

# **THE APPLICATION OF CARBON DIOXIDE IN A BUILDING SERVICES ENVIRONMENT**

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## **ABSTRACT**

The paper will identify the specific benefits that the use of carbon dioxide could deliver for Building Services, in place of the standard chilled water and DX systems that presently prevail. It will examine the practicality of such installations; addressing issues of system, piping, heat exchanger and component design. The implications for the safety of personnel that installing a high pressure and potentially asphyxiating fluid system in occupied space will also be explored. The opportunity for capital cost and energy savings is also considered, based on specific applications.

## **INTRODUCTION**

There has been a renaissance in the use of carbon dioxide in the last 5 years. The driver has been its use for low temperature freezing applications where its characteristics offer refrigeration solutions that are benign, in environmental and human terms, and commercially attractive. Its development has not only been limited to low temperature applications, but has seen its use across a range of temperatures from -54°C to +10°C, for freezing, cold storage, chill storage and defrosting applications.

However, the notion of using carbon dioxide as a replacement for chilled water in the building services environment has gained little ground. This is probably due to it being viewed as an “industrial” refrigerant which would add cost to an application that is considered mature and cost sensitive. Particularly as there is a “catalogue engineering” approach when it comes to specifying water chillers and chilled water systems.

It may surprise some that carbon dioxide was used in the early days of building air conditioning and, at that time, was perceived to be a safer alternative to use than sulphur dioxide or ammonia (Bodinus, 1999). Theatres, restaurants, hotels and nightclubs all used carbon dioxide systems for comfort cooling. The largest installations for department stores in the USA provided over 1000kW of cooling and used large slow speed reciprocating compressors. The introduction of R12 in the 1930s, with its excellent thermodynamic properties and relative ease of installation, eclipsed the use of carbon dioxide in building services and in many other refrigeration applications.

Moving forward to the present day, refrigeration is all around us from small split cooling units rated for a few kilowatts for individual rooms, through to large multi-megawatt integrated chilled water systems for complete office buildings. There are also high heat intensity applications for data centres where direct and indirect cooling systems are employed.

The conventional approach to these services is to utilise synthetic HFC refrigerants in a DX system to extract heat from the room mounted evaporators, or to use water as a secondary heat transfer fluid through a distribution system to cool the local heat exchangers. The former case generally uses copper pipework to convey the refrigerant, whereas the latter uses copper, steel or even plastic for water distribution.

However, the drive to reduce the energy cost for buildings as required by Part L of the UK Building Regulations has provided an opportunity for a more innovative approach to heating and cooling provision. Also concerns over the high intrinsic Global Warming Potential (GWP) of the HFC

refrigerants have forced building designers and owners to consider sustainable alternatives using natural fluids. This has resulted in the installation of a number of ammonia chillers in the UK for government and commercial buildings, applications that would normally have been the preserve of HFC or HCFC refrigerants. By a combination of careful design of the installation to meet the safety regulations for ammonia and charge minimisation, the benefits of high efficiency, long life and future proofed refrigeration plants have been proved. There is also now a place for carbon dioxide in the building services sector for occupied and un-occupied rooms.

### **CHARACTERISTICS OF CARBON DIOXIDE**

Carbon dioxide is a colourless, odourless, naturally occurring fluid which exists in the gaseous form at atmospheric pressure. It is present in the atmosphere in concentration of around 0.037%, although the levels are rising due to industrialisation and contributing to global warming. Without man's intervention the equilibrium level of carbon dioxide is maintained in a natural cycle with animals exhaling excess gas which is then absorbed by vegetation during photosynthesis.

There are a number of characteristics that commend carbon dioxide as a refrigerant. These are: good thermodynamic properties, non-flammable, non-toxic, chemically stable and inert, environmentally benign, low cost and easy availability. It also operates very efficiently at low temperatures down to  $-54^{\circ}\text{C}$ .

Limitations on the application of carbon dioxide have resulted from its relatively low critical point of  $31^{\circ}\text{C}$  which has made it impractical to use when condensing directly to air for many applications.

The other major challenge is its high operating pressures. At the triple point of  $-56.6^{\circ}\text{C}$ , the saturation pressure is 5.18 bara and at  $0^{\circ}\text{C}$  this rises to 34.9 bara. These pressures are considerably higher than those typically occurring in the refrigeration and HVAC sectors and until recently it would have been difficult to source standard and cost effective components suitable for this regime.

The challenge for system designers for building services applications is to source equipment and components that are safe, reliable, readily available and affordable.

### **COMPONENTS**

The focus of this paper is in the use of carbon dioxide as a volatile secondary fluid, as a substitute for chilled water systems. Typically, chilled water systems operate in the temperature range  $6/12^{\circ}\text{C}$  for air conditioning systems requiring dehumidification and  $14/17^{\circ}\text{C}$  for sensible working loads. The equivalent carbon dioxide systems would be designed for the mid temperature evaporation range i.e.  $9^{\circ}\text{C}$  and  $15.5^{\circ}\text{C}$  respectively, equating to 49.3 bara and 51.5 bara saturation pressures. The system design pressure will require to be able to cope with standstill conditions associated with higher ambient temperatures and this would be in the order of 90 bara.

#### ***High side plant***

The volatile secondary carbon dioxide system operates in cascade with a high side refrigeration plant. This plant would typically be a conventional HFC system, evaporating approximately 5 K lower than the carbon dioxide temperature and using air cooled condensers. For larger duties,  $> 200\text{kW}$ , it would be feasible to use ammonia as the high side refrigerant as an alternative to HFCs. Ammonia has comparable efficiency to R404a at these conditions and has the added benefit of providing an "all natural" solution in conjunction with carbon dioxide. Evaporative condensers provide a more efficient alternative to air cooled, albeit there are additional costs and responsibilities associated with the water management regime.

### ***Carbon Dioxide Condenser***

Plate and shell heat exchangers combine the benefits of close approach, compact plate heat exchangers with the high integrity, high pressure capabilities of the shell and tube heat exchangers. For process applications they are capable of operating at up to 120 bara and temperature -200 to 900°C. They have been used in carbon dioxide systems as both evaporators and condensers in the temperature range -54 °C up to 10 °C and for capacities 12kW up to 1700kW.

The shell is constructed in carbon steel with the plates being 316 stainless steel. Welded nozzles are provided on the plate side for carbon dioxide connections. Compressor oil is contained in the high side circuit, so there is no contamination of the carbon dioxide system.

A liquid receiver vessel is required for large systems with multiple heat exchangers.

### ***Carbon Dioxide Pumps***

The pumps have to operate at the normal evaporating pressure of 52 bara and generate sufficient head to overcome the system resistance through piping and carbon dioxide heat exchangers. Commercially available hermetic centrifugal pumps are not yet able to operate at these pressures although they have been used for low temperature carbon dioxide pumped overfeed installations. Belt driven reciprocating pumps are capable of withstanding operating pressures of at least 90bar and have been used successfully in volatile secondary carbon dioxide system at temperatures above 10 °C.

The number and size of pumps required will depend on system size and overfeed required. However practical experience, from a large chill store operating with carbon dioxide at -5 °C, indicates that supplying liquid at 1.5 times the evaporation rate is realistic. At least 2m head of liquid above the pump suction should be incorporated in to the plant layout to avoid cavitation (Pearson/Cable, 2003).

### ***Valves***

In contrast to ammonia, carbon dioxide is suitable for use with most commonly used valve materials. Although, some substitution of standard valve seal materials is required for operation with carbon dioxide.

Major refrigeration component manufacturers are now able to provide a range of stop, check, regulating, solenoid and motorised valves with special versions up to 50 bar design pressure suitable for carbon dioxide (Danfoss, 2002). For operation above 50 bar, suitable valves have been found from other industries.

Installation of safety valves is to be carried out with the valve outlet open to atmosphere. This is because when the carbon dioxide pressure falls below the triple point of 5.2 bara, it will change state to the solid and vapour phase with the potential risk of blocking any pipework downstream of the safety valve.

### ***Pipework***

The line sizes of a volatile secondary carbon dioxide are considerably reduced in comparison with the equivalent incompressible fluids. The piping will require to be designed to suit a higher pressure but will still result in reduced weight and lower loads to be supported in the building.

For larger systems it would be appropriate to design the main distribution headers to be installed in fully welded stainless steel. Connections off to individual heat exchanger coils can be made using flexible braided hoses as are currently used for modern chilled water systems. High pressure

compression fittings are commercially available with burst pressures up to 280 bar can be used to connect the evaporators to the main system.

The complete piping installation will be pressure tested with OFN prior to installation of the carbon dioxide evaporators with typically, 10% radiography of welds or as codes require. In the UK, all pressure systems above 0.5 barg must conform to the PED and be CE marked. This applies to all systems – water, glycol, HFC, ammonia and carbon dioxide. It is accepted that more expertise is necessary for the installation of the carbon dioxide piping than is traditionally used on chilled water systems.

Thermal insulation of piping can be carried out using commercially available materials in the same way as other heat transfer fluids.

### ***Heat Exchangers***

Various designs of evaporator have been used in volatile carbon dioxide systems. Standard copper tubing about one gauge higher than usual for water systems is extremely strong. Burst tests over 200 bar have been carried out on 11mm OD tubing.

Multiple evaporator systems will require orifices or capillary tubing to be fitted at each inlet pipe to ensure good distribution. This is a much simpler process than the use of balancing valves which require to be fitted and set up on chilled water systems to each heat exchanger to ensure even flow to each unit.

### **SAFETY ISSUES**

There are undoubted hazards associated with the adoption of carbon dioxide as a secondary refrigerant in the building services environment, however this is no different to other potentially hazardous systems already in buildings which have to be managed with care in design, installation and conformance with regulations.

### ***Pressure***

We are completely at ease with hydraulic systems operating at pressures measured in thousands of bar and indeed many of us do not think of the fact that every day we sit in our motor vehicles, which have high pressure fuel and oil systems no more than 1 metre away. Because carbon dioxide pressures are significantly higher than those typically used in the HVAC sector, this does not mean that this fluid is unsafe.

All components provided for the building services applications will be pressure tested and carry PED certification.

For small systems, a fade out pressure vessel can be installed to ensure that the complete carbon dioxide charge can be contained within the refrigeration circuit, in the vapour phase, even at standstill condition. For systems with a large distributed charge, such as in office buildings, a separate small refrigeration unit can be run to ensure the carbon dioxide is held in the liquid condition, even when the main plant is not operating. The system will be designed to vent carbon dioxide harmlessly to atmosphere if normal pressure limits are exceeded.

### ***Personnel***

Carbon dioxide is categorised by ASME/EN 378 as an A1 category refrigerant which is non-toxic and non-flammable. Nevertheless, like HFC and HCFC refrigerants, it is potentially hazardous when released in a confined space and displaces oxygen.

The consequences of inhalation in various concentrations for a healthy adult are as follows (Danfoss 2002):

<b>Carbon Dioxide Concentration</b>	<b>Symptoms associated with inhalation of air with increasing carbon dioxide concentrations</b>
2%	50% increase in respiration
3%	10 minute short term exposure limit
3%	100% increase in respiration
8%	Short term exposure limit
8-10%	Headache after 10 to 15 minutes. Dizziness, buzzing in ears, rising blood pressure and pulse rate, nausea.
10-18%	After a few minutes, cramps similar to epileptic fits, loss of consciousness. Victims recover quickly in fresh air.
18-20%	Symptoms similar to those of a stroke.

It is essential that in the application of carbon dioxide in the building services environment that the system and building are designed to minimise the potential for leakage and that the consequences of any leakage can be safely managed to protect the occupants.

Building insurers require that carbon dioxide systems be installed in conformity with the Pressure Systems Regulations with regular site inspections. Risk assessments must be carried for the proposed system, as is the case for ammonia plants and leak detection equipment must be fitted to provide warning to occupants in the event of a carbon dioxide release. Care must be taken in the routing of distribution piping and in particular, risers being ventilated to prevent the accumulation of carbon dioxide at the bottom of ducts. In comfort cooling applications in open plan offices, the carbon dioxide distribution mains require to have automatic valves on supply and return side to isolate zones of coolers which can be shut off by the leak detection system. After isolating the source of carbon dioxide, the gas would be safely dispersed by the building ventilation system.

Special care requires to be taken with regard to the use of carbon dioxide circuits in smaller rooms and basement areas to ensure any release can be safely dispersed.

### **SYSTEM COMPARISONS**

Two typical installations are considered in this paper:

- A) Large office complex with chilled beams
- B) Computer room cooling

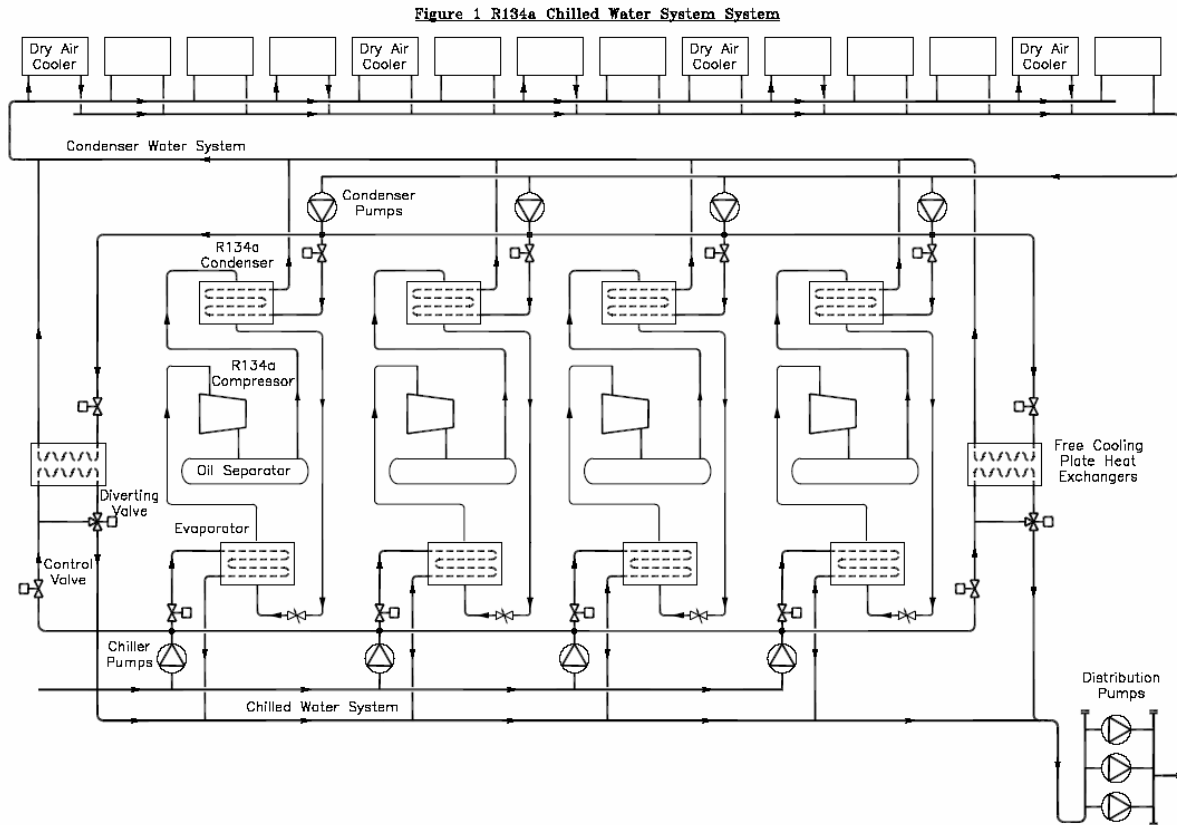
A) The first system under consideration is an actual office complex comprising 2 main loads:

- 2MW of office cooling using chilled beams with water temperatures 14 to 17 °C
- 1.9MW of air cooling during higher ambient conditions with water temperatures at 6 to 12°C.

The system arrangement (Figure 1) comprises:

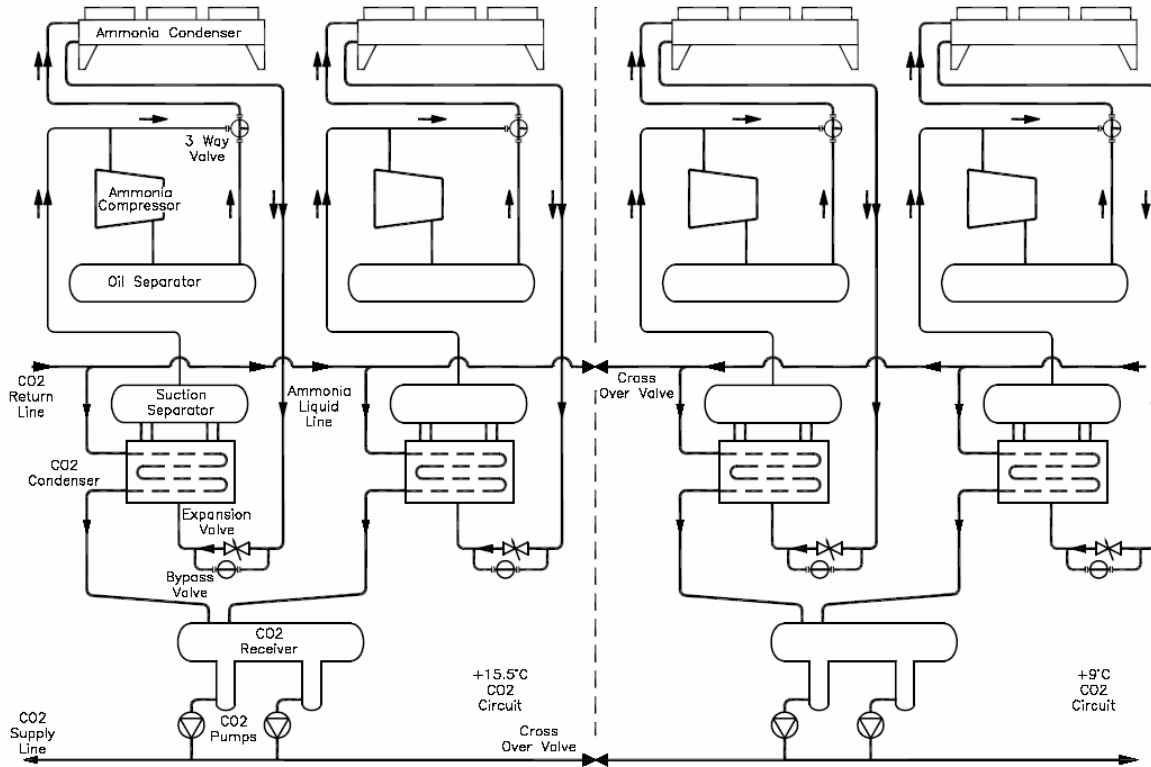
- 4 x 1300kW R134a chillers arranged in parallel
- 14 x dry air coolers to reject heat from the glycol cooled condensers

- 2 x 1MW plate heat exchangers to provide “free cooling” using dry air coolers when ambient temperature is below 10 °C with changeover valves
- 4 x condenser and 4 x chiller distribution pumps
- 3 x secondary distribution pumps and 12 x chilled beam circulating pumps
- Pipe headers diameters for the condensers (450mm), chiller headers (400mm) and secondary distribution piping from 350mm down to 15mm diameter for individual beams
- Glycol and water dosing, pressurisation, filtration and expansion systems
- System heat exchangers comprising chilled beams and air handling units



The alternative natural refrigerant solution is based on using ammonia packaged chillers condensing directly to atmosphere with a volatile secondary system instead of chilled water (Figure 2). By splitting the circuits to service the 2 temperature regimes and also setting the chillers to operate in a thermosyphon arrangement, significant running cost savings are achieved.

Figure 2 Ammonia/CO2 Volatile Secondary System



The following comparisons are relevant.

System	R134a / chilled water	Ammonia / Volatile carbon dioxide
Design evaporating temp. (°C)	2.5	5.5 and 12
Design condensing temp. (°C)	45	41
Compressor Coefficient of Performance	3.5	5.0 and 6.3
Distribution temperatures ((°C)	6 to 12 and 14 to 17	9 and 15.5
Condenser glycol circulation (kg/h)	950,000	None
Chilled fluid circulation (kg/h)	558,500 (water)	150,000 (carbon dioxide)
Annualised pumping power (kWh)	709,000	145,600
Annualised compressor power (kWh)	1,117,000	572,700
Annualised total power (kWh)	1,826,000	718,300
System Coeff. Of Performance	4.38	11.1
Annual operating cost (£)	£82,197	£32,323

Figures are based on £0.045/ kWh electrical tariff. Condenser/ dry air cooler figures have been omitted from the comparison as it is assumed systems loads are similar. The figures assume an annual cooling load of 8008MWh with the building load diminishing with reducing ambient air temperatures.

The comparison of pipework sizes is as follows:

System	R134a/ Chilled water	Ammonia/ Volatile carbon dioxide
Condenser heat rejection	1 x 450mm dia supply & return headers 14 x 150mm dia in & out connections	4 x 125mm dia discharge lines 4 x 50mm dia liquid line
Distribution headers	Primary water circuit 1 x 400mm dia supply and return lines Secondary water circuit 1 x 350mm dia supply and return lines	CO2 9°C circuit 1 x 125mm dia liquid line 1 x 150mm return line CO2 15.5°C circuit 1 x 125mm dia liquid line 1 x 200mm return line

The pipeworks systems in both cases reduce in size as the heat transfer fluid is distributed to the various loads throughout the main office complex.

The above tables show that the carbon dioxide system has significantly lower running costs due, in part, to the reduced quantity of secondary fluid being pumped and also as the result of more efficient ammonia compressors condensing directly to atmosphere. The extra water pumping power is also adding heat load to be extracted by the R134a chillers. In this case, “free cooling” using the thermosyphon principle is available at for longer periods in the year when ambients are below 14°C compared to the 10°C threshold for the R134a / chilled water system.

The maintenance costs for the carbon dioxide system will be lower based on less hours run by the plant, use of inexpensive refrigerants, no need for chemical dosing of water and glycol systems and reduced system complexity.

Generally, package chillers have an expected life of 10 to 15 years compared to 20 to 30 years for industrial refrigeration plant resulting in higher plant replacement costs for the R134a units.

The capital cost comparison is more complex. The ammonia chillers cost £540,000 compared to £340,000 for packaged chillers. The carbon dioxide receivers and pump skids are also expected around the same cost as the chilled water pumps, plate heat exchangers and ancillaries. However significant savings are anticipated in the cost of the carbon dioxide distribution system offsetting these differences to some extent.

In overall terms, the through life costs of the carbon dioxide installation will be lower and this is consistent with analysis carried out on another large system comparison between volatile carbon dioxide and glycol circuits for a chill distribution store in the UK (Pearson/Cable, 2003).

B) The problem of providing computer cooling using multiple rack units is becoming increasing acute. With computer power and heat outputs continuing to rise, the conventional method of ducting chilled air from floor grills to circulate around the racks has limited effectiveness.

Loss of cooling in this application can be expensive if server equipment is damaged through overheating. Worst still, the failure of IT equipment belonging to major financial institutions can be catastrophic and for this reason, cooling systems with high reliability and redundancy are usually deployed for this service.

Conventional water systems used to provide cooling to computer systems have limitations on the heat transfer available and can cause severe damage to this high value equipment in the event of leakage. The benefits of using carbon dioxide in this case are that high heat transfer coefficients are available using smaller heat exchanger surfaces and also carbon dioxide is not an electrical conductor which would damage the electronic circuits if released through component failure.

As rack server rooms are not usually occupied rooms, the consequences of an unexpected release of carbon dioxide are unlikely to be harmful to systems or personnel.

The result from preliminary work that has been conducted indicates that a high rate of heat extraction can be achieved using a volatile carbon dioxide system.

From these examples carbon dioxide offers:

- Simplified system design with no condenser glycol circuits
- Lower running costs and through life costs
- More free cooling potential due to higher evaporating temperatures
- More environmentally friendly solution and future proofing
- Longer system life using industrial components
- Smaller pipe line sizes and reduced pumping requirement
- Effective cooling of high heat loads

### **CONCLUSIONS**

1. The trend towards increasing use of natural refrigerant instead of synthetics in the building services industry will create new opportunities for the reintroduction of carbon dioxide.
2. Carbon dioxide offers benefits of smaller pipe sizes and reduced running costs compared to chilled water systems for large building comfort cooling applications. It can also be applied in specialist applications where use of water in close proximity to sensitive electrical equipment is undesirable.
3. Major equipment and components are now becoming commercially available to operate at the high system pressures required for volatile carbon dioxide services.
4. Close liaison is required between refrigeration engineers and building designers to ensure a safe, reliable and maintainable carbon dioxide installation.
5. In the medium to longer term, development of compressors which can operate at transcritical pressures will allow carbon dioxide to be used in smaller air conditioning applications currently handled by HFC direct expansion systems (Pearson, 2004).
6. There are companies with the requisite experience and knowledge who can now install these volatile secondary carbon dioxide systems in modern buildings.

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