Violent explosion after inadvertent mixing of nitric acid and isopropanol – Review 15 years later finds basic accident data corrupted, no evidence of broad learning

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Abstract

At a brewery in 1997, an operator confused filling nozzles for two commonly used acid cleaning agents and transferred nitric acid into a tank with P3, a proprietary phosphoric acid based cleaner that also contained 5-15 percent isopropanol. 10-15 minutes later the mixture exploded violently. The stainless steel tank disintegrated with such force that fragments lodged in walls of concrete. The explosion ravaged the cellar, destroyed equipment, blew out a masonry wall and released large amounts of nitrous oxide fumes. Likely, 62 percent nitric acid (CAS 7697-37-2) and isopropanol (2-propanol, CAS 67-63-0) reacted to produce isopropyl nitrate (nitric acid 1-methylethyl ester, CAS 1712-64-7), a rocket propellant. It is argued that the accident has broad learning potential because of the widespread usage of the two chemicals across industries, the innocent nature of the human error and the severity of the consequence.

A review 15 years later of lessons learned finds that information dissemination has followed a tradition of informal meetings in small industry sector associations but impact is unclear. There is no useful mention of the accident in open sources. Although the Danish Working Environment Authority took the brewery to court for negligence, they did not report or investigate the accident, or attempt to disseminate information available to them. Today, the general literature is silent on the explosion hazards of mixing the two chemicals.

The paper argues that without institutional support, learning opportunities are missed and broader cross-sector learning is limited or non-existent.

Keywords:

- clean-in-place (CIP)
- nitric acid
- chemical incompatibility
- explosion
- learning from past accidents

Research highlights

- Clean-in-place (CIP) chemicals present serious chemical incompatibility hazards
- Inadvertent mixing produced a violent explosion with multiple fatality potential
- The accident company took effective precautions to prevent recurrence
- There is no evidence of broader learning, indeed the accident has disappeared from open sources
- It appears critical to provide institutional support and to set up systems that facilitate learning

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1 Introduction

1.1 Learning from accidents

Learning from accidents and misfortune is not a novel accident prevention strategy, humans have learned from their mistakes from ages past. In its modern form, key characteristics are that past mishaps shall be recorded and analysed to extract lessons learned, which in turn shall be disseminated through broad feedback loops in order to prevent future similar, and not just identical, accidents. This feedback is one of the pillars of a safety management process and an essential tool in the framework of prevention. Evidently, it makes good sense to share the lessons learned from unwanted outcomes in order to minimize the number of times the same lessons have to be learned (Hedlund and Andersen, 2006; Dien et al. 2012).

The idea has been championed and popularized by e.g. Trevor Kletz in the book "What went wrong?" (Kletz 1988). A later book by the same author titled "Still going wrong" (Kletz 2003) hint that although learning from past accidents is a conceptually simple idea, major obstacles to practical implementation do exist and opportunities are foregone, see also Kletz (2004).

Learning from accidents has been an active area of safety research for at least two decades and a substantial body of literature exits. Lindberg et al. (2010) offer a description of the CHAIN model for experience feedback, which comprise six activities (1) reporting, (2) selection, (3) investigation, (4) dissemination, (5) prevention, and (6) evaluation. The CHAIN model summarizes ideas that are well-known from the accident investigation literature and it is truly a chain in the sense that the process as a whole fails if any one of its links fails.

Lindberg et al. (2010) observe that most of the literature is concerned with certain parts of the experience feedback process, in particular the accident investigation methodology. Much less has been written on the activities that take place before or after the accident investigation, such as initial reporting, dissemination and uptake of lessons learnt. This paper deals with precisely these activities in examining the immediate post-accident phase after a serious chemical incompatibility accident. The case also offers an opportunity to study the learning that subsequently took place: the technical measures taken at the site to prevent recurrence, the extent to which the new explosion risk insights were understood and communicated to the safety community at large, and sharing the lessons learned with peers and other potential beneficiaries.

1.2 An accident case with broad learning potential

In 1990s, a Danish brewery used two acidic cleaning agents in its clean-in-place (CIP) system: nitric acid and P3 Trimeta HC (henceforth: P3), a speciality tank cleaner for the brewing industry. The data sheet for P3 described the product as an "Acid cleaning agent based on an aqueous solution of phosphoric acid, phosphonic acids, non-ionic surfactants and stabilizers". The product also contained some isopropanol. The brewery received concentrated solutions of both cleaning agents. In 1997, an operator confused two nozzles when topping up CIP tanks and transferred 62 percent nitric acid into the P3 tank, which exploded shortly after. The severity of the explosion indicates that a detonation took place. In all likelihood, nitric acid and isopropanol reacted to produce isopropyl nitrate, a rocket propellant.

Nitric acid and isopropanol are very common industrial chemicals in the food and drinks industry and elsewhere, often handled manually, and trivial errors such as inadvertent mixing are to be expected, unless special precautions are taken. The explosion hazard was unknown to the brewery; to the Danish Working Environment Authority, and to the national vendor of P3. We argue that the lesson learned from this accident, that mixing of two common industrial chemicals can produce a potent explosive with multiple fatalities potential, would be a prime candidate for experience feedback and learning as it has broad relevance for industry, authorities and safety professionals working with preventive risk analysis.

1.3 The two CIP cleaning agents

Nitric acid is highly suitable for removing mineral deposits (scale) and other alkaline deposits commonly encountered in the foods and drinks industry, in piping systems, heat exchangers and tanks. Nitric acid does not corrode stainless steel and the cost is a fraction of that of phosphoric acid. It is therefore a popular cleaning agent, often in solutions of one percent or less.

The P3 product was a speciality cleaning agent developed for breweries based on phosphoric acid. Additives comprised isopropanol, surfactants, anti-foaming agents, corrosion inhibitors and fungicides against unwanted moulds and yeasts encountered in brewing operations (Table 1).

Table 1 Composition of P3, an acidic speciality CIP cleaner

Ingredient	CAS	Content	Hazard symbol
Phosphoric acid	7664-38-2	>30 percent	Corrosive (C)
Isopropanol	67-63-0	5-15 percent	Highly flammable (F)
Fatty alcohol ethoxylate	Not stated	< 5 percent	None
Butyl diglycol	112-34-5	< 5 percent	None

Tri isobutyl phosphate	126-71-6	< 5 percent	Irritant (Xi)
Fatty alcohol propoxylate	Not stated	< 5 percent	None
Phosphonate	Not stated	< 5 percent	None

Source: Danish safety data sheet for P3-trimeta HC, 1994

1.4 Ambiguous SDS information on chemical incompatibilities

The brewery's Safety Data Sheets (SDS) for nitric acid stated acute health effects, the chemical's corrosive and irritant action and ability to produce chemical burns, skin ulcerations, damage to mucous membranes and eyes. The SDS warned that being a strong oxidizing agent, reactions with concentrated nitric acid often liberates much heat, at times violently, and that combustible materials may ignite. It listed two risk phrases: R8 - Contact with combustible material may cause fire; and R35 - Causes severe burns. The SDS emphasized that reactions often produce toxic red-brown coloured fumes of nitrous oxides. They are feared because poisoning initially can be non-symptomatic with fatal complications (lung oedema) developing hours later - the SDS mentioned a past fatal accident of this type at Carlsberg, another Danish brewery.

The SDS for P3 stated its corrosive and irritant properties and potential to produce chemical burns and eye damage. Of chemical incompatibilities, the concern was acidity: that mixing with chlorine (hypochlorite) cleaners could liberate chlorine gas, and that reaction with certain metals could produce hydrogen, an explosive gas. The SDS listed one risk phrase: R34 - Causes burns.

1.5 Sources

After the explosion, the Danish Working Environment Authority took the brewery to court for violation of its general obligations to plan and execute work in a safe manner. The court proceedings and other documents, which constitute the basis for this paper, comprise:

- A police investigation report
- Correspondence between the brewery, the P3 vendor and the Danish Working Environment Authority.
- A Danish translation of a German laboratory's investigation of the hazards of mixing P3 and nitric acid.

The brewery kindly provided access to court documents, correspondence, photographs and an April 2012 site visit and interview with the then production supervisor. The brewery has been helpful and forthcoming but has asked not to be named.

2 Accident sequence and severity

2.1 Layout

The brewery kept chemicals for the CIP system in tanks in a cleaning hall known as cellar 11. The tanks were connected to nozzles mounted on an outside wall panel. The panel had seven nozzles, from left: nitric acid, P3, caustic soda (NaOH), hot and cold water, air and glucose. The nozzles for nitric acid and P3 were identical, the others were different. When the level of a chemical tank ran low an operator would fetch a drum or pallet tank, connect the discharge hose of a portable dip pump to the correct nozzle at the panel and transfer the contents. The same dip pump and discharge hose was used for nitric acid and P3. At the time, the brewery simply viewed the two chemicals as “acids”.

In cellar 11, the stainless steel tanks for nitric acid and P3 were identical. Detailed drawings no longer exist. Brewery workers recall that the tanks were pressure less - an overflow pipe routed excess material to a floor drain under the tanks. The volume was 1.7 m^3, construction material was probably 316L, shell thickness minimum 3 mm, possibly 5 mm.

Cellar 11 is a basement with approximate dimensions length x breadth x height 20 x 15 x 7 m (Figure 1). Strong concrete walls and pillars help support the load of beer fermentation tanks originally located on the floor above. The two CIP tanks were located between a caustic tank, a tank with recycled water and a filter unit. Two heated glucose tanks were located in an insulated compartment. At the centre rear, a couple of concrete steps lead up to a walkway and access doors leading to the neighbour cellar. Next to the concrete steps, a metal staircase provided access to an elevated platform.

2.2 The explosion

On November 28, 1997, an afternoon shift operator checked the level gauges: the nitric acid tank was almost empty, and the P3 tank almost full. He fetched an intermediate bulk container (IBC) pallet tank at the outdoor chemicals storage area and brought it to the nozzle panel. The dip pump was already connected to a receiving nozzle. He did not realize that the hose was connected to the wrong nozzle and started the transfer.

The explosion took place 10-15 minutes after the onset of the transfer when about 100 – 250 litres of nitric acid had been transferred. Thick clouds of reddish-yellow nitrous oxides billowed out of the damaged building

Moments before the explosion, another operator had walked through cellar 11 on his way to the filter room. He would have passed the P3 tank at close distance, perhaps 2-3 m, but did not notice anything unusual. The many people working day shift had recently left the premises. Fortuitously, nobody was in the area at the time of the explosion, and there were no casualties.

The fire and rescue services dosed the area for hours to knock down fumes and dilute the acid. A light wind took fumes away from nearby residential areas. Warnings were broadcast over the local radio station and from police cars with loudspeakers urging town centre residents (several thousand) to close doors and windows and stay indoors for about two hours. The fire and rescue services said that siren warnings and evacuations would have been necessary, had the wind direction been less favourable.

According to meteorological data (Wundergrund) from an airport 40 km away, the wind came from the east at 2-3 m/s. The sky was partly cloudy and twilight was setting in. The temperature over the prior 12 hours had ranged from -2°C to +1 °C.

2.3 Explosion damage

The explosion ravaged cellar 11, destroying equipment and blowing out a 3x4 m wall section behind the glucose tanks. Bricks were scattered outside over perhaps 10-15 m. A 3x5 m wall panel with door and windows frames blew out landing 20 m away in front of a single story office building, some parts landed at the other side of the building, approximately at distance 40 m. Glass fragments from shattered windows were found lodged in wood clad surfaces, e.g. a contractor trailer at distance 25 m. Doors to the adjacent cellar were blown out. Ceiling panels and lighting armatures fell down.

The force of the explosion flattened stainless steel piping. The upper part of the caustic tank was deformed and the tank leg facing the P3 tank was bent 45 degrees upwards. The adjacent filter unit was destroyed (Figure 2).

The severity of the explosion is perhaps best revealed by fragmentation damage. The P3 tank disintegrated and tore the adjacent nitric acid tank apart. Tank steel fragments lodged into the solid concrete wall (Figure 3). A stainless steel flange with an estimated weight of 8-10 kg originating from the bottom of the P3 tank traversed the hall, penetrated an electrical cabinet and caused a black-out (Figure 4). The nearby water tank was pockmarked by fragment impact, mostly at the lower part of the tank. Scattered crumbled tank fragments, damaged machinery and a deformed metal handrail is evidence of other forceful impacts. The concrete pillars had corners knocked off.

The material damage was estimated at 8.7 mio. DKK (1.2 mio EUR). Despite initial concerns about business interruption, makeshift equipment and improvised procedures permitted cleaning operations to continue. The accident resulted in a severe business disruption but in little actual production downtime.

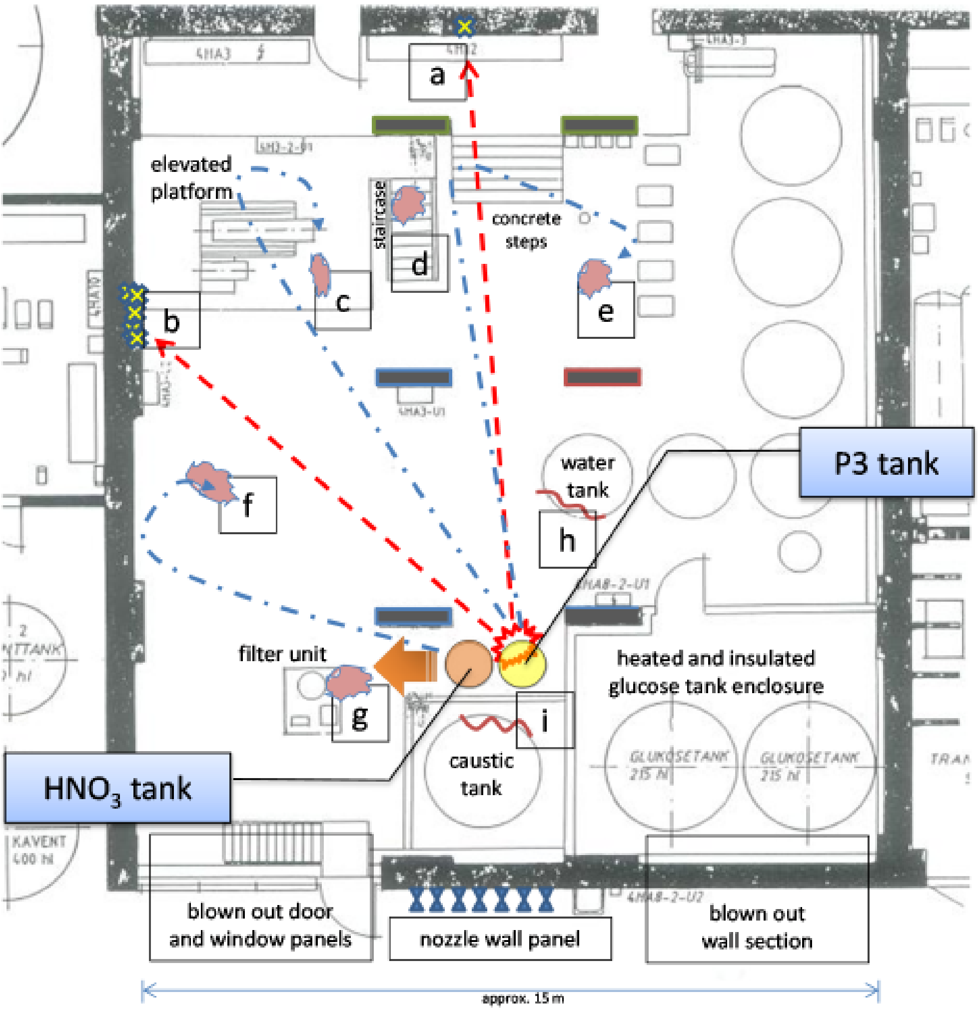

Figure 1 *Overview of accident basement. The P3 steel tank disintegrated with such force that a flange (a) penetrated an electrical wall cabinet, fragments (b) lodged into solid concrete walls and crumbled tank portions (c-g) were scattered. Nearby tanks were pockmarked by fragment impact (h-i).*

Figure 2 *Right: damaged filter unit, left: caustic tank. Note flattened steel piping (arrow). Photo courtesy of company.*

Figure 3 *Tank fragments lodged in heavy concrete wall (marked as location b in Figure 1). Photo courtesy of company.*

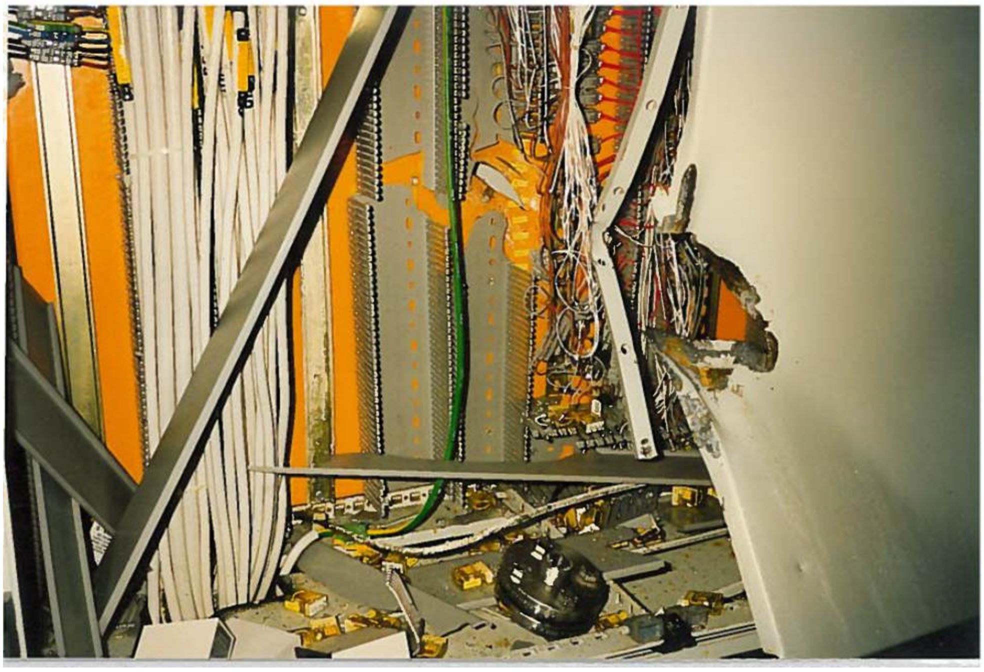

Figure 4 Flange from lower section of P3 tank penetrated an electrical cabinet and caused a black out (marked as location a) in Figure 1. Photo courtesy of company.

2.4 Investigation of reaction hazards

The Danish Working Environment Authority requested the vendor of P3 to provide information on what had caused the violent reaction. The vendor contracted a German laboratory to investigate the hazards of mixing. The laboratory carried out a desk study and produced a 1½ page report in which they considered two potential types of reactions: 1) oxidation of isopropanol and other organic compounds in P3 under the formation of aldehydes, ketones and carboxylic acids accompanied by the formation of nitrous oxides; 2) the formation of organic nitrates by reaction of isopropanol (and other alcohols) with nitric acid

The report said the first type of reaction may be violent due to generation of heat and gasses whereas the second type of reaction leads to explosives, in this case isopropyl nitrate, similar to nitroglycerin and nitrocellulose. Since the explosion happened after a short period of time, the German laboratory concluded that formation of an organic nitrate was likely.

3 Discussion

3.1 Isopropyl nitrate

Isopropyl nitrate (IUPAC name: nitric acid 1-methylethyl ester) is a white liquid with an ether like smell and a known monopropellant of low explosive sensitivity (Gizir, et al., 2005). It has been used since the end of the Second World War for guided weapons propulsion (Abbott, 1980). It has since lost popularity and been replaced by safer alternatives. It is also a sensitizer in military explosives, promoting mixture ignition and transition to detonation (Zeng, et al., 2007). At present there is interest in its potential use as a fuel or fuel additive for pulse detonation propulsion systems (Liu, et al., 2011). This incomplete list of useful properties suffices to characterize isopropyl nitrate as a substance most industries would consider an unwelcome visitor, certainly unannounced appearances.

3.2 Chemical incompatibility hazards

Developments in information technology permit a more extensive literature review than the one carried out in 1997. Google Scholar finds a US patent (Hinkamp, et al., 1956), which devises a production process for both isomers of propyl nitrate. Alcohol is reacted in a mixture of sulphuric acid and nitric acid, with a stoichiometric excess of nitric acid. The authors claim to have overcome earlier difficulties with side reactions that consume the alcohol. Such side reactions not only decrease the yield, but may be so extensive as to cause the reaction to "become uncontrollable and hazardous". Direct nitration "is attendant with considerable risk" because of the high order of reactivity of the alcohol and the reactivity of the product. The reaction temperature should be maintained between -8 °C and 0 °C for the production of isopropyl nitrate (Hinkamp, et al., 1956).

An experimental thermometric study (El Shayeb, et al., 1987) reports that isopropanol is readily oxidized by nitric acid at room temperature with the evolution of a considerable amount of heat. The study suggests that the reaction occurs after an induction period, i.e. a time lapse before the reaction starts. With an initial temperature of 23 °C the duration of the induction period was 4-6 minutes. A low initial temperature increased the induction period. It is noteworthy that the authors make no mention of potential experimental hazards such as liberation of nitrous gasses or formation of isopropyl nitrate.

We conclude that isopropyl nitrate likely formed. The nitric acid stored outdoors was at about 0 °C. The temperature of the indoor P3 tank was probably about 18 °C. We speculate if the tank inlet pipe was dipped to prevent splashing and the cold and slightly denser[1] nitric acid accumulated at the bottom of the P3 tank. Plausibly, temperature conditions were favourable to the formation of isopropyl nitrate, rather than oxidation side reactions which liberate heat and nitrous oxides. This would be consistent with the fact that an operator walked past moments before the explosion not noticing anything unusual. It is unlikely that he would have missed a release of nitrous oxides from the overflow pipe to the floor drain. We speculate that after an induction period, oxidative run-away triggered explosion of the isopropyl nitrate. A detonation in the bottom of the tank explains the forceful ejection of fragments, producing deep dents in the lower part of the nearby water tank, while only lightly deforming the upper part of the caustic tank.

Ambiguity remains however, in particular the absence of concentrated sulphuric acid, which the patent application emphasizes should comprise up to 68 percent by weight of the reaction mixture in order to eliminate unwanted oxidation reactions. The superficial investigation by the German laboratory did not mention any experimental work to verify the proposed reaction chemistry and we have no means to investigate this issue experimentally ourselves.

3.3 Learning processes at the brewery

The brewery changed its chemicals handling practice. It now stores the two CIP chemicals in a small separate building and the receiving nozzles to the tanks are of different dimensions. Deliveries are by two different vendors and access to a nozzle requires two keys of which the truck driver brings one. Although the ingenuity of human error is immense, the likelihood of accidental mixing during raw materials handling appears to be remote with this arrangement.

3.4 Learning processes at the industry association?

The brewery said it presented the accident and lessons learned at brewery industry association meetings. Information exchange activities in such forums can be effective as attendees comprise industries where identical mixing errors could take place. The absence of written records however, makes such information exchange dependent on precarious personal contacts and memory.

The safety committee of the Association of Danish Process Industries (FDKI) has published updated SDSs for about 250 chemicals since the 1960s. The work was discontinued in 2011 due to lack of funding. In the most recent edition (KS, 2010) the SDS for nitric acid only mentions spontaneous ignition and liberation of nitrous fumes in case of accidental mixing, not the formation

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[1] The density of 62 percent nitric acid @ 0 °C is 1.4039 g/cm^3 (Perry & Green, 1984) (Perry and Green 1984:3-81), The datasheet for P3 states the density @ 20 °C is 1.35 g/cm^3

of a potent explosive. The omission indicates that the impact of information exchange in industry forums is limited.

3.5 Learning processes at the vendor?

Written inquiries to the vendor of P3 for information if other chemical incompatibility incidents have taken place were fruitless. Reached telephonically, the vendor said isopropanol is no longer an ingredient in the vendor's CIP cleaner. Isopropanol was merely acting as a solvent and stabilizer to keep other additives in solution and this functionality could be achieved using other additives.

From a learning perspective it is relevant to speculate if the substitution of isopropanol was motivated in concerns over chemical incompatibility hazards. The fragmented and circumstantial evidence available to us suggest this is unlikely. Google finds P3 safety data sheets in Swedish and Czech languages dated in 2005 and 2006 with a product composition similar to the Danish 1994 data sheet, indicative that an unmodified product was sold in these countries at least nine years after the Danish accident. The data sheets are silent on the incompatibility hazards with nitric acid. We observe that the substitution of isopropanol had other benefits; in particular it eliminated the flammability rating of the product.

3.6 Learning processes at the Danish authorities?

The police investigation followed a standard police crime scene procedure with no attention paid to process safety issues, e.g. there are no registrations of tank levels, flow rates or temperatures; no recordings of fragment size, weight, trajectory and position; no attention given to underlying systemic deficiencies or root causes.

The Danish Working Environment Authority made no effort to investigate the accident themselves but relied on the police investigation and the vendor study. The Authority took the brewery to court for violation of its general obligations to plan and execute work in a safe manner. The Authority pointed to a chemical safety citation the year before, in which a batch of caustic had been neutralized with nitric acid exposing workers to acid fumes in excess of the threshold value. The citation is entirely irrelevant from a chemical reaction hazard point of view. Nevertheless, the Authority stated, with considerable public brouhaha, that the citation warranted an above-normal penalty. The court agreed and the brewery was convicted and fined DKK 80,000 (10,700 EUR), about one percent of the property damage.

The Authority's local branch office has since closed. All persons originally involved with the case have retired or moved on to other jobs. Two were reached telephonically; to their knowledge no dissemination efforts took place. The dominant perception at the time was that the brewery gave insufficient managerial attention to workplace safety and health issues. The main priority of the Authority was to rectify the managerial attention deficit, using available enforcement powers.

3.7 Survival of basic accident information

We have argued that the 1997 accident highlighted an incompatibility hazard which has broad relevance for industry, authorities and safety professionals working with preventive risk analysis. It is therefore noteworthy that it has all but disappeared from open sources. Some media articles can be located in Infomedia, a Danish proprietary media article repository well hidden behind a pay-wall, but the articles only report the explosion event, the legal aftermath and the penalty.

The kind of information necessary for safety professionals to understand the case and prevent recurrence is wholly absent - there is no mention of the chemical incompatibility with isopropanol. Articles in newspapers with nationwide circulation are marred with misleading factual errors, misstating nitrous oxides as chlorine, such as “Chlorine fumes released in town centre” (Berl, 1997). The explosion is briefly mentioned in a report for the Danish EPA on chemical facility hazard analysis (Taylor, 2007); incorrectly however, as the isopropanol reactant is misstated as formaldehyde (!). We conclude that the information available in the public or pay regime is garbled beyond recognition. We also note that the accident is absent[2] in the EU major accident reporting system (MARS).

3.8 Information on the explosion hazard available to accident prevention professionals

We have not been able to locate a SDS on nitric acid or isopropanol that mentions the explosion hazard upon accidental mixing. Some information can be found in specialized reference works on chemical incompatibility hazards available at university libraries. Bretherick's handbook of reactive chemical hazards (Urben, 2012) provides the most comprehensive description. The entry for nitric acid states that it is the common chemical most frequently involved in reactive incidents and if anywhere near stoichiometric composition, a homogeneous mixture of nitric acid and virtually any organic is a sensitive high explosive. A case is presented in which the reaction of five litres of isopropanol reacted with concentrated nitric acid, which bursted the reactor. Bretherick's entry for isopropanol makes no mention of the explosion hazard, however. Wiley’s handbook to Chemical Incompatibilities (Pohanish & Greene, 2009) states that nitric acid will “react violently” with a long list of

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[2] It probably meets reporting obligation criteria of the Seveso II Directive (96/82/EC, 1997) , as it led to “evacuation *or confinement* of persons for more than two hours, (persons x hours): the value at least 500” (96/82/EC, 1997). However, this directive was only implemented in Danish law much later, by executive order 106 dated 2000. At the time of the accident, only the earlier Seveso I directive was in effect, by executive order 520 dated 1990, where reporting criteria are unspecific.

substances, alcohols included –explosion is not mentioned. Wiley's entry for isopropanol similarly merely states that it will "react violently" with nitric acid.

We found passing mention (Whetton & Armstrong, 1994) of the same accident mentioned in Bretherick's involving five 1itres of isopropanol. Some laboratory incidents involving nitric acid and alcohols are available (American Industrial Hygiene Association, no date), (American Industrial Hygiene Association, 2004) but these case descriptions were very difficult to retrieve, and laboratory flasks may have burst due to gas evolution and internal overpressure rather than due to formation of an explosive.

Specialists in organic chemistry inform us that the reaction between concentrated nitric acid and alcohols is "well known", in particular the reaction to produce glyceryl trinitrate (nitroglycerine). This reaction normally requires an excess of highly concentrated (fuming) nitric acid, or the presence of concentrated sulphuric acid however, and such conditions were clearly not met in this accident. Any effect of the presence of phosphoric acid in the P3 is unknown. The German laboratory's rudimentary report is silent on these issues.

A frequently cited handbook on hygiene control in the food industry pays surprisingly little attention to incompatibility hazards of CIP chemicals. A case with nitric acid is presented in which the consequence was evolution of nitrous gasses –the potential formation of explosives is not mentioned (Rosner, 2005).

We conclude that the available literature is sparse on the formation of a potent explosive whereas the comparatively more benign evolution of nitrous oxides upon mixing of concentrated nitrous acids with organics is well-known. We have serious doubts if the average chemist would identify the explosion hazard when faced with a routine chemical incompatibility enquiry – even more if the average safety professional would do so.

3.9 Barriers to reporting, investigation, dissemination, learning

The vendor of P3 has met our request for information to this article with reluctance. Such reluctance is natural. Common sense suggests that a company will not aggressively inform its customers and competitors about product issues which could potentially lead to brand damage and hurt sales. Using principal–agent theory, Fauchart (2006) argues that information asymmetries are at play which can be a source of moral hazard that impedes learning.

To the brewery the accident was a traumatic event and they have since taken effective safety precautions to prevent recurrence. The production supervisor expressed genuine concerns about mixing hazards, and some frustration - these chemicals are used "everywhere". The brewery's work practices improved but it has not engaged in broad lessons-learned dissemination activities. This is only to be expected. Milton Friedman's dictum "The business of business is business" implies that spending company resources to investigate and report lessons learned for the benefit of others would make a weak business case. Only expenses are visible; negative publicity is a concern and benefits are at best uncertain and intangible.

The Danish Working Environment Authority viewed the accident as a management deficit, a workplace and organizational dysfunction, an inability to prevent a foreseeable human error. The Authority pursued a narrow legal court case approach, myopically seeing the explosion as the result of brewery-specific chemicals, involving a fuzzy chemical product "P3", not identifying the culprit as isopropanol, even less realizing that other alcohols exhibit a similar incompatibility hazards with nitric acid. To the Authority, assigning managerial blame and winning the court case defined a mission complete. Although the Working Environment Authority appears to have been the party with the best overview of events, access to the largest resource base, and the broadest accident prevention mandate, there is no evidence of investigation, dissemination, broader learning, or organizational memory.

It is particularly troubling that the Authority seems to have overlooked the significance of the chemical incompatibility, that this accident could well have happened elsewhere. We speculate that the German laboratory's superficial desk study report came late, when the case had moved to the Authority's legal department, who were narrowly concerned with issues of compliance, culpability and penalty, not accident prevention.

3.10 Learning revisited

Returning to the CHAIN model of Lindberg et al. (2010) we conclude that the experience feedback chain was disrupted at the very introductory steps: the accident was neither properly investigated nor reported. Because the process is truly a chain in the sense that the process as a whole fails if any one of its links fails, only site specific learning took place, opportunities for broader learning were wholly missed.

4 Conclusion

Inadvertent mixing of 62 percent nitric acid with a proprietary chemical comprising 5-15 percent isopropanol likely formed isopropyl nitrate, a rocket propellant, which exploded violently. The accident clearly had multiple fatalities potential. We argue that the widespread usage of the two chemicals across industries, the innocent nature of the human error and the severity of the consequence would make this accident a prime candidate for accident investigation and broad dissemination of lessons learned.

We conclude that in this case such learning opportunities were wholly missed. Information in open sources available to safety professional today, some 15 years later, indicate that the hazards of mixing isopropanol and nitric acid relate to the formation of heat and poisonous fumes of nitrous oxides, not the formation of a potent explosive. A determined individual with prior knowledge of the 1997 explosion accident, sifting through available sources in the public or pay regime, can only find information garbled beyond recognition, with no useful facts for chemical incompatibility accident prevention.

The trend in industrial accident prevention in Denmark over the past two decades has been a shift away from standards and codes that define specific minimum safe practices towards a risk based approach where each cased is judged on its own merits. For a risk-based approach to be effective, availability of relevant information, e.g. the severity of the consequences, is critical - or risks may be scored too low. Companies are likely to take more precautions to avoid a sudden accidental violent detonation than to avoid an accidental release of nitrous oxides, presumably with a slow onset.

The Polluter Pays Principle plays an important role in Danish policy. This case indicates that care should be taken not to misapply this principle to accident investigation and learning, delegating such obligations to the parties directly affected. We argue, as do Dien et al. (2012) and Dechy et al. (2012), that investigations should be independent. We furthermore argue, as do Fauchart (2006), that it appears critical to provide some sort of institutional support to facilitate learning.

Major chemical accidents cannot be prevented solely through command and control regulatory requirements but by understanding the fundamental root causes, widely disseminating the lessons learned, and integrating these lessons learned into safe operations. Few would argue that these goals are wrong. Yet they appear to be difficult to achieve in practice.

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