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DANGERS CRÉÉS PAR LES PRODUITS DE COMBUSTION ET LA DIMINUTION DE LA CONCENTRATION D'OXYGÈNE DANS LES ESPACES HABITÉS

par

A. D. Kent

RÉSUMÉ

Dans un espace mal aéré, les occupants peuvent être exposés à des conditions d'air dangereuses attribuables à une diminution de la concentration d'oxygène ou à une augmentation de la concentration de bioxyde de carbone. L'emploi d'appareils à combustibles sans tuyaux d'évent crée en plus un danger d'empoisonnement par le monoxyde de carbone. Les effets de quantités variables de ces gaz sur les fumeurs et les non-fumeurs sont énumérés et une méthode est indiquée pour déterminer les exigences de ventilation face à une production déterminée de gaz toxiques. Des résultats d'essais sur des appareils types sans tuyaux d'évent employés pour le camping, sur les bateaux et utilisant une variété de combustibles sont donnés. Ces résultats indiquent que certains appareils nécessitent des précautions spéciales de ventilation. Des suggestions sont soumises aux usagers de tels appareils afin d'éviter des situations dangereuses dans les espaces fermés.

HAZARDS FROM PRODUCTS OF COMBUSTION AND OXYGEN DEPLETION IN OCCUPIED SPACES

by A. D. KENT*

In a poorly ventilated space the occupants may be exposed to hazardous air conditions of reduced oxygen content or increased carbon dioxide concentration. If unvented fuel-burning appliances are used for heating or cooking there is the possibility of further danger from carbon monoxide poisoning. The effects of these gases in varying quantities upon smokers and non-smokers are enumerated and a method is outlined for the determination of the ventilation requirements for specific quantities of toxic gas production. Results are given of tests of typical unvented camping and boating appliances using a variety of fuels, and these indicate that certain models warrant special ventilation precautions. Guidelines are suggested for users of such equipment to avoid hazardous atmospheres in confined spaces.

Outdoor air, free from contamination, consists of about 78 per cent nitrogen (N_2) and 21 per cent oxygen (O_2) by volume, the remaining 1 per cent being composed of various inert gases and oxides of carbon. Carbon dioxide (CO_2) is normally present to the extent of 0.03 per cent by volume and carbon monoxide (CO) only one or two parts per million (ppm) in uncontaminated air. In the city, gaseous products of combustion of hydrocarbon fuels from motor vehicles, industrial processes and building heating equipment may increase the CO and CO_2 concentration figures to undesirably high levels. Man himself adds to the contamination by his own private "combustion" process. Breathing at a rate of about 18 cu. ft. of air per hour when seated or mildly active a man will inhale about 4 cu. ft. of oxygen per hour, and use about ¼ of this to combine with his blood's haemoglobin and myoglobin to be exhaled ultimately as oxides of carbon and hydrogen along with waste heat from the process. His expired air contains about 16 per cent unused O_2 and 4 per cent CO_2 with about 14 ppm of CO unless he is a cigarette smoker, in which case, the CO would average about 35 ppm.

This amount of human air pollution is of course insignificant outdoors but may present a problem indoors unless the space is adequately ventilated. The ventilation rate provided by normal infiltration, even in residences with tight windows and exterior doors, may be as much as one air change every two hours (1) due to wind pressures or to chimney effect caused by indoor-outdoor air temperature differences. With less tight windows and doors still greater air changes occur from natural effects. In crowded quarters such as a tent, cabin or trailer or in a closed motor vehicle, where the volume

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of air per person is small, the infiltration rate is usually sufficient for adequate ventilation. With tightly fitted closures, however, precautions might be necessary to prevent the concentration of exhaled CO_2 from exceeding the safe limit. With the use of unvented fuel-fired cooking or heating appliances, the danger of CO_2 intoxication becomes important and the additional hazard of CO production from incomplete combustion of the fuel may require special precautions. These hazards become even more pronounced as the weather becomes colder, since heaters would then be operated at higher firing rates and there would be a natural tendency to close off ventilation air to conserve heat. It is most important, therefore, that persons in such situations be aware of the dangers and be knowledgeable enough to recognize the symptoms before a fatality occurs.

TABLE 1

EFFECTS OF OXYGEN CONCENTRATION ON NORMAL PEOPLE AT NORMAL ATMOSPHERIC PRESSURE (0 FT ELEVATION)

Oxygen Content of Inhaled air, per cent	Effects
21	Normal air.
17	Safe limit for prolonged exposure.
15	No immediate effects except sense of fatigue.
10	Dizziness, shortness of breath; deeper and more rapid respiration; quickened pulse, especially on exertion.
7	Stupor sets in; memory and judgment are affected.
5	Minimal concentration compatible with life.
2–3	Death within a few minutes.

The effects on the human body of oxygen depletion, carbon dioxide and carbon monoxide concentrations have been determined over a long period of time by experiments of medical research, physiologists and various specialists all over the world and more recently by several shelter habitability studies and submarine trials in the U.S.A. The limits of human tolerance to toxic gases are under constant review by such bodies as the American Conference of Governmental Industrial Hygienists (ACGIH) whose established figures of threshold limit value (TLV) are recognized almost universally as the safe upper limit of concentration for extended periods based upon an exposure of 8 hours per day (2).

OXYGEN DEPLETION

Oxygen deficiency in itself is not nearly so great a problem in confined and poorly ventilated quarters as is generally supposed. Instead the combustion process of man and appliances produces carbon dioxide at a more harmful rate than it uses up oxygen and unconsciousness or death would occur from high CO_2 concentration before the corresponding O_2 deficiency would have a serious physiological effect upon the occupants. The normal oxygen intake when a person breathes will be reduced with increased altitude above sea level, so that unless the person is used to this altitude the rate of breathing will increase to compensate for the reduced pressure of oxygen in the lighter air. At sea level, the concentration of oxygen may drop from the normal 21 per cent to as low as 15 per cent before breathing begins to be noticeably accelerated, as long as the CO_2 content in the blood remains normal and the body is at rest. A summary of the effects of oxygen depletion is contained in Table 1.

CARBON DIOXIDE

Increase in the carbon dioxide concentration of an atmosphere affects the respiratory process particularly if accompanied by decrease in oxygen concentration. In addition to the gradual increase in depth and frequency of breathing with increasing concentration, the hearing, blood pressure and

TABLE 2

EFFECTS OF CO_2 CONCENTRATION ON NORMAL PEOPLE AT NORMAL ATMOSPHERIC PRESSURE

Carbon Dioxide Content of Inhaled air, per cent	Effects, with Oxygen Content Normal
0.04	Normal air.
0.5 (TLV)	Safe limit for prolonged exposure.
1.5	Can be tolerated for prolonged periods without affecting performance and basic physiological functions but calcium phosphorus metabolism may be affected.
2.0	Breathing deeper; air inspired per breath increased 30 per cent.
3.0	Deterioration of performance; alterations in physiological functions expressed in changes of weight, blood pressure, pulse rate. Breathing double normal rate.
4.0	Breathing much deeper; rate quickened to slight panting; considerable discomfort.
5.0	Breathing extremely laboured; heavy panting; almost unbearable for many individuals; nausea may occur; 30-minute exposure produces signs of intoxication.
7–9	Limit of tolerance; violent panting; unconsciousness in about 15 minutes.
10–11	Inability to coordinate; unconsciousness in about ten minutes.
15–20	Symptoms increase but probably not fatal in one hour.
25–30	Diminished respiration; falloff of blood pressure, coma; loss of reflexes; anesthesia; death after some hours.

pulse rate are affected, the symptoms being headache, sweating and tremor. The effects of increasing CO_2 concentration with normal oxygen content are contained in Table 2.

CARBON MONOXIDE

The rate of carbon monoxide intoxication depends upon the CO concentration in the inspired air, the depth and rate of respiration, the duration of exposure, and to some extent whether the subject is accustomed to inhaling carbon monoxide, for example, by smoking. Carbon monoxide poisoning by exposure to small concentrations over a long period can often be more harmful than a brief exposure to a very high concentration. Heavy labour, especially in high ambient air temperatures or at higher elevations, will increase the effect.

Carbon monoxide poisoning is characterized by the formation of carboxyhaemoglobin (COHb) and carboxymyoglobin (COMb), in a ratio of 4 to 1 respectively, which replace the normal oxyhaemoglobin and oxymyoglobin of the blood's haemoproteins. Haemoglobin is said to have from 200 to 300 times the affinity for CO as it has for O_2, (3 to 5) but the return to normal haemoglobin after moderate poisoning can be readily achieved with normal air, or 8 to 10 times more rapidly with pure oxygen. Cigarette smoking is claimed to subject the lungs to a CO concentration of about 475 ppm for 6 minutes per cigarette (6) and for those who smoke heavily, the resultant, COHb may be from 5 to 8 per cent (7), sufficient to impair night vision significantly.

It is claimed by Bartlett (8) that CO from cigarette smoke and CO in the air are not additive in their biologic effect, so that a smoker whose COHb is, say, 5 per cent from smoking would not absorb further CO from the environment unless the concentration were 30 ppm or more. Smokers' long-term average COHb concentrations are reported to be slightly higher in the presence of environmental CO than in its absence, since their CO elimination between cigarettes would be less than in pure air. Goldsmith and Landaw (5) state that recent animal exposure studies suggest that exposure to low concentrations of CO may have a role in the development of human heart disease.

The effects of CO on myoglobin are less well known than on haemoglobin, but are considered less significant (8) since the relative affinity of myoglobin for CO over O_2 is reported to be about 40, or roughly $\frac{1}{6}$ of the value for haemoglobin. The effects of CO inhalation are summarized in Table 3.

Tables Nos. 1 to 3 give the symptoms and effects when the concentration of a single gas is changed, the information being derived from several sources and studies (2, 4, 7 to 9). The literature on the combined effects of two or more gases is less prevalent, although there appears to be general agreement that effects are additive to some degree. Cumming and Horn

(10), have studied the effects of acetylene flames of miners' lamps, and state that it appears possible that a man could remain alive in an atmosphere containing 14 per cent O_2 and 7 per cent CO_2. Schulte (11) reports that 108 healthy men between 17 and 37 years of age suffered no harmful effects following exposure in a submarine for 72 days to an atmosphere of 19.7 per cent O_2, 1.04 per cent CO_2, 1 per cent H_2, 44 ppm CO, 15 ppm refrigerant 12, and approximately 78 per cent N_2.

TABLE 3

EFFECTS OF CO CONCENTRATION ON NORMAL PEOPLE AT NORMAL ATMOSPHERIC PRESSURE

Carbon Monoxide Content of Inhaled air		Corresponding Carboxyhaemoglobin in blood at equilibrium, per cent		Effects
per cent	ppm	non-smoker	smoker	
0.0002	2	1	2 to 10	Normal conditions.
0.0025	25	2 to 4	4 to 14	Slight impairment of vision.
0.005(TLV)	50	8 to 10	10 to 20	Safe limit for prolonged exposure.
0.01	100	15 to 20	15 to 27	No effects for 3-hr exposure but perceptible effects after 6 hr. Headache and nausea after 9 hr. Continuous exposure poisonous but not lethal.
0.02	200	25 to 30	25 to 35	Possible mild frontal headache after 2 to 3 hr. Continuous exposure probably results in at least permanent blindness if not death.
0.04	400	40 to 45		Deep breathing; dimness of vision. Frontal headache after 1 to 2 hr; rear-of-head headache after 2½ to 3½ hr. Probable coma after 5 hr. Continuous exposure, certain death.
0.08	800	60 to 65		Headache, dizziness and nausea in ¾ hr; collapse and possible unconsciousness in 2 hr. Possible death in about 4 hr.
0.64	6400			Headache in 1 or 2 min. Danger of death in 10 to 15 min.
1.28	12800			Immediate effect; danger of death in 1 to 3 min.

VENTILATION

In a confined room or enclosure where the volume of air per person may be low, e.g. a crowded fallout shelter, it would be necessary to dissipate body heat, moisture and odours. Without cooling or ventilation to limit the effective temperature* to 85° F the occupants would be decidedly uncomfortable, their body temperatures would rise above the normal

* *Effective temperature (E.T.) is an arbitrary index which combines into a single value the effect of temperature, humidity and air movement on the sensation of warmth or cold felt by the human body. The numerical value is that of the temperature of still, saturated air which would induce an identical sensation.*

range of 97° to 99° F and, if no relief were possible, would eventually die. We are told that those unfortunates trapped in the infamous Black Hole of Calcutta died not from lack of oxygen but from heat exhaustion. Indeed, long before the oxygen would have become critically deficient the carbon dioxide concentration would have reached the intoxication level sufficient for death. In the last several years, there have been many investigations on the subject of man's physiological needs for survival in protective underground shelters, a summary of which is contained in Chapter 15 of the 1968 Guide and Data Book (Applications) (12). The ventilation requirements are associated with a complex heat balance and moisture balance, the chemical composition of the air and other variables, such as the number of people to be sheltered and their length of stay. In many cases, the ventilation requirements of an occupied enclosure depend primarily upon the heat and moisture dispersal requirements. For example, 5 persons seated in a shelter at 80° F effective temperature (85° F dry bulb (DB) and 75° F relative humidity (RH)) would give off in latent and sensible heat a total of about 2000 Btu per hr and about 0.86 lb water per hr. If the incoming air were at 70° F DB and 80% RH as in a summer-time basement situation, the air required to dissipate the heat and moisture and prevent the conditions from rising above 80° F E.T. would be about 70 cfm or 14 cfm per person. If the heat and moisture were absorbed or otherwise dissipated by means other than by ventilation air, the critical values become those associated with odours or the toxicity of the gases present. Thus odour removal often determines the ventilation rate. Under emergency conditions, however, as would be encountered in fallout shelters, odours may be disregarded since, although unpleasant, they pose no direct health hazard. Control of odours generally requires from 10 to 30 cfm per person, depending upon the source.

The problem of toxic gas removal involves the relationship between room volume, number of people, gas production rate, gas concentration and ventilation rate. When people enter a ventilated room that has a normally fresh atmosphere, the CO_2 concentration will begin to rise and a state of equilibrium will be reached when the rate of exhaust of CO_2 in the room air equals the CO_2 production rate. With adequate mixing of the room air, a minimum ventilation rate can thus be established which will prevent the gas concentration from exceeding any predetermined value. If the predetermined value selected is the threshold limit value (TLV) for the gas concerned, then:

$$Q_p\,n = \frac{vA(TLV)}{100} \quad \text{or} \quad A = \frac{100\,Q_p\,n}{v(TLV)}$$

Where Q_p = toxic gas production per person, cu ft/hr
n = number of persons
v = room volume, cu ft
A = air changes per hr
TLV = gas concentration (at TLV) per cent by volume.

Then the minimum ventilation rate for carbon dioxide would be

$$A = \frac{100\ Q_p\ n}{v(0.5)} = \frac{200\ Q_p\ n}{v} \text{ air changes/hr}$$

$$\text{or if} \quad K = Av = \text{ventilation rate in cu ft/hr}$$

$$\text{then} \quad K = 200\ Q_p\ n \text{ cu ft/hr}$$

$$= 3.33\ Q_p\ n \text{ cfm.}$$

The allowance for each person then becomes 3.33 Q_p cfm.

Thus, with 5 persons seated in a fallout shelter, each producing 0.63 cu ft/hr of CO_2, the ventilation rate to ensure that the TLV of 0.5 per cent CO_2 is never exceeded would be

$$K = 200 \times 0.63 \times 5 = 630 \text{ cu ft/hr} = 10.5 \text{ cfm.}$$

The allowance for each individual at rest then becomes 2.1 cfm per person for adequate CO_2 dispersal.

For persons standing or seated, the breathing rate, and therefore the CO_2 production rate, would be somewhat higher and consequently the ventilation allowance should be increased by about 50 per cent. A figure of 3 cfm per person is generally recognized as the average minimum outdoor air requirement to ensure an acceptable limit on CO_2 free air for shelter occupants. Heavy work or exercise would require up to ten times this amount for CO_2 dispersal.

The volume of the space or the cubic footage per person will affect the time required after entering the space to reach a steady CO_2 concentration. The time to reach a given concentration of gas can be approximated by the formula

$$T = \frac{x_2 - x_1}{[(Q_p\ n)/(v)] - A(x_2 + x_1)/2}$$

where x_1 and x_2 are the initial and final concentrations of the gas.

For a normal carbon dioxide concentration in air of 0.03 per cent, this equation becomes:

$$T = \frac{0.0047}{[(Q_p\ n)/(v)] - 0.00265\ A}$$

Thus, if the shelter in the example above were 1000 cu ft in volume, i.e. 200 cu ft per person, it would take 3.15 hours to reach a steady balance at the TLV of 0.5 per cent CO_2 with a ventilation rate of 2.1 cfm per person.

If the shelter had been perfectly sealed with a ventilation rate of zero, the equation becomes

$$T = \frac{0.0047\ v}{Q_p\ n}$$

and the time to reach the CO_2 TLV would be 4.7/3.15 or 1½ hours in the 1000-cu-ft shelter in the example.

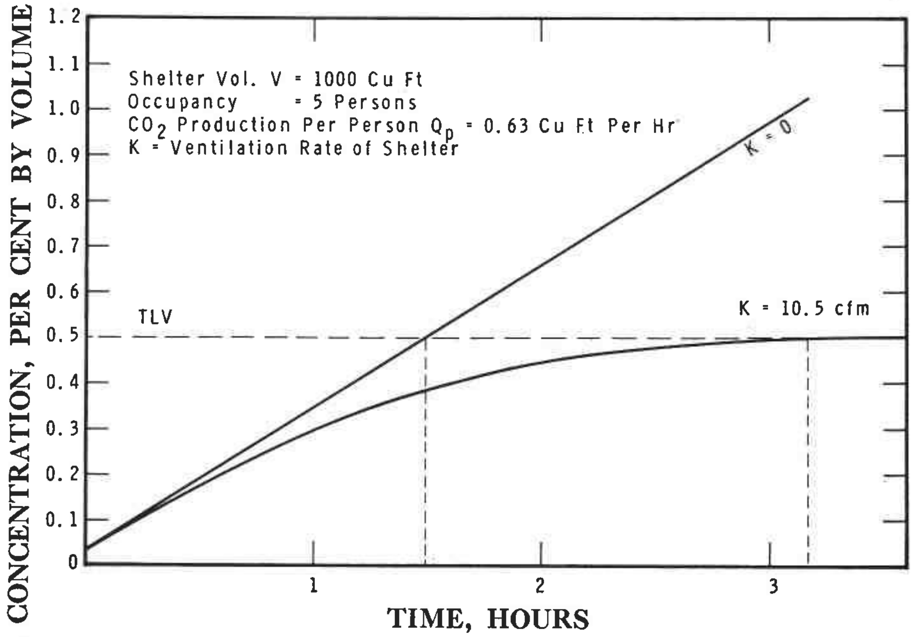


FIGURE 1

CO_2 CONCENTRATIONS WITH VARYING SHELTER VENTILATION RATE

Figure 1 illustrates the conditions for the shelter situation outlined in the example.

The foregoing considerations are based upon the assumption that the air in the shelter or other confined space is completely mixed so that gas concentrations are uniform throughout the space considered. In fact, unless a circulating fan or similar device is used, there will be considerable stratification and the air temperatures and CO_2 concentrations will vary from floor to ceiling. The forces of convection will be such that the heat emitted by people and to a greater extent by any fuel-fired appliance will rise and be more or less confined to the ceiling or around an upper vent opening; the colder "fresh" air will be concentrated at the floor and especially at any bottom inlet vent opening.

FUEL-FIRED APPLIANCES

Ordinary combustion of hydrocarbon fuels is characterized by the production of heat and the combinations of oxygen and hydrogen to form water and of oxygen and carbon to form CO_2 and usually small quantities of CO. The weight ratio of CO_2 produced to O_2 consumed, assuming complete combustion, is approximately 0.9. For every unit of fuel consumed, the approximate amount of CO_2 produced can be obtained from Table 4. With adequate oxygen supply and a burner that promotes good combustion, the CO_2 production can thus be calculated knowing the fuel consumption rate of any appliance. If combustion is not complete, CO will be produced and perhaps a quantity of unburned fuel. These are more difficult to estimate.

The amount of CO produced is dependent upon the design of burner, the primary air to fuel ratio, the amount and method of introduction of secondary air for combustion, and upon flame temperature. Flame temperature is, in turn, dependent upon the flame's environment, particularly with regard to radiation from adjacent surfaces such as the combustion chamber wall of furnaces or boilers. The surfaces of pans or other cooking utensils extending into the inner cone of the flame of a cooking appliance instead of remaining completely above the flame will be sufficient to "cool" the flame and thus to produce CO, the quantities being greater as the utensil is further immersed (3). Furthermore, if the atmosphere is allowed to decrease in oxygen content, with a corresponding increase in CO_2 content, CO production of wick-type burners may increase due to the reduction in the flame size. With other types of burners, notably the pressure-type, the air-fuel ratio is upset due to the reduction in oxygen, a yellow flame rather than blue is promoted, the flame temperature is correspondingly reduced by the fuel-rich mixture, and unburned fuel and CO production result.

TABLE 4

APPROXIMATE WEIGHT AND VOLUME OF CARBON DIOXIDE IN COMBUSTION PRODUCTS

Type of Fuel	Formula	Approximate Weight of CO_2 (gm/gm of fuel)	Approx. vol. of CO_2 cu ft per gal* fuel
Kerosine	C_nH_{2n+m}	3.1	224
No. 1 (stove) oil	C_nH_{2n+m}	3.1	232
Methyl alcohol	CH_3OH	1.375	98
Ethyl alcohol	C_2H_5OH	1.915	133
Isopropyl alcohol	$(CH_3)_2CHOH$	2.220	153
Lighting naphtha	C_nH_{2n+m}	3.1	181
Aliphatic solvent	C_nH_{2n+m}	3.1	187
Marine (white) gasoline	C_nH_{2n+m}	3.1	187
Auto (leaded) gasoline	C_nH_{2n+m}	3.1	187
L P gas (propane)	C_3H_8	3.0	154

**at room temperature (70° F)*

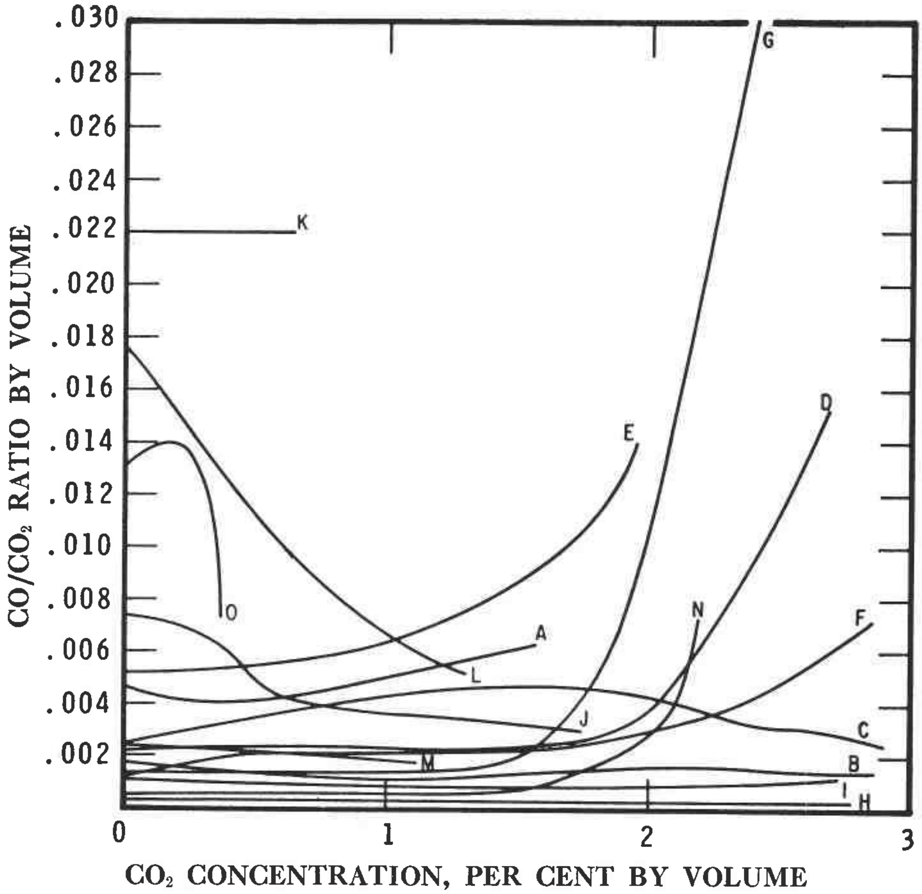
The CO productions of a single appliance under various fuel inputs and those of various appliances must be brought to a common denominator to be compared. The common denominator in this case is the fuel consumption rate, and if one assumes a direct relationship between fuel consumption and CO_2 production, the rating of the appliance can be based upon the ratio of the CO and CO_2 productions. Laboratory tests can be conducted to establish the CO/CO_2 ratio of the appliance based on the concentrations of the gases in the combustion products under various operating conditions. For example, the British Standards Institution have established a specification (13) which limits the CO/CO_2 ratio to 0.02 at rates of burning between maximum rated capacity and half this capacity or between maximum and minimum rated capacities if the minimum rate is less than half the maximum. The figure of 0.02 is obtained by the ratio of the CO and CO_2 allowable British values of 0.01 per cent CO and 0.5 per cent CO_2 and implies that the rate of CO production shall not be so great as to reach the limiting CO concentration before the CO_2 limit is reached. This combustion test is, of course, only one of several operation and safety tests which the appliance must pass to be qualified to bear the certification mark of the B.S.I. In Canada, the Canadian Standards Association is in the process of producing a similar standard, B140.9, for portable, kerosine, room heaters based upon a set of tentative laboratory requirements first produced in 1953. The allowable CO/CO_2 ratio of this proposed standard is 0.01 which agrees with the now acceptable limit of 0.005 per cent for CO.

In addition to the evaluation of the appliance for CO and CO_2 production under ordinary atmospheric conditions of adequate oxygen, it is well to know its behaviour in a high CO_2 atmosphere with reduced oxygen supply such as in an emergency shelter with insufficient ventilation or where mixing of the air may increase the CO_2 concentration and decrease the O_2 concentration in the air for combustion. In addition, CO tests may be warranted where cooking is being done with an unvented stove, to determine the CO production with a standard cooking utensil in place at normal cooking level and with varying degrees of flame impingement.

TOXICITY STUDIES

Recently, a number of portable fuel-fired appliances for heating, illuminating and cooking were studied to determine their combustion characteristics, notably with regard to their CO/CO_2 production ratio when operating under conditions of both adequate and reduced oxygen supply.

The tests were carried out in a large testing laboratory maintained at reasonably constant temperature conditions in which an insulated wood-frame structure had been erected and equipped with a closely controlled refrigeration system and instrumentation for continuous measurement of air temperature, relative humidity, CO and CO_2 concentrations, as well as periodic fuel consumption. Air in the test chamber was continually and thoroughly mixed to give as far as practicable an homogeneous atmosphere in order to simplify the measurement of gas concentrations by a single sample location and to promote uniform temperature and humidity conditions within the test structure.



A Double Flat Wick Stove
Special Kerosine
B Circular Wick Stove
Special Kerosine
C Reflective Heater
Special Kerosine
D Pressure Burner Stove
Special Kerosine
E Vaporizer Stove
Methyl Hydrate
F Wick-Type Heater
Methyl Hydrate
G Pressure Burner Stove (No. 1)
Automobile Gasoline
H Pressure Lantern
Lighting Naphtha
I Pressure Burner Stove (No. 2)
Lighting Naphtha
J No. 6 Catalytic Combust. Heater
Aliphatic Solvent
K No. 4 Catalytic Combust. Heater
Aliphatic Solvent
L No. 5 Catalytic Combust. Heater
Aliphatic Solvent
M No. 3 Stove — Jellied Alcohol
N No. 5 Stove — LP Gas
O No. 4 Stove — Jellied Alcohol
(Without Heat Intensifier)

FIGURE 2

CO/CO_2 PRODUCTION RATIOS OF VARIOUS APPLIANCES

In addition to the fuel intended to be used with each appliance, other fuels with which the appliance might have to operate in an emergency situation were used in supplementary tests. Although fitted with a multiple-pane, fixed glass window and a walk-in refrigerator-type door, the test chamber was found to have an air-exchange rate with the laboratory air of about 45 cu ft per hr which included the 2 cu ft per hour of continuous extraction of the room air for CO and CO_2 analysis. The net room volume was 390 cu ft, and the ventilation rate was therefore approximately 1/9 of an air change per hour. The results of the tests are contained in Table 5, which gives the initial CO/CO_2 production ratio, that is with no accumulation of CO_2 or depletion of O_2 and the fuel rate under these conditions. As each test progressed and further readings were taken with increasing CO_2 concentration, the performance of the appliances changed as illustrated by the curves of Figs. 2 and 3. In these diagrams, the scale of increasing CO_2 concentration can be considered also as a scale of decreasing O_2 concentration in the atmosphere in which the appliance was operating.

These studies showed that most of the appliances tested gave a satisfactory performance but some could be considered more dangerous than others from the standpoint of emission of CO. In general, the amount of carbon dioxide produced was in proportion to the fuel burned although some unaccounted-for fuel consumption signified some unburned fuel in some trials. The carbon monoxide generated was less when the burner design was such that the fuel and air were properly mixed, vaporized and ignited and when the heat intensity of the combustion process was higher.

In the case of catalytic combustion heaters, it appeared that little CO was given off when the appliance was operated at a low capacity, as can be obtained with a "slow" start using a limited amount of starting alcohol. But when ample alcohol was used for a "quick" start, the ensuing fuel consumption was doubled and a considerable amount of CO and unburned fuel was given off at the burner head. Under the circumstances, a lighted match held over the glowing metal gauze would ignite these unburned gases and produce a flame. Of the three catalytic heaters tested, one would be considered unsafe by the standards of CO/CO_2 ratio used by the British Standards Institution in connection with kerosine-burning heaters, and two would not pass the 0.01 CO/CO_2 ratio limitation of the proposed Canadian Standard.

Of the kerosine-burning appliances, the wick-type stoves gave a reasonably constant CO/CO_2 production ratio regardless of CO_2 concentration, even though the fuel rate fell considerably with higher CO_2 concentrations. The pressure burner stove, however, showed a slight increase in fuel rate at higher CO_2 concentrations and a marked increase in CO/CO_2 ratio with CO_2 concentrations above 1½ per cent. The reflective heater, equipped with a kindler wick and sleeve burner with dome-shaped wire screen partly surrounded by a heat reflector, showed an increase in CO output when operated at ¾ capacity and especially at ½ capacity. This heater and the circular wick stove both gave off objectionably pungent

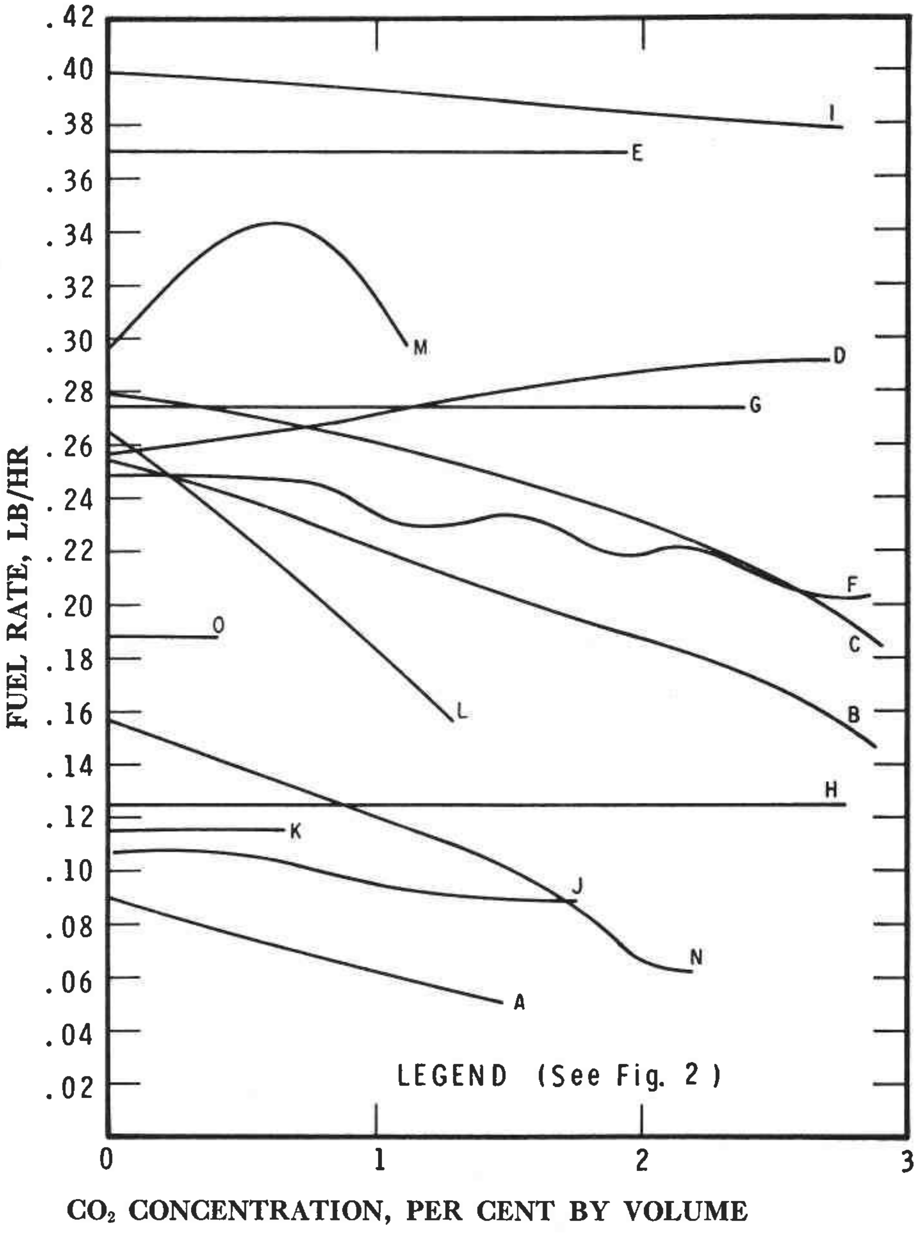


FIGURE 3

FUEL RATES OF VARIOUS APPLIANCES

odours immediately after flame extinguishment until the burner head had cooled down. Of the four types of kerosine appliances tested, all except the reflective heater were able to operate on No. 1 (stove) oil and even No. 2

(furnace) oil although the resultant carbon formation necessitated considerable maintenance.

Of the two alcohol-burning appliances tested, the wick-type burner gave consistently lower CO outputs with different alcohols than the vaporizer burner. The vaporizer burner stove tested provided far less CO when operating with difficult-to-obtain fuels such as ethyl alcohol and pure isopropyl alcohol than with the more prevalent methyl alcohol, methyl hydrate and commercial isopropyl alcohol.

Of the gasoline- and naphtha-burning appliances — not including the catalytic combustion units — the pressure lantern and one pressure burner stove showed low CO output on either lighting naphtha or aliphatic solvent regardless of CO_2 concentration. As the warning label implied, these became quickly inoperative when leaded gasoline was used for fuel. Another pressure-burner stove, when operating on its intended fuel (leaded gasoline), operated with low CO output except at the higher CO_2 concentrations. Fuel-rate figures in Table 5 for the two pressure-burner stoves are based on one burner only. Miniature stoves performed well with reasonably low CO/CO_2 ratios.

The small picnic stove operating on liquefied petroleum (LP) gas showed a very low CO output except when CO_2 concentrations rose above $1\frac{1}{2}$ per cent and fuel consumption rate had dwindled to about half normal. This stove is probably more suited to summer operation than winter since the LP gas fuel would have difficulty in evaporating properly at low temperatures. Some "bottled-gas" stoves are equipped with a special orifice for such operation (14).

The alcohol jelly stoves, intended for short-term cooking like the LP gas cartridge stove are relatively expensive to operate but give a reasonably low CO/CO_2 ratio with an open flame.

The charcoal-burning stoves should be confined to outdoor operation or if used indoors should be placed in a fireplace so that the products of combustion can be vented to the outdoors. The production of CO is so large that even in a relatively large-well-ventilated room, the CO concentration could easily reach the danger point. Their use in tents or cabins should be prohibited unless special venting arrangements are made.

In summary, there are many types of appliances on the market that could be used for heating of relatively confined areas, which will operate satisfactorily and safely under ordinary circumstances. They will consume the fuel for which they were designed more or less efficiently with little unburned fuel and, except for a few cases, with only small amounts of carbon monoxide generated as long as oxygen supply is adequate. The effect of reduced oxygen on the increased production of carbon monoxide is quite substantial in some models and their use would require special precautions with regard to adequate ventilation. It must be kept in mind

TABLE 5

INITIAL CO/CO_2 PRODUCTION RATIOS AND FUEL RATES FOR VARIOUS APPLIANCES AND FUELS

	Special Kerosine						Std. Kerosine		No. 1 (Stove) Oil		No. 2 (Furnace) Oil	
	Full capacity		¾ capacity		½ capacity		Full capacity		Full capacity		Full capacity	
	CO/CO_2 ratio	Fuel rate lb/hr.	CO/CO_2 ratio	Fuel rate lb/hr.	CO/CO_2 ratio	Fuel rate lb/hr.	CO/CO_2 ratio	Fuel rate lb/hr.	CO/CO_2 ratio	Fuel rate lb/hr.	CO/CO_2 ratio	Fuel rate lb/hr.
Double flat wick stove	.0046	.092	.0052	.060	.0072	.046	.0050	.058	.0036	.074	.0060	.062
Circular wick stove	.0019	.253	.0019	.190	.0025	.141	.0012	.221	.0022	.245	.0013	.231
Reflective heater	.0034	.278	.0061	.190	.0148	.145	.0032	.318	.0037	.180*	.0048	.238
Pressure burner stove	.0023	.258	.0020	.190	.0022	.136	.0016	.269	.0014	.268	.0012	.290

	Methyl alcohol		Ethyl alcohol		Methyl hydrate		Isopropyl alcohol (Pure)		Isopropyl alcohol (Commercial)		Jellied alcohol	
	Full capacity		Full capacity		Full capacity		Full capacity		Full capacity		Full capacity	
Vaporizer stove	.0114	.345	.0030	.370	.0050	.370	.0027	.450	.0048	.450	—	—
Wick-type heater	.0028	.280	.0016	.252	.0017	.247	.0023	.186	.0022	.239	—	—
No. 3 stove	—	—	—	—	—	—	—	—	—	—	.0023	.298
No. 4 stove	—	—	—	—	—	—	—	—	—	—	.0130+	.188

	Lighting naphtha		Aliphatic solvent		Marine (white) gasoline		Auto (leaded) gasoline		LP gas		Charcoal	
Pressure burner stove No. 1	.0042	.325	.0039	.278	.0051	.267	.0012	.274	—	—	—	—
Pressure burner stove No. 2	.0011	.400	.0013	.322	.0016	.220=	.0017	.390	—	—	—	—
Pressure lantern	.0002	.124	.0005	.114	.0007	.121	.0008	.126	—	—	—	—
No. 6 catalytic heater	.0014	.043=	.0073	.106	—	—	—	—	—	—	—	—
No. 4 catalytic heater	.0245	.117	.0220	.115	—	—	—	—	—	—	—	—
No. 5 catalytic heater	.0148	.216	.0171	.263	—	—	—	—	—	—	—	—
No. 5 stove	—	—	—	—	—	—	—	—	.0004	.154	—	—
Miniature stove No. 1	.0010	.304	—	—	—	—	—	—	—	—	—	—
Miniature stove No. 2	—	—	.0026	.330	—	—	—	—	—	—	—	—
Charcoal stove	—	—	—	—	—	—	—	—	—	—	.1620	.065

NOTES: * *Estimated value*
= *Half capacity*
+ *Without "heat intensifier" but with cooking utensil on flames.*

that the CO values given in the Tables and in the Figures herein are based on laboratory tests where the air in the enclosure was purposely stirred continuously and that under ordinary conditions of occupancy, the toxic gases would be expected to be far less diluted by the mixing action of ordinary infiltration. Certain appliance models are known to consume a greater weight of fuel than can be accounted for by calculations based on carbon dioxide production. Some catalytic combustion heaters may produce unburned fuel even under ordinary atmospheric conditions, that is, with no reduction in oxygen concentration. Further study is necessary to determine a simple method of measuring unburned fuel.

In addition to the toxicity hazards inherent in the appliance itself, there is the hazard from carbon monoxide when cooking operations are carried out with insufficient ventilation. Users should be aware that an appliance that normally produces insignificant amounts of CO with an open and free flame can become a menace when the flame is allowed to impinge upon a cooking vessel. Stoves that are designed for partial immersion of the cooking utensil in the flame should display a warning sign with respect to the use of the appliance within a tightly closed space.

There are, of course, other dangers present when using unvented fuel-fired appliances that are not covered in this study, such as temperature of surfaces, dangers of overturning or of fuel spillage in filling. One serious hazard with certain appliances that have valve-operated fuel supply is that, under conditions of reduced oxygen leading to reduced rate of burning, the rate of fuel supply might then exceed the rate of fuel consumption and a fuel flooding situation could occur, presenting a distinct fire hazard. Additional problems occur when lighted appliances are subjected to wind currents or drafts. Under these circumstances, those without wind shielding may flash flames outside the bounds of the appliance, not only increasing considerably the amount of unburned fuel but also creating a serious fire hazard. On barometric tank heaters, it is important to shield the fuel tank against such wind-blown flame so that vapourization of the fuel does not take place within the tank and cause excess pressure and consequent fuel flooding.

PRACTICAL CONSIDERATIONS

The use of unvented appliances in confined quarters creates a problem in ventilation to dilute the toxic gas concentration that may endanger health and life. The problem takes on fresh significance with the increased use of these appliances by campers, hunters and boaters and the season for their use is continually extending further into the spring and fall seasons and even into winter when the toxicity dangers are worst. Some simple guidelines for users of such equipment would be:

1. Use appliances that are known to be inherently safe.
2. Follow the manufacturer's instructions for use.

3. Use only the fuel intended for the specific appliance.
4. Ventilate the premises well especially during cooking or over-night.
5. Locate bunks or other sleeping facilities at the floor or lower level when there is a floor-to-ceiling temperature gradient.
6. Know the symptoms of toxic gas inhalation and be on guard at all times.

The choice of an appliance that is proven to be free from hazards is not an easy one. Certification by a recognized testing agency would be desirable so that the purchaser could be assured of a certain degree of protection against malfunction. If the appliance manufacturer were able to supply figures for the normal fuel burning rate and the CO/CO_2 production ratio of his products based on laboratory tests, it would be theoretically possible for the user to calculate the production rates for both carbon dioxide and carbon monoxide.* Then considering these in relation to the size of the room or space to be heated, a calculation could be made of the ventilation rate necessary to stay within the maximum allowable concentrations for the toxic gases. Unfortunately, it is very difficult to tell when such a ventilation rate is achieved in practice. At the present stage, one can merely allow in a general way for the hazards of toxicity by increasing ventilation when conditions are suspected to be critical. About the only simple guide to a hazardous CO_2 condition is the flame of a wick-type appliance which will indicate roughly by its flame size the CO_2 concentration. Half-normal flame size indicates roughly 1½ per cent CO_2 and at flame extinguishment the CO_2 concentration will have reached roughly 3 per cent which is still not too late to avoid a tragedy.

Carbon monoxide is even more difficult to detect since the flame might appear quite normal while giving off considerable CO: Catalytic heaters when operating at "high" fuel rate sometimes show a deceivingly pleasant red glow, usually associated with complete combustion, while in fact CO is being produced at a significant rate. In this respect, catalytic heaters are a partial exception to the general rule that carbon monoxide production is usually associated more with low fuel-flow conditions such as a turned down heater, an automobile engine idling or smouldering fires, where the heat intensity is insufficient to combine completely the carbon and oxygen. Smouldering wood in fireplaces, like charcoal broilers, is notorious for CO production and the user should be alert to the possibility of a downdraft from a fireplace filling a poorly ventilated space quickly with CO. One case is reported of a near fatality in a tightly closed cabin where a space heater and a fireplace had been in operation in the evening and later at night, a person sleeping on the floor of the room containing both appliances was almost overcome when the fire died down and the space heater "chimney" effect caused a downdraft in the fireplace.

* *A small stove burning ½ pint (approx. ½ lb) of fuel per hour produces about 10,000 Btu per hr of heat and about 12 to 12½ cu ft of CO and CO_2 per hour. With proper combustion, the CO output should be less than 0.04 per cent by volume, i.e. less than ½ cu ft per hr.*

There are many technological methods of detecting and measuring CO, including the use of palladium sulphate, palladium chloride, hopcalite, iodine pentoxide, silica-gel impregnated with a complex silico-molybdate compound or a palladium-molybdenum complex, as well as gas chromatography and infra-red analysis. In the field, less sophisticated methods must be employed. The colorimetric method of detecting CO has been used in mines and tunnels for some time and kits are available which the camper or tourist could use. Unfortunately, their use presents the problem of disposal of broken glass ampules and the expense would be high. Recent developments that warrant attention are a simple colour-indicating tablet that renews its original yellow colour after CO exposure and thus can be used for several exposures (15) and a simple and inexpensive electrically heated nickel filament apparatus (16).

In the final analysis, when unvented appliances are to be used in a confined space, the appliance should be one with an established low production of carbon monoxide, and adequate ventilation should be maintained to ensure freedom from toxic effects of products of combustion.

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