An Analysis of Methods to Measure

Carbon Monoxide in Residential

Construction

by

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ABSTRACT

To understand how propane combustion affected the indoor air quality of a construction site, various industrial hygiene sampling techniques were used to measure the level of carbon monoxide (CO) present. The levels of CO produced by two different heating sources on two separate days were compared to the OSHA construction industry Permissible Exposure Limit (PEL) of 50 ppm. The CO values collected for a natural-gas-fired, forced-air furnace and a propane-fueled, direct-fired heater were well below the statutory time weighted average (TWA) of 50 ppm.

CO presents a non-apparent hazard in residential construction. Because the toxic gas is odorless and colorless, it is imperative that instrumentation be used to assess its presence. Within this study, a CO sampling methodology successfully quantified a CO risk, and simultaneously vetted the usefulness of five types CO sampling technology. Of the five instruments used to measure CO, two returned easily discernable data that are

recommended for use by residential contractors. The values were collected during the 06/07 winter construction season in Minnesota in a single family home under construction.

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Chapter One: Introduction

Construction poses a variety of hazards to workers and the public, each of which has a distinct level of risk. Some of these hazards are easily identifiable including: cave-in hazards stemming from open trenches; fall hazards from roofs or ladders; and electrical hazards associated with damaged cords or bad cord ends. On the other hand, the hazard of carbon monoxide (CO) overexposure from propane area heaters falls into a category of hazards that may not be readily measurable by traditional and simple hazard assessment techniques. This is largely due to the fact that CO is an odorless, colorless gas that requires detection via specialized equipment.

To understand how propane combustion contributes to indoor air quality on construction sites, two things are required: 1) the application of industrial hygiene sampling techniques to measure the level of CO, and 2) an appropriate exposure standard such as the OSHA Permissible Exposure Limit (PEL). CO exposure stemming from temporary area heating devices on a construction site is a good candidate for assessment and control because area heating may be necessary for three or more months in winter construction seasons. During winter construction, as air temperatures fall below freezing (32° F, 0° C), there must be some form of protection along foundation footings on the interior of a structure to prevent frost heaving; this is generally done by providing temporary heat. Furthermore, as winter construction progresses, steady streams of trade people are exposed to basement area heating environments. A list of the trades likely exposed includes, among others: carpenters, masons, plumbers, HVAC installers, electricians, insulators, and sheet rockers and tapers.

Statement of Problem

Beyond poorly understood statutory requirements, there is little guidance from both government agencies and the construction industry on how to measure and assess CO exposures on a jobsite.

Purpose of Study

This study will apply three readily accessible technologies: CO monitors, detector tubes, and electronic gas detector's to assess CO generated by temporary heaters and then compare those values to CO statutory requirements and professional CO guidelines. The CO samples will be collected within a single family home under construction during the 06/07 winter season in Minnesota.

Goals of the Study

This study will apply a select set of industrial hygiene sampling techniques to:

1. Continuously monitor CO over 8 hours.
2. Collect CO area exposure data logging using three gas meters capable of providing continuous readings, peak values and TWA values.
3. Supplement CO data logging with periodic CO colorimetric tube samples.
4. Measure approximate air exchange values in the sampling setting using an anemometer.
5. Make recommendations regarding the efficacy and usability of the various methods for residential contractors.

Background and Significance

There are a significant number of construction hazards that are difficult to recognize, and/or to measure. Examples include: off-gassing from organic materials in trenches; silica dust present during the mixing of mortar; and solvent vapor present during the sealing of hardwood floors. However, the difficulty of identifying specific risks on a construction site does not absolve a construction company of the need to identify those risks. In effect, construction safety management must satisfy the Occupational Safety and Health Administration (OSHA) Act General Duty Clause (OSHA, 2006, n.p.):

> Each employer shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees. (Each employer) shall comply with occupational safety and health standards promulgated under this Act.

To meet the intent of the OSHA Act General Duty Clause, a robust hazard recognition method is required.

Elizabeth Aton (2004) promoted an industrial hygiene approach of Recognition → Evaluation → Control. This is a challenge in residential construction due to the likelihood of significant changes occurring on a jobsite on any given day. A perceived exposure recognized on a given day may not last long enough to facilitate evaluation, and as a consequence the generation of a control measure for that perceived hazard (St. John Holt, 2001). However, area heating is a potential hazard that can be focused and assessed using the paradigm of Recognition → Evaluation → Control. Effectively measuring CO requires methods such as manually drawn detector tubes, electronic gas detectors, or carbon monoxide monitors (Crump, 1998) that are not traditionally found onsite during residential construction projects.

Construction companies ultimately will have to decide what their workplace exposure goals will be. They may decide simply to meet the OSHA PEL statutory requirement of 50ppm for CO (OSHA, 2007a). Or as an alternative, they may decide to satisfy the Threshold Limit Value (TLV) guidelines put forth by the American Conference of Governmental Industrial Hygienists (ACGIH) of 25ppm. A third alternative would be to meet the National Institute of Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) of 35ppm. The CO ppm exposure goal of a given construction company may ultimately be determined by the challenges presented by the working conditions they typically face.

As put forth in the introduction of this paper, winter construction presents a challenging environment to work in safely. After the cement pour(s) for a home's foundation, large (6' x 20' x 6") frost blankets provide a reasonable amount of frost protection. When these protective frost blankets become impractical, or need to be removed for any reason, it becomes necessary to raise the localized air temperatures along, or inside of a foundation to above freezing (Krylov, 1998). If the ground below poured concrete is allowed to freeze, frost heaving has the potential to lift and structurally damage concrete footings and/or walls. It is in this context that propane area heat is often applied. When site-framed basement walls and floors are covered with sheeting goods, a reasonable amount of heater-generated CO can be trapped within a basement level. As construction progresses, this basement level CO is allowed to migrate up into the shell of a building under construction. Additionally, as each layer of cladding is applied to the walls and ceilings, a greater amount of CO is trapped within the overall structure, creating a hazard for all workers.

Importance of Topic

This study is of relevance to a construction safety professional or manager because:

1. Residential construction managers are generally not trained to assess the severity of risk of CO hazards (St. John Holt, 2001). To understand the risks associated with propane area heat, it is first necessary to measure concentration levels of CO. This study will show that CO measurements can be taken in the field with readily accessible instrumentation.

2. Residential construction bids are typically won on a competitive bid basis. In general, applying industrial hygiene sampling strategies would be a significant expense for a contractor or subcontractor. This study will show that readily available off-the-shelf measuring devices can be used to effectively measure CO levels. With equipment costs quantified, and hazard data in hand, a company would more accurately assess their safety related operations (St. John Holt, 2001).

Assumptions of Study

It is assumed that the sampling environment provided by the residential home builder is representative of their day-to-day operations.

Definition of Terms

The following terms are defined to clarify the strategies of this field problem.

Concentration – "The amount of a given substance in a stated unit of measure" (DiNardi, 2003, p. 1257).

Frost Blanket – "reusable commercial blankets … to insulate the concrete from cold" (Dobrowolski & Waddell, 1993, p. 4.14).

Gas Detectors or Multi-gas Meter – "measure the lower explosive limit (LEL) of various gases and vapors … other electrochemical sensors … measure carbon monoxide" (Boss & Day, 2001, p. 14-15).

Industrial Hygiene – "A science devoted to the protection and improvement of the health and well-being of workers exposed to chemicals and physical agents in their work environment" (NIOSH, 2006a, n. p.).

Off-gassing – "the release of chemicals from non-metallic substances under ambient or greater pressure conditions" (White Sands Test Facility, n. d., n. p.).

Permissible Exposure Limit – "Established by OSHA (see 29CFR1910.1000 Subpart Z). The permissible concentration in air of a substance to which nearly all workers may be exposed 8 hours a day, 40 hours a week, for 30 years without adverse effects" (DiNardi, 2003, p. 1284).

Personal Protective Equipment (PPE) – "Equipment (e. g., gloves, eye protection, respirators) designed to protect individuals from biohazards" (DiNardi, 2003, p. 1284).

Silica Dust – "found in nature in several forms, including quartz … silica is a major ingredient of portland cement" (Wikipedia, n.d., n. p.).

Threshold Limit Value (TLV) – "Used by the ACGIH to designate degree of exposure to contaminants and expressed as parts of vapor or gas per million parts of air by volume at 25° C and 760mm Hg pressure" (DiNardi, 2003, p. 1299).

Chapter Two: Review of Literature

Introduction

As a precursor to the sampling methodology of this paper, it is first necessary to review a select group of topics related to carbon monoxide (CO). Those topics include: CO health risks, CO ppm statutory requirements and recommendations, CO exposure studies, winter construction conditions, CO sources in construction and lastly CO sampling.

Carbon Monoxide Health Risks

The ACGIH TLV Gateway document (2001) stated that the symptoms of carbon monoxide poisoning can range from a headache and lightheadedness to unconsciousness and death via asphyxiation. The primary route of exposure to CO is inhalation. It is the high affinity between CO and the hemoglobin in the blood (200 to 250 times that of O_2) that can make CO exposure acutely toxic. Increasing levels of carboxyhemoglobin (COHb) can put hypoxic stress (oxygen deficiency) on the body. To account for this form of stress, the body can compensate via increased respiration and a faster heart rate. When levels of CO reach the criteria of 1200ppm in an environment, the exposure is referred to by the National Institute of Occupational Safety and Health (NIOSH, 2006b) as Immediately Dangerous to Life and Health (IDLH).

Carbon Monoxide Statutory Requirements and Recommended Limits

OSHA has adopted the time weighted average (TWA) value of 50ppm for the construction industry. This value is found in Appendix A of 29CFR1926.55 in the code of federal regulations. This value is not meant to fully protect those individuals who have a compromised respiratory system, heart disease, or women who are pregnant. The state administered OSHA program in Minnesota (MNOSHA) too has adopted the federal OSHA TWA of 50ppm for construction, while adopting the value of 35ppm for general industry.

As an alternative to the OSHA statutory requirement for CO, the ACGIH TLV Gateway document (2001) has put forth a TLV-TWA of 25ppm. This value does attempt to protect a broader population of individuals in the workplace. The ACGIH believes that this value has the potential to keep COHb levels below 3.5%. By maintaining a lower level of COHb, it is believed that pregnant women, individuals with compromised respiratory systems, and those with heart disease will be less susceptible to the negative effects of CO.

NIOSH (2006b), in its' Pocket Guide to Chemical Hazards, put forth a recommended exposure limit (REL) of 35 ppm, which matched MNOSHA's general industry value. An important additional criteria put forth by NIOSH was a ceiling (C) limit value of C 200 ppm. Unlike a Short Term Exposure Limit (STEL) value which can be experienced in 15 minutes or less, a C value is not meant to be experienced at any time during the day. OSHA, MNOSHA, and the ACGIH do not put forth a ceiling value.

Carbon Monoxide Exposure Studies

While there are a number of studies concerning CO exposure that could be reviewed, it was a challenge to find CO studies specific to winter construction much less those concerning temporary heat. As a substitute, three studies were reviewed that touched on aspects of CO exposure that are related to this field problem. The first was an often referenced winter time CO study done in the Washington, DC and Denver, Colorado areas. A second was a paper done for Washington State concerning CO exposure violations. A third paper touched on the topic of direct fired combustion in a tightly sealed space.

Denver, Colorado and Washington, DC Winter CO Study

Over the winter months of November through February of 1982 – 1983 Akland, Hartwell, Johnson and Whitmore (1985) compared the personal CO exposures of nonsmokers to fixed ambient CO values recorded in the same metropolitan area. The study measured CO values in Washington, DC and Denver CO. A three stage sample targeting procedure was applied to identify subgroups of the Denver and Washington populations.

The first stage of the sampling procedure divided the two geographic areas into census block groups (250 Washington and 100 Denver) with addresses and telephone numbers compiled. In the second stage of the procedure, phone interviews were conducted with a representative of the household to determine specific demographics such as smoking habits. Lastly, in the third stage of the sample procedure, individuals were asked to carry personal exposure monitors for 1 day in Washington and 2 days in Denver. The continuously running monitors collected 1hr and 8hr TWA's. In addition to the monitor data logging, a daily diary was kept, and an exhaled air sample was collected in a 600ml plastic carboxyhemoglobin bag at the end of sample period. A study goal was to collect 1000 person day samples (100 days at 10 samples/day) in each area, Washington and Denver.

The study participation rate was 58% in Washington and 43% in Denver. Though the authors of the study acknowledged the response rates were less than ideal, they countered that the qualitative collection of CO samples was less susceptible to response rate factors than attitudinal surveys of other studies. The results of the study were varied, though they did show some trends.

The most influential data showed the poor correlation of fixed site CO data collected at EPA fixed sites (15 in Denver and 10 in Washington) with CO personal exposure 1hr values. In both the Washington and Denver areas, average fixed site CO 1hr values in the 90th percentile were only equal to the mean of the 1hr personal exposure values. In the minds of the study authors, the EPA fixed site data was of little value in predicting personal exposure values.

For the purposes of this paper, an additional trend was found that was of interest. While the presence or absence of gas stoves in a residence, whether vented, or non-vented showed 1hr mean differences of less than 1ppm, there were significant 1hr mean differences at 15.77ppm between individuals deemed to have high verses low occupational exposures. The twenty-nine occupational exposures deemed to have high CO exposures included truck drivers, automobile mechanics, and garage workers. The common thread of the twenty-nine occupations was being around gas combustion while at work. Though construction occupations were not categorized in the study, it is valid to say that construction site personnel are often in the presence of internal combustion engines.

Washington State Occupational CO Violations

In 2002, Lofgren of the Washington State Department of Labor and Industry generated a study that compared industrial insurance claims data regarding CO to occupational CO violations (COV). The study carried out a search of the state of Washington's Integrated Management Information System (IMIS) for violations that contained the text "carbon monoxide" or "CO" in the citation text. The results gathered were categorized by their respective 4 digit Standard Industrial Classification (SIC) code. The search collected 142 inspections with violations over the years 1994 – 1999.

Reviewing the inspection reports brought to light the fact that 60% of the investigations with violations were instigated by complaints or referrals. According to Lofgren (2002), of the inspections, 39% occurred on construction sites and 22% at manufacturing facilities. While construction and manufacturing accounted for 17% and 12% of CO claim incidents (incidents involving insurance payments) respectively, they both lagged behind wholesale operations, which comprised 20% of claim incidents, while only generating 9% of inspections. These numbers reflected a repeated point of this study, that inspections are not necessarily focused on the areas of industry with the greatest CO risk to workers.

While the use of forklifts in poorly ventilated wholesale facilities presented the greatest CO risk in the study's data, it was also pointed out that the reliance on safe work practices to control CO exposures alone should be discouraged. It was a common theme in the violations to find poor hazard communications practices cited. Quite often in the investigations it was stated that the individuals exposed had little understanding of CO risks (Lofgren, 2002).

Within the study, an inspection that included CO sampling of a propane heater found it to exceed the NIOSH ceiling level of 200 ppm over 5 minutes (Lofgren, 2002). In total, temporary heating devices were noted in 6% of the inspections. It is important to note that a number of serious incidents from the industrial insurance claims data were not inspected due to the delay of claim processing. It is unfortunate, as the study noted

(Lofgren, 2002), that the hospital or clinics were not required in the state of Washington to report CO poisoning admissions. Due to this fact, it is likely that potentially dangerous settings involving CO were not inspected, absent of a claim, or referral.

Greenhouses

At the University of Florida, an Agricultural and Biological Engineering document titled "Heating Greenhouses" put forth by Bucklin, Buffington, Henley, and McConnell (1992) addressed issues specific to tightly sealed enclosures. While the location of the greenhouses referenced was Florida, there was some overlap with issues regarding CO exposure. The lack of outside air directly supporting combustion inside the greenhouse enclosures was of particular concern to the authors of the document.

The authors of the paper noted a combination of factors that impacted the greenhouse environment, some of those factors included: excess carbon dioxide (beyond desired levels) as a byproduct of combustion, elevated CO levels, sulfur dioxide, and unburned hydrocarbons. It was observed that the inefficiency of heating sources could be improved by various means. One key factor mentioned above concerns adding a combustion air supply vent, which the paper suggested should be six to eight inches for a single unit heater. This recommendation is less accurate than an estimate that quantifies British Thermal Unit (BTU) output, and is simply a rule-of-thumb. A second factor concerned exhausting combustion gases. The recommendation was to ensure that exhaust stacks/pipes extend 48 inches above the peak of structures (greenhouses) to minimize the potential to cause the recirculation of exhaust gases into the combustion air supply vent. While this was a sound recommendation, it is a challenge in new construction where mechanical vents for high efficiency water heaters and furnaces are typically vented via plastic piping at the ground level.

Winter Construction and Heating Requirements

A wide variety of construction phases require ambient air temperatures to be above freezing. When outside temperatures are below freezing, interior temperatures must be raised. Reviewed below are just three phases of construction requiring supplemental heat in the winter months. They include: pouring concrete slabs, installing plaster wallboard and painting interior surfaces.

Pouring Concrete

The American Concrete Institute (ACI) document (2001) "Cold Weather Concreting, ACI 303-88" listed a set of best practices and recommendations regarding concrete pours that are done when temperatures are at or below 32° F (0° C). Concrete must not be allowed to freeze prior to it reaching a minimum compressive strength of 500 pounds per square inch (psi). For reference, the concrete slab in a new home under construction must meet the minimum specifications of 2500 psi.

ACI (2001) defined a cold weather application as one where outside temperatures over a period of 3 successive days are below 40° F (5° C) and not above 50° F (10° C) for a 12 hour period on any one of the days. This recommendation does build in a safety factor and it is important to note that it requires the need to predict temperature conditions. In variable temperature conditions, it may be the case that concrete contractors are reluctant to risk materials and labor and instead choose to heat the environment that they pour concrete within. In regards to this field problem, a relevant condition would be a basement concrete slab pour heated by any number of temporary sources.

Gypsum Wallboard Installation

The United States Gypsum (USG) (2007) company has put forth a best practices document titled the "Gypsum Construction Handbook." The document provides a number of recommendations regarding the installation of wallboard specific to temperature and moisture. A key recommendation is to install gypsum products at uniform temperatures above 55° F. This minimum temperature should be maintained according to the recommendations for 48 hours prior to, and 48 hours after wallboard installation. To reinforce the importance of this specification in the "Planning, Execution and Inspection" chapter of the handbook, it noted that if wallboard is installed at 28° F and the wallboard temperature is raised to 72° F, it will expand 1/2 inch every 100 linear feet. While 1/2 inch may seem a modest amount, it could bring with it significant costs in re-taping joints and repainting walls in a home. It is clear according to the recommendations that some form of heat must be applied when outside temperatures fall below 50° F over sustained periods.

Interior Painting

Painting in residential construction can be challenging due to a number of factors. A short list of those factors includes: site dust, human traffic, moisture and temperature. The company Bennette Paint (2007) emphasized in its lab notes for "Cold Weather Painting" the benefits of painting in temperature conditions above 50° F. Their recommendations were based on sustained temperatures over the drying cycle of a given paint. The benefits of painting at or above 50° F temperatures includes the reduced risk of lapping, ghosting, or mudcracking, all of which can significantly deteriorate the quality of touchup paint. Most builders would likely ascribe to the need to deliver quality painting services on the interior of a home irrespective of outside temperatures.

Construction Sources of Carbon Monoxide

It is the focus of this field problem to assess propane fueled temporary heater emissions. As a part of assessing what these emissions might be, it is important to review at least two operating manuals for propane fueled area heaters. Following are excerpts from two such manuals.

Red Dragon Portable Construction Heater

CO poisoning is just one of a number of items listed in the "General Hazard Warning" for Flame Engineering's (1993) Red Dragon models AG-235, AG-235A, and AG 235B. The general hazard warnings are listed on the first page of the operating instructions for this series of construction heaters. On page two, additional items are listed under the "Warnings" heading. Of interest to this field problem are recommendations that, "Adequate ventilation must be provided. DO NOT POSITION HEATER IN A LOCATION WHERE VENTILATION OR COMBUSTION AIR IS OBSTRUCTED … DO NOT LEAVE HEATER UNATTENDED!!" (p.2), adherence to the second point is often poor. It is quite common for temporary construction heaters to burn unattended over evenings, weekends and during slack periods in scheduling.

Gas-Fired Infrared Portable Construction Heater

As with the Red Dragon, the cover page of the "Operating Instructions and Owners Manual" for the Mr. Heater (2003) models HS125NG, MH125LP, and HS125LP construction heaters listed a number of items including CO in a "General Hazard

Warning." A difference between the Red Dragon Flame Engineering (1993) and Mr. Heater (2003) manual was in regards to ventilation. Within the "Ventilation" section on page two of the Mr. Heater manual, there was a bolded section stating that the appliance is unvented and must be used in a "well ventilated" area. The recommendation goes further and puts forth guidance regarding ventilation. Specifically noted regarding ventilation was that the heater users provide two openings ideally located on opposite sides of the heater, each directly accessing outside air. Specifically, for each 1000 BTUs, it is required that three square inches of intake and exhaust area are provided.

For reference purposes, the MH125LP and HS125LP heaters are rated at 125,000 BTUs with propane fuel. In order to account for the intake and exhaust openings, 2.6 ft^2 (((125,000 BTU / 1000) x 3 in^2) / 144 in, for each opening) would need to be provided to meet the manufacture's criteria, Mr. Heater (2003), of either heater operating at its peak level. Applying this formula to the Red Dragon AG 235 construction heater rated at 250,000 BTUs would require two openings at 5.2 ft^2. This larger figure is very close to the minimum egress requirement of a single bedroom window for fire escape at 5.3 ft^2. It is probable that in new construction that at least one basement window would meet the egress standard, and consequently the potential for combustion air intake area for heaters operating in the range of 250,000 BTUs.

Industrial Hygiene Toxic Gas Sampling

A wide variety of instrumentation exists to measure the toxic gases that might be present in a work environment. Single gas meters, multi gas meters, colorimetric tubes, and passive dosimeters each provide data that at a minimum gives a snap shot of site conditions. The following sections will expand upon the technology of gas meters, colorimetric tubes, and home CO detectors. To close out the industrial hygiene toxic gas sampling section, the methods of a sampling protocol will be presented.

Single Gas and Multi-Gas Meters

Toxic gas sensing equipment comes in a variety of configurations. Small personal data logging units might measure a single gas, whereas multiple sensors units record data regarding a number of different gases. Either unit could employ an electrochemical sensor and/or a catalytic diffusion sensor. Combustible gases such as propane might be measured via a catalytic diffusion sensor, while oxygen and CO can be measured via an electrochemical sensor.

Catalytic diffusion sensors are widely used to measure combustible gases. Separate coiled sensor wires, one doped with a catalyst and the other without, are placed in a circuit and heated to very high temperatures. As a combustible gas comes into contact with the doped coil, its temperature rises. The temperature difference between the doped and non-doped coil causes an unbalanced circuit, which gives out a positive combustion signal. The positive signal is interpreted according to the calibration of the instrument.

Electrochemical sensors employ two or three electrodes housed in a cell holding an electrolyte solution. The electrolyte is held within the cell by a semi permeable membrane that in turn allows the reference gas to enter the cell. A sensing electrode interacts with the reference gas causing either an oxidation or a reduction reaction. Depending on the type of reaction, electrons either flow to a second counter electrode, or from the counter electrode to the sensing electrode. For reference, a CO electrochemical reaction is an oxidation reaction causing a flow of electrons to the counter electrode. An oxygen electrochemical reaction is a reduction reaction.

Colorimetric Tubes

The use of colorimetric tubes typically requires no electronic components for sampling. Samples are typically drawn using a vacuum generated by retracting or compressing an air chamber. Ambient air, along with a toxic gas of interest, is drawn into the end of a glass tube allowing it to react with some type of a sorbent inside the tube. Toxic gas levels are quantified by the amount of color change relative to a graduated scale printed on the glass. It is important to note that colorimetric tubes readings are limited by humidity, temperature, atmospheric pressure, and cross sensitivity with other chemicals. The tubes are one time instruments, typically drawn into over a time span of one to five minutes.

Passive colorimetric tubes can be used to generate approximate TWAs and short term exposure limits (STELs). Absent the need of a pump, this type of instrument operates internally (regarding color changes) as does the short term pump drawn tubes. Quantitative measurements are determined by dividing the tube reading (color change) by the total amount of time the sample was collected. While limited in terms of accuracy, this type of colorimetric tube can better quantify a work shift than a short term colorimetric tube.

Home CO Detectors

While MNOSHA (2006) guidelines clearly stated that, "Residential carbon monoxide detectors are not intended to be used as survey instruments in workplace settings" (p. 1), what protection level do they afford those in a home, apartment, or business? The Consumer Products Safety Commission (CPSC) HUD (2005) recommended that homeowners purchase CO alarms that meet the Underwriters Laboratories (UL) 2034 standard. This standard established that regardless of sensor type, a home CO detector alarms in: 4 – 15 minutes at 400 ppm CO, 10 – 50 minutes at 150 ppm CO and 1 – 4 hours at 75 ppm CO. It is acknowledged in this criterion that the COHb levels could reach 10% in an individual before an alarm condition. For reference, this 10% level is nearly three times the ACGIH recommended COHb level of 3.5%. One last component of the UL 2034 standard stated that monitors will not display values below 30 ppm.

Sampling Strategy

The NIOSH 6604 sampling method and the OSHA ID 209 sampling method each employ toxic gas meters to measure CO exposure. The NIOSH method prescribed a portable direct reading monitor employing an electrochemical sensor. The monitor is to be zeroed in CO free air ideally with humidity and temperature conditions similar to the sampling setting. For area monitoring, the monitor should be placed 60 to 70 inches from the floor in an area with good air movement. The CO sensor should be calibrated per manufacturer guidelines from a pressurized cylinder. Lastly, the meter should receive a calibration check daily with recalibration done when the meter varies from the CO span gas by 5% or more.

Chapter Three: Methodology

Introduction

The sections of this chapter include instrument types, setting, heating sources, measurement tool specifics, and the limitations of the study.

Instrument Types

The equipment used in this study included a hand pump with CO colorimetric tubes, one calibrated single gas meter (CO), two calibrated multi-gas meters (CO and O_2), and a residential CO monitor. An anemometer was used to determine approximate air exchange values. The specifics of each instrument can be found in Appendix A. The CO sampling strategy is listed below in the categories of setting, heating sources, and measurement tools.

Setting

The setting section is divided into two categories, home characteristics and temperature/humidity, and jobsite activities. Under the home characteristic list are specific criteria about the home. The temperature/humidity and jobsite activities list gives specifics regarding the setting conditions.

Home Characteristics

Following are five categories listing information regarding the home. They include:

- Stories of house including basement
- Volume of house in cubic feet
- Plan view of house including the positioning of temporary mechanical equipment and metering equipment positioning

- Isometric interior view of house including the positioning of temporary mechanical equipment and metering equipment positioning
- Fixed combustion air sources

Temperature/Humidity and Jobsite Activities

Following are the categories concerning the jobsite setting:

- Temperature tracked inside the home in the basement level
- Temperature tracked outside the home, out of direct sunlight
- Temperatures recorded approximately on the hour for the interior, and every two to three hours for the exterior
- Periodic humidity readings taken inside the home in the basement, approximately every two hours
- Human and equipment traffic in and out of the building with activities logged in a journal

Heating Sources

Temporary heat and semi-permanent heating sources (see Appendix A for specific information) were categorized by five elements:

- Heater Type
- Fuel source
- Combustion air source, whether mechanical or improvised
- Combustion exhaust method, whether mechanical or improvised
- Temperature control via thermostat or by manual method

Measurement Tool Specifics

Each electronic gas meter was calibrated prior to sampling. CO detectors were placed approximately 60 inches above the floor to approximate an upright individual's breathing zone. CO levels were recorded with a visual reading from each instrument, on the hour. Oxygen levels were recorded visually at two meters, on the hour. Two meters provided data logging over the sampling period. At alternating meter locations (four total), a single colorimetric tube was drawn on the hour. The colorimetric tube inlet was placed within 12 inches of the corresponding meter. As found in Appendix A, CO sampling equipment was listed with the following categories of information:

- Manufacturer
- Model
- Sensitivity
- Calibration requirements
- Temperature range

An anemometer was used to record air flow rates into the house on day two. The anemometers manufacturer, model, sensitivity, calibration requirements, battery check and temperature range were recorded.

Limitations of the Study

Key limitations to this study's methodology were the non-static nature of the sample environment and the margins of error inherent to the instruments used to measure CO.

1. CO detectors have margins of error. The calibrated CO detectors provided numbers that were only approximations of the actual environmental conditions.

2. Due to building design variability, the CO levels measured were only relevant to the conditions of the house sampled.

3. Building environments are not static, and changes are expected to occur. These continually changing conditions did not facilitate a traditional experimental design.

4. CO exposure can come from a variety of potential sources. It was not the scope of this study to assess all sources of CO that might contribute to a jobsite, only to list their presence.

5. Colorimetric detector tubes with margins of error of ±25% are a descriptive but imprecise method of detection.

6. Gas samples were only collected over one eight hour period on each day.

Chapter Four: Results and Discussion

Results

Results are listed in the order presented by the methods. That order was setting, heating sources and measurement tools.

Setting

Home Characteristics

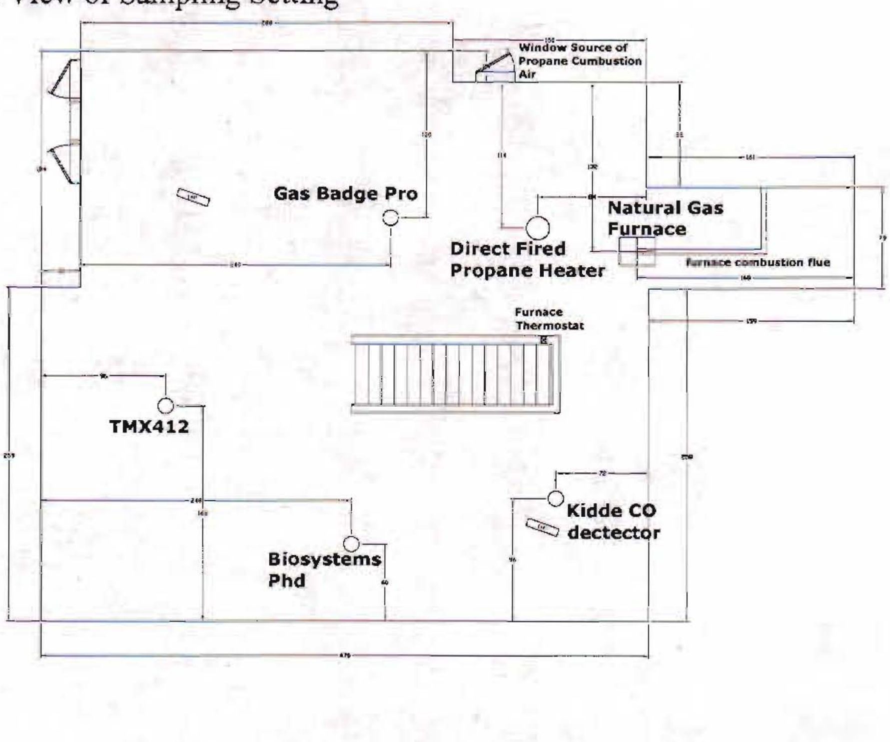
Number of Stories – The house was a rambler design with a main level, no upper floors and a full basement.

Volume of House – The basement level interior cubic volume of the house was approximately 14,313ft³. The main level interior cubic volume of the house was approximately 14,109ft³. The total interior cubic volume of the house was roughly 28,422ft³.

Plan View – Figure 1 represents the plan view of the sampling setting.

Figure 1

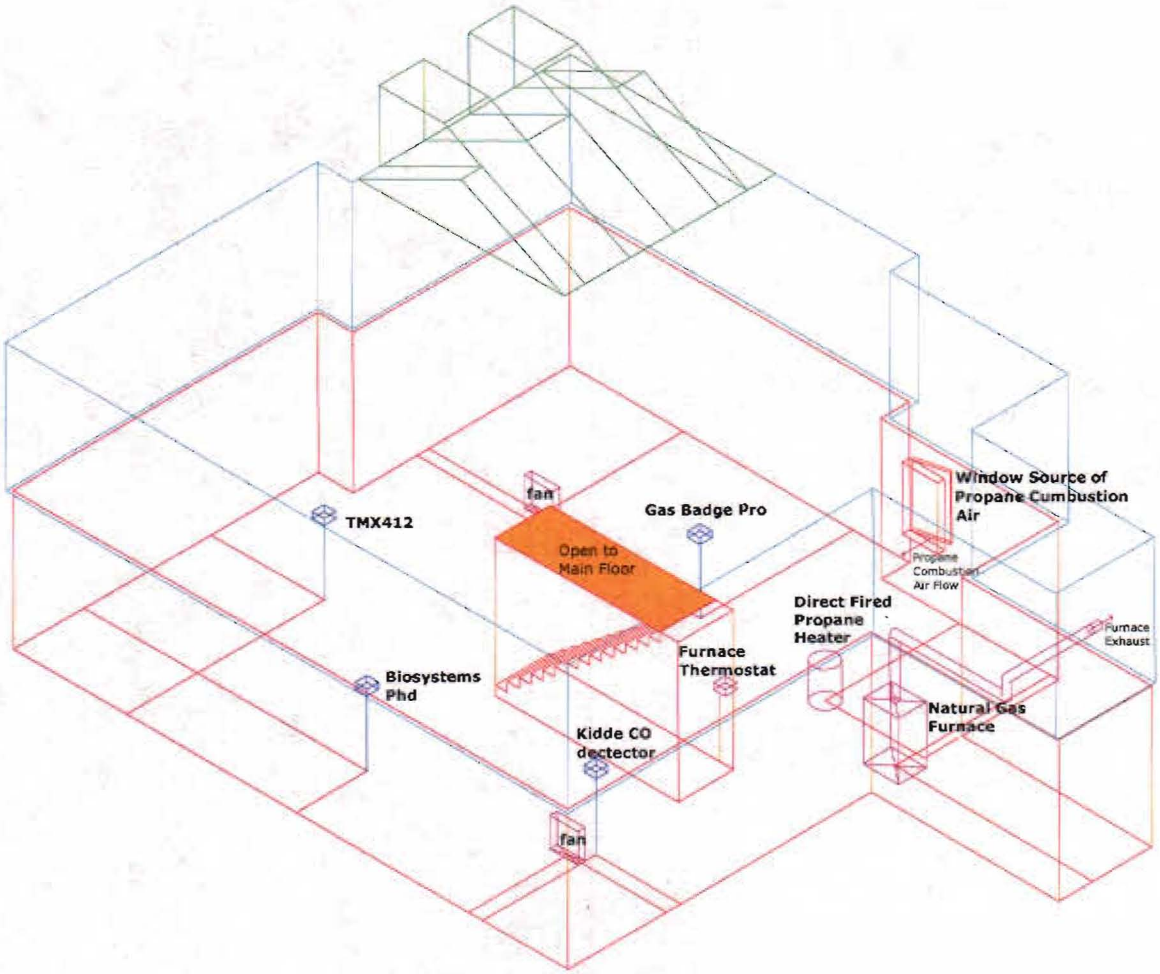
Plan View of Sampling Setting



Isometric View – Figure 2 represents a isometric view of the sampling setting.

Figure 2

Isometric View of Sampling Setting



Fixed Combustion Air Sources

Combustion air had the potential to be drawn into the building from a number of nonspecific sources all located along the main level rim joist, they included:

- An air exchanger intake which was 8" diameter flexible ducting compressed and gathered up inside a joist space.

- An air exchanger exhaust which was 8" diameter flexible ducting compressed and gathered up inside a joist space.
- A dryer vent a 4" metal duct.
- A mechanical room combustion air make up, which was an 8" diameter galvanized metal vent cut into the rim joist.
- The water heater exhaust which was a 4" diameter PVC pipe.

Temperature/Humidity and Jobsite Activities

Interior temperatures for day one and day two are listed in tables A and B respectively. Exterior temperatures for day one and day two are listed in tables C and D respectively. Humidity levels for day one and day two are listed in tables E and F respectively. There was no precipitation on either day of sampling with overcast skies.

Table A
Day One Interior Temperatures

Time	Temperature °F
11:08	57
11:00	59
11:59	62
12:28	64
1:58	65
3:01	67
3:58	68
5:00	68

Table B
Day Two Interior Temperatures

Time	Temperature °F
9:00	57
10:14	58
11:08	59
12:06	61
1:08	62
2:00	62
2:56	62
3:57	60

Table C
Day One Exterior Temperatures

Time	Temperature °F
9:40	14
1:57	18
4:51	16

Table D
Day Two Exterior Temperatures

Time	Temperature °F
9:08	14
1:41	16
4:20	16

Table E
Day One Interior Humidity Levels

Time	Humidity Percentage
9:38	55
10:54	52
12:33	56
1:11	56
3:02	54
4:53	54

Table F
Day Two Interior Humidity Levels

Time	Humidity Percentage
9:48	42
11:10	41
1:07	45
2:27	49

There was no human/equipment traffic into and out of the structure during the sampling period with the exception of the researcher. Movement in and out of the structure was through main level doors which were only left open long enough to pass through them.

Heating Sources

Semi-Permanent Furnace

Heater Type – A forced air furnace with no mechanical ducting connections other than a single piece of sheet metal arched over the top of the heat exchanger, see Figure 3.

Figure 3

Semi-Permanent Furnace

Fuel Source – Natural Gas

Combustion Air Source – The combustion air came from several nonspecific sources listed in the "Setting/Fixed Combustion Sources" section above.

Combustion Exhaust Method – The furnace exhaust was vented through 6" galvanized metal piping elbowed at three points. The piping was run through the mechanical room combustion air makeup vent located along the main level rim joist.

Temperature Control – A standard battery powered non-programmable household thermostat with a minimum setting of 45° F was installed to operate the furnace and adjust temperatures.

Temporary Heater

Heater Type – A direct fired heater with no mechanical ducting, see Figure 4.

Figure 4

Temporary Direct Fired Heater

Fuel Source – Propane

Combustion Air Source – The primary source of combustion air was through a casement window opened on the basement level within 10 feet of the heater. In addition, the combustion air came from the sources listed in the "Setting/Fixed Combustion Sources" section above.

Combustion Exhaust Method – The heater exhausted directly into the basement level and indirectly into the rest of the house interior. Main level double-hung windows were opened approximately 3" (top sash down) to allow some amount of interior air to exhaust out of the building. Twelve windows were opened in this fashion and their average width was 30". The windows were not opened during the sampling period for the temporary furnace.

Temperature Control – The temperature was varied by the researcher manually adjusting a gas valve on the heater in an attempt to approximate the temperatures of day one sampling.

CO Measurements

The levels of CO and oxygen recorded from the gas meters of day one and day two are listed in Tables G and H respectively. The CO levels recorded by the Dräger colorimetric tubes for day one and day two are listed in Tables I and J respectively.

Table G
CO and O_2 Levels Taken on Day One

Meter →	GasBadge Pro	TMX412		Phd Ultra		Kidde CO Detector	
Time ≈	CO ppm	CO ppm	O_2 %	CO ppm	O_2 %	CO ppm	CO ppm
10:00	0	0	20.9	-4	21.1	0	0
11:00	0	0	20.9	-3	20.9	0	0
12:00	0	0	20.8	-4	20.9	0	0
1:00	0	0	20.8	-3	20.9	0	0
2:00	0	0	20.7	0	20.9	0	0
3:00	0	0	20.7	-3	20.9	0	0
4:00	0	0	20.7	0	20.7	0	0
5:00	2	0	20.7	N/A	N/A	0	0

Table H
CO and O_2 Levels Taken on Day Two

Meter →	GasBadge Pro	TMX412		Phd Ultra		Kidde CO Detector	
Time ≈	CO ppm	CO ppm	O_2 %	CO ppm	O_2 %	CO ppm	CO ppm
8:00	0	0	21.3	-2	21.2	0	0
9:00	2	0	20.7	-4	20.9	0	0
10:00	3	3	20.5	-4	20.9	0	0
11:00	4	4	20.4	-4	20.9	0	0
12:00	4	4	20.4	-3	20.9	0	0
1:00	4	4	20.4	-3	20.7	0	0
2:00	5	4	20.3	-4	20.7	0	0
3:00	5	4	20.4	-3	20.9	0	0
4:00	4	3	20.5	-4	20.9		

Table I
Results of Dräger CO Colorimetric Tubes drawn Day One

METER→ Location	GasBadge Pro	TMX412	Phd Ultra	Kidde
TIME ↓	CO ppm	CO ppm	CO ppm	CO ppm
9:00	NO COLOR			
10:00		NO COLOR		
11:00			NO COLOR	
12:00				NO COLOR
1:00	NO COLOR			
2:00		NO COLOR		
3:00			SLIGHT ≈1	
4:00				NO COLOR
5:00	SLIGHT ≈1			

Table J
Results of Dräger CO Colorimetric Tubes drawn Day Two

METER→ Location	GasBadge Pro	TMX412	Phd Ultra	Kidde
TIME ↓	CO ppm	CO ppm	CO ppm	CO ppm
8:00	NO COLOR			
9:00		SLIGHT <2		
10:00			SLIGHT <2	
11:00				2
12:00	SLIGHT <2			
1:00		SLIGHT <2		
2:00			2	
3:00				NOT TAKEN
4:00	SLIGHT <2			

In Appendix A at the end of this study resides a consolidated listing of information regarding the sampling equipment.

Air Flow into the basement through the casement window was measured with a TSI Velocicalc 8355 anemometer. Measurements were taken at the center of 18 boxes within a matrix that subdivided the opening of the window. The matrix was laid out at the interior edge of the extension jamb as shown in Figures 5 and 6.

Figure 5

Interior View of Window Matix

Figure 6

Angled View of Window Opening

Table K lists the face velocity values recorded at 3 separate times on day two. The basement window opening at the inside of the jamb measured 26.25" wide by 51.75" tall. The window area came to 9.43 cubic feet. The average face velocity of each run was used to calculate a cubic volume (Q), or flow rate value using the equation Q = Area x Face Velocity. The average flow rate of the three runs was 553 ft^3/min. Each hour on average, 33,180 ft^3 (553 ft^3/min x 60 min) of outside air entered the basement through the window. Dividing 33,180 ft^3 by the house cubic volume (28,422 ft^3) yields the value 1.17 air intakes per hour into the basement window.

Table K

Window Matrix Face Velocity Values and Cubic Volume / Minute

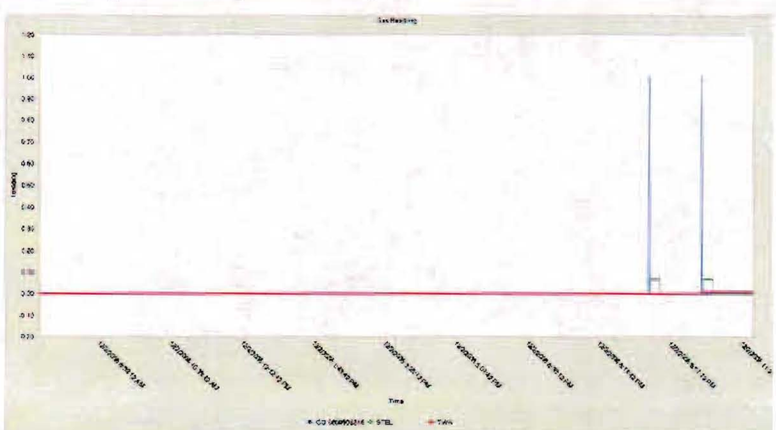
Cell Width (in)		8.75	Cell Height (in)		8.63	Instrument: TSI Velocicalc		
Velocity Values ft/min First Run 9:30 AM			Velocity Values ft/min Second Run 10:25 AM			Velocity Values ft/min Third Run 1:30 PM		
4	14	28	7	63	46	13	24	31
39	71	115	11	32	58	15	25	88
41	67	64	26	41	121	35	52	89
45	50	136	31	35	199	36	48	128
77	86	101	31	74	107	20	76	94
45	102	60	37	47	37	84	48	109
Average Face Velocity ft/min		Flow Rate ft^3/min	Average Face Velocity ft/min		Flow Rate ft^3/min	Average Face Velocity ft/min		Flow Rate ft^3/min
64		603	56		528	56		528

Data Logging Meters

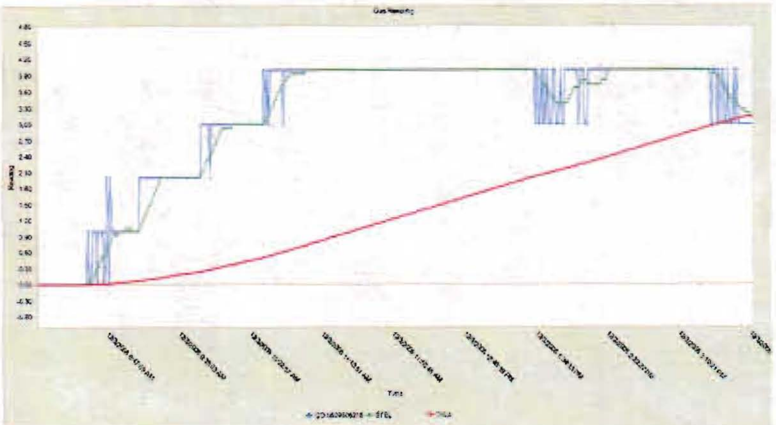
The GasBadge Pro recorded an eight hour TWA of 0, and an STEL of 0 for day one sampling, this can be seen in Figure 7. On day two the same meter recorded an eight hour TWA of 3 and STEL of 4, this can be seen in Figure 8. While the TMX412 returned similar results to the GasBadge Pro as seen in Tables G and H the software for the TMX412 did not facilitate graphing TWA and STEL.

Figure 7

GasBadge Pro Day One Graph



GasBadge Pro Day Two Graph



Discussion

The propane fueled temporary heater was rated at 250,000 BTUs. This maximum output would correspond to 5.2 ft^2 of air intake area (((250,000 / 1,000) x 3) / 144) if the ventilation recommendation of the Mr. Heater manual was applied (three square inches per 1,000 BTUs). The methodology of this field problem did not allow for the calculation of BTUs. It can only be said that as of 12:00 PM on day two, the propane heaters gas valve was opened fully. Despite this fact, the interior air temperature on day two stalled at 62° F and actually fell to 60° F by the end of the days sampling. In effect, it was not possible to match the interior temperatures of day one and day two sampling. A review of a propane vaporization chart (see Table L) reveals that with exterior temperatures between 10° F and 20° F, it could only be expected that the maximum BTU output of the 100 lbs cylinder would be 167,000 BTUs initially. Using the table as a guide, throughout the sampling period of day two, the maximum output of the propane heater steadily decreased.

Table L

Propane Vaporization Rate of 100lbs Cylinders at 0° F and 20° F

Pounds of Propane in Cylinder	BTU output of one tank at 0° F	BTU output of one tank at 20° F
100	113,000	167,000
90	104,000	152,000
80	94,000	137,000
70	83,000	122,000
60	75,000	109,000
50	64,000	94,000
40	55,000	79,000
30	45,000	66,000
20	36,000	51,000
10	28,000	38,000

While exterior temperatures were very consistent over day one and day two sampling, the interior humidity values collected were of little value. This is due to the reality that the humidity gauge used onsite on day one, was not available on day two. The substitute humidity gauge used on day two, showed poor correlation to the day one instrument. As a consequence, no meaningful comparison can be made regarding humidity for days one and two.

Significant amounts of moisture were present in the building in day two (see Figure 9). This is evidenced by the water condensed on and dripping from the building envelope ceiling plastic. Because the building had no plaster wall board on the ceiling, there was no insulation in the attic space with the exception of the eves. In effect, the attic space environment was very cool. It was apparent as well, that the main level windows though open, did not exhaust a significant amount of water produced by the propane combustion.

Figure 9

Interior Moisture Condensation Day Two

Errors

A closer review of the Phd Ultra gas meter capabilities may have determined the limitations of the instrument in temperatures below 60° F. The meter appeared to be challenged in regards to CO data on each day of sampling, despite pre and post calibration. Similar CO results using three separate gas meters would have strengthened the data of this study.

Meaningful humidity levels collected for day two would have would have been helpful regarding recommendations. However, the humidity gauge used on day one was left at a different location on day two and unfortunately was not accessible. High humidity levels evidenced by the water condensation on the plastic, argue that day two humidity levels exceeded those on day one when no perceptible condensation was seen.

Chapter Five: Conclusions and Recommendations

Introduction

It was the purpose of this study to use three separate technologies to assess the interior environment of a home under construction in regards to CO gas. To accomplish this, five separate instruments were used to measure CO. The time frame was an eight hour sample collected on day one and day two, respectively. One of the instruments the GasBadge Pro with a single sensor for CO gas delivered meaningful TWA and STEL values. In addition to the CO values, an approximation of the air exchange rate was determined on day two with the use of a TSI Velocicalc anemometer.

Conclusions

The conclusions of this study are presented in the following sections, they include: setting, heating types, heating byproducts and sampling procedures.

Setting

The single story, rambler designed home with a full basement, was a fair representation of the residential homes being built in the Twin Cities metro area of Minnesota. How quickly these homes are connected to a permanent electrical supply will have a direct effect on the type of the heating source used to warm the interior environment during construction. It is important to note, that having permanent electrical power does not automatically ensure the use of a semi-permanent forced air furnace. This is due in part to the cost and wear on a semi-permanent furnace during construction. The dust and debris present in a home under construction can significantly damage any forced air furnace. It is because of this likelihood that permanent forced air furnaces, if planned for, are typically not used to provide heat during early construction activities (i.e. insulating, sheet-rocking, finish carpentry, painting).

Heating Types

General contractors will perform an assessment of the utilities present at a home site initially and when completed. The time of year a home is constructed in conjunction with the utility situation will determine the temporary heating needs. Natural gas or propane utilities will take either the form of underground lines (natural gas) or semi-permanent tanks (propane). In the setting of this study, an underground natural gas utility line facilitated the use of a semi-permanent forced air furnace. The day two moisture levels in the home revealed that the forced air furnace was a much more ideal method of providing heat, verses the propane fueled direct fired temporary heater.

Interior temperature adjustability limitations, condensation and CO gas all made the propane fueled direct fired heater a poor choice with the interior building envelope of plastic applied. Though propane temporary heat may be sufficient for the pouring of concrete when high interior moisture levels actually slow the curing of concrete, generally speaking excess moisture is very problematic. Once the concrete floor facilitates the transition to forced air heat (assuming a permanent electrical hookup), temperature, CO and moisture are handled much more effectively with a forced air furnace.

Heating Byproducts

CO as a byproduct of combustion appeared to be well within the MNOSHA requirements. While CO levels rose from day one to day two, the CO TWA at 3 ppm was approximately one tenth of the general industry CO PEL of 35 ppm, and 6% of the construction CO PEL of 50 ppm. As for the CO STEL at 4 ppm it was well below the NIOSH CO ceiling value of 200 ppm. Assuming similar conditions of use in a building basement, over the first eight hours of operation, propane fueled direct fired heaters should not significantly raise the levels of CO gas, assuming a +1 air exchange value is achieved.

Oxygen levels were tracked as a secondary safety measure. It appeared that the O_2 levels decreased and stabilized at levels close to 20.9% on each day of sampling. Oxygen levels above 19.5% and below 22% are considered acceptable (OSHA; 2007b). Whether O_2 levels would have dropped further on day two, with the basement window closed, is probable. However, it was not the scope of this study to test, or asses that scenario. Such a scenario could be the basis for a future look at temporary heat provided by propane fueled direct fired heaters.

Sampling Procedures

The electronic gas meters used, provided meaningful data whether in the form of CO gas or O_2. Despite operational issues with the Phd Ultra regarding CO, the O_2 data the meter produced correlated well with the O_2 values returned by the TMX 412. Similarly the CO values of the GasBadge Pro and TMX 412 correlated within 1 ppm with the exception of the 9:00 reading. It can be said regarding the Kidde CO Detector, that CO values whether current or peak were of little value. The MNOSHA regulatory statement, paraphrased that these home style detectors are not to be used to establish compliance, is partially validated by this studies results.

Calibration procedures were done, but an elaboration of those procedures was not the purpose of this study. It can be said that the more simplified the calibration procedure, the more practical the use of a CO gas meters becomes. It took approximately 15 minutes to calibrate the GasBadge Pro using a CO calibration cylinder. The Phd Ultra and TMX 412 were less convenient, though calibration times were less than 30 minutes, whether pre or post sampling.

A colorimetric detector tube was tested with a known CO concentration. This was done using a Teflon sample gas bag containing CO gas at approximately 20 ppm. The detector tube used to measure the concentration of the bag returned a value of 20 ppm at the leading edge of the stain. In the field, the Dräger hand pump was compressed, and the use of an unbroken tube showed no perceptible leakage of the pump over one minute. Despite the aforementioned test, the values in Tables I and J showed poor correlation between the colorimetric detector tube CO values and those returned by the GasBadge Pro, or TMX 412 at the same time of day. It is due to this poor correlation that a conclusion of this study is that despite convenience, colorimetric detector tubes do not provide easily perceptible data when measuring CO in single digits.

Recommendations

Mentioned in part in the conclusions above, propane fueled direct fired temporary heat has few properties conducive to a home under construction for the following reasons. First, the placement of the heater is restricted due to radiant, convective and direct flame. Along this line of reasoning it is likely that concrete workers may suspend this type of heater above the basement fill and below the joists. Doing so brings the heater to close to a combustible material per manufacturer recommendations. Second, excess moisture while conducive to concrete curing, in most if not all other instances contributes to: mold growth, longer plaster drying time, swelling of wood products and extended paint drying times. Third, the ability of this type of heater to raise interior temperature is limited by the combustion air make up of a window, or opening allowing in exterior air. As was the case in this study, temperatures on day two sampling were below those recommended for ideal wall board installation and interior painting. Despite the real limitations mentioned above it cannot be said, as evidenced by the CO data collected, that the CO levels produced by the heater alone are reason to avoid its use.

In Table M below, titled Instrument Recommendations, are some of the pros and cons of using a specific instrument to measure CO and or O_2. While the single gas meter was the most user-friendly and capable of producing quality CO data, a judgment will have to be made in terms of tracking O_2. In the initial tracking of company specific settings it is recommended that CO and O_2 are simultaneously measured. This will either require two single gas meters, or one multi-gas meter. If representative construction environments consistently show O_2 within the 19.5% to 22% range it may sufficient to track CO alone. However, if it is shown that O_2 moves out of the 19.5% to 22% range in an enclosed space, O_2 must be tracked as well (OSHA; 2007b).

If area sampling is used to measure CO compliance, electronic meters (excluding home detectors) should be placed 60" above the floor to approximate the breathing zone of a worker. Whether suspended, or supported, the meters should be on the same level of which work is being performed. The meters must be unobstructed by material that might shield the sensor from detecting indoor air. As opposed to personal sampling, area monitoring affords continuous sampling over a work shift. In addition, audible alarms can likely warn all individuals within, or entering into a specific indoor environment. Data logging meters will produce easily recordable numbers to determine compliance.

Table M

Instrument Recommendations

Measurement Tool	Pros of use	Cons of use
GasBadge Pro	MNOSHA compliant CO sensitivity range Operating temperature range Durability and size of meter Ease of use TWA, STEL and C values	Single sensor, unable to track O_2 and CO simultaneously
TMX412	MNOSHA compliant CO sensitivity range O_2 sensitivity range Operating temperature range TWA, STEL and C values	Calibration Time Size of meter Ease of use
Phd Ultra	MNOSHA compliant CO sensitivity range O_2 sensitivity range TWA, STEL and C values	Calibration Time Size of meter Ease of use
Dräger Accuro with 2 – 6 ppm colorimetric tubes	MNOSHA compliant Simplicity of operation Compact	Poor CO sensitivity at single ppm 25% margin of error No TWA, STEL or C values
Kidde Carbon Monoxide Alarm	While not of compliance value, a worst case scenario alarm method	Not acceptable for establishing MNOSHA compliance

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Appendix A: *Instrumentation Specifics and Heating Source Information*

Electronic Gas Meters

Meter: Manufacturer & Model →	Industrial Scientific GasBadge Pro	Industrial Scientific TMX412	Bio Systems Inc. Phd Ultra	Kidde Carbon Monoxide Alarm
Serial Number	06110A9-100	9611012-001	00276 Demo	KN-COPP-B
Sensor One	CO	CO	CO	CO
Sensitivity Range	0 – 1500 ppm	0 – 999 ppm	0 – 1000 ppm	11 – 999 ppm
Margin of Error	± 5% or 1 ppm at calibration temperature, or ± 15% over operating temperature range	± 5% or 1 ppm at calibration temperature, or ± 15% over operating temperature range	± 10% over operating temperature range	± 25 ppm at 80° F and 40% humidity, display reading + 20% + 15ppm
Sensor Two	N/A	O_2	O_2	N/A
Sensitivity Range	N/A	0 – 30%	0 – 30%	N/A
Margin of Error	N/A	± 0.5% at calibration temperature, or ± 0.8% over operating temperature range	± 0.2% over operating temperature range	N/A
Operating Temperature Range	-40° F to 140° F	-4° F to 122° F	-22° F to 140° F	40° F to 100° F
Calibration Method in Field Problem	Calibration bottle	Fresh Air and span gas bag for CO	Fresh Air and span gas bag for CO	Factory CO calibration
CO Calibration flow method	Critical orifice valve on bottle	Draw Pump	Draw Pump	N/A

Additional Instrumentation:

- Teflon Span Gas Bag filled with CO nominal 20 ppm, CO actual 19.8 ppm
- GasBadge Pro Calibration Bottle, CO at 100 ppm

- Dräger Accuro, Colorimetric Draw Pump

Serial Number ABEJ-F022

- Dräger Carbon Monoxide 2/a (67 33051), Colorimetric Tubes 2 – 60 ppm, Margin

of Error ± 15%

- TSI Velocicalc Model 8355, Anemometer

Serial Number 210082 Rev U

- Taylor Humidity Gauge
- Springfield Precise Temp. (combination electronic temperature/humidity gauge)

Temporary Furnace Information:

- 80% Efficient Forced Air Furnace

Max Output 100,000 BTU

Propane Heater Information and Fuel Source:

- LB White Model 341H, Direct Fired Construction Heater

Max Output 250,000 BTU fueled by one 100 lbs propane cylinder