Chapter 10:

Refrigeration Cycles

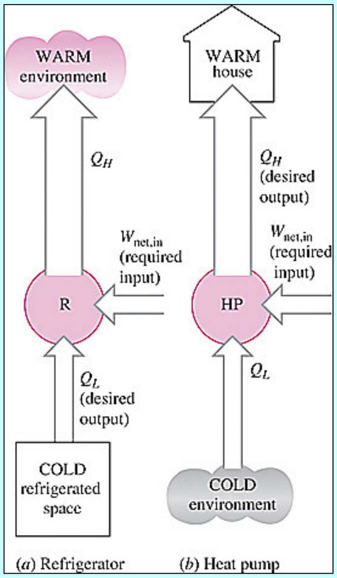
REFRIGERATORS AND HEAT PUMPS

- The transfer of heat from a low-temperature region to a high-temperature one requires special devices called **refrigerators**.
- Refrigerators are cyclic devices, and the working fluids used in the refrigeration cycles are called **refrigerants**.
- Another device that transfers heat from a low-temperature medium to a high-temperature one is the **heat pump**.
- The performance of refrigerators and heat pumps is expressed in terms of the **coefficient of performance** (COP), defined as:

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}}$$

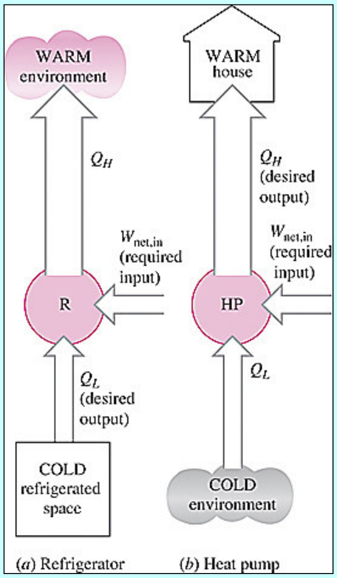
$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = COP_R + 1$$



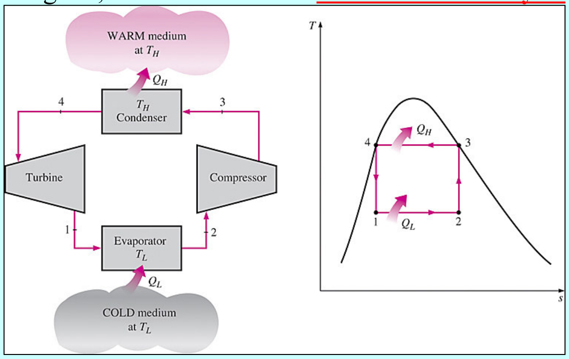
REFRIGERATORS AND HEAT PUMPS

- The *cooling capacity* of a refrigeration system—that is, the rate of heat removal from the refrigerated space—is often expressed in terms of **tons of refrigeration.**
- The capacity of a refrigeration system that can freeze 1 ton (2000 lbm) of liquid water at 0°C (32°F) into ice at 0°C in 24 h is said to be 1 ton.
- One ton of refrigeration is equivalent to 211 kJ/min or 200 Btu/min.
- The cooling load of a typical 200-m^2 residence is in the 3-ton (10-kW) range.



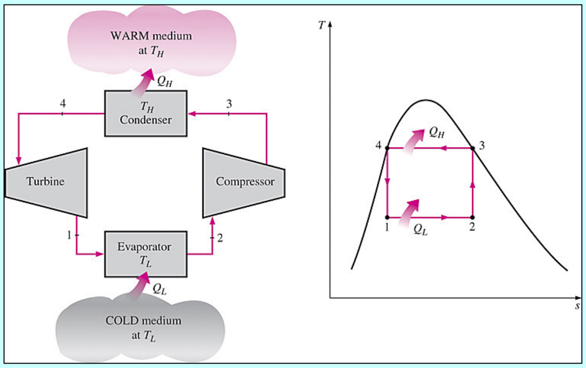
THE REVERSED CARNOT CYCLE

- Since Carnot cycle is a reversible cycle, all four processes that comprise the Carnot cycle can be reversed.
- Reversing the cycle does also reverse the directions of any heat and work interactions.
- The result is a cycle that operates in the counterclockwise direction on a *T-s* diagram, which is called the **reversed Carnot cycle.**



THE REVERSED CARNOT CYCLE

- The reversed Carnot cycle is the *most efficient* refrigeration cycle operating between two specified temperature levels.
- However, processes 2-3 and 4-1 cannot be approximated closely in practice. This is because process 2-3 involves the compression of a liquid–vapor mixture, which requires a compressor that will handle two phases, and process 4-1 involves the expansion of high-moisture-content refrigerant in a turbine.



Therefore, we conclude that the reversed Carnot cycle cannot be approximated in actual devices and is not a realistic model for refrigeration cycles.

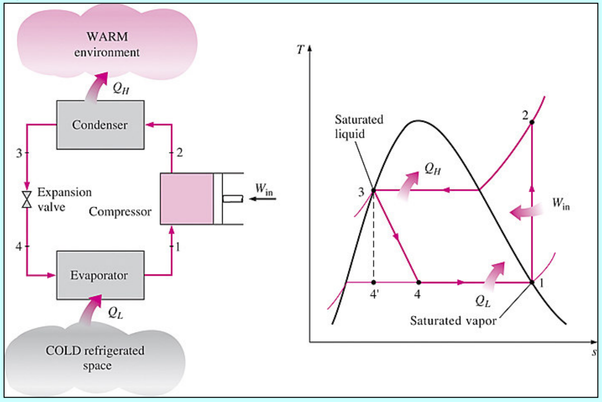
THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

- Many of the impracticalities associated with the reversed Carnot cycle can be eliminated by vaporizing the refrigerant completely before it is compressed and by replacing the turbine with a throttling device, such as an expansion valve or capillary tube.
- The cycle that results is called the **ideal vapor-compression refrigeration cycle**, and it is shown schematically and on a *T-s* diagram.
- The vapor-compression refrigeration cycle is the most widely used cycle for refrigerators, air-conditioning systems, and heat pumps.
- It consists of four processes:
  - 1-2 Isentropic compression in a compressor
  - 2-3 Constant-pressure heat rejection in a condenser
  - 3-4 Throttling in an expansion device
  - 4-1 Constant-pressure heat absorption in an evaporator.

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

The refrigerant enters the compressor at state 1 as saturated vapor and is compressed isentropically to the condenser pressure. The temperature of the refrigerant increases during this isentropic compression process to well above the temperature of the surrounding medium.

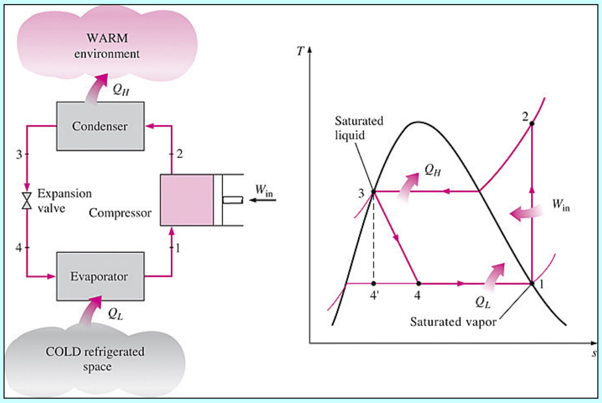
The refrigerant then enters the condenser as superheated vapor at state 2 and leaves as saturated liquid at state 3 as a result of heat rejection to the surroundings.
The temperature of the refrigerant at this state is still above the temperature of the surroundings.



THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

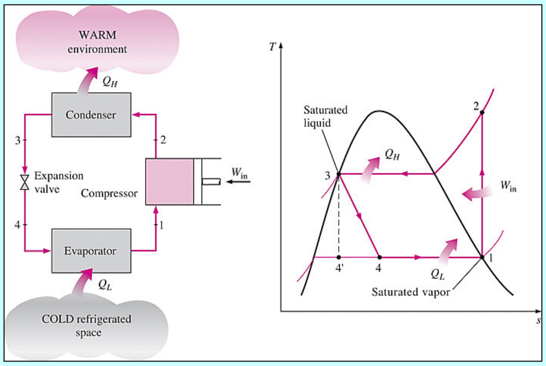
The saturated liquid refrigerant at state 3 is throttled to the evaporator pressure by passing it through an expansion valve or capillary tube. The temperature of the refrigerant drops below the temperature of the refrigerated space during this process.

The refrigerant enters the evaporator at state 4 as a low-quality saturated mixture, and it completely evaporates by absorbing heat from the refrigerated space.
The refrigerant leaves the evaporator as saturated vapor and reenters the compressor, completing the cycle.



THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

Notice that unlike the ideal cycles discussed before, the ideal vapor compression refrigeration cycle is not an internally reversible cycle since it involves an irreversible (throttling) process. This process is maintained in the cycle to make it a more realistic model for the actual vapor-compression refrigeration cycle. If the throttling device were replaced by an isentropic turbine, the refrigerant would enter the evaporator at state 4' instead of state 4.

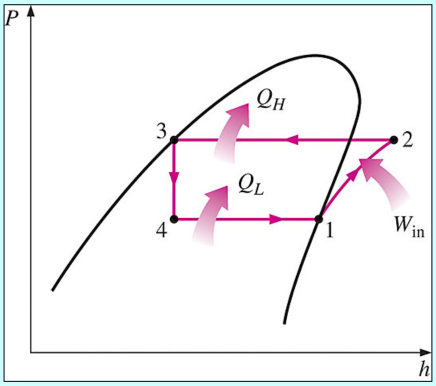


As a result, the refrigeration capacity would increase (by the area under process curve 4'-4) and the net work input would decrease (by the amount of work output of the turbine). Replacing the expansion valve by a turbine is not practical, however, since the added benefits cannot justify the added cost and complexity.

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

Another diagram frequently used in the analysis of vapor-compression refrigeration cycles is the *P-h* diagram, as shown.

The area under the process curve 4-1 represents the heat absorbed by the refrigerant in the evaporator, and the area under the process curve 2-3 represents the heat rejected in the condenser.



On this diagram, three of the four processes appear as straight lines, and the heat transfer in the condenser and the evaporator is proportional to the lengths of the corresponding process curves.

A rule of thumb is that the *COP improves by 2 to 4 percent for each °C the evaporating temperature is raised or the condensing temperature is lowered.*

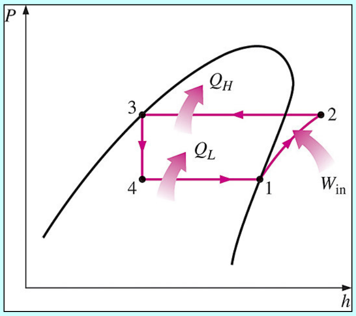
THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

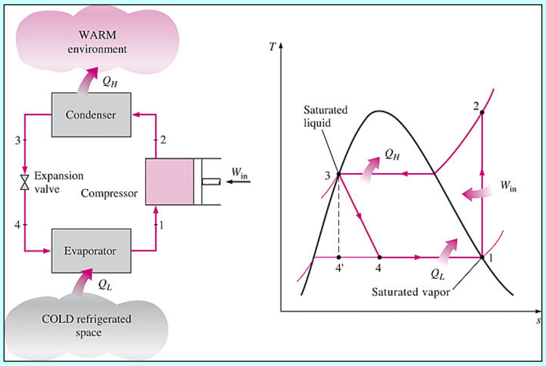
$Compressor\ (s = const.)$ $\quad w_{in} = h_2 - h_1$

$Condenser\ (P = const.)$ $\quad q_H = h_2 - h_3$

$Throttle\ Valve\ (\Delta s > 0)$ $\quad h_4 = h_3$

$Evaporator\ (P = const.)$ $\quad q_L = h_1 - h_4$





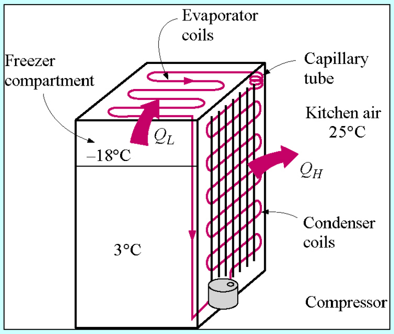
$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

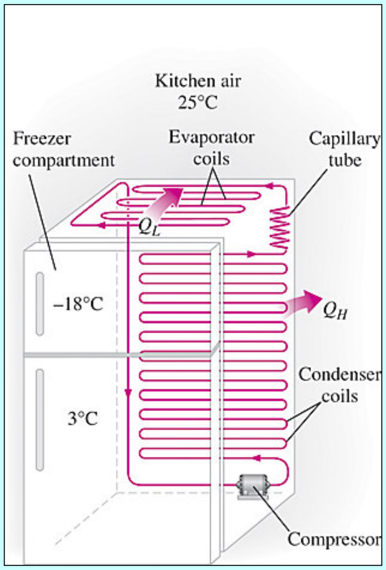
$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

In a household refrigerator, the tubes in the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator.

The coils behind the refrigerator, where heat is dissipated to the kitchen air, serve as the condenser.





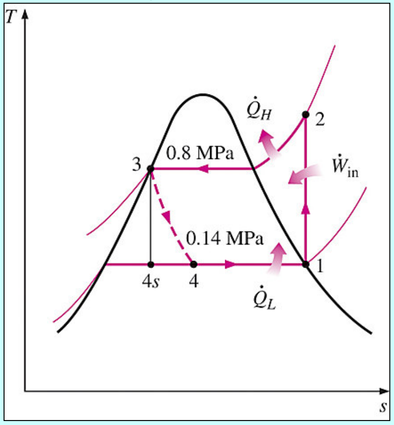
EXAMPLE 10–1

The Ideal Vapor-Compression Refrigeration Cycle

- A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.14 and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine:
- (*a*) the rate of heat removal from the refrigerated space and the power input to the compressor,
- (*b*) the rate of heat rejection to the environment, and
- (*c*) the COP of the refrigerator.

$$\text{COP}_R = 3.9$$

- That is, this refrigerator removes about 4 units of thermal energy from the refrigerated space for each unit of electric energy it consumes.

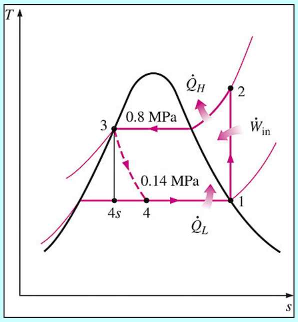


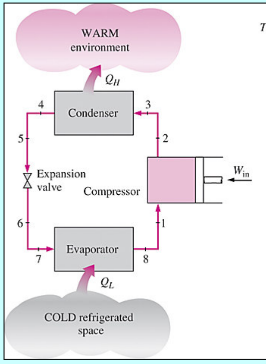
THE ACTUAL VAPOR-COMPRESSION REFRIGERATION CYCLE

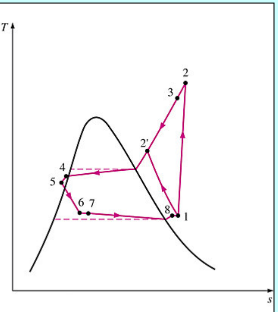
An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the irreversibilities that occur in various components.

Two common sources of irreversibilities are fluid friction (causes pressure drops) and heat transfer to or from the surroundings.

The *T-s* diagram of an actual vapor-compression refrigeration cycle is shown.

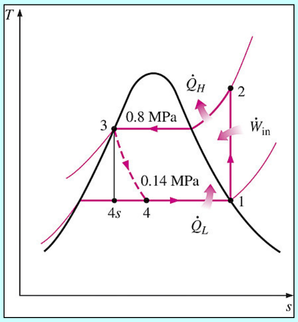


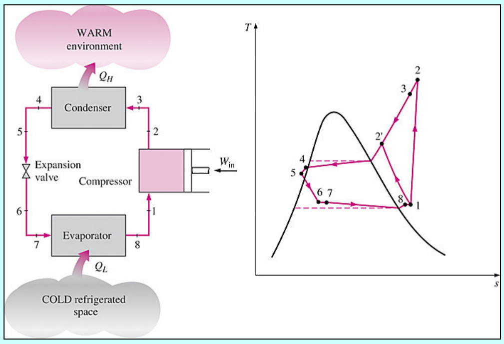




THE ACTUAL REFRIGERATION CYCLE

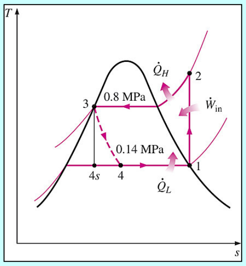
In the ideal cycle, the refrigerant leaves the evaporator and enters the compressor as *saturated vapor*. In practice, however, it may not be possible to control the state of the refrigerant so precisely. Instead, it is easier to design the system so that the refrigerant is slightly superheated at the compressor inlet. This slight overdesign ensures that the refrigerant is completely vaporized when it enters the compressor. The result of superheating and pressure drops in the evaporator and the connecting line is an increase in the specific volume, thus an increase in the power input requirements to the compressor.

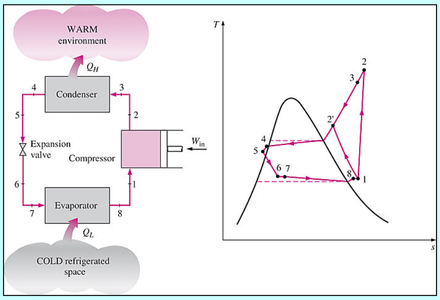




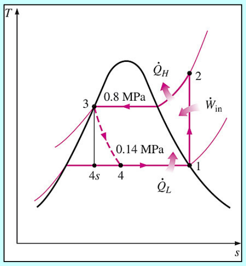
THE ACTUAL REFRIGERATION CYCLE

The *compression process* in the ideal cycle is internally reversible and adiabatic, and thus isentropic. The actual compression process, however, involves frictional effects, which increase the entropy, and heat transfer, which may increase or decrease the entropy, depending on the direction. Therefore, the entropy of the refrigerant may increase (process 1-2) or decrease (process 1-2') during an actual compression process, depending on which effects dominate. The compression process 1-2' may be even more desirable than the isentropic compression process since the specific volume of the refrigerant and thus the work input requirement are smaller in this case. Therefore, the refrigerant should be cooled during the compression process whenever it is practical and economical to do so.

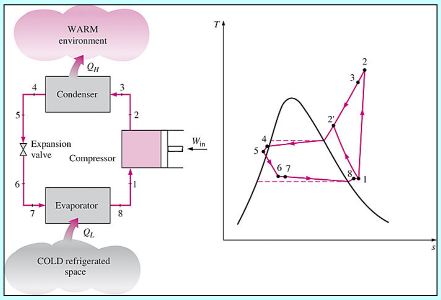




THE ACTUAL REFRIGERATION CYCLE



In the ideal case, the refrigerant is assumed to leave the condenser as *saturated liquid* at the compressor exit pressure. In reality, however, it is unavoidable to have some pressure drop in the condenser as well as in the lines connecting the condenser to the compressor and to the throttling valve. Also, it is not easy to execute the condensation process with such precision that the refrigerant is a saturated liquid at the end, and it is undesirable to route the refrigerant to the throttling valve before the refrigerant is completely condensed.

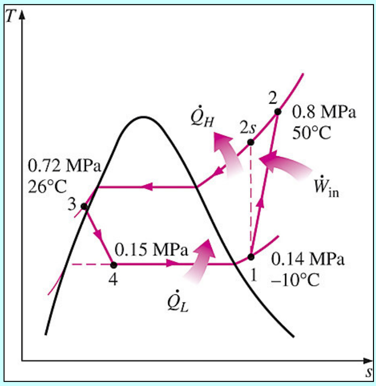


Therefore, the refrigerant is subcooled somewhat before it enters the throttling valve. We do not mind this at all, however, since the refrigerant in this case enters the evaporator with a lower enthalpy and thus can absorb more heat from the refrigerated space. The throttling valve and the evaporator are usually located very close to each other, so the pressure drop in the connecting line is small.

EXAMPLE 10–2

The Actual Vapor-Compression Refrigeration Cycle

- Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10°C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50°C. The refrigerant is cooled in the condenser to 26°C and 0.72 MPa and is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, determine:



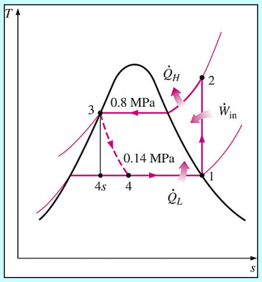
- (*a*) the rate of heat removal from the refrigerated space and the power input to the compressor,
- (*b*) the isentropic efficiency of the compressor, and
- (*c*) the coefficient of performance of the refrigerator.

SELECTING THE RIGHT REFRIGERANT

When designing a refrigeration system, there are several refrigerants from which to choose, such as chlorofluorocarbons (CFCs), ammonia, hydrocarbons (propane, ethane, ethylene, etc.), carbon dioxide, air (in the air-conditioning of aircraft), and even water (in applications above the freezing point).

The right choice of refrigerant depends on the situation at hand.

Of these, refrigerants such as R-11, R-12, R-22, R-134a, and R-502 account for over 90 percent of the market in the United States.



Two important parameters that need to be considered in the selection of a refrigerant are the temperatures of the two media (the refrigerated space and the environment) with which the refrigerant exchanges heat.

SELECTING THE RIGHT REFRIGERANT

To have heat transfer at a reasonable rate, a temperature difference of 5 to 10°C should be maintained between the refrigerant and the medium with which it is exchanging heat.

If a refrigerated space is to be maintained at -10°C, for example, the temperature of the refrigerant should remain at about -20°C while it absorbs heat in the evaporator.

The lowest pressure in a refrigeration cycle occurs in the evaporator, and this pressure should be above atmospheric pressure to prevent any air leakage into the refrigeration system.

Therefore, a refrigerant should have a saturation pressure of 1 atm or higher at -20°C in this particular case.

Ammonia and R-134a are two such substances.

SELECTING THE RIGHT REFRIGERANT

The temperature (and thus the pressure) of the refrigerant on the condenser side depends on the medium to which heat is rejected.

The temperature of the refrigerant in the condenser cannot fall below the temperature of the cooling medium (air at about 20°C for a household refrigerator), and the saturation pressure of the refrigerant at this temperature should be well below its critical pressure if the heat rejection process is to be approximately isothermal.

Lower temperatures in the condenser (thus higher COPs) can be maintained if the refrigerant is cooled by liquid water instead of air.

The use of water cooling cannot be justified economically, however, except in large industrial refrigeration systems.

Other desirable characteristics of a refrigerant include being nontoxic, noncorrosive, nonflammable, and chemically stable; having a high enthalpy of vaporization (minimizes the mass flow rate); and, of course, being available at low cost.

SELECTING THE RIGHT REFRIGERANT

The industrial and heavy-commercial sectors were very satisfied with *ammonia,* and still are, although ammonia is toxic.

The advantages of ammonia over other refrigerants are its low cost, higher COPs (and thus lower energy cost), more favorable thermodynamic and transport properties and thus higher heat transfer coefficients (requires smaller and lower-cost heat exchangers), greater detectability in the event of a leak, and no effect on the ozone layer.

The major drawback of ammonia is its toxicity, which makes it unsuitable for domestic use.

Ammonia is predominantly used in food refrigeration facilities such as the cooling of fresh fruits, vegetables, meat, and fish; refrigeration of beverages and dairy products such as beer, wine, milk, and cheese; freezing of ice cream and other foods; ice production; and low-temperature refrigeration in the pharmaceutical and other process industries.

SELECTING THE RIGHT REFRIGERANT

It is remarkable that the early refrigerants used were highly toxic.

A leaks will result in serious illnesses and even death which limit the use of these refrigerants.

This create a need for the development of a safe refrigerant for household use.

At the request of Frigidaire Corporation, General Motors' research laboratory developed R-21, the first member of the CFC family of refrigerants.

Of several CFCs developed, the research team settled on R-12 as the refrigerant most suitable for commercial use and gave the CFC family the trade name "Freon."

The versatility and low cost of CFCs made them the refrigerants of choice.

CFCs were also widely used in aerosols, foam insulations, and the electronic industry as solvents to clean computer chips.

SELECTING THE RIGHT REFRIGERANT

R-11 is used primarily in large-capacity water chillers serving air-conditioning systems in buildings.

R-12 is used in domestic refrigerators and freezers, as well as automotive air conditioners.

R-22 is used in window air conditioners, heat pumps, air conditioners of commercial buildings, and large industrial refrigeration systems, and offers strong competition to ammonia.

R-502 (a blend of R-115 and R-22) is the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets because it allows low temperatures at evaporators while operating at single stage compression.

The ozone crisis has caused a major stir (worry) in the refrigeration and air-conditioning industry and has triggered a critical look at the refrigerants in use.

SELECTING THE RIGHT REFRIGERANT

It was realized in the mid-1970s that CFCs allow more ultraviolet radiation into the earth's atmosphere by destroying the protective ozone layer and thus contributing to the greenhouse effect that causes global warming.

As a result, the use of some CFCs is banned by international treaties.

Fully halogenated CFCs (such as R-11, R-12, and R-115) do the most damage to the ozone layer.

The non-fully halogenated refrigerants such as R-22 have about 5 percent of the ozone-depleting capability of R-12.

Refrigerants that are friendly to the ozone layer that protects the earth from harmful ultraviolet rays have been developed.

The once popular refrigerant R-12 has largely been replaced by the recently developed chlorine-free R-134a.