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Carbon dioxide, caves and you

CARBON DIOXIDE, CAVES and YOU

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Member of the Newcastle & Hunter Valley Speleological Society - NSW Australia and the Australian Speleological Federation.

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Carbon Dioxide (CO_2) is the body's regulator of the breathing function. It is normally present in the air at a concentration of 0.03% by volume. Any increase above this level will cause accelerated breathing and heart rate. A concentration of 10% can cause respiratory paralysis and death within a few minutes. In industry the maximum safe working level recommended for an 8 hour working day is 0.5% .

Caves often contain elevated levels of Carbon Dioxide (CO_2), consequently cavers may be putting themselves at risk without really knowing the full potential danger.

A cave atmospheres containing greater than 1% Carbon Dioxide (CO_2) is called **Foul Air.** This is the most likely hazard to be encountered in deep limestone caves with relatively still atmospheres. Having said that, one must be aware that there are many caving areas around Australia, where Foul Air is not a significant problem.

To the novice caver the first encounter with foul air is often a frightening experience. Typically there is no smell or visual sign associated with foul air and the first signs are increased pulse and breathing rates. Higher concentrations of CO_2 lead to clumsiness, severe headaches, 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.

Because an elevated CO_2 concentration in caves, corresponds to a depletion in O_2, cavers have for many years used the naked flame test to determine whether the cave atmosphere contained an elevated level of CO_2. The naked flame test involves lighting a match or cigarette lighter in the cave air, or carrying a burning candle into a suspected foul air area of the cave and the flame would extinguish when a particular concentration was reached. This test has in the past been widely accepted by the caving fraternity as a fairly accurate indications of percentage concentrations. During January 1997, I undertook extensive testing in controlled atmospheres which revealed that **the Naked Flame Test is not a reliable test of CO_2 concentrations**, other than to indicate that the cave atmosphere is most likely dangerous to human life. In fact the naked flame is only measuring the O_2 concentration and the CO_2 has such a small influence over combustion that it can be ignored within the concentration range found in caves. For example a 1% increase in CO_2 concentration will raise the O_2 concentration required to support combustion of a given fuel by less than 0.05% O_2 .

Without sophisticated measuring instruments a caver cannot determine the CO_2 concentration as the flame test only measures a lack of oxygen. To make things really complicated, it is not the lack of Oxygen which is the real danger in the majority of cave atmospheres, but the elevated CO_2 concentration.

Elements required for Combustion

Most people are aware that before combustion can occur, three conditions must be satisfied.

1. There must be a fuel or substance which can be burnt.

2. The fuel must be heated to its *ignition temperature*. That is the lowest temperature at which combustion can begin and continue.

3. There must be enough oxygen to sustain combustion, either in the surrounding air or present in the fuel.

Without going into the subject too deeply, one can see that the naked flame test is actually measuring the concentration of O_2 required to sustain combustion of various fuels, such as the match, butane cigarette lighter fluid or paraffin candle wax. The results are shown in the table below.

Table 1. Condition of flame in relation to percentage of oxygen in the controlled atmosphere.

Match	Candle	Butane Cigarette lighter
21% - 18% easily burns all of match .	>19% normal flame.	
17.5% Burns head and flame transfers down paraffin to wooden splint on most occasions	17% - 16.5% burns with elongated flame.	
17% - 16.5% ignited head and on nearly every occasion, burns down onto paraffin coating then extinguishes.	16.5% - 16% flame begins to shrink, but candle remains alight.	
16% - 15.5% ignited head just ignites paraffin coating on splint (some matches only)	16% burns slowly with small flame	
15% - head burns briefly with whispery flame & goes out.	< 15.0%, A burning paraffin candle is extinguished.	> 15% O_2, A Butane Cigarette Lighter can easily be lit and will stay alight.
		14.5% - weak blue flame with orange top, just stays alight
		<14.25% - Flame will extinguish
14% match head burns very briefly & goes out. (burns due to the O_2 in potassium chlorate contained in the head.)		14% - 13% Large flashes of flame but will not stay alight.
<13% head flares & extinguishes immediately (less than 0.5 seconds)		12.5% sparks with partial ignition, small fireballs
		<10% - no ignition, only hot sparks from flint.

Footnote on Safety Matches

Wooden "Safety" matches are generally made of poplar wood, which is dried to reduce moisture content to below 7%, then the "splint" is treated with an anti-afterglow solution (retardant) which prevents embers from forming after a flame is blown out. The second stage in production is dipping approximately 10 mm of the tip end into paraffin. This provides a base to carry the flame from the head to the wood. Then the tip (sometimes called a bulb) is added. Some match manufacturers add a final chemical coating that protects the match from moisture in the air.

Interesting phenomena with cigarette lighter in O_2 deficient air.

A cigarette lighter when lit in an atmosphere which will support combustion of butane will burn with the flame extending directly from the jet. When this lit cigarette lighter is slowly lowered into an atmosphere that will not support combustion (lower O_2, higher CO_2 concentration), an interesting phenomena occurs. The flame will magically stay burning where the atmosphere will support combustion, just above the interface between the high and low CO_2 concentration, while the lighter is several centimetres below the interface.

In the CO_2 Pit of Gaden Cave (WE-2) NSW Australia, a demonstration by Mike Lake showed that the flame extended to about 100 mm above the lighter as it was gradually lowered into the higher concentration in the Pit. At one stage a 25mm high flame flickered some 75 mm away from the lighter. Because of the low concentration of O_2 (proportional to high concentration of CO_2) there was no flame for the first 75mm out from the lighter jet.

This phenomena can not occur with the other solid fuels, such as matches and candles, as the heat from the flame is required to vaporise the volatiles which then burn.

HOW CO_2 GETS INTO CAVES.

It is a proven fact that CO_2 enters caves by several methods. Each method has a bearing on the gas ratio composition of the cave atmosphere and its variation to that of the above-ground atmosphere. **The two main methods in which CO_2 gets into caves are:-**

1. 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. This water percolates through the rock strata and enters the cave system, usually taking part in the calcite deposition cycle. In this instance the addition of extra CO_2 to the cave atmosphere displaces O_2 and nitrogen (N_2).

2. Secondly, CO_2 may be a by-product of organic and micro-organism metabolism or respiration by fauna such as bats or humans. Simply the oxygen concentration is reduced in proportion to the increase in CO_2. The N_2 concentration stays constant.

3. The other factor which one has to consider is that in deep caves where air movement is minimal, CO_2 will build up in the lower part of the cave. So, even though the CO_2 may have entered the cave by one of the two above mentioned methods, a very still cave atmosphere may allow CO_2 to sink to the deepest part of the cave and displace O_2 and N_2. Thus building up the concentration of CO_2 to a higher concentration, at the lowest point in the cave.

Even though CO_2 is 1.57 times heavier than nitrogen and 1.38 times heavier than O_2, it will have a tendency to disperse in an isolated volume of air, due to molecular diffusion. In other words a mixture of gasses will not separate into layers of various density gases if they are left for a long time in a still chamber. A possible explanation of the high concentration of CO_2 in deep caves (with a relatively still atmosphere), is that CO_2 is being produced metabolically or entering the cave via ground water at a greater rate than the gas can diffuse into the cave atmosphere, thus settling at the bottom of the cave because it is a dense gas.

EFFECTS OF CO_2 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 CO_2.

Table 2. Generally accepted physiological effects of CO_2 at various concentrations by volume.

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).
1.0%	Symptoms may begin to occur, such as feeling hot and clammy, lack of attention to details, fatigue, anxiety, clumsiness and loss of energy, which is commonly first noticed as a weakness in the knees (jelly legs).
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.

Effects 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 following manner.

Table 3. Generally accepted physiological effects of reduced O_2 concentrations.

O_2% by volume.	**Symptoms**
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. 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 THE HUMAN BODY GETS RID OF CO_2.

The human body under average conditions inhaling air which contains approximately 21% oxygen and 0.03% carbon dioxide. The air breathed out of the lungs contains approximately 15% oxygen and 5.6% CO_2. A person at rest inhales and exhales approximately 6 litres of air per. minute but in times of stress, this may increase to more than 100 litres per minute.

The CO_2 level in the blood is an important stimulus to respiration. Nerve receptors in the aorta near the heart and in the carotid artery that goes to the brain, monitor changes in the CO_2 in the body. If the amount of CO_2 in the blood increases, both the rate and depth of breathing increases. Changes in oxygen levels are also monitored, but the receptors are not as sensitive to changes in oxygen as to CO_2.

The exchange of the two gases (CO_2 and oxygen) 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 carbon dioxide moves in the opposite direction. Then the gases are transported between cells and the lung by the blood circulation.

The principle by which diffusion occurs dictates that a gas in high concentration will move to an area of relatively low concentration, until an equilibrium is reached. This enables CO_2 in the body at a higher concentration to diffuse to the inhaled air.

Humans expire air during normal breathing, composed of approximately 5.6% CO_2 and 14 to 15% oxygen. This is sufficient to revive a person with Expired Air Resuscitation. (EAR).

WHAT TO DO WHEN ENCOUNTERING CO_2.

A test should be made as soon as foul air is suspected and if a naked flame test fails, then all members of the party should immediately exit the cave in an orderly manner without panicking. Inexperienced cavers in the group should be especially watched and guided to the entrance.

When undertaking vertical pitches in caves suspected of foul air the first person down should make thorough checks for CO_2. Besides carrying ascenders, a safety belay is a wise option in the event that the first person down may be overcome when suddenly descending into an area of high concentration.

A safety belay should be mandatory with all pitches where a ladder is more than just a hand-hold.

Cavers should only enter areas of foul air during special circumstances, such as search and rescue operations, exploration and scientific work. Under these circumstances special precautions should be taken to ensure the safety of the group. For more information regarding safety precautions refer to ASF Cave Guidelines.

CONCLUSION

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 CO_2. 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.

Laboratory tests have proven that combustion of a match, candle or butane cigarette lighter will cease at about 14.5% to 15% concentration of oxygen. Twenty one percent (21%) being the oxygen concentration in normal atmosphere. Bearing 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 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 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 levels, a simple naked flame test will fail to ignite. This is a sure sign of foul air and it is time to get out.

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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