

# Using CO<sub>2</sub> in Supermarkets

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The timing of supermarkets' transition from CFCs to HCFCs in the 1990s and then on to HFCs is location specific. For instance, the shift to HFCs came much later in North America than Europe. However, in parts of Scandinavia and Central Europe, carbon dioxide systems appeared in the early 1990s and became commonplace by 2000.

A trial installation constructed in 1991 in Kilmarnock, Scotland,<sup>1</sup> provided valuable learning experience, but the concept was shelved. One difficulty was the installation of site pipe work, which used compression fittings. The change in temperature from installation to operation was too great, so many of the fittings leaked when cold.

The installation used ammonia as the high side refrigerant of the cascade sys-

tem, but it was too small to be economical with ammonia. The plant was oversized using the smallest available ammonia screw compressor running at half speed. Carbon dioxide was condensed in the ammonia evaporator on the roof of the store and was pumped to display cabinets and cold storage rooms, with no compressor in the carbon dioxide circuit. This concept was published in patents in Great Britain, France, Germany and the United States,

but was not commercialized. The basic system is shown in the illustration from the patent (*Figure 1*).

Although the idea stalled in Britain, it was adopted in Sweden where it quickly gained acceptance.<sup>2</sup> Further installations followed in Norway, Denmark and Switzerland, giving these countries a leading position in the use of carbon dioxide. In Britain the search for alternatives to fluorocarbons continued with many alternatives tested, but none achieving general acceptance. Such systems included installations with ammonia chillers circulating

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glycol to the shop floor, and chillers with heat transfer fluids such as polydimethylsiloxane or potassium formate solution and water-cooled integral units with low charge propane plant. Meanwhile, the conversion from R-12 in North America was mainly to R-22 with some stores experimenting with glycol or the other heat transfer fluids.<sup>3</sup>

Scandinavia and Central Europe led the way on further development. In these systems carbon dioxide is compressed to a high pressure and rejects heat directly to ambient. The evaporating pressure is below the critical point, but the heat rejection stage is above it, so these are called transcritical systems. This requires a completely new way of thinking about equipment design and configuration even to the vocabulary used.<sup>4</sup> Transcritical operation presents some significant challenges to the system designer, and many system designs were produced to overcome them.

A great difficulty is that there is no scope for refrigerant inventory in the high-pressure side as the heat rejection is accomplished by gas cooling, not by condensation. Most designers incorporate a receiver somewhere on the low-pressure side, either as an intermediate flash tank part way through a two-stage expansion or as a suction trap after the evaporator.<sup>5</sup> The heat rejection side of the system must also be able to switch from operation as a gas cooler in higher ambient to operation as a more traditional condenser in colder weather to achieve best efficiency. The high operating pressure required does not present a problem, but if the design pressure for site installed pipe work is above 40 bar (580 psig), then brazed joints cannot be used due to the annealing effect of the brazing process on the copper tube.

Use of carbon dioxide has evolved into three distinct groups:

1. As a phase-changing secondary fluid for chiller and low-temperature applications;
2. In a cascade, where a carbon dioxide compressor raises the gas from low-temperature conditions up to an intermediate temperature and a separate refrigerating system provides the heat extraction from the carbon dioxide condenser; and
3. In a transcritical arrangement, where there is no need for an additional refrigerating system (as heat is rejected from the carbon dioxide to ambient in a supercritical gas cooler).

These systems are described in detail in a comprehensive review by Madsen<sup>6</sup> and are shown in *Figure 2*. To date, transcritical systems have been widely accepted in Europe, have

been used only in a small number of trial installations in Britain, and have not yet been deployed in North America.

Variants of each system exist, and sometimes they are used in combination. A cascade system for low-temperature cabinets might be coupled to a secondary system for the chill cases, or to a transcritical chill unit. Some novel approaches to pumping have also been used, such as a secondary system using subcooling of the high-stage liquid line to generate the driving force for the carbon dioxide liquid circulation without using a pump.<sup>7</sup>

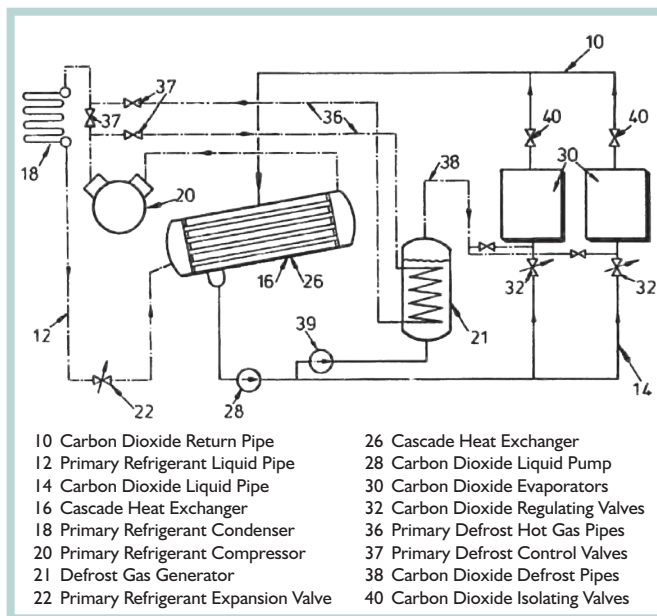
Secondary loops are the simplest to operate but are expensive to install, if the cost of the high-stage plant is included. However, installations that retain the existing system, and are reconfigured to work with an adjacent carbon dioxide pump set, offer a relatively low cost route into carbon dioxide use while the sales floor is being refurbished.

Cascade systems are more complex, but for low-temperature applications, a cascade plant will be cheaper than a secondary, which requires the primary refrigerant to run at very low temperature. Transcritical systems offer the lowest cost alternative, but the technology is generally viewed as too experimental in Britain and America, despite the hundreds of systems already in operation in Denmark, Sweden, Norway, Germany, Luxembourg, Belgium, Switzerland and Italy. Concerns are regularly voiced about the energy efficiency of these systems.

Madsen<sup>6</sup> showed that in Northern Europe air-cooled systems can be up to 5% more efficient, but in the south, there was a penalty of up to 5%. Adiabatic cooling has been used to overcome this.<sup>8</sup> Hybrid condensers or compact evaporative units offer further

improvement. It is also probable that greater use will be made of the high temperature water heating capability of transcritical units, offering a utility not currently available from standard supermarket packs.<sup>9</sup>

These systems share some common disadvantages. The design pressure of the low pressure side of the system is around 40 bar (580 psig) for chill and either 40 bar (580 psig) or 27 bar (390 psig) for low temperature. It is necessary to limit the pressure in the event of a prolonged plant stoppage. This might be a standby generator powering a small condensing unit, or a thermal storage tank somewhere in the system. Often, it was simply a pressure relief arrangement that would gradually blow the charge to atmosphere to provide the necessary cooling effect. This is acceptable when a refrigeration technician is on hand to recharge the system once power is restored, but once the systems



**Figure 1: Carbon dioxide as a secondary refrigerant.**



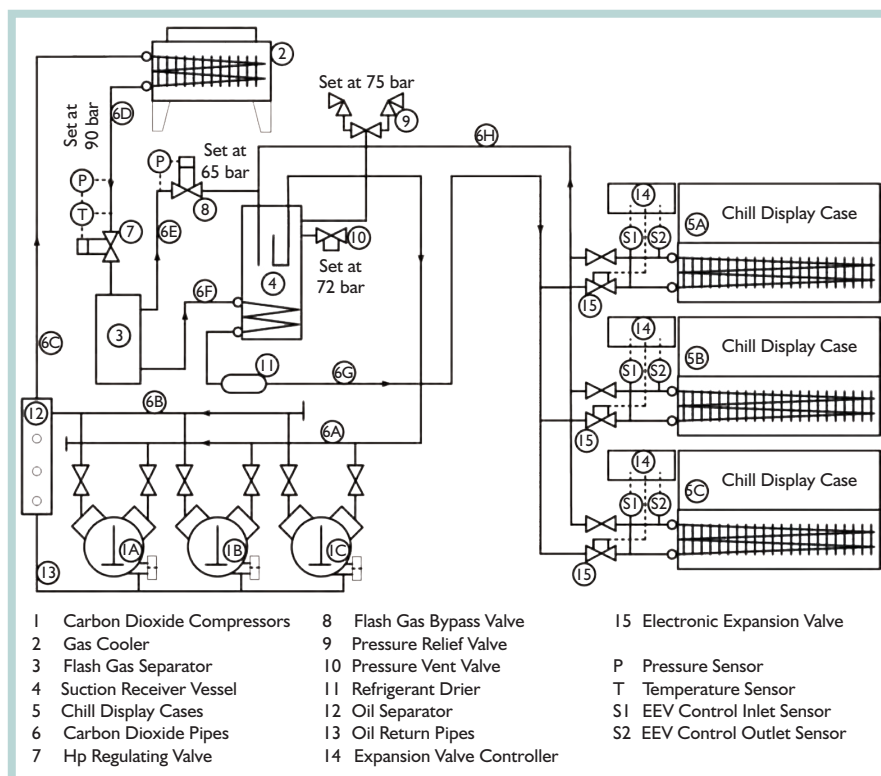
is a receiver on the high pressure side of the low-temperature packs, which also provides fade-out capability.

In warmer weather the chill plants will operate in transcritical mode, with the refrigerant flow from the gas cooler regulated by an expansion valve, which is set to maintain optimum compressor discharge pressure. The expanded refrigerant, a mixture of liquid and gas, passes through a gas separator to electronic expansion valves at each of the evaporators. The gas separator is a small in-line fitting. It does not have to separate all liquid out of the gas stream, but only to ensure that there is no gas in the liquid stream. The expansion valves at the evaporators are of a standard pulse-modulated type and use a standard controller, but with slightly different software. Whereas a normal controller is set to optimize superheat, with a minimum superheat value of 2 K (3.6°F), the revised software is configured to aim for a maximum value of 2 K (3.6°F). The evaporators are, on average, overfed with some liquid returning to the suction receiver. This, together with the small amount of liquid from the gas separator, provides the cooling for the gas cooler outlet. The result is that the enthalpy of the liquid fed to the expansion valves is as low as possible, the evaporator surface is more effectively used and the suction pressure can be a few degrees higher as there is no need for superheat at the evaporator outlet.

When the weather is colder the main expansion valve drives wide open, allowing the compressor discharge gas to condense in the gas cooler. The condensed liquid is fed at higher pressure to the case expansion valves, which operate in the same control mode as before. Although the evaporators are always flooded, and return some liquid in the suction line, the compressors are protected by the suction receiver, which is large enough to act as a liquid separator. A patent application for the design of the chill system was submitted in February 2009. *Figure 3*, from the patent application, shows the schematic circuit of the system.

The low-temperature packs also have three semihermetic compressors, operating sub-critically with a constant discharge pressure of about 35 bar (about 500 psig). The evaporating condition is about 15 bar (about 220 psig). The three brazed plate condensers are controlled using pulse modulated electronic expansion valves. If one of the condensers fails the discharge pressure only has to rise by 2 K (3.6°F) for the other units to carry the full load, giving maximum resilience on the low-temperature side. One of the compressors on each pack is speed controlled and the other two are fixed speed.

The pack capacity is controlled by an industry-standard system, which also provides a graphic user interface for the system.



*Figure 3: Transcritical supermarket system, from patent application, 2010.*

The control is modular, so that failure of any one component does not prevent the rest of the system from running.

A test unit was constructed in Derby, England late in 2008 and has provided stable and reliable operation since then. This system has six chill cases and three low-temperature cabinets, representing about one-third of the capacity of the standard packs. This means that it is not possible to give reliable performance figures for the design concept as it is only lightly loaded, but the control philosophy and evaporator performance are meeting the design intent, and it is expected that overall running costs (without allowing for any heat recovery) will be up to 10% lower than a typical HFC system. The test unit for the chill system is shown in *Photo 1*.

The major challenges in constructing the test unit were to find control components suitable for the design pressure of 75 bar (1100 psig) and to install a suitably rated piping system. Components including the expansion valves were adapted to meet the pressure requirement, and operated satisfactorily throughout the test. The piping was installed using a permanent type of compression fitting capable of withstanding over 100 bar (1450 psig). The joints can be made as quickly as a brazed joint, and unlike the joints used in 1991 there were no leaks when the piping was down to temperature. A section through one of the fittings is shown in *Photo 2*. A modest investment in tooling is required, but this can be reused many times, so the cost per project is not significant.

The first two supermarkets were equipped with the new system at the end of 2009. Early indications are that the predicted performance improvement over more conventional transcritical



	Chill Cases	Frozen Cases
<b>Secondary System</b>	Cheapest and simplest option if existing high side equipment is reused. Can be as efficient as existing HFC systems.	Expensive and less efficient than other CO <sub>2</sub> options, but easier to install. Simplest system to service and maintain.
<b>Cascade System</b>	Not used for chill systems.	Requires 40 bar (580 psig) compressor and condenser. Can be served by any high side equipment (HFC, glycol, HC, ammonia or transcritical CO <sub>2</sub> ).
<b>Transcritical System</b>	Cheapest option for new installations or if all existing equipment is to be replaced. Less familiar for service and maintenance. Requires higher pressure components. There is scope for further improvements in gas cooling techniques, capacity and efficiency.	Can be the low stage of a two-stage system, or served by a separate cascade plant. This requires an extra heat exchanger, but gives the benefit of higher reliability. Each low-stage pack can be served by several high-stage packs in parallel, giving further reliability.

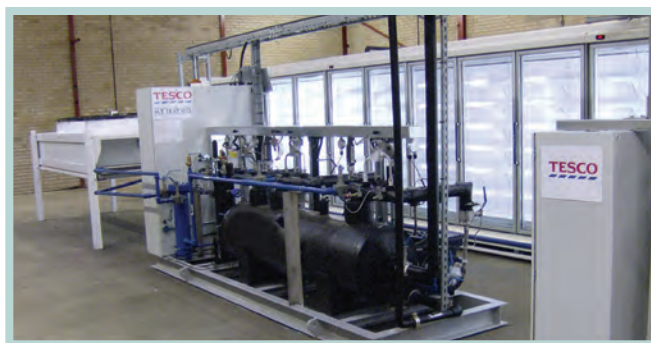
**Table 1: Summary of secondary, cascade and transcritical systems used for chill and frozen cases.**

designs is being achieved, with the saturated suction temperature of the chill cases about 7 K (12.6°F) higher than the conventional designs. This suggests that the annual energy consumption will be about 20% less than for other CO<sub>2</sub> transcritical systems. Further development is planned, including testing scroll compressors for the low-temperature packs and incorporating the parallel compression method of economizing to the chill packs to provide increased capacity and improved efficiency. Although initially there will be a premium on the capital cost of about 40% compared to conventional systems, the supermarket aims to achieve cost parity within 18 months. The initial additional cost will be recouped through improved efficiency and reduced repair costs (including the cost of replacement refrigerant) in less than three years. (The system types are summarized in Table 1.)

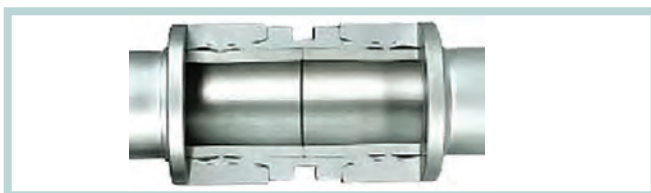
The majority of supermarkets around the world do not use carbon dioxide, but the transition from HFCs is gathering pace. Most users who decide to adopt carbon dioxide choose to implement a combination of secondary and cascade systems, but continued development of products and system design for transcritical plants make CO<sub>2</sub> an increasingly attractive option. Transcritical plants probably will become the norm for European supermarkets within five years, and North America will not be far behind. This transition may be faster if additional restrictions on the use of HFCs are introduced, or if the price of HFCs is raised significantly through taxation or reduced production quotas.

The only development likely to stop this progress is the introduction of a new fluorocarbon that is suitable as a replacement for R-404A in large commercial systems, and offers low global warming potential and better efficiency. However, no such product is close to being placed on the market.

If carbon dioxide system cost cannot be reduced, then the progress will be slower, but higher capital cost will not stop the transition, only slow it down. Higher energy costs will tend to encourage the adoption of carbon dioxide, perhaps in more highly integrated systems that offer heat recovery for on-site or neighborhood use. The widely held belief that carbon dioxide systems are inherently less efficient than typical HFC installations will be shown to be false as system designers become more familiar with the techniques required to optimize systems.



**Photo 1: Transcritical chill unit on test, Derby, England.**



**Photo 2: Section of compression fitting.**

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