Naked Fame Tests for, and Human Tolerance to, Foul Air in Caves

. . . . .Garry K. Smith

Abstract

The paper examines the reliability of the "Naked Flame Test" for measuring the concentration of carbon dioxide (CO_2) in caves. It reviews the ways in which carbon dioxide gets into caves, how it forms pockets of high concentration and the composition of the atmospheres in these pockets. A cave air index is used to generate theoretical tables of cave atmosphere compositions for two scenarios composed of carbon dioxide from differing sources. Conditions for combustion together with levels of carbon dioxide and oxygen (O_2) required to extinguish flames are stated. The fuel components of various combustible materials available for the Naked Flame Test are described. The paper presents and discusses the results of the laboratory tests on matches, candles and butane cigarette lighter in reduced oxygen atmospheres. It reviews the physiological effects of low O_2 and high CO_2. It is concluded that the Naked Flame Test measures O_2 concentrations and is unreliable for measuring CO_2 concentrations. Elevated CO_2 levels are recognised as being the life threatening component of most cave atmospheres, however, it is also concluded that the Naked Flame Test is still the safest way for an inexperience caver to test for hazardous cave atmospheres.

Cavers are quiet aware that if they are breathing heavily, have a headache or feel tired and lethargic, there may be a high concentration of carbon dioxide (CO_2), or "foul air" in the cave atmosphere. For those without sophisticated instruments, a simple "Naked Flame Test" is often done to confirm this suspicion. This "Rule of Thumb" method of measuring the approximate percentage of CO_2 in caves has been used for many years. This raises a number of questions.

They include:
- Are CO_2 concentrations or low oxygen (O_2) concentration in the cave being measured when a naked flame is extinguished?

- How reliable is the Naked Flame Test for measuring CO_2 concentrations?

- Should low oxygen concentrations be considered as the life threatening component of the cave atmosphere instead of elevated CO_2 concentrations?

- Can butane fuelled cigarette lighters (eg. common disposable gas type) be added to the list below?

A simple naked flame methods of testing for CO_2 uses the following flames as indicators of CO_2 concentration (Australian Caver 1990).

1% CO_2	a lighted match will go out
4% CO_2	a lighted candle will go out
6% CO_2	a carbide lamp will go out

To answer the question of how reliable are these tests, it is necessary to examine CO_2 and O_2 concentrations required to support combustion of various materials. To find out what is the most life threatening situation (low O_2 or high CO_2), it is necessary to examine the concentrations of these gases which are harmful to humans.

How CO_2 gets into caves and forms pockets of high concentration

As discussed in more detail in the article "Caves, Carbon Dioxide & You", (Smith 1993), CO_2 is produced in the cave in two major ways.

In the first, **Scenario 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, enters the cave system, and degasses its CO_2 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). See Table 3.

Under specific conditions, soil CO_2 concentrations can reach as high as 12%, however most values range between 0.15% and 0.65%. Therefore the 24% value listed at the bottom of Table 3 is unrealistic. It is shown as an example of what concentration is required to reduce the cave atmosphere oxygen concentration to a level which will not support combustion.

Halbert (1982), relates this "Foul Air Type 1" cave atmosphere to the introduction of CO_2 into the cave atmosphere and all other components are diluted - the source of the CO_2 is immaterial. An atmosphere resulting from purely a type 1 process occurs quite slowly and it requires five percent CO_2 to reduce the O_2 level by one percent.

In the second, **Scenario 2**, the CO_2 is a product of organic decomposition by micro-organism metabolic processes and respiration by fauna such as bats or humans. In this instance the oxygen concentration is reduced in proportion to the increase in CO_2. See Table 4.

Halbert (1982) "Foul Air Type 2" describes in great detail the relationship between consumption of O_2, and production of CO_2 in the metabolic process of living organisms. Essentially the volume ratio of CO_2 produced to O_2 consumed, called the "respiratory quotient" (RQ) is not constant and can vary between 0.7 and 1, depending on organic matter involved. i.e. carbohydrates, fats or protein. If fats were utilised solely in the metabolic process the RQ = 0.7, and would result in a consumption of O_2 with a relatively smaller amount of CO_2 volume being produced.

In the third, **Scenario 3**, "Foul Air Type 3", 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 sulfide 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 influenced by this mechanism.

Also falling into Halbert's (1982) "Foul Air Type 3", is an atmosphere which has resulted from a combination of scenarios 1&2 with addition of another mechanism which alters the gas concentrations. In general cave atmospheres with a mixture of Type (3+1) or (3+2) are classed as a "Foul Air Type 3".

The CO_2 to O_2 relationship in caves has been discussed in more detail by Halbert (1982) and Osborne (1981).

The two major gases in the atmosphere are oxygen and nitrogen. Table 1 shows the density, molecular weight and % in a normal atmosphere for these gases and carbon dioxide. At a given temperature, a volume of CO_2 is 1.57 times heavier than the same volume of N_2 (43.99/28.01 molecular weight ratio) and CO_2 is 1.38 times heavier than the same volume of O_2 (43.99/31.98 molecular weight ratio).

Gas	Density 25 °C g L^{-1} at 1 atm	Molecular weight	% in normal atmosphere
CO_2	1.931	43.99	0.03
O_2	1.404	31.98	21
N_2	1.229	28.01	78
Rare Gases			0.97

Table 1.   Statistics of gases

Properties of Carbon Dioxide

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 gases will not separate into layers of various density gases if they are left for a long time in a still chamber. On the other hand various gases purged separately into a closed container will become uniformly mixed over a period of time. A possible explanation of the high concentrations of CO_2 in caves with relatively still atmospheres, 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. This would explain why foul air, with a high CO_2 concentration is found in pockets at the lower sections of a cave. Frequently there appears to be a definite boundary between good air and foul air. This would indicate that dispersion of the CO_2 was occurring at a relatively slow rate compared to the gas production. These atmospheres can be attributed to 'Foul Air Types' 1 or 2, or a combination of both, however the CO_2 is being introduced into a relatively still cave atmosphere and molecular diffusion is not sufficient to disperse the gas with an even gradient over the vertical range of the cave.

Another possible scenario in caves with relatively still atmospheres, is that CO_2 is being produced faster than it can diffuse into the rest of the cave atmosphere (by molecular diffusion) and it sinks to the lowest point in the cave thus building up in concentration.

It should be noted that foul air will not build up in caves with two entrances at different elevations, as

temperature gradients cause air flows which flush the cave atmosphere. Long branch passage in these caves may not be cleared of foul air by air movement between entrances.

Carbon dioxide is "regarded as a `hot gas' due to its low thermal conductivity, heat is not conducted away as rapidly as in normal air, so a person standing in it feels warm about his lower limbs" (Strang, 1990).

Calculation of Gas Concentrations in a Cave Atmosphere

In dry air, the total pressure of a mixture of gases is equal to the sum of their partial pressures.

The atmospheric or barometric pressure of dry air
$$= pN_2 + pO_2 + pRG + pCO_2 \text{ (RG = Rare Gases)}$$
However since most cave atmospheres have high humidity, a water vapour (H_2O) component should be included in the equation.

Barometric pressure = $pN_2 + pO_2 + pRG + pCO_2 + pH_2O$.

Water vapour constitutes about 0.5% by volume of a saturated cave atmosphere at 20 °C and is 0% in a dry atmosphere. Halbert (1982) uses the Cave Air Index (CAI) to characterise gas mixtures found in caves on a dry atmosphere basis. The water vapour component in the calculation, slightly changed the concentrations of CO_2 and O_2, but did not affect the arguments derived from his data. For simplicity, cave atmospheres may be considered to consist of O_2, CO_2, and a residual fraction (RF) composed of rare gases, N_2 and water vapour.

$$\text{Cave Air Index} \quad = \quad \frac{CO_2 \text{ concentration}}{21 - O_2 \text{ concentration}}$$

Table 2 shows the relationship between possible mixes of the scenarios described in this paper, Foul Air Type and CAI.

Foul Air Type (after Halbert 1982)	Possible Mixes	Cave Air Index
1		$4 \leq CAI \geq 5$
1 + 2 combination	1 + 3	$1 \leq CAI < 4$
2	2+1, 2+3, 1+3	$0.75 \leq CAI < 1$
2 + 3 combination	1+3	$0 < CAI < 0.75$
3	-	$CAI = 0$

Table 2.   Possible mixes of cave air scenarios and correlation with Halbert's "Foul Air Type" & Cave Air Index.

The "Foul Air Type 3", where CAI = 0, is rare in caves. In general cave atmospheres with CAI of < 0.75 are regarded as falling into the Foul Air Type 3. Halbert (1982) gives the example of "Foul Air Type 3" atmospheres containing 1% CO_2, 17% O_2, and 82% RF and another with 4.5% CO_2, 10.5% O_2, and 85% RF. He points out that a low absolute O_2 concentration does not need to be present. However in practice "Foul Air Type 3" atmospheres likely to be encountered in caves will have low O_2. In addition this type of foul air may have deceptively low CO_2. Some readings at Bungonia suggest a "Foul Type 3". They include atmospheres in Grill Cave with a composition of 1.4% CO_2, 12.0% O_2, 86.6% RF which gives a CAI of 0.16 and readings in Odyssey Cave of 2.8% CO_2, 14.5% O_2, 80.3% RF which gives a CAI of 0.43. (Halbert 1982).

The following tables 3, and 4 illustrate the changes in oxygen and residual fraction for atmospheres with elevated carbon dioxide sources as in scenarios 1 and 2.

$CO_2\%$	$O_2\%$	RF%
1	20.75	78.25
2	20.50	77.50
3	20.25	76.75
4	20.00	76.00
5	19.75	75.25
6	19.50	74.50
8	19	73.00
10	18.50	71.50
12	18	70.00
24	15.00	61.00

Table 3. Calculations of major gas concentrations in a cave atmosphere using scenario 1 with a CAI of 4

$CO_2\%$	$O_2\%$	$N_2\%$
1	20	79
2	19	79
3	18	79
4	17	79
5	16	79
6	15	79
8	13	79
10	11	79
13	8	79

Table 4. Calculations of major gas concentrations in a cave atmosphere using scenario 2 with a CAI of 1, i.e. RQ =1

Conditions Required for Combustion

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.

Levels of CO_2 and O_2 required to extinguish flames

When fighting a fire, the aim is to dilute O_2 to a concentration which will not support combustion and this is the main flame extinguishing mechanism of CO_2. The same effect can be obtained by adding an inert gas such as nitrogen, argon, neon or helium, to an atmosphere at about 17% concentration by volume. By the addition of these gases O_2 can be diluted to a life threatening level. (Safe Handling of Compressed Gases 1992).

The Le Chatelier's principle states that *"any system in equilibrium shifts the equilibrium, when subjected to any constraint, in the direction which tends to nullify the effect of the constraint"*. Using butane (cigarette lighter fuel) as an example, then:

butane + oxygen → carbon dioxide + water

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O$$
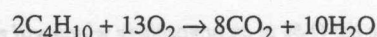
Simply this means that if the CO_2 concentration is raised and/or the O_2 concentration is reduced, then the reaction will slow down and eventually stop. Increasing the CO_2 concentration will have a smaller effect than the decreasing the O_2 concentration. The experimental data in this paper and that of Kuchta (1985), indicate that a 1% increase in CO_2 concentration will raise the O_2 concentration required to support combustion of a given substance by less than 0.05% O_2.

In the majority of cave atmospheres, it is the low concentration of O_2 which stops combustion, not the high concentration of CO_2.

Vapour	CO_2 to air	O_2 %	N_2 %	CO_2 %	Rare Gas %
Carbon disulfide	1.59	8.11	30.12	61.40	0.37
Hydrogen	1.54	8.27	30.71	60.64	0.38
Ethylene	0.68	12.50	46.43	40.49	0.58
Ethylether	0.51	13.91	51.66	33.79	0.64
Ethanol	0.48	14.19	52.7	32.45	0.66
Propane	0.41	14.89	55.32	29.1	0.69
Acetone	0.41	14.90	55.32	29.1	0.69
n-Hexane	0.40	15.0	55.71	28.6	0.69
Benzene	0.40	15.0	55.71	28.6	0.69
Methane	0.33	15.79	58.65	24.83	0.73

Table 5. Minimum volume ratios of CO_2 to air (column 2)which are required to prevent burning of various vapours at 25 °C (column 1)andthe composition of the resulting atmosphere resulting from addition of CO_2 (columns 3 to 6).(After Friedman. R., 1989. Data calculated from tabulations by Kuchta (1985)).

To calculate the final volume percentages of each gas from the (volume ratio) of CO_2 added to air.

$$R + V = Y$$

Where   R = Volume of CO_2 required to give

CO_2 / air volume ratio. (from table No.6)

V = Volume of air which CO_2 added to (= 1)

Y = Total volume of gases in CO_2 air mixtures

To find the percentage of gases in the new atmosphere (which will not support combustion of the various vapours because the O_2 has been diluted). The known percentage of gases in normal air are used. i.e. O_2 = 21%, N_2 = 78%, CO_2 = 0.03% and rare gases = 0.97%. It should be noted that R must be added to air CO_2 of 0.03%.

Gas% (fire retarding atmosphere) = Gas% (in normal air) / Y

Example.
To calculate the O_2% in an atmosphere which will not support combustion of propane vapour, CO_2/ air ratio is 0.41 (Table 5)

Therefore Y = 0.41+ 1

*   Y = 1.41*

* O_2% = 21/1.41 = 14.89 in new atmosphere.*

From Table 5, it can be seen that the addition of CO_2, to dilute the O_2 concentration, will result in a CO_2 rich atmosphere which will not support human life (see Table 8). For this purpose much higher concentrations of CO_2 are present, than would be found in the majority of caves.

Nitrogen can also be used to dilute the O_2 concentration. However, since N_2 is less dense than CO_2 a comparison of Table 5 and Table 6 shows that almost twice the volume of N_2 is required to extinguish flames from the same fuel.

Vapour	N_2 to air ratio	O_2 %	N_2 %	CO_2 %	Rare Gas %
Carbon disulfide	3.0	5.2	94.5	0.0075	0.423
Hydrogen	3.1	5.1	97	0.0073	0.237
Ethylene	1.00	10.5	89	0.015	0.485
Ethylether	0.97	10.66	88.83	0.015	0.492
Ethanol	0.86	11.3	88.17	0.016	0.522
Propane	0.78	11.8	87.64	0.0169	0.545
Acetone	0.75	12.0	87.43	0.017	0.554
n-Hexane	0.72	12.2	87.21	0.0174	0.564
Benzene	0.82	11.54	87.91	0.0165	0.533
Methane	0.63	12.9	86.5	0.0184	0.595

Table 6.   Minimum volume ratios of N_2 to air (column 2) which are required to prevent burning of various vapours at 25°C (column 1) and composition of the resulting atmosphere resulting from the addition of N_2 (columns 3 to 6). (After Friedman. R., 1989. Data calculated from tabulations by Kuchta (1985)).

Flame sources used for the Naked Flame Test

Matches

There are two main types of matches, "Strike-anywhere" and "Safety". This paper will only deal with "Safety" matches as they are the only type readily available in Australia. In general, "Safety" matches can only be lit by striking them across a special surface on the side of their box or packet. The head is made of a mixture containing potassium chlorate, sulfur and other components, which will ignite at a temperature of approximately 182 °C. The coating on the box is made of amorphous phosphorus and sand.

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 air.

When a match is scraped across the box striking surface, it begins a chemical reaction between the potassium chlorate and amorphous phosphorus which in turn ignites the sulfur component of the head. The heat generated in the head vaporises the paraffin coating on the splint and the flame is drawn down from the head. Moisture is driven out of the timber, the retardant is burnt off, allowing the wood volatilise to vaporise and ignite. The head will fizz and not burst into full flame when there is a lack of O_2 in the atmosphere, as it's partial burn is due to the O_2 in the potassium chlorate contained in the head.

Book matches are a type of "Safety" match made of heavy paper (called *paperboard*) and the row or rows (called *combs*) of matches are bound into a paperback cover. The paperboard is also treated with an anti-afterglow solution and paraffin as with wooden matches (The World Book Encyclopedia 1992).

Candles

A candle burning in an area without draught will produce a steady flame. The flame's heat vaporises just enough candle wax to keep the flame burning at the same height. This is influenced by the length and type of wick and the type of wax. The wick serves as a place for the flame to form. When lit by another heat source, the heat from the burning wick melts the wax at its base and the liquid is drawn up the wick to the flame by capillary action. The heat in the flame vaporises the molten wax which then burns. Most candles today consist of beeswax or paraffin. The latter being the most common.

Paraffin is a wax obtained from petroleum and is a mixture of hydrocarbons which melt between 32 to 66 °C and vaporises at between 150 and 300 °C

Cigarette Lighter (Butane type)

Butane is a colourless, flammable gas which can be readily kept in a liquid state while under pressure at ordinary temperatures. Once the pressure in the lighter reservoir drops below 265 kPa at 25 °C, the liquid butane begins to vaporise until the pressure increases to an equilibrium point and further vaporisation ceases. When the lighter is operated, gas from the reservoir is liberated through a fine jet and a hot spark from the flint easily ignites the gas. Ignition temperature of butane can vary between 482 and 538 °C, however the hot flint spark is sufficient to begin combustion of the gas. At atmospheric pressure the normal vaporisation point of butane is -0.5 °C.

Butane lighters 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 phenomenon occurs. The flame will magically stay burning where the atmosphere will support combustion, just above the interface between the high and low O_2 concentrations, while the lighter is several centimetres below this interface.

In the CO_2 Pit of Gaden Cave, Wellington, New South Wales, Micheal Lake demonstrated the above phenomenon. When a lit butane lighter was gradually lowered into Pit, the 25 mm high flame stayed burning just above the oxygen deficient interface. The lighter body continued to be lowered until the 25 mm flame remained burning some 75 mm away from the lighter, in other words, the base of the 25 mm flame was 75 mm away from the cigarette lighter jet. Clearly at this depth in the pit the O_2 was now insufficient to support the combustion of butane as it issued from the lighter but 75 mm higher there was sufficient oxygen. This phenomenon can not occur with solid fuels, such as matches and candles, as the heat from the flame is required to vaporise the volatiles which then burn. When lowered further into the CO_2 Pit the butane lighter flame was totally extinguished.

A cigarette lighter which does not have adjustment for the flame can also be used to some degree to check for low O_2 concentrations. A subtle change in the flame height occurs as the O_2 concentration decreases - it becomes longer as the O_2 concentration decreases. This test is environmentally more desirable than the matches or candle method as unpleasant odours are not produced. However this method is not recommended for the novice as it requires some experience for reliable interpretation of O_2 concentration.

Laboratory Combustion Tests

To verify the O_2 concentrations required to support the flames of matches, candles and cigarette lighters, a series of tests were conducted in a controlled atmosphere chamber. A large inflatable glove chamber made of clear plastic was filled with normal air. The "Glove Bag[TM]" Model X-37-27, was pre-loaded with all the components required for the experiment, then sealed from the outside atmosphere. A stand was used to hold a burning candle and another stand held a mini video camera (ELMO 120 with 15 mm lens). The chamber full of normal air, was then purged with argon to reduce the O_2 concentration. The O_2 concentration (as % by volume) was measured using a Teledyne Portable Oxygen Analyser, (Model 320). A small bleed line, vented excess hot air and fumes from the chamber as the argon gas reduced the O_2 concentration. At each 0.5% drop in O_2 concentration, four separate matches ("Kangaroo" brand) were lit and a video recording made of their burning. The lowest O_2 concentration reached in the chamber was 7.5%.
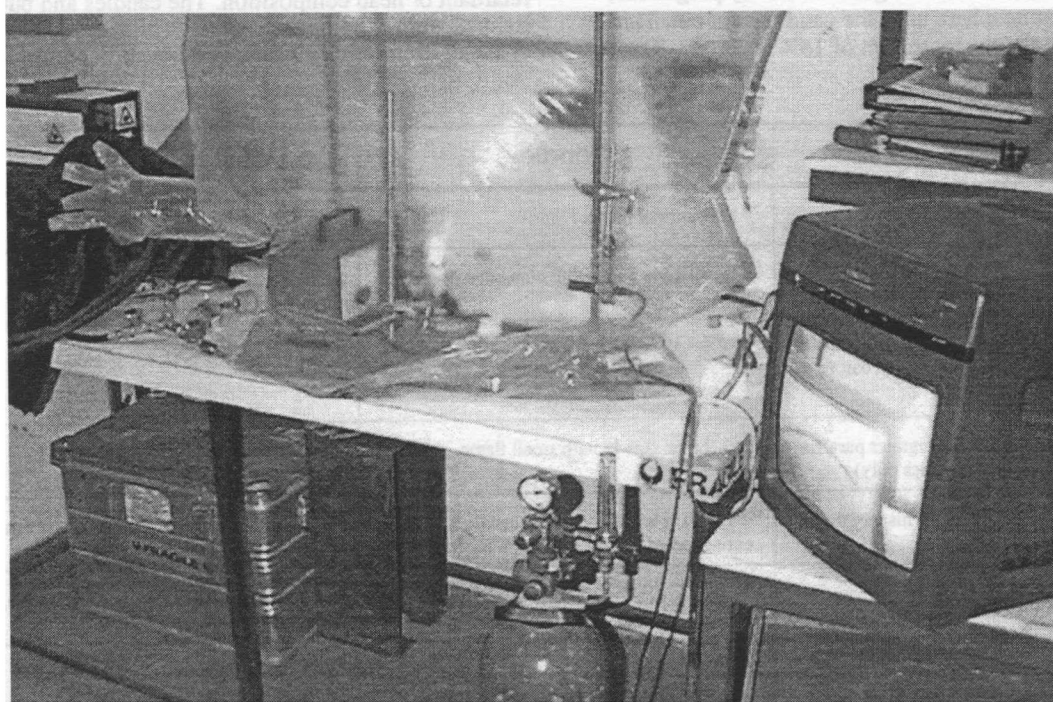

Plate 1. Testing setup using a Teledyne Portable Oxygen Analyser, and large inflatable glove chamber to measure oxygen concentrations which would extinguish various fuels. i.e. matches, candles and butane cigarette lighter.
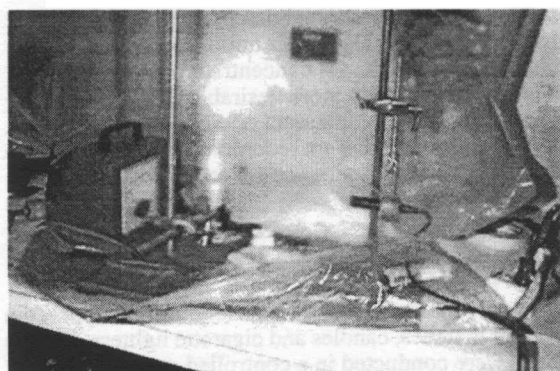
Plate 2. Close-up of experiment.
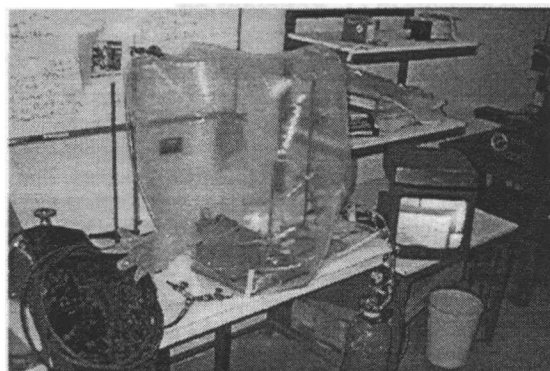*Note mini video camera centre right.*

Plate 3. Overall view of experimental
setup. Video recorder and argon gas bottle.

When the match tests were complete, the chamber was slowly re-filled with fresh air and a butane cigarette lighter was struck at each 0.5% rise in oxygen concentration. The level at which the butane would remain alight was noted. Then the O_2 concentration was reduced to verify the exact percentage which would extinguish the flame. Both ignition and extinguishing of the flame occurred between 14.25% and 14.5% O_2.

The atmosphere in the chamber was then returned to normal air and a candle lit. Argon was slowly purged into the enclosed atmosphere until the candle went out. This occurred at an O_2 concentration of 15%.

Results

The results of the tests are summarised in Table 7. On the whole the match tests were consistent, with about half a percent variation in the O_2 concentration required for the ignition of paraffin on different matches from the same box observed. The test with "Kangaroo" brand matches (made in Sweden) did not show any sign of fizzing slowly like a sparkler as has been observed in caves It is assumed that the matches used in a cave on those occasions had absorbed some moisture which retarded combustion of the match head or that different brands behave differently because of variations in retardant or head composition. The candles and butane lighters were extremely sensitive to changes in O_2 concentrations at their critical combustion points.

Match	Candle	Butane 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.		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.

Table 7.   Gives conditions of flame in relation to O_2 % in the controlled atmosphere

Physiological effects of reduced O_2

In atmospheres consisting of just N_2 and O_2, and where O_2 is at a lower concentration than the normal atmosphere, the human body would be affected in the following manner (Laboratory Safety Manual 1992).

- **O_2 reduced from 21 to 14% by volume**. First perceptible signs with increased rate and volume of breathing, accelerated pulse rate and diminished ability to maintain attention.
- **O_2 concentration between 14 to 10% by volume.** Consciousness continues, but judgment becomes faulty. Rapid fatigue following exertion. Emotions effected, in particularly ill temper is easily aroused.
- **O_2 reduced from 10 to 6% by volume**. 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.
- **O_2 reduced below 6% by volume**. Gasping breath. Convulsive movements may occur. Breathing stops, but heart may continue beating for a few minutes - ultimately death.

These points indicate that there is very little difficulty is caused by short-term exposure to O_2 / N_2 mixtures down to about 10% O_2. From Tables 3 and 7 it can be seen that the percentage of O_2 which will just not support combustion is approximately 15%. This is well above the concentration which will not support human life. In Tables 3 & 4, the theoretical cave atmospheres contain sufficient O_2 concentration to support life, however the CO_2 concentrations is sufficiently high to be dangerous to cavers.

Physiological effects of increased CO_2

Table 8 summarises the way in which the human body responds to elevated CO_2 in an atmosphere. Gases which create a hazard simply by displacing oxygen are called simple asphyxiants. However it is not the lack of oxygen in a cave which causes the physical symptoms or in extreme cases death, rather it is the increased concentration of CO_2. For example a person can survive several hours in an atmosphere with 3% 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.

The exact percentage and timing will depend on the individuals physiological make-up and tolerance. However, several minutes exposure to a concentration of >10% CO_2 will certainly result in death. For instance exposure to 25% CO_2 or greater, will result in death within one minute, even if there is 20% O_2 in the atmosphere. 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). This is the concentration that will cause irreversible physiological effects after 30 minutes exposure.

Exposure to just 1 to 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 is greater than 44 mm 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. "Intracellular buffering, via red cell haemoglobin, phosphate, and protein, exchange intracellular sodium and potassium for the excess extracellular hydrogen ion. In addition, hypercapnia leads to an increase in renal hydrogen ion secretion and net acid excretion, as well as an increase in bicarbonate reclamation. Although this response begins early, the maximum effect takes several days." (Clinical Management of Poisoning & Drug Overdose, 1996).

Treatment for exposure to CO_2

For persons exposed to high concentrations of CO_2, remove to a well ventilated atmosphere, keep the person warm and avoid exertion. In severe cases administer oxygen if available but be aware that vomiting and nausea often follow. Persons who have been exposed for short periods, generally recover without serious after effects.

Fire fighting research and CO_2

Fields (1992) studied the use of a new fire extinguishing gas mixture, designed to be used in enclosed spaces. While the actual percentages are not given in the paper, the gas called "Inergen" appears to consist chiefly of argon (Ar) with some CO_2 added. The function of the gas mixture is to reduce the ambient oxygen concentration to less than 15%. The study then goes into great detail about the affect on human life when the O_2 concentrations are reduced to between 15.0% and 12.4%, while the CO_2 concentration is increased to between 3.1% and 4.3%. The research found that the

CO_2%	Comments
0.03	Nothing happens as this is the normal concentration of carbon dioxide in air.
0.5	Lung ventilation increases by 5%.
2.0	Lung ventilation increases by 50%, headache after several hours exposure.
3.0	Lung ventilation increases by 100%, panting after exertion, headaches.
5 -10	Violent panting and fatigue to the point of exhaustion and severe headache. Prolonged exposure 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 - 30	Extremely high concentrations will cause coma and convulsions within one minute of exposure.

Table 8. Physiological effects of CO_2 at various concentrations (Strang, 1990)

addition of CO_2 was beneficial as it induced an immediate and sustained stimulus to increase breathing rates of persons caught in areas flooded with this gas mixture. It was the increase in CO_2 and to a much lesser extent the decreased O_2 which stimulated the respiratory response. For fire fighting Inergen, would be injected into an enclosed space at between 0.4 and 0.7 cubic metres for every cubic metre of room volume. At 40% dilution there would be 3.1% CO_2 and 15.0% O_2, while at 70% dilution there would be 4.3% CO_2 and 12.4% O_2. The paper concludes that the elderly or people with heart diseases (eg. coronary artery disease) but not heart failure would be at some risk of clinically significant hypoxia when breathing 70% Inergen mixture at sea level, but not when breathing a 40% mixture. The use of Inergen was considered at altitudes with barometric pressure down to 650 mm Hg, (Sea level atmospheric pressure ≈ 760 mm Hg). There was an overall increase in risk, however not significant enough to warrant a change in the mixture. At sea level an average healthy person would be at low risk of suffering any affects other than reducing their capacity for physical exertion, to less than half the maximum they could normally sustain while breathing fresh air.

An increase in CO_2 would cause increased breathing rates and could impose serious limitations on the degree of physical exertion achievable by a person with lung disease, cardiovascular disease, anaemia or carbon monoxide poisoning.

This paper fails to mention exposure times in relation to effects on humans at various concentrations of CO_2 and O_2 as would be expected after the addition of different Intergen to an enclosed atmosphere.

Inergen in air	N_2%	Ar%	CO_2 %	O_2%	trace gases %
40%	70.0	11.4	3.1	15.0	0.5
70%	66.5	16.4	4.3	12.4	0.4

Table 9.   Resulting volume % of gases in an inergen air mixtures which extinguish fire.

Conclusion

The results and discussion in this paper have clearly answered the four questions posed in the introductory paragraph.
- The Naked Flame Test is primarily measuring the low O_2 concentration.
- It is not reliable for measuring CO_2 concentrations.

   The Naked Flame Test using different fuels can reliably indicate the O_2 concentration in a cave atmosphere.
- Examination of the literature has shown that a high (>6%) CO_2 concentration is the most life threatening situation encountered underground. A life threatening low (<10%) O_2 concentration is rarely encountered in caves.
- Can the butane lighter be added to the following list of CO_2 indicators (Australian Caver 1990)?

   1% CO_2 a lighted match will go out

   4% CO_2 a lighted candle will go out

   6% CO_2 a lighted carbide lamp will go out.

   A butane lighter can be added to the list of Naked Flame indicators of foul air, however as already

determined by controlled atmosphere experimental work in this paper, all flame tests are measuring the O_2 content of the atmosphere. CO_2 concentrations at the levels which can be encountered in caves, have no real influence on the Naked Flame Test. Therefore extinguishing of a naked flame is indicating a potentially dangerous cave atmosphere, which is low in O_2 and most likely has an elevated concentration of CO_2. The exact CO_2 concentration can not be determined by the flame test as the cave atmosphere may have been influenced by type 1, 2 or 3 Foul Air or a combination of these. It can only be assumed that instrument inaccuracies occurred when the rule of thumb CO_2 test was originally determined during the early 1970's, in mainly type 2 Foul Air at Bungonia Caves, NSW.

It could be concluded that the Naked Flame Test adopted as part of the ASF Cave Safety Guidelines, 27th Jan. 1990 (Australian Caver 1990) is essentially meaningless. Without sophisticated measuring instruments, one can only speculate about the exact concentration of CO_2, so if any one of these flame indicators will not burn, it is time to exit the cave.

Cavers 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.

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 elevated concentrations of CO_2. Ideally cavers should become aware of the subtle changes to a cigarette lighter flame associated with O_2 concentrations down to 13%. 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.

Acknowledgments

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