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Laboratory Explosion Accidents: Case Analysis and Preventive Measures

Qi-Zheng Yang, Xi-Ling Deng, and Shi-Yao Yang*

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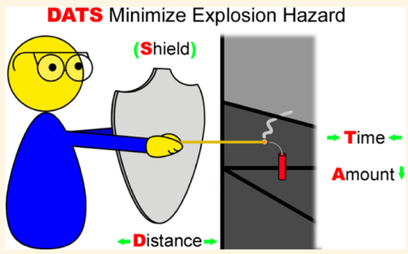
ABSTRACT: This paper collected 22 cases of explosion accidents in laboratories in China in the past 10 years, analyzed the causes of the accidents, and put forward measures of preventing and mitigating the hazards of explosion accidents by identifying the explosion hazards in laboratories, assessing the explosion risks, minimizing the explosion hazards, and preparing for possible explosion accidents. Specific preventive measures are the DATS principles: keep the Distance as far as possible, use the minimum Amount of explosives, shorten the residence Time, and use appropriate Shielding.



KEYWORDS: *accidents, explosion, safety, prevention, deflagration, magnesium, DATS*

1. INTRODUCTION

Explosion is a common serious accident in the laboratory. When an explosion occurs, energy is released instantaneously and the high temperature and high pressure spread rapidly. The transmission speed far exceeds the reaction of human beings.

The explosions are also followed by frequent fires, resulting in burns and poisoning. At the same time, the explosion causes mechanical injury to personnel, and severe injuries such as cuts and bruises can occur, making it extremely difficult for the personnel to escape and seek first aid. Because of this, explosions are the leading cause of death and injury in laboratory accidents.[1−3]

In reality, explosion does not require dangerous explosives or special chemical agents to occur, as people often think. Many commonly used substances can cause explosions. For example, common flammable gases such as gas, vapors of flammable liquids, vessels with pressure difference, and reagents commonly used in laboratories such as nitric acid may be initiators of explosion accidents. Therefore, explosions (including detonation and deflagration), as well as fires that are mutually causal, have become the biggest causes of common laboratory accidents and serious laboratory accidents. Hence, how to prevent explosion accidents is one of the most urgent and important issues in laboratory safety.

In fact, looking back at the fatal accidents in laboratories in the past 10 years, it can be seen that most of them are explosion accidents. In the review article "A review and critique of academic lab safety research"[1] published in Nature Chemistry in 2019, in the serious cases of international laboratory accidents reviewed, the death toll caused by explosion accounted for more than 50% of the total death toll.

Deaths caused by explosions in university laboratories in China in recent years have caused much concern in laboratory safety among researchers.[2] Over the past 2 decades, there has been an increase in university laboratory accidents in China, and the literature paper entitled "Current status, challenges, and future directions of university laboratory safety in China"[3] makes a census and analysis of accidents. The distribution of accidents in university laboratories based on physical effect types since 2000 shows that the incidents of fire and explosion account for 82% of the total, but explosions are the biggest cause of death, and explosions account for 60% of the total deaths. Fire accounted for only 10%.

In the past 10 years, from the perspective of information dissemination on the internet, the number of laboratory explosion accidents in scientific research institutions such as universities and colleges in China has increased significantly. This has a certain relationship with the rapid expansion of the scale of scientific research, the rapid increase in the number of postgraduates, the intensified pressure of scientific research competition, and the improvement of the convenience of information dissemination. Only a small number of accidents have a comprehensive, detailed, and in-depth investigation and review. Most accidents are not carefully recorded, analyzed and summarized. The academic community lacks a channel to report these accidents. More often than not, only scattered

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information is released by individuals around the scene at that time through the internet, and there are many more minor accidents that have not entered the public eye.[2]

The above references made general comments on the safety conditions of all laboratories but did not provide specific details of the explosion accident nor did they analyze and study the specific causes of the explosion accident, especially did not provide specific preventive measures for the explosion hazard. For laboratory explosion accidents, we should collect and analyze typical laboratory explosion accident cases, analyze the specific reasons, and propose feasible and effective preventive measures to prevent explosion hazards.

However, for obvious reasons, many accidents, especially those that did not result in fatalities, were not recorded or reported. Worst of all, in some cases, serious casualties were not investigated in detail. This made it impossible to know the cause of the accident. Those who suffered the accident paid the price of precious life or health in vain, and future generations failed to learn from it. This situation is unacceptable for the quest of accident avoidance and in reducing the occurrence of similar accidents and reducing the losses caused by the accidents.

This paper collects some explosion accidents in the laboratories of Chinese universities and scientific research institutions in the past 10 years through various means, analyzes the direct cause of the explosion, the accident process, and consequences, and makes a detailed and in-depth analysis. Preventive measures are suggested for the explosion accident avoidance and to improve laboratory safety in general.

2. ACCIDENTS

2.1. Strong Reducing Agents. *2.1.1. Accident 1: Magnesium Powder Explosion Fire.* On December 26, 2018, the horizontal scientific research project of landfill leachate sewage treatment at the School of Municipal and Environmental Engineering, Beijing Jiaotong University, stored 1 ton of magnesium powder and other materials in the laboratory. An explosion and fire accident occurred during the experiment, causing three graduate students on site to burn to death. The accident investigation report was released on February 2019.[4] The investigation report confirmed that the direct cause of the accident was the process of stirring and reacting magnesium powder and phosphoric acid with a mixer. The hydrogen generated in the hopper ignited and was exploded by the sparks generated by the metal friction and collision at the rotating shaft of the mixer, which in turn caused the explosion of magnesium powder dust cloud, resulting in the secondary explosion. The surrounding magnesium powder and other combustibles burned, and during the rescue attempts, the magnesium powder and other chemicals stored in the laboratory continued to explode uncontrollably.

2.1.2. Accident 2: Magnesium–Aluminum Powder Deflagration. On October 24, 2021, a powder metallurgy laboratory on the third floor of the School of Materials Science and Technology of Nanjing University of Aeronautics and Astronautics exploded. A video circulating on the internet showed that someone was staying on the balcony of the laboratory that caught fire, and other people in the adjacent corridor were helping to sprinkle water to cool down and help the trapped people. At this time, the laboratory exploded. The accident resulted in two deaths and nine injuries. It was reported that the cause of the accident may be related to the deflagration of magnesium–aluminum powder. However, no further specific information has been found a year later.

2.1.3. Accident 3: Aluminum Powder Deflagration. On April 20, 2022, an aluminum powder deflagration accident occurred in the laboratory of the School of Materials Science and Engineering, in a university in central China. A doctoral student suffered extensive burns during the accident. The high-temperature metal powder entered the trachea and esophagus of the injured, covering more than 80% of the body's skin, and continued to burn inside the body. So far, no further specific information has been released for more than half a year.

2.1.4. Accident 4: Explosion of Sodium Metal in Contact with Water When Disposing of Waste Reagents. On July 9, 2019, safety managers found an unlabeled plastic bottle containing strong brown liquid and lumpy solids when disposing of used reagents in a laboratory in south China. The safety managers tried adding a small amount of water to the bottle after testing the liquid (actually hydrocarbons) as neutral with pH paper, which quickly caused a deflagration. Fortunately, the victim was able to retreat in time and was only slightly injured. After on-site investigation and analysis, there were several massive metallic sodium at the scene, and it was judged that this bottle of reagent contained chunks of metallic sodium (the surface was brown).

2.1.5. Accident 5: Metal Hydride Explosion during Disposal of Waste Reagent Bottles. On July 27, 2021, a doctoral student was cleaning up the items left by the previous graduates in a laboratory in south China. There was an unknown white solid in a 1 L flask. The flask burst with water, and the glass fragments pierced the arteries of the student's arm. The student was then sent to the hospital for treatment. The white solid most likely contains sodium or calcium hydride that reacts violently with water. More than a year later, no further specific information can be found.

2.1.6. Accident 6: Explosion Occurred in n-Butyllithium Bromine Extraction Reaction. On October 12, 2020, a doctoral student carried out the *n*-butyllithium bromine extraction reaction in a laboratory in east China: a flask was evacuated to remove water and oxygen; bromopentafluorobenzene (10.8 mL) and *n*-hexane (40 mL) were added and cooled to −78 °C under nitrogen protection; with stirring, *n*-butyllithium (40 mL, 1.6 M/*n*-hexane) was slowly added. After 1 h of reaction, the flask was taken out, shaken a little bit, and put back into the low-temperature bath. When the operator put his face close to the reaction bottle and observed with a flashlight, the container suddenly exploded. It is speculated that *n*-butyllithium reacted violently with bromopentafluorobenzene due to shaking, and the exothermic reaction was violent. The uneven heat and cold shrinkage caused the reaction bottle to burst. With the help of students nearby, the injured graduate student took an emergency shower and went to the hospital for treatment after hemostatic bandage of the wound. The accident resulted in slight burns to the eyes of the injured person and two wounds on the face.

2.1.7. Accident 7: Deflagration of Azide–Lithium Aluminum Hydride–Diethyl Ether Reaction. On November 6, 2020, in a laboratory in east China, a doctoral student carried out the reduction reaction of trimethylsilylmethyl azide. In a round-bottomed flask, 11.7 g of lithium aluminum hydride was added to 200 mL of ether, cooled at −50 °C for 30 min, and then transferred to a fume hood to warm up gradually, and 0.3 mol of trimethylsilylmethyl azide was added dropwise with stirring. The reaction solution suddenly reacted violently,

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flushed the flip plug, and sprayed outwards. After 2 s, deflagration occurred in the fume hood. The graduate student stood beside the fume hood and was partially burned by the flames sprayed from the bottom of the fume hood sash. The graduate student quickly picked up a fire extinguisher to put out the fire, showered his face and neck, and rushed to the hospital for treatment.

2.1.8. Accident 8: Explosion Occurred in the Reaction of Preparing Organophosphorus from White Phosphorus. On August 4, 2020, when a research assistant in a laboratory in the east of China walked by a fume hood, suddenly the flask in the fume hood exploded, causing the person scratched by glass fragments on her chin, neck, right upper abdomen, and arms, and she was sent to the hospital for treatment. The experimental operator himself was not around at the time and was not injured. The cause of the accident was the operator, a graduate student carried out the synthesis of *S*,*S*,*S*-triethyl phosphate, and the end point of the reaction was not monitored. When handling the reactants, a small amount of white phosphorus that may still exist came in contact with air, resulting in small sparks or instantaneous exothermic reaction causing a flash explosion of a small amount of *n*-hexane or ethyl acetate vapor in the flask. During the experiment, the sash of the fume hood was not pulled to the lowest position according to the specifications, which resulted in the lack of protection of the explosion-proof glass of the fume hood when the explosion occurred, which was also one of the reasons for the injury.

2.2. Strong Oxidants. *2.2.1. Accident 9: Sodium Nitrate–Sodium Thiocyanate Explosion.* On May 23, 2016, a graduate student and two workers of the company conducted a pilot scale-up experiment of a phase-change energy-storage material in the workshop of a Wax Industry Co., Ltd., which was run by a graduate tutor of an east China university. The explosion occurred when 50 kg of sodium nitrate and sodium thiocyanate were mixed and heated, killing three people on the spot. Before the accident, the graduate student conducted several small-dose experiments of mixing and heating the same mixture in the school laboratory. A series of court proceedings ensued, and the tutor was sentenced to 2 years of probation. Detailed reasons can be obtained from various reports, but no accident investigation report can be found.

2.2.2. Accident 10: Concentrated Sulfuric Acid–Potassium Permanganate–Graphene Explosion Accident. On September 21, 2016, a laboratory in the School of Chemistry, Chemical Engineering and Bioengineering of Donghua University exploded while preparing graphene oxide. During the experiment, 750 mL of concentrated sulfuric acid was placed in an open conical flask and mixed with graphene, followed by potassium permanganate (100 g). The experiment procedure required that the temperature be kept at 5 °C. When the temperature was exceeded, a spoonful of unweighed potassium permanganate was added, and an explosion instantaneously occurred. Two students facing the experimental device were seriously injured, and one student whose back was facing the experimental device was slightly injured. The graduate students did not wear lab coats and goggles during the experiments. There was no shower device in the laboratory, and the eyes could not be washed with water, and no first aid measures were taken before admission to the hospital. The explosion caused chemical reagents such as concentrated sulfuric acid and potassium permanganate to burn the face and eyes, as well as multiple injuries caused by glass fragments, resulting in severe visual impairment in the eyes of the seriously injured person, with a vision of 0.01 in the left eye, blindness in the right eye, and facial disfigurement. The accident has entered legal proceedings, and the detailed reasons can be obtained from various sources.

2.2.3. Accident 11: Reagent Bottle Containing Concentrated Nitric Acid Burst. On June 15, 2020, a graduate student in a laboratory in southern China cleaned the silicon wafer with ultrasonic waves in a glass reagent bottle, poured out the water, then treated the silicon wafer with 40 mL of 68% concentrated nitric acid, and tightened the bottle cap. Five min later, the reagent bottle burst, and part of the concentrated nitric acid was sprayed onto the graduate student's face and neck. The graduate student was not using personal protective equipment (PPE) at the time of the accident. The graduate student immediately rinsed the face and neck with plenty of tap water for more than 7 min, then went to the hospital, and was diagnosed with partial epidermal damage on the face and neck. The cause of the accident may be that the nitric acid decomposes when exposed to light and heat to generate gas, causing the closed reagent bottle to rupture under pressure.

2.2.4. Accident 12: Explosion Occurred When Heating Nitric Acid–Hydrogen Peroxide to Clean the Hydrothermal Reactor. On August 20, 2019, an explosion occurred in the oven when a master student was using it to clean a hydrothermal reactor in the corridor in a chemical engineering building in eastern China. 20 mL of dilute nitric acid, a few drops of hydrogen peroxide, and 30 mL of water were added to a 100 mL pressure reactor, and the oven temperature was set at 180 °C. The strong pressure generated by the explosion pierced through the top plate of the oven, the oven door was knocked off, and the hydrothermal reactors flew out (Figure 1). Fortunately, no one passed by at the time, and no one was injured.

Figure 1. Front and side views of the oven after explosion of the hydrothermal reactor.

2.2.5. Accident 13: Explosion of Perchloric Acid–Dimethylformamide Digestion Reaction. On November 18, 2016, in a laboratory in southern China, a small-scale explosion occurred when a graduate student used perchloric acid (3 mL) to digest the reaction solution (the main component was dimethylformamide) for the preparation of metal@MOFs. The digestion experiment was carried out in a colorimetric tube in a fume hood by heating with an electric heating mantle. The graduate student pulled down the sash of the fume hood and

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observed the digestion process by the side. After about 1.5 h, the graduate student left the scene. About 5 min after leaving, the digesting solution exploded. The explosion shattered the tempered glass on the front of the fume hood (Figure 2). No personal injury was caused.

Figure 2. Fume hood damaged by explosion of perchloric acid−organic compounds digestion reaction. (Reproduced with permission from Professor Qin Kuang.)

2.2.6. Accident 14: Acetone−Hydrogen Peroxide Explosion. On December 21, 2019, in a laboratory in eastern China, a graduate student used hydrogen peroxide to oxidize trivalent phosphorus intermediates (which may contain a small amount of residual solvent acetone) to obtain pentavalent phosphate esters (about 1.5 g). The product was extracted with 60 mL of ethyl acetate. Next, the ethyl acetate was removed under reduced pressure using a rotary evaporator. When the concentration was about to end (the water bath was 45 °C), the round-bottomed flask exploded. Fortunately, the students in the laboratory were all far away, and no casualties were caused. The reason should be that hydrogen peroxide and the residual solvent acetone (acetone has been removed by rotary evaporation, but there may still be residues) will react to form the explosive triacetone triperoxide, which will enter the organic layer during extraction. Toward the end of the rotary evaporation, the concentration of organic peroxides increased while heating causing the explosion.

2.3. Flammable Gases and Flammable Liquids. *2.3.1. Accident 15: Methane−Air Mixed Gas Cylinder Explosion Accident.* On April 5, 2015, researchers at the Research Laboratory of the School of Chemical Engineering, China University of Mining and Technology were doing a methane gas mixture combustion experiment when a methane gas mixture cylinder suddenly exploded. The accident resulted in one death, one severe injury and amputation, and three perforated eardrums. The cause of the accident was the gas cylinder was filled with a mixture of methane, oxygen, and nitrogen, and the methane content in the cylinder reached the explosion limit. The accident investigation report was released on May 10, 2015.[5]

2.3.2. Accident 16: Hydrogen Cylinder Explosion Fire. On December 18, 2015, an explosion and fire occurred in a laboratory of the Department of Chemistry of Tsinghua University, and a postdoctoral fellow who was conducting an experiment died on the spot. The accident may have been caused by hydrogen explosion and fire. Afterward, the school deactivated a batch of similar cylinders due to the quality of the cylinders. Rumor has it that the postdoc tapped the cylinder with a wrench in order to make it release more hydrogen. However, the exact cause of the accident is yet unknown, although the accident has attracted much attention because it happened to a postdoctoral researcher at a top Chinese university.

2.3.3. Accident 17: Explosion Occurred during Extraction Experiment in a Teaching Laboratory. On November 11, 2018, a laboratory of the Hanlin College of Nanjing University of Traditional Chinese Medicine exploded. A strong shock wave blew the door of the laboratory, glass slag was everywhere, and many teachers and students in the laboratory were injured. It was reported on the internet that many students suffered severe burns. A police report was issued that day, but no further follow-up information was found after that. Rumor has it that the cause was an accident during an extraction experiment involving the use of ethanol in a teaching laboratory.

2.3.4. Accident 18: Leakage of Solvent through Column and Deflagration of Electric Spark. On August 31, 2019, in a laboratory in east China, a doctoral student performed silica gel chromatography in a fume hood. Since the storage ball was not fixed with a clip, the eluent hexane escaped from the gap between the storage ball and the column under pressure. The graduate student unplugged the pressurized pump to prevent further escape of the hexane; possibly sparks from the unplugging ignited the hexane in the fume hood, causing deflagration. The graduate student suffered burns on both arms and face because he did not wear a lab coat and protective goggles as required and did not pull down the fume hood sash during the experiment. After being injured, he went to the bathroom to rinse with water and was sent to the hospital for treatment and recovered in about half a month.

2.3.5. Accident 19: Explosion during Centrifugation of Organic Solvent. On April 30, 2014, a teacher in a laboratory in southern China was exposed to an explosion when he was using a centrifuge for solid−liquid separation and immediately caught fire. Nearby graduate students rushed to put out the fire with a fire extinguisher. The teacher suffered deep second-degree burns to his jaw and wrist. The solvent was a few milliliters of petroleum ether or methanol. The reason might be that the solvent vapor was ignited by the brush spark of the centrifuge causing an explosion (Figure 3).

2.3.6. Accident 20: Silane Gas Deflagration. On May 20, 2020, a deflagration accident of residual gas in the pipeline of experimental instruments occurred in a laboratory. Preliminary investigations showed that when the lab dismantled the silane gas cylinder, the two engineers were doing it for the first time. According to the experimental requirements, they should work together with the laboratory safety officer, but the two did not strictly implement the experimental safety operation procedures. In the absence of the laboratory safety officer, the two did not strictly implement the safety operation procedures and did not take personal experimental protective measures, resulting in explosion of silane gas left in the pipeline of the experimental instrument, and one person was burned.

2.4. Pressure Vessel Accidents (Including the Previous Two Cylinder Explosions; Accidents 15 and 16). *2.4.1. Accident 21: Autoclave Explosion.* On March 31, 2021, a safety accident occurred in the Nano Laboratory of the Institute of Chemistry in northern China. It was suspected that due to improper operation of the postgraduate, the autoclave was forcibly opened before cooling down, and the pressure in

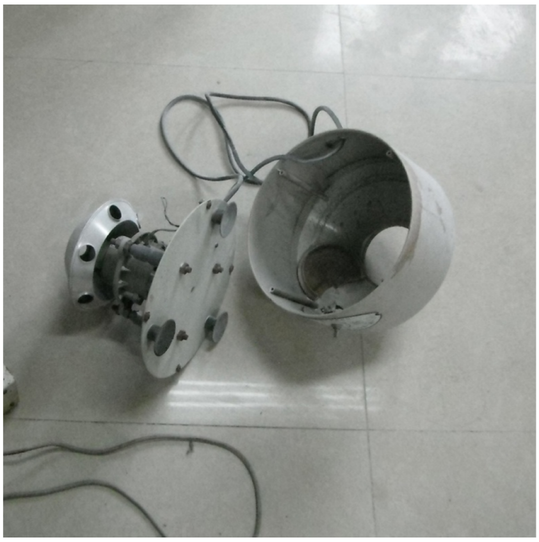

Figure 3. Exploded centrifuge fell to the ground. The ground had been swept.

the autoclave was not completely relieved, resulting in an explosion, and caused the student to die on the spot. No further specific information is available.

2.4.2. Accident 22: Explosion of Glass Container. On June 7, 2022, a glass container exploded in a laboratory in southern China. A doctoral student was injured in the face, neck, and arms. The tendons of his fingers were exposed, and the skin of his right mandible was blown out as a knuckle-deep wound. The hole, the carotid sheath, was blasted, and further 0.2 mm deep would be life-threatening. The graduate student was rushed to the hospital for surgery in time, and the broken glass pieces were removed. There are rumors that high-pressure glass bottles such as sealed tubes might have exploded. No further details of the accident were available.

3. DISCUSSION

3.1. Safety Ethics. Working safely, avoiding unnecessary risks, and taking responsibility for safety are the primary responsibilities of everyone who studies and conducts chemical research. Risk factors in the laboratory need to be recognized, assessed, minimized, and prepared for possible accidents (RAMP).[6] However, in the actual learning and research process, there are many challenges to ensure safety, and laboratory safety faces many difficulties. This is manifested in the following aspects.

3.1.1. Lack of a Beneficial Safety Culture. From the perspective of the overall environment, the construction of safety culture is far from the level it should have. There is insufficient attention to laboratory safety, and the risk of explosions has not been taken seriously. There has been no serious investigation, analysis, summary, and announcement of the accidents that have occurred. In some units where an explosion accident occurred, the first thing the management did was to block the news, prohibit the public dissemination of relevant information, avoid discussion of the cause of the accident, and refuse or reluctant to respond to media attention and interviews.[2]

Some organizations often express severe punishment in safety management, trying to curb the occurrence of accidents by means of administrative punishment afterward but neglect the investigation of specific causes and the elimination of specific risk factors. This is mainly manifested in the neglect of preserving the first-hand information of the accident, the neglect of the preservation of the physical objects involved in the accident, and neglect of the preservation of video material or image evidence.

After the accident, a considerable part of the parties and their research groups were secretive about the cause of the accident and refused to cooperate with the investigation. This has something to do with their fear of being punished and of their own reputation being damaged. This kind of self-protection is understandable, but doing so is detrimental to the investigation of the accident, and it is not helpful to prevent similar accidents in the future.

For example, in the above-mentioned serious explosion accidents, in addition to accident 1, the explosion accident at Beijing Jiaotong University, which killed three people, has a huge impact, and the accident investigation report was released 1.5 months later. Several other serious accidents did not disclose any further information. Among them, with regard to accident 2, 1 year has passed; accident 3 occurred 6 months back; accident 21 occurred 1.5 years back. Judging from past experience, if it were not for some accidents that had a huge impact at the time and some accidents that entered the judicial process later, the academic community would have no chance to learn more about the accident, and the specific cause of the accident may never be known. Even if there were accidents reported by the public media at that time, there would be no more objective summaries.

After an accident occurs, attention should be devoted to serious investigation and analysis of the specific cause of the accident and to announce it to the academic community in a timely manner to issue safety warnings to their peers. Punishing the parties involved in the accident will inevitably lead to the parties' concealment of minor accidents, mistakes, and violations. This leaves an opportunity for more major accidents to happen in the future. No one is willing to suffer an accident. In fact, graduate students who were injured by an accident have suffered physical and psychological harms, which is likely to be more serious than any administrative punishment. It can be seen that the safety culture of scientific research institutions such as universities urgently needs to shift from blame culture to beneficial culture.[7]

3.1.2. Lack of Safety Information Sharing Channels. According to Heinrich's law, for every serious accident, there will be 30 accidents and 300 near misses. Past accidents are extremely important reference materials for the prevention of future accidents. The academic community should establish an information transmission channel as soon as possible, so that colleagues can share laboratory safety information in a timely manner, including those minor accidents or near misses that have not yet caused serious consequences, which is of great help in preventing subsequent similar accidents. Paying attention to explosion accidents is a prerequisite for prevention, and the warning function of accidents that have occurred needs to be conveyed to researchers, especially graduate students who face the direct threat of explosion accidents. The current web network technology can help to establish a platform for academic circles, such as online forums or accident reporting and prevention websites.[8] Failure to pay attention to near misses will eventually lead to major accidents.

Under normal circumstances, although certain investigations will be carried out within the institution after the accident occurs and the responsible persons will be punished, the

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specific cause of the accident is not disclosed, making it difficult for information to be transmitted outside the institution. It is not conducive to the prevention of similar accidents by other institutions. The cost of life and the health of accident victims are not valued.

If the accident cannot be notified and the cause of the accident is unknown, the accident of the same cause will reoccur in other laboratories. For example, in accident 18, 2019, a laboratory overflowed the solvent when passing through the chromatographic column. Electric spark ignited solvent deflagration when pressurized pump was unplugged, causing burns to the experimenter. Because the doctoral student involved was an international exchange student, the relevant information was kept strictly confidential for 50 days after the accident before a notification was issued within the institution. Apart from the internal, no accident warning was issued to the public. Later, the author learned that the same accident happened again in another institution, and detailed information was not available.

Past accidents, including not only laboratory accidents, but also industrial accidents, have extremely important implications and direct reference value. For example, in the past 10 years, there have been several major explosion accidents caused by active metal dust in industrial enterprises: On August 5, 2012, an aluminum dust explosion occurred in Wenzhou City, Zhejiang Province, killing 13 people; on August 2, 2014, a particularly serious aluminum dust explosion occurred in Kunshan City, Jiangsu Province, killing 97 people; on March 31, 2019, a magnesium alloy waste deflagration accident occurred in Kunshan City, Jiangsu Province, killing 7 people. However, none of these major industrial accidents that caused huge shocks caused the scientific research community to learn the lessons. Just after that, there were three consecutive laboratory active metal dust explosion accidents with similar causes in colleges and universities: December 26, 2018, accident 1, Beijing Jiaotong University, 3 people died; October 24, 2021, accident 2, Nanjing University of Aeronautics and Astronautics accident, 2 people died; April 20, 2022, accident 3, Central South University, severe burns one person. These are extremely regrettable tragedies that do not need to happen.

3.1.3. Difficulty in Risk Assessment and Control. Usually, due to the free exploratory nature, complexity, diversity, and specialty of scientific research, the development trend is difficult to predict, and the research process cannot be carried out exactly as planned. At the same time, the competition of scientific research activities is keen, and the pressure for publication is overwhelming. Therefore, there are many risk factors in scientific research laboratories, the causes are complex, and the management and control are difficult. It is difficult to have a set of widely applicable and specific relevant safety regulations, and the tedious and time-consuming professional risk assessment cannot be applied to each specific step of each research topic. Every year, graduate students are constantly replaced by new and old ones, and they face the pressure of publishing and graduation, which makes the supervision of graduate students in a state of out-of-control chaos, making safety training and supervision extremely difficult.[1]

Because the safety issues of the research laboratories have not been treated in the same way as that in the teaching laboratories,[1,9] the accident risk faced by the research laboratory is far greater than that of the teaching laboratory. The accident cases listed in this article, except accident 9, occurred in the factory, accident 17 occurred in the teaching laboratory, and all others occurred in the scientific research laboratory. Relatively speaking, teaching laboratories generally carry out experiments in accordance with the teaching plan, mature content, clear plans, and relatively known and controllable risks, and experiments are carried out during working hours under the supervision and guidance of teachers. As a result, risk management is relatively good, and there are significantly fewer serious accidents. However, in practice, there is also a risk of explosion in teaching laboratories, and serious accidents can occur, for example, accident 17.

3.1.4. Disadvantaged Position of Graduate Students. In the research group, the relationship between supervisors and postgraduates is similar to the inheritance relationship between mentors and apprentices, which is relatively closed and exclusive, and the postgraduate relationship is undoubtedly in a weak position. Graduate students are the implementers of the research plan, carry out specific experimental procedures in the laboratory, are the specific operators of the experimental procedures, and face the direct threat of accidents, but they do not have the right or the power to change the laboratory environment; therefore, it is difficult to eliminate the explosion risk they face. For example, in accident 1, the explosion of Beijing Jiaotong University, the graduate students were aware of the major risks in the laboratory before the accident: a large amount of explosives, magnesium powder, were stored in the laboratory, and they reported that their supervisor hoped for rectification. However, the instructor disagreed and did not make any changes. The graduate students also complained to the environmental protection department in the society, trying to eliminate the risk with the help of external factors, but it was also unsuccessful. In the end, an extremely regrettable tragedy occurred.

Graduate students also face condescending administration at their universities or research institutions, where they have no influence over policy making and implementation. Scientific research institutions such as colleges and universities are closed to a certain extent and seem to be relatively isolated from the society. It seems that the regulations and supervision applicable to factories and enterprises cannot be directly extended to laboratories of scientific research institutions such as colleges and universities. This makes some of the major risk factors found in the laboratory often difficult to eliminate, leaving hidden dangers for serious accidents. In the explosion accident cases that caused the death of people listed in this article, a total of 11 people were killed, of which 8 were graduate students and 1 was a postdoctoral fellow. Graduate students are the main force of scientific research, but they face the most serious and direct safety risks, which is not commensurate with their huge efforts and contributions to scientific research.

3.1.5. Insufficient Awareness of Risk Prevention among Graduate Students. Identifying risk factors, assessing risks, preventing accidents, and strengthening safety protection require a certain investment of energy, financial resources, and time, which is a cost or price to scientific research. Therefore, under the pressure of scientific research, safety issues are often easily overlooked. In addition, PPE sometimes poses practical problems. Wearing thick lab coats and goggles in summer, for example, does hinder comfort. In addition, goggles are easy to fog up due to sweating, which also brings certain safety problems. Therefore, it is common that the proportion of graduate students wearing goggles is not high, which is lower than that of wearing lab coats.

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In recent years, although more and more universities have set up experimental safety courses, the effect seems to be unsatisfactory, and various laboratory accidents still occur from time to time. Some researchers, possibly due to insufficient laboratory safety education and training, lack of subjective safety awareness, weak awareness of abiding by rules, and weak safety awareness, do not pay attention to safety. Although minor accidents in the laboratory are not uncommon, serious accidents are still low-probability events, so that graduate students who face the greatest accident risk are personally negligent, do not pay enough attention to safety, fail to identify dangers, and fail to carefully assess risks, not to mention the last line of defense, the use of PPE, leading to serious consequences in the event of an accident. For example, in accident 10, the postgraduate student in the explosion accident at Donghua University did not fully assess the risk when he knew that there was a risk and still did not take personal safety precautions, indicating that the postgraduate did not receive proper safety education when he received undergraduate education at southern university, did not establish enough safety awareness, and also did not get the necessary safety education when entering the postgraduate stage, so that the accident occurred and led to serious consequences.

3.2. Safety Technology. With reference to the RAMP rules for laboratory safety,[6] we will deal with laboratory explosions from the following aspects.

3.2.1. Recognize Explosion Hazards. Identifying potentially explosive hazardous materials or mixtures can help reduce explosion incidents. According to the reference materials, checking the presence of dangerous substances in the laboratory is the first task that everyone who will work in the laboratory must complete.[10]

There are many kinds of substances that may cause explosions in chemical laboratories. Material Safety Data Sheet or Safety Data Sheet is a useful tool for predicting explosion accidents. For some substances with unknown properties, some methods and properties can be used, for example, the possibility of explosion can be predicted from the chemical composition of the substance, which is the "oxygen balance" of a substance. The judgment standard can be used as a reference for identifying explosion hazards.[6]

In fact, there is a more direct and reliable basis, that is, explosion accidents that have occurred, including industrial accidents. The best way to identify explosion hazards is to collect and study past accidents. More attention should be paid to accidents that have occurred in similar laboratories, including those minor, unrecognized, and unrecorded incidents or near misses. Many laboratory explosions are actually repeats of previous incidents. For those accidents that have already occurred, the possibility of reoccurrence is very high, and the above-mentioned accidents are the best examples. Establishing an extensive safety information sharing channel among academics as soon as possible is an important condition for hazard identification.

In 2017, Yang published a paper titled "Analysis of Typical Aluminum Dust Explosion Accidents Case and Fire Safety Countermeasures,"[11] analyzed nine typical aluminum dust explosion accident cases in factories and enterprises from 1963 to 2016, and discussed main technical measures to prevent aluminum powder dust explosion and general disposal methods and precautions after aluminum powder dust accidents occur. Since then, there have been three serious magnesium−aluminum powder explosion accidents in colleges and universities.

In 2020, after serious explosion accidents (accident 1 in 2018 and accident 15 in 2015), Yang and Qiu published a paper entitled "Analysis and Control of Explosion Accidents in College and University Laboratory Based on Similar Systematics Principle,"[12] a detailed and professional analysis of the two accidents.

These two safety papers published in Chinese journals are unlikely to be as eye-catching as those published in international journals with high impact factors. If they are not specifically searched by keywords such as safety, explosion, and so forth there is no chance to enter the eyes of researchers.

If the articles published in inconspicuous professional journals failed to attract the attention of the scientific research community, then the major industrial accidents widely reported in the public media, for example, the above-mentioned 2012−2019 years of many enterprise magnesium−aluminum powder explosion accidents caused heavy casualties and social concerns, should have attracted the attention of relevant researchers. However, the reality is, still not!

It can be seen that identifying dangers is not so easy, and it is not something that can be solved by several publicity activities and frequent safety inspections. If the danger is not recognized, it is impossible to do the relevant risk assessment, and necessary precaution measures cannot be taken to prevent or mitigate the harm of explosion accidents.

3.2.2. Assess Explosion Risk. Although laboratory safety accidents seem to be common in news media reports in recent years, many uncertain factors make it difficult to draw a simple conclusion on whether the accident rate is increasing or decreasing, and the assessment of accident risk remains a challenging subject.[3]

The main reasons for this situation are as follows: (1) Incomplete accident data: there is no statistical plan to systematically collect, organize, analyze and report accidents, and a large number of accidents of unknown number have not been recorded. (2) The number of college students, especially graduate students, has increased substantially, and the scale of scientific research activities has increased rapidly. (3) The safety training of relevant majors in colleges and universities is also being carried out, and the atmosphere of attaching importance to experimental safety is gradually forming. (4) The dissemination of news brings convenience and makes it difficult to block accident news. (5) With the improvement of technical conditions, more and more automation equipment, safety equipment, and PPE are used, reducing the risk of personal exposure and injury.

Reference[12] made a detailed professional analysis of two explosion accidents, accident 1 and 15. These two accidents, and only these two accidents, could find the accident investigation report, so it was possible to do a more in-depth analysis. However, such a careful analysis and assessment of the risks of all research topics is practically difficult to achieve. Therefore, it is necessary to propose some simple and easy methods to assess the explosion risk for researchers in chemistry-related disciplines.

3.2.2.1. Under What Conditions There is a Risk of Explosion. From basic chemical principles, the further away from the state of natural conditions, the higher the risk of explosion. The natural condition is that elements such as hydrogen, oxygen, and carbon exist in the form of water and air at a standard atmospheric pressure (oxygen 20.9%, nitrogen 78.1%, CO_2 0.03%), and active metals form salts or oxides. If water is decomposed into hydrogen, carbon is formed into hydrocarbons, nitrogen is converted into a compound state, and the active metal is reduced to an elemental state, then it deviates from the natural state. The more the deviation, the greater the possibility of explosion. Oxygen is ubiquitous in the environment we live in. The more dispersed the combustible material is, the better the contact with air, and the higher the risk of explosion. Of course, careful evaluation is necessary for a given environment.

3.2.2.2. What Types of Laboratories are at Risk. Judging from the accident cases listed in this article (some of which have been reported publicly), scientific research laboratories are undoubtedly the hardest hit areas for explosion accidents. Not only chemical laboratories but also professional laboratories related to hazardous chemicals such as environment, materials, pharmacy, and so forth have experienced serious explosion accidents.

A typical chemical professional laboratory has many types of dangerous species, but the number is generally not large, except for laboratories that use a lot of flammable organic solvents. The key to ensuring safety is to manage and control explosive dangerous substances, and the seriousness of the consequences of explosions is not very big. In some laboratories conducting pilot scale-up experiments, the quantity of dangerous substances is larger, the risk of accidents is much greater, and the consequences of accidents will be much more serious, for example, accidents 1 and 9. Table 1 lists the relationship between the explosion accident and the quantity of dangerous substances according to the severity of the accident.

Table 1. Explosion Accidents by Accident Severity and Quantity of Dangerous Substances

accident	hazardous chemicals	amount	consequence
1	Mg powder, (H_2)	>66 kg	3 dead
9	$NaNO_3$, NaSCN	50 kg	3 dead
2	Mg or Al powder	unknown	2 dead, 9 injured
15	methane 17%—air cylinder	41.7 L, 2.0 MPa	1 dead, 1 injured
16	hydrogen cylinder	unknown	1 dead
21	autoclave	unknown	1 dead
10	concentrated sulfuric acid, $KMnO_4$, graphene	750 mL, 100 g	1 seriously injured
others	various hazardous materials	grams and below	serious or minor injury

One might expect that teaching labs would be better safe than research labs, and at least so far, the fatalities have been in research labs. However, accident 17, a laboratory deflagration accident on November 11, 2018, had serious consequences. This reminds us that the explosion-proof problem of teaching laboratories also needs attention and must be carefully evaluated and dealt with.

3.2.2.3. Which Substances Require Special Attention to Their Explosion Hazards. It is necessary to enumerate several classes of particularly dangerous substances, which have caused serious explosion accidents, resulting in the death of a large number of people.

1. Combustible gases, vapors of flammable liquids. Combustible gases are the most common cause of explosion accidents, such as accidents 15−20. Gas or vapor is invisible, colorless, and odorless (such as hydrogen, carbon monoxide, and methane). Although some organic solvents have odors, these odors may not attract special attention in a laboratory environment, therefore, their leakage, volatilization, and formation of an explosive mixture with air are difficult to detect, so the risk of explosion is very high. Since the oxygen content in air is 20.9%, and the explosion limit of most low-boiling point hydrocarbons or organic solvents is between about 1 and 10%, this is a dangerous state that is fairly easy to achieve in closed or semienclosed rooms. Organic solvents are often used in large quantities in the laboratory, and the risk of explosion is significant.
2. Powder active metal, aluminum powder, magnesium powder, and other metal powders. In accidents 1, 2, and 3, five people were killed, and many were seriously injured. Such explosions account for 46% of the total number of fatalities in the explosions listed in this article.
3. Nitric acid and nitrates. In accident 9, an explosion occurred when 50 kg of sodium nitrate and sodium thiocyanate were mixed and heated, and three people died on the spot. In accidents 11 and 12, nitric acid, in the absence of a typical reducing agent, was not mixed with a significant amount of organic substance and still exploded violently. In fact, explosives are basically nitrates of organics—organic nitro compounds. In addition, compounds containing multiple-bonded nitrogen elements (e.g.,, azo, diazo, azide) are explosive, such as in accident 7. A graduate student in the author's research group once encountered a dangerous situation when synthesizing azo compounds, and the reaction was violent during feeding, and material injection occurred, so the related research was stopped.
4. Perchloric acid. In accident 13, perchloric acid was mixed with organics and heated, resulting in a violent explosion. The strong explosive tendency of perchloric acid should be the common knowledge of chemical professionals. Research work using perchloric acid and its salts should include an explosion warning in the paper, alerting readers to the risk of explosion.
5. Organic peroxides. In accident 14, hydrogen peroxide reacted with acetone to form triacetone triperoxide. Although the amount was small, it had a strong explosive force. The round-bottomed flask exploded with a loud noise.
6. Pressure vessel and combustible gas cylinder, accident 15 and 16; high pressure reactor, accident 21; sealing tube, accident 22.

3.2.2.4. Disposal of Waste Hazardous Materials. This is a high-risk activity because the container may lack labels, which makes the type, nature, quantity, and other information of the dangerous chemicals missing, and the handling can easily lead to accidents, such as accidents 4 and 5

Another small accident: In June 1995, one of the authors, while recovering the platinum remaining after the synthesis of the complex, treated the residue containing black platinum powder with a few milliliters of aqua regia in a porcelain crucible in a fume hood and heated it in an electric furnace. A small explosion suddenly occurred in the crucible, the lid of the crucible burst, and a yellow slurry was sprayed on the front of the operator's upper body, one of which splattered into the

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right eye. The injured were immediately flushed with plenty of tap water for several minutes and deionized water and then taken to the hospital for treatment. After examination by the doctor, no obvious damage to the eye was found. The reason for the explosion should be that the nitric acid reacted with the organic substances in the residue, such as filter paper, triphenylphosphine, and methanol, to cause an explosion. At the time, the author did not take any protective measures, and the fume hood sash was not pulled down.

The explosive nature of nitric acid, which can occur at any time, should always be considered, so goggles should be used at all times in the laboratory.

3.2.3. Minimize Explosion Risk. From the hierarchical model of hazard control, elimination is the most effective, followed by replacement, engineering control, supervision, and personal protection.

If the hazard cannot be eliminated, substitution is an effective control method, substituting less hazardous chemicals for more hazardous chemicals. The control of the amount of hazardous chemicals, that is, replacing a large amount with a small amount or microquantification, can also be regarded as a form of substitution, and it is the simplest and most effective method. Amplifying the amount of hazardous chemicals can significantly increase the risk of explosion. For example, in the explosion accident at Texas Tech, a graduate student enlarged the amount of explosive energetic substance from the limit of 100 mg to 10 g and 5 g, which caused an explosion accident and caused serious injuries.[8]

3.2.3.1. Amount Reduction. To prevent an explosion and to minimize the damages when it occurs, the most effective way is to reduce the quantity of hazardous chemicals.

The explosion accidents discussed in this paper are listed according to the severity of the accident and the quantity of hazardous chemicals (3.2.2.2. Table 1). It can be seen from the table that the greater the quantity of hazardous chemicals involved in the explosion, the more serious the consequences. In the accident at Nanjing University of Aeronautics and Astronautics, a huge mushroom cloud with a height of tens of meters was formed after deflagration. It was estimated that the amount of hazardous chemicals was not small, and it is guessed that the amount of hazardous chemicals should be in the kilogram level, but there is no detailed information so far. The other explosion accidents listed in this article involve a relatively small quantity of hazardous chemicals, which are at the gram level and below, causing serious or minor injuries to people, and the severity of the consequences is much less severe.

Of course, the severity of the consequences of the explosion is also related to many accidental factors, such as whether the person is close to the explosion point at the moment of the explosion, the direction of the flying metal or glass fragments formed by the container in the explosion, and so on.

It is worth noting that even with strict compliance with regulations, the potential for serious explosion accidents still exists. Because some regulations are too lenient, large quantities of dangerous substances are allowed to be stored, for example, 50 L of flammable solvents are allowed to be stored in laboratories.

3.2.3.2. Avoid Routes of Energy Release. When an explosion occurs, in the case of a large amount of explosives, people located near the explosion site, especially those in the same room, will suffer death or serious injury (accidents 1, 2, 9, 15, 16, and 17). Keeping away from the explosion point can avoid casualties. For example, in accident 12, no one passed in the corridor when an explosion occurred in the oven; in accident 13, perchloric acid digestion, the operator just left when the explosion occurred; in accident 14, when the organic peroxide explosion occurred, the graduate students in the same laboratory were far away from the rotary evaporator. Even if the same person is near the explosion point, facing the explosion or facing away from the explosion, the severity of the consequences can vary greatly. For example, in accident 10, the graduate student who faced the explosion was blinded in one eye and had severe vision loss in the other, and the other graduate student who had his back to the explosion suffered only minor injuries.

The energy of the explosion propagates in the form of spherical waves, so its energy propagation is inversely proportional to the square of the distance. The energy carried by the fragments formed by the explosion does not decay significantly, but the probability of hitting a human body also decreases rapidly with the increase of the distance. Therefore, keeping away from substances or equipment with risk of explosion can significantly reduce the harmful consequences of explosions. Distance protection—away from the place where explosion may occur, is the easiest, the most economical, and the most effective way of protection.

Metal materials and glass materials are hazardous, to say the least! After the explosion, the container shattered to form sharp and hard metal fragments (accidents 15, 16, and 21) or glass fragments (accidents 5, 6, 10, and 22), which had a strong lethal effect on the human body. However, these two types of materials, especially glass, are the main materials of experimental container equipment, and there is no possibility of them being replaced at present.

3.2.3.3. Reduce Time at High-Risk Locations. It is impossible to accurately predict when the explosion will occur, but try to avoid staying in places with high explosion risk as much as possible and shorten the stay time at the dangerous point, which can effectively avoid explosion hazards. For example, in accidents 12, 13, and 14, the explosions did not cause injury because the operators left when the explosions occurred, and no one was near the explosion site. In accidents 5, 6, 7, 10, 11, 14, 18, 19, and 20, someone happened to be at the scene, causing injuries. Of course, in the accidents that caused deaths, there were people on the scene, and the operators or bystanders suffered injuries. In particular, in accident 14, an explosion caused by white phosphorus, the operator himself left the scene at that time, and the research assistant who just passed by was injured.

Due to the advancement of technology, there are now many devices in the laboratory with automatic control functions. When heating or reacting, automatic control equipment can be used. After the personnel leave and wait for the completion of the reaction program, the temperature drops to room temperature, the pressure drops to close to the surrounding environment, and then the subsequent operations are carried out. For example, the temperature-controlled hydrothermal reaction operation involves a pressure reactor, but the risk is very low.

3.2.3.4. Shielding. If the explosion risk cannot be eliminated, then shielding is required to mitigate the explosion hazard. Use engineering controls, such as fume hoods, and use blast glass or at least tempered glass with blast film for protection. The second is the use of explosion-proof screens, and the last is the use of explosion-proof masks and goggles.

There is a risk of explosion in the laboratory, and it is impossible to predict exactly when it will explode, so goggles should always be worn in the laboratory. A Texas Tech graduate student took off his goggles, and the explosion caused eye damage.[8]

In accident 10, because the graduate student did not take adequate protection and did not wear goggles, permanent vision damage and severe facial damage were caused. In accident 6, the great value of goggles was shown. In the explosion accident, the graduate student put his face a few centimeters away from the flask in order to observe the inside of the reaction vessel of the low-temperature bath. The explosion occurred at this time, and the goggles greatly reduced the consequences of the injury. The graduate student's forehead and other two places were cut by glass fragments, and his eyes were only slightly burned. He has recovered after diagnosis and treatment. Comparing accident 10 and accident 6, the benefits of a pair of goggles costing tens of dollars cannot be underestimated.

In accident 18, the doctoral student did not pull down the fume hood sash when operating the chromatographic column and did not wear goggles; nor did he wear a lab coat due to the hot weather but wore only a pair of gloves. After the deflagration of the leaked solvent, it caused burns to the face, neck, and arms.

Currently in the lab, a higher percentage of graduate students wear lab coats but fewer wear goggles. In addition to the above-mentioned neglect, insufficient safety training, and poor supervision, the main reasons are also related to specific problems in the use of goggles: wearing goggles is uncomfortable, especially if you have already worn prescription glasses (contact lenses are not allowed in the laboratory), and goggles may fog up and restrict vision, especially in summer. Goggle fogging itself is also a safety hazard that needs to be addressed.

3.2.4. DATS: the Four Principles for Minimizing Explosion Hazard. Taken together, we combine the above four protective measures and propose the four principles for minimizing explosion hazard, with the acronym DATS:

1. Distance: keep Distance as far as possible from the risk of explosion;
2. Amount: use the minimum Amount of explosive material;
3. Time: minimize the Time spent in areas where there is a risk of explosion;
4. Shield: use appropriate Shielding, reliable isolation protective equipment.

Three of the four principles, Distance, Time, and Shield, are in fact consistent with the ALARA rules (As Low As Reasonably Achievable) against ionizing radiation damage.[6] Therefore, the DATS principles are applicable to ionizing radiation hazards and can also be applied to prevent and mitigate flammable, highly toxic, and corrosive hazards.

3.2.5. Prepare for a Possible Explosion. 3.2.5.1. Environmental Factors for Laboratory Explosion Accidents. Safety exit is the life channel of laboratory personnel, and it should always be unobstructed, which is the basic guarantee of laboratory safety.

As early as 57 years ago, laboratory design considerations required that each laboratory or other potentially hazardous area should have two exits that are as far apart as possible from each other and can be easily found and utilized.[13] However, to this day, there are still serious errors in the design of laboratories, and the exits are not designed according to this standard, which makes it difficult to escape in emergency situations. For example, in accident 2, after a fire broke out in the laboratory, people were trapped in the balcony and could not be evacuated in time, and then a deflagration accident occurred, causing heavy casualties.

The use and management of buildings must also ensure that safety exits are unblocked at all times. However, in actual use, the exits are often subject to various restrictions, and this is a fairly common violation of laws and regulations. For example, especially during the pandemic, strict control, locking other exits other than the main channel, main channel requiring identity authentication when entering and leaving, swiping cards, swiping faces, measuring body temperature, and other management methods, which will cause traffic obstruction in emergency situations, make it difficult to quickly evacuate people.

Laboratory design must ensure effective ventilation so that flammable gases do not accumulate to explosive limits. Air conditioning is widely used in modern buildings and the buildings are highly enclosed, making the laboratories vulnerable to explosive conditions in all seasons. Due to the working nature of most laboratory facilities and the nature of the chemicals used, fire and explosion hazards are much greater than other campus buildings. Therefore, in all laboratory buildings where special hazards exist, automatic fire and explosion detection and protection equipment should be designed and installed, such as combustible gas detectors, automatic fire extinguishing, explosion venting, and other equipment, that can issue alarms on site.[13]

3.2.5.2. First Aid after an Explosion. For trauma, the bleeding should be treated immediately on the spot, so it is necessary to prepare first aid medicines such as bandages and dressings in advance. For burns without skin damage, similar to first aid for burns, flushing with water immediately can quickly reduce the temperature of the skin tissue and prevent further worsening of burns caused by the high temperature. Immediate flushing of the contaminated skin with plenty of water is the key to first aid for chemical corrosion injuries. Only by water flushing, the easiest way of first aid, can the body's natural state be restored most quickly, and further damage can be effectively avoided. Any stringent requirements for first aid conditions, such as requiring a special drug (if it is not always available, should be checked frequently to confirm that it can be easily taken at any time), normal saline, and so forth, are all delays in first aid for burns, resulting in irreversible damage consequences.

In accident 10, because the graduate student was not properly protected and did not wear goggles, after the explosion, the face was sprayed with reagents such as concentrated sulfuric acid, potassium permanganate, and so forth. Instead of washing it with water immediately, he went directly to the hospital for treatment, causing permanent damage to vision and serious, irreparable facial mutilation.

As for other professional medical emergencies, you can only call for help and wait for the medical staff to arrive.

4. CONCLUSIONS

We analyzed 22 laboratory explosion accidents and found that they were the combined results of various deficiencies. The main reason is that in concept, relevant responsible persons at all levels do not pay enough attention to laboratory safety, and

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in the actual operation of the laboratory, there is a lack of correct technical protection measures. Therefore, we put forward the following suggestions to prevent the occurrence of explosion accidents, mitigate the consequences of explosion accidents, and enable researchers to have a safe environment to carry out scientific research.

First of all, we should build a beneficial safety culture and earnestly respect the life and health of researchers. On this basis, researchers should be provided with sufficient funds and technical equipment to ensure safety.

Second, reasonable and feasible protective measures should be taken in practice to minimize the physical effects of explosions on researchers, namely, the DATS principle: keep the Distance as far as possible, use the minimum Amount of explosives, shorten the residence Time, and use appropriate Shielding. The DATS principles can also be applied to prevent and mitigate ionizing radiation, flammable, highly toxic, and corrosive hazards.

AUTHOR INFORMATION

Corresponding Author

Shi-Yao Yang − *College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, China*; orcid.org/0000-0003-1316-6782; Email: syyang@xmu.edu.cn

Authors

Qi-Zheng Yang − *College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, China*

Xi-Ling Deng − *State Key Laboratory for Marine Corrosion and Protection, Luoyang Ship Material Research Institute (LSMRI), Xiamen 361100, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.chas.2c00083

Author Contributions

CRediT: **Qi-Zheng Yang** data curation (equal), formal analysis (equal), investigation (equal), resources (equal), software (equal), writing-original draft (equal), writing-review & editing (equal); **Xi-Ling Deng** investigation (equal), writing-original draft (supporting), writing-review & editing (equal); **Shi-Yao Yang** conceptualization (lead), data curation (equal), formal analysis (equal), funding acquisition (lead), investigation (equal), project administration (lead), supervision (lead), writing-original draft (lead), writing-review & editing (lead).

Notes

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REFERENCES

(1) Ménard, A. D.; Trant, J. F. A review and critique of academic lab safety research. *Nat. Chem.* **2020**, *12*, 17−25.

(2) Silver, A. Fatal lab explosion in China highlights wider safety fears. *Nature* **2022**, *601*, 176−177.

(3) Bai, M.; Liu, Y.; Qi, M.; Roy, N.; Shu, C.-M.; Khan, F.; Zhao, D. Current status, challenges, and future directions of university laboratory safety in China. *J. Loss Prev. Process Ind.* **2022**, *74*, 104671.

(4) Beijing municipal government accident investigation team, *Beijing Jiaotong University "12.26" Large Explosion Accident Investigation Report*, February 13, 2019.

(5) Xuzhou municipal government accident investigation team, *China University of Mining and Technology "4.5" Explosion Fatality Investigation Report*, May 10, 2015.

(6) Hill, R. H.; Finster, D. C. *Laboratory Safety for Chemistry Students*, 2nd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, 2016.

(7) Chung, A. B.; Moyle, A. B.; Nyansa, M. M. S.; Powell, J. A. Shifting Culture from Blame to Gain: A Call for Papers to Openly Discuss Chemical Incidents. *ACS Chem. Health Saf.* **2022**, *29*, 240−241.

(8) U.S. Chemical Safety and Hazard Investigation Board, Texas Tech University Laboratory Explosion, No. 2010-05-I-TX, *Texas Tech University Case Study*. September 30, 2011.

(9) Hill, R. H., Jr. Undergraduates Need a Safety Education! *J. Chem. Educ.* **2016**, *93*, 1495−1498.

(10) Leggett, D. J. Identifying and Evaluating Hazards in Research Laboratories. *Process Saf. Prog.* **2012**, *31*, 393−397.

(11) Yang, L. Analysis of Typical Aluminum Dust Explosion Accidents Case and Fire Safety Countermeasures. *Yunnan Chem. Technol.* **2017**, *44*, 126−128.

(12) Yang, F.; Qiu, D. Analysis and Control of Explosion Accidents in College and University Laboratory Based on Similar Systematics Principle. *Saf. Environ. Eng.* **2020**, *27*, 92−97.

(13) Steere, N. V. Safety in the Chemical Laboratory, XIX. Laboratory Design Considerations, Part I. *J. Chem. Educ.* **1965**, *42*, A583−A586.

https://doi.org/10.1021/acs.chas.2c00083
ACS Chem. Health Saf. XXXX, XXX, XXX−XXX