

Non Toxic “Foul Air” Can Kill.

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This foul air article isn't about the resulting strong aroma the morning after your best friend's feast of garlic, baked beans and cabbage.

'Foul Air', sometimes called 'Bad Air', is an atmosphere which has a noticeable abnormal physiological effect on humans. Some concentrations of gases as can occur in caves, mines, sewers, drains, buildings, ships and other confined spaces can be lethal.

There are many regulations governing workers exposure to various gas mixtures and concentrations, but emergency services personnel are often exposed to much higher concentrations than are permitted in the workplace. When we talk about dangerous gases, most people instantly think of the poisonous or flammable ones such as: methane, ammonia, hydrogen sulfide and carbon monoxide, to name just a few. So often overlooked is an elevated concentration of carbon dioxide (CO₂). This colourless, odourless and non-combustible gas is the body's regulator of the breathing function.

The addition of CO₂ from a leaking gas bottle into a poorly ventilated basement laboratory, could easily alter the enclosed atmosphere by dispersing Oxygen (O₂) and Nitrogen (N₂). Since CO₂ is 1.57 times heavier than nitrogen and 1.38 times heavier than O₂, it will have a tendency to form a layer across the floor. If left undisturbed for some time (possibly days) it will disperse, into an enclosed atmosphere, due to molecular diffusion. On the other hand, air movement from a fan or air conditioner can result in a homogenous mixture in a very short time. The addition of 10% CO₂ to an enclosed atmosphere will only reduce the O₂ concentration from 21% down to 19%. In other words, the introduction of CO₂ into an atmosphere, dilutes other components (N₂ and O₂), thus it requires five percent CO₂ to reduce the O₂ concentration by one percent. So what you say, there is plenty of O₂ to support life since we can revive a person with mouth to mouth resuscitation, when our expired air contains just 15% O₂ and 4.6% CO₂. - besides CO₂ isn't poisonous. Well think again, because a concentration of 10% CO₂ can cause respiratory paralysis and death within a few minutes even if there was 21% O₂ in the atmosphere.

It all has to do with red cell haemoglobin in the blood, which transports O₂ and CO₂ 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 CO₂ 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 CO₂ in the body at a higher concentration to diffuse to the inhaled air.

In simplified terms, if the inspired air, “Foul Air” contains a relatively high concentration of CO₂ the haemoglobin is unable to get rid of the body's waste CO₂, thus the haemoglobin is not free to take on fresh O₂. The result is asphyxiation and death.

FOUL AIR IN CAVES

In limestone caves, 'foul air' can be described as containing greater than 0.5% carbon dioxide (CO₂) and/or lower than 18% oxygen (O₂) by volume. As a comparison, normal air contains approximately 0.03% CO₂ and 21% O₂ by volume. Although not a significant problem in the majority of caves around the world, those containing concentrations of foul air may become death traps for cavers not familiar with the signs and symptoms of the gases involved.

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 CO₂ lead to clumsiness, severe headaches, loss of

energy, dizziness and even death. Experienced foul air cavers can notice a dry acidic taste in their mouth, however the average caver may not notice this effect.

In the overwhelming majority of foul air in caves, it is not a lack of O₂, but rather the elevated concentration of CO₂ which could be life threatening. For example a person could survive many hours in an atmosphere with 3% CO₂ and 12% O₂. On the other hand an atmosphere of 8% CO₂ and 18% O₂ **could** result in suffocation and death within a few minutes. The exact percentage and timing will depend on the individuals physiological makeup and tolerance, however several minutes exposure to a concentration of >10 CO₂ will certainly result in death

TYPES OF FOUL AIR IN CAVES

Speleologists have categorised cave “Foul Air” in three main types.

1. “Foul Air Type 1”, is produced when CO₂ is introduced into the cave atmosphere from ground water. This occurs because CO₂ 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 before the CO₂ is liberated to the cave atmosphere. In this instance it takes the addition of five percent CO₂ to reduce the O₂ level by one percent.
2. In “Foul Air Type 2” the CO₂ is a by-product of organic and micro-organism metabolism or respiration by fauna such as bats or humans. In this instance the oxygen concentration is reduced in proportion to the increase in CO₂. The N₂ 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 O₂ as well as CO₂ stripping by water. Another example is “stink damp” so named because it often contains hydrogen sulfide and the O₂ 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.

HOW DO THE GASES AFFECT HUMANS?

EFFECT OF CO₂ ON HUMANS.

As each persons body has a slightly different reaction and tolerance to stressful situations the following symptoms are general, however nobody is immune to the dangers of CO₂.

Table 1. Generally accepted physiological effects of CO₂ 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% CO₂, 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 CO₂ (pCO₂) 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% CO₂ as the ‘Threshold Limit Value Time Waited Average’ (TLV-TWA). 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% CO₂ and above as being ‘Immediately Dangerous To Life and Health’ (IDLH).

EFFECTS OF O₂ DEFICIENCY ON HUMANS.

If we consider an atmosphere consisting of just N₂ and O₂, where the O₂ is at a lower concentration than the normal atmosphere, the human body would be effected in the manner shown in Table 2.

Table 2. Generally accepted physiological effects of reduced O₂ 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.

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 CO₂ is an indication of a reduced O₂ concentration. If sophisticated gas measuring equipment is not readily available, then a Naked Flame Test will indicate air quality to some degree.

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 O₂ concentration drops below 15% and a butane lighter when O₂ is reduced to 14.25%. 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 this test is a rough guide and does not tell you the concentration of the CO₂ other than it is elevated.

The cheapest and most reliable measurement system on the market is the Draeger Gas Analyser. It uses disposable single use tubes to accurately measure CO₂ 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% CO₂. A half hour at this concentration was almost unbearable for a group of experienced cavers,



Jenny Whitby demonstrates how a naked flame from a butane cigarette lighter, burns remotely from the lighter jet when the oxygen content of the cave atmosphere is just sufficient to support combustion. Note in good air the flame extends right down to the lighter jet. There is no flame adjustment on this lighter. Photo Garry K. Smith

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.

The Australian Speleological Federation has adopted guidelines for caving in Foul Air. Part thereof is listed below;

All cavers, and most particularly Party Leaders, should recognise the fact that exposure to foul air has an effect on a person's ability to function normally. The likelihood of an accident is therefore greatly increased. All care and precautions should be taken. Under special circumstances such as search and recovery operations, exploration and scientific work, it may be decided to enter into foul air deliberately. Under such circumstances the following is recommended:-

In mild foul air where breathing rate is up

- a) A CO₂ tester should be carried - if nothing else is available, use a lit candle or frequently test with a butane cigarette lighter. If the flame goes out - get out slowly.
- b) Cavers with no experience of foul air should be introduced to it gradually by an experienced leader.

In foul air where the flame test fails

Only experienced foul air cavers should enter these regions.

- a) A CO₂ tester must be carried. eg. a Draeger Gas Analyser.
- b) An "oxygen rebreathing" apparatus should be taken (one kit to four people). The rebreather set should go down the cave with the first person.

In cave atmospheres containing greater than 6% CO₂ and/or less than 11% O₂, breathing apparatus is necessary and all the precautions against equipment failure taken, as is required in mines rescue and cave diving.

ARE YOU LIKELY TO BE INVOLVED IN A CAVE RESCUE?

The Cave Rescue Groups who regularly train at Bungonia Caves NSW, are well aware of the affects of "Foul Air" which contains elevated concentrations of CO₂ and reduced O₂. Needless to say, that experienced cavers who frequent these caves and others containing "Foul Air", are also aware of this hazard. The real problem is inexperienced recreational cavers who don't realise when they are in "Foul Air", then get into difficulty.

Because there are other caves around Australia which also contain “Foul Air”, rescue groups would be well advised to prepare for such emergencies. Certainly if a rescue group is unfamiliar with working in “Foul Air” and is called to an underground emergency, then a wise option is to contact some experienced local Caving Club members for assistance. Most caving clubs around Australia are members of the Australian Speleological Federation and would also have contacts for many other willing and able-bodied helpers if necessary.

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 labored breathing, headaches, clumsiness, loss of energy or any of the other signs associated with elevated concentrations of CO₂. Ideally cavers should use a cigarette lighter flame. This will reduce the amount of unpleasant fumes 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. (It is especially emphasised that in mines, sewers, buildings and other areas where flammable gases are likely to be, 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 - definitely none 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. 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 carbon dioxide (CO₂) concentration which is the main 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 carbon dioxide 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. Accurate measurement of CO₂ concentrations in “Foul Air” can be achieved by using a Draeger Gas Analyser. 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.

FURTHER READING ON THIS SUBJECT

“Naked Flame Tests for CO₂ in Limestone Caves & The Effect of CO₂ and O₂ on Humans.” Published in the “ASF 21st Biennial Conference Proceedings” 1997, Pages 40-52.

“Naked Flame Tests for, and Human Tolerance to, Foul Air in Caves”. Published in “Helictite” Journal of Speleological Research Council Ltd. V. 34 (2) 1996, P 39-47.