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Investigation of Odour Fade, and Subsequent Natural Gas Explosion at the San Diego Bayfront Hilton Hotel

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An accidental gas explosion occurred at the Hilton Bayfront hotel in San Diego, California on May 19, 2008, while the hotel was in the final stages of construction. The mechanical and plumbing contractor had finished installing natural gas plumbing to the primary mechanical room on the fifth floor, and workers were in the process of purging the air in these lines with natural gas. This was accomplished by disconnecting a coupling from the primary gas manifold to a bank of water boilers and establishing gas flow directly into the fifth floor mechanical room. The contractor did not install a temporary vent line to the outside and did not monitor natural gas concentration within the area where the gas was venting. Instead, workers relied upon the distinctive odour of natural gas to determine when the lines had been purged of air.

Gas records indicate the flow of gas continued for approximately one hour, releasing 113.3 m^3 (4000 ft^3) of natural gas into the relatively confined mechanical room. Since the steel gas line was completely new, the Tetrahydrothiophene (THT) and Tetra-Butyl Mercaptan (TBM) based odorant in the gas was completely adsorbed by the pipe wall and none of the workers smelled gas during the purging operation. The resulting explosion caused considerable damage to the hotel, 15 workers were injured and construction was delayed for 1 year. Exponent conducted an engineering investigation of the accident, examined the gas delivery lines, and reviewed gas service records from the utility company. Our findings confirmed that, even though the natural gas was odorized to required levels at the meter, the gas became deodorized after it came in contact with new steel pipes within the hotel. The amount of gas that was vented by the workers was sufficient to cause the explosion.

Post-incident investigation by various regulatory agencies, including the Occupational Safety and Health Administration, suggested that, while the actions of the contractor violated certain requirements, there were no explicit regulations or standards that governed gas purging. Due to this explosion and similar incidents at a power plant in Connecticut and a food manufacturing facility in North Carolina, the United States Chemical Safety Board recommended that the National Fire Protection Association formulate a new standard for fire and explosion prevention during cleaning and purging of flammable gas piping systems. The primary author is a member of the Technical Committee of this new NFPA standard, and the lessons learned section of this paper includes corrective measures required by this standard, which should prevent similar incidents.

1. Introduction

On May 19, 2008 at 14:15, a gas explosion originated on the fifth floor of the San Diego Hilton Bayfront hotel. The hotel was still under construction, and contractors were in the process of connecting and commissioning hot water boilers servicing the kitchen, laundry, and other hot water requirements. The explosion was centred in the fifth floor mechanical room, used to house six water boilers, several pumps, and a large hot water tank. Fifteen contractors were injured, and there was extensive damage to the equipment and the framing and windows for the fourth, fifth, and sixth floors (Figure 1a, 1b, and 1c). Following the explosion, the utility company shut off the natural gas supply at the meter and also pinched the plastic supply line 100 meters (300 ft.) upstream as an additional precaution (Figure 1d).

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Figure 1: Damage to the hotel (1a, 1b, 1c). gas pinch point (1d)

1.1 Natural gas delivery

Natural gas is delivered to the site via a 10.2 cm (4 in), 308 kPa, absolute (30 psig) plastic pipe routed from the nearby convention centre (Figure 2a). The plastic pipe terminates at the meter set assembly (MSA) (Figure 2b). On the customer side, the pressure is regulated down to 136 kPa (5 psig), and a series of steel pipes deliver natural gas to various locations within the property. A 6.4 cm (2.5 in) line runs from the floor level to the fifth floor mechanical room supplying fuel to six Raypak water heaters. The pressure is then regulated to 103 kPa (8 inch-water), before it is supplied to a common 5.7 cm (2.25 in) manifold (Figure 2c). Each water boiler is fed via a 2.5 cm (1 in.) line with a ball valve and an electronic shutoff switch to prevent over pressurization (Figure 2d).

1.2 Natural gas odourization

Natural gas does not have an odour and therefore utilities blend certain additives into their product so that leaks can be detected by the human sense of smell. Since shortly after the First World War, the United States Code of Federal Regulations requires that gas distributed to end consumers must be detectable by a person with a normal sense of smell at one-fifth of the Lower Explosive Limit (LEL) (49 CFR 192.625). The LEL for natural gas is 5 % in air; therefore, the average person must be able to detect odorized gas at a concentration of 1 % in air. Odorants should be nontoxic at the concentration they are used, easily detectable at low concentrations, and sufficiently stable such that a gas leak can be identified. The most common odorizing agents are based on sulphur compounds and have a pungent smell, similar to that of rotten eggs.

A single compound incorporating all desired odorant properties has not been identified. All sulphur-based odorants decompose when exposed to oxygen and at high temperatures. There are also significant limitations with preferential adsorption of the odorants when the leaking gas flows through porous media. Tertiary Butyl Mercaptan (TBM) has low odour threshold, gassy odour, good soil penetration, and high resistance to oxidation. However, its high freezing point (1 °C) results in the need for blending with other components and it is susceptible to pipeline oxidation (Usher, 1999). Another commonly used odorant, Thiophane (Tetrahydrothiophene or THT), is chemically stable and most resistant to pipeline oxidation. However, it has relatively poor soil penetrability performance and can be adsorbed by the soil, which can cause de-odourization of the gas during an underground leak. Accordingly, THT is mixed with Tertiary Butyl Mercaptan (TBM) to improve the detection of gas leaks in soil (Lehman, 1976). The odorizing agent added by the utility in San Diego incorporated a mixture of 50 % TBM, and 50 % THT (Scentinel T-50, Material Safety Data Sheet, 2005). While 0.011 kg/28,000 m^3 (0.025 lbs./MMSCF) of natural gas produces an easily recognizable odour at 1 % LEL, the gas industry in the United States typically odorizes at 20X the required amounts, nominally using 0.22 kg per 28,000 m^3 of natural gas (Powell and Vandaveer, 1968). Further addition of odorant has been shown to be costly and counterproductive (Jacobus, 2002).

1.3 Odour loss

Odour fade is the unintended reduction or loss of concentration of the natural gas odour, making it difficult to detect via the sense of smell. A known problem is odour fatigue/olfactory adaptation, which is the temporary, normal inability to distinguish a particular odour after a prolonged exposure. Another mechanism is odour fade due to oxidation (e.g., by air, water or rust in steel pipes) or adsorption of the odorant by the soil during an underground leak. The oxidation of the mercaptan to the less odorous disulphide can be represented by the following reaction:

$$2R - SH + \frac{1}{2}O_2 \rightarrow R - SS - R + H_2O \tag{1}$$

For certain odorants, this reaction might be very slow in the gas phase, but can be significantly accelerated when the oxygen is supplied by iron oxide, such as rusted pipes (Kniebes, 1971).

Figure 2: Gas delivery: incoming line (2a), meter set assembly (2b), 5th floor fuel manifold (2c), and water boiler feed (2d)

2. Investigation

Exponent inspected the explosion site within one week of the explosion, after access was permitted by the Occupational Health and Safety Administration (OSHA), and the local fire department. Our investigation established that a coupling below the ball valve to a water boiler in the mechanical room had been disconnected (Figure 2d). This allowed natural gas to be directly released into the mechanical room when the valve was opened. Witnesses described that, just before the explosion, two plumbing contractors disconnected the coupling to purge the lines. The plumbing contractors also confirmed that they actuated the ball valve several times to purge the air in the line. A channel lock found on the floor behind the boilers is believed to be the tool used to disconnect the gas line coupling. Our review of the digital meter records established that 113.3 m^3 (4,000 ft^3) of gas was supplied to the hotel between 13:00 and 14:00, just prior to the explosion. Review of work activities indicated that gas was not used anywhere else, confirming that this volume was released into the fifth floor mechanical room during the purging operation. Field tests confirmed that the flow rate from the ball valve exceeded 120 m^3/h. There were several potential ignition sources, including non-explosion proof and energized electrical panels, electrical motors and fans, welding activities, and a cigarette lighter found behind one of the water boilers.

The natural gas utility collected gas samples at the meter set point and at the pinch point approximately 100 m (300 ft.) upstream. Following the removal of loose debris from the mechanical room, a gas sample was also collected from the trapped gas within the plumbing. All three samples were submitted for chemical analysis. An operator from the gas company also conducted *in situ* odour verification tests at the pinch point and at the meter set, and demonstrated that odorant levels in the supplied gas exceeded federal requirements. A pressure test was then conducted at 60 psig to recertify the plumbing within the building (California Building Code, 2004). Fuel gas service was restored to the hotel in June 2008.

An *in situ* measurement at the disconnected coupling in the fifth floor mechanical room failed to register any detectable odour level when gas was released through the disconnected coupling. However, combustible gas indicators (CGI) measured 100 % natural gas at the pipe exhaust. An extension pipe was connected to the coupling, and flowing gas was routed to a temporary stack off the balcony. Another measurement was conducted a half hour later after flowing 56.5 m^3 (2,000 ft^3) of gas through the piping, and no odour was detected again. At this point, all testing was stopped, and gas was shut off to the building until the pipes could adequately treated (pickled) before restoring service.

3. Analysis

A review of the plumbing diagrams indicated that the total volume of gas pipe from the meter set to the fifth floor mechanical room was ~ 2.35 m^3 (83 ft^3). Given a delivery pressure of 136 kPa (5 psig), it took the gas approximately 1.25 min to flow from the meter set to the outlet at the disconnected elbow. It is obvious that, on the day of the incident, the workers flowed much more gas than was necessary to purge the piping. An additional 2,000 ft^3 of gas was flowed during Exponent's tests, and the *in situ* measurements demonstrated that the new steel pipe was still adsorbing the odorants at a very rapid rate. Since the workers did not use a combustible gas indicator and only relied on their sense of smell to detect gas, they would not have known to shut off the valve before a flammable concentration developed within the mechanical room.

Utility companies in the United States typically treat (pickle) new gas transmission piping before placing it into service by running high concentrations of odorant through the new sections. This saturates and thereby passivates the iron oxide layer. However, this practice does not extend to pipes that are installed by the customer. Interviews with contractors and review of the gas records confirmed that the steel pipes were not pickled prior to being sold by the supplier or before they were installed.

3.1 Gas release, lower explosive limit (LEL)

A mathematical model was constructed to calculate gas concentrations within the mechanical room and identify the duration required to reach lower explosive limits (LEL). The model assumes a uniform gas flow and a well-stirred room (Harris, 1983).

$$C_{gas}(t, ACH) = \frac{(100Q_{gas})\left[1 - e^{-\left(Q_{gas}+Q_{air}(ACH)\right)\frac{t.hr}{V_{total}}}\right]}{Q_{gas}+Q_{air}(ACH)} \tag{2}$$

Where V_{total} is the effective volume of the fifth floor mechanical room (409.2 m^3), Q_{gas} is the gas flow rate from our field experiments (0.031 m^3/s), and Q_{air} is a parametric value for air exchange rate. Figure 3 shows gas concentration as a function of time and demonstrates that explosive limits were met during most of the purging operation.

3.2 Pressure rise

The instantaneous pressure rise inside the mechanical room due to gas ignition was computed as (Harris 1983):

$$P_m = P_v + 23\left[\frac{W_{glass} {S_T}^2 K_{avg}}{{V_t}^{0.3}}\right] \tag{3}$$

Where, P_v is failure pressure for 5 mm thick glass (typically, 6.5 kPa), S_T is the turbulent flame speed (2 m/s), K_{avg} is the ratio of wall to glass (measured at 0.833), W_{glass} is the glass weight per unit area (measured at 1.4 g/cm^2) and V_t is the effective volume (409.2 m^3). The instantaneous rise was determined as:

$$P_m = 129\ kPa\ (4\ psig) \tag{4}$$

This value is consistent with the damage observed to glass, drywall, sheet metal and light equipment. It is also consistent with damage in typical gas explosions as calculated in a CFD study (Pedersen and Middha, 2012). No damage was observed to the concrete slabs or the steel framing of the hotel.

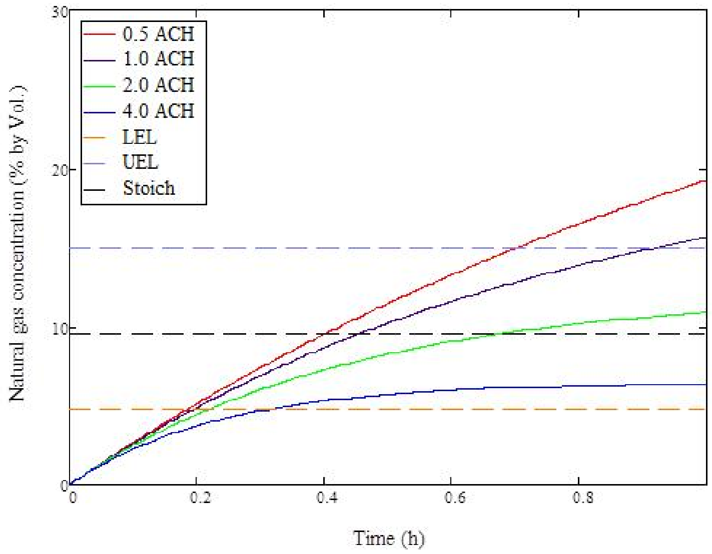

Figure 3: Gas concentration in the mechanical room for various air exchange rates

3.3 Gas sample analysis

The gas samples at 1) the plastic pipe pinch point (100 m) upstream of the meter set, 2) the meter set servicing the hotel, and 3) the fifth floor mechanical room were collected in Tedlar bags and submitted for testing within 24 h to minimize oxidation. The results (Table 1) showed a distinct difference between odorant concentration at the pinch point and at the customer meter, and a complete absence of odorant at the fifth floor. These results confirm the *in situ* field measurements, and demonstrate that the TBM and THT were destroyed within the new and unpickled steel pipe that was installed in the hotel. The cause for the drop between the pinch point and the meter set was not investigated at the time, but was attributed to residual air in the pipe put in by the utility following the explosion.

Table 1: Component analysis for gas samples from different locations

Component	Pinch point	MSA	5^{th} Floor mech. room
H2S	0	0	0 (ppm)
TBM	0.57 (ppm)	0.16 (ppm)	0 (ppm)
THT	0.02 (ppm)	0.02 (ppm)	0 (ppm)
Methane	95.21 (mol %)	95.07 (mol %)	95.14 (mol%)

4. Conclusions

The incident was triggered by a deliberate release of natural gas within a semi-confined space. Records indicate that the amount of gas released was 113.3 m^3. Analysis indicated that, for mixing and air exchange conditions, LEL concentrations would have been reached within approximately 12 minutes after gas was released into the mechanical room. Several credible ignition sources, including non-explosion proof and energized electrical equipment and welding activities, triggered the explosion.

4.1 Key findings

The purging process did not incorporate a vent stack to remove the gas from areas where it could accumulate. The plumbing contractors also relied on their sense of smell to detect the presence of gas and did not incorporate a combustible gas indicator to monitor gas levels. Although the gas supplied by the utility was odorized to a level that was consistent with United States Code of Federal Regulations, the gas was completely de-odorized by the time it reached the fifth floor mechanical room. The odorants were rapidly adsorbed by the new and untreated steel pipes. Field tests by Exponent confirmed that the odorants within the gas could be destroyed within 1.25 min.

4.2 Code review

Review of applicable regulations demonstrated that there are several gaps in the procedures for purging new fuel pipe installations. Installation of new fuel gas pipe in California is regulated by the California Plumbing Code (CPC, 2001), and the California Mechanical Code (CMC, 2001). Both documents cite the National Fire Protection Association National Fuel Gas Code (NFPA 54, 2001) as a mandatory reference standard. Section 4.3.1 of NFPA 54 requires that gas should be vented outdoors to a ventilated area of sufficient size to prevent accumulation of flammable mixture. Section 4.3.3 requires that the open end of piping systems being purged shall not discharge into confined spaces or areas where there are sources of ignition unless precautions are taken to perform this operation in a safe manner. However, NFPA 54 does not require use of CGI to monitor LEL levels, nor does it address the possibility of odour fade.

The explosion at the Hilton San Diego Bayfront hotel was one of several recent high profile accidents in the United States. Based on similar incidents at a power plant in Connecticut and a food manufacturing facility in North Carolina, the United States Chemical Safety Board recommended that the National Fire Protection Association formulate a new standard for fire and explosion prevention during cleaning and purging of flammable gas piping systems. Although the new standard, NFPA 56 (Standard for Fire and Explosion Prevention During Cleaning and Purging of Flammable Gas Piping Systems, 2012), does not explicitly include piping systems that are already covered by NFPA 54, it does provide guidelines to prevent a repeat of this accident, and addresses safe installation, cleaning, and removal of flammable gas piping. The standard specifies training requirements for fuel gas plumbing personnel and requires trained fuel gas plumbers to develop site-specific purge procedures, evaluate environmental/work location hazards, communicate their plans to all personnel involved, control ignition sources, ensure that purging activities are adequately monitored, and that reliable instruments are used to monitor combustible gas levels in the work area.

5. Recommendations

The root cause of this accident was incorrect gas purge procedures and a lack of awareness of the possibility of odour fade. Procedure/knowledge based failures represent approximately 19 % of the incidents in the chemical process industry (Kidam, Hurme and Hassim, 2010). Contractors and installers of fuel gas piping in new structures should follow the guidelines of the newly developed NFPA 56 whenever they install, clean, or remove fuel gas pipes. Training procedures required by this standard should emphasize that odour fade can occur within new steel pipes.

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