Foul Air in Caves, Can Be Life Threatening

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My interest in 'foul air' goes back to well before 1993 when I wrote an article on this subject. A number of in-depth studies and articles followed. So more than 30 years later I feel compelled to once again highlight the dangers of 'foul air' as new generations of speleologists explore the underground. Foul air sometimes called "bad air", can be life threatening and cause death if the warning signs are not heeded.

Where is foul air likely to occur in caves and how can one determine a dangerous level? This article should answer many of the questions on this subject and provide information to assist in identifying this unseen danger.

Definition

Foul air is typically defined as any atmosphere which has a noticeable abnormal physiological effect on humans. In limestone caves, 'foul air' can generally be described as containing greater than 0.5% carbon dioxide (CO_2) and/or less than 18% oxygen (O_2) by volume. As a comparison, normal air (above ground) contains approximately 0.04% CO_2 and 21% O_2 by volume (Smith 1996, 1997a, 1999a,b). However, there are some isolated caves which could contain atmospheres influenced by other gases such as methane, ammonia, hydrogen sulphide or carbon monoxide, but these gases are very rarely found in limestone caves (Smith 1998a).

CO_2 properties and effect on humans

To the novice caver the first encounter with foul air is often a frightening experience. Typically there is no smell or visual sign and the first physiological effects are increased pulse and breathing rates. Higher concentrations of CO_2 lead to physiological signs such as clumsiness, severe headaches, feeling hot and sweaty, loss of energy, dizziness and even death (Smith 1996, 1997a-d). Experienced foul air cavers can notice a dry acidic taste in their mouth, however the average caver may not notice this effect. Note, that at high altitudes (i.e. caves in high mountains) the physiological effects are increased.

Prolonged breathing of air containing around 2% CO_2 or greater will disturb the bodies function by causing the tissue fluids to become too acidic. The body then releases other chemicals to try and counteract the acidity. Thus some of the symptoms, such as feeling weak and lethargic may last for hours or days after exiting the cave.

An elevated CO_2 concentration as opposed to depleted O_2, is usually the most life-threatening foul air scenario found within limestone caves. CO_2 is a colourless, odourless and non-combustible gas. It is a heavy gas and tends to accumulate at the bottom of deep caves in areas with minimal air flow (Fig. 1). However, it can still be found in some shallow caves with a vertical range of less than 10 metres (Smith 1999b). In general, cave passages containing very active stream-ways do not contain foul air as the water flow dissipates the CO_2 and replenishes the O_2 (James and Dyson 1981).

CO_2 is the body's primary regulator of the breathing function. There are exceptions to this generalisation which may occur in people suffering from chronic obstructive pulmonary disease (COPD) where a reduction in O_2 concentration has become their body's primary breathing regulator (Smith 2003). However, for the overwhelming majority of humans, elevated CO_2 concentration is the body's primary breathing regulator and a lack of O_2 is the secondary regulator. For more in-depth information on this topic refer to the paper, Smith 2003.

Why is CO_2 so dangerous?

It all has to do with red cell haemoglobin in the blood, which transports O_2 and CO_2 around our body. The exchange of the two gases takes place in the lungs by diffusion across the walls of the air sacs (alveoli). Oxygen from inspired air diffuses across the lining of the air sacs and enters the circulation, while CO_2 moves in the opposite direction. The gases are transported between cells and the lung by the blood circulation. Diffusion occurs because a gas in high concentration will move to an area of relatively low concentration, until an equilibrium is reached. When breathing good air, this enables CO_2 in the body at a higher concentration to diffuse to the inhaled air (Smith 1993, 1998b, 1999b).

In simplified terms, if the inspired air, (foul air) contains a relatively high concentration of CO_2 the haemoglobin is unable to get rid of the body's waste CO_2, thus the haemoglobin is not free to take on fresh O_2. The result is asphyxiation and death.

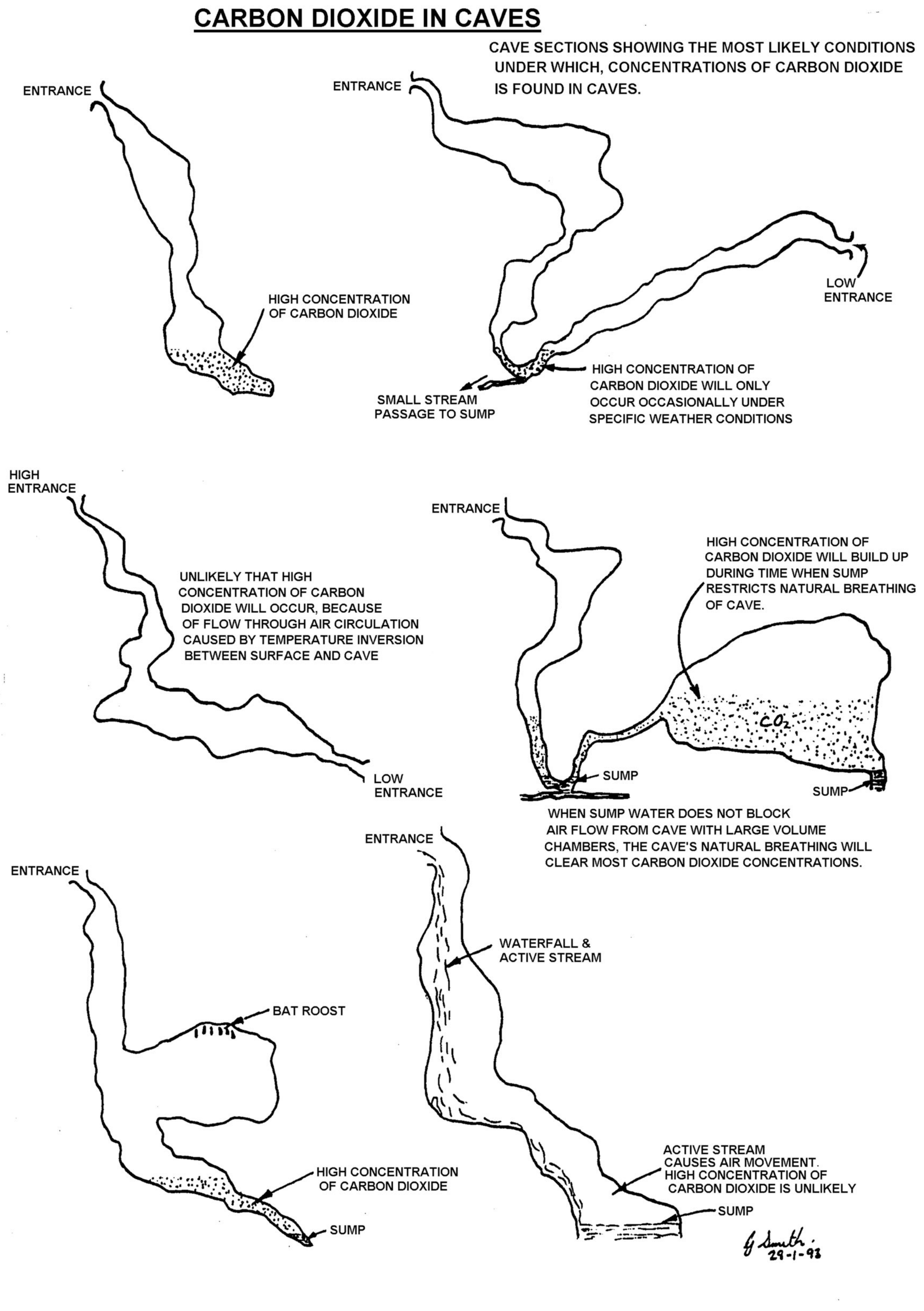

Fig 1. Likely location of foul air in caves. Reproduced from the 21st ASF Biennial Conference Proceedings p.39. © Garry K. Smith

CO_2 versus O_2

You're probably asking at this stage why an elevated concentration of CO_2 is more likely to be the dangerous atmosphere in caves as opposed to a low concentration of O_2. It all comes back to the concentrations usually encountered in cave atmospheres. Human tolerance between individuals can vary, but if we take the generally accepted tolerance of a healthy human, an atmosphere containing greater than 7% CO_2 or less than 10% O_2 are considered to be the thresholds at which humans will die. This can be either just one of the above gas concentrations despite the other gas being within acceptable limits. For example a person could survive many hours in an atmosphere with 4% CO_2 and 12% O_2. On the other hand, an atmosphere of 8% CO_2 and 18% O_2 **could** result in suffocation and death within a few minutes.

A cave's atmosphere directly correlates with how the CO_2 entered the cave. There are three basic methods in which CO_2 gets into a cave (Halbert 1982, Smith 1996). The types of 'foul air' are detailed in more depth, later in this article.

How CO_2 gets into caves

Elevated concentration of CO_2 can be due to one or more of the following mechanisms: carried by ground water into the cave and released from solution during deposition of secondary deposits creating speleothems, a by-product of micro-organism metabolism, respiration by fauna such as bats, humans or respiration from tree roots in caves. In volcanic areas magmatic CO_2 may be dissolved in water deep within the earth's crust and transported into caves.

In summary if a metabolic process is introducing CO_2 along with the reduction of O_2 (typically 1:1), then a critical elevated concentration of CO_2 is reached before a critical reduced concentration of O_2. On the other hand, if CO_2 is being introduction to a cave atmosphere, while displacing both O_2 and nitrogen (N_2) equally, then a dangerous CO_2 is reached well before the O_2 drops to a dangerous concentration. Hence this is why CO_2 concentration is typically the most life threatening.

How can we detect foul air?

It must be stressed here that the majority of Australian caves and indeed around the world, DO NOT contain foul air. However as shown earlier, an elevated concentration of CO_2 is an indication of a reduced O_2 concentration. If sophisticated gas measuring equipment is not readily available, then a 'Naked Flame Test' will indicate air quality to some degree. This test is actually measuring the O_2 concentrations required to support combustion of various materials – i.e. allow a naked flame to burn (Figs. 2 and 3).

Fig 2. The first sign that reduced O_2 is present and most likely elevated CO_2 is when the cigarette lighter flame is elongated and separated from the lighter jet.

The 'naked flame test' can be undertaken by igniting a match or butane cigarette lighter or carrying a lit candle into suspected foul air. If the flame is extinguished, foul air is present. Extensive experimentation by the author, in controlled atmospheres shows that matches and candles extinguish when the O_2 concentration drops below 15% and a butane lighter when O_2 is reduced to

14.25% (Smith 1996, 1997a,b,c). A video taken during these experiments can be viewed at https://www.youtube.com/watch?v=8nSdTRHw3os

Where possible a butane cigarette lighter should be used to reduce unpleasant fumes emitted from matches burnt by people testing air quality in the confines of a cave. However, the 'flame test' is a rough guide and does not tell you the actual concentration of the CO_2 other than it is elevated.

Fig 3. Cindy Li performing a party trick demonstrating the foul air interface in Moores Cave Timor. When the cigarette lighter flame is lit in good air the flame extends directly from the lighter jet. As the lit cigarette lighter is then lowered into a layer of foul air, the flame remains burning in air which can just support combustion. Keep lowering the cigarette lighter and the flame will extinguish.

The cheapest and most reliable measurement system on the market is the Dräger-Tube gas analyser (Fig. 4). It uses disposable single use tubes containing chemical reagent crystals, that change colour to accurately measure CO_2 concentrations. These instruments are extensively used in mines where naked flames would cause explosions. Various tubes are available to measure concentrations of different gases. This instrument has been used by the author on many trips into caves containing 'foul air'. One particular cave atmosphere was measured at 6.5% CO_2. Fifteen minutes at this concentration was almost unbearable for a group of experienced cavers, with most experiencing severe headaches and all noticeably affected by lack of energy, gasping for breath and heart rates of around 148 bpm and above, while at rest. A rescue in these conditions would be extremely difficult without breathing apparatus.

Types of foul air in caves

Foul Air can be categorised in three main types (Halbert 1982).


Fig 4. Dräger-Tube gas analyser is showing by the change in tube colour to purple, that there is a 4% CO_2 concentration in Moores Cave, Timor, NSW.

1. "Foul Air Type 1", is produced when CO_2 is introduced into the cave atmosphere from ground water. This occurs because CO_2 is absorbed by the ground water as it passes through surface soil containing high concentrations of the gas, due to the decay of vegetation. The resulting weak carbonic acid percolates through the rock strata and enters the cave system, usually taking part in the calcite

deposition cycle (creation of speleothems) before the CO_2 is liberated to the cave atmosphere. In this instance it takes the addition of five percent CO_2 to reduce the O_2 level by one percent.

2. In "Foul Air Type 2" the CO_2 is a by-product of organic and micro-organism metabolism or respiration by fauna such as bats, humans or tree roots. In this instance the oxygen concentration is reduced in proportion to the increase in CO_2. The N_2 concentration stays constant.

3. "Foul Air Type 3", is a cave atmosphere which has resulted from the introduction of other gasses, such as methane and nitrogen and the non-respiratory uptake of O_2 as well as CO_2 stripping by water. Another example is "stink damp" so named because it often contains hydrogen sulphide and the O_2 is significantly more depleted than in "Type 2".

   Foul air consisting strictly of "Type 3" is rare in Australian caves, although some samples collected at Bungonia do suggest a few caves contain atmospheres partly influenced by this mechanism (James 1977, Osborne 1990).

How do the gases affect humans?

Effect of CO_2 on humans

As each person's body has a slightly different reaction and tolerance to stressful situations the following symptoms are general (Table 1), however nobody is immune to the dangers of CO_2.

Table 1. Generally accepted physiological effects of CO_2 at various concentrations.

Concentration	Comments
0.03%	Nothing happens as this is the normal carbon dioxide concentration in air.
0.5%	Lung ventilation increases by 5 percent. This is the maximum safe working level recommended for an 8 hour working day in industry (Australian Standard).
2.0%	Lung ventilation increases by 50 percent, headache after several hours exposure. Accumulation of carbon dioxide in the body after prolonged breathing of air containing around 2% or greater will disturb body function by causing the tissue fluids to become too acidic. This will result in loss of energy and feeling run-down even after leaving the cave. It may take the person up to several days in a good environment for the body metabolism to return to normal.
3.0%	Lung ventilation increases by 100 percent, panting after exertion. Symptoms may include:- headaches, dizziness and possible vision disturbance such as speckled stars.
5 - 10%	Violent panting and fatigue to the point of exhaustion merely from respiration & severe headache. Prolonged exposure at 5% could result in irreversible effects to health. Prolonged exposure at > 6% could result in unconsciousness and death.
10 - 15%	Intolerable panting, severe headaches and rapid exhaustion. Exposure for a few minutes will result in unconsciousness and suffocation without warning.
25% to 30%	Extremely high concentrations will cause coma and convulsions within one minute of exposure. Certain death.

Exposure of between 1 and 2% CO_2, for some hours will result in acidosis, even if there is no lack of oxygen. This acid-based disturbance will occur in the human body when the increase in partial pressure of CO_2 (pCO_2) is greater than 44mm Hg. Acidemia will result and secondary mechanisms are initiated by the body that attempt to prevent drastic changes in pH and tend to return the pH toward normal. Although this response begins early, the maximum effect takes several days.

Prolonged breathing of air containing around 2% or greater will disturb body function by causing the tissue fluids to become too acidic. This will result in loss of energy and feeling run-down even after leaving the cave. It may take the person up to several days in a good environment for the body metabolism to return to normal.

The "Laboratory Safety Manual (1992)", quotes 0.5% CO_2 as the `Threshold Limit Value Time Waited Average' (TLVTWA). This is the concentration to which a person may be exposed, 8 hours a day, 5 days a week, without harm. The manual also quotes 5% $CO_2$ and above as being `Immediately Dangerous To Life and Health' (IDLH).

Effect of O_2 deficiency on humans

If we consider an atmosphere consisting of just N_2 and O_2, where the O_2 is at a lower concentration than the normal atmosphere, the human body would be affected in the manner shown in Table 2.

Table 2. Generally accepted physiological effects of reduced O_2 concentrations.

O_2% by volume.	**Symptoms** (at sea level)
reduced from 21 to 14%	First perceptible signs with increased rate and volume of breathing, accelerated pulse rate and diminished ability to maintain attention.
between 14 to 10%	Consciousness continues, but judgment becomes faulty. Rapid fatigue following exertion. Emotions effected, in particularly ill temper is easily aroused.
10 to 6%	Can cause nausea and vomiting. Loss of ability to perform any vigorous movement or even move at all. Often the victim may not be aware that anything is wrong until collapsing and being unable to walk or crawl. This is followed by unconsciousness and death. Even if resuscitation is possible, there may be permanent brain damage.
below 6%	Gasping breath. Convulsive movements may occur. Breathing stops, but heart may continue beating for a few minutes - ultimately death.

Cave rescues in foul air

The ASF Australian Cave Rescue Commission (ACRC), along with other groups such as the NSW Cave Rescue Squad, regularly train at areas affected by foul air such as Bungonia Caves NSW. Their members are well aware of the effects and hazards of foul air. Generally speaking, experienced cavers who frequent these caves and others containing foul air, are aware of this hazard. The real problem is inexperienced cavers who don't realise when they are in foul air, then get into difficulty. So, if you come across inexperienced cavers in known foul air caves, take the time to explain the signs and symptoms to those cavers. You may avert a rescue or save a life.

ASF Safety Guidelines

The Australian Speleological Federation (ASF) has adopted safety guidelines relating to foul air. These can be found on the ASF website. It is recommended that speleologists take the time to read these guidelines and adhere to them. In particular Appendix 3: Toxic (foul) air.

Summary

If sophisticated measuring equipment is not available, the best advice is to carry out a "Naked Flame Test" when you or a member of your group experiences the first signs of laboured breathing, headaches, clumsiness, loss of energy or any of the other signs associated with an elevated CO_2 concentration. The naked flame test is actually measuring the O_2 concentration, however reduced O_2 typically indicates elevate CO_2.

Ideally cavers should use a cigarette lighter flame. This will reduce the amount of unpleasant fumes and smoke emitted from matches burnt by people experimenting in the confines of a cave. The best advice is, "If in doubt, get out", in an orderly manner. NOTE- that in mines, sewers, buildings and other areas where flammable gases are likely to occur, the naked flame test **should not** be attempted. There are only a hand-full of limestone caves around the world where it is possible that explosive gas mixtures exist - none are known in Australia.

Laboratory tests have proven that combustion of a match, candle or butane cigarette lighter will cease at about 14.25% to 15% concentration of oxygen (Smith 1996). Twenty one percent (21%) being the oxygen concentration in normal atmosphere. Bear in mind that humans on average breath out air containing 15% oxygen and this is enough to revive a person using mouth to mouth resuscitation. In fact humans can survive in an atmosphere containing as low as 10% oxygen, so when the flame test just fails it is still measuring an atmosphere containing enough oxygen to survive.

The real danger is the CO_2 concentration which is the primary trigger for the human body to increase the breathing rate. Prolonged exposure to a concentration of just 5 or 6% may be enough to cause suffocation. In the majority of cases, if a person has any of the symptoms of elevated CO_2 concentration, a simple naked flame test will fail to ignite. This is a sure sign of foul air and it is time to get out of that area of the cave or completely out of the cave. Accurate measurement of CO_2 and O_2 concentrations in 'foul air' can be achieved by using a Dräger-Tube Gas Analyser with the appropriate tubes or one of the many other gas analysers on the market. These readings can be used to more accurately assess the possible danger of the cave atmosphere.

Carbon dioxide when treated with respect is no worse than the other dangers in caves. Despite the possible dangers, caving is still safer than driving a motor vehicle, which most of us take for granted.

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