Short Communication

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Electrostatic energy: the hidden enemy of chemical plants

Abstract

In recent years, chemical plants have experienced several accidents that resulted in fires, explosions, and even loss of life. After investigations, it is sometimes found that the root cause could have been prevented by performing crucial activities, such as grounding the equipment. The lack of knowledge about electrostatic energy itself is one of the major problems in this type of industry. This article presents several measures to mitigate the risks posed by this hidden enemy: electrostatic electricity.

Keywords: electrostatic discharges, sparks, chemical plants, safety

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Introduction

Several catastrophic events involving chemical plants have been reported in recent years, some of which were found to have electrostatic discharges as the root cause. A selection of such cases (89 in total) is compiled in the review by Restuccia *et al.*[1] Several major accidents in chemical plants have been categorized according to their location. Some of the identified root causes include negligence, inappropriate handling methods, poor maintenance, and cost-saving practices. All these incidents involved fires initiated by electrostatic discharges.

On the other hand, Shi also reported a compilation of accidents caused by electrostatic discharges in China. These studies reviewed brief reports of more than 1,900 chemical accidents. The most significant root causes identified were runaway reactions, material strength defects, and issues related to process technology.[2] Handling solids is also a potential source of explosions. For example, Pak reported case studies of dust explosions in Korea over the past 30 years. Specifically, 53 dust explosions were documented, 25% of which occurred in the chemical industry.[3] The static discharges also were impacted chemical laboratories, to illustrate this problem in Hawaii a laboratory was exploded. Sadly, some near-miss reports were generated before the problem, and no actions were taken.[4] In addition, Fukuoka reported another study related to accident prevention in chemical laboratories. Although this topic is beyond the scope of the present article, it is important to mention it.[5] Ohsawa, for his part, reported a study analyzing the root causes of 150 accidents in the chemical industry in Japan. The analysis revealed that 70% of these accidents were attributed to electrostatic discharges. In addition, 70% of the incidents occurred in flammable atmospheres generated by vapor, and 90% took place during ordinary unit operations. Additional information indicates that these events commonly occurred during solvent transfers, cleaning activities, maintenance work, operations involving pressurized or drained lines, and powder handling.[6] Roman, for his part, reported in his article *"One Spark"* information related to accidents caused by electrostatic discharges, referring to this hazard as "the invisible danger."[7] Although there are many potential sources of accidents, one of the most common and invisible root causes is the electrostatic discharge or spark. A spark, when combined in determined conditions with fuel and oxygen (the fire triangle), can initiate a fire and eventually lead to a catastrophe.

But what exactly is a spark or electrostatic energy? All materials contain electrons and protons in their structure. Under certain conditions, the equilibrium between these particles can change, leading to an accumulation of electrons on one side and a deficiency of electrons or a positive charge on the other. A classic example is combing hair with a plastic comb, which can generate charge accumulation that is eventually released as a spark. In general, there are three mechanisms that lead to charge accumulation.

1. **Electrification by contact:** In this mechanism, two materials come into contact and are then separated. As a result, one of the materials becomes negatively charged due to an excess of electrons, while the other becomes positively charged due to electron deficiency. A common industrial example is the loading of solid materials into a reactor.
2. **Double-layer charging:** This type of charge accumulation occurs when a liquid is transferred through a pipe or equipment. As the liquid flows, charges are generated at the interface between the liquid and the solid surface. To compensate for these charges, a second layer of opposite charge forms, creating what is known as the electric double layer. This phenomenon can occur in both solid–liquid and liquid–liquid systems. It is referred to as "double-layer charging" because two parallel layers of opposite charges are formed.
3. **Induction charging:** Another mechanism for generating electrostatic charges is induction. In this case, an insulated object develops a temporary charge distribution due to the presence of another nearby charged object. If the induced charges accumulate sufficiently and the conductor reaches a critical potential difference, an electrostatic discharge may occur.[8] These three mechanisms are shown in Figure 1.

Additionally, there are two more important concepts to mention: bonding and MIE.

Bonding: To distribute the electrical potential across all pipelines, it is necessary to connect all the components that are part of the equipment. This connection is made through a wire that links all the screws that hold the structure together (Figure 2). This bonding is crucial for safely dissipating electrostatic charges to the ground, since O-rings are typically used to prevent leaks in the pipelines. Moreover, periodic inspection of the installation is of great importance to eliminate all the rust of the equipment. Using stainless steel screw is a good option to maintain the facilities free of rust.

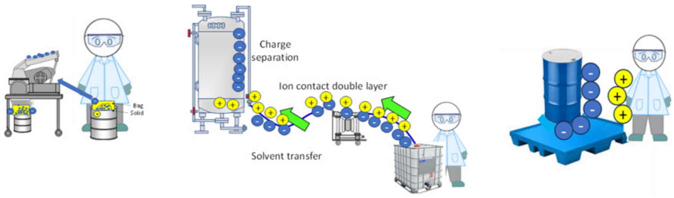

Figure 1 Electrification methods.

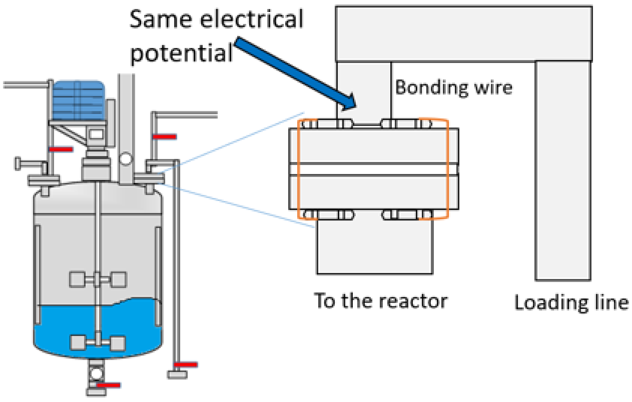

Figure 2 Bonding equipment.

MIE: Minimum Ignition Energy (MIE) is the lowest amount of energy required to ignite the most easily ignitable mixture of a combustible or a dust cloud. This concept is important because some reagents or starting materials have a very low MIE; consequently, these materials in a very easy manner can generate fires or even deflagrations, causing significant damage. An alternative for handling these materials is the use of Powder Transfer Systems (PTS), which are mechanical systems that load materials by vacuum, accumulate them within the system, blanket them, and then transfer them to the reactor using nitrogen pressure. This system allows materials to be charged into a reactor in a safe manner to safely use of raw materials with low MIE.

Unit operations in the synthesis of pharmaceutical ingredients

Pharmaceutical ingredients are manufactured in chemical plants, where several unit operations must be performed to synthesize the desired product. For example, during the reaction stage, all raw materials are charged into the reactors, and the appropriate reaction conditions such as heating or cooling are established. Once the reaction is complete, the excess reagents are quenched using procedures such as cooling or adding deactivating agents; this step is known as *deactivation*. The next step is to create a suspension in which the product exists as a solid while impurities and residual reagents remain dissolved in the mother liquors (*isolation*). The solids are then separated by centrifugation. The isolated product, which still contains residual solvents, is subsequently dried. Finally, the dried material undergoes particle-size reduction and product homogenization (Figure 3).[9]

All these unit operations carry an inherent risk of fire and explosion due to the generation and accumulation of static energy. The National Fire Protection Association established Guideline 77 (NFPA – Recommended Practice on Static Electricity), which defines measures to prevent accidents and incidents caused by electrostatic energy. This guideline includes concepts such as friction, material separation, material handling, and sparks. It also addresses control methods, including grounding, bonding, and flow and atmosphere control, among others. Additionally, it describes critical scenarios. Overall, this document provides specific guidelines to prevent static electricity from becoming an ignition source in industrial environments.[10]

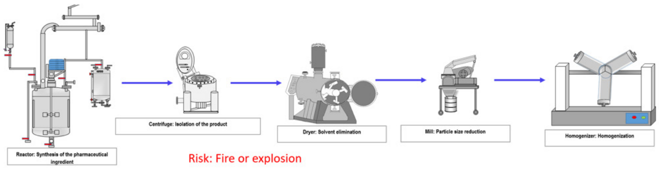

Figure 3 Most common unit operation in the synthesis of active substances.

In Mexico, static electricity in workplaces is regulated by the guideline NOM-022-STPS-2015, "Static Electricity in Work Centers."[11] This guideline establishes the requirements that facilities must meet regarding hazards associated with electrostatic discharges. For industrial installations, it is necessary to implement grounding systems, antistatic or conductive flooring and walls, and lightning protection systems. When handling explosive materials, all equipment must be properly grounded. The guideline also specifies additional technical requirements intended to minimize the accumulation of electrostatic energy. In addition to these equipment-related measures, it is also essential to train all personnel on the risks associated with electrostatic discharges, particularly those working in job positions where such risks are inherent. Proper training ensures that workers understand both the hazards and the preventive actions required to maintain a safe operating environment. An excellent reference is the book of Crowl and Luvar, specifically for this topic chapter seven related to fire and explosions.[12]

Avoiding electrostatic discharge risk in the synthesis of pharmaceutical ingredients

According to Hu et al,[13] seven root causes were identified across ninety-nine events related to accidents caused by electrostatic discharges. In addition, other root causes observed during twenty years of experience working in chemical plants have been included.

The combined set of root causes is as follows:

1) Improper loading during loading and unloading
2) Unloading materials
3) Poor grounding
4) Static in human bodies
5) Materials
6) Different mix of materials
7) Failures in storage tanks
8) Negligence
9) Lack of awareness
10) Lack of knowledge

Therefore, taking these root causes into account, it is possible to prevent many electrostatic discharges by implementing appropriate corrective and preventive actions. In this context, we will propose a series of mitigation measures in the following paragraphs. Before presenting these measures, it is important to focus on the specific activities involved in the synthesis of active pharmaceutical

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substances, an area in which extensive operational experience has been accumulated.

The unit operations used to manufacture pharmaceutical ingredients involve significant material movement, which in turn generates the movement of electrons within equipment surfaces and leads to the accumulation of electrostatic charges. These charges remain stored until an opportunity arises for them to be released. The main concern with such a release is that the resulting discharge can produce a spark, creating the potential for a fire. Fire consists in the combination of three components (fire triangle): a spark (ignition source), fuel, and oxygen. It is evident that fuel is always present in pharmaceutical synthesis, either in the form of raw materials or solvents. Oxygen can be minimized typically inside closed equipment through blanketing (blow nitrogen to displace oxygen), but it cannot be eliminated totally because it will remain approximately 5% of oxygen. Consequently, the only element of the fire triangle that can be effectively controlled is the generation of sparks (Figure 4).

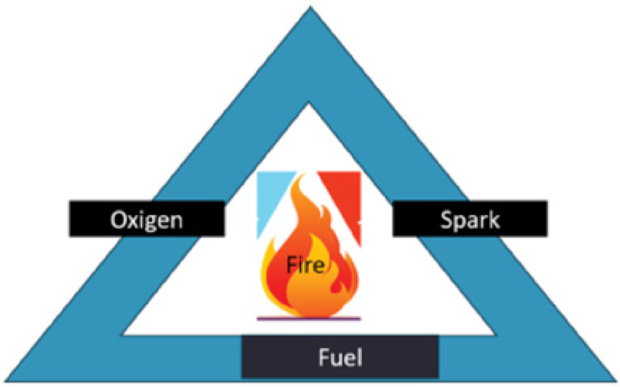

Figure 4 Fire triangle.

Reaction: During the reaction stage, organic compounds and solvents are charged into an industrial-scale reactor, which typically involves handling several metric tons of materials. As mentioned previously, the fire triangle must be interrupted to ensure safe conditions. An important concept is blanketing or inerting. The oxygen concentration in the atmosphere is approximately 20%, and this concentration is similar inside equipment such as reactors, centrifuges, or dryers. The fire triangle consists of fuel, an ignition source, and oxygen. If one of these factors is eliminated the risk of fire is reduced. Therefore, it is necessary to reduce the oxygen concentration within equipment to safely handle and load reagents and raw materials. For example, in a reactor or a vacuum rotary dryer, it is necessary to apply a vacuum and then restore the pressure using an inert gas, most commonly nitrogen. This process is typically repeated at least three times to reduce the oxygen concentration to approximately 5% (Figure 5). This level is considered safe for carrying out the process, minimizing the risk of electrostatic discharge. In the case of centrifuges, a continuous stream of nitrogen is used to purge the oxygen until its concentration is reduced to around 5%.

Another useful set of unit operations involves loading solids through powder transfer systems, which are particularly valuable when handling materials with low ignition points. These systems operate by applying vacuum to draw the powder into an intermediate vessel and then transferring it into the reactor using nitrogen pressure, the same inert gas used during blanketing. This method significantly reduces the risk associated with charging hazardous or highly flammable solids. In addition, powder transfer systems help mitigate ignition hazards by maintaining a closed, inert environment throughout the operation. The material is collected under vacuum and subsequently discharged into the reactor using a nitrogen stream, ensuring that the receiving vessel remains properly blanketed before transfer.[14]

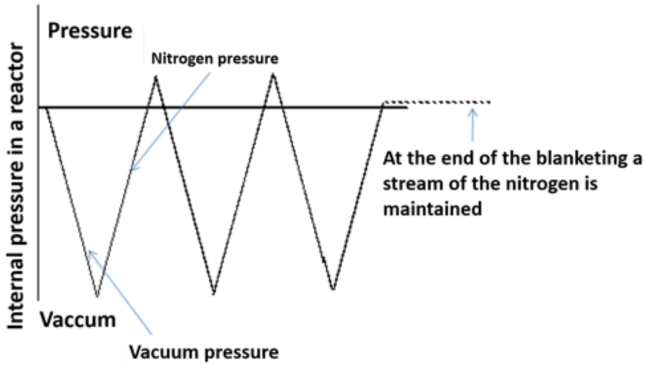

Figure 5 Blanketing process in an equipment.

Personnel clothing: Another potential ignition source during material loading is static accumulation on personnel clothing. To minimize this risk, operators must wear antistatic clothes, such as cotton garments, which help prevent electrostatic charge buildup and reduce the likelihood of spark generation. This practice also includes dissipative shoes because normal shoes are insulated.

Isolation: During the isolation stage, the reaction mixture may be cooled, an additional solvent may be added, pH adjustment may be performed, and in some cases phase separation occurs. To manage these operations, flexible hoses are commonly used to connect some reactors. These hoses must have an internal Teflon surface and an embedded grounding wire to ensure proper dissipation of electrostatic charges. Transfers between equipment are often the weakest point in the system because houses and their connections are sometimes not properly grounded. Therefore, periodic inspections of all hoses used in operations must be carried out. Both external and internal physical inspections are required. The use of an internal inspection camera is recommended to verify the integrity of the hose lining, which can help prevent future failures or accidents. A critical element of these inspections is confirming that grounding is effective specifically, verifying the continuity between the hose and the grounding wire, and ensuring that both ends are properly connected to a grounded system. In Figure 6 is represented the connection between reactor though hoses. Also is showed the internal structure of hoses.

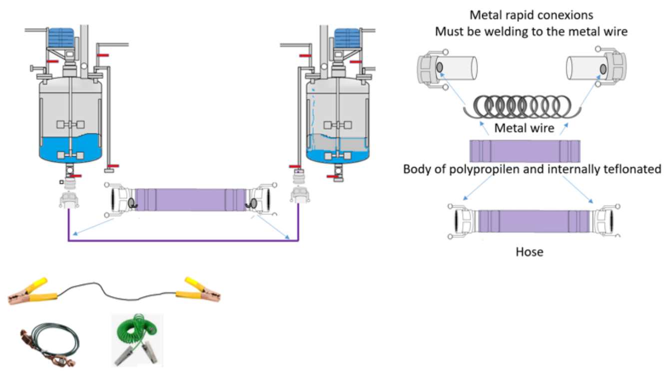

Figure 6 Importance of hoses in the transfer between equipment.

Centrifugation: Like reactors, centrifuges are operated under an inert atmosphere by maintaining a continuous stream of inert gas.

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However, unlike reactors, centrifuges generally cannot undergo vacuum–nitrogen purge cycles; therefore, oxygen displacement is achieved solely through a steady flow of nitrogen.

It is also important to note that some solvents require longer relaxation times for dissipating accumulated electrostatic charges. For example, polar solvents such as methanol, ethanol, and isopropanol dissipate electrostatic energy more readily than apolar solvents such as toluene, methyl tert-butyl ether, or heptane. This difference is related to the electrical conductivity of the solvent: polar solvents have higher conductivity and therefore allow charges to relax more efficiently, whereas apolar solvents tend to retain electrostatic energy for longer periods, increasing the risk of ignition.

Material discharge: Discharging material from centrifuges always carries an inherent risk because the solids typically contain residual solvents. To mitigate this risk, it is essential to use antistatic bags, as conventional plastic bags significantly increase electrostatic hazards. Several antistatic options are available on the market, including conductive, dissipative, and multi-layer bags designed specifically to minimize charge accumulation during solids handling.

Drying process: During the drying process, the material is typically subjected to vacuum and elevated temperatures. Under these conditions, the risk of electrostatic discharge within the dryer itself is generally low. However, significant hazards arise during the loading and discharging of solid material, as solids can generate friction and accumulate static electricity, which may ultimately lead to a spark capable of triggering an explosion. To mitigate risk during loading, inert gas blanketing is applied to create and maintain an inert atmosphere inside the dryer. This reduces the oxygen concentration and minimizes the possibility of ignition during material transfer. For the discharge of dried solids, it is critically important to use antistatic bags or containers. Conventional plastic bags can accumulate substantial static charge, making them unsuitable for handling solvent-containing or highly combustible solids. Antistatic or conductive bags ensure safer dissipation of electrostatic energy, thereby reducing the likelihood of sparks during unloading operation.

Milling: The process of particle-size reduction generates significant accumulation of static energy due to the intense friction between particles and equipment surfaces. To mitigate this hazard, it is essential to ensure that all milling equipment is properly grounded. In addition, antistatic bags or containers must be used during material collection and discharge to minimize the risk of electrostatic buildup. Implementing these measures reduces the likelihood of spark generation during milling and subsequent handling of the milled product. It is also worth mentioning that some pharmaceutical ingredients tend to accumulate charge inherently due to the triboelectric effect. This charge buildup significantly increases the hazards associated with handling solid materials, as electrostatic accumulation may occur even in the absence of obvious friction.[15] To minimize this additional risk, it is essential to properly ground the drums used during product unloading. Furthermore, the use of antistatic bags is mandatory to ensure safe dissipation of electrostatic charge during the transfer and handling of these solids.

Others:

Anti-spark tools: An uncontrolled source of ignition can arise from the use of conventional metallic tools, especially during the handling of pyrophoric materials such as hexyllithium, grignards or other organometallic reagents. Even a small leak combined with a mechanical spark can initiate a fire and potentially lead to an explosion. To eliminate this risk, non-sparking tools—typically made of bronze or other spark-resistant alloys must be used when operating valves or opening containers associated with these highly reactive substances. The use of such tools significantly reduces the likelihood of spark generation during critical operations.

Facilities maintenance: One important root cause of accidents is inadequate maintenance of industrial facilities. Numerous incidents in the chemical industry have occurred because pipelines or equipment deteriorated often through corrosion without being detected in time. Regular and systematic maintenance of the facility is critically important for preventing such failures. Implementing routine inspections, corrosion monitoring, and timely replacement or repair of damaged components significantly reduces the likelihood of accidents related to structural degradation.

Lockout–Tagout (LOTO): This refers to a safety procedure used to de-energize equipment and prevent it from being restarted during maintenance work. This procedure ensures that operators remain safe while servicing or repairing machinery. Basically, the procedure consists of placing a lock that physically keeps the machine in a safe, non-operational state. Additionally, this isolation is reinforced with a tag that identifies the worker who applied the lock and indicates the reason for the maintenance work.[16]

ATEX connections: To ensure safety in workplaces where there is a risk of explosive atmospheres, specific guidelines have been established to protect these environments. The European ATEX guideline—an abbreviation of ATmosphères EXplosibles (French)—defines the requirements for working in potentially explosive atmospheres caused by gases, vapors, mists, or combustible dust. In general, this guideline regulates the design of equipment, systems, and components to ensure they are intrinsically safe. A common application in the chemical industry is in loading and transfer areas, where solid materials and solvents are frequently handled. In these areas, ATEX-certified connections allow safe electrical or power system connections, preventing spark generation and reducing the risk of ignition.[17]

Gemba walks: To identify opportunities for improvement, it is essential to understand the facilities directly by going to the workplace and observing conditions firsthand. There is no substitute for physically visiting operational areas to detect small but critical details, as any of these details may become a source of electrostatic sparks which, under the right conditions, can lead to a fire or deflagration. Recently, Gemba walks have been reported as an effective tool for reducing accidents in chemical plants, demonstrating positive results in identifying unsafe practices and improving operational discipline.[18]

Develop self-awareness: One of the most important factors in preventing electrostatic discharges is the human element. In many operations, ensuring electrical continuity such as connecting equipment to a proper grounding system depends entirely on the actions of the operator. For example, grounding is required when unloading tankers containing solvents, transferring solvents from drums, or grounding dryers prior to cleaning activities. In all these cases, the operator's attention, discipline, and awareness of risk are critical. Where possible, *poka-yoke* (error-proofing) systems can be implemented to reduce human error. For instance, pumps can be configured so they cannot operate unless the equipment is properly grounded. However, in some operations such as transferring solvents directly from drums it is more difficult to ensure perfect grounding through automation or mechanical interlocks. For this reason, developing strong self-awareness regarding electrostatic hazards is one of the most effective methods to prevent accidental discharges. Operators must clearly understand the risks, recognize the conditions

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that promote static accumulation, and consistently apply grounding and bonding procedures. Cultivating this mindset significantly reduces the likelihood of electrostatic ignition events.

Pallets: The use of pallets to move materials is widespread in industry; however, they are often made of plastic or wood. These materials can isolate the handled products, such as drums, creating a potential risk of electrostatic discharge. In this context, the use of metallic or antistatic pallets represents a better alternative, as they ensure electrical continuity and help dissipate electrostatic energy.

Training: A complementary activity to strengthen self-awareness is continuous training. It is essential to consistently reinforce safety concepts among personnel, as familiarity with routine tasks can lead to complacency and increase the likelihood of errors. Periodic training sessions on the risks associated with electrostatic discharges are therefore necessary to maintain awareness and ensure that operators correctly apply grounding, bonding, and other preventive measures. Sustained training helps keep safety at the forefront of daily operations and significantly reduces the probability of spark-related incidents (Figure 7).

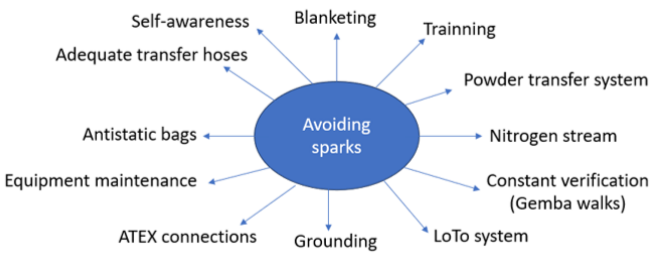

Figure 7 Ways to avoid electrostatic discharges.

Near-Miss incident: A near-miss incident is an event that could have resulted in an accident but, due to some circumstance, is stopped before causing any damage. Other definitions are compiled by Sheikhtaheri. For example, the World Health Organization defines a near miss as an error that has the potential to cause an adverse event but fails to do so either by chance or because it is intercepted.[19] The Occupational Health and Safety Assessment Series (OHSAS) defines a near miss as a potential hazard or incident in which no property damage occurs and no personal injury is sustained. OHSAS also proposes a template to report near-miss incidents, including the following data:[20]

a. Department

b. Area

c. Date and time

d. Type of near miss

e. Type of concern

f. Description of the incident

g. Description of the deviation from safety procedures

h. Incident site inspection

i. Recommendations

j. Supervisor review

The near-miss report is an excellent tool for preventing accidents, as warning signs often appear before an actual incident occurs. A recent example of this approach has been reported in academia.[21] Near-miss reporting can help improve the system by eliminating unsafe conditions through corrective or preventive actions, enabling continuous improvement. To complement this system, lessons learned from previous incidents are also an excellent source of knowledge for enhancing safety performance.

Conclusion

The inherent risks of fire and explosion caused by accumulated electrostatic charge are a persistent reality in the chemical industry, particularly because the root cause is often hidden (electrostatic energy), commonly recognized as a spark. Preventing this energy from being released requires the implementation of multiple tools and safety practices designed to mitigate the hazard. Regular verification of equipment grounding is the most fundamental requirement for avoiding electrostatic discharges. However, developing self-awareness among personnel is equally crucial for maintaining a fire free chemical plant. This work has presented several practical actions that can be implemented to eliminate or significantly reduce spark related risks. These measures are not exclusive to the pharmaceutical or chemical sectors; they can be applied to any industry where flammable materials and electrostatic hazards coexist.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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