Review and analysis of the explosion accident in Drevja, Norway: A consequence of fire in a mobile explosives manufacturing unit (MEMU) carrying precursors for the on-site production of bulk explosives.

HIGHLIGHTS

- Detailed and technical review of the explosion accident in Drevja, Norway, 2013
- Explosion caused by uncontrollable fire in a mobile explosives manufacturing unit carrying ammonium nitrate-based products
- Fragment scattering and ballistic simulations are used to analyze and evaluate the event
- The use of aluminum tanks as a safety measure and current regulations and classification paradigms are discussed

ABSTRACT

On December 17, 2013, in Drevja, Nordland county, Norway, an uncontrollable fire in a mobile explosives manufactory unit (MEMU) carrying ammonium nitrate-based products and gassing agents for the on-site production of bulk explosives, culminated in an explosion almost 2.5 hours after the fire was first noticed. Even though explosive events during storage and transport of ammonium nitrate are rare, the consequences are often disastrous and have thus been the cause of some of the largest industry- and transport-related accidents to date. Most of them have involved uncontrollable fires. As part of the governmental investigation of the disaster, the accident area was thoroughly inspected, eye-witnesses were interviewed and pictures taken during the incident were examined. In addition, more than 340 fragments were collected and registered and used for further analyses and assessments. Based on these findings, we present a technical and detailed review of the accident. This includes the use of ballistic calculations in the ensuing analysis of the explosive event, followed by discussions on current regulations and hazard classification tests. These underline both the governmental and industrial need for profound, technical knowledge in the risk profiling of the transport of precursors for the on-site production of ammonium nitrate-based explosives.

KEYWORDS

Ammonium nitrate; fire; explosion; road transportation; safety

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1. Introduction

Ammonium nitrate (AN) has been the cause of some of the greatest industrial explosion disasters throughout history. Several of these have been the consequence of fire such as the explosions at the port of Texas City, US and Brest, France (both in 1947), and the more recent in West, US (2013), resulting in numerous fatalities and damages. As a consequence, numerous publications, reviews and reports on such disaster have been published, as these types of accidents, though infrequent, keep on taking place. Exactly 8 months after the disaster in West, an explosion accidents involving AN under fire exposure took place in Drevja, Nordland county, Norway, on December 17, 2013. Here, a mobile explosives manufacturing unit (MEMU) arrived to prepare a blast at a quarry in connection to a county road construction. The truck carried porous ammonium nitrate prills (ANPP) and ammonium nitrate based emulsion (ANE), together with other relevant chemicals for on-site explosives production. In the explosives industry, AN-based explosives have substituted most products based on dynamite formulations due to its improved cost-efficiency and safety profile, both in transport and handling. In addition, on-site production of AN-based explosives has emerged as a more practical and cost-efficient manner to use civil explosives. The greater cost-efficiency is due to cheaper transportation and storage options, since starting materials such as pure AN is not considered or classified as explosive materials at normal conditions. When contaminated or at elevated temperature and pressure though, AN represents an explosion risk. Uncontrollable fires are therefore of great concern during transportation and storage of such materials.

Herein we present a detailed and technical review based on first-hand information from the incident in Drevja, an incident which involved large amounts of AN-based materials and a truck-fire. This is the first known explosion accident due to fire in a MEMU-vehicle. Furthermore, a timespan of almost 2.5 hours from the fire commenced until the explosion took place is, to the best of our knowledge, the longest ever reported in an explosion accident involving road transportation of AN-based materials as cargo.

2. Accident description

At noon on December 17, 2013, a fully loaded MEMU-truck arrived at its destination in Drevja. The MEMU was parked in an 11° slope with its rear-end pointing uphill towards the blast area. The operator commenced the production and pumping process immediately after arrival, a process which was monitored on the left rear side of the truck where the operator console was situated.

After running for almost an hour, the power supply unexpectedly shut down at approx. 1.00 p.m. The operator heard the characteristic sound of an air leakage followed by the engine shutting down. While walking up towards the cabin, the operator noticed smoke evolving from the right front side of the vehicle. As he opened the passenger side door to turn off the main power supply, he observed flames from both the in- and outside of the vehicle. The cabin was filled with black smoke and flames blazed

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towards him from underneath the dashboard. First, the operator, aided by two constructors at the site, commenced fire-fighting measures. These were aimed at the fuse-box positioned on the right-hand side of the dashboard inside the cabin, as it was thought to be the origin of the fire. After several unsuccessful attempts, the fire-fighting was continued from the outside towards the engine compartment. Still, the fire could not be extinguished and evacuation was commenced at 1.07 p.m., followed by a manual activation of the automatic fire-fighting system in the engine compartment as a last attempt to quench the fire. However, this also failed. Shortly after the fire-department was informed at 1.11 p.m., all contractors and local residents in a range of 500 m were being evacuated. Both the color of the fumes and the intensity of the fire varied throughout the event (Fig. 1a-e).

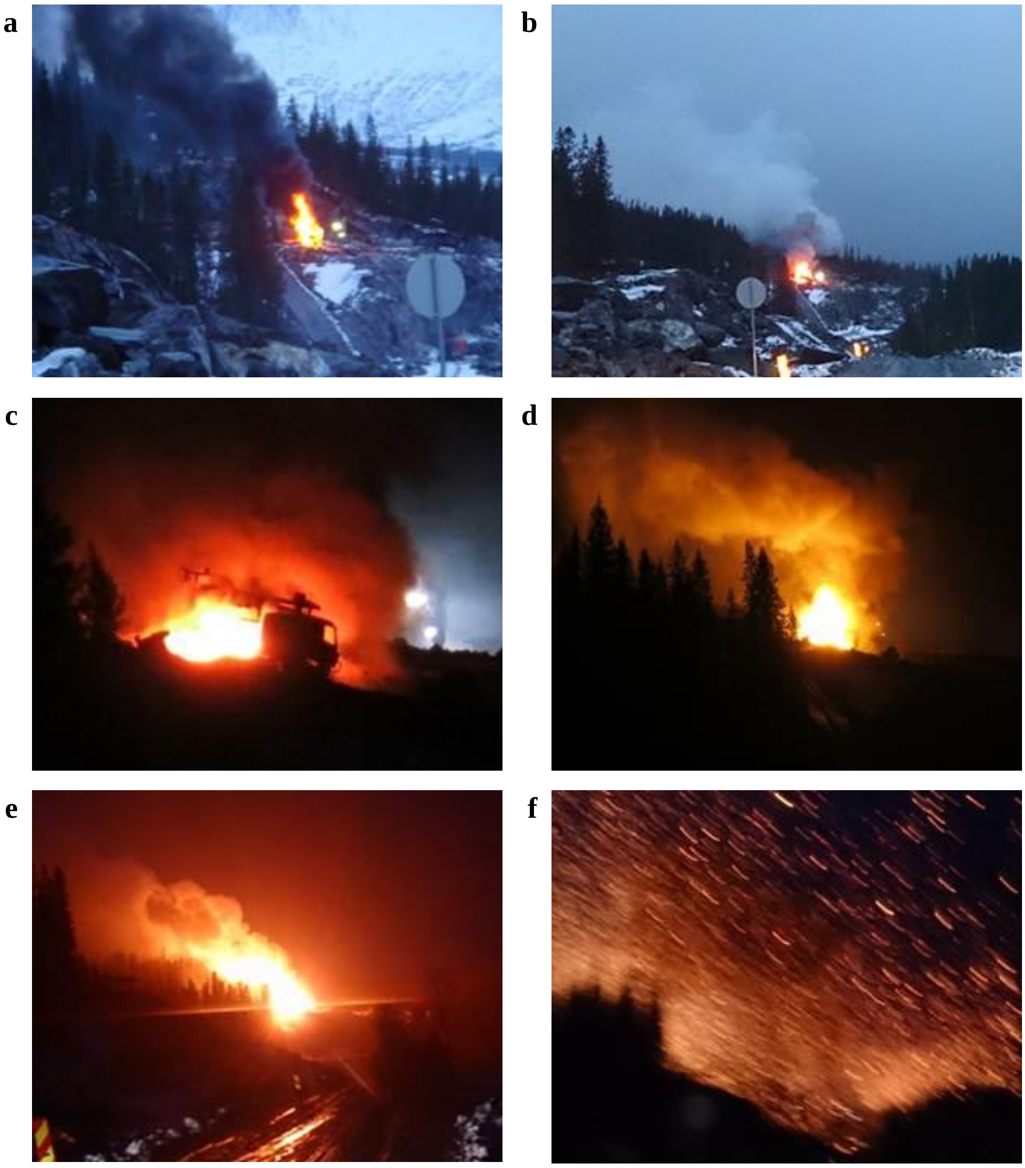

Fig. 1: Pictures showing the course of the fire: a) 1:26 p.m.: Intense fire accompanied by black smoke. The cabin is completely engulfed by the flames. Flames can also be seen on the ground in front of the truck. b) 2:23 p.m.: The cabin is almost burned out and the fire has propagated backwards. The truck load is now immersed in flames. Large white and grey fumes are observed. c) 3:15 p.m.: the fire has been calm for over 30 minutes. The cabin in completely burned out while the remaining tanks are incandescent. d) 3:21 p.m.: The fire suddenly intensifies and immerses the truck. e) 3:26 p.m.: The fire intensifies towards the rear of the truck with high flames seconds before the explosion. f) 3:26 p.m.: Glowing droplets filling the sky few seconds after the explosive event.

The fire seemed to calm down after 2 hours as the cabin was completely burned out while the tanks were incandescent (Fig. 1c). However, after being calm for over half an hour, the fire suddenly intensified at 3:21 p.m., resulting in flames that enveloped the whole truck (Fig. 1d). Eventually, the flames propagated towards the rear of the truck and finally culminated in an explosion at 3:26 p.m., 2 hours and 26 minutes after the fire was discovered (Fig. 1e). Immediately after the explosion, glowing droplets filled the sky (Fig. 1f).

2.1 Materials and explosives manufacturing

A MEMU-vehicle carries a number of precursors used for the on-site production of AN-based explosives and consists of several tanks, bulk containers, processing equipment and pumps. At the time of arrival, the MEMU in Drevja carried ANPP, ANE, aqueous sodium nitrate (SN) solution and aqueous acetic acid (AA). The MEMU was also equipped with a diesel tank for explosives manufacturing purposes in addition to the vehicle's fuel- and hydraulic oil tank (Fig. 2). The ANPP tank was situated directly behind the cabin while the ANE tank was placed at the rear of the truck. These two tanks, which were the largest tanks on the vehicle, were separated by an 800 L water tank.

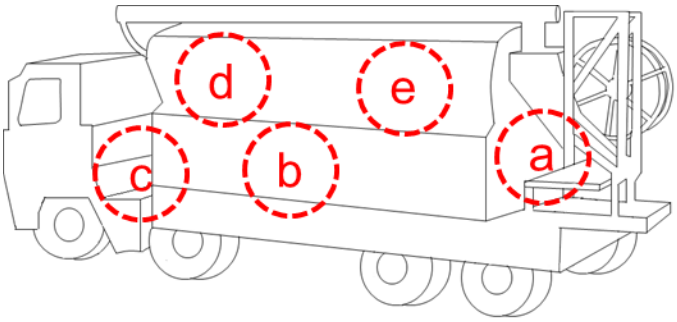

Fig. 2: Schematic drawing of the approximate position of cargo tanks containing a) production diesel; b) gassing agents; c) fuel tank; d) ANPP and e) ANE.

All tanks, except the vehicle fuel- and hydraulic oil tank, were constructed in aluminum. It has been estimated that 950 kg of the emulsion explosive had been produced at the time of evacuation (Table 1) [1].

Table 1: Materials and chemicals carried by the MEMU-truck at arrival and estimated amounts at evacuation.

Material	Original amounts [kg]	Estimated amounts at evacuation [kg]
ANPP	5000	4670
ANE	8000	7380
$NaNO_2$ (25%)	90-100	84-96
AcOH (60%)	90-100	84-96
Diesel oil (production)	450 L	427 L

During manufacture, diesel, ANPP and ANE, respectively, are pumped into the mixing auger in appropriate amounts to obtain the desired blend. The porous AN prills used in the manufactory process are of a porous quality which is particularly suited for explosives formulations. The ANE is a water-in-oil emulsion, mainly comprising an aqueous AN solution, fuel oil and emulsifiers. Sodium nitrite is added later on as a gassing agent. This process is usually catalyzed by the addition of acetic acid, particularly at lower temperatures, and provides the acquired porosity of the finished explosives product. Due to production irregularities in the production unit at Drevja, diesel was introduced after mixing ANPP and ANE. This is problematic as it yields a poorer explosives blend since the ANPP will not be able to efficiently absorb the diesel. However, this is not believed to have had any influence on the explosive event [1].

3. Investigations and fragment analysis

3.1 Post-blast inspections

As the accident area was cordoned off until the next day, the post-blast inspections started in the afternoon of December 18, 2013. The most surprising observation was the almost complete lack of fragments at the explosion site (Fig. 3a). The loading hose was, however, found more or less intact approximately 40 meters from the site, still containing the explosives product mixture (Fig. 3b). The residues were later analyzed by the respective supplier and found to comply with all governmental regulations [1].

All cartridge explosives, initiators and boreholes (located 8-10 meters from the vehicle) were found intact and only a few of the borehole plugs were affected by the high temperatures. In contrast to this, apparatus and equipment close to the site were clearly affected by the shock wave as indicated by damages such as shattered windows and bended steel parts (Fig. 3c-d). Residences up to 350 m away from the site were also greatly affected (Fig. 3e-f). In addition to this, a residential house had been ignited by fragments and burned to the ground. In total, 20 buildings were affected and 22 people were evacuated. Fortunately, there were no human injuries or fatalities.

No obvious impact crater was identified after the event. This was a bit unexpected seeing that an explosive charge usually will create an explosion crater if set off on a surface. Its dimensions will depend on the size, shape and type of charge, as well as the charge's distance from the surface and the properties of the rock surface. According to geological surveys of the quarry conducted prior to the accident, the rock surface at the explosion site consisted mainly of mica schist [1]. Mica schist, a crystalline metamorphic rock, has a foliated or plated structure with a tendency to split into layers. The breaking rate of mica schist during blasting is known to be very low due to its high ductility, a property which is defined as a rock's ability to deform under high stress without being fractured. Thus, even during regular blasting operations, mica schist is a problematic type of rock concerning its resistance to destruction [2]. When taking into account the low brisance of AN-based explosives and

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the non-ideal blasting conditions, the lack of an explosion crater under these circumstances is probably not anomalous.

Fig. 3: Pictures of damages at the accident site: a) Point zero one day after the explosion. No explosion crater can be seen. b) The only remaining part of the truck at point zero. The hose was still intact, containing the explosives product. c) An excavator at the quarry with shattered windows. d) A trailer standing few meters from the explosion shattered from the shock wave. d) Structural damages to a pig house 226 m from point zero. e) Shattered windows on a residential home, 210 m from point zero.

Inspections of the rock surfaces where the MEMU-truck was located during the fire revealed newly appeared rust colored stains (Fig. 4a-b). As the stains were not subjected to chemical analysis, it is impossible to determine their direct cause, nevertheless, the geological investigations suggested that this could only have been caused by the energetic event as the stains were embedded in the rock material. A plausible source to the stains could be iron-containing minerals. In fact, small amounts of pyrite (FeS_2) had been identified sporadically in the rock surfaces in the quarry (Fig. 4c-d), a mineral that is not uncommon to find in the metamorphic mica schist. When subjected to high temperatures and/or oxidizing agents, pyrite decomposes to yield iron salts such as rust (Fe_2O_3) [3]. Such an agent could simply be atmospheric oxygen, but it is also well-known that pyrite reacts with ammonium nitrate also to produce Fe_2O_3 [4, 5]. Lacking empirical evidence, any discussions on linking the cause of the stains and the initiation of the explosion will be dubious and will thus not be implied or debated here. However, these observations at least underline the extreme temperatures and conditions present during the event and may also suggest that material from the tanks can have leaked out and reacted with the rock surface.

Fig. 4: a-b) The red-stained rock surface observed after the incident; c-d) Rock specimens at the quarry in Drevja showing pyrite ores.

3.2 Fragment scattering and ballistic assessments

In June 2014, a thorough search for fragments was performed at the accident site in Drevja. More than 340 fragments were collected and registered, including the engine block, gear box, parts of the pump and augers and a large amount of aluminum and steel parts from the chassis and tanks (Fig. 5). The collected amount totaled of approximately 1/3 of the original weight of the truck's non-combustible material, 1/3 of these consisted of aluminum while the remaining 2/3 were made of steel.

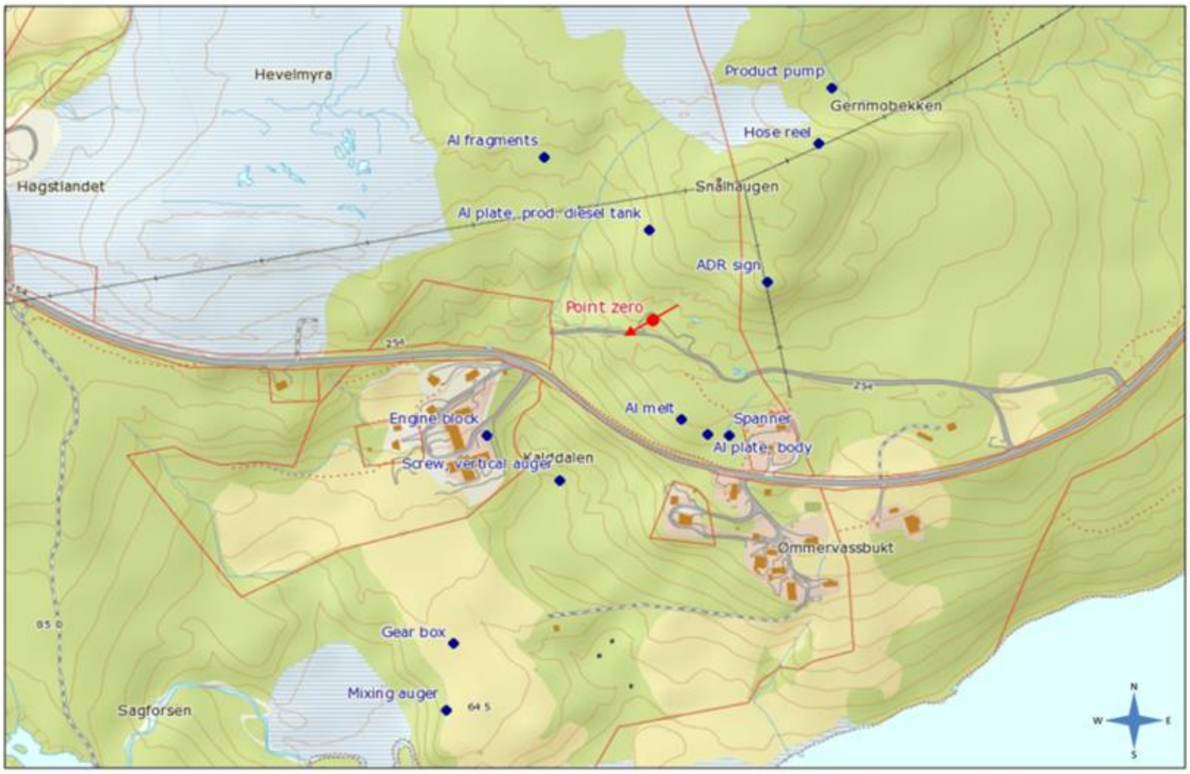

Fig. 5: Overview map of selected vital fragments. UTM coordinates for the zero point are 33W E425637 N7319534, 110 m above sea level. The arrow represents the original position of the MEMU truck with its front pointing in the arrows' direction.

3.2.1 Vital fragments from tanks and the production unit

Even though a large amount of fragments were collected, some of them were of particular importance. The pump and all mixing augers from the manufactory unit were retrieved, however; even though these parts must have contained the final explosive product when the fire started, they did not show any signs of internal explosions (Fig. 6a-c). Indeed, the retrieved parts of the pump did contain a large amount of intact product residues, making it highly unlikely that these parts were involved in any initiation of the explosion.

The recovery of bended and twisted steel parts and tools indicated fire temperatures close to the melting point of steel (Fig. 6d). Larger steel fragments were also visibly affected by the high temperatures (Fig. 6b and 6e). As the fire started in the front of the vehicle and propagated backwards, the front ANPP tank must have been exposed to more heat over a longer timespan than the rear ANE tank. This notion is supported by the fact that the parts originating from the rear of the truck looked less affected by the heat compared to the parts from the front (Fig. 6f-h). Several melted lumps of aluminum were found in the area (Fig. 6i), which implies that at least one of the cargo tanks must have melted due to the elevated temperatures. This is a quite interesting observation as the use of aluminum transportation tanks for these types of AN-based compositions actually is a general approach in the Nordic countries [1]. It is regarded as a safety measure which prevents confinement by the virtue of aluminums ability to weaken, melt and rupture at far lower temperatures than steel.

a: Product pump
332 m, 80 kg

b: Screw, vertical auger
211 m, 18 kg

c: Mixing auger
502 m, 100 kg

d: Spanner from toolbox
157 m , 0.3 kg

e: Hose reel
274 m , 50 kg

f: ADR rear sign
135 m, 0.8 kg

g: Aluminum plate, production diesel tank
103 m, 1 kg

h: Aluminum body plate
145 m, 4 kg

i: Aluminum melt
118 m, 1 kg

j: Aluminum fragments
Collected in a 200 m^2 range from 33W E425636 N7319640

k: Engine block
205 m, 950 kg

l: Gear box
430 m, 72 kg

Fig. 6: Pictures of selected vital fragments with their respective weights and travelling distance (their respective retrieval points can be found in Fig. 5). Weights > 5 kg are estimates based on weights of original parts.

A large amount of small aluminum fragments were also collected (Fig. 6j). In average, the aluminum fragments weighed less than 50 grams and were smaller than 10 cm^2. Most of them were found up to 200 meters from the explosion site, mainly in the direction behind and on the lateral sides of the vehicle's original position, while very few were found in the front. When reviewing the appropriate Gurney equations in this case, fragments of these sizes could only have travelled such a distance if the metal was in direct contact with the explosive material during detonation. Furthermore, the lack of aluminum pieces in the front suggests that the cabin must have blocked the fragments moving in this direction, thus indicating that the explosion must have taken place quite close to the cabin. If the detonation took place farther behind, more aluminum fragments should have travelled in a forward direction. The size, shape and scattering of aluminum fragments imply that an explosion took place in at least one of the tanks. If the rear tank did not detonate, larger parts of this would probably have been found. The fact that no large fragments of any tank were retrieved, strongly suggests that a detonation took place in both tanks.

3.2.2 Retrieving the engine block and simulation of its trajectory

The engine block was by far the largest fragment collected, with an approximate weight of 950 kg (Fig. 6k). It was retrieved 200 meters from and 32 meters below the zero point (Fig. 5). Simple, ballistic calculations indicate an initial velocity of at least 40 m/s. In order to find whether this distance and velocity complies with the amount and location of the explosive, the load on the engine block was simulated.

The explosive event was simulated by using the finite element program tool IMPETUS Afea Solver [6]. The IMPETUS solver is well adapted to problems as the one issued here since the explosive, the detonation products and the air are all represented by a large number of particles. The software has previously been successfully applied to model the impact on a vehicle by the detonation of a landmine buried in dry sand [7].

In our case, the engine is represented as a rigid block with the appropriate dimensions and positioning and a weight of 900 kg (Fig. 7). The ground is represented as a solid wall. Thus, the interaction between the air and the explosive, and that between the engine and the gases, as well as the reflection from the ground, should be well represented. It is the transfer of impulse from the detonation products to the engine that propels the engine. The explosive charge was modeled as TNT since the properties of AN-based explosives were not available in the program settings. However, this will not have any great influence on the final results. The explosive load was varied between 300-900 kg and its shape was varied between a sphere, hemisphere and a cone. Furthermore, the distance between the ground level and the engine block was fixed at 0.5 m while the horizontal distance between the engine block and the explosive was varied (Table 2). Since there are no indications on where the detonation was initiated, it is presumed that the detonation takes place instantly in the whole explosive mass.

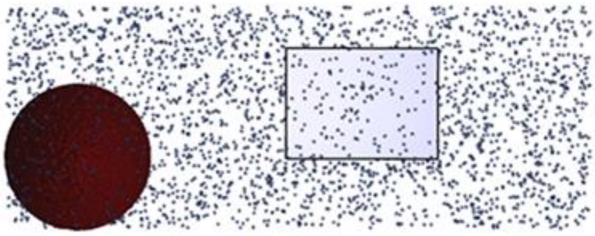

Fig. 7: General configuration used for simulations showing the explosive charge to the left (sphere) and the engine block (rectangle, 1.1 x 0.8 x 0.5 m) positioned slightly to the right of the center. 200,000 particles were in general used as a standard. The vertical position between the engine block and the ground was fixed at 0.5 m while the horizontal distance block-to-explosive distance was varied. The explosive charge was modeled as TNT.

In total, 37 simulations were performed where the shape, amount and position of the explosive charge were altered. Four of these configurations represented results where the size of the explosive charge, initial velocity and launch angle resulted in the engine-block reaching its appropriate target (Table 2).

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Table 2: Experimental results from simulations on the engine block performed in IMPETUS. The block-to-explosive distance is the shortest distance between the lower back edge of the block and the surface of the explosive.

Simulation #	Size of explosive load [kg TNT]	Shape of explosive load	Explosive distance to engine block [cm]	Initial velocity [m/s]	Launch angle [°]
1	600	Hemisphere	4	51	67
2	750	Cone on disk-shaped bottom	45	48	68
3	900	Cone on disk-shaped bottom	18	44	24
4	900	Hemisphere	24	44	25

Some general conclusions from the resulting calculations can be deduced: If the explosive charge is positioned 0.5-1.0 m from the engine, it is crucial that the charge is of an explosive yield greater than 900 kg TNT. This is necessary to provide the appropriate initial velocity. However, if the explosive charge is positioned less than 0.5 m from the engine, an explosive equivalent of 600 kg TNT will be sufficient. In addition, the calculations implied that the charge must be close to and partly below the engine block to give an elevated trajectory. Several other configurations could probably provide similar results but, it is highly likely that these would be of very similar character with only small variations in angle, velocity and positioning of the explosive charge.

According to the simulations, the engine block could only have reached its site of retrieval in two ways; either by an almost horizontal ejection angle caused by a detonation above ground, indicating a scenario whereby the block could have hit the ground downhill and then ricocheted further, or by an elevated trajectory that would bring it directly to its site of rest. The latter, would imply that a substantial part of the detonation took place partially below the engine, i.e. at the ground. In contrast, the first possibility implies that the explosion started inside the front tank. This can, however, be ruled out based on the retrieval of the gearbox (Fig. 6l). This item was found in almost the same direction as the engine, but 430 m away from the zero point. As the gearbox is smaller and its shape enables it to catch more impulse per weight compared to the engine, it would be expected that its ejection velocity is higher. Since the gearbox could not have reached its retrieval site other that by an elevated trajectory, it strongly indicates that the load originated from a point below the engine and the gearbox. As a consequence, the detonation must have initiated in a leaked-out content, most likely from a tank in close proximity to the engine.

4. Discussion and remarks

The hazards of AN during fire has been a widely discussed topic for more than a century. Even if these incidents are rare, the consequences are often disastrous, and identifying precautionary measures to prevent them is evidently of uttermost importance.

The collected fragments and calculation of the engine block trajectory at Drevja, all point towards a rupturing of at least one of the cargo tanks and a consequential release of its contents. This mechanism complies with the earlier mentioned strategy which promotes the use of tanks made of aluminum or fiber-reinforced plastic in the transportation of materials with the UN classification number UN3375 (used for ANE products) [1]. This measure is based on three large-scale tests which investigated the consequence of a fire when ANE is transported in ADR[1] approved steel- and aluminum tanks, respectively [8-10]. These tests showed that the weakening and rupturing of the aluminum tanks at fire temperatures relieved and prevented confinement. Nevertheless, as a safety precaution it must be concluded to have been inadequate to prevent the explosion in Drevja. The MEMU-truck at Drevja, however, carried not only ANE, but also large amounts of pure, porous AN together with sensitizing solutions, all in separate aluminum tanks. The aluminum tank safety approach is based on tests performed only on UN3375 products. Furthermore, its use in transporting ANPP (UN classification number UN1942) has, to the best of our knowledge, not been investigated in a similar manner.

Even though ANE consists of large amounts of AN, it does not behave in an undistinguishable manner from ANPP under fire conditions. Actually, ANE and pure AN has been reported to have different thermochemical behavior, where ANE displays a somewhat improved safety profile at elevated temperatures compared to that of pure AN [11]. This is believed to be partly due to the emulsion's ability to prevent the vaporization of AN during decomposition, an event which is responsible for promoting the exothermic decomposition pathways of AN. Furthermore, reports on the heat-conducting properties in ANPP and ANE, respectively, clearly illustrates that ANE has a much greater ability to distribute heat compared to ANPP [12]. The increased ability to convey heat prevents local heating, which is believed to be greatly involved in the unpredictability of AN subjected to fire. These are important properties to bear in mind concerning the Drevja incident, as the ANPP tank was much closer to the origin of the fire for a much longer time-period than the ANE tank. Both simulations and the fragment scattering suggest that the explosion was initiated close to and under the engine block, which strongly indicate an involvement of leaked material from the ANPP tank in the explosion initiation.

In the transport and storage of AN-based materials, confinement caused by its own container during fire is a concern of which the aluminum tank measure seeks to prevent. However, this measure seems to overlook the potential consequences of emptying the pure (and probably partly melted and thus sensitized) material in the midst of a fire as the container ruptures. Hence, the use of this approach will simply substitute one impending hazard with another. This makes the proposed safety advantages of aluminum tanks compared to that of steel debatable. Such a debate is especially relevant when considering co-transportation of AN with other hazardous materials in tanks that are designed to release material under fire conditions. Due to the current lack of empirical knowledge in this area, the only way to establish which materials and technical solutions that rule most advantageous, is to

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[1] Accord européen relatif au transport international des marchandises Dangereuses per Route (The European Agreement concerning the International Carriage of Dangerous Goods by Road), a 1957 United Nations treaty.

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perform investigations that address the overall hazardous issues with AN during fire and directly compares different tank materials under realistic test conditions.

The most obvious way to avoid these kinds of accidents is first and foremost to prevent the fire happening in the first place, which was also recently discussed in a comprehensive paper concerning explosions of fertilizer AN in storage and transportation [13]. But, due to the nature of road transportation, developing realistic and economically feasible measures which completely diminishes the chance of uncontrolled fires is often more problematic compared to that of storage buildings. In the US, approximately one out of every seven reported fires is a road vehicle fire. Most of them are in automobiles, but for all vehicles the same fact applies: close to 3/4 of the vehicle fires are caused by mechanical or electrical failures [14]. Similar numbers can be found in other countries [15]. Even though these types of fire incidents clearly have been greatly reduced the last two decades, fire prevention, especially in the case of transportation of AN and on-site production units, must be supplied with alternative risk preventable measures which are able to reduce the consequences of AN being present under fire conditions when such accidents actually do take place. Thus, it is necessary to endorse research in this area which can lead to optimized and updated suitability of transport tests and classification paradigms.

Where UN numbers are applied, hazardous compounds are identified, evaluated and classified through a series of tests found in the UN test manual as part of the recommendations from United Nations Committee of Experts on the Transportation of Dangerous Goods. For a chemical substance such as AN, where over a century of research still has not been able to establish any complete and reproducible tests that demonstrates when and why AN explodes only by the means of heat, it can be quite difficult to understand how it still is classified only using a set of quite general sensitivity- and explosive small scale tests, such as test series 2 found in the UN test manual.

In such a context, the international UN regulations and its accompanying tests must be said to suffer from being poorly updated in relation to the existing knowledge of AN and not well enough adapted to the current transported amounts and applications of AN and AN-based products. Especially in bulk production of explosives for civil purposes, such as the type employed in Drevja, the use of AN-based products is becoming dominant. Thus, new technologies and new transportation needs are arising rapidly. Here, both regulatory authorities and the industry has a common responsibility to keep up with this progress and apply detailed risk evaluations concerning areas such as co-transportation of materials, transportation tank material, formulations and so on based on profound scientific knowledge and technology developments. In this way, improved and more complete risk-assessments leading to greater protection of life and properties can be accomplished, hopefully avoiding other perhaps even more severe cases like the accident seen in Drevja.

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