# Science

150. John Fairley, *Shivling*, acrylic on board, 310x610mm, 2008

PAUL RAMSDEN

# The Silent Killer

## Carbon Monoxide: a Mountaineer's Perspective

151. Beware, the 'silent killer'. Mick Fowler regards the stove while on Manamcho, Nyenchen Tanglha East, Tibet, April 2007. *(Paul Ramsden)*

There are two facts to remember about carbon monoxide (CO). Firstly all stoves can produce CO and secondly the CO levels that will produce a headache at sea level could be fatal at high altitude.

While CO is one of the most common source of poisoning in the 'civilised' world, its dangers in extreme polar and mountain environments has never been fully understood.

My own experiences of CO poisoning have in retrospect been many and varied. A particularly memorable episode of headache, dizziness, nausea and partial unconsciousness while at the Bivouac des Dames Anglaises, halfway along the *Peuterey Integral*, won't be forgotten in a hurry. Equally a period of depression and manic behaviour after spending two weeks tent-bound in Alaska now starts to make sense.

People who have read about my climbs are often surprised to hear that I am actually a health and safety consultant during office hours. Recently I completed an MSc in Occupational Health. My dissertation involved

experimental work on CO poisoning in tented accommodation, in conjunction with the British Antarctica Survey. While my research was based on Antarctica I realised that much of the information was of relevance to anyone using stoves in cold locations, especially at higher altitudes.

**Where does the CO come from?**

All camping stoves require the burning of hydrocarbon fuels such as propane and paraffin. Upon heating the hydrocarbons' molecular bonds break down or disassociate. At 800-900°C, carbon bonds are cleaved by the heat to form carbon radicals. At 1150°C, carbon radicals are stripped of hydrogen atoms forming acetylene. This in turn is decomposed creating free hydrogen molecules and carbon atoms.[1] The hydrogen molecules are broken down into hydrogen atoms by thermal dissociation before reacting with oxygen to form water, which in turn releases energy, thereby heating up the surrounding carbon atoms. The heated free carbon bonds with free oxygen atoms (similarly caused by the heating of $O_2$), forming CO.

$$C + O = CO + \text{energy}$$

The release of energy makes the flame hotter. With sufficient heat (1000°C) and the presence of oxygen, the CO will link up with more free oxygen to form $CO_2$. Therefore in the presence of oxygen, CO burns with a blue flame forming $CO_2$.

$$CO + O = CO_2 + \text{energy}$$

In simplistic terms, hydrogen burns rapidly at the base of the flame maintaining the combustion process. A little further up the flame carbon and oxygen combine to form CO. If the flame is hot enough, $CO_2$ will be formed further up the flame. However, if the flame does not reach the required temperature CO is released.

The flame can be inhibited from reaching high temperatures due to oxygen depletion or by coming into contact with a cooler object such as a pan. This process is known as quenching. Any object in the flame acts as a heat sink, draining energy from the flame reaction process. The surface will also act as a means of breaking the chain of flame propagation. Flame quenching will increase as the surface to volume ratio of the combustion area increases.

In most cases, the less contact the flame has with any surface the more complete the combustion process will be and the less potential for CO release will exist. However, in reality the situation is more complex than this, as a pan in contact with a quenched flame will heat quicker than one positioned well above a more efficiently combusting flame.

In addition, there are associated direct factors such as the way a pan may cause more flame turbulence resulting in new areas of flame propagation resulting in faster heating. There are also indirect factors, such as concerns over pan stability in an elevated position and the flame's resistance to wind dispersal.



The fact that CO is formed first and at cooler temperatures in a quenched flame is a critical factor in flame chemistry and the unwanted generation of CO.

The first scientific reference to flame quenching in camping stoves was in a paper by Henderson and Turner published in 1940 in *Nature*. 'That part of the flame which impinges upon the kettle or other vessel is cooled below the temperature requisite for complete combustion and CO is formed.'[2] This subject was again touched upon in a publication from 1942 entitled 'Carbon Monoxide from Melting Snow' by Davis from the University of Alaska, Fairbanks.[3]

Interestingly, there is no further scientific reference to this phenomenon in camping stoves from that date forward. For information on quenching in camping stoves today, it is necessary to review specialist online camping discussion groups such as www.backpackinglight.com that contains some very useful and interesting, though unpublished, work by Roger Caffin.[4]

Very little, if any, work has been carried out on the effects of high altitude and its associated reduced oxygen levels in the flame combustion processes. However, it is probably safe to presume that its effects will be detrimental to efficient combustion and that the potential for CO production will be increased.

**What are the health effects of CO poisoning?**

Carbon monoxide (CO) is a colourless, odourless gas known as 'the silent killer'. About 50 people die and 200 are severely injured as a result of CO poisoning in the UK every year.[5]

The main symptoms of CO poisoning develop in those organ systems most dependent on oxygen such as the central nervous system and the heart.[6] The initial symptoms of acute CO poisoning include headache, nausea, malaise and fatigue.[7] Headaches are the most common symptom of acute CO poisoning; it is often described as dull, frontal and continuous.[8] Increasing CO exposure produces cardiac abnormalities such as fast heart rate, low blood pressure and cardiac arrhythmia. Central nervous system symptoms include delirium, hallucinations, dizziness, unsteady gait, confusion, seizures, central nervous system depression, unconsciousness and respiratory arrest.[9]

One of the significant concerns following acute CO poisoning is the severe delayed neurological manifestations that may occur. Problems may include difficulty with higher intellectual functions, short-term memory loss, dementia, amnesia, psychosis, irritability, a strange gait, speech disturbances, Parkinson's disease-like syndromes and a depressed mood. Depression may even occur in those who did not have pre-existing depression.[8]

Delayed neurological conditions may occur in up to 50% of poisoned patients after 2 to 40 days.[10] It is however difficult to predict who will

**Table 1. Summary of symptoms and their relationship to carbon monoxide exposure** [13][14][15]

| CO concentration (ppm or ppm/exposure time when expressed) | Symptoms | COHb Concentration % |
|---|---|---|
| 35 | Headache and dizziness within 6 - 8 hours of constant exposure | 0-20 |
| 100/8hr to 200/4hr | Mild frontal headache within 2 hours | 10-20 |
| 200 | Loss of judgement | - |
| 400 | Frontal headache within 1 - 2 hours of constant exposure | - |
| 500/2hr | Headache ± tachycardia | 20-30 |
| 200-1200 | Steady symptom progression | - |
| 300 | Collapse | 30-40 |
| - | Coma | 50-60 |
| >1000 | Chemical asphyxiate actions | - |
| 650-1000 | Dizziness, nausea, and convulsions within 45 minutes, insensible within 2 hours | 60-70 |
| 1600 | Headache, tachycardia, dizziness, and nausea within 20 min, death in less than 2 hours | - |
| 2000 | Death in less than 1 hour | 80-90 |
| 3200 | Death in less than 30 minutes | 90-100 |
| 6400 | Headache and dizziness in one to two minutes. Convulsions, respiratory arrest, and death in less than 20 minutes | - |
| 8000 | Death in less than 10 minutes | - |
| 10000 | No symptoms before collapse and death | - |

develop delayed symptoms, though old age, unconsciousness while poisoned and initial neurological abnormalities may increase the chance of developing delayed symptoms.[11]

Carbon monoxide binds very strongly to haemoglobin with an affinity 210 times greater than oxygen. This leads to elevated carboxyhaemoglobin (COHb) levels and subsequently a diminished oxygen carrying capacity of the blood. For a normal non-smoker, the average COHb concentration is <1% rising up to 15% in heavy smokers.[12] Symptoms usually begin when the COHb concentration rises above 10%, with coma and death associated with levels above 40%.

While opinions vary on the exact relationship between CO exposure, COHb levels in the blood and the onset of symptoms there is, however, a broad consensus that headaches may begin with exposures to CO of as low as 35ppm, but will consistently develop with exposures in the range of 100-200ppm. Loss of judgment is expected with exposures as low as 200ppm with collapse occurring at concentrations as low as 300ppm. In most cases this refers to long-term eight-hour exposures, with short-term exposures requiring higher concentrations to have an effect. At



650-1000ppm, convulsions may start in 45 minutes and unconsciousness within two hours. At 1600ppm, death will occur in less than two hours.

The CO tolerance level for an individual is altered by many factors, including activity level, rate of ventilation, the presence of a pre-existing cerebral or cardiovascular disease, cardiac output, barometric pressure and metabolic rate.[7]

**The effects of higher altitudes**

The human lung works based on the gradient pressure difference between blood and air. Therefore, a decrease in inhaled oxygen pressure will have an adverse effect on how much oxygen can enter the blood. While moderately elevated COHb levels at sea levels might go unnoticed or result in moderate symptoms, at high altitudes these effects may be much more significant. Work done by Forbes et al published in 1945 showed that four out of 17 health subjects, at a simulated altitude of 4725 metres collapsed when their COHb levels reached between 9 and 19%. At sea level this would normally occur between 30 and 40%.[16]

Altitude contributes to the danger of CO exposure, firstly by decreasing the oxygen uptake into the body and secondly through the effect that the reduced pressure effect of altitude will have on increasing the time it takes for CO to be cleared from the body. In addition, at higher altitudes faster respiration rates allow inhalation of more CO, if present.[17] Higher altitudes are always colder and windier, therefore increasing the likelihood that tent ventilators will be closed, with the resultant increased potential for elevated CO levels, often sustained for long periods.

**Research on CO exposures in tents**

Research in this area has been very sparse. Leigh-Smith's review 'Carbon Monoxide Poisoning in Tents' details most of the previous work investigating CO production from stoves in tents up to 2003.[13] In all of this work CO production was found to be lowest with a freely burning flame and was found to increase by the addition of a pan in contact with the stove.

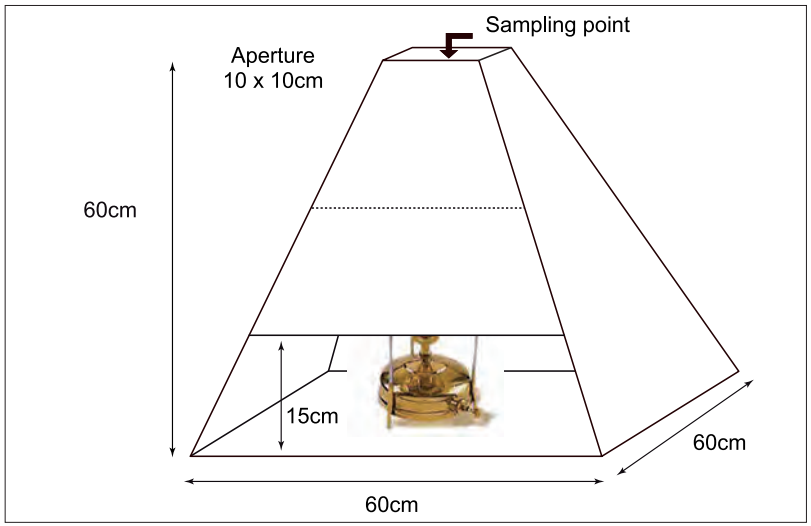
Irving et al were the first to mention the prevention of CO accumulation through improved tent ventilation and increased tent fabric permeability.[18] Pugh noted that this might be inhibited by snow and ice accumulation and condensation.[19] Turner et al noted the decreased ventilation rates from tents in zero wind conditions.[20] Keyes et al found elevated COHb concentrations when a stove was used for cooking as compared to simply heating the tent.[21]

Leigh-Smith et al found that the while a blue flame is present, pan temperature had no effect on CO concentrations, with elevated CO levels only occurring when the flame was dispersed by another object.[22] Pugh's studies showed that CO production did not reduce as the pans contents got hotter.

Leigh-Smith et al did find that as pan size increased there was a significant increase in the levels of CO generated.[23] This is likely to be due to

the increased flame quenching effect of the larger pan's surface area. They also found that in conditions of poor ventilation, stoves failed to maintain a blue flame, but continued to burn at lower temperatures producing increased CO levels. Schwartz et al demonstrated significant differences in the CO produced by different fuel types, with paraffin generating more CO than any other liquid fuel. [24]

My work in this area (as yet unpublished) focused on the use of the venerable Primus stove, still the stove of choice for the British Antarctic Survey. While this stove is unlikely to appear on your next alpine bivvi ledge, I believe that the lessons learnt in my research are directly applicable




152. The design of the stove testing enclosure.

to the modern setting.

In order to replicate stove tests under standard conditions I constructed an enclosure. This was based on a 60cm high pyramid funnel design with a base measurement of 60cm x 60cm tapering to a vent aperture of 10cm x 10cm. The enclosure was sealed on three sides with ventilation on one side via a 15cm high and 60cm wide vent. The CO monitoring point was located in the centre of the exhaust aperture, 1cm below the top edge.

Stove trials were carried out both at room temperature and at -20C in a cold room provided courtesy of the British Geological Survey.

I was able to show that ambient air temperature, pan temperature and pan size had no significant effect on CO generating. However the presence of any object directly in the combustion zone of the flame could have a very significant effect on the levels of CO generated. In the case of the Primus stove the pan and pan support plate resulted in a x100 increase in the CO generated as compared to a flame burning without obstruction.

While carrying out this research on the Primus I was able to carry out a variety of trials on my own more high tech cooking systems with some quite startling results. It appeared that the current range of more fuel-efficient pans and stoves had the potential to generate significantly more CO than a standard camping stove and pan arrangement.



Many of the cooking set-ups likely to be used by the modern mountaineer enhance their fuel efficiency through maximising the pan's contact with the flame through an arrangement of metal fins welded to the base of the pan. Examples of this include the MSR Reactor and Jetboil stoves. In addition a variety of pans are available for standard stoves with fins in place on the base to maximise the surface area such as the Optimus Heat Exchanger Pan.

While this equipment clearly works in terms of fuel efficiency, their increased quenching effect on the flame has a corresponding increased potential for CO generation.

**What can the mountaineer do about CO?**

Before I give the impression that I think the new style of energy efficient cooking arrangements are excessively hazardous, I should state that on all my recent expeditions I have used an MSR Reactor (modified to hang but that's another story) and I will continue to use this stove until something better becomes available, as its incredible fuel efficiency has halved the weight of gas cylinders I have to carry and increased the amount of time I can comfortably stay on the mountain.

What I am saying, however, is that using this equipment requires a higher level of vigilance than you would normally devote to your stove. Cook outside if you can; if cooking in the tent, keep it well ventilated and be extra careful of nodding off while cooking. Remember that frost or a covering of snow can render highly breathable bivvi tents completely impervious, so yes that vent does need to be open!

The second point to make is that when we think of CO poisoning we tend to think of death as the health effect to be concerned about. However I believe that the low level exposure to CO and its associated effects on brain function are of much more concern. Symptoms such as hallucinations, dizziness, unsteady gait and confusion could easily be missed and simply put down to the altitude, when in fact they could be easily avoidable.

I am convinced that many of the well-known incidents at high altitude involving peculiar decision making, poor route choice and incorrect use of equipment or individuals making unexplained mistakes are potentially caused, or at the very least contributed to, by CO poisoning and not necessarily just due to the altitude as we often say.

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# The Ngozumpa Glacial Lake Imaging Project

*The Ngozumpa is one of the giant glaciers of the Nepal Himalaya, snaking southwards from Cho Oyu. Its debris-covered surface is a familiar sight for climbers and trekkers heading up the Gokyo valley in the Khumbu – and on each visit there seems to be less of it. Some 20km from Cho Oyu, towards the snout of the glacier, an enormous lake is growing behind a wall of rock debris; called 'Spillway' the lake has the potential to be about 6km long, 1km wide and 100m deep. The threat of downstream flooding may not be immediate but the dynamics of the surface lakes need to be better understood. In this preliminary report researcher Ulyana Horodyskyj from the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado, Boulder, details attempts to monitor the lakes of the Ngozumpa.*

The formation and evolution of supraglacial (surface) lakes constitutes a major catalyst for removing ice stored in debris-covered valley glaciers. Hitherto their contribution to ice loss has been conjectural and largely qualitative. The lakes contribute to the demise of debris-covered glaciers that would otherwise be insulated from solar melt processes (due to the thickness of the debris) through the development of bare ice vertical walls that migrate, typically northward, from melting, backwasting and collapse (eg, Benn et al, 2001; Sakai et al, 2002; Sakai et al, 2000). The ponded lakes, once formed, can lead to catastrophic mobilization (flooding) at the vulnerable villages downstream. They also contribute to major loss of water (volume) from the glacier. It is important that we not only use satellite and aerial imagery in our analyses of these glacial lakes, but 'boots on the ground' tactics, as well as oblique angle, real-time imagery of lake processes, to better understand the causes of on-going events and to develop models which can forecast future changes.

Our pilot study (June 2011) on the Ngozumpa glacier revealed that multiple fill/drain events occur in lakes during the melt season (Horodyskyj et al, 2011). Time-lapse imagery focused at an oblique view and taking one photo per hour (Fig 1), allowed us to quantify water inputs and outputs in realtime during the course of the melt season. This reveals that satellite imagery may alias the net loss from the system by at least a factor of two, and perhaps by an order of magnitude, especially given that they consist of 'snapshots' spaced months or years apart.

Ngozumpa is one of Nepal's largest and longest glaciers, flowing 25 kilometres from Cho Oyu (8201m) and Gyachung Kang (7952m). Its lower