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Engineering evidence for carbon monoxide toxicity cases

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Abstract

Unintentional carbon monoxide poisonings and fatalities lead to many toxicity cases. Given the unusual physical properties of carbon monoxide—in that the gas is odorless and invisible—unorganized and erroneous methods in obtaining engineering evidence as required during the discovery process often occurs. Such evidence gathering spans domains that include building construction, appliance installation, industrial hygiene, mechanical engineering, combustion and physics. In this paper, we attempt to place a systematic framework that is relevant to key aspects in engineering evidence gathering for unintentional carbon monoxide poisoning cases. Such a framework aims to increase awareness of this process and relevant issues to help guide legal counsel and expert witnesses.

Keywords

Expert witness, law, toxicology

Introduction

When Bogart found Hepburn trying to commit suicide via exhaust gas in the 1954 movie *Sabrina*, awareness of carbon monoxide (CO) poisoning dangers were still at their infancy. During the same year, a correspondence letter sent by Mr J. Hynes published in the British Medical Journal stated[1] "I am wondering how many non-fatal CO poisoning are occurring…the practice of heating bedroom by means of portable paraffin heaters is common…the gas cooker may also be a source of slow poison to the unsuspecting housewife".

After many years of advanced medical insight, sensor technology advances, product design optimization and many years of social awareness, it is estimated that the total number of Emergency Department visits for CO poisoning is at a staggering 50,000/year in the USA.[2] Moreover, CO is the leading cause of poisoning deaths in the USA. Most patients with CO poisoning who receive maximal hospital emergency care survive, although they may suffer long-term neurological effects. However, on a positive note, policy has helped reduce intentional and unintentional CO deaths over the past 30 years. Low-cost CO detectors have become ubiquitous thanks to legislation mandating their compulsory use. In California for instance, the Senate Bill 183, Chapter 19 now mandates CO detector requirements for all existing single-family dwellings, all existing dwellings and multi-family buildings such as apartment buildings. Such policies will have a profound effect on reducing CO injuries. Take the national vehicle emissions policies and practices set by the 1970 Clean Air Act as an example. Following the introduction of the automobile catalytic converters in 1975, CO emissions from automobiles decreased by an estimated 76.3% of 1975 levels and unintentional motor vehicle-related CO death rates declined from 4.0 to 0.9 deaths per 1 million person-years. Rates of motor vehicle-related CO suicides declined from 10.0 to 4.9 deaths per 1 million person-years.

But more can be done. Take, for example, the common household CO detectors than can be purchased for less than US$15 each. Such a product can be further enhanced to save even more lives. With a few dollars extra, a relay switch can be integrated to these detectors to function as an interlock device that could disable any form of combustion appliance when ambient CO levels are too high. Such functionality can further be used in automobiles, to switch off the engine when a suicide attempt is taking place or switch off a water furnace when

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back drafting is occurring. Appliance manufacturers are aware of such capability, but for whatever reason, consciously disregarded the rights and safety of the general public when designing appliances.[3] Like most societal challenges, however, policy lags behind technology progress. But no matter the lag time, poorly designed products, sloppy construction and dangerous appliance installation continue to prevail, burdening society with CO poisoning incidents that at times results in subsequent legal action.

Lawsuits related to CO poisoning and toxicity cases can be traced back to the 1920s where CO exposure was rampant in coal mining due to use powder or dynamite explosions in blowing down coal.[4] Such lawsuits usually fall under the umbrella of negligence, personal injury, product defect and liability. Individuals poisoned usually file suits on those thought to be responsible or parties liable such as manufacturers of furnaces, maintenance and equipment/appliance installers, builders and contractors, property management and landlords.

Given the unusual physical properties of CO, in that the gas is odorless and invisible, it seems to cause baffling and unorganized methods in obtaining hard physical evidence for such cases. Furthermore, aspects of evidence gathering spans domains such as building construction, Heating, Ventilation and Air Conditioning Systems (HVAC), appliance installation, industrial hygiene, mechanical engineering, combustion and physics—in which such a discipline is not methodologically taught nor simultaneously practiced. Given these anomalies, we attempt to place a systematic framework that is relevant to key aspects in engineering evidence gathering for unintentional CO poisoning cases. In doing so, the focus turns toward two primary aspects that are most likely to be the center of a legal CO poisoning case. These two areas include (1) causation, exposure to CO and (2) evidence to quantify CO concentration in an amount sufficient to cause injury, particularly from low-level chronic CO exposure where non-fatal injuries have occurred and a victim's lifestyle has been degraded.

Carbon monoxide site inspection

From an engineering perspective, it is of upmost importance to begin the investigation by identifying and verifying the culprit production source of carbon monoxide. In a household environment, emissions from natural gas or propane-burning appliances are the most common suspects. Secondary sources are also problematic, such as exhaust from a neighbor's gasoline generator, an automobile idling within an attached garage, or flue gas entering from an adjacent apartment. In any case, one must first visually identify all combustion sources, locate these and begin to systematically examine likely CO air diffusion and mechanically propelled paths to the occupied space. It should be noted here that all appliance-related data for fossil fuel-burning appliances likely to have caused poisoning should be obtained. Key information such as compliance with mandatory CO product warning labeling, such as 16 CFR Part 1407 *Portable Generators Labeling Requirements*, and any state EPA exhaust certification should be verified.

Most times, CO causation can be visually identified due to obvious tell-tale signs such as cracked flue vents or physical soot formation and deposits. But more often than not, more investigation is required to identify misdirected exhaust or natural air diffusion that transports contaminants into the occupant space. For instance, typical causation and failure modes may include a poorly installed furnace creating backdrafting, obstructed or misdirected flue ventilation or a cracked furnace exchanger. In such cases, defining and quantifying air paths from source to occupant requires (1) verification and (2) quantification.

Carbon monoxide measurements

Carbon monoxide field measurements become pivotal in non-fatal and chronic CO exposure cases, where victims suffer neurological effects where normal day-to-day living can become severely degraded. In such cases, quantifying CO exposure, such as where, when and how, becomes crucial in evidence gathering. In cases where a fatality is concerned, and it is evident that acute CO exposure has taken place, causation and failure modes can be identified and death confirmed via high carboxyhemoglobin levels (COHb) readings; unless challenged or foul play has occurred, field measurements and event reconstruction may not be warranted.

An expert that follows ASHRAE and best practices test protocols, as depicted in Hanzlick[5], should be engaged to undertake such measurements. Field measurements fall into two categories. The first order of business in field measurement analysis is the need to quantify contaminant emission levels coming from the contamination source. Contaminant measurement of flue gas requires combustion gas analysis to derive the CO ‘‘air-free’’ value, otherwise known as ‘‘source concentration’’. This approach does not quantify the inhaled ‘‘ambient’’ concentration level, but provides a key data point to determine appliance failure identification (causation) and key parameter input to determine ambient CO levels and exposure levels via modeling. As a guideline to determine problematic sources, Table 1 highlights the maximum allowable CO air-free carbon monoxide emissions from various appliances.

It should be emphasized these CO limits are not ‘‘ambient air’’ levels but CO threshold levels related to emission, and are best thought of as ‘‘red flag’’ warning signs. If an appliance falls below these limits toxicity and poisoning could still occur, particularly if the CO gas is leaking in a confined space. To

Table 1. Maximum allowable CO air-free carbon monoxide emissions from various appliances.

Reference	Appliance type(s)	CO limit
ANSI Z21.1	Household gas cookers	800 ppm
ANSI Z21.10.1	Storage water heaters (<75000 BTU)	400 ppm
ANSI Z21.11.2	Un-vented room heaters	200 ppm
ANSI Z21.13	Low-pressure steam and hot water boilers	400 ppm
ANSI Z21.47	Gas-fired central heating furnaces	400 ppm
ANSI Z21.60	Decorative gas appliances for installation in solid fuel-burning fireplaces	400 ppm

highlight this distinction, let us take an example. Let us assume CO air-free field measurements are recorded at 50 ppm. This is emitted from a 40,000 BTU/hr furnace. Due to poor flue plumbing, the furnace disperses combustion exhaust within a tight (air changes per hour (ACH) < 0.4) and small indoor environment (1300ft^3). Under these circumstances, ambient CO levels can reach beyond 25 ppm, becoming dangerous particularly after prolonged exposure periods. If the same appliance was emitting 200 ppm CO air-free, then CO levels would be over 130 ppm, a dangerous situation indeed. This simple example demonstrates that even if a fossil fuel-burning appliance is operating within the ANSI emission limits, misdirected combustion coming from a "normally operating" appliance to a breathing zone can create a situation where poisoning would be imminent even if a household CO detector is not triggered.

Once the problematic CO source is verified and quantified, two options then exist. The first option is to proceed in obtaining "ambient" CO measurements. Obtaining ambient field measurements of CO concentrations is more complex than analyzing air-free exhaust gas due to the non-restrictive air dynamics one finds in an environment such as a home. Walking with a CO meter in hand is unacceptable. The act of walking with the monitor creates microplumes that distort CO data readings, which would be a point of contention. Another common oversight is the detector's response time. A detector requires a minimum time to reach the maximum detectable ambient level, which is typically in the order of about 60 s. Engineering protocols exist that accurately determine a time series of rapidly time-varying concentrations, such as for locations close to an active point source or near moving traffic. Response time for ambient home measurement, for instance, is an important consideration, as taking CO ambient measurements by walking from room to room will not allow the CO detector sufficient time to reach stable levels.[6] Unlike air-free measurements that may take 15 min or so, ambient CO testing may require several hours to correctly capture stable, repeatable and representative ambient concentrations of the polluted environment under different scenarios. Ambient measurements should be taken with at least two independent CO meters having better than 1 ppm of CO measurement resolution with minimum detection limits of at least 3 ppm. Before the day's testing, all detectors should be calibrated to NIST-certified gas bottles following manufacturer instructions. Evidence of correct and accurate test equipment is essential. If multiple tests are undertaken in the same day, ensure to calibrate at least once per day. All calibration data should be saved and documented, since accurate detection is often a contested issue during the discovery process. Furthermore, CO meters should be sitting on stands and placed at a height most representative of the occupant's breathing height. Most CO poisonings occur at home while victims are asleep,[7] which indicates the bedroom is often acting as a gas chamber. This has been the case even with very early accounts of domestic CO poisonings, dating as far back as 1885.[8] Other gas chamber-like spaces include home offices and small apartments, where occupants are sedentary for long periods of time, allowing carboxyhemoglobin levels to accumulate. In such cases, testing protocols should be adjusted to mimic occupant inhalation characteristics. For sleeping situations such as ambient CO measurement in a bedroom, CO meters should be located at bed height close to the pillow area (Figure 1). Notation of distance from any ventilation point sources is extremely important to deduce if proximity effects are at play (to be discussed later). Before datalogging occurs, ensure that all doors, windows, vents and HVAC settings are set at the most typical that occurred during CO exposure. Altering one variable at a time would be necessary to deduce the effect on the ambient CO concentration (Figure 2). For instance, this may be during the sleep period where a bath door is open, a bedroom door is

Figure 1. Measurements taken with CO detectors placed on a pillow to mimic exposure while the occupant is sleeping. To increase accuracy, two CO monitors per location is recommended.

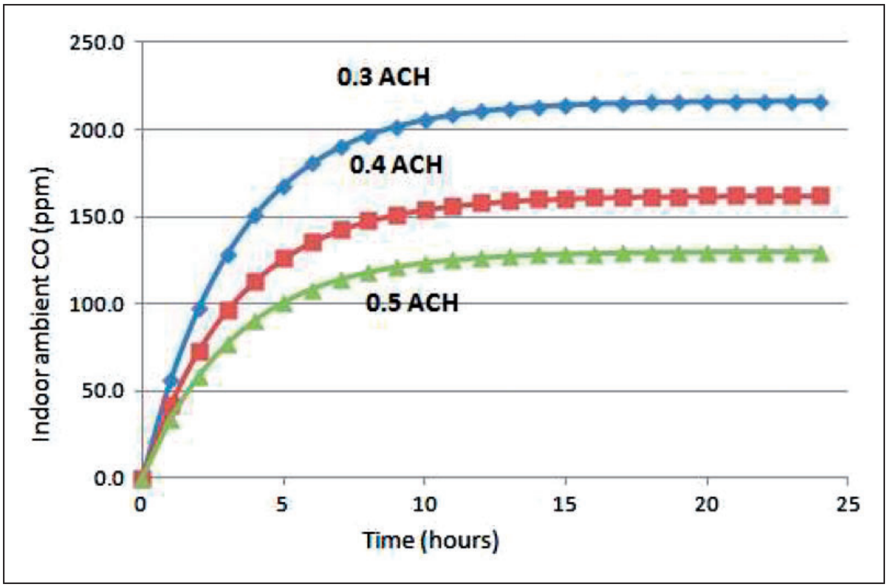

Figure 2. Mass-balance modeling of a polluted indoor room with ambient CO concentration increasing over a 24-hour period.

closed, windows are closed and the HVAC system in ON, and so on. Interviewing the victims to assess occupant behavior, indoor settings, HVAC settings, and sleeping and movement patterns is an important step to ensure that test protocols mimic those most experienced by the victim. When reporting results, it is important to consider the detector's accuracy specifications, and in doing so, error bars should be used to represent data points as appropriate.

Carbon monoxide modeling

Ambient field measurements are valuable, but often not possible due to change of appliance or venting that has rectified the CO source or leakage problem. On the contrary, CO contamination may still persist but concentration levels may be too high or too dangerous for testing. If so, one would need to "reconstruct" the ambient CO concentration using modeling methods where variables such as volume, ACH and time can be varied to better understand the contaminated environment. The modeling task requires some key data points to be obtained in order to avoid a "junk-in junk-out" problem. Variables such as contaminant volume (ft^3), CO source concentration (ppm) and appliance rating (BTU/hr) are the minimum set of variables required to determine first approximation ambient concentrations. ACH estimates based on home construction, ASHRAE recommendations and adjustment for home age is also necessary. For example, studies have shown that as a home ages, joints and seals degrade, leading to a increasing ACH. Some studies have shown this degradation to be between 0.04 to 0.07 ACH/year.[9,10] If resources and time permit, a blower door test can be undertaken to obtain the home's ACH value; if not, a range of ACH values can be used during the modeling exercise. If the home is large (>2000 sq ft) and being serviced by multiple air handler/HVAC systems, it is recommended that the home be compartmentalized in multiple zones where ACH values are independently obtained for each zone. Such procedures will enable more accurate ACH determination for more accurate modeling. Other key aspects for modeling include defining HVAC air flow volumes, air flow vents and register locations, and defining contaminant leakage paths. Anemometer measurements, air capture hoods and visual inspection to define these variables may be required. Notation and mapping of vents and return registers and all HVAC specifications will be necessary for the modeling effort, particularly if contamination is not isolated within one zone and the HVAC air flow encourages contaminant mixing. Furthermore, location and distance of point sources from vents to occupant breathing zone should be noted to determine the extent of the proximity effect.

The proximity effects are often ignored in CO poisoning cases. It has been well documented that personal exposure to air pollutants can be substantially higher in close proximity to an active source due to non-instantaneous mixing of emissions.[11,12] This phenomenon is known today as the proximity effect,[13] and was even evidenced in the 1970s when some of the early CO exposure experiments using cigarettes were being undertaken.[14] Mass-balance contaminant modeling software does not take such important phenomena into consideration, hence leading to errors. In addition, most CO monitors and analyzers are not able to capture such phenomena due to the time-average algorithms used,[6] since the microplume concentration changes are in the timescale of seconds. The concept of the proximity effect is analogous to a smoker (point source); when smoke exhalation occurs, a jet stream made up of expanding turbulent microplumes is generated. With time, the air dynamics and plume activity subsides, allowing the smoke particles to evenly diffuse throughout a confined space. From this example it is clear that as a cigarette smoker exhales, the smoke concentration is at a maximum at the point source and at close vicinity to the smoker. This is a classic example of non-instantaneous mixing. Only when smoking has stopped and time has passed does the room homogenously fill with smoke. It has been well documented that the proximity effect under-predicts exposure by as much as 20 times compared with mass-balance approaches,[15] hence the importance of taking the proximity effect in consideration when modeling.[13,15]

Carbon monoxide detector compliance

Beyond source and ambient CO measurements and modeling efforts, questions regarding the operability of the CO detectors are often raised. In such cases, CO laboratory measurements can verify correct operation and compliance with UL2034 *Single and Multiple Station Carbon Monoxide Alarms*. CO detectors employ electrochemical sensors to detect CO molecules. These sensors are known to have reliability challenges, but due to their low cost, have become ubiquitous in household CO detectors. Even more expensive optical CO sensors, that are thought of as superior alternatives among sensor technologists, have experienced product reliability problems.[16] In one sensor evaluation study,[17] the performance of different CO detector brands was found to be very variable; non-compliance with UL 2034 for sensitivity to CO was reported to be 47% in the worst six brands (at 50% relative humidity), compared with 0% in the top three brands; the combined failure rate was 25%. In addition, false alarms in the worst brands were reported in 8%, and alarming with interference gas in 30%. Failure rate at low humidity (5% relative humidity), in the worst six brands, was found to be even higher, at 79%. If it is deemed that CO detector alarm and sensor verification of compliance is required, then CO detectors should be tested using NIST-certified CO calibration gas with controlled gas flows using a small-volume gas chamber (<4 liters). Environmental variables such as temperature and humidity should be controlled and kept constant during testing. Test protocols that alter temperature and humidity should be undertaken, as well as testing to conditions that best mimic the living environments of the client.

Carbon monoxide detector placement

Beyond CO detector reliability and operability, the placement location of a CO detector can affect alarming reliability and may be a focal point during the discovery process. If the CO detector is placed a far distance from an air vent, then CO transport and natural diffusion may take more time. One interesting study showed that a difference of 8 feet in CO measurement points can result in a CO detector taking an extra 100 minutes to register high enough levels to alarm.[18] In a more extreme case, microturbulence air pockets (dead space) may occur in an indoor environment via furniture placement, roof design or other obstacles that may create air pockets, such that CO-contaminated air is not detected. In any case, the placement location of a CO detector is paramount, and verification and documentation is required along with analysis to verify compliance with the CO detector instruction manual and with National Fire Protection Association NFPA 101 or NFPA 720 *Standard for the Installation of Carbon Monoxide Detection and Warning Equipment*.

Conclusions

The progress of low-cost sensor technology allows for CO detectors to be placed ubiquitously in household and occupational spaces. Similarly, at a small cost, CO sensors can be integrated into nearly all fossil fuel-burning appliances to provide adequate alarming or even shut-off capability that would drastically save lives and reduce injuries from unintentional CO poisoning. Until such ubiquitous use of sensor technology and design occurs and/or is mandated by policy, our society will continue to be burdened with CO-related poisoning cases. Dealing with these cases via the legal system, from an engineering evidence gathering viewpoint, requires a multidisciplinary approach. Both hard (field measurements) and soft methods (modeling) have evolved that allow reconstruction of contamination exposure incidents, providing invaluable insight and evidence for CO poisoning and toxicity cases.

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