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Importance of Safety Management and Safety Culture for Storage with Explosion Risk: Lesson Learnt from the Beirut Disaster

Martin Lyubomirov Ivanov[1], Wan Ki Chow[2*]

1. Academy of the Ministry of Interior, Sofia, Bulgaria
2. Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[*]E-mail: wan-ki.chow@polyu.edu.hk

Abstract: There are many places storing combustible materials with explosion risk at residential or urban areas. Different explosions occurred all around the world thought the years. The latest case for a big explosion in the middle of a big modern town is the 2020 ammonium nitrate port explosion in Beirut, the capital city of Lebanon. More people are worrying about places with explosion risk, such as warehouse for combustibles with explosion risk, oil tanks, liquefied petroleum gas and petroleum refilling stations in downtown under tall building, explosion hazards of using hydrogen as clean fuel, etc. It takes a long time to upgrade the fire protection systems. Safety management and safety culture in those high-risk areas of explosion in big fires are very important. The recent AN explosion is a warning signal to enhance fire safety. This case is reviewed in this study as a way for looking forward in handling that kind of explosion hazard. New ways for research are proposed, including modeling experiments and numerical simulations.

Keywords: Explosion in urban areas; Fuel storage tanks; Nitrate explosion; Safety management; Safety culture.

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1. Introduction

There are many places storing combustible materials with explosion risk at or near to or even inside residential or urban areas. Many different explosions occurred in urban areas all around the world thought the years from Wanggongchang explosion and Leiden gunpowder disaster in the Early modern period till the present age accidents like Buncefield explosions, Tianjin explosions and many more. The latest case for a big explosion in the middle of a big modern town is the port explosion in Beirut, the capital city of Lebanon, with more than 180 losses of human life and more than 6500 injured with loss of more than $565 million. As a result of these events, more and more people are worrying about places with explosion risk, such as warehouse for combustibles with explosion risk, numerous oil tanks in residential areas, liquefied petroleum gas (LPG) and petroleum refilling stations in downtown under tall buildings, explosion hazards of using hydrogen as clean fuel, etc. There are always excuses not to upgrade the fire protections systems. Firefighters have to have additional training and equipment. The recent ammonium nitrate (AN) explosion is a warning signal to enhance fire management as well as emphasizing the importance of safety culture on alerting the responsibility of owners.

There are different reasons for damages in urban environment caused by shock waves. Damages caused by explosions inside the building or outside near the buildings like the Beirut case are so unpredictable [1, 2]. This major accident in Beirut will be used for an in-depth specific research for emphasizing the importance of safety management and safety culture.

AN is usually used in blasting rocks, quarrying, mining, and in civil construction [3]. When a carbonaceous or organic substance such as fuel, oil, nut hulls, or carbon black is added and mixed with AN, the mixture could become a blasting agent. Such oxidizing materials can yield oxygen upon decomposition under fire conditions and will, therefore, under favorable conditions of mixing, vigorously support combustion if involved in a fire with combustible materials. AN is capable of undergoing detonation with about half the blast effect of explosives, if heated under confinement that permits high-pressure build-up, or if subjected to strong shocks, such as those from an explosive [4].

Usually, after every big accident, the national authorities start to review and discuss the prevention work. When there are no strict requirements or there are requirements but they are not observed and there is no strict control by the authorities, it is not unexpected that such accidents occur.

2. Importance of Safety management and Safety Culture

Safety management is a combination of principles, framework, processes, and measures to prevent accidents, injuries, and other adverse consequences in emergencies. The four main components can be summarized as safety policy, safety risk management, safety assurance, and safety culture. Safety management can be significantly improved by promoting safety culture to ensure a better level of safety management.

There are a lot of different models describing effective safety culture schemes. The E's model [5] developed by the National Safety Council in US in 1974 is the stepping stone for further research. The main elements of this model are "Engineering", "Enforcement" and "Education", where engineering and enforcements are classified as separate points, as educations is a bridge between them from the one hand and a part from the both points from the other hand. The next logical step is to put inside the scheme the human factor. Three models are so similar in this respect - the Total Safety Culture Model by Geller [6] comprising three dimensions "Environment", "Behavior" and "Person"; the Reciprocal Safety Culture Model by Cooper [7], where "Person" is classified as internal psychological factor, "Situation" and "Behavior" are part of the external observable factors; and the P2T Model by Reniers et al. [8], where "Technology", "Procedures" and "People" constituent parts are separated. One of the latest researches, summarizing and combining the ideas from the previous four models is The Egg Aggregated Model [9]. It separates the three main domains "Technological domain", "Human domain" and "Organisational domain" showing deeply the consistency and the relations between them.

There are different views in different cultures [10-12] such as ensuring safety by a tripod as in Figure 1 with safety culture. Smoke impact [13] in big fires inside dense urban areas should also be watched. After summarizing the research, it can be noted that safety culture is extremely important, but unfortunately it is no easy to establish. The latest Beirut explosion case is one simple example where a big amount of AN had been stored in a downtown warehouse without the necessary safety measures for the last six years when more than 2700 tons of it was seized from an abandoned ship.

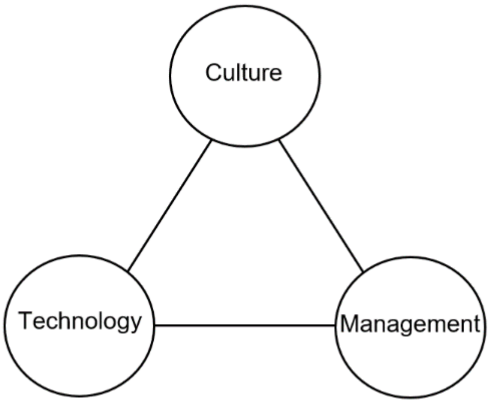

Figure 1. Safety tripod [11]

3. Explosion hazards in urban environment

AN explosion is considered as an extreme event, which rarely occurs. There are a lot and different explosion hazards in urban environment which are much possible - from fires and explosions in residential buildings [14-16], LPG and petroleum refilling stations in downtown under buildings, liquefied petroleum gas/hydrogen cars explosions in garages [17-20] and clean refrigerant leaked in an underground plant room [21] to big accidents like oil tanks accidents near urban areas [22], chemical plant explosions [23], etc.

Oil tanks in urban environment are very dangerous; however they are commonly forbidden in dense areas according to the safety codes. An interesting example can be seen in Hong Kong, where oil tanks were allocated on the Tsing Yi Island before developing the areas about fifty years ago. That area was an isolated island with a power plant, fuel tanks, storage areas, factories and shipyards, with a low population density. It is now an urban area linked up by bridges and tunnels with the Kowloon peninsula [22].

LPG is widely used as a fuel in many places all around the world. Fire risks associated with LPG vehicle systems were reported by Chamberlain and Modarres, suggesting that LPG buses are 2.5 times more prone to fire fatality risk than diesel buses [24]. LPG explosions can occur either outdoors with technical malfunctions of a car or also indoors when repairing such cars. An explosion while repairing LPG taxis in a garage located at the ground level of an old residential building in Hong Kong was reported in 2015 [18]. Gas stations in the downtown areas and hydrogen cars explosion are also possible scenarios in urban environment [19, 20].

These examples are only a little part of the explosion scenarios possible to occur in urban environment and show the necessity for bigger attention to the safety management and safety culture as a minimum requirement. Firefighters have already put in additional equipment and more training on handling some fires. Environmental impact due to smoke emission in big fires in dense urban areas is another concern.

4. A Proposed Safety Management Scheme

The recent AN explosion is a warning signal to enhance fire protection engineering and safety management. In this respect, Safety Management Scheme is proposed for the current research. Four main points shall be considered for minimizing the risks and impacts from future accidents:

i. *IDENTIFICATION*
Identification of events/accidents that could have negative consequences for the population and critical infrastructure with the help of the safety authorities, mainly fire services, on the one hand, and taking into account the opinion of the population about hidden potential risk, on the other hand.

ii. *PRIMARY ASSESSMENT*
Assessment of the likelihood of these events/accidents and the potential negative consequences for the population and critical infrastructure with risk assessment procedures and standards [25, 26], including a description of all risks that could have an impact in the area and characterization of their likelihood and consequences, qualitative risk assessment, risk assessment and prioritization and identification of potential impact measures through prevention, preparedness, response and recovery.

iii. *PROACTIVE ACTIONS*
Necessary actions to minimize the potential causes and consequences of such events/accidents through prevention and preparedness.

iv. *REACTIVE ACTIONS*
Necessary reactive actions identification if such event/accident occurs through response and recovery.

v. *FINAL ASSESSMENT*

5. Beirut explosion review and general overview of different tools for assessment

Experiments for such kinds of big blasts and damages cannot be carried out in a laboratory and that is a good reason to explore and use this explosion as a kind of “full-scale experiment”. Several articles about the Beirut Explosion were published up to now. Most of the authors estimated the energy yield from the fireball time evolution, which can be clearly seen in independent social media videos in combination with Google Maps, Google Street view and other tools sources.

Just several days after the Beirut Explosion, Lu made the first estimation of the energy released after the blast [27]. This research was based on formulas introduced by Taylor for measuring the energy yield of nuclear explosions [28, 29]. Lu used video footage to obtain an energy estimation of 2.65×10^{12} J and reported that the exploded AN is equivalent to 662 tons of TNT. Rigby et al. presented a method for calculating explosive yield based on the analysis of 16 online posted videos with a clear line-of-sight to the explosion at different distances from 85 to 2380 m [30]. They correlated the calculated distance-time relationship with semi-empirical equations by the method introduced by Kingery and Bulmash in 1984 [31]. Here the best estimate and reasonable upper limit of the AN explosion determined from this method are 500 tons of TNT and 1120 tons of TNT, respectively. Two papers were published by Aouad et al. [32, 33] referring again to Taylor’s method mentioned above. Six different videos were examined for the research. It was concluded that the fireball expansion reached an asymptotic limit at around 140 meters and the total energy yield was around 1.289×10^{12} J with a lower bound of 0.98×10^{12} J and an upper bound of 1.7×10^{12} J (or the equivalent of around 308 tons of TNT with a lower bound of 235 tons of TNT and an upper bound of 406 tons of TNT). Stennett et al. [34] made a computational research using different publicly available tools and data, including the CONWEP programme, UN Safer Guard web-based calculator, “Avidemux” visual analysis application, “Audacity” audio analysis application, and Movable-type scripts distance calculator. This research estimated the Beirut Explosion to have been equivalent to around 637 tons of TNT, with a lower bound of 407 tons of TNT and an upper bound of 964 tons of TNT. Interesting research was carried out by Agapiou [35] aiming at producing damage maps of the buildings over the area of blast in Beirut as observed from the Copernicus sensors “Sentinel-1” and “Sentinel-2”. Another research of this kind was reported by Pilger et al. [36] in measuring the yield estimation of the explosion using open-access waveform and remote sensing data, including GEOFON, IRIS, International Monitoring System, again Copernicus Open Access Hut and Interferometric Synthetic Aperture Radar. Here three independent methods were applied (seismic moment tensor inversion, acoustic yield relations and satellite radar image analysis), which consistently estimated the range of the yield to be between 800 and 1100 tons of TNT equivalent. Blast operational overpressure model [37] was also used. In Diaz’s research [38] comparison between Trinity and Beirut Explosion was made to estimate the energy yield of the Beirut Explosion based on four publicity available videos. Here the total energy yield was found to be around 2.3×10^{12} J with a lower bound of 1.2×10^{12} J and an upper bound of 3.4×10^{12} J (or the equivalent of around 600 tons of TNT with a lower bound of 300 tons of TNT and an upper bound of 900 tons of TNT). An interesting work [39] by researchers in the European Commission Joint Research Centre presented a framework to generate a 3D large-scale urbanistic finite element model, where the desired geospatial data are extracted from the open-source world map OpenStreetMap. The model is used to simulate blast wave propagation effects in a wide urban area taking into account the reflections at building surfaces via a sophisticated Fluid-Structure interaction technique integrated into the EUROPLEXUS explicit finite-element method software. The paper is considered as a demonstration by Valsamos et al. [39] of the potential of a newly developed tool that may improve existing ones. That potential did not really appear yet in the paper as its resolution is not adequate enough to show clearly the effects of street canyons, shock reflections and damping. In the latest research by Yu et al. [40], an extensive consequence analysis was made based on the crater size and physical effects for the estimation of the quantity of exploded AN. The TNT equivalent mass of exploded AN was approximately defined as 950 tons.

A lot of ways for research are available, including modeling experiments [41], numerical simulations, 3D large-scale urbanistic finite-element model [39], FLACS software [42, 43], etc. The current study found that a large amount of work has been done and a lot of interesting and novel techniques have been used for the Beirut explosion assessment for about two years after the explosion.

6. Copernicus Emergency Management Service Mapping

European Union has a lot of available tools for fire, explosions and disaster assessment. Copernicus Emergency Management Service (CEMS) provides detailed information for selected emergency situations that arise from natural or human-made disasters anywhere in the world [44].

Just some hours after the explosion the European Civil Protection and Humanitarian Aid Operations activated both the on-demand mapping modules of CEMS, Rapid Mapping and Risk and Recovery Mapping, in succession to support response decisions and coordination of disaster management professionals. Although in the beginning the activation was classified as “Sensitive” shortly after it was triggered (i.e. not open-access online), the European External Action Service agreed to share the results of the analysis with organizations that had expressed interest in accessing this information for use in their operations, like World Food Program, Lebanese Red Cross, French and German Civil Protection, Swiss Agency for Development Aid and Cooperation and others. On the 14th of August, the sensitivity label was removed and all products were made available on the Copernicus EMS Mapping web portal [45].

As a visual example, the base of Figure 2 is [EMSN081] Lebanon - BEIRUT Industrial accident (Explosion) map from CEMS [46]. The map shown here is a detailed damage assessment map and analyses over affected areas. Four different areas of buildings damage grading are derived - destroyed (in dark red color), severe damage (in red), moderate damage (in orange) and possible damage (in yellow). The CEMS reported that a total of 11611 buildings are affected by the blast.

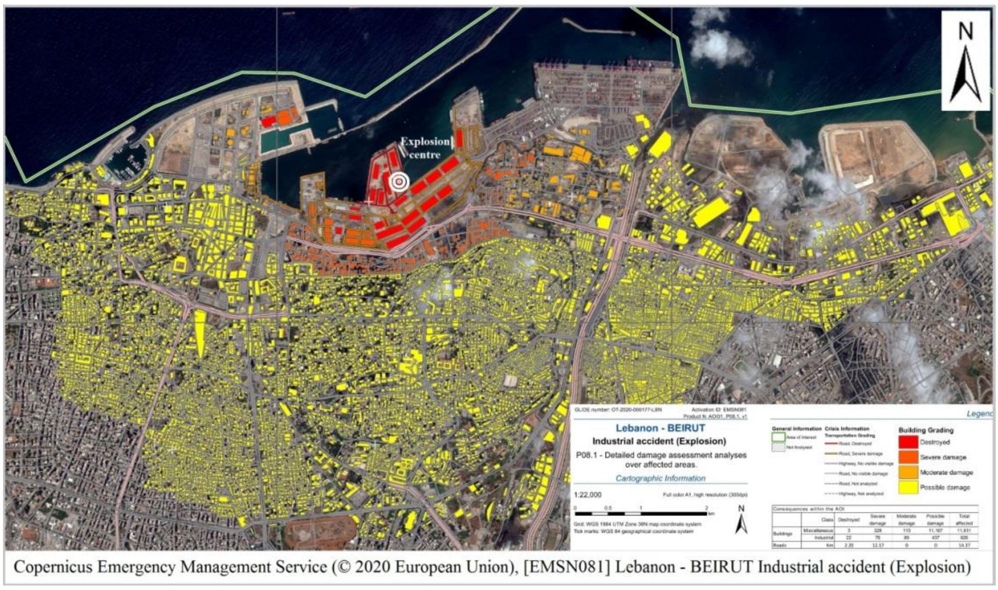

Figure 2. Detailed damage assessment map and analyses over affected areas [46]

7. Conclusion

Usually, after every big accident, the national authorities start to review and discuss the prevention work. When there are no strict requirements or there are requirements but they are not observed and there is no strict control by the authorities, it is not unexpected that such accidents occur.

It is common to have 'strict' requirements for usage, storage and transportation of AN all around the world, but after this case, the effectiveness of the regulations about production, storage, transportation and usage of AN must be checked. Some recommendations for dramatical reduction of the possibility of AN accidents with such big losses are: factories for producing AN and related materials as well as warehouses for storage these materials must be only out of urban arias; an interesting future scientific task is to use an alternative material of AN, which can be used as a plant fertilizer but is not explosive; banning the production and usage of AN for blasting purposes; storing of AN must be in concrete buildings with no other goods around, excluding any combustion materials fires near the AN; strictly controlling the temperature in production and storage spaces with sprinklers.

Safety systems and requirements are needed but they are not adequate on their own. The safety system would not be successful without effective safety management and safety culture.

The recent AN explosion is shown in this research as a warning signal to enhance fire protection engineering and safety management. This case is reviewed as a way for looking forward in handling that explosion hazard. New ways for research are proposed, including modeling experiments and numerical simulations. The importance of safety management and safety culture in those high-risk areas of explosion in big fires are considered as very essential. These include keeping oil tanks in developing residential areas, LPG and petroleum refilling stations under tall buildings, explosion of hydrogen clean fuel, etc. As observed in recent bigger fires, smoke emission on environment impact is the minimum effort to take, even though thermal effects are not significant.

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