Hazard Evaluation and Technical Assistance Report
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Carbon Monoxide Intoxication and Death in a Newly Constructed Sewer Manhole

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I. Summary

This report describes three cases of carbon monoxide (CO) poisoning in a manhole, including one fatality, from CO migrating through soil after nearby use of explosives. A municipal sewer project involved installation of new pipes and manholes. Work of the general construction contractor was interrupted when a subcontractor detonated 265 pounds of nitroglycerin-based explosive 40-60 feet south of the manhole to break up underlying rock. A construction worker who descended into the manhole 45 minutes after the explosion collapsed within minutes, and two co-workers descended into the manhole to rescue him. One rescuer retrieved the unconscious worker, and the other rescuer died in the manhole. All workers had elevated carboxyhemoglobin levels.

In the subsequent NIOSH investigation, air monitoring was conducted with real-time instruments, and air samples were collected in Tedlar bags. Laboratory analyses of the bag samples collected near the bottom showed 1905 parts per million (ppm) CO, 19.5% oxygen, and 3% carbon dioxide. Direct reading instruments showed progressively higher concentrations as the sensor was lowered into the manhole. Subsequent chamber tests on sample explosive yielded 27 liters CO per kilogram detonated. Based on this value, the surface blast at the construction site may have produced about 3,250 liters (114.8 cubic feet) CO.

The CO in this incident most likely was released from the nearby explosion and migrated through soil and fractured rock into the manhole. The blasting and construction industries should be made aware of this previously unrecognized CO exposure hazard associated with surface blasting. The extent of CO exposure from explosives used in construction is not known, and additional information on the extent of CO exposure must be collected. In addition, confined space entry procedures (including monitoring confined space atmospheres before entry) should be observed; CO monitoring of confined spaces in the presence of blasting can prevent future incidents such as this one.

II. Introduction

On August 4, 1997, a construction worker of the general contractor was overcome by CO in a recently installed manhole. Two other workers were overcome while rescuing him, and one of those rescuers died. This manhole was not connected to any existing municipal storm sewer, sanitary sewer, or water lines. On August 5, the Centers for Disease Control and Prevention (CDC) received a request to investigate the incident, and on August 6 a team from CDC's National Institute for Occupational Safety and Health (NIOSH) initiated an investigation.

III. Description of incident

As part of a municipal project to upgrade the sewer system, a contracting company was installing new pipes and manholes in a residential area (Figure 1). The installation was begun in a low-lying area where the ground consisted of a 6-foot surface layer of soil and clay underlaid by solid gneiss (a metamorphic rock). To excavate pipeline trenches and manholes pits, 2.5-inch diameter holes are drilled to a depth of about 18 feet, and explosive charges are detonated in those holes to break up the subsurface rock. These explosions are called "surface blasts." A backhoe is then used to excavate the soil and broken rock. After the concrete pipe and precast concrete manhole sections are lowered into the excavation, the excavation is filled with dirt. The sanitary sewer lines are 18-inch diameter concrete pipe. Manholes consist of precast concrete sections including a base with a floor, intermediate sections ("risers") which are stacked to achieve the desired height, and a cap which tapers to receive a cast iron lid.

In late July, the site was prepared with several surface blasts. A trench for the pipeline manhole was dug in the east-west direction between two streets in a residential neighborhood, and approximately 100 feet of pipe was laid and covered. On July 31, a pit was dug at the west end of this pipe run to install a new manhole (designated A18), and several sections of precast concrete riser were installed to keep the hole open over the weekend. Because the water table in this low-lying area was high, an electric sump pump at the bottom of the manhole pit was used to keep the manhole dry (a few inches water remained). A portable Ingersoll-Rand diesel generator on site was used to generate electricity for the sump pump; the generator was located 22 feet west of the manhole and 6 feet above the manhole on a slight slope. The generator was shut down over the weekend, allowing water to completely fill the manhole.

On Monday, August 4, a five-man crew of the general contractor returned to the site and restarted the generator. After the pump had drained the manhole, the crew used a backhoe to lift the temporary risers out of the hole, and working from above, poured gravel into the manhole pit to serve as a foundation for the final structure. A trench box was lowered into the hole to prevent collapse of the walls, after which construction worker “A” (a pipe layer) descended by ladder to level the gravel. He reportedly expressed no comments about any unusual conditions, odors, or health symptoms. When he emerged, the precast base, risers, and cap of the 12-foot deep manhole were lowered into the pit. The manhole had two openings near the bottom for connecting pipes, and one of these was to be connected to the new pipeline extending east. The other opening was left open for later connection to a future pipeline which would extend south. A sheet of plywood over the opening kept earth from collapsing inwards, but ground water poured in freely and was evacuated by an electric sump pump. By now, it was about 1:00 pm, and the crew broke for lunch.

At 1:30 pm the crew resumed work by re-entering the pit outside the manhole to lay a section of pipe; this pipe connected the manhole with the east end of the previously laid 100 feet of pipe. Afterwards, at about 2:00 pm, the crew emerged without incident and used a backhoe to lift the trench shield from the hole and then filled the space around the manhole with earth. Then worker “A” and the crew foreman descended into the manhole for about 10 minutes to set up a laser apparatus used to ensure that the pipe was installed in a straight line. The two men emerged from the manhole, and the crew spent the next several hours installing additional lengths of pipe at the east end of the pipeline about 150 feet away.

The work was interrupted at 3:40 pm for 15 minutes while a surface blast was fired 40 to 60 feet south of the manhole to prepare the ground for future pipe-laying operations. The surface blast was fired by an explosives subcontractor. Two hundred sixty-five (265) pounds of the explosive Goma (Union Espanola de Explosivos, S.A., Madrid) were distributed in 22 boreholes for the shot. This blast reportedly raised an earth mound several feet high, and construction worker “B” (an equipment operator of the general contractor) used a bulldozer to level the ground. Some of the raised earth may have been pushed closer to the manhole. The crew then resumed work at the distant end of the pipeline.

At about 4:30 pm, the crew completed their work on the east end of the pipeline. At this point, the only remaining tasks were in the manhole: the pipe that had been connected to the manhole was to be sealed with a jointing compound, and the laser sighting equipment was to be removed. Worker “A” descended into the manhole to perform both tasks; the rest of the crew remained on the surface, and the foreman walked to his nearby truck to store equipment and complete paperwork. As in other entries into the manhole that day, confined space entry precautions, including air monitoring in the manhole, were not utilized.

Within a few minutes after worker “A” descended into the manhole, his coworkers above noted that he had collapsed, and they shouted to the foreman. In a later interview, worker “C” (a laborer of the general contractor) reported that worker “A” did not mention any unusual odors or other conditions before worker “A” collapsed. The foreman ran over, saw the situation and reportedly instructed the crew members not to enter the hole. He then ran back to his truck to call 911 on his cellular phone. In the meantime two crew members, workers “B” and “C,” climbed down into the manhole to retrieve construction worker “A.” Worker “C” later reported that he did not smell any unusual odors or note any other unusual conditions while in the manhole, but he and worker “B” began to feel dizzy and had difficulty “catching our breath.” Workers “B” and “C” lifted worker “A” up the ladder to the others on the surface. Worker “C” then climbed out and collapsed on the surface. Worker “B” tried to ascend the ladder but collapsed at the bottom of the manhole.

At this time the foreman left the scene in his truck and went to the project field offices about a mile away, where he obtained a harness and a rope. While he was gone, the the first city fire department responders arrived. The Battalion Chief was first on the scene, followed by Engine Company Alpha. These units had been dispatched with a report that they were responding to a construction accident with an entrapment. By now the foreman had returned with the rescue harness. One fire fighter from Engine Company Alpha, reportedly acting upon orders, descended into the manhole without wearing any breathing apparatus. As suspicions grew that this incident involved a hazardous atmosphere, he was instructed to climb out before he had completed his effort to put the harness on the now-unconscious construction worker “B.” Now Engine Company Beta arrived, and as its crew walked to the scene, they wore only turnout gear. When they saw two construction workers on the ground, they too became concerned about a possible hazardous atmosphere and returned to their engine to obtain their self-contained breathing apparatus (SCBA). A fire fighter wearing SCBA climbed into the manhole and put the harness on construction worker “B,” and those on the surface hauled construction worker “B” out. On the surface, construction worker “B” was unconscious, not breathing, and without detectable pulse, and the rescuing fire fighters noted that his pupils were dilated and his skin color was deep red. They began basic life support and oxygen, while at the same time the two other workers were being given supplemental oxygen. A fire department medical response unit arrived and began advanced cardiac life support of construction worker “B.”

The hazardous materials unit was the last unit to arrive on scene. The hazardous materials unit crew lowered real-time air monitoring instruments into the hole. Although the level to which these instruments were lowered was not ascertained, the sampling probe on one of them is long enough to suggest that the measurements were taken approximately six feet below the surface. The instruments indicated levels of approximately 600 ppm CO, 12 ppm hydrogen sulfide, and over 25% of the lower explosive limit (LEL); the LEL indicator on the instrument was calibrated for pentane. The local fire department’s protocol calls for the use of explosive atmosphere precautions for any LEL reading over 25%.

Because of the hydrogen sulfide reading, water was used to hose off the victims and rescuers before transport. The three affected workers, as well as five fire fighters, were taken to area hospitals for examination and treatment as needed. The fire fighter who had entered the manhole without breathing apparatus had a carboxyhemoglobin of 14%; he was treated with oxygen and released. The other fire fighter, who had assisted the rescue from the surface, had a carboxyhemoglobin of 1.4%. Three other fire fighters were taken to the emergency room at another hospital, but were released after examination and did not have carboxyhemoglobin levels measured.

The three construction workers also were taken to emergency rooms at local hospitals. Construction worker "A" was taken to hospital #1. The ambulance transport record does not indicate the time that the ambulance arrived at the incident scene, but states that worker "A" was put on a 100% oxygen nonrebreathing mask and was taken to hospital #1, where he arrived at 5:52 pm. An arterial blood gas measurement taken at 5:57 pm showed a carboxyhemoglobin level of 33%. He was transferred to the hospital's hyperbaric chamber where he was treated for 90 minutes with 100% oxygen at 2.5 atmospheres pressure. Following this treatment, his carboxyhemoglobin level was 0.0%, and he was transferred to an intensive care unit. Although his mental status was initially confused, it improved and he was discharged from the hospital on August 8.

Construction worker "C" was initially taken to the emergency room of hospital #2. No information on his treatment was available from hospital #2. He was transferred to hospital #3, where records indicate that at hospital #2 his admission carboxyhemoglobin level was 23%, and he was treated with sodium nitrate for possible cyanide poisoning. Upon admission to hospital #3 he was treated in that hospital's hyperbaric chamber for 90 minutes with 100% oxygen at 2.8 atmospheres pressure. He was released the next day and was reportedly feeling well.

Construction worker "B" was also transported to the emergency room of hospital #2, where he was pronounced dead. According to the County Medical Examiner's office, where an autopsy was performed, the only abnormality noted during the autopsy was the pronounced red color of the skin. Blood samples obtained at autopsy showed a carboxyhemoglobin level of 32.6%.

IV. Investigation

The NIOSH investigation team initially consisted of an industrial hygienist and an occupational medicine physician; a NIOSH mining engineer who specialized in explosives was involved by telephone and arrived on scene several days later. We first visited the construction site on Wednesday, August 6, and found the manhole filled with water. The Ingersoll-Rand diesel generator was started shortly before noon to power the electric sump pump. An auxiliary gasoline-powered pump (a Honda Thrash

Pump with a 163 cm^3 engine 4-stroke engine) was also used and was situated approximately 10 feet away from the manhole. The manhole was almost completely drained by 4:00 pm, at which time real-time air monitoring was conducted using a Gastech GX-82; the instrument sensor was gradually lowered into the manhole using a long cable. CO concentrations over 999 ppm (the highest possible reading on this instrument) were measured at the surface of the water, 118 inches below the top of the manhole (see Table 1).

To verify the Gastech readings, air samples were collected in Tedlar bags with SKC 222 low flow (approximately 0.2 liters/minute) battery-powered air pumps. The air samples were analyzed by gas chromatography at the NIOSH Pittsburgh Research Laboratory. The analyses confirmed the presence of CO at a concentration of 1905 ppm just above the water at the bottom of the manhole (Table 2). No hydrogen sulfide was detected with Draeger colorimetric tube samples taken from the bags shortly after sampling, and this finding was consistent with the laboratory analysis results. It is possible that the bag samples correctly indicate that hydrogen sulfide was not present in the manhole. A fire chief with the hazardous materials unit reported that when he contacted the manufacturer of their direct-reading instrument after the incident, he was told that CO was an interfering gas for the hydrogen sulfide sensor and high CO levels could cause a false indication of hydrogen sulfide. Had hydrogen sulfide been present, however, it might have been lost from our samples by the time they were analyzed at the laboratory.

As determined by laboratory analysis, the sample for CO in exhaust emitted from the diesel generator showed 289 ppm. This finding was consistent with measurements taken with the Gastech GX-82 meter. An Ingersoll-Rand representative indicated that their tests showed that this engine could produce up to 1447 ppm CO.[1] Our results may have been lower due to atmospheric dilution. We were not able to place the sampling probe directly into the exhaust pipe due to heat, so our samples were taken in the exhaust stream about 2 inches from the exhaust pipe. Differences in engine tuning (the engine may have been running lean) may also affect emissions. Regardless, while the generator was operating, CO was not detectable (via real-time meter or laboratory analysis) around the vicinity of the manhole or between the manhole and the generator. There was a slight variable breeze (less than 0.5 miles per hour), reportedly similar to that on the day of the incident. The temperature was 80.0^{o}F and the relative humidity was 60.1%.

CO is essentially the same density as air (the ratio of CO density to that of air is 0.97)[2], and it is therefore unlikely that CO from the generator would have settled to the bottom of the manhole in a few hours and concentrated there. However, the NIOSH investigators tested the possibility that the CO source was the generator by stopping the generator and sump pump the evening of August 6 and allowing the manhole to fill with ground water overnight. On August 7, the sump pump was operated using electricity from a nearby residence, so no combustion engines were operated in the area. The water had drained again by the morning of August 8, at which time 472 ppm CO were measured at the bottom of the manhole (Table 1). During the late afternoon of August 8, the fire department ventilated the manhole with a 5,000 cubic feet per minute fan for approximately 20 minutes. Shortly after the ventilation was discontinued, CO concentrations in the manhole were again increasing (202 ppm a few minutes following the ventilation). These findings were convincing evidence that the CO source was something other than the diesel generator.

CO levels continued to decline over time. During the weekend of August 9-10, the manhole was again allowed to fill with water and was pumped out overnight on August 10-11. On August 11, the CO concentration measured at the bottom of the manhole was only 6 ppm (Table 2). However, carbon dioxide levels were still elevated, and oxygen levels were below normal. CO was not detected in the manhole on September 8 (Table 2).

V. Description of CO Toxicology

CO is a colorless, odorless, non-irritating gas produced as a byproduct of incomplete combustion of carbonaceous materials. These materials include petroleum products, coal, natural gas, wood, and plastics. CO can be produced at toxic levels by internal combustion engines, structural fires, industrial operations, and improperly vented heating or cooking appliances.[3]

The toxicity of CO results from the way it interferes with the body’s ability to transport oxygen using hemoglobin. Hemoglobin molecules are found in red blood cells and allow the red blood cells to transport oxygen. All cells throughout the body use oxygen and produce carbon dioxide as a waste product. As red blood cells flow through fine blood vessels in the lungs, oxygen from inhaled air diffuses into the red blood cells and binds to hemoglobin. Up to four molecules of oxygen bind to each molecule of hemoglobin. The red blood cells flow through blood vessels to the rest of the body, where the oxygen is released from the hemoglobin molecule and carbon dioxide binds in its place. When the red blood cells return to the lungs, they give up the carbon dioxide (which is exhaled) and take up oxygen again.[3]

Hemoglobin with CO bound to it is called carboxyhemoglobin. Because of its molecular structure, carbon monoxide binds to hemoglobin about 210 times more strongly than oxygen, and blocks oxygen from binding there. In addition, even if carbon monoxide binds to only one, two, or three of the four places on a hemoglobin molecule, it reduces the ability of oxygen to be released from the other sites. Therefore, in CO poisoning, red blood cells are less able to pick up oxygen for transport from the lungs to the rest of the body, and are also less able to release whatever oxygen they do pick up.[3]

The degree of CO poisoning is related to the percentage of body hemoglobin that is bound to CO (this is measured in a laboratory test as the percent carboxyhemoglobin, or % COHb). Because CO is produced in low amounts by the body's normal breakdown and replacement of red blood cells, people not exposed to external CO typically will have 0.3 to 0.7 % COHb and will have no symptoms. Cigarette smokers have elevated levels, although most are still below 9 % COHb. Symptoms appear and increase in severity with increasing percent carboxyhemoglobin, although not all affected persons show the same symptoms at the same percent carboxyhemoglobin. In general, the first symptoms include headache, fatigue, and lightheadedness. At higher carboxyhemoglobin levels, skin flushing, rapid heart rate, and lowered blood pressure occur. As carboxyhemoglobin rise, decreased attention span is followed by nausea, vomiting, impaired coordination, fainting, coma, convulsions, and finally death. Persons with existing coronary artery disease may experience chest pain and decreased exercise capacity. Table 3 lists approximate COHb levels and the symptoms with which they are associated.[3]

CO poisoning is treated by administering oxygen to the patient. If the patient is breathing normal room air, the time it takes half the CO to be released from hemoglobin and exhaled (known as the half-life of CO) is 4 to 6 hours. If the patient is breathing 100% oxygen, the half-life is reduced to 40 to 80 minutes. If the patient receives oxygen at higher pressures, in a hyperbaric chamber (where the air pressure is 2-3 times sea-level), the half-life is further reduced to 15 to 30 minutes.[4]

In general, patients recover well after treatment for CO poisoning. However, long-term effects have been reported in some patients whose poisoning had been so severe as to cause coma. These patients experienced problems such as memory or personality disturbances, or nervous system disorders affecting muscle control or sense of touch. Sometimes these symptoms did not appear until days or weeks after recovery from the acute poisoning.[3]

The NIOSH recommended exposure limit (REL) for CO is 35 parts per million (ppm) as an 8-hour time-weighted average (TWA). The NIOSH REL of 35 ppm is designed to protect workers from health effects associated with COHb levels in excess of 5%. Individuals with atherosclerotic narrowing of the coronary arteries may be affected by lower CO exposures.[3] NIOSH also recommends a ceiling limit of 200 ppm which should not be exceeded at any time during the workday.[2] The immediately dangerous to life and health (IDLH) concentration for CO is 1200 ppm.[2] The IDLH concentration is an exposure that is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment.

VI. Description of Explosives Used

The explosive used in the trench blast on August 4, 1997, was a nitroglycerin-based high explosive manufactured by Union Espanola de Explosivos, S.A., Madrid, Spain under the trade name Goma 2E-C. The explosive is imported into North America by ETI Explosives, North Bay, Ontario, Canada. Goma 2E-C is well suited for the wetness and hard rock found at the blast site. The manufacturer's data sheet for Goma 2E-C indicated it was a Fume Class 1-equivalent explosive. This classification refers to the industry standard promulgated by the Institute of Makers of Explosives (IME). According to this classification, Goma 2E-C is formulated to produce less than 0.16 cubic feet (4.5 liters) of CO per 1-1/4 inch diameter by 8 inch long cartridge. IME Fumes Class 1 explosives produce less CO than all the other classes.

According to the blast monitoring report, 265 pounds of Goma in 2 inch by 16 inch cartridges were used in the trench blast on August 4, 1997. Two chamber tests conducted by the NIOSH Pittsburgh Research Laboratory showed that Goma from the same lot number produced between 27.0 - 28.7 liters CO per kilogram detonated.[5] These findings were consistent with data provided by the explosives manufacturer. Based on the value of 27.0 liters per kilogram, the August 4, 1997 trench blast would have produced about 3250 liters (114.8 cubic feet) of CO. Less than 10 liters of CO from the blast would have been needed to produce a concentration >2000 ppm in the manhole.

VII. Discussion and Conclusions

We hypothesize that the August 4 explosive blast at 3:40 pm resulted in elevated levels of CO in the surrounding earth; this CO migrated into the manhole and resulted in the exposures to the construction workers and rescuer. Although some products of detonation would have been released to the atmosphere, some of the gas would have been trapped in voids in the sandy clay soil and fractures in the rock created by the explosion. Furthermore, the rock and soil between manhole A18 and the trench blast had been previously fractured and loosened by blasts 1-2 weeks earlier. Given that the explosives were detonated as close as 40 feet from the manhole, it is probable that the high pressure of the explosion forced the detonation gases through the loosened soil and fractures in the underlaying rock. The manhole openings had not been sealed, and water and gases could readily enter the manhole from the surrounding earth. About 140 gallons per minute of water was continuously being pumped from the manhole; a water-related transport mechanism for CO has been suggested, but cannot be proven at this time.

The possibility of sources for the CO other than blasting are unlikely for several reasons. First, the chronology of the events that day strongly suggests a blasting-related source. Extensive work had been done at this site before the August 4 surface blast, starting about a week prior to the fatality. There were no reports of symptoms suggesting CO poisoning among the construction workers involved in this prior work.

On August 4, the crew worked in the hole without difficulty as late as 1:30 pm. The nearby surface blast took place at about 3:40 pm. The workers next entered the manhole at 4:30 pm and were exposed to CO. . This chronology suggests that CO was not present as late as 1:30 pm on August 4. A below-ground source, if it existed, most likely would have produced CO in a more constant fashion.

Second, the highest level of CO we recorded in the manhole was 1905 ppm, measured 2 days after the fatality. Given that measurements on successive days progressively declined to near zero, extrapolation suggests that the CO level on the day of the fatality was even higher. Although soil microbial processes can produce CO,[6] the amounts produced could not account for the concentrations found in the manhole. It has been speculated that an underground source of combustion might result in diffusion of CO to the manhole; this has been suggested as a source of CO exposure in homes above abandoned coal mines where uncontrolled fires burn.[7] In the case of the present incident, however, it is unlikely that such underground combustion could occur in the presence of the high water table in the area. This water table is so high that overnight the manhole fills to within a foot of the surface unless pumping is maintained. Additionally, coal deposits are not present in this area of the country, and no evidence of underground combustion sources has been identified.

Finally, above-ground sources of the CO contamination are unlikely. CO would not be expected to travel 22 feet from the diesel generator to the manhole and sink and concentrate at the bottom of the manhole in a few hours.

Our literature review did not find reports of similar events involving CO migration into manholes following blasting. Other reports, however, describe cases of CO poisoning following CO migration through soil from other sources. A British report from World War I described a technique used in trench warfare in France, wherein a tunnel was dug forward under “no man’s land” and explosives were detonated in the tunnel to cause a surface collapse that formed a surface crater. Troops could then advance from the British lines and take cover in the newly formed crater. However, CO from the loosened soil sometimes accumulated in the crater, and in such cases soldiers were frequently overcome.[8] A later report described a case in which CO escaped from a gas line, migrated through soil, and followed an electrical duct to accumulate in a night watchman’s kiosk; one watchman died and another was overcome the next evening before the CO exposure was recognized.[9] Migration through soil of other gases, such as radon and carbon dioxide, has been described in a variety of circumstances.[10,11]

In addition, we are aware of five incidents in which CO found in residences was thought to have migrated through soil from explosive blasting used in nearby construction projects. In 1988, two Pennsylvania teenagers became CO-intoxicated in the basement of a home; local officials concluded that the CO source was explosives used in a construction project across the street.[12,13] In Maryland, CO that migrated from blasting operations next door to residences was also the reported cause of CO found in basements in 1993 and 1994.[14] A Pennsylvania couple was treated for CO intoxication in 1995 after blasting was conducted near their home. [15] Most recently, the Environmental Protection Agency (EPA) investigated a highway trench blasting operation in Pennsylvania, where CO was thought to have migrated into a residential basement. The presence of permeable soil, along with a French drain and abandoned water pipe around the homes, may have served as a facilitating pathway for CO to travel into the homes.[16]

The hazards of gases produced by explosives are well understood in underground applications such as mining and tunneling. However, the hazards of subterranean migration of these gases in surface applications are apparently not well recognized. In surface applications, the blaster's primary concerns are controlling flying debris and ensuring that all the explosives have detonated. Although surface blasters appear to understand that the explosives they use generate toxic gases, they are generally not familiar with hazards associated with underground gas migration. Although the material safety data sheet provided with Goma 2EC discusses nitrogen oxide products of detonation, no mention is made of CO.

The fatality and near-fatalities in this incident occurred in a manhole, a confined space. A confined space can be broadly defined as a space which, by design, has limited openings for entry and exit, unfavorable natural ventilation which could contain or produce dangerous air contaminants, and is not intended for continuous employee occupancy. As in other confined space fatalities, the two major factors that led to the death and hospitalizations in this incident were the failure to recognize and control the hazards associated with confined spaces, and inadequate or incorrect emergency responses. Despite the novel source of the CO, incidents of this type can be prevented by following standard precautions for entering confined spaces. All manholes should be considered confined spaces with potentially hazardous atmospheres, and appropriate air monitoring should be conducted before entering. In particular, air monitoring should be conducted prior to each entry into a manhole. Even if appropriate monitoring had been conducted earlier in the day, the fatality might have still occurred if the manhole had not been monitored for CO subsequent to the blasting.

This incident involved a "chain reaction" death, a well-known danger associated with confined space rescues. "Chain reaction" deaths are so named because after the first victim is found in a confined space, a rescuer enters without proper precautions and is overcome, a subsequent rescuer enters and is likewise overcome, and so on. This occurs because would-be rescuers act on their instinctive concern for the victim and their desire to rescue the victim quickly. Unfortunately, these would-be rescuers fail to recognize the need for appropriate precautions and so become additional casualties. "Chain reaction" deaths are all too common; in a review of NIOSH investigations of confined space fatalities, rescuers accounted for 36% of the deaths. In addition, national surveillance of occupational fatalities indicated that 23% of confined space deaths were multiple-victim incidents.[17] In the present incident, one rescuing worker died in a "chain reaction," another was overcome, and a fire fighter was spared only because he was immediately ordered out of the manhole after he had entered without personal protective equipment.

"Chain reaction" deaths can be prevented in several ways. First, and most importantly, workers should be trained to recognize what constitutes a confined space and the hazards that may be encountered in them. This knowledge will prevent a worker becoming the initial victim. If a victim must be rescued from a confined space, entering rescuers must use appropriate precautions which include the use of air monitoring, supplied air or self-contained breathing apparatus, lifelines or rescue harnesses, and protective clothing. Rescuers should have prior training and practice in confined space assessment and rescue operations.

Although the carboxyhemoglobin levels reported in the medical records are less than those typically associated with unconsciousness and death (Table 3), these measurements were made on blood samples taken after the workers had been treated by emergency crews with oxygen. Because the half life of carboxyhemoglobin is considerably reduced by oxygen therapy, it is likely that the workers' carboxyhemoglobin levels were higher at the time of their exposure and rescue.

VIII. Recommendations

1. The city and its contractors should ensure that proper confined space training and proper procedures are utilized before entry into any confined space. Guidance on confined space entry can be found in Appendix A of this report. Confined space training for all rescuers, including fire fighters and commanders, should be a routine component of training provided by the employer. Confined space rescue training is available from several providers, including courses specifically offered for fire fighters at no cost to the employer.

2. Procedures should be used by blasting contractors, in collaboration with other contractors working in the job area, to reduce the possibility of exposure to employees and surrounding residents. The blasting industry should develop materials to educate blasters about the possibility of CO exposures associated with surface blasting and precautions that can be taken to minimize CO exposures. Training should include discussions on the possibility of CO migration through soil. All workers and managers working on construction sites involving surface blasting should be trained to recognize the possibility of CO exposures associated with blasting. The material safety data sheets provided

with explosives used in surface blasting should indicate when CO is among the likely hazardous gases produced by detonation.

3. Although the explosive blasting is the most likely source of the CO in the manhole, an environmental evaluation should be considered to rule out other speculated underground CO sources.

4. Factors affecting the migration of explosive generated gases underground should be better understood. Although the explosives were the most logical source of CO in this incident, practically nothing is known about underground transport mechanisms. This prevents NIOSH from making specific recommendations about the distance gases from blasts can travel underground. Research could determine the extent geologic conditions influence the migration of explosive generated gases.

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Table 1. CO levels measured in manhole. All measurements were obtained with a Gastech GX-82 monitor.

Location	August 6, 1997	August 8, 1997	August 11, 1997
Surface	0	77	0
45 inches depth	15	72	0
85 inches depth	42	130	2
118 inches depth	>999	472	6

[a]Measurement exceeded the instrument's maximum reading (999 ppm).

Table 2. Results of laboratory analyses of gas samples collected from the bottom of the manhole. All values are in parts per million (ppm)

Component	8/6/97[a]	8/8/97[b]	8/11/97[c]	9/8/97[d]
Hydrogen	393	ND[e]	ND	ND
Carbon Dioxide	29,710	28,960	29,560	6,276
Nitrogen	763,500	765,600	763,500	778,700
Argon	9,124	9,150	9,125	9,306
Oxygen	195,000	195,700	197,700	205,700
CO	1,905	381	7	ND
Methane	427	167	63	36
Ethane	28	7	ND	ND
Ethylene	30	6	ND	ND
Propane	2	ND	ND	ND

[a] Additional substances analyzed but not detected included acetylene, 1-butane, *n*-butane, propylene, 2-pentane, propylene, *i*-pentane, *n*-pentane, and nitrous oxide.
[b] Average of results from two bag samples.
[c] Results of one of three samples taken. The two other samples were voided due to possible atmospheric contamination.
[d] Results from one bag sample. Sample analyzed in duplicate.
[e] ND = non-detected. The detection limit for carbon monoxide was 3 ppm.

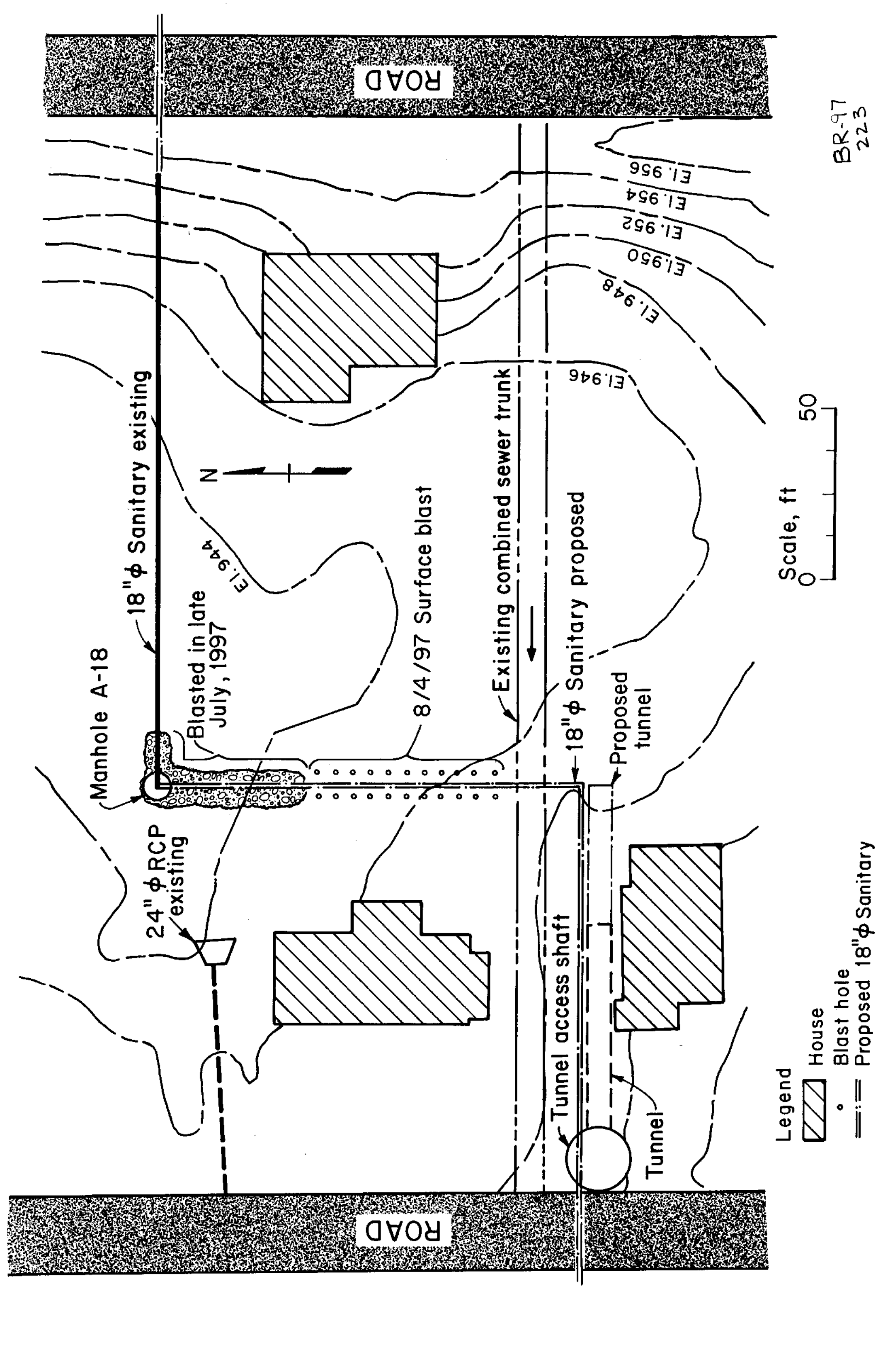
Analytical Method:

The samples were analyzed by gas chromatography using thermal conductivity and flame ionization detectors. Specifically, Hewlett Packard 5880 and 5890 gas chromatographs, each equipped with flame ionization and thermal conductivity detectors, were used in conjunction with an auxilliary column oven. The analysis requires the simultaneous use of three columns and four detectors, as explained below.

Two sample loops are located on separate gas sampling valves. Upon injection, the contents of one loop are introduced into a Porasil B column linked to a flame ionization detector for the separation and quantification of C1 - C5 hydrocarbons. The sample in the second loop is introduced onto a Porapak N column, where a composite peak consisting of hydrogen, oxygen, nitrogen, methane, and carbon monoxide is separated from carbon dioxide, nitrous oxide, C2 hydrocarbons and hydrogen sulfide. The composite peak exiting the Porapak column is diverted into a molecular sieve 5A column for separation into its components; the balance of the Porapak analytes are quantified by thermal conductivity detection. Components eluting from the mole sieve column are first quantified by thermal conductivity detector before passing through a nickel catalyst where hydrogen is introduced to reduce carbon monoxide to methane. Both the methane separated from the original sample and the carbon monoxide-generated methane are analyzed by a flame ionization detector linked in series with the converter.

Table 3. Carboxyhemoglobin levels and associated medical symptoms.[3]

Blood Saturation COHb (%)	Symptoms
0.3 - 0.7	Normal range, no symptoms
2 - 5	Reduced exercise tolerance in patients with coronary artery disease
5 - 10	Laboratory findings suggest possible (and reversible) neurologic effects
10 - 20	Slight headache, fatigue, lightheadedness
20 - 30	Moderate headache, nausea, flushing, rapid heart rate, impaired fine manual dexterity
30 - 40	Severe headache, nausea, vomiting, low blood pressure, difficulty walking
40 - 50	Fainting
50 - 65	Coma, convulsions
Over 65 - 70	Fatal if not treated


ROAD
ROAD
Manhole A-18
18"ϕ Sanitary existing
Blasted in late July, 1997
8/4/97 Surface blast
Existing combined sewer trunk
18"ϕ Sanitary proposed
Proposed tunnel
24"ϕ RCP existing
Tunnel access shaft
Tunnel
N
El. 944
El. 946
El. 948
El. 950
El. 952
El. 954
El. 956
Scale, ft
0
50
Legend
House
Blast hole
Proposed 18"ϕ Sanitary
BR-97
223

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Appendix A: ELEMENTS OF A CONFINED-SPACE PROGRAM

The worker who is required to enter and work in a confined space may he exposed to a number of hazards, ranging from an oxygen-deficient or toxic atmosphere, to the release of hazardous energy (electrical mechanical/hydraulic/chemical). Therefore, it is essential for employers to develop and implement a comprehensive, written confined-space-entry program The following elements are recommended as a guide in developing a confined-space program.
A confined-space-entry program should include, but not be limited to, the following:

- identification of all confined spaces at the facility/operation
- posting a warning sign at the entrance of all confined spaces
- evaluation of hazards associated with each type of confined space
- a job safety analysis for each task to he performed in the confined space
- confined-space-entry procedures
    - initial plan for entry
    - assigned standby person(s)
    - communications between workers inside and standby
    - rescue procedures
    - specified work procedures within the confined space
- evaluation to determine if entry is necessary—can the work he performed from the outside of the confined space
- issuance of a confined-space-entry permit—this is an authorization and approval in writing that specifies the location and type of work to be done, and certifies that the space has been evaluated and tested by a qualified person and that all necessary protective measures have been taken to ensure the safety of the worker
- testing and monitoring the air quality in the confined space to ensure that
    - oxygen level is at least 19.5% by volume
    - flammable range is less than 10% of the LFL (lower flammable limit)
    - absence of all toxic air contaminants
- confined-space preparation
    - isolation/lockout/tagout
    - purging and ventilation
    - cleaning processes
    - requirements for special equipment and tools
- safety equipment and protective clothing to be used for confined-space entry
    - head protection
    - hearing protection
    - hand protection
    - foot protection
    - body protection
    - respiratory protection
    - safety belts

  - lifelines, harness
  - mechanical-lift device—tripod

- training of workers and supervisors in the selection and use of
  - safe entry procedures
  - respiratory protection
  - lifelines and retrieval systems
  - protective clothing
- training of employees in confined-space-rescue procedures
- conducting safety meetings to discuss confined-space safety
- availability and use of proper ventilation equipment
- monitoring the air quality while workers are in the space.

The NIOSH criteria document, Working in Confined Spaces,[1] was developed to provide the user a means for significantly reducing worker injury and death, associated with entering, working in, and exiting confined spaces. This document will provide more detailed information in developing a comprehensive confined-space-entry program. Additional information on confined-space safety is available from other NIOSH publications and journal articles.[2-9]

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