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CHARACTERIZATION OF THE EXHAUST GAS FROM A HEATPAC PERSONAL HEATER

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The potential health hazard from the carbon monoxide and nitrogen oxides contaminants in the exhaust gas of the HEATPAC personal heater is discussed. The tests carried out include concentration measurements of the respective gases, and the exhaust gas flow rate at various heat–powers of the heater was recorded. The determined formation rates of the contaminants show that the carbon monoxide gas is the most critical component regarding toxicological hazard. Most of the time in the use of the heater the catalytic converter functions properly, removing the carbon monoxide gas almost completely. In the burn out periods of the fuel elements, however, the low temperature leads to catalyst extinction. The formation rate of carbon monoxide in this period then reaches 10 millilitres per minute, and under special conditions 25 millilitres may be approached.

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ABSTRACT (continued)

The mentioned formation rates compare with the 40 millilitres per minute carbon monoxide production by a kerosene cooking stove with flames quenching against a cold pan. Carbon monoxide formation in a total failure of the catalyst is also discussed. It is presumed that a complete failure is unlikely to occur.

The general conclusion is that the level of contaminants from the personal heater is unlikely to constitute a toxicological hazard given adequate ventilation when using the heater in small rooms. The required ventilation rate corresponds to that of a liquid–fuelled cooking stove.

CHARACTERIZATION OF THE EXHAUST GAS FROM A HEATPAC PERSONAL
HEATER

1   INTRODUCTION

The charcoal–fuelled personal heater constituting the fundament of the HEATPAC system has a
great number of military and civilian applications. Heat is generated by the combustion of a
charcoal stick. The heat is delivered by a stream of warm air which can be ducted in a variety of
ways in accordance with the specific type of application.

The flow of warm air is completely separated from the exhaust gas which is discharged through
the exhaust tubing. There is a potential risk that the toxic carbon monoxide and nitrogen oxides
contained in the exhaust gas may accumulate and represent a health hazard. The purpose of the
present study is to demonstrate by experiments to what extent such a risk exists. This report
presents a thorough discussion of the theme and is a supplement to earlier reports (1,2) from the
Norwegian Defence Research Establishment (NDRE) and from US Army Medical Bio-
engineering Research Laboratory Fort Detrick (3,4).

2   ASPECTS OF THE COMBUSTION PROCESS OF THE CHARCOAL STICK

The HEATPAC personal heater is started by lighting the fuse which sticks out of the end of the
fuel element box. The closing of the heater shutter shortly after lighting activates the fan which
provides combustion air for the glowing process of the primer strips and for the subsequent
glowing of the charcoal stick.

Smoke evolves a few seconds after start during the combustion of the primer strips. The odour
of the formed smoke, containing hydrochloric acid, nitrogen oxides and unburned hydrocar-
bons, is unpleasant, and it should always be exhausted to open air.

The main constituents of the charcoal stick are ground charcoal with relatively small amounts of
binders. The combustion characteristics regarding exhaust gases are essentially similar to those
of pure charcoal.

In the combustion of charcoal some amount of noxious carbon monoxide gas is generally for-
med simultaneously with the carbon dioxide. The purpose of the monolithic honeycomb cata-
lyst, located in the bottom of the combustion chamber of the heater, is to reduce the amount of
carbon monoxide by oxidation to carbon dioxide.

The catalytic converter is heated by the glowing charcoal stick. The converter starts functioning
as soon as the temperature exceeds the characteristic converter ignition temperature which is
about 180°C. The removal of carbon monoxide in the working period of the converter is almost
complete. In the burn–out period of the charcoal stick the temperature again drops below the
ignition point. The following extinction of the catalytic after–burning process results in a rise
again of the carbon monoxide concentration in the exhaust gas.

It is noted that substances contained in the charcoal stick liberate odorizing agents with the exhaust gas when the charcoal stick is burning. The presence of these agents serves to indicate the function of the catalyst. A working catalyst deodorizes the exhaust gas almost completely by the catalytic afterburning of the odorous components.

3   PROCEDURES

The data required for the present study stem from measurements of the concentrations of carbon dioxide, carbon monoxide and nitrogen oxides in the exhaust gas. The measurements also include exhaust flow rates and temperature records.

The concentration measurements were carried out using a dual beam Leybold Binos infrared recorder for continuous registration of CO_2 and CO concentrations in the exhaust gas. A Bendix model 8102 instrument was used for simultaneous photometric detection of NO_x by chemiluminescence. The warm air temperature at the outlet from the heater was recorded with a thermocouple.

A thermistor anemometer circuit (5,6) was designed to provide a simple electronic instrument for measurements of exhaust gas flow rates. The thermistor responds to the flow rate while operating in a self-heated mode. Temperature compensation for variations in the exhaust gas temperature is included in the circuit. The exhaust gas was cooled in a condenser before measuring the exhaust gas flow rate. Concentrations, temperatures and flow rate data were collected on a squirrel logger for further processing on a computer. The heat power of the HEATPAC personal heaters used in the experiments was varied. This was accomplished simply by varying the thermal insulation surrounding each heater. The thermostat system of the heater then regulates the heat power. High insulation results in low power requirement and low burning rate. The charcoal stick then burns for a longer period of time.The fan of the heaters was driven with standard alcaline D–cell batteries to simulate normal use of the heater. The non–uniform capacities of these batteries, however, influence the reproducibility of the performance data of the heater. This lower reproducibility is not assumed to be essential regarding the characterization of the heater.

4 RESULTS AT NORMAL OPERATION OF THE HEATER

Figure 4.1 below shows three characteristic curves representing the warm air temperature at high, medium, and low heat power of the HEATPAC personal heater. Each curve describes the course of one fuel element.
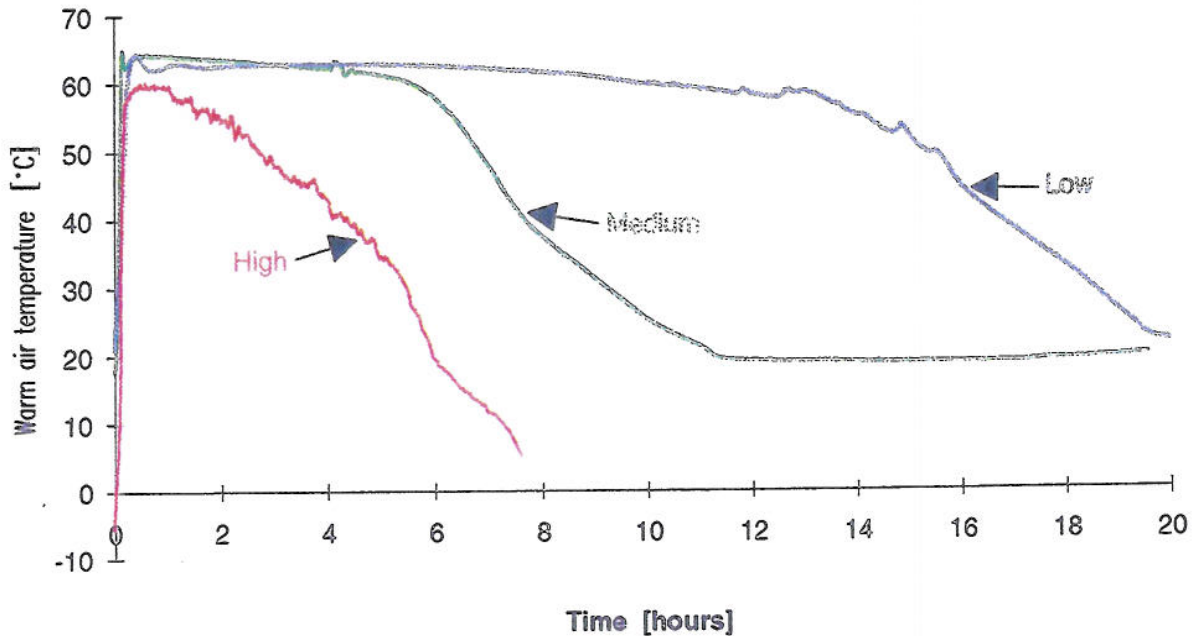

Figure 4.1   *Warm air temperature of a HEATPAC personal heater at high, medium and low heat power.*

With reference to the above curves, it is noted that the ambient temperatures differ. The measurements at high heat power were done at temperatures below freezing point, and medium and low power at room temperature.

It is noted that the warm air temperature is lower at high heat power than at medium and low power. This is explained by the restriction in the combustion air supply caused by the layer of ash forming on the upper surface of the glowing charcoal stick. The combustion air supply becomes critical at high heat power.

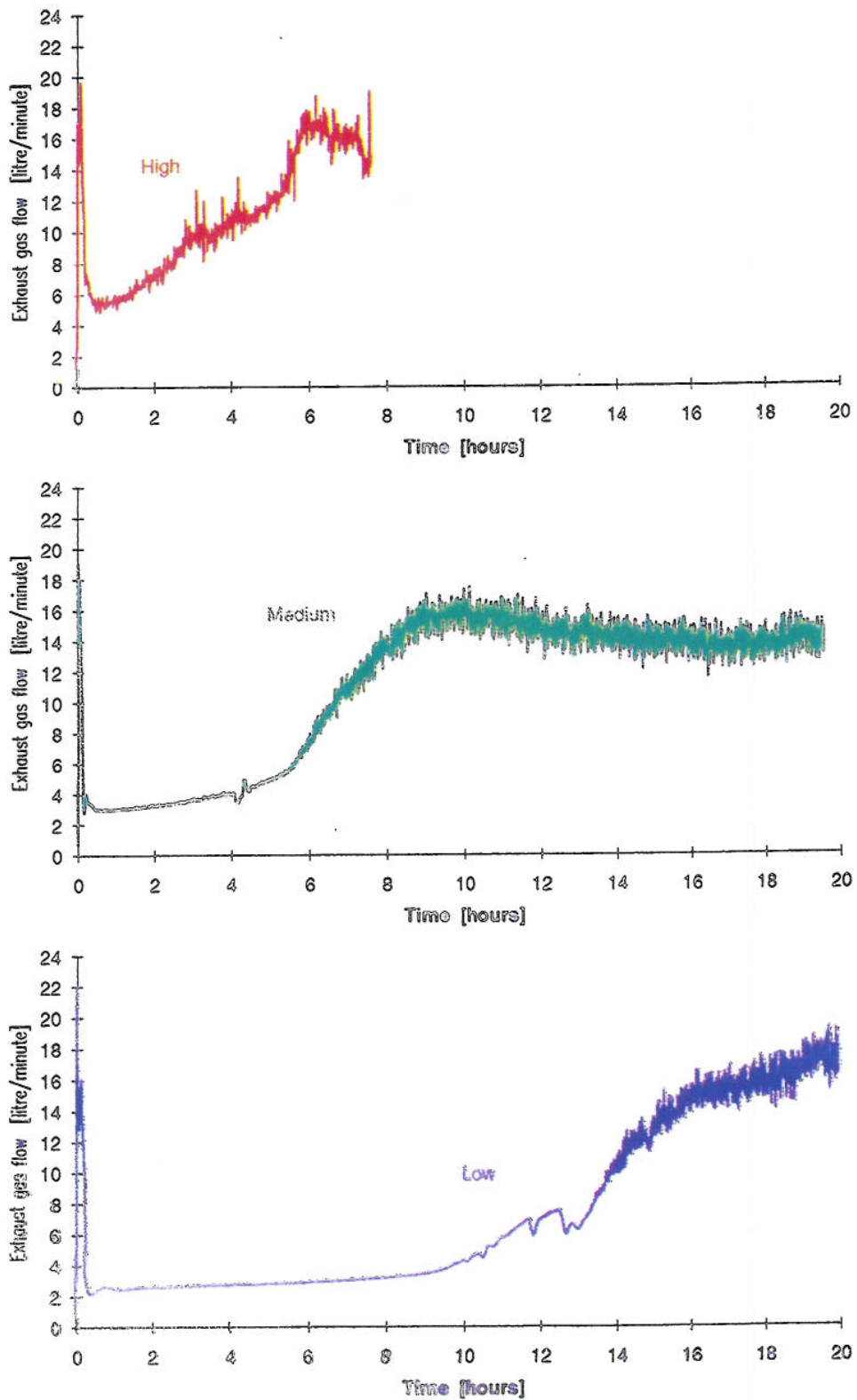The corresponding exhaust flow diagrams are shown in figure 4.2:

Figure 4.2   *Exhaust gas flow rate at high, medium and low heat power.*

The heat power of the heater can be estimated from the following equation:

$$P = 2,85F \cdot X_{CO_2}(Watts) \tag{4.1}$$

where F is the exhaust gas flow rate (litres per minute) and X_{CO_2} (the per cent) fraction of carbon dioxide. The equation is based on 34 MJ/kg heat of combustion of charcoal. The heat power at three characteristic courses is evident from figure 4.3:
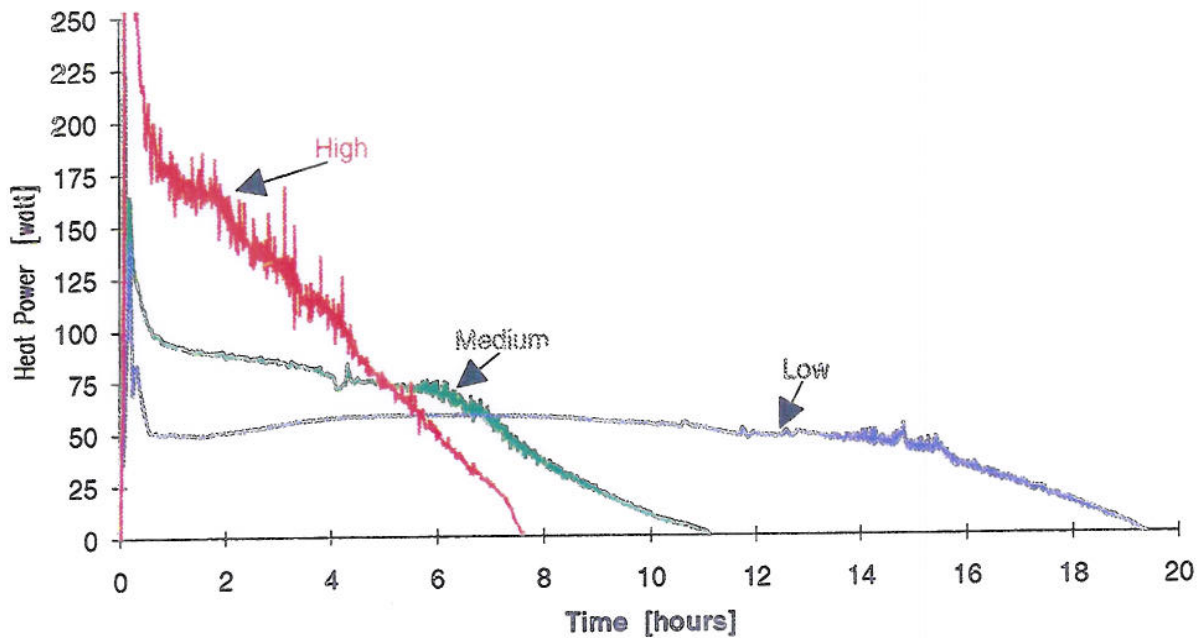

Figure 4.3   Characteristic courses of the heat power of the personal heater.

The lifespan of the fuel element can be estimated from the figure. These are the figures: 5 hours at high heat power, 8 at medium and about 17 hours at low power. The flow of carbon dioxide gas which equals the rate of oxygen consumption, can be evaluated by the following equation:

$$F_{CO_2} = F \cdot X_{CO_2} \cdot 10(litre/minute) \tag{4.2}$$

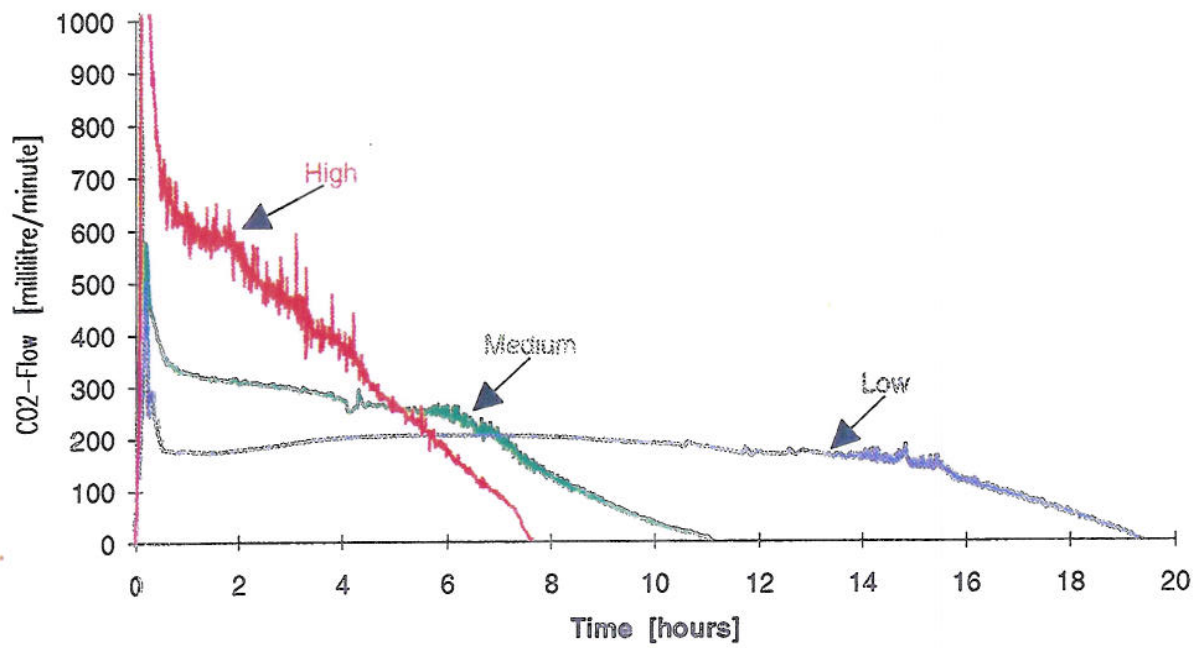F_{CO_2} is plotted in the following diagram:

Figure 4.4   Formation of carbon dioxide gas at high, medium and low heat power.

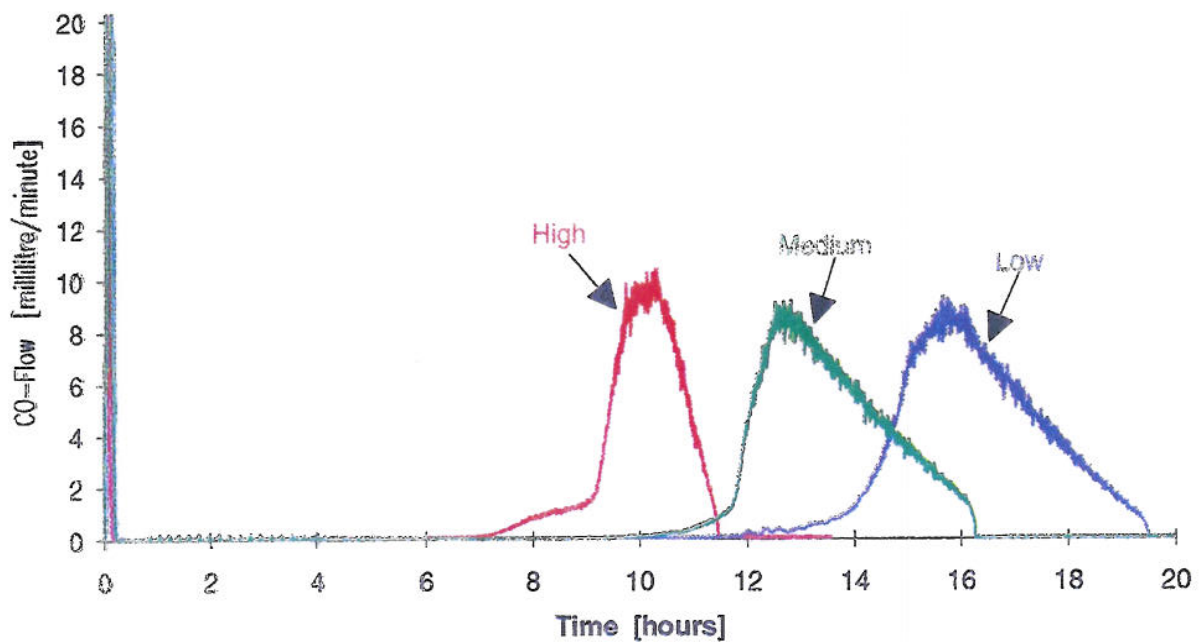The next diagram shows the corresponding CO flow:

Figure 4.5   Formation of carbon monoxide at high, medium and low heat power.

The figure reveals that the carbon monoxide formation is low except in the initial and the burn out periods of the fuel element. The total amounts of carbon monoxide liberated during the burn out periods are found by integrating the above curves. The results are 1000, 1400 and 1600 millilitres at high, medium and low heat power respectively.

The formation of NO_x gas is found correspondingly:
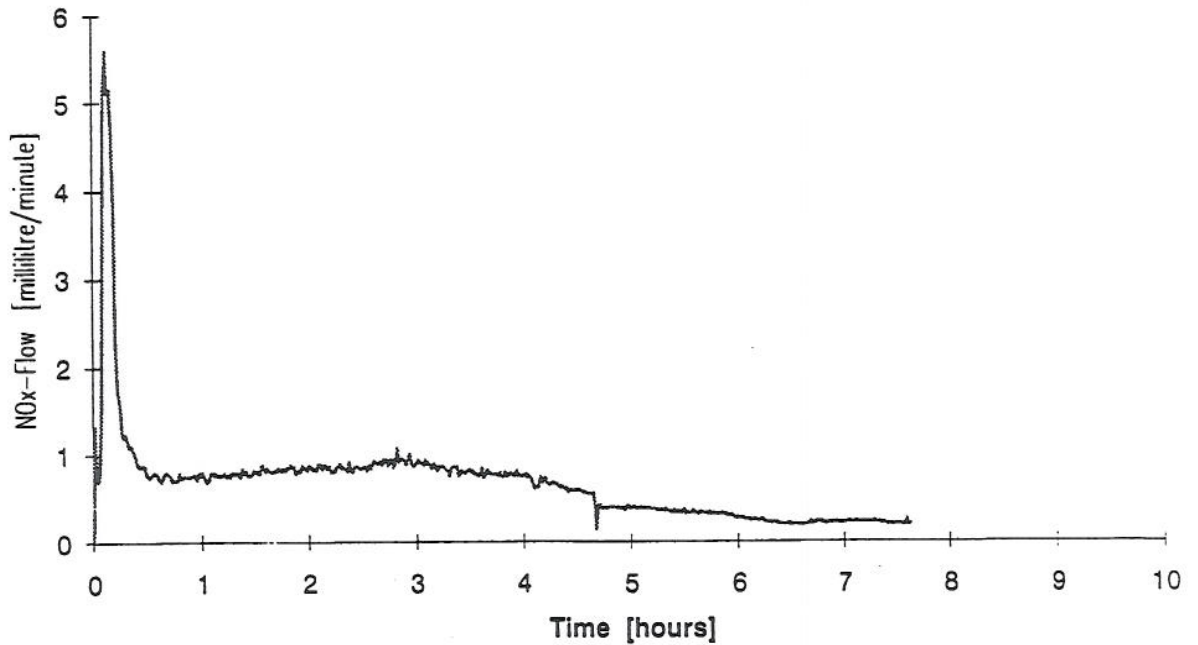
Figure 4.6   Formation of nitrogen oxides by the combustion of the charcoal stick at high heat power.

The amount of NO_x formed per unit time follows, as an estimate, in proportion to the heat power of the heater. The measurements show that more than 90% of the NO_x composition arises from NO. The catalytic converter of the personal heater which removes CO almost completely does not, however, affect the NO_x concentration. The total amount of NO_x liberated is about 300 millilitres.

So far the period of time after the start–up period of the heater has been considered. The following figures 4.7, 4.8 and 4.9 characterize the initial 20 minute period of the combustion process:
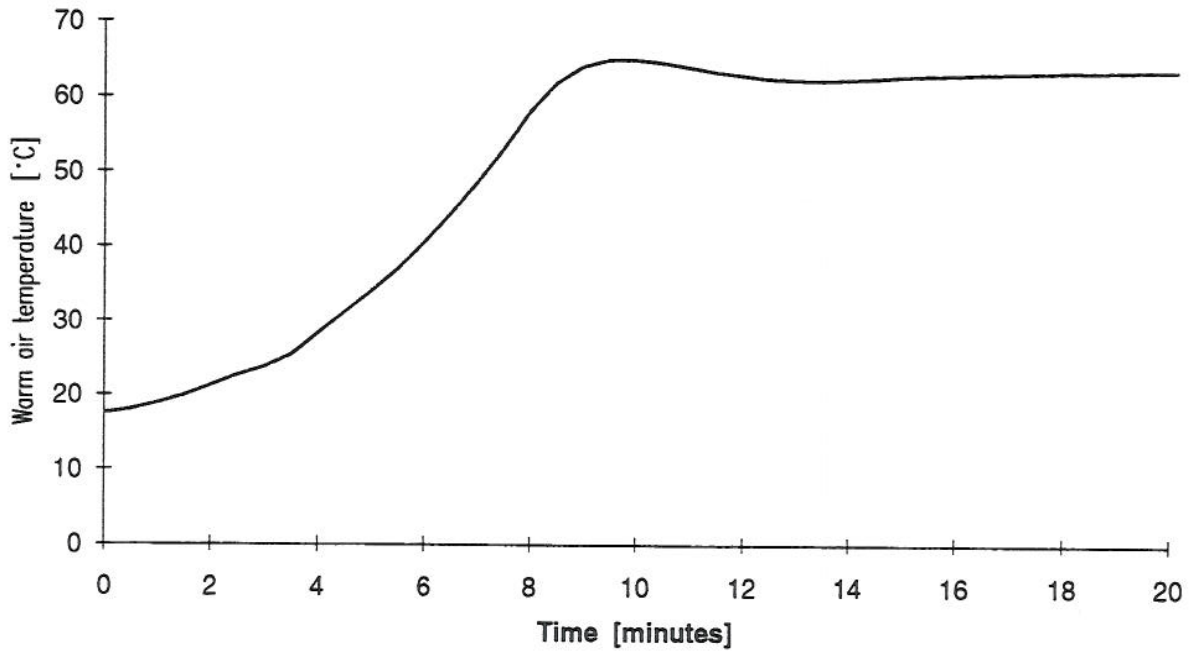
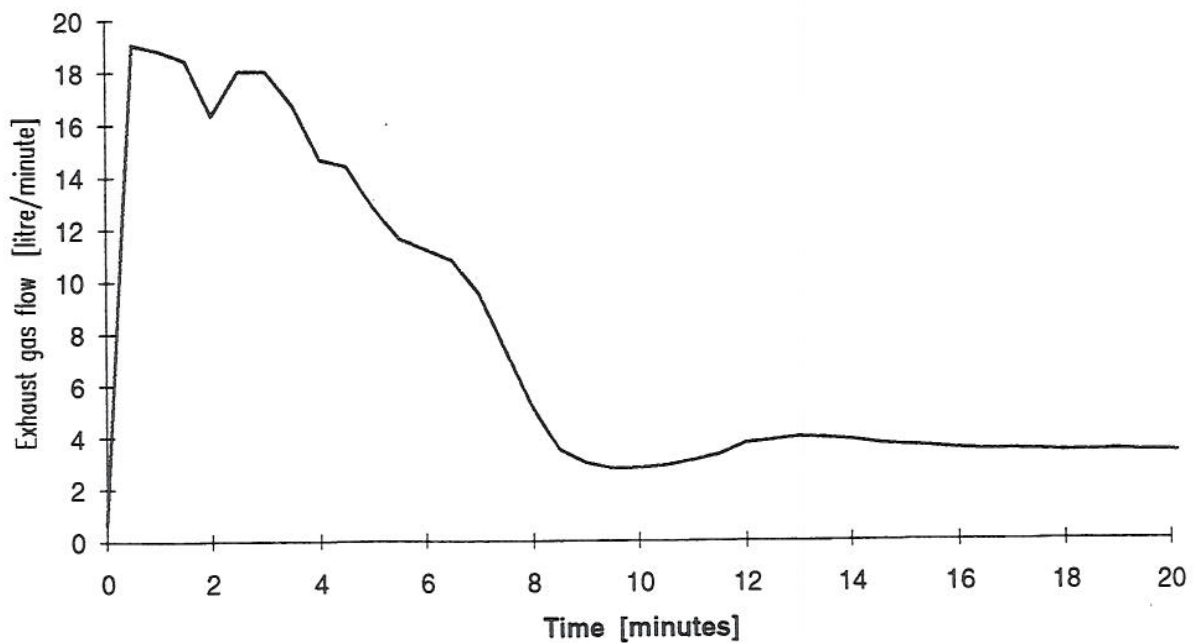Figure 4.7   Warm air temperature in the start up period.

Figure 4.8   Exhaust gas flow.
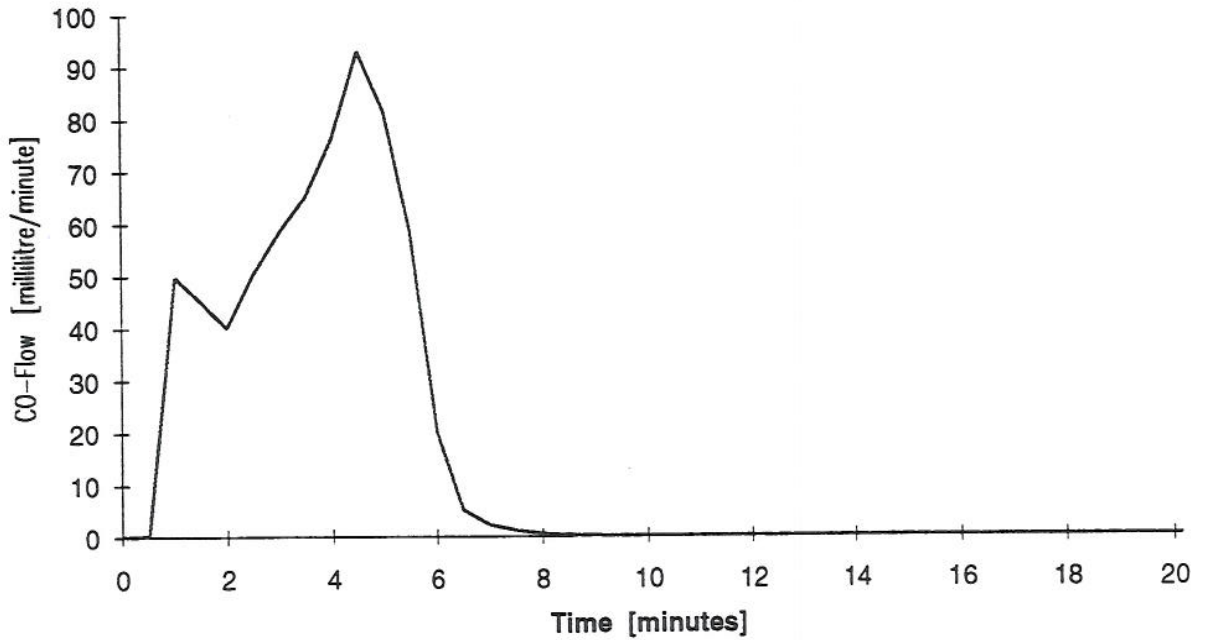
Figure 4.9   *Production of carbon monoxide in the start–up period.*

The integrated amount of carbon monoxide liberated in the start–up period is 400 millilitres.

The characteristics given here are typical of the start–up period. Some variations are, however, to be expected from one fuel element to another and from varying heat powers of the heater.

5   RESULTS WITH UNUSUAL OPERATION OF THE HEATER

When the HEATPAC personal heater is run at a very low heat power, it is to be expected that the catalytic converter temperature will drop below the catalytic ignition temperature. This results in no removal of the carbon monoxide gas. Figure 5.1 shows such a case.

Figure 5.1   Production of carbon monoxide at low (approximately 50 watts) heat power in a heater with no reflecting shield.
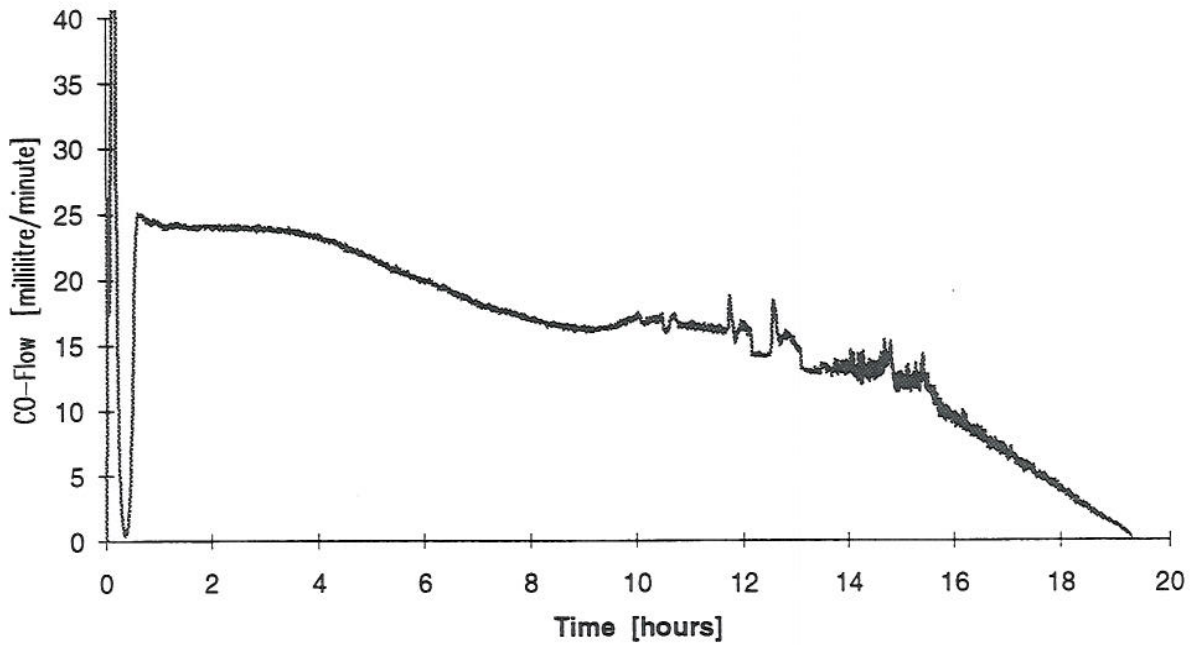
The picture given here varies with various models of the heater. In a later model of the heater, a heat reflecting shield on the combustion chamber has been introduced. The resulting higher temperature of the catalytic converter result in catalytic activity even down to about 20 watts heat power. The corresponding course of production of carbon monoxide at 50 watts in this later model is shown in figure 4.5.

The next diagram shows the CO formation in a heater from which the active honeycomb structure of the catalytic converter has been removed. This experiment was designed to simulate total failure of the converter.
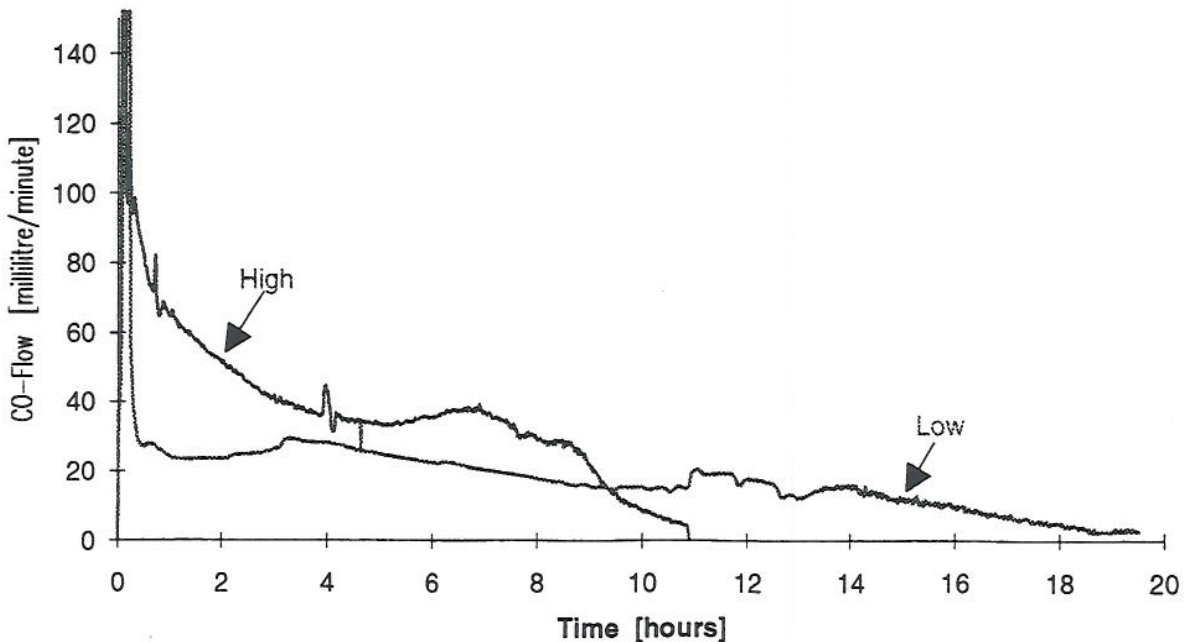

Figure 5.2   Carbon monoxide formation in a non–catalyzing heater at high and low heat power.

6 EXHAUST EMITTED IN A CLOSED SLEEPING BAG AND A TENT

The purpose of the following experiment was to test the concentrations of CO and NO_x when all the exhaust gas from a standard HEATPAC heater is exhausted inside a sleeping bag with the opening tied shut. As was expected, the carbon monoxide level increases in the burn out period. Figure 6.1 shows the peak value, 300 ppm, occuring after 9.5 hour.
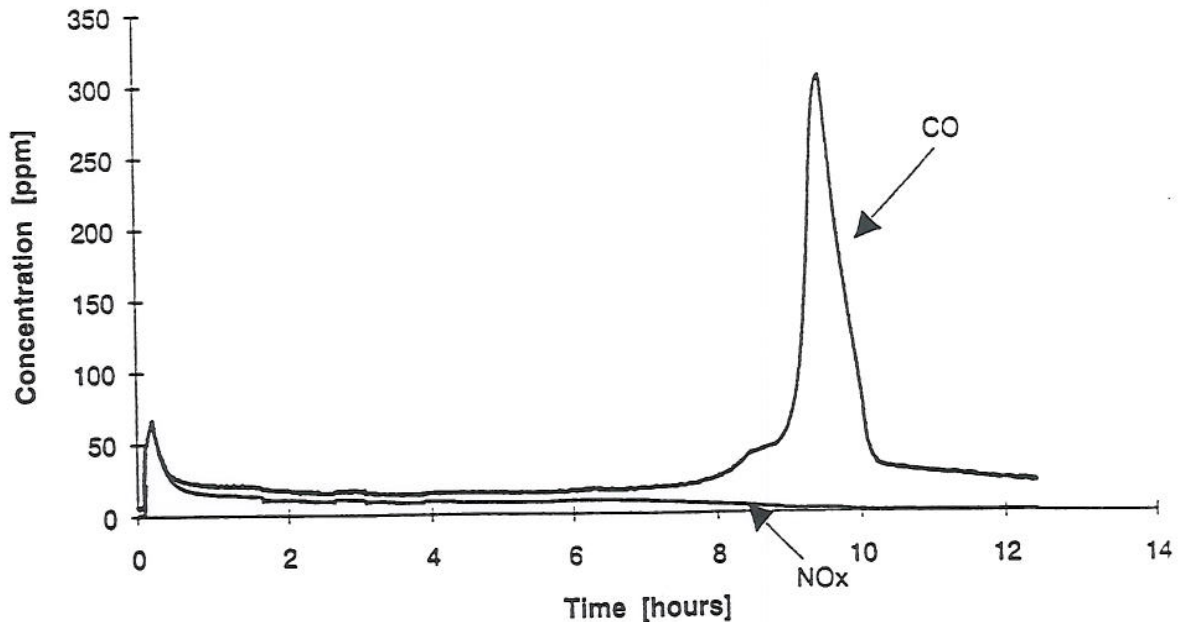

Figure 6.1   *Concentrations of carbon monoxide and nitrogen oxides in a closed sleeping bag. Ambient temperature –15°C.*

In the second experiment a heater was used from which the catalytic active material had been removed. The heater was put in a closed standard 14 square metre army tent. The walls of the tent were wet with rain and there was no wind so that the relative natural exchange rate of the inner air with ambient air was low.

The exchange rate was measured by using propane as a tracer gas. A fan operating at a moderate speed provided continuous mixing of the tracer gas and the heater exhaust gas with the inner air of the tent. Stationary values of the tracer gas concentration were obtained after two hours. The calculated exchange rate was about one cubic metre per minute corresponding to three total exchanges per hour of the inner air of the tent. The recorded maximum of the CO concentration was 60 ppm, occuring when the heater was run at moderate high heat power.

It was anticipated that heating the tent with a stove would increase the air exchange rate. In the next experiment, the kerosene stove yielded about 10 kilowatts of heat. Now the carbon monoxide from the heater at high heat power, with no catalyst, reached 35 ppm with 15 ppm in fairly stationary conditions.

7   DISCUSSION

7.1   Actual gas formation and toxic properties

It is necessary to give a brief review of the toxic properties of the actual gases. Carbon dioxide (CO_2) is produced by combustion processes. The metabolic production of CO_2 of a resting man is about 200 millilitres per minute. In the combustion of charcoal the rate of CO_2 formation equivalates the rate of oxygen consumption. The Occupational Safety and Health Administration (OSHA) threshold CO_2 concentration limit for 8 hours exposure is 5000 ppm or 0.5% (7).

The amount of CO_2 in the respiration air is 2–4% and tolerable concentrations of CO_2 in short time exposures are considerably higher. The oxygen deprivation is represented by the CO_2 concentration. The physiological response to oxygen deprivation is synergic with the CO_2 response.

Carbon monoxide gas (CO) is formed by incomplete combustion and is always formed when charcoal burns in open air. The OSHA threshold CO concentration limit for 8 hours exposure is 50 (7) or 0,005%. Carbon monoxide is a poisonous gas which has a high affinity with hemoglobin. Figure 7.1 shows the physiological effect of various CO exposure intensities as a function of time (8).
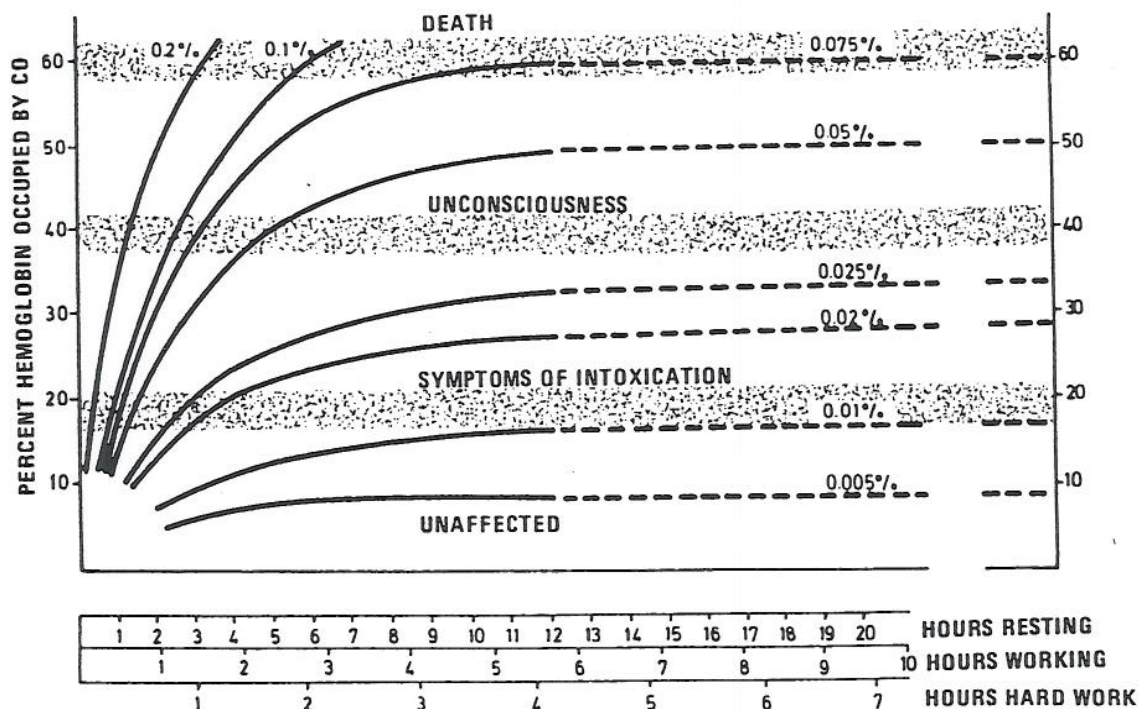
Figure 7.1   *The human reaction to carbon monoxide is related to the relative amount of hemoglobin occupied by CO. As indicated by the horizontal axis, the human CO response is strongly dependent on the physiological work load. For instance, exposure over a period of one hour of a hard working man corresponds to three hours of exposure of a resting man (given the same concentration).*

There is no physiological response to 0.005% exposure, whereas a concentration of 0.02% (200 ppm) causes symptoms of intoxication after one hour in a hard working man and three hours in a resting person. In real life we are exposed to carbon monoxide from a number of sources: in table 7.1 are some examples which may be compared to the figures in chapters 4, 5 and 6.

SYSTEM	RATE OF CO FORMATION (ml/min)	TOTAL AMOUNT OF CO FORMED (ml)
Smoking one cigarette (9)		30–60
Charcoal handwarmers at maximum heat power 10 watts. Weight charcoal stick 6 grams	4	600
Kerosene cooking stove with flame quenching against a cold pan (10,11)	40	
Barbecuing using one kilogram of charcoal per hour. CO/CO_2 ratio 1: 6	5 000	
Car at idling speed 1% CO in the exhaust gas, using 1 litre of gasoline per hour	10 000	

Table 7.1   Formation of carbon monoxide from various systems.

Nitrogen oxides are also emitted by charcoal combustion as shown in figure 4.6. The oxides originate from fuel bound nitrogen compounds and are liberated in the combustion process. The nitrogen monoxide (NO) OSHA threshold limit is 30 ppm. The limit of the nitrogen dioxide (NO_2) is 5 ppm (7). Since NO constitutes more than 90% of the NO_x composition, it is correct to use the 30 ppm limit when comparing toxicity with CO.

Prediction of the toxic environments that may be created by the exhaust gas from the HEAT-PAC personal heater is difficult because most often the air exchange rate of the space in which the heater is located is unknown. In fact, the air exchange rate or the ventilation is decisive for the possible development of the toxic environment. One can get around the problem by comparing with known carbon monoxide sources in common use and applied in similar spaces. An example here is the comparison of the HEATPAC personal heater with the kerosene cooking stove mentioned in table 7.1.

7.2   Formation rates of carbon monoxide

In the burn out period presented in figure 4.5, there will be emissions of carbon monoxide at a rate of up to 10 millilitres per minute. The potential hazard in this case is considerably higher for carbon monoxide than for carbon dioxide. The maximum CO formation rate is one fourth of the rate of the cooking stove emitting 40 millilitres per minute as shown in table 7.1. Integrating the curves of figure 4.5 over the burn out periods reveals a total amount of carbon monoxide

formed in these periods from 1000 millilitres at high heat power and up to 1600 millilitres at low power. These amounts compare with the amounts formed by smoking 20–30 cigarettes, over the same number of hours.

Figure 4.9 shows the carbon monoxide formation in the start–up period. The CO formation rate rises to a maximum of about 90 millilitres per minute. Normally this gas will be exhausted to open air with the noxious primer gases. The period of relatively high CO formation lasts until the catalytic converter starts functioning. The total amount of CO liberated, found by integrating the curve in figure 4.9, is about 400 millilitres, the same as from 8 cigarettes. The odor of the smoke in the start–up period is, however, quite unpleasant and it should be released outside closed rooms.

Function failure of the catalytic converter as a result of the low temperature at low heat powers of the heater is represented in figure 5.1. The carbon monoxide formation rate of this heater with non–shielded combustion chamber is at most about 25 millilitres per minute. The flame quenched cooking stove, table 7.1, produce about twice the heater's CO value. The integrated total value of the CO formation of the low power heater over an 18 hour period is 17000 milli-litres. This is an appreciable amount of carbon monoxide gas. As with the cooking stove, provision for adequate ventilation should be made when using the heater in small rooms.

If the catalytic converter failed, the maximum carbon monoxide formation rate of the heater, refering to figure 5.2, could exceed that of the quenched cooking stove by a factor of two. There is, however, evidence that a complete failure of the catalytic converter is unlikely to occur. The converter is of the same type as is used in purging car exhaust gas. The load on the catalyst in the heater is, however, considerably lower. The reliability of the catalytic converter was demonstrated by the Norwegian Expedition to Antarctica 1989/90 (12). Two heaters were run continuously for five weeks for cold protection of medicines. The catalytic converter efficiencies of the two heaters were tested after return, and no degradation of the catalytic converter could be observed. High reliability is also due to the combustion chamber–catalytic converter design. As a consequence, should the catalyst casing with the ceramic honeycomb catalyst unit accidently dismount, the heater would stop functioning because the combustion air would by-pass the fuel element.

There is a risk that the catalytic efficiency of the converter could be reduced by a coating of ash from the fuel element covering the upper surface of the catalytic active material. This has been observed with heaters having been used over prolonged periods. The ash layer can be removed by rinsing with water as recommended in the HEATPAC Technical Handbook (13).

7.3   Concentrations of carbon monoxide in the sleeping bag and in the tent

Figure 6.1 illustrates the CO concentration in the closed sleeping bag. Again the concentration to be concerned about is in the burn out period where the concentration peak value comes up to 350 ppm. A person breathing inside the closed bag would after a short period of time get problems with carbon monoxide poisoning. Even a relatively small opening around the head of the person would probably improve the picture drastically. Anyhow, the personal heater should be used with the exhaust tube sticking out of the bag as recommended.

The tent experiment described in chapter 6 shows that the carbon monoxide concentration in the tent will probably not exceed the threshold limit, even in the improbable case of total failure of the catalytic converter. According to figure 5.2 the carbon monoxide production of the heater used in the tent is expected to be in the range of 40 millilitres per minute, the same as the flame quenched cooking stove. Also the required air exchange rate or ventilation rate to maintain the low carbon monoxide concentrations in the tent is therefore similar for the heater with non functioning catalyst and for the flame quenched cooking stove. The rate should exceed the measured value, namely one cubic metre per minute.

7.4 Formation rates of carbon dioxide and nitrogen oxide

According to figure 4.4 a personal heater operating at a high heat power produces about 600 millilitres of CO_2 per minute. This equivalates the CO_2 production of three resting persons or the same number of candles. Experience has shown that this CO_2 production and the corresponding oxygen consumption only present a problem in small confined spaces, like snow caves, with insufficient ventilation. However, adequate ventilation is always required in this situation . The CO_2 concentration and oxygen deprivation are the limiting factors for the use of the personal heater in small confined spaces when the catalytic converter is functioning. The problem met here corresponds to that of over–crowded rooms.

The nitrogen oxide concentration is not affected by the catalytic converter. Figure 4.6 shows that the maximum NO_x formation rate, excluding the NO_x formation in the start up period, is one millilitre per minute. The same amount would be released by smoking cigarettes at a rate of one cigarette (9) per two minutes. The health hazard connected to NO_x is considered to be lower than for CO in all situations.

8 CONCLUSION

Most of the time when running the heater, the catalyst removes the carbon monoxide almost completely. The only hazard then present is the possible development of a high carbon dioxide concentration and oxygen deprivation when using the heater in small confined spaces. The maximum carbon dioxide production and oxygen consumption of the heater correspond to three resting persons. Therefore the ventilation requirement for the heater is similar to that for three persons occupying the same room.

In the time of burn–out of the fuel element, carbon monoxide may be formed at a rate of 10 millilitres per minute, and under special circumstances 25 millilitres per minute. This represents a potential hazard in the use of the HEATPAC personal heater related to the carbon monoxide gas. The carbon monoxide formation rates mentioned are still lower than those for the cooking stove with flame quenching against a pan.

If all the exhaust from a normally operating heater is released in a sleeping bag, the CO concentrations are still not considered to be hazardous. It is always recommended to use the exhaust tube of the heater and let the gases out of the sleeping bag.

In the case of a complete catalyst converter failure, the amount of carbon monoxide formed might exceed the cooking stove by a factor of two. It is, however, concluded that a total catalyst

failure is not likely to occur. In any event, the level of contaminants is unlikely to constitute a toxicological hazard. Ventilation is required when using the heater in small confined rooms. As a guideline, the ventilation necessary corresponds to that of the kerosene stoves.

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