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Common Causes and Corrections for Explosions and Fires in Improperly Inerted Vessels

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ABSTRACT

Causal factors and corrective actions surrounding improperly inerted vessel incidents are developed and compared. Several case studies of flash fires or explosions involving these improperly inerted process vessels are utilized for the development. In industry, vessels that contain or have contained flammable vapors are commonly inerted for many reasons but one of the most common is explosion prevention. Common inerting gases are carbon dioxide, nitrogen, steam and air depending upon the specific application. Causes ranged from procedures to design issues, but a general set has been produced for application to the problem of explosion prevention in process vessels. Each case study is compared to safety standards to show how safe work practices could have prevented the accidents, but rigid adherence to safety standards may not be sufficient to prevent an accident. The application of a safety standard should be tempered by the situation-specific circumstances. Some specific recommendations for preventing explosions include methods for improved mixing of the inert gas, the use of blinds, filling the vessel with water, improved work procedures and improved monitoring procedures.

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Introduction

Inerting of vessels is a common and necessary procedure in the chemical process industries. By definition, an inert is a chemical species, that when added to a reactive mixture will not participate in the reaction. Inert species can be used to aid heat transfer, control reaction selectivity, and most importantly to control reaction rates. For the purposes of this paper, the term "inerting" is also applied to the general case of either the removal or prevention of accumulation of a combustible mixture in a vessel known respectively as purging and blanketing. Where a combustible mixture exists within a vessel or operating area, risk of ignition and resulting serious damage are greatly increased. Experience dictates that most accidental ignitions produce non-detonating fires and explosions also known as deflagrations.

During start-up, shutdown, and preparation for maintenance, process vessels may contain or accumulate combustible mixtures. Purging the vessel can serve the purpose of diluting the flammable components or removing the combustible mixture. The conditions and species used for the purging can vary widely depending upon the system and application. After the combustible mixture has been removed, vessels may be protected through blanketing with an inert species to prevent formation of a combustible atmosphere.

This article discusses the general standards that can be applied to the inerting process and general requirements for engineering an inerted system. Six case studies where the inerting process failed and the lessons learned from those case studies are used to underscore the engineering requirements.

Background

Some authors choose to describe the inerting process as removal of the oxygen from the system and others as removal of flammable vapors (Kinsley, 2001; Blakely and Orlando, 1984). Depending upon the system and the operation involved, either one or both of the above descriptions may apply. Most of the available literature focuses on the case of "perfect mixing," but the truth is that this seldom happens in real systems. Along the same lines, the lower flammable limit (LFL) is the standard reference point for explosive concentrations. The concept of the LFL assumes uniform concentration within the vessel when, in fact, this seldom exists in practice. For the case of addition of flammable vapors to a vessel, they travel from areas of greater concentration to lesser concentration whether by diffusion or convection. If oxygen is present, then within this gradient from combustible to non-combustible condition, a pocket of an explosive mixture can be present (Ogle, 1999). The standards apply a general rule of thumb, which appears to be consistent with the adiabatic explosion model of Ogle, of establishing a threshold minimum of 10% of the LFL (API 2015).

Why Inert?

Three components are sufficient for a deflagration to occur within or near a process vessel. When present in the necessary amounts, fuel, oxidizer, and ignition energy always produce combustion. Fuels are most commonly organic-based materials but can also include metals and other inorganic compounds prone to oxidation. Fuel can be supplied as a solid, liquid, or vapor. Typical solid fuels are organic or metal dusts - fine powders with a particle size range of 420 μm or less (NPFA 69; NFPA 77). Air is the most common oxidizer present to participate in combustion. Depending upon the relative amounts of fuel and oxidizer, several sources of energy are sufficient to cause ignition. Some of these are an open flame, a hot surface, or a spark. The inerting process can be used to remove the fuel and/or oxygen. By removing these components, a safe, non-combustible atmosphere can be created within the vessel.

What Operations Require Inerting?

Inerting is often applied to systems which may contain combustible mixtures either as a part of normal operation, non-routine operation, or maintenance. Abnormal operation can be characterized as start-up or shutdown for both batch and continuous processes.

It is well known to the process industries that performing maintenance, especially hot work on a vessel or pipe, which has contained a combustible or flammable material, is dangerous. The consequences of igniting a flammable mixture contained within a vessel or pipe is most often disastrous. The explosion or flash fire that ensues can cause significant damage to the facility and injure or kill personnel. For this reason, vessels and piping are typically inerted prior to commencing work, but due to various reasons the inerting process is not always effective.

Guidance Documents

Several guidance documents have been developed to aid the designer in inerting vessels. However no single source contains all the necessary information, and these standards are unclear about how to monitor. Sound engineering and experience dictate that the immediate area, connecting ducts or piping, and remote connected areas should be tested for flammable vapors. For example, NFPA 51B states that cutting or welding shall not be permitted "in the presence of explosive atmospheres…or explosive atmospheres that can develop inside … improperly prepared drums, tanks or other containers." It goes on to say that the "area" should be inspected prior to commencement of hot work. This standard understates the responsibility of not only monitoring for a flammable concentration in the area but also of recognizing that alternate pathways can transport flammable vapors, and the flammable vapor concentration can change with time.

The goal of these documents is the same; to provide guidance on how to displace or dilute the vessel, equipment, or pipe's internal oxygen and/or flammable vapor concentration.

The lower flammable limit (LFL) is the minimum concentration of a flammable vapor in air that will propagate a flame if ignited. This concentration is less than the stoichiometric condition for the fuel air mixture. The concept of LFL is often applied to vessels when inerting is required, but it is inappropriate to use this concept globally. Most industrial deflagrations occur in vessels with global flammable vapor concentrations less than the LFL. In practice, the vapor concentration is not uniform throughout the vessel and stagnant pockets of explosive mixtures can remain in a vessel even after purging (Ogle, 1999). A point source combustible gas measurement is just that and does not necessarily reflect the overall flammable vapor concentration within the vessel.

The threshold value for oxygen is referred to as the Limiting Oxygen Concentration (LOC) (NFPA 69; Kinsley, 2001). Below this value (which must be determined for each system) the vessel contents are no longer flammable, and the equipment can be operated, or work can be performed safely. However, it must be understood that conditions can change and oxygen concentrations at the onset of the work may not remain constant throughout the procedure. Additionally, the adjacent equipment and any connecting piping need to be identified as alternate pathways that can transport flammable vapors.

In contrast to NFPA 69, API 2015 is very specific in the requirements for ongoing atmospheric monitoring, searching out areas of hidden fuels that may be released during the operation, and inerting options. The standard suggests continued ventilation to minimize accumulation of flammable vapors from hidden or time-varying sources.

Explosion Prevention Options

There are two general types of explosion protection - prevention and mitigation. Explosion vents and isolation valves are common methods for explosion mitigation. These will help dissipate the energy released from a primary explosion and minimize the damage that this energy release can do to other areas of the process. This article focuses on several methods of explosion prevention, and the consequences when deviation from these methods occurs. Selection of inert gas and inerting method, understanding of inerting hazards, and pragmatic monitoring are key facets of preventing fires and explosions in process vessels.

Selection of Inert Species

NFPA 69 Sec. 2-3.2 has a good list of purge gases which includes the following:

- Nitrogen, carbon dioxide, argon, and helium supplied from high pressure tanks, cylinders, or from air separation plants.
- Oxygen deficient purge gases produced by gas generators that burn or catalytically oxidize hydrocarbons.
- Combustion products from process furnaces or boilers.
- High purity nitrogen from ammonia oxidation.
- Fuel gases such as natural gas and methane.

Care must be taken in engineering the inerted system. The inert source must be reliable and able to provide a sufficient quantity of inert gas to protect the vessel for the duration of the operation. The operation, which the inert species protects, must be one of the major considerations in choosing which inert species to use. Inert species used to prepare for maintenance are typically benign while inert species used as part of process operation can be much more exotic. Cost, personnel safety, and material considerations among others should be considered. Additionally, the purge gas selected must be compatible with the chemical species present inside the equipment to be protected, as well as the materials of construction for the equipment.

Using gases is not the only method of inerting equipment; water and sand can also be used to displace the internal atmosphere of the equipment. These species displace both the oxygen and fuels present inside the equipment and provide the highest level of protection against ignition of fugitive vapors. However, these methods are sometimes impractical due to the cleanup, wastewater generated, and general infeasibility for protecting a large vessel.

Methods of Inerting

The most common methods of inerting and the guidance documents that describe these methods can be seen in Table 1. Adherence to other common safety practices such as lock-out tag-out and confined space entry for vessels is a necessary requirement for safely inerting a process vessel during maintenance. Good operational practices will also ensure successful inerting during normal operation.

Table 1. Inerting Options Versus Standard

Method	NFPA 327	AWS F4.1	NFPA 51B	API 2015	NFPA 77	NFPA 69
Water Displacement	X	X		X		
Sand Displacement		X				
Air Purge (Dilution)	X			X	X	X
Inert Gas Purge (Dilution)	X			X		X
Followed by Air Ventilation	X			X		
Inert Gas Blanket (Displacement)	X	X		NA	X	X
Steam Cleaning/Ventilation	X			X	X	
Natural Ventilation				X		

Water or Sand Displacement

Filling an entire vessel or pipe with sand or water will completely eliminate the presence of internal oxygen and fuel. These methods are typically the most reliable methods for eliminating the risk of explosion and flash fires. However these methods are not practical for every situation.

Steam Cleaning

For obvious reasons, steam is a likely source as inert species. Steam is readily available in process plants. Steam can also volatilize residual flammable liquids and remove scale or other deposits from the vessel. A major hazard with steam, though, is condensation. Care must be taken if steam is used to inert a vessel. The entire vessel must be heated to a temperature high enough that the steam will not condense. Steam condensation can actually short circuit attempts to purge a large or complex vessel.

Batch Purging

Batch purging methods are applied to operations requiring intermittent inerting such as maintenance. The more common purge methods are termed siphon, vacuum, and pressure purging. These active methods displace and dilute the vessel's flammable contents. These processes may need to be repeated to ensure that non-combustible conditions have been reached. Ventilation to the atmosphere can also be utilized in a passive manner in a very few operations by letting the vessel sit open for from several hours to several days.

Siphon Purging

In this displacement method, a vessel is filled with liquid and a purge gas stream is added to the vapor space. The liquid is drained and the vapor space is filled with the inert gas as the liquid level drops. Care must be taken to ensure that adequate inert gas is supplied and solid scale deposits, pockets of gas, and other hidden sources for fuel accumulation are mitigated with this method. Further active purge methods may be required beyond the initial siphon purge if hidden fuel sources are possible.

Vacuum Purging

A vacuum is drawn on a vessel and the vacuum is broken with the addition of a purge gas. This method is essentially a negative pressure displacement followed by dilution of the remaining vapor contents with an inert species. The vacuum is used to decrease the partial pressure of the flammable gas to a non-combustible range.

Pressure Purging

An enclosure is pressurized with a purge gas, and the contents are then vented to the atmosphere. Similar to vacuum purging, this method is also used to decrease the partial pressure of the combustible components. This method is applicable where the vessel has a high enough design pressure and source pressure for inert gas to effectively reduce the concentration of the flammable vapor.

Continuous Purging Methods

Continuous purging methods use a continuous feed of an inert to either displace or dilute the combustible mixture in the vessel. These methods can be employed subsequent to one or more of the above batch purging methods to maintain a non-combustible mixture in the vessel. Continuous purging is also used successfully in complex situations such as those where vessel has a large volume or a complex geometry. Since most cases involve purging a vessel of its vapor contents using another gas as an inert, success of the purge is closely tied to the extent of mixing (dilution) within the vessel.

Sweep-Through Purging

Sweep-through purging is a term described in the standard which covers the continuous feed of a purge gas into one opening on a vessel while allowing the mixed vapor contents to escape through a second opening, presumably at the opposite end of the vessel. This is the typical type of purge method employed to clean or purge a vessel prior to maintenance. The concentration of flammable vapor is dependent upon the volumetric feed of inert gas and flow patterns within the vessel. Simple correlations are based upon a mass balance approach to this process assuming perfect mixing and return a purge time or multiple of vessel volumes for purge gas given the volume of the vessel and volumetric flow rate of inert gas (Kinsley, 2001; Blakely, 1984; NFPA 69).

Air Ventilation

Ventilation to the atmosphere is one of the most common sweep-through purging methods. API 2015 discusses several methods for forced ventilation. Compressed air or steam eductors can be used to draw the vapor contents out of the vessel, but care must be taken to adequately bond and ground the eductor line to prevent static discharge. The vessel contents are especially susceptible to ignition at the vessel exit because the flammable vapors almost certainly pass through the flammable range upon mixing with outside air. Other mechanical means such as electric-powered blowers can be used to force air into the vessel and dilute the contents. Forced ventilation obviously requires at least one entrance and one exit to the vessel. Gas flow patterns through the vessel are important and can be short circuited with improper entrance/exit configurations.

Fixed Rate Application

When non-combustible conditions need to be maintained during normal operation, an inert gas can be added to the vessel and process piping as a blanket to displace and dilute fugitive fuel vapors and/or oxygen. The inert species is added to the vessel at a constant rate. This type of application disregards any process fluctuations, and therefore, the supply rate should be sufficient to supply the peak requirements for inert gas. This type of application has the advantage of being mechanically simple and relatively maintenance free. But disadvantages include continuous loss of product with the inert gas stream and increased quantity of purge gas required (over variable rate application).

Variable Rate Application

Variable rate application is similar to fixed rate with the addition of a more complex control system looped to the process. In this way, process fluctuations can be matched with corresponding flows of inert gas. The system must be capable of matching any process peaks and has the opposite advantages and disadvantages as the fixed rate application.

Hazards of Inerting

In the process of inerting a vessel, the flammable contents are removed to a location outside the vessel. In many cases, these contents are removed to the atmosphere in working areas of a facility. Special care must be taken to beware of producing flammable vapor clouds near the vessel. The strategy of designing inerting methods must therefore extend beyond the immediate vessel to ensure safe operation. Personnel and equipment safety must include plans for either capturing or dispersing the displaced combustible mixtures safely.

Asphyxiation is an ever-present hazard when inerting a vessel for maintenance. By their nature, most inert gases present an asphyxiation hazard to personnel both upon entry and nearby inerted process vessels. Some inert gases are heavier than air and can collect in seemingly open retention basins or other depressions. Oxygen monitoring and sound confined space entry practices should accompany any personnel access to vessel areas where the risk of asphyxiation is present.

Monitoring

Clearly the selection of the inerting method and species are important, but an often overlooked and underestimated aspect is monitoring. The success of any inerting procedure can be judged by two methods: (1) monitor the flammable vapor and oxygen concentration and (2) watch to see if the vessel explodes. Since all facilities would rather used method (1) some thought should be given to monitoring. By its nature, monitoring of a large vessel involves a point source measurement, which clearly cannot represent the global concentration within the vessel unless the vessel contents are uniformly well mixed. It is important to check the atmosphere with ongoing O_2 and CGI (combustible gas indicator) monitoring to both establish and continually verify changing conditions, but consideration of the vessel size and geometry must also accompany design of the monitoring process. Complex vessels can be equipped with remote monitoring ports near likely stagnant areas or other ways of remote monitoring options can be developed for a specific vessel. For explosion prevention, a common criterion is to either ensure the decrease below some threshold level for two of the three components required for combustion (API 2015).

Survey of Case Studies

The six case studies described below resulted in one fatality, four serious injuries (primarily burns) and millions of dollars in property damage. Each case study illustrates the consequences of an improperly inerted vessel. Some of the nonessential details have been changed to protect the confidentiality of the parties involved.

Case Study No. 1 - Hydrocarbon Vapors in a Surge Tank

A plant produced polypropylene pellets from propylene feedstock. Liquid propylene, liquid butane and hydrogen gas are mixed in the presence of a catalyst in a large polymerization reactor. The reaction occurs at a pressure on the order of 20 atmospheres. The reactor product is a suspended polypropylene powder in a solution of unreacted propylene, hydrogen and the carrier butane. The unreacted monomer and other remaining volatiles are vaporized in a dryer. The resulting powder stream still contains a significant amount of adsorbed and absorbed hydrocarbon vapors. This powder stream then passes through a nitrogen gas stripper to remove these hydrocarbon vapors. The stripped powder passes through a rotary valve and into a pneumatic nitrogen transport system that carries the powder to a series of surge bins. The powder layer on top of the rotary valve produces a seal and prevents hydrocarbon vapors from passing into the nitrogen system. Powder removed from the surge bins is extruded to produce product polypropylene pellets.

The facility was operating at normal production capacity when routine monitoring revealed that some of the powder surge bins contained lumps that hindered powder addition to the extruder. The surge bins had a carbon steel shell and 3000 ft^3 capacity. These bins were isolated from the nitrogen conveying system by closing slide valves at the bins. The reactor was isolated and a process gas purge was performed on the dryer and stripper. Contrary to written procedures, the stripper and nitrogen conveying lines were not isolated and the nitrogen lines were not shut down. Process gas passed through the residual powder and rotary valve into the nitrogen conveying system. The system was equipped with hydrocarbon monitoring sensors, but the taps had a tendency to plug with powder. The particular sensor for this nitrogen line was overdue for inspection and cleaning. The hydrocarbon monitoring sensor failed to detect dangerous levels in the nitrogen conveying system. The slide valves allowed a sufficient amount of hydrocarbons to pass into the bins.

The oxygen and combustible gas concentrations were measured outside the bin prior to starting the powder removal. A contractor who was using vacuum equipment to remove the powders was also smoking and ignited the hydrocarbon vapors near the bin. The area was clearly designated as a non-smoking area by placards on the surrounding enclosure. The resulting explosion killed one worker and severely damaged the bin storage area. The root cause of the accident was the failure to isolate the hydrocarbon stream from the nitrogen conveying system. Contributing causes were the hydrocarbon monitoring instrument failure, assumed perfect seal of the slide valve in the bin, and failure to constantly monitor the changing conditions near the bin.

Case Study No. 2 - Elemental Sulfur Dust in a Baghouse

A recently commissioned continuous fertilizer plant had been operating for less than six months. The facility produced a pelletized sulfur-containing product that was packaged and shipped in super bulk sacks. The raw sulfur-containing compound was ground into a very fine powder on the order of 200 mesh size or less. The powder was a known fire and explosion hazard, and thus the grinding equipment was inerted using a nitrogen atmosphere. After grinding, the powder was conveyed to equipment where it was agglomerated with water and an organic binder. These agglomerated pellets were then dried in an air atmosphere. The resulting product was sized then packaged. The process equipment was interconnected via ducted conveyors. Other than the grinding operation, all other equipment operated in air. A dust collection system controlled fugitive dusts from equipment and conveyors.

During normal operation, a series of explosions occurred in the production line. These explosions resulted in fires at several pieces of process equipment and in the dust collection system. The primary explosion originated in a pulsed baghouse and was ignited by a static electric discharge. The baghouse was not properly bonded and grounded. The primary explosion caused secondary explosions and fires as it propagated through the process equipment via the product conveyor system. Explosion vents on the baghouse functioned properly, but the conveyor system lacked explosion protection.

The root cause of this accident was the failure to recognize the continued hazard posed by dust during processing. The hazard potential of the dust was known, but the hazard was assumed to be associated only with the powder grinding operation. The danger of powder formed in other parts of the process was unrealized even though the presence of the dust was confirmed by design of the dust collection system. Explosive powder was formed in the presence of air within the conveyors, dryer and other non-inerted process equipment. Corrective actions to remove the hazard include placing the entire process system under an inert atmosphere, installing oxygen sensors within the system, bonding and grounding all equipment, and installing explosion isolation valves within the conveyors. These corrective actions fall into two different categories - prevention through oxygen removal and mitigation through explosion isolation.

Case Study No. 3 - Xylene Vapor in a Polymerization Reactor Vessel

New piping was being installed to facilitate the addition of equipment to a 9500-gallon polymerization reactor vessel. The facility was a PSM facility that manufactured industrial coatings. Three contractor employees were performing the work that required an oxyacetylene cutting torch. All of the contractor employees has site-specific training, and had been onsite previously. Not all of the penetrations into the pipe had been blinded off. Some organic material was observed on the inside of the vessel, coating the internal steam coils. The reactor was rinsed first with water then rinsed with xylene.

A hot work permit was issued and the oxygen and CGI were measured at the start of the work. The vessel was blanketed with nitrogen. Two of the contractors were performing the work, while one was acting as a fire watch. During the hot work, the steam coils inside the reactor were inadvertently activated. The hot coils volatilized solvent that had been absorbed by the solid residue on the vessel walls. The solvent vapor ignited from the welding torch resulting in a flash fire and explosion which damaged the reactor, caused modest structural damage to the facility and caused non-lethal injuries to two of the contractor employees.

The root causes of this accident were the failure to blind all of the vessel openings and the inadvertent activation of the steam heating coils. The explosion occurred when the welder struck an arc on an attached pipe that had not been blinded. The welding arc ignited an explosive mixture in the pipe and the ensuing flame traveled into the vessel itself causing a much larger deflagration. The secondary explosion injured the workers and caused the property damage. The proper use of blinds would have prevented ignition of the secondary explosion.

The inadvertent activation of the steam heating coils is believed to have cause the release of flammable vapor into the vessel. Prior to the steam, the fuel vapor was not detected. The most likely explanation for the release of the fuel vapor is that xylene, which was used in the cleaning of the vessel, was trapped in the solid residue clinging to the vessel walls and heating coils. Once steam was applied, xylene was volatilized from the residue. In the absence of the steam, it is unlikely that there would have been an accident.

Contributing causes were the use of a nitrogen blanket instead of a nitrogen purge and the failure to detect the change in the fuel concentration inside the vessel. The nitrogen blanket did not sweep air out of the vessel. It only provided a gaseous barrier on top of the air at the bottom of the vessel. Thus, undiluted air remained in the lower half of the vessel. More frequent monitoring could have detected the change in fuel concentration within the vessel. The use of a nitrogen purge and more frequent monitoring could have mitigated, if not prevented the accident.

Case Study No. 4 - Trimethylhydroquinone Powder in a Reactor

Trimethylhydroquinone (TMH) powder, a reactant for a pharmaceutical product, was being loaded into a semi-batch reactor with a capacity of 3200 gallons. The TMH was unloaded from a 1000 pound flexible intermediate bulk container (supersack) into a hopper system. The hopper system was a gas-tight enclosure with a nitrogen gas purge and a dust control system. The electrical wiring and components in the area were explosion proof. The reactor and hopper system were properly bonded and grounded.

Two operators were involved in the loading procedure. Due to the bridging characteristics of the TMH powder, the operators were required to facilitate the unloading by manually clearing any blockages in the hopper. A glove box provided access to the hopper. To further assist the unloading, the induced draft fan on the dust control system was operating. It is believed that an electrostatic charge developed on the powder during its loading into the reactor (TMH is an electrical insulator.) An explosion occurred, which resulted in damage to both equipment and the structure. Both operators received burns from the ensuing flash fire. Despite the nitrogen purge, fugitive air entered the system.

The root cause of the accident was the inflow of fugitive air into the hopper system. Fugitive air entered the hopper system via the glove box (which leaked) and the vacuum break vent on the hopper. Contributing causes were the inadequacy of the hopper system design, which required both operators to be physically close to the hopper system during loading, and the lack of oxygen monitoring in the hopper system.

Case Study No. 5 - Phenylethylamine Vapor in a Batch Distillation Column

A batch differential distillation column was used in the manufacture of organic chemicals for the pharmaceutical industry. The facility was covered by OSHA PSM. The column is three feet in diameter, 20 feet high connected to the top of a still pot used to heat the organic mixture. The column was manufactured out of Hastelloy and filled with a fine Hastelloy mesh. The vapors produced by the column were treated through a scrubber system. At the completion of a batch of material, the still bottoms were cooled while under a nitrogen purge. Nitrogen was injected at the base of the column and exited at an atmospheric vent connected to the scrubber system.

The distillation of a batch of a flammable organic liquid was completed and allowed to cool under the nitrogen purge until an operator opened the drain valve on the still pot to remove the product. The air vent was kept open and the nitrogen remained on. Several hours after the product was removed smoke was observed in the building and traced to the distillation column. The facility's Emergency Response Team found small fires immediately surrounding the column. When a section of the column's insulation was removed, the column was observed to be glowing red. The exterior fires were extinguished with dry chemical extinguishes, and the fire inside the column was extinguished with water.

The standard operating procedure at the facility was to keep both the drain valve and the air vent open while under nitrogen purge after the product had been removed from the still pot. The nitrogen volumetric flow rate was low compared to the volume of the column and pot. This allowed air to enter the column through the drain valve. The flammable vapor ignited inside the column causing extensive damage to the column and the packing material. The root cause of this accident was the failure to ensure that an oxidizer was not able to enter the column during nitrogen purging. A contributing factor to the severity of the loss was the shut down of all instrumentation equipment which would have alarmed as the temperature in the column began rising.

Case Study No. 6 - Ethanol Vapor in a Fermentation Reactor

A 540,000-gallon fermentation tank was being prepared for entry to repair an internal agitator. The design on the tank required a pipe to be cut open to install blinds required to isolate the tank. This tank was one of more than a dozen fermentation tanks at a large corn and soybean processing facility. A four-person team of contractor employees performed the work. Prior to the repair, the tank had contained corn protein, water, and ethanol. Two manways into the tank were open, and the work crew was using a carbide bladed saw to cut open the pipe.

Prior to beginning the work, the tank had been isolated according to the facility's lock-out/tag-out procedure. The tank had been "steam cleaned" for eight hours and a hot work permit was issued. The oxygen and combustible gas concentrations were measured outside the tank, where the hot work was being performed. No measurements were taken inside the tank or inside the pipe that was being cut. The steam cleaning procedure used to inert the tank had no written procedure, and no basis had been established for when the cleaning was sufficient. Ethanol vapor ignited inside the tank from sparks produced during the cutting. This resulted in an explosion that destroyed the tank, severely damaged several neighboring tanks, caused minor injuries to the contractors, spilled three million gallons of product, and significantly reduced the production capacity of the facility.

The root cause of this accident was the inadequate cleaning and purging of the vessel. The procedures themselves were inadequate since the operations were carried out as prescribed. The difficulty of cleaning and purging a large vessel must be recognized. Where steam is used to purge a vessel, the entire volume of the vessel should achieve and maintain a temperature in excess of 100 °C (the steam saturation temperature corresponding to atmospheric pressure) otherwise the steam will condense and not displace the flammable vapors. There is no simple solution that will work at all facilities for all vessels. Successful cleaning and purging must be verified by atmospheric monitoring. A contributing cause of the accident was the failure to take CGI readings inside the pipe and vessel. It is likely that CGI measurements would have detected the presence of an explosive atmosphere. Corrective actions include providing adequate monitoring procedures and improved purging procedures.

Discussion

The discussion that follows addresses two points: the lessons learned from these accidents and a conceptual design strategy for using inert gases to create non-flammable atmospheres.

Lessons Learned

Specific lessons learned from these case studies are summarized below. These lessons learned are used in part to formulate a conceptual design strategy for properly inerting vessels.

Lesson #1: The supply flow rate of inert gas must meet or exceed the design objective.

In three of the six cases, the supply rate of inert gas was arbitrarily selected, i.e., the flow rate was not based on a design objective to reduce the fuel or oxidant concentration to some specific level. Inert gas flows that are too small cannot achieve the desired concentration level in the vessel. Conversely, inert gas flows that are too large may present unnecessary operational or logistical problems.

Lesson #2: Stagnant zones must be minimized.

In five of these six case studies, an explosion or flash fire occurred despite the use of an inert gas inside the vessel. The accident occurred because stagnant zones were present in which the inert gas did not reduce the flammability hazard of the vessel atmosphere. The degree of mixing of the inert gas with the vessel atmosphere must be maximized to the extent that is practical.

Lesson #3: The degree of mixing in the vessel should be determined through atmospheric monitoring.

The only way to verify that the desired level of mixing has been achieved is to measure the fuel and air concentrations in various locations of the vessel. The specific goal of atmospheric monitoring should be to search for stagnant regions within the vessel where the inert gas has not achieved the desired effect. Corrective actions can then be taken to either eliminate these stagnant regions or to accept them and apply additional safeguards to manage the vessel's fire and explosion hazards.

Design Considerations for an Inerted System

Based upon the case studies, lessons learned, standards, and good engineering practice, an inerted system must be engineered to reduce the risk of fires and explosions. A suggested design strategy for engineering the system can be summarized as having five components:

1. Specify the inerting design objective.
   Determine the flammable components which may be present, their flammability limits, limiting oxygen concentration, and duration of inerting requirement.

2. Specify the inerting medium.
   Select an inert gas and method of supply that are compatible with the operation and meet appropriate personnel safety constraints.

3. Determine the minimum quantity of inert gas required to achieve the design objective.
   Calculate the minimum amount of ideal species based upon perfect mixing assumptions.

4. Promote good mixing of the inert gas with the vessel atmosphere.
   Select an appropriate method to promote good mixing of the vessel contents and ideal species and calculate the required amount of inert species.

5. Verify the successful achievement of the design objective by atmospheric monitoring.
   Select a monitoring method for the vessel contents to verify attainment of safe, non-combustible conditions.

The first step in designing an inert system is to determine what flammable species are present and a target minimum concentration. This target minimum concentration should be based upon the lower flammable limit (LFL) considering the mixing conditions within the vessel. For large vessels, deflagrations can still occur even if the overall vessel contents are below the LFL when stagnant pockets of flammable gas mixtures exist (Ogle 1999). The LFL is the minimum concentration of the flammable species within the vessel that will propagate a flame. If the oxygen concentration can be controlled, the limiting oxygen concentration can be used as a target for the inerting process. NFPA 69 contains LOC values for several chemicals and describes appropriate methods for determining the LOC.

Several factors weigh in on the choice of inert species and method of introduction. The choice of the inert species can most readily be based upon what the facility already has on hand. The most suitable inert species may not be a truly inert gas such as nitrogen or argon; in some cases flue gas or other process streams may be utilized. Consideration of the chemical compatibility of the inert species, the contents of the vessel, and the vessel components themselves are of prime importance. The source of the inerting species may be an onsite storage tank, gas generator, or another process unit must be of continuous sufficient supply to fulfill inerting requirements. Likewise, the contaminated purge streams that exit the vessel must be either collected or directed to nonhazardous locations. The designer must recognize that the flammable mixture removed from the vessel may produce a hazard downstream or outside the vessel.

With the inerting design objective specified and the inerting agent selected, the quantity of inert gas can be calculated. The relevant methods are presented in NFPA 69. These calculations assume perfect mixing. Perfect mixing represents an ideal condition which may or may not accurately describe the degree of mixing in a real vessel. Good mixing, the real-world approximation of perfect mixing, can be promoted through several techniques:

- Arrange the inert gas outflow point to be offset from the axis of the inert gas inflow point
- Use multiple inert gas inflow points
- Install a blower into the inerted vessel
- Install temporary baffles in the inerted vessel

These techniques can be used individually or in combination.

If the inerting agent is to be the only means of explosion prevention in a vessel, then it is imperative to check the degree of mixing by atmospheric monitoring. If stagnant regions are found, they should be eliminated if possible. If it is not possible to eliminate stagnant regions, or if atmospheric monitoring is not feasible, then serious consideration should be given to the use of additional explosion safeguards (Ogle and Carpenter, 2001).

Conclusions

This paper has examined the basics of using an inert medium for fire and explosion protection in vessels which contain a flammable atmosphere. Despite the numerous guidance documents available to assist the engineer, fires and explosions can and do occur in inerted vessels. Six accidents in inerted vessels were examined and from these case studies three lessons were inferred:

- The supply flow rate of inert gas must meet or exceed the design objective.
- Stagnant zones must be minimized.
- The degree of mixing in the vessel should be determined through atmospheric monitoring.

Based in part on these lessons learned, design considerations were offered to assist the engineer in developing a more effective inerting strategy.

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