PRINCIPLES OF REFRIGERATION - PART 1

By: Paul Reed

THE ELEMENTS

Everything in, on, or around the earth, sun, moon and stars, including our bodies themselves, is made up of one or more of 92 basic "elements." Some of the most common of these elements are:

Carbon. It is the principal element in coal, wood, paper, cloth, natural gas, gasoline, and oil, and is present in many gases–carbon dioxide, methyl chloride, the fluorocarbon refrigerants, etc. Normally–that is, at atmospheric pressure and temperatures–carbon exists as a solid.

Iron, Aluminum, Lead, Copper, Zinc, Tin, Nickel, Silver, Gold, Tungsten, Cadmium, Chromium. These elements are called metals and are often used by themselves, but they are also found in mixtures with one another called alloys or in chemical combinations with other elements. These elements normally exist as solids.

Silicon, Calcium, Sodium, Potassium, Sulphur. These are found in many materials, but nearly always in a chemical combination with some other elements. These elements normally exist as solids.

Nitrogen. Ordinary air is about 78% nitrogen. Nitrogen is a very important element in plant life. Nitrogen normally exists as a gas.

Oxygen constitutes 21% of air. It is absolutely essential to all animal life. Oxygen is a very active element and combines readily with most of the elements to form "oxides" or more complex chemicals. Oxygen normally exists as a gas.

The remaining 1% consists of the gases, Argon, Carbon Dioxide, Hydrogen, Neon, Krypton, Helium, Ozone, and Xenon.

Hydrogen. Hydrogen is an important element in oil, fuels, acids and many compounds. It is the lightest of the elements. It rarely exists alone in nature, but is normally a gas. Water is formed when hydrogen is burned, that is, when hydrogen unites with oxygen.

THE ATOM

Each of the elements consists of many billions of tiny particles called "atoms." An atom is so small that it cannot be seen, even with the most powerful microscope, and yet scientists can measure it and weigh it, and they know many things about the atom. How they can know these things if they cannot see the atoms, is outside the scope of this discussion; we must merely accept these facts in order to understand the subject.

An atom is the basic particle of which each element is composed, and still have the characteristics of that element. Thus, an atom of iron is iron, and it is different from an atom of carbon. For our purpose, we must consider the atom as being indivisible and unchangeable. That is, we cannot divide an atom by ordinary means, and whatever we do to it, physically and chemically, it still retains the characteristics of that element. Moreover, atoms of all of the elements are different. Iron is composed of iron atoms; lead of lead atoms, etc.

(However, an atom is itself composed of still smaller particles, called protons, neutrons and electrons.) Scientists have found how, by "extra-ordinary means" to change some of the atoms to other kinds of atoms, that is to change them to other elements. Scientists have been able to split some kinds of elements, such as uranium, in two. For our purpose, we can consider the atom as the very smallest possible particle of matter; that all of the elements are composed of atoms; and that the atoms of the different elements are different.

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THE MOLECULE

The next larger particle of a material is called a "molecule". It consists of one or more atoms. If the molecule consists of only one kind of atom, then the molecule will be a molecule of an element. The molecule of most of the elements has only one atom in it. However, a molecule may have several atoms in it, even though they are all the same kind of atoms. For example, a molecule of oxygen has 2 atoms of oxygen in it; a molecule of iron has but 1 atom of iron in it; a molecule of sulphur usually has 8 atoms of sulphur in it; and so on, for all of the elements. A small piece of any element consists of billions of molecules; and each of those molecules consists of one, two, or several atoms of that element.

CHEMICAL COMPOUNDS

On the other hand, a molecule may consist of two or more atoms of different elements. In such an instance, the material becomes entirely different, and usually does not resemble either of the elements which comprise it. For example, if the molecule consists of 1 atom of iron and 1 atom of oxygen, it becomes iron oxide which is quite different from iron.

How different the material itself can be from the elements of which it is composed, is illustrated by water. The molecule of water (or ice or steam) consists of two atoms of the element hydrogen, a very light, highly flammable gas, and one atom of the element oxygen, also a gas. The combination of these two elements, both gases, produces a liquid, water, which is exceedingly unlike either hydrogen or oxygen.

Sometimes the molecule is quite complex and may have several kinds of elements in it. Refrigerant-12, normally a colorless gas, is an example of this.* The Refrigerant-12 molecule consists of 1 atom of carbon (normally a black solid), 2 atoms of chlorine (normally a yellow-green gas), and 2 atoms of fluorine (normally a pale-yellow gas).

***In references to basic elements of modern refrigerants and discussion of their function, application and reaction under varying conditions, only fluorocarbon refrigerants will be used as examples since they are most widely used.**

You will note that, for convenience in terminology, a simple refrigerant numbering system had been universally adopted by the industry, i.e.

Dichlorodifluoromethane has a standard designation of refrigerant 12... or R12, monoclorodifluoromethane is designated refrigerant 22... or R22.

The complete standard refrigerant numbering system is covered in 'SAM' Section 620–12, titled, "Standard Refrigerant Numbering Systems and Properties at Saturation." Reference to this section is recommended for a thorough understanding of the method of identification of all commonly used refrigerants.

Refrigerant-21 and Refrigerant-22 are even more complex. The Refrigerant-21 molecule consists of:

1 atom of the element carbon

1 atom of the element of hydrogen

2 atoms of the element chlorine

1 atom of the element fluorine

The Refrigerant-22 molecule consists of:

1 atom of the element carbon

1 atom of the element hydrogen

1 atom of the element chlorine

2 atoms of the element fluorine

Please note how similar the molecules of Refrigerant-21 and Refrigerant-22 are. They consist of the same elements and of the same number of atoms of carbon and hydrogen; the only difference being, that Refrigerant-21 has two atoms of chlorine and one of fluorine, while Refrigerant-22 has one atom of chlorine and two of fluorine.

Nevertheless, that seemingly slight change means a great deal of difference in the two refrigerants. Refrigerant-21 boils at 48°F and Refrigerant-22 boils at 41.4°F at standard atmospheric pressure.

Many, many of the common substances that we use daily are "chemical compounds." That is, their molecules consist of atoms of two or more different elements. A few instances of these are:

Table salt ($NaCl$). One atom of sodium and one atom of chlorine.

Muriatic (hydrochloric) acid (HCl). One atom of hydrogen and one atom of chlorine.

Calcium Chloride ($CaCl_2$). One atom of calcium and two atoms of chlorine.

Baking Soda ($NaHCO_3$). One atom of sodium, one atom of hydrogen, one atom of carbon and three atoms of oxygen.

There are many thousands of existing and possible combinations, in different proportions of the 92 elements, into chemical compounds.

CHEMICAL SYMBOLS

Rather than write out the composition of the molecules of various compounds, chemists have developed a method of abbreviation known as chemical symbols. Each element has one or two letters that stand for that element; H for hydrogen, O for oxygen, S for sulphur, Ca for calcium, Fe for iron (from the Latin word ferrum for iron), etc. A small number just below the letter indicates the number of atoms of that element in the molecule. A letter without a number indicates that there is only one atom of that element in the molecule. For example, H_2O is the chemical symbol for water, and indicates that a molecule of water consists of two atoms of hydrogen and one atom of oxygen.

MOTION OF THE MOLECULES

Mechanical refrigeration is a physical rather than a chemical process, so we deal with molecules and their movements, and rarely have need to go into chemical processes, which involve breaking down the molecule into its constituent atoms, or the union of atoms to form molecules. Nevertheless, we feel that it is necessary to have an elementary understanding of the composition of matter, in order to more easily understand how gases, liquids and solids behave under various conditions.

So all matter, whether gaseous, liquid or solid, consists of billions of molecules.

If the material is in solid form, such as iron, wood, stone, ice, etc., the molecules are held together by their attraction for one another. This mutual attraction of like molecules is called cohesion. The molecules are not tightly jammed together, nor are they motionless. There are spaces between them, and they move somewhat, but their motion is quite limited, being more of a shifting than free motion.

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The colder a solid is, the less motion the molecules have. If the material had absolutely no heat in it, that is, if it were at a temperature of "absolute zero", which is about -460°F, there would be no motion of the molecules. If the very cold material is slightly warmed by adding a little heat, the molecules begin to move somewhat, and the motion of the molecules becomes greater the warmer the material becomes.

SENSIBLE HEAT OF A SOLID

It takes energy to cause movement or to do work. The molecules must be given heat, which is one form of energy, in order to give them motion. So the more heat energy the molecules get, the greater their motion and the faster they move.

The heat that we add to raise the temperature of the solid material, and give the molecules more movement, is called "sensible heat", for we can tell that heat has been added by one of our senses, the sense of feeling, which tells us that the solid is warmer than before.

If we continue to add heat energy to the solid, it gets warmer, and the molecules move faster, but still within a very limited space, for they are still held to one another by their mutual attraction.

MELTING OR FUSION

Finally, however, they get enough heat energy to partly overcome their attraction for one another. Then the molecules can move freely about and thus become what we call liquid. This process of breaking away from one another and changing from a solid to a liquid is called "melting" or "fusion."

The attraction of the molecules of a solid for one another is great, so the molecules must receive a great deal of heat energy to allow the solid to become a liquid. The heat energy required to melt a solid is relatively a great deal more than the amount of heat required to warm it somewhat and raise its temperature a few degrees.

We call the heat required to break up the mutual attraction of the molecules and to change the material from a solid to a liquid–that is, to melt it–the “Latent” Heat of Melting, or more correctly, the Latent Heat of Fusion. Latent means "hidden", and this heat is hidden, for it goes into partly overcoming the mutual attraction of the molecules, and not to changing the temperature. The temperatures of the solid immediately before it melts and immediately afterward when it has become a liquid, are exactly the same. The latent heat of fusion has gone into causing a change in "state" of the material–from the state, or form, or condition, of a solid to the state of a liquid.

The molecules are now moving more freely and are not held together. The material can no longer stand rigidly by itself, and must have some container such as a cup, tank or other vessel to support it. The speed of movement of the molecules is much greater but yet not enough to overcome the force of gravity so they are held downward in the vessel, but the liquid can be poured from a higher container to a lower one, or pumped from a lower to a higher container.

So a material in the liquid state must have more heat in it than when it was in the solid state; and except at the exact melting temperature, must always be warmer.

Since the molecules are much more free as a liquid than as a solid, they become more separated. The liquid requires more room than the solid, so we say that the volume of the liquid is greater than that of the solid of the same weight.

SENSIBLE HEAT OF A LIQUID

The molecules in a liquid have a considerable amount of heat energy, so they move about in a lively manner and at a rather rapid speed. They bump into one another and into the side of their container.

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As heat energy is added to the liquid, it becomes warmer, and the speed of its molecules increases. As in the case of the solid, it takes energy to give the increased motion to the molecules, and the heat energy that is added to do this is again called "sensible" heat, but this time, sensible heat of the liquid. It is the heat added to a liquid that causes the liquid to become warmer.

EVAPORATION

All of the molecules do not move at the same speed; in fact, some of the molecules in the top part of the liquid may get enough speed to fly entirely out of the liquid and into the space or air above the liquid and escape. Some of them get out of the liquid temporarily, but do not have enough speed nor energy to entirely escape so they fall back into the liquid.

Some of these molecules do get clear away and get mixed into the air or other gas above the liquid. Thus, some of the molecules are constantly escaping, and they themselves form a gas or vapor blanket above the liquids, and this vapor tends to diffuse into and mix with the air above the liquid.

We call this process of some of the molecules escaping from the surface of the liquid, "evaporation", for it is a process of forming a vapor.

An example of evaporation of a liquid, is water in an open vessel. Some of it evaporates into a gas "water vapor", and eventually all of the water disappears. The warmer the water is, the faster it evaporates, for more heat energy has been added, and more molecules get enough velocity to escape from the liquid.

SUBLIMATION

We have said that the molecules in a solid are held rather closely together by their cohesion. However, some of the molecules near the surface break away from the rest of the molecules and jump clear away from the solid. They fly off into the air or other space and never come back. That is, they become vapor.

This process is called "sublimation" and is somewhat similar to evaporation of a liquid to a vapor. In sublimation, the solid turns directly into a vapor without going through the liquid state, that is, without melting.

Examples Of Sublimation Are:

- **Wet cloths on a line in below-freezing weather are said to "freeze dry." Actually, the water freezes into ice, which gradually sublimes into the air as water vapor, leaving the clothes dry.**
- **Ice on sidewalks in zero weather gradually disappears, for it sublimes into water vapor and diffuses into the air.**
- **One of the outstanding examples of sublimation is that of solid carbon-dioxide. Under normal conditions it does not melt into a liquid, but turns to a gas directly from a solid. Since it does not melt and become wet it is therefore known as "dry-ice."**

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BOILING OR VAPORIZATION

If we keep adding heat to the liquid above the melting temperature, the liquid becomes warmer and warmer and the molecules move faster and faster, until finally, when enough heat energy has been added, the molecules are moving so fast that they lose all restraint and fly out of the liquid, much the same as in evaporation, but in far greater numbers.

At this temperature, the liquid "disintegrates", and breaks loose from even the force of gravity, and the molecules fly in all directions. We now call this condition a gas or a vapor. As a vapor, the material takes up a great deal more room than when it was a liquid or a solid, for the molecules are flying about and are therefore widely separated. Thus, the volume of the vapor is much greater than when the material was a liquid.

We call this process of changing from a liquid to a vapor "boiling" or "vaporization", and the temperature at which it occurs, the boiling temperature.

For the molecules to get enough speed or velocity to break clear away from one another, to overcome the power of mutual attraction and of gravity, and to fly out and away, they must be given a great deal of heat energy. In fact, the amount of this energy must be rather tremendous, as compared to the amount required normally to warm the solid or the liquid a degree or so, or even to change the solid to a liquid.

This very large amount of heat energy required to get the liquid to boil, and to give the molecules enough energy to escape from the liquid and to form a vapor, is called the Latent Heat of Boiling or, more correctly, the Latent Heat of Vaporization. As in the case of melting, this heat is latent or hidden, for it goes to overcome the forces that hold the molecules together as a liquid and to give them enough energy to become quite free.

If the liquid is water in an open vessel, the molecules that escape from the liquid into the air, form what is known as water vapor, which is also called "moisture" in the air. Any liquid can and does have its own vapor that forms just above the surface of the liquid, but which also diffuses or spreads through the space above the surface of the liquid.

SENSIBLE HEAT OF A VAPOR

A vapor or gas can be warmed, just as a solid or liquid can. If heat energy is added to the molecules, their speed or "velocity" increases and we say that the vapor is warmer. The heat that is added to a vapor and that causes it to become warmer, is called the Sensible Heat of the Vapor. It is also called superheat.

CHANGES OF STATE

The terms vapor and gas mean about the same, for any gas is really the vapor from some material that can exist as a liquid or a solid. Oxygen, hydrogen, nitrogen and the other gases that normally exist as gases, can also exist, under the proper conditions, as liquids or solids.

If we cool oxygen enough, that is, take enough heat away from it, the molecules do not have enough energy to remain free and will have to go back into liquid form. If the liquid oxygen is cooled further, it cannot remain as a liquid and will have to return to a solid.

The temperatures required to do this are extremely low, -297°F to cause oxygen to liquify, and -361°F to cause it to solidify.

A more familiar example is water vapor or "steam", which is the usual name for very hot water vapor. If it is cooled, it turns to water, a liquid. If the liquid is further cooled, it becomes ice, the solid form of water.

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The heat that we must remove from water vapor to return it to a liquid (water) will be:

1. The sensible heat of the vapor to cool it down to the boiling temperature, 212°F.
2. The latent heat of vaporization or condensation to change the vapor at 212°F to water at 212°F.

Then we can further remove sensible heat from the liquid and thus cool it down to as low as 32°F, but it will remain a liquid.

The heat that we must remove from water to return it to a solid (ice) will be:

1. The sensible heat of the water to cool it down to the melting temperature of 32°F.
2. The latent heat of fusion or solidification to change the water at 32°F to ice at 32°F.

If we wish, we can further cool the ice below 32°F, down to about any temperature we want, by removing the sensible heat of the ice, but of course it will still remain as ice.

The Total Heat is a term that refers to the amount of heat required to get any certain material up to any chosen temperature from a lower temperature. We would expect that this base temperature would be Absolute Zero, which is the temperature at which, in theory at least there would be no heat at all in the material. However, it is customary to usually use -40° as the base temperature, for -40°F and -40°C, are the same.

So the total heat above -40°, of water at 65°, would be the total of these three:

1. The Sensible Heat of Ice from -40F° to 32°F.
2. The Latent Heat of Fusion of Ice at 32°F.
3. The Sensible Heat of Water from 32°F to 65°F.

The Total Heat above -40°of steam at 400° would be the total of these five:

1. The Sensible Heat of Ice from -40°F to 32°F.
2. The Latent Heat of Fusion of Ice at 32°F.
3. The Sensible Heat of Water from 32°F to 212°F.
4. The Latent Heat of Vaporization of Water at 212°F.
5. The Sensible Heat of Steam from 212°F to 400°F.

MEASURING THE AMOUNT OF HEAT ENERGY

To be able to fully understand and apply these principles, we must be able to measure temperature changes and the amounts of heat. If we cannot measure a material, an action, a process, we really do not properly understand it, and certainly we cannot use it very well.

Heat is an energy, just as electricity is an energy. Energy does work; causes things to happen. Energy is not a solid, liquid, or gas; it cannot be measured in inches, gallons, or cubic feet. It must be measured by what it does; the effect it produces.

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Adding heat to water raises its temperature, so we measure this heat by how much it raises the temperature of the water. We start with one pound of water (which is approximately one pint) at about 60°. It takes a certain amount of heat to raise the temperatures of that pound of water one degree, say from 63° to 64°. So we adopt that as our standard of measuring the amount of heat; namely, the amount of heat required to warm one pound of water one degree F. British scientists long ago decided on that standard unit of measuring heat, so it has come to be called a British thermal unit (thermal meaning heat), abbreviated Btu. Since much of our system of standard weights and measures come from the British, we use the Btu as our standard heat unit.

Some countries use the metric system, with the calorie as their heat unit, and the calorie is also used even in the United States, in most scientific laboratories. The calorie is the amount of heat required to raise one gram of water one degree Celsius.

So the Btu is a measure of the amount of heat, and the degree of temperature is a measure of the effect of that heat on one pound of water. Therefore, the amount of water must be known, for obviously, it would take twice as much heat (2 Btu) to warm two pounds of water one degree, as it would to warm one pound of water one degree. Moreover, it would take twice as much heat (2 Btu) to warm one pound of water two degrees as it would to warm one pound of water one degree.

To warm five pounds of water five degrees would therefore require 25 Btu to be added to the five pounds of water. So the amount of heat in Btu, to warm any amount of water through any number of degrees of temperature is found by merely multiplying the number of pounds of water by the number of degrees the temperature is to be raised, and the answer is the number of Btu of heat that must be added to the water.

Let us not forget that the heat (energy) added to the water goes into increasing the movement of the molecules of the water to make them more active, to give them more rapidity of motion, and this increased rapidity of motion produces the effect that we call a rise in temperature.

SPECIFIC HEAT

But materials vary in the amount of heat required to heat them one degree. It so happens that, compared to other materials, whether solid, liquid or gaseous, water requires a great deal of heat energy to warm it. Oil requires only about one-half as much as water, so it takes only one-half a Btu to warm one pound of oil one degree. Gasoline, kerosene and crude oil also require about one-half Btu per pound per degree to warm them. Mercury requires only about one-thirtieth Btu; alcohol about three-fifths Btu; chloroform about one-fourth, etc.

Gases vary a great deal in the amount of heat required to warm them, depending upon their temperature and pressure, but at atmospheric pressure and room temperature, they are: air, oxygen, nitrogen and carbon dioxide, 1/5 to 1/4 Btu per pound of the gas per degree; sulphur dioxide about 1/6 Btu; ammonia about 1/2 Btu; Refrigerant-12 about 1/7 Btu etc.

The amount of heat required to raise one pound of material one degree is called its Specific Heat. For water, the Specific Heat is one, for it takes one Btu to raise one pound of water one degree. The Specific Heat of oil, gasoline, and kerosene is about 1/2 or in decimals, .50. Tables of Specific Heats are usually given in decimals, as ice (at 20°) .48; water vapor .46, iron .13 to .17, etc.

To calculate the amount of heat required to raise a material from one temperature to a higher temperature, we first figure the number of Btu just as if the material were water, by multiplying the number of pounds of the material by the number of degrees it is to be warmed. Then we multiply this amount by the Specific Heat of that particular material.

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Example: How many Btu are required to raise the temperature of 20 pounds of ice from 20° to 32°? If the ice were water, it would take 20 × 12 or 240 Btu, but the Specific Heat of ice is .48, so 240 × .48 = 115.2 Btu to warm 20 pounds of ice from 20° to 32°.

LATENT HEAT OF FUSION

To change one pound of ice at 32°F to water at 32°F requires that we add the Latent Heat of Fusion of ice, which is 144 Btu, so it will take 144 × 20 or 2,880 Btu to melt 20 pounds of ice.

If we now want to warm the 20 pounds of water to 50°F (an additional 18°), we will have to supply another 20 × 18 or 360 Btu.

If we want to heat the water from 32°, to the boiling point of 212° (through 180°), instead of just to 50°, we will have to add 20 × 180 or 3,600 Btu.

The Latent Heat of Fusion also varies with the material.

For some other solids the Latent Heats of Fusion are:

Aluminum	167.5	Btu/lb
Copper	78.0	Btu/lb
Silver	43.9	Btu/lb
Iron (Grey Casting)	40.0	Btu/lb
Gold	28.7	Btu/lb
Tin	25.4	Btu/lb
Lead	9.8	Btu/lb

LATENT HEAT OF VAPORIZATION

To boil the water at 212°F and turn it into steam also at 212°F, requires Latent Heat of Vaporization. For water in an open pan, it is 970 Btu per pound, so 20 pounds of water at 212° requires 20 × 970 or 19,400 Btu to turn it into steam or water vapor, also at 212°F.

Then if we want to "superheat" this steam to 300°, that is, raise its temperature above the 212°, we must add 20 × 88 × .46 (the Specific Heat of steam) or 809.6 Btu.

To warm 20 pounds of ice from 20° to 32°, change it to water, heat the water to 212°, change the water to water vapor (steam) and heat the steam on up to 300, will require:

Heat To Change 20 Pounds Of Ice At 20°F To Steam At 300°F.

To warm 20 Pounds of ice from 20° to 32° (20 × 12 × .48) =	115.2 Btu
To change the 32° ice to water at 32° (20 × 144) =	2,880.0 Btu
To warm 20 pounds of water from 32° to 212° (20 × 180 × 1) =	3,600.0 Btu
To change the 212° water to steam at 212° (20 × 970) =	19,400.0 Btu
To warm 20 pounds of steam from 212° to 300° (20 × 88 × .46) =	809.6 Btu
Total, to change 20 pounds of ice at 20° to steam at 300°	26,804.8 Btu

From these figures, it will be seen that the latent heats of fusion and of vaporization are very large compared with the sensible heats (to raise their temperatures). Moreover, the latent heats of fusion and vaporization of water (to change their states from a solid to a liquid and from a liquid to a vapor) are quite large compared to other materials. Most materials have far less heat capacities than ice, water, and steam.

REMOVING HEAT — COOLING

Thus far, we have spoken mostly of the addition of heat; adding sensible heat to raise the temperature of a solid, liquid or gas; or adding latent heat to change a solid to a liquid, or a liquid to a gas. For any material, these amounts are fixed, and known; they can be found in tables. Thus, we can accurately calculate how much heat will be required under specified conditions.

Let us now speak of removing heat; removing sensible heat to lower the temperature of a solid, liquid, or gas, or removing latent heat to change a gas to a liquid, or a liquid to a solid.

In cooling, does a material give up the same amount of heat required to heat it? Yes, under the same conditions; for example:

Example:

To warm a pound of water (to raise its temperature) from 63° to 64°, requires that we add one Btu. In cooling one degree, from 64° to 63°, the pound of water gives up as much heat as it received to warm it one degree. There is no loss; it is what is known as a "reversible" process. So to cool one pound of water one degree, we must remove one Btu.

The same applies in changing from a solid to a liquid, or from a liquid to a gas; or the reverse from a gas to a liquid, or a liquid to a solid.

To change one pound of ice at 32° to one pound of water at 32°, requires that 144 Btu must be added. If that pound of 32° water is refrozen back to ice, 144° Btu are given up by the water.

When we added the 144 Btu per pound to change the ice to water, we called it the Latent Heat of Melting or Fusion. If we remove 144 Btu per pound to change the water back to ice, we call it the Latent heat of Solidification, but it is the same amount. To change one pound of water at 212° to steam at 212° requires that 970 Btu must be added. If that steam at 212° is cooled, 970 Btu are released when it all turns back to water at 212°.

When we added the 970 Btu per pound to water to change it to vapor, we called it the Latent Heat of Vaporization. If we remove 970 Btu per pound to change the vapor back to water, we call it the Latent Heat of Condensation, but it is the same amount.

Just as we can calculate how much heat is to be added to warm a material, or change it from a solid to a liquid, or from a liquid to a gas, we can calculate how much heat will be released by a material when it cools, or when a gas changes to a liquid, or a liquid to a solid.

We use the same specific heats and the same latent heats as given above, and we can calculate them in the same manner.

A pound of water cooling from 75° to 35° releases 40° Btu. Twenty pounds of water cooling from 212° to 32° releases 3,600 Btu (20 × 180). When 20 pounds of water at 32° freezes to ice at 32°, 2,880 Btu (20 × 144) are released. Further cooling 20 pounds of ice at 32° down to 20° releases 115.2 Btu (20 × 12 × .48).

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Twenty pounds (by weight not pressure) of 212° steam, superheated to 300°, releases 809.6 Btu (20 × 88 ×.46) when it is cooled to 212°. If the 20 pounds of steam at 212° is cooled until the steam all turns to water at 212°, 19, 400 Btu are released (20 × 970).

So cooling 20 pounds of 300° steam superheated from 212°, down to 212°, condensing it into water at 212°, cooling the 212° water to 32°, freezing the water at 32° into ice at 32°, and further cooling the ice down to 20°, releases 26,804.8 Btu of heat, which is the same amount of heat that was added to heat 20° ice until it becomes 300° steam, superheated from 212°.

CONSERVATION OF ENERGY

We have emphasized that heat is energy–"heat energy." There are other kinds of energy–electrical energy, mechanical energy, and chemical energy, being the most common kinds besides heat energy. Energy can be changed from one kind to another. Chemical energy in coal can be changed into heat energy in the steam. Heat energy in the steam is changed into mechanical energy in the turbine and then into electrical energy in the generator. Electrical energy can then be changed back into heat energy in the toaster, to mechanical energy in the motor, or to chemical energy in the storage battery. In each of those steps, all of the electrical energy in the motor did not go into mechanical energy, power; some of it was "lost" as heat. We say "lost", for we did not get any use out of the heat of the motor, but actually it was not "lost", for the heat was energy, transformed from electrical energy.

So energy cannot be destroyed, nor can it be created. It can merely be transformed, to or from some other kind of energy. This principle is known as the Law of Conservation of Energy. It is well to remember it, for it explains many things.

It explains efficiency, for example; in changing from electrical energy to the motor, some went into mechanical energy (or power) and some into heat. The efficiency is percentagewise that part of the electricity that becomes power. That is, the mechanical energy (the output energy) determines the efficiency. If three-fourths of the electrical energy became mechanical energy, then the efficiency is 75% (3 ÷ 4 = .75 or 75%).

Even in a good boiler, over 1/3 of the heat energy in the coal burned goes up the chimney or is radiated from the boiler; about 2/3 goes into heat energy in the steam, so the efficiency is about 60% to 65%.

So efficiency is the useful output energy from a machine, divided by the input energy to the machine, and expressed as a percentage. The difference is lost as far as doing useful work is concerned, but it actually is not "lost", for energy cannot be destroyed nor "made." There is as much energy, but no more, now as there was in Christ's time. We have changed some of it, but it still exists, although in a different form.

HEAT FLOW

We have defined heat as the energy of the motion of the molecules. This motion is transmitted to other molecules that have less motion. Some of the molecules gave up some of their energy to other molecules that had less energy.

Another way of saying this is that the heat flowed from the material at a higher temperature to a material at a lower temperature. Heat therefore always flows "downhill", from hot to warm, warm to cool, cool to cold, - never from a low temperature to high temperature.

In fact, that is how we get heat to flow. We place a hot object near or touching a colder one, and let the heat flow from the hot one to the colder. Actually we do not "add heat" nor "remove heat."

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Heat moves in three ways; radiation, conduction and convection.

Radiation: If we place a hot object near a cooler one, heat jumps across the space between, to warm the cooler object. There does not have to be any gas or other material in the space. An excellent example of radiation is the heat from the sun, which radiates through 92 million miles of vacuum to reach the earth.

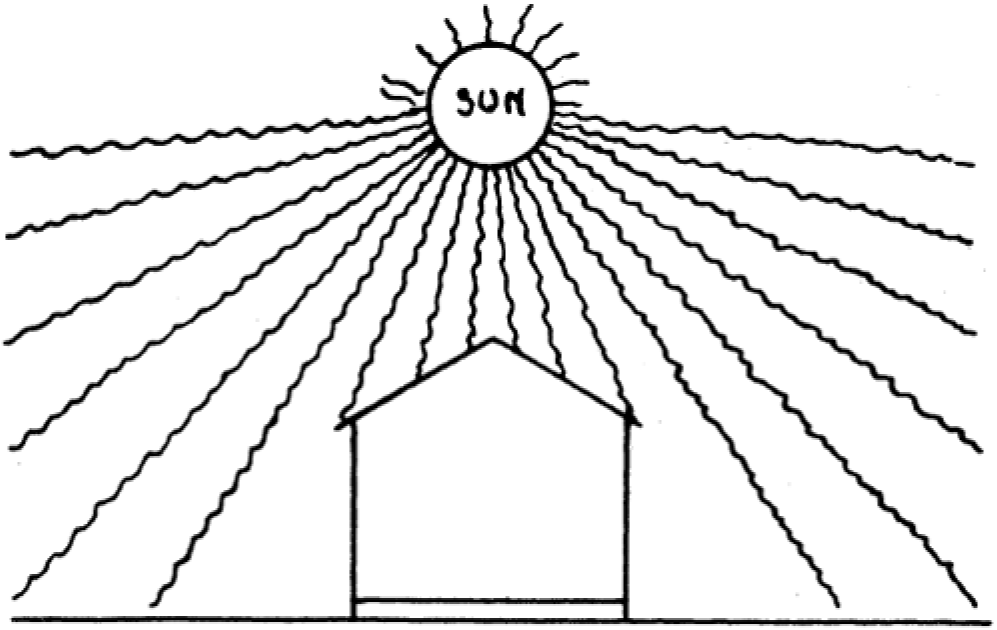

Figure 2F08
Sun's rays radiated to earth

Conduction: If we heat one side of a material, the heat travels through it from the hot side to the cooler side, from which in turn heat may be conducted to another cooler object touching it, or radiated to a cooler object at some distance away.

This transfer of heat through a material is conduction. The hot side gives motion to the molecules, which give motion to nearby molecules, and so on through the material. In doing so, some of the heat energy is given up to the molecules and stays there as heat energy so all of the heat does not get through.

A material that transmits heat easily, with little loss, is called a "conductor" of heat. Some of the best conductors are copper, silver, aluminum, and steel.

A material that does not conduct heat through itself easily is called an "insulator." Some of the better insulators (poor conductors) are cork, cotton, air, and many other materials that are composed of thousands of tiny air cells.

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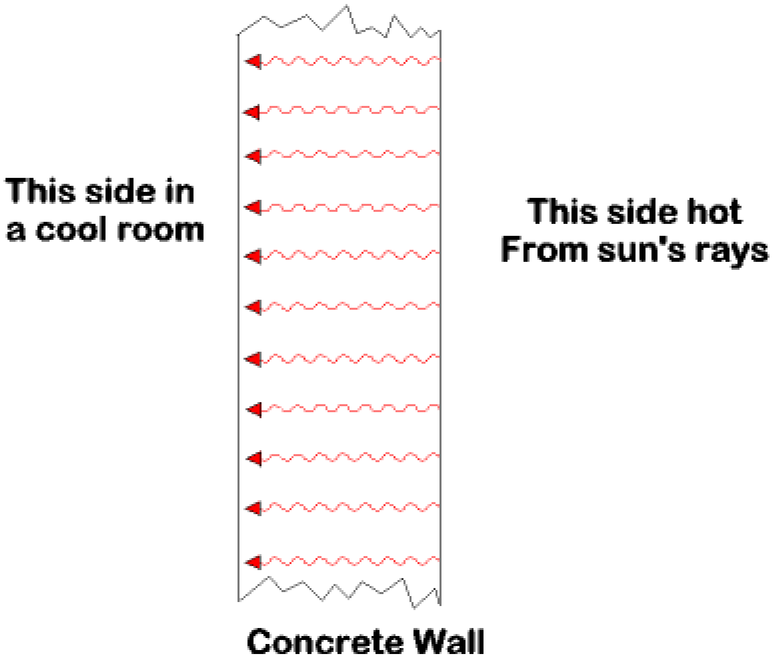

Heat traveling through a solid wall by conduction

Figure 2F09A

Convection: Convection occurs only in fluids (fluids include both liquids and gases or vapors). We know that when a material is warmed, it expands in volume and therefore becomes lighter per cubic foot. In case of fluids, the cooled fluid is therefore heavier and as a result, crowds out the lighter, warmer fluid thus pushing it upward. As illustrated in, Figure 2F09B, this sets up a cycle of circulation of the fluid. This circulation of the fluid carries heat upward on one side and downward on the other side. This means of conducting heat is called convection. It is very important in refrigeration and heating, where a large part of the process is cooling or heating fluids, - water, oil, water vapor, air, etc., - although on many cases we only cool the fluids as a means of carrying heat away or to, foods, human beings or other objects.

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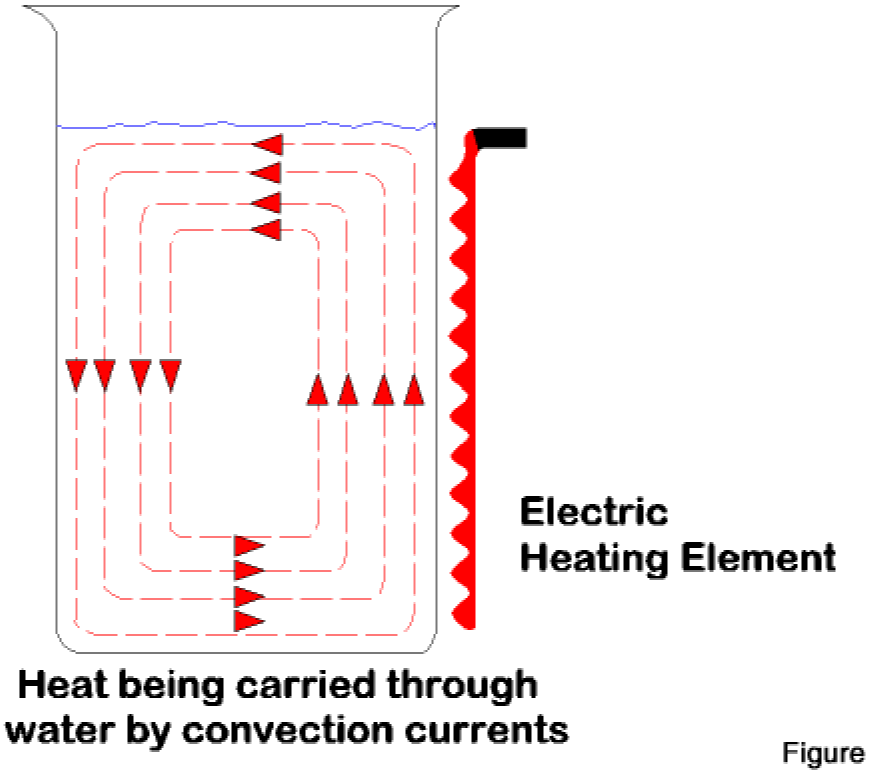

Figure 2F09B

A more detailed explanation of Heat Transfer is given in the "Insulation" section.

EXPANSION AND CONTRACTION

As we mentioned previously, when a solid is warmed, the molecules become more active and move somewhat farther apart, which causes the solid material to become larger, or expand. Some materials expand more than others even with the same rise in temperature.

The rate of expansion of many solids has been measured, and is available in tables. It is necessary for engineers to take this into consideration in designing machines and structures. For example, the rate of expansion of a shaft must be allowed for, to keep it from expanding with the heat and seizing in the bearing. Architects must allow for expansion with heat in designing buildings and bridges to keep them from buckling in hot weather.

In solids, we are usually more interested in the linear (or expansion of one dimension) than in the cubical expansion (overall increase in size or volume). The expansion of a bridge is most important as to its length, for the expansions of all parts of the lengthwise members add together, so a large bridge may be a foot or so longer in summer than in winter. Slip joints are put into the bridge to take up the summer expansion.

The lengthwise expansion (or more accurately, the expansion of one dimension, length, width, or thickness) is measured by what is known as the "Coefficient of Linear Expansion", which is the percentage of increase in length (or width or thickness) of the material for each degree rise in temperature.

For most solid materials, it is a very small fraction of one percent, but if the material is quite long, and if it is warmed through quite a few degrees, the total expansion can be considerable. For example, a 500 foot span of a steel bridge would vary as much as about one-half a foot in length between winter and summer. A 500 foot span of copper power line would vary even more.

In the case of liquids, we are usually more interested in the increase in volume, or cubical expansion, than in the increase in just one dimension. We are well aware what can happen if a refrigerant cylinder is completely filled with liquid refrigerant in a cool room and is then allowed to become warmer. The liquid expands, and since the steel cylinder does not expand at the same rate, the cylinder bursts, not only ruining the cylinder and losing the contents, but more important, perhaps seriously injuring someone.

For example, a Refrigerant-12 service cylinder has an internal volume of about 105 cubic inches. Suppose that we fill it entirely full of liquid Refrigerant-12, leaving no room for expansion, and that the liquid is at 70° when we fill the cylinder. The 105 cubic inches of liquid Refrigerant-12 at 70° weighs 5 lbs. We put this completely filled cylinder into the truck. The cylinder and Refrigerant-12 warm up. When they get to 80°, the Refrigerant–12 has expanded to a little over 106 cubic inches, but the cylinder has expanded very little. Liquid Refrigerant-12 can be compressed so little, that it is almost negligible. When it expands, it exerts a very high hydrostatic or hydraulic pressure against the inner walls of the cylinder, probably about 1,000 pounds per square inch instead of the 70 pounds per square inch pressure of this same Refrigerant–12 at 70°. The cylinder was built to withstand only about 450 to 500 pounds per square inch, so it bursts.

Some cylinders are equipped with pressure relief valves, which open automatically when a predetermined maximum pressure is reached, and close when some of the pressure is purged out.

Suppose that we put only 4-1/2 pounds of Refrigerant-12 at 70° into the cylinder. It will take up only 94 cubic inches, leaving 11 cubic inches for expansion. The cylinder would then have to warm up to 133° before the 94 cubic inches of Refrigerant-12 would have expanded to 105 cubic inches and again filled the cylinder entirely full of liquid. So the cylinder would be safe up to 133°.

NOTE:

Some service cylinders are somewhat larger and will therefore safely hold up to about 5 pounds of Refrigerant-12. See the section entitled "Refrigerant Cylinders", for full information on sizes, capacities and other information on refrigerant cylinders.

MEASURING TEMPERATURE

The expansion of a liquid is used in our most common form of instrument for measuring temperature, the mercury or alcohol thermometer. It starts with a glass tube with a very small bore. A bulb is blown on the bottom end of this tube, and the bulb and part of the tube is filled with a liquid, usually mercury or alcohol which do not freeze at normal temperatures and which have relatively high rates of expansion. A very low vacuum is then drawn on the tube above the liquid, and the top end of the tube is heated and sealed.

It is now ready for calibration. Methods of calibration vary, but the following is one basis of calibration that could be used.

The bulb of the thermometer is put in crushed ice which is 32°. A mark is put on the tube or stem, at the level of the mercury, and this is labeled 32°. The thermometer is then put in boiling water. The liquid in the bulb expands and pushes up into the tube. The bore of the tube is so small that it does not take much additional liquid to cause the level of the mercury to change a great deal.

The top level of the liquid, when the thermometer is in boiling water, is marked 212. Then the distance in between is evenly spaced into 180 marks, and the numbers put on.

The rate of expansion and contraction of the liquid is approximately the same below 32°F and above 212°F, so the same scale is used and marked on the stem, and evenly spaced marks are added below 32°F and above 212°F.

This is the Fahrenheit thermometer, which is the one most commonly used in the United States, Great Britain, Canada, Australia and Germany.

The Celsius thermometer is commonly used in most other countries. On it, the crushed ice temperature is marked 0° and boiling water is marked 100°; the space in between being divided into 100 spaces of 1 degree each. The same-sized spaces are added below 0° and above 100°.

Therefore, 100° Celsius degrees are equal to 180° Fahrenheit degrees, so one Celsius degree is equal to 1.8 Fahrenheit degrees. Conversely, one Fahrenheit degree is only 5/9 of a Celsius degree.

But since the zero of the Celsius thermometer is 32 Fahrenheit degrees or 17.8 (5/9 × 32) Celsius degrees above the Fahrenheit zero, it is necessary to add those 32 degrees when converting from Celsius to Fahrenheit after multiplying by 1.8 (9/5), or subtract the 32 degrees when converting from Fahrenheit to Celsius before multiplying by 5/9. For example:

What is the Fahrenheit reading equivalent to 50° Celsius?

First: 50 × 1.8 = 90

Second: 90 + 32 = 122

So 122°F is equivalent to 50°C.

To convert from Fahrenheit to Celsius is just the reverse. For example:

1. What is the Celsius reading equivalent to 50° Fahrenheit?

   First: 50 - 32 = 18

   Second: 18 × 5/9 = 10

   So, 10°C is equivalent to 50°F.

2. What is the Celsius reading equivalent to 5° Fahrenheit?

   First: 5 - 32 or 32 - 5 = 27 Second: 27 × 5/9 = 15

   However, since 32°F is equivalent to 0°C, and since 5°F is less than 32°F, the C equivalent of 5°F will be below 0°C; therefore, will have a minus sign.

   So -15°C is equivalent to 5°F.

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3. What is the Celsius reading equivalent to -13° Fahrenheit?

   First, since -13°F is below zero F, we must add 32 to get to 0°C, so 13 + 32 = 45.

   Second, 45 × 5/9 = 25

   Again, it is obvious that this is minus 25°C, so -25°C is equivalent to -13°F.

   Expressed algebraically:

   -13 + (-32) = -45

   -45 × 5/9 = -25

There are other means of measuring temperatures; electrically, by thermocouples (two metals together, which, when warmed, generate a very small electric current, and the electric current is then measured by a meter and converted to degrees of temperature); also, electrically, by resistance thermometers (a resistance element whose resistance changes with temperature change, so the current passing through it is measured and converted to degrees); gas thermometers (that use a gas instead of a liquid); and other means.

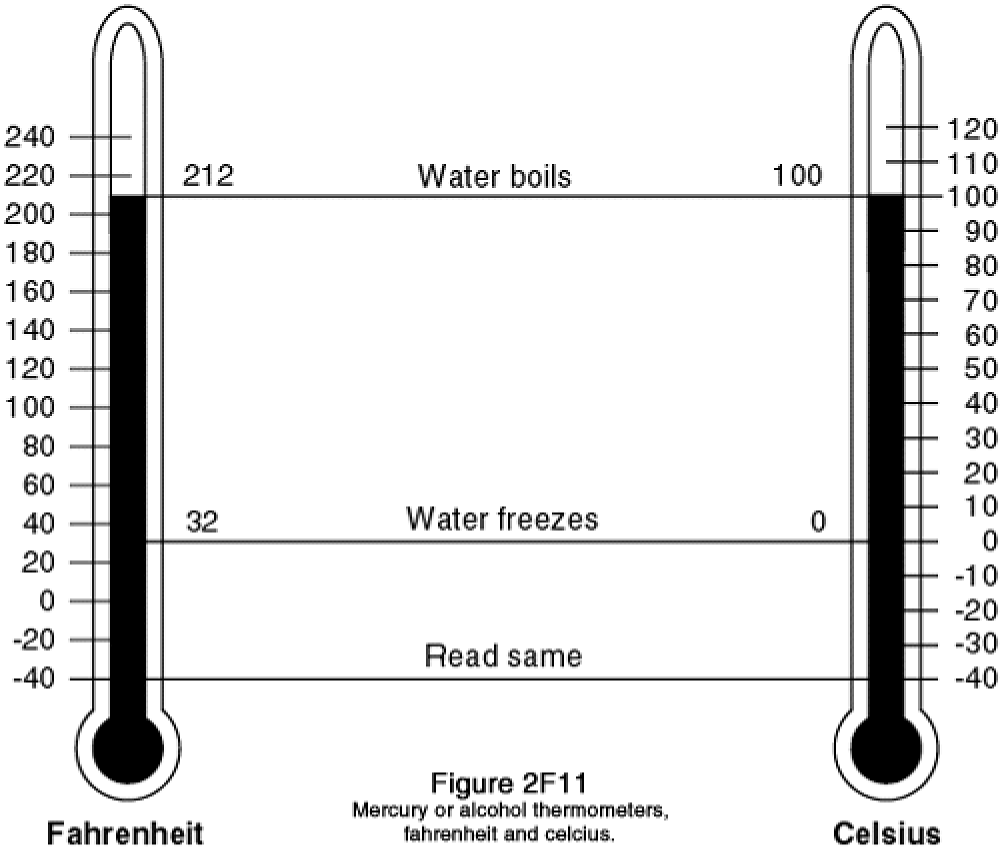

Figure 2F11
Mercury or alcohol thermometers, fahrenheit and celcius.

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ABSOLUTE TEMPERATURES

We said earlier that absolute zero, the point at which there would be no heat whatever and no motion of the molecules, is -460°F below 0°F. (In the Celsius scale, absolute zero is -273°C). Then to convert ordinary thermometer temperatures in Fahrenheit to absolute, we merely add the 460° to the thermometer reading, if it is above 0°F; if it is below 0°F, we subtract it from 460°. For example

1. Convert 50°F thermometer reading to absolute.

   50 + 460 = 510

   So 50°F thermometer is 510° absolute.

2. Convert -20°F to absolute temperature.

   460 - 20 = 440

   So -20°F thermometer, is 440° absolute (abbreviated abs).

ABSOLUTE PRESSURES

We live at the bottom of a sea of air mixed with water vapor, some 50 miles deep. Air and the water vapor in it, has weight. A column of this air and water vapor one square inch in cross sections extending upward from sea level weighs 14.7 (exactly 14,696) pounds, so every square inch of the sea and of land level with the sea, and every ship, person and article, is carrying this weight of 14.7 pounds on each square inch of its surface.

If this one inch square column of air was based on Denver, which is one mile above sea level, the column would not be as long and would therefore weigh less, for we would have to subtract the weight of the air and water vapor one mile long, from sea level up to Denver. Thus, the normal atmospheric pressure at Denver is 12 pounds per square inch.

The farther up we go above sea level, the less the atmospheric pressure. Moreover, the air and water vapor become rarified or thinner, for they do not have as much weight of air and water vapor on them from above that tends to compress them.

At sea level, not only is the pressure of the air and water greater, but the density of the air and water vapor is greater. This is shown by the fact that people have more trouble breathing enough air at high altitudes, where there is less air per cubic foot - its density is less than at sea level.

If there were no air or water vapor surrounding the earth (as is true on the Moon) there would be no atmospheric pressure, - there would be a perfect vacuum and the pressure would be zero absolute.

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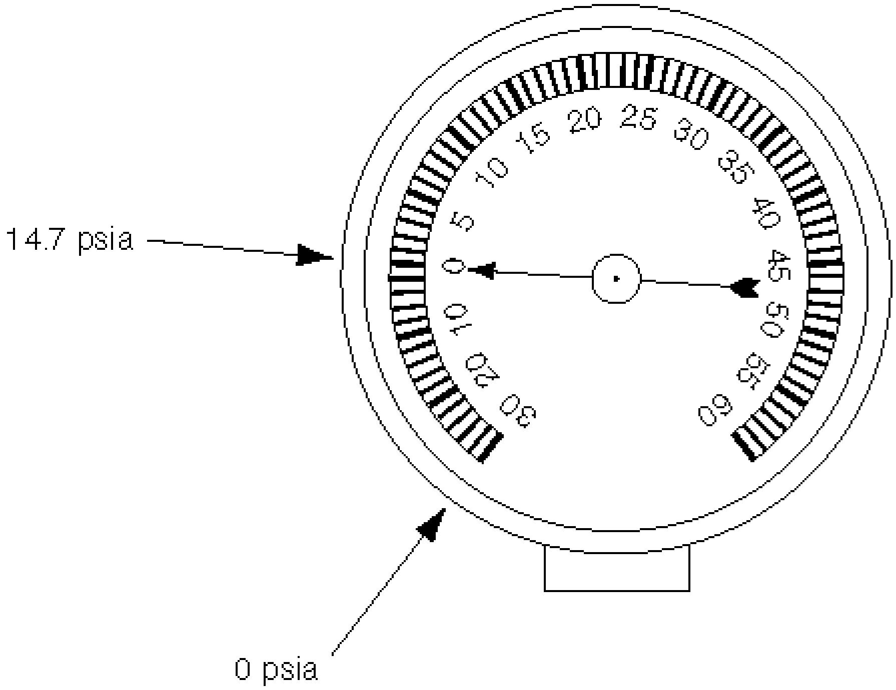

Figure 2F12A Compound pressure gauge, calibrated in psig and in. Hg. vacuum.

We are so accustomed to being in and working in this atmospheric pressure that our pressure gages start at atmospheric pressure, so atmospheric pressure of 14.7 pounds per square inch absolute (abbreviated psia) is zero pounds per square inch gage, (abbreviated psig).

In some types of work, atmospheric pressure is referred to in inches of mercury, abbreviated in.Hg (Hg stands for the Latin word for mercury.) One cubic inch of mercury weighs .491 pounds, so it takes 2.036 cubic inches to weigh one pound. A pressure of 14.696 pounds is therefore equivalent to 29.921 (2.036 × 14.696) inches of mercury.

This is shown by making a U tube each leg of which is 30 inches or over. Mercury is poured into the tube to about halfway. Then all of the air is pumped out of one tube. The air pressure of 14.696 psia will therefore push the mercury upward into the tube having the vacuum; so that the difference in the two mercury levels is 29.921 inches.

This instrument is called a barometer, and is used to measure atmospheric pressure, for atmospheric pressure is not only different according to the altitude of the place, but it also varies from day to day, according to the density of the air and water vapor at that time.

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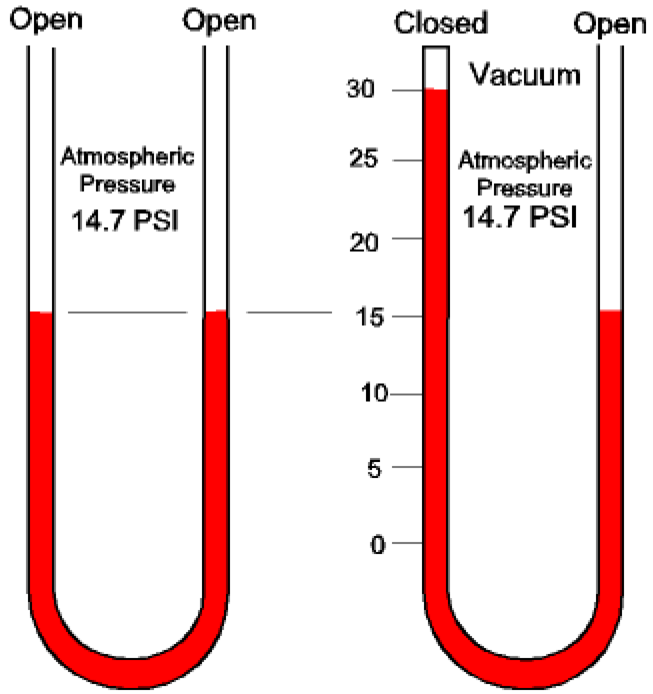

Figure 2F12B

Mecury U Tube and Barometer to measure atmospheric pressure.

Barometric pressure in inches or mercury can be converted to pounds per square inch abs by dividing barometric pressure by 2.036. for example, the barometric pressure at a certain place and at a certain time was 29.27. What was the atmospheric pressure in pounds per square inch absolute?

29.27 ÷ 2.036 = 14.38 psia

Since atmospheric pressure varies from time to time and for different altitudes, 14.696 psia or 29.921 in.Hg. barometer are considered as standard at sea level.

Table 2TI3 shows the standard barometric pressures in inches of mercury and in psia for various altitudes.

Table 2T13 Air Pressures at Different Altitudes

Altitude in Feet	Atmospheric In.Hg.	Pressures Psia
-1000 (Below Sea level)	31.03	15.23
-500 (Below Sea level)	30.47	14.97
-100 (Below Sea level)	30.03	14.76
0 - (Sea level)	29.921	14.696
100 (Above Sea level)	29.81	14.65
200	29.71	14.60

500	29.38	14.44
1000	28.85	14.17
1500	28.33	13.90
2000	27.82	13.67
2500	27.32	13.40
3000	26.82	13.18
3500	26.33	12.92
4000	25.84	12.71
4500	25.36	12.45
5000	24.89	12.23
5500	24.43	11.90
6000	23.98	11.79
7000	23.09	11.35
8000	22.22	10.90
9000	21.39	10.51
10000	20.57	10.08
15000	16.88	8.30
20000	13.75	6.76
25000	11.10	5.45
50000	3.45	1.69
75000	1.04	.51

In refrigeration work, we often refer to pressures below atmospheric pressure, as "inches of vacuum" meaning of mercury pressure less than atmospheric pressure, and our compound gages are calibrated in inches of mercury vacuum below zero on the gage. We can easily convert inches of mercury vacuum (in.Hg vac.) into pounds per square inch absolute (psia), or vice versa.

1. In.Hg.vac. to psia. Subtract the in.Hg.vac. from 29.92 and then divide by 2.036 (or multiply by .491 if you prefer, or for most work, take one-half).

Example -

Convert 18.5 in.Hg.vac. to psia.

First: 29.92 - 18.5 = 11.42

Second: 11.42 ÷ 2.036 = 5.6 psia.

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2. Psia to in.Hg.vac. Multiply psia by 2.036 and subtract it from 29.92.

Example -

Convert 10 psia to in.Hg.vac.

First: 10 × 2.036 = 20.36

Second: 29.92 - 20.36 = 9.54 in.hg.vac.

EXPANSION OF GASES

The expansion and contraction of solids and liquids with change in temperature are enough that they must be considered in many situations, but they are comparatively small, for the molecules of the solids and liquids are held rather closely, and not allowed to fly off by themselves, as is true of gases.

Therefore the expansion and contraction of gases with change of temperature are very large, compared to those of solids and liquids. Moreover, the volume of the gas varies with the container. A gas automatically fills any container that it is put into, regardless of whether the container is small or large. Neither a liquid nor a solid does this. A container for solids or liquids can be partly filled, but a gas container is always full.

PRESSURE VARIES DIRECTLY WITH ABSOLUTE TEMPERATURE, IF VOLUME STAYS THE SAME

Due to the fact that a gas adapts itself to its container, regardless of size, or the amount of gas in the container, another factor is introduced–pressure. If the container is already filled, then a rise in temperature due to adding heat, cannot cause an increase in volume, but it does result in an increase in the pressure of the gas against the inner walls of the cylinder.

Not only do we know that this is true, but the change in pressure with a change in temperature can be easily calculated, - as long as the volume stays the same, as of course it will in a gas cylinder.

It is very simple; the gas pressure goes up at the same rate as the temperature. If the temperature rises 25% or 1/4, the pressure goes up 1/4. If the gas cools down to 2/3 its temperature, the pressure goes down to 2/3 of what it was. Years ago a scientist named Charles discovered this principle, so it is called "Charles' Law."

Charles' Law says that, if the volume remains the same, the absolute pressure of a gas varies as the absolute temperature.

There is one string to this law; the temperatures and pressures must be expressed in absolute temperatures and pressures. But these are easy to determine.

We said that the absolute pressure of a gas in a cylinder changed at the same rate as the absolute temperature of the gas, - if the volume is constant. We can say this mathematically; The first absolute temperature divided by the second absolute temperature equals the first absolute pressure divided by the second absolute pressure, or

$$\frac{\text{First Temperature, abs}}{\text{Second Temperature, abs}} = \frac{\text{First pressure, abs}}{\text{Second pressure, abs}}$$

$$\frac{T_1}{T_2} = \frac{P_1}{P_2}$$

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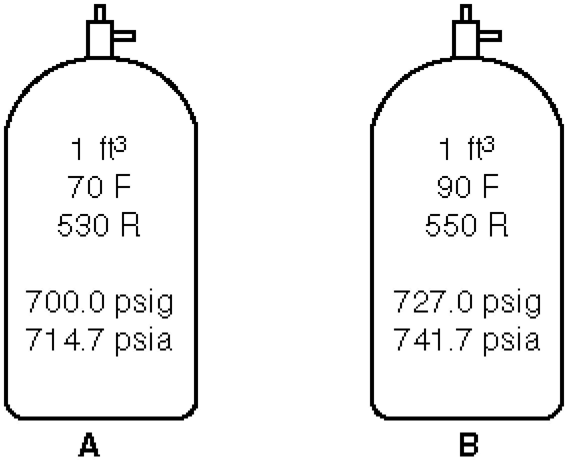

For example, we have a cylinder of nitrogen at 70°, and a gage on it shows a pressure of 700 psig. What will the gage show if the room temperature is raised to 90° (assuming that we wait long enough to be sure that the nitrogen and its container come up to 90°).

70° + 460° = 530° abs or T_1

90° + 460° = 550° abs or T_1

700 + 14.7 = 714.7 psia or P_1

Then

$$\frac{530}{550} = \frac{714.7}{P_2 \text{(the new pressure at 90°)}}$$

To solve this, multiply the 550 by 714.7 and then divide by 530. The answer will be the new pressure.

550 × 714.7 = 393,085

393,085 ÷ 530 = 741.7

So the new pressure at 90° is 741.7 psia or 727 psig (741.7 - 14.7).

VOLUME VARIES DIRECTLY WITH ABSOLUTE TEMPERATURE, IF PRESSURE STAYS THE SAME

Now suppose that instead of having this gas in a steel cylinder that keeps the gas from expanding (its volume remains constant), the gas is in a cylinder that had a loose bottom that can slide up and down in the cylinder just like a piston in a compressor. Then if the gas in the cylinder is warmed, it can expand and push the piston downward, but the pressure inside the cylinder would remain the same, for the piston would merely slide downward if the pressure inside the cylinder tended to become greater than that outside the cylinder and below the piston.

Now we have a condition of the volume changing with change of temperature, but the pressure remaining constant. Is there a way to predict what the volume will be, with a change in temperature, but with the pressure constant?

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There is, and it is very much the same as when the volume remained constant and the pressure changed. This principle is, that the volume changes as the change in temperature, but again it is as the absolute temperature change. This principle is called Gay-Lussac's Law.

We Can Say This Mathematically: If the pressure remains constant, the first absolute temperature divided by the second absolute temperature equals the first volume divided by the second volume or:

$$\frac{\text{First Temperature, abs}}{\text{Second Temperature, abs}} = \frac{\text{First Volume}}{\text{Second Volume}}$$

$$\frac{T_1}{T_2} = \frac{V_1}{V_2}$$

For example, we have a cylinder as shown in Figure 2F14B, with the loose piston, so that the pressure remains the same. The original volume with the piston in the upper position is 1 cubic foot (1728 cubic inches). The temperature is 70°. What will the volume be at 90°?

70° + 460° = 530° abs or T_1

90° + 460 = 550° abs or T_2

$$\frac{530°}{550} = \frac{1\text{ cu ft}}{V_2\text{, the new volume at }90°}$$

Cross multiplying and dividing:

1 × 550 = 550

550 ÷ 530 = 1.04 cu ft

Thus, the volume changed from 1 cu ft to 1.04 cu ft. when the temperature rose from 70° to 90°.

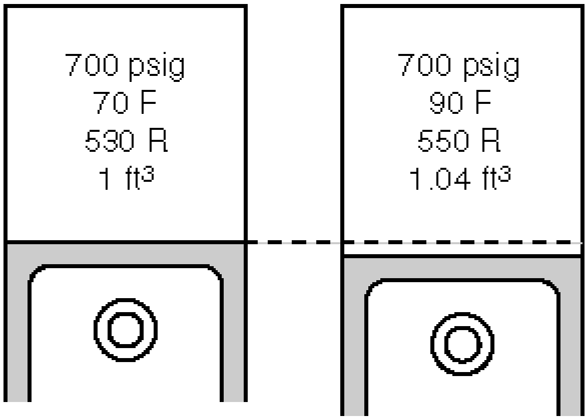

Figure 2F14B Illustrating Gay-Lussac's Law

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PRESSURE VARIES INVERSELY WITH VOLUME IF THE TEMPERATURE STAYS THE SAME

There is a third condition; what happens to the pressure if the volume changes, but the temperature stays the same?

In the two previous conditions: Charles' Law (change of pressure with change of temperature, with volume constant) and Gay-Lussac's Law (change of volume with a change in temperature, with the pressure constant) the proportion was direct; that is, the pressure and volume went up as the temperature went up, and down as the temperature went down.

In this third condition, with the temperature constant, the pressure goes down as the volume goes up, or vice versa, the pressure goes up as the volume goes down, so it is what is called an inverse ratio.

This is called Boyle's law. Mathematically, it is stated:

$$\frac{\text{First Volume}}{\text{Second Volume}} = \frac{\text{Second pressure, abs}}{\text{First pressure, abs}}$$

or

$$\frac{V_1}{V_2} = \frac{P_2}{P_1}$$

For example, Figures 2F15A and 2F15B show a cylinder with a loose piston, and with the position of the piston shown in Figure 2F15A the volume of the cylinder above the piston is one cubic foot and the pressure is 20 pounds per square inch gage or 34.7 psia. In Figure 2F15B the piston has been slowly lowered twice as far, so now the volume is two cubic feet. What happens to the pressure? It goes down in the same proportion as the volume went up, so:

$$\frac{\text{1 cubic foot}}{\text{2 cubic feet}} = \frac{P_2\text{, the second pressure, abs}}{\text{34.7 psia}}$$

Cross multiplying and dividing:

1 × 34.7 = 34.7

34.7 ÷ 2 = 17.35

So the pressure drops to 17.35 psia or 2.65 psig (17.35-14.7). Therefore, with the volume doubled, the absolute pressure is one-half, but the gage pressure drops from 20 psig to a little over 2.5 psig.

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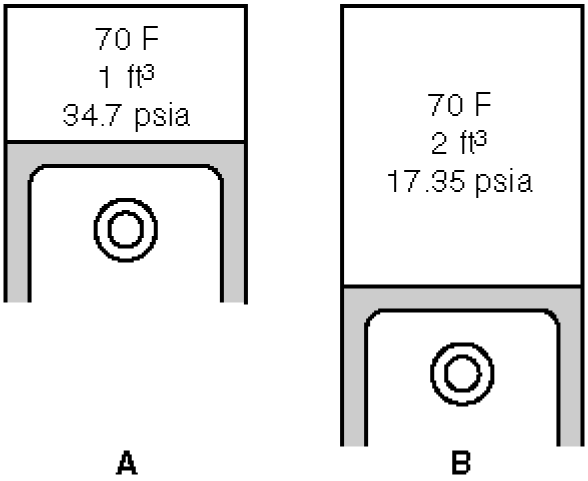

Figure 2F15A and 2F15B Illustrating

This holds true if the second pressure becomes less than zero gage, that is, into a vacuum. For example, we have a cylinder with 2 cubic feet above the piston, and with a pressure of 10 pounds per square inch gage or 24.7 psia, as in Figure 2F15C.

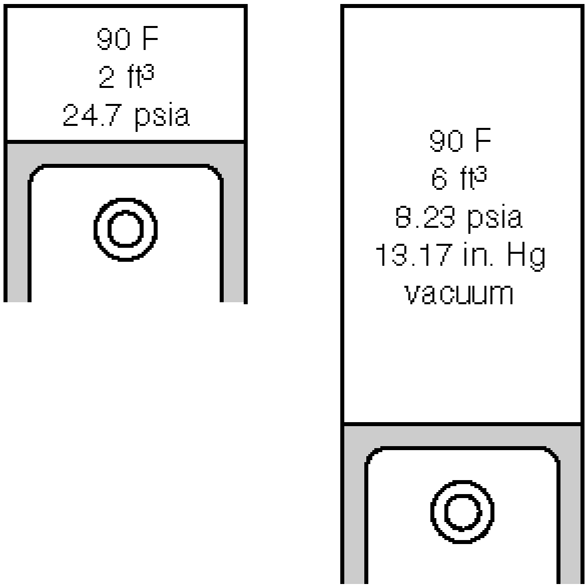

Figure 2F15C Boyle's Law, also those of Charles and Gay-Lussac, apply to vacuum when expressed in psia

The piston is lowered, but this time to three times as far. The volume becomes 6 cubic feet instead of 2 cubic feet.

$$\frac{2}{6} = \frac{P_2\text{, the second pressure, abs}}{24.7\text{ psia}}$$

Cross multiplying:

2 × 24.7 = 49.4

49.4 ÷ 6 = 8.17 psia

But 8.17 psia is less than 14.7 psia or atmospheric pressure, so the second pressure is actually into a vacuum. If we want to express it in inches of vacuum, we can convert it:

14.7 - 8.17 = 6.53

6.53 × 2.036 = 13.3 in.Hg

Thus, by increasing the volume three times we have cut the absolute pressure to one-third of the original, but the gage pressure has been reduced from 10 psig to 13.3 inches of vacuum.

Obviously, if the piston is pushed upward slowly to one-half its height, the volume becomes one-half, and with the temperature remaining the same, the absolute pressure is doubled, so if the cylinder above the piston is originally 2 cubic feet and its pressure is 5 psig or 19.7 psia, and the piston is slowly pushed up halfway, then:

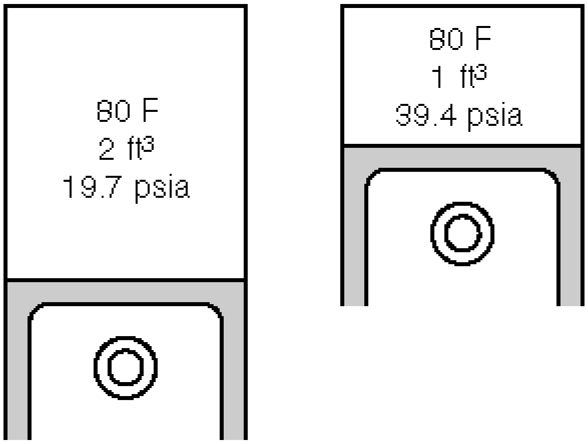

Figure 2F16 Boyle's Law in volume reduction

$$\frac{2}{1} = \frac{P_2\text{, the second pressure, abs}}{19.7\text{ psia}}$$

Cross multiplying:

2 × 19.7 = 39.4

39.4 ÷ 1 = 39.4 psia

To reduce 39.4 psia to gage pressure, we subtract 14.7, leaving 24.7 psig. So although the absolute pressure was doubled by halving the volume, the gage pressure was increased from 5 psig to 27.7 psig; over 5 times.

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WHAT HAPPENS WHEN TEMPERATURE, PRESSURE, AND VOLUME ALL CHANGE?

In Charles' Law, the volume remains constant, and the pressure changes with change of temperature.

In Gay-Lussac's Law, the pressure remains constant, and volume changes with change of temperature.

In Boyle's Law, the temperature remains constant, and the pressure changes with change in volume.

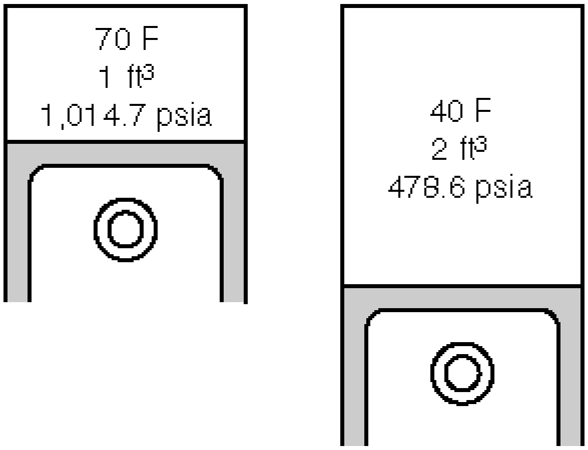

Figure 2F16B Temperature, volume & pressure all vary

All three of these help us in understanding how pressures, volumes, and temperatures change in containers of gas, and in fact we can calculate the pressures, volumes, and temperatures, as shown in the foregoing examples.

It will be noticed, however, that in each of these three laws, something remained constant, - the pressure, the volume, or the temperature. Gases are not always so considerate; all three, pressure, volume and temperature, may change at the same time; that is, none of them remain constant.

To overcome this difficulty and allow us to still calculate values with all three properties varying at the same time, the three formulas can be combined, so we now have:

$$\frac{\text{First Temperature}}{\text{Second Temperature}} = \frac{\text{First Press.} \times \text{First Vol.}}{\text{Second Press.} \times \text{Second Vol.}}$$

or

$$\frac{T_1}{T_2} = \frac{P_1 \times V_1}{P_2 \times V_2}$$

Remember that the pressures and temperatures must be given in absolute values. To show how this combined formula may be used:

We have a cylinder of 1 cubic foot capacity filled with nitrogen at a pressure of 1,000 psig (1,014.7 psia) and at a temperature of 70°F. We pass this into a cylinder of two cubic feet capacity, and we find that in doing so, the temperature has dropped to 40° for when the gas expands from 1 cubic foot to 2 cubic feet, it takes heat energy to allow the molecules to separate, so the gas cools.

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$$\frac{70+460}{40+460}=\frac{1014.7\times 1}{\text{Second pressure}\times 2}$$

Cross multiply

Second Pressure × 2 × 530 = 500 × 1014.7 × 1

Second Pressure × 1060 = 507,350

Second Pressure = 507,350 ÷ 1060

Second Pressure = 478.6 psia

Second Pressure = 478.6 - 14.7 or 463.9 gage

or approximately 464 psig

Suppose that we now let this cylinder stand until it warms up to the room temperature of 70°. Using Charles' Law, the absolute pressures vary as the absolute temperature, if the volume remains the same; and in this instance, it will, for the gas stays in the 2 cubic foot cylinder. Now the First Temperature is 40°F (500° abs), and the Second Temperature 70°F (530 abs). Since the First Pressure is 463.9 psig (478.6 psia) the solution will be:

$$\frac{500}{530}=\frac{478.6}{\text{Second pressure}}$$

Cross multiplying and dividing:

Second Pressure × 500 = 530 × 478.6

Second Pressure = 253,658 ÷ 500

Second Pressure = 507.3 psia

Second Pressure = 492.6 psig

So the one cubic foot of nitrogen at 70° and at a pressure of 1,000 pounds gage, drops to 40° and a pressure of 464 pounds gage when put into a 2 cubic foot cylinder. If then allowed to warm up to 70°, the pressure of the nitrogen in the 2 cubic foot cylinder rises to 492.6 pounds gage.

DENSITY OF MATERIALS

Up to this point we have spoken only of temperature, pressure, and volume, of the gas. We have not said anything about the amount or weight of the gas, and certainly gas has weight, the same as a liquid or solid does, although not as much weight for the same volume.

If we have a piece of ice, a gallon of water, or a cylinderful of gas, we have a definite volume of those materials, and that volume of the material has a certain weight.

If we cut the piece of ice exactly in half (reduce the volume to one-half) we also cut the weight in half, A half gallon of water weighs only one-half as much as a full gallon of water (at the same temperature). A 1 cubic foot capacity cylinder can hold only one-half as much nitrogen or other gas by weight (at the same pressure and temperature) as a 2 cubic foot cylinder.

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So there is a definite connection between volume and weight of the material. That connection is referred to as Density, and it is based on the weight per cubic foot.

It is often said that lead is heavier than wood, or that water is heavier than oil. These are not correct statements, for they do not take the size, or volume, into consideration. Certainly a quart of water is not as heavy as a gallon of oil.

We can correctly say that lead is heavier per cubic foot than wood, or that water is heavier per cubic foot than oil, but it is much easier to say merely that lead has a greater density than wood, or that water has a greater density than oil; for then everyone knows that we are talking about the weight per cubic foot, for density always means per unit volumes

Remember that the volume of materials changes with temperature. A cubic foot of ice at 5°F weighs 57-3/4 pounds, so its density is 57-3/4 lbs. per cu ft. If this cubic foot of ice is warmed to 32°F, it will expand to a volume of 1.004 cu ft. To get it back down to 1 cubic foot at 32°F, we would have to shave off 7 cubic inches, which weighs 1/4 pound. Thus, 1 cubic foot at 32°F would weigh less and its density would become 57-1/2 pounds per cubic foot.

For ordinary solids and liquids at room temperatures, the change in density with change in volume may not be enough to require consideration, but the densities of some materials, especially some liquids and gases, vary widely with change in temperature, so it must be borne in mind that density depends upon temperature. For accuracy, we must give the temperature of the material when we refer to its density.

Table 2T23 shows the densities of some common materials and the temperatures at which those densities are measured.

Table 2T23 Approximate densities at normal room temperatures, given in pounds per cubic foot

Material	Density
Solids	
Aluminum	165
Brass	534
Brick, hard	128
Brick, soft	103
Bronze	509
Cinders	40 to 45
Clay, dry	63
Clay, damp	110
Coal, hard	97
Coal, soft	84
Coke	7
Copper	556
Cork	15
Dirt, loose, dry	76
Dirt, loose, damp	78
Fats	58
Flour	28

Glass	162
Gold	1205
Granite	159
Hay, baled	20
Ice 32°F	57.5
Ice 5°F	57.75
Iron, cast, gray	442
Iron, wrought	485
Lead	710
Leather	59
Limestone	153
Marble	156
Paper	58
Potatoes	44
Rubber	94
Salt	48
Sand, gravel, loose, dry	90 to 105
Sand, gravel, loose, wet	126
Sandstone	110
Silver	656
Steel, machine	487
Steel, tool	481
Tar	75
Tin	459
Wood, birch	44
Wood, cedar	22
Wood, cypress	29
Wood, fir, Douglas	32
Wood, hickory	48
Wood, maple, hard	43
Wood, maple, soft	33
Wood, pressed	82
Zinc	440
Liquids	
Alcohol, ethyl, 100%	49
Alcohol, methyl, 100%	50
Acid, muriatic, 40%	75
Acid, nitric, 91%	94
Acid, sulfuric, 87%	112
Gasoline	45
Kerosene	50

Mercury	847
Oils, vegetable	58
Oils, mineral, lubricants	57
Petroleum	54
Turpentine	54
Water, 39°F	62.43
Water, 32°F	62.42
Water, 72°F	61.94
Water, 212°F	59.83
Gases, dry, at 68°F and 14.7 psia	
Acetylene	0.06754
Air	0.07528
Ammonia	0.0442
Carbon dioxide	0.1142
Ethylene	0.0728
R-12	0.31362
R-22	0.22433
HFC-134a	0.29411
Hydrogen	0.00523
Methyl chloride	0.1309
Nitrogen	0.07274
Oxygen	0.08305
Sulfur dioxide	0.1663

SPECIFIC VOLUME OF MATERIALS

In some problems or discussions, it is easier to compare volumes of materials instead of weights, but just as with density it is necessary to have some standard weight on which to base the volume. In density we deal in weight per standard volume, - pounds per cubic foot. So compare volumes we simply reverse this and deal in volume per standard weight, cubic feet per pound.

This we call Specific Volume and it is the reciprocal of density, that is, it is equal to one divided by the density. Example: Dry cinder block has a density of about 100 pounds per cubic foot. Therefore, one pound of dry cinder block must occupy 1/100 or .01 of a cubic foot, which is the specific volume of dry cinder block. The density of dry cork is about 15 pounds per cubic foot; so the specific volume of dry cork is 1/15 or .067 cubic feet per pound. The density of kerosene is 50 pounds per cubic foot, so its specific volume is 1/50 or .02 cubic feet per pound.

The above densities and specific volumes are based on a temperature of 39°F. At higher temperatures, the densities will be less, and the specific volumes greater; at lower temperatures, the densities will be more and the specific volumes less.

Instead of referring to the density, as so many pounds per cubic foot, it has been customary with certain materials, especially liquids and in certain industries, to refer to their Specific Gravity, which compares their density with that of water. If a material has a specific gravity of 5, that means that it is 5 times as "heavy" as water. Since the density of water (at 39° which is considered standard) is 62.4 pounds per cubic foot, the density of a material that has a specific gravity of 5 would be 5 × 62.4 or 312 pounds per cubic foot. Lubricating oils have a specific gravity of about .913 or 91.3%, so their density is .913 × 62.4 or about 57 pounds per cubic foot.

A material that has a specific gravity of 1, would have the same density as that of water, 62.4 pounds per cubic foot, for the specific gravity of water is 1.

MEASURING CHANGES IN SPECIFIC VOLUME, DENSITY, PRESSURE OR TEMPERATURE

Now let us get back to our study of how gases behave with changes of temperature, volume, or pressure. When we were studying them, we did not mention weight nor density. We assumed, however, that we did not change the amount or weight of the gas, for then the statements we made could not have held true. For example, if we added nitrogen to a cylinder while we were warming the nitrogen, naturally the pressure would go up much faster than the temperature. So we were assuming that the weight of the gas in the cylinder remained the same.

In other words, when comparing the volumes we had to keep in mind that the two volumes must weigh the same, that is, they must be the same amount of gas by weight.

In Boyle's Law, for example, which says that if the temperature remains the same, the absolute pressure varies inversely as the volume, then we can use the specific volumes which are cubic feet per pound. This formula was:

$$\frac{V_1}{V_2} = \frac{P_2}{P_1}$$

and cross multiplying

$V_1 \times P_1 = V_2 \times P_2$

Now if V_1 and V_2 are specific volumes of cubic feet per pound of gas, and P1 and P2 are pressures in pounds per square inch absolute, this tells us that if the temperature does not change and that if we multiply the number of cubic feet per pound of any gas by its absolute pressure, we always get the same answer, because the pressure is large for a small volume and small for a large volume.

If we knew what that amount was, we could use it very handily, for then at the same temperature, we could divide that number by the pressure and get the volume, or divide the number by the volume and get the pressure.

But what about for other temperatures? Do we have to have a different number for each temperature? Yes, but it has been found that this number always equals the absolute temperature multiplied by a constant amount, regardless of what the temperature is.

That constant amount is called the Gas Constant, and it is the same for all temperatures, pressures and volumes of the same gas, but each gas has its own Gas Constant. Reference handbooks give tables showing the Gas Constants for the various gases as shown below.

Gas Constants

Gas	Gas Constant
Air	53.30
Oxygen	48.31
Nitrogen	55.16
Hydrogen	766.80
Carbon Dioxide	35.13
Ammonia	90.77
Sulphur Dioxide	24.13
Methyl Chloride	30.62
Freon 12	12.79
Freon 22	17.88

*The gas constant of any gas can be found by dividing the number 1546, by the Molecular Weight of that gas, which may also be found in handbooks.

There is only one "catch" to this, and that is that the pressure must be given in pounds per square foot absolute, instead of the usual pounds per square inch absolute. This is easily done, for there are 144 square inches in a square foot, so we merely multiply the pressure in pounds per square inch absolute by 144, and we have the pounds per square foot absolute (abbreviated psfa).

For example: We have a cylinder of nitrogen in a 70° room. The pressure gage showed 2,250 pounds per square inch gage, which would be 2,264.7 psia, when the cylinder was full, and the cylinder weighed 92 pounds 14 ounces. With the cylinder empty, and the nitrogen pumped out to a 29.9 inch vacuum, the cylinder weighed 70 pounds 4 ounces, so the nitrogen itself weighed 22 pounds 10 ounces or 22-5/8 lbs. (92 lb 14 oz − 70 lb 4 oz). What is the internal volume of the cylinder?

The formula is written:

PV = RT (R is the Gas Constant)

Press. × Spec.Vol = Gas Constant × Temp.abs

The absolute pressure in psia is 2,250 + 14.7 or 2,264.7; in pounds per square foot, it is 2,264.7 × 144, or 326,117. The absolute temperature is 70 + 459.6 or 529.6 and the gas constant for nitrogen is 55.16, so the formula becomes:

326,117 × Spec.Vol. = 55.16 × 529.6

326,117 × Spec.Vol. = 29,213

Spec. Vol. = 29,213 ÷ 26,117

Spec. Vol. = .0896 cu. ft. per lb.

Then at 70°, one pound of nitrogen at a pressure of 2,250 pounds gage occupies a volume of .0896 cu.ft. Since the weight of the nitrogen was 22.625 pounds (92 lb. l4 oz. - 70 lb. 4 oz.) the volume of the cylinder would be the total weight of the nitrogen multiplied by the volume of one pound of nitrogen, or 22.625 × .0896 = 2.03 cubic feet.

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Thus, we find that the internal volume of this cylinder is 2.03 cubic feet. This formula is useful in many other ways also.

MIXTURES OF GASES

It will be remembered that the molecules of a gas are quite free, and fly at high velocities in a straight line until they strike the walls of the cylinder or other container, or they may strike other molecules. At any rate, they are in motion, but very far apart.

If a very small amount of gas, say 1 cubic inch, is put into a 1 cubic foot cylinder, the 1 cubic inch of gas rapidly expands 1,728 times to entirely fill the 1 cubic foot (1,728 cubic inches); that is, the molecules are no longer limited to the 1 cubic inch space and are free to fly to the limits of the 1 cubic foot space.

What we call "pressure" is the force of the molecules striking the container, and of course it is exerted against all of the walls of the cylinder in the same amount, so wherever we measure the pressure in the cylinder it is always the same.

The pressure must be less in the 1 cubic foot cylinder than in the 1 cubic inch, for there are much fewer molecules striking a square inch of the larger cylinder than the small one.

In any cylinder containing a gas only, there are relatively large spaces between the molecules, for they are relatively far apart. In fact, they are so far apart and there is so much empty space between them, that if we let in a cubic inch of some other gas, the molecules of this second gas rapidly fly to all parts of the 1 cubic foot cylinder; consequently, the second gas also completely fills the cylinder just the same as if the first gas were not there at all.

When the second gas is first let into the cylinder, there is some opposition by the first gas, for the molecules strike one another. Soon, however, the second gas completely fills the cylinder the same as if the first gas was not there at all, that is, the same as if it were a perfect vacuum.

The molecules of this second gas strike the walls of the cylinder and thus create its pressure independently of the first gas, so not only do each of the two gases occupy the cylinder, but each exerts its own individual pressure.

However, the total pressure on each square inch of the walls of the cylinder must be due to the pressure of each of the two gases, that is, the total pressure is equal to the pressure of each of the two gases added together. Each gas has its own partial pressure, but the total pressure is the sum of these two partial pressures.

This is known as the law of partial pressures and is called Dalton's Law, after the scientist who first discovered it.

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PARTIAL AND TOTAL PRESSURES

Let us take an example: In a 70° room we have a cylinder with an internal volume of 1 cubic foot. We pump a "perfect" vacuum on it, so there is nothing in the cylinder. Into this we now introduce 2 ounces of nitrogen also at 70°. These 2 ounces of nitrogen expand to fill the 1 cubic foot. In expanding, it cools itself below 70°, but after awhile warms back up to 70°. We can calculate the pressure by means of the gas law (PV = RT), using the gas constant for nitrogen of (55.16) as R. The specific volume of the gas will be 8 cubic feet per pound (1 ÷ 1/8 of a pound per cubic foot, which is the weight of .2 ounces of nitrogen in a 1 cubic foot cylinder) and the temperature 530° or (460° + 70°) so,

$$PV = RT; \quad P = \frac{RT}{V}(\text{psfa})$$

$$\text{pressure, psia} = \frac{55.16 \times 530}{8 \times 144} = \frac{29{,}234.8}{1{,}152}$$

Partial Pressure = 25.38 psia, or 10.68 psig.

Now on top of this nitrogen we put 1 pound of R-12, and we can calculate the pressure for R-12 only, the same as we did for the nitrogen and just as if the nitrogen were not in the cylinder.

The density of the R-12 will be 1 lb per cu.ft., so the specific volume will be 1 ÷ 1 or 1 cubic foot per pound. The gas constant for R-12 is 12.79. At first the R-12 will cool itself, but finally it will warm up to 70°F (or 530° absolute). So the partial pressure of the R-12 will be:

$$144\,PV = 12.79 \times 530$$

$$P = \frac{6{,}778.7}{144 \times 1}$$

Partial pressure = 47 psia, or 32.3 psig.

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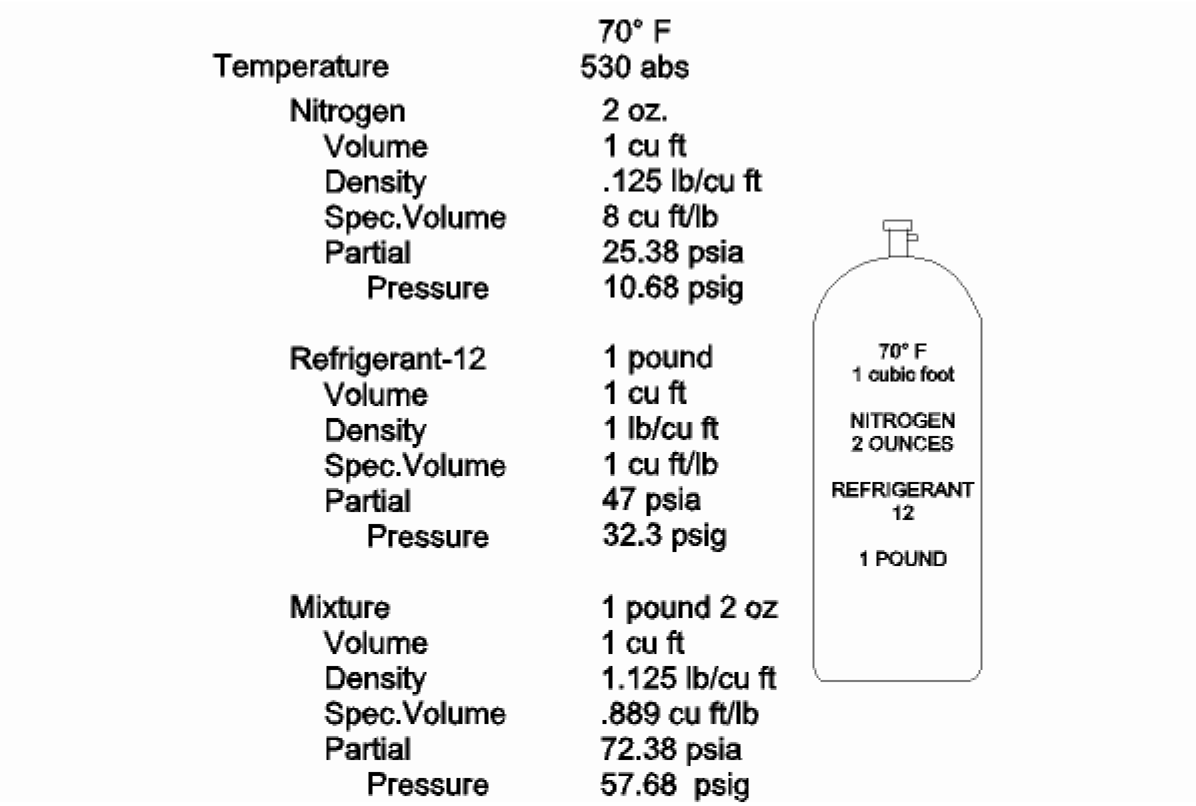

Temperature	70° F 530 abs
Nitrogen	2 oz.
Volume	1 cu ft
Density	.125 lb/cu ft
Spec.Volume	8 cu ft/lb
Partial Pressure	25.38 psia 10.68 psig
Refrigerant-12	1 pound
Volume	1 cu ft
Density	1 lb/cu ft
Spec.Volume	1 cu ft/lb
Partial Pressure	47 psia 32.3 psig
Mixture	1 pound 2 oz
Volume	1 cu ft
Density	1.125 lb/cu ft
Spec.Volume	.889 cu ft/lb
Partial Pressure	72.38 psia 57.68 psig

Figure 2F20 Illustrating Dalton's Law

So in this 1 cubic foot cylinder we have 2 ounces of nitrogen and 1 pound of R-12. The size of the cylinder has not changed, but it now contains 1 pound 2 ounces of gasses. The density of the mixture is 1.125 pounds per cubic foot and its specific volume is .889 cubic feet per pound (1 ÷ 1.125).

The nitrogen has a partial pressure of 25.38 psia, and the Refrigerant-12 a partial pressure of 47 psia; so the total pressure is 72.38 psia or 57.68 psig.

Therefore, if we had a gage on this cylinder, it would read 57.68 psi in a 70° room.

If we connect a nitrogen cylinder to this 1 cubic foot cylinder and add some more nitrogen, we could build the nitrogen partial pressure up, and this would raise the total pressure, but the partial pressure of the R-12 would remain unchanged at 47 psia. The only way to change the partial pressure of the R-12 would be to warm the cylinder up a few degrees, or put in some more R-12. Warming the cylinder would also raise the partial pressure of the nitrogen, but putting in more R-12 would not affect the partial pressure of the nitrogen.