http://www.warpig.com/paintball/technical/gasses/co2dynamics.shtml#1

Some CO2 Physics

This CO2 Physics FAQ for Paintball lists a number of frequently asked questions about CO2 dynamics and their answers. It is intended mainly for paintball players who wish to understand CO2 dynamics, especially as it applies to their paintguns. The answers are first given as just a simple answer to a question and then afterwards a physical explanation is given for the more technically oriented. It would help to have a copy of the PV diagram for CO2 which is available from WARPIG at:

http://www.warpig.com/paintball/technical/gasses/co2pv.gif

Also, you might want to take a look at Rick Muncy's Article in the February 1997 issue of PCRI.

Heres the list of questions so far. If you have some others questions or data that you think are relevant, or if you think some of my answers are wrong, please email me (Paul Reiser) at lewis@mtolympus.ari.net. (It would definitely help if you would use "CO2 PAGE" as the subject line.)

Question List

What precautions should I take?

1. Keep your CO2 bottle cool, away from direct sunlight, fire, radiators, etc. Don't leave bottles inside your automobile on hot days. Even though CO2 bottles have safety valves, it doesn't make sense to press your luck.
2. Don't try to fill your own bottle unless you are qualified to do so. If you have to ignore this precaution, at least remember to never overfill a bottle beyond its rated capacity. Don't try to fill a bottle without an accurate weighing scale. Filling a bottle "by ear" is only for experts and idiots.
3. Don't install or remove valves, etc. unless you are qualified to do so. Overtightening fittings can be extremely dangerous because they may be weakend enough to break below the burst pressure of the safety valve.

How do I interpret the CO2 diagram?

The CO2 diagram is a PV diagram for carbon Dioxide. If you know the %fill of your bottle and its temperature, you can find the CO2 pressure in that bottle. For example, if your bottle is a 20 ounce bottle but it weighs 15 ounces over its empty weight, you know it is 75% full. If the temperature is 90 degrees Fahrenheit, you can determine the pressure by finding the 75% point on the lower (horizontal) axis and then moving up until you find the 90 degree line. Move across to the vertical axis to read the pressure, which in this case will be about 1100 psi. There is a large "hump" in the middle of the graph with all lines being horizontal below it. This is the region where the CO2 in the bottle exists as both a liquid and a gas. Any change in the amount of fill will NOT change the pressure when the CO2 is in this region. That is because whenever you draw gas from the bottle, the liquid will quickly evaporate and restore the gas to its original pressure. In actual practice, the evaporation drops the temperature somewhat, in the same way that water evaporating on your skin cools you down. This means that after releasing some gas, the liquid will not bring you back to the original pressure, but the diagram is still correct.

The region to the left of the hump is the "ideal gas" regime, where all the liquid has left the bottle and you are running on CO_2 gas alone. In this region, the physics is easy, its the old PV=NRT law which determines the pressure. Playing paintball is difficult in this region because your pressure drops rapidly with each shot, and pretty soon you won't be playing your best game.

The region to the right of the hump is the dangerous region. Here the CO_2 expands and fills the whole tank and behaves much like a liquid. Any increase in temperature causes a large increase in pressure, and the bottle is very susceptible to blowout. It's pretty apparent that even though you could fill a CO_2 tank beyond its 100% fill point, you would, under normal conditions, be entering this dangerous region. This is why CO_2 tanks are only partially filled to about 34% liquid.

The point at the top of the hump is called the "critical" point of CO_2. It is a point where the CO_2 is in between all of the above mentioned regions. It doesn't behave anywhere near like an ideal gas and it certainly doesn't behave like a liquid. The pressure is a complicated function of temperature AND volume. You can see that the critical temperature is about 88 degrees fahrenheit, and the critical pressure is about 1080 psi. At the critical point, the bottle will be at about 73% of its rated fill.

What's the pressure in a CO2 tank?

As long as there is liquid in the tank, the pressure in a CO_2 tank is determined ONLY by the temperature. At room temperature (70 degrees F) its about 853 psi. (You can check this and the pressure for other temperatures in the little table at the top left of the CO2 diagram.)

The pressure in a CO_2 cartridge, as long as there's any liquid in it, can be calculated roughly from:

$$p = p_0 * \exp(T/T_0)$$

where p is pressure in psi, T is temperature (Fahrenheit), and

$p_0 = 314.04$ psi
$T_0 = 69.64$ F

This works pretty well between 0 and 80 degrees F as long as your bottle is filled to 100% or less of its rated fill. To get a more accurate estimate, use the CO2 diagram.

Once all the liquid is used up, there's only gas in the bottle, and then pressure drops pretty quickly. 88 degrees F is the critical point for CO_2, where all the liquid sort of evaporates no matter what (kind of complicated). Any way, above 88 degrees, the pressure depends on bottle volume again, but this is not too important since bottles should never get this warm.

How much liquid is in a "full" tank? Why not fill it up?

A "full" tank contains about 34% liquid CO_2. If it is filled any more, the CO_2 will become very sensitive to temperature changes, with a small increase in temperature causing a large increase in pressure. This is a dangerous situation which is avoided by only partially filling the CO_2 bottle.

One cubic inch of water weighs 0.577 oz and the specific gravity of liquid CO_2 is 1.977 gm/cc so one ounce of liquid CO_2 has a volume of 0.877 cubic inches. CO_2 bottles generally have a full-fill to volume ratio of about 2.57 cubic inches per ounce of CO_2, so that one ounce of CO_2 will take up 0.877/2.57 = 34% of the total volume of the bottle.

The figure of 68% is often quoted as the volume of liquid in a full bottle, but this error probably stems from translating "ounce" into volume using water as the standard. Water is 1.00 gm/cc, or about half the density of liquid CO_2 so that if a CO_2 bottle is filled to its rated capacity with water, it will be 68% liquid by volume.

Why does my gun have problems in cold weather?

Because the pressure of the CO_2 in your tank is lower for lower temperatures, when it gets cold, there's not enough pressure in the tank to make your gun operate properly. For some guns, which run well on liquid, a "siphon" tube can be installed in the tank. This is a tube that extends into the liquid in your tank, and the pressure of the CO_2 in the tank always forces liquid into the gun. These kinds of guns work well in the cold weather. Others, like the Automag, cannot stand to have liquid in them, and usually one needs to have an "anti-siphon" tube in the tank that makes sure that only gas is fed to the gun. These kinds of guns are most sensitive to temperature, because they feed on the gas directly.

How can I prevent "hot gun" penalties in tournament play?

Even though most paintball guns have regulators which will regulate the pressure behind the paintball and therefore its velocity, these regulators are not perfect. When the pressure in the CO_2 bottle rises, the pressure of the gas ejecting the paintball will increase as well, although not as much. Hot gun penalties usually occur when either your gun or the bottle are warmer at the end of a game than at the beginning. This can come about from having the gun warm up from body heat or the sun. If at all possible, don't allow this to happen. A light insulation on a remote bottle will help to prevent body heat from warming the bottle, although insulation may not be allowed on bottles attached directly to the gun because it may be interpreted as "bounce control". Also, remember that firing the gun cools the gun and the CO_2 bottle so that it will help to have fired a few rounds before leaving the field. Keep in mind that some tournaments require that a player not fire his or her gun after being eliminated. Hot gun problems can happen in cool weather as well as the result of efforts to warm up a cold gun which accidently overheat the gun.

Why do they chill the bottle before filling it?

CO_2 tanks are usually filled from a "bulk tank". These tanks have siphon tubes which extend down into the liquid of the tank, and when you open the valve on the bulk tank, the pressure in the tank will force liquid out of the valve. The problem is, once you force a little bit of liquid into the gun bottle, it will evaporate and raise the pressure in the gun bottle to the same as the bulk bottle, and no more liquid can flow into the gun bottle. In order to fill the gun bottle, it must be at a lower pressure than the bulk bottle, and since its only the temperature that determines the pressure, you have to lower the temperature of the gun bottle below that of the bulk bottle. This is done by either putting the gun bottle in a freezer (if you have time), or by blowing off some liquid that is already in the gun bottle. This works because evaporation is a cooling effect.

What's the burst pressure?

CO_2 bottles contain copper "burst disks" which will blow out above a certain pressure and release the contents of the bottle into the air in a relatively safe manner. The blowout pressure of burst discs vary with manufacturer but the minimum value is about 2200 psi and the maximum value is about 2800 psi.

How much should I underfill my bottle on hot days?

Referring to the graph, you can see that even for a bottle that is filled to 100% of rated fill, overpressure should not be a problem. Nevertheless, it is probably wise to try to stay under 1500 psi. On really hot days where you can't prevent the sun from raising the temperature of the bottle beyond 100 degrees Fahrenheit filling to 80% is a good idea.

Why does it get cold after I shoot a lot?

There is usually both liquid and gas in the CO_2 bottle. When the gun is fired, some gas is drawn out of the bottle. The remaining liquid evaporates to restore the pressure in the bottle, and just as water evaporating from your skin cools you off, the CO_2 evaporating from the liquid in the bottle cools off the whole bottle, liquid, gas, and all.

The molecules of the liquid CO_2 are in constant motion, some moving faster than average, some moving slower. The average speed of the molecules is related to temperature, the higher the temperature, the faster they move, on average. However, when molecules evaporate from a liquid, it is only the faster "hot" molecules that can jump into the gas phase. They lose some of their speed breaking away from the liquid, but the liquid that is left behind is colder than it was because it lost its "hot" molecules to the gas.

Important numbers for CO_2 dynamics Calculations

Bottle Volumes:

Bottle size (oz)	Volume (cu in)
3.5	9.0
7.0	18.0
12.0	31.0
20.0	51.0

Roughly, the volume of a CO2 bottle (cu in) is about 2.57 times the bottle size (oz)
Specific Gravity of CO2 is 1.977 gm/cc Thus the weight of 1 cu inch of liquid CO2 is 1.140 oz.