R-22 is a hard act to follow. Significant disadvantages are associated with all possible substitutes. Some provide less capacity, some have lower critical temperatures (and will tend to be less efficient in use), some have higher global warming potentials (GWPs), some are flammable, some are toxic, and some are inherently expensive to produce.

Ammonia can be applied to any type and size of refrigeration system from domestic refrigeration to commercial refrigeration and air-conditioning to industrial refrigeration. However, it is desirable to minimize the charge to prevent toxic effects and, sometimes to use secondary refrigerants, such as volatile carbon dioxide, to keep ammonia away from the general public.

This article describes a method by which the toxic refrigerant ammonia can be used in low-charge automatic systems with maximum efficiency and minimum risk.

Possible Alternatives to R-22

Phaseout of R-22 is taking place under the Montreal Protocol because R-22 contains chlorine, which can damage the ozone layer. However, the ozone depletion potential (ODP) of R-22 is only 0.055, which probably would not have had significant long-term effects on the ozone layer if R-22 had been effectively confined within the systems in which it is used. The main damage to the atmosphere associated with R-22 has resulted from a by-product of the production of R-22, namely R-23, which has a very high GWP of 12,000. Recently, responsible producers of R-22 have been destroying their unwanted R-23, but in the past much of it was vented to atmosphere.

Some hydrocarbons are good substitutes for R-22, but for code and safety reasons they should be limited to small, fully sealed systems.

A recently promoted family of refrigerants, the hydrofluoroolefins (HFOs), has zero ODP and very low GWP. However, these refrigerants are not yet in full

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commercial production, and they will be very expensive to produce. It is unlikely that HFOs will develop into universal replacements for the once ubiquitous R-22.

Carbon dioxide has been used in European supermarkets to a significant extent, but it is inherently inefficient in use compared to R-22 except when used in cascade with another refrigerant. Subcritical carbon dioxide systems are less efficient than ammonia systems, and transcritical systems are even less efficient. It will be difficult to justify the use of carbon dioxide as a general substitute for R-22 except in cool and temperate regions.

Table 1 compares some physical properties of R-22 with properties of other refrigerants that might be considered as a substitute. All the refrigerants in the table are non-flammable except for ammonia, which has a minimal fire risk when used in small systems. R-23 is included for comparison although it would not be a credible substitute.

The table shows that ammonia (R-717) is the only substitute for R-22, having zero GWP. Ammonia also has a high critical temperature that tends to make systems using ammonia more efficient than systems using other refrigerants. Despite their very different properties, the volumes of vapor to be pumped to produce similar amounts of refrigeration are similar for ammonia and for R-22. This is not the case with the widely used R-134a that requires about 30% more swept volume and has significant global warming potential.

**Challenges Presented by Ammonia**

The main challenge presented by ammonia when used as a refrigerant is its acute toxicity. Ammonia has a good safety record in refrigeration. This is largely because of adherence to well-established codes and practices, and because ammonia vapor in the atmosphere becomes very unpleasant at concentrations on the order of 25 ppm, whereas it does not become lethal until concentrations of more than 1,000 ppm are reached. However, the unpleasant smell of ammonia could cause panic within an occupied space and ammonia systems should be kept well away from the general public.

Ammonia does not present a major fire hazard, even in larger systems, because it is difficult to ignite and will not sustain combustion. However, precautions must be taken if the charge of ammonia is sufficient to produce flammable proportions in the air within any space into which the refrigerant might leak. If the charge is small and the high-pressure side of the ammonia system is effectively in the open air, then it usually will be found that risk of fire due to ammonia leakage is negligible.

Ammonia has a great affinity for water. An ammonia system contaminated with water will not freeze up as a halocarbon system would do under similar circumstances. However, this is a rather mixed blessing. Most ammonia refrigerating systems are contaminated with water to an extent that would be unacceptable in a halocarbon system. The drawback of having water present within an ammonia system is that it tends to concentrate in the low-pressure side of the system, where it may form sludge with lubricating oil, and it will interfere with the operation of any conventional thermostatic expansion valve. Thermostatic expansion valves are unpopular with practical ammonia engineers and for good reason. The valves tend to demand continual adjustment to compensate for the effects of water, with the result that the superheat is set to such a low value that systems flood over and damage the compressor.

Ammonia is incompatible with copper and zinc. This rules out the use of brazed copper tubing, which is cheap to install and is reliable in operation. Larger ammonia systems tend to use welded steel piping, which is more expensive to install and is much less convenient. Smaller ammonia systems could use aluminum or stainless steel pipe with special fittings that could eliminate site welding. Such fittings are already in use for carbon dioxide systems in supermarkets.

It is technically feasible to produce hermetic or semi-hermetic compressors for use with ammonia but, at present, only a few are available. It remains to be seen whether small, sealed, compressors will be developed for use with ammonia.

By coincidence, a refrigerating system was developed in 1972 that allows the challenges of applying ammonia to small refrigerating systems to be overcome.1

**Low-Pressure Receiver System**

The low-pressure receiver system (LPR) comprises a circuit that drains the condenser under some form of automatic control and feeds all refrigerant flow through the expansion device to the evaporator from which it returns to the compressor via a suction trap associated with a heat exchanger that subcools high-pressure liquid by heat exchange with low-pressure liquid collecting in the bottom of the suction trap. By this means the evaporator is slightly overfed with refrigerant while the compressor is completely protected against liquid flood back.

Figure 1 is a simplified version of the circuit with a Mollier diagram of the system, which is self balancing. It can be shown that the amount of overfeed is a function of the heat exchanger surface, the latent heat of the refrigerant and the condensing and evaporating temperatures.2

In an ideal world, the overfeeding of the evaporator would produce high heat transfer coefficients without requiring the high-temperature differences required for stable operation of a thermostatic expansion valve as in a conventional system.
Unfortunately, when applying the low-pressure receiver to ammonia systems, the situation is far from ideal. Properties of ammonia result in low mass flow, low vapor fraction by mass and very low density of the vapor fraction. The result is a tendency to produce, in the tubes of an air-cooling evaporator, stratified flow that persists throughout the evaporator because there is not sufficient evaporation to get the vapor velocity high enough to break up the stratified flow.

This tendency was exacerbated when tube material of low conductivity, such as stainless steel was used. The challenge was overcome by substituting aluminum for stainless steel in the cooler. Figure 2 shows the relative proportions of stainless steel tubing and of aluminum that were used in comparative tests under practical conditions in an operating cold store. The figure also illustrates the type of stratified flow that can be experienced.

Performance of the aluminum cooler was also improved by treating the internal surface of the tube to promote “wicking” as is done in heat pipes.

Site testing of the coolers indicated that overall performance of the treated aluminum cooler was at least twice as good as that of a comparable stainless steel cooler, and that performance of the aluminum cooler was less dependent on internal velocity than was the performance of the stainless steel cooler.

Figure 3 shows the performance of the coolers at varying heat flux. It can be seen that, under low flux conditions, the overall heat transfer coefficient related to the outside surface of the cooler is about 1.3 Btu/h·ft²·°F (7.4 W/m²·K) whereas the coefficient for the treated stainless steel cooler is about 3.7 Btu/h·ft²·°F (21 W/m²·K).³ The apparent decrease in heat transfer coefficient with increasing heat flux in the aluminum cooler may be a pressure effect, but it is more likely that heat transfer coefficient is more or less independent of heat flux in this design of cooler.

These figures mask a remarkable difference. If the cooler dimensions and calculated outside coefficient of heat transfer are used to infer the internal coefficient of heat transfer, it is found that the calculated internal coefficient for the stainless steel cooler is only 31.8 Btu/h·ft²·°F (181 W/m²·K) whereas the internal coefficient in the aluminum cooler is 220.1 (1250 W/m²·K). It was concluded from these figures that the internal surface of the stainless steel tube was only wetted to an extent of about 15%. Photo 1 shows an aluminum cooler with cross-over connections for use in a cold store.

Changing to the use of treated aluminum coolers in ammonia low-pressure receiver systems was a significant breakthrough.
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Ammonia LPR systems have now been successfully applied to continuous air-blast freezing systems and to low-temperature cold stores with economized screw compressors where it had not previously been possible to take full advantage of the economizing.

Photo 1 shows a low-temperature cold store for frozen foods with an external machinery room containing ammonia low-pressure receiver systems.

Ammonia LPR With Treated Aluminum Air Coolers

The system operates with minimum possible refrigerant charge because the high-pressure side is drained of liquid refrigerant, the “liquid” line to the evaporator contains flash gas, the wet suction line contains only a small percentage of liquid, and the evaporator also contains the smallest amount of liquid that is required to wet the treated tubes.

The system operates with minimum possible pressure drop through the evaporator and in the wet return line. Evaporators operate efficiently at a minimum temperature difference because there is no need to produce a superheat signal for a thermostatic expansion valve, which is not required for this type of system.

Unlike other direct expansion systems, the LPR system is tolerant of small quantities of water that tend to remain in the LPR and do not interfere with the operation of the expansion device. A low, the system, provided that it is not overcharged, gives complete protection against flood back to the compressor.

The system lends itself to application of reversed cycle defrosting (Figure 1), which, for a variety of reasons, has proved to be significantly more efficient than the so-called hot gas defrosting method. And, the system can be constructed so that all valves and controls are on the packaged unit, reducing risk of leakage in the vicinity of the evaporator.

The system can be designed for automatic return of oil to the compressor, eliminating risk associated with oil drainage. And, it can be applied to very small installations although, so far, most applications have been to medium-sized plants.

Limitations of the Ammonia LPR System

Because it is an essentially high-pressure float controlled system, it is not well suited to refrigeration from a central machinery room, providing refrigeration to multiple and diverse refrigeration loads. However, it is practical to provide refrigeration to up to four similar evaporators. In practice, a cold store requiring four coolers would normally be served by two independent LPR systems, limiting the charge per system and increasing reliability.

The LPR system requires very good distribution to the individual circuits of coolers because the amount of overfeed produced is usually less than 10%. Conventional liquid distributors do not work sufficiently well because of the volumes of flash gas in the liquid line. Special distributors that work on a gravity principle have been developed.

Four-port reversing valves have been developed for defrosting. Conventional slide valves do not withstand ammonia and are too sensitive to dirt to withstand conditions often (regrettably) found within ammonia systems.

LPR systems are not well suited to applications such as vertical plate freezers, where heat transfer rates are very high and load varies significantly during the freezing cycle. In practice, because of their simplicity and robustness, LPR systems have been used on fishing vessels, but freezing times were more than 10% greater than times that could be achieved using pumped circulation. The extended freezing time was considered to be caused by lack of refrigeration during pull down.

Applications of Small LPR Systems

There is no lower limit to the size of system that can be refrigerated using the LPR. However, where refrigerant charges are very small it can be more convenient to use flammable hydrocarbon refrigerants, as can be seen with domestic refrigerators. If the charge is small enough and if the refrigerator does not provide possible sources of ignition, risk of fire caused by refrigerant leakage is negligible. About 80 million domestic refrigerators worldwide use R-600a (isobutane). Incidence of fires caused by domestic refrigerators does not seem to have increased.

There will always be applications that are best served by non-toxic refrigerants that do not cause an alarm when they leak. Such applications include window air conditioners and systems to provide cooling where the general public may be present or where those present are restricted in their ability to move as in a hospital or in a prison. However, there are many applications where the fully automatic, low charge, ammonia LPR system will prove to be the most efficient and reliable choice. Such systems include cold stores, freezers and chillers of various kinds.

The high-pressure side of the system should be in the open air or in a special machinery room. Air-cooled systems using small screw compressors are well suited to the new LPR design because the single-stage screw compressor can be economized and the high critical temperature of ammonia provides
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higher efficiency than could be achieved at high condensing temperatures using halocarbon refrigerants. Using screw compressors avoids problems of high discharge temperature, which would occur were ammonia to be used with reciprocating compressors in an air-cooled system.

Fatalities caused by leaks of halocarbon refrigerants worldwide seem to be greater than fatalities caused by leaks of ammonia. In both cases, the rates are lower than the risk of being killed by a lightning strike. In the case of fatalities caused by leakage of ammonia from refrigerating systems, these usually occur within a few meters of the leaking machinery and almost invariably affect an individual working on the system. Bystanders and members of the public are not involved.4

It would be almost impossible to cause a fatal poisoning within a cold store refrigerated by a low-charge ammonia LPR system. Even if the whole charge were to be vented into the cold store from the coolers it would take a long time before concentrations within the cold store reached dangerous levels. Long before dangerous levels were reached, anyone who had been working in the cold store would have been forced to leave because of the unpleasant smell of ammonia. Ammonia vapor in the air becomes intolerable at levels between 25 and 35 ppm (v), but it is not lethal until concentrations well over 1,000 ppm (v).

Designs of cold stores and freezers need an arrangement where the packaged LPR system, including the air cooled condenser, is placed outside the insulated structure but close to the air coolers. Preferred location would be on the cold store roof adjacent to a pent-house for the coolers, but it's also possible to site the packaged unit beside the wall of the cold store close to the coolers.

A simpler version of the LPR system has been devised for small systems to reduce cost and improve reliability (Figure 4). Instead of an expansion valve remotely controlled from a float at the condenser outlet the system is fitted with two short-tube expansion devices, one drawing from the high-pressure region at the top of the heat exchanger and one drawing from the high-pressure region in the lower part of the heat exchanger.

The system works as a level control because this type of orifice is capable of passing a much greater mass flow of subcooled liquid than of wet vapor under a similar pressure difference. Assuming that the orifices together are capable of passing more subcooled liquid than required by the refrigerating system but that the lower orifice is sized to pass rather less than is required, the liquid level will rise in the heat exchanger until the upper orifice passes the required balancing amount. Liquid level in the heat exchanger will
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fluctuate about the level of the upper orifice, producing a level control effect. The mass flow of vapor passing through the upper orifice will be negligible compared to the combined mass flow of liquid.

Payne and O’Neal \(^5\) carried out experiments on mass flow of several refrigerants through short tube orifices in 2004 and produced empirical formulae that matched the data.

Sandy Small of Glasgow used their empirical equations to estimate orifice performance of the environment-friendly refrigerants R-717 (ammonia), R-152a, R-1234ze (E), R-1234yf, R-290 (propane) and R-747 (carbon dioxide).

Figure 4 shows the calculated mass flow of ammonia through an orifice 0.08 in. (2 mm) in diameter and 0.5 in. (12 mm) in length when condensing temperature is 113°F (45°C) under varying inlet conditions from dry saturated to 45°F (25 K) subcooled. It can be seen that mass flow is very dependent on inlet condition, indicating that the proposed method of control is feasible.

A further advantage of the simplified system is that refrigerant charge is even further reduced because the liquid line between the condenser and heat exchanger is drained.

Conclusions
There would appear to be an opportunity to replace R-22 systems in certain applications with well-tried low-charge ammonia systems that could be fully automatic and even more efficient than the systems being replaced. The best alternative refrigerant, apart from ammonia, would appear to be R-410A (Table 1). However, it has a much lower critical temperature, which means it cannot match efficiencies achieved by ammonia systems.

References
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