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Analysis of causes of combustible mixture explosions inside production floor areas

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Abstract. The work provides a cause analysis for major industrial explosions and a review of the causes of combustive air-gas mixture generation in a production environment. It has been established that during operation of explosive production facilities, it is process equipment that, as a rule, creates explosive environment inside the floor area. A qualitative method for determination of a potential accident has been reviewed. Analysis of the nature of explosion effect on building structures and equipment has shown that exposions characterised by absence of equipment and building structure disintegration normally have a localized character. It has been identified that during explosions inside process equipment, the largest structural damage occurs in spots hit by equipment debris. Complete destruction of building structures and equipment is caused by explosions inside equipment containing large quantities of combustible products. It has been identified that most explosions are accompanied by partial or total destruction of building structures and equipment. Therefore, measures taken to protect equipment and buildings from explosion effects lack efficiency.

In most cases, generation of explosive gas-air mixture within a building is related to leakages and accidental releases of combustible gases to the atmosphere of the floor area. Thus, out of 1,200 industrial explosions registered in the US over a five-year's period, 50% are accounted for by the use of combustible gas/steam-air mixtures in production [1-3]. According to the analysis conducted by the American Insurance Association, the causes of major explosions are distributed as follows: equipment breakdown: 31%, process order violations: 17%, incorrect estimation of explosiveness of products used in the production process: 20% [4]. Moreover, the most frequent cause of combustible substance leakages and releases (50% of all cases) is breakdown or technical failures of process line equipment; 20% can be attributed to errors and negligence of operations personnel during equipment operation.

The examined causes of combustible gas-air mixture generation in a production floor atmosphere have necessitated development of the following explosion-safety measures: prevention of gas leakages or of their movement in an inadvertent direction; implementation of complex production mechanization and automated remote control.

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Statistics of intra-building accidental explosions are not systematized; therefore, in order to obtain a cause-based picture of explosion distribution, 134 category accidents have been analyzed, which occurred at different times at domestic chemical and petrochemical facilities.

The analysis of accidents occurring during operation of explosive industrial facilities has been based on accident investigation protocols, in-situ facility examinations and data materials published in a number of open-source research works [5-8].

As a result:

1. The accident causes in terms of explosiveness of an operated production site are: low-quality installation of process equipment; faulty control and instrumentation equipment; errors in design documents; defective equipment parts; faulty elements of main process equipment; errors in development of the process order; violated operation safety rules for process equipment; low-quality preventive maintenance of equipment; errors in development of the process order; violation of equipment repair rules; corrosion in the walls of equipment parts and pipelines; other causes.
2. The main equipment parts causing formation of intra-facility combustible mixtures have been identified: vessels and tanks; process columns; compressors; condensers; cubes; pumps; generators; process kilns/furnaces; scrubbers; mixers; piping; flanged pipeline joints; shut-off and adjustment fittings and other elements, unidentified or omitted from the documentation;
3. The dependence of the explosion number on the type of the gas-air mixture ignition source has been demonstrated: open process fire; open fire used for repair; electric welding sparks; sparks generated during collisions and friction of metal against metal; sparking occurring inside electrical equipment or caused by short circuits in electrical equipment; static discharge sparks; heated surfaces of process equipment; product self-ignition on contact with air, and other causes, unidentified or omitted from the documentation;
4. Distribution of explosions at production facilities is presented based on their destructive effect on building structures and equipment: intra-premise explosions with no destruction of building structures and equipment; same with partial destruction of building structures and equipment; same with complete destruction of building structures and equipment; same with partial destruction of structures of neighboring buildings.

During operation of explosive industrial facilities, process equipment creates explosive environment inside the floor area. In order to develop preventive measures against explosions and to select protection methods, it is essential to know equipment elements, which most often create a combustible environment.

Combustible gases present in process equipment may penetrate the production floor environment in case of equipment destruction. When a device housing is damaged or a cover is blown off, combustible gas may be instantly released into the premises and an explosive concentration of a significant volume may generate within seconds. When a pipe is broken, the combustible medium is emitted in the form of a jet. As a result, an explosive concentration may be generated in the floor environment within minutes.

During a slow gas leakage, e.g. through shut-off fittings, explosive mixture is formed within a time quite sufficient to actuate the emergency exhaust ventilation or to take other fire- and explosion preventive measures.

In each case, the amount of gas penetrating the floor atmosphere may be approximately estimated if the device or the group of devices potentially capable of causing the accidental formation of explosive mixture are known.

The operations personnel must continuously monitor production equipment belonging to potential sources of explosive mixtures in the floor area. Normally operated equipment works without accidents, expensive repairs or outages, which disorganize the production.

Operating machines and devices mainly lose their operability due to destruction of individual parts or their surface layers because of mechanical or corrosion wear whose degree depends on the operating environment. As a result, equipment loses its strength, and its capacity and productivity is decreased. These critical parameters are restored by means of repair.

Chemical and petrochemical facilities deploy a scheduled preventive maintenance system, which has proven itself practically. The repair system is based on the summarized experience of equipment operation and repair at chemical and petrochemical facilities. It uses empirical and statistical repair reference materials of chemical and petrochemical facilities, research and design institutes, and materials related to the design of new equipment and upgrade of operating equipment accumulated by the chemical machine building industry.

The main goal of the scheduled preventive equipment maintenance system representing a combination of organizational and technical measures to monitor and maintain equipment, including utilities, is prevention of equipment accidents. The main parameter for determination of the equipment repair type is operating hours between overhauls (running repair, medium, major overhauls). Knowledge of the group of elements most likely to cause an accident (based on available data on known failure-free operation hours of each element) will bring one closer to tackling the task of determining the potential volume of combustive mixture generated within a floor area during an accident.

All equipment on a production floor able to release combustible gases can be divided into "K" number of groups, each of them in its turn consisting of a range of independent homogenous elements. Since it is impossible to accurately forecast failure of an element due to the incidental nature of this event, it is naturally possible to use the methods of the probability theory in this situation and to construct a probability model [9-15]. We will now consider a model used in the reliability theory.

Given is "K" number of equipment groups, consisting of n_1; n_2…, n_k homogenous independent elements. We will call the sequence of element failures over time a failure stream.

The failure stream of the given *i*-group shall be characterized by the number λ_i - an average number of failures over a time unit. Due to the independent character of element failures, the average number of faliures in the group of n_i elements shall equal $n_i\lambda_i$. We will call the stream of simultaneous failures in all groups a cumulative failure stream. Due to the independence of the groups, the average number of the cumulative stream failures will equal:

$$\Lambda = \sum_{i=1}^{k} n_i\lambda_i. \quad (1)$$

The reliability theory has proven that if the failure stream is generated from a larger number of minor intensity streams (λ_i – minor), its qualities are close to the properties of a so-called simple stream. We have a similar picture in the problem under consideration. Therefore, we will assume the resulting failure stream as a simple stream.

The cumulative failure stream is a simple stream with the failure intensity parameter equal to Equation 1. It means that the probability P_m of occurrence of m failures over the time τ is governed by the Poisson law.

$$P_m = \frac{\lambda\tau^m}{m!} e^{-\Lambda\tau} \quad (2)$$

The probability of no failure over the time τ equals $P_0 = e^{-\Lambda\tau}$. The average failure-free operation hours shall be

$$T_{cp} = \frac{1}{\lambda}. \tag{3}$$

If τ is minor, then

$$P_i \text{ (failure)} = 1 - e^{-n_i\lambda_i\tau} = n_i\lambda_i\tau + 0(\tau), \tag{4}$$

and

$$P \text{ (failure)} = 1 - e^{-\sum_{i=1}^{k} n_i\lambda_i\tau} = \sum_{i=1}^{k} n_i\lambda_i\tau + 0(\tau) \tag{5}$$

The hazard potential of the 1st group of equipment can be estimated as

$$B_i = \frac{P_i}{P} \cong \frac{n_i\lambda_i\tau}{\sum n_i\lambda_i\tau} = \frac{n_i\lambda_i}{n_1\lambda_1+n_2\lambda_2+\cdots+n_k\lambda_k} \tag{6}$$

However, such qualitative method of determination of a potential accident does not exclude other methods. For this method to be used, the equipment operating modes, operating life and margin of safety need to be clarified in terms of quantity.

During accident investigation, it is often difficult to identify the real source of explosive mixture ignition. Available materials on accidental explosions in most cases indicate a possible ignition source, which significantly complicates development of grounded preventive measures [16-18].

It has been identified that most explosions are accompanied by partial or total destruction of building structures and equipment. This testifies to the importance of the problem under consideration and of the necessity for preventive measures targeted both at prevention of explosions and at mitigating their destructive effect on equipment and building structures.

When analyzing the character of explosion effect on building structures and equipment, the following conclusions can be drawn.

Explosions characterized by absence of equipment and building structures disintegration normally have a localized character. These are explosions of minor intensity occurring inside process equipment or within smaller local volumes of combustible mixtures formed as a result of penetration of small amounts of combustible gases through loose spots in shut-off fittings or pipes.

Explosions involving partial destruction of equipment or building structures occur both inside the equipment and the production floor, and the destruction amount depends on the type of the combustible mixture, its volume and concentration. During explosions inside process equipment, the largest structural damage occurs in spots hit by equipment debris. In this case, destruction is manifested by through-holes or deformation of structure parts at the spots hit by equipment parts.

Destruction in building structures is more severe during explosions of gas-air mixtures inside production premises than during explosions inside process equipment. Most often, lightweight envelope structures are destroyed; while out of main bearing elements reinforced concrete structures are prone to disintegrate more often that metal ones.

It has been identified from past accident protocols that explosions involving complete destruction of building structures are preceded by significant damage of process column vessels, compressors, pumps, piping, shut-off fittings, flange joints and by formation of large volumes of explosive concentrations of combustible mixtures in production floor areas. Here, the most probable ignition sources are open process fire during repair, hot surfaces of process equipment or product self-ignition upon contact with oxygen.

Complete destruction of building structures and equipment is also caused by equipment internal explosions involving large quantities of combustible products.

During explosions of external units and intra-premise explosions, mainly destruction of lightweight envelope structures (i.e. windows, doors or gates) of neighboring buildings is observed. The character and degree of destruction depend of the explosion intensity and on the distance to the explosion site.

Conclusions

Thus, based on the accident cause analysis, the following conclusions can be drawn.

During operation of explosive facilities, most explosions are due to violation of safety operation rules and low-quality preventive equipment repairs, as well as due to imperfect solutions in design documentation and defective equipment parts (15.1%). Moreover, low-quality installation of process equipment and faulty control and instrumentation equipment also cause a significant number of accidents (12.4%).

Most often, explosive mixtures are generated as a result of malfunctioning of shut-off and adjustment fittings and flange joints in pipelines; therefore, the time between preventive inspections and repairs of shut-off fittings and pipe joints should be reduced, and preventive inspections and repairs should be done according to special schedules.

When assessing explosiveness of a production, one should also take into account equipment elements, which cause generation of combustible mixtures.

Statistical data for explosion causes show that most often explosions are caused by open fire (22.1%), product self-ignition upon contact with air oxygen (15.7%), and heated surfaces of process equipment (14.2%). Explosions may also be initiated by faulty electrical equipment (18.5%), spark discharges of static electricity and collision and friction of metal against metal (7.5%).

Most explosions (54.9%) are accompanied by partial or total destruction of building structures and equipment. Therefore, measures taken to protect equipment and buildings from explosion effects lack efficiency. Statistical data related to accidental explosions demonstrate that even the current state of the art does not eliminate explosions at explosive sites as a result of breakdowns or failures of process equipment and some other reasons. Besides, human interference in the production process cannot be eliminated, while people by their nature are not guaranteed against mistakes.

In this connection, in order to ensure explosion safety in production buildings in case of explosions caused by various reasons, special technical solutions should be provisioned.

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