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# Mechanical Integrity of Process Installations: an Assessment Based on Bow-Ties

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Research was carried out in an ammonia plant of OCI Nitrogen, located at the Chemelot site in Geleen, The Netherlands. It focuses on the development of process safety accident processes in which loss of mechanical integrity is one of the root causes. A significant share of the mechanical integrity scenarios originate from corrosion mechanisms which develop over a relatively long time period, possibly taking months, years or even longer before turning into an event. Based on an example, a failure mechanism is worked out and visualized using a bow tie. Bow-ties have shown a good visual representation of the 'early warnings' and the barriers in place. The monitoring of the 'early warnings' and barriers can provide information about the current probability of the scenario in order to intervene prematurely.

## 1. Introduction

OCI Nitrogen, a producer of ammonia, fertilizer and melamine has experienced a number of process safety incidents at its two ammonia plants at the Chemelot site in Geleen, the Netherlands. According to an internal investigation, these incidents were mainly caused by a wrong choice of materials and unforeseen mechanical failure mechanisms. Especially this last aspect plays an important role. The mechanical failure mechanisms were not identified in previously conducted safety studies, nor were they checked during regular inspections. The 'leak for break' incidents always came as a surprise and occurred without any advance warning. Due to these incidents, the ammonia plant at issue had to be stopped unscheduled. The question was raised if these incidents were related to ageing and to what extent this contributed to the likelihood of occurrence (Swuste and Jongen, 2018). Although the two ammonia plants of OCI Nitrogen are well maintained, they are nearly 50 respectively 35 years old.

This manuscript describes a method for assessing scenarios for static equipment due to mechanical failure mechanisms. It is part of a larger investigation, which aims to timely take measures to prevent process safety incidents in the future. A connection is made between incident scenarios, barriers and indicators. A correct selection of indicators can provide information about the current probability of accident processes. The method is explained on the basis of an example i.e. a steam superheater. The following research question is formulated:

Which mechanical failure mechanisms can cause a catastrophic failure of the steam superheater and which role can indicators play in preventing this scenario to occur?

Ageing is not explicitly mentioned in the above research question, despite the ammonia plants of OCI Nitrogen are relatively old and a number of incidents seem to be related to the incidents that occurred. Research shows that 'ageing' manifests itself in a significant proportion of the major accidents (TNO, 2015, SZW, 2016, HSE, 2010). The degradation of onshore process plants due to ageing related failure mechanisms is becoming an important issue on a global scale (Candreva and Houari, 2013). However, there are two arguments why this substudy has not focused on ageing. Firstly, the term ageing is somewhat misleading. It is not just related to the age of a plant, system or equipment, as becomes clear by the definition of Comah (2010): "Overall, an aging plant is a plant which is, or may be, no longer considered fully fit for purpose due to deterioration or obsolescence in its integrity or functional performance. Ageing is not directly related to chronological age" or

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the HSE UK (2006): "Ageing is not about how old the equipment is; it is about its condition and how that is changing over time." According to CCPS (2018), ageing is about physical and functional changes as a result of exposure to all sorts of conditions and loads, from which it can be concluded that it is better to look at fulfilling of function and condition of the plant than sec to age. Secondly, mechanical failure mechanisms, such as corrosion, erosion or fatigue, develop over time, so time always plays a role in mechanical failure mechanisms. As far as there is ageing in the sense of time or age, this aspect will automatically come forward.

## 2. Method and theory

Bow-ties are appropriate and user-friendly for the mapping of scenarios (Chevreau et al., 2006, de Ruijter and Guldenmund, 2016). It is a metaphor for an accident process and shows the initiating event of a scenario, the consequences and the barriers that can stop the scenario from happening (Swuste et al., 2016). The simple, sequential design of bow-ties is strongly reminiscent of the 'Swiss cheese model' by Reason (1990) with the cheese slices as barriers. Figure 1 shows a bow-tie of which the explanation is included in a paper of Swuste et al., entitled "Process safety indicators, how solid is the concept?" and also published in the LP 2019 conference proceedings.

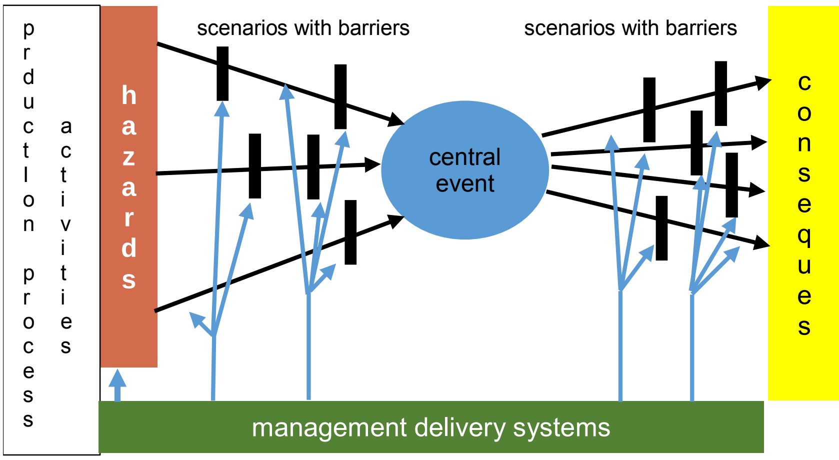


*Figure 1: Bow-tie metaphor (Visser, 1998)*

### 2.1 Root causes

A weak mechanical integrity and ageing of equipment is often a major cause of incidents in the industry. This is also the case on the Chemelot site: approximately 50% of the 'loss of containment' incidents at the North part of Chemelot were due to weak mechanical integrity in the period 2011 - 2015 (Hoedemakers, 2016). A majority of these incidents were not foreseen. In other words, the failure mechanisms were not known to the plant organization. Hoedemakers (2016) investigated the technical causes on the basis of 89 mechanical integrity incidents and has identified five categories:

1) Corrosion under insulation;
2) Contact with aggressive chemicals;
3) Vibrations that are continuously present in a working plant;
4) Extreme process conditions including frequent starting / stopping and heating / cooling of the plant;
5) Mechanical stress in the material.

Based on this, Hoedemakers has identified four root causes for mechanical failure:

1) External conditions, such as the weather, the environment and (plant) emissions;
2) Internal process conditions due to (aggressive) chemicals;
3) Maintenance activities, for example, assembly under stress or wrong material selection;
4) Process conditions like vibrations, pressure peaks, extreme temperatures, rapid temperature changes.

### 2.2 Method

The scenarios were discussed in a multidisciplinary team that was able to understand the construction and material selection of the equipment, to understand the mechanical failure mechanisms and to explain the deviations in the operating conditions (such as during start-up and shut down). The expertise within the team consisted of knowledge of the process, design and construction of equipment, materials and corrosion and execution of inspections. The casuistry was investigated not only from OCI Nitrogen but also from other ammonia producers to determine the probability of the different failure mechanisms. In addition, during the preparations extensive discussions were held with control room and field operators on how the plants are being operated, in particular during start-up and shut down situations. It was important to check to what extent is deviated from the normal operating window and to what reason.

In the first phase of the assessment, the mechanical failure mechanisms have been selected that can occur in normal, but also in deviating operations, such as start-up and shut down situations and, for example, catalyst reductions. Attention was paid to barriers that have already proven their efficiency by preventing the failure mechanism from developing into a central event. Such efficient barriers can create the delusion of an inherently safe design or a very unlikely scenario. In order to break this line of thought, the barriers in place should be considered as not present. This means that it is necessary to examine the influence of the process conditions and the process medium on the materials as if there were no forms of protection present. The probability P of the failure mechanisms is divided into four categories, as indicated in table 1. The difference between a P3 and P4 value is that the failure mechanism at P4 (very likely) has already occurred at OCI Nitrogen, whereas at P3 (likely) this is not the case. The difference between P1 and P2 is that an unlikely scenario (P2) cannot be completely ruled out and could occur under extreme circumstances or process conditions.

*Table 1: numerical value of P, D and B*

| Numerical value | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| P (probability) | Very unlikely | Unlikely | Likely | Very likely |
| D (detection & monitoring quality) | Very good | Good | Reasonable | Bad or not present |
| B (barrier(s) reliability) | Very good | Good | Reasonable | Bad or not present |

Next, it must be investigated to what extent the failure mechanism can be detected before it forms a threat. Dokas et al (2013) call this an early warning and define early warnings as an observable collection of data that indicate the errors and threats of a system in time. Early warnings can initiate monitoring of the failure mechanism, whereby the combination can be considered a full barrier. To this end, a thorough procedure must exist, where an early warning initiates a follow-up assessment to investigate the risk. It is evident that the presence of an 'early warning' is preferable to a latent failure mechanism.

Table 1 shows the numerical values of the probability (P) of the failure mechanism based on a qualitative description. In addition, also the quality of the detection and monitoring (D) of the failure mechanism and the reliability of the existing barrier(s) (B) are qualitatively indicated according to standards accepted in industry. After an inventory of the present preventive barriers, it should be assessed whether the scenario is sufficiently safeguarded. To this end, the criticality C is calculated according to the formula C = P x D x B. If the criticality is 16 or higher, the scenario has a too high risk and additional or better barriers are required. This threshold has been chosen somewhat conservatively. Many companies also include an ALARP (as low as reasonably practicable) range in their risk assessments.

The assessment is done by the multidisciplinary team. If it turns out that the equipment is insufficiently protected against the failure mechanism (i.e. the criticality is 16 or higher) and that it is not possible to include or improve barriers, a redesign, for example a different choice of material, must be considered in order to prevent a catastrophic failure.

## 3. Results

The ammonia process consists of two parts. In the cracking section, natural gas ($CH_4$) is cracked to hydrogen ($H_2$) under very high temperature. In the synthesis section the $H_2$ formed is converted with nitrogen ($N_2$) to ammonia ($NH_3$) under very high pressure and temperature. The steam superheater belongs to the cracking section. It has been taken as an example for its simple implementation of an early warning and its final variety in barriers.

In the steam superheater, high pressure steam of 125 bar is superheated by means of hot process gas, which consists of about 35% hydrogen. The process gas decreases from 600 °C to 475 °C. Figure 2 shows the flow of the process gas which is led upwards via the internal heat exchanger and returns along the wall after which it exits on the right-hand side. The process gas that leaves the internal heat exchanger at the top passes the internal brickwork (refractory) that protects the outer wall against a too high temperature. Two time-related mechanical failure mechanisms have been identified, which can cause the steam superheater to fail catastrophically, i.e. a sudden, unstoppable, total loss of the containment. In the case of damaged refractory,

the outer wall can be exposed to excessive heat for a prolonged period of time which may lead to creep (slow plastic deformation under the influence of stress and temperature) and Nelson hydrogen attack (diffusion of H-atoms into the metal causing methane to form stresses cracking).
In contrast to the upstream waste heat boiler, few incidents at other ammonia producers have been reported with regard to this equipment. Singh et al (2003) report pipeline leakages as a result of under deposit corrosion due to phosphate deposits. Given the construction, however, it is not possible for a leak of steam to affect the refractory. Own casuistry shows that although minor defects have been detected in the refractory, this has not led to a local overheating of the wall. Larger damage to the wall that can lead to hot spots, however, cannot be ruled out. Based on experiences with other equipment supplied with refractory this scenario is estimated to be likely.
In case of refractory defects hot spots can occur on the outside of the wall. Although they can be observed visually during an operator round, they can easily be overlooked. The quality of the current detection and monitoring of the failure mechanism (D) is classified as poor. The internal refractory is inspected every four years during a turn-around. As indicated above, only minor defects have been found. This barrier is therefore qualified as good. In the current situation, the criticality C (P x D x B) is equal to 24 (3 x 4 x 2). The scenario must be provided with extra or improved barriers.

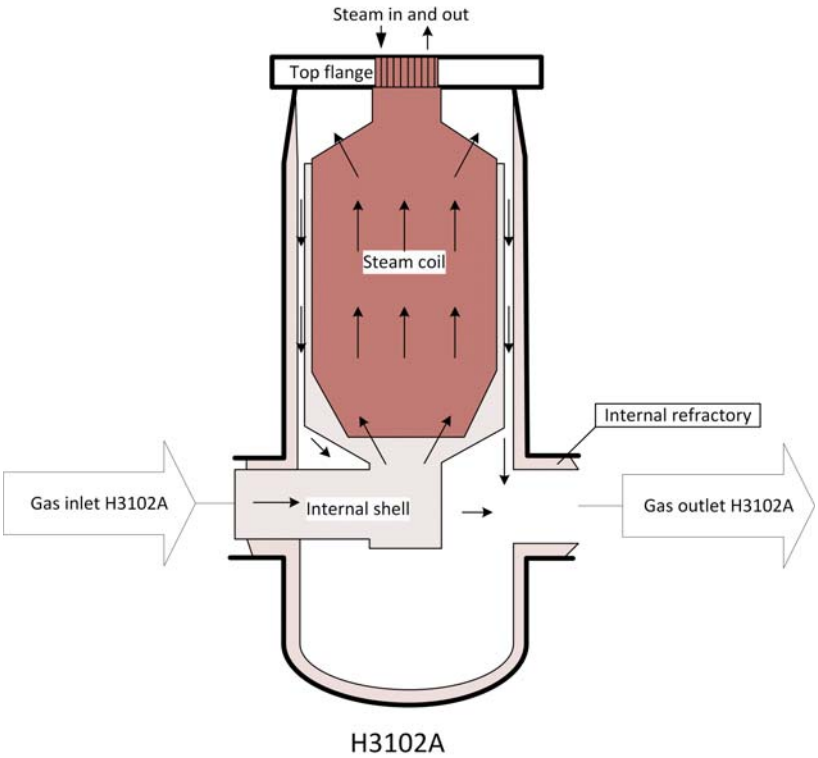


*Figure 2: Steam superheater*

It appears that it is possible to provide this heater on the outside with indicator paint, which discolors on the hot spot due to the higher surface temperature where the internal refractory is no longer intact. Indicator paint reduces the chance that hot spots are overlooked. In addition, the outer wall can be provided with a number of temperature measurements that alarm at a high temperature. In case of a discolored indicator paint and / or one or more temperature alarms, the wall can be examined with an IR camera in order to determine whether a 'fitness for service' (FFS) analysis should be carried out. This should then indicate whether an inspection is necessary. The inspection should reveal the need for replacement or repair. If this procedure receives management attention, the quality of the detection and monitoring of the failure mechanism (D) can be regarded as good in accordance with equivalent procedures within the company. The procedure should not only be included in the safety management system but also contain some kind of management involvement when in use. In addition, the temperature alarms should not only raise an alarm in the control room but also be passed on to those who are responsible for the integrity and asset management. The criticality in the improved situation is 12 (C = P x D x B = 3 x 2 x 2) and thus the scenario is sufficiently safeguarded. No additional barriers are required if the detection and monitoring are implemented as proposed above.

Figure 3 shows the bow-tie of the scenario with the newly implemented detection and monitoring. Together with the internal refractory, this forms a 1-out-of-2 system, that is to say that the scenario is provided with two barriers connected in series. The existing internal refractory is a technical barrier, whereas the proposed detection and monitoring of the failure mechanism is a non-technical, procedural barrier. The latter consists of a detection via the indicator paint, temperature alarms and IR measurement after which a procedure with management attention should ensure monitoring of the failure mechanism in the form of an FFS analysis and inspection. The temperature alarms can be seen as an 'early warning' regarding the failure mechanisms creep and Nelson hydrogen attack.
The figure below also shows which different departments or 'management delivery systems' support and maintain the various barrier components. The influence of the organizational factors on the barriers and how this influence can be monitored is beyond the scope of this research.

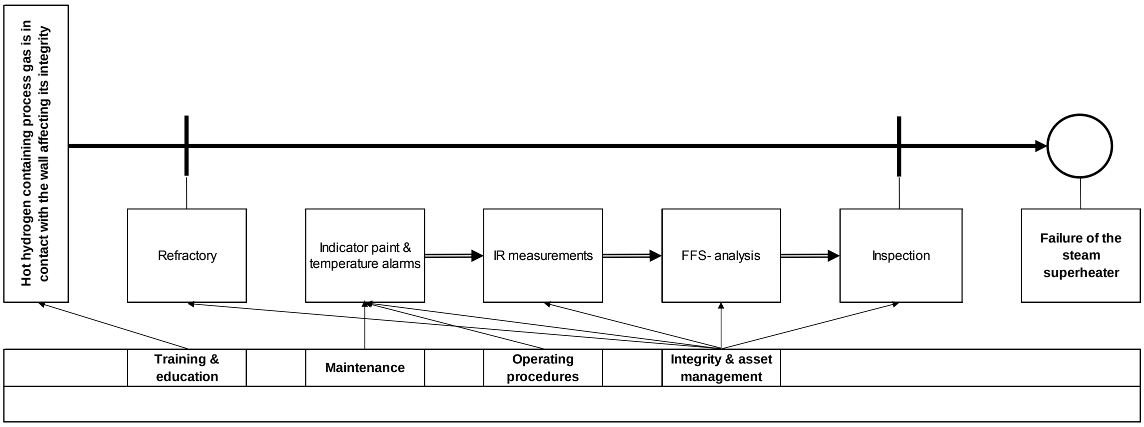


*Figure 3: Bow-tie with regard to creep and Nelson hydrogen attack of the steam superheater*

## 4. Discussion and conclusion

This substudy of mechanical failure mechanisms has three high-level results: 1. Important, missing information about, for example, design, material selection and inspection methods, but also about potential incidents has come to light; 2. Additional scenarios have been found because, unlike previous assessments, all operational modes have been looked at; 3. Assessing the scenarios as if the barriers are not present has led to some of the failure mechanisms now being classified as likely.
Process indicators in the form of 'early warnings' are not always available. Where a scenario develops latently, it will have to be stopped by one or more (available) barriers. In order to visualize the quality and thus the availability of the existing barriers, process indicators can be introduced and then monitored. This means that process indicators can be used to indicate whether a mechanical failure mechanism has been set in motion, but also to assess the availability and reliability of the barriers. Process indicators thus provide an indication of the instantaneous probability of occurrence of the central event.
Inspections are an inseparable part of 'condition monitoring' of equipment (Utne et al, 2012). The bow-tie shows that inspections can be performed on the basis of 'early warnings'. These process indicators report that the relevant mechanical failure mechanism may occur. To what extent this is actually the case, will have to be investigated in more detail i.e. by a 'fitness for service' analysis and subsequent inspection. If an inspection is considered urgent and cannot be carried out during operation, the plant will have to be shut down. The quality of the inspection greatly influences the reliability of the results. And the results of the inspection determine to what extent the failure mechanism has already developed. While Hassan and Khan (2012) made a proposal for process indicators regarding (the implementation of) inspections, the results of the inspections themselves can also be used as an indicator. The speed of which and the extent to which a mechanical failure mechanism takes place depends on a number of factors that cannot always be overseen. In this substudy such a consideration has not been further elaborated.
In identifying mechanical failure mechanisms, the operation of the plant was also considered outside the normal 'operating window', particularly with regard to start-up and shut down situations. Many mechanical failure mechanisms occur during these deviating process conditions as stated by Hoedemakers (2016), which are often not looked at in the design. The expected (mechanical) lifetime can be considerably reduced when the process is operated outside the normal 'operating window', referred to by Lagad and Zaman (2015) as 'integrity operating window'. As the aforementioned definition of Dokas et al (2013) shows, the early warnings can be used to draw up such an 'integrity operating window'.

This research has given an objective impulse to identify potential incidents based on mechanical failure mechanisms and to make them transparent. Bow-ties have shown a clear, visual representation of the 'early warnings' and the barriers in place. They can provide insight into the current probability of the scenario. The influence and added value of process indicators will be subject of further study. The management delivery systems will then also be included. Li et al (2017) have already given a qualitative impetus for this.
The approach chosen in this substudy is somewhat reminiscent of the model of risk-based inspections (RBI) in a sense that inspections are carried out when considered necessary from a risk assessment. Yet this is only partly true. The difference is that in the approach chosen here, inspections are only necessary if there is a demonstrable probability that the failure mechanism and thus the scenario is taking place. Inspections within the legal framework have been left out of consideration. RBI, on the other hand, is a systematic approach whereby an inspection program is established in advance on the basis of a risk assessment (API 581, 2008). With a view to the historical development from breakdown maintenance to preventive and predictive maintenance and RBI, this may be a new step in the area of maintenance efficiency.

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