Lessons Learned from High Pressure Process Boiler Failure

After 13 months of service, a new 1500 psig (103 bar g) secondary reformer effluent process boiler developed a severe leak. After stabilizing the plant, operators identified the nature of the issue. Precautions were taken during the shutdown that were successful in preventing catalyst damage in the secondary reformer and shift converters due to the leak of BFW into the process gas. The tube bundle was removed and replaced with a spare. The immediate cause of the failure was identified and a metallurgical analysis was performed on the failed and adjoining tubes. Possible contributing factors were considered. Metallurgical analysis results are consistent with the cause identified. Recommendations are shared on promptly recognizing this type of failure, shut down precautions, and prevention.

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Introduction

PCS Nitrogen Fertilizer LP operates a 2425 stpd (2200 mtpd) ammonia plant at Augusta, Georgia, USA. The plant was started up in 1978 with a capacity of 1500 stpd (1360 mtpd) and has been debottlenecked in several steps. During a maintenance and expansion turnaround in 2012, the 1500 psig (103 barg) process waste heat boiler was replaced with a new larger boiler designed by KBR. This boiler cools secondary reformer effluent by steam generation. The process effluent feeds the high temperature shift converter (HTS).

Process Boiler Installation

The process boiler uses forced-circulation of water on the tube side, and a rod baffle design to minimize the process pressure drop on the shell side. Please refer to figure 1. The tube count is 708 one inch U tubes and the design duty is 336 MMBtu/hr (98.5 MW). Design vaporization is 20% by weight of the circulating water. The exchanger has a removable bundle of U tubes and...
is mounted vertically with the tube sheet at the top. Shell side flow is single pass. The tubes are Inconel 625 based on our very good experience with its resistance to metal dusting in this service. The operating steam to carbon ratio is 3.0 mol/mol. The exchanger has internal refractory lining on the shell side.

Start up was normal and the exchanger achieved the expected performance for heat duty and pressure drop.

**Failure symptoms**

On November 24, 2013 the following symptoms were observed by the operations team:

1) Sudden 20% drop in high pressure steam generation. This caused loss of speed on the syngas turbine and high syngas compressor suction pressure.

2) Drop in high temperature shift converter inlet temperature from 662 F (350 C) to 605 F (318 C).

3) High level in process condensate separator upstream of the CO2 absorber

4) Initial drop in level in the CO2 stripper, after which the level lined out

5) Drop in phosphate level in the continuous high pressure steam drum blow-down

6) Presence of phosphate in a process condensate sample taken upstream of the HTS vessel.

The drop in high pressure steam generation was caused by the quenching effect of a major boiler circulation water leak into the process. Based on a heat balance, the BFW leak into the process was 122,000 lb/hr (55.3 mt/hr)! The leak also caused the drop in the HTS inlet temperature of 57 F (32 C). The high level in the process condensate separator was also caused by this additional water. The leaked water was vaporized before the HTS but was then condensed in the CO2 reboilers. This extra condensate was separated in the process condensate separator and overloaded the process condensate pump, resulting in high level.

The condensation of this water in the CO2 reboilers increased stripping steam and caused the initial loss of solution level in the CO2 stripper. The level became so high in the process condensate separator that condensate carryover developed into the CO2 absorber. This led to the sta-
bilitation of the solution inventory in the system as shown by the CO2 stripper level lining out. The condensate carry over offset the additional boiling and the stripper level stabilized.

The high pressure boiler chemistry is monitored by analyzers on the continuous blow-down from the steam drum. The analyzer showed low phosphate indicative of excess blow-down which was occurring through the leak into the process. The operators pulled a sample of process gas upstream of the HTS vessel, condensed the process steam in the sample, and tested for phosphate. The presence of phosphate indicated a leak of boiler circulation water into the process.

The operations team was able to stabilize the plant and steam system, and plan an orderly shutdown to repair the major leak.

**Shutdown precautions**

It was essential to prevent the leaking boiler circulation from backflowing into the secondary reformer or carrying forward into the HTS vessel. We also wanted to minimize wetting of the refractory lining in the process boiler and secondary reformer. Although HTS catalyst can tolerate some wetting, our experience was that hot secondary reformer catalyst is damaged when quenched with water. The result is higher pressure drop on the secondary reformer. The following precautions were taken to prevent the leaking boiler circulation water from reaching either the secondary reformer catalyst or HTS catalyst during the shutdown:

1) Prompt opening of all available drains around the secondary reformer, process boiler, and HTS vessel
2) Prompt pressure reduction of the 1500 psig (103 barg) steam system to reduce inflow of boiler water through the leak into the process side of the boiler
3) Modification of the normal post shutdown process purging procedure. Once the steam system pressure was equalized with the process pressure, the leak would stop. Normally during shutdown the process is fully depressured and purged three times with nitrogen. This removes process steam and flammable gases, after which the process can be placed under low nitrogen pressure. This procedure was modified to pressure up just once with nitrogen and hold the nitrogen pressure until the steam system pressure was lower than the process (nitrogen) pressure. This stopped the leakage as soon as possible.

These precautions were successful in preventing damage to the secondary or HTS catalyst. Augusta’s HTS converter is a radial flow design from Casale SA. The radial flow design, with its large flow surface area, is excellent protection from solids build-up due to boiler leaks. HTS pressure drop was unchanged as a result of the tube failure.

**Bundle removal and first inspection**

On removal of the bundle, a ruptured tube was found. Some minor damage was also visible to a few tie rods and rod baffle attachment welds. This was likely due to thermal stresses in the bundle caused by the large leak and local quenching effect.

Several pieces of debris were found on the inlet tube sheet. In addition to some spiral wound gasket media and some loose weld slag, we also found two thin carbon steel strips. One was 3” x
1” x 3/16” (75 mm x 25 mm x 5 mm) and the other was 1-1/2” x 1” x 3/16” (38 mm x 25 mm x 5 mm). Each of the metal strips showed some wear. The longer strip showed two faint but distinct wear circles the same diameter as the tubes. Two half circles were faintly visible on the smaller strip. It was apparent that these strips were sitting on the inlet tube sheet and blocking boiler circulation flow into the tubes on which they rested. The strips must have sat there for some length of time for the wear patterns to develop. The tube to tubesheet welds create slight ridges on the tube sheet at the inlets of the tubes. These ridges had worn slightly into the metal strips. The wear patterns can be discerned in the photograph.

Figure 3 - debris found on tube sheet showing imprint of tubes

Since the steam drum internals were modified during the turnaround when the new boiler was installed, we carefully reviewed the drawings for any components of the approximate size of the two metal strips found. There were no matches, so the source of the metal strips is unknown at present. During the next turnaround, we will inspect the steam drum internals for any missing or loose pieces.

Precautions taken during restart

The plant was down for five and a half days to remove the damaged tube bundle, inspect the internal refractory lining, install the spare bundle, and restart the plant. The internal refractory lining was in excellent shape and withstood the quench water flow well.

We were fortunate to have a spare bundle on site. If we did not have a spare, we would have conducted a field eddy current inspection of each tube. The damaged tubes would have been identified, plugged, and the exchanger returned to service. The duration of the outage would have been longer.

There was potential for water exposure to several process areas: Secondary reformer catalyst and refractory lining, the refractory lining of the process boiler, the HTS catalyst and potentially even the low temperature shift (LTS) catalyst. The leak would have created extra process steam and raised the LTS vessel inlet dew point, possibly resulting in wetting of this catalyst as well.

We followed vendor’s recommendations by conducting a dry out procedure as part of the start up. Nitrogen was circulated using the feed gas compressor. This was accompanied by gradual heating and holding as water was recovered in the suction separator for the feed gas compressor.

After start up, we checked for the presence of any new hot spots on the shell of the process boiler – none were found. This indicates the refractory was not significantly affected. Catalyst pressure drops also appear to have been unaffected.

Bundle inspection and repair

The bundle was transported to the vendor’s shop for thorough inspection and repair. An eddy current technique was used to inspect each U-tube. This inspection found one bulged tube adjacent to the failed tube. No other tubes showed any damage or defects. Finding a damaged tube adjacent to the failed tube is consistent with the wear pattern on the longer strip. It appears the strip was blocking these two tubes, resulting in damage to both and eventual failure of one.

Each U-tube was also pigged in the shop to ensure that there was no debris lodged in any tube.
PCS Nitrogen’s representatives worked in concert with specialists from KBR to develop a plan to repair the minor tie rod and rod baffle weld damage. PCS Nitrogen elected to replace the two damage tubes. This would require removing and replacing 44 tubes to gain access to the damaged tubes. All repairs were performed in the vendor’s shop.

Metallurgical failure analysis

Samples of the failed tube and some tube sections from undamaged tubes were submitted for metallurgical analysis. The samples of undamaged tubes came from tubes that were removed to gain access to the damaged tubes.

The metallurgical analysis was performed by IMR Metallurgical Services of Louisville, Kentucky, USA. The chemical composition and average wall thickness were consistent with the design specifications for the tubes, specifically Inconel 625 Grade 1 annealed tubing with 0.080 inch (1.27 mm) average wall thickness. Tensile strength was tested and found to be good. Tube hardness was slightly higher than expected, but a ductility test showed the ductility was adequate for the bending needed to make the U-tubes. IMR concluded there were no fabrication or material deficiencies in the tube samples.

Unusual failure mechanism

At first glance the failed tube appeared to have suffered a fish mouth rupture very typical of severe overheating. Closer examination revealed that substantial thinning had occurred prior to the failure, and that the failure itself was brittle in nature. IMR reported that heavy deposits were found in the failed area of the failed tube. Deposit depth in sound tubes was minimal and as expected for this service. IMR reported that corrosion associated with the deposits caused the tube thinning which led to the tube failure. This is supported by our own stress calculations based on the observed thickness at the failure site and expected temperature.

The blockage at the tube inlet must have been partial, and not complete. Deposits were formed where the combination of low circulation water flow and high heat flux produced higher than intended vaporization. Corrosion associated with the deposits gradually thinned the tube until the brittle failure occurred.

Lessons Learned

We suggest that operations teams review together the symptoms of secondary reformer effluent
process boiler leaks, so they can be promptly recognized and a quick but orderly shutdown can be executed. Not all leaks will be as severe as the one described here, but when several of the six symptoms listed above are found, a leak is indicated.

Operations teams can also review and plan the precautions to be taken during shutdowns when a leak is evident or suspected. This will help avoid damage to refractory or catalyst. Occasional checking of drains is also needed since they have a tendency to plug with loose refractory or catalyst dust. With appropriate safety precautions, plugged drains can be cleared with the plant on line. These process drains will be essential during shutdown should a leak occur.

After any piping or convection coil modifications, we suggest using temporary strainers in the pump suction of forced-circulation boiler systems _even when careful flushing has been planned and executed_. It is seldom possible to flush with water velocities as high as normal operation, so debris not removed during flushing may find its way to the inlet tubesheet area and cause boiler damage due to restricted flow. After our leak, as a precaution, we elected to install temporary strainers in our circulation pump sucktions. These will be removed next turnaround if they are found clean.

It is also possible to include a permanent debris strainer or basket in the design of a process boiler. Such a strainer or basket would be located in the exchanger channel just prior to the inlet tube sheet. Its advantage is its permanent location and the fact that it is downstream of all piping, and can catch any debris, including debris originating downstream of the circulation pump.

In a new plant design, a forced-circulation boiler could have a vertical orientation with the channel/tube sheet on the bottom and the U tube bends at the top. Any loose debris that entered the channel would sink to the bottom, and not block any tubes.

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