How to assess the probability of the risk of explosion in AN storage ?

By

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Preamble: This article is about storage of technical grade LDAN (low density ammonium nitrate), i.e. oxidizer 5.1, UN1942, and with a density below 0.9 (cf SAFEX guideline).

Introduction:

Ammonium Nitrate (AN) is handled every year in millions of tons, stored, transported, consumed. To assess the risk of these activities is crucial, because the risk exists, and the consequences can be devastating in case of an explosion.

This article is focused on how to evaluate the probability of explosion of an LDAN storage. This is typically evaluated by making statistical analysis of past accidents. Different figures can be found in the literature, but often not how these figures were determined, with the risk that the figure may not be applicable to the case and/or making it difficult to attribute credit to safeguard when it is unclear if the base figure already includes it or not.

Therefore the methodology proposed here is:

1) an attempt to determine the probability of fire-leading -to-an-explosion scenario when there are no safeguard in place (worst worst case scenario, a lousy storage with AN engulfed in fire),

2) permitting to attribute consciously fair credit for best practices properly implemented (fault-tree analysis and risk reduction)

The aim of this paper is fundamentally to generate feedback and industry consensus.

Worst case scenario:

The worst thing that can happen with ammonium nitrate is a massive explosion, devastating the surrounding area. Such accidents happened occasionally along history, and still today.

FGAN, West Texas explosion, 2013. See CSB report, published on internet.

Deterministic versus probabilistic Risk Assessment

In a deterministic risk assessment study, let us say a QD approach (QD quantity distance), the occurrence of the explosion is simply assumed and thus not related to possible accident scenarios of the sensitivity of the material. Still the sensitivity of the material must be considered in the fraction of product that actually would explode, and the possibility or not of sympathetic detonation to other stacks.

In a probabilistic risk assessment, let us say a QRA (quantitative risk assessment), the probability of the unwanted event to occur is taken into account, and credits can be considered for the safeguards and best practices being applied. Performing a QRA involves estimating both the Probability of the event occurring and the Consequences if it does occur.

In both deterministic and probabilistic cases, the risk assessor has to define the energy release and its modelling. A traditional approach is to use TNT-equivalent which is for AN a conservative to very conservative approach. There exists today tools such as IMESAFR that treats AN as AN, not as TNT, for consequence (and risk) calculations.

QRA sensitivity

Quantitative risk assessment (QRA) is a probabilistic approach. The individual risk ("Ri") to people is quantified according to formula such as:

$$Ri = P \times C$$

P is the probability that the accident occurred, C is the consequence of it if it would occur. The calculated risk is compared to a threshold decided to be an acceptable risk, with typical figures such as maximum of 1E-5 or 1E-6 as individual lethality risk for a person from the general public.

The group risk or societal risk is then calculated as the summation of the respective Ri of the persons exposed.

The overall calculated risk is very sensitive to the inaccuracy of any of these factors, because it is not a sum but a multiplication. If P or C is wrong by one order of magnitude, the overall risk is over or under estimated by one order of magnitude.

The factor "C" relies on scientific, medical and historical evidence, and the number of exposed people "N" relies on data that are available at the time of the study, they can be considered as accurate and explainable.

Two remarks:

- Estimating the energy released (thus the fraction of AN to explode) is a decision and it will obviously influence the final result (the factor "C"), but the scaled distance in $Q^{(1/3)}$ buffers it ; The amount of AN involved in the explosion depends on the situation, type and amount of product, lay out of the storage, possible mix with incompatible fuels or not, type of insult to the product, etc and it is not one figure fits all. This is however not the topic of this paper.
- The number of people "N" may evolve over time, and this must be reflected on (land use planning), as urbanization growth getting closer can modify the original risk assessment.

The probability of event, “P”, is of a different nature. Indeed “**P” is the estimated frequency of a *__future__* accident** for *__the__* site being considered (asset, operation,…).

In situations where reliable data are available for similar cases under similar conditions, the *future* probability can be estimated with reasonable accuracy, based on solid data. This is one of the basis of preventive maintenance plans, based on probability of failure.

But with AN, it is different. The accidents exist but are relatively rare, and many occurred in conditions that may not be representative, or not representative any more, of the product and type of site that is being considered.

To get sufficient number of accidents and build a statistic, one may be tempted to cover a long period of time, for example back to early XXth century. But it is not representative. For example, most AN products which were considered “on-spec” products some decades ago would be classified off spec and classified as 1.5 today. Such as AN involved in the massive explosions in Texas City or in Brest, soon after WWII. Also, some practices such as the use of explosives in caked product, that led to catastrophic accidents after WWI (e.g. Oppau in 1921 and Kreuwald some weeks earlier also in 1921) and still some decades later (Tessenderlo, 1942), are unconceivable today. Or the manufacture of AN using acid that was containing some nitroglycerine.

The knowledge of these accidents is key, it is necessary to know the past to build a better future, but it is not relevant to evaluate P for a well-managed and state-of-the-art storage today.

Looking into more recent accidents: The explosions in West Texas (2013) or Saint Romain-en-Jarez (France, 2003) are not representative in terms of probability of what can happen in a state-of-the-art storage in a manufacturing plant, respecting best practices.

But the truck accidents in Arkansas (no official report yet) or Angellala creek (very valuable public information available) are representative of road accidents with today’s products.

All these accidents are strong reminder of the dangers of AN, that must never be forgotten.

For ammonium nitrate, what would be an appropriate P? Literature review

1)Safex guideline

The Safex guidelines for storage of TGAN (technical grade ammonium nitrate) mentions baseline event likelihoods in ~5E-5 for a manufacturing site, said to be derived from historical incident data. Unfortunately it does not detail the source data.

Table B.3. shows baseline event Likelihoods based on history of such events. These Likelihoods can be reduced based on implementation of "best practice" control measures.

Table B.3: Baseline Event Likelihoods (F_{event}) for an AN Manufacturing Site [15]

STORAGE TYPE	F_{event} BY INITIATION MECHANISM			
	Contamination	Fire	High Energy Impact	Malicious Acts
AN Bulk (Per pile up to 5,000 tonnes)	[10×10^{-6}/yr]	[50×10^{-6}/yr]	[10×10^{-6}/yr]	Consult National Security Authority
Off-spec pile (Per pile up to 500 tonnes)	[50×10^{-6}/yr^{-1}]			
AN Bags or Containers (Per stack up to 2,500 tonnes)	[25×10^{-6}/yr]	[50×10^{-6}/yr] (with pallets) [25×10^{-6}/yr] (no pallets)	[5×10^{-6}/yr]	

Figure B.2 shows the probability of fatality (both indoor and outdoor) for a given overpressure ($P_{fatalOP}$). The overall Likelihood of fatality (R_{fatal}) is a combination of these two measures, and is the Risk of fatality.

$$R_{fatal} = F_{event} \times P_{fatalOP}$$

[15] Derived from historical incident data

The Safex guidance rightly mentions that these probabilities can be reduced, based on implementation of best practice control measures. The difficulty is of course that it is not clear which safeguards may already be in place in the base-line figure expressed in 1E-5.

Nevertheless the intent is clear:

1) These SAFEX figures cannot be used for a lousy storage
2) These figures can be used as conservative generic figure for a storage respecting best practices.
    a. If the quantified risk is deemed acceptable, there's no need to spend much further effort on the "mathematics", but of course all efforts to be spent on the best practices, well managed, quality-ensured over time and controlled.
3) If using this generic Safex probability the quantified risk is deemed too high, then it is possible to refine the probability to a lower figure, providing sound arguments, fault-tree analysis, and this is the whole idea of the present article.

2)Canvey Island report

It is interesting to notice that some other data with similar order of magnitude in 1E-5 circulate in the literature and are sometimes used as reference. For example, the Canvey Island report (UK), that indicates a P of 8.5E-5. The fact that a second figure is close to the first one should however not be considered as a confirmation that the first one is right.

The origin of this Canvey Island figure is very illustrating of the risk of picking up a figure, without checking the background of it, and is presented in Lees as summarized below:

- The challenge for the risk assessment in the Canvey island was about hot AN solution, 92% concentration, stored in large tanks close to a railway.
- The only scenario of accident that was identified as potentially possible was the following: a petroleum train derailing, a pool of fuel taking fire, and AN leaking from the tanks that would have been damaged by the derailment, the AN melt getting mixed with the burning fuel and then finally exploding.
- The probability of event was then estimated starting from the probability of a train derailing per km in average, considering the number of train per year on that railway, the length of fence along the railway, the fact that train may derail on the right side or on the left (thus divide by 2 the probability of leading to an accident with the AN), and at the end calculated as 8.5E-5.

Most probably this approximation was sufficient to justify this specific operation as it was at that time. As the reasoning was conservative, with some non-credible conservative assumptions, there were therefore no need to tune further the figure.

It is clear that it would make no sense to use it for any other storage. The reasoning, still, is interesting.

Conclusion: The key-learning here is to not pick up a figure from the literature without checking its background and applicability.

3)IMESAFR

IMESAFR uses ~1E-6 as generic figure, confirming that the 1E-5 is too pessimistic for a "good" storage.

4)Probability of accidental explosion used for real explosives

For certain categories of explosives, probabilities of 1E-4 to 1E-5 are considered applicable by regulators in different countries (see for example https://www.hse.gov.uk/comah/assessexplosives/step2.htm), providing they are stored according to best practices.

Similar figures are used as default value in IMESAFR (typical figure of 2.8E-5 for explosives in IMESAFR).

Conclusion: a figure in 5E-5 for AN is by far too pessimistic when comparing to figures used for explosives. Providing AN is also stored according to best practices, the probability for AN must be lower by some orders of magnitude.

What is the most credible scenario?

The most credible scenario of explosion in AN storage is probably a fire leading to an explosion.

As AN does not burn itself, this scenario requires combustible material to be present… which is not compatible with a well-managed state-of-the-art storage.

In a high-standard storage, fires still can occur, but AN will hardly be engulfed in the fire.

- if the fire is generated by e.g. a forklift taking fire while in operation close to the AN and that it cannot be moved away nor extinguished soon enough. Forklift or vehicles shall never be unattended inside a AN storage.
- A fire can also start on the belt conveyor and a best practice is to have sprinklers on the conveying systems entering the warehouse (fire wall) or inside the warehouse.

But in some storages, combustibles can be present in large amounts. Below some examples (and best practice reminder between brackets):

- it can be the building itself (a state-of-the-art AN storage is not built in combustible material)
- a pile of pallets (pile of pallets must be stored far away from the AN, preferably in another building; AN use of pallets should be avoided whenever possible)
- some vehicles (vehicles in the AN storage shall never be left unattended),
- other goods co-stored nearby, such as solid or liquid fuels, metal powder, etc (only compatible goods can be stored next to AN, such as sodium or calcium nitrate), …
- All these practices are worsening factors.

Worth noting, when the product is bagged, the packing material is obviously combustible, however it is not a worsening factor (packing in today's bags, not in bags such as in "Texas City" after WWII).

This being said, it is very difficult to initiate accidentally an explosion of AN. Just as an illustration, no explosion could be achieved in the full scale tests of ANFO truck fire, that were performed in Canada after the Walden explosion, despite purposely worsening factors.

An explosion requires a combination of worsening factors in addition to the fire itself, such as:

- incompatible products to be present (e.g. the stuff that is currently burning), confined conditions, large amount of fuel from the vehicle, etc; and/or
- conditions that are created by the fire, e.g molten AN flowing into a closed sewage and reacting with incompatible products present there, molten aluminum, strong mechanical impact (for example generated by a gas bottle engulfed in the fire) into a pool of molten AN, etc

How to define appropriate probability of event for the risk assessment: use of the truck accidentology

In order to quantify the fault-tree analysis requires a systematic study of the potential causes, thus allocate fair reduction of the probability (typically by a factor 10 to 100 from an independent safeguard on a given branch of the fault tree).

A baseline is required, ideally under "worst worst" case situation, so that credit can later be applied for the safeguard, applied fairly, but also applied only once.

The accidentology of truck accidents, catching fire and leading to explosions, can be a very valuable basis to determine the probability of a fire involving AN and leading to an explosion, under "worst worst" case conditions, without safeguard. Why:

- A truck contains significant amount of combustible material
- The accident can involve other vehicles transporting other goods
- A truck accident on the road can involve many uncontrollable elements and worsening factors.
- When an explosion, AN or at least a fraction is engulfed in the fire
- There can be confinement (e.g. in case of roll-over, or in a close gutter under the road etc, etc)
- Multiple wrong combinations can occur: Fuel and AN can get mixed, fuel and molten AN, molten AN and molten Aluminum can get mixed, etc.
- It is possible to build sound statistics on truck accidents because:
    - Quite some data are accessible and are public
    - AN truck fire leading to explosion do occur unfortunately (every 5 to 10 years)
    - The global truck transport can be estimated since all LDAN will be, at a time or another of its lifetime, be transported by truck, allowing to make a more accurate correspondence between LDAN transport accidental explosions and a global tonnage of LDAN, as explained below.

From the road accidents, the aim is to determine a probability over a sufficient period of time of the "Number of explosions divided by the Number of truck fire involving the cargo of AN" in order to quantify the baseline fire-to-explosion probability under worst case conditions.

The selected time period is 1989-2019, why: because 30 years is sufficiently long to build statistics, because with the development of the globalization and the changes in China, Russia, etc, information became further more accessible after 1989, and because the LDAN products over this time period are basically similar to the products of today in year 2020.

What are the explosions with LDAN transport that did occur over 30 years 1989-2019: The explosion of Angellala Creek in Australia is well documented. The explosion of a MEMU in Norway is not a transport accident, so it may or not be considered in this evaluation. Considering the fact that some information may not be public, also that it is not clear which product exploded in China (Zhenganzhai), two LDAN explosions are considered in this approach, over these 30 years. All known explosions in Spain, Romania, Brazil, USA, that involved FGAN or HDAN, and are also considered below.

On the other hand, the number of truck fires involving the AN cargo can be challenging to quantify. Many fires, involving or not the cargo, remain simply not reported, therefore an interesting approximation is to use national data of "significant fire" per truck.km, and to estimate the total kilometers made by trucks transporting LDAN.

A probability of 8.8E-9 serious fire per truck.km (7E-8 fire; 1 out of 8 serious) was recalculated from French statistic (2013). "Serious fire" is understood here as involving the cargo and/or being sufficiently large fire. To consider all fires even minor ones would reduce artificially the probability (false safety)

This figure was counterchecked using Australian statistics (insurance statistics, crossed with transport statistics) to estimate the number of fires of trucks with major financial impact (approx. 183 fires divided by 19.4 billion truck.km in 2019), thus an estimate of 9.5E-9 major fire per truck.km.

The approach is summarized in the table below, with references of the sources:

Period	30 years	Remark

Number of LDAN trucks that exploded in the years 1989-2019	2	(remark there were more truck explosions, but involving FGAN or HDAN)
Number of significant fire per truck.km (AN involved and engulfed)	9E-9	Crosschecked statistics
How many truck.km of AN per year	10000000/20*500=7.5E9	10 millions of LDAN divided by 20 tons per truck, transported on 500km in average.
Probability P	2 divided by [30 years] divided by [7.5E9] divided by [9E-9] = 3E-2 Or 1 explosion out of 34 worst fires involving LDAN under degraded conditions	Running the same approach using 45 million tons of HDAN & LDAN, and 7 explosions over the last 30 years, lead to a similar figure of 2.3E-2 or 1 explosion out of 43 fires.

Considering that, in general, the number of transport accidents in the transport is usually lower than the number of accidents for all goods, data specific for AN were also evaluated using as reference a study from AEISG in Australia (2016, non-public), indicating for Australia on average one incident involving a significant fire on an ammonium nitrate vehicle every year, for a market of ~2 million tons a year.

On a 10 years review on Australian accidentology, considering only the worst three fires with AN (out of the 10), with AN engulfed in the fire, mixed with burning fuel or tires, allows to calculate a frequency of 1.5E-7 worst fire per year per ton AN, and allows to recalculate a frequency of explosion of 3.5E-2 per worst fire (1 explosion for 30 worst fires).

Using public data from e.g. Western Australia (20000 double road-trains per year, about 1 million ton of AN per year) combined with 3 major fires involving AN per 10 years in Australia, the probability of explosion for each long transport is ~1 to 2E-7 per voyage.

Considering this "worst worst" case baseline and performing a thorough fault-tree analysis, overall probability with an order of magnitude in 1E-7 or lower can be established for well-managed state-of-the-art LDAN storages.

Conclusion

Reminder: The aim of this paper is fundamentally to generate feedback and industry consensus

Generic probability figure must be handled with care: Figure with an order of magnitude in e.g. 1E-5 is very conservative for a well-managed storage of LDAN. But it is too optimistic for a lousy storage.

To estimate **the expected frequency of a *future* accident** for ***the*** site being considered is not easy.

It requires ideally knowing what would be the "worst worst" case probability (i.e. no safeguard, no respect of the best practices, AN co-stored with incompatible goods, engulfed in a massive fire, etc…) in order to fairly attribute a quantified credit for each safeguard put in place.

The conclusion of this study is to propose for this “worst worst” case probability of a fire-to-explosion scenario with AN engulfed in the fire, if no safeguard would be in place and best practices would not be respected, a figure of **3.5E-2 for LDAN**, i.e. one explosion out of thirty worst fires, engulfing AN.

This means that for well-managed state-of-the-art LDAN storages, probability of 1E-7 or lower can be reached after thorough fault-tree analysis study.

Last but not least, it is good to remind that a risk assessment is not a mathematic exercise but is about

1)identifying, knowing and mitigating the risks

2)ensuring that the risks remain mitigated and that safeguards are controllable/auditable

3)evaluating potential deviation of the safeguards and have sufficient margin coping with it

4)planning for and implementing improvements

5)finally to consciously agree and decide that the risk is acceptable. Or not.

This article is the fruit of teamwork . Many thanks for the numerous contributors who helped me in the preparation of this document or for determining the relevant frequency of worst fires per truck.km.