The CO_2 Cartridge … an Under-Appreciated Marvel of Technology!

Figure 1: Sectioned 12 gram CO_2 cartridge shows thin (pierced) plug and far thicker walls.
It is compared with two equivalent energy sources: two .22 Long-Rifles or one .38 Special.

INTRODUCTION

Many fine pellet guns are powered by the12-gram CO_2 Powerlet®. These cartridges are 50-cent commodity items, yet the basic physics of this power source are virtually unknown by the average shooter. The technical elegance embodied in this solution and the sophistication of its fabrication deserve explanation.

The Powerlet wraps 31.5 grams of deep-drawn steel around 12 grams of liquid and gaseous carbon dioxide (CO_2), locking it in a hermetically sealed vault with a minimum burst-pressure of 7000 pounds per square inch pressure (psi). The bottle is smooth and seamless, providing a precisely controlled 14 cc volume sealed by a pierceable steel plug welded to the bottle's neck.

The Powerlet contains a considerable amount of energy (over 280 ft-lb or 380 Joule). This is approximately equivalent to two high-velocity .22 long-rifle shells, or one .38 Special (+P) cartridge.

To place this in another perspective, the contained energy is sufficient to light a 100-Watt bulb for nearly four seconds. Any one of these equivalents is clearly capable of injuring you; the CO_2 cartridge must be treated with care and respect!

When used near room temperature, it is capable of delivering most of this stored energy as useful muzzle energy. Fifty (slow fired) shots of 600 foot per second (fps) velocity with a 7.1 grain pellet (5.7 ft-lb muzzle energy) is a reasonable expectation. If the firing pace is slow and deliberate, these shots will exhibit remarkably consistent velocity, owing to the "built-in pressure regulation", provided by thermodynamic interplay between the liquid and gas *phases* of CO_2.

Figure 2: Evolution of the bottle shape from shallow cup to finished cartridge.
Photo courtesy of Leland Limited

BUILDING THE BOTTLE

The disposable gas bottles are formed from sheet steel in a continuous multi-stage stamping operation. A disk is first sheared from plated steel roll-stock and initially stamped into a shallow cup. Subsequent stampings evolve this cup shape, with each press-stroke increasing the length, decreasing the diameter and forming the bottom dome. Finally, the process focuses upon forming the neck in a series of heading operations.

The genius of the process is that it is performed continuously using *transfer presses*, huge machines that automatically perform multiple forming operations simultaneously. The parts-in-process are sequentially passed from one die-set to the next. Each time a press falls, several (typically10 to 12) different operations are performed simultaneously.

Typically, three transfer presses are employed to produce 12-gram Powerlets. The first accepts raw steel stock and produces a cupped blank 12 cycles later. The second takes the cups and deepens them while decreasing the diameter in 10 sequential steps. Before entering the third press, the parts are conveyed through a ribbon-style *induction furnace*, which anneals or softens the work-hardened neck-ends by heating them to nearly 2200° F. The final press then forms the neck shape in 10 steps.

Thus, raw steel stock enters the fabricating process and emerges 33 operations later as a precisely finished part in a matter of seconds. Enormous forces are involved in the process, necessitating building-sized machines to fabricate these small parts.

FILLING THE FLASK

The fully formed cartridges are twice cleaned in an alkaline bath, rinsed and then baked and blown dry. The puncture caps are separately formed from thin (0.011” typical) steel, pre-stressed and cleaned. These components and the CO2 charge are brought together in a highly automated process, the details of which, in the words of a leading manufacturer, “are guarded as zealously as the Colonel's chicken recipe!”

Figure 3 presents a schematic representation of the sequential filling and capping process, performed by a computer-controlled *filling head*. A filling head is basically an indexing rotary-table augmented by robot arms, position sensors, CO_2 dispensing sub-system, an induction welding head and a high precision weighing system. The “magic” required here is to perform each step in a fraction of a second, bringing parts, charge, forces and heat together at exactly the right instant to accomplish each task. This carefully choreographed continuous manufacturing process is made possible only by major facility investment and significant engineering forethought

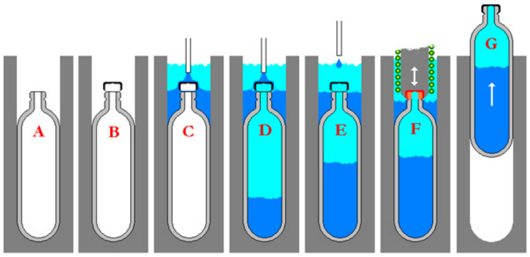

Figure 3: Stages of filling the bottle with liquid CO_2 and welding it shut (artistic liberties taken).

A cartridge enters the charging process by being automatically inserted in a tight-fitting chamber in a multi-chamber rotary table as shown at **A** in Figure 3. The table rotates in chamber-spaced angular increments and a new operation is performed at each indexed position. At **B**, a fully formed cap is positioned over the neck of the cartridge. A sensitive weighing system then records the weight of the empty cylinder and cap to a resolution of .05 gram. At position **C**, the chamber is flooded with liquid CO_2, which chills the components. CO_2 gas, being almost twice as heavy as air, begins to displace the air in the cartridge and condenses as liquid at its bottom as shown in **D**. This metered filling process continues until 10.5 cc of *liquid* CO_2 have moved into the bottle, filling 75% of its volume at **E** (the rest now contains gaseous CO_2). The cap is then pressed to the bottle by a large force while a high electrical current is pulsed through an *induction welding head* at **F**. The strong magnetic field produced induces eddy currents to flow freely through the cap and cartridge. At their juncture, electrical resistance to this current is high. This causes the local area to heat rapidly, fusing the cap and cartridge together in a gas-submerged welding process. At **G**, the charged and sealed Powerlet is ejected from the chamber. Each finished cartridge is weighed again and compared against the empty weight of step **B**. Cartridges that meet the charge requirement within a fraction of a gram are passed on for final inspection, roll-labeling and packaging. The occasional under or over-charged units are automatically placed into a salvage-process disposal line.

THE GENIE IN THE JUG

Like water, CO_2 can exist in three *phases*, solid liquid and gas. We are all familiar with points of *state-change* for water: it melts or freezes at 32° Fahrenheit and evaporates or condenses at 212° F. However, these observations are both made when the water is at atmospheric pressure (about 14.7 psi absolute pressure or 0.0 psig “gauge pressure”). These transition temperatures change, as shown in Figure 4, if the water is at a different pressure. For example, the boiling point of water is lower than 212° F at high altitude (where the pressure is lower) and higher within a pressure cooker.

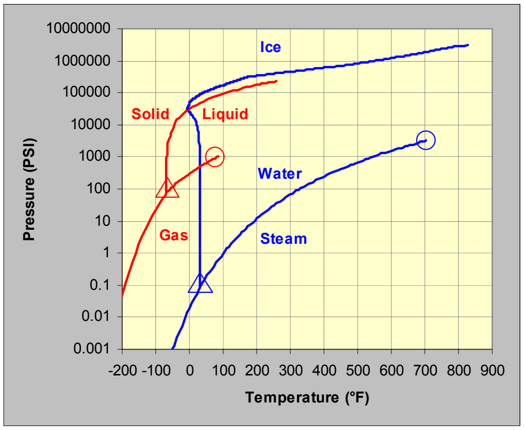

Figure 4: Phase Diagrams for water (blue) and CO_2 (red). Triangles mark Triple Points and circles mark Critical Points.
Data courtesy of ChemicaLogic Corporation

Did you know that ice, water and steam actually *coexist* at a temperature of 32.017° F under 0.08852 psia pressure? This unique condition is called the *triple point* and it is used as the basis of very precise thermometer calibration. It is marked by a blue triangle in Figure 4.

Water exhibits another interesting limit state, termed the *critical point*, at 705° F and 3210 psia. This marks the upper end of the pressure-versus-temperature *saturation line* separating the liquid and vapor states. Water's critical point is marked by a blue circle. When the temperature exceeds the 705 ° F *critical temperature*, water exists solely as a gas or vapor (steam) *regardless of the pressure applied*.

CO_2 exhibits remarkably similar properties. At its *triple point* (–69.8° F and 75.1 psia), CO_2 exists in all three phases simultaneously. Lowering the temperature or increasing the pressure from this point (red triangle in Figure 4) assures that it exists only as solid *dry ice*. Under an atmospheric pressure, dry ice *sublimes* to gas (without passing through a liquid state) at about -110° F; at higher temperatures it melts and then evaporates to gas. Above the critical point (87.9° F and 1060 psia) marked by a red circle, CO_2 can no longer exist as a liquid.

The CO_2 *saturation line* (between the red triangle and circle in Figure 4) is especially important to shooters. This pressure-versus-temperature curve marks the boundary between the liquid and gaseous phases of CO_2. The pressure at any temperature along this line is termed the *vapor pressure*. Below the *saturation line* CO_2 exists as a gas; above the line it exists as a liquid.

Along the saturation line, CO_2 coexists in both states, simultaneously, with the properties shown in Figure 5.

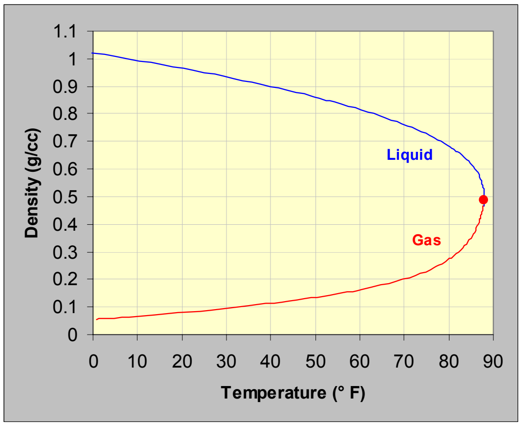

Figure 5: Density of liquid and gaseous CO_2 along the Saturation Line.

Figure 5 presents the *density* (mass-per-volume) of the gaseous and liquid CO_2 components along the saturation line of Figure 4. As temperature increases, the liquid expands to become less dense while the gas compresses to a denser state. At the *critical temperature* (87.9° F), the two components become indistinguishable; they exhibit a common *critical density* of 0.468 g/cc. Above this temperature, the CO_2 behaves like a gas, and *no amount of applied pressure can cause the liquid phase to appear*.

The 87.9° F *critical temperature* of CO_2 is of particular importance to air-gunners. As shown in Figure 6, below this temperature both gas *and liquid* CO_2 can coexist in the Powerlet. Above this temperature, only gas can be present. The cartridge exhibits a natural pressure-regulating mechanism, but only at temperatures lower than 87.9° F.

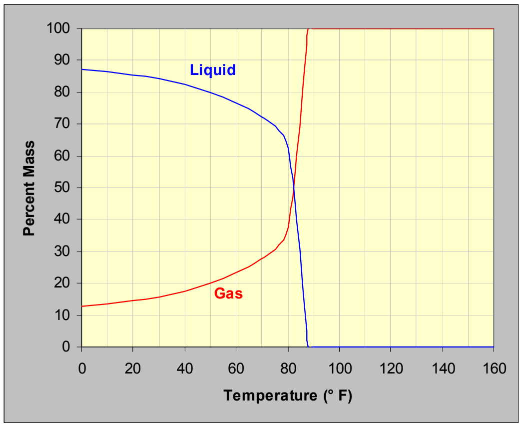

Figure 6: Below 89.7 ° F, the cartridge contains liquid CO_2 as well as gas. Above this critical temperature, all of the CO_2 “boils” to gas.

At low temperature, the bulk of the entrained CO_2 is in liquid state. As the ambient temperature rises, heat enters the cartridge and some of the liquid boils to gas; the percentage of gas in the mixture increases, as does the pressure. Below 87.9° F, the boiling stops when the pressure reaches the *vapor pressure* determined by the ambient temperature as long as some liquid remains. Above this *critical temperature*, all the CO_2 boils to gas.

When a shot is made, some CO_2 gas exits the cartridge rapidly and the ratio of gas-to-liquid is instantaneously reduced. The loss of gas instantaneously reduces the pressure within the cartridge, causing some of the liquid to boil or vaporize to “fill the void”. This vaporization extracts heat from the mixture, cooling it.

The mixture continues to boil liquid to gas, increasing the pressure while drawing heat from the ambient temperature surroundings. Eventually, the mixture warms back to the ambient temperature and the boiling stops when the pressure reaches the *vapor pressure*.

Hence the next shot will be made from exactly the same pressure source. This is the natural *pressure-regulation* mechanism provided by CO_2.

Figure 6 illustrates the content of a cartridge with a full 12-gram charge. As CO_2 is consumed, it is the *liquid* component that diminishes.

SHOOTING PRESSURE … THE REAL STORY

Consider what happens when a mass of CO_2 is sealed in a fixed-volume container. If the mass-to-volume *charge density* is equal to the 0.468 g/cc *critical density*, the pressure within the container will exactly equal the *vapor pressure* for any temperature below the 87.9° F *critical temperature*. If a larger (or smaller mass) of CO_2 is present, the pressure-versus-temperature line will depart from the *saturation line* at a temperature *below* 87.9° F, as shown in figure 7.

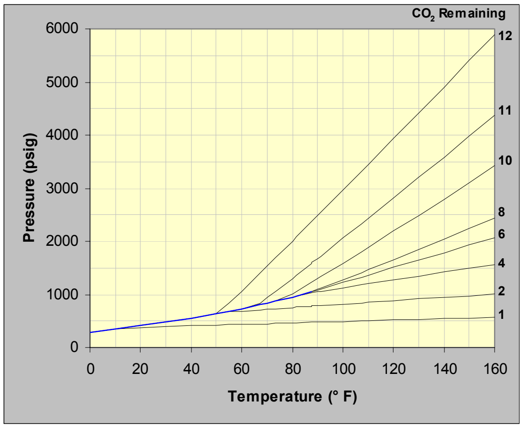

Figure 7: Pressure-versus-temperature lines for different remaining CO_2 charges.

Figure 7 presents the pressure within a Powerlet as a function of temperature with varying amounts (1 to 12 grams) of CO_2 remaining in the bottle. Note the blue segment partially common to all of these traces; this is the *saturation line*.

A CO_2 charge of 6.55 grams remaining in the 14 cc cartridge volume (0.468 g/cc) will exhibit a pressure-versus-temperature curve that follows the *saturation line* all the way to 87.9° F. All other charges depart from the blue line at a *lower* temperature.

The point of departure from the blue segment is termed the *transition point*, defining a *transition temperature* and a *transition pressure*. Above the *transition temperature*, the CO_2 *behaves as a gas* with pressure rising with increasing temperature.

When the Powerlet is essentially full, the slope above the transition point is very steep and pressure rises rapidly with temperature *to potentially dangerous levels*. When the cartridge is nearly depleted, the transition point marks the end of useful life. This is the point at which all of the *liquid* CO_2 has been consumed.

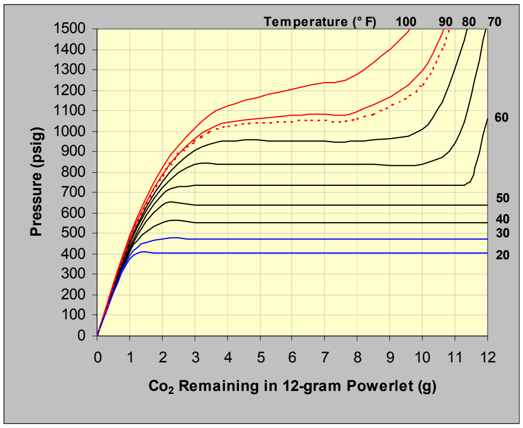

Figure 8: Pressure-versus-charge lines for different ambient temperatures.

The data of Figure 7, presented in a different format, make the natural regulation process blatantly evident. Figure 8 presents a family of pressure-versus-mass lines, each for a different ambient temperature.

Note the broad constant-pressure (horizontal) segment evident in each constant-temperature curve below the (dotted) 87.9° F curve. Theses segments are at the *vapor pressure* associated with the chosen temperature and indicate mass-independent pressure regulation.

Figure 8 shows that the Powerlet can deliver a constant pressure source over a broad range of remaining CO_2 charge when operating at constant temperature. It is clear that the mass-range for regulated behavior is broadest at low temperature and that the regulated pressure provided increases with temperature. Most airgun manufacturers recommend use within a 40 to 80° F temperature range. This assures a regulated source pressure between about 550 and 950 psig. (Note that initial shots may be significantly above the regulated pressure, much as with PCP guns that are charged beyond their optimum air pressure.)

CO_2 regulation is summarized by figure 9, overleaf, which presents the regulated pressure and the mass-limits to achieve regulation as a function of temperature.

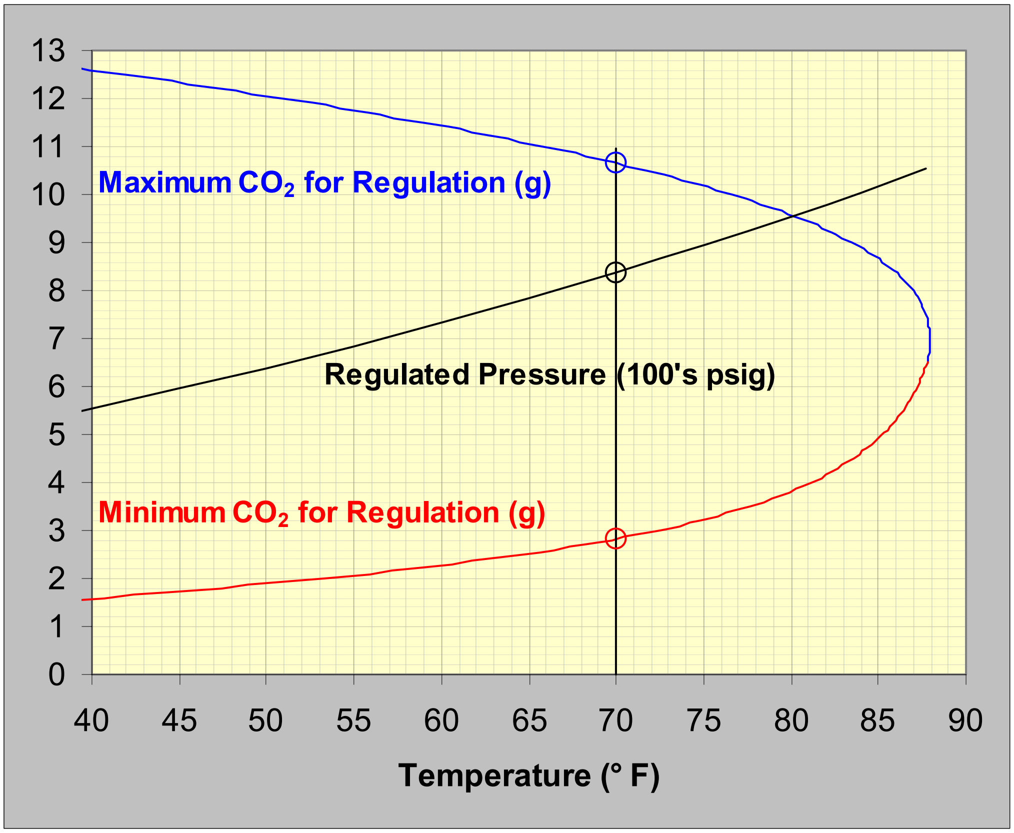

Figure 9: Summary of CO_2 regulation showing pressure and mass-limits by temperature.

To use figure 9, mark the ambient temperature on the horizontal scale and read the corresponding pressure and mass limits directly above it. For example, on a 70° F day, a regulated pressure of 840 psig will be provided as long as the Powerlet holds at least 2.8 grams but not more than 10.6 grams of CO_2. Hence the first few shots will be "hot" until you use 1.4 grams from a new Powerlet. You will "run out of liquid" when 2.8 grams of gas remain in the cartridge.

At 70° F, the slopes of all three curves are quite modest. The regulated pressure slope is about 12 psig/° F, the minimum mass slope is 0.07 g/° F and the maximum mass slope is 0.08 g/° F. This means that small temperature changes of a few degrees will have very little impact on muzzle velocity.

Figures 5 through 9 reflect steady-state or *static equilibrium* conditions. In fact, an airgun in use is a study in thermo*dynamic* activity. Matters of timing are all important. As with water, a quantity of CO_2 does not boil or condense instantaneously. It takes some *time* for the process to settle to a new steady-state when the conditions are perturbed.

When the CO_2 is at a different temperature than its surroundings, it takes some time for the mixture to warm or cool to the equilibrium conditions illustrated.

When the gun is fired, a mass of gas flows from the Powerlet to propel a pellet. The discharge of this mass and its associated energy is accompanied by an immediate reduction in temperature, most notably at the small exit hole of the bottle. This gas is expanding rapidly as it is entering another volume at much lower (initial) pressure. The pressure drop decreases the gas's energy and it becomes much colder.

At the same time, the pressure within the cartridge has dropped dramatically owing to the exit of mass (and its energy) from its volume. This causes an immediate and significant drop in the mixture's temperature. Subsequently, it draws heat from the surroundings, which warms the mixture, and any liquid CO_2 begins to boil to gas.

External heat entering the cartridge to warm it to ambient temperature first traverses the *saturation line*. In this region, the heat causes the liquid component to boil to gas. *When the boiling stops*, the pressure is equal to the *vaporization pressure* associated with the ambient temperature. As long as the ambient temperature is constant and a sufficient quantity of liquid exists, the mixture will return to this same vapor pressure after every shot and all shots will be made from the same source pressure. This natural pressure-regulating characteristic works until the Powerlet is depleted of *liquid* CO_2.

Above the *transition temperature*, the behavior is quite different because the entire liquid component has already boiled to gas. In this region, the steady-state pressure within the Powerlet is proportional to both *temperature* and the *mass* of gas present. This means the source pressure *drops* with every shot fired.

PARTING SHOTS

When shots are fired slowly (as with a bolt-action rifle in serious target work), sufficient time elapses between the shots for the system to warm back to the ambient temperature. This, in turn, assures that the pressure has return to the same level just employed. As long as the ambient temperature remains constant and below 87.9° F, every shot will be made from the same source pressure. This means each shot will extract the *same* mass of CO_2 gas and therefore the same energy, providing consistent *muzzle energy* to every shot. In concert with consistent *pellet mass* this assures minimum variation of muzzle velocity.

When rapid-fire is undertaken (as with a double-action pistol), the waiting-time between shots is inadequate for full thermal recovery to equilibrium. This leads to *reduced power with every shot* as the CO_2 mixture is working its way from right-to-left along the saturation line of *figure 7*. The muzzle velocity of a rapidly fired pistol will quickly drop below an acceptable level, normally leading you to change the cartridge.

But, stop and think before you open the gun and dispose of that Powerlet! Rapid-fire essentially caused the gun to use *less* CO_2 than an equal number of slower paced shots. You're throwing that "battery" away too soon … it's not fully discharged, it's merely cold. Put the gun down and let it warm up; you'll find new life returns to your dead cartridge!

A 40 to 80° F *operating* temperature range is normally recommended for CO_2 guns. Colder temperatures normally result in unacceptably low pellet velocities. Some airgun manufacturers suggest use up to as much as 100° F; I submit this higher limit is unrealistic.

Exceeding the *critical temperature* may result in a "gas-lock" wherein the gun won't fire as excessive backpressure on the gas-release valve prevents it from opening when struck by the hammer. At minimum, the excessive pressure will retard valve-lift and reduce the time the valve is open, *reducing* the mass of gas released and thus the muzzle velocity. In short, if you're comfortable with the temperature, your CO_2 gun will perform properly.

It would be remiss to close this discussion without mention of storage safety considerations. *Every* manufacturer of 12-gram CO_2 cartridges prints a warning on the package that subjecting their product to *temperatures in excess of 120° F can result in dangerous overpressure and possible explosion*. They mean it!

Figure 10 illustrates a Powerlet that was deliberately exploded in a manufacturer's test. This cartridge was briefly heated to 180° F within a safety enclosure. Note that the rupture opened the entire bottle violently. It did not merely burst the thin piercing plug as intuition might suggest. There is always the risk of shrapnel disbursement with such an explosion. *Use common sense; don't let you CO_2 cartridges get overheated!*

Figure 10: Powerlet ruptured by exposure to 180° F temperature in manufacturer's test.

Accidents with these cartridges are a very rare event. One manufacturer cited only a single (non injuring) accident reported over a decade's sale of well over 100,000,000 units. That's a pretty impressive safety record and it speaks well of the fundamental design and the care with which it is reproduced.

ACKNOWLEDGEMENTS

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REFERENCES

Technical information for the preparation of this paper was obtained from the Internet:

1. The *CO_2 Phase Diagram* and *CO_2 Mollier Chart* (generated by ChemicalLogic **CO_2Tab**™, V1.0) provided the initial CO_2 data. This was obtained from **ChemicaLogic Corporation** at: www.chemicalogic.com.

2. Confirming CO_2 properties information was obtained from **Wittman Carbon Dioxide Equipment** at: www.carbon-dioxide-equipment.com.

3. Detailed information regarding disposable gas-filled cylinders was obtained from **Leland Ltd.** at: www.lelandltd.com.