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Importance of proper BFW quality in Pool Condenser plants

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Stamicarbon 75 YEARS

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1. INTRODUCTION

In 2016 severe damage occurred in the tube sheet of a Pool Condenser (constructed in X2CrNiMo25-22-2, BC.05) in a Stamicarbon CO2 stripping plant in China (Stamicarbon Urea 2000^Plus technology). The damage did not occur at the high pressure process side containing the highly corrosive ammonium carbamate. In this case specific case, the damage occurred unexpectedly at the low pressure steam / condensate side.
The root cause of this mishap was poor management of the boiler feed water (BFW) quality. The damage was not expected, since water treatment of steam systems is well known and considered normal practice in the industry.
This resulted in severe erosion-corrosion damage of the carbon steel underneath the weld overlay of the tube sheet. This failure mode is also referred to as Flow Accelerated Corrosion (FAC).
Repair of the tube sheet was challenging and temporarily. The repaired Pool Condenser operated without any problems until it was replaced with a new one.
Based on the outcome of this root cause analysis, counter measures were taken in order to prevent similar mishaps in other Pool Condensers and Pool Reactors. Furthermore, changes are implemented in the design of new Pool Condensers and Pool Reactors. A guideline to control the quality of the BFW and an in-service inspection program are developed to be able to identify any damages during planned turn arounds. All licensees operating plants containing a Pool Condenser or Pool Reactor are informed with respect to possible risk for erosion-corrosion and advised on proper counter measures.
This paper discusses in brief the damage, the repair, the results of the root cause analysis and the mitigation actions taken.

2. CASE HISTORY SEVERLY DAMAGED POOL CONDENSER IN 2016

2.1. TECHNICAL DETAILS

The Pool Condenser is a horizontal shell and tube heat exchanger, equipped with a U-bundle, see figure 1. The U-tubes (X2CrNiMo25-22-2, BC.05) are connected to the tube sheet by a so-called internal bore weld (IBW). The tube sheet is made from 20Mn5V carbon-steel with a thickness of 425 mm + 22 mm X2CrNiMo25-22-2 weld overlay.

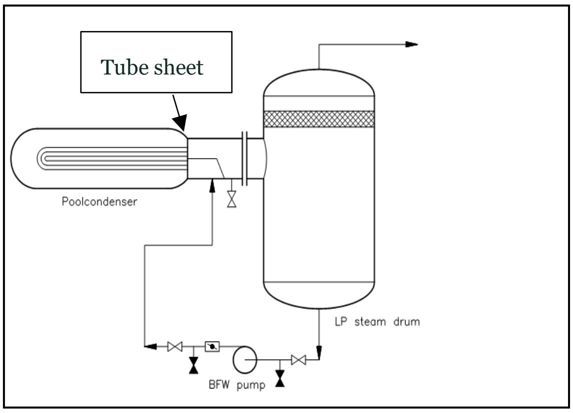
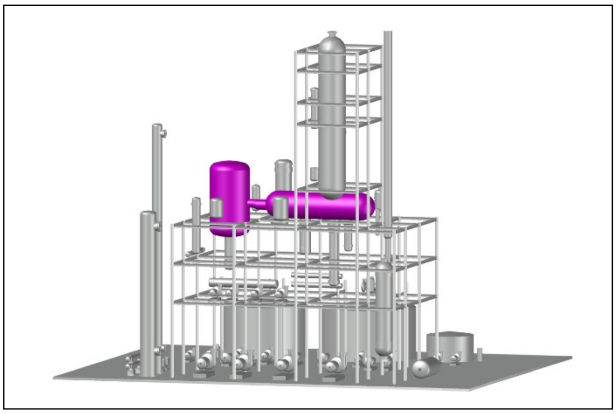


Figure 1: Pool Condenser and LP Steam Drum



Stamicarbon Urea 2000^Plus technology

The inner diameter of the holes in the carbon steel tube sheet is Ø 19 mm. The internal bore weld (IBW) connecting the U-tube to the weld overlay on the tube sheet s schematically presented in figure 2.

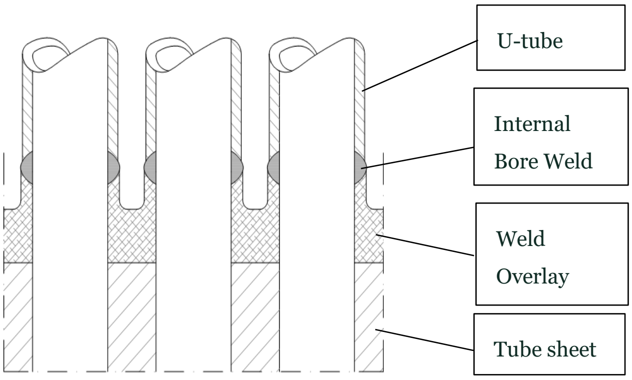


Figure 2: Internal Bore Weld connection of U-tube to the tube sheet; connected to the X2CrNiMo25-22-2 (BC05) weld overlay

2.2. TUBE SHEET DAMAGE

Due to a sudden increase in the conductivity of the steam condensate circulating through the U-bundle of the Pool Condenser, a leak was suspected and the urea plant was shut down for inspection. Upon opening the Pool Condenser at the LP steam side, the holes in the tube sheet were visibly enlarged up to Ø 22 mm, see figure 3.

A video endoscope inspection revealed cavities in the carbon steel part of the tube sheet, just underneath the weld overlay at the upper outlet side, see figure 4. Almost all holes at the outlet side were affected. The holes at the condensate inlet side (lower part of the tube sheet) were not affected at all.

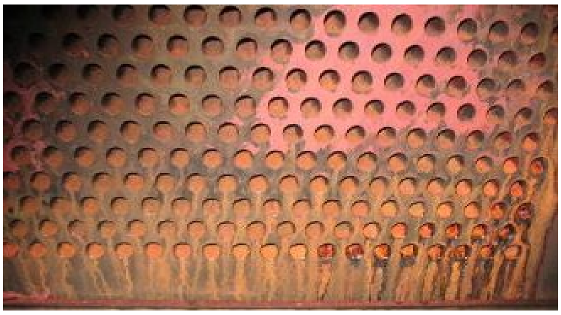


Figure 3: Carbon steel tube sheet from LP tube side;

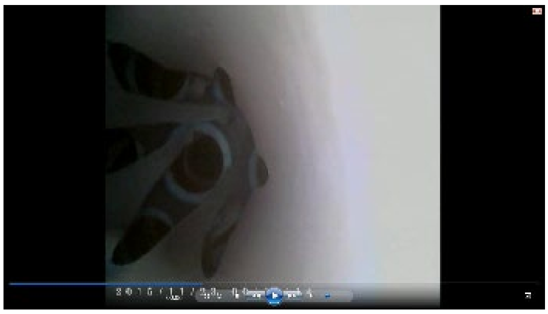


Figure 4: Cavity inside the holes near the tube sheet holes enlarge weld overlay

Inspection of the shell side of the Pool Condenser further revealed severe bending of the tube bundle, as well as inward bulging of the weld overlay in the top part of the tube sheet, see figure 5.

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Figure 5: Bent U-bundle and stay rods

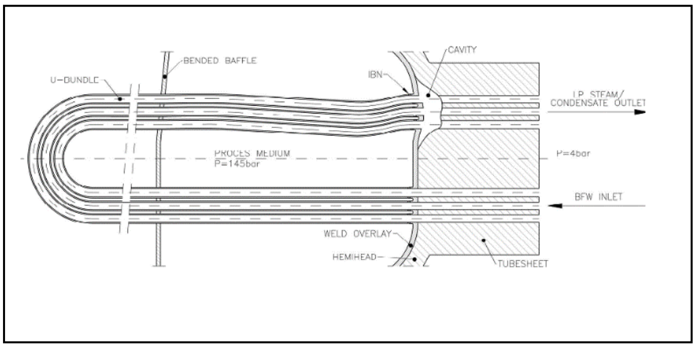

Figure 6: Schematically presentation of the cavity in the tube sheet

At the bottom part of the U-bundle no bending was observed, however the upper part of the baffle plates were bent towards the tube sheet.

These observations suggested that a large cavity was formed in the top half of the tube sheet (2-phase steam/steam condensate outlet) as is schematically presented in figure 6.
Due to the difference in pressure between the synthesis (P=145 bar) on the shell side and the pressure in the cavity (P= 4 bar) the overlay weld is pressed into the cavity. This leads to a (torsion) stress on the tube bundle and the tube bundle/weld overlay connections. As a result of this stress apparently a leak was formed, either in the weld overlay or in one of the U-tubes or internal bore welds. This necessitated the plant owner to shut down the plant.

2.3. REPAIR PROCEDURE

A repair was only feasible in case the integrity of the bent weld overlay and the twisted IBW connections were still acceptable. Therefore, the first step was to check the integrity of the weld overlay and the IBW connections in the top part of the tube sheet. For this reason it was decided to remove completely the remaining carbon steel in this area, to have full access to the weld overlay. After removing more than 400 mm of carbon steel, the weld overlay became assessible (see figure 7 and 8). Inspection showed that the condition of the weld overlay was still sufficient for a repair of the tube sheet. The repair procedure and execution of the repair was done in cooperation with SBN Austria, the original equipment manufacturer (OEM) of the Pool Condenser. The leak spot was identified in the weld overlay and repaired by welding and in general the weld overlay suffered only from shallow radial cracks, which were grinded out without weld repair.

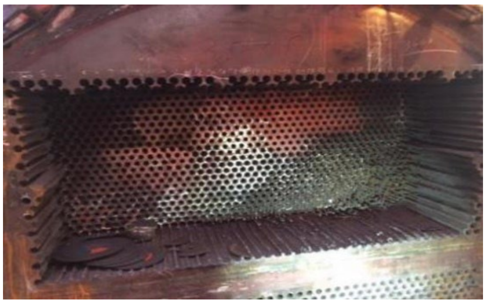

Figure 7: Cavity in tube sheet

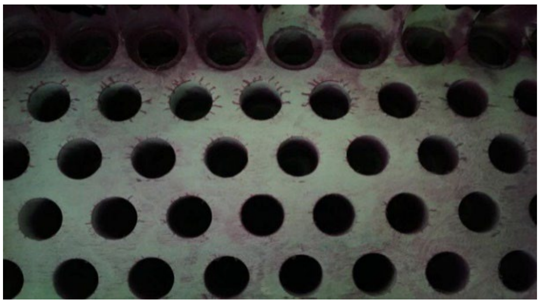

Figure 8: Cracks in weld overlay

For restoring the strength of the tube sheet, it was decided to close the cut-out with the help of 10 mm thin plates, welded layer by layer into the window (see figure 9). This quite thin size was chosen to reduce welding distortion and to simplify handling on-site.

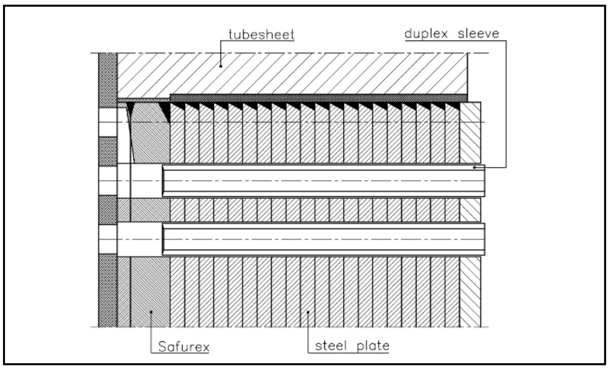

Figure 9: Drawing of the repair

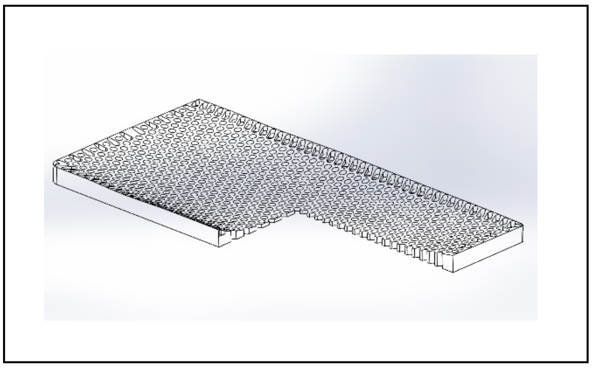

Figure 10: Adapter piece made of Safurex® plate, contour fits to the deformed weld overlay of the tube sheet

Due to the pre-damage of the weld overlay, and therefore the possibility that a leak might occur again after the repair, a solution was necessary to protect the carbon steel in such a case. Only then, the repair could guarantee keeping the Pool Condenser in operation until the new one would arrive. Therefore the first layer plate closest to the damaged weld overlay was made of Safurex®.
Since the weld overlay was deformed up to 50 mm, the Safurex® plate needed to compensate this and had to have on one side the same shape as the deformed weld overlay.
For this purpose a 3D-laser-scan of the deformed surface was made, in order to mill the Safurex® plate, shown in figure 10.
After welding in of the layer plates, duplex sleeves were inserted in the tube holes and hydraulically expanded.

3. ROOT CAUSE ANALYSIS

After analysing the process data as well as the quality of the steam condensate used at the tube side of the Pool Condenser, it was concluded that the cavity in the tube sheet was a result of erosion-corrosion or so-called Flow Accelerated Corrosion. The corrosive medium is the mixture of steam and steam condensate droplets leaving the tube bundle via the carbon steel tube sheet with relative high velocities. The abrasive components are the condensate droplets present in the steam vapor. The steam to condensate exit ratio was approximately 2 kg/kg (as per design).

It is concluded that the quality (pH, conductivity and oxygen content) of the steam condensate was not controlled properly over a prolonged period of time which eventually resulted in severe damage of the tube sheet. Fortunately, the plant was taken out of service in time (leak indication) to avoid a potential catastrophic failure of the Pool Condenser.

3.1. EROSION-CORROSION

Erosion-corrosion is the acceleration or increase in rate of attack of a metal surface because of relative movement between a corrosive fluid or vapor and the metal surface. Metal is removed from the surface as dissolved ions, or it forms solid corrosion products which are mechanically swept from the metal surface. Erosion-corrosion is characterized in appearance by grooves, gullies, waves, rounded holes and valleys and usually exhibits a direction pattern. Erosion-corrosion may occur in a relatively short time.
Carbon steel is susceptible to erosion-corrosion damage by steam vapors containing condensate droplets. The erosive action destroys the protective Hematite (Fe_2O_3) / Magnetite (Fe_3O_4) layer causing direct contact

between active metal and steam vapor/droplets. A Magnetite layer forms a hard, dense, adherent, and continuous film, the Hematite layer is less stable and provides less protection. A tight Magnetite layer is formed easily at higher temperatures; at lower temperatures a less protective Hematite layer is formed. The temperatures prevailing in the LP steam section of the Pool Condenser plant are unfavorable to form a tight Magnetite layer. Therefore the tube sheet and LP Steam drum are mainly protected by a relative weak Hematite layer. Erosion-corrosion is observed in particular at places where high velocities prevail and/or strong turbulences occur.

3.2. PREVENTIVE MEASURES TO MITIGATE RISK OF EROSION-CORROSION

As can be found in open literature, see [ref 3], [ref 4], [ref 5], [ref 6], the resistance to erosion-corrosion of carbon steel depends on the formation and maintaining a protective Magnetite (Fe_3O_4) or Hematite (Fe_2O_3) layer. This will depend on the following parameters.

- Grade of carbon steel; quantities of Cr and Mo will increase erosion-corrosion resistance.
- Turbulences; high turbulences can prevent proper formation of a protective layer or destroy an existing layer.
- Velocity of steam containing condensate droplets; higher velocities create more damages, due to the higher impact energy of the droplets onto the metal surface.
- Temperature; higher temperatures are beneficial for Magnetite formation, which gives more protection compared to a Hematite layer, which is formed at lower temperatures.
- pH; a protective layer can only be formed at a pH above 9.5. Preferably, the pH should be maintained at around 10.
- Presence of oxygen; a small amount in the ppb-range is beneficial to form a protective layer, which is an iron oxide.

In figure 11 and 12 (source: [ref 6]) the effect of temperature, pH and oxygen content on the resistance to erosion-corrosion is demonstrated.

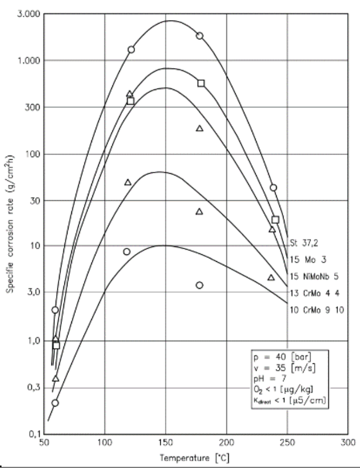

Figure 11: Formation of protective layer is poor at 150 °C (LP steam temperature)

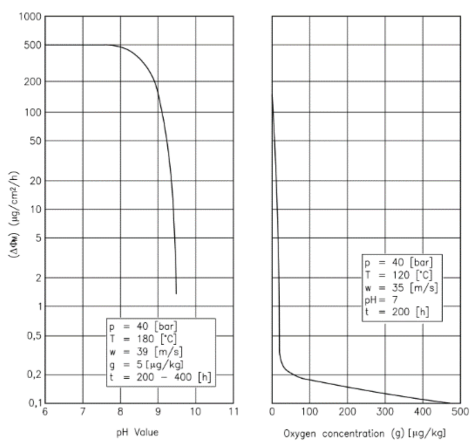

Figure 12: High protection at pH> 9.5 and Oxygen content > 10 ppb

4. MITIGATION ACTIONS

Erosion-corrosion damages of the Pool Condenser tube sheet as occurred in the presented case could lead to a catastrophic failure of the tube sheet. In the present case the client was triggered by a leak in the weld overlay, which was detected by a conductivity increase in the steam condensate. However, when no leak occurs in the stainless steel weld overlay, the carbon steel tube sheet will fail before leak (Break Before Leak scenario). Several cases were evaluated by using the a finite element method analysis (FEM). All scenarios resulted in a break before leak scenario. At all times damaging the tube sheet by erosion-corrosion should be avoided. Therefore Stamicarbon prepared several mitigation actions, which are discussed below.

4.1. INFORMING ALL LICENSEES

All licensees operating a Pool Condenser and/or Pool Reactor plant are informed on the potential risks of erosion-corrosion damages in the tube sheet. Advises are given to monitor and control the chemistry of the BFW and to check the tube sheet for erosion-corrosion damages on a regular basis during plant turnarounds.

4.2. PROPER CHEMISTRY OF BFW

As mentioned above, the quality of the BFW should be controlled to avoid or minimize the risk for erosion-corrosion. For this purpose Stamicarbon developed a guideline for the BFW used in the low pressure steam system, see [ref. 2]. This guideline is sent to all licensees.

The main controlling parameters are listed below.

- pH > 9.5 – 10 (measured at a temperature of 25 °C)
- Total conductivity < 10 µS/cm
- Acid conductivity < 0.2 µS/cm
- Oxygen (O_2) < 0.02 mg/liter
- Iron (Fe) < 0.02 mg/liter

It is the pH of the steam condensate from the U-bundle to LP steam drum V904 which should be minimum 9.5. It is not possible though to sample/measure that particular stream. The pH of the BFW from LP steam drum V904 to the U-bundle is however virtually the same as the pH of the steam condensate from the U-bundle. Therefore Stamicarbon introduced an on-line pH measurement in the suction of BFW pump P906 – see figure 13.

The quality of the imported steam to the urea plant should be adequate to secure the above mentioned requirements. If it is not possible to secure a minimum pH of 9.5 for the U-bundle feed water through control of the quality of the imported steam, an additional 'All Volatile Treatment' (AVT) is advised. This can be done by dosing e.g. ammonia or any other effective volatile agent in the discharge of the BFW pump to the Pool Condenser or Pool Reactor, P906.

The additionally required amount of ammonia or other agent depends on the feed water quality and the distribution coefficient of the used agent. The distribution coefficient is the concentration ratio of the agent in the steam over the steam condensate under a the given temperature. Ammonia has a relatively high distribution coefficient, meaning that only a relatively small part of ammonia dosed in the discharge of P906 will have a pH-increasing effect for the steam condensate leaving the U-bundle. If the acid conductivity of the feedwater is < 0.2 µS/cm, and, for argument sake, if no pH controlling agent is present in the imported steam to the urea plant, about 5 ppm of ammonia is required in the BFW to the Pool Condenser/Pool Reactor to reach a pH > 9.5 in the steam condensate leaving the U-bundle. This condensate leaving the bundle would then have an ammonia concentration of about 1.3 ppm and the steam leaving the U-bundle would then have an ammonia concentration of about 14 ppm, resulting in an ammonia concentration of the export steam condensate of about 11 ppm. These values are probably too high for further use of the export steam condensate to BL and any export LP steam to BL. These values will reduce though when the imported steam to the urea plant has been treated to a certain extent and this treatment can even be such that no additional AVT is required at all in the urea plant. Other AVT agents generally have much lower distribution coefficients and would be more effective in that sense.

Apart from the water chemistry, which is of primary importance, Stamicarbon also reduced the design steam to condensate exit ratio from 2 to 1 kg/kg. Also Stamicarbon introduced a flow control in the BFW circulation loop to the Pool Condenser/Pool Reactor for the BFW flow to be controlled as per design – see also figure 13. These two measures are to limit the amount of steam condensate leaving the U-bundle. This has no meaning for the tube sheet outlet of the U-bundle when duplex sleeves are installed – see paragraph 4.5, but still have a positive effect on erosion-corrosion in the LP outlet channel of the Pool Condenser/Pool reactor and in LP steam drum V904.

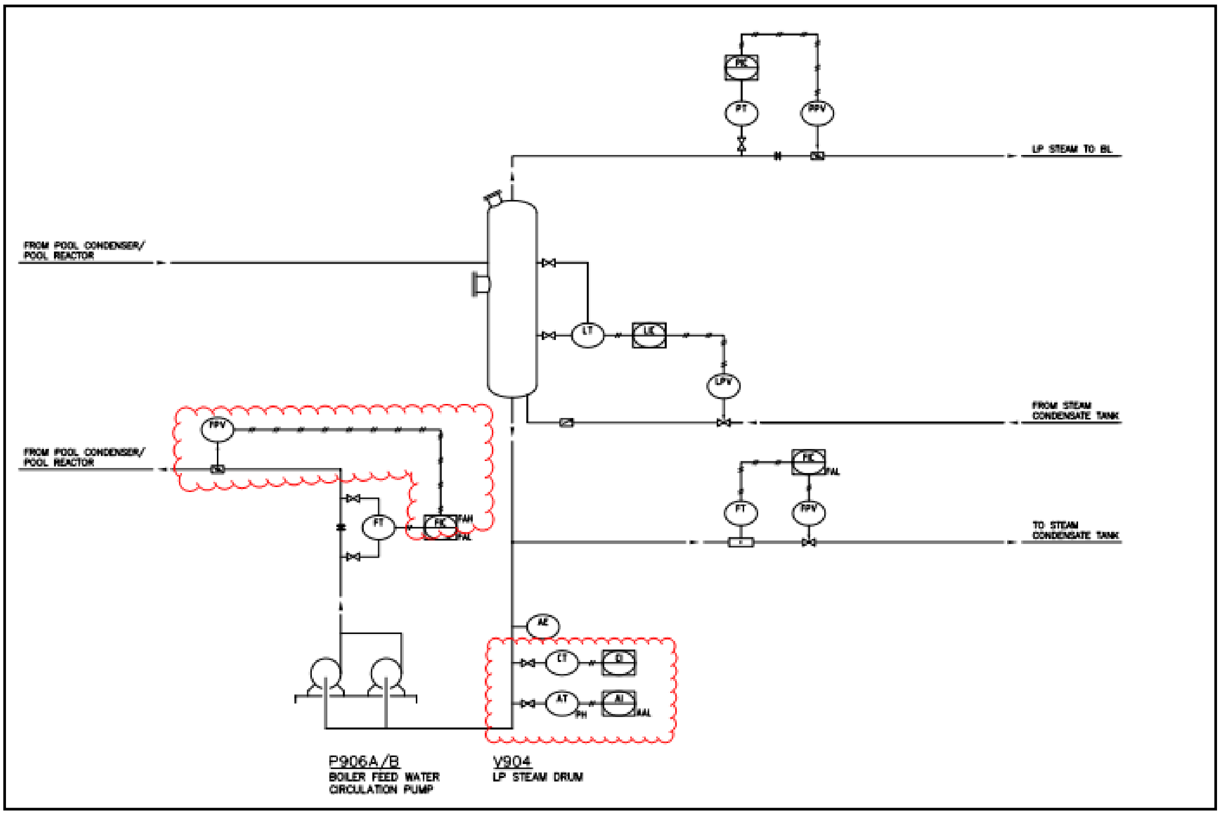

Figure 13: Changes in P&ID to accommodate proper control of the BFW quality and flow

4.3. INSPECTION PROGRAM

It is advised to check the tube sheet at the LP steam side for erosion-corrosion damages on a regular basis during planned turn arounds. The inspection program entails a video endoscopic inspection of the holes in the top (vapor exit side) half of the tube sheet. Figure 14 shows an example of small erosion-corrosion damage just behind the weld overlay.

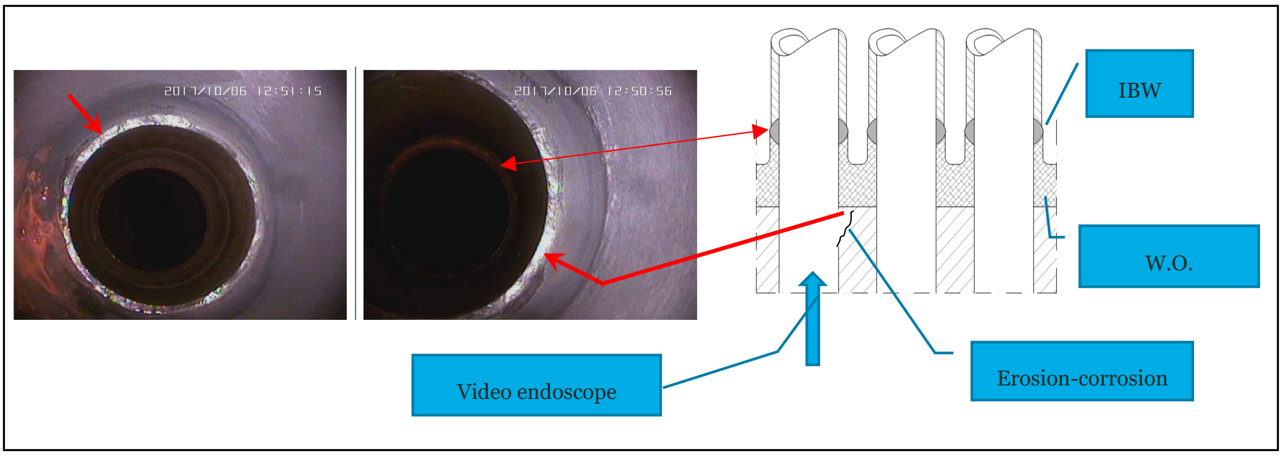

Figure 14: Video endoscope image of a hole in tube sheet, showing small erosion-corrosion damages (increase hole size) of carbon steel just behind the stainless steel weld overlay

When erosion-corrosion damage is observed, it is advised to measure the extent of the damages in each tube. The increase in hole size can be measured by eddy-current method and the hole size can be plotted in a tube sheet lay-out, see figure 15.

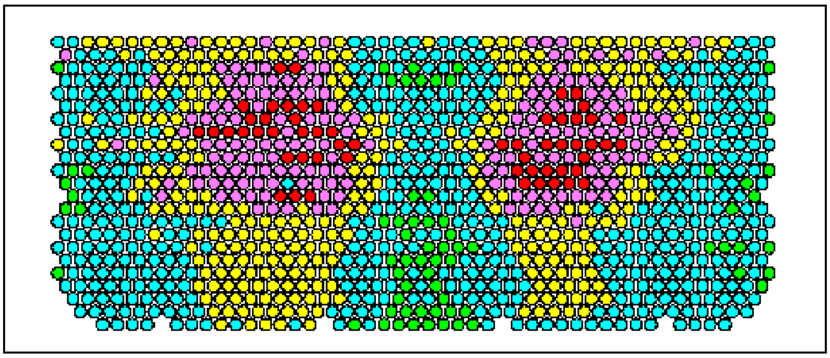

Figure 15: Measurement of hole size in an affected tube sheet due to erosion-corrosion. Non affected holes are colored green, affected holes are colored blue, yellow, purple and red (in order of increasing hole size)

In case erosion-corrosion is detected a strength calculation is advised, to check if the damaged tube sheet still meets the design rules. If this is not the case, a so-called Fitness For Purpose (FFP) assessment is advised, using Finite Element Analysis (FEM calculations). Based on the tube sheet strength assessment, further mitigation actions and/or a repair plan needs to be defined.

4.4. MITIGATION AND PREPAIR STRATEGY

Depending of the severity of the erosion-corrosion damages, several mitigation and or repair scenarios can be followed.

Scenario 1. The erosion-corrosion damage is minor and the tube sheet still meets the design requirements with respect to the strength. One can decide to only improve the BFW chemistry to stop the further development of erosion-corrosion. Future inspections are needed on regular basis.

Scenario 2. The tube sheet strength does not meet the design requirements, but the tube sheet is still fit for use based on the FEM assessment. In this case, it is advised to completely stop any further erosion-corrosion damages in the outlet part of the tube sheet, by changing the outlet side to the bottom part of the tube sheet. The upper part will become the water inlet side and further erosion-corrosion damages at the affected top side will be avoided, see figure 16.

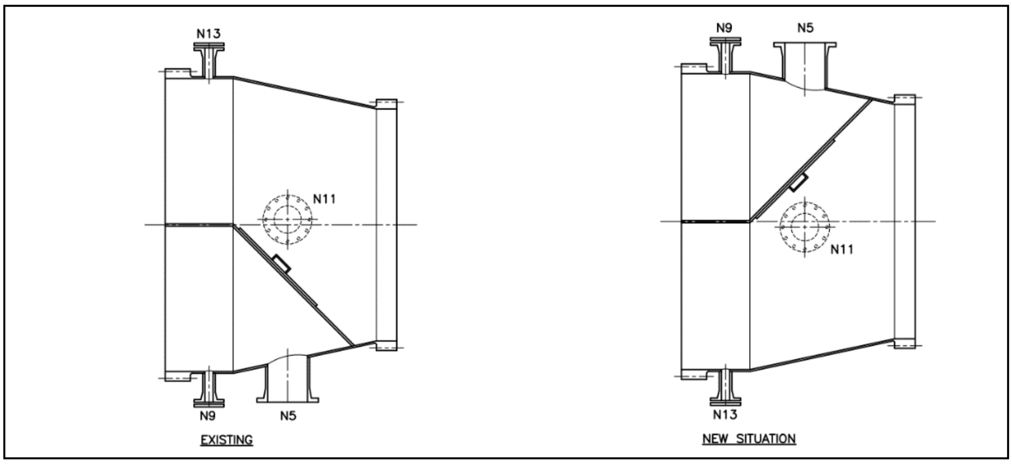

Figure 16: existing design (left); water inlet box at bottom tube sheet; (left) and modification, water inlet at top tube sheet (right)

The bottom side of the tube sheet can be protected for erosion-corrosion by installing duplex stainless steel sleeves (BE.03), see figure 17.

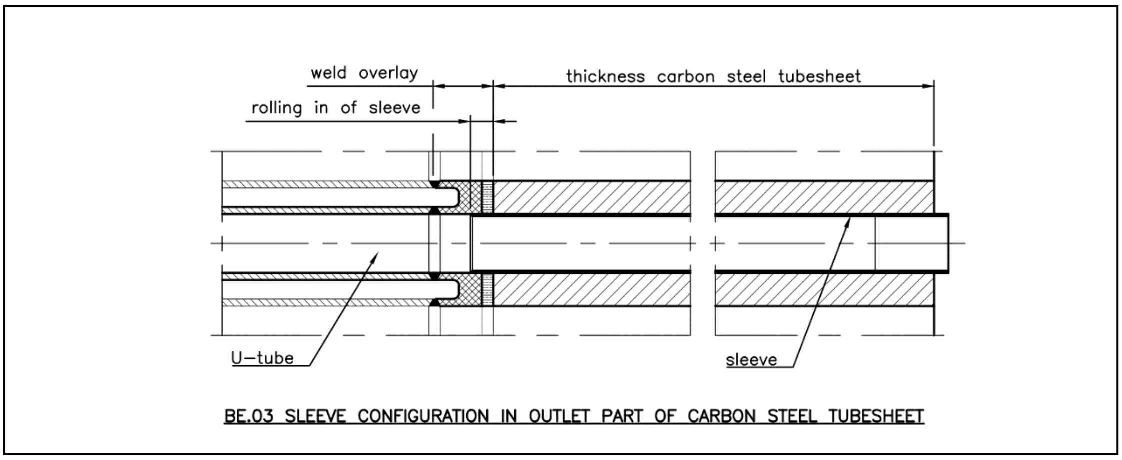

Figure 17: In-situ installation of duplex sleeves (BE.03) to protect the tube sheet holes from erosion-corrosion

This repair strategy is already executed in two Pool Condensers and several other repairs are planned. To date both of these sleeved Pool Condensers have been inspected and the sleeves performs well and still in place, see figure 18.

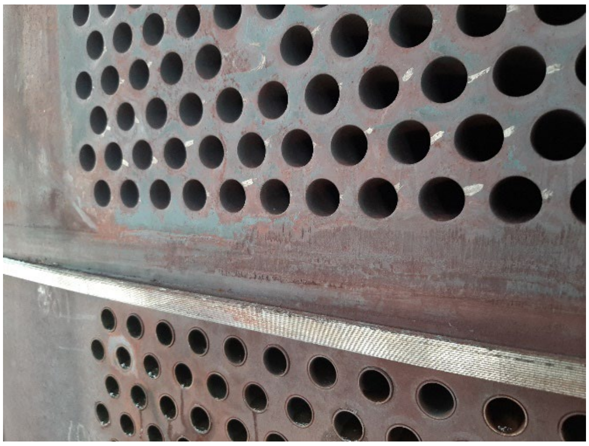

Figure 18: Condition of the sleeves installed in the bottom part of the tubesheet after two years on-stream time.

Scenario 3. The erosion-corrosion damage is severe and the FFP analysis demonstrated that the tube sheet is not fit for use anymore. The tube sheet should be reinforced to be able to operate the vessel until the vessel can be replaced by a new one. Reinforcement of the tube sheet must be designed upon the actual damage profile. A worst case scenario is presented in chapter 2.

4.5. DESIGN MODIFICATION OF NEW POOL CONDENSERS/POOL REACTORS

The following design modifications have been implemented to eliminate the risk of erosion-corrosion in the tube sheet of all new to build Pool Condensers and Pool Reactors.

1) Change the Material of Construction of the tube sheet and BFW inlet box into a more erosion-corrosion resistant material.
2) Installation of duplex stainless steel sleeves in all holes in the upper part of the tube sheet (steam vapor outlet side), see figure 16.

5. STATUS TO DATE

In total 37 Pool Condenser and Pool Reactor plants are in operation. Stamicarbon made a risk assessment for all plants, to assess the likelihood that erosion-corrosion could occur based on following data.

- Process and mechanical design data:
  - Plant capacity
  - Installed BFW pumps versus design flow
  - Expected steam condensate velocities
  - Material of construction
- Client information on BFW quality (if available)
- Client information on inspection results (if available)
- Inspection data obtained by Stamicarbon
- On-stream time (oldest Pool Condenser is 25 years in operation). The China Pool Condenser was 13 years in operation when the mishap was detected.

Based on this risk assessment, plants are divided in several categories (risk profiles) defining the risk for developing erosion-corrosion damages:

- High risk: 8 plants
- Medium to high risk: 7 plants
- Medium to low risk: 11 plants
- Low risk: 11 plants

To date Stamicarbon has inspected more than 15 Pool Condenser and Pool Reactor plants at the tube side for erosion-corrosion damages. In some of the inspected equipment erosion-corrosion issues were observed. In five cases sleeves were installed to prevent further damages. The number of inspections is limited, since the tube side of Pool Condensers and Pool Reactors were not inspected for erosion-corrosion damages before 2016.

A representative overview of findings in relation to the risk level is summarized in table 1

Risk Profile	Erosion-corrosion damage	Mitigation actions	BFW quality
High	Severe damage (case described in this paper)	Complex repair of tube sheet to restore integrity and finally replaced by new Pool Condenser	Was poor, is improved, but not up to specification of Stamicarbon; further improvement is advised
High	Some erosion-corrosion observed; tube sheet strength still in accordance to design	In- and out-let changed. New outlet side (bottom size) protected by sleeves	BFW was not up to standard, is improved
Medium to high	Hardly any damage in tube sheet observed	No actions done	No information received, but advised to improve
Medium to high	Hardly any damages observed	Client decided to change inlet and outlet and to install sleeves as a preventive action	Was not up to standard but is improved
Medium to high	Hardly any damages observed	No actions yet, but advised to change in- and out-let and install sleeves	No information received, but advised to improve
Medium to high	Very small indications of erosion-corrosion	No actions taken	No information received, advised to improve
Medium to low	Very minor indications	Not known	No information received, advised to improve
Medium to low	Very minor indications	Not known	No information received, advised to improve
Medium to low	Very minor indications	Not known	No information received; advised to improve
Low	Very small indications	Client decided to change in- and out-let and install sleeves	Poor BFW quality, which cannot be improved (integrated BFW system)
Low	Very small indications	Not known	No information, but probably poor quality

Table 1: representative summary of inspection findings

From the inspection results and feedback from licensees (see table 1), following observations can be made.

- Pool Condensers / Pool Reactors which were categorized as high risk do not always show severe erosion-corrosion damages.
- On the other hand, equipment with a low risk profile in some cases do show small erosion-corrosion damages.
- Based on the provided information with respect to the BFW chemistry in said plants, one may conclude that controlling a proper water chemistry is the most critical parameter to avoid severe erosion-corrosion damages, despite the fact of unfavorable design and other operational conditions (i.e. steam velocity, plant load and high BFW flow to the Pool Condenser).

More statistics will be compiled in the coming years.

6. CONCLUSIONS AND RECOMMENDATIONS

- In general Pool Condensers and Pool Reactors in Stamicarbon urea plants show hardly any corrosion problems at process (carbamate side).
- Experiences with X2CrNiMO25-22-2 equipment shows minor issues and in Safurex® equipment to date no corrosion has been found at process side.
- The severe damage at LP steam side of a Pool Condenser in China presented in this paper was unexpected. Water treatment in water-steam systems is considered common practice in the industry and the risks of erosion-corrosion are well known in the literature.
- Therefore, operating a urea plant with a Pool Condenser or Pool Reactor with improper or poor water chemistry, especially in the low pressure steam system, poses a potential risk for damages of the tube sheet in the Pool Condenser/Pool Reactor.
- In the Pool Condenser/Pool Reactor reaction heat is dissipated in steam condensate to produce steam in a U-bundle. The relatively high speed of the steam containing condensate droplets can lead to erosion-corrosion damages of the tube sheet, when the contact surface material is carbon steel. This is mainly the case when the BFW chemistry is of poor quality. Since (existing) Pool Condensers and Pool Reactors differ from each other, with respect to design as well as actual plant operating conditions, some vessels are more prone to develop such damages (different risk profiles) compared to others.
- Based on the mishap in 2016, Stamicarbon took several precautions to avoid similar occurrence in all existing plants and changed the design of new Pool Condensers/Pool reactors.
    - For new Pool Condensers/Pool Reactors, the tube sheet is foreseen with sleeves at the steam-condensate outlet side. In this way erosion-corrosion damages cannot occur anymore, also in case the plant is operated with poor water quality.
    - To mitigate severe damages in existing Pool Condenser/Pool Reactor plants, Stamicarbon informed all licensees to take care of a proper water chemistry (water guideline) and to perform inspections on regular basis. Also it is advised to install sleeves preventively.

- In conclusion, the risk for severe damages in Pool Condensers, Pool Reactors in existing plants is under control under the pre-requisite that all mitigating actions are in place. For new design plants this failure mode is non-existing.

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