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Case study

How is it possible? Why didn't we do anything? A case history!

H.J. Pasman[a,*], R. Grollier Baron[b]

[a] TNO Defence Research, Schoemakerstraat 97, P.O. Box 6006, 2600 JA Delft, The Netherlands
[b] 46 Les Sabines, 69130 Ecully, France

Abstract

Two similar serious accidents occurred at a metal refining process installation within a 6-month time interval. The first one killed ten people, and the second accident one person. The accidents provide a typical case history of how a safety management system and a corresponding organisation could have prevented the occurrence of such an accident or, at least, have reduced its effects. The case is also interesting because it illustrates the physico-chemical complexities forming the root cause of the accidents. © 2002 Elsevier Science B.V. All rights reserved.

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1. The process installation

A metallurgical refinery produced, amongst other products, zinc metal from zinc ore. At one stage of the process cadmium-rich zinc was stripped off from zinc by distillation. Zinc boils at atmospheric pressure at a temperature of 906 °C and cadmium at 765 °C. At the top of a distillation column one condenses an alloy of 20% cadmium, 80% zinc and at the bottom pure zinc is obtained containing only 30 ppm cadmium. The liquid pure zinc runs out over a siphon called sump. At normal functioning the column contained 7 t zinc of about 900 °C. The feed rate is of the order of 2.5 t/h.

The distillation column consists of about 50 trays; both column and trays are made of silicon carbide bricks. Like in a common distillation column, the trays function by each providing a local vapour–liquid equilibrium stage. The liquid flows down from one tray to the other, and the vapours rise from the bottom to the top, passing along the liquid surface of each tray continuously increasing in cadmium concentration. The feed inlet is located about midway of the column.

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* Corresponding author. Fax: +31-15-262-7319.
E-mail address: pasman@do.tno.nl (H.J. Pasman).

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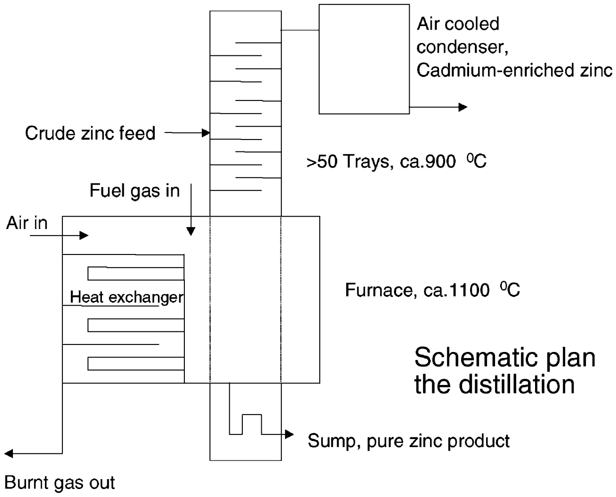

Fig. 1. Plan of a distillation column for the purification of zinc. The operating temperature is around 900 °C.

Contrary to a traditional column, there is no reboiler at the bottom, but the lower part is heated to 1100 °C by burning natural gas in a furnace built around the column, see Fig. 1. The top part is connected to an air-cooled condenser.

The instrumentation was rather limited. By measuring the temperatures at various locations in the furnace, the flow rates of inlet air and fuel gas, and the pressures and oxygen content of the combustion gases, the conditions in the furnace were monitored. Additionally, the temperature of the metal at the inlet and in the connecting pipe between the condenser and the column were measured. There was no way to directly determine the amount of metal in the column as there was no accurate measurement of the mass or volume feed flow rate of the zinc, nor measurement of the exit flows. Unlike in a classical distillation column, there was no reboiler with level indication. As mentioned before, the furnace heated the lower part of the column. So there was entirely no indication of the hold-up of the column. Hence control of the process was rather loose. The long time constants of process fluctuations could lead to severe bias. This unsatisfactory situation was even aggravated because before the first accident some instruments had ceased functioning.

Due to the severe operating conditions the operational life of a column was rather short: roughly 18 months. The end of life was actually indicated by multiple zinc leaks. The hot zinc ignited in the air and the leaks appeared as small burning jets into the furnace and other places. The column was then cooled down, demolished, and rebuilt with new materials and components.

2. The first accident

Following an electricity breakdown during the start-up of a new column, one observed anomalies in the functioning. These appeared as vibrations of the column, intriguing metallic-like noises, cracking of bricks and abnormal temperature fluctuations. During several days the operators tried in vain to get a normal course of the process. Several severe zinc leaks occurred, which at the beginning were repaired. Amplitude and frequencies of the anomalies grew. Distillation yield was bad. The temperature in the connection between column and condenser started to decrease slowly. The furnace started to function badly too. Inspection of the furnace revealed that zinc jetted from the column into the chamber, but the heat exchanger still looked clean. An adjustment was made to allow for additional air. The fuel gas supply rate was increased.

At a moment when a crew of 10 persons, including two engineers, had assembled around the column to discuss the measures to be taken, a fierce explosion took place. All 10 persons died of severe burns either immediately or after some time.

Several trays in the lower part of the column were recovered broken in several fragments. Justice authorities assigned metallurgical experts to carry out an investigation; further an official investigation from a governmental technical inspectorate took place, and specialists of a gas company did a third investigation. All three investigations concluded that there had been a gas explosion in the furnace and correlated all phenomena observed prior to the event with that scenario. It was recommended to improve the control of the combustion system and at start-up of the column to raise the temperature of the column progressively to avoid thermal shock.

3. The second accident

Six months later the column had been rebuilt with great care. The company had also introduced new procedures. Emphasis was put on a very slow increase of the temperature, which prolonged the time of start-up.

After some days the same anomalies of noises and vibrations and also slow oscillations of the temperature at the top of the column, which had preceded the previous accident, started to occur. It was also noted that the exit flow of zinc at the sump diminished and the colour of bricks and metal temporarily became reddish, which caused the crew to poke into the sump. The decision to keep away all personnel from the vicinity of the column was taken. Because the oxygen content of the combustion gases appeared to be 0%, despite an adjustment to increase the exhaust draught, one decided to cut the fuel supply. However, the furnace temperature further increased. Minutes later an explosion followed. Unfortunately one member of the maintenance personnel had not been notified to keep out and was killed by the flame/blast.

4. Analysis of the technical cause

An international committee of technical experts was formed whose members came from universities and from the branch of industry involved. The committee concluded that the main power of the explosion was due to the combustion of zinc vapour and aerosol. Zinc had been dispersed after a primary gas explosion of the furnace, which had destroyed the lower part of the column. This dispersed zinc vapour and aerosol produced a destructive, secondary explosion. This explanation did not, however, explain why the process running in various countries over many years had been considered rather safe. The root cause had to be found in relation with the anomalies observed in the days before the explosion.

Two particular conditions drew the attention of the examining committee:

1. The prolonged duration of start-up:
    1.1. in the first accident due to the electricity breakdown;
    1.2. in the second accident due to the avoidance of thermal shock.
2. A diminished flow rate of zinc product at the sump. In the second accident this occurred to such an extent that the operator increased the inlet flow rate in order to overcome the reduced tap rate at the bottom sump.

Both findings can be related to the phenomenon of liquid zinc forming a viscous foam or paste when it is mixed with zinc oxide. The density of zinc liquid is about 7 t/m^3 and that of zinc oxide is about 2.5–3 t/m^3. When in contact with air molten zinc of 900 °C is readily oxidised, and the solid oxide floats as a surface layer on the liquid. When the liquid then drips and trickles down to lower trays and also, in reverse direction, the gas consisting of air and zinc vapour bubbles through liquid zinc, the mass gets well stirred. It then starts to become a thick, viscous and foamy mass or paste. Laboratory tests have shown the thickening mechanism described above clearly. (The same mechanism also occurs with other metals like lead.) Air enters the column through the sump as long as the sump siphon is not filled with liquid metal. Prior to that as a rather ineffective precaution, the entry of air is limited by putting a ball of so-called kao-wool (a mineral fibrous mass) in the exit hole.

On the basis of the assumption of air entering the column in the start-up phase and of the mechanism of paste formation, the phenomena observed preceding the accident event could be explained:

- The increase in liquid zinc viscosity causes a decrease of the liquid flow rate exiting the sump.
- It also causes a steady rise of the hold-up mass of zinc in the column. This fills the trays with liquid zinc, causing an upward pressure on the tray above, which, due to its lower density, causes it to float and break. Fragments could have further obstructed the flow.
- The heating in the furnace causes the zinc to vaporise. The zinc vapour, together with remaining air, starts to bubble through the liquid mass producing more oxides and increasing the viscosity. The lowering of the output evoked the reaction of the operators to increase the heating to stimulate the distillation function.
- Because of the relatively large density difference between zinc liquid and atmospheric zinc vapour, the passing of large vapour/air bubbles caused vibrations, experienced as metallic-like sounds, and the cracking of the column.
- The vibrations and the overload with molten zinc cause the trays and column to crack. As mentioned before, after the accidents definite proof was found that in the lower part of the column one or more trays were broken before the explosion. Also the fissures in the column with the zinc jetting to the outside of the column are explained this way.
- The zinc jets formed in the furnace section provide additional fuel and thus reacted with oxygen. Therefore the operators noted very low oxygen content in the exhaust gas. The powdery zinc oxide formed clogged the off-gas channels, which increased the pressures.

All this caused the operators to increase the admission of the air. The primary explosion was caused by the sudden combustion of the unburned fuel gas, created by the previous fuel-rich condition. The resulting collapse of the column and the release of zinc aerosol and vapour caused a more powerful secondary explosion.

More thoughts were given to the quality of the carborundum bricks of which the columns were constructed. A very detailed material investigation was even made. No indication was obtained of defects that could have caused the accidents.

5. Corrective measures after the accidents

Although a detailed analysis of what happened only took place at a later stage, a number of precautions were already taken soon after restart of the process:

- Restricted access of personnel to the column area.
- Steel gauze was installed to protect against debris in case of explosion.
- A pressure gauge was mounted under the column to monitor the hold-up.

6. Analysis of the cause of the accidents from a management and human factor point of view

Clearly the thickening mechanism of liquid zinc with zinc oxide in a situation of forced mixing was unknown. Hence, one can speak of an *unidentified risk*. Similar accident cases abroad had been ignored and, although made known in information exchange meetings, these had not been analysed. Nor had the company’s first accident been analysed. So there had not been a sufficient “ploughing back of experience”. The belief by three groups of experts that the cause of the first accident had been a furnace gas explosion can be called an *error of representation*. The operators, on the basis of their mental image of the process, supposing to control the process by increasing the coarse zinc feed and the fuel gas flow and the admission of air in reality actually worsened the conditions and directed the process to a catastrophic sequence of events. They too made an error of representation. Although it may not be their fault, their error is still known in the literature on human factor as an *unsafe act*.

All precursors had been left unexplained or ignored. Intuitive feelings on the “work floor” of an approaching catastrophe, of which there are several in the witness reports, were not picked up by the higher management. Hence one can speak of a lack of communication from bottom to top. This points to the typical problems in an organisation that is underdeveloped from the point of view of safety management.

In fact, all trouble started many years before when top management decided to place the safety function under “personnel”. This made an item of personal safety rather than linking it to process safety and neglecting the value of the process safety aspect.

This is a sure sign that integral safety was not in the minds of top management and it explains why for example written procedures were developed so slowly. This laid the ground for the occurrence of the operator’s error of representation.

Table 1
Elements of a Safety Management System to improve the performance of an organisation

1	Accountability, i.e. clarity in objectives (who is responsible for what, which lines of communication, how to report and audit)	ad 1	No clear objective in reporting of problems No auditing procedures
2	Process knowledge and documentation, records of design criteria and management decisions	ad 2	Very limited or completely absent
3	Critical project review and design procedures for new or existing plants, expansion and acquisition	ad 3	No critical reviews
4	Process risk management, including encouragement of clients and suppliers to conform	ad 4	No activity
5	Management of change of technology, facility or organisation, both temporary and permanent	ad 5	Changes were installed without critical review, e.g. when following a different preheating procedure at start-up
6	Process and equipment integrity (reliability, materials, installation, inspection, maintenance, alarms)	ad 6	This point was reasonably covered
7	Human factors (error assessment, task design, man–machine interface, ergonomics)	ad 7	No human factor assessment was done
8	Training and performance (development of programs, design of procedures, manuals)	ad 8	Insufficiently done
9	Incident investigation (near-miss reporting, accidents, follow-up)	ad 9	No near-miss reporting; insufficient accident investigation and follow-up
10	Standards, codes and laws (internal and external)	ad 10	Reasonably covered
11	Audits and corrective actions	ad 11	Insufficient or absent
12	Enhancement of process safety knowledge by research and improvement of predictive techniques	ad 12	None

When we examine the 12 elements of a Safety Management System for the first time listed by CCPS, 1989 as reproduced in Table 1, we find 10 out of 12 to be weakly and insufficiently represented.

Also, there was no continual improvement scheme as in a quality assurance scheme with possible improvement feedback loops on, for example, a daily, annual or 5-year interval basis, as shown in Fig. 2 as control, correction and improvement loops, respectively.

In the accidents described here, the typical causation sequence can be recognised as presented in the Shell Tripod publications. The three “feet” of this method are the incident itself, active failures, and latent failures. Active failures are physically noticeable and appear usually shortly before the accident. They consist of breached system barriers and unsafe acts. Barriers, also called layers of protection or defences, are systems or devices like (active) control systems and overpressure vents, which act in case of an incident. These have a finite reliability, already because of infrequent use. So they may fail due to local technical faults, atypical conditions, and severe environmental conditions. Latent failures cause preconditions for the accident. Preconditions are conditions which determine how readily an error is committed, e.g. a state of stress, poor motivation, or ignorance. Line management can influence them. The causes may have been in the organisation already for a long time

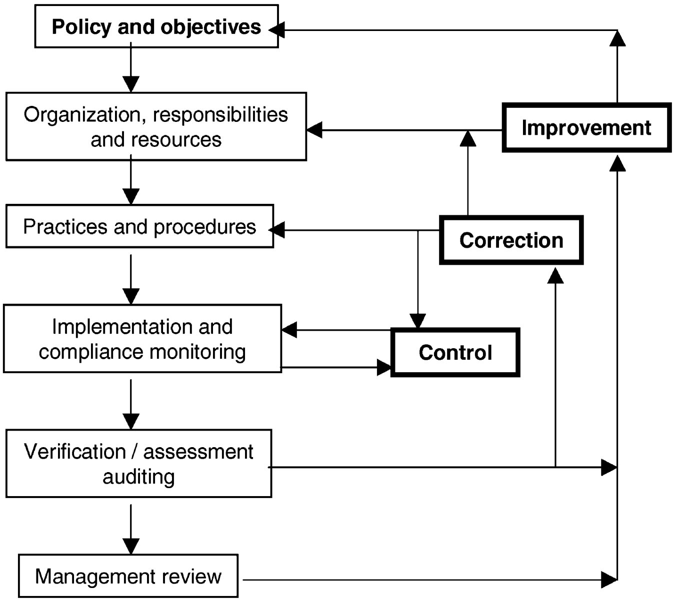

Fig. 2. Typical structure of key elements in a Safety Management System, also shown are the improvement feedback loops. Source [1]: EPSC Safety Management Systems.

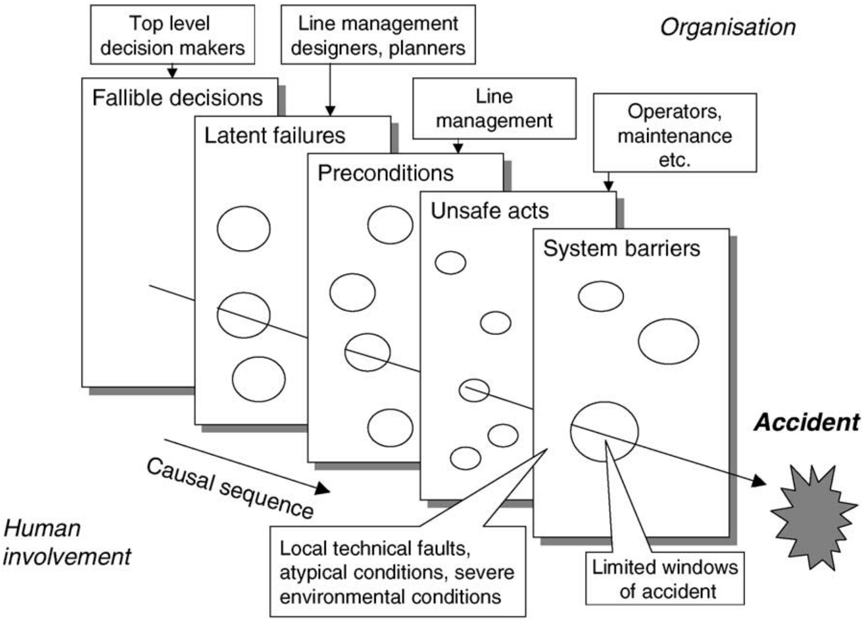

Fig. 3. Windows in the accident causation sequence as seen in the Tripod model (e.g. [2]).

and may be attributed to wrong decisions of designers and planners. Even further in the past there may have been situation resulting in fallible decisions of top-level decision-makers. Unsafe acts are carried out by personnel in direct contact with the equipment or structure, which leads to the accident. The whole sequence is illustrated in Fig. 3.

The plane of breached system defences in this case shows a relatively large window for the occurrence of an accident in the event “furnace exploding”. This occurs because the structure of the column is vulnerable and a relatively small pressure wave destroys the column, resulting in the release of a large amount of zinc aerosol. Therefore control of the furnace in relation with the window of operator unsafe acts is decisive for preventing an accident from occurring. The existing preconditions were also very bad. Stress because of simultaneous incidents elsewhere in the plant and, as we have seen, misperceptions and ignorance increased the risk of the accidents. These preconditions are partly due to latent failures in design and planning of process and procedures. The root causes are the fallible decisions by top management not to implement an integral safety policy and to provide the means and tools for such policy.

7. Conclusions

1. The organisational conditions and human factors leading to the accidents described are a typical example of how a process can become uncontrolled resulting in a serious accident. The case history clearly demonstrates how important the attitude of top management is with respect to safety culture and to what extent a Safety Management System in process operations can contribute to obtain a high safety level.
2. That the mechanism of the thickening liquid zinc by zinc oxide formed by air in contact with molten zinc, in situations of zinc liquid dripping down or of air bubbling through the liquid, was not recognised before the accident can be considered as the basic technical cause of the accidents. It caused choking and clogging of the column, which went by unnoticed and which finally led to multiple leaks of liquid zinc from the column, also into the furnace. This puts the furnace out of control, fouling it with zinc oxide powder and making it fuel-rich. When additional air was admitted, this fuel-rich situation caused the primary explosion to occur. In turn a zinc aerosol from the destroyed column was dispersed into the surrounding air reinforcing the initial explosion by the effect of its extra combustion energy resulting from oxidation of the zinc.
3. The case shows clearly how a thorough investigation of the causes of an accident down to its deepest roots pays good dividends in the end.

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