To Minimize Risks of Catastrophic Failure in Urea Plant Process Lines Requires RBI Methodologies

In the high pressure synthesis section of a urea plant the prevailing process conditions (ammonium carbamate solutions) are highly corrosive, which poses a potential risk for catastrophic failure. However the structural integrity of process equipment and piping is also compromised from outside: atmospheric corrosion and corrosion under insulation.

In urea plants, HP equipment are inspected on regular basis during planned turnarounds, however the interconnecting HP process lines specific and piping systems in general, do not always get the same attention. This lack of attention is not justified, as is demonstrated in three cases. A more systematic approach is needed covering the total life cycle of piping systems, based on a RBI methodology.

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Introduction

It is well established in the chemical industry that the failure of pipelines is more likely to occur than the failure of static process equipment [1].

The main reason is the fragmentation of responsibilities throughout the total life cycle of pipelines; i.e. different groups are responsible for design, construction, operation, inspection, maintenance, modifications, repairs, and finally decommission. This is much more fragmentized compared to (critical) static process equipment. Another difference is the wide spread of pipelines across the plant, leading to difficulties in allocating responsibilities, especially when pipes crosses boundaries of plants. Finally it is almost impossible to do internal visual inspections of pipelines (as compared to many static process equipment), which makes integrity assessment of piping much more difficult. Inspection of pipelines should therefore focus on the highest risk areas using techniques such as Risk Based Inspection (RBI) methodologies.

Understanding of the failure modes in this respect is of paramount importance. Especially in the high pressure synthesis section of a urea plant the prevailing process conditions (ammonium carbamate) are highly corrosive, which poses a potential risk for catastrophic failure. However, the structural integrity of piping systems is also compromised from outside: atmospheric corrosion or corrosion under insulation.
These risks are managed by selecting and developing appropriate corrosive resistant construction materials, selecting adequate welding methods during fabrication, application of coating system and insulation, scrupulous quality control, application of corrosion control and monitoring systems during operations, as well as applying effective inspection and maintenance programs during the entire service life of the plant.

In urea plants, HP equipment are inspected at regular intervals during planned turnarounds, however the pipelines, also the critical HP process piping, in general get less attention by plant management. This is not justified, since catastrophic failures of critical pipelines in the HP urea synthesis section do happen, as is demonstrated in three cases below.

This lack of attention calls for a more systematic approach to minimize the risks of catastrophic failure of piping systems in urea plants. Based on experience, Stamicarbon developed specifications, guidelines and recommendations for the different phases of the life cycle of pipelines in urea plants, as presented in table 1. These specifications contain proprietary information and are only available to licensors of Stamicarbon urea plants.

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*Table 1: Overview of Stamicarbon specifications, requirements for piping systems in urea plants*

Stamicarbon also developed a Risk Based Inspection (RBI) system using a so-called “Plan - Do - Study - Act (PDSA)” cycle as commonly used in Total Quality Management [2]. The Plan phase concerns the preparation of inspection and monitoring programs on the basis of a criticality ranking depending on the failure mechanisms identified. The Do phase covers the implementation of the program and recording of observations and failures. The Study phase comprises the evaluation and analysis of the results of the program. The Act phase consists in adding fresh insights to the inspection and monitoring programs and to the documents, or databases, on which they are based; i.e. closing the circle.
1. Case histories

The next three cases describe catastrophic failures of pipelines in urea plants. It is of importance to assess the root cause of the failures and to incorporate the lessons learned in one or more phases of the total life cycle.

Case 1: Failure of HP gas pipeline

The first case is the catastrophic failure of a HP gas pipeline between the urea reactor and the HP Scrubber in a urea plant (see Figure 1).

![Figure 1: Catastrophic failure HP gas line](image)

The failure is a result of material weakening due to stress corrosion cracking (SCC) starting from process side (inner pipe surface) (see Figure 2). In this particular urea plant, several upset conditions preceded the catastrophic failure of the HP gas pipeline. The failure occurred during normal operations and fortunately no persons were injured or killed.

![Figure 2: Longitudinal crack in pipe](image)

The upset conditions resulted in fouling of the synthesis equipment and piping with a hard crystalline deposit.

Cleaning was done by condensate flushing as well as by mechanical means. After cleaning, inspections were carried out on the fouled HP equipment; however, the affected pipelines were not checked!

Metallographic investigations showed unambiguously the presence of stress corrosion cracks starting for process side (SCC). Most probably the stress corrosion cracking is related to the upset conditions. Finding the root cause is of importance in order to define and implement the appropriate counter measures. This is still under investigation.

Case 2: Failure of a drain line header

During normal operations of a urea plant, the header of the drain system of the high-pressure synthesis section ruptured causing a release of a huge amount of liquid spilled over the grade floor. Mainly urea solution was spilled as well as release of ammonia gasses. Three persons needed first aid care, however no fatalities were reported.

Material of construction of the drain system is a 316L UG quality.

The drain system is equipped with several drain valves (316L UG material). In this urea plant the drain system is kept under pressure with water during normal operations (pressure higher than the synthesis pressure). In this particular case, one of the drain valves was leaking (see Figure 3).
Figure 3: Drain system indicating leaking drain valve and location of pipe rupture

The leaking drain valve was maintained several times during planned turnarounds but the said valve kept leaking. Since the drain system was kept under over-pressure, the leak was not noticed during normal operations. Due to this leakage and despite the overpressure in the drain system, carbamate solution could enter the drain system. This resulted in stagnant carbamate conditions. Since the drain system was traced, ideal conditions were present for carbamate corrosion at the hot spots (steam tracing in contact with the drain line). Due to local wall thinning, the weakest point eventually ruptured.

A root cause analysis was carried out and following counter measures were implemented:
- In this particular plant the existing drain system (material of construction: 316L UG) is replaced by a higher corrosion resistant material (resistant for stagnant carbamate solutions) Safurex®.
- Stamicarbon changed in the process design the material of construction of drain systems including drain valves into Safurex®.

- Drain system in this particular plant is included in the regular inspection program.

Case 3: Failure weld-o-let HP pipe

Two weeks before a planned shutdown of a urea plant, a leak occurred in the weld-o-let (see Figure 4) of a thermo-well located in the HP pipeline between the urea reactor and HP Stripper. The urea plant was for more than 20 years in operation.

Figure 4: Schematic sketch of leaking weld-o-let

The pipeline carries a urea – carbamate solution with a temperature of 183 °C and pressure of 140 bars.

In order to keep the plant running until the planned shutdown it was decided by plant management to temporarily repair the leak. During this repair activity the weld-o-let ruptured suddenly, killing and injuring several persons.

The weld-o-let ruptured due to severe corrosion (see Figure 5).

To assess the root cause of this failure, metallographic examination was carried out.
The investigation revealed that the leakage and subsequent rupture of the weld-o-let occurred due to severe intergranular corrosion in the heat affected zone of the weld.

The microstructure of the weld-o-let was found to be normal. However the Chromium content of the material was 15.3 % which is far below the required 17% according Stamicarbon specification for a 316L urea grade material (which was specified). The low Chromium content in the base material resulted in a too low corrosion resistance under the prevailing process conditions.

Apparently during construction of the plant a weld-o-let with the wrong material quality (316L instead of 316L UG) was installed. Since this kind of mistake can never be ruled out, Stamicarbon advises plant owners to investigate corrosion of weld-o-lets in aging plants. A non-intrusive in-service inspection is possible using on-stream radiography (see Figure 6).

Also it is strongly advised not to do a temporarily leak repair in the high pressure urea synthesis pipelines. This case study also demonstrates that a PMI check should be part of the QC program during erection of the plant as well as to be incorporated in a mechanical integrity program.

2. Risk Based Inspection approach

The RBI method is aiming to prioritize items for inspection based on a criticality rating. Criticality is a combination of the failure probability and the effects of failure. Assessment of failure probability starts with listing all possible failure modes. The next step is to estimate the probability of failure. The effects of failure may refer to both the economic consequences, such as plant outage and repairs, as well as safety, health and environmental effects, such as injuries and pollution.

After prioritizing the components, the next step is to develop an inspection and monitoring program. One of the most difficult aspects in this phase is to determine the maximum allowable inspection interval.

3. RBI approach for pipelines in urea plants

To establish the criticality of the pipelines in urea plants a stepwise approach is suggested. The first step is to analyze the criticality from process point of view.
Subsequently, the pipelines should be prioritized with respect to the risks related to atmospheric corrosion and corrosion under insulation (CUI).

In the next paragraphs, the analysis is limited to the critical HP process pipelines in a urea plant. This assessment should be carried out by a team of experts of different disciplines within the company. As a minimum requirement, following experts should participate in a RBI team:

- Operations
- Maintenance
- Inspection
- Engineering (piping, civil)
- Procurement

The team should be facilitated by an expert on RBI methodology. Also it should be considered to invite contractors involved in maintenance of pipelines, especially involved in painting and insulation work.

### 3.1 Risks from process side

In urea plants carbon steel as well as stainless steel materials are used for the process pipelines. Carbon steel piping (ammonia liquid lines) is normally not insulated but coated to combat atmospheric corrosion. In urea plants all piping carrying process media containing carbamate are constructed in stainless steels grades such as 304L, 316L UG, X2CrNiMo25-22-2 or Safurex®. From the process point of view (to avoid crystallization) and from the corrosion point of view (to avoid condensation of gasses), almost all process piping are insulated and or traced.

The following process media are present in urea plants:

- Liquid ammonia
- Carbon dioxide gas (dry and wetted)
- Carbamate, urea, ammonia, water solutions
- Ammonia, water, carbon dioxide, inert gas mixtures.
- Ammonia water
- Urea melt solutions

Furthermore the process streams my contain contaminants such as for instance Chlorides and Sulfides, which has to be considered in the failure mode analysis.

Possible failure modes which can be identified in urea plants are:

- Passive / active (overall) corrosion in ammonium -carbamate water solutions, especially in the synthesis section where higher carbamate concentrations and higher temperatures prevail. Passive corrosion of a 316L UG stainless steel is typically ~ 0.15 mm/y; active corrosion can be as high as 100 mm/y! Important is to keep the stainless steel in a passive state by adding oxygen to the process.
- Condensation corrosion in the gas phase. Normally in the gas phase corrosion will not occur in presence of ammonia, carbon dioxide and water vapor. Upon condensation at the stainless steel surface, an aggressive liquid film will form resulting in corrosion which is typically two to three times higher compared to the passive corrosion rate observed in the liquid phase. Condensation in gas phases should therefore be avoided. An example of condensation corrosion is presented in Figure 7.

Figure 7: Condensation corrosion in the gas outlet line of a HP Stripper (316L UG material)

- Crevice corrosion in carbamate solutions. Severe corrosion will occur due to the depletion of oxygen in the crevice.
• Pitting and Stress Corrosion Cracking, due to contamination of Chlorides, Sulfides in the process stream.
• Stress Corrosion Cracking by liquid ammonia in carbon steel pipelines; risk of this failure mode depends strongly on the quality of the carbon steel, presence of oxygen (accelerating) and water (inhibiting).
• Corrosion of carbon steel by wetted carbon dioxide.
• Mechanical vibrations, fatigue, mechanical wear at supports.

In analyzing the criticality, the highest risks prevail in the high pressure synthesis section. For two reasons:
• High pressures and presence of large amount of ammonia
• Highest temperatures increasing the corrosiveness of the carbamate solution.

In the low pressure downstream sections of the urea plant (recirculation section, evaporation section, and waste water treatment) the corrosiveness of the process media is low or even non-existent.

3.2 Risks for atmospheric corrosion and CUI

Forms of atmospheric corrosion and corrosion under insulation (CUI) are:
- Crater type corrosion of unprotected carbon steel and at damaged areas of coated carbon steel piping. An example is given in Figure 8. Severe corrosion occurred in an ammonia pipeline passing through a concrete floor. The coating was damaged by the clamp and corrosion was accelerated by water spillage.

Figure 8: Severe corrosion of NH3 pipeline in a urea plant due to atmospheric corrosion; coating damaged by clamp

- Crevice corrosion at supports of carbon steel piping.
- Stress corrosion cracking due to nitrides in carbon steel pipelines.
- Stainless steel piping under insulation can suffer from chloride stress corrosion cracking.
- Stainless steel piping can suffer from Chloride stress corrosion under c-steel clamps, supports and in direct contact with c-steel steam tracing.
- Corrosion by intermitted use of pipelines.

A pre-requisite for corrosion under insulation is the presence of an electrolyte; i.e. moisture at the pipe surface. A defect in the insulation sheeting may result in moisture to migrate to the pipe surface.

Beside rain fall the following sources of moisture are possible such as for instance:
- Vapor resulting of “breathing” due to cyclic temperature changes
- Cooling tower
- Fire fighting drills
- Water cleaning
- Steam vents
- Leakages (tracing)

Critical areas for CUI are:
- Penetration of jacketing at supports, valves, fittings, …
- Damaged insulation sheeting
- Wrong installed insulation sheeting
- At lowest point in vertical pipelines
- Other areas such as:
  - Exposed to water sources
  - Leaking tracing
  - Deteriorating coatings
  - Cold service equipment (see Figure 9)
  - Intermittent service (see Figure 9)
  - Vibrations inflicting damages to jacketing
  - Damages to jacketing by personnel (i.e. during shut down)

Eliminating insulation will drastically lower the risk for atmospheric corrosion.

Step 3: Is piping system coated under insulation?
Coated piping have less risk for CUI compared to uncoated. However, experiences show that the application of coating systems is often not in accordance with the specifications and guidelines. This may result in same corrosion risks and problems as for non coated pipelines.

Step 4: Criticality assessment
After prioritizing the piping system with respect to risks for CUI the final step is a detailed criticality assessment, by analyzing the likelihood and consequences of the failure.

4. Inspection strategies and methods

Based on the critical assessment, the pipelines are prioritized and the next step is to define an inspection and maintenance program, as well as a mitigation plan.

Several inspection strategies or combinations thereof are possible to deal with the wide spread of pipelines across the plant, the often difficult accessibility of critical areas, the presence of insulation and very limited assess ability for internal (visual) inspection, such as:
  - Removal of the insulation
  - Inspection through the insulation
  - Combination of both

The choice of inspection method is determined by:
  - Availability and reliability of inspection method
  - Pipe material and insulation thickness
  - Damage and repair history
  - Purpose of inspection; survey or damage evaluation
  - Accessibility
  - Economics

Figure 9: Cold intermittent service of bypass of a 10” valve of ammonia Jetty pipeline

With respect to atmospheric corrosion and CUI following steps are proposed in the RBI analysis [3].

Step 1: Only insulated piping systems operating in the critical temperature range for CUI has to be considered. Critical temperature range for:
carbon-steel is: \(-4 \, ^\circ\text{C} < T < 175 \, ^\circ\text{C}\)
Stainless Steel: \(50 \, ^\circ\text{C} < T < 175 \, ^\circ\text{C}\)

Step 2: Challenge the need for insulation. If insulation is not needed from process point of view, from corrosion point of view or from process safety point of view one may question the need for insulation. Examples are:
  - Personal protection
  - Noise control
4.1 Inspection methods

When insulation is removed, traditional Non Destructive Testing (NDT) methods are the best choice, such as Dye Penetrant Test, Magnetic Particle Test or Ultrasonic measurements.

With respect to non intrusive surveys of insulated piping systems several methods and techniques are available, such as for instance:

- Profile Radiography
- Flash Radiography (see Figure 10)
- Real time Radiography
- Digital Radiography
- Guided wave Ultrasonic’s
- Pulsed Eddy Current
- Infrared Thermography
- Neutron Backscattering

Also new techniques are under development for non-intrusive pipe surveys [4].

Examples specific for urea plant pipelines are presented below.

5. Mitigation strategies

Besides having an effective inspection and maintenance program, risks of corrosion in the piping systems can be mitigated by several other control parameters. Precautions can be applied in several phases of the life cycle of piping systems, such as for instance in the design phase, or during operations.

5.1 Process related failure modes

Mitigation strategies in urea plants are for instance (but not limited) the following:

- Supply of 0.6 vol% of oxygen to the synthesis section to keep the stainless steels process lines in a passive corrosion state.
- Application of insulation and/or tracing to avoid condensation corrosion in gas lines.
- To avoid moisture in carbon dioxide gas in carbon steel piping or to change the material of construction into stainless steel.
- Supply water and avoid ingress of oxygen in liquid ammonia to minimize risk for SCC in the carbon steel piping.
- Avoid contamination of Chlorides and Sulfides to reduce risk for pitting corrosion and SCC in stainless steel process lines.
- Avoid dead pockets and stagnant conditions in process lines.
- Avoid crevices.

5.2 Atmospheric and corrosion under insulation

- Apply an appropriate coating system on insulated stainless steel pipelines.
- Supervise the coating application and insulation works to guarantee quality.
- Apply more advanced coating systems on carbon steel pipelines, such as aluminum by thermal spraying technique.
- Apply insulation material for stainless steel piping having less than 10 ppm Chloride.
- Avoid direct contact of c-steel tracing on stainless steel by using spaces.
- Wrap stainless steel pipelines with aluminum foils to prevent Chloride Stress corrosion cracking.
- Wrap the stainless steel pipeline with glass fiber tape or non-absorbing PTFE at carbon-steel supports, clamps, etc.
6. Implementation

A very important pre-requisite for the successful implementation of the developed inspection and maintenance program is the awareness by plant management and plant operators on the risks involved for piping systems in urea plants, especially with respect to atmospheric corrosion and corrosion under insulation. Also responsibilities must be clear between all stakeholders.

Some considerations in this respect are:

- Atmospheric corrosion and corrosion under insulation should have continuous attention of all parties involved. Damages of insulation or coating systems should be reported immediately and actions taken. Figure 11 shows an example where no action was taken to repair damaged insulation sheeting. Ingress of moisture not only resulted in growth of vegetation, but also increased the risk for corrosion under insulation.

![Figure 11: taken in an ammonia plant next to a urea plant](image)

- For economical and practical reasons spread out the inspection and maintenance program over several years; complete piping system cannot be inspected in one TA.
- Therefore an inspection program should be divided in on-stream inspection during normal operations of the plant and inspections to be scheduled in a planned TA.
- Especially after each TA, an inspection should be carried out to detect any damages, missing or wrong installed insulation on piping systems and repairs should be carried out immediately.
- Repair damaged coatings immediately; repair or application of a coating system should be done according the guidelines and recommendations of the vendor. Contractors should be instructed and inspection should be carried out during the coating and insulation activities.
- It is advised to start the inspection and maintenance program not later than 10 years after commissioning of the plant.
- Based on a thorough RBI analysis all critical areas will be identified for inspection. By experiences, this will be about 20 % of the total piping length. Inspection of these critical areas will reveal about 80 % of the corrosion problems.

More specific recommendations based on experiences in urea plants:
- Incorporate the HP synthesis drain system in the inspection and maintenance program; lessons learned from Case 2.
- Change the material of construction of the HP drain system including the drain valves into Safurex®; lessons learned from Case 2.
- Incorporate on-stream inspection of weld-o-leots installed in the HP synthesis loop by on-stream radiography; lessons learned from Case 3.
- Incorporate PMI checks in critical areas; lessons learned from Case 3
- Avoid metal – metal contact between carbon steel steam tracing and stainless steel piping; use spaces to avoid any hot spot; lessons learned from Case 2.
- Incorporate inspection findings, unexpected experiences in an updated inspection and maintenance program; close the PDSA circle; lessons learned from Cases 1, 2 and 3.
7. Conclusions and Recommendations

Piping systems in general get less attention in the (petro) chemical process industry, whereas the likelihood of failure in piping systems is higher compared to static process equipment. The main reasons are the fragmentation of responsibilities; pipelines are widespread across the plant and poor accessibility for inspections and maintenance of piping systems. Piping systems get even lesser attention when it comes to threats from outside; atmospheric corrosion and corrosion under insulation.

In urea plants the situation is not different. Even the HP process pipelines in general get less attention compared to the HP static equipment. The lack of attention is not justified, since the process conditions in this part of the plant are extremely corrosive.

The integrity of piping systems must be secured in all phases of the life cycle. An effective inspection and maintenance program should be based on a RBI analysis. New insights and lessons learned from failures should be incorporated in the RBI program.

Having a good RBI program alone will not guarantee successful risk management. Awareness and commitment of all stakeholders involved in the total life cycle of piping systems, including external contractors is a prerequisite for effective risk management.

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