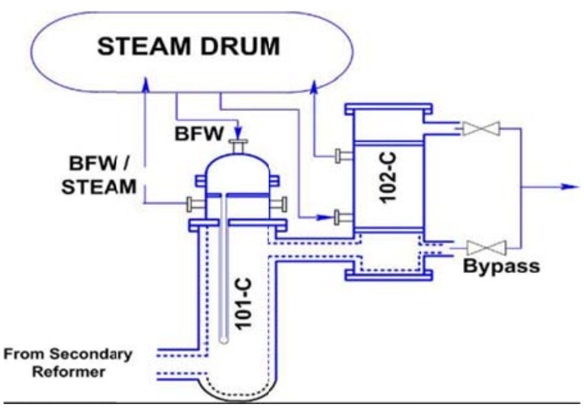



Figure: 1 – Legacy Kellogg Waste Heat Boilers

**LEGACY KELLOGG DESIGN**

The legacy Kellogg waste heat boiler is protected by a water jacket on the outside and a single layer of refractory on the inside. The metal shell is designed for about 200 ºC. The refractory also has a metal liner. The exchanger baffle diameter and the inside diameter of the metal liners are carefully selected so that at operating temperatures a reasonably tight seal is formed. This tight seal avoids gas by-passing the heat transfer area.

Each exchanger, 101-CA/CB, has multiple tubes to transfer the required duty. The inner tubes (bayonet) are 1” (25.4 mm) and are open at both ends. The outer tubes, referred to as scabbards, are 2” (50.8 mm) in diameter and are closed at the bottom.

To keep bayonet and scabbard (inner and outer) tubes separated by a somewhat uniform distance, nail-like projections are welded to the outside of bayonets.

Nameplate design of these exchangers was with a BFW to steam ratio of 10. With increased plant rate and higher heat transfer duty this ratio reduces to seven or less. Refer to Figure 2.

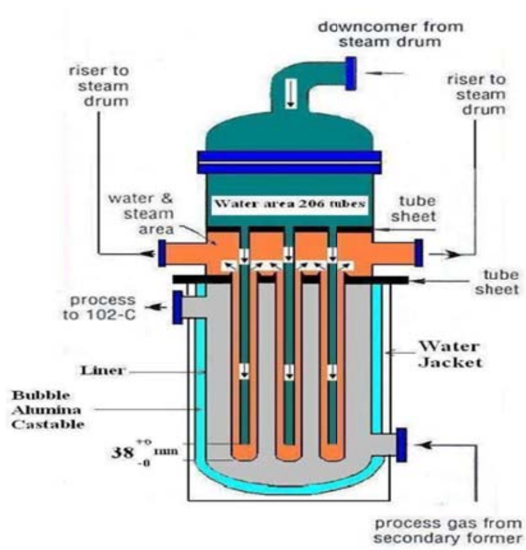



Figure: 2 – Bayonet Style Waste Heat Boilers, 101-CA/CB

## PAST ISSUES WITH LEGACY KELLOGG DESIGN

1. Metal liner – During operation the metal liner warps and gets out of shape. When the exchanger tube bundle is to be pulled it does not come out easily as the exchanger baffle binds with the liner. In some cases the metal liner is forcibly removed with the tube bundle.

2. Nails on the outside of the bayonets – Nails or spacers disrupt the flow pattern and can create hot spots. The clearance between the spacers and scabbard increases with use. This causes the nails to rub against scabbard more vigorously. This rubbing removes the protective magnetite layer and leads to tube failure by corrosion.

3. Deposits at the bottom of the scabbards – BFW and steam change direction at the bottom of the scabbards. Any debris will deposit at the bottom and form scale leading to hot spots and higher rates of failure.

## HOW ARE WASTE HEAT BOILER PROBLEMS SOLVED TODAY?

All ammonia producers strive for greater reliability and many achieve four years between a plant turnaround. Major ammonia producers are striving for six years between plant turnaround. As a corporate policy, spare tube bundles are maintained or the ammonia plant participates in a spare parts sharing pool with other plants. At a regular interval, approximately every four or six years, 101-CA/CB tube bundles are replaced. No effort is made to analyze problems or improve on the design.

One east European ammonia producer has an excellent plant workshop where they fabricate their own tube bundles.

In extreme cases some have replaced their bayonet Waste Heat Boilers with a Fire-tube style exchanger. This is an expensive solution, made without cost benefit analysis and without considering legitimate low cost options. Fire-tube boilers have their own set of pluses and minuses.

## LOW COST (BUT INCOMPLETE) SOLUTION

Replacing the existing 101-CA/CB shells with dual layer refractory and no metal liner will help expedite removal of the tube bundle. The tube bundle is replaced with new and improved design with upgraded materials.

The new in-kind replacement design cannot address debris deposits at the bottom of the scabbard tubes. The new design cannot address the issue of disturbances caused by spacers. Thus, this upgrade will not increase the expected life of the bundle. However, removal and insertion of the bundle will be much faster, thus greatly reducing downtime on the failure of a bundle.

Replacing the shell with a refractory lined upgrade could be done in an extended turnaround. Due to heavier weight, the structural steel may need to be modified. If this change is done, 102-C should be replaced with the current design that is more reliable.

## CURRENT DESIGN: A TOTAL SOLUTION

In newer plants, KBR has maintained the good aspects of the legacy 101-CA/CB design. Features like the proven design of the refractory lining and water jacketing on the outside are maintained.

The new design is also based on natural thermo-syphon. The BFW from the elevated Steam Drum, 101-F is taken through the exchanger, and HP Steam plus BFW are returned to the drum like the legacy design.

In the new design, all three Waste Heat Boilers, 101-CA/CB and 102-C, are replaced with one exchanger. The High Temperature Shift inlet temperature is controlled with a bypass on the exchanger.

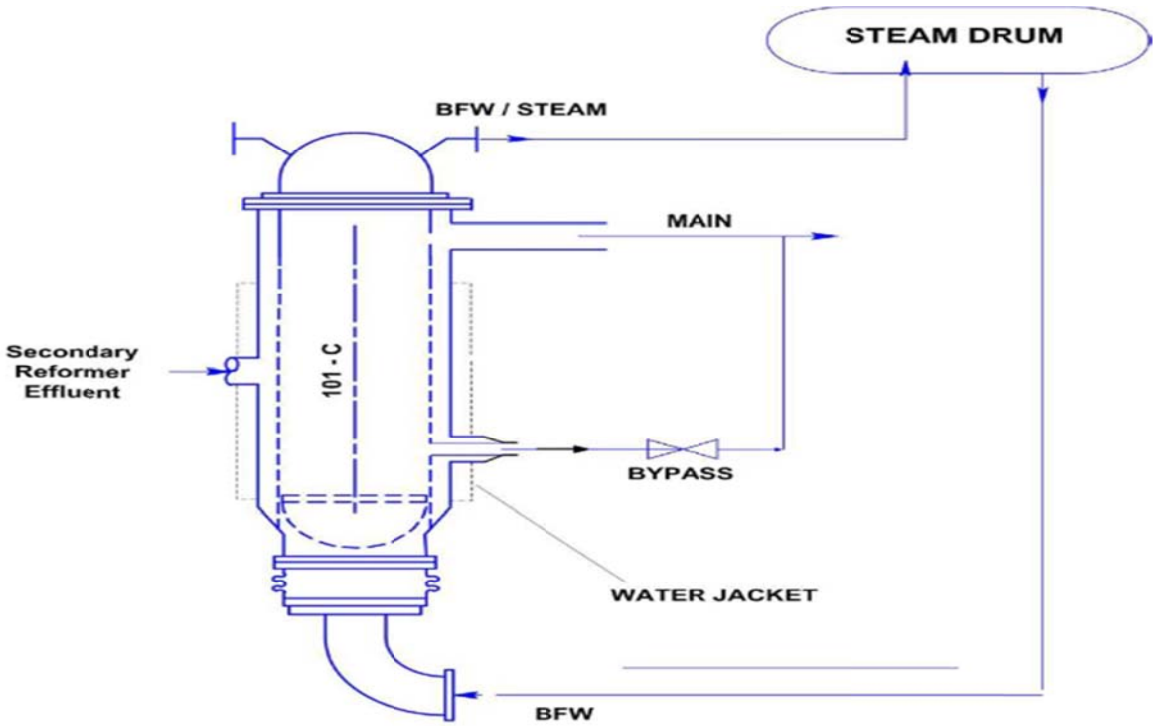



Figure: 3 – KBR Water-tube Waste Heat Boiler

**WATER TUBE BOILER DESCRIPTION**

The exchanger shell in the current KBR design has dual layer refractory. The inner layer is for heat conservation and outer layer for erosion protection. There is no metal liner in this design. The exchanger baffle diameter and the inside diameter of the refractory are set such that they form a tight seal at operating conditions. At ambient conditions there is enough clearance between the refractory and baffles that the tube bundle comes out easily.

BFW from the elevated Steam Drum, 101-F, flows to the bottom of the exchanger and up through the tubes. Secondary Effluent gas at around 1,000 ºC enters shell side of the exchanger through an inlet gas distributor. The inlet gas distributor is a special proprietary KBR design. The gas distributor avoids direct impingement of the hot gases on the tubes.

**REPLACING BAYONET EXCHANGERS WITH KBR FLOATING HEAD EXCHANGER**

All three exchangers are replaced with new one floating head exchanger. The new exchanger (101-C) is designed for the higher duty required for increased capacity. Almost all legacy Kellogg Secondary Reformers, 103-D, have two outlets, one for each 101-Cs. These Secondary Reformer outlets are combined together with one water jacketed transfer line which sends hot reformed gases to the new heat exchanger.

The new exchanger is installed outside the existing structure and parallel to the Secondary Reformer. Since the new exchanger (101-C) is on a new foundation, it is installed while the plant is in operation.

High pressure boiler feed water lines to and from the drum require modifications, and proper piping stress analysis is necessary to assure reliable upgrade.

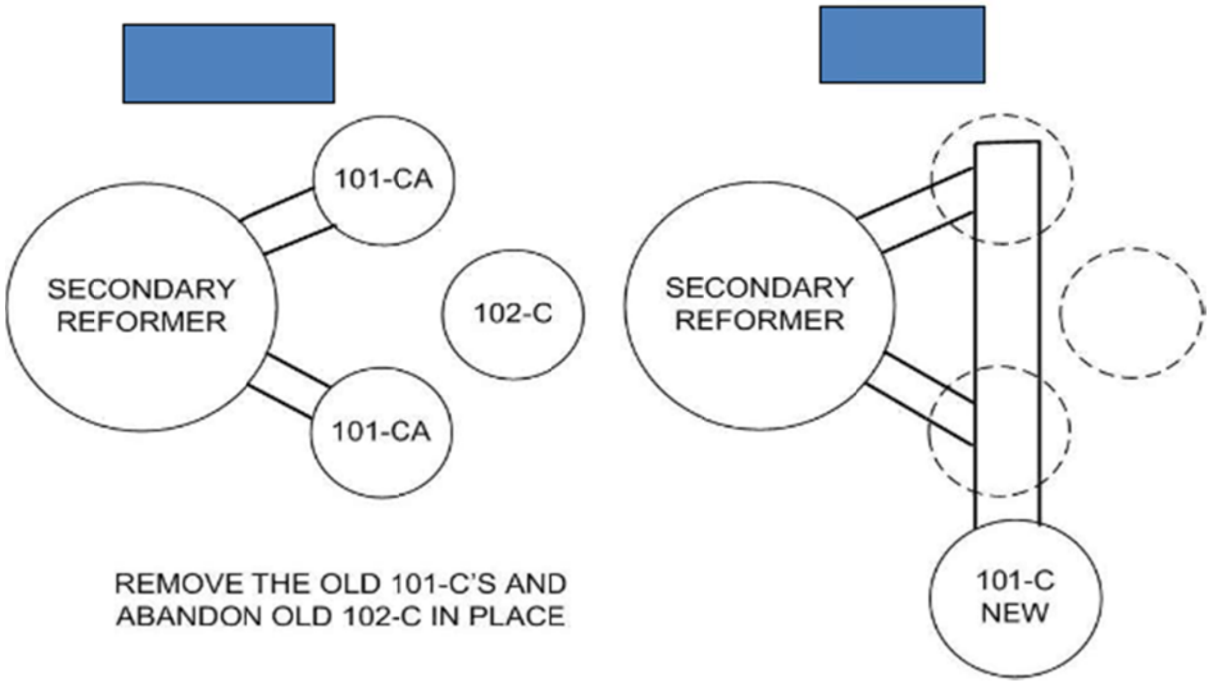



Figure: 4 – Replacing Bayonet Exchangers with New Floating Head Exchanger

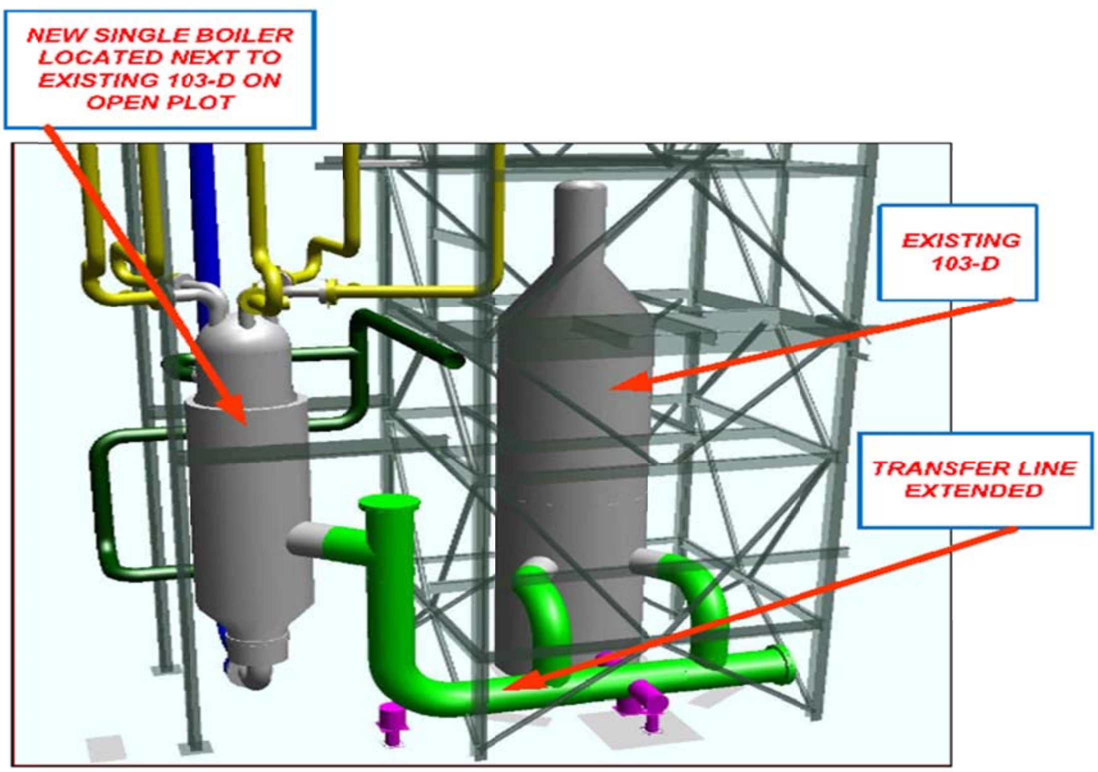



Figure: 5 – Replacing Bayonet Exchangers with New KBR Floating Head Exchanger

**BFW QUALITY**

No matter how good the design, one still must pay close attention to the Boiler Feed Water quality. The main conclusion of P. Orphanides and R. Michel in their 2008 paper was: "Keep your boiler surfaces clean and you will not suffer damage."

## 3.0 Synthesis Loop Waste Heat Boilers

With HP steam generated in the synthesis loop since the late 1980's, different steam system configurations have emerged in the ammonia industry as various technology providers reconfigured the steam system of the plant. Considering the significant distance between the syn-loop waste heat boiler and the steam drum of the front-end, most plants have a separate steam drum for the synthesis loop. Some configurations have used synthesis loop waste heat boilers with their integral steam drums as vendor designed items while others provided separate drum in the synthesis loop. While following this approach where the syn-loop has two separate ammonia converters with multiple boilers, plants may also have more than one HP steam drum in the synthesis loop.

KBR has used a different approach in integrating the steam system in modern energy efficient ammonia plants. While producing high pressure steam in the syn-loop, KBR uses only one common high pressure steam drum, located near the reforming section, for the ammonia plant. The common HP steam drum is located close to the secondary reformer waste heat boiler to support thermo syphon water circulation. BFW and steam from the boilers located at the exit of HT shift converter and ammonia converter, flow into this common, steam drum. The deaerated BFW is preheated and then split between the two heat recovery trains – one recovers heat in the frontend exit of the HT shift converter and other recovers heat in the synthesis loop exit of the ammonia converter. Steam is produced in the HP drum by force feeding two-phase steam plus BFW mixture from these two trains as seen in FIGURE-1.

Several different configurations are used by other licensers. For example, the front-end may have a dedicated secondary reformer waste heat boiler with a piggy back HP steam drum that is integrated with the boiler downstream of the HT shift. The synthesis loop uses vendor designed vertical boilers with integral HP steam drums in such plants. Where plants have a second ammonia converter in series, two such vertical boilers with their dedicated drums are used as seen in FIGURE-2.

**SYNTHESIS LOOP WASTE HEAT BOILER**

Rather than using a complex waste heat boiler, KBR uses two shell and tube exchangers in series (see FIGURE-3) in the syn-loop to generate high pressure steam. These exchangers use a removable U-tube configuration having special details where water is placed inside the tubes. This configuration is more tolerant to transient operating conditions in this severe service, thus provides high reliability. Other configurations including fixed tube-sheet designs or inverted U tubes with hot gas inside having an integral steam drum are more prone to failure as seen in operating plants. A portion of the boiler feed water required in the common steam drum is fed through this exchanger to the common steam drum. A significant portion of water is vaporized and the two-phase stream of steam plus water is routed to the common steam drum following a specially executed robust piping arrangement that has no restriction on its length.

The unique KBR steam system provides a simple, user friendly and low-cost arrangement. KBR uses two shell & tube exchangers in this demanding operating service of the syn-loop. This is preferred compared to other complex mechanical designs including those with integral drums. The common steam drum approach is proven to be very user friendly as there are no routine operation and maintenance needs in the synthesis loop as typically associated with each steam drum, e.g. level control, drum water analysis, chemical dosing and individual drum blow-down requirements. This system, proven in numerous KBR plants, is also very user friendly during operational transients as the operator has fewer things to manage such as only one drum level .

Due to its unique features, compared to other complex designs, this exchanger arrangement in KBR plants is relatively more forgiving to possible transients in the water treatment regime and to process upset conditions usually seen over the life cycle of ammonia plants. High reliability of this system contributes to the exceptionally high on-stream factor of KBR ammonia plants. This simple compact waste heat boiler with fewer associated system items (e.g. no level control) in the steam system assists in reducing installed cost of KBR ammonia plants.

## CONCLUSION

Maximum recovery of process waste heat for producing high pressure steam is required in modern, efficient ammonia plants. This requires a system to supply HP BFW and to collect HP steam from heat exchangers located all over the plant. Although several complex systems are used in industry, including vendor designs with separate steam drums, HP steam generation systems in KBR ammonia plants provide simple, robust, low cost and user friendly systems that ensures profitable ammonia operations.

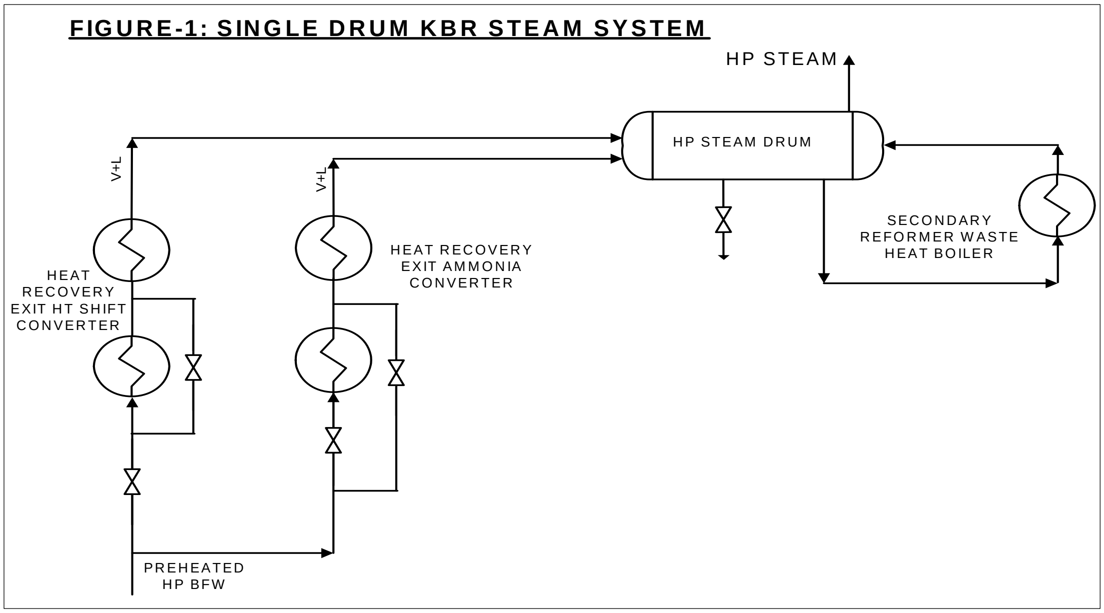


FIGURE-1: SINGLE DRUM KBR STEAM SYSTEM
HP STEAM
HP STEAM DRUM
V+L
V+L
HEAT RECOVERY EXIT AMMONIA CONVERTER
SECONDARY REFORMER WASTE HEAT BOILER
HEAT RECOVERY EXIT HT SHIFT CONVERTER
PREHEATED HP BFW

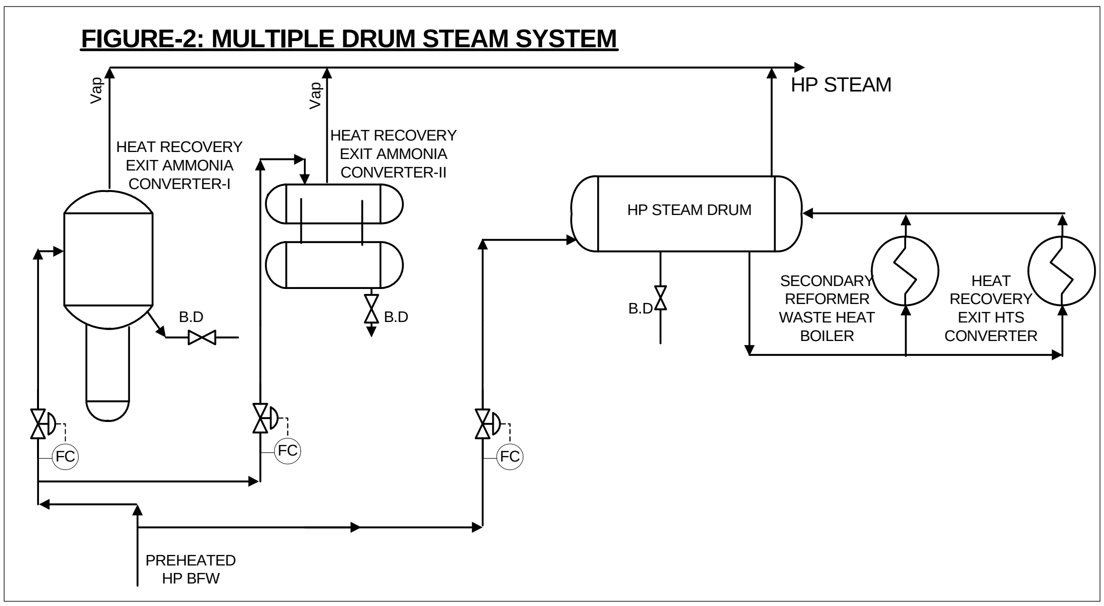


FIGURE-2: MULTIPLE DRUM STEAM SYSTEM
Vap
Vap
HP STEAM
HEAT RECOVERY EXIT AMMONIA CONVERTER-I
HEAT RECOVERY EXIT AMMONIA CONVERTER-II
HP STEAM DRUM
B.D
B.D
B.D
SECONDARY REFORMER WASTE HEAT BOILER
HEAT RECOVERY EXIT HTS CONVERTER
FC
FC
FC
PREHEATED HP BFW


FIGURE-3: Ammonia Converter exit waste heat boiler

## References

1. Mahesh Gandhi, Shashi Singh & Robert Burlingame, KBR Inc. (Houston) 'Enhance Ammonia Plant Reliability by Replacing Aging Bayonet Type Boilers with KBR's Floating Head Waste Heat Boiler' – N2+Syngas Conference 2014

2. Shashi Singh, KBR Inc. (Houston) 'User Friendly High Pressure Steam Generation System Contributes to High Reliability of KBR Ammonia Plants' – Asian N2+Syngas Conference 2013

# Failure of the New RG Waste Heat Boiler of Ammonia 5 at Qafco

Marco van Graefschepe
Head of Ammonia 5
QAFCO
Qatar

## AFA Process Waste Heat Boilers workshop Dec. 1-3, 2014 Doha, QATAR

# Failure of the new RG Waste Heat Boiler of Ammonia 5 at Qafco

Qafco's Ammonia 5 plant is one of the 2 new ammonia plants at Qafco, that came with the Qafco 5 and 6 major expansion project, increasing Qafco's Urea and Ammonia capacitities by 1.6 and 2.8 million Metric Tons (MT) per year respectively.
The new plants are located at the new site for Qafco 5 and 6 at about 3 km west of the old site of Qafco 1 to 4 plants and were commissioned from 2011 to 2012.

On Sept. 9$^{th}$ 2011 the RG Waste Heat Boiler of Qafco's Ammonia 5 plant experienced a major leaking of boiler water to the process side, only shortly after commissioning and start-up of the new plant. Two tubes were found ruptured and almost half of the tubes showed cracks in the tube to tube sheet welds at inlet side.

Inspection, analysis and repair took more than 4 months, after which the plant was restarted and operated at reduced plant load and lower HP steam pressure.

Only about 2 weeks later, when the plant experienced a shut down, again leaking of the WHB was observed. This time the main damage was at the outlet tube sheet, especially the tube sheet itself showed severe cracks in the base material.

The plant could be restarted after 3 months. But again after 2 weeks leaking of the WHB was observed and the plant was stopped. Few tube leaks were found at the inlet tube sheet. After a 1 month repair period the plant was started and the WHB didn't fail anymore until its replacement during the scheduled Warranty Shut down in Februari 2014.

This article describes the process observations and root causes of the failures

***Marco van Graefschepe***

*Qatar Fertilizer Company (Qafco)*

## Failure of the new waste heat boiler E0308

The Qafco Ammonia 5 plant primary reformer furnace was lit for the first time on August 16th 2011 and the front-end reached stable operation on August 26th. During the start up activities the primary reformer experienced 4 process trips. Synthesis convertor reduction started on August 27th at 80% plant load and was completed on Sept. 4th. First liquid ammonia production was achieved on Sept. 1st. Plant load reached 100% on Sept. 4th.

On the evening of September 8th 2011 the plant was running stable with normal process conditions at approximately 100% load. At around 20:30hrs, during his routine plant survey, one of the field operators observed a small fire from E0309 (HP-steam super heater) channel flange. He immediately informed the shift supervisor and DCS operator via the radio.

The fire was put-off shortly after by operational staff using a trolley mounted dry chemical powder extinguisher. It was observed that process gas was leaking from E0309 channel flange (process gas temperature was 370 deg C). Nitrogen and steam was applied with hoses on the leak spot in order to dilute the leaking gas. Meanwhile key people from Contractor and Company were contacted and briefed about the leakage and fire. Upon arrival of this key personnel, the situation of the leakage was reviewed and it was jointly decided to shut down the plant and attend to the leak. Shutdown activities started at 23:30hrs on September 8th and at 04.00hrs September 9th primary reformer shut down was completed.

## Plant shutdown:

Decision to shutdown the plant was taken at 23:30hrs on the September 8th due to fire discovered at E-0309 flange channel cover. The various sections were systematically taken out of operation as follows:

- From 23.30hrs to 02.30 hrs plant load was reduced from 100% to 60%
- At 02:30hrs plant back-end was taken out of operation
- At 03:10hrs methanator & CO2-removal system (including LTG/LTS) were taken out of operation.
- At 3.30hrs front-end plant load was reduced to 30%
- At 03:38hrs remaining process air to secondary reformer was cut-off
- At 03:43hrs the primary reformer shutdown was initiated from DCS after observation of heavy steam/gas leak and loud sound from temperature control valve TV03175 (process gas bypass of HP-steam super heater E0309). (Figure 1). This observation is significant to the analysis of the failure of the waste heat boiler ( E0308).
- The full plant shut down was completed without any automatic trip initiation.

*Figure 1: Leaking Process gas bypass valve of E0309*

## First visual observations with respect to waste heat boiler E0308:

- While preparing steam superheater E0309 for inspection, the primary reformer loop was fully depressurized on September 12th evening. In parallel, the HP-steam circuit (consisting of steam drum V0301 and the 3 waste heat boilers E0308, E0410 and E0801) was pressurized with nitrogen to purge the system and keep it under inert media as the shutdown was estimated to last for a longer period.
- During this activity, drop wise water leakage was observed from TV03175 bonnet (E0309 bypass valve) and E0308 gas side outlet compartment drain. Based on these observations, HP Waste heat boiler (E0308) upstream and down stream side manholes were opened and heavy leakage was observed from some the E0308 tubes from both sides.
- On September 14th, when E0308 could be entered for first time after cooling down, the following observations were made:

  Heavy water leakage was observed from 2 tube-tube sheet joints at the inlet tube sheet (Figure 2). The process gas bypass (center pipe) was found slightly deformed at the inlet tube sheet (also Figure 2).

*Figure 2: Heavy water leakage was observed at the inlet tube sheet*

Most of the ferrules were found in damaged condition. Debris of ferrules and refractory was found at E0308 inlet compartment (Figure 3).

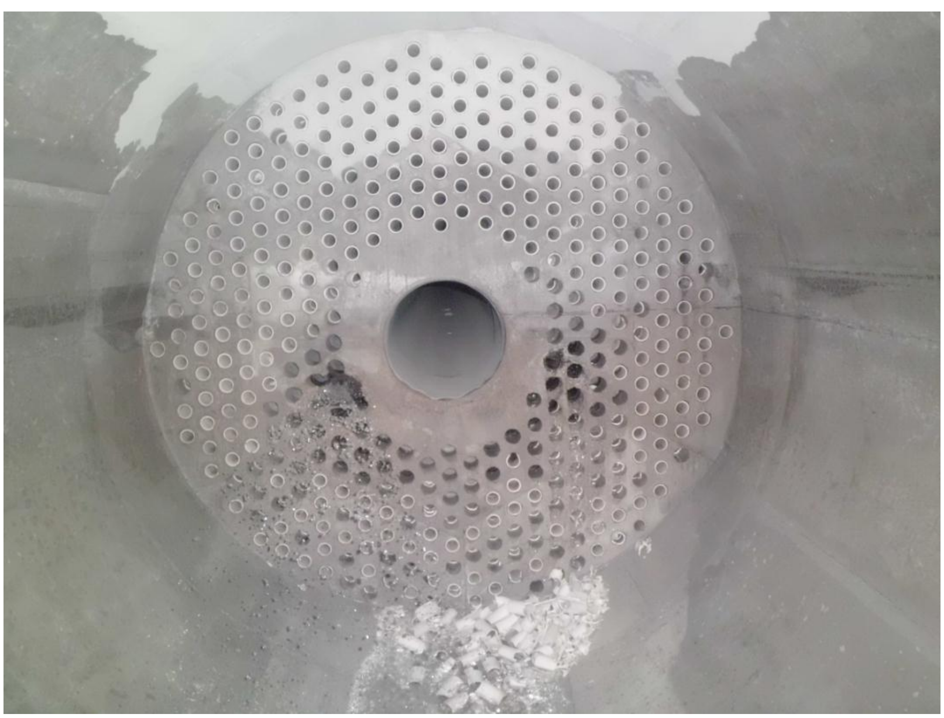


*Figure 3: Most of the ferrules were found damaged and debris of ferrules and refractory was found at the entrance in front of the tube sheet.*

Also broken ferrule pieces went through the pipes to the outlet compartment and water had traveled from E0308 to E0309. (Figure 4)

*Figure 4: Water and debris was found at the outlet compartment*

## Analysis of process parameters before/during/after the fire incident

After above observations on E0308, the relevant process parameters were collected and analyzed to understand at what stage in time this major leaking had occurred and if any operational abnormality could explain for this failure to happen.

Based upon first analysis of trends it became clear that major leakage had occurred during the shut down around 3.40hr, after the process air was cut off. Several significant parameters show a sharp change here.

From the further analysis no indications were found which could give a reason for the failure as such. All parameters were moving as per process requirement and expectation. No abnormal temperatures or pressures were observed which could have put the boiler under too high stress and which could lead to this failure.

Following were the main observations during the shut down taken around the “E0308 failure” (referring to the time around 03.40hrs)

1) **<u>Waste heat boiler E0308 inlet temperature (Figure 6 and Table 1):</u>** Before the failure, the waste heat boiler inlet temperature increased from 896 deg C (03:20hrs) to 996 deg C (03:39hrs), due to increasing primary reformer outlet temperature. After that, this temperature came down suddenly to 965 deg C (03:40hrs) and dropped further to 365 deg C (03:41hrs) and reached 241 deg C ( 03:42hrs) (Figure 7 and Table 1). Note that there are actually 4 thermo couples measuring at approximately 1,4m distance from E0308 inlet tubesheet (TI03171 and TX03177/A/B/C) (Figure 5). Almost sure the observed temperature drop (Figure 7 and Table 1) is caused by the boiler water spraying under high force out of the leaking tubes.

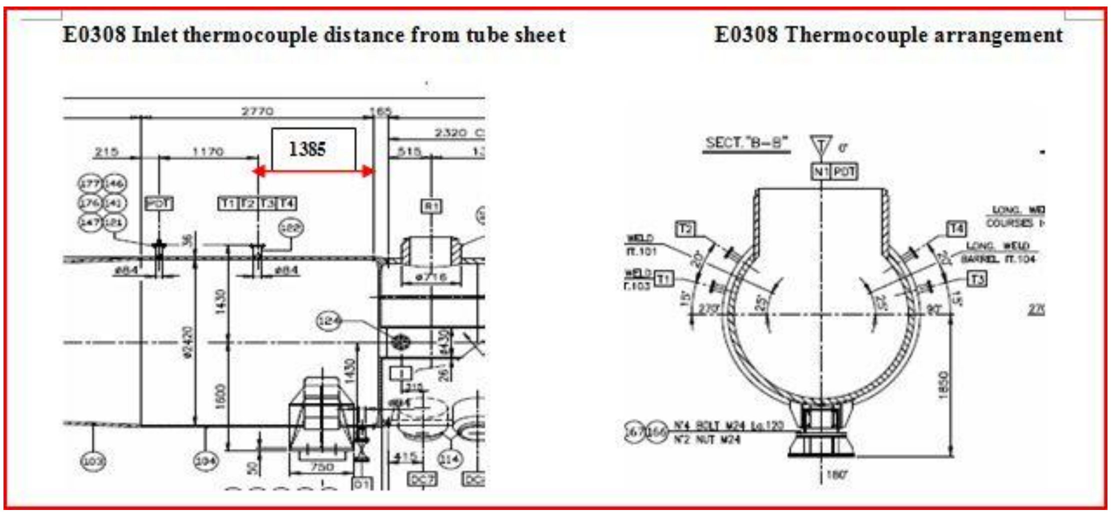



*Figure 5: Thermo couple locations at the E0308 inlet side*

Later analysis of operational data revealed that 1 of the thermo couples (TI03171) during 2 earlier front-end trips showed a sudden drop for several minutes. Most likely some extent of leaking was already present at that time and water was spraying on this specific temperature element (Figure 6).

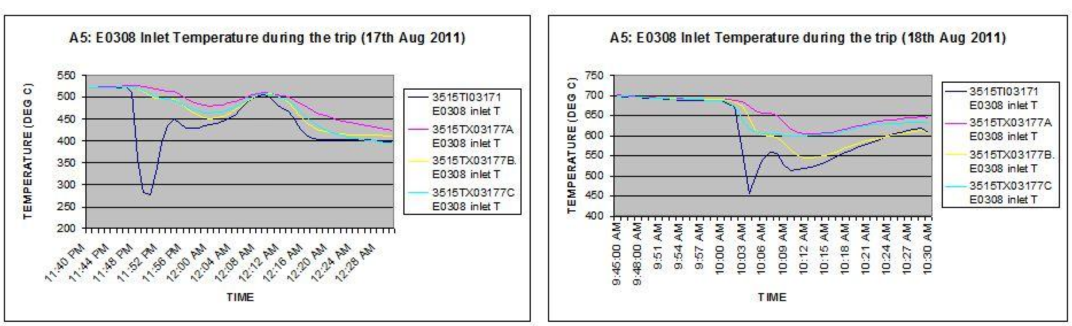



*Figure 6: One of the inlet thermo couples inlet E0308 showing temporarily a drop in temperature.*

2) **V0301 (steam drum) Level (Figure 7 and Table 1):** Before the moment of the major failure the level and pressure of the steam drum were still normal. From the moment of failure, the level of the steam drum came down from 52.42% (03:39hrs) to 30.26% (03:43hrs) but stayed above the trip value. Also the boiler feed water flow rate to V0301 increased from 88 T/hr to 193 T/h in same time and reached a maximum of 324 T/hr around 03.50 hrs.

3) **E0308 (WHB) outlet temperature (Figure 7 and Table 1):** The outlet temperature of E0308 came down from 436 deg C (03:39hrs) to 250 deg C (03:42hrs). Note that this outlet temperature at this point of time is higher than the inlet temperature of the WHB!

4) **Reformer system pressure (Figure 7 and Table 1):** the front-end pressure measured at the high temperature shift converter R0401 increased from 2060 kPaG to 2770 kPaG. Almost sure due to sudden vaporization of the leaking BFW water from the WHB entering the process side.

5) **Leakage from SSH E0309 gas bypass valve TV03175:** One of the field operators observed a heavy steam/gas leak and loud sound coming from temperature control valve TV03175 (process gas bypass of steam super heater E0309), which lead to the decision to initiate shut down of the primary reformer. This leakage from the flange bonnet seems to have occurred when above mentioned sudden front-end pressure increase happened due to the BFW entering the system, as it was discovered at the same time. Note that it was found later that the bonnet gasket was damaged and that the bonnet joint bolts were loose i.e. not properly tightened.

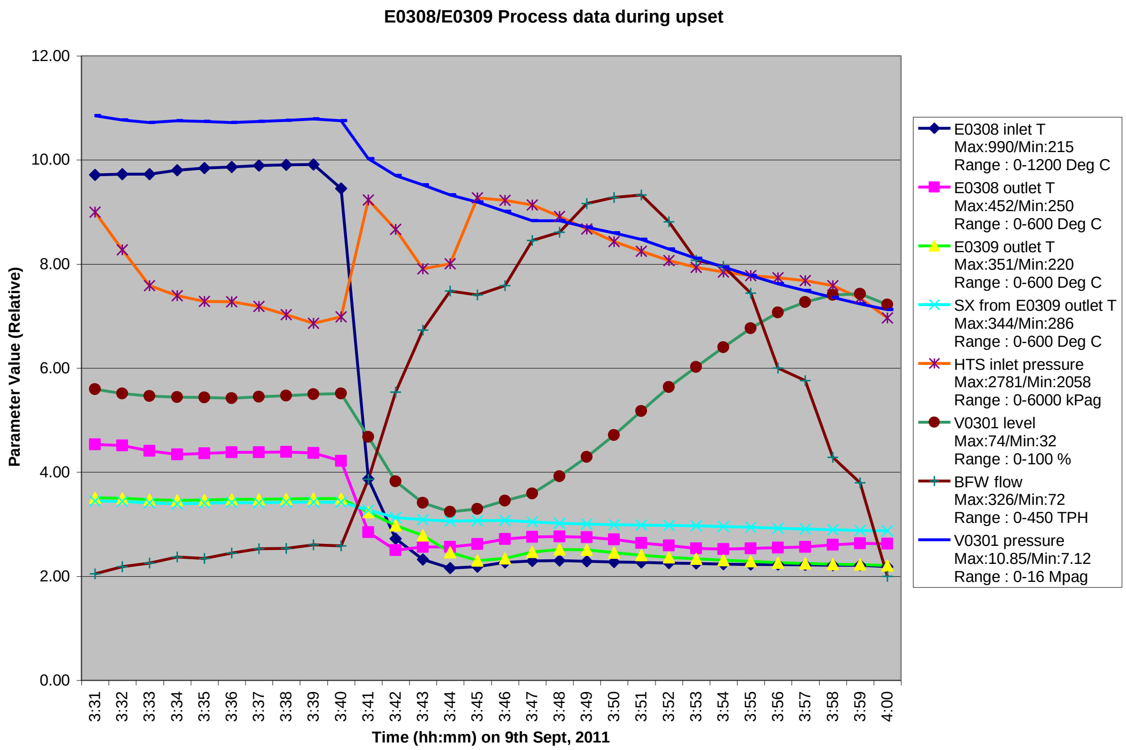



*Figure 7: Main process parameters around time of E0308 failure*

| Date | Time | E0308 inlet T<br>Max:990/Min:215<br>Range : 0-1200 Deg C | E0308 outlet T<br>Max:452/Min:250<br>Range : 0-600 Deg C | E0309 outlet T<br>Max:351/Min:220<br>Range : 0-600 Deg C | SX from E0309 outlet T<br>Max:344/Min:286<br>Range : 0-600 Deg C | HTS inlet pressure<br>Max:2781/Min:2058<br>Range : 0-6000 kPag | V0301 level<br>Max:74/Min:32<br>Range : 0-100 % | BFW flow<br>Max:326/Min:72<br>Range : 0-450 TPH | V0301 pressure<br>Max:10.85/Min:7.12<br>Range : 0-16 Mpag |
|---|---|---|---|---|---|---|---|---|---|
| 9/9/2011 | 3:31 | 9.71 | 4.53 | 3.51 | 3.45 | 9.00 | 5.60 | 2.05 | 10.85 |
| 9/9/2011 | 3:32 | 9.73 | 4.51 | 3.50 | 3.44 | 8.27 | 5.51 | 2.19 | 10.77 |
| 9/9/2011 | 3:33 | 9.73 | 4.41 | 3.47 | 3.41 | 7.59 | 5.46 | 2.25 | 10.72 |
| 9/9/2011 | 3:34 | 9.80 | 4.34 | 3.46 | 3.39 | 7.39 | 5.44 | 2.37 | 10.75 |
| 9/9/2011 | 3:35 | 9.85 | 4.36 | 3.47 | 3.41 | 7.28 | 5.44 | 2.34 | 10.74 |
| 9/9/2011 | 3:36 | 9.86 | 4.38 | 3.48 | 3.42 | 7.28 | 5.42 | 2.45 | 10.72 |
| 9/9/2011 | 3:37 | 9.89 | 4.38 | 3.48 | 3.41 | 7.18 | 5.45 | 2.53 | 10.74 |
| 9/9/2011 | 3:38 | 9.90 | 4.39 | 3.48 | 3.42 | 7.03 | 5.47 | 2.53 | 10.76 |
| 9/9/2011 | 3:39 | 9.92 | 4.37 | 3.49 | 3.42 | 6.86 | 5.50 | 2.60 | 10.79 |
| 9/9/2011 | 3:40 | 9.45 | 4.22 | 3.49 | 3.43 | 6.99 | 5.51 | 2.58 | 10.75 |
| 9/9/2011 | 3:41 | 3.87 | 2.84 | 3.23 | 3.27 | 9.23 | 4.68 | 3.87 | 10.02 |
| 9/9/2011 | 3:42 | 2.72 | 2.50 | 2.98 | 3.13 | 8.67 | 3.83 | 5.54 | 9.70 |
| 9/9/2011 | 3:43 | 2.32 | 2.56 | 2.78 | 3.09 | 7.91 | 3.41 | 6.73 | 9.52 |
| 9/9/2011 | 3:44 | 2.16 | 2.56 | 2.46 | 3.06 | 8.00 | 3.24 | 7.48 | 9.33 |
| 9/9/2011 | 3:45 | 2.18 | 2.62 | 2.30 | 3.07 | 9.27 | 3.29 | 7.40 | 9.19 |
| 9/9/2011 | 3:46 | 2.27 | 2.72 | 2.34 | 3.07 | 9.22 | 3.45 | 7.58 | 9.01 |
| 9/9/2011 | 3:47 | 2.29 | 2.75 | 2.46 | 3.05 | 9.13 | 3.59 | 8.45 | 8.83 |
| 9/9/2011 | 3:48 | 2.30 | 2.77 | 2.51 | 3.02 | 8.92 | 3.92 | 8.61 | 8.83 |
| 9/9/2011 | 3:49 | 2.29 | 2.75 | 2.51 | 3.00 | 8.67 | 4.29 | 9.16 | 8.71 |
| 9/9/2011 | 3:50 | 2.28 | 2.71 | 2.45 | 2.99 | 8.43 | 4.71 | 9.28 | 8.60 |
| 9/9/2011 | 3:51 | 2.26 | 2.64 | 2.40 | 2.98 | 8.25 | 5.17 | 9.32 | 8.47 |
| 9/9/2011 | 3:52 | 2.25 | 2.59 | 2.36 | 2.98 | 8.07 | 5.64 | 8.81 | 8.29 |
| 9/9/2011 | 3:53 | 2.24 | 2.53 | 2.33 | 2.97 | 7.94 | 6.02 | 8.07 | 8.11 |
| 9/9/2011 | 3:54 | 2.23 | 2.52 | 2.31 | 2.96 | 7.84 | 6.40 | 7.96 | 7.94 |
| 9/9/2011 | 3:55 | 2.23 | 2.54 | 2.29 | 2.94 | 7.78 | 6.77 | 7.44 | 7.78 |
| 9/9/2011 | 3:56 | 2.22 | 2.55 | 2.26 | 2.92 | 7.73 | 7.07 | 6.00 | 7.62 |
| 9/9/2011 | 3:57 | 2.22 | 2.56 | 2.24 | 2.91 | 7.68 | 7.27 | 5.76 | 7.49 |
| 9/9/2011 | 3:58 | 2.21 | 2.60 | 2.24 | 2.89 | 7.58 | 7.41 | 4.29 | 7.36 |
| 9/9/2011 | 3:59 | 2.21 | 2.63 | 2.22 | 2.88 | 7.35 | 7.43 | 3.80 | 7.23 |
| 9/9/2011 | 4:00 | 2.19 | 2.63 | 2.20 | 2.87 | 6.96 | 7.22 | 2.00 | 7.12 |

*Table 1: Main process parameters around time of E0308 failure*

6) **R0401 (HTS convertor) temperature profile behavior around the time of E0308 failure (Figure 8 and Table 2):**

a) R0401 catalyst bed temperatures were decreasing after the E0308 failure. R0401 inlet temperature dropped from 347 deg C (03:40hrs) to 143 deg C (04:35hrs).
b) One hour after the failure, 7 out of 8 catalyst bed temperatures indicated a temperature of around 145 deg C. All these catalyst bed temperatures had come down gradually from a range from 350 to 420 deg C to this 145 deg C.
c) Up to this instant, the outlet temperature of R0401 was always higher than the inlet temperature. At 04:37hrs the outlet temperature came down dramatically from 229 deg C at 04:37hrs to 149 deg C at 04:42hrs (about 80 deg C within five minutes). This may indicate an amount of water which has entered the catalyst bed.
d) The temperature at the outlet of R0401 increased again after that but at 04:54hrs dropped back to slightly below R0401 inlet temperature. This most likely indicated that the water after entering the catalyst bed had further settled.

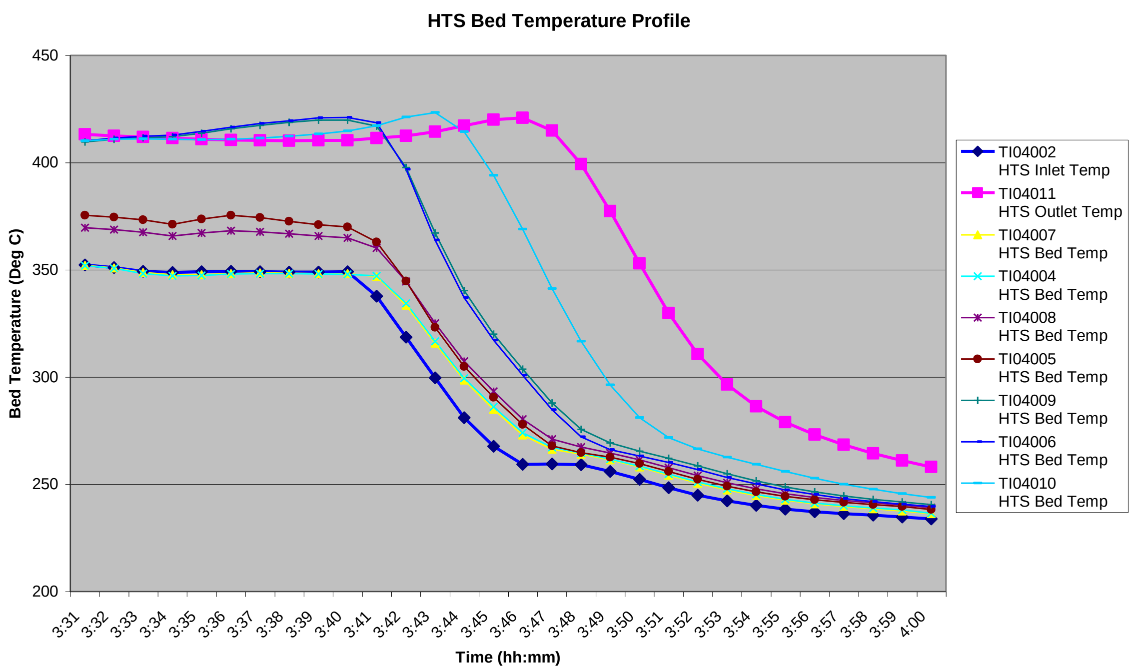



*Figure 8: HTS catalyst bed temperatures behavior around time of E0308 failure*

| Time | TI04002 HTS Inlet Temp | TI04011 HTS Outlet Temp | TI04007 HTS Bed Temp | TI04004 HTS Bed Temp | TI04008 HTS Bed Temp | TI04005 HTS Bed Temp | TI04009 HTS Bed Temp | TI04006 HTS Bed Temp | TI04010 HTS Bed Temp | PDI04001 |
|---|---|---|---|---|---|---|---|---|---|---|
| 3:31 | 352.34 | 413.22 | 352.11 | 352 | 369.65 | 375.52 | 409.6 | 410.26 | 410.22 | 8.91 |
| 3:32 | 351.01 | 412.53 | 350.84 | 350.65 | 368.85 | 374.57 | 410.82 | 411.44 | 410.83 | 7.6 |
| 3:33 | 349.31 | 411.89 | 348.85 | 348.28 | 367.58 | 373.26 | 411.64 | 412.26 | 411.1 | 10 |
| 3:34 | 348.83 | 411.39 | 347.75 | 347.17 | 365.75 | 371.28 | 412.13 | 412.85 | 410.93 | 9.87 |
| 3:35 | 349.07 | 410.86 | 347.77 | 347.37 | 367.2 | 373.75 | 413.7 | 414.57 | 410.73 | 8.49 |
| 3:36 | 349.29 | 410.55 | 348.27 | 348.1 | 368.18 | 375.41 | 415.72 | 416.56 | 410.94 | 8.44 |
| 3:37 | 349.06 | 410.37 | 348.51 | 348.31 | 367.75 | 374.41 | 417.29 | 418.16 | 411.49 | 9.29 |
| 3:38 | 348.91 | 410.25 | 348.48 | 348.16 | 366.79 | 372.68 | 418.74 | 419.56 | 412.32 | 9.81 |
| 3:39 | 348.95 | 410.32 | 348.26 | 348.07 | 365.73 | 371.13 | 419.85 | 420.79 | 413.39 | 8.99 |
| 3:40 | 349.05 | 410.43 | 348.21 | 347.92 | 364.88 | 370 | 419.84 | 421.1 | 414.69 | 22.75 |
| 3:41 | 337.76 | 411.44 | 346.76 | 347.14 | 360.17 | 362.94 | 417.09 | 418.68 | 417.19 | 40.5 |
| 3:42 | 318.58 | 412.48 | 333.55 | 334.35 | 344.53 | 344.68 | 397.79 | 396.84 | 421.18 | 67.81 |
| 3:43 | 299.72 | 414.4 | 315.8 | 316.6 | 325.01 | 323.18 | 367.16 | 363.91 | 423.26 | 56.32 |
| 3:44 | 280.98 | 417.13 | 298.59 | 299.45 | 307.38 | 304.93 | 340.38 | 337.08 | 414.3 | 44.24 |
| 3:45 | 267.79 | 419.98 | 284.97 | 286.13 | 293.35 | 290.61 | 320.05 | 317.24 | 394.11 | 31.67 |
| 3:46 | 259.27 | 420.85 | 272.97 | 274.05 | 280.43 | 277.86 | 303.77 | 300.92 | 368.92 | 38 |
| 3:47 | 259.41 | 415 | 266.33 | 267.16 | 271.05 | 267.82 | 287.93 | 284.77 | 341.25 | 35.17 |
| 3:48 | 259.08 | 399.35 | 263.97 | 264.48 | 267.4 | 264.75 | 275.57 | 272.09 | 316.63 | 35.71 |
| 3:49 | 255.91 | 377.29 | 261.32 | 261.81 | 264.58 | 262.65 | 269.25 | 266.06 | 296.32 | 35.07 |
| 3:50 | 252.21 | 353.06 | 257.99 | 258.44 | 261.35 | 259.58 | 265.5 | 263.14 | 281.1 | 33.92 |
| 3:51 | 248.38 | 329.74 | 254.2 | 254.73 | 257.7 | 255.97 | 262.02 | 260.17 | 271.76 | 33.98 |
| 3:52 | 244.99 | 310.66 | 250.56 | 251.09 | 253.96 | 252.3 | 258.55 | 256.78 | 266.47 | 33.1 |
| 3:53 | 242.25 | 296.52 | 247.39 | 247.88 | 250.66 | 249.18 | 254.92 | 253.23 | 262.65 | 31.89 |
| 3:54 | 240.12 | 286.36 | 244.82 | 245.21 | 247.93 | 246.53 | 251.64 | 250.09 | 259.28 | 30.23 |
| 3:55 | 238.46 | 278.94 | 242.58 | 243.04 | 245.64 | 244.37 | 248.79 | 247.45 | 255.99 | 29.13 |
| 3:56 | 237.25 | 273.16 | 240.83 | 241.22 | 243.83 | 242.73 | 246.49 | 245.21 | 252.81 | 27.35 |
| 3:57 | 236.4 | 268.44 | 239.61 | 240.05 | 242.48 | 241.5 | 244.55 | 243.42 | 250.05 | 25.6 |
| 3:58 | 235.69 | 264.44 | 238.65 | 238.98 | 241.43 | 240.52 | 243.02 | 242 | 247.71 | 24.62 |
| 3:59 | 234.68 | 261.02 | 237.59 | 237.99 | 240.35 | 239.58 | 241.81 | 240.77 | 245.68 | 20.11 |
| 4:00 | 233.81 | 258.02 | 236.4 | 236.57 | 239.1 | 238.28 | 240.58 | 239.63 | 243.84 | 16.12 |

*Table 2: HTS catalyst bed temperatures behavior around time of E0308 failure*

Operational staff reported at a later point in time that a considerable amount of water had been drained downstream of R0401, upstream of R0403 (LTG).
Also water was drained from the process gas side inlet - and outlet compartments of 2$^{nd}$ waste heat boiler E0410, located directly downstream of R0401.
When the E0309 tube bundle was pulled out from its shell, pieces of ferrule and refractory material were found. Therefore it was suspected that debris consisting of ferrule and refractory material also had reached the top layer of the catalyst bed of R0401.
While taking samples from the top layer indeed this debris was found. Analysis results of samples taken from the catalyst top layer indicated phosphate depositing from the boiler feed water, so confirming also that water had entered the vessel. Based upon further tests on the catalyst it was decided to take out all the catalyst and replace it with a full new charge that was available as spare.

Above findings clearly evidence the leaking of the waste heat boiler.
During the shut down the combination of operational parameters pointing together towards a leaking waste heat boiler was not immediately recognized as such.
Main reason was that the alarm management system had not been optimized yet, the DCS-operators were still flooded with alarms of different priorities.
Also the plant was just for a few days in normal operation so there was still little experience with the behavior of the new running plant.
Nobody expected a leaking waste heat boiler in a new plant just after start-up.
The incident happened in the weekend, supervision at night shift was limited.
After bringing the plant to shutdown the focus was on E-0309, to prepare for inspection and repair. Earlier after the shut down, when opening the 2 drains at the inlet and outlet chambers of E0308 only little water came out (due to plugging of the drains with debris from refractory and ferrules as was found later). All together this resulted in the fact that the leak of the waste heat boilers, was only discovered some days after the shutting down the plant for E0309.

## Observations and root cause analysis

Observations and analysis

During first observations two tubes were found ruptured and almost half of the tubes showed cracks in the tube to tube sheet welds.

Further inspection, analysis and repair took more than 4 months, after which the plant was restarted and operated with relieved conditions for the WHB: at reduced plant load and with lower HP steam pressure.

Failure mode was found to be brittle fracture in HAZ of welds repaired before operation, due to high residual stresses and high hardness.

Root cause

The root cause for these high residual stresses and high hardness is most likely not a single one. After extensive analysis, the following were found to be the most likely root causes:

- The relative complex design of the WHB (although following ASME code): the chosen materials, the length, the thin tube sheet combined with thick shell/bypass pipe) and the local PWHT requirement in work shop (which made it difficult to control the temperature equally)

- The lack of proper control of manual repairs on site, before in operation (several defects like excess/lack of penetration, lack of fusion, carburization and root undercut, which are very difficult to detect or undetectable with UT, especially on the tube side)

The damage refractory and broken ferrules were considered to be a result of the tube failure, not the cause, most likely broken due to high water/steam pressure impact. Ceramic ferrules have high thermal resistance but are mechanically less strong (sensitive in case of rapid quenching water/steam force and when no proper decoupling between rigid and flexible elements).

Lessons learnt:

Choose more conservative design, with more easy to control PWHT (if possible furnace PWHT)

Choose metal alloy i/o ceramic ferrules for this application of high temperature/pressure with relative thin tube sheet (and where there is always a chance of leaking tube sooner or later)

## Second and Third failure of the waste heat boiler

Second failure and root cause

Only about 2 weeks later, when the plant experienced a shut down, for the second time leaking of the WHB was observed. When the drain on the outlet compartment was opened to check for a possible leak, water was coming out. After opening in- and outlet man ways, the findings were at the outlet tube sheet, especially the tube sheet itself showed severe cracks in the base material (Figure 9 and 10). The plant was restarted 3 months after failure.

This 2nd failure of the WHB was found to be due to stress corrosion in areas around welded tube plugs with high remaining stresses and local (phosphate) deposition in crevices.


*Figure 9 and 10: Cracks in outlet tube sheet*

<u>Third failure and root cause</u>
After 2 weeks of operation increased flow of boiler feed water to the steam drum was observed and confirmed leaking of the RG WHB again. This time a few leaking tubes were found at the inlet tube sheet. Root cause here was found to be insufficient stress relieve of few repair welds on earlier repaired tubes (which were in a difficult to reach area of the tube sheet)

Plant was restarted after 1 month repair and since then WHB E0308 has not leaked anymore. The unit was replaced by one of different design during the warranty shutdown in Febr. 2014. Ammonia 5 plant is now operating at 105% of its design capacity.

Process Waste Heat Boilers
Integrity and Reliability
Qatar : 01-03 December 2014

# Lessons Learned from FERTIL-1 Waste Heat Boiler Operation


**Ali AL HOSANI**

**Ammonia-1 Process Engineer**

**FERTIL**

**UAE**

# Lessons Learned from FERTIL-1 Waste Heat Boiler Operation

**Presented in : AFA Workshop**

Waste Hear boiler Reliability and Integrity

1-3 Dec. 2014 , Qatar

**Presenter:**



# Content

**FERTIL Profile**
- Profile
- Photos
- Awards

**WHB**
- Turnaround intervals
- WHB location
- WHB function
- s/d history

**Problem**
- Causes
- Solution
- Applied practice

www.fertil.com

# FERTIL's Profile


| | | | |
|---|---|---|---|
| **Location** | Ruwais (250 km west of Abu Dhabi) | | |
| **Established** | 1980 | | |
| **Shareholders** | ADNOC (2/3) & TOTAL (1/3) | | |
| **Plants** | | **FERTIL 1** | **FERTIL 2** |
| **Established/ Started Up** | | Oct.1980 / Nov.1983 | Nov. 2009 / June 2013 |
| **Products, Name plate capacity** | Ammonia (MT/Day) | 1,300 | 2,000 |
| | Urea (MT/Day) | 2,300 | 3,500 |



# Plants Photo

FERTIL-1

FERTIL-2

# FERTIL's Awards

- ✓Several Awards in ADNOC HSE Performance
- ✓ Occupational Health & Safety certification OHSAS 18001
- ✓Several Award s of Royal Society for the Prevention of Accidents (RoSPA) including Sector Award
- ✓ Environmental Quality Certification ISO 14001
- ✓12 Years without Lost time Incident (LTI) award
- ✓ ISO 9001 for Quality Management System
- ✓ Dubai Quality Appreciation Program Award for industrial sector
- ✓Sheikh Khalifa Excellence Award for industrial sector
- ✓ISO 50001 for Energy management system




# Background

## Turnaround Intervals

- **1984 - 1990** • Every year
- **1990 - 1996** • Every 2 years
- **1996 - 1998** • Every 2 ½ years
- **1998 ~** • **Every 3 years**

# Background

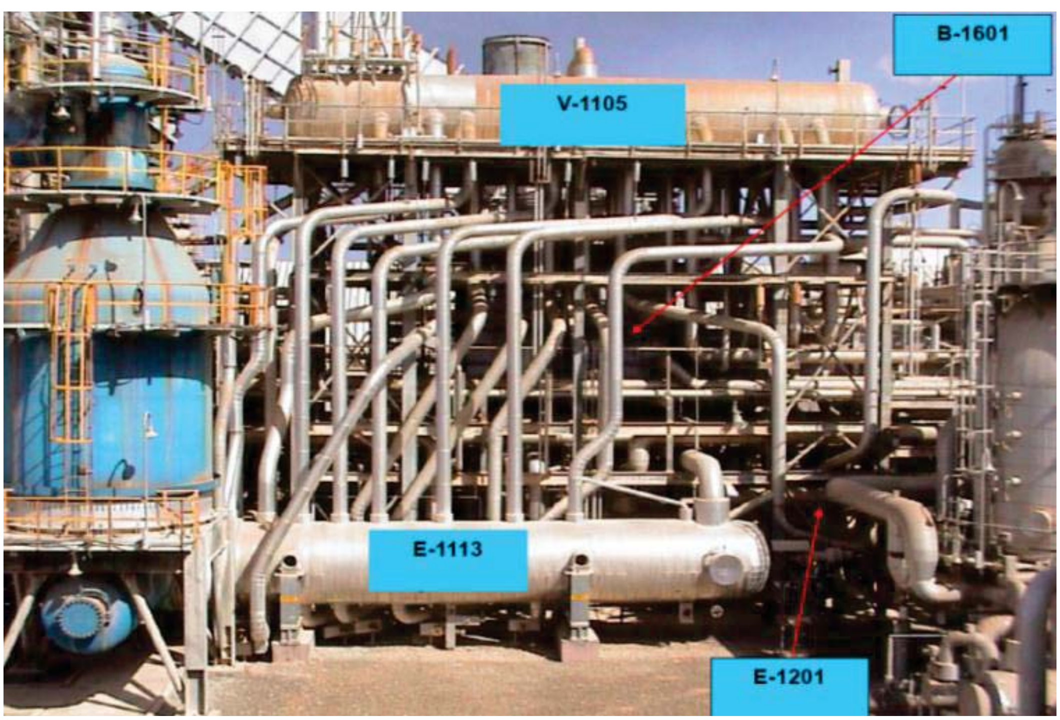
## FERTIL-1 WHB function

1. • cools reformed gas to the temperature required for CO conversion in the HTSC
2. • produces high-pressure (HP) steam by using available process heat from Secondary Reformer
3. • produces about 170 t/h of HP steam at the present load.



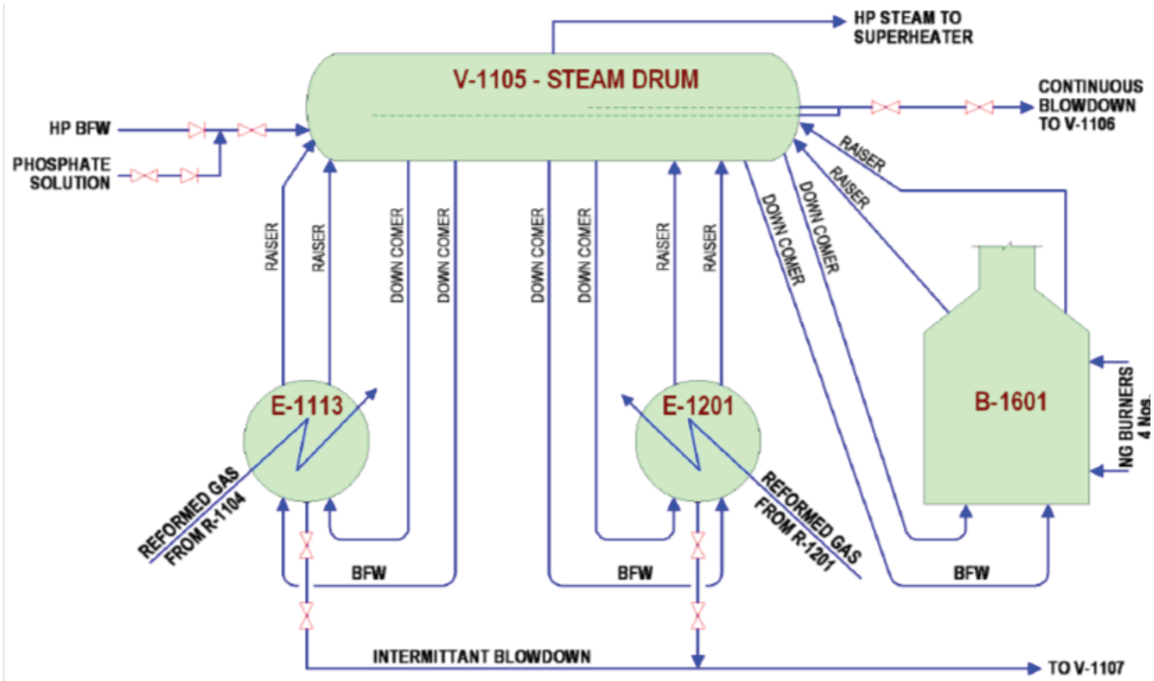
# Background

## FERTIL-1 WHB Location



# Background

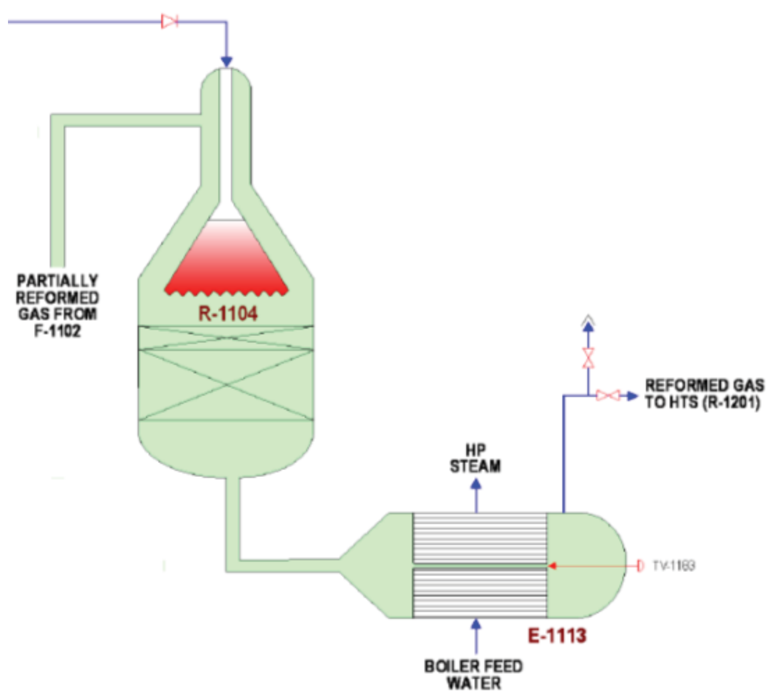
## HP Steam Generation






# Background

## WHB and Secondary Reformer



# WHB History

- **1984** s/d for 25 days for repair of refractory in inlet channel of WHB as hot spots were noticed
- **1989** s/d due to tube to tube-sheet weld failure
- **1991** three shutdowns due to waste heat boiler tube leakage
- **1992** partly re-tubed. Stress relieving of the re-tubed boiler could not be done due to practical constraints
- **1993** Failure again occurred
- **1994** Post Welding Heat Treatment was done but results were not successful
- **1996** replace this boiler

118% Amm. production
↓
75,628 MT MT Amm. loss
↓
109,460 MT Urea loss



# Causes of Failure

After an investigation by Borsig, the causes of the frequent boiler failures were identified as:

1. High heat flux near the hot end of the boiler and suspected lower than required circulation ratio resulting in steam blanketing

2. Suspected lapses in the BFW quality

# Action Taken

1. In the design of the new boiler, the previous factors were given due consideration
   - some design parameters were changed.
   - the new boiler is larger in size.
   - Some additional down comers and risers added.

2. the BFW quality was improved and providing on line analyzer, conductivity and Na-meters enhanced better monitoring.

3. BFW conductivity is now maintained at less than 0.2µS/cm2 as compared to 1.0µS/cm2.

**The new boiler is performing satisfactory till date**



# Objectives and Applied Practices

**A general action plan was made in 1996 to meet the following objectives:**

- Improve Availability and Reliability by analyzing all shutdown causes and determine remedial action
- Maximize the through-put of the plant by identifying the plant load limitation and define remedial action
- Sustain the plant integrity
- Elaboration of Standard Operations Procedures and check-lists

# Thank You

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Process Waste Heat Boilers
Integrity and Reliability
Qatar : 01-03 December 2014

# Technical Assessment of SAFCO-4 Synthesis Loop Waste Heat Boiler-II


Ekambaram Manavalan
Inspection Manager

Abdulrahman Al Johani
Inspection Engineer

SAFCO
Saudi Arabia

# TECHNICAL ASSESSMENT OF SAFCO-4 SYNTHESIS LOOP WASTE HEAT BOILER-II LEAKAGE

BY:
MR. EKAMBARAM MANAVALAN
MR. ABDULRAHMAN AL JOHANI

CHEMISTRY THAT MATTERS™

## BACKGROUND

- Saudi Arabian Fertilizer Company (SAFCO), an affiliate of Saudi Arabian Basic Industries Corporation (SABIC) is the first petrochemical company in Kingdom of Saudi Arabia.
- SAFCO is one of the leading producers of Ammonia and Urea in the world with annual production capacity of around 2.3 million tons of Ammonia and 2.6 million tons of Urea.
- In our SAFCO-4 Ammonia plant back end Synthesis loop waste heat boiler # 2, tube leak was observed within 6 years of service. Premature failure of this critical Equipment is a great concern.
- This presentation explain the problem history, Equipment details, technical assessment, mitigation, inspections and repairs carried after leak to operate the Equipment without affecting the Safety and integrity.

# HISTORY

- SAFCO-4 Ammonia plant Synthesis loop waste heat boiler#2 (41-E-612) was commissioned during 2006 and performing satisfactorily till January 2012.
  (Process Licensor: Uhde;   Equipment manufacturer: OLMI, Italy)

- During January 2012, Ammonia plant tripped due to power failure. After the plant start-up, higher conductivity was reported from condensate blow down. Minor tube leakage was confirmed by process analysis.

- Equipment was in operation in same leak condition with close monitoring until April 2012.

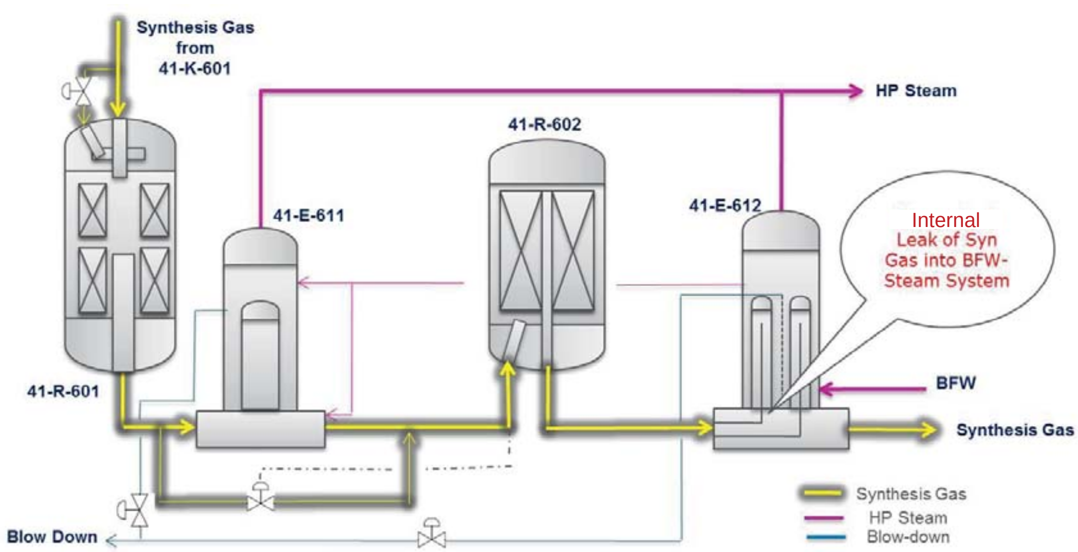
- During April 2012 Turnaround, Equipment was internally inspected and leak was attended. There was no further leak until July 2013.

- Higher conductivity again reported during July 2013. Process evaluation confirmed tube leakage. Equipment was in operation with leak condition with close monitoring until January 2014.

- Equipment was internally inspected and leak was attended during January 2014 shutdown. There is no further leak and Equipment is now performing satisfactorily.



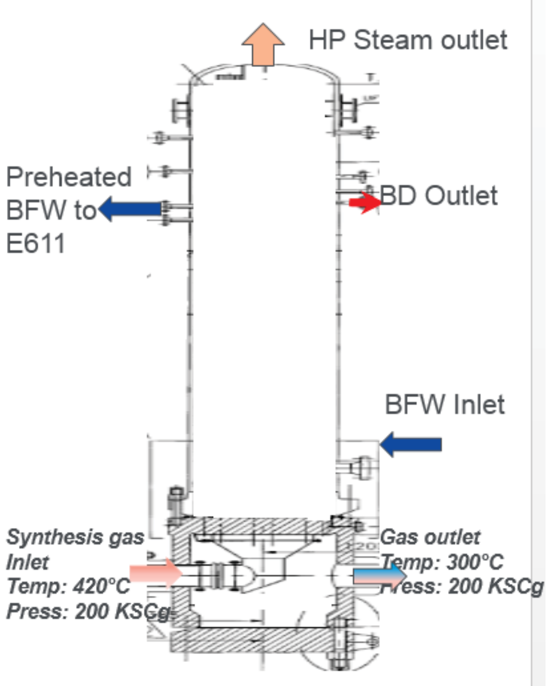
# PROCESS DESCRIPTION

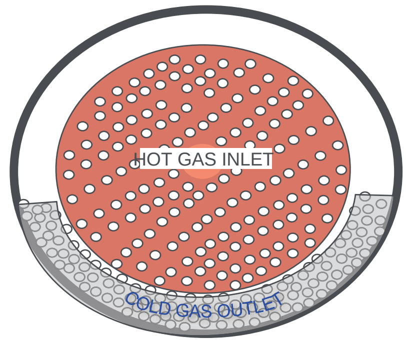



- Partially converted synthesis gas (~21% Ammonia & 48% $H_2$ and rest $N_2$, $CH_4$ & Ar) at pressure of ~200 Kg/cm$^2$g and temperature ~ 420°C from converter II enters 41E612 waste heat boiler-II tube side.

- Preheated BFW from BFW preheaters enters the shell side of 41E612 boiler at ~125 Kg/cm$^2$g , a part of BFW converts to HP steam after cooling the synthesis gas and rest directed to waste heat boiler-I (41E611) for cooling synthesis gas coming from converter I.

# EQUIPMENT SCHEMATIC




Equipment size: 1360mm shell ID x 10152mm overall length



# MATERIAL OF CONSTRUCTION

- Shell / Head: 20 MnMoNi 4.5 (~ ASTM A553)
- Internal Barrel: ~ ASTM A515 Gr 70
- Tube: ~ Alloy steel 2 ¼ Cr-1 Mo; Total tubes: 290 U, Size: 30mm O.D x 3.2 mm thick.
- Tube sheet: ~ Alloy steel 2 ¼ Cr-1 Mo, Weld overlay with Inconel 600.
- Channel: ~ Alloy steel 2 ¼ Cr-1 Mo
- Gas guide plate : ~ SS 321
- False Tube sheet: ~ SS 321
- Ferrule: ~ SS 304

## IMPACT OF THE LEAK

| Process Upsets | Impact | Mitigation Action | Elimination action |
|---|---|---|---|
| High conductivity / Ammonia in turbine condensate going to Utility | • Higher ionic load on mixed bed polisher leading to lower cycle time and production<br>• More waste generation (sustainability) | • Arrange Ammonia removal unit<br>• Arrange draining facility for contaminated turbine condensate<br>• Import polish water from SF3 & IBB<br>• Reduce plant load | • Inspect & Repair leaking tube.<br>• Replace the boiler during next TA2015. |
| Presence of H2 and inert in steam | • H2 in the condenser ejector & de-aerator vents (Safety concern)<br>• Vacuum disturbance | • Measure explosive on platforms / working area<br>• Restrict hot jobs in plant area<br>• Line up spare ejector to maintain vacuum | |



## INSPECTION FINDINGS & REPAIR DONE DURING 2012

- Shell side hydro test revealed one tube leaking from tube in-bore welding due to circumferential crack on the weld.
- Total no of tubes: 290-U tubes (580 single length).
- Tube inspection by Eddy Current Testing (by Delta test) were done for 368 out 580 tubes and the test result was found satisfactory without any wall loss or any abnormality. ECT could not be performed for 144 tubes due to fouling of false tube sheet gas guide plate and 68 tubes due to weld protrusion.
- Tube in-bore welding UT inspection (by Olmi) was done for accessible 394 tube welds and the test result was satisfactory except for 1 leaky tube and 2 additional tube welds which was found with weld liner indication. Inspection could not be performed for 179 tube welds due to fouling of false tube sheet gas guide plate and 7 tubes due to weld protrusion.
- 3 tubes (one leaking tube and 2 tubes having weld linear indication ) were plugged.
- Boroscopic inspection from shell side nozzles revealed that there was no corrosion of tubes outer surface.

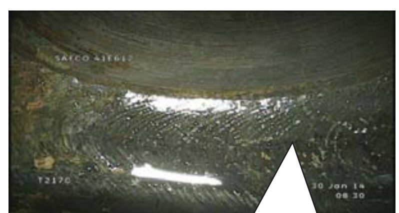
## INSPECTION SCOPE DURING 2014

- Perform visual / DPT inspection of channel head internals, gas inlet chamber, expansion bellow, ferrules, tube- sheet weld overlay and, nozzle welds.
- Shell side hydro test at design pressure
- Remove all ferrules for tube inspection.
- Modification of false tube sheet guide plate for full assess of tube inspection.
- 100% Tube inspection by Eddy Current Testing (using modified probe to assess inaccessible tubes which were not tested during 2012).
- 100% Tube in-bore welding UT inspection (after modification of false tube sheet guide plate for full assess of tube inspection).
- 100% Boroscopic inspection of tubes in-bore welding.
- Tubes plugging for leaky tubes as per approved procedure provided by Uhde/OLMI
- Additional sensitive pneumatic leak test to detect minute tube leak.



## INSPECTION FINDINGS & REPAIR DONE DURING 2014

- Shell side hydro test revealed one tube leaking from tube in-bore welding due to circumferential crack on the weld.
- Tube inspection by Eddy Current Testing (by Delta test) were done for all tubes (except the 3 tubes which were plugged during 2012). Result was found satisfactory without any tube wall loss or any abnormality.
- Tube in-bore welding UT inspection (by Olmi) was done for all tubes. In-bore weld of one leaky tube was found crack along the weld axis and in-bore welds of 5 other tubes revealed linear indication. All defects were in cold side of the tube sheet.
- 6 tubes (one leaking tube and 5 tubes with welding linear indication ) were plugged.
- Boroscopic inspection from shell side nozzles revealed that there was no corrosion of tubes outer surface.
- Total tubes plugged so far: 9.



Longitudinal Crack in in-bore weld

## CONCLUSION

- Original fabrication defect (which was not detectable) propagated during service due to plant upsets is considered as the main cause for the tube weld failure.

- During the procurement of new Equipment, more focus shall be given to avoid any fabrication defect by increasing the scope of NDT and quality checks.

# DAY 2: Tuesday December 0 2, 2014

# Technical and Economic Feasibility Assessment for a CHP System with

**David Alonso**
**CEO**
**DVA Global Energy Services**
**Spain**

DVA Global Energy Services

# Technical and Economic Feasibility Assessment for a CHP System with ORC Technology



## INDEX

## Objetive

- A feasibility study is performed for assessing the profitability of a new CHP (Combined Heat and Power) plant, for energy supply to an oil refining site:
  - ✓ Power generation technology: gas turbine.
  - ✓ Electrical power limit 50 MW (legislation)
  - ✓ GT Exhaust gases are used to:
    - Replace two furnaces generating process thermal oil.
    - Produce cooling water in an absorption refrigeration system, to replace mechanical chilled.
- Study of the performance of an organic Rankine cycle (ORC) for additional power generation.
- Feasibility of different modifications (maximum profitability of cogeneration).

## Hot oil demand

Hot oil currently generated by 2 furnaces:

- **Furnace B8401**

  Duty: 27 MWe

  Inlet temperature: 260ºC

  Outlet temperature: 320ºC

  Hot oil flow: 700 t/h

- **Furnace B401N**

  Duty: 41 MWe

  Inlet temperature: 260ºC

  Outlet temperature: 320ºC

  Hot oil flow: 1049 t/h

## Cooling water demand

Process air currently requires cooling water generated by chillers:

✓ **Fenol II Line**

- Cooling power: 921 kW
- Chilled water (20% ethylene glycol): 170 m3/h
- Inlet chilled water: 5ºC
- Outlet chilled water: 0ºC

✓ **Fenol III Line**

- Cooling power: 1.354 kW
- Chilled water (20% ethylene glycol): 250 m3/h
- Outlet chilled water: 0ºC
- Inlet chilled water: 5ºC

**Total Cooling Power: 2.275 kW**



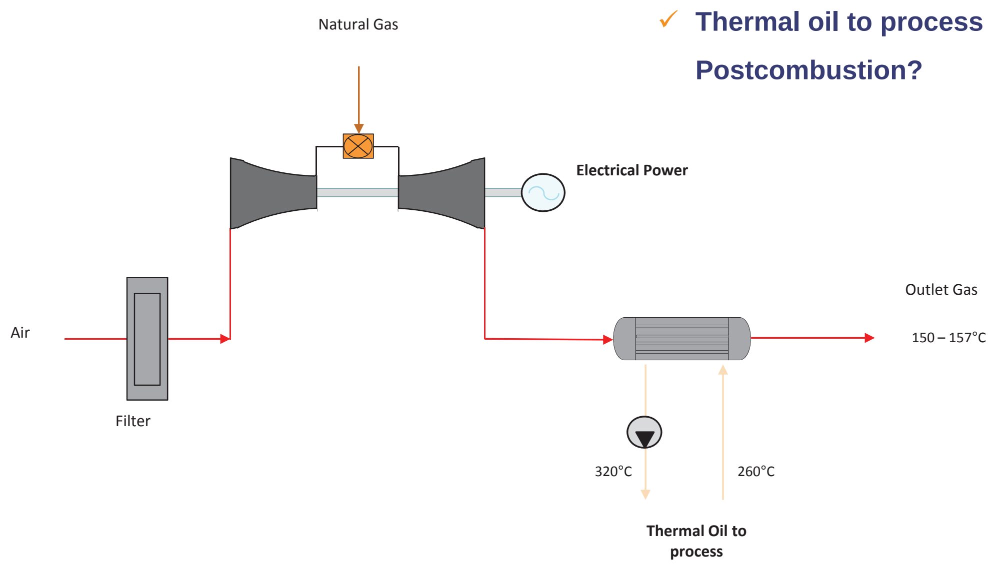
## Electricity

- Cogeneration NO designed in base on electricity demand of the site
- Sell all the electricity to the grid and purchase 100% electricity demand
- Maximum electrical power : 50 MW (legislation)
- Legislative framework beneficial: bonus on sale price of the electric energy to the grid

## GT + HRSG

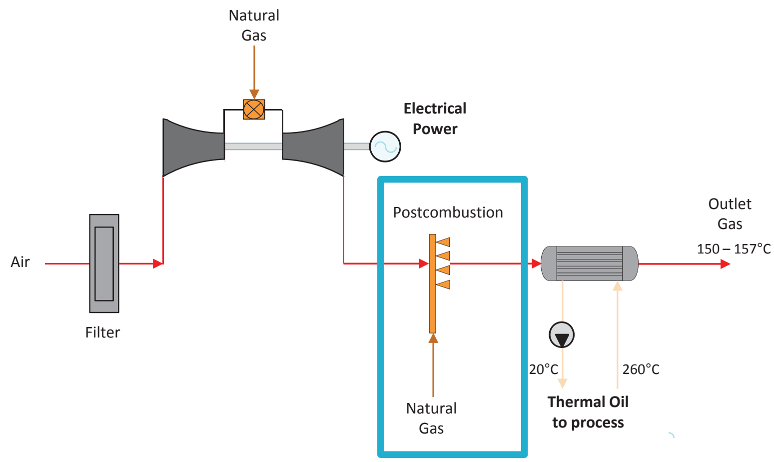
**Basic CHP:**

- ✓ Gas turbine
- ✓ Thermal oil to process
- Postcombustion?



## 3. CHP base configuration 11

### GT + HRSG + PSC

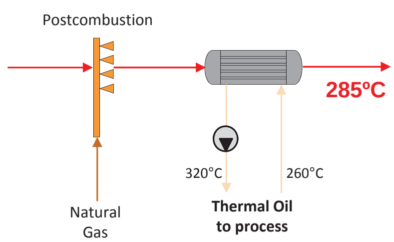



- ✓ **PSC to increase hot oil production**
- ✓ **Gases temperature limit after combustion: 800ºC**

## 3. CHP base configuration 12

### POSTCOMBSUTION?

- **Objetive :** Increase hot oil production
- **Advantage:** Increase **EEE**




✓ Total PSC is transfered to thermal oil

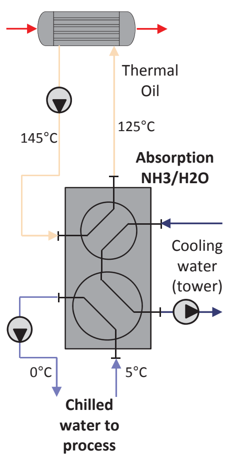
✓ For larger sizes selected gas turbines meet both furnaces demand: operative benefit

- **Disadvantages:** It requires a design of gas/oil heat exchanger according to the rules provided for process furnaces (40-50% cost overrun)

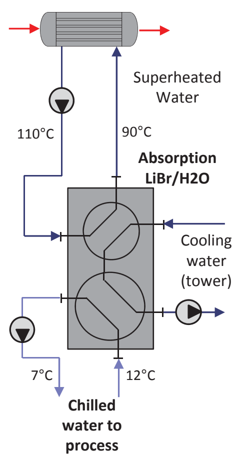
**Economical evaluation PBT: beneficial. PSC reduces 1 -1,5 años el PBT**

## 4.1A Cooling Absorption System (CAS)

### NH3/H2O




### BrLi/H2O

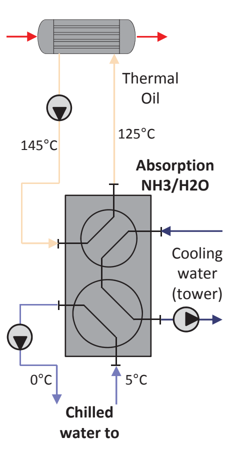



- ✓ Include an oil/gases exchanger to feed cooling absorption system
- ✓ Chilled water generated by absorption system is used to supply the cooling process
- ✓ Chilled water temperature required 0/5°C (supply /return)
- ✓ Both BrLi/H2O and NH3/H2O CAS have been considered to refrigerate water, with different options for CAS thermal feeding: low pressure steam, superheated water and thermal oil

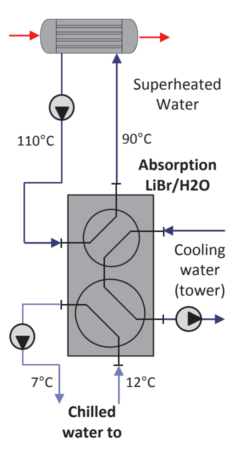


## 4.1A Cooling Absorption System (CAS)

### NH3/H2O




### BrLi/H2O




### Main differences NH3/H2O vs BrLi/H2O CAS

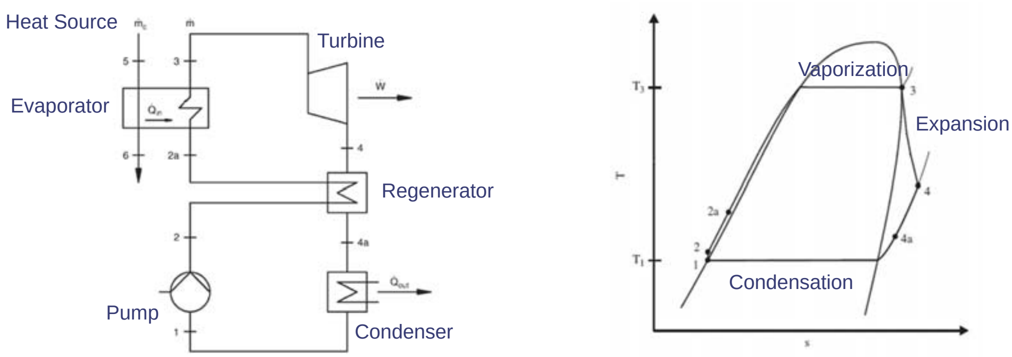
✓ **Cooling demand**

- **Brli**: partial replacement cooling demand, water is cooled to 7ºC
- **NH3**: total replacement cooling demand, water is cooled to 0ºC

✓ **NH3/H2O CAS** requires higher temperature of thermal feeding

## 4.1B Organic Rankine Cycle (ORC)

- Cycle power generates electricity from heat source medium or low temperature (300-180ºC)
- Organic fluid: low vaporization temperature and pressure, expansion outside of biphasic zone
- Variety of cycles: simple, regenerated supercritical



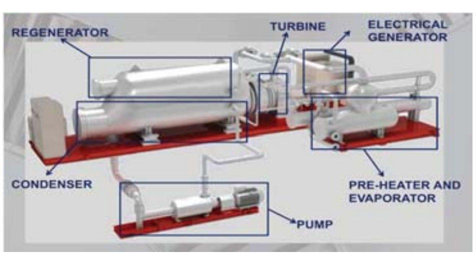

ORC cycle



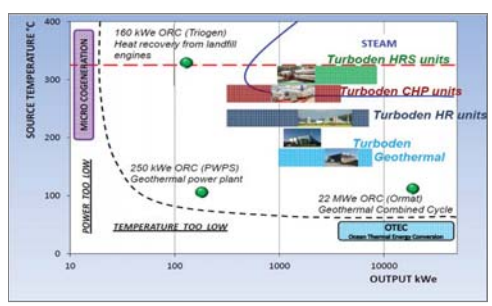
## 4.1B Organic Rankine Cycle (ORC)

***ORC typologies***

- **CHP** Thermal source **300ºC**. Generates electricity and water to **90ºC**
  Gross electrical efficiency: **19%**
- **HR** Thermal source **300-240ºC**. Only electricity. Gross electrical efficiency : **22% - 17%**
- **HRS** Thermal source **310ºC**. Only electricity. Gross electrical efficiency : **24,5%**




Feeding the evaporator: Heat oil, hot water or saturated steam




ORC produces electricity from waste heat

**Options:**

- ✓ Two stages evaporator
  - ✓ Step 1 Feed: heat oil (300-240ºC)
  - ✓ Step 2 Feed: hot water (155°C)
- ✓ Use of higher temperature range of the thermal source

* Source: TURBODEN

# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

### *ORC and absorption system integration*

Study of several configurations of gas recovery system:

1) Absorption fed by steam + ORC
2) Absorption fed by superheated water + ORC
3) ORC + Absorption fed by hot oil
4) ORC  with doble stage evaporator

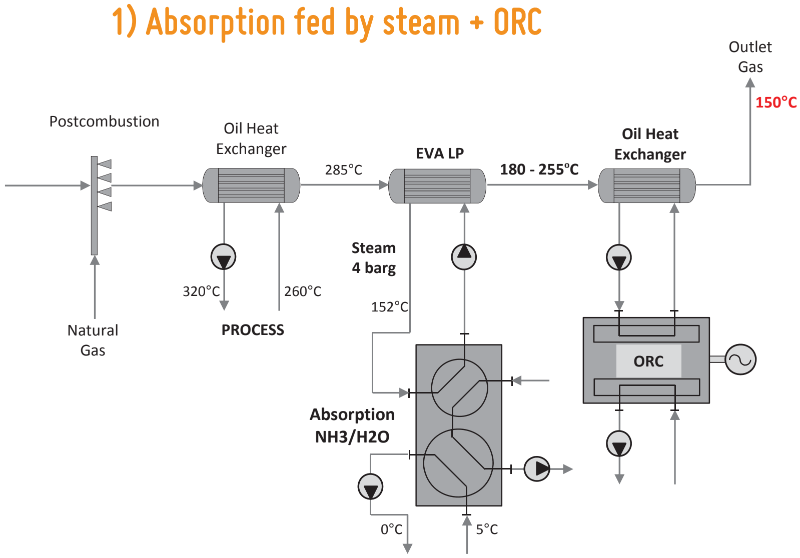


# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

### *ORC and CAS integration*

Study of several configurations of gas recovery system.

## 1) Absorption fed by steam + ORC




Outlet temperature gases of LP evaporator to high temperature

It is possible to reduce stack temperature to 150 ° C ...

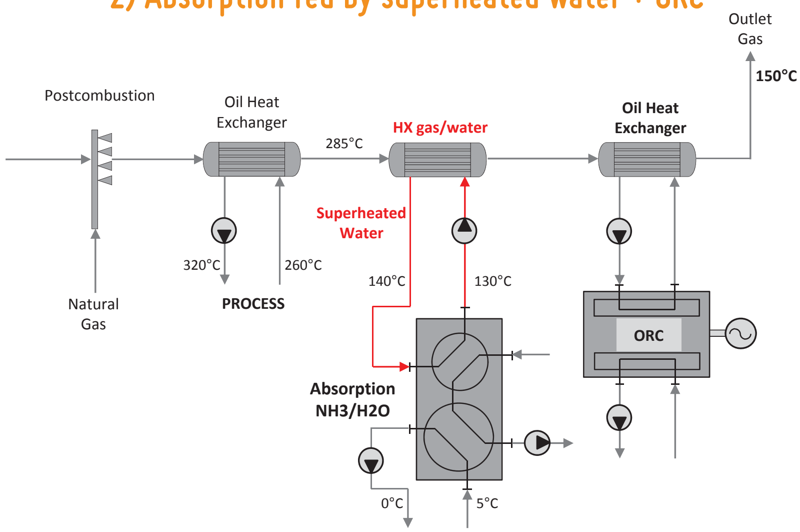
… operating  ORC  with low temperature

# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

## *ORC and CAS integration*

Study of several configurations of gas recovery system.

### 2) Absorption fed by superheated water + ORC




**Changes**

Absorption is fed with superheated water instead of steam.

**Advantages**

**Lower cost of gas/superheated-H2O exchanger due to the lack of evaporator.**

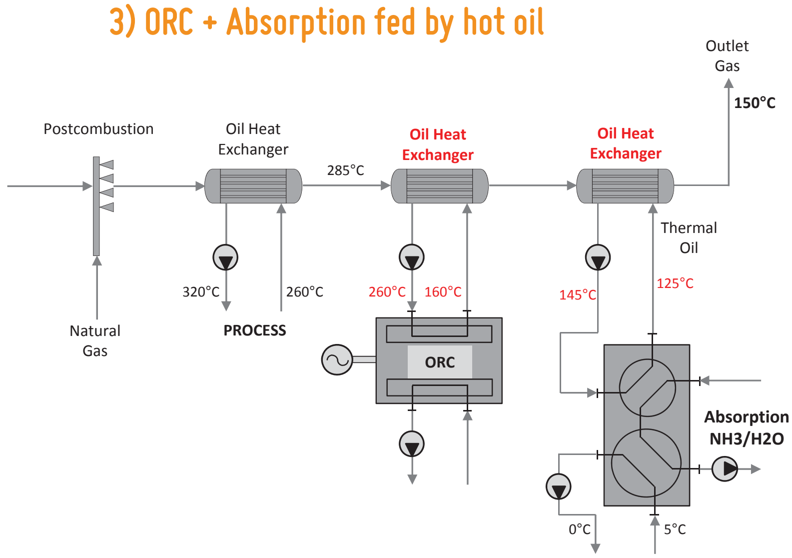


# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

## *ORC and CAS integration*

Study of several configurations of gas recovery system.

### 3) ORC + Absorption fed by hot oil




**Changes:**

- Inverted order between absorption and ORC.
- Heat oil instead of superheated water for absorption.

**Advantages:**

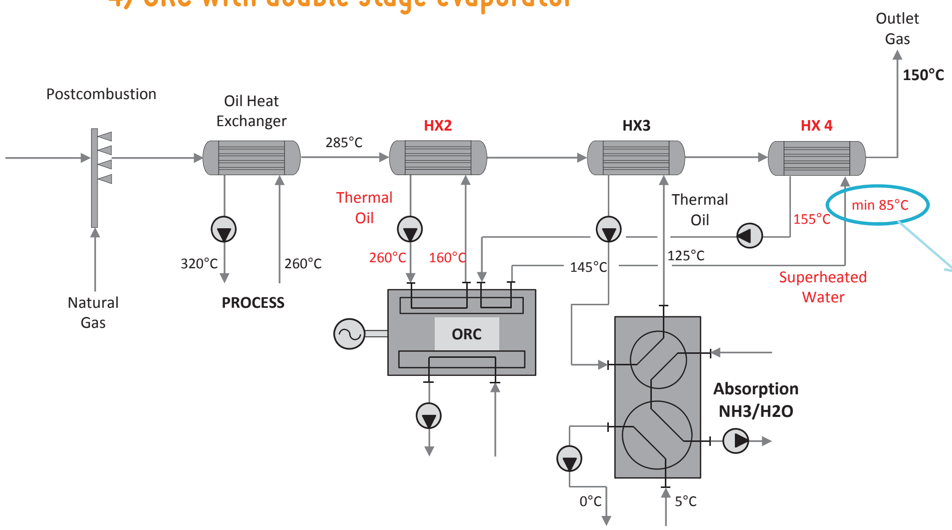
- **Increase ORC efficiency (higher temperature thermal source)**

# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

## *ORC and CAS integration*

Study of several configurations of gas recovery system.

### 4) ORC with double stage evaporator




**Changes:**

**ORC with double stage evaporator.**

**It´s possible to reduce temperature stack to 100/110ºC.**

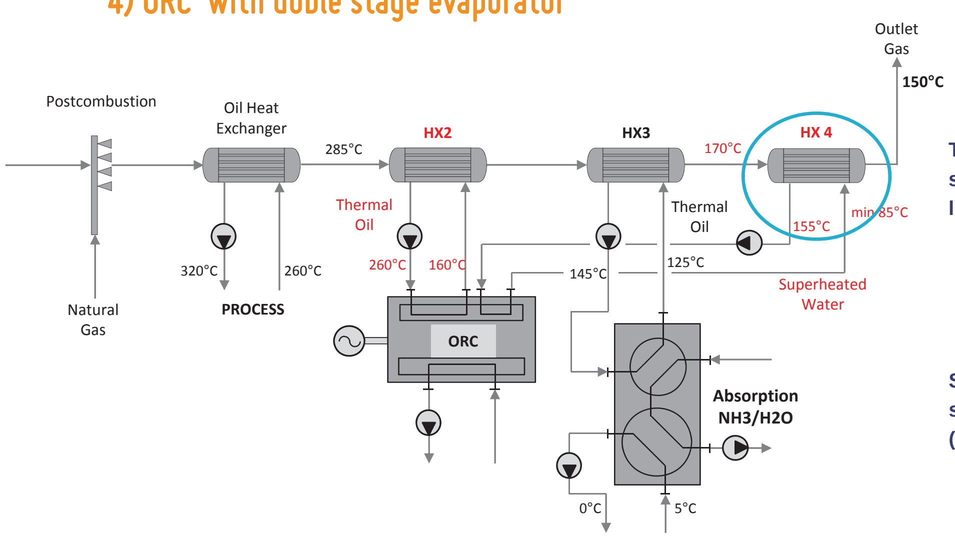


# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

## *ORC and CAS integration*

Study of several configurations of gas recovery system.

### 4) ORC with doble stage evaporator




**Thermal recovery in the second stage ORC is limited.**

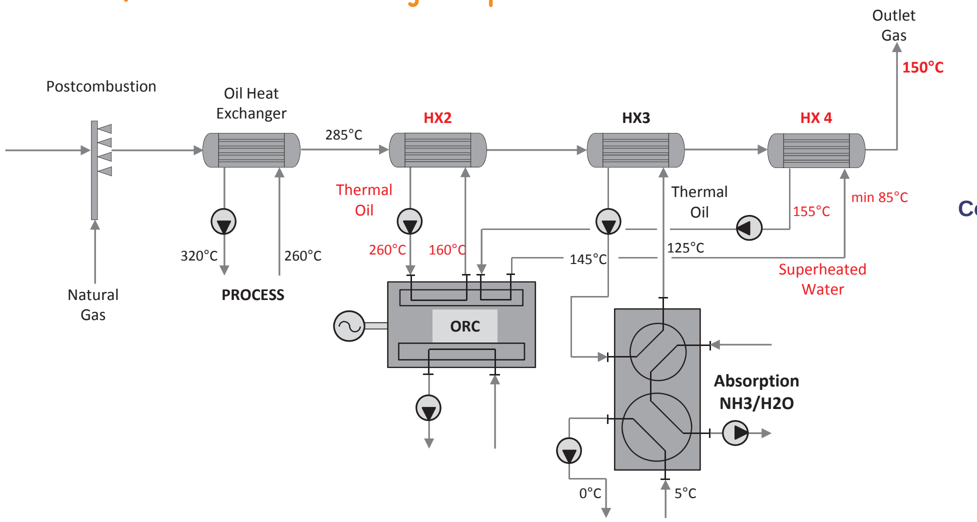
**Stack temperature is similar to previous case (150ºC approx.)**

# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

### *ORC and CAS integration*

Study of several configurations of gas recovery system.

## 4) ORC with double stage evaporator




**Conclusions:**

**NO advantages**

**Disadvantages:**

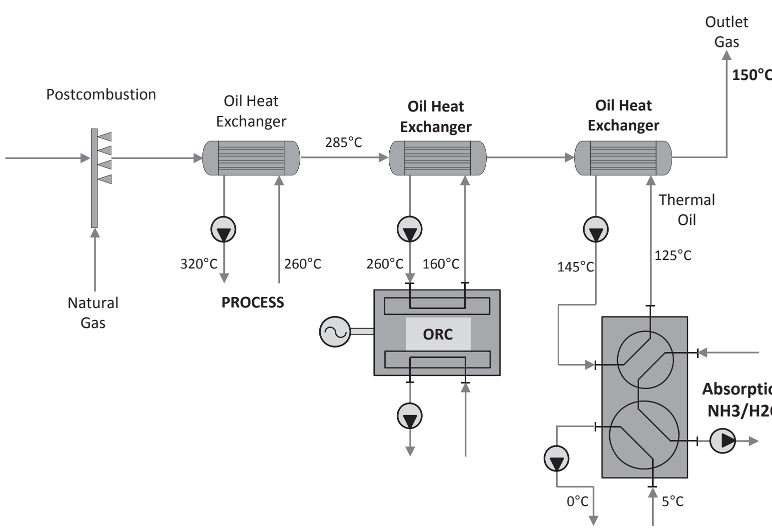
**Higher cost of ORC**



# 4.1 Cooling Absorption System (CAS) and Organic Rankine Cycle (ORC)

### *ORC and CAS integration*

## Final configuration: ORC single stage + absorption heat fed by hot oil




**Advantage**

- Use thermal oil for absorption implies:
  - **Lower costs compared to steam (not evaporator).**
- ORC before absorption:
  - **Supplying 100% cooling demand.**
  - **More efficiently ORC.**

# INDEX







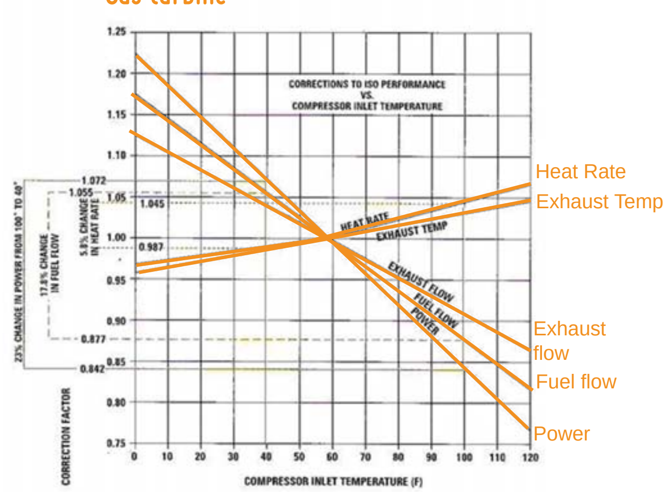
# 4. Improvements to basic CHP configuration



## 4.2 GT air inlet cooling (GTAIC)

- GTAIC is included in the proposed configuration of the CHP system with BrLi-H2O Absorption, to compensate GT electrical output decrease during summer season.
- A study of GT cooling power requirement is carried out, as a function of yearly variable ambient temperature.

### Gas turbine




Increase electrical power output

Increase fuel consumption

} Decrease Heat Rate

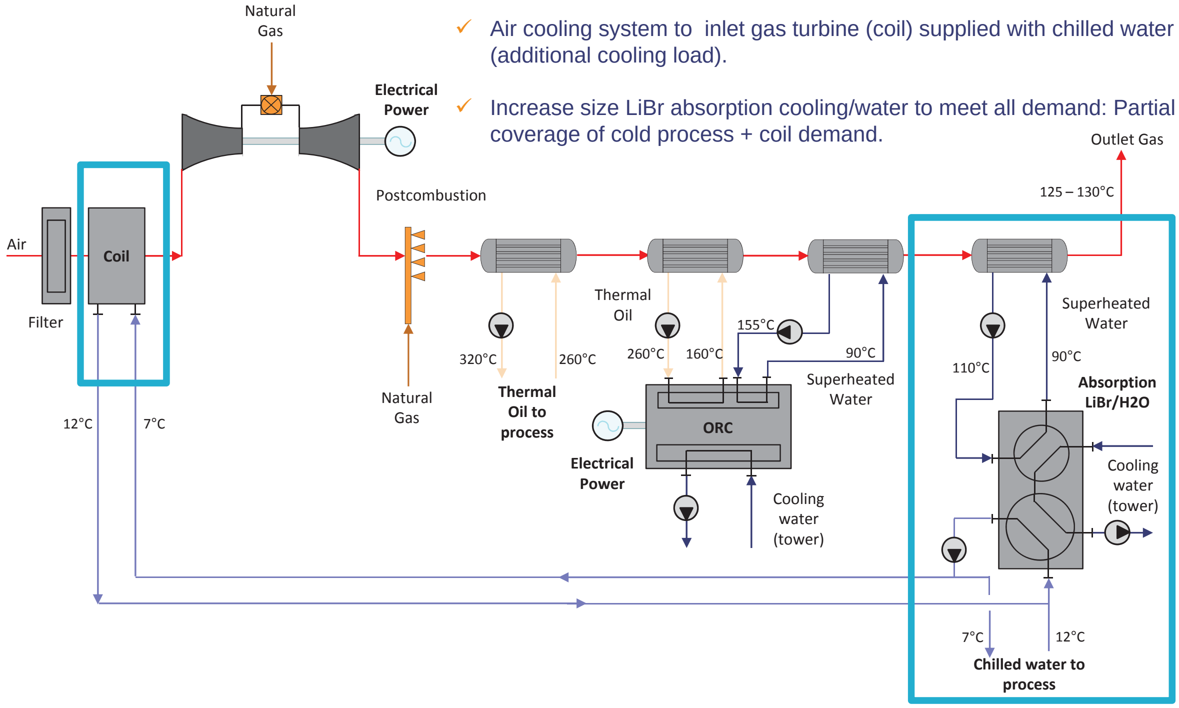
Increase flow in the gases

Exhaust temperature reduction

} Higher thermal content in the exhaust gases of the turbine

## 4.2 GT air inlet cooling (GTAIC)

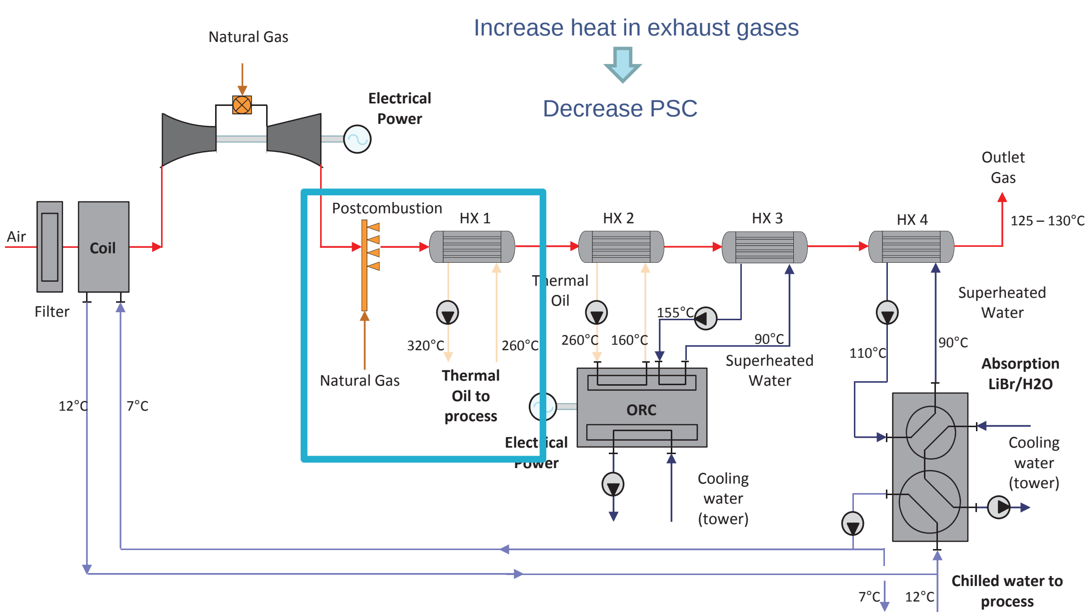
- ✓ Air cooling system to inlet gas turbine (coil) supplied with chilled water (additional cooling load).
- ✓ Increase size LiBr absorption cooling/water to meet all demand: Partial coverage of cold process + coil demand.






## 4.2 GT air inlet cooling (GTAIC)

### Effects: 1.- PSC and hot oil exchanger



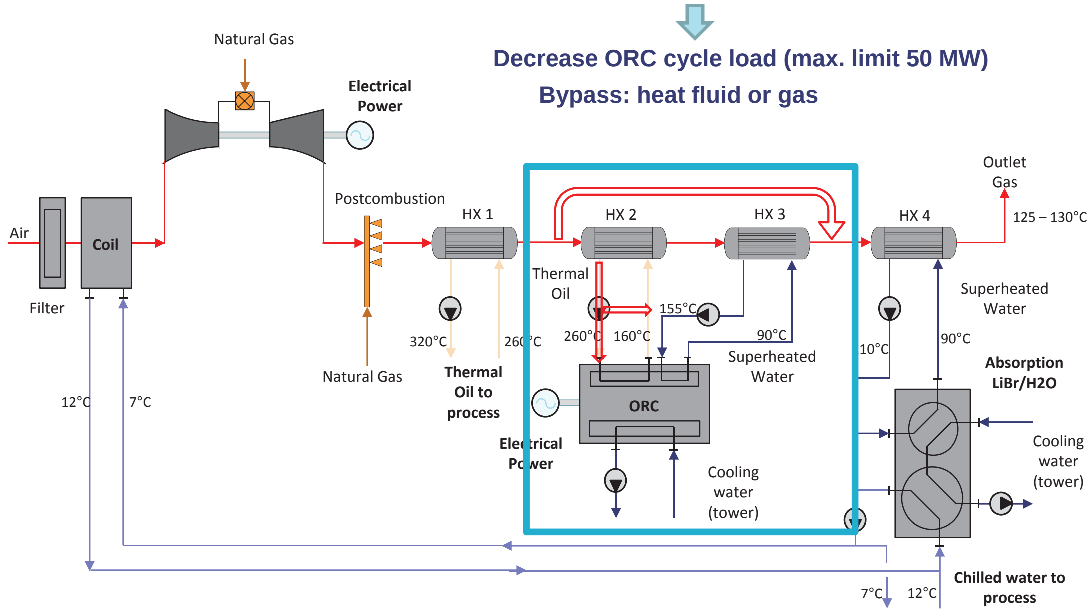
# 4.2 GT air inlet cooling (GTAIC)

## Effects: 2. ORC cycle

Increase electrical power GT

**Decrease ORC cycle load (max. limit 50 MW)**

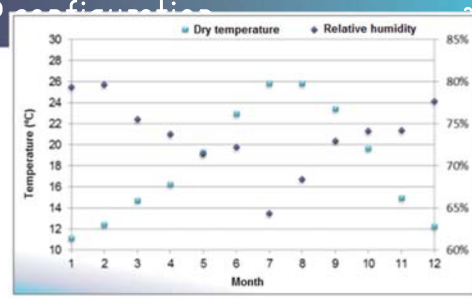
**Bypass: heat fluid or gas**





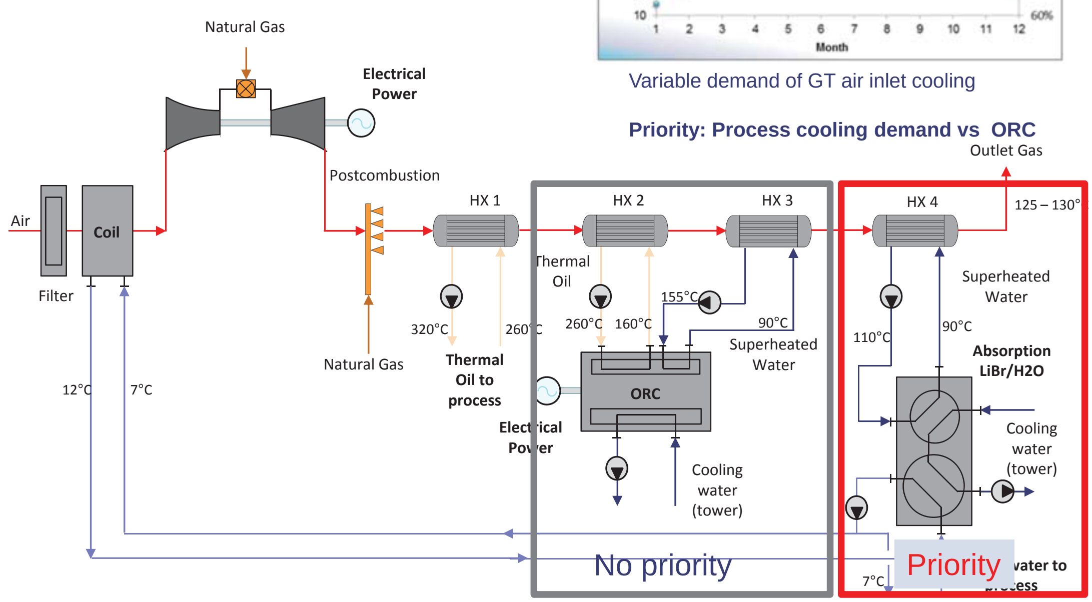

# 4.2 GT air inlet cooling (GTAIC)

## Effects: Absorption LiBr-H2O



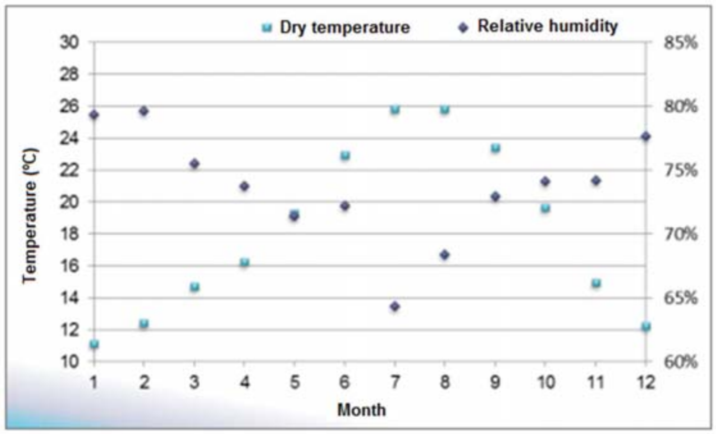

Variable demand of GT air inlet cooling

**Priority: Process cooling demand vs ORC**



## 4.2 GT air inlet cooling (GTAIC)

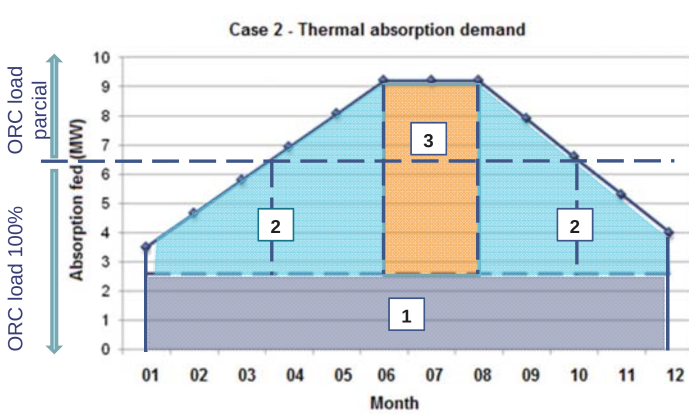
### Mensual base study: Air temperature and humidity






## 4.2 GT air inlet cooling (GTAIC)

### Monthly base study




Thermal absorption demand:

- **Constant** part

1 Partial coverage of the cold process

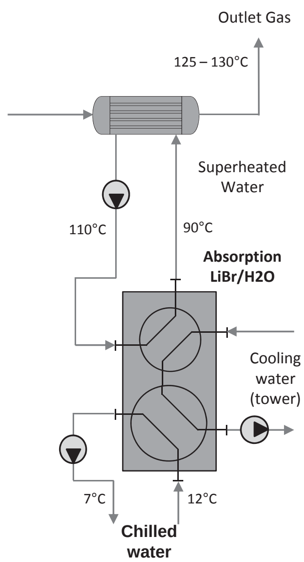
- Part **Load** **(air cooling GT)**

2 Part Load absorption ($T_{amb}$ moderate)

3 Absorption at full load (high $T_{amb}$)
ORC works part-load

# 4.2 GT air inlet cooling (GTAIC)

## Cooling capacity absorption




**Cooling to process + Cooling to air**
**1,8 MW + ? MW**

**PRELIMINARY STUDY:**

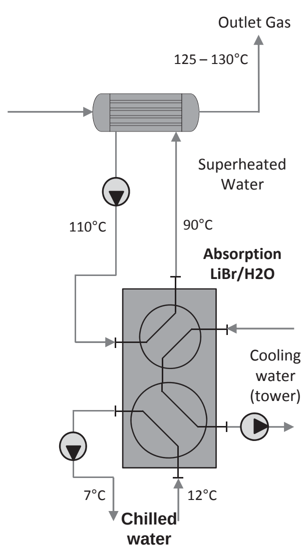
Define CAS capacity to cool air inlet to GT

Analysis 4 **GT** (from 40 to 47 MW).

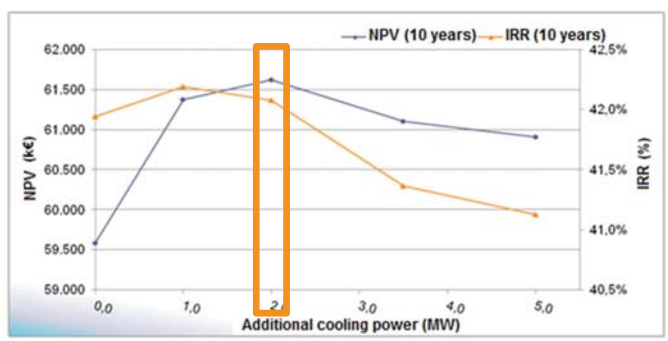


# 4.2 GT air inlet cooling (GTAIC)

## Cooling capacity absorption: additional cooling power between 1 y 5 MW




**Cooling to process + Cooling to air**
**1,8 MW + ? MW**



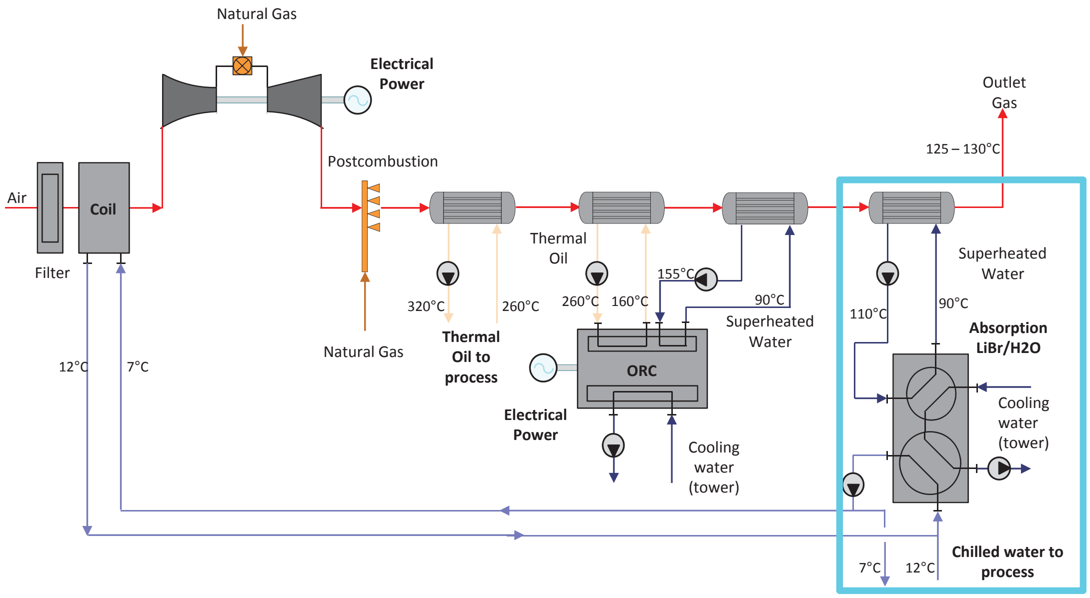

* 0 MW additional cooling

- ✓ Maximum values of IRR and NPV for 1 and 2 MW
- ✓ NPV reaches maximum for 2 MW

## 4.2 GT air inlet cooling (GTAIC)

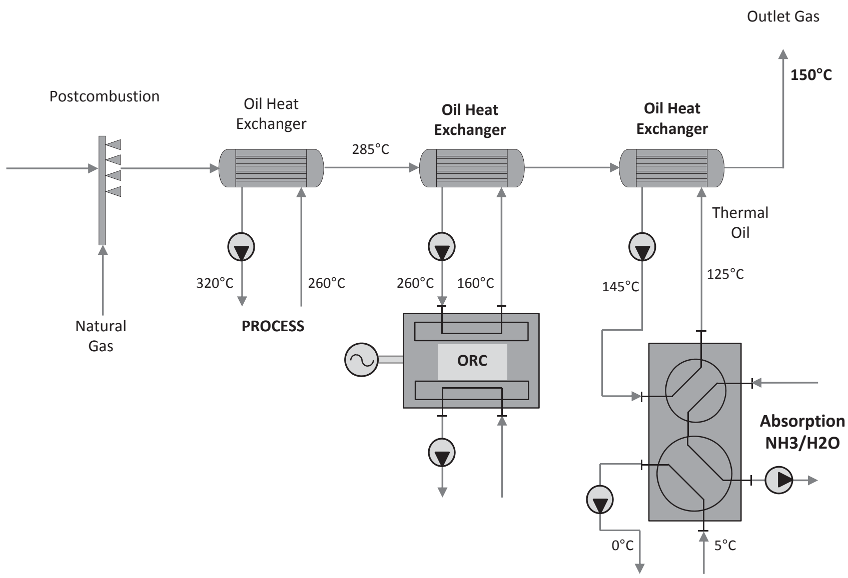
### *Conclusions*

Power absorption refrigerating equipment: 1,8 MW + 2 MW
**(Process) (cooling air admission)**



## Summary studied configuration

### 1) BASE CONFIGURATION (NH3 Abs): **GT + PSC + HO exchanger + ORC + NH3 Cooling**






## Commercially available GT

- **First selection of commercially available GT**
  - ✓ Generate electricity at 50 Hz
  - ✓ Nominal electric power from **15 MW to 50 MW**
  - ✓ Results: **41 turbines** considered in the study

**Performance gas turbine**

| Gas Turbine Model | Power (MW) | Exhaust temperature (°C) | Air flow rate (t/h) | Heat Rate (kJ PCI/kWh) | Heat Rate (adim) |
|---|---|---|---|---|---|
| Solar Titan 130-20500S | 15,002 | 497 | 176 | 10.226 | 2,841 |
| Hitachi H15 | 15,086 | 546 | 188 | 11.257 | 3,127 |
| GE LM1800e Low Power | 16,575 | 486 | 217 | 10.545 | 2,929 |
| GE LM1800e High Power | 17,725 | 494 | 224 | 10.418 | 2,894 |
| Kawasaki GPB180D | 18,045 | 533 | 211 | 10.576 | 2,938 |
| Siemens SGT-500-A2 | 19.065 | 369 | 348 | 10.683 | 2,968 |
| **Solar Titan 250-T30000S** | **21,730** | **463** | **241** | **9.263** | **2,573** |
| GE LM2500PE (") | 21,822 | 529 | 246 | 10.133 | 2,815 |
| **Siemens SGT-600** | **24,630** | **542** | **279** | **10.513** | **2,920** |
| P+W FT8 Swift Pac 30 | 25,048 | 463 | 296 | 9.543 | 2,651 |
| GE 5371 PA | 26,589 | 483 | 444 | 12.580 | 3,494 |
| P+W FT8 Swift Pac 30 | 27,555 | 480 | 307 | 9.437 | 2,621 |
| RR RB211-G RT62 | 27,697 | 504 | 330 | 10.132 | 2,814 |
| GE LM2500 PK | 29,276 | 521 | 312 | 9.685 | 2,690 |
| RR RB211-GT RT62 | 29,401 | 504 | 339 | 9.975 | 2,771 |
| **GE LM2500 PR** | **29,846** | **528** | **314** | **9.704** | **2,696** |
| GE LM2500 PV | 30,340 | 500 | 299 | 9.033 | 2,509 |
| **Siemens SGT-700** | **31,200** | **528** | **332** | **9.901** | **2,750** |
| Hitachi H25 | 31,820 | 557 | 341 | 10.329 | 2,869 |
| Siemens SGT-700-33 | 32.215 | 538 | 330 | 9.764 | 2,712 |
| RR RB211 GT RT61 | 32,435 | 511 | 335 | 9.418 | 2,616 |
| **GE LM2500 RD (G4)** | **32,606** | **526** | **324** | **9.398** | **2,611** |
| GE LM2500 RC (G4) | 32,835 | 524 | 326 | 9.376 | 2,604 |
| GE LM2500 RA (G4) | 33,337 | 524 | 326 | 9.234 | 2,565 |
| Siemens SGT-750 | 35.925 | 462 | 403 | 9.295 | 2,582 |
| GE 6581B ("") | 42,088 | 546 | 524 | 11.228 | 3,119 |
| **GE 6581B** | **42,100** | **546** | **524** | **11.183** | **3,106** |
| GE LM6000 PD | 42,751 | 452 | 450 | 8.687 | 2,413 |
| **GE LM6000 PF** | **42,751** | **452** | **450** | **8.687** | **2,413** |
| GE 6591 C | 42.950 | 568 | 423 | 9.885 | 2,746 |
| GE LM6000 PC | 43,498 | 451 | 456 | 8.656 | 2,404 |
| GE LM6000 PC | 43,517 | 451 | 459 | 8.666 | 2,407 |
| **Siemens SGT-800** | **47,000** | **544** | **463** | **9.590** | **2,664** |
| GE LM6000 PF SPRINT 15 | 47,093 | 447 | 471 | 8.715 | 2,421 |
| GE LM6000 PC SPRINT | 47,179 | 448 | 468 | 8.684 | 2,412 |
| GE LM6000 PC SPRINT | 47,182 | 448 | 471 | 8.690 | 2,414 |
| GE LM6000 PD SPRINT | 47,333 | 447 | 471 | 8.672 | 2,409 |
| **GE LM6000 PF SPRINT 25** | **47,958** | **450** | **472** | **8.659** | **2,405** |
| **GE LM6000 PH** | **48,717** | **475** | **497** | **8.778** | **2,438** |
| Siemens SGT-900 | 49,500 | 514 | 620 | 10.946 | 3,041 |
| **GE LM6000 PH SPRINT** | **51,039** | **471** | **503** | **8.774** | **2,437** |

## Preliminary analysis

- **Define more attractive GT**
  - ✓ Previous simulations of 41 turbines
  - ✓ Main selection criteria: EEE cogeneration
  - ✓ Priority: GT with low NOx combustion

| Performance gas turbine | | | | | | Cogeneration data | | | |
|---|---|---|---|---|---|---|---|---|---|
| Gas Turbine Model | Power (MW) | | (t/h) | Heat Rate (kJ PCI/kWh) | Heat Rate (adim) | Electricity (MW) | Combustible (MW PCI) | Useful heat (MW) | EEE |
| Solar Titan 130-20500S | 15,002 | 497 | 176 | 10.226 | 2,841 | 15,556 | 59,301 | 32,443 | 66,9% |
| Hitachi H15 | 15,086 | 546 | 188 | 11.257 | 3,127 | 15,733 | 62,115 | 34,357 | 65,7% |
| GE LM1800e Low Power | 16,575 | 486 | 217 | 10.545 | 2,929 | 17,446 | 69,872 | 38,984 | 65,7% |
| GE LM1800e High Power | 17,725 | 494 | 224 | 10.418 | 2,894 | 18,651 | 72,742 | 40,100 | 66,2% |
| Kawasaki GPB180D | 18,045 | 533 | 211 | 10.576 | 2,938 | 18,870 | 70,640 | 38,026 | 66,5% |
| Siemens SGT-500-A2 | 19.065 | 369 | 348 | 10.683 | 2,968 | 20,930 | 103,508 | 59,883 | 56,6% |
| **Solar Titan 250-T30000S** | **21,730** | **463** | **241** | **9.263** | **2,573** | **22,787** | **81,326** | **42,812** | **67,5%** |
| GE LM2500PE (") | 21,822 | 529 | 246 | 10.133 | 2,815 | 22,918 | 82,283 | 43,610 | 67,7% |
| **Siemens SGT-600** | **24,630** | **542** | **279** | **10.513** | **2,920** | **25,981** | **94,450** | **48,875** | **64,7%** |
| P+W FT8 Swift Pac 30 | 25,048 | 463 | 296 | 9.543 | 2,651 | 26,531 | 97,611 | 51,587 | 65,8% |
| GE 5371 PA | 26,589 | 483 | 444 | 12.580 | 3,494 | 29,217 | 134,092 | 72,364 | 54,4% |
| P+W FT8 Swift Pac 30 | 27,555 | 480 | 307 | 9.437 | 2,621 | 29,123 | 102,972 | 53,342 | 66,6% |
| RR RB211-G RT62 | 27,697 | 504 | 330 | 10.132 | 2,814 | 29,443 | 108,516 | 57,011 | 65,2% |
| GE LM2500 PK | 29,276 | 521 | 312 | 9.685 | 2,690 | 30,882 | 105,998 | 54,139 | 67,4% |
| RR RB211-GT RT62 | 29,401 | 504 | 339 | 9.975 | 2,771 | 31,216 | 112,864 | 58,447 | 65,1% |
| **GE LM2500 PR** | **29,846** | **528** | **314** | **9.704** | **2,696** | **31,468** | **107,176** | **54,458** | **67,4%** |
| GE LM2500 PV | 30,340 | 500 | 299 | 9.033 | 2,509 | 31,846 | 104,196 | 52,065 | 68,7% |
| **Siemens SGT-700** | **31,200** | **528** | **332** | **9.901** | **2,750** | **32,961** | **114,065** | **57,330** | **65,4%** |
| Hitachi H25 | 31,820 | 557 | 341 | 10.329 | 2,869 | 33,651 | 117,225 | 58,766 | 64,8% |
| Siemens SGT-700-33 | 32.215 | 538 | 330 | 9.764 | 2,712 | 33,942 | 114,428 | 57,011 | 66,4% |
| RR RB211 GT RT61 | 32,435 | 511 | 335 | 9.418 | 2,616 | 34,219 | 115,148 | 57,809 | 67,2% |
| **GE LM2500 RD (G4)** | **32,606** | **526** | **324** | **9.398** | **2,611** | **34,305** | **112,898** | **56,054** | **67,8%** |
| GE LM2500 RC (G4) | 32,835 | 524 | 326 | 9.376 | 2,604 | 34,550 | 113,671 | 56,373 | 67,7% |
| GE LM2500 RA (G4) | 33,337 | 524 | 326 | 9.234 | 2,565 | 35,052 | 113,664 | 56,373 | 68,7% |
| Siemens SGT-750 | 35.925 | 462 | 403 | 9.295 | 2,582 | 38,212 | 135,379 | 68,657 | 64,7% |
| GE 6581B ("") | 42,088 | 546 | 524 | 11.228 | 3,119 | 45,335 | 157,160 | 72,364 | 59,1% |
| **GE 6581B** | **42,100** | **546** | **524** | **11.183** | **3,106** | **45,347** | **156,671** | **72,364** | **59,5%** |
| GE LM6000 PD | 42,751 | 452 | 450 | 8.687 | 2,413 | 45,425 | 148,332 | 72,364 | 66,9% |
| **GE LM6000 PF** | **42,751** | **452** | **450** | **8.687** | **2,413** | **45,425** | **148,332** | **72,364** | **66,9%** |
| GE 6591 C | 42.950 | 568 | 423 | 9.885 | 2,746 | 45,439 | 148,641 | 71,848 | 66,0% |
| GE LM6000 PC | 43,498 | 451 | 456 | 8.656 | 2,404 | 46,219 | 149,590 | 72,364 | 66,8% |
| GE LM6000 PC | 43,517 | 451 | 459 | 8.666 | 2,407 | 46,261 | 149,600 | 72,364 | 66,9% |
| **Siemens SGT-800** | **47,000** | **544** | **463** | **9.590** | **2,664** | **49,775** | **156,367** | **72,364** | **65,5%** |
| GE LM6000 PF SPRINT 15 | 47,093 | 447 | 471 | 8.715 | 2,421 | 49,930 | 158,816 | 72,364 | 63,7% |
| GE LM6000 PC SPRINT | 47,179 | 448 | 468 | 8.684 | 2,412 | 49,992 | 158,623 | 72,364 | 63,9% |
| GE LM6000 PC SPRINT | 47,182 | 448 | 471 | 8.690 | 2,414 | 50,019 | 158,556 | 72,364 | 64,0% |
| GE LM6000 PD SPRINT | 47,333 | 447 | 471 | 8.672 | 2,409 | 50,170 | 158,831 | 72,364 | 64,0% |
| **GE LM6000 PF SPRINT 25** | **47,958** | **450** | **472** | **8.659** | **2,405** | **50,802** | **159,670** | **72,364** | **64,1%** |
| **GE LM6000 PH** | **48,717** | **475** | **497** | **8.778** | **2,438** | **51,755** | **157,927** | **72,364** | **66,8%** |
| Siemens SGT-900 | 49,500 | 514 | 620 | 10.946 | 3,041 | 53,489 | 174,768 | 72,364 | 56,7% |
| **GE LM6000 PH SPRINT** | **51,039** | **471** | **503** | **8.774** | **2,437** | **54,123** | **163,805** | **72,364** | **64,9%** |



## Results

- **11 selected turbines** to analyse in depth

| | Performance gas turbine | | | | | | Cogeneration data | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ref | Gas Turbine Model | Power (MW) | Exhaust temperature (°C) | Air flow rate (t/h) | Heat Rate (kJ PCI/kWh) | Heat Rate (adim) | Electricity (MW) | Combustible (MW PCI) | Useful heat (MW) | EEE |
| | Solar Titan 130-20500S | 15,002 | 497 | 176 | 10.226 | 2,841 | 15,556 | 59,301 | 32,443 | 66,9% |
| | Hitachi H15 | 15,086 | 546 | 188 | 11.257 | 3,127 | 15,733 | 62,115 | 34,357 | 65,7% |
| | GE LM1800e Low Power | 16,575 | 486 | 217 | 10.545 | 2,929 | 17,446 | 69,872 | 38,984 | 65,7% |
| | GE LM1800e High Power | 17,725 | 494 | 224 | 10.418 | 2,894 | 18,651 | 72,742 | 40,100 | 66,2% |
| | Kawasaki GPB180D | 18,045 | 533 | 211 | 10.576 | 2,938 | 18,870 | 70,640 | 38,026 | 66,5% |
| | Siemens SGT-500-A2 | 19.065 | 369 | 348 | 10.683 | 2,968 | 20,930 | 103,508 | 59,883 | 56,6% |
| 1 | **Solar Titan 250-T30000S** | **21,730** | **463** | **241** | **9.263** | **2,573** | **22,787** | **81,326** | **42,812** | **67,5%** |
| | GE LM2500PE (") | 21,822 | 529 | 246 | 10.133 | 2,815 | 22,918 | 82,283 | 43,610 | 67,7% |
| 2 | **Siemens SGT-600** | **24,630** | **542** | **279** | **10.513** | **2,920** | **25,981** | **94,450** | **48,875** | **64,7%** |
| | P+W FT8 Swift Pac 30 | 25,048 | 463 | 296 | 9.543 | 2,651 | 26,531 | 97,611 | 51,587 | 65,8% |
| | GE 5371 PA | 26,589 | 483 | 444 | 12.580 | 3,494 | 29,217 | 134,092 | 72,364 | 54,4% |
| | P+W FT8 Swift Pac 30 | 27,555 | 480 | 307 | 9.437 | 2,621 | 29,123 | 102,972 | 53,342 | 66,6% |
| | RR RB211-G RT62 | 27,697 | 504 | 330 | 10.132 | 2,814 | 29,443 | 108,516 | 57,011 | 65,2% |
| | GE LM2500 PK | 29,276 | 521 | 312 | 9.685 | 2,690 | 30,882 | 105,998 | 54,139 | 67,4% |
| | RR RB211-GT RT62 | 29,401 | 504 | 339 | 9.975 | 2,771 | 31,216 | 112,864 | 58,447 | 65,1% |
| 3 | **GE LM2500 PR** | **29,846** | **528** | **314** | **9.704** | **2,696** | **31,468** | **107,176** | **54,458** | **67,4%** |
| | GE LM2500 PV | 30,340 | 500 | 299 | 9.033 | 2,509 | 31,846 | 104,196 | 52,065 | 68,7% |
| 4 | **Siemens SGT-700** | **31,200** | **528** | **332** | **9.901** | **2,750** | **32,961** | **114,065** | **57,330** | **65,4%** |
| | Hitachi H25 | 31,820 | 557 | 341 | 10.329 | 2,869 | 33,651 | 117,225 | 58,766 | 64,8% |
| | Siemens SGT-700-33 | 32.215 | 538 | 330 | 9.764 | 2,712 | 33,942 | 114,428 | 57,011 | 66,4% |
| | RR RB211 GT RT61 | 32,435 | 511 | 335 | 9.418 | 2,616 | 34,219 | 115,148 | 57,809 | 67,2% |
| 5 | **GE LM2500 RD (G4)** | **32,606** | **526** | **324** | **9.398** | **2,611** | **34,305** | **112,898** | **56,054** | **67,8%** |
| | GE LM2500 RC (G4) | 32,835 | 524 | 326 | 9.376 | 2,604 | 34,550 | 113,671 | 56,373 | 67,7% |
| | GE LM2500 RA (G4) | 33,337 | 524 | 326 | 9.234 | 2,565 | 35,052 | 113,664 | 56,373 | 68,7% |
| | Siemens SGT-750 | 35.925 | 462 | 403 | 9.295 | 2,582 | 38,212 | 135,379 | 68,657 | 64,7% |
| | GE 6581B ("") | 42,088 | 546 | 524 | 11.228 | 3,119 | 45,335 | 157,160 | 72,364 | 59,1% |
| 11 | **GE 6581B** | **42,100** | **546** | **524** | **11.183** | **3,106** | **45,347** | **156,671** | **72,364** | **59,5%** |
| | GE LM6000 PD | 42,751 | 452 | 450 | 8.687 | 2,413 | 45,425 | 148,332 | 72,364 | 66,9% |
| 6 | **GE LM6000 PF** | **42,751** | **452** | **450** | **8.687** | **2,413** | **45,425** | **148,332** | **72,364** | **66,9%** |
| | GE 6591 C | 42.950 | 568 | 423 | 9.885 | 2,746 | 45,439 | 148,641 | 71,848 | 66,0% |
| | GE LM6000 PC | 43,498 | 451 | 456 | 8.656 | 2,404 | 46,219 | 149,590 | 72,364 | 66,8% |
| | GE LM6000 PC | 43,517 | 451 | 459 | 8.666 | 2,407 | 46,261 | 149,600 | 72,364 | 66,9% |
| 7 | **Siemens SGT-800** | **47,000** | **544** | **463** | **9.590** | **2,664** | **49,775** | **156,367** | **72,364** | **65,5%** |
| | GE LM6000 PF SPRINT 15 | 47,093 | 447 | 471 | 8.715 | 2,421 | 49,930 | 158,816 | 72,364 | 63,7% |
| | GE LM6000 PC SPRINT | 47,179 | 448 | 468 | 8.684 | 2,412 | 49,992 | 158,623 | 72,364 | 63,9% |
| | GE LM6000 PC SPRINT | 47,182 | 448 | 471 | 8.690 | 2,414 | 50,019 | 158,556 | 72,364 | 64,0% |
| | GE LM6000 PD SPRINT | 47,333 | 447 | 471 | 8.672 | 2,409 | 50,170 | 158,831 | 72,364 | 64,0% |
| 8 | **GE LM6000 PF SPRINT 25** | **47,958** | **450** | **472** | **8.659** | **2,405** | **50,802** | **159,670** | **72,364** | **64,1%** |
| 9 | **GE LM6000 PH** | **48,717** | **475** | **497** | **8.778** | **2,438** | **51,755** | **157,927** | **72,364** | **66,8%** |
| | Siemens SGT-900 | 49,500 | 514 | 620 | 10.946 | 3,041 | 53,489 | 174,768 | 72,364 | 56,7% |
| 10 | **GE LM6000 PH SPRINT** | **51,039** | **471** | **503** | **8.774** | **2,437** | **54,123** | **163,805** | **72,364** | **64,9%** |

DVA Global Energy Services



## Results

- **11 selected turbines** to analyse in depth

| | Performance gas turbine | | | | | | Cogeneration data | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ref | Gas Turbine Model | Power (MW) | Exhaust temp (°C) | Air flow rate (t/h) | Heat Rate (kJ PCI/kWh) | Heat Rate (adim) | Electricity (MW) | Combustible (MW PCI) | Useful heat (MW) | EEE |
| 1 | Solar Titan 250-T30000S | 21,730 | 463 | 241 | 9.263 | 2,573 | 22,787 | 81,326 | 42,812 | **67,5%** |
| 2 | Siemens SGT-600 | 24,630 | 542 | 279 | 10.513 | 2,920 | 25,981 | 94,450 | 48,875 | **64,7%** |
| 3 | GE LM2500 PR | 29,846 | 528 | 314 | 9.704 | 2,696 | 31,468 | 107,176 | 54,458 | **67,4%** |
| 4 | Siemens SGT-700 | 31,200 | 528 | 332 | 9.901 | 2,750 | 32,961 | 114,065 | 57,330 | **65,4%** |
| 5 | GE LM2500 RD (G4) | 32,606 | 526 | 324 | 9.398 | 2,611 | 34,305 | 112,898 | 56,054 | **67,8%** |
| 6 | GE LM6000 PF | 42,751 | 452 | 450 | 8.687 | 2,413 | 45,425 | 148,332 | 72,364 | **66,9%** |
| 7 | Siemens SGT-800 | 47,000 | 544 | 463 | 9.590 | 2,664 | 49,775 | 156,367 | 72,364 | **65,5%** |
| 8 | GE LM6000 PF SPRINT 25 | 47,958 | 450 | 472 | 8.659 | 2,405 | 50,802 | 159,670 | 72,364 | **64,1%** |
| 9 | GE LM6000 PH | 48,717 | 475 | 497 | 8.778 | 2,438 | 51,755 | 157,927 | 72,364 | **66,8%** |
| 10 | GE LM6000 PH SPRINT | 51,039 | 471 | 503 | 8.774 | 2,437 | 54,123 | 163,805 | 72,364 | **64,9%** |
| 11 | GE 6581B | 42,100 | 546 | 524 | 11.183 | 3,106 | 45,347 | 156,671 | 72,364 | **59,5%** |

DVA Global Energy Services



## Energy Results

| Option | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Power** | | **21,23 MW** | **23,65 MW** | **29,19 MW** | **30,54 MW** | **31,69 MW** | **40,30 MW** | **46,52 MW** | **46,83 MW** | **47,13 MW** | **49,80 MW** | **42,27 MW** |
| **Gas turbine** | | **Solar Titan 250 T30000S** | **Siemens SGT 600** | **GE LM2500 PR** | **Siemens SGT 700** | **GE LM2500 RD G4** | **GE LM6000 PF** | **Siemens SGT 800** | **GE LM6000 PF SPRINT** | **GE LM 6000PH** | **GE LM6000 PH SPRINT** | **GE PG 6581** |
| Operation of the site | h | 8.760 | 8.760 | 8.760 | 8.760 | 8.760 | 8.760 | 8.760 | 8.760 | 8.760 | 8.760 | 8.760 |
| Operation of the cogeneration (CHP) | h | 8.400 | 8.400 | 8.400 | 8.400 | 8.400 | 8.400 | 8.400 | 8.400 | 8.400 | 8.400 | 8.400 |
| **ELECTRICITY BALANCE** | | | | | | | | | | | | |
| Electricity of the gas turbine | MWh/year | 169.714 | 187.824 | 232.268 | 242.348 | 251.983 | 319.351 | 370.079 | 372.380 | 374.934 | 396.715 | 332.002 |
| ORC electricity | MWh/year | 8.658 | 10.837 | 12.928 | 14.188 | 14.188 | 19.152 | 20.708 | 20.971 | 20.971 | 21.626 | 23.062 |
| **Generation in terminals** | **MWh/year** | **178.372** | **198.661** | **245.196** | **256.537** | **266.172** | **338.503** | **390.787** | **393.352** | **395.905** | **418.341** | **355.064** |
| Electricity used for the CHP | MWh/year | 4.454 | 4.967 | 5.738 | 6.017 | 6.055 | 7.600 | 8.234 | 8.267 | 8.298 | 8.571 | 7.819 |
| Electricity exported | MWh/year | 173.918 | 193.694 | 239.458 | 250.520 | 260.117 | 330.904 | 382.553 | 385.084 | 387.607 | 409.770 | 347.245 |
| **STEAM BALANCE / THERMAL OIL / WATER** | | | | | | | | | | | | |
| Thermal oil generated by the CHP | MWh/year | 329.003 | 382.612 | 425.678 | 454.146 | 440.194 | 571.200 | 571.200 | 571.200 | 571.200 | 571.200 | 571.200 |
| Water chiller exported by the CHP | m3/año | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 |
| Cooling energy | MWh/year | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 |
| Heat generated for absorption production | MWh/year | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 |
| Heat for natural gas to furnaces | MWh/year | 0 | 0 | 0 | 0 | 0 | | | | | | |
| Air for services and instruments | m3/year | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 | 20.000 |
| **Useful heat (formula > 0°C)** | **MWh/year** | 348.592 | 402.200 | 445.267 | 473.735 | 459.782 | 590.789 | 590.780 | 590.789 | 590.789 | 590.789 | 590.789 |
| **Useful heat** | **MWh/year** | **365.963** | **419.572** | **462.638** | **491.106** | **477.154** | **608.160** | **608.152** | **608.160** | **608.160** | **608.160** | **608.160** |
| **FUEL BALANCE** | | | | | | | | | | | | |
| Gas turbine fuel | MWhPCI/year | 453.718 | 579.793 | 645.700 | 690.295 | 684.272 | 807.475 | 1.019.332 | 927.444 | 946.260 | 1.000.222 | 1.065.271 |
| Postcombusters fuel | MWhPCI/year | 219.467 | 195.796 | 234.217 | 248.212 | 242.046 | 387.979 | 256.637 | 374.909 | 341.418 | 338.209 | 213.704 |
| **Total fuel** | **MWhPCI/year** | **673.184** | **775.589** | **879.917** | **938.507** | **926.318** | **1.195.454** | **1.275.968** | **1.302.353** | **1.287.678** | **1.338.431** | **1.278.976** |
| **Efficiency** | | | | | | | | | | | | |
| Electric efficiency | | 26,5% | 25,6% | 27,9% | 27,3% | 28,7% | 28,3% | 30,6% | 30,2% | 30,7% | 31,3% | 27,8% |
| Thermal efficiency | | 54,4% | 54,1% | 52,6% | 52,3% | 51,5% | 50,9% | 47,7% | 46,7% | 47,2% | 45,4% | 47,6% |
| **EEE (> 0°C)** | | **62,4%** | **60,4%** | **63,7%** | **62,2%** | **64,1%** | **62,8%** | **63,1%** | **60,9%** | **62,7%** | **61,3%** | **57,0%** |
| **EEE** | | **66,9%** | **64,2%** | **67,0%** | **65,3%** | **67,2%** | **65,1%** | **65,1%** | **62,8%** | **64,7%** | **63,1%** | **58,9%** |
| Total CO2 | t/year | 135.983 | 156.669 | 177.743 | 189.578 | 187.116 | 241.482 | 257.746 | 263.075 | 260.111 | 270.363 | 258.353 |
| **ENVIRONMENT** | | | | | | | | | | | | |
| Primary energy consumption of reference | MWhPCI/year | 361.773 | 510.416 | 557.877 | 588.548 | 588.802 | 592.652 | 925.983 | 669.498 | 745.823 | 777.082 | 969.801 |
| PES (Primary Energy Savings) | year | 147.829 | 169.407 | 201.608 | 207.315 | 212.035 | 240.138 | 280.666 | 246.689 | 267.096 | 265.216 | 227.299 |
| PESR (Primary Energy Savings Ratio) | | 41% | 33% | 36,1% | 35% | 36% | 41% | 30% | 37% | 36% | 34% | 23% |
| CO2 emission savings | t/year | 29.861 | 34.220 | 40.725 | 41.878 | 42.831 | 48.508 | 56.694 | 49.831 | 53.953 | 53.574 | 45.914 |
| CO2 associated to electricity generation | t/year | 53.845 | 62.498 | 73.907 | 79.352 | 80.022 | 104.984 | 121.249 | 126.577 | 123.613 | 133.865 | 121.855 |
| Total CO2 | t/year | 135.983 | 156.669 | 177.743 | 189.578 | 187.116 | 241.482 | 257.746 | 263.075 | 260.111 | 270.363 | 258.353 |

## Energy Results

| Option | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Power | | 21,23 MW | 23,65 MW | 29,19 MW | 30,54 MW | 31,69 MW | 40,30 MW | 46,52 MW | 46,83 MW | 47,13 MW | 49,80 MW | 42,27 MW |
| Gas turbine | | Solar Titan 250 T30000S | Siemens SGT 600 | GE LM2500 PR | Siemens SGT 700 | GE LM2500 RD G4 | GE LM6000 PF | Siemens SGT 800 | GE LM6000 PF SPRINT | GE LM 6000PH | GE LM6000 PH SPRINT | GE PG 6581 |

**It is always covered the entire cooling process demand, for all selected turbines.**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ELECTRICITY BALANCE** | | | | | | | | | | | | |
| Electricity of the gas turbine | MWh/year | 169.714 | 187.824 | 232.268 | 242.348 | 251.983 | 319.351 | 370.079 | 372.380 | 374.934 | 396.715 | 332.002 |
| ORC electricity | MWh/year | 8.658 | 10.837 | 12.928 | 14.188 | 14.188 | 19.152 | 20.708 | 20.971 | 20.971 | 21.626 | 23.062 |
| **Generation in terminals** | **MWh/year** | **178.372** | **198.661** | **245.196** | **256.537** | **266.172** | **338.503** | **390.787** | **393.352** | **395.905** | **418.341** | **355.064** |
| Electricity used for the CHP | MWh/year | 4.454 | 4.967 | 5.738 | 6.017 | 6.055 | 7.600 | 8.234 | 8.267 | 8.298 | 8.571 | 7.819 |
| Electricity exported | MWh/year | 173.918 | 193.694 | 239.458 | 250.520 | 260.117 | 330.904 | 382.553 | 385.084 | 387.607 | 409.770 | 347.245 |
| **STEAM BALANCE / THERMAL OIL / WATER** | | | | | | | | | | | | |
| Thermal oil generated by the CHP | MWh/year | 329.003 | 382.612 | 425.678 | 454.146 | 440.194 | 571.200 | 571.200 | 571.200 | 571.200 | 571.200 | 571.200 |
| Water chiller exported by the CHP | m3/año | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 | 3.528.000 |
| Cooling energy | MWh/year | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 | 19.110 |
| Heat generated for absorption production | MWh/year | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 | 36.960 |
| Heat for natural gas to furnaces | MWh/year | 0 | 0 | 0 | 0 | 0 | | | | | | |

**Partial coverage of thermal oil demand for GT from 1 to 5, total from 6 to 10.**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FUEL BALANCE** | | | | | | | | | | | | |
| Gas turbine fuel | MWhPCI/year | 453.718 | 579.793 | 645.700 | 690.295 | 684.272 | 807.475 | 1.019.332 | 927.444 | 946.260 | 1.000.222 | 1.065.271 |
| Postcombusters fuel | MWhPCI/year | 219.467 | 195.796 | 234.217 | 248.212 | 242.046 | 387.979 | 256.637 | 374.909 | 341.418 | 338.209 | 213.704 |

**Different EEE, between 63% y 67%, and PES (primary energy savings), between 33% y 41%.**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electric efficiency | | 26,5% | 25,6% | 27,9% | 27,3% | 28,7% | 28,3% | 30,6% | 30,2% | 30,7% | 31,3% | 27,8% |
| Thermal efficiency | | 54,4% | 54,1% | 52,6% | 52,3% | 51,5% | 50,9% | 47,7% | 46,7% | 47,2% | 45,4% | 47,6% |
| **EEE (> 0°C)** | | **62,4%** | **60,4%** | **63,7%** | **62,2%** | **64,1%** | **62,8%** | **63,1%** | **60,9%** | **62,7%** | **61,3%** | **57,0%** |
| **EEE** | | **66,9%** | **64,2%** | **67,0%** | **65,3%** | **67,2%** | **65,1%** | **65,1%** | **62,8%** | **64,7%** | **63,1%** | **58,9%** |
| Total CO2 | t/year | 135.983 | 156.669 | 177.743 | 189.578 | 187.116 | 241.482 | 257.746 | 263.075 | 260.111 | 270.363 | 258.353 |
| **ENVIRONMENT** | | | | | | | | | | | | |
| Primary energy consumption of reference | MWhPCI/year | 361.773 | 510.416 | 557.877 | 588.548 | 588.802 | 592.652 | 925.983 | 669.498 | 745.823 | 777.082 | 969.801 |
| PES (Primary Energy Savings) | year | 147.829 | 169.407 | 201.608 | 207.315 | 212.035 | 240.138 | 280.666 | 246.689 | 267.096 | 265.216 | 227.299 |
| PESR (Primary Energy Savings Ratio) | | 41% | 33% | 36,1% | 35% | 36% | 41% | 30% | 37% | 36% | 34% | 23% |
| CO2 emission savings | t/year | 29.861 | 34.220 | 40.725 | 41.878 | 42.831 | 48.508 | 56.694 | 49.831 | 53.953 | 53.574 | 45.914 |
| CO2 associated to electricity generation | t/year | 53.845 | 62.498 | 73.907 | 79.352 | 80.022 | 104.984 | 121.249 | 126.577 | 123.613 | 133.865 | 121.855 |
| Total CO2 | t/year | 135.983 | 156.669 | 177.743 | 189.578 | 187.116 | 241.482 | 257.746 | 263.075 | 260.111 | 270.363 | 258.353 |



## Economic Results

| Option | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Power | | 21,23 MW | 23,64 MW | 29,19 MW | 30,53 MW | 31,69 MW | 40,30 MW | 46,51 MW | 46,83 MW | 47,13 MW | 49,80 MW | 42,26 MW |
| Gas turbine | | Solar Titan 250 T30000S | Siemens SGT 600 | GE LM2500 PR | Siemens SGT 700 | GE LM2500 RD G4 | GE LM6000 PF | Siemens SGT 800 | GE LM6000 PF SPRINT | GE LM 6000PH | GE LM6000 PH SPRINT | GE PG 6581 |

| | |
|---|---|
| Total investment | k€ |
| Specific cost | k€/MW |
| **INCOME** | |
| Electricity exported | k€/year |
| Thermal oil heating | k€/year |
| Chilled water production | k€/year |
| Natural Gas heating | k€/year |
| **Total income** | **k€/year** |
| **COSTS** | |
| Natural Gas | k€/year |
| $CO_2$ cost | k€/year |
| Air instruments cost | k€/year |
| Cooling water (tower) cost | k€/year |
| Electric toll cost | k€/year |
| O&M cost (variable) | k€/year |
| O&M cost (fixed) [1] | k€/year |
| **Total costs** | **k€/year** |

**Income and cost of each GT and for 3 studies cases**

**Fuel, electricity and utilities assessed with 10-year forecasts**

[1] Insurances included

## Investment for each case

| INVESTMENTS |
|---|
| **Configuration** |
| **Gas turbine** |
| *Values in k€* |
| **MAIN EQUIPMENT** |
| Gas turbine |
| Burner |
| Oil to process/gas heat exchanger |
| ORC |
| Absorption cooler |
| Coil |
| **SECONDARY SYSTEMS** |
| High voltage electricity and power transformers |
| Low voltage electricity |
| Outlet and bypass gasses |
| Gas combustible system |
| Piping system |
| Control and supervision system |
| Instrumentation and monitoring of emissions |
| **CIVIL WORKS** |
| **ADDITIONAL SYSTEMS** |
| **TOTAL PHYSICAL INVESTMENT** |
| **ENGINEERING, CIVIL WORKS DIRECTOR, MANAGEMENT, LEGALIZATIONS** |
| **TOTAL INVESTMENT** |
| **Specific cost (k€/MW)** |

*Example: Results for cogeneration Modif 1 (BrLi Abs)



## Financial scenary

- Period analysis: **10 years**
- Hours of operation of cogeneration: 24 hours/day
- Availability of cogeneration: 8400 hours/year
- Planned stops:
  - ✓ Stop hot parts (€ 1.5 million) and higher stop (€ 2.5 million)
  - ✓ Every four years, alternately
- Financing Method: **100% itself**
- Depreciation method: **linear to 10 years**
- Residual value: 4 times the cash flow last year

## Financial Results

| Option | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Power | 21,23 MW | 23,64 MW | 29,19 MW | 30,53 MW | 31,69 MW | 40,30 MW | 46,51 MW | 46,83 MW | 47,13 MW | 49,80 MW | 42,26 MW |
| Gas turbine | Solar Titan 250 T30000S | Siemens SGT 600 | GE LM2500 PR | Siemens SGT 700 | GE LM2500 RD G4 | GE LM6000 PF | Siemens SGT 800 | GE LM6000 PF SPRINT | GE LM 6000PH | GE LM6000 PH SPRINT | GE PG 6581 |

| | |
|---|---|
| Total investment | k€ |
| Specific cost | k€/MW |
| **INCOME** | |
| Electricity exported | k€/year |
| Thermal oil heating | k€/year |
| Chilled water production | k€/year |
| Natural Gas heating | k€/year |
| **Total income** | **k€/year** |
| **COSTS** | |
| Natural Gas | k€/year |
| $CO_2$ cost | k€/year |
| Air instruments cost | k€/year |
| Cooling water (tower) cost | k€/year |
| Electric toll cost | k€/year |
| O&M cost (variable) | k€/year |
| O&M cost (fixed) [1)] | k€/year |
| **Total costs** | **k€/year** |
| **RESULTS** | |
| Operating profit year 2012 [2)] | k€/year |
| Net profit for the year 2012 | k€/year |
| PBT | years |
| IRR (10 years) | |
| NPV (10 years) | k€ |

**Investment from 25,6 to 41,3 MM€**

**Specific cost from 1,21 to 0,83 MM€ / MW**

**Net operating profit from 4,8 to 9,1 MM€ / year**

**PBT very attractive for all turbines ranging analysed from 3,5 to 4,5 years**

**High values of the IRR, from 30% to 39%**

[1)] Insurances included [2)] Profit before interest, taxes, depreciation and amortization

*Example: Results for base configuration



## Selection of the best cases

Selection of the best two turbines for each configuration studied:

| | | BASE CONFIGURATION Abs NH3 | | Modification 1 Abs LiBr | | Modification 2 GT Air Cooling | |
|---|---|---|---|---|---|---|---|
| | | Siemens SGT 800 | GELM6000 PH | Siemens SGT 800 | GE LM6000 PH | Siemens SGT 800 | GE LM6000 PF |
| **ENERGY RESULTS** | | | | | | | |
| Electrical power | MW | 46,52 | 47,13 | 47,05 | 47,69 | 48,9 | 45,6 |
| Useful heat | MW | 72,4 | 72,4 | 69,8 | 69,8 | 69,8 | 69,8 |
| Total fuel | MW | 151,9 | 153,3 | 151,9 | 153,3 | 154,8 | 148,3 |
| **REE** | | **65,1%** | **64,7%** | **63,3%** | **63,0%** | **63,3%** | **64,4%** |
| Electrical efficiency | | 30,6% | 30,7% | 31,0% | 31,1% | 31,6% | 30,8% |
| Thermal efficiency | | 47,7% | 47,2% | 46,5% | 46,1% | 45,6% | 47,6% |
| **PES** (percentage of primary energy savings) | | **30%** | **36%** | **30%** | **35%** | **29%** | **38%** |
| CO2 savings | t/year | 56.694 | 53.953 | 52.945 | 49.640 | 53.878 | 48.296 |
| **FINANCIAL RESULTS** | | | | | | | |
| Total investment | k€ | | | | | | |
| Specific cost | k€/MW | | | | | | |
| Operating profit year 2012 | k€/year | | | | | | |
| Net profit for the year 2012 | k€/year | | | | | | |
| **PBT** | **years** | | | | | | |
| **IRR (10 years)** | | | | | | | |
| NPV (10 years) | k€ | | | | | | |

**Very attractive results:**

**Siemens SGT 800,**
**GE LM6000 PH and GE LM6000 PF**

- Attractive financial results:

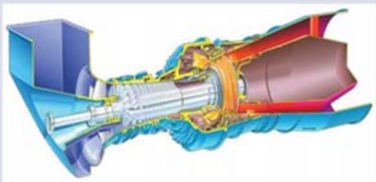
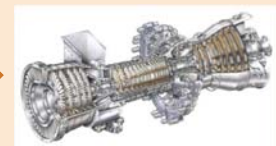
  **IRR: 39 – 42%** **PBT :**

- Best turbines selected:

  ✓ Base Configuration
  ✓ Modif 1 (Abs LiBr) → **Siemens SGT 800 & GE LM6000 PH**

  ✓ Modification 2 (GT Air cooling) → **Siemens SGT 800 & GE LM6000 PF**

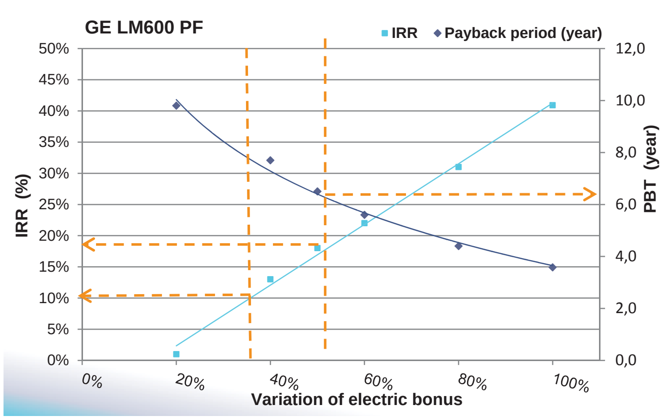
## Summary of the selected turbines

| Siemens SGT 800 (47,0 MW) | GE LM6000 PH (48,7 MW) | GE LM6000 PF (42,8 MW) |
|---|---|---|
|  |  |  |
| Results independent of the settings selected: NH3 or BrLi Abs or GT air cooling | Results valid for:<br>✓ Base Configuration (NH3-H20 Abs)<br>✓ Modif 1 (LiBr Abs) | Only for **Modif 2** (GT Air Cooling) |



## Efectos de la reducción de los incentivos EE

- Study conducted on the basis of the incentives provided by the RD 661/07.
- Need to analyse the sensitivity of the results to reductions EE final prices




**CONCLUSIONS**

- 50% **reduction** on incentives not impair the profitability of projects:
  - ✓ PBT increases **from 3,5 to 6,5 years.**
  - ✓ IRR decreases **from 41% to 18%.**
- The minimum level of return **(IRR = 10%)** was achieved when the incentives take 35% of the current value.

DVA Global Energy Services

# Technical and Economic Feasibility Assessment for a CHP System with ORC Technology

# Ammonia Synloop Waste Heat Boiler Failure Analysis Repair Methodology

**Hossam Naiem**
**Abu-Qir Fertilizer Co.**
**Egypt**

# Ammonia Syn loop Waste Heat Boiler Failure In Ammonia Plant III

Prepared by

Eng Hossam Naiem

# ABU QIR FERTILIZERS

Consists of three plants producing 6000 tpd from nitrogen fertilizers

Abu Qir I    Abu Qir II    Abu Qir III

# ABU QIR I


**Ammonia plant** *Producing 1150 tpd*

**Urea plant** *Producing 1650 tpd*

# ABU QIR II


**Ammonia plant** *Producing 1000 tpd*

**Nitric acid plant** *Producing 1800 tpd*

**Ammonium nitrates plant** *Producing 2400 tpd*

# ABU QIR III


**Ammonia plant** *Producing 1200 tpd*

**Urea plant** *Producing 2000 tpd*

# AMMONIA SHIPLOADING

Capital Investment

Fully covered by Company's own funds

**Capacity 100000 tpy**

## Vessel Characteristic

Length : 150 m Width: 21 m Max Draft : 7.5 m

Capacity : 7000-11000 M.T

## First Shipment 1990

# ABSATRACT

- Waste heat boiler is located down stream of ammonia converter .
- Waste heat boiler showed an internal leakage from tube side to shell side after 4.5 years from commissioning.
- This report describes the case, how to detect the leakage and how to manage this problem, the possible causes and the final action.



# INTRODUCTION

- ABU QIR 3 plant was commissioned in October 1998, it consists of two main plants, ammonia plant with capacity 1200 ton and Urea plant with capacity 2000 ton. Granulated urea.

- After 4.5 years from start up the plant a gas leakage from tube side to shell side of synthesis loop waste heat boiler happened , and repeated for five times.

# INTRODUCTION

- **The synthesis loop consists of :-**
- **1- Ammonia converter with three beds Radial Flow**
- **2- Waste heat boiler**
- **3- Gas gas heat exchanger**
- **4- Gas cooler**
- **5- Cold exchanger**
- **6- Loop chiller I & II**
- **7- Separator**
- **8- Flash drum**



## Syntheses Loop Waste Heat Boiler Specifications:-

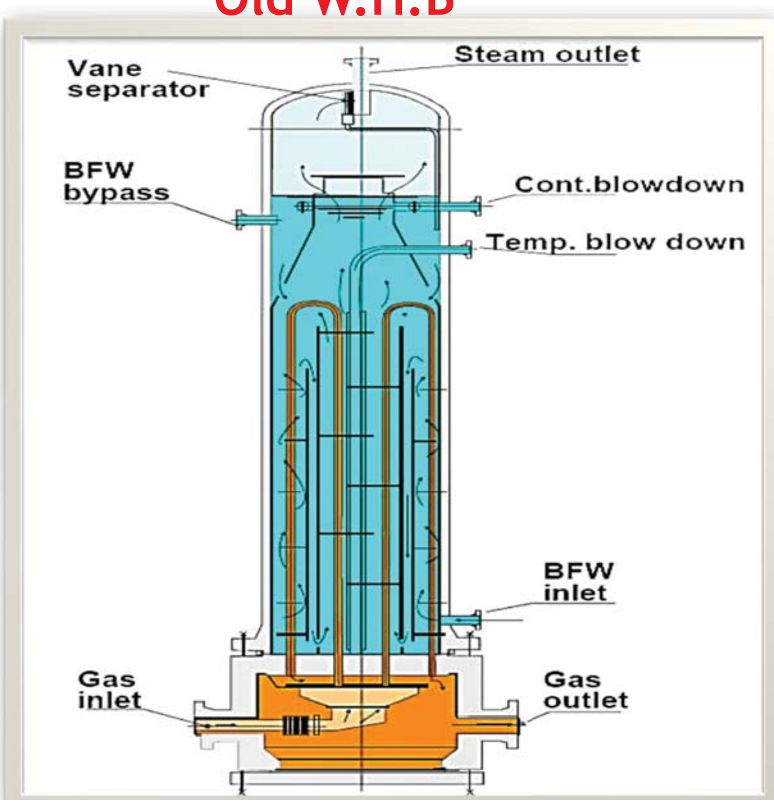
- The number of the tubes is 400- U-Tubes with 2 passes.
- The tube length is 5760 mm, tube outside diameter is 25 mm and tube wall thickness is 2.5 mm.
- The number of baffles is 26 and the boiler inside shell diameter is 1390 mm.

# Material of Construction

- The tubes of the waste heat boiler are made of :
- (10 CrMo910), tube sheet is made of (12 CrMo910), the shell, head, and shell flange are made from (20 MnMoNi45).
- **The waste heat boiler cools down the gases outlet ammonia converter from 465 $^{0}$C to about 306 $^{0}$C and generates saturated steam with 329 $^{0}$C, the converted gases are introduced in the tube side at an operating pressure of 184.8 bars and the steam is generated in the shell at 125 bars absolute and temperature of 329 $^{0}$C.**



## Old W.H.B



## History of Internal leakage in W.H.B

## <u>The first leakage:-</u>

It occurred in the morning shift on 6th march 2003, at this day the values of the PH, Cond. and ammonia of generated steam from W.H.B increased to dangerous limits:-



## History of Internal leakage in W.H.B

| Tag Name | | Conductivity | | PH | | $NH_3$ | |
|---|---|---|---|---|---|---|---|
| | | Before Leakage | After Leakage | Before Leakage | After Leakage | Before Leakage | After Leakage |
| BFW | | 6.5 | 9.5 | 9.3 | 9.4 | 1.9 | 2.5 |
| Steam Drum | Blow Down | 6.6 | 6.8 | 9.1 | 9.3 | ---- | 1.2 |
| | HP Steam | 8.6 | 9.8 | 9.3 | 9.4 | ---- | 2.1 |
| Waste Heat Boiler | Blow Down | 6.9 | 72 | 9.1 | 10.3 | ---- | 100 |
| | HP Steam | 9.1 | 110 | 9.3 | 10.5 | ---- | 122 |
| Package Boiler | Blow Down | 5.8 | 8.6 | 9.1 | 9.2 | ----- | 1.2 |
| | HP Steam | 7.7 | 10 | 9.3 | 9.5 | ----- | 2.1 |

## History of Internal leakage in W.H.B condensate samples

| Tag Name | Conductivity | PH | $NH_3$ |
|---|---|---|---|
| Ammonia Compressor 309 | 46 | 10 | 33 |
| Synthesis Compressor 307 | 46.7 | 10 | 33 |
| Process Air Compressor 302 | 47 | 10 | 33 |
| $CO_2$ Compressor 320 | 47 | 10 | 33 |
| Generator 385 | 47 | 10 | 33 |



## History of Internal leakage in W.H.B

| Tag Name | Conductivity | PH | $NH_3$ |
|---|---|---|---|
| Condensate tank 329D001 | 42 | 9.4 | 26 |
| Condensate from Steam Drum 329D005 | 28 | 9.3 | 12 |
| Condensate Return from Compressor | 47 | 9.9 | 26 |

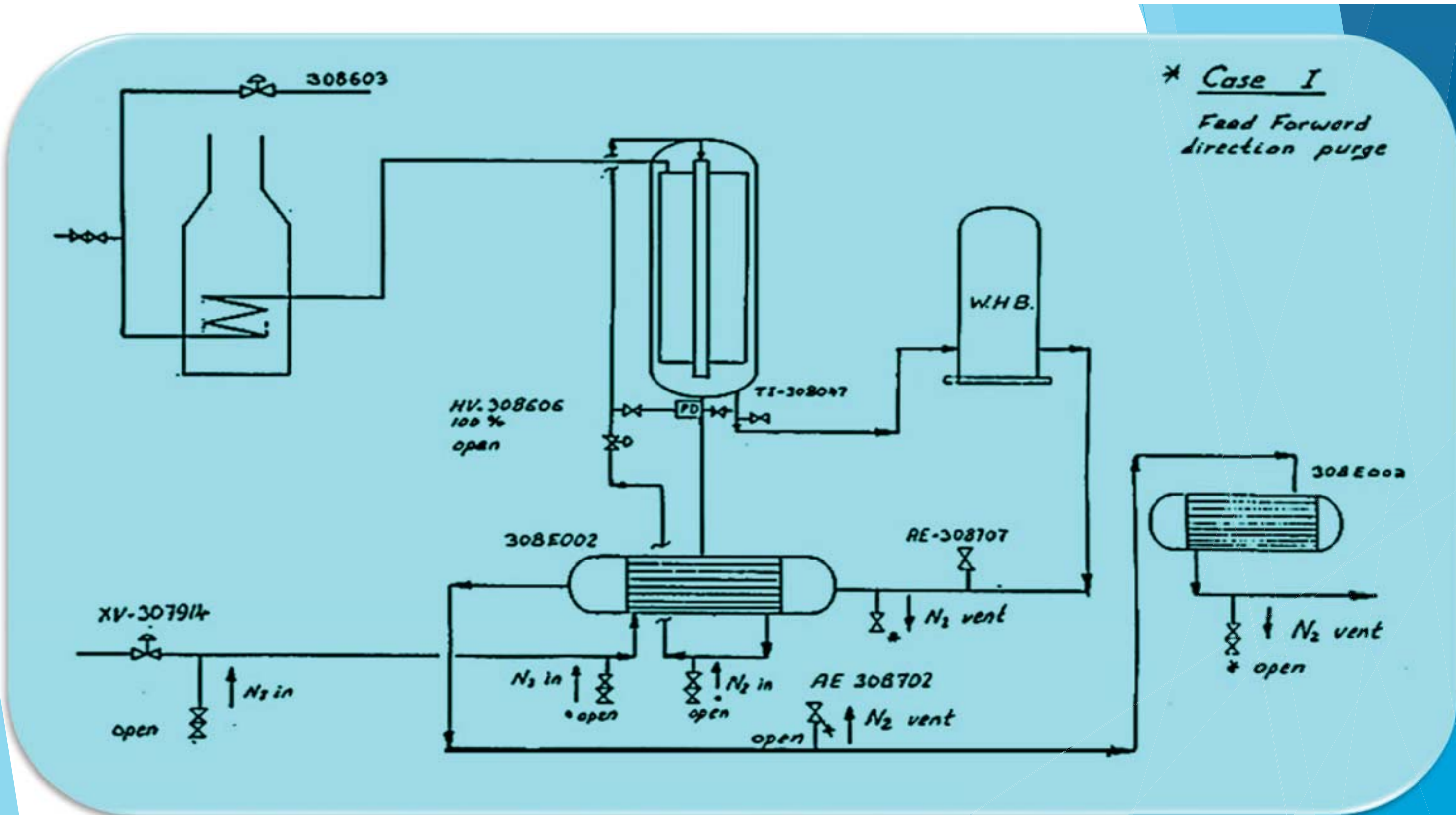
# The steps of preparation to Repair the W.H.B

1) During shutdown of the synthesis loop , at 120 bar cooling down for Ammonia converter & W.H.B was done by opening Quench valves HV 308604 & 605 for about 4 hr. steam pressure was kept lower than synthesis loop pressure.

2) Depressurize the synthesis loop gradually, at 20 bar transfer $NH_3$ from ammonia separator & flash drum to ammonia storage tank, then continue decreasing Syn. loop pressure till 3 bars.

3) $N_2$ purge in the forward direction of gas flow and vent through the drain valves, the purge should have done first for about 8 hr. and samples should be taken every 1hr.





# ***The steps of preparation to Repair the W.H.B***

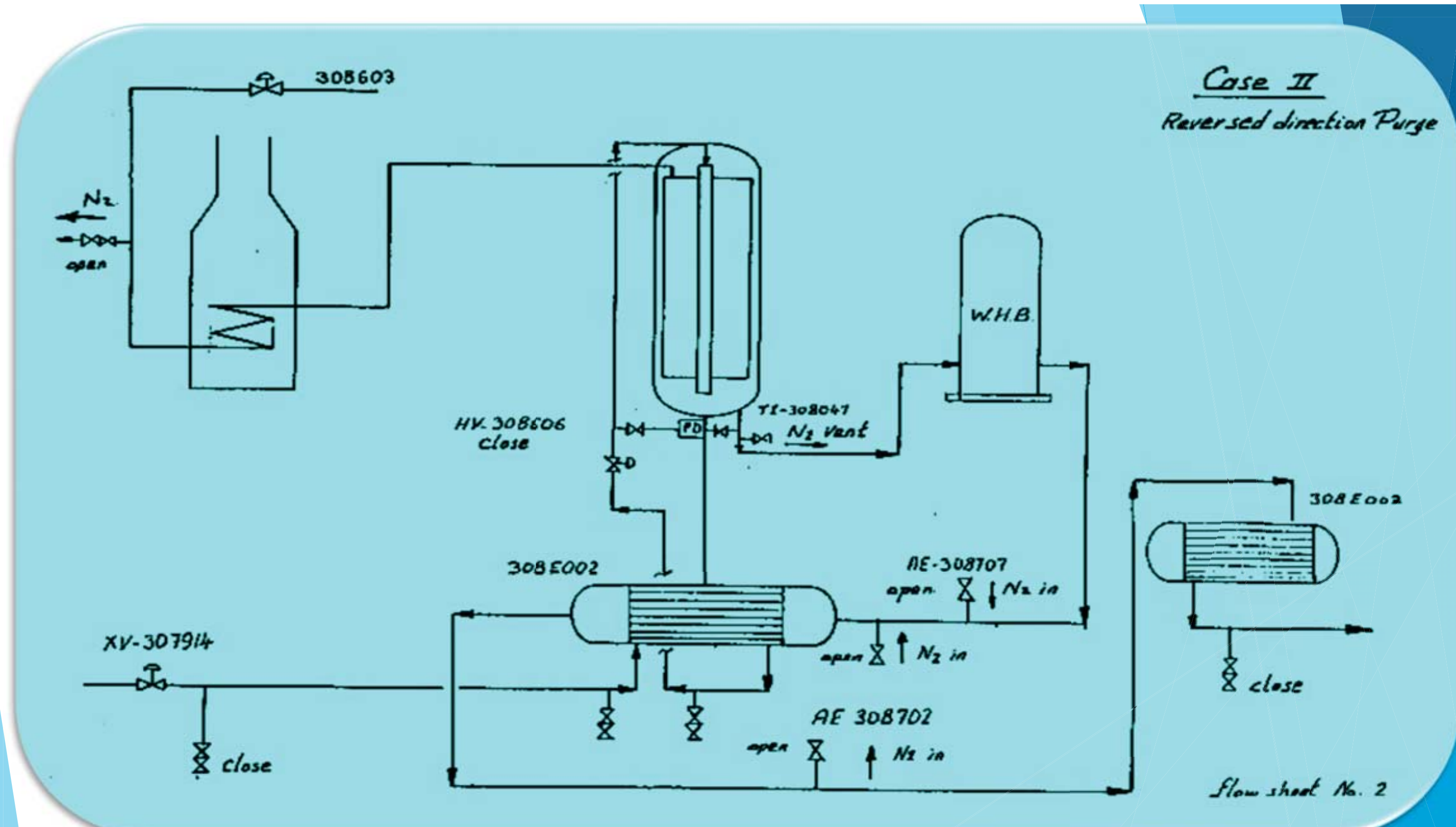
4) After the analysis of the last two samples showed constant value at the end of forward direction purge, then, $N_2$ purge in the reverse direction started for 8 hr.

5) Take samples every 1 hr.

6) Cooling down of W.H.B by means of B.F.W at 120 $^0$C ,then using deionate water at 25 $^0$C for about 10 hrs.

7) Dismantle the thermo well of gas exit Ammonia converter to vent $N_2$ and erect a manual valve on this point,Sampling from this Ti is an indication for the gas inside waste heat boiler.





## The steps of preparation to Repair the W.H.B

7) **During cutting the lower weld seal of waste heat Boiler:-**

- Put $N_2$ hose on Ti-308049 (exit converter) and crack it open.
- Take samples from the drain of PDI-308206 ($H_2$ & $NH_3$) must be Nil.
- Exit $N_2$ will be from drains of start up heater.
- During cutting $N_2$ hose must be directed with small flow till the end of cut.

## The steps of preparation to Repair the W.H.B

- The cutters and welders should wear special safety clothes.
- Cut about 3-4 Cm of the welding and take measurements for $H_2$ & $NH_3$.
- If the measurements are Ok open more than one $N_2$ hose and continue cutting to 30-40 Cm and stop for more measurements.
- Then continue cutting.
- Remove the internal expansion joint connected to the cone, and erect a blind flange inside the waste heat boiler on the gas header outlet the converter.
- Erect $N_2$ hose with PI indicator on the gas header outlet the converter to adjust the $N_2$ pressure at 0.3 bars inside Ammonia converter.


## Repair Procedure:-

- Detecting the defected tubes in the waste heat boiler specially the hot inlet side by filling.
- Removing the ferrules of the failed tubes.
- Enlarging the Secondary tube sheet to insert the plugs.
- Insert the tube plugs up to the primary tube sheet.
- Preheating before welding and weld plugs to the primary tube sheet.
- Annealing for the welded plugs tube sheet.

## Repair Procedure:-

- Make a rolling expanding for the plug to depth approximately 2/3 of the tube sheet thickness.
- Inspection for the welded plugs.
- Hydraulic test up to 120 bars and holding time for half an hour.
- Welding the cover of the enlarging part in the secondary tube sheet.
- Welding the cover of the outer diaphragm disk, $N_2$ flow must be opened with continuous measuring the explosion mixture.
- Pressure test must be done by filling the shell with deionate and increasing the pressure to 40 bars.

## The Steps To Close The Waste Heat Boiler:-

1) Erect the cyclone.
2) Put $N_2$ hose at the point of PDI-308206 to protect Ammonia converter.
3) Remove the blind flange and erect the_expansion joint.
4) Open the $N_2$ hose from gas-gas heat exchanger to the waste heat boiler and take analysis of $H_2$&$NH_3$.
5) When $H_2$&$NH_3$ analysis approximately Nil. , then put the disk and crack open the $N_2$ from PDI-308206 and start welding with continuous $H_2$&$NH_3$ analysis.

| start | end | no. of plugged tubes |
|---|---|---|
| 3/6/2003 | 3/13/2003 | 7 |
| 4/13/2003 | 4/17/2003 | 2 |
| 5/26/2003 | 5/31/2003 | 15 |
| 7/5/2003 | 7/8/2003 | 10 |
| | | total 34 tubes |

***The waste heat boiler leaking repeted five times and total plugged tubes were 34 tubes from a total of (400) tubes

## Inspection by Eddy Current (EC):-

1. Inspection of the tubes was limited to a length of 250 Cm above the tube sheet.
2. Most defected tubes were found in the area between 129 Cm and 193 Cm above the tube sheet (in the area between tube sheet and the first baffle).
3. The leakage was caused by reducing the thickness from outside.
4. 17% of the tubes were defected by reducing the average wall thickness more than 50%.
5. All defected tubes are located in the inner pass of the exchanger (hot gas entrance and boiling zone).
6. In the outer pass (cold gas outlet water preheated zone)………No defect was found.

## Analysis of the problem and the expected reasons for the failure:-

- By Visual inspection by endoscope for the shell from the drain nozzles N 11 A/B, it was observed flakes of deposition from one side only at the tube sheet, which was magnetite deposits.
- The possible reasons for the tubes failure of the synthesis loop waste heat boiler is not very clear but most of the corrosion is found under the baffle plate of the hot side.
- The steam blanketing for inlet tubes led to drying and wetting for the outer surface of the tubes, natural recirculation and this phenomenon led to crack the passive layer ($Fe_3O_4$) and these continuous cycles led to loss the tube thickness and finally failure .
- Hot gas entrance due to inclination in the inlet tube.

## Actions for prolong the life of the waste heat boiler

1) The pressure test was carried out at lower pressure than recommended (40 Bar) to save the weak tubes from leakage.
2) At any shut down or start up for the synthesis loop the pressure drop between tube side and shell side was restricted to keep it at lower as possible.
3) Increase the blow down rate to maximum.
4) Take complete analysis from N6 every week

# The Decision for ordering a new waste heat boiler

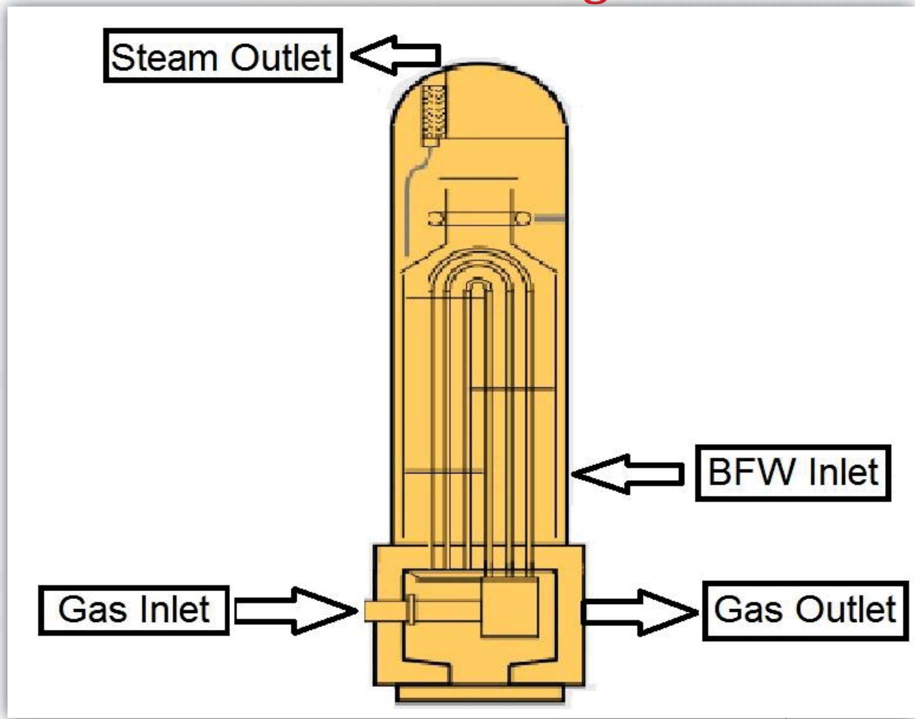
With comparing production losses, money paid for the temporary shell, and the expected risk with adjustment , with the price of the new shell ,it was decided to order a new complete waste heat boiler with the new modification in the:-

- Hot gas inlet
- Number and height of the baffles of the inner pass

The new W.H.B


The old W.H.B

# New WHB Design




# Procedures for changing waste heat boiler

1) N2 purge in the normal direction of the gas flow about 8 hr.

2) N2 purge in reverse direction also about 8 hr.

3) Cutting the weld seal in the gas inlet the waste heat boiler and also the gas line outlet

4) After the cutting, two flanges with N2 hose were erected to gas gas heat exchanger inlet line and outlet converter line.

# ***Procedure to clean the new waste heat boiler***

## ***Boiling Out***

## The first boiling out

A) Fill waste heat boiler with Boiler feed water to normal level (60%) and the vent of the waste heat boiler must be opened and add 2 lit. hydrazine.

B) Prepare the chemicals in a tank:-
1- 30 kg. of caustic soda with concentration of 50%
2- 21 kg. of tri-sodium orthophosphate -12H2O with concentration of 97.5% 1.5 lit hydrazine

C) Inject the chemicals to waste heat boiler and then heat the water by using medium pressure steam.

## The first boiling out

D) Increase the temperature by 50 C/ hr.

E) Adjust the pressure in waste heat boiler at 12 bar by closing the vent

F) After 12 hr. the first boiling out is finished

G) The steam must be close and drain the waste heat boiler from N11A/Band be sure that the vent is fully opened.

H)After finishing the drain of waste heat boiler it must be pressurized by N2

## Boiling Out W.H.B Analyses

### Boiling Out W.H.B

**Using Alkaline Trisodium phosphate**

**Sample from Tank of chemical additives**

| pH | %NaOH | $N_2H_4$ mg/l | $PO_4$ mg/l |
|---|---|---|---|
| 13.1 | 1.6 | 140 | 3000 |

**Sample from Rinsing WHB with BFW**

| pH | $SiO_2$ mg/l | Cond µs/cm | Turbidity NTU | Fe mg/l | $KMnO_4$ Cons. (mg/l) |
|---|---|---|---|---|---|
| 8.3 | 0.1 | 44 | 152 | 18 | 12 |

**Boiling Out WHB at 12 bar (1st stage)**

| Date | Time | pH | Fe mg/l | $N_2H_4$ mg/l | $KMnO_4$ Cons. (mg/l) | $PO_4$ mg/l | TSS mg/l | $Na^+$ mg/l |
|---|---|---|---|---|---|---|---|---|
| 30/9/2004 | 14:30 | 12.4 | 15 | 16 | 85 | 150 | 4.0 | 900 |
| | 18:30 | 12.4 | 10 | 12 | 90 | 170 | – | |
| | 24:00 | 12.3 | 8.0 | 12 | 100 | 190 | 4.0 | |

**Sample after flushing with BFW**

| Date | Time | pH | Fe mg/l | $N_2H_4$ mg/l | $KMnO_4$ Cons. (mg/l) | $PO_4$ mg/l | $Na^+$ mg/l |
|---|---|---|---|---|---|---|---|
| 1/10/2004 | 8:30 | 10.8 | 0.8 | 1.2 | 18 | 39 | 42.7 |

# The second boiling out

1 - The same 4 steps in the first boiling out.

2 - Adjust the pressure in waste heat boiler at 16 bar by closing the vent and adjust the temp. at 200 C°.

3 - The vent of waste heat boiler opened fully every 30 min. for 5min.

4 - After 12 hr. the boiling out was finished

5 - The steam must be closed and drain the waste heat boiler from N11A/B. and be sure that the vent is fully opened.

6 - After finishing the drain of waste heat boiler it must be pressurized by N2 .

# Boiling Out W.H.B Analysis

**Boiling Out WHB at 16 bar ($2^{nd}$ stage)**

| Date | Time | pH | Fe mg/l | $N_2H_4$ mg/l | $KMnO_4$ Cons. (mg/l) | $PO_4$ mg/l | TSS mg/l | $Na^+$ mg/l |
|---|---|---|---|---|---|---|---|---|
| 1/10/2004 | 10:45 | 12.2 | 0.6 | 25 | 127 | 290 | 2.0 | 1000 |

## ***Flushing the waste heat boiler***

1 - Open the waste heat boiler vent fully.

2 - Fill the waste heat boiler with boiler feed water and then drain it under $N_2$ pressure.

3 - Repeat the flushing of waste heat boiler and take analysis

# ***Conclusion***

- Since the waste heat boiler is one of the vital equipment in the ammonia plant, so it should be taken in consideration during design, precommissioning, and normal running of this equipment.
- During design, the number of baffles, its height and distribution at the evaporation zone should be carefully calculated to avoid the concentration of the heat load at a certain zone.
- Gas inlet pipe should be carefully treated in the design step to prevent heat localization.
- During precommissioning, the boiling out of the waste heat boiler should be carefully handled, cleaning and flushing with measuring the pH should confirm that the equipment is free from any chemicals that are used during the boiling out.

# With our best wishes

Hosam Naiem

Process Waste Heat Boilers
Integrity and Reliability
Qatar : 01-03 December 2014

# Primary Waste Heat Boiler Failure Analysis Repair Methodology and

Ahmed Al-Mulhim
ALBAYRONI
Saudi Arabia

# PRIMARY WASTE HEAT BOILER

# FAILURE ANALYSIS
# REPAIR METHODOLOGY AND REPLACEMENT

ABSTRACT:

After eight years of trouble free operation, hot spots were noticed on the inlet channel of primary waste heat boiler of Ammonia Plant. Rightly diagnosed failure and timely shutdown helped in averting the serious consequences.
This expensive boiler is one of the most critical equipment because of its severe operating conditions, unique thin tube sheet design supplied by limited designers, difficult repair and long delivery period.
Here are discussed the failure analysis, repair methods adopted, post failure operating experience with couple of repeated failures, few design modifications in new boiler, removal/installation procedures and custom made alkali boil out procedure. Also briefed is the unique core tube philosophy conceived and adopted in this boiler on its own by ALBAYRONI.

## INTRODUCTION:

Al Jubail Fertilizer Co. (ALBAYRONI) operates a 1000 MT/D nameplate capacity Kellogg design ammonia plant at Al-Jubail, Saudi Arabia. In ammonia plant, Primary waste heat boiler (101-C), located at the downstream of secondary reformer, is Borsig make, fire tube type horizontal exchanger. This boiler had been operating satisfactorily since commissioning in 1983 and no abnormality was observed in operation or regular inspection until 1990. As a first abnormality, the hot spot was noticed on the inlet channel in February 1991. No one knew then that, it was the beginning for a two-year long trouble full period for ALBAYRONI.

## BOILER DETAILS:

The waste boiler was designed to cool reformed gas from 996°C to 371°C and produce high-pressure steam at 104 bara. The boiler is illustrated in Figure-1 and main specifications are furnished in Table-1.

The Shell is made of SA516 Gr 70 and tubes of SA 213 T12. The exchanger has an internal bypass tube with control valve at cold end to control the outlet temperature. The SA387 Gr 12 CI 2 tube-sheet is protected from erosion and collapse by 5mm thick incoloy 800H liner. The hot gas is directed into tubes through the refractory by incoloy 800H ferrules. SA387 Gr CI 2 alloy steel inlet channel is lined with two layers of refractory material, 96% bubbled alumina castable and 25% alumina insulating castable. The principal feature of this waste heat boiler is its thin reinforced tube sheets.

Another important feature of this waste heat boiler is its core tube design. The original boiler purchased in 1983 was without core tubes. But, during commissioning in 1983, repeated severe fouling was observed inside the tubes and the tubes at the cold end. This was attributed to the substantial velocity drop from hot end to cold end, which in turn was due to equivalent reduction in temperature. To overcome this problem, during commissioning stage only, in house developed and designed core tubes were inserted from cold end side to increase the velocity at cold ends. Process licensor as well as boiler manufacturer approved this modification. The core tubes were 6 meter long 1/2” SS304 sch.40 pipes.

INCIDENT:

Ammonia plant was running at 110% load. As usual, 101-C inlet temperature was conservatively maintained at 930-940 degC, much less than design fluid temperature 996 degC. On February 10, 1991, during the normal inspection, a hot spot was noticed on the inlet channel of Primary Waste Heat Boiler (101-C).

At the area of hot spot, the green pyro paint turned into white, indicating temperature in excess of 480$^{o}$C. Thereafter, temperatures were regularly monitored by infrared pyrometer 'HEATSPY' and were found in the range of 520-590$^{o}$C. Steam Cooling arrangement was provided to cool the hot spot area. Infrared thermography was also carried out to confirm the temperature and to determine the area of damage.

Based on the thermography results, the plant was shut down on February 23,1991 to inspect and repair 101-C.

OBSERVATION:

On opening of manhole of inlet channel, following were observed.

i A pool of water was found in channel, indicating the tube leakage. At hot spot area, bottom layer of refractory was totally missing and cracks were found on surrounding areas, towards shell.

ii At bottom of the channel, the refractory was found completely broken disintegrated and soaked in water

iii Near Hot Spot Area on the tube-sheet, incoloy 800H liner was completely damaged, ferrules in tubes were also damaged. Some ferrules were dislocated from their positions and found at bottom of the channel. Castable covering the tube-sheet was completely damaged, thus exposing the tubesheet to hot gases. Cracks on tube-sheet were observed in both longitudinal and transverse directions. At some places, cracks were found throughout the thickness of the tube-sheet.

iv Opposite to manhole and also on top side of channel cover, refractory was found broken and shrouds were exposed.

v By-pass tube was found cracked at tip at both inlet and outlet channel ends. The incoloy 800H liner of by pass tube was also found cracked at one location.

FAILURE LOGIC :

**A. Refractory and Tubesheet Failure :**

It was established that the problem was initiated by the tube leak from the bottom row towards manhole side. The release of high-pressure boiler feed water caused erosion and thermal shocks to refractory. Due to complete failure of refractory, shell as well as tube-sheet, both of alloy steel and not compatible at 931$^{o}$C, started cracking. Tube-sheet had completely cracked at some places and shell cracked up to the depth of 12mm.

Crazed pattern of cracks on tube-sheet indicate that it had been subjected to thermal fatigue, i.e. alternate heating and cooling cycles.

**B. Tube Failure**

Following are the frequently contributing factors for tube failures in similar service

1. Dry Out Phenomenon
2. Water Quality

1. **The dry out phenomenon was ruled out because of following reasons:**
   i. Generally, the dry out phenomenon would result in the failure of tubes in top rows. Whereas, in this case the tubes has failed only in bottom rows.
   ii. Although, coincidentally and emergency shutdown was faced only one month before this incident, no water loss or steam drum low level operation was observed during this emergency and also during normal operation.
   iii. In addition to 101-C, one gas fired water tube type auxiliary boiler and another fire tube type waste heat boiler are also connected to the same steam drum. And no abnormality was observed in any of these other two boilers.
2. **Water Quality**

   Boiler Water quality was believed to be the most probable cause for following reasons.
   i. Most of the plant operators generally believe that the boiler feed water quality is controlled and monitored strictly within the specified limits in their plants. In spite of, the quality of water fed to the boilers has been frequently found to be a major contributory factor to many of such failures.
   ii. Boiler water irregularities can cause deposits, which get collected at bottom of the shell in a horizontal fire tube type waste heat boiler. This leads to an aggressive under deposit corrosion, especially in high heat flux areas, i.e. at tube inlet side. Failure in bottom row of tubes also explains this phenomenon.

Boiler manufacture also believed this to be the most probable reason. Later, it was known that similar failures are not unusual after several years of services.

To avoid under deposit corrosion problem, periodic chemical cleaning from waterside may be considered.

REPAIR WORK:

The tube sheet was very badly damaged by hot gases and cracked in both longitudinal and transeverse directions near hot spot area. At some places, grinding was carried out to find the depth of cracks, which were found throughout the thickness of the tube-sheet. Due to this it was decided to put a patch on tube-sheet covering 14 tubes and filler weld with the tube-sheet at both sides i.e. inlet and outlet side.

On inlet channel shell, depth of cracks were determined by Ultrasonic testing and found to be 12mm. The same was also repaired by complete grinding followed by welding. After welding, it was inspected by penetrant test and post-welding heat-treating (PWHT) was carried out.

After PWHT, in order to do Hydro test, boiler drum 101-CF and shell of 101-C were filled with water. With the head pressure of @1.5Kg/cm$^2$, patch welding at inlet and outlet channel over plugged tubes started leaking from heat affected zone.

After draining out water from shell side, gouging was carried out from leaking area followed by welding. Inspection by penetrants and PWHT was carried out.

After PWHT, leak test was carried out by air at 5.0psi. Further, it was leak tested by water at 30kg/cm2 for 30 minutes. After leak test, refractory was replaced in bottom half and on the tube-sheet. Incoloy 800 liner was placed on tube-sheet and followed by curing of refractory.

POST REPAIR EXPERIENCE:

The significant difference between pre- and post failure operation was in boiler water control limits. For some parameters, the control limits were made stricter by following the VGB guidelines. These control limits are furnished in Table-2. However with the kind of damage this boiler material had suffered and the severe operating conditions it was undergoing, long run future reliability was very much in doubt. Early replacement was recommended.
Not unexpectedly, the failure repeated after five months of operation on 18 August 1991. This time extra cautious operating staff identified the failure immediately, thanks to the thermocouple located at the bottom of the inlet channel. This immediate symptom was sudden drop of @ 23-30 degC in inlet temperature, presumed as the result of water spillage at bottom side. This time, two tubes were found leaking, again in bottoms rows of tubes but little away from fist failure.

The plant was restarted with no further change in operating conditions. To our disappointment, the boiler failed within two months of operation on 07 October 1991, by displaying the same symptoms. This time, nine tubes had leaked in the bottom most row. Including this, total blocked tubes were now @7%. The tube failure layout is placed at Figure-2.

The plant load reduced to 100% and the inlet temperature was brought down to 900°C. With these changes, the boiler did not fail anymore till the replacement in January 1993.

NEW BOILER:

Right form the first failure observations; it was decided to order a new boiler at the earliest, based on the factual saying "A single failure can easily result in a profit loss equal to the total cost of the boiler". Also important was that this specially designed boiler is supplied by very few fabricators and with long delivery time.

The same design and manufacturer were selected based on the following reasons.

1. This boiler has performed satisfactorily at least for eight years of operation.
2. More number of boilers, of same make and design, compared to the nearest competitor were operational with satisfactory performance.
3. The alternative design required many changes in down comer and riser piping with the common steam drum for other two boilers; it looked unwise to go for outright changes.

The new boiler was purchased with some, but not significant changes. The new and old boiler specifications are compared in Table-1.

REPLACEMENT AND CHEMICAL CLEANING:

This particular equipment is situated in a very congested layout. To replace this equipment, structures and high pressure pipe lines had to be cut and re welded.

The replacement job was completed within thirty-five days. These included the four days of chemical cleaning operation.

As described earlier, this boiler is part of a wide network of steam/ bfw pipelines and equipment's. The chemical cleaning of other equipment's/ piping was not required, rather preferred to avoid. To meet this requirement, the chemical cleaning of 101-C only was carried out by inserting the chemical circulation hoses into the riser openings of 101-C through steam drum manhole. The multiple outlets were taken from the blowdown valves available at the bottom of 101-C.

## CONCLUSION:

Severe operating conditions and special design features provide little operational flexibilities and demand very strict water quality control. Statistically, failure frequency of such kind of waste heat boilers is high and post-repair life is very low. Inspection including tube thickness measurement in every turnaround is highly recommended. It is advisable to order the new boiler at the earliest as delivery of this boiler is very long and "A single failure can easily result in a profit loss equal to the total cost of the boiler"

# ATTACHMENTS:

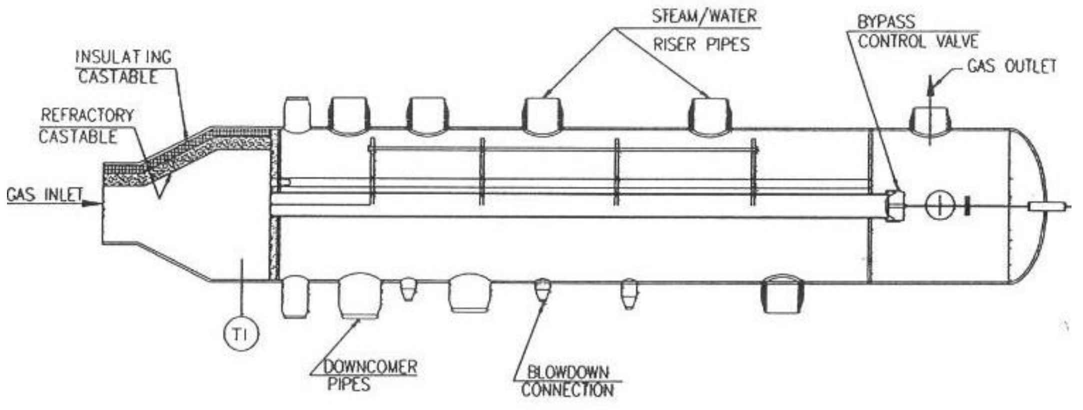
## TABLE-1: 101-C SPECIFICATIONS

| SL.# | PARAMETER | NEW 101-C | | OLD 101-C | |
|---|---|---|---|---|---|
| | | SHELL | TUBE | SHELL | TUBE |
| 1 | Fluid | BFW / Steam | Process Gas | BFW / Steam | Process Gas |
| 2 | Fluid Flow, Kg / Sec (100% Load) | 558 | 41.76 | 558 | 41.76 |
| 3 | Temp. In / Out, Deg. C | 314 / 314 | 996 / 371 | 314 / 314 | 996 / 371 |
| 4 | Operating Press., bar (E) | 103 | 30.3 | 103 | 30.3 |
| 5 | Circulation Ratio | 12 : 1 | - | 12 : 1 | - |
| 6 | Heat Duty, MM Kcal / Hr | 51.5 | | 51.5 | |
| 7 | Surface Area, M2 | 461.3 | | 472 | |
| 8 | Design Pressure, Bar (E) | 118 | 34 | 118 | 34 |
| 9 | Design Temp., Deg. C | 343 | 1010 In / 480 Out | 343 | 1010 In / 480 Out |
| 10 | No. of Tubes | 460 | | 420 | |
| 11 | Tube Length, MM | 8,450 | | 8,450 | |
| 12 | Tube OD / THK, MM | 38 / 5 | | 42.4 / 4.5 | |
| 13 | Tube Pitch, MM | 51 / 91 | | 56 / 96 | |
| 14 | Shell OD / THK, MM | 2206 / 96 | | 2234 / 110 | |
| 15 | Tube Material | SA 213 T 12 | | SA 213 T 12 | |
| 16 | Shell Material | SA 302 GR C | | SA 516 GR 70 | |
| 17 | Tubesheet Material | SA 387 GR 12 CL 2 | | SA 387 GR 12 CL2 | |
| | Inlet Channel | | | SA 387 GR 22 CL2 | |
| | Outlet Channel | | | SA 387 GR 12 CL2 | |
| 18 | Bypass Pipe, ID MM | 252.4 | | 265 | |
| 19 | Core Tubes | 2.65 M : 16 MM ϕ SS<br>2.0 M : 12 MM ϕ SS | | 21.3 MM OD SS, 6 M LONG | |
| 20 | Refractory for Inlet Channel | Petrolite D40K (Reinforced) / Plicast LWI 22 R/G (200 MM) | | Plicast D40K / Plicast Petrolite (150 MM) | |
| 21 | Refractory for Tubesheet | Priblico 39K | | Plicast Petrolite 39K | |

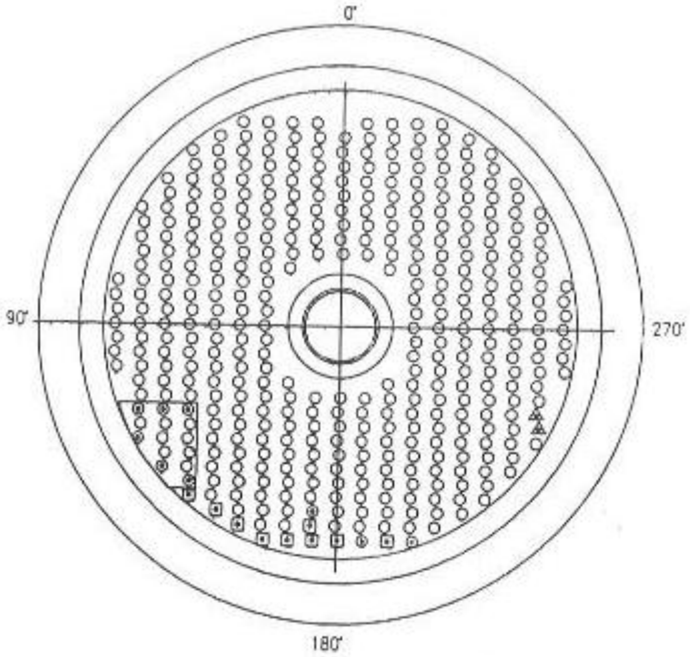
## TABLE-2: WATER QUALITY CONTROL LIMITS

| PARAMETER | UNIT | NEW LIMITS | OLD LIMITS |
|---|---|---|---|
| A. BOILER FEED WATER : | | | |
| pH at 25 deg. C | - | 9.0 - 9.6 | 8.8 - 9.2 |
| SiO2 | ppb | <10 | - |
| N2H4 | ppb | 20 - 100 | >20 |
| B. BOILER WATER : | | | |
| pH at 25 deg. C | – | 9 - 10 | 9.2 - 9.9 |
| Conductivity at 25 deg. C | us / cm | <50 | <100 |
| Sio2 | ppb | <300 | <1000 |
| Phosphate as PO4 | ppm | 2 - 6 | 5 - 10 |

## FIGURE-1: PRIMARY WASTE HEAT BOILER (101-C)



## FIGURE-2: TUBE FAILURE LAYOUT




| TOTAL TUBES (42.4odx4.5t): 420 | | | |
|---|---|---|---|
| NO. OF COVERED/PLUGGED TUBES | | | |
| SHUT DOWN | NO. OF TUBES | DATE | SYMBOL |
| 1ST | 17 | 10-3-91 | ⊙ ⊡ |
| 2ND | 2 | 25-8-91 | △ |
| 3RD | 9 | 10-10-91 | ⊡ |

Process Waste Heat Boilers
Integrity and Reliability
Qatar : 01-03 December 2014

# Summary of History of Waste Heat Boiler in Ammonia IV (E3205) -PIC


**Mohammed Folad**
**Plant Engineer**
**PIC**
**Kuwait**

# DAY 3: Wednesday December 0 3, 2014

# Waste heat recovery in fertilizer industry: OCP case study

Hamid Mazouz
Researcher

Abdelaaziz Ben El Bou
Production Manager

OCP SA
Morocco

## AFA Workshop on
## Process Waste Heat Boilers Integrity and Reliability

# WASTE HEAT RECOVERY IN FERTILIZER INDUSTRY: OCP CASE STUDY

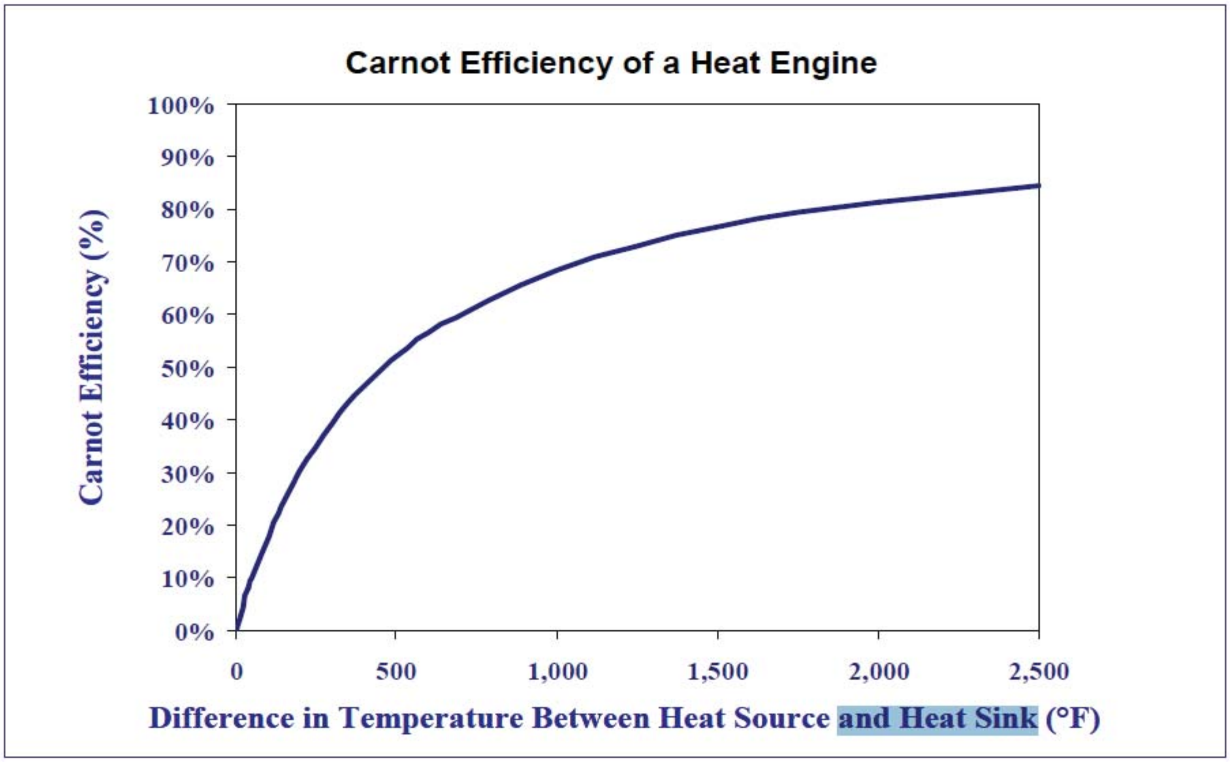
*H.MAZOUZ & A.BEN EL BOU*
*OCP SA*

Qatar : 1-3/12/2014

## THE FACT OF WASTE HEAT IN INDUSTRY

- Roughly one-third of the energy consumed by industry is discharged as thermal losses directly to the atmosphere or to cooling systems,
- These is the result of process inefficiencies,
- In USA it is estimated that between 20 to 50% of industrial energy input is lost as waste heat,
- Recovering waste heat losses provides an attractive opportunity for an emission free and lesscostly energy resource,
- Numerous technologies are commercially available for waste heat recovery, However, in many cases heat recovery is not economical or even possible,

# WASTE HEAT RECOVERY (WHR) FEASIBILITY AND EFFICIENCY






# WASTE HEAT RECOVERY OPPORTUNITY

**Temperature Classification of Waste Heat Sources and Related Recovery Opportunity**

| Temp Range | Example Sources | Temp (°F) | Temp (°C) | Advantages | Disadvantages/ Barriers | Typical Recovery Methods/ Technologies |
|---|---|---|---|---|---|---|
| High >1,200°F [> 650°C] | Nickel refining furnace | 2,500-3,000 | 1,370-1,650 | High-quality energy, available for a diverse range of end-uses with varying temperature requirements<br><br>High-efficiency power generation<br><br>High heat transfer rate per unit area | High temperature creates increased thermal stresses on heat exchange materials<br><br>Increased chemical activity/corrosion | Combustion air preheat<br><br>Steam generation for process heating or for mechanical/ electrical work<br><br>Furnace load preheating<br><br>Transfer to med-low temperature processes |
| | Steel electric arc furnace | 2,500-3,000 | 1,370-1,650 | | | |
| | Basic oxygen furnace | 2,200 | 1,200 | | | |
| | Aluminum reverberatory furnace | 2,000-2,200 | 1,100-1,200 | | | |
| | Copper refining furnace | 1,400-1,500 | 760-820 | | | |
| | Steel heating furnace | 1,700-1,900 | 930-1,040 | | | |
| | Copper reverberatory furnace | 1,650-2,000 | 900-1,090 | | | |
| | Hydrogen plants | 1,200-1,800 | 650-980 | | | |
| | Fume incinerators | 1,200-2,600 | 650-1,430 | | | |
| | Glass melting furnace | 2,400-2,800 | 1,300-1,540 | | | |
| | Coke oven | 1,200-1,800 | 650-1,000 | | | |
| | Iron cupola | 1,500-1,800 | 820-980 | | | |
| Medium 450-1,200°F [230-650°C] | Steam boiler exhaust | 450-900 | 230-480 | More compatible with heat exchanger materials<br><br>Practical for power generation | | Combustion air preheat<br>Steam/ power generation<br>Organic Rankine cycle for power generation<br>Furnace load preheating, feedwater preheating<br>Transfer to low-temperature processes |
| | Gas turbine exhaust | 700-1,000 | 370-540 | | | |
| | Reciprocating engine exhaust | 600-1,100 | 320-590 | | | |
| | Heat treating furnace | 800-1,200 | 430-650 | | | |
| | Drying & baking ovens | 450-1,100 | 230-590 | | | |
| | Cement kiln | 840-1,150 | 450-620 | | | |
| Low <450°F [<230°C] | Exhaust gases exiting recovery devices in gas-fired boilers, ethylene furnaces, etc. | 150-450 | 70-230 | Large quantities of low-temperature heat contained in numerous product streams. | Few end uses for low temperature heat<br><br>Low-efficiency power generation<br><br>For combustion exhausts, low-temperature heat recovery is impractical due to acidic condensation and heat exchanger corrosion | Space heating<br><br>Domestic water heating<br><br>Upgrading via a heat pump to increase temp for end use<br><br>Organic Rankine cycle |
| | Process steam condensate | 130-190 | 50-90 | | | |
| | Cooling water from: | | | | | |
| | furnace doors | 90-130 | 30-50 | | | |
| | annealing furnaces | 150-450 | 70-230 | | | |
| | air compressors | 80-120 | 30-50 | | | |
| | internal combustion engines | 150-250 | 70-120 | | | |
| | air conditioning and refrigeration condensers | 90-110 | 30-40 | | | |
| | Drying, baking, and curing ovens | 200-450 | 90-230 | | | |
| | Hot processed liquids/solids | 90-450 | 30-230 | | | |

Source: US department of energy

## ENERGY PRODUCTION IN PHOSPHORIC ACID PLANT

- ❑ Phosphoric acid process uses phosphate and Sulfuric acid to produce phosphoric acid,

- ❑ Sulfuric acid processing is an exothermic process, the heat released is used for steam production and electrical power generation,

-70% recovered → to produce steam & to generate power

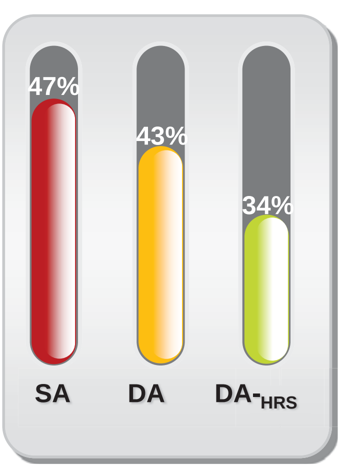
**-28%** → **lost by acid cooling**

**- 2%** → **lost by radiation**

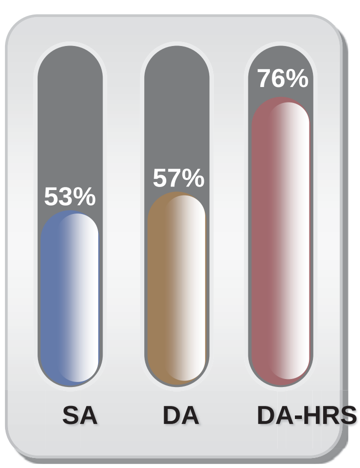


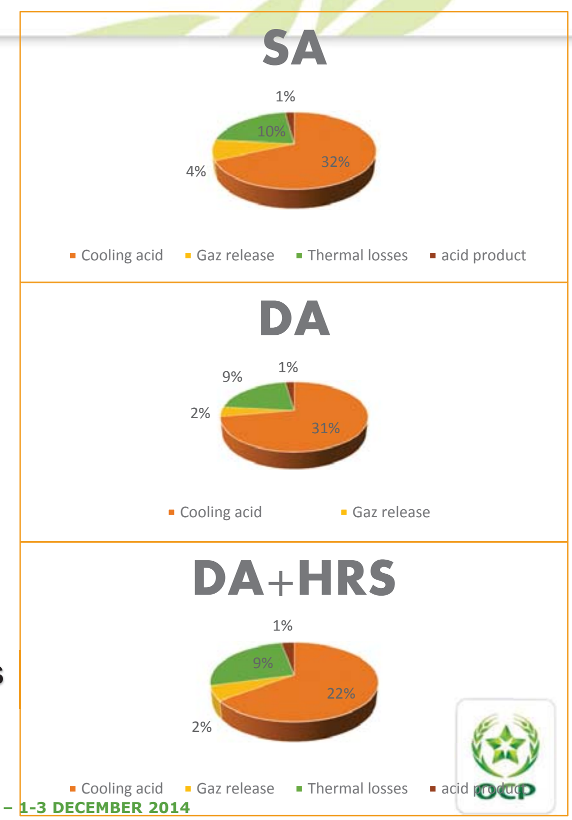
## PROCESS CONTACT ENERGY EFFICIENCY

**Energy waste**

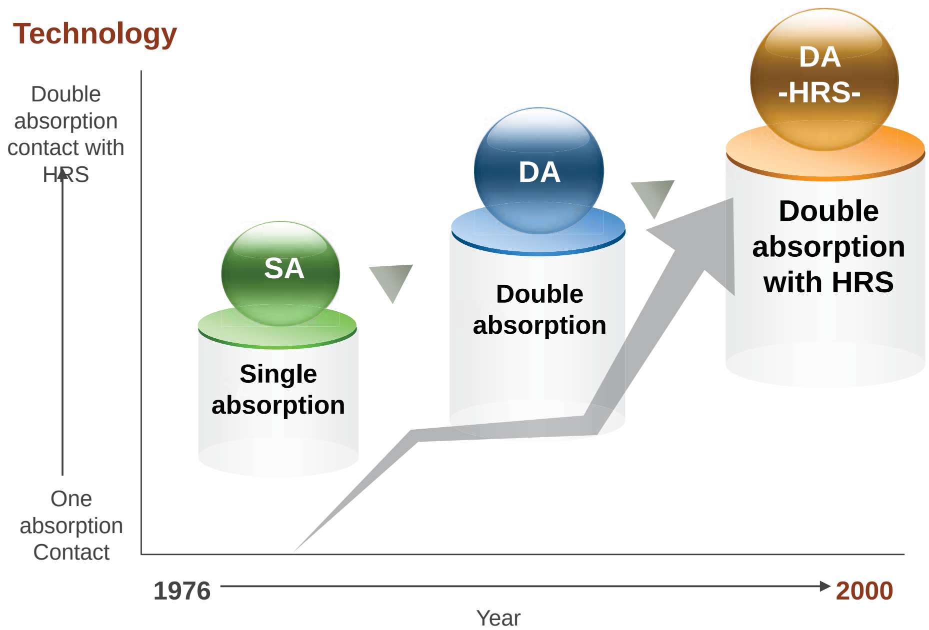



**Energy recovery**



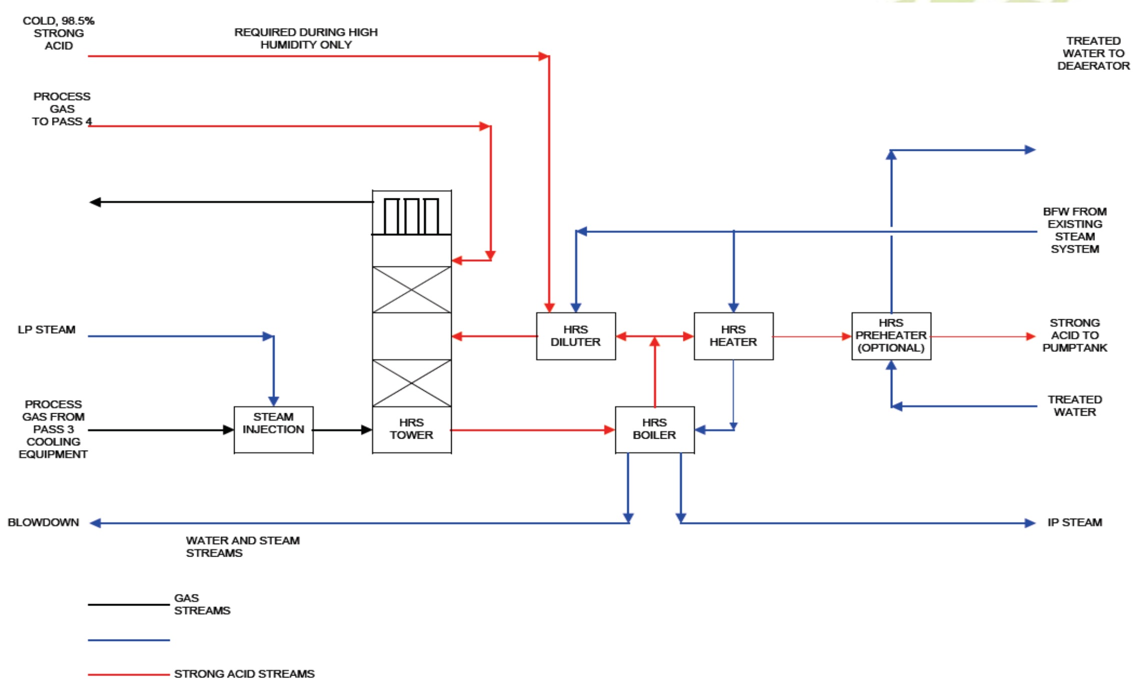



# EVOLUTION OF TECHNOLOGIES USED IN SULFURIC ACID PLANT FOR WASTE HEAT RECOVERY



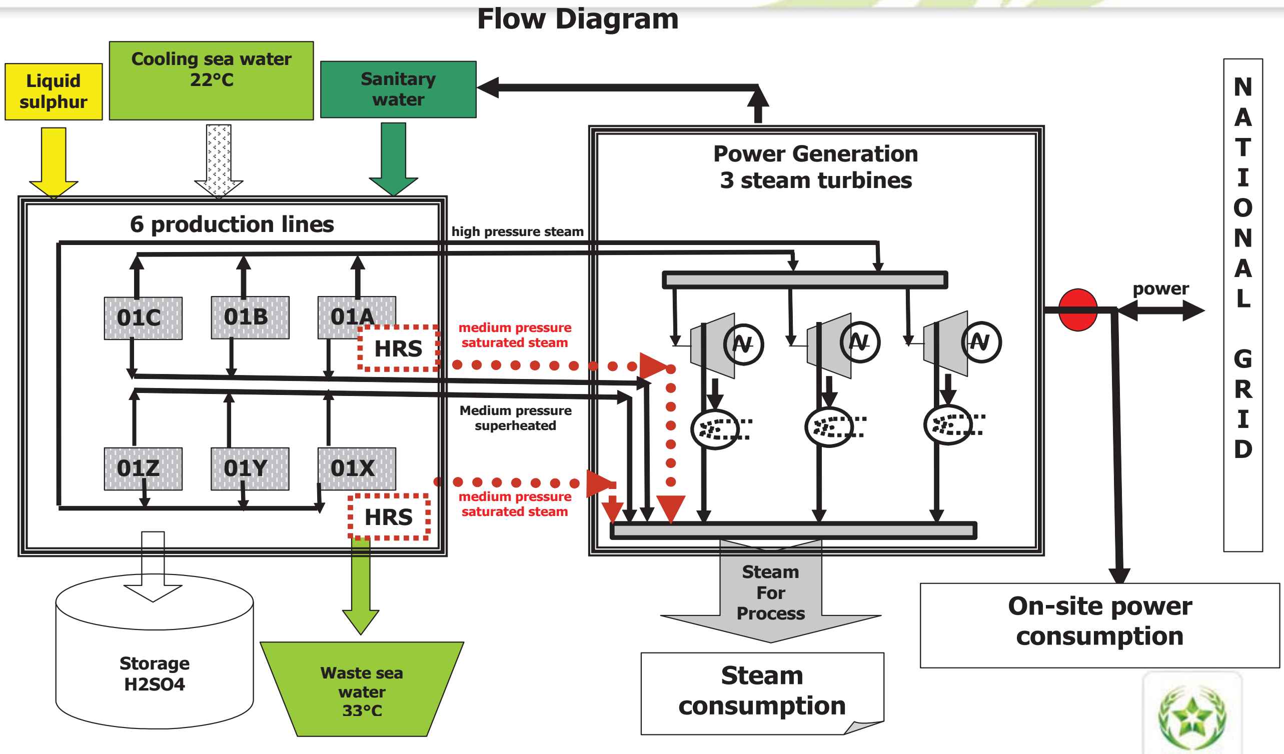



# 2 STAGE HRS FLOWSKETCH




Source: sulfur and sulfuric acid conference 2009

# (HRS) IMPLEMENTATION IN OCP SULFURIC ACID PLANT



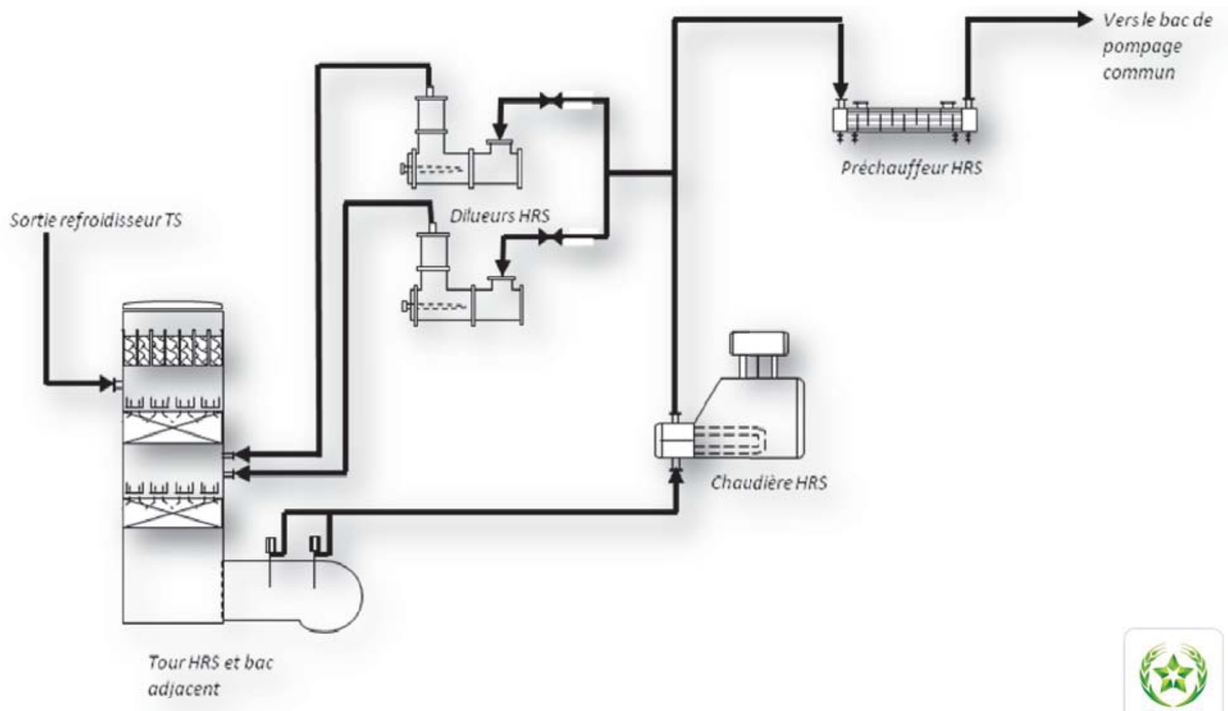



# PRODUCTION EFFICIENCY INCREASED WITH HSR

Installation of two heat recovery systems (HRS) in sulfuric acid unit that led to:

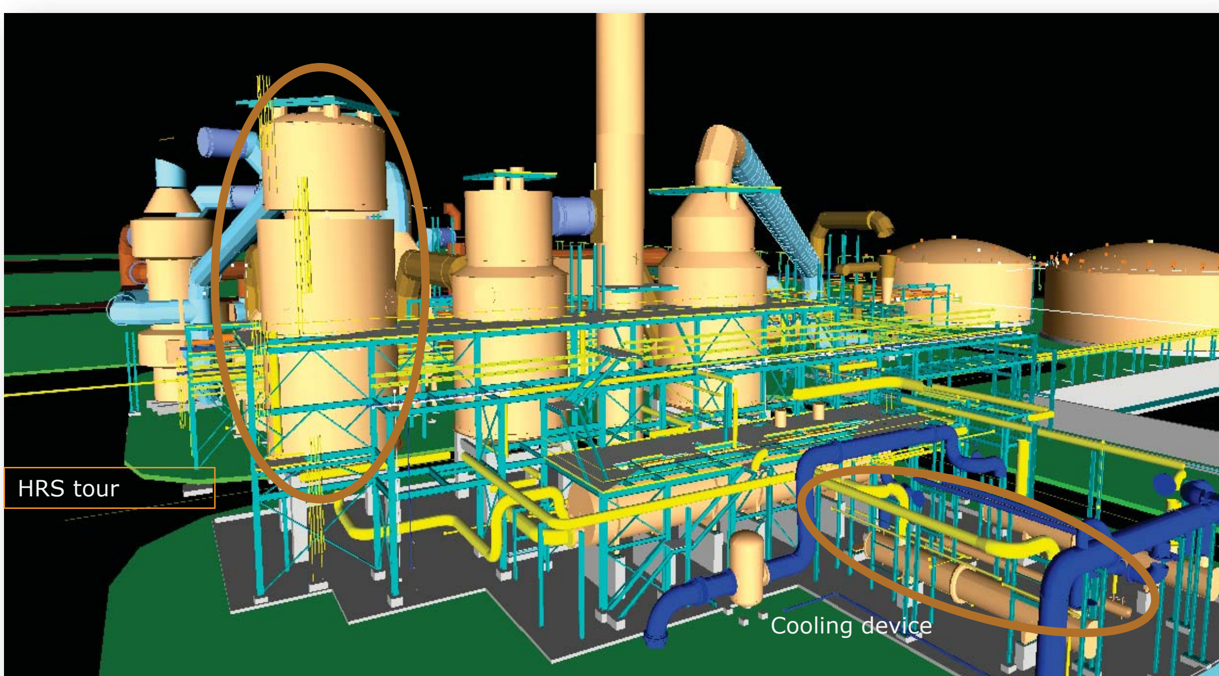
- ❑ Additional production of sat. steam : 50 t/hr at 9,5 bars
- ❑ Additional power capacity : 16 MW
- ❑ Reduction of atmospheric pollutants SO2, NOx, CO

## REPLACEMENT OF 2 UNIT (SA) BY 1 UNIT WITH HRS

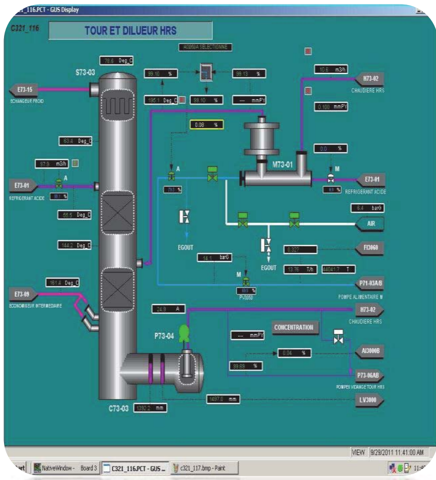


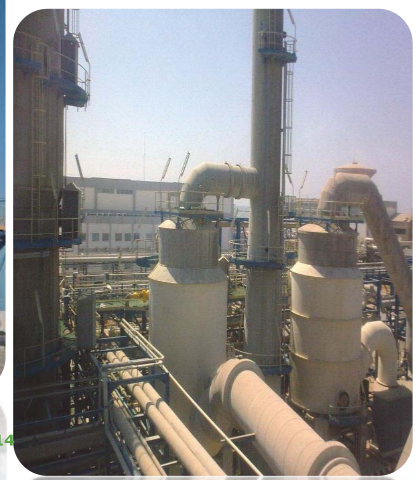



## THE NEW SULFURIC ACID UNIT WITH HRS SYSTEM



# CONSTRUCTION OF THE NEW SULFURIC ACID UNIT



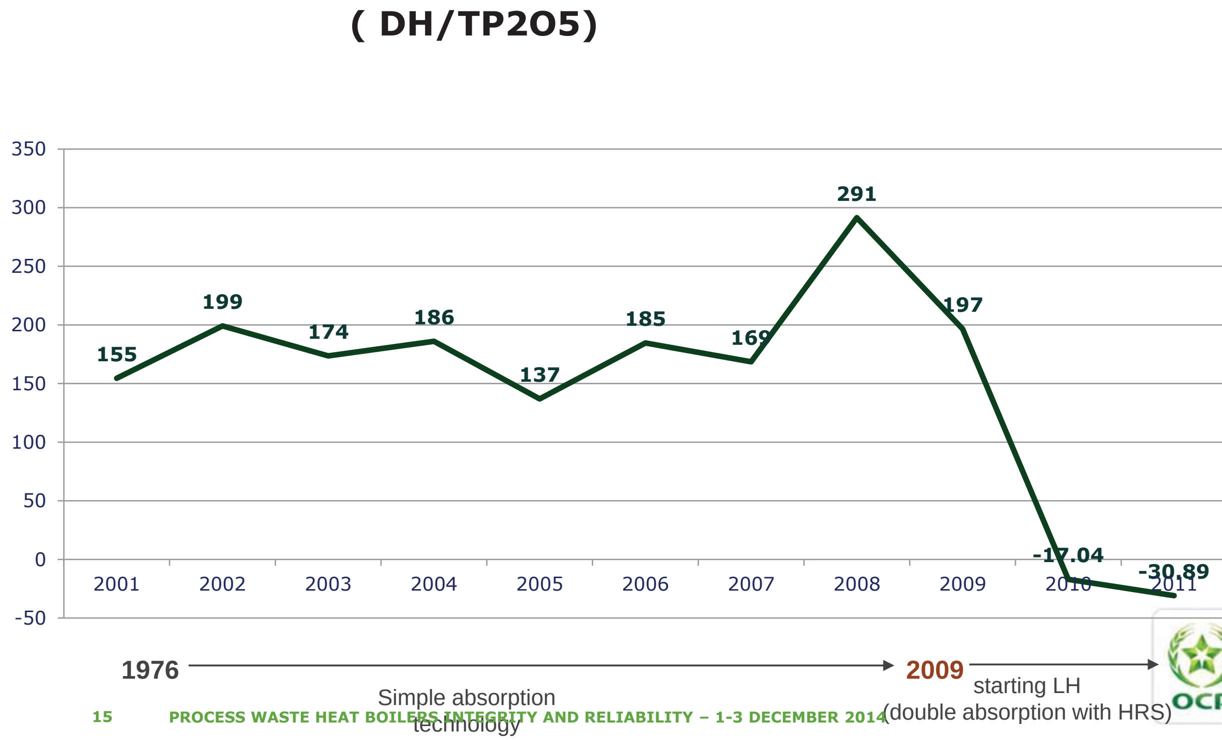





# PERFORMANCE OF THE NEW SULFURIC ACID UNIT

| | Ligne H | Ligne B & D |
|---|---|---|
| Technology | Double absorption avec HRS | Simple absorption |
| Starting date | 2009 | 1976 |
| Production capacity | 3410 TMH/J | 1500 TMH/J |
| Conversion yield | 99,7 | 98 |
| Specific production VHP | 1,19 | 1,11 |
| pecific production VBP | 0,47 | 0 |
| Emissions | ≤417ppm | ≤2000ppm |

## ENERGY COST REDUCTION WITH HRS SYSTEM






## CONCLUSION

- Recovering waste heat losses provides an attractive opportunity for an emission free and lesscostly energy resource.
- The mean factors that affect the heat recovery are: heat quantity, heat quality and temperature,
- The implementation of HRS in OCP sulfuric acid unit led to:
  - Increase in steam production,
  - Increase in power generation,
  - Decrease in gas emission $CO_2$ and NOx

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# Replacing of Waste Heat Boiler in Sulphuric Acid Plant


**Ibrahim Makhamreh**
**Plant Manager**
**JPMC**
**Jordan**

# Gas side corrosion of stack gas heat recovery economizer in oil-fired

**Osama KHALIL**

**Chemical Supervisor**

**APC**

**Jordan**

# AFA Workshop on Process Waste Heat Boilers Integrity & Reliability Doha, 2014

CASE STUDY on

## Gas side corrosion of stack gas heat recovery economizer in oil-fired high pressure steam boiler

**Arab Potash Company**
Power & Water Dept.

*Prepared by Eng. Osama Khalil/Power Plant Chemical Supervisor*

*Reviewed by Eng. Fuad Al-Zoubi, Power and Water Manager*

*INTRODUCTION*

*This is a case study carried out by APC to investigate a gas side corrosion problem that resulted in repetitive tube failures and a severe fouling occurring on economizer heating surfaces of boiler unit No.2 at its thermal power plant.*

*The study relied on physical examination of the economizer tube, field data, collected at various boiler loads, reviewing the performance data and the economizer and boiler design.*

*An evaluation has been done and solutions including immediate corrective actions and future more efficient alternatives are discussed and presented. The study presents description of the failure, possible causes and mechanisms followed by conclusions and recommendations.*

*The study concluded that the severe corrosion at the lower section of the economizer is due to sulfuric acid condensation and the heavy fouling on the economizer tubes is due to the present economizer configuration and arrangement that resulted in ineffective soot blowing*

*For immediate operation and in order to restore the boiler reliability in a short time, the corrosion was minimized by increasing the economizer feed water temperature from 138°C to about 170 °C with the consequence loss in the boiler efficiency*

*Future opportunities and alternatives to improve the boiler efficiency while controlling the fouling and corrosion problems were addressed and presented.*

**PROBLEM:**
APC cogeneration thermal Power Plant consists of 2 steam boiler units and one auxiliary steam boiler unit with a back pressure steam turbine and the according auxiliary systems

Boiler unit No.2 (SG4-Boiler) has a design capacity of 110 t/h process steam at 64 bar, 478°C. The boiler with first commissioning at 1982 was completely replaced in 2004. The economizer which made of carbon steel is a separate unit with plane casing and external reinforcement and external insulation. One year after commissioning, the economizer started facing repetitive tubes and bends ruptures in its lower part.

In addition to the corrosion and tube failures there was severe fouling occurring on the economizer heating surfaces, preventing efficient heat transfer to the economizer tubes, which resulted in a high flue gas exit temperature and hence a reduction in boiler efficiency and increase in fuel consumption.

**DATA GATHERING AND ANALYSIS**

Heavy fuel oil is fired in the boiler. The oil contains about 4.0 % sulfur by weight and also vanadium and potassium in ash. Feed water was originally supplied at 126 °C increased later to 138 °C from a deaerator operating at 2.4 kg/cm2a and further heated by steam in a HP heater.

The study relied on physical examination of the economizer tube, field data collected at various boiler loads, reviewing the performance data and the economizer and boiler design. The influence of fouling on the behavior of some operational parameters such as the pressure in furnace and pressure drop in economizer and pipe metal temperature, among others, has been verified.

An evaluation has been done and the solutions including immediate actions and the future long-term solutions are discussed and presented in this study.

## BOILER FEED WATER TEMPERATURE CONCERN

Combustion calculations and estimation of acid dew point was the starting point for the analysis of the problem.

The calculations and the analysis clearly indicated that the feed water temperature and hence the tube wall temperature in the inlet portions of the economizer were below the sulfuric acid dew point temperature, sulfuric acid was condensing on the economizer tubes. Hence the back end of the finned tube economizer were facing severe acid corrosion (see figure 1) and tube failures were occurring within weeks of repair/replacement


Figure 1: severe acid corrosion of economizer tube

## Combustion and Acid dew point Calculations

Combustion calculations and estimation of acid dew point is the starting point for the analysis of the problem. The following fuel data (table 1) was used as the basis:

Table 1: heavy fuel oil **HFO** analysis

| **Fuel Oil Analysis (% by weight)** | |
|---|---|
| Carbon | 84.19% |
| Hydrogen | 11.21% |
| Sulphur | 4.38% |
| Nitrogen | 0.22% |
| | 100.00% |

Table 2 shows the flue gas analysis on wet and dry basis in % volume at various excess air levels at an ambient temperature of 35℃ and 60 % relative humidity:

Table 2: flue gas analysis on wet/dry basis

| composition of flue gases | | | | | | |
|---|---|---|---|---|---|---|
| **Component** | **mole %** | **mole %** | **mole %** | **mole %** | **mole %** | **mole %** |
| | Wet | Dry | wet | Dry | Wet | Dry |
| % Excess Air | 10% | 10% | 15% | 15% | 20% | 20% |
| CO2 | 12.33% | 14.2% | 11.82% | 13.6% | 11.35% | 13.0% |
| SO2 | 0.24% | 0.28% | 0.23% | 0.26% | 0.22% | 0.25% |
| O2 | 1.75% | 2.0% | 2.52% | 2.9% | 3.22% | 3.7% |
| N2 | 72.43% | 83.5% | 72.58% | 83.3% | 72.73% | 83.1% |
| H2O | 13.25% | --- | 12.85% | --- | 12.48% | |
| Total | 100% | 100.0% | 100% | 100.0% | 100% | 100.0% |

The next step is the computation of acid dew points. There are a few correlations for acid dew points and the following correlation is widely used:

Sulfuric acid dew point "Tdp" in˚K is given by:
1000/Tdp=2.276 - 0.0294*LNpH2O - 0.0858*LNpSO3 + 0.0062 *LNpH2O* LNpSO3

PSO2 vw (SO2 volume percent in wet gas)

pSO3 = (partial pressure of SO3, mmHg) =PSO2vw/100*CF/100*stack presure

PH2O vw (volume percent in wet gas) = (partial pressure of H2O, mmHg) =(PH2O vw/100)*stack pressure

The major portion of sulfur in fuel is burned and appears as sulfur dioxide in the stack gas; a small portion (2 to 4 percent) is further oxidized to sulfur trioxide. These oxides combine with the moisture in the flue gas to form sulfurous and sulfuric acid vapors. When in contact with a surface below the acid dew point, condensation takes place.Table 3 shows the acid dew point calculations at different excess air levels:

Table 3: sulfuric acid dew point calculations

| Composition of Wet Flue Gases (mole %) | | | | | | |
|---|---|---|---|---|---|---|
| % Excess Air | 10% | 10% | 15% | 15% | 20% | 20% |
| Conversion factor,% of So2 to So3 | 2% | 4% | 2% | 4% | 2% | 4% |
| CO2 | 12.33% | 12.33% | 11.82% | 11.82% | 11.35% | 11.35% |
| SO2 | 0.24% | 0.24% | 0.23% | 0.23% | 0.22% | 0.22% |
| O2 | 1.75% | 1.75% | 2.52% | 2.52% | 3.22% | 3.22% |
| N2 | 72.43% | 72.43% | 72.58% | 72.58% | 72.73% | 72.73% |
| H2O | 13.25% | 13.25% | 12.85% | 12.85% | 12.48% | 12.48% |
| SO3 ppmv (volume/volume) | 48 | 96.2 | 46.1 | 92.3 | 44.3 | 88.6 |
| Sulfuric acid dew point(˚C) | 156.6 | 164.0 | 155.9 | 163.3 | 155.2 | 162.6 |

Hence the acid dew point varies from 155 to 163 C.

It should be noted that due to steam soot blowing, the moisture content will increase for brief periods locally when the dew point temperature can be slightly higher. Also, the ash particulates present in the flue gas deposit on the tubes lowering the tube wall temperatures further causing condensation. Considering these issues and some margin in the correlation, a safe value for acid dew point would be 170 C if no other measures were taken to help in lowering this value.

## Solving the corrosion problem

**Increasing the feed water temperature**

As sulfuric acid dew point calculated above based on the field data ranges 155 °C to 163 °C, so for immediate operation, the feed water temperature was increased to 170 °C by using an auxiliary steam heat exchanger, which already installed between the deaerator and the economizer to prevent condensation of acid vapor on tubes and thus minimize acid dew point corrosion concerns. The exit gas temperature became higher in the range of 215 °C to 225 °C. This is much higher than the value shown by the boiler supplier for the original design (namely 157 ℃) with about 3% consequence loss in the boiler efficiency.

**Utilization of Fuel Additives:**

The study considered a further method for reducing the sulfuric acid dew point by the use of fuel additives.

The plant already utilizes magnesium hydroxide slurry and organometallic additives for protection against low- and high-temperature corrosion and for avoiding and neutralizing high corrosive settlements on boiler tubes and economizers.

By applying these additives, reduction in the conversion of SO2/SO3 and thus decreasing the acid dew point could be achieved.

The study considered increasing the magnesium hydroxide slurry dosage rate and decreasing the feed water temperature in a controlled manner. This enabled us working safely below the sulfuric acid dew point calculated above, and reducing the loss in boiler efficiency by about 1%.

Gradually increasing the fuel additive dosage rate from 250 ppm to 400 ppm with consequent decreasing of the feed water temperature form 170°C to 155°C was successfully accomplished. A close monitoring of ash pH downstream the economizer and the behavior of some operational parameters such as the pressure in furnace and pressure drop in the economizer while allowing sufficient trial time was necessary to guarantee success. Table 4 shows the results obtained:

Table 4: fuel additive dosage rate versus feed water temp and ash pH

| Feed Water Temp. °C | Magnesium Hydroxide ppm | Trial Period, months | Ash PH, range |
|---|---|---|---|
| 170 | 250 | 3-4 | 5.0 – 6.0 |
| 165 | 300 | 3-4 | 4.8 - 5.9 |
| 160 | 350 | 3-4 | 4.4 – 5.5 |
| 155 | 400 | 3-4 | 4.1- 4.9 |

The results indicate a successful reduction in the feed water temperature and hence reduction in boiler efficiency loss.

### Replacement of the economizer's lower section

The study concluded that the heavy fouling on the economizer tubes is due to its current configuration and arrangement as it has been designed with staggered arrangement at close tube spacing. This will be discussed later.

Though the above conclusion and to restore the boiler reliability in a short time, the heavily corroded lower section was replaced with the same tube arrangement; due to difficulties of the inline arrangement as lower fin density needs extra spaces and modification on the existing flue gas duct arrangement.

## ECONOMIZER ARRANGEMENT CONCERNS

There are some other concerns with the present design of the economizer

- The boiler economizer has been designed with staggered arrangement at close tube spacing. For a clean fuel such as natural gas, a staggered-tube arrangement may be used. For heavy oil fuel, an in-line arrangement is necessary to combat tubing deposit buildups and to avoid plugging. The presence of the layer of dust or particulates will in turn lower the tube wall temperatures further, thereby causing further condensation of acid vapor. Staggered arrangement is not recommended when flue gases contain ash or dust particulates, though small in quantity. Over a period of time, the accumulation can become large as can be seen from the failed tubes. Fig 1 shows Inline and staggered arrangement of tubes

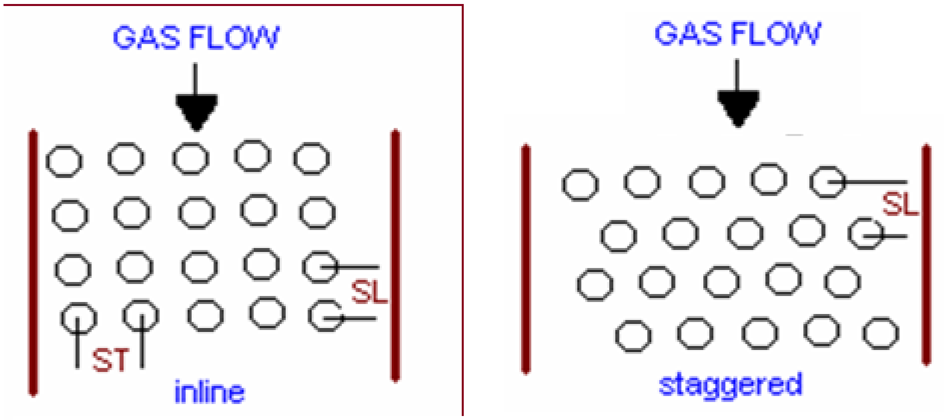


Fig 1: Inline and staggered arrangement of tubes. Staggered is difficult to clean with ash/dust laden gases

- The use of 3 fins/in for this situation is also not a good choice for the design of the economizer. As can be seen from the failed tubes, the ash and dust settles on the tubes and is difficult to clean. Frequent soot blowing also is a concern as it increases the moisture and makes the ash wet and sticky, besides increasing the acid dew point temperature. The acid then corrodes and eats away the tubes and fins. Hence a lower fin density is recommended for the tubes for better cleaning and lesser fouling.
- Field data were collected at 76 t/h and 107 t/h as shown below in table 5 and the boiler calculations were reconciled to provide predicted data close to the field data for both the cases. The fouling factor for the economizer had to be raised to a very high value, namely 0.006 to 0.01 m2hC/kcal to match the field data. This is a very high fouling factor. Normal fouling factor is in the range of 0.001 m2hC/kcal for heavy oil firing.

Table 5: data used for performance evaluation and predictions

| Case | Field data | Predict | Field data | Predict | Heat balance | Predict |
|---|---|---|---|---|---|---|
| Steam flow, t/h | 107 | 107 | 76 | 76 | 110 | 110 |
| Pressure,kg/cm2g | 60 | 60 | 49 | 49 | 64 | 64 |
| Steam temperature,C | 488 | 488 | 476 | 476 | 487 | 487 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Feed water temp,C | 150 | 150 | 165 | 165 | 138 | 138 |
| Water temp leaving eco,C | 256 | 263 | 252 | 251 | 239 | 267 |
| Steam temp before spray,C | 380 | 430 | 370 | 414 | 409 | 434 |
| Steam temp after spray,C | 351 | 366 | 340 | 350 | 301 | 367 |
| Spray water flow,kg/s | - | 1.8 | - | 1.24 | 0.9 | 1.97 |
| Gas temp to eco,C | >510 | 529 | 445 | 467 | 602 | 533 |
| Gas temp leaving eco,C | >200 | 205 | 216 | 208 | 157 | 174 |
| Oxygen % vol dry | 2.5 | 2.5 | 3.2 | 3.2 | 2.4 | 2.4 |
| Eco fouling,m2hc/kcal | | **0.0061** | | **0.01** | 0.001 | 0.001 |

The study recommended replacing the economizer's bottom section which faced severe fouling with equivalent finned tubes in inline arrangement with 2 fins/in instead of the existing 3 fins/in staggered arrangement. This option needs some modifications on the flue gas duct and extra space. It is possible that with inline arrangement and lower fin density, soot blowing will be more effective and fouling will be less and hence exit gas temperature may not be that high, say 10 to 15 C lower.

## BOILER ARRANGEMENT CONCERNS

The study shows some other concerns with the design of the boiler; it indicates that the boiler design was not optimized and could have been better. The evaporator size should have been larger with a lower gas temperature entering the economizer. This will help to have a higher economizer approach temperature and will also reduce the duty of the economizer. The surface area for the economizer also would have been reduced. This would permit operation without economizer steaming even if the superheater and evaporator surfaces got fouled up over a period of time.

## Future opportunities and alternatives to improve the boiler efficiency

It's worth mentioning that reducing excess air will reduce the "cold-end" corrosion problem. Reducing the excess air decreases the quantity of sulfuric acid vapor within the stack gas. Research indicates a direct relationship between sulfur trioxide formation and excess oxygen (or air) levels. With reduced excess air, stack gas volume is also reduced. Stack gas temperature is also reduced because gas velocities are reduced, allowing the gas to spend more time inside the boiler where the heat can be absorbed. The economics are attractive. As a rule of thumb, boiler efficiency can be increased one percent for each 1.8 reduction in excess oxygen or 20 C reduction of stack gas temperature

Future opportunities and alternatives to improve the boiler efficiency while controlling the fouling and corrosion problems:

1. The study recommended replacing the economizer's bottom section which faced severe fouling with equivalent finned tubes in inline arrangement. This option needs some modifications on the flue gas duct and extra space. It is possible that with inline arrangement and lower fin density, soot blowing will be more effective and fouling will be less and hence exit gas temperature may not be that high, say 10 to 15 C lower. The study concluded that due to the smaller evaporator surface, it will be difficult to add more surfaces to the economizer to improve the efficiency as steaming of economizer can occur, which is to be avoided.

   The estimated cost of this option; equivalent carbon steel inline arrangement and lower fin density, is 200,000 USD; the improvement in the boiler efficiency will be about 0.5% equivalent to 175,000 USD annually.

2. Using Teflon coated tubes for the lower section or stainless steel finned tubes or duplex tubes and operate at better efficiency with a lower feed water temperature. This alternative prolongs the life of the economizer and allows operation even with some acid condensation and so the economizer exit gas temperature can be lower and boiler efficiency can be higher. These are however expensive materials and some modifications to the existing system will be required to implement this option as liquid sulfuric acid can be formed.

   It is important that when implement this option, the stack gas exit temperature be maintained above the acid dew point to avoid corrosion downstream of the economizer.

   By the implementation of this option the feed water temperature will be reduced to the minimum while keeping flue gas temperature leaving the economizer above 160 C to prevent stack corrosion. The estimated cost of this option using 2205 duplex tubes, inline and low fin density arrangement is 450,000 USD the improvement in the boiler efficiency will be about 2.0 % equivalent to USD 700,000 annually.

## CONCLUSIONS

The study concluded the following immediate actions and future more efficient opportunities and alternatives

The following immediate actions have been taken to restore the boiler reliability in a short time:

1. The sulfuric acid dew point calculated based on the field data ranges 155 °C to 165 °C, so for immediate operation, the feed water temperature was increased to 170 °C with the consequence loss in boiler efficiency of about 3%.
2. To mitigate this high loss of efficiency, the magnesium hydroxide slurry fuel additive used to decrease the feed water temperature gradually from 170 °C to 155 °C. This reduced the efficiency loss by around 1%.
3. To restore the boiler reliability in a short time, the heavily corroded lower section was replaced with the same tube arrangement; due to difficulties of the inline arrangement as lower fin density needs extra spaces and modification on the existing flue gas duct arrangement.

Future opportunities and alternatives to improve the boiler efficiency while controlling the fouling and corrosion problems:

1. The study recommended replacing the economizer's bottom section which faced severe fouling with equivalent finned tubes in inline arrangement. It is possible that with inline arrangement and lower fin density, soot blowing will be more effective and fouling will be less and hence exit gas temperature may not be that high, say 10 to 15 C lower.

2. Using Teflon coated tubes for the lower section or stainless steel finned tubes or duplex tubes and operate at better efficiency with a lower feed water temperature.

References:


- The Nalco Guide to Boiler Failure Analysis, Nalco Chemical Company, Authored by Robert D. Port, Harvey M. Herro, McGraw-Hill, Inc.1991
- NCEL Technical Note, Boiler Stack Gas Heat Recovery, September 1987 By P.C. Lu. T.T.Fl. Sponsored By Naval Facilities
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AFA WORKSHOP ON PROCESS WASTE HEAT BOILERS INTEGRITY AND RELIABILITY

# CASE STUDY ON

# GAS SIDE CORROSION OF STACK GAS HEAT RECOVERY ECONOMIZER IN OIL-FIRED HIGH PRESSURE STEAM BOILER

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Power & Water Dept.
Prepared by Eng. Osama Khalil/Power Plant Chemical Supervisor
Reviewed by Eng. Fuad Al-Zoubi, Power and Water Manager



# *INTRODUCTION*

- *This is a case study carried out by APC to investigate a gas side corrosion problem that resulted in repetitive tube failures and a severe fouling occurring on economizer heating surfaces of boiler unit No.2 at its thermal power plant.*
- *The study relied on physical examination of the economizer tube, field data collected at various boiler loads, reviewing the performance data and the economizer and boiler design.*
- *An evaluation has been done and solutions including immediate actions and future more efficient alternatives are discussed and presented.*

## PROBLEM

- Boiler unit No.2 (SG4-Boiler) has a design capacity of 110 t/h process steam at 64 bar, 478°C. The boiler with first commissioning at 1982 was completely replaced in 2004. The economizer which made of carbon steel, it started facing repetitive tubes and bends ruptures in its lower part one year after commissioning
- Severe fouling occurring on the economizer heating surfaces, preventing efficient heat transfer to the economizer tubes, which resulted in a high flue gas exit temperature and hence a reduction in boiler efficiency and increase in fuel consumption.



## PROBLEM

# DATA GATHERING AND ANALYSIS
## BOILER FEED WATER TEMPERATURE CONCERN

- Heavy fuel oil is fired in the boiler. The oil contains about 4.0 % sulfur by weight and also vanadium in ash. Feed water was originally supplied at 126 °C increased later to 138 °C from a deaerator operating at 2.4 kg/cm2a and further heated by steam in a HP heater.
- Combustion calculations and estimation of acid dew point is the starting point for the analysis of the problem. The following fuel data was used as the basis:



# DATA GATHERING AND ANALYSIS
## BOILER FEED WATER TEMPERATURE CONCERN

| Fuel Oil Analysis (% by weight) | |
|---|---|
| Carbon | 84.19% |
| Hydrogen | 11.21% |
| Sulphur | 4.38% |
| Nitrogen | 0.22% |

# DATA GATHERING AND ANALYSIS

## BOILER FEED WATER TEMPERATURE CONCERN

| flue gas analysis on wet and dry basis in % volume at various excess air levels at ambient temperature of 35̊C and 60 % relative humidity | | | | | | |
|---|---|---|---|---|---|---|
| Component | mole % | mole % | mole % | mole % | mole % | mole % |
| | Wet | Dry | wet | Dry | Wet | Dry |
| % Excess Air | 10% | 10% | 15% | 15% | 20% | 20% |
| CO2 | 12.33% | 14.2% | 11.82% | 13.6% | 11.35% | 13.0% |
| SO2 | 0.24% | 0.28% | 0.23% | 0.26% | 0.22% | 0.25% |
| O2 | 1.75% | 2.0% | 2.52% | 2.9% | 3.22% | 3.7% |
| N2 | 72.43% | 83.5% | 72.58% | 83.3% | 72.73% | 83.1% |
| H2O | 13.25% | --- | 12.85% | --- | 12.48% | ----- |
| Total | 100% | 100.0% | 100% | 100.0% | 100% | 100.0% |



## BOILER FEED WATER TEMPERATURE CONCERN

### Combustion and Acid dew point Calculations

- The next step is the computation of acid dew points. There are a few correlations for acid dew points and the following correlation is widely used:
- Sulfuric acid dew point "Tdp" in˚K is given by: 1000/Tdp=2.276 - 0.0294*LNpH2O - 0.0858*LNpSO3 + 0.0062 *LNpH2O* LNpSO3

## BOILER FEED WATER TEMPERATURE CONCERN
## Combustion and Acid dew point Calculations

| Composition of Wet Flue Gases (mole %) | | | | | | |
|---|---|---|---|---|---|---|
| % Excess Air | 10% | 10% | 15% | 15% | 20% | 20% |
| Conversion factor,% of So2 to So3 | 2% | 4% | 2% | 4% | 2% | 4% |
| CO2 | 12.33% | 12.33% | 11.82% | 11.82% | 11.35% | 11.35% |
| SO2 | 0.24% | 0.24% | 0.23% | 0.23% | 0.22% | 0.22% |
| O2 | 1.75% | 1.75% | 2.52% | 2.52% | 3.22% | 3.22% |
| N2 | 72.43% | 72.43% | 72.58% | 72.58% | 72.73% | 72.73% |
| H2O | 13.25% | 13.25% | 12.85% | 12.85% | 12.48% | 12.48% |
| SO3 ppmv (volume/volume) | 48 | 96.2 | 46.1 | 92.3 | 44.3 | 88.6 |
| **Sulfuric acid dew point(°C)** | **156.6** | **164.0** | **155.9** | **163.3** | **155.2** | **162.6** |



## BOILER FEED WATER TEMPERATURE CONCERN
## Combustion and Acid dew point Calculations

It should be noted that the critical factors governing the sulfuric acid dew point corrosion include

- the presence of corrosive quantities of sulfur trioxide,
- the presence of moisture in the flue gas, and
- the presence of metals whose surface temperature is below the sulfuric acid dew point

The dew point increases as the quantity of sulfur trioxide in the flue gas and the moisture content of the flue gas increase

## BOILER FEED WATER TEMPERATURE CONCERN
## Solving the corrosion problem

The following immediate actions have been taken to restore the boiler reliability in a short time

1. **Increasing the feed water temperature**

- As sulfuric acid dew point calculated above based on the field data ranges 155 °C to 163 °C, so for immediate operation, the feed water temperature was increased to 170 °C by using an auxiliary steam heat exchanger
- The exit gas temperature became higher in the range of 215 °C to 225 °C. This is much higher than the value shown by the boiler supplier for the original design (namely 157 °C) with about 3% consequence loss in the boiler efficiency



## BOILER FEED WATER TEMPERATURE CONCERN
## Solving the corrosion problem

**2- Utilization of Fuel Additives:**

- The study considered a further method for reducing the sulfuric acid dew point by the use of fuel additives.
- The plant already utilizes magnesium hydroxide slurry and organometallic additives for protection against low- and high-temperature corrosion and for avoiding and neutralizing high corrosive settlements on boiler tubes and economizers.
- By applying these additives, reduction in the conversion of $SO_2/SO_3$ and thus decreasing the acid dew point could be achieved.
- This enabled us working safely below the sulfuric acid dew point calculated above, and reducing the loss in boiler efficiency by about 1%.

## BOILER FEED WATER TEMPERATURE CONCERN
### Solving the corrosion problem

| fuel additive dosage rate vs. feed water temp and ash pH | | | |
|---|---|---|---|
| Feed Water Temp. °C | Magnesium Hydroxide ppm | Trial Period, months | Ash PH, range |
| 170 | 250 | 3-4 | 5.0 – 6.0 |
| 165 | 300 | 3-4 | 4.8 - 5.9 |
| 160 | 350 | 3-4 | 4.4 – 5.5 |
| 155 | 400 | 3-4 | 4.1- 4.9 |



## BOILER FEED WATER TEMPERATURE CONCERN
### Solving the corrosion problem

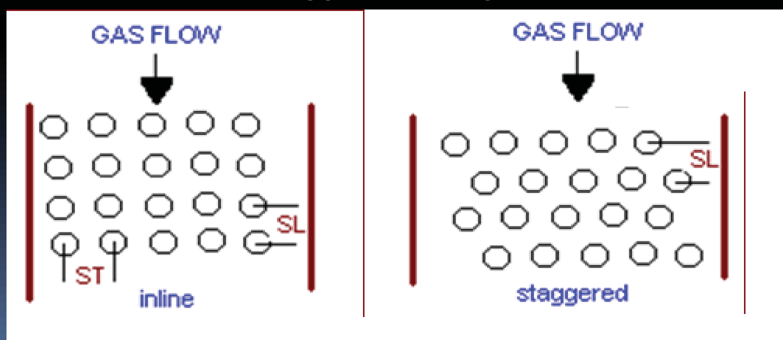
3- Replacement of the economizer's lower section

- The study concluded that the heavy fouling on the economizer tubes is due to its current configuration and arrangement as it has been designed with staggered arrangement at close tube spacing. This will be discussed later.
- Though the above conclusion and to restore the boiler reliability in a short time, the heavily corroded lower section was replaced with the same tube arrangement; due to difficulties of the inline arrangement as lower fin density needs extra spaces and modification on the existing flue gas duct arrangement.

# ECONOMIZER ARRANGEMENT CONCERNS

- The boiler economizer has been designed with staggered arrangement at close tube spacing. For a clean fuel such as natural gas, a staggered-tube arrangement may be used. For heavy oil fuel, an in-line arrangement is necessary to combat tubing deposit buildups and to avoid plugging.

Inline and staggered arrangement of tubes






# ECONOMIZER ARRANGEMENT CONCERNS

- The use of 3 fins/in for this situation is also not a good choice for the design of the economizer. As can be seen from the failed tubes, the ash and dust settles on the tubes and is difficult to clean. Frequent soot blowing also is a concern as it increases the moisture and makes the ash wet and sticky, besides increasing the acid dew point temperature. The acid then corrodes and eats away the tubes and fins.
- Field data were collected at 76 t/h and 107 t/h as shown in the table below and the boiler calculations were reconciled to provide predicted data close to the field data for both the cases. The fouling factor for the economizer had to be raised to a very high value, namely 0.006 to 0.01 m2hC/kcal to match the field data. This is a very high fouling factor. Normal fouling factor is in the range of 0.001 m2hC/kcal for heavy oil firing

# ECONOMIZER ARRANGEMENT CONCERNS

| Case | Field data | Predict | Field data | Predict | Heat balance | Predict |
|---|---|---|---|---|---|---|
| Steam flow, t/h | 107 | 107 | 76 | 76 | 110 | 110 |
| Pressure,kg/cm2g | 60 | 60 | 49 | 49 | 64 | 64 |
| Steam temperature,C | 488 | 488 | 476 | 476 | 487 | 487 |
| Feed water temp,C | 150 | 150 | 165 | 165 | 138 | 138 |
| Water temp leaving eco,C | 256 | 263 | 252 | 251 | 239 | 267 |
| Steam temp before spray,C | 380 | 430 | 370 | 414 | 409 | 434 |
| Steam temp after spray,C | 351 | 366 | 340 | 350 | 301 | 367 |
| Spray water flow,kg/s | - | 1.8 | - | 1.24 | 0.9 | 1.97 |
| Gas temp to eco,C | >510 | 529 | 445 | 467 | 602 | 533 |
| Gas temp leaving eco,C | >200 | 205 | 216 | 208 | 157 | 174 |
| Oxygen % vol dry | 2.5 | 2.5 | 3.2 | 3.2 | 2.4 | 2.4 |
| **Eco fouling,m2hc/kcal** | | **0.0061** | | **0.01** | 0.001 | 0.001 |



# Future opportunities and alternatives to improve the boiler efficiency while controlling the fouling and corrosion problems:

1. Replacing the economizer’s bottom section which faced severe fouling with equivalent carbon steel inline arrangement and lower fin density
   - in-line arrangement is necessary to combat tubing deposit buildups and to avoid plugging
   - a lower fin density is recommended for the tubes for better cleaning and lesser fouling.
   - The estimated cost of this option is 200,000 USD; the improvement in the boiler efficiency will be about 0.5% equivalent to 175,000 USD annually

## Future opportunities and alternatives to improve the boiler efficiency while controlling the fouling and corrosion problems:

2- Using Teflon coated tubes for the lower section or stainless steel finned tubes or duplex tubes and operate at better efficiency with a lower feed water temperature. This alternative prolongs the life of the economizer and allows operation even with some acid condensation and so the economizer exit gas temperature can be lower and boiler efficiency can be higher.

- These are however expensive materials and some modifications to the existing system will be required to implement this option as liquid sulfuric acid can be formed.



## Future opportunities and alternatives to improve the boiler efficiency while controlling the fouling and corrosion problems:

- It is important that when implement this option, the stack gas exit temperature be maintained above the acid dew point to avoid corrosion downstream of the economizer.
- By the implementation of this option the feed water temperature will be reduced to the minimum while keeping flue gas temperature leaving the economizer above 160 C to prevent stack corrosion. The estimated cost of this option using 2205 duplex tubes, inline and low fin density arrangement is 450,000 USD the improvement in the boiler efficiency will be about 2.0 % equivalent to USD 700,000 annually.

# Thank You

# Delegate List

Arab Fertlizer Association
since 1975

Process Waste Heat Boilers Integrity & Reliability

# Delegate Report

| Country | Name | Position | Company | Telephone | Fax | Email |
|---|---|---|---|---|---|---|
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