Assessment of the Potential Impacts of Vent-Free Gas Products on Indoor Air Quality In Residential Energy Conservation Structures

Prepared for:

The Propane Education & Research Council
1140 Connecticut Avenue, NW, Suite 1075
Washington, DC 20036-4017

Prepared by:

Gary K. Whitmyre, D.A.B.T.
toXcel, LLC
7140 Heritage Village Plaza
Gainesville, Virginia 20155

and

Muhilan D. Pandian, Ph.D.
infoscientific.com
6 Karsten Creek Court
Henderson, Nevada 89052

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TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

The Propane Education & Research Council (PERC), a coalition of members of the propane gas industry, promotes the safe and efficient use of odorized propane gas as an energy source through investments in research, safety, and consumer initiatives. PERC is a world leader in propane safety and training programs and products. PERC has commissioned this study to investigate the impacts of vent-free gas products on indoor air quality (IAQ) in residential energy conservation structures, specifically energy-efficient homes. Such homes are usually characterized by low air exchange rates with outdoor air, and high insulation (R) values.

Modeled indoor air quality (IAQ) levels of 5 combustion-related chemicals, including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), oxygen (O_2), and water vapor (H_2O) were compared to nationally- and internationally-recognized IAQ guidelines and standards. This research is built upon existing research and modeling tools that have a proven track record of predictive power for unvented gas heating appliances. These appliances include gas logs, fireplace systems, fireplace inserts, free-standing gas stoves, and heaters, which collectively are referred to as “unvented” or “vent-free” heaters.

Work related to the use of these appliances in a broad range of houses was originally conducted in 1996 using the vent-free gas appliance model developed by the American Gas Association Research (AGAR) Division (GRI 1996). This model has been fully validated in instrumented test homes. The AGAR model has been used to focus on the output distribution for relative humidity for “normal” houses having air exchange above 0.35 air changes per hour, or ACH (risksciences 2002) and for NO_2 levels in “tight” homes with air exchange rates of less than 0.35 ACH (toXcel 2012).

The current project updates the past work to address houses that are in compliance with current construction standards for energy-efficient homes. The current work employs the AGAR model in conjunction with a probabilistic modeling software known as Crystal Ball, a product of Oracle. This pairing allows sequential selection of input parameter values from the range of possible values from their assigned distribution curves, and insertion of the values into the vent-free AGAR model in order to produce a distribution curve of model output results.

In the probabilistic analysis, values for room volume, size of connected space (i.e., freely-communicating airspace outside of the room of use), house volume, number of walls with external contact, water vapor emission rates for other sources, number of people in the room, air exchange rates, and outdoor relative humidity were varied. Because of endogenous production of small amounts of carbon dioxide, carbon monoxide, and water vapor by people, the number of individuals in the room of product use does have an impact on the modeled concentrations of these chemicals.

Outdoor temperatures were set at the 1,000 hour heating temperature for a given DOE Region. At least 20,000 simulations of the AGAR vent-free model were run for each DOE Region for cases involving a range of possible values of connected volume. In these model runs, it was assumed that there was equal probability of occurrence of any possible connected volume value up to the size of the room of vent-free heating product use, including zero (i.e., no connected volume). Regarding relative humidity, the modeling incorporated all sources of water vapor in the home, including outdoor relative humidity, human generation of water vapor indoors (e.g., via human breath), the vent-free appliance itself, and other sources such as showering, cooking, and household appliances.

The percentile values from the model output distributions were obtained for each of the chemicals of interest. For all of the DOE Heating Regions, i.e. Region I (Florida and the Gulf Coast) through DOE Heating Region V (New England and the Northern Central Plains), all percentiles of the time-average[1] carbon monoxide (CO) levels in the room of vent-free product use, including the 100th percentile, were well below the 8-hour benchmark of 9 ppm established by the USEPA. For carbon dioxide (CO_2), all of the simulated cases for the time-averaged levels in the room of vent-free product use were below the Canadian benchmark of 3500 ppm for all regions.[2] The time-averaged oxygen levels in the room of vent-free gas product use were consistently between 20.5 and 20.9 percent for all simulated cases. These levels are associated with a high degree of safety, and are well above the ODS trigger of 18 percent, which would cause the vent-free appliance to shut off.

All of the simulated cases for the maximum level of NO_2 in a room containing a vent-free gas heating appliance, including the 100th percentile, were at or below the lowest indoor air quality guideline for NO_2 of 0.110 ppm (World Health Organization) for DOE Heating Regions I, II, III, and IV. For DOE Heating Region V, 99.9 percent of all simulated cases were below this lowest benchmark for NO_2. Across all DOE Heating Regions, all of the modeled cases for the maximum level of NO_2 were below the CPSC standard of 0.3 ppm and below the Health Canada standard of 0.25 ppm. The contribution of outdoor NO_2 levels to indoor NO_2 levels was not addressed in this work. However, outdoor NO_2 levels are not anticipated to make a significant contribution to indoor NO_2 levels, based on the limited infiltration of outdoor air in energy conservation homes.

The results for water vapor, per relative humidity (RH) levels, are as follows. Based on the probabilistic analysis, the median (50th percentile) relative humidity with all water sources included, ranged from 26.5% RH for DOE Heating Region V to 46.1% RH for DOE Heating Region I. The 95th percentile total indoor relative humidity in winter with all sources considered (including a vent-free gas heating appliance), ranged from just under 70% RH for DOE Heating Region I to 47.3% RH for DOE Heating Region V. Across all DOE Heating Regions, 95.2 to 99.5 percent of all simulated cases were associated with relative humidity levels below 70% RH, which is the threshold of concern for active mold and mildew growth. From a sensitivity analysis conducted in a previous work (risksciences 2002), it is known that the higher indoor relative humidity in Region I is largely attributable to infiltration of moist outdoor air containing high water content.

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[1] Time-averaged over 8-hours, including the duration of use of the vent-free gas heating appliance.

[2] There is no residential indoor air standard for carbon dioxide in the U.S.

Our analysis does not assume that the various sources of water in the home always turn “ON” at the same time the vent-free product is “ON”. Relative humidity in the home is dynamic and ever changing, and the short-term spikes produced by various sources may or may not co-occur. The relative humidity in a given room of the house will vary over time as (1) sources turn on and off; (2) sources move within the home (e.g., movement of people between rooms and in and out of the house); (3) moisture is re-distributed within the home due to air transport to other rooms by diffusion and due to the central HVAC system; and (4) mechanical ventilation removes moisture from certain rooms (e.g., kitchens and bathrooms). Vent-free appliances are typically used for a few hours at a time and, as a result, there will only be a limited short-term impact on indoor relative humidity. Further, the relative humidity impacts of vent-free gas appliances are probably overestimated due to a number of conservative assumptions, including the conservative range of 50% to 90% outdoor relative humidity for all DOE Regions. This range does not include actual minimum outdoor relative humidity, which approaches 20% in some Regions during winter.

The results of the current study indicate that the use of vent-free gas heating appliances in energy conservation homes does not result in adverse indoor air quality (IAQ) impacts in nearly all cases for each of the DOE Heating Regions for which simulations were conducted. The work in this current study applies to “low-rise” residential structures, focusing primarily on detached single-family homes.

II. INTRODUCTION

Almost 22 million consumers currently use vent-free gas heating products, based on sales figures in the last 33 years. Vent-free gas heating products are approved for use in most jurisdictions, and are certified under an ANSI national product standard. Vent-free products produce safe, clean, and efficient heat, and provide the additional advantage that they can be installed without a vent. The term “vent-free gas product”, as used in this report refers to all types of vent-free products: convection blue-flame and infrared plaque heaters, and hearth products including gas logs, fireplace systems, fireplace inserts, and free-standing stoves. Recently, questions have been raised regarding the contribution of vent-free gas products to the indoor air concentrations of combustion chemicals in “tight” energy-efficient homes.

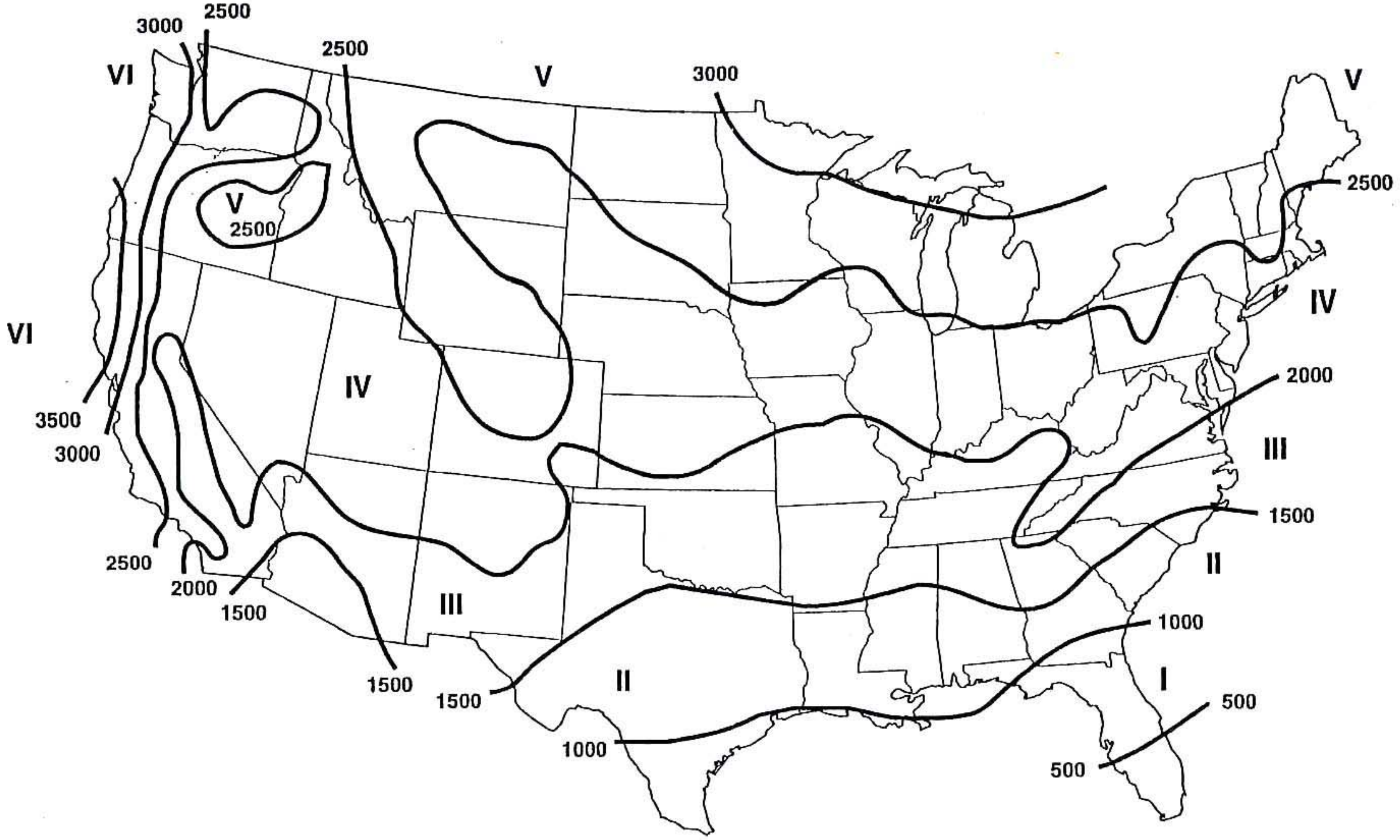
As part of its research program, the Propane Education & Research Council (PERC) has commissioned new research to address the impact of vent-free gas appliances on combustion chemicals in residential energy-efficient conservation structures. These chemicals of interest include carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), oxygen (O_2), and water vapor (H_2O). Currently, no evidence exists in the peer-reviewed scientific literature to indicate that vent-free gas heating products manufactured in accordance with current ANSI codes and maintained according to the manufacturer’s instructions are the cause of any health-related issues in the home from normal anticipated emissions. Nor is there evidence that the small amounts of carbon dioxide, carbon monoxide, or nitrogen dioxide produced as normal combustion products from ANSI code-compliant vent-free gas heating appliances exceed applicable standards for indoor environments. Neither is there evidence that the Oxygen Depletion Sensors (ODSs) are being triggered by use of these devices in “tight” homes. The emergence of national green building codes and standards presents a unique challenge to the vent-free gas products industry. Yet a comprehensive study to determine the impacts of vent-free gas heating products on indoor air quality in residential energy-conservation structures across the country is lacking.

Accordingly, this research project has focused on predicting the impact of unvented gas heating appliance operation on the indoor air quality (IAQ) inside residential structures complying with the most energy-efficient green construction requirements of the International Code Council (ICC). These requirements are memorialized in the International Energy Conservation Code (IECC), the National Green Building Standard (NGBS) and the International Green Construction Code (IGCC). This project is built upon the foundation of existing research on vent-free gas heaters. This foundation includes notable work by (1) the Gas Research Institute (GRI) and the American Gas Association Research (AGAR) Division in developing an indoor air model customized to assessing the IAQ impacts of vent-free gas appliances; (2) development of NO_2 measurement methods by Arthur D. Little; (3) a probabilistic assessment of the impacts of vent-free gas heaters on relative humidity and mold growth indoors (risksciences 2002); and (4) a probabilistic assessment of the levels of NO_2 indoors from use of vent-free gas heating appliances in energy-efficient “tight” homes (toXcel 2012).

In the current research, minimum, maximum, and mid-range values were defined for each of the model input parameters, along with the form of the distribution (e.g., uniform, triangular). The AGAR vent-free model was run in conjunction with the Crystal Ball simulation software; the latter selects input values from each of the input parameter distribution curves at random, enters the values into the AGAR model, and outputs the results. The model output of the probabilistic analysis consisted of distribution of the levels of each of the combustion-related chemicals across 20,000 simulated homes for each DOE Region (see Figure 1), representing different housing characteristics for each set of model runs. This allowed the estimation of the indoor concentrations of the 5 combustion-related chemicals -- carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), oxygen (O_2), and water vapor (H_2O) -- across a wide range of housing types. This report presents the results of the current research, as well as technical background for the reader.

The next section (Section III) provides background information on the combustion-related chemicals of concern assessed in this study, including toxicological effects. Section IV provides an overview of regulatory standards and guidelines for the 5 chemicals. Section V provides an overview of the vent-free model. Section VI of this report presents the technical approaches used and the results obtained in the probabilistic modeling. Section VII provides a discussion of the significance of the findings of the research, and Section VIII provides key references.

Figure 1. DOE Heating Region Map



III. BACKGROUND ON COMBUSTION CHEMICALS

A. Nitrogen Dioxide

Nitrogen dioxide (NO_2) is a deep lung irritant if inhaled in sufficient concentration for sufficiently long a time (Costa and Gordon 2013). NO_2 can also cause irritation of the eyes, nose, and throat at sufficient concentration. Exposure of normal human subjects to levels of less than or equal to 4 ppm NO_2 does not produce consistent impairment of respiratory function (Costa and Gordon 2013). Slightly enhanced airway reactivity may occur in the 1.5 to 2 ppm range of NO_2 for more susceptible individuals. Compliance of vent-free gas heating devices with the ANSI standards results in anticipated levels of NO_2 in rooms where vent-free heating appliances are located that will be significantly below these levels.

Most of the data on the effects of human exposures to NO_2 come from epidemiological studies of populations in urban areas exposed to ppm to sub-ppm levels of NO_2. These studies are confounded by co-exposure to other air pollutants that have pulmonary effects, such as ozone (Costa and Gordon 2013). People routinely experience elevated levels of NO_2 while riding in vehicles or near roadways (on the order of 0.5 ppm). Animal studies, in which test species are exposed via NO_2 inhalation, usually involve concentrations that are higher than those to which humans are exposed. Animal studies suggest that the presence of NO_2 can result in greater susceptibility to infections when challenged with live viruses; however, such studies in humans have been inconclusive (Costa and Gordon 2013). Very high levels of NO_2 are sometimes encountered occupationally (such as the 75 to 100 ppm experienced in enclosed spaces from fermenting silage). Such high levels of NO_2, which are not encountered in residential environments, may be associated with edema and other serious structural and functional damage to the lungs (Costa 2001).

NO_2 reacts with surfaces and other chemicals in the air and, thus, disappears from indoor air at a rate that is higher than accounted for by dilution and air exchange alone. Based on a synthesis of available data, the "reactivity" rate constant has been reported to be on the order of 0.2 to 1 per hour (Spicer *et al*. 1993; Spicer *et al.* 1989; Yang *et al*. 2004; Traynor *et al.* 1985; Traynor 1999; Yamanaka 1984).

B. Carbon Monoxide

Carbon monoxide (CO) is produced in small amounts as a minor combustion product whenever any fuel such as natural gas or propane is combusted. Because CO has a high affinity for binding to hemoglobin (which is the protein that carries oxygen in the bloodstream), exposure to CO may reduce the blood's ability to carry oxygen to tissues in the body. The interaction of CO and hemoglobin results in formation of carboxyhemoglobin (COHb), which has a reduced ability to carry oxygen compared to "free" hemoglobin. The amount of COHb in the blood of an individual is a measure of very recent exposure to CO. Normal metabolism in most individuals results in production of small amounts of CO. Therefore, a concentration of about 0.5 percent COHb is a normal background level (Costa 2001).

No overt human health effects have been attributable to COHb levels below 2 percent in the blood. Continuous exposure of humans to 30 ppm CO in the air leads to an equilibrium level of 5 percent COHb in the blood. Human responses to CO vary depending on concentration and duration of exposure. Most healthy individuals are unlikely to experience significant health effects from *brief* exposures to less than 70 ppm in air. At a longer exposure (90 minutes) at 50 ppm, which results in a COHb level of 2.5 percent in the blood, there is mild to moderate impairment in neurological function tests. Headache, fatigue, and nausea occur for prolonged exposures to 70 ppm CO in air. If CO concentrations increase above 150 to 200 ppm, disorientation, unconsciousness and death may even occur (Costa 2001). Some outdoor levels of levels of CO range from 10 to 40 ppm in urban areas. Some of the highest levels of CO to which individuals are exposed occur daily from commuting in heavy traffic (Costa 2001). Indoor air levels of CO are typically much less.

If appliances that burn natural gas or propane are properly maintained and used according to instructions, the amount of CO produced is not hazardous. The American National Standards Institute (ANSI) maintains a stringent standard for vent-free gas heating appliances known as Z21.11.2, under which all vent-free appliances must be compliant. Under this standard, CO must make up less than 0.02 percent of combustion products "air-free" (i.e., calculated not including the contribution of air to the emissions volume). Further, vent-free heating appliances are required to have a built-in oxygen depletion sensor, which shuts down the unit if conditions for incomplete combustion exist (i.e., should the oxygen level near the unit fall below 18 percent). This prevents significant concentrations of CO from being generated from use of a vent-free gas heating appliance if its performance is adversely affected. With regard to CO emissions, the standard for vent-free gas heating appliances is much more stringent that for direct-vent gas heating appliances.

C. Water Vapor

Vent-free gas appliances emit water vapor as a normal combustion product. There are many sources of water in the home, including (1) appliances (dishwasher, clothes washer, clothes dryer); (2) human activities (showering, cooking); (3) outdoor relative humidity that enters the house; and (4) water infiltration into the structure of the house (e.g., leaking plumbing, roof leaks, gutter overflow and infiltration into the basement). Human breath is also a source of water vapor in the home, releasing significant amounts of moisture into the air.

When air contains all the water vapor that it can possibly hold at a given temperature and the maximum capacity is reached, the air is said to be saturated. Relative humidity refers to the percent saturation of air with water vapor. The amount of water vapor that air can hold depends on temperature; warm air can hold more mass of water per unit volume of air (g/m^3) than cold air. Relative humidity is the ratio of the amount of water vapor in the air at a specific temperature (i.e., actual g/m^3) to the total water capacity of air at that temperature (i.e., the maximum possible g/m^3). At saturation, the relative humidity of the air is 100%. If the relative humidity is high, the air feels "sticky" or "muggy", in part because evaporation of water off the skin (and its resulting cooling effect) is impeded as the air approaches saturation. The relative humidity will change whenever the amount of water vapor in the air changes (e.g., due to water vapor sources in the home) and whenever the capacity of the air changes (such as when air temperature decreases or increases).

Proper humidity control in the home is essential to health and comfort. Too little humidity in the air will result in loss of moisture from hydrated matrices such as skin (leading to dry, cracking, uncomfortable skin), and from fabrics, wood, and carpet fiber leading to conditions that result in generation of static electricity (as when walking across a carpet). Furthermore, low humidity in the home can result in drying of the throat and mucous membranes, and decreased clearance of foreign particles by the mucous-ciliary clearance mechanism in the respiratory tract. During the heating season, moisture provided by combustion sources such as a vent-free heater may be beneficial, and many individuals utilize supplemental humidification during this period (Liebmann 1965).

Too much humidity can lead to discomfort and, under some conditions, mold and mildew growth can occur. Molds produce spores which are tiny dormant forms of fungi that can be easily re-suspended (e.g., by walking) and carried by air currents throughout the residence. High-efficiency and electronic furnace filters, and increased use of central air conditioning and dehumidifiers tend to be associated with lower fungal levels in some homes (DeKoster and Thorne 1995). When spores land on a surface, they can germinate when adequate moisture becomes available. Spores, when released, are a resistant form of the organism that can be transported to new locations by air currents.

Molds and mildews require moisture, oxygen, and a carbon source in order to grow. Mold spores are everywhere in the environment including outdoor air, soil, plant leaves, indoor air, carpets, clothing, and indoor surfaces. Controlling moisture in the home is the best way to control mold growth. A relative humidity level of 70 percent or higher must be attained on a surface for active growth of mold and mildew (Morey *et al*. 1984).

Besides damaging affected materials, mold and mildew can trigger allergic and asthmatic responses in certain individuals. Flannigan *et al*. (1993) reported a median count of fungi of 94 colony-forming units[3] per cubic meter (CFU/m^3) for “non-complaint” houses with no history of need for remediation for dampness, compared to a median of 624 CFU/m^3 for “complaint” houses with a history of dampness and mold, based on data collected on houses in Scotland. Of 40 homes monitored in Victoria, Australia in which one or more residents suffered from respiratory symptoms such as asthma and allergy, 25 percent of the homes had viable mold counts higher than 2,000 CFU/m^3, and roughly 12 percent of the homes had viable mold counts higher than 10,000 CFU/m^3 (Godish *et al*. 1993).

A number of frequently cited guidelines have been proposed by individuals based on data that relate mold counts in the air to symptoms (e.g., allergic responses), or based on experience. Quantitative standards and guidelines range from less than 100 to greater than 1,000 CFU/m^3 (total fungi) as the upper limit for “non-contaminated” indoor environments (Rao *et al* 1996).[4] In the United States, one of the most citable benchmarks is the 1995 guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH). In the ACGIH guidelines, < 100 CFU/m^3 is considered to represent a “low” and acceptable level of fungi for general indoor environments, though more typically characteristic of institutions (e.g., hospitals) than residences. A level of 100 to 1,000 CFU/m^3 is considered to be intermediate, and a level of >1,000 CFU/m^3 is considered to be high for residential settings (Rao *et al*. 1996). The American Industrial Hygiene

Association (AIHA) also considers greater than 1,000 CFU/m^3 to represent an atypical situation. If indoor microbial aerosols are consistently more than double outdoor levels for a specific building, and levels exceed 1,000 CFU/m^3, it is recommended that the structure should be investigated further (Rao *et al*. 1996; Burge *et al*. 2001).

There have been a few publicized cases of toxic mold syndrome, involving lung damage and hemorrhaging caused by species of the mold *Stachybotrys*. However, such cases are rare and do not reflect the more minor effects of molds more commonly found in the home (e.g., *Penicillium*, *Aspergillus*). *Stachybotrys* is usually associated with extremely wet conditions indoors (Burge 2001), such as water-damage inside the wall structures of homes caused by construction-related errors.

D. Carbon Dioxide

Carbon dioxide (CO_2) is a gas that is present in the atmosphere at concentrations around several hundred parts-per-million (ppm). It is produced in humans and exhaled as a by-product of normal metabolism. Humans can tolerate levels of CO_2 around 15,000 ppm (1.5 percent in air) for prolonged periods of time without adverse effects. CO_2 is generally associated with low toxicity in mammals; when inhaled at concentrations around 30,000 ppm (3 percent in air), it may produce a mild narcotic effects and cause both blood pressure and pulse to rise. Signs of toxicity occur at 50,000 ppm (5 percent in air) when the exposure duration is at least 30 minutes. Exposure to CO_2 at 70,000 to 100,000 ppm (7 to 10 percent of air) for just a few minutes produces unconsciousness. At very high concentrations it can cause death by asphyxiation, depending on the concentration present and the duration of exposure (ACGIH 2001).

E. Oxygen

Oxygen (O_2) is not of toxic concern; rather it is essential for normal respiration and metabolism in all animals and humans. The use of vent-free gas heating appliances consumes a limited amount of oxygen in the room where the vent-free appliance is located, as a result of normal combustion processes. The normal level of O_2 in the atmosphere is around 21 percent of air; the minimum level considered to be safe for humans in 18 percent of air (ACGIH 2001). Submarine crews restricted to atmospheres containing only 15 to 17 percent O_2 in air have reported ill effects (ACGIH 2001). In contrast, artificially elevated levels of oxygen can present a combustion risk when flammable chemicals or materials are present.

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[3] For fungi, one colony forming unit (CFU) corresponds with one mass of mycelial growth on a culture dish containing culture media following inoculation of the culture dish with spores or live organisms.

[4] For the purposes of this discussion, a standard is defined as a requirement and a guideline is defined as a recommendation.

IV. REGULATORY STANDARDS AND GUIDELINES

A. Nitrogen Dioxide

National and international standards currently exist for the allowable short-term and long-term levels of nitrogen dioxide (NO_2) in indoor and outdoor environments. These are summarized in Table 1.

Table 1. Airborne Standards for Nitrogen Dioxide in Indoor and Outdoor Environments

Agency	*Type of Standard*	*Applicability*	*Averaging Period*	*Numerical Value*	
				ppm	*mg/m^3*
USEPA[e]	NAAQS[a]	Outdoor	Annual[b]	0.053[d]	0.100
	NAAQS[a]	Outdoor	1-hour[c]	0.100	0.19
CPSC[e]	Residential	Indoor	1–hour	0.300	0.56
WHO[e]	----	Indoor/Outdoor	1-hour	0.110	0.20
Health Canada	Residential	Indoor	24-hour	0.050	0.094
		Indoor	1-hour	0.25	0.47

[a] National Ambient Air Quality Standards; see 75 FR 6474, February 9, 2010, and 61 FR 52852, October 8, 1996.

[b] Primary and secondary NO_2 standard; primary standards provide protection of public health; secondary standards provide protection from decreased visibility and from damage to animals, crops, vegetation, and buildings.

[c] Primary NO_2 standard equivalent to 100 ppb in outdoor air as the 98th percentile 1-hour average over 3 years.

[d] Equivalent to 53 ppb in outdoor air as an annual mean.

[e] Agency abbreviations: USEPA = U.S. Environmental Protection Agency; CPSC = Consumer Product Safety Commission; WHO = World Health Organization.

With regard to short-term standards for NO_2, the Consumer Product Safety Commission (CPSC) level of 300 ppb (0.3 ppm, or 0.56 mg/m^3) may be the most directly applicable standard for an unvented gas heating appliance in the U.S. This standard is similar to the 0.25 ppm 1-hour Health Canada indoor residential benchmark. The short-term (1-hour) outdoor NO_2 standard by the United States Environmental Protection Agency (USEPA) and the World Health Organization standard based on 1 hour periods (0.10 ppm and 0.11 ppm, respectively) are more restrictive by comparison. The available long-term (annual) standard to NO_2 of 0.053 ppm promulgated by the U.S. Environmental Protection Agency (USEPA) is similar to the 24-hour standard established by Health Canada, which is 0.050 ppm (24-hour).

B. Carbon Monoxide

Regulatory standards and guidelines for CO exposure have been established. The USEPA has set CO standards for outdoor air of 9 ppm as an 8-hour average, and 35 ppm as a 1-hour average. The Consumer Product Safety Commission (CPSC) has recommended a 1-hour average level of 15 ppm as being protective of sensitive populations such as children, pregnant women, and the elderly. The standards for CO are shown in Table 2.

Table 2. Airborne Standards for Carbon Monoxide (CO)

Agency	*Type of Standard*	*Applicability*	*Averaging Period*	*Numerical Value*	
				ppm	*mg/m*^{3}
USEPA	NAAQS[a]	Outdoor	8 hour	9	10
	NAAQS[a]	Outdoor	1-hour	35	40
CPSC	----	Indoor	1-hour	15	17

[a]NAAQS = National Ambient Air Quality Standard.

C. Water Vapor

A number of relative humidity benchmarks have been established, as shown below in Table 3. The American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) has set an indoor relative humidity range of 40 to 60 percent as desirable for comfort, as shown in Table 3. The USEPA has set a range of 30 to 60 percent as a desirable range for mold and mildew control. The USEPA has suggested that if there is mold growing on a surface, relative humidity has been at greater than 70 percent locally at the surface (risksciences 2002).

Table 3. Benchmarks for Other Combustion-Related Chemicals

Chemical	*Type of Benchmark*	*Applicability*	*Numerical Value*	*Comments*
Oxygen	Normal Level	Indoor and Outdoor	21 %	----
	ODS (flame out)	Indoor	18 %	Next to pilot flame
Water Vapor	Comfort	Indoor	40 – 60 %	ASHRAE
	Mold Growth	Indoor/Outdoor	70 %	Active mold growth above this limit
Carbon Dioxide	8-hour	Confined Space	5,000 ppm	OSHA/NIOSH
	----	Indoor Air Quality	3,500 ppm	Canada

D. Carbon Dioxide

There are no health-based standards for carbon dioxide (CO_2) for outdoor settings. The Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) have recommended an 8-hour workplace standard of 5000 ppm. Canada has a recommended level of 3,500 ppm as a benchmark of acceptable indoor air quality. Because humans exhale a certain amount of carbon dioxide, crowded and poorly-ventilated spaces may be associated with elevated levels of CO_2.

E. Oxygen

The issue relating to oxygen for use of unvented gas heating appliances is with respect to oxygen consumption, not oxygen generation. A normal indoor space would contain 21% oxygen (O_2) in air. The ODS built into every unvented gas heating appliance triggers at roughly 18 % O_2.

V. OVERVIEW OF THE VENT-FREE MODEL

In the mid-1990's, the American Gas Association Research (AGAR) Division developed an indoor air quality model for the Gas Research Institute (GRI) that simulates how indoor air quality varies with time in a well-mixed space heated by a vent-free gas appliance (GRI 1996). A conceptual overview of the AGAR vent-free model is shown in Figure 2 for the illustrative case of water vapor. This AGAR vent-free gas heating appliance model was used in the current work to determine the impact of various parameters on indoor relative humidity in the room where the vent-free appliance is used. The model considers a number of parameters, including heat losses from the ceiling, walls, and floor of the room of product use; the volume of the room where the vent-free appliance is used; the volume of connected space outside of the room of use that provides dilution for combustion products; the air exchange rate; house volume; and outdoor conditions.

The model uses known emission characteristics of the vent-free products, and incorporates the anticipated on/off cycling of the product during use. The AGAR vent-free appliance model also accounts for heat losses and gains. Heat flows to indoor air include (1) energy required for heating cold infiltrating outdoor air; (2) energy losses conducting through exterior walls, floors, and ceiling; and (3) heat accumulated by sinks such as ceiling, floor and furniture during the “ON” cycle of the device. The heat sources accounted for by the model include the gross input rate minus the latent heat of combustion (during the “ON” cycle), and heat accumulated by interior surfaces (during the “OFF” cycle).

In the original research (GRI 1996), the vent-free model was validated using actual measurements conducted in 2 fully-instrumented research homes: the AGAR research house in Cleveland and the GRI house in Chicago. The model performed well in predicting airborne levels of combustion chemicals associated with normal anticipated uses of vent-free products, as well as accurately predicting the indoor air levels of other combustion products under the conditions tested. Prior work (GRI 1996) indicates that because of the dynamic nature of air exchange and air movement in a house, airborne concentrations of combustion products from vent-free appliances level off in the room of product use after just a few hours of operation, and an equilibrium value (asymptote) is attained until conditions change or the vent-free product is turned off. Then, the airborne levels indoors decline over time due to dilution by air exchange, or chemical reactivity or decay (e.g., as in the case of NO_2.)

In calculating relative humidity, specifically, the vent-free model considers all sources of water vapor in the home, including the vent-free product, water generation by people (breathing), and “other” sources of water (e.g., cooking, showering, washing and drying clothes). In this respect, the model is comprehensive with regard to water vapor sources. The vent-free gas heater and the people in the room where the product is located are assumed to directly contribute water vapor to that room, whereas water vapor from “other” sources are assumed to be diluted into the whole volume of the house. Additionally, the model assumes dilution of combustion products from the room of use into available connected space, i.e., adjacent space immediately outside of the room of use with which the air of the room freely communicates.

The model also takes into account the following considerations:

(1) The characteristics of the heated space in which the vent-free gas product is located (room volume, house volume, heat loss, air exchange rate, connected space);

(2) The initial indoor air conditions (air specific heat, air density, temperature set point, initial indoor air concentrations of each combustion chemical);

(3) The outdoor air characteristics (outdoor air temperature, relative humidity);[5] and

(4) The vent-free appliance characteristics (temperature control, gross heat input; emission rates).

For ease of use, the BASIC computer program VENTF1.BAS was converted to a Microsoft Excel spreadsheet for ease of use, and was customized for this particular modeling exercise. The vent-free model, including modifications, is described along with the source code in Attachment A.

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[5] The modeling work incorporated outdoor humidity as a contributor to indoor humidity; values of zero were assigned for outdoor CO, NO_2, and CO_2 as a simplifying assumption, given that energy conservation homes would have very little infiltration of outdoor air into the home.

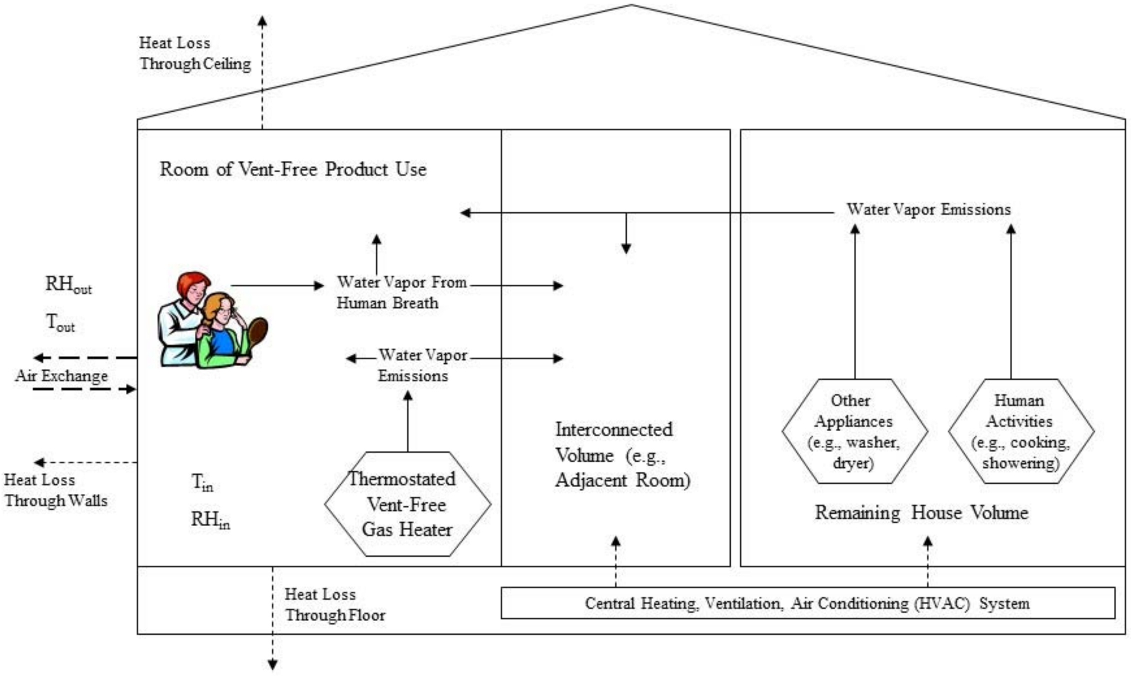

Figure 2. Conceptual overview of the AGAR vent-free gas appliance model for the illustrative case of water vapor (where T_{out} and RH_{out} represent outdoor temperature and outdoor relative humidity, respectively, and T_{in} and RH_{in} represent the indoor temperature and relative humidity, respectively, in the room where the vent-free gas appliance is used in the residence).

VI. PROBABILISTIC ANALYSIS

A. Background on Probabilistic Analysis

A probabilistic or distributional approach, also known as a Monte Carlo analysis, is one way of quantifying the uncertainties in a modeling analysis (Whitmyre *et al*. 1992a, 1992b). It is called a "probabilistic" approach because it estimates the probability or likelihood of a specific value occurring in the output distribution of the model. It can also be referred to as a "distributional" approach because the output is a continuous distribution or curve of possible model output values across a large number of simulation cases. In such an analysis, the input parameter distributions are sampled to obtain one value for each parameter; this is accomplished using a random approach to select a value for each parameter based on the range of values available in that parameter's input distribution (Price *et al*. 2001). Once values are selected for each input parameter, the model is run with the selected set of parameter values to obtain a model output, and the output value is stored. The input parameter distributions are then sampled to obtain a different set of parameter values and the model is run again and the output value is stored. This process is repeated a large number of times (e.g., 10,000 or 20,000 times). Thus, based on the input parameter distributions, the output distribution is "filled out" using the simulation methods (Whitmyre *et al*. 1992a). Statistical analyses are conducted and graphical displays of the output data (e.g., histograms, cumulative distribution curves) can be developed.

B. Technical Approach

For conducting the probabilistic analysis, a Microsoft Excel application of the AGAR vent-free model was connected to a simulation software known as *Crystal Ball*^{TM}. Using this pairing of software, key model parameters were varied simultaneously across the respective ranges of possible values. Parameters varied included the size of the room in which the product is used, the size of the house, outdoor relative humidity, air exchange rate, number of people in the room, input rate (Btu/hr), size of the connected space, number of room walls with outdoor contact, heat loss factors, and type of water source. Specific distribution forms for each input parameter were assumed, for example, uniform or triangular distribution forms. A uniform distribution assumes that each value for a model parameter has an equal chance of occurring within its predicted range of values. A triangular distribution assumes that some central tendency value is associated with the greatest frequency of occurrence, and that values toward the low end or high end of the distribution curve occur progressively less frequently. Some parameter values, where it made sense, were kept as fixed values and were not varied. For example, the outdoor temperature for a given DOE Heating Region was kept fixed at the 1,000 hr heating temperature for the given region to simplify what would otherwise be a very complicated function reflecting day-to-day temperature variations. The rate of generation of a combustion chemical by the vent-free appliance was kept constant, as was the per-person generation of water vapor by breathing, for example. Some variables were scaled to the number of people in the room where the vent-free gas appliance is located. An example is the water vapor generation by "other" sources from the prior research (GRI 1996), which was scaled on a per-person basis to represent a variety of water use scenarios in the living space of the house.

A total of 20,000 simulations (equivalent to 20,000 different house scenarios) were conducted for each DOE Region. Values in distributions of maximum values (specifically for NO_2 for comparison to 1-hour standards) were subjected to truncation of the distribution at the 95 percentile to remove outliers resulting from unlikely combinations of parameter values. The distributions of airborne levels of CO, CO_2, O_2, and water vapor are based on time-averaged concentrations for comparison to time-averaged benchmarks. The statistical output from each of the probabilistic runs included the mean, various percentile values (including the maximum or 100th percentile), and the percent of cases below or above a benchmark value, such as the percent of simulated cases resulting in indoor relative humidity values less than 70 percent. Histogram plots (frequency of occurrence vs. output value) for measures of the indoor air levels of CO were developed as examples.

C. Selection of Input Parameter Ranges

1. *Size of Room*: The National Association of Home Builders (NAHB) collected data on typical room sizes in houses in 1986 and 1992 (Ahluwalia 1992). In 1986, the "typical" living room ranged from 174 ft^2 to 340 ft^2. In 1992, the "typical" living room ranged from 185 ft^2 to 485 ft^2. Examining the range of means across both surveys and across various house sizes, a range of 174 ft^2 (13.2 ft x 13.2 ft) to 485 ft^2 (22 ft x 22 ft) was obtained for floor area (see Table 4). A uniform distribution was assumed.

2. *Size of House*: Across the 1986 and 1992 surveys, the NAHB reported data for houses ranging from 1,600 ft^2 to 6,000 ft^2 (Ahluwalia 1992). This is equivalent to house volumes of 12,800 ft^3 to 48,000 ft^3 if we assume an *average* 8-foot ceiling height across the house. There are states that typically contain a range of smaller homes. For example, the median (50th percentile) residential volume in California was determined to be around 10,000 ft^3 (Wilson *et al*. 1996). To be conservative in the current analysis, a lower bound of 8,000 ft^3 (equivalent to a 1,000 ft^2 home with an 8-foot ceiling) and an upper end of the range NAHB focused on (48,000 ft^3) were used to define the range for house volume for the probabilistic assessment. The range of 8,000 ft^3 to 48,000 ft^3 was assumed to be distributed as a uniform distribution.[6] There may be larger houses that we have not included, but there are probably not too many houses smaller than 1,000 ft^2.

3. *Outdoor Relative Humidity*: NOAA (2001) has assembled 30-year local climatological data, including outdoor relative humidity for specific locations in the United States for the period 1971 through 2001. Three specific locations within each DOE region were selected to reflect the range of possible conditions across each region. Monthly average minimum, average maximum, and mean outdoor relative humidity data are presented in Table 5. Based on the NOAA data for the heating season November/December/January/February 1971-2001, a range of 50% to 90% outdoor relative humidity was selected to encompass all the statistically-averaged range limits and data points (average minimum, average maximum, and mean value) for all Regions.

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[6] In order to represent contemporary living rooms and great rooms in energy efficient homes, the ceiling height in the room where the vent-free gas heating appliance is used was varied from 8 ft to 10 ft. Other rooms in each house were assigned a ceiling height of 8 feet.

Table 4. Summary of Allocation of Floor Area in Different Sized Homes, Based on 1986 and 1992 NAHB Surveys[a]

Area	Floor Area Allocation (sq. ft.) — 1986 NAHB Survey				Floor Area Allocation (sq. ft.) — 1992 NAHB Survey					
Exterior Measurements	1,600	2,000	2,600	3,700	1,600	2,000	2,600	3,700	4,400	6,000
Interior Measurements	1,433	1,740	2,316	3,380	1,472	1,712	2,350	3,390	3,790	4,800
Entry Foyer	27	68	116	160	51	93	100	165	210	220
Living Room	174	220	230	340	185	176	225	320	445	485
Dining Room	118	153	165	190	100	118	175	170	255	320
Family Room	193	198	230	380	194	255	305	390	350	465
Den/Study Room	---	---	110	180	---	94	100	190	205	400
Kitchen	173	213	265	370	190	202	250	370	370	500
Bedroom	501	567	780	970	500	505	850	980	1,110	1,380
Bathroom	145	195	235	545	146	151	220	550	565	660
Hallway	71	84	140	165	65	66	75	170	195	245
Utility Closet	31	42	45	80	41	55	50	85	85	125

[a] Source: Ahluwalia (1992)

Table 5. Averaged Outdoor Relative Humidity Statistics for the Period November through February, 1971 to 2001[a]

DOE Region	Location	Nov.-Feb. Average Minimum for:		Nov.-Feb. Average Mean for:		Nov.-Feb. Average Maximum	
		Location	Region[b]	Location	Region[b]	Location	Region[b]
I	Jacksonville, Florida	56.8	59.5	75.5	75.4	87.5	87.1
	Tampa, Florida	57.3		74.5		86.8	
	Corpus Christi, Texas	64.3		76.3		87.0	
II	Dallas, Texas	56.5	58.2	67.3	70.8	79.8	83.4
	Jackson, Mississippi	60.8		75.3		87.8	
	Montgomery, Alabama	57.3		69.8		82.5	
III	Raleigh, North Carolina	53.3	57.0	66.8	67.9	80.3	79.5
	Oklahoma City, Oklahoma	56.5		67.0		77.8	
	Nashville, Tennessee	61.3		69.8		80.5	
IV	Pittsburgh, Pennsylvania	64.0	64.6	69.8	70.9	76.0	76.9
	Des Moines, Iowa	65.8		72.0		77.8	
	Salt Lake City, Utah	64.0		71.0		77.0	
V	Syracuse, New York	67.8	69.0	74.3	75.0	78.8	79.7
	Lansing, Michigan	72.3		78.8		83.5	
	Minneapolis, Minnesota	66.8		71.8		76.8	

[a] Source: NOAA Local Climatological Data (NOAA 2001)
[b] Based on the 3 selected cities in each region.

This is a conservative approach because a true minimum of 15 to 20 percent outdoor relative humidity can occur in winter in specific locations (Sullivan 2002). Conversely, storm events or fog corresponding to 100 percent humidity do occur, but are infrequent and short-lived in most locations (Sullivan 2002). Therefore, shortening the distribution of outdoor relative humidity to 50 to 90 percent is adequately conservative because it would potentially result in a somewhat higher mean indoor relative humidity than would the full range of outdoor humidity of 20 to 100 percent.

4. *Volume of connected space*: For the purpose of modeling, "connected" space was defined as additional volume that constitutes contiguous airspace with the room where the vent-free gas heating appliance is used. This could be an adjacent hallway, room, or foyer if the airspace is open and continuous. It was assumed that connected space could range from a value of zero to an area the size of the room. The form of the distribution of values for this parameter was assumed to be a uniform distribution, meaning equal probability of occurrence of values.

5. *Type of house structure*: In the model the type of housing stock is assigned an integer value to reflect the degree of "leakiness." The "P" values are 1 (tight), 2 (average), or 3 (loose). For the purpose of this modeling exercise, all simulations involve houses with a "P" value of 1.

6. *Air Exchange Rate*: 0.10 to 0.35 hr^{-1}. These air exchange rates are consistent with energy-conservation homes, and are conservative in that the lower portion of this range reflects very small air exchange rates that may not be commonly attainable. The air exchange range of 0.35 is the limit below which mechanical ventilation may be required under some U.S. building codes. This range corresponds to roughly the lower quartile (1st to 25th percentile) air exchange rates for the Eastern U.S. for non-summer seasons (Pandian *et al*. 1998).

7. *Number of People in Room*: The original research (GRI 1996) included this term because exhalation of breath from individuals does add some CO_2 and water vapor to an occupied room, as well as a small amount of CO as an endogenous by-product of normal metabolism. For our analysis, we assumed a uniform distribution of values of either 1 or 2 individuals being present. Because vent-free gas appliances are easily controlled, some via hand-held remote, it was assumed that a vent-free gas fireplace would be turned off upon leaving the room of product use.

8. *Outside Temperature*: The 1,000 hr average temperature for each DOE Heating Region is a statistically robust representative value and was used, as follows:

Region I: 56 F
Region II: 45 F
Region III: 36 F
Region IV: 26 F
Region V: 13 F

9. *Number of External Walls*: A room containing the vent-free gas appliance could have 1, 2, or 3 walls in contact with the outside environment. Thus, it was assumed that 1, 2, or 3 external walls could occur as a uniform distribution, with a mid-range value of 2.

10. *Input Rate*: A cross-section of manufacturers' products was discussed with industry experts as part of this research effort to document the range of input rates represented by different kinds of products. Across all product categories, the range of rated inputs is from approximately 10,000 to 40,000 Btu/hr, the maximum allowable input rate. A triangular distribution with a minimum of 10,000, a midpoint of 20,000 Btu/hr, and a maximum of 40,000 Btu/hr was assigned.

11. *Heat Loss Factors*: U factors (heat loss factors) consider energy required for heating cold infiltrating outside air, and heat losses by conduction through the floor, ceiling, and walls of the room of use. U factors were assigned based on regional considerations and air exchange rate. The model, as originally designed (GRI 1996), assigns different point values for U factors (heat loss factors) for ceilings, walls and floors. Air exchange was "binned" into 2 categories covering the 0.1 to 0.35 ACH range. U factors based on geographic zone are available from the ICC's current National Green Building Standards (ICC-700 2012), ICC's International Energy Conservation Code (IECC 2012), and ASHRAE 90.2-2007 (Energy-Efficient Design of Low-Rise Residential Buildings). ICC-700 2012 and IECC 2012 have similarly low U-factor values.[7] Table 6 shows the slightly lower U-values from IECC-2012 (i.e., more restrictive in requiring a higher level of insulation) that were assigned here when the air exchange rate (ACH) is in the 0.1 to 0.225 range. U-factor values from the 2012 National Green Building Standards were assigned when the ACH is in the range >0.225 to 0.35, as shown in Table 7. The ASHRAE 90.2-2007 U factors are less restrictive than the 2012 IECC or the National Green Building Standards and were not used.

Table 6. U-Factors for Low-Rise Residential Structures per IECC 2012[a]

DOE Heating Region	*Climate Zone*	*U-Factor[b] Values for Portions of "Tight" Residential Structures (ACH = 0.1 to 0.225 ACH)*		
		Ceiling	*Frame Walls*	*Floor*
---	1	----	----	----
1	2	0.030	0.082	0.064
2	3	0.030	0.057	0.047
3	4	0.026	0.057	0.047
4	5	0.026	0.057	0.033
5	6	0.026	0.048	0.033

[a] IECC 2012 = ICC's 2012 International Energy Conservation Code.
[b] U = 1/(R Factor); where R is in units of (m^2 °C/W).

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[7] U factors from the cited 2012 code documents were used for performing the modeling; subsequent to completion of the work, a 2015 version of the ICC's International Energy Conservation Code (IECC) was released.

Table7. U-Factors for Low-Rise Residential Structures per Green Building Standards[a]

DOE Heating Region	*Climate Zone*	*U-Factor[a] Values for Portions of "Tight" Residential Structures (ACH > 0.225 ACH to 0.35 ACH)*		
		Ceiling	*Frame Walls*	*Floor*
---	1	----	----	----
1	2	0.035	0.082	0.064
2	3	0.035	0.082	0.047
3	4	0.030	0.082	0.047
4	5	0.030	0.057	0.033
5	6	0.026	0.057	0.033

[a] U = 1/(R Factor); where R is in units of (m^2 °C/W).

[b] ICC's 2012 National Green Building Standard (ICC 700-2012).

12. <u>NO_2 reactive decay rate</u>. A decay constant range of 0.25/hr to 1/hr is available from a synthesis of the literature. For the current modeling exercise, a triangular distribution of values was assumed with a minimum of 0.25/hr (GRI 1996), a rounded maximum of 1/hr and a midpoint of 0.70/hr (midpoint based on Traynor 1999; and Traynor *et al*. 1985), which is close to the average of 0.8/hr from Spicer *et al*. (1989).

13. *Rate of Water Vapor Production.* The rate of water vapor production by a vent-free gas appliance was held constant at the original model default of 0.0000362 kg per second-kW. The rate of water vapor production by people exhaling was held constant at the original model default of 0.0000126 kg per second per person. The rate of water vapor generation from "other" sources (e.g., cooking, clothes dryer, showering, dishwashing, other activities) was up to 0.00001718 kg per second per person. It is not known whether these "other" water vapor sources co-occur in time with the water vapor releases from human breath and vent-free heating appliance products in the room of product use. Accordingly, this parameter was varied as a uniform distribution over the range of zero to 0.00001718 kg per second per person.

D. Results

Frequency histograms for carbon monoxide were developed for each DOE Region, as examples. Histograms for DOE Heating Regions I and V are shown in Figures 3 and 4. The distribution for Region I is relatively "tight", appearing to be almost a normal "bell-shaped" distribution when N = 20,000. The distribution form for the model output distribution of a given combustion chemical becomes more "spread out" and more distinctly lognormal in form as one approaches colder areas (e.g., Region V). Exemplary histograms for all regions for carbon monoxide, as an example, are shown in Attachment B.

The results of the modeling effort are described in Table 8 in terms of percentile indoor air concentration values, and in Table 9 as the percent of cases exceeding the relevant benchmark reflecting the acceptable airborne concentration of a combustion chemical. The time-average carbon monoxide (CO) levels for all of the simulated cases, including the maximum time-weighted value (which is the 100th percentile), are associated with airborne levels of CO (in the room where the vent-free gas heating appliance is located) that are below both the 8-hour USEPA NAAQS standard of 9 ppm and the CPSC standard of 15 ppm.

The maximum nitrogen dioxide (NO_2) levels for all of the simulated cases in all DOE Regions are associated with airborne levels of NO_2 that are below the 1-hour CPSC benchmark of 0.3 ppm (the most appropriate benchmark), and the Health Canada 1-hour benchmark of 0.25 ppm. All of the simulated cases for NO_2 for DOE Heating Regions I, II, III, and IV are below the World Health Organization (WHO) indoor air quality guideline of 0.11 ppm. For DOE Heating Region V, 99.9 percent of all modeled maximum cases for NO_2 are below the WHO 1-hour benchmark. For the time-averaged concentrations of carbon dioxide (CO_2), a non-toxic gas, all of the simulated cases are below the Canadian standard of 3500 ppm and, thus, below the 8-hour OSHA standard of 5000 ppm. Due to the abundance of oxygen in a residential setting and the nature of the ventilated space in the home, there is virtually no impact of the use of a vent-free gas heating appliance on oxygen levels in the room of product use. All of the time-averaged concentrations for oxygen for all DOE Regions are in the range of 20.5 to 20.9 percent. This range for oxygen concentrations is above the standard benchmark of 19.5 percent O_2 for what is considered a partially depleted atmosphere (GRI 1996). It is also well above the 18 percent cutoff for triggering the Oxygen Depletion Sensor (ODS), which acts as a fail-safe for turning off the vent-free gas heating appliance when impaired combustion conditions exist.

Table 8. Indoor Air Levels of Combustion-Related Chemicals Predicted in Energy Conservation Homes With a Vent-Free Gas Heating Appliance, Based on IAQ Modeling Using the AGAR Vent-Free Gas Appliance Model

Region 1		Region 2		Region 3		Region 4		Region 5	
Percentile	CO ppm	Percentile	CO ppm	Percentile	CO ppm	Percentile	CO ppm	Percentile	CO ppm
50	0.21	50	0.30	50	0.38	50	0.44	50	0.54
60	0.23	60	0.33	60	0.42	60	0.48	60	0.58
70	0.25	70	0.36	70	0.45	70	0.52	70	0.63
80	0.28	80	0.39	80	0.50	80	0.57	80	0.70
90	0.33	90	0.45	90	0.57	90	0.65	90	0.80
95	0.36	95	0.50	95	0.63	95	0.72	95	0.88
99	0.43	99	0.58	99	0.75	99	0.85	99	1.05
100	0.56	100	0.72	100	0.95	100	1.04	100	1.31

Region 1		Region 2		Region 3		Region 4		Region 5	
Percentile	CO_2 ppm	Percentile	CO_2 ppm	Percentile	CO_2 ppm	Percentile	CO_2 ppm	Percentile	CO_2 ppm
50	398	50	440	50	484	50	519	50	574
60	448	60	491	60	536	60	571	60	630
70	514	70	551	70	598	70	634	70	697
80	598	80	632	80	679	80	719	80	783
90	748	90	766	90	816	90	854	90	927
95	900	95	899	95	948	95	984	95	1061
99	1227	99	1201	99	1239	99	1266	99	1355
100	2073	100	1974	100	2147	100	2071	100	1984

Table 8. Indoor Air Levels of Combustion-Related Chemicals Predicted in Energy Conservation Homes With a Vent-Free Gas Heating Appliance, Based on IAQ Modeling Using the AGAR Vent-Free Gas Appliance Model (cont'd.)

Region 1		Region 2		Region 3		Region 4		Region 5	
Percentile	NO_2 ppm	Percentile	NO_2 ppm	Percentile	NO_2 ppm	Percentile	NO_2 ppm	Percentile	NO_2 ppm
50	0.02	50	0.03	50	0.04	50	0.04	50	0.05
60	0.03	60	0.03	60	0.04	60	0.04	60	0.05
70	0.03	70	0.04	70	0.04	70	0.05	70	0.06
80	0.03	80	0.04	80	0.05	80	0.05	80	0.06
90	0.03	90	0.04	90	0.05	90	0.06	90	0.07
95	0.04	95	0.05	95	0.06	95	0.06	95	0.08
99	0.04	99	0.05	99	0.07	99	0.08	99	0.09
100	0.06	100	0.07	100	0.09	100	0.10	100	0.13

Region 1		Region 2		Region 3		Region 4		Region 5	
Percentile	% O_2	Percentile	% O_2	Percentile	% O_2	Percentile	% O_2	Percentile	% O_2
50	20.9	50	20.9	50	20.9	50	20.9	50	20.8
60	20.9	60	20.9	60	20.9	60	20.8	60	20.8
70	20.9	70	20.9	70	20.8	70	20.8	70	20.8
80	20.9	80	20.8	80	20.8	80	20.8	80	20.8
90	20.8	90	20.8	90	20.8	90	20.8	90	20.8
95	20.8	95	20.8	95	20.8	95	20.8	95	20.7
99	20.7	99	20.7	99	20.7	99	20.7	99	20.7
100	20.6	100	20.6	100	20.5	100	20.5	100	20.5

Region 1		Region 2		Region 3		Region 4		Region 5	
Percentile	RH	Percentile	RH	Percentile	RH	Percentile	RH	Percentile	RH
50	46.1	50	38.7	50	33.7	50	29.1	50	26.5
60	48.6	60	40.8	60	35.7	60	31.1	60	27.6
70	51.6	70	43.5	70	38.3	70	33.8	70	29.9
80	55.7	80	47.3	80	42.0	80	37.5	80	33.5
90	62.4	90	54.4	90	48.6	90	44.2	90	40.2
95	69.6	95	61.2	95	55.5	95	51.2	95	47.3
99	81.8	99	77.0	99	72.4	99	68.3	99	63.7
100	91.5	100	93.3	100	94.7	100	95.3	100	96.4

Table 9. Percent of Simulations Producing Indoor Air Levels of Combustion-Related Chemicals Below Benchmarks (N = 20,000 Simulations per Region)

Percent of Cases Below Benchmark[b]									
Region 1		**Region 2**		**Region 3**		**Region 4**		**Region 5**	
CO	100.0	**CO**	100.0	**CO**	100.0	**CO**	100.0	**CO**	100.0
CO_2	100.0	**CO_2**	100.0	**CO_2**	100.0	**CO_2**	100.0	**CO_2**	100.0
NO_2	100.0	**NO_2**	100.0	**NO_2**	100.0	**NO_2**	100.0	**NO_2**	99.9
O_2	100.0	**O_2**	100.0	**O_2**	100.0	**O_2**	100.0	**O_2**	100.0
RH	95.2	**RH**	97.8	**RH**	98.7	**RH**	99.2	**RH**	99.5

*Except for oxygen, for which the percent of simulations <u>above</u> the benchmark of 18% for triggering the ODS are shown.

[b] The benchmarks are as follows: For carbon monoxide (CO) 9 ppm; for carbon dioxide (CO_2) 3500 ppm; for nitrogen dioxide (NO_2) 0.110 ppm; for oxygen (O_2) 18 percent; for water vapor 70 percent relative humidity (RH).

The results for the time-averaged indoor relative humidity in winter, with all sources of water vapor considered, varied depending on the geographic region. In DOE Heating Region V (New England and the extreme northern edge of the Central Plains), 99.5 percent of the simulated cases were associated with a total indoor relative humidity less than the threshold for mold and mildew growth. In DOE Heating Region IV, 99.2 percent of the simulated cases were associated with a time-averaged total indoor relative humidity (RH) less than the threshold for mold and mildew growth. In DOE Heating Region III, 98.7 percent of the simulated cases were associated with a time-averaged total indoor relative humidity less than 70 percent RH.

In DOE Heating Region II, almost 98 percent of the simulated cases were associated with a time-averaged total indoor relative humidity less than the 70 percent RH threshold for mold and mildew growth. In DOE Heating Region I (Florida and the Gulf Coast), 95.2 percent of the simulated cases were associated with a time-averaged total indoor relative humidity less than the 70 percent RH threshold for mold and mildew growth.

Thus, the great majority of simulated cases were associated with a time-averaged indoor relative humidity that was below the level associated with actual growth of mold and mildew. The higher indoor relative humidity in Region I was largely attributable to the higher contribution of outdoor humidity to total indoor relative humidity levels in Region I, as verified in previous work (risksciences 2002). The upper quartile range (75th to 100th percentile) of the indoor relative humidity distributions represent extreme examples of extreme cases, and must be interpreted with caution.

The modeling performed here is generic for both natural gas and propane as potential fuels. While some minor differences in emissions are possible due to differences in combustion stoichiometry for the two fuels, the differences in airborne levels of the 5 chemicals in the home due to structural and housing stock-related issues are likely to vastly outweigh any minor differences due to fuel type. Further, heating value for a given fuel type varies somewhat depending on the source of the fuel. It is significant that ANSI Z21.11.2 makes no distinction between propane and natural gas fuels in terms of the emission requirements in the standard.

Figure 3. Carbon Monoxide Distribution: DOE Region I
(During Use of Vent-Free Gas Heating Appliance; Outdoor Temperature = 56 °F)

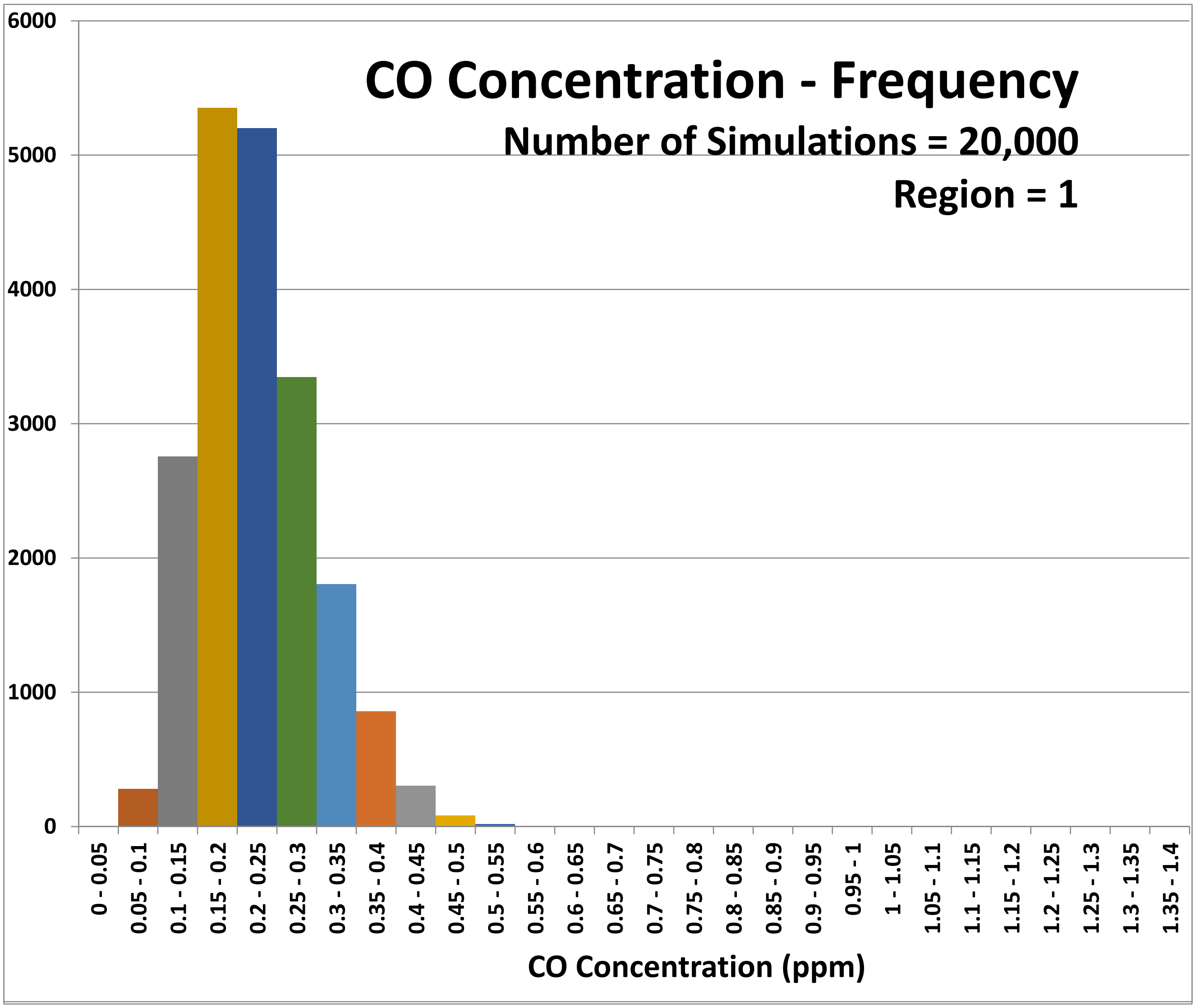
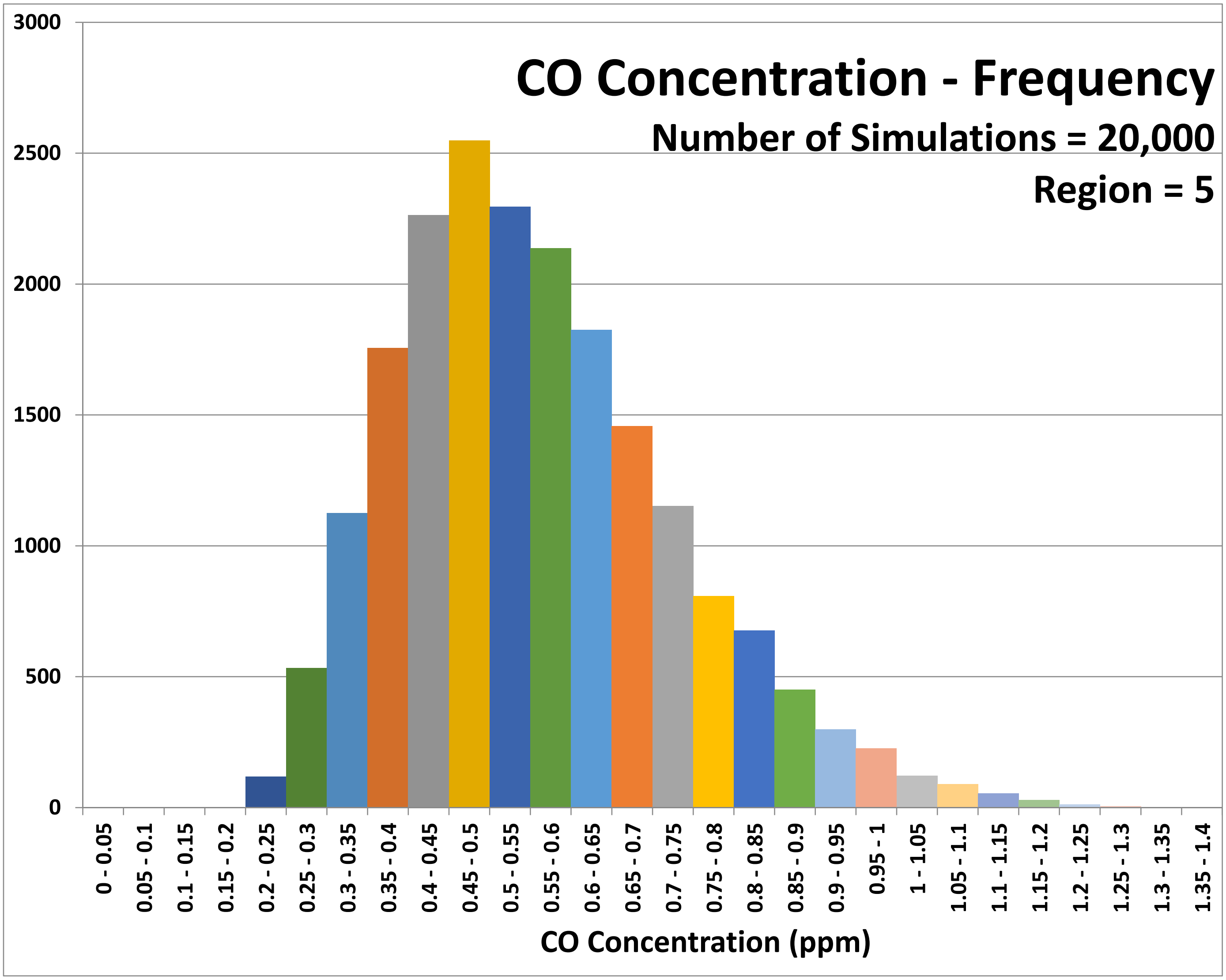


Figure 4. Carbon Monoxide Distribution: DOE Region V

(During Use of Vent-Free Gas Heating Appliance; Outdoor Temperature = 13 °F)



VII. SUMMARY AND DISCUSSION

The contribution of vent-free products to the indoor air levels of combustion-related chemicals, including carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), oxygen (O_2), and water vapor (H_2O), were predicted though the current research program. The focus of this effort has been on energy-efficient energy conservation residential structures that are compliant with current energy efficiency standards, including the National Green Building Standard and the IECC 2012 codes. The modeled indoor air concentrations of these chemicals were compared to nationally- and internationally-recognized Indoor Air Quality (IAQ) guidelines and standards. Although the AGAR vent-free gas heating appliance model was developed in 1996, and some improvements in burner technology and performance have occurred since then especially with regard to NO_2, the model results still “bracket” the range of possible vent-free units, including those that could theoretically emit the maximum allowable level of NO_2 under ANSI Z21.11.2.

With respect to the results for relative humidity, the overall water vapor burden in the house from all sources, and construction-related issues may impact the ability of the house to sustain water vapor loading without engendering significant mold and mildew growth. The relative humidity in a given room of the house will vary over time as (1) sources turn on and off; (2) sources move within the home (e.g., movement of people between rooms and in and out of the house); (3) moisture is re-distributed within the home due to air transport to other rooms by diffusion and the central HVAC system; and (4) mechanical ventilation removes moisture from certain rooms.

The results of this analysis with respect to all 5 combustion-related chemicals may overstate the indoor air quality impacts of vent-free gas appliances in energy-conservation homes because they are based on maximum (in the case of NO_2), or time-average conditions that are established after up to 4 hours of operation of the vent-fee unit, consistent with the “burn” time used in the original GRI modeling (GRI 1996). From available use data, it is known that average use periods are typically shorter, on the order of 2 hours. For example, in a survey of 35 California homes, Wilson (1999) reported an average burn time of 2.8 hours per use, with a median (50th percentile) of 2.3 hours per use. In most cases, vent-free appliances will only be used for a few hours. Further, the relative humidity impacts of vent-free gas appliances are probably overestimated due to a number of conservative assumptions, including the conservative range of 50% to 90% outdoor relative humidity for all DOE Regions. This range does not include the true minimum winter outdoor relative humidity, which may approach 20% in some regions of the U.S. These results indicate that the use of vent-free gas heating appliances does not result in adverse IAQ impacts in residential energy conservation structures in nearly all cases for each of the DOE Heating Regions for which simulations were conducted.

It is important to realize that is impossible to “oversize” a vent-free unit for a given room, because the amount of fuel burned and the amount of heat produced by the vent-free gas appliance will be determined by heat demand on the unit, as influenced by the set point, heat loss factors and U values, room volume, and air exchange rate. Thus, a green or energy-efficient home that is associated with low air exchange rates and high insulation values (i.e., high R values, or conversely low U values) lets less cold air in and is associated with lower heat loss than a standard home. Thus, a vent-free heating appliance would use less fuel and generate fewer emissions. It is a self-limiting process.

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ATTACHMENT A

Description and Source Code for The AGAR Vent-Free Gas Appliance Model and Modifications

INTRODUCTION

In earlier work (DeWerth et al. 1996), the computer program VENTF1.BAS that simulates how indoor air quality varies with time in a well-mixed space heated by a vent-free gas appliance was described. In this attachment, the model source code is presented. The model assumes a thermostated product in the given room of use and calculates the airborne concentrations of combustion products in that room when the vent-free product is in operation.

1. INPUT PARAMETERS

1.1 Heated Space Characteristics:

⇒ The heated space as described by room volume (V), height of the room (L), total house volume (Vh), volume of connected space (Vc), type of house structure (P) and the number of people in the room (Np).

⇒ The rates of production of CO, H_2O, and O_2 per person (DeWerth et al. 1996, page 17 and Appendix 3).

⇒ Miscellaneous sources of H_2O production and NO_2 reactive decay value , (DeWerth et al. 1996, pages 17 and 13, respectively and Appendix 3).

1.2 Air Characteristics

1.2.1 Air properties:

⇒ Air specific heat (kJ/kg°C) and air density (kg/m^3) are specified.

1.2.2 Indoor air characteristics:

⇒ Includes indoor air temperature set point (°F), initial indoor minimum relative humidity (%), and initial concentrations (ppm) of combustion products (CO, CO_2, O_2, NO_2).

⇒ Indoor air minimum and maximum humidity values represent a comfort range in accordance with ASHRAE standards.

1.2.3 Outdoor air characteristics:

⇒ Includes outdoor air temperature (°F), outdoor relative humidity (%), and initial concentrations (ppm) of combustion products (CO, CO_2, O_2, NO_2).

1.3 Vent-free Appliance Characteristic

⇒ The thermostat temperature control span ΔT_{span} characterizes a temperature variation in the room over time. For example, a thermostat temperature control span of 2°F means that the temperature in the room will be in the range of $T_{setup} \pm 1$ °F, where T_{setup} is the thermostat set point.

⇒ The number of cycles per hour was calculated in part based on the gross heat input of the vent-free device.

⇒ The duration of appliance operation is **until equilibrium is attained.**

⇒ Rate of production of CO, CO_2, NO_2, H_2O, and O_2 by the vent-free appliance per DeWerth et al. 1996, page 17 and Appendix 3). Note that the rate of O_2 production is negative since the appliance consumes oxygen for combustion.

2. PREPARATION FOR CALCULATIONS

2.1 Assigning "U" Factors and Air Change Rates (ACH)

⇒ "U" factors used for calculations were evaluated using the ASHRAE "U" method (DeWerth et al. 1996, pages 11 and 12; ASHRAE 1993, pages F20, F21 and F27.1-27.7).

⇒ Values of ACH rates: see DeWerth et al. (1996), page 11.

2.2 Minimum and Maximum Temperatures in the Room

⇒ Plus or minus one degree Fahrenheit around the set point (i.e., setup temperature).

2.3, 2.4 and 2.5 – Conversion Units to Metric System

⇒ Standard conversion factors (see following source code).

2.6 Conversion Pollutants and O_2 Concentration From ppm to kg/m^3

⇒ Conversion is done by the multiplication of the density of the combustion chemical or O_2 by 10^{-6}. For example, the density of carbon monoxide (CO) is 1.16 kg/m^3. To convert the CO concentration in ppm to kg/m^3, we multiply the value in ppm by 1.16×10^{-6}.

2.7 Preliminary Calculations

⇒ Floor surface area (A1) = ceiling surface area (A2) = (room volume)/(room height).

⇒ When calculating the wall length (L2), it is assumed that the room is square (all four walls have the same length). This assumption was made only to simplify the use of the computer program.

⇒ When calculating the surface area of external walls, it is assumed that only the specified number out of four walls in the room being heated are external (i.e., have contact with outside air). This assumption was made on the basis that vent-free appliances are used as supplemental heaters and are not being used as the sole heat source for the whole house. Any room in the house where a vent-free appliance may be installed as a supplemental heater has at least one interior wall.

⇒ A correction factor for the connected space Kr is introduced to calculate an actual space volume (V11) where pollutants from the vent-free appliance will be diluted (this is for the case when a vent-free appliance is installed in the room that freely communicates with other spaces in the house). If the vent-free appliance is installed in an isolated room the correction factor Kr=1.

⇒ The "effective" heat loss (U) factor is an area-averaged factor that incorporates the different heat loss factors and areas for ceilings, walls, and floors.

⇒ The initial indoor O_2 concentration is assumed equal to 21%.

⇒ When calculating a production rate of H_2O vapors by miscellaneous sources, it is assumed that the miscellaneous sources of water vapor generation are spread uniformly throughout the house. In this case, the miscellaneous sources in the room being heated by the vent-free appliance are proportional to the ratio of the room volume to the volume of the whole house.

2.8 Calculation of Initial Steady State Indoor Relative Humidity

This subprogram calculates an initial steady state relative humidity in the house before the vent-free appliance is turned on. The initial steady state relative humidity depends on the indoor air temperature, outdoor air temperature, outdoor air humidity and air change rate in the house.

Calculations are based on using formulas presented in ASHRAE (1993), pages 6.7-6.9. DeWerth et al. (1996), pages 18-19, describes in details the algorithm for these calculations. If the calculated initial relative humidity in the house is less than 25% (a minimum allowable indoor humidity per ASHRAE standards) then this parameter is assigned to be 25%.

2.9 Calculation of OFF Cycle Duration

This subprogram calculates durations of both OFF and ON cycles of the vent-free appliance operation. It is a three-step procedure. First, the subprogram calculates the duration of the full cycle TAUcycle (a sum of OFF and ON cycles) knowing the number cycles per hour that is a given parameter.

At the second step, the subprogram calculates duration of the OFF cycle (TAUoff). The duration of the OFF cycle is defined as a time needed to cool the indoor air from the maximum value ($T_{setup}+\Delta T_{span}/2$) to the minimum indoor temperature ($T_{setup}-\Delta T_{span}/2$). The calculation of the OFF cycle duration is based on the solution of the transient heat balance equation for the indoor air in the room being heated by the vent-free appliance. The thermal energy introduced by the appliance over the duration of the ON cycle is equal to the sum of the heat looses through the room exterior walls, ceiling and floor and heat required for heating the cold infiltrated outdoor air up to the indoor temperature over the duration of both the ON cycle and the OFF cycle.

$$(Q_{loss} + Q_{air}) \cdot (\tau_{on} + \tau_{off}) = Q_{net} \cdot \tau_{on}$$

Where:

Q_{los} – heat losses by conduction through the exterior room structure, W
Q_{air} – energy required to heat the infiltrated air up to the room temperature, W
τ_{on} – duration of ON cycle, sec
τ_{off} – duration of OFF cycle, sec
Q_{net} – vent-free appliance net heat input ($0.904 \cdot Q_{gross}$), W

It is assumed, that during the appliance OFF cycle, the indoor air is cooled only by mixing with the infiltrated cold outdoor air.

The duration of the appliance ON cycle TAUon (a final step of this subprogram) is determined simply by the subtraction of the OFF cycle duration from the full cycle duration (TAUon = TAUcycle - TAUoff).

2.10 Calculation of Appliance Net Input Rate, ON Cycle Duration and Number of Cycles Per Hour

This subprogram calculates the appliance net input rate as well as a minimum appliance net input rate required to compensate the heat losses in the room (a definition of the term "net input rate" is discussed below). If the appliance net input rate is less than the heat losses in the room the program stops calculations and the message "Appliance input rate is too small to compensate room heat losses" appears on the screen.

When calculating the thermal energy introduced by the vent-free appliance into the room, note the difference between the appliance gross input rate and the appliance net input rate. A vent-free appliance tag shows the appliance gross input rate. The gross input rate is a total energy that can be obtained from combustion of a specific fuel (in case of vent-free appliances, a natural gas). This energy includes the latent heat of vaporization of the water vapor formed by combustion of the hydrogen in the gas. The latent heat of vaporization of the water vapors does not release in the room being heated since we assume that the temperature in the room is above the dew point (in other words, the indoor humidity is less than 100% and the water vapors do not condense in the space being heated and therefore they do not release the latent heat). For an "average" natural gas, the net heating value is about 90.4% of its gross heating value. Therefore, to determine the appliance net input rate we multiply the appliance gross input rate by 0.904.

The subprogram also calculates both the duration of the appliance ON cycle (TAUon) and the number of cycles per hour of the vent-free appliance operation. The duration of the ON cycle is calculated based on the solution of the heat balance equation for the room being heated (see Section 2.9 above). The thermal energy introduced by the appliance over the duration of the ON cycle is equal to the sum of the heat loses through the room exterior walls, ceiling and floor and heat required for heating the cold infiltrated outdoor air up to the indoor temperature over the duration of both the ON cycle and the OFF cycle.

The number of cycles per hour of the vent-free appliance operation is calculated by the following formula:

$$\text{Ncycle} = 60/(\text{TAUoff} + \text{TAUon})$$

Where TAUoff and TAUon are durations of the OFF cycle and ON cycle in minutes.

2.11 Preparation of Printing Results of Calculations

See the following source code.

3. BASE CALCULATIONS

This subprogram calculates current concentrations of water vapor, oxygen and vent-free appliance emissions in the room during ON and OFF cycles. The subprogram calculates average values of CO, CO_2 and NO_2 in the room for the whole period of the vent-free appliance operation.

The subprogram "Basic Calculations" calculates the above parameters in three steps using subprograms #1, #2 and #3. Calculations start with considering an appliance ON cycle (parameter K2 that identifies the ON or OFF cycle is assigned equal to 1). Then, the subprogram

#1 checks whether the value of the current time (TAU) does not exceed the given total duration of the vent-free appliance operation (TAUend). At the beginning of calculations, the value of the current time is 0 (TAU=0). Therefore the program skips printing, calculates the value of the current time TAU and initiates subprogram #2.

Subprogram #2 calculates pollutants and O_2 concentrations and relative humidity at the end of the ON cycle using subroutine "Concentration". The input parameters for this subroutine are the vent-free appliance input rate Qnet and the duration of the time period considered TAU2. In this case TAU2 is assigned equal to TAUon (to duration of the ON cycle).

Note that the subroutine "Concentration" uses in turn two other subroutines "GeneralSolution" and "Average". Subroutine "GeneralSolution" is basically a solution of the differential mass and heat balance equations for the indoor air presented in Section 2.9. The subroutine "Average" calculates average values of CO, CO_2 and NO_2 in the room over each ON and OFF cycle as well as a cumulative value of the emissions.

After the calculations are completed by subroutine "Concentration", Subprogram #2 prints the calculation results. Then, it assigns parameter K2=0 and returns to subprogram #1. Subprogram #1 checks again whether the value of the current time (TAU) does not exceed the given total duration of the vent-free appliance operation (TAUend). If that's the case, Subprogram #1 skips printing, calculates the value of the current time TAU and initiates Subprogram #3 since parameter K2=0.

Subprogram #3 calculates pollutants and O_2 concentrations and relative humidity at the end of the OFF cycle using subroutine "Concentration". However, in contrast to Subprogram #2, Subprogram #3 uses the value of the vent-free appliance input rate equal to 0, and the duration of the time period considered TAU2 equal to TAUoff. After the calculations are completed by subroutine "Concentration", subprogram #3 prints the calculation results. Then, it assigns parameter K2=1 and returns to Subprogram #1.

The above cycling calculations performed by Subprograms #1, 2 and 3 stop when the value of the current time exceeds the given duration of the vent-free appliance operation.

4. VERIFICATION OF VENTF1.BAS COMPUTER CODE

To verify the VENTF1.BAS computer code, we conducted calculations of the vent-free appliance emission rates for the same set of input parameters from DeWerth et al. (1996) that was used in the example presented in Appendix 2. In our calculations, we used as a given parameter the value of the appliance input rate that was calculated by the program VENTF.BAS (3.337 $kBtuh/ft^3 \cdot 2000ft^3 = 6{,}674Btuh$). Note, that the value of the appliance input rate presented in Appendix 2 in DeWerth (1996) is 3.34 Btuh, which is a rounded number of the actual input rate of 3.337 Btuh.

5. REFERENCES

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2. ASHRAE Handbook, Fundamentals, SI Edition, 1993.

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APPENDIX 1

SOURCE CODE FOR VENT- FREE GAS HEATER EMISSIONS CALCULATION COMPUTER PROGRAM VENTF1.BAS

QuickBASIC Version 4.5

```
'The program is a version of the program VENTF.BAS.  In contrast to the
'program VENTF.BAS, in this computer code, the appliance input rate is
'a given parameter and the number of cycles per hour of the appliance
'operation is calculated.  The other input and output parameters in
this
'program are the same as in the program VENTF.BAS.

CLS

'1. INPUT PARAMETERS

'1.1  Heated Space Characteristics

'Volume of the room, V, ft^3
V = 2000
'Height of the room, L, ft
L = 8
'Volume of the house, Vh, ft^3
Vh = 10800
'Volume of the connected space, Vc, ft^3
Vc = 0
'Type of the house structure, P
P = 1           '1-Tight, 2-Average, 3-Loose
'Number of people in the room, Np
Np = 0
'Rate of O2 consumption per person, QC4p, kg/(sec*person)
QC4p = .0000079
'Rate of CO2 production per person, QC2p, kg/(sec*person)
QC2p = .0000091
'Rate of H2O production per person, QH1p, kg/(sec*person)
QH1p = .0000126
'Miscellaneous sources of H2O production in the house, QMSC, kg/sec
QMSC = .0000687
'NO2 decay, NO2dec, 1/hr
NO2dec = .45
```

```
'1.2  Indoor and Outdoor Air Characteristics

'1.2.1  Air Properties

'Air specific heat, Ca, kJ/(kg*C)
Ca = 1
'Air density at 20 degree C, Ra, kg/m^3
Ra = 1.205

'1.2.2  Indoor Air characteristics

'Indoor air setup temperature, F
Tio = 72
'Indoor air minimum humidity, Hmin, %
Hmin = 25
'Initial indoor CO concentration, C10, ppm
C10 = 0
'Initial indoor CO2 concentration, C20, ppm
C20 = 0
'Initial indoor NO2 concentration, C30, ppm
C30 = 0
'Initial indoor O2 concentration, C40, %
C40 = 21

'1.2.3  Outdoor Air Characteristics

'Outdoor air temperature, Tout, F
Tout = 26
'Outdoor air humidity, Hout, %
RHout = 50
'Outdoor CO concentration, C11, ppm
C11 = 0
'Outdoor CO2 concentration, C22, ppm
C22 = 0
'Outdoor NO2 concentration, C33, ppm
C33 = 0
'Outdoor O2 concentration, C44, %
C44 = 21

'1.3  Vent-free Appliance Characteristics

'Appliance gross input rate, Qgross, Btuh
Qgross = 2000 * 3.337
'Thermostat temperature control span, Tspan, F
Tspan = 2
'Duration of appliance operation (end of calculations), TAUend, min
TAUend = 100
'Rate of CO production per 1kW of appliance input rate, QC1,
kg/(sec*kW)
QC1 = .0000000515#
'Rate of CO2 production per 1kW of appliance input rate, QC2,
kg/(sec*kW)
QC2 = .0000485
'Rate of NO2 production per 1kW of appliance input rate, QC3,
kg/(sec*kW)
QC3 = 8.459999999999999D-09
```

```
'Rate of O2 consumption per 1kW of appliance input rate, QC4,
kg/(sec*kW)
QC4 = .000068
'Rate of H2O production per 1kW of appliance input rate, QH1,
kg/(sec*kW)
QH1 = .0000362

'2.  PREPARATION FOR CALCULATIONS

'2.1  Assigning "U" Factors and ACH for Different House Structures

IF P = 1 THEN
   U1 = .137                              'W/(m^2*sec)
   U2 = .261
   U3 = .636
   ACH = .35                                  '1/hr
     ELSE
       IF P = 2 THEN
          U1 = .305
          U2 = .305
          U3 = .966
          ACH = .5
            ELSE
              IF P = 3 THEN
                 U1 = .778
                 U2 = .778
                 U3 = 1.34
                 ACH = 1
    END IF
  END IF
END IF

'2.2  Minimum, Maximum and Average Temperatures in the Room

'Minimum temperature in the room, Timin, F
Timin = Tio - Tspan / 2
'Maximum temperature in the room, Timax, F
Timax = Tio + Tspan / 2
'Average temperature in the room, Tiav, F
Tiav = (Timax + Timin) / 2

'2.3  Conversion "ft^3" to "m^3" and "ft" to "m"

V1 = V * .0283                            'Room volume in m^3
Vc1 = Vc * .0283                          'Connected space volume in
m^3
L1 = L * .305                             'Ceiling height in m

'2.4  Conversion Degrees "F" to Degrees "C" and "Btuh" to kW

Timax = (Timax - 32) / 1.8                'Temperatures in degree C
Timin = (Timin - 32) / 1.8
Tiav = (Tiav - 32) / 1.8
Tio = (Tio - 32) / 1.8
Tout = (Tout - 32) / 1.8

Qgross = Qgross * .293 / 1000              'Gross input rate in kW
```

```
'2.5  Conversion Air Change Per Hour to Air Change Per Second

ACH = ACH / 3600                           'Air change rate, 1/sec

'2.6  Conversion Pollutants and O2 Concentrations in ppm and % to
kg/m^3

C11 = C11 * 1.16 / 10 ^ 6           'Concentrations, kg/m^3
C22 = C22 * 1.82 / 10 ^ 6
C33 = C33 * 1.9 / 10 ^ 6
C44 = C44 * 1.32 / 100

'2.7  Preliminary Calculations

A1 = V1 / L1                 'Floor surface area
A2 = A1                      'Ceiling surface area
L2 = A1 ^ .5                 'Wall length (assuming that the room is
square)               '
A4 = L1 * L2                 'One wall surface area
A3 = .75 * 4 * A4        'Surface area of the external walls (assuming
that
                         'three out of four walls in the room are
external)

Kr = 1 + Vc1 / V1    'Correction factor for the connected space
V11 = Kr * V1        'Actual space volume for dilution of combustion
products

U11 = A1 * U1 + A2 * U2 + A3 * U3          'Effective "U" factor

C40 = C44                           'Initial indoor O2 concentration,
kg/m^3

QMSC = QMSC * V / Vh   'Production of H2O in the room by miscellaneous
                       'sources, kg/sec

'2.8  Calculation of Initial Steady State Indoor Relative Humidity

T1 = Tout
GOSUB H2OPressure                   'Saturated pressure of water vapors
for
Pwsout = Pws                        'outdoor temperature

Pwout = (RHout / 100) * Pwsout        'Pressure of outdoor water
vapors, atm
Wout = .622 * Pwout / (1 - Pwout)     'Humidity ratio of outdoor water
vapor
Raout = Ra * (20 + 273) / (T1 + 273)  'Outdoor air density, kg/m^3
H1out = ACH * V11 * Wout * Raout      'Water mass flow from outside,
kg/sec

T1 = Tio
GOSUB H2OPressure                         'Saturated pressure of water
vapors
Pwsin = Pws                               'at indoor temperature, atm
```

```
Rain = Ra * (20 + 273) / (Tio + 273)      'Density of inside air,
kg/m^3

QH = QH1p * Np + H1out + QMSC    'Water generation rate in the house,
kg/sec

B = QH / V1                     'Water generation rate per 1 m^3,
kg/(sec*m^3)

Win1 = B / ACH                       'Initial indoor water concentration,
kg/m^3
Wino = Win1 / Rain                   'Initial indoor humidity ratio,
kg/kg(air)
Pwin = Wino / (.622 + Wino)          'Initial indoor water vapor pressure

RHin = Pwin * 100 / Pwsin             'Initial indoor humidity, %
Wino1 = Wino * Rain                   'Initial water vapor concentration,
kg/m^3

IF RHin < 25 THEN                     'If initial indoor humidity less
than 25%
   RHin = 25                          '(minimum allowable per ASHRAE
standards)
   Pwin = RHin * Pwsin / 100          'it is assigned to be 25%.
   Wino = Pwin * .622 / (1 - Pwin)
   Wino1 = Wino * Rain
END IF

'2.9  Calculation of OFF Cycle Duration

a = ACH
B = (Timin - Tout) / (Timax - Tout)

TAUoff = -LOG(B) / a      'Duration of the OFF cycle obtained from the
solution
                          'of the air heat balance equation assuming
that
                          'during the OFF cycle the air is cooled only
by
                          'mixing with the infiltrated air from outside,
sec

'2.10  Calculation of Appliance Net Input Rate and ON Cycle Duration

Mair = Rain * V1 * ACH          'Air mass flow through the room per
second, kg
Qair = Mair * Ca * (Tiav - Tout)        'Heat required for heating
infiltrated
                                        'air per second, kW
Qloss = U11 / 1000 * (Tiav - Tout)  'Conduction heat losses per second,
kW

Qnetmin = Qloss + Qair      'Minimum appliance net input rate required
                            'to compensate for room heat looses, kW
Qnet = Qgross * .904        'Appliance net input rate, kW

IF Qnet >= Qnetmin THEN
```

```
   TAUon = (Qair + Qloss) * TAUoff / (Qnet - Qair - Qloss)   'Duration
of
    ELSE                                                     'ON cycle,
sec
      PRINT "Appliance input rate is too small to compensate room heat
losses"
    END
END IF

TAUcycle = (TAUon + TAUoff) / 60             'Duration of the full
cycle, min
Ncycle = 60 / TAUcycle                       'Number of cycles per hour

'2.11  Preparation for Printing Results of Calculations

IF P = 1 THEN
   PRINT "Tight house,";
      ELSE
         IF P = 2 THEN
         PRINT "Average house,";
             ELSE
                 IF P = 3 THEN
                    PRINT "Loose house,";
     END IF
  END IF
END IF

IF Kr = 1 THEN
   PRINT " isolated room,";
       ELSE
            PRINT " non-isolated space,";
END IF

IF P = 1 THEN
   PRINT " ACH=.35,";
       ELSE
         IF P = 2 THEN
            PRINT " ACH=.5,";
                ELSE
                  IF P = 3 THEN
                     PRINT " ACH=1.0,";
      END IF
   END IF
END IF

PRINT " Tout=";
PRINT USING "###"; Tout * 1.8 + 32;             'Conversion to degree F
PRINT "F,";
PRINT " q=";
PRINT USING "##.##"; Qgross / .293 * 1000 / V; 'Conversion to Btuh and
ft^3
PRINT " Btuh/ft^3"
PRINT "Number of cycles per hour=";
PRINT USING "##.#"; Ncycle
PRINT
PRINT TAB(7); "Time,min";
PRINT TAB(17); "Ti, F";
```

```
PRINT TAB(27); "CO, ppm";
PRINT TAB(37); "CO2, %";
PRINT TAB(47); "NO2, ppm";
PRINT TAB(57); "O2, %";
PRINT TAB(67); "H2O, %"
PRINT TAB(7);
PRINT USING "###.#"; 0;
PRINT TAB(17);
PRINT USING "##.#"; Timin * 1.8 + 32;           'Conversion to degree
F
PRINT TAB(27);
PRINT USING "##.##"; C10 * 10 ^ 6 / 1.16;       'Conversion to ppm
PRINT TAB(37);
PRINT USING "####"; C20 * 10 ^ 6 / 1.82;        'Conversion to ppm
PRINT TAB(47);
PRINT USING "#.##"; C30 * 10 ^ 6 / 1.9;         'Conversion to ppm
PRINT TAB(57);
PRINT USING "##.##"; C40 * 100 / 1.32;          'Conversion to %
PRINT TAB(67);
PRINT USING "##.#"; RHin

'3.  BASE CALCULATIONS

K2 = 1  'K2 is a parameter used to identify the ON or OFF cycle. If K=1
it is
        'ON cycle, if K2=0 it is OFF cycle. Calculations starts with ON
cycle.

'3.1  Subprogram #1

'Subprogram #1 determines whether to stop calculations and to print
'average values for concentrations of pollutants and O2, or to continue
'calculations by using either Subprogram #2 (calculations during ON
cycle)
'or Subprogram #3 (calculations during OFF cycle).

1 IF TAU >= TAUend THEN     'TAU is the current time (TAU=0 at the
beginning
                            'of calculations).  TAUend is duration of
the
                            'appliance operation.
     PRINT
     PRINT "Average CO Concentration  = ";
     PRINT USING "##.##"; C1cum / TAU / 60;  'Ccum is cumulative
concentration
     PRINT " "; "ppm"
     PRINT "Average CO2 Concentration = ";
     PRINT USING "####"; C2cum / TAU / 60;
     PRINT " "; "ppm"
     PRINT "Average NO2 Concentration = ";
     PRINT USING "##.##"; C3cum / TAU / 60;
     PRINT " "; "ppm"
     PRINT
     END
     ELSE
        IF K2 = 1 THEN
           TAU = TAU + TAUon / 60            'Current time, sec
```

```
           GOTO 2                             'Calculations for ON cycle
            ELSE
              TAU = TAU + TAUoff / 60         'Current time, sec
              GOTO 3                          'Calculations for OFF
cycle
    END IF
END IF

'3.2  Subprogram #2 - Calculation of Concentration of Pollutants and O2
                     'During ON Cycle

2  Qg = Qgross
   Qg2 = Qg
   TAU2 = TAUon
   GOSUB Concentration
   PRINT TAB(7);
   PRINT USING "###.#"; TAU;
   PRINT TAB(17);
   PRINT USING "##.#"; Timax * 1.8 + 32;
   PRINT TAB(27);
   PRINT USING "##.##"; C1 * 10 ^ 6 / 1.16;
   PRINT TAB(37);
   PRINT USING "####"; C2 * 10 ^ 6 / 1.82;
   PRINT TAB(47);
   PRINT USING "#.###"; C3 * 10 ^ 6 / 1.9;
   PRINT TAB(57);
   PRINT USING "##.##"; C4 * 100 / 1.32;
   PRINT TAB(67);
   PRINT USING "##.#"; RHin
   K2 = 0
   GOTO 1

'3.3  Subprogram #3 - Calculation of Concentration of Pollutants and O2
                     'During OFF Cycle

3 Qg = 0
  Qg2 = 0
  TAU2 = TAUoff
  GOSUB Concentration
  PRINT TAB(7);
  PRINT USING "###.#"; TAU;
  PRINT TAB(17);
  PRINT USING "##.#"; Timin * 1.8 + 32;
  PRINT TAB(27);
  PRINT USING "##.##"; C1 * 10 ^ 6 / 1.16;
  PRINT TAB(37);
  PRINT USING "####"; C2 * 10 ^ 6 / 1.82;
  PRINT TAB(47);
  PRINT USING "#.##"; C3 * 10 ^ 6 / 1.9;
  PRINT TAB(57);
  PRINT USING "##.##"; C4 * 100 / 1.32;
  PRINT TAB(67);
  PRINT USING "##.#"; RHin
  K2 = 1
GOTO 1

END
```

```
'4.  SUBROUTINES

Concentration:

Q1C1 = QC1 * Qg2 + ACH * V11 * C11
Q1C2 = QC2 * Qg2 + QC2p * Np + ACH * V11 * C22
Q1C3 = QC3 * Qg2 + ACH * V11 * C33
QH = QH1 * Qg2 + QH1p * Np + H1out + QMSC
Q1C4 = -QC4 * Qg2 + ACH * V11 * C44 - QC4p * Np

B = Q1C1 / V11
a = ACH
Yo = C10
GOSUB GeneralSolution
GOSUB Average
C1av = Cav * 10 ^ 6 / 1.16
C1cum = C1cum + C1av * TAU2
C1 = Y
C10 = C1

B = Q1C2 / V11
a = ACH
Yo = C20
GOSUB GeneralSolution
GOSUB Average
C2av = Cav * 10 ^ 6 / 1.82
C2cum = C2cum + C2av * TAU2
C2 = Y
C20 = C2

B = Q1C3 / V11
a = ACH + NO2dec / 3600       'Correction for NO2 reactive decay rate
Yo = C30
GOSUB GeneralSolution
GOSUB Average
C3av = Cav * 10 ^ 6 / 1.9
C3cum = C3cum + C3av * TAU2
C3 = Y
C30 = C3

B = Q1C4 / V11
a = ACH
Yo = C40
GOSUB GeneralSolution
C4 = Y
C40 = C4

B = QH / V11
a = ACH
Yo = Wino1
GOSUB GeneralSolution
Win1 = Y                                  'Indoor H2O concentration,
kg/m^3
Win = Win1 / Rain                         'Indoor humidity ratio,
kg/kg(air)
```

```
Pwin = Win / (.622 + Win)                    'Indoor water vapor
pressure, atm
RHin = Pwin * 100 / Pwsin                    'Indoor humidity

Winol = Win1

ALFA = LOG(Pwin * 1.03 * 10 ^ 5)

IF Ti > 0 THEN
   Td = -35.957 - 1.872 * ALFA + 1.1689 * ALFA ^ 2        'Dew point, C
    ELSE Td = -60.45 + 7.032 * ALFA + .37 * ALFA ^ 2
END IF

K3 = 1

RETURN


GeneralSolution:    'Concentration calculation from the solution of the
                    'basic mass balance equation
Y = B * (1 - EXP(-a * TAU2)) / a + Yo * EXP(-a * TAU2)
RETURN


Average:           'Average pollutant concentration calculation during
                   'ON or OFF cycle
Cav = B / a + (B / a - Yo) * (EXP(-a * TAU2) - 1) / (a * TAU2)
RETURN


H2OPressure:       'Determination of saturated H2O pressure

T2 = T1 + 273                  'Conversion from degree C to degree K
P1 = -5800.2 / T2
P2 = 1.391
P3 = -.0486 * T2
P4 = .41765 * T2 ^ 2 / 10 ^ 4
P5 = -.1445 * T2 ^ 3 / 10 ^ 7
P6 = 6.546 * LOG(T2)

P7 = -5674.54 / T2
P8 = 6.3925
P9 = -.96778 * T2 / 10 ^ 2
P10 = .62216 * T2 ^ 2 / 10 ^ 6
P11 = .2074783 * T2 ^ 3 / 10 ^ 8
P12 = -.9484 * T2 ^ 4 / 10 ^ 12
P13 = 4.1635 * LOG(T2)

IF T1 >= 0 THEN
   P111 = P1 + P2 + P3 + P4 + P5 + P51 + P6
     ELSE
        P111 = P7 + P8 + P9 + P10 + P11 + P12 + P13
END IF

Pws = (EXP(P111)) / (1.013 * 10 ^ 5)

RETURN
```

```
PROGRAM PERC VENT-FREE

INITIALIZE t1, t2, pws, y, b, a, tau2, yo, cav, q1c1, qc1, qg2, ach, v11, c11, q1c2, qc2, qc2p, np, c22, q1c3,
qc3, c33, qh, qh1, qh1p, h1out, qmsc, q1c4, qc4, c44, qc4p, c10, c1av, c1cum, c1, c20, c2av, c2cum, c2,
no2dec, c30, c3av, c3cum, c3, c40, c4, wino1, win1, win, rain, pwin, rhin, pwsin, alfa, ti, td, k3, tauend,
hmin, benchCO, benchCO2, benchNO2, benchO2, benchH2O, nbenchCO, nbenchCO2, nbenchNO2,
nbenchO2, nbenchH2O, maxCO, maxCO2, maxH2O, maxNO2, minO2, totcount, totCO, totCO2, totH2O,
temp1count, temp2count, temp3count, decayfactor, decaytime, rhinzero, c10zero, c20zero, c30zero,
c40zero, simmax, simnum, detpro, dummy

Program MAIN
nbenchCO = 0
nbenchCO2 = 0
nbenchNO2 = 0
nbenchO2 = 0
nbenchH2O = 0
READ detpro, simmax
simnum = 1
Do Until simnum > simmax
  maxCO = 0
  maxCO2 = 0
  maxH2O = 0
  maxNO2 = 0
  minO2 = 1000
  totcount = 0
  totCO = 0
  totCO2 = 0
  totH2O = 0
  tempcount = 0
  VENTFREE
  If (tauend < 480) Then
    temp2count = Int((480 - tauend) * temp1count / tauend)
    temp3count = 1
    decayfactor = (-1) * ach * 60
    Do Until temp3count > temp2count
      decaytime = (temp3count / temp2count) * (480 - tauend)
      totCO = totCO + (c1 * 1000000 / 1.16) * Exp(decayfactor * decaytime)
      totCO2 = totCO2 + (c2 * 1000000 / 1.82) * Exp(decayfactor * decaytime)
      rhintemp = rhin * Exp(decayfactor * decaytime)
      If (rhintemp < hmin) Then rhintemp = hmin
      totH2O = totH2O + rhintemp
      temp3count = temp3count + 1
    Loop
    totcount = totcount + temp2count
  End If
  maxCO = totCO / totcount 'not maximum but average calculation
  maxCO2 = totCO2 / totcount 'not maximum but average calculation
  rhin = totH2O / totcount 'not maximum but average calculation
```

```
  rhinwrite = 100
  If (rhin < rhinwrite) Then rhinwrite = rhin
  OUTPUT simnum, maxCO, maxCO2, rhinwrite, maxNO2, minO2
  If (maxCO < benchCO) Then nbenchCO = nbenchCO + 1
  If (maxCO2 < benchCO2) Then nbenchCO2 = nbenchCO2 + 1
  If (maxNO2 < benchNO2) Then nbenchNO2 = nbenchNO2 + 1
  If (minO2 > benchO2) Then nbenchO2 = nbenchO2 + 1
  If (rhin < benchH2O) Then nbenchH2O = nbenchH2O + 1
  simnum = simnum + 1
Loop
  OUTPUT (nbenchCO * 100 / simmax), (nbenchCO2 * 100 / simmax), (nbenchNO2 * 100 / simmax),
    (nbenchO2 * 100 / simmax), (nbenchH2O * 100 / simmax)
End Program

Sub VENTFREE
READ v, l, vh, vc, p, np qc4p, qc2p, qh1p, qmsc, no2dec, ca, ra, tio, hmin, c10, c20, c30, c40, tout, rhout,
  c11, c22, c33, c44, qgross, tspan, tauend, qc1, qc2, qc3, qc4, qh1, nwalls, ach, u1, u2, u3, benchCO,
  bench CO2, bench NO2, benchO2, benchH2O
rhinzero = hmin
c10zero = c10
c20zero = c20
c30zero = c30
c40zero = c40
timin = tio - tspan / 2
timax = tio + tspan / 2
tiav = (timax + timin) / 2
v1 = v * 0.0283                    'Room volume in m^3
vc1 = vc * 0.0283                  'Connected space volume in m^3
l1 = l * 0.305                     'Ceiling height in m
timax = (timax - 32) / 1.8               'Temperatures in degree C
timin = (timin - 32) / 1.8
tiav = (tiav - 32) / 1.8
tio = (tio - 32) / 1.8
tout = (tout - 32) / 1.8
qgross = qgross * 0.293 / 1000           'Gross input rate in kW
ach = ach / 3600                   'Air change rate, 1/sec
c11 = c11 * 1.16 / 10 ^ 6          'Concentrations, kg/m^3
c22 = c22 * 1.82 / 10 ^ 6
c33 = c33 * 1.9 / 10 ^ 6
c44 = c44 * 1.32 / 100
a1 = v1 / l1             'Floor surface area
a2 = a1                  'Ceiling surface area
l2 = a1 ^ 0.5            'Wall length (assuming that the room is square)             '
a4 = l1 * l2             'One wall surface area
If nwalls = 1 Then
  a3 = 0.25 * 4 * a4       'Surface area of external walls
ElseIf nwalls = 2 Then
  a3 = 0.5 * 4 * a4
```

```
Else
  a3 = 0.75 * 4 * a4
End If
a3 = 0.75 * 4 * a4
kr = 1 + vc1 / v1    'Correction factor for the connected space
v11 = kr * v1        'Actual space volume for delution of combustion products
u11 = a1 * u1 + a2 * u2 + a3 * u3         'Effective "U" factor
c40 = c44                         'Initial indoor O2 concentration, kg/m^3
qmsc = qmsc * (v + vc) / vh 'Production of H2O in the room by miscellaneuos, added vc
t1 = tout
H2OPressure                 'Saturated pressure of water vapors for
pwsout = pws                      'outdoor temperature
pwout = (rhout / 100) * pwsout       'Pressure of outdoor water vapors, atm
wout = 0.622 * pwout / (1 - pwout)    'Humidity ratio of outdoor water vapor
raout = ra * (20 + 273) / (t1 + 273)  'Outdoor air density, kg/m^3
h1out = ach * v11 * wout * raout      'Water mass flow from outside, kg/sec
t1 = tio
H2OPressure                       'Saturated pressure of water vapors
pwsin = pws                          'at indoor temperature, atm
rain = ra * (20 + 273) / (tio + 273)      'Density of inside air, kg/m^3
qh = qh1p * np + h1out + qmsc    'Water generation rate in the house, kg/sec
b = qh / v11                 'Water generation rate per 1 m^3, kg/(sec*m^3), corrected v1 to v11
win1 = b / ach                  'Initial indoor water concentration, kg/m^3
wino = win1 / rain                'Initial indoor humidity ratio, kg/kg(air)
pwin = wino / (0.622 + wino)       'Initial indoor water vapor pressure
rhin = pwin * 100 / pwsin          'Initial indoor humidity, %
wino1 = wino * rain                'Initial water vapor concentration, kg/m^3
If rhin < 25 Then                  'If initial indoor humidity less than 25%
   rhin = 25                     '(minimum allowable per ASHRAE standards)
   pwin = rhin * pwsin / 100       'it is assigned to be 25%.
   wino = pwin * 0.622 / (1 - pwin)
   wino1 = wino * rain
End If
a = ach
b = (timin - tout) / (timax - tout)
tauoff = -Log(b) / a     'Duration of the OFF cycle obtained from the solution
mair = rain * v1 * ach        'Air mass flow through the room per second, kg
qair = mair * ca * (tiav - tout)       'Heat required for heating infiltrated
qloss = u11 / 1000 * (tiav - tout)  'Conduction heat losses per second, kW
qnetmin = qloss + qair     'Minimum appliance net input rate required
qnet = qgross * 0.904      'Appliance net input rate, kW
  If qnet >= qnetmin Then
    tauon = (qair + qloss) * tauoff / (qnet - qair - qloss)
  Else
    OUTPUT “Appliance input rate too small to compensate room heat losses"
    End
  End If
  taucycle = (tauon + tauoff) / 60#
```

```
  ncycle = 60# / taucycle
  If ((c10 * 1000000# / 1.16) > maxCO) Then maxCO = c10 * 1000000# / 1.16
  If ((c20 * 1000000# / 1.82) > maxCO2) Then maxCO2 = c20 * 1000000# / 1.82
  If ((c30 * 1000000# / 1.9) > maxNO2) Then maxNO2 = c30 * 1000000# / 1.9
  If ((c40 * 100# / 1.32) < minO2) Then minO2 = c40 * 100# / 1.32
  If (rhin > maxH2O) Then maxH2O = rhin
  k2 = 1
1 If tau >= tauend Then
    GoTo 4
  Else
    If k2 = 1 Then
      tau = tau + tauon / 60
      GoTo 2
    Else
      tau = tau + tauoff / 60
      GoTo 3
    End If
  End If
2 qg = qgross
  qg2 = qg
  tau2 = tauon
  CONCENTRATION
  If ((c1 * 1000000# / 1.16) > maxCO) Then maxCO = c1 * 1000000# / 1.16
  If ((c2 * 1000000# / 1.82) > maxCO2) Then maxCO2 = c2 * 1000000# / 1.82
  If ((c3 * 1000000# / 1.9) > maxNO2) Then maxNO2 = c3 * 1000000# / 1.9
  If ((c4 * 100# / 1.32) < minO2) Then minO2 = c4 * 100# / 1.32
  If (rhin > maxH2O) Then maxH2O = rhin
'Relative Humidity correction above 100
  If (rhin > 100) Then rhin = 100
'Calculate Totals (for Average)
  totcount = totcount + 1
  totCO = totCO + (c1 * 1000000 / 1.16)
  totCO2 = totCO2 + (c2 * 1000000 / 1.82)
  totH2O = totH2O + rhin
  temp1count = temp1cout + 1
  k2 = 0
  GoTo 1
3 qg = 0
  qg2 = 0
  tau2 = tauoff
  CONCENTRATION
  If ((c1 * 1000000# / 1.16) > maxCO) Then maxCO = c1 * 1000000# / 1.16
  If ((c2 * 1000000# / 1.82) > maxCO2) Then maxCO2 = c2 * 1000000# / 1.82
  If ((c3 * 1000000# / 1.9) > maxNO2) Then maxNO2 = c3 * 1000000# / 1.9
  If ((c4 * 100# / 1.32) < minO2) Then minO2 = c4 * 100# / 1.32
  If (rhin > maxH2O) Then maxH2O = rhin
'Relative Humidity correction above 100
  If (rhin > 100) Then rhin = 100
```

```
' Calculate Totals (for Average)
  totcount = totcount + 1
  totCO = totCO + (c1 * 1000000# / 1.16)
  totCO2 = totCO2 + (c2 * 1000000# / 1.82)
  totH2O = totH2O + rhin
  temp1count = temp1count + 1
  k2 = 1
  GoTo 1
4 dummy = 1
End Sub

Sub CONCENTRATION
q1c1 = qc1 * qg2 + ach * v11 * c11
q1c2 = qc2 * qg2 + qc2p * np + ach * v11 * c22
q1c3 = qc3 * qg2 + ach * v11 * c33
qh = qh1 * qg2 + qh1p * np + h1out + qmsc
q1c4 = -qc4 * qg2 + ach * v11 * c44 - qc4p * np
b = q1c1 / v11
a = ach
yo = c10
GENERALSOLUTION
AVERAGE
c1av = cav * 10 ^ 6 / 1.16
c1cum = c1cum + c1av * tau2
c1 = y
c10 = c1
b = q1c2 / v11
a = ach
yo = c20
GENERALSOLUTION
AVERAGE
c2av = cav * 10 ^ 6 / 1.82
c2cum = c2cum + c2av * tau2
c2 = y
c20 = c2
b = q1c3 / v11
a = ach + no2dec / 3600      'Correction for NO2 reactive decay rate
yo = c30
GENERALSOLUTION
AVERAGE
c3av = cav * 10 ^ 6 / 1.9
c3cum = c3cum + c3av * tau2
c3 = y
c30 = c3
b = q1c4 / v11
a = ach
yo = c40
GENERALSOLUTION
```

```
c4 = y
c40 = c4
b = qh / v11
a = ach
yo = wino1
GENERALSOLUTION
win1 = y                          'Indoor H2O concentration, kg/m^3
win = win1 / rain                 'Indoor humidity ratio, kg/kg(air)
pwin = win / (0.622 + win)        'Indor water vapor pressure, atm
rhin = pwin * 100 / pwsin         'Indoor humidity
wino1 = win1
alfa = Log(pwin * 1.03 * 10 ^ 5)
If ti > 0 Then
  td = -35.957 - 1.872 * alfa + 1.1689 * alfa ^ 2      'Dew point, C
   Else: td = -60.45 + 7.032 * alfa + 0.37 * alfa ^ 2
End If
k3 = 1
End Sub

Sub GENERALSOLUTION
 y = b * (1 - Exp(-a * tau2)) / a + yo * Exp(-a * tau2)
End Sub

Sub AVERAGE
 cav = b / a + (b / a - yo) * (Exp(-a * tau2) - 1) / (a * tau2)
End Sub

Sub H2OPressure
 t2 = t1 + 273              'Conversion from degree C to degree K
 p1 = -5800.2 / t2
 p2 = 1.391
 p3 = -0.0486 * t2
 p4 = 0.41765 * t2 ^ 2 / 10 ^ 4
 p5 = -0.1445 * t2 ^ 3 / 10 ^ 7
 p6 = 6.546 * Log(t2)
 p7 = -5674.54 / t2
 p8 = 6.3925
 p9 = -0.96778 * t2 / 10 ^ 2
 p10 = 0.62216 * t2 ^ 2 / 10 ^ 6
 p11 = 0.2074783 * t2 ^ 3 / 10 ^ 8
 p12 = -0.9484 * t2 ^ 4 / 10 ^ 12
 p13 = 4.1635 * Log(t2)
 If t1 >= 0 Then
  p111 = p1 + p2 + p3 + p4 + p5 + p6
 Else
  p111 = p7 + p8 + p9 + p10 + p11 + p12 + p13
 End If
 pws = (Exp(p111)) / (1.013 * 100000#)
```

```
End Sub
```

ATTACHMENT B:

Histograms for Indoor Combustion Chemical Levels: Probabilistic Runs for Carbon Monoxide

Figure B-1. Carbon Monoxide Distribution: DOE Region I

(During Use of Vent-Free Gas Heating Appliance; Outdoor Temperature = 56 °F)

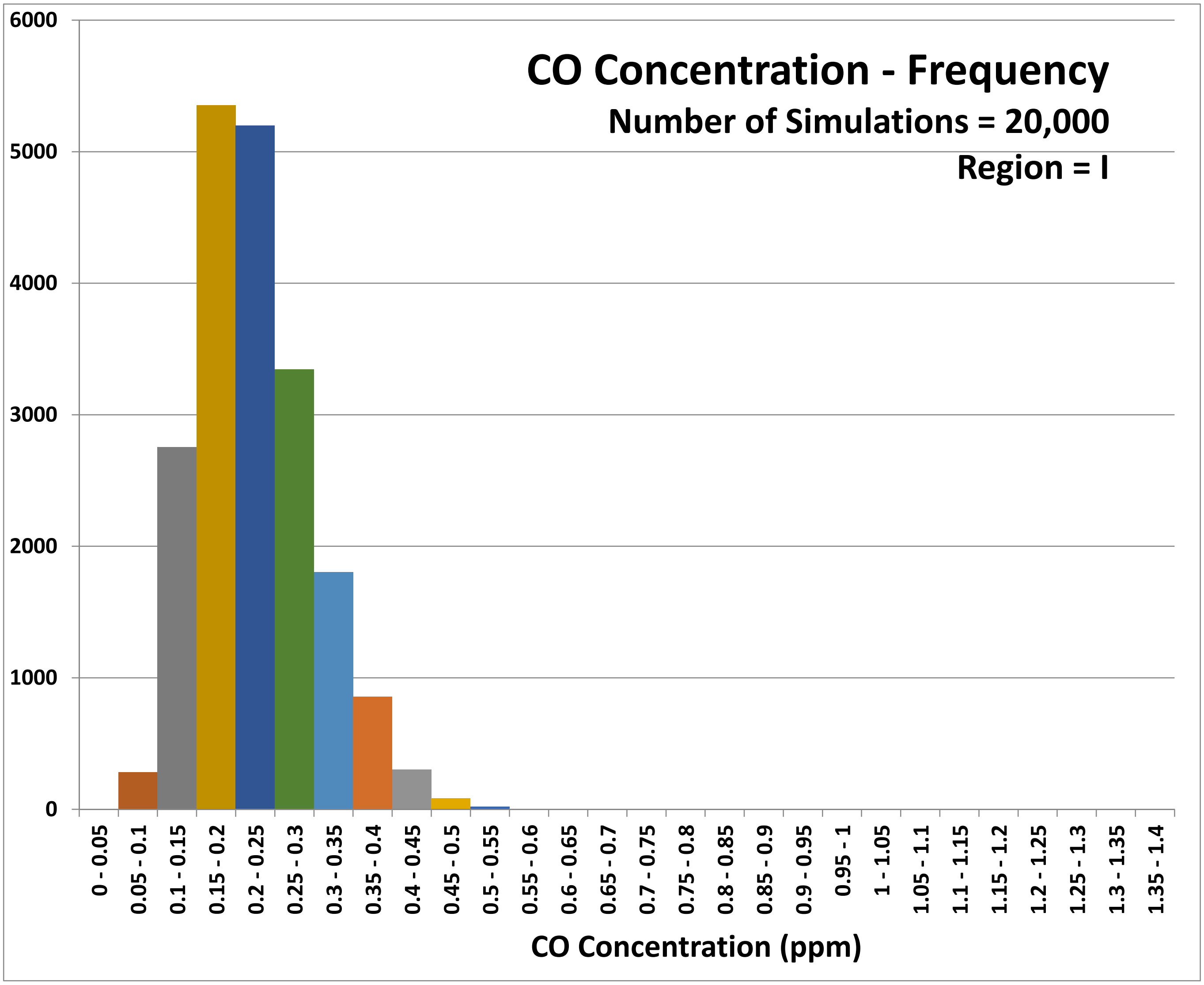

Figure B-2. Carbon Monoxide Distribution: DOE Region II

(During Use of Vent-Free Gas Heating Appliance; Outdoor Temperature = 45 °F)

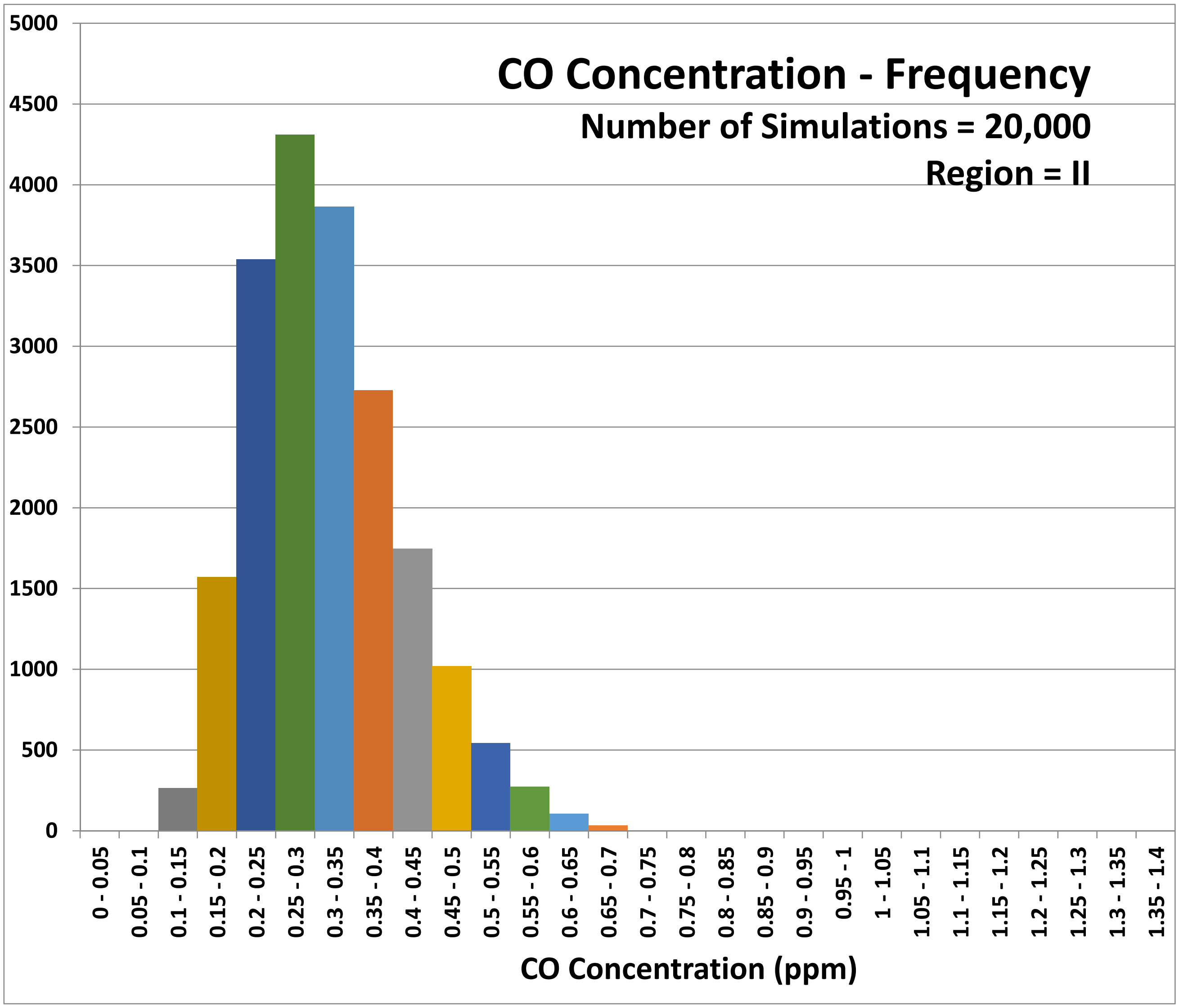

Figure B-3. Carbon Monoxide Distribution: DOE Region III

(During Use of Vent-Free Gas Heating Appliance; Outdoor Temperature = 36 °F)

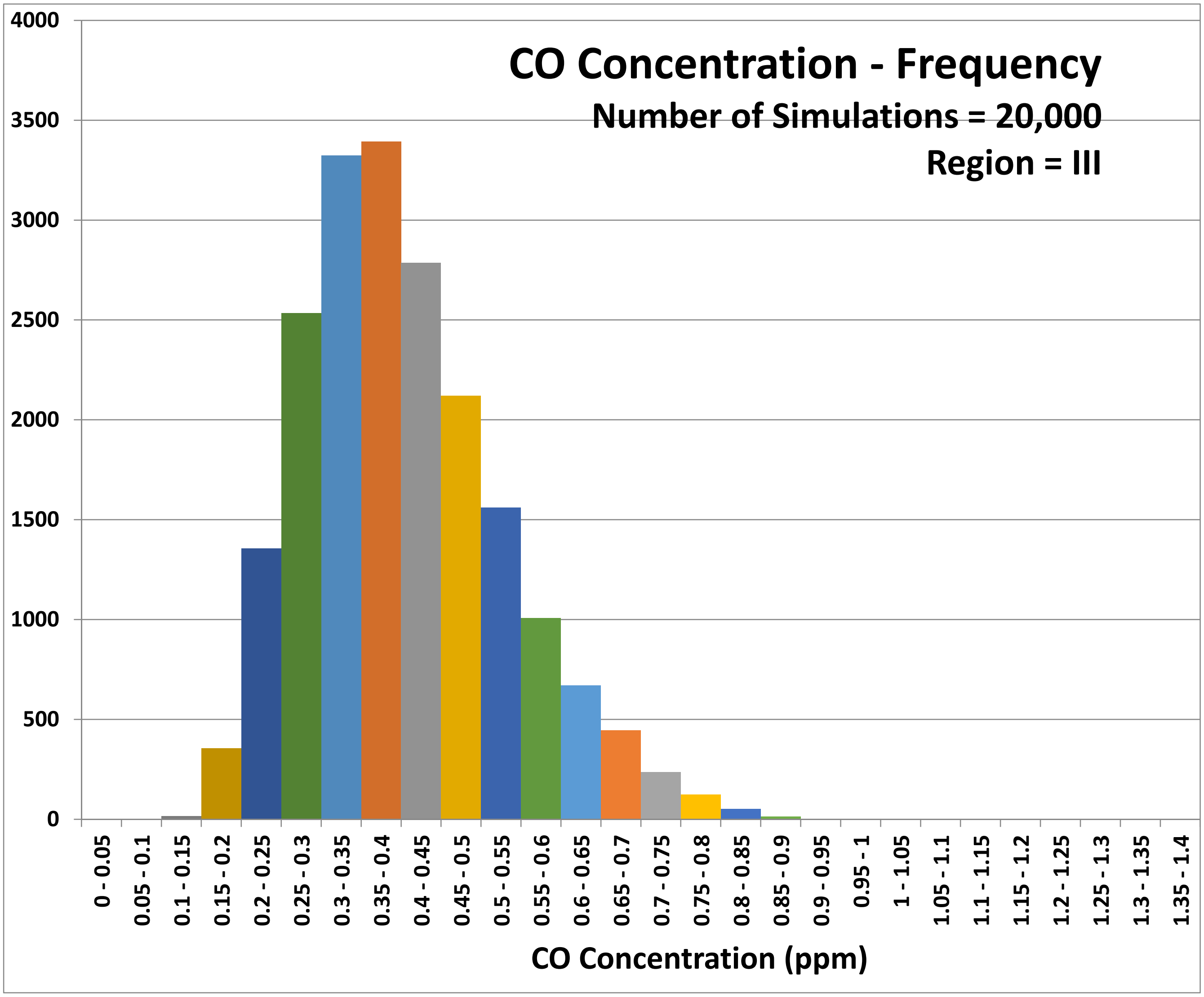

Figure B-4. Carbon Monoxide Distribution: DOE Region IV

(During Use of Vent-Free Gas Heating Appliance; Outdoor Temperature = 26 °F)

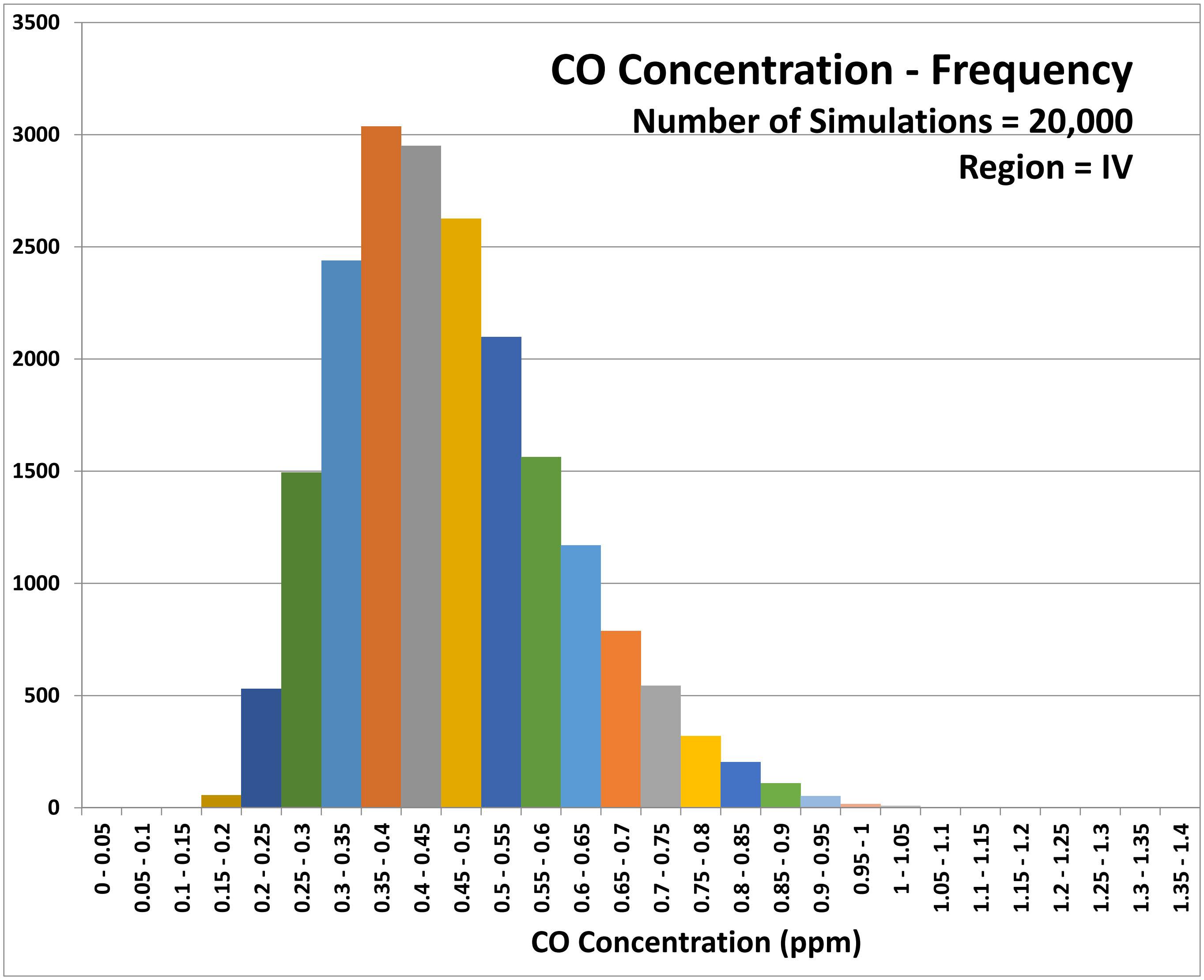

Figure B-5. Carbon Monoxide Distribution: DOE Region V

(During Use of Vent-Free Gas Heating Appliance; Outdoor Temperature = 13 °F)