Achieving Equipment Reliability through Understanding Precursor Failures[1]

The catastrophic or major incident is immediately investigated, but what about the near misses or precursors to major incidents? Are they investigated? Major failures often do not occur as one isolated issue or event; there are often less severe precursors to a major event. This paper presents a best practice and arguments for reviewing apparently minor ammonia plant failures in order to avoid major events as demonstrated through the judicious analysis of small equipment failures. Multiple small equipment case histories and the lessons learned from these failure investigations are presented to encourage investigation of what may initially appear as insignificant failures, for their value in prevention of major incidents.

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Introduction

Sites readily recognize the need for investigating hazardous incidents, and even the "near miss" or "close call" incidents as essential to maintaining their site's integrity. However, such "precursor" events that could also point to an impending hazard are sometimes not acted upon for a variety of reasons, particularly in the case of minor equipment failures, where the line between normal wear and tear and a looming hazard can be blurred. Certain equipment failures can provide valuable insight into active problems at plant sites that may not be immediately evident or understood. Investigating unexpected equipment and piping failures can reveal precursors vital to avoiding major safety or reliability incidents.

Using the example of small equipment failures, this paper provides insight into the benefits, barriers, and good practices for robust programs that access the value of understanding incurred failures in order to avoid future incidents. This paper is based upon API RP 585 - Pressure Equipment Integrity Incident Investigation, the developed practices of Koch Fertilizer, LLC in proactive incident investigation, and the process safety and mechanical integrity program and investigative resources of BakerRisk.

Identifying Precursors

A precursor is an event or circumstance that precedes a recognized failure incident. United States OSHA and the National Safety Council define a near miss as an unplanned event that did not result in injury, illness, or damage – but had the potential to do so. Only a fortunate break in the chain of events prevented an injury, fatality or damage.

Some process safety precursor events are closely related to operations, and are easily recognized by operators for their potential consequences, such as:

- Excursions of process parameters beyond critical control limits,
- Activation of layers of protection such as rupture disks, pressure relief valves, interlocks, and alarms, or
- Activation of emergency shutdown equipment.

Other issues are more related to maintenance or mechanical integrity issues, such as:

- Corrosion and or cracking, requiring repair,
- Piping leaks,
- Damaged flange sealing surface, bolt, or gasket requiring repair, or
- Worn packing to be replaced on a pump.

While an "emergency repair" for mechanical integrity issues may be recognized as a hazard consequence, mechanical issues may also be relegated to acceptance as normal maintenance issues to be addressed and the tendency is to "replace in kind" . For example, a cylinder was "replaced in kind", but the replacement cylinder had a sharp 90° angle at the corner rather than a rounded corner like the original. The sharper corner resulted in a stress riser that eventually cracked in operation; the cylinder was simply "replaced in kind" before the problem was recognized.
Sometimes higher priced material substitutions are done, driving up the cost, when the real cause is not known.

Failures can be precursors that reveal flaws in preventive programs where unexpected failures occur or are not understood. Without correction, a failure may occur multiple times, and with increasing risk of serious consequences. Risk from failure is often considered using two separate terms - the likelihood that a failure will occur and the consequence of a failure [1].

The likelihood that a major event will occur is greater when precursor events are not trended or understood. The consequence of an event may or may not be significant, but if the consequence is not even addressed, significant precursors could be missed. Without considering unusual conditions as potential precursors, failures or events can become accepted as "normal."

An ammonia plant operator can enable risk reduction by identifying precursor events and assuring that proper investigations are performed. To reduce the probability of a major incident, it is important to know how and why a smaller event happened. That information can provide valuable insight toward making a change to prevent a release or loss of containment.

Why Are Precursors not Investigated?

Although investigating precursors can be valuable, the ammonia industry can miss these learning opportunities for a variety of reasons, including the following:

1. Front-Line personnel are not informed as to what they should report and the hazard consequence that may result.

For small equipment failures, the input and feedback from front line maintenance or inspection personnel is critical. Maintenance personnel should be able to identify many potential precursors, but may not be able to, due to a gap in awareness or lack of reporting workflow process. Field or front line supervisory personnel may not understand what to look for or the need and method for reporting unusual conditions for further evaluation as precursors. Maintenance personnel may also be less likely than operators or technical support personnel to understand the hazard or consequence that can result.

For example: *Packing on a pump had to be replaced, but the instructions for proper installation were not clear and the consequence for a packing blow-out was not understood by the field personnel. The packing blew out, releasing ammonia into the work area.*

2. Management and Technical Support may exhibit limited vision when it comes to recognition of precursors. Management staff need to take on active roles to enact the workflow for precursor recognition:

    - By interfacing with front line personnel for gathering unusual conditions and acting with judicious follow-up.
    - By seeking precursors in their project, maintenance, reliability, and inspection programs, such as repeat or similar failures, or issues with a new vendor supply.
    - By taking on proactive leadership. Reporting of unusual conditions or precursors may not occur if items reported in the past have not been acted upon, the results of an inquiry were not shared—*perhaps due to liability concerns,* or if reporting has been discouraged.
    - By providing incentives when precursors are reported.

Management can encourage the reporting of unusual conditions at all levels! Ensure that reporting of an unusual condition is recognized as part of the job, that there is a workflow for a condition to be recognized as a potential precursor, and that the results of investigations and potential hazards flow back to the field in order to reinforce reporting of such events.

3. Not recognizing indicators of a potential problem: precursors are more readily recognized for investigation if unusual conditions are reviewed with a critical eye for certain precursors.

    - Precursors will have characteristics (depending on type) that can point to their value for investigation or consideration of the hazard.

As applied to small equipment failures, indicators or characteristics with more value for investigation include:

- Cracking mechanisms, such as fatigue or brittle fracture.
- Localized corrosion, including on welds.
- Overheating of piping and heater tubes.
- Damage mechanisms not picked up by the MI inspection program.
- Unexpected or premature failures.
- Failure of new equipment or designs.
- Failure of equipment obtained from a different vendor.
- Repeated failures on the same piece of equipment or its replacement-in-kind.
- Failures of a similar type or of similar equipment occurring in different areas.
- Hazard of loss of containment for the equipment.

4. Not recognizing patterns or trends: precursors can be missed where sites lack a method, personnel, or time for identifying how a number of small close calls or failures may be related.

Does your site do a review of close calls and incidents for patterns of failures? Who would conduct it? Does your site identify problem pieces of equipment, or "bad actors" and take action, or are these occurrences normalized?

For example: *An audit of incident investigations across a site revealed a number of piping-related failures. Fatigue cracking was identified as the typical failure mechanism, and potential causes for fatigue were identified. The resulting follow-up identified that pump foundations and pipe supports were generally in poor condition due to the age of the plant and environmental conditions, leading to excess piping vibration and failures.*

5. Lacking the desire to understand the cause: Precursors may not be evaluated because the value they provide is not available until the results are known. Where a failure is not understood, a gap in understanding has led to a gap in proactive preventive programs. If a failure is not understood, then facilities are left vulnerable to its repetition and the resulting impacts of such a failure.

6. Revealing precursor history: Concerns may arise about collecting information on precursor events, and such action may even be discouraged for a number of reasons, including:

   - Concerns that the investigation will result in inaccurate or un-resolvable situations: Good investigation and documentation techniques and appropriate technical support, such as failure analysis of failed small equipment parts, can provide real solutions with significant results, and help avoid the hazards of repeat failures. Proper investigation guidance avoids pitfalls, such as overly broad conclusions. If concerns arise regarding investigation recommendations, from a regulatory or liability standpoint, legal advice can be a valuable resource.
   - Concerns that outsiders may claim the site had knowledge of near misses, indicating an underlying unsafe condition at the facility. However, the lack of precursor/near-miss reporting may be an indication of gaps in investigation or training programs, and the consequences may be considerably more severe if a pattern of normalization of hazards is present.

7. Concern about time and cost constraints: Personnel from the front line to site managers may naturally avoid drawing attention to failures, particularly when short term costs and time constraints are pressing.

   - Investment in properly investigating precursor failures reaps cost and time benefits for making the right changes to avoid repeats or more serious incidents. Understanding this trade-off is a good incentive to support a training program on precur-

sor recognition, and management communicating its value demonstrates good leadership.

Recommended Investigative Approach for Precursors

There are effective tools and guidance provided to the industry for performing investigations. In 2014, API RP 585 - Pressure Equipment Integrity Incident Investigation, was issued to assist plants to investigate not only major incidents but just as important precursor events [2]. This document describes how an effective investigation could be structured so organizations can learn from Process Equipment Integrity (PEI) incidents. One driver for the API RP 585 was recognizing that smaller events were precursors to major events, but often precursors were overlooked and not investigated. This recommended practice highlights the value of investigating low and medium consequence pressure equipment integrity incidents. The goal is for everyone working in the mechanical integrity (MI) field to be able to conduct investigations on lower consequence incidents and near failures regarding pressure equipment loss of containment, so organizations can learn from smaller failures. Three levels of investigation are mentioned:

Level 1 is a simple 1-2 person investigation often with a low to middle consequence. The experience of the investigator and judgment is used to determine the cause. These investigations will utilize subject matter experts as needed to investigate and document the findings.

Level 2 is a small team that investigates medium consequence. More time is allowed to gather and analyze the data.

Level 3 is a major investigation with a large team of multiple disciplines which often involve gathering of evidence and conducting in-depth analysis over several weeks. Level 3 investigations are typically used for incidents that either already have, or have the potential for, significant or catastrophic consequences.

All three levels of investigation are intended to identify immediate cause and contributing causes. Level 2 and 3 investigations may be performed to identify the root cause using a structured Root Cause Analysis (RCA) methodology.

A decision has to be made when an event occurs. Figure 1 shows a decision tree flow diagram that illustrates the concept of reporting all occurrences and then deciding which have high learning value and should be investigated [3]. The flow diagram shows where precursors are being tracked and trended.

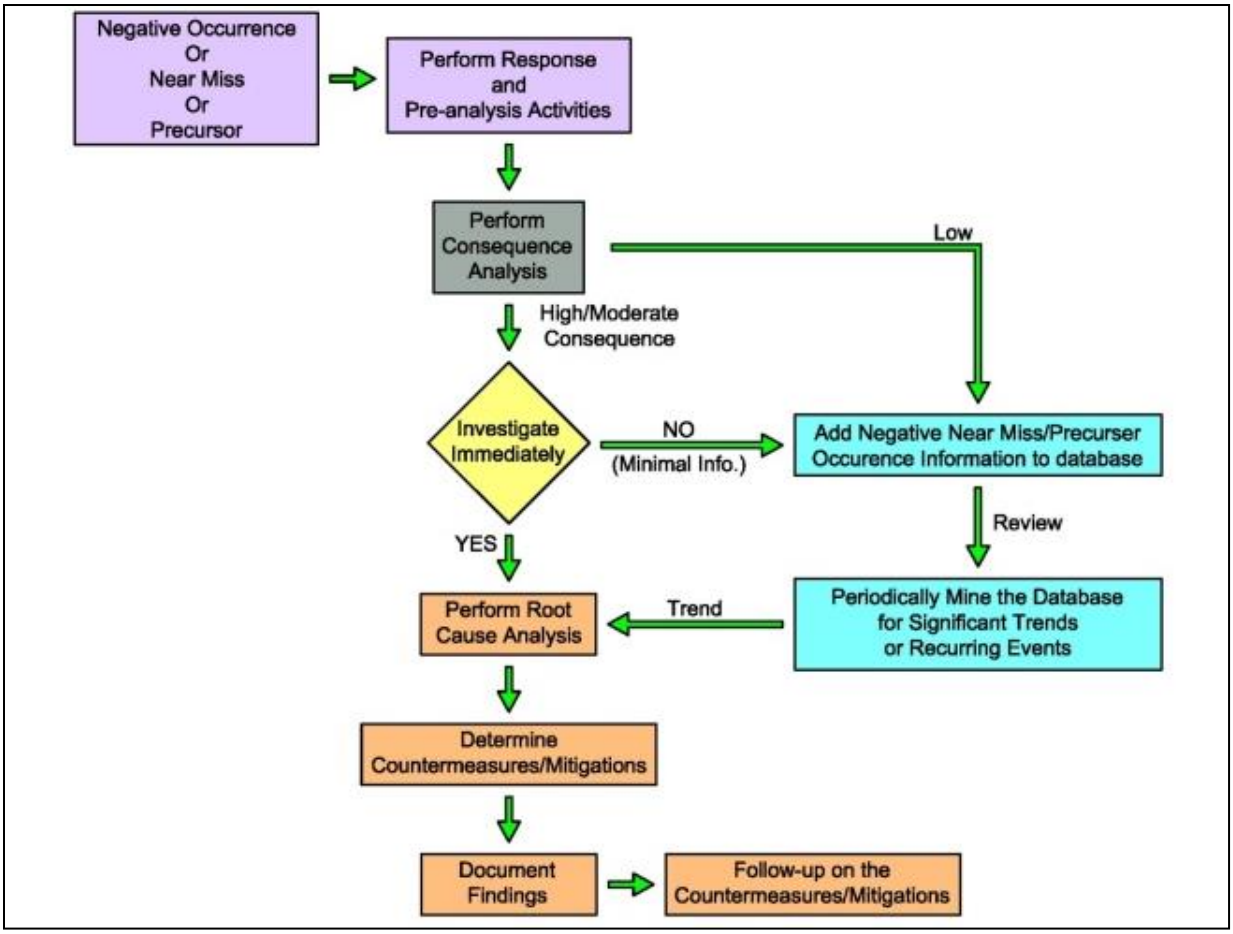

Figure 1. Decision Tree Analysis Approach

Koch Fertilizer's Approach to Precursor Events

In accordance with OSHA 1910, all incidents and precursor events that led or could have led to a major incident at Koch Fertilizer are reviewed by the management team and evaluated for further investigation.

Multiple elements of OSHA's PSM 1910 are involved in this process, including but not limited to; Incident Investigation, Management of Change (MOC), Mechanical Integrity, Operating Procedures, Process Safety Information (PSI), and Employee Participation.

Consequence Consideration:

At Koch Fertilizer, incidents or precursor events are investigated according to the potential consequence, such as impact to personnel safety, the environment, the surrounding community, property damage, or economic loss. These incidents can be a result of Equipment Failure, Human Interaction, Process Upset, etc., or a combination of any of the above. Using a Risk Matrix, the potential severity of the consequence drives the rigor of the investigation. More complex investigation tools, more experienced resources and management oversight are employed for higher potential incidents. The incident investigation findings and conclusions are used to drive the necessary changes to prevent future failures and avoid a major incident.

If an investigation is required, or desired based on potential risk and consequences, the incident is assigned to an owner with a deadline to com-

plete the investigation within 30 days from occurrence. Complex investigations that require more than 30 days to complete may be granted extensions by the plant manager or site leadership. The investigation owner is then expected to lead a team through the investigation, determining the contributing factors, and if possible the root cause. This is where an accurate failure analysis is important, as the actual cause of the incident is not easily determined in most cases, but proper identification can drive the required change that is needed, based on facts, not assumptions [4].

Koch Fertilizer's Decision Model

Koch Fertilizer uses the Market Based Management (MBM) 5 dimensions' process developed by Charles Koch, outlined in his book, **Good Profit**, [5] as a guide to determine how to investigate these failures. The MBM process helps ensure the appropriate action is taken, and the most value from any incident is captured.

These five dimensions are:

Vision**:** Using a risk matrix, Koch Fertilizer's team decides whether or not an investigation is needed to drive the required change to prevent major incidents.

Virtue & Talents: Koch Fertilizer assigns an owner to lead the investigation. Individuals with the appropriate virtue & talents are selected to lead the investigations, with the expectation of reaching out to anyone having the additional knowledge to properly investigate the incident.

Knowledge Processes: Koch Fertilizer assigns an owner to lead the investigation. Forms of programs and processes, such as PI Historian, equipment files, inspection data, process data, failure analysis, etc. can be utilized for investigating the incident. Koch Fertilizer utilizes investigation tools such as Cause Mapping or TapRoot®.

Decision Rights: Koch Fertilizer management gives individuals the authority to make a decision and the resources to complete the investigation. The decision rights that are given are to ensure the individuals have the required resources and authority to correctly evaluate the failure and implement the correct actions once the root cause is determined.

Incentives: The main incentive for Koch Fertilizer to complete the investigation is to ensure that Koch Fertilizer has no major incidents. Koch Fertilizer is continuing to address precursors to avoid a major incident.

Documentation and Trending:

Documentation of the event and the findings from the event are important, to check for any possible trends. Koch Fertilizer uses an incident tracking software tool for tracking all incidents; this tool shows all incidents that have occurred across all Koch Fertilizer facilities and can reveal whether there are certain trends occurring.

Implementing Findings: Once the findings are determined, Koch Fertilizer considers what required change is needed and then implements these changes. Preventative actions are also tracked in the software system to ensure completion. It is important that not only the root cause is determined but also the actions to prevent it from happening again. Examples of actions that could come out of the investigation are any of the items listed below or a combination of any of them. It is very important that the management of change process is followed while implementing these changes.

1) Revise Operating/Maintenance Procedures
2) Update Engineering Standards: "pipe specifications"
3) Update Process Safety Information
4) Revise Inspection Test Plans
5) Update Safe Operation Conditions and Limits(SOCL)/Trips
6) Ensure appropriate training and employee awareness of the change.

Precursor Case History Examples

The following four case histories are precursor events that happened at Koch Fertilizer. These cases would all be considered an API RP 585 Level 1 or Level 2 investigation that involved one or two staffers and a subject matter expert. These precursor events were evaluated based on the potential consequence and action was taken to investigate the cause for the event. At Koch Fertilizer, all incidents are evaluated using the Koch Fertilizer Combined Risk Matrix. The potential consequence is important to evaluate what could have happened. For these investigations, the actual causes were not obvious until a failure analysis was completed. The findings from the investigations were documented and the necessary actions were taken afterward.

Case 1- Erroneous Level Readings in a Vessel

Precursor Event: Erroneous level readings in the ammonia unit on the raw gas separator.

Potential Consequence: Unit trip, potentially causing harm to personnel and the environment.

Background on the Equipment: The titanium 3Al-2.5V float was in the ammonia unit, Equipment No. A1-LT-78B. The titanium float system is a magnetic level indicator that consists of a chamber and a magnet-equipped titanium float that raises and lowers with the fluid level. Koch Fertilizer operators reported problems with the float and erroneous level readings to site supervision. The titanium float, shown in Figure 2 was removed for investigation and was found cracked, as shown in Figure 3.

Figure 2. The titanium float

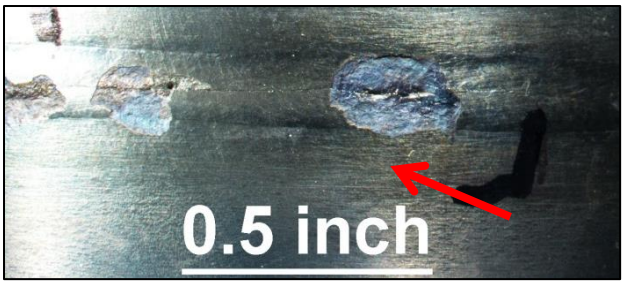

Figure 3. Close-up of the weld showing cracks

The typical operating temperature was 271 °F (133 °C), the typical pressure was 400 psig (2.8 MPa), and the process medium included: Water 10.4%, Hydrogen 54.7 %, Nitrogen 18.3 %, and CO_2 15.9%.

Findings: Metallurgical analysis determined that the cracking and spalling of the titanium float was due to the excessive pick-up of hydrogen [6]. The gas analysis of the weld region showed absorption of excessive amounts of hydrogen at the weld and heat affected zone. The weight percent of hydrogen was as much as 0.479% in the weld compared to 0.015 wt.% in the non-cracked sheet metal.

Hydrogen when present above specification can result in metal embrittlement, hardening, cracking and spalling due to the formation of hydrides in the metal.

The most likely source of the hydrogen was from the operation in a hydrogen, steam and ammonia environment. The areas where the most hydrogen was absorbed were at the weld and weld heat affected zones, likely due to residual stresses. These regions were also harder. Figure 4 shows the affected weld and HAZ.

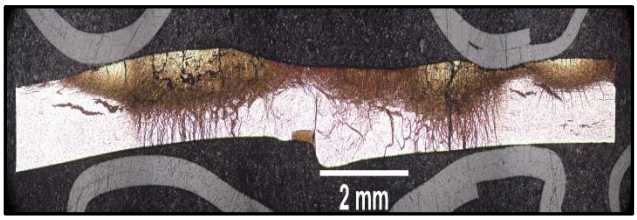

Figure 4. Cross section through the weld and HAZ showing the cracking and hydrides

Actions Taken: Because the titanium absorbed hydrogen, action was taken to include a design change by applying a PTFE (Teflon-like) coating over the titanium float to prevent the cracking from occurring. The manufacturer suggested that the PTFE be applied and were the ones that applied the coating; other materials were not considered for replacement.

Significance: Investigating this precursor event identified a gap within the specification process of wetted parts internal to instrumentation devices. A more thorough review of the specification process considering wetted parts internal to instrumentation devices has driven the correct change needed.

Case 2 – Lube Oil Leak from Braided Hose

Precursor Event: While completing regular rounds, an operator observed lube oil on the deck from the braided hose.

Potential Consequence: Lube Oil Fire on Syngas Compressor

Background on the Equipment: The Type 304 stainless steel braided hose, shown in Figure 5, was found leaking lube oil when the operator was conducting routine rounds. A lube oil leak was observed on the deck. The braided hose was connected to the syngas compressor.

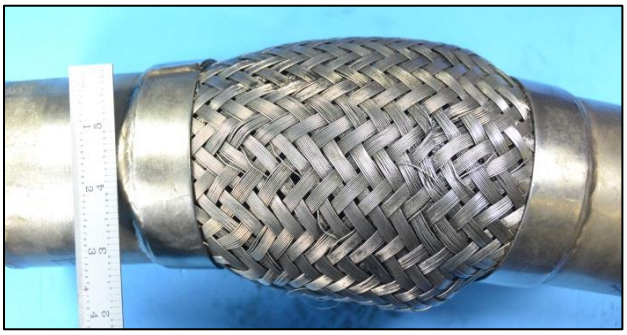

Figure 5. Stainless Steel Braided Line

The typical operating temperature was 105 °F (41 °C), the typical pressure was 108 psig (0.75 MPA), and the process medium included clean lube oil.

Findings: The braided hose with the internal bellows failed, due to the presence of a pinhole in the bellows [7]. The pinhole occurred due to mechanical abrasive damage to the bellows from the surrounding braid, which allowed lube oil to leak from the hose.

The braid that surrounded the bellows was removed so that the outside surface could be examined. However, visual examination of both the inside and outside surface of the bellows did not reveal a leak location.

To find the source of the leak, a simple water pressure test was performed on the braided hose. The pressurized bellows was sprayed with a soap solution in order to identify the location of the leak. A pinhole leak was found when the pressurized water left a water trail, as shown in Figure 6.

Figure 6. Pressurized water leak test showing the leak location

After removing the stainless steel braiding and examining the leak location, it was observed that some of the bellow convolutions had damage marks, as shown in Figure 7. This damage pattern matched the braid pattern. The exterior surfaces of the bellows show evidence of mechanical abrasive damage that occurred prior to the pinhole leak.

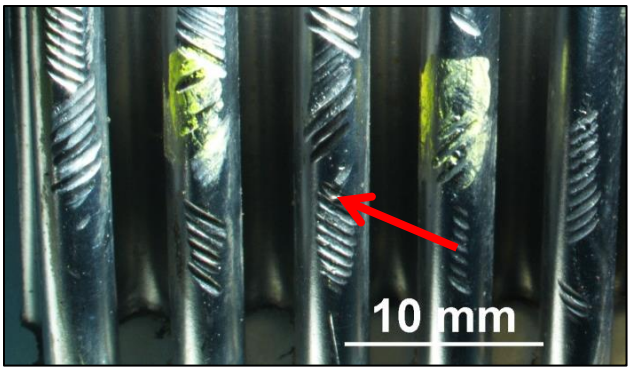

Figure 7. Mechanical damage on bellows convolutions. The arrow indicates the leak location.

The pinhole leak, shown in Figure 7, occurred on top of the bellows in one of the most damaged locations. The damage was nearly as deep as the bellows wall thickness of 0.025 inch (0.6 mm). Close-up images of the pinhole indicated the pinhole diameter was less than 0.1mm (0.004 inch), as shown in Figure 8.

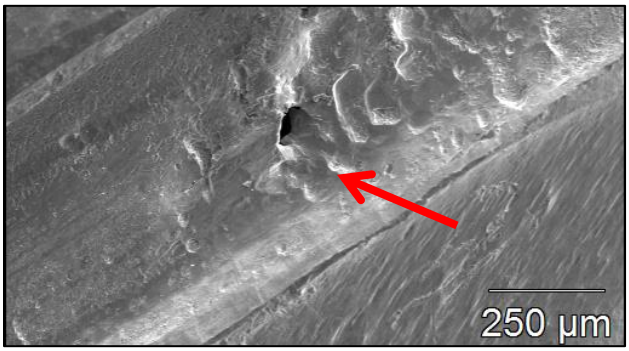

Figure 8. SEM image of the 0.004-inch (0.1mm) diameter pinhole

Actions Taken: Fretting occurred, likely due to how the braided hose was installed. The braided hose was likely not damaged by being stepped on because it was not in a walkway. Action was taken to modify the installation procedures to ensure the proper installation of braided hoses in order to prevent fretting of the bellows. Operators and craft personnel were trained on the new procedures.

Significance: The investigation of this precursor event identified the importance of proper braided hose installation. If not for the investigation, the potential for future leaks would still exist and an upgraded style of more costly braided hose would have been specified that would not have resolved the problem.

Case 3: Small Valve Leaking in Nitric Acid Section of UAN Unit

Precursor Event: Small valve leaking

Potential Consequence: Loss of containment of nitric acid, causing potential harm to personnel and the environment.

Background on the Equipment: At the UAN Unit of an ammonia plant, a Type 316 stainless steel valve, shown in Figure 9, was observed leaking at the location of the valve stem and the packing nut. The plastic handle was also observed deteriorated from the leaking.

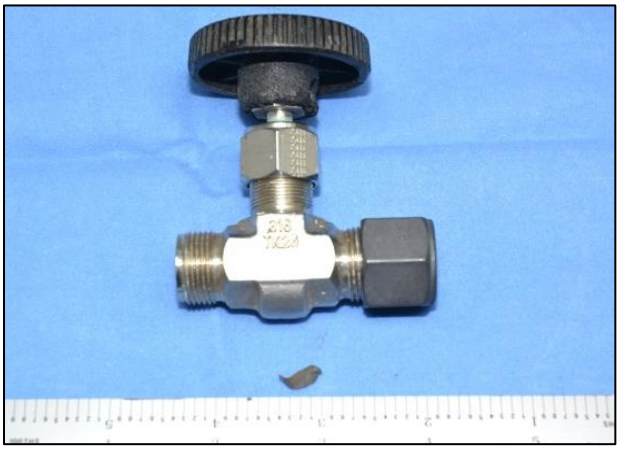

Figure 9. Leaking valve and metal fragment

The typical operating temperature was 114 °F (46 °C), the typical pressure was 126 psig (0.87 MPa), and the process medium included: Ammonia nitrate, water and nitric acid.

Findings: The valve leaked at the stem due to corrosive attack of a brass seal washer and PTFE (Teflon) seal wear [8]. Foreign metal found inside the valve may have affected valve tightening.

Figure 10 and Figure 11 show the cross section of the nut assembly and Teflon washer and the selective corrosive attack of the brass insert.

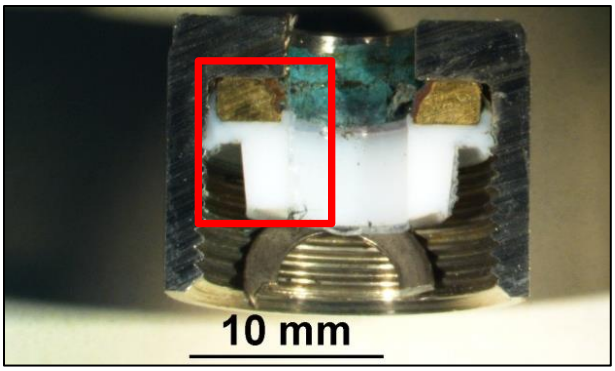

Figure 10. Cross section of the nut assembly

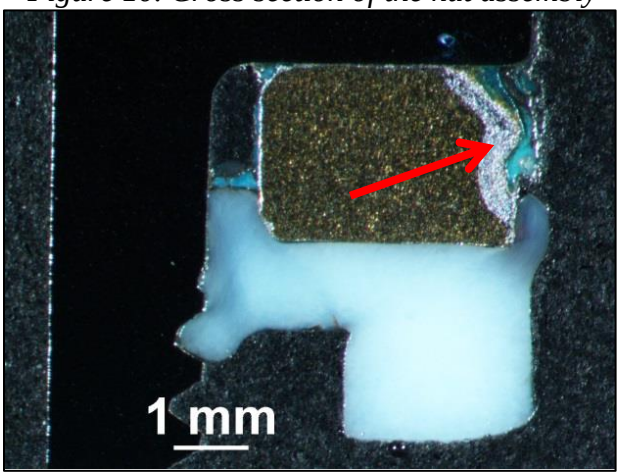

Figure 11. Cross section showing the selective leached region of the brass insert

Actions Taken: It was unknown that the valve had a brass insert. Action was taken to control the use of copper-based alloys such as brass in ammonia and nitric acid service.

The purchasing specifications were modified to clearly define that copper-based alloys are no longer allowed in valves.

Significance: The investigation of this precursor event helped identify the need to specify the correct internal parts of valves to prevent releases and prevented upgrading the rating of the valve, which would in turn drive costs up.

Case 4: Pressure Relieve Valve Leak

Precursor Event: Leaking Pressure Relief Valve

Potential Consequence: Release of Ammonia to the environment

Background on the Equipment: The pressure relief valve in the Ammonia Unit on the syngas loop recycle was found leaking from the vent. Figure 12 shows an illustration of the PRV. The PRV had only been in service less than a year. The pilot was sent for rebuild and replaced. During rebuild, the blowdown O-ring (arrow on the sketch in Figure 12) was found fragmented.

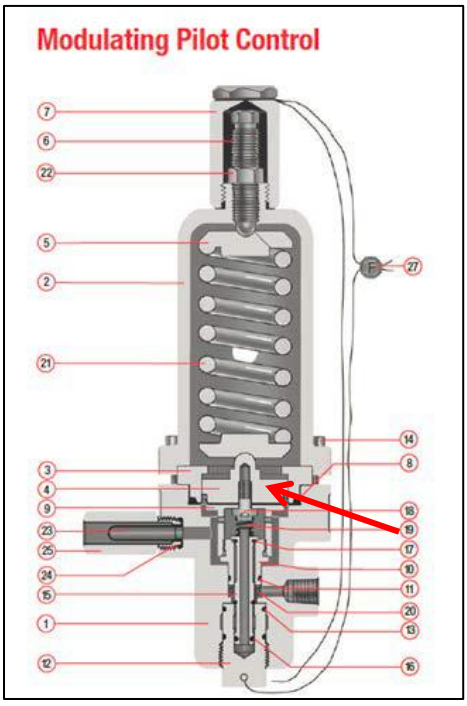

Figure 12. Illustration of the PRV and the location of the O-ring, arrow

The O-ring was specified to be ethylene propylene rubber (EPR). The damaged O-ring and remaining original O-rings from the pressure pilot valve were collected for analysis. Figure 13 shows the fragmented O-ring. The material on the filter was also collected for analysis.

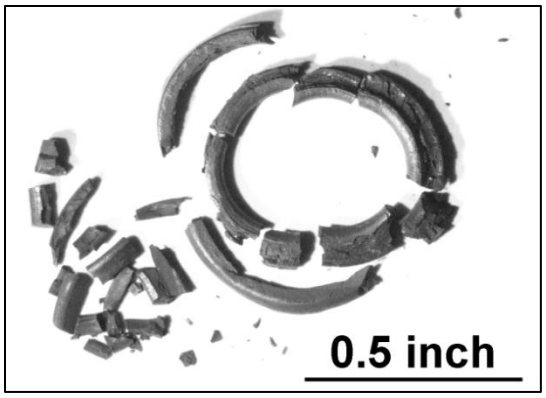

Figure 13. Fragmented O-ring

The typical operating temperature was 132 °F (56°C), the typical pressure was 1978 psia (13.6 MPa), and the process medium included: hydrogen, nitrogen, ammonia, methane, and argon.

Findings: Using FTIR, the O-rings were determined to be fluorosilicone type rubber, not the ethylene propylene rubber (EPR), as originally thought [9]. Additionally, these O-rings contained a large amount of inorganic filler. The primary failed item, known as the blowdown O-ring or seat seal, had become brittle and was deteriorated and fragmented. Figure 14 shows the brittle fracture features on one fragment. The other O-rings were generally soft and pliable.

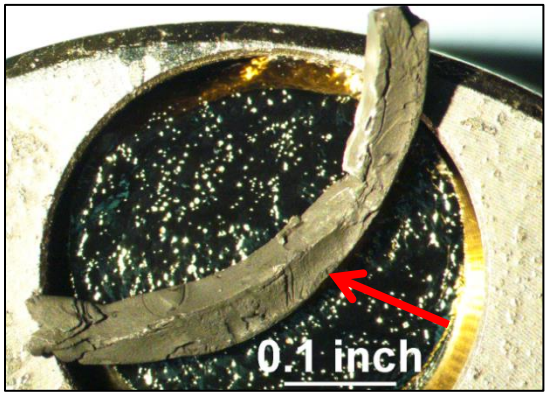

Figure 14. A fragment of the O-ring.

Bending a longer piece of O-ring resulted in a brittle fracture, indicating that the material had hardened and degraded. Analysis indicates the O-rings were not all of the same material. The specific cause of the embrittlement was not confirmed by testing, but it was probably due to either thermal degradation or chemical attack. Since the reported temperature of operation was too low to have caused thermal degradation, chemical attack is suspected. Fluorosilicone rubbers are not recommended for use in ammonia environments.

Actions Taken: Action was taken to control that the proper O-ring is used, and the Relief Device repair shop was informed that incorrect material O-rings had been installed in the relief valve. The shop threw away all of the O-rings from that specific lot and informed the O-ring manufacturer. The Relief Device repair shop has since tightened up their quality control on soft goods that will be used in relief device repair.

Significance: The investigation of this precursor event helped identify the root cause of the O-Ring failure; without the root cause, future installations would be prone to failure and ammonia releases and an upgraded O-Ring would have been specified, which in turn would have driven up the cost of all relief device repair in ammonia service.

Conclusions

Major incidents involving ammonia plant equipment may be prevented through investigation of precursor failures. Although there can be reasons for overlooking or not fully understanding precursor events, it is important to identify such events, not minimize them. Koch Fertilizer is being proactive by investigating those precursor events and implementing sustainable preventative actions. Consideration of the potential consequence will help determine which events should be investigated further, but all events should be tracked. The cause for failure is often not obvious, as demonstrated in these four small equipment cases. The cases substantiate the need for conducting investigations with an objective of understanding the cause, and utilizing tools such as failure analysis when necessary. Good investigative practices that document appropriate findings and then communicate them to the plant staff can help prevent further occurrence and reinforce good practices. Im-

plementation and follow-through of the findings can also help avoid the next occurrence.

References

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