Section 1

BASIC REFRIGERATION PRINCIPLES

Most users normally associate refrigeration with cold and cooling, yet the practice of refrigeration engineering deals almost entirely with the transfer of heat. This seeming paradox is one of the most fundamental concepts that must be grasped to understand the workings of a refrigeration system. Cold is really only the absence of heat, just as darkness is the absence of light, and dryness is the absence of moisture.

THERMODYNAMICS

Thermodynamics is that branch of science dealing with the mechanical action of heat. There are certain fundamental principles of nature, often called laws of thermodynamics, which govern our existence here on Earth, several of which are basic in the study of refrigeration.

The first and most important of these laws is the fact that energy can neither be created or destroyed, but can be converted from one type to another. A study of thermodynamic theory is beyond the scope of this manual, but the examples that follow will illustrate the practical application of the energy law.

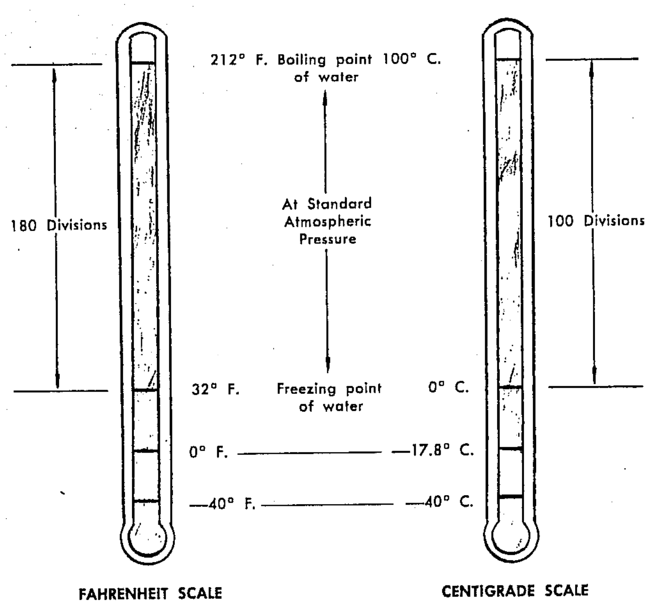
HEAT

Heat is a form of energy, primarily created by the transformation of other types of energy into heat energy. For example, mechanical energy turning a wheel causes friction which creates heat.

Heat is often defined as energy in transfer, for it is never content to stand still, but is always moving from a warm body to a colder body. Much of the heat on the Earth is derived from radiation from the sun. A spoon in ice water loses its heat to the water and becomes cold; a spoon in hot coffee absorbs heat from the coffee and becomes warm. But the terms warmer and colder are only comparative. Heat exists at any temperature above absolute zero, even though it may be in extremely small quantities. Absolute zero is the term used by scientists to describe the lowest theoretical temperature possible, the temperature at which no heat exists, which is approximately 460 degrees below zero Fahrenheit. By comparison with this standard, the coldest weather we might ever experience on Earth is much warmer.

TEMPERATURE

Temperature is the scale used to measure the intensity of heat, the indicator that determines which way the heat energy will move. In the United States, temperature is normally measured in degrees Fahrenheit, but the Centigrade scale (sometimes termed Celsius) is widely used in other parts of the world. Both scales have two basic points in common, the freezing point of



COMPARISON OF TEMPERATURE SCALES

water, and the boiling point of water at sea level. Water freezes at 32° F. and O° C., and water boils at sea level at 212° F. and 100° C. On the Fahrenheit scale, the temperature difference between these two points is divided into 180 equal increments or degrees F., while on the Centigrade scale the temperature difference is divided into 100 equal increments or degrees C. The relation between Fahrenheit and Centigrade scales can always be established by the following formulas:

Fahrenheit = 9/5 Centigrade + 32°
Centigrade = 5/9 (Fahrenheit — 32°)

HEAT MEASUREMENT

The measurement of temperature has no relation to the quantity of heat. A match flame may have the same temperature as a bonfire, but obviously the quantity of heat given off is vastly different.

The basic unit of heat measurement used today in the United States is the British Thermal Unit, commonly expressed as a BTU. A BTU is defined as the amount of heat necessary to raise one pound of water one degree Fahrenheit. For example, to raise the temperature of one gallon of water (approximately 8.3 pounds) from 70° F. to 80° F. will require 83 BTU's.

$$8.3 \times (80 - 70) = 83$$

HEAT TRANSFER

The second important law of thermodynamics is that heat **always** travels from a warm object to a colder one. The rate of heat travel is in direct proportion to the temperature difference between the two bodies.

Assume that two steel balls are side by side in a perfectly insulated box. One ball weighs one pound and has a temperature of 400° F., while the second ball weighs 1,000 pounds and has a temperature of 390° F. The heat content of the larger ball is tremendously greater than the small one, but because of the temperature difference, heat will travel from the small ball to the large one until the temperatures equalize.

Heat can travel in any of three ways: radiation, conduction, or convection.

Radiation is the transfer of heat by waves similar to light waves or radio waves. For example, the sun's energy is transferred to the Earth by radiation. One need only step from the shade into direct sunlight to feel the impact of the heat waves, even though the temperature of the surrounding air is identical in both places. There is little radiation at low temperatures, and at small temperature differences, so radiation is of little importance in the actual refrigeration process. However, radiation to the refrigerated space or product from the outside environment, particularly the sun, may be a major factor in the refrigeration load.

Conduction is the flow of heat through a substance. Actual physical contact is required for heat transfer to take place between two bodies by this means. Conduction is a highly efficient means of heat transfer as any serviceman who has touched a piece of hot metal can testify.

Convection is the flow of heat by means of a fluid medium, either gas or liquid, normally air or water. Air may be heated by a furnace, and then discharged into a room to heat objects in the room by convection.

In a typical refrigeration application, heat normally will travel by a combination of processes, and the ability of a piece of equipment to transfer heat is referred to as the overall rate of heat transfer. While heat transfer cannot take place without a temperature difference, different materials vary in their ability to conduct heat. Metal is a very good heat conductor, while asbestos has so much resistance to heat flow it can be used as insulation.

CHANGE OF STATE

Most common substances can exist as a solid, a liquid, or a vapor, depending on their temperature and the pressure to which they are exposed. Heat can change their temperature, and also can change their state. Heat is absorbed even though no temperature change takes place when a solid changes to a liquid, or when a liquid changes to a vapor. The same amount of heat is given off when the vapor changes back to a liquid, and when the liquid is changed to a solid.

The most common example of this process is water, which exists as a liquid, can exist in solid form as ice, and exists as a gas when it becomes steam. As ice it is a usable form of refrigeration, absorbing heat as it melts at a constant temperature of 32° F. If placed on a hot stove in an open pan, its temperature will rise to the boiling point (212° F. at sea level). Regardless of the amount of heat applied, the temperature cannot be raised above 212° F. because the water will completely vaporize into steam. If this steam could be enclosed in a container and more heat applied, then the temperature could again be raised. Obviously the boiling or evaporating process was absorbing heat.

When steam condenses back into water it gives off exactly the same amount of heat that it absorbed evaporating. (The steam radiator is a common usage of this source of heat.) If the water is to be frozen into ice, the same amount of heat that is absorbed in melting must be extracted by some refrigeration process to cause the freezing action.

The question arises — just where did those heat units go? Scientists have found that all matter is made up of molecules, infinitesimally small building blocks which are arranged in certain patterns to form different substances. In a solid or liquid, the molecules are very close together. In a vapor the molecules are much farther apart and move about much more freely. The heat energy that was absorbed by the water became molecular energy, and as a result the molecules rearranged themselves, changing the ice into water, and the water into steam. When the steam condenses back into water, that same molecular energy is again converted into heat energy.

SENSIBLE HEAT

Sensible heat is defined as the heat involved in a change of temperature of a substance. When the temperature of water is raised from 32° F. to 212° F., an increase in sensible heat content is taking place. The BTU's required to raise the temperature of one pound of a substance 1° F. is termed its specific heat. By definition the specific heat of water is 1.0, but the amount of heat required to raise the temperature of different substances through a given temperature range will vary. It requires only .64 BTU to raise the temperature of one pound of butter 1° F., and only .22 BTU is required to raise the temperature of one pound of aluminum 1° F. Therefore the specific heats of these two substances are .64 and .22 respectively.

LATENT HEAT OF FUSION

A change of substance from a solid to a liquid, or from a liquid to a solid involves the latent heat of fusion. It might also be termed the latent heat of melting, or the latent heat of freezing.

When one pound of ice melts, it absorbs 144 BTU's at a constant temperature of 32° F., and if one pound of water is to be frozen into ice, 144 BTU's must be removed from the water at a constant temperature of 32° F. In the freezing of food products, it is only the water content for which the latent heat of freezing must be taken into account, and normally this is calculated by determining the percentage of water content in a given product.

LATENT HEAT OF EVAPORATION

A change of a substance from a liquid to a vapor, or from a vapor back to a liquid involves the latent heat of evaporation. Since boiling is only a rapid evaporating process, it might also be called the latent heat of boiling, the latent heat of vaporization, or for the reverse process, the latent heat of condensation.

When one pound of water boils or evaporates, it absorbs 970 BTU's at a constant temperature of 212° F. (at sea level) and to condense one pound of steam to water 970 BTU's must be extracted from it.

Because of the large amount of latent heat involved in evaporation and condensation, heat transfer can be very efficient during the process. The same changes of state affecting water apply to any liquid, although at different temperatures and pressures.

The absorption of heat by changing a liquid to a vapor, and the discharge of that heat by condensing the vapor is the keystone to the whole mechanical refrigeration process, and the movement of the latent heat involved is the basic means of refrigeration.

LATENT HEAT OF SUBLIMATION

A change in state directly from a solid to a vapor without going through the liquid phase can occur in some substances. The most common example is the use of "dry ice" or solid carbon dioxide for cooling. The same process can occur with ice below the freezing point, and is also utilized in some freeze-drying processes at extremely low temperatures and high vacuums. The latent heat of sublimation is equal to the sum of the latent heat of fusion and the latent heat of evaporation.

SATURATION TEMPERATURE

The condition of temperature and pressure at which both liquid and vapor can exist simultaneously is termed saturation. A saturated liquid or vapor is one at its boiling point, and for water at sea level, the saturation temperature is 212° F. At higher pressures, the saturation temperature increases, and with a decrease in pressure, the saturation temperature decreases.

SUPERHEATED VAPOR

After a liquid has changed to a vapor, any further heat added to the vapor raises its temperature so long as the pressure to which it is exposed remains constant. Since a temperature rise results, this is sensible heat. The term superheated vapor is used to describe a gas whose temperature is above its boiling or saturation point. The air around us is composed of superheated vapor.

SUBCOOLED LIQUID

Any liquid which has a temperature lower than the saturation temperature corresponding to its pressure is said to be subcooled. Water at any temperature less than its boiling temperature (212° F. at sea level) is subcooled.

ATMOSPHERIC PRESSURE

The atmosphere surrounding the Earth is composed of gases, primarily oxygen and nitrogen, extending many miles above the surface of the Earth. The weight of that atmosphere pressing down on the Earth creates the atmospheric pressure in which we live. At a given point, the atmospheric pressure is relatively constant except for minor changes due to changing weather conditions. For purposes of standardization and as a basic reference for comparison, the atmospheric pressure at sea level has been universally accepted, and this has been established at 14.7 pounds per square inch, which is equivalent to the pressure exerted by a column of mercury 29.92 inches high.

At altitudes above sea level, the depth of the atmospheric blanket surrounding the Earth is less, therefore the atmospheric pressure is less. At 5,000 feet elevation, the atmospheric pressure is only 12.2 pounds per square inch.

ABSOLUTE PRESSURE

Absolute pressure, normally expressed in terms of pounds per square inch absolute (psia) is defined as the pressure existing above a perfect vacuum. Therefore in the air around us, absolute pressure and atmospheric pressure are the same.

GAUGE PRESSURE

A pressure gauge is calibrated to read 0 pounds per square inch when not connected to a pressure producing source. Therefore the absolute pressure of a closed system will always be gauge pressure plus atmospheric pressure. Pressures below 0 psig are actually negative readings on the gauge, and are referred to as inches of vacuum. A refrigeration compound gauge is calibrated in the equivalent of inches of mercury for negative readings. Since 14.7 psi is equivalent to 29.92 inches of mercury, 1 psi is approximately equal to 2 inches of mercury on the gauge dial.

It is important to remember that gauge pressures are only relative to absolute pressure. Table 1 shows relationships existing at various elevations assuming that standard atmospheric conditions prevail.

Table 1

PRESSURE RELATIONSHIPS AT VARYING ALTITUDES

Altitude	Psig	Psia	Pressure in Inches Hg	Boiling Point of Water
0 ft.	0	14.7	29.92	212° F.
1000 ft.	0	14.2	28.85	210° F.
2000 ft.	0	13.7	27.82	208° F.
3000 ft.	0	13.2	26.81	206° F.
4000 ft.	0	12.7	25.84	205° F.
5000 ft.	0	12.2	24.89	203° F.

The absolute pressure in inches of mercury indicates the inches of mercury vacuum that a perfect vacuum pump would be able to reach. Therefore, at 5,000 feet elevation under standard atmospheric conditions, a perfect vacuum would be 24.89 inches of mercury, as compared to 29.92 inches of mercury at sea level.

At very low pressures, it is necessary to use a smaller unit of measurement since even inches of mercury are too large for accurate reading. The micron, a metric unit of length, is used for this purpose, and when we speak of microns in evacuation, we are referring to absolute pressure in units of microns of mercury.

A micron is equal to 1/1000 of a millimeter and there are 25.4 millimeters per inch. One micron, therefore, equals 1/25,400 inch. Evacuation to 500 microns would be evacuating to an absolute pressure of approximately .02 inch of mercury, or at standard conditions, the equivalent of a vacuum reading of 29.90 inches mercury.

PRESSURE—TEMPERATURE RELATIONSHIPS, LIQUIDS

The temperature at which a liquid boils is dependent on the pressure being exerted on it. The vapor pressure of the liquid, which is the pressure being exerted by the tiny molecules seeking to escape the liquid and become vapor, increases with an increase in temperature until at the point where the vapor pressure equals the external pressure, boiling occurs.

Water at sea level boils at 212° F., but at 5,000 feet elevation it boils at 203° F. due to the decreased atmospheric pressure. If some means, a compressor for example, were used to vary the pressure on the surface of the water in a closed container, the boiling point could be changed at will. At 100 psig, the boiling point is 327.8°, F., and at 1 psig, the boiling point is 102° F.

Since all liquids react in the same fashion, although at different temperatures and pressure, pressure provides a means of regulating a refrigerating temperature. If a cooling coil is part of a closed system isolated from the atmosphere and a pressure can be maintained in the coil equivalent to the saturation temperature (boiling point) of the liquid at the cooling temperature desired, then the liquid will boil at that temperature as long as it is absorbing heat — and refrigeration has been accomplished.

PRESSURE—TEMPERATURE RELATIONSHIPS, GASES

One of the basic fundamentals of thermodynamics is called the "perfect gas law." This describes the relationship of the three basic factors controlling the behavior of a gas — pressure, volume, and temperature. For all practical purposes, air and highly superheated refrigerant gases may be considered perfect gases, and their behavior follows the following relation:

$$\frac{\text{Pressure}_1 \times \text{Volume}_1}{\text{Temperature}_1} = \frac{\text{Pressure}_2 \times \text{Voume}_2}{\text{Temperature}_2}$$

Although the "perfect gas" relationship is not exact, it provides a basis for approximating the effect on a gas of a change in one of the three factors. In this relation, both pressure and temperature must be expressed in absolute values, pressure in psia, and temperature in degrees Rankine or degrees Fahrenheit above absolute zero. (°F. plus 460°). Although not used in practical refrigeration work, the perfect gas relation is valuable for scientific calculations and is helpful in understanding the performance of a gas.

One of the problems of refrigeration is disposing of the heat which has been absorbed during the cooling process, and a practical solution is achieved by raising the pressure of the gas so that the saturation or condensing temperature will be sufficiently above the temperature of the available cooling medium (air or water) to insure efficient heat transfer. When the low pressure gas with its low saturation temperature is drawn into the cylinder of a compressor, the volume of the gas is reduced by the stroke of the compressor piston, and the vapor is discharged as a high pressure gas, readily condensed because of its high saturation temperature.

SPECIFIC VOLUME

Specific volume of a substance is defined as the number of cubic feet occupied by one pound, and in the case of liquids and gases, it varies with the temperature and the pressure to which the fluid is subjected. Following the perfect gas law, the volume of a gas varies with both temperature and pressure. The volume of a liquid varies with temperature, but within the limits of practical refrigeration practice, it may be regarded as incompressible.

DENSITY

The density of a substance is defined as weight per unit volume, and in the United States is normally expressed in pounds per cubic foot. Since by definition density is directly related to specific volume, the density of a gas may vary greatly with changes in pressure and temperature, although it still remains a gas, invisible to the naked eye. Water vapor or steam at 50 psia pressure and 281° F. temperature is over 3 times as heavy as steam at 14.7 psia pressure and 212° F.

PRESSURE AND FLUID HEAD

It is frequently necessary to know the pressure created by a column of liquid, or possibly the pressure required to force a column of refrigerant to flow a given vertical distance upwards.

Densities are usually available in terms of pounds per cubic foot, and it is convenient to visualize pressure in terms of a cube of liquid one foot high, one foot wide, and one foot deep. Since the base of this cube is 144 square inches, the average pressure in pounds per square inch is the weight of the liquid per cubic foot divided by 144. For example, since water weighs approximately 62.4 pounds per cubic foot, the pressure exerted by 1 foot of water is $62.4 \div 144 = .433$ pounds per square inch. Ten feet of water would exert a pressure of $10 \times .433 = 4.33$ pounds per square inch. The same relation of height to pressure holds true, no matter what the area of vertical liquid column. The pressure exerted by other liquids can be calculated in exactly the same manner if the density is known.

Fluid head is a general term used to designate any kind of pressure exerted by a fluid which can be expressed in terms of the height of a column of the given fluid. Hence a pressure of 1 psi may be expressed as being equivalent to a head of 2.31 feet of water. (1 psi $\div$ .433 psi/ft. of water). In air flow through ducts, very small pressures are encountered, and these are commonly expressed in inches of water. 1 inch of water $= .433 \div 12 = .036$ psi.

Table 2

PRESSURE EQUIVALENTS IN FLUID HEAD

Pounds per Square Inch	Inches Mercury	Inches Water	Feet Water
.036	.07	1.0	.083
.433	.80	12	1.0
.491	1.0	13.6	1.13
1.0	2.03	27.7	2.31
14.7	29.92	408	34.0

FLUID FLOW

In order for a fluid to flow from one point to another, there must be a difference in pressure between the two points to cause the flow. With no pressure difference, no flow will occur. Fluids may be either liquids or gases, and the flow of each is important in refrigeration.

Fluid flow through pipes or tubing is governed by the pressure exerted on the fluid, the effect of gravity due to the vertical rise or fall of the pipe, restrictions in the pipe resisting flow, and the resistance of the fluid itself to flow.

For example, as a faucet is opened, the flow increases, even though the pressure in the water main is constant and the outlet of the faucet has no restriction. Obviously the restriction of the valve is affecting the rate of flow. Water flows more freely than molasses, due to a property of fluids called viscosity, which describes the fluid's resistance to flow. In oils, the viscosity can be affected by temperature, and as the temperature decreases the viscosity increases.

As fluid flows through tubing, the contact of the fluid and the walls of the tube create friction, and therefore resistance to flow. Sharp bends in the tubing, valves and fittings, and other obstructions also create resistance to flow, so the basic design of the piping system will determine the pressure required to obtain a given flow rate.

In a closed system containing tubing through which a fluid is flowing, the pressure difference between two given points will be determined by the velocity, viscosity, and the density of fluid flowing. If the flow is increased, the pressure difference will increase since more friction will be created by the increased velocity of the fluid. This pressure difference is termed pressure loss or pressure drop.

Since control of evaporating and condensing pressures is critical in mechanical refrigeration work, pressure drop through connecting lines can greatly affect the performance of the system, and large pressure drops must be avoided.

EFFECT OF FLUID FLOW ON HEAT TRANSFER

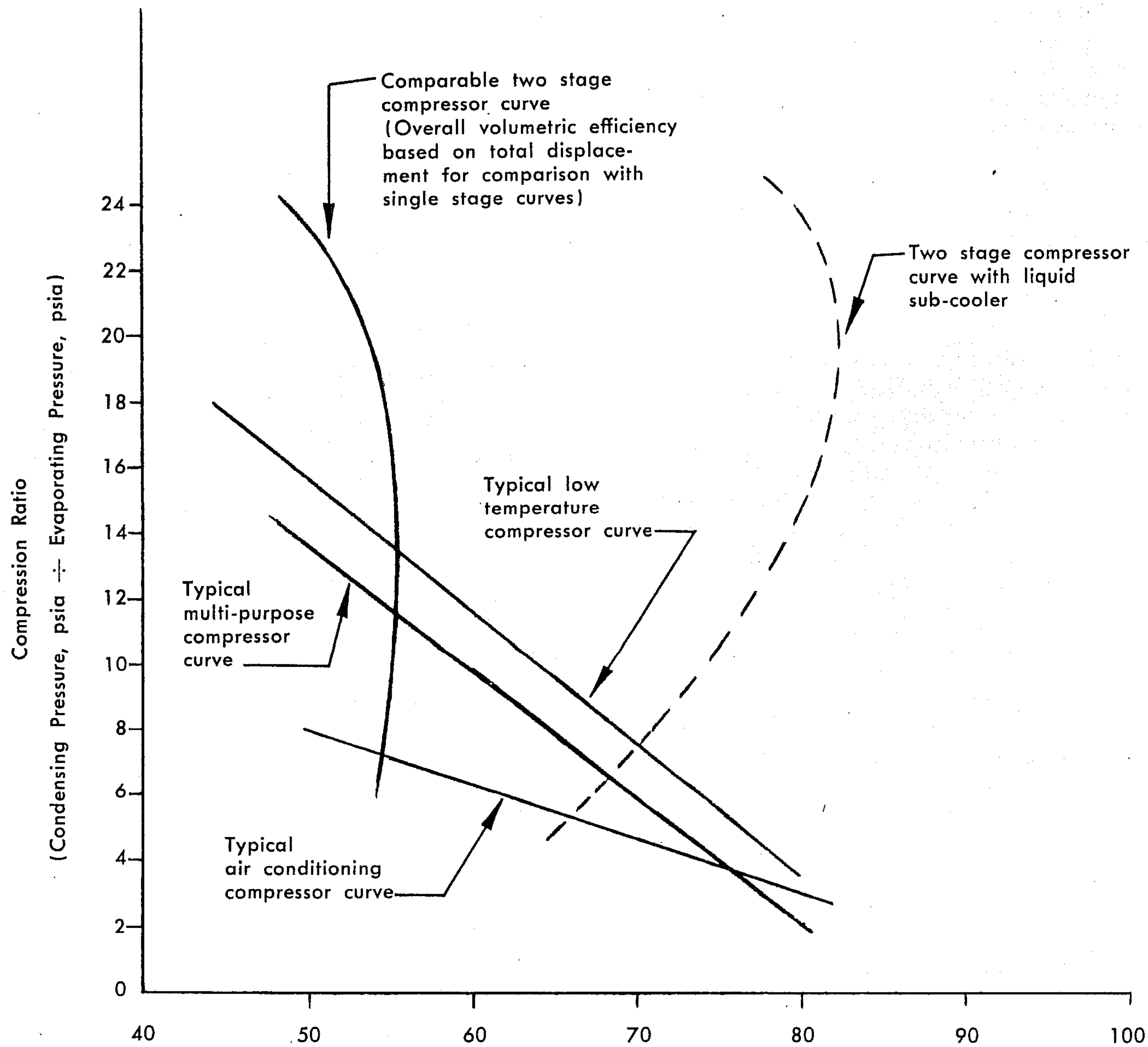
Heat transfer from a fluid through a tube wall or through metal fins is greatly affected by the action of the fluid in contact with the metal surface. As a general rule, the greater the velocity of flow and the more turbulent the flow, the greater will be the rate of heat transfer. Rapid boiling of an evaporating liquid will also increase the rate of heat transfer. Quiet liquid flow on the other hand, tends to allow an insulating film to form on the metal surface which resists heat flow, and reduces the rate of heat transfer.

VOLUMETRIC EFFICIENCY OF THE COMPRESSOR

Volumetric efficiency is defined as the ratio of the actual volume of refrigerant gas pumped by the compressor to the volume displaced by the compressor pistons. The efficiency of a compressor can vary over a wide range, depending on the compressor design and the compression ratio.

The compression ratio of a compressor is the ratio of the absolute discharge pressure (psia) to the absolute suction pressure (psia).

Several design factors can influence compressor efficiency including the clearance volume



TYPICAL COMPRESSOR VOLUMETRIC EFFICIENCY CURVES

Figure 5

above the piston, the clearance between the piston and the cylinder wall, valve spring tension, and valve leakage. For a given compressor, the effect on compressor efficiency because of design is fairly constant, and volumetric efficiency will vary almost inversely with the compression ratio.

Two factors cause a loss of efficiency with an increase in compression ratio. As the gas is subjected to greater compression, the residual gas remaining in the cylinder clearance space becomes more dense, and since it does not leave the cylinder on the discharge stroke, it re-expands on the suction stroke, thus preventing the intake of a full cylinder of gas from the suction line. The higher the pressure exerted on the residual gas, the more dense it becomes, and the greater volume it occupies on re-expansion.

The second factor is the high temperature of the cylinder walls resulting from the heat of compression. As the compression ratio increases, the heat of compression increases, and the cylinders and head of the compressor become very hot. Suction gas entering the cylinder on the intake stroke is heated by the cylinder walls, and expands, resulting in a reduced weight of gas entering the compressor.

Typical volumetric efficiency curves are shown in Figure 5. Air conditioning compressors are usually designed with greater clearance volume, so the efficiency drops off much faster with an increase in compression ratio.

While the volumetric efficiency of each stage of a two stage compressor would resemble the typical single stage curves, the overall volumetric efficiency of a two stage compressor has a relatively constant efficiency over a wide compression ratio range. Since the use of a liquid subcooler with a two stage compressor can increase the capacity so dramatically, a dotted curve has been added for comparison purposes.

EFFECT OF CHANGE IN SUCTION PRESSURE

Other factors remaining equal, as the suction pressure is reduced, the specific volume of the gas returning to the compressor increases. Since a given compressor's pumping capacity is fixed by its speed and displacement, the reduction in density of the suction gas decreases the weight of the refrigerant pumped, with a resulting reduction in compressor capacity. The loss of capacity with a reduction in suction pressure is extremely rapid. Since the energy input required by the compressor to perform its work does not decrease at the same rate, the BTU/watt ratio, which reflects the performance of the compressor per unit of electrical energy consumed, also decreases rapidly with a drop in suction pressure. Therefore for best capacity performance and operating economy, it is most important that a refrigeration system operate at the highest suction pressure possible.

EFFECT OF CHANGE IN DISCHARGE PRESSURE

An increase in the condensing pressure, commonly termed the discharge pressure or head pressure, results in an increase in the compression ratio, with a consequent loss of volumetric efficiency. While the loss of capacity is not as great as that caused by an equivalent decrease in suction pressure, it is still severe.

For operating economy and maximum capacity, the discharge pressure should be kept as low as practical.

EFFECT OF SUBCOOLING LIQUID REFRIGERANT WITH WATER OR AIR

When the hot high pressure liquid refrigerant is fed into the evaporator through the expansion valve, the refrigerant must first be reduced to the evaporating temperature in the evaporator before it can start absorbing heat. This is accomplished by almost instantaneous boiling or flashing of a portion of the liquid into vapor, the latent heat of vaporization involved in the change of state absorbing the heat from the remaining liquid refrigerant.

The resulting flash gas can produce no further refrigeration, and in effect the refrigerating capacity of the refrigerant has been reduced by the heat absorbed in lowering the liquid temperature. If a portion of this heat could be extracted from the liquid prior to its entry into the evaporator, then the effective capacity of the system could be increased.

This can be accomplished by subcooling the liquid refrigerant after condensing by means of water or air. If condensing temperatures are relatively high, capacity increases of 5% to 15% are easily obtainable. Since no power is required other than that involved in moving the cooling medium, subcooling the liquid can result in substantial savings in operating cost.

EFFECT OF SUBCOOLING LIQUID RERIGERANT BY SUPERHEATING THE VAPOR

A suction gas to liquid refrigerant heat exchanger is frequently used for the following reasons:

1. To raise the temperature of the return suction gas so frosting or condensation will not occur on the suction line.

2. To subcool the liquid refrigerant sufficiently to offset any pressure drop that might occur in the liquid line, and prevent the formation of flash gas in the liquid line.

3. To provide a source of heat to evaporate any liquid refrigerant which might have flooded through the evaporator, thus preventing the return of liquid refrigerant to the crankcase.

4. To increase total system capacity.

As pointed out in the previous section, subcooling the liquid refrigerant increases the refrigerating capacity per pound of the refrigerant circulated. In a perfectly insulated system with negligible heat transfer into the suction line outside the refrigerated space, a liquid to suction heat exchanger theoretically will increase system capacity slightly (a substantial increase in the case of R-12) since the heat transferred from the liquid refrigerant to the refrigerant vapor is greater than the capacity reduction at the compressor resulting from the increase in specific volume of the vapor.

As a practical matter, there may be a substantial capacity increase with all refrigerants. In most systems the suction lines are uninsulated and most of the superheat in the suction gas comes from the ambient air. If the low temperature suction gas can be used to subcool the liquid refrigerant, it is possible that only a small penalty will be paid in the form of higher return gas temperatures, particularly on units with long suction lines. The temperature difference between the suction line and the surrounding air will be smaller, and the heat transfer rate correspondingly less.

EFFECT OF SUPERHEATING THE VAPOR LEAVING THE EVAPORATOR

It is essential that the temperature of the gas returning to the compressor be a minimum of 15° F. above the evaporating temperature to avoid carrying liquid refrigerant back to the compressor. If this heat is added to the vapor inside the refrigerated space, the heat absorbed increases the refrigeration capacity, while the increase in specific volume of the gas decreases the compressor capacity. These two factors tend to offset one another, with a negligible effect on capacity.

Heat entering the refrigerant through the suction line from the ambient air outside the refrigerated space results in a net loss of system capacity. Since such losses may be as high as 10% to 15%, insulation of the suction line can be a worthwhile investment, and may be necessary to prevent the return gas temperature from rising too high.

EFFECT OF PRESSURE DROP IN THE DISCHARGE LINE AND CONDENSER

Pressure drop due to friction as the refrigerant gas flows through the discharge line and condenser reduces compressor capacity due to the resulting higher compressor discharge pressure and lower volumetric efficiency. Since the condensing temperature is not greatly affected, pressure drops of less than 5 psig have very little effect on system capacity.

However, compressor power consumption will increase because of the higher compressor discharge pressure, and for best operating economy, excessively high pressure drops in the discharge line should be avoided.

EFFECT OF PRESSURE DROP IN LIQUID LINE

If the pressure of liquid refrigerant falls below its saturation temperature, a portion of the liquid will flash into vapor to cool the liquid refrigerant to the new saturation temperature. This can occur in a liquid line if the pressure drops sufficiently due to friction or due to vertical lift. If flashing occurs, the feed through the expanson valve may be erratic and inadequate for the evaporator demand.

Subcooling of the liquid refrigerant after condensing by an amount sufficient to offset the pressure drop normally will insure solid liquid refrigerant at the expansion valve. At 120° F. condensing temperature, 10° F. liquid subcooling will protect against flashing for pressure drops as follows:

R-12	21.3 psi
R-22	33.9 psi
R-502	34.5 psi

Refrigerants 12, 22, and 502 are slightly heavier than water, and a head of two feet of liquid refrigerant is approximately equivalent to 1 psi. Therefore if a condenser or receiver in the basement of a building 20 feet tall is to supply liquid refrigerant to an evaporator on the roof, a pressure drop of approximately 10 psi for the vertical head must be provided for in system design.

EFFECT OF PRESSURE DROP IN THE EVAPORATOR

Pressure drop occuring in the evaporator due to frictional resistance to flow results in the leaving evaporator pressure being less than the pressure of the refrigerant at the entrance of the evaporator. For a given load and coil, the required average refrigerant temperature is fixed. The greater the pressure drop, the greater the difference between the average evaporator refrigerant pressure and the leaving evaporator refrigerant pressure.

As the suction pressure leaving the evaporator is decreased, the specific volume of the gas returning to the compressor increases, and the weight of the refrigerant pumped by the compressor decreases. Therefore pressure drop in the evaporator causes a decrease in system capacity, and it is important that the evaporator be sized so that abnormally high pressure drops do not occur.

EFFECT OF PRESSURE DROP IN SUCTION LINE

The effect of pressure loss in the suction line is similar to pressure drop in the evaporator. Since pressure drop in the suction line does not result in a corresponding decrease in the refrigerant evaporating temperature, pressure drop in the suction line can be extremely detrimental to system capacity, and suction lines must be sized to prevent excessive pressure losses.

For example, on a typical 7½ HP compressor operating on R-12:

Evap. Temp.	Line Pressure Drop	Pressure At Comp.	BTU/hr. Capacity
—10° F.	1 psi	3.5 psig	32,400
—10° F.	2 psi	2.5 psig	30,100
—10° F.	3 psi	1.5 psig	27,800
—10° F.	4 psi	.5 psig	25,600

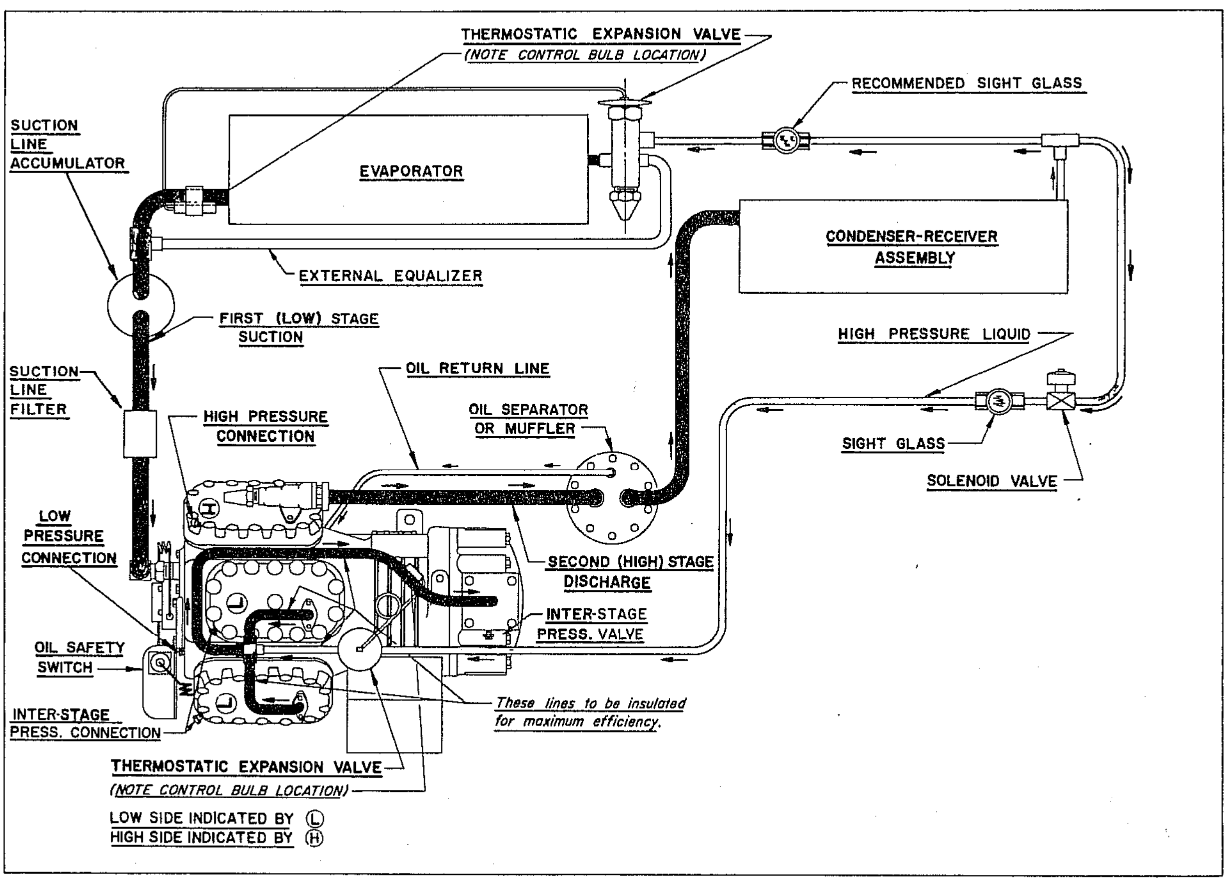
TWO-STAGE SYSTEMS

As the compression ratio increases, the volumetric efficiency of the compressor decreases and the heat of compression increases. For low temperature applications, the decreasing efficiency and excessively high discharge temperatures become increasingly critical and −40° F. is the lowest recommended evaporating temperature for compressors operating on the simple single stage compression cycle.

In order to increase operating efficiency at low temperatures the compression can be done in two steps or stages. For two stage operation with equal compression ratios, the compression ratio of each stage will be equal to the square root of the total compression ratio (approximately ¼ of the total compression ratio for the normal two-stage operating range.) Since each stage of compression then is at a much lower compression ratio the compressor efficiency is greatly increased. The temperature of the refrigerant vapor leaving the first stage and entering the second stage may be high due to the heat of compression, which can result in overheating the second stage cylinders and valves. To prevent compressor damage, liquid refrigerant must be injected between stages to properly cool the compressor.

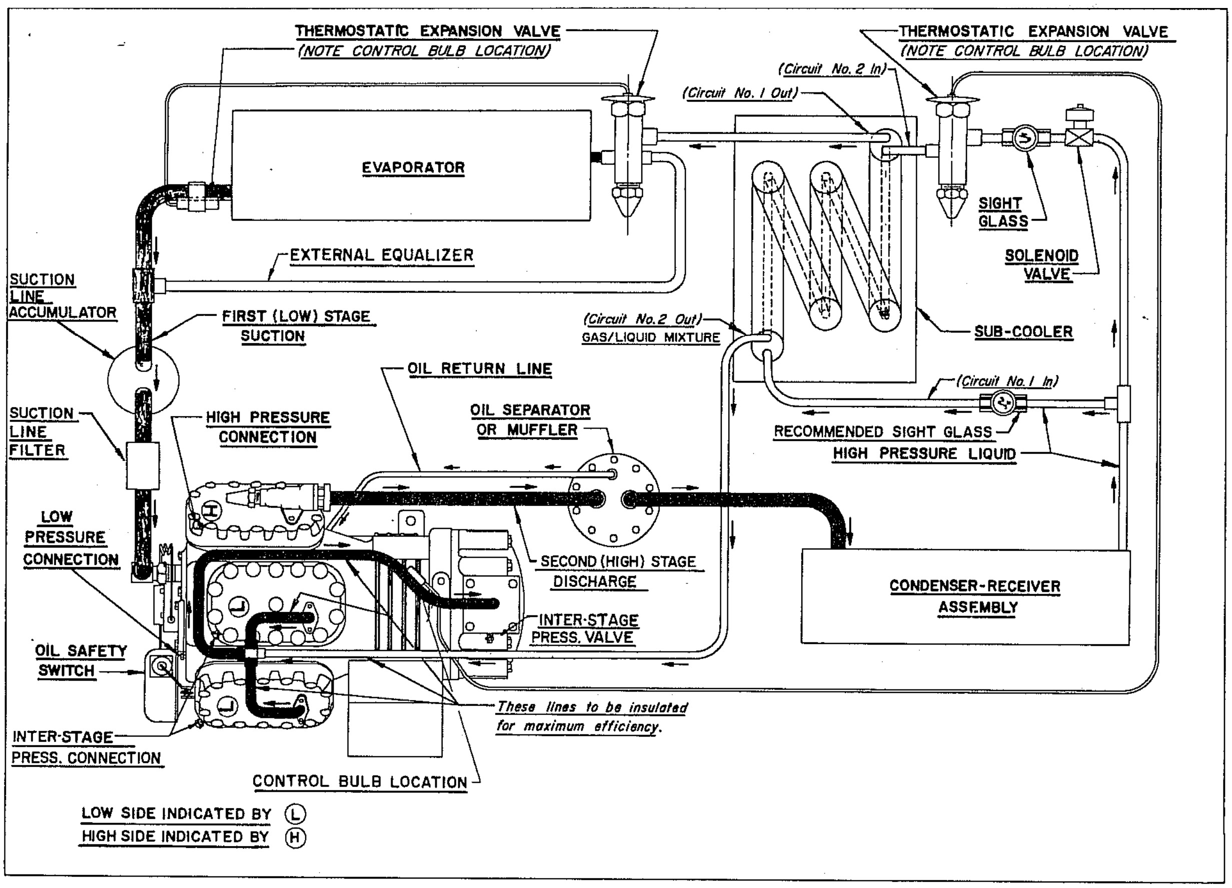
Two-stage compression may be accomplished with the use of two compressors with the discharge of one pumping into the suction inlet of the second, but because of the difficulty of maintaining proper oil levels in the two crankcases, it is more satisfactory to use one compressor with multiple cylinders. A two-stage compressor is designed so that suction gas is drawn directly into the low stage cylinders and then discharged into the high stage cylinder or cylinders. On Copelametic two-stage compressors the ratio of low stage to high stage displacement is 2 to 1. The greater volume of the low stage cylinders is necessary because of the difference in specific volume of the gas at the low and interstage pressures.

Figures 6 and 7 illustrate typical two-stage compressors as applied to low temperature systems. Two-stage refrigeration is effective down to evaporator temperatures of −80° F. to −90° F. Below that level, efficiency drops off rapidly.



SYSTEM WITH 6-CYLINDER COMPRESSOR (WITHOUT LIQUID SUB-COOLER)

Figure 6



SYSTEM WITH 6-CYLINDER COMPRESSOR (WITH LIQUID SUB-COOLER)

Figure 7

CASCADE SYSTEMS

In order to operate satisfactorily at even lower evaporating temperatures, and to increase the flexibility of system design, multiple stage refrigeration can also be accomplished by using separate systems with the evaporator of one serving as the condenser of the second by means of a heat exchanger. This type of design is termed a cascade system, and allows the use of different refrigerants in the separate systems. Refrigerants with characteristics and pressures suitable for ultra-low temperature refrigeration can be used in the low stage system, and cascade systems in multiples of two, three, or even more separate stages make possible refrigeration at almost any desired evaporating temperature. Cascade systems composed of both single and two-stage compressors can be used very effectively.

REFRIGERATION CYCLE DIAGRAMS

Occasionally, in order to analyze system performance, or to visually represent the refrigeration cycle, diagrams and charts are used. The most common of these is the pressure-enthalpy diagram on which the refrigeration cycle is plotted.

Figure 8 is a pressure-enthalpy diagram with R-502 properties plotted. Lines have been drawn on the basic chart for constant enthalpy, constant pressure, constant entropy, constant temperature, constant volume, saturated vapor, and saturated liquid. Charts of typical compression cycles have been superimposed on the R-502 data so that single and two stage cycles can be compared. All cycles are shown with 130° F. condensing temperature and −40° F. evaporating temperature.

PRESSURE-ENTHALPY DIAGRAM
(PRELIMINARY)

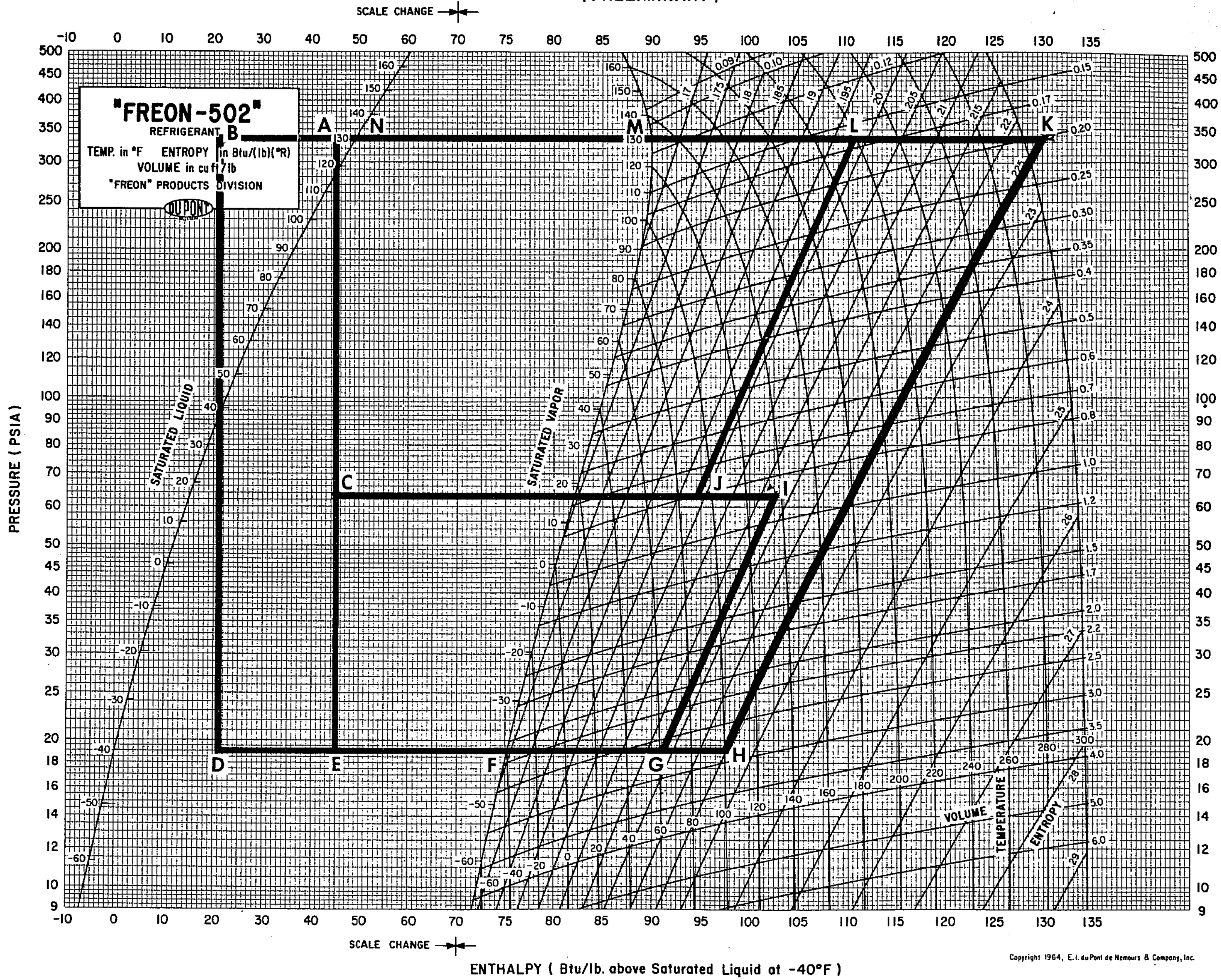


Figure 8

1. Single Stage Cycle

A typical single stage cycle with R-502 refrigerant would follow the processes illustrated by the diagramAEHKA on Figure 8. At point A, the refrigerant is sub-cooled liquid at 332.7 psia pressure and 115° F. temperature.

The line AE represents the throttling process as liquid refrigerant passes through the expansion valve. Since no heat transfer has taken place, the enthalpy has not changed, but the pressure is reduced to 19.0 psia.

Line EF represents the change of state from liquid to gas during the evaporating process at a constant temperature of −40° F. and a constant pressure of 19.0 psia. As heat is absorbed, the enthalpy of the refrigerant increases. Line FH illustrates superheating of the vapor. For this illustration, it was assumed that the gas returning to the compressor was superheated to 60° F., and an additional temperature rise to 100° F. was caused by the compressor prior to entering the compressor cylinders.

Line HK represents the compression process. Since compression is very rapid, very little heat transfer will take place to or from the refrigerant, and the process may be considered adiabatic (a process during which no heat transfer takes place and entropy value is constant). There is an increase in enthalpy because of the conversion of mechanical energy to heat energy in the refrigerant vapor. The process follows a constant entropy line, until the condensing pressure is reached. As a result of the increase in enthalpy, **the temperature of the gas increases to almost 310° F.**

Line KM represents the desuperheating of the hot gas, and at point M condensation begins and continues to point N at a constant temperature of 130° F. and a constant pressure of 332.7 psia. At point N, condensation is complete, and line NA represents liquid subcooling in the condenser to 115° F., where the cycle starts once again.

2. Two Stage Cycle Without Liquid Subcooler

While a pressure-enthalpy diagram can dramatically illustrate the difference in temperatures and pressures resulting from two-stage operation, it does not reflect compressor efficiency because of the lower compression ratios, since all enthalpy values are plotted on the basis of BTU/lb. The difference in capacity between single stage and two stage operation is best shown by a comparison of volumetric efficiency curves. (See Fig. 5).

A typical two stage cycle without liquid subcooling is represented by the diagram AEGIJLA. In addition, the line CJ represents the interstage cooling process.

The cycle again starts with liquid refrigerant at 332.7 psia subcooled to 115° F. The line AE illustrates the throttling process through the expansion valve for liquid refrigerant entering the evaporator. However, on two stage systems, a portion of the liquid refrigerant is used for cooling the refrigerant gas between stages of compression, and the line AC also represents liquid refrigerant passing through the interstage expansion valve.

Evaporation of the liquid refrigerant in the evaporator takes place as before at a constant temperature of −40° F. and a constant pressure of 19.0 psia along the line EF to point F. At point F the liquid is completely vaporized, and superheating of the vapor takes place to point G. In Copelametic two stage compressors, the suction gas returning from the evaporator does not pass over the compressor motor, but enters the cylinders directly, and again it is assumed for this illustration that the gas is superheated to 60° F. as it enters the compressor.

First stage compression takes place along the constant entropy line from G to I. At point I the gas is discharged from the first stage cylinders at the interstage pressure of 62.4 psia at a temperature of 130° F.

At this point the hot gas is mixed with the liquid refrigerant fed through the interstage expansion valve. Line CJ represents the increase in enthalpy for the interstage cooling refrigerant. Line IJ represents the decrease in enthalpy of the first stage discharge gas. The resulting mixture of refrigerant gas passes over the compressor motor and enters the compressor second stage cylinder or cylinders at a temperature of approximately 90° F. and at the interstage pressure of 62.4 psia.

Second stage compression takes place along the line JL to the condensing pressure of 332.7 psia. Note however that the compressor discharge gas temperature is only 220° F. as compared with 310° F. at the same point in the single stage cycle.

Desuperheating of the discharge gas and condensation takes place along line LN as before with liquid subcooling to point A, where the cycle is complete.

3. Two Stage Cycle With Liquid Subcooling

Two stage systems may operate either with or without liquid subcoolers, in which the liquid refrigerant going to the evaporator is cooled in a heat exchanger by means of the same liquid refrigerant feed used for interstage cooling. The effective capacity of a two stage compressor can be greatly increased by means of a liquid subcooler since the liquid entering the evaporator has a much lower enthalpy content, and hence a greater heat absorption capability.

A typical two stage cycle with liquid subcooling is represented by a combination of diagrams BDGIJLB and ACJLA.

As before, the cycle is started at point A with liquid refrigerant at 332.7 psia subcooled to 115° F. Liquid flowing to the evaporator is subcooled along the line AB to 35° F. by liquid fed through the interstage expansion valve along line CJ. Line BD shows the throttling process through the expansion valve for liquid refrigerant entering the evaporator.

Evaporation occurs along line DF, and the balance of the cycle is identical to that of a two stage cycle without a subcooler. A greater quantity of refrigerant must be fed to the interstage expansion valve to accomplish both the liquid subcooling and the interstage cooling.

Figure 9 is a pressure-enthalpy diagram for R-22 similar to the R-502 diagram. Again the single stage cycle, a two stage cycle without liquid subcooling, and a two stage cycle with liquid subcooling are shown. The basic cycles are similar to those described previously for Figure 8.

One very important comparison between R-22 and R-502 is illustrated in these diagrams. The temperature at point K, the single stage discharge temperature, is 390° F. with R-22 as opposed to 310° F. with R-502. It is because of these temperature characteristics that Copeland recommends R-502 in place of R-22 for low temperature single stage systems.

PRESSURE-ENTHALPY DIAGRAM

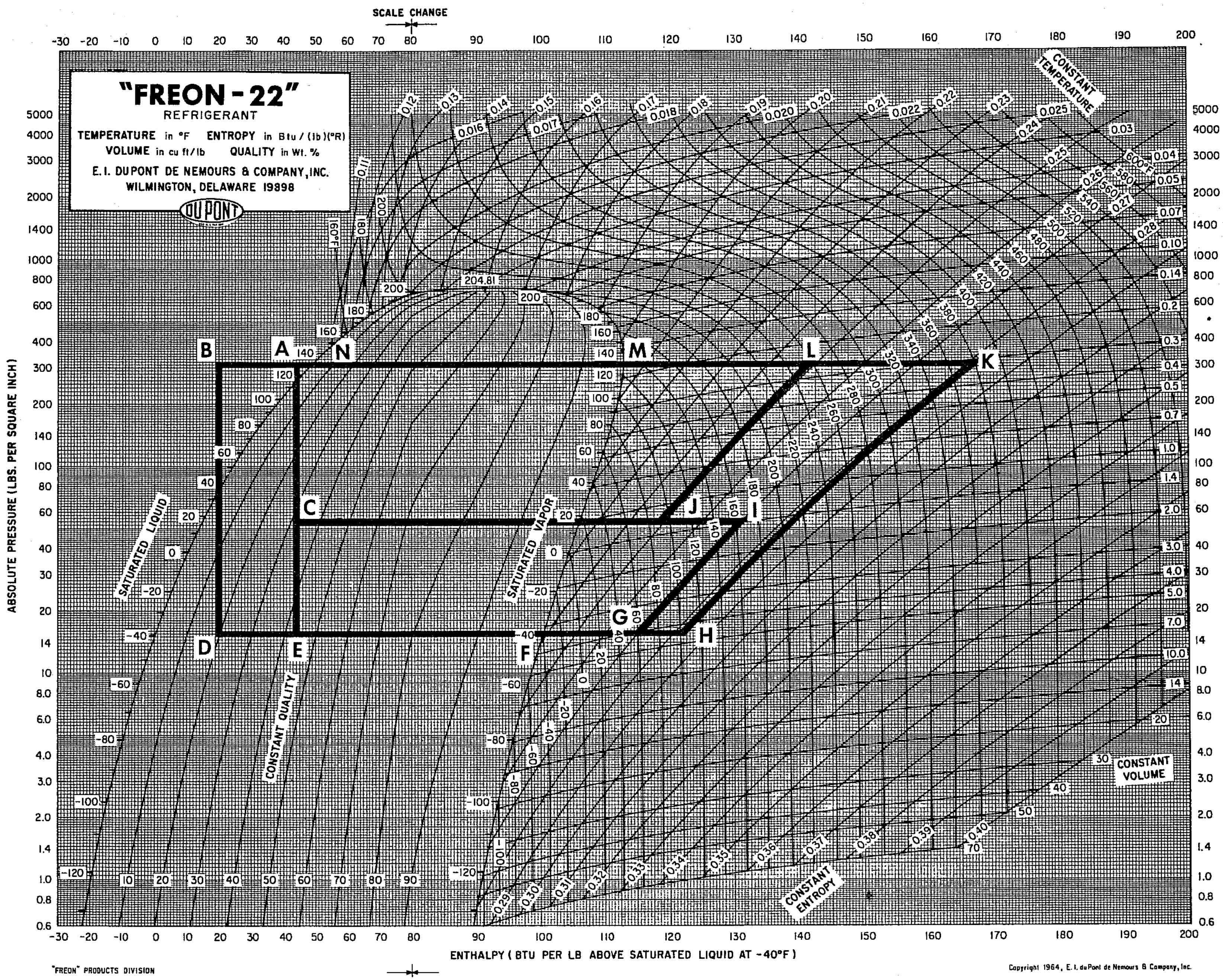


Figure 9