ENERGY

The term energy is often used in reference to the capacity of doing work. In physics, the term specifically refers to the force required to displace a body a certain distance. (You will see that in Cryogenics the term energy is used in a slightly different way.)

The most commonly thought of unit of energy is the **watt**. A watt is not exclusively electrical, even though electrical power is measured in watts. (Power consumption of an incandescent light can also be expressed in horsepower.) A watt is a unit of power equal to about 1/746 horsepower (HP), or 1 HP is equal to 746 watts. The Research Department's satellite refrigerators require ~600 watts @ 4.2°K.

In normal refrigeration, British thermal units (BTU's) are the units used to describe the size or capacity of a refrigerator. A **BTU** is the energy needed to raise the temperature of 1 pound of water from 63°F to 64°F. A ton of refrigeration is based on the number of BTU's required to melt a ton of ice (or freeze a ton of water) in 24 hours (288,000 BTU). 1 ton of refrigeration equals 12,000 BTU/hr.

A **joule** is the most commonly used term in reference to units of work. The unit of force is the newton, which is the force that gives a standard kilogram an acceleration of 1m * s^{-2}. The unit of distance is the meter. A joule is equal to 1 *newton meter* (1 N * M). (To translate this into something a little more tangible, a joule is approximately equal to the energy produced by the friction of rubbing your thumb and forefinger together.)

The efficiency of a cryogenic system is dependent on its methods of energy transfer through the performance of work and the transfer of heat. These concepts will be further explained in the sections on **Refrigeration and Liquefaction Principles** and in **Expansion Engines**.

CONVERSION FACTORS

1 lb. = 453.6 gms.
1 cu. ft. = 28.316 liters = 7.481 gal.
1 gal. = .1337 cu. ft. = 3.785 liters =231 cu. in..
1 BTU = 1054.8 joules
1 watt = 3.413 BTU/hr.

Helium @ 70° F, 1 atm	Air @ 70° F,1 atm
1Kg = 213.23 cu. ft.	1 Kg = 29.42 cu. ft.
1g = .21323 cu. ft.	1g = .02942 cu. ft.
60 g/s = 12.7938 CFS	60 g/s = 1.7652 CFS
60 g/s = 767.628 CFM	60 g/s = 105.912 CFM

HEAT TRANSFER

There are three forms of heat transfer; **conduction**, **convection**, and **radiation**. Heat is always transferred from the higher temperature to the lower temperature. It is important to understand that there is no cold, only a lower level of heat. Think of it this way, the amount of heat in ice is lower than that in a cup of hot coffee.

> **Conduction**...when an object is warm on one end and cold at the other there is heat transfer from the warm end to the cold end. Heat transfer stops when equilibrium is reached. (Heat is CONDUCTED through the walls of a house or through the walls of a pipe.) The rate of conductive heat transfer is proportional to the temperature difference and to the thermal conductivity.
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> **Convection**...when a fluid at one temperature flows over an object at a different temperature, heat transfer occurs. (Air blowing over a hot surface is an example of CONVECTION, as is water flowing over a hot surface.) The rate of convective heat transfer is proportional to the temperature difference, the velocity of the flow, and the type of fluid.
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> **Radiation**...takes place without any medium. (As in solar RADIATION, or with heat radiating from a fire.) The rate of radiative heat transfer is proportional to the temperature difference and the emissivity of the surface. Emissivity is the relative ability of a surface to radiate energy (heat) as compared with that of an ideally black surface. It is also a ratio of how much heat is absorbed to the total radiation energy.
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> Example: If you were to take a hot branding iron and touch it, the heat would burn your hand through **conduction**. If you placed your hand above the branding iron, you would feel the warmth of the iron carried by **convection** through the upward moving air currents. And finally, you could feel the hot iron's heat **radiation** by putting your hand along side or under the branding iron.

The major problem of any helium cryogenic system is that of heat leaks. There may be conduction up the heat exchanger and internals, or radiation heat leaks from various points between the refrigerator and the magnets. Heat leaks can be minimized by the use of **vacuum jackets** and **nitrogen shields**. These and other design techniques can significantly reduce heat leaks and their resulting draw on energy and lost efficiency.

ENTHALPY (HEAT)

An engineer will define enthalpy by the equation $H = U + PV$, where U is the internal energy, PV is the product of pressure and volume, and H is the enthalpy. It's common to hear an engineer explain that the change in enthalpy is a measure of the heat absorbed by a system in a constant pressure process. More simply, you could call it a measure of the energy of a system per unit mass.

Operators might better concentrate on understanding the following three terms; **sensible** heat, **latent** heat, and **total** heat.

> **Sensible heat**... is a <u>change in temperature</u> of a substance <u>with no change in state</u>. Water, as it exists between 32°F and 212°F, represents sensible heat in the heating of 1 lb. of water. It takes approximately 180 BTU's to make this temperature change of 32°F to 212°F.
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> **Latent heat**... is the heat required to <u>change the state</u> of a substance with <u>no change in temperature</u>. Water at 32°F represents the latent heat required to convert water to ice or ice to water. (The latent heat of fusion of 1 lb. of water is ~140 BTU's.) Water at 212°F represents the latent heat required to convert water to steam or steam to water. (The latent heat of vaporization of 1 lb. of water is ~970 BTU's.)
>
> **Total heat**... includes both latent heat and sensible heat. In this case, it takes ~1290 BTU's to convert 1 lb. of ice to 1 lb. of steam at 14.7 psia. You can have ice colder than 32°F and steam hotter than 212°F, but that adds to the total BTU's. (For your information; 1290 BTU/hr = 378 watts.)

THERMODYNAMIC LAWS

A simple understanding of the three laws of thermodynamics would be useful and necessary for anyone working with cryogenic systems, but a simple explanation will leave much ground uncovered. However, here's an attempt:

1. The energy output of an engine, in the form of mechanical work, shall equal the difference between the energies absorbed and rejected in the form of heat.

2. No engine can have a thermal efficiency of 100%.

These first two laws are always taught in conjunction with each other. This is largely because the first law denies the possibility of creating or destroying energy (work in equals work out), and the second law denies the possibility of utilizing energy in a particular way (you can't have the work out of an engine drive the work in of an engine, thereby creating a perpetual motion machine).

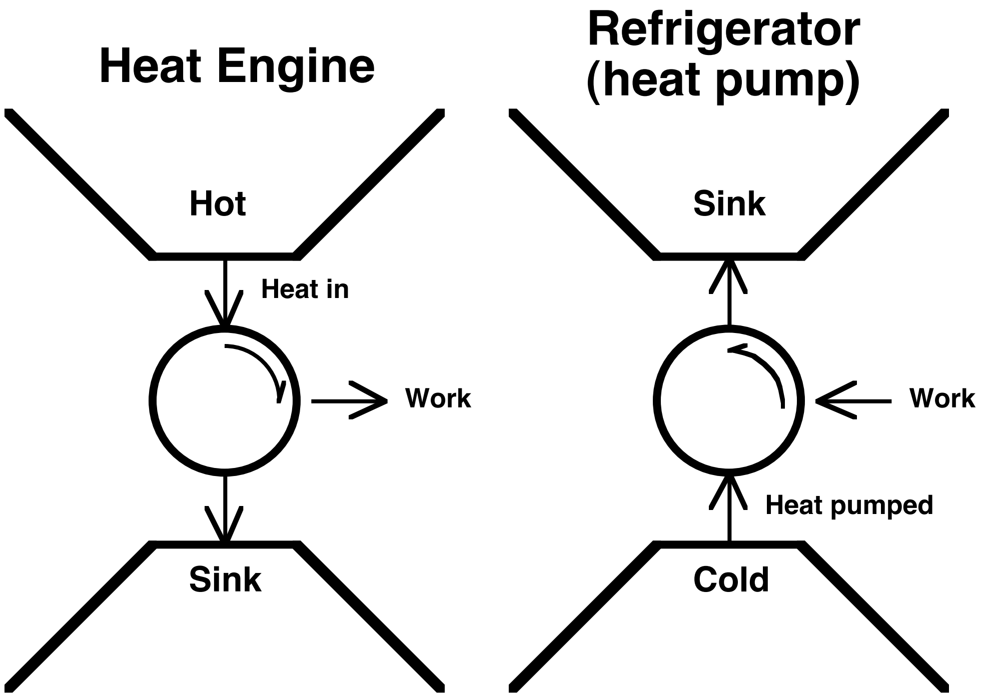
Why is this true? It is true because heat cannot be made to flow from a cold body to a hot body without the addition of work or energy. Here are some examples of the second law of thermodynamics at work:

- Heat always flows spontaneously from a hotter to a colder body.
- Gases always seep through an opening spontaneously from a region of high pressure to a region of low pressure.

- Gases left by themselves always tend to mix.
- Salt dissolves in water, but a salt solution does not separate by itself into pure salt and pure water.
- Rocks weather and crumble.
- Iron rusts. (Sears 342)

All these examples of irreversible processes express the one-sidedness of the second law of thermodynamics. (This is also referred to as **entropy**: a measure of the degree of disorder in a substance or a system: entropy always increases and available energy diminishes in a closed system, as in the universe.)

How is this applicable to cryogenics? The heat engine is reversed to act as a heat pump.



The heat pump absorbs heat at a low temperature, below ambient, and rejects the heat at a higher temperature into the environment through the absorption of work. Here's the important point: work is required to pump the heat from a low temperature to a higher environmental temperature(Scurlock 26).

> The first law demands that the difference between the heat and work for the two paths must be equal in magnitude but opposite in sign.
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> The second law of thermodynamics is concerned with the conversion of heat into work and the efficiency with which this can take place(Van Sciver 10).

Carnot, a French physicist, developed a formula for expressing the efficiency of an ideal engine, that is, a theoretical engine that has no heat loss:

$$W/Q = T_E / T_L - 1$$

W/ Q shows the specific power ratio of <u>work</u> (**W**) performed in watts to <u>heat</u> pumped (**Q**) in watts, in relationship to the (**T_E**) <u>environment temperature</u> and the (**T_L**) <u>low temperature</u> required. If you add to this formula the efficiency of a real refrigerator, it will divide the quantity [**T_E / T_L -1**] by something less than a Carnot device. With this new formula you find that the energy required to reach the "absolute zero" of temperature is infinite. This result brings us to the third law of thermodynamics in regards to cryogenics:

3. Absolute zero is unattainable(Scurlock 27, Van Sciver 13).

JOULE-THOMSON EFFECT

When air is compressed at room temperature, there is a reduction in its enthalpy, or heat content, the amount varying with pressure. On expanding the compressed air (or most any compressed gas) through a valve to atmospheric pressure there is a reduction in temperature, and in the steady state, this cooling is a function of the decrease in enthalpy during compression. By adding a heat exchanger between the compressor and the expansion valve, progressively lower temperatures are reached. With a sufficiently high pressure, and appropriate insulation, the air is liquefied. The cooling effect is due to the non-ideality of air — with an ideal gas no cooling would occur.

With some of the so-called permanent gases such as helium and hydrogen, there is an increase in enthalpy on compression at room temperature, and heating occurs on expansion through a valve. The gas must first be pre-cooled to a lower temperature before a cooling effect on expansion is achieved.

Joule-Thomson expansion is not thermodynamically reversible, and an increase in entropy occurs during expansion. This method of liquefaction was used in early refrigeration plants(Scurlock 181).

For the J-T method of cooling to work with helium, it is necessary to begin below the inversion curve, which implies an initial temperature below about 40°K.

The J-T valve performs an isenthalpic expansion of the high-pressure stream. Provided the inlet temperature is below the inversion curve, the J-T expansion can produce a two-phase mixture of liquid and vapor helium. An enthalpy balance between the incoming high-pressure stream and the two coexisting phases at ambient pressure (Van Sciver 289) determines the yield of the expansion stage.

MAKING LIQUID HELIUM

"Helium is the most difficult of all gases to liquefy because of its very low boiling point, 4.2°K, and its low inversion temperature for the JT effect, about 40°K. When liquefying helium for laboratory use, economy of power is seldom a consideration. The major expenses are for the complex machinery and for the human effort needed to operate it"(Scott 57). The JT effect spoken of here is the result of research by Joules and Thomson, which was just explained, and is the common way of referring to the Joule-Thomson Effect.

The helium atom is spherically symmetrical, and smaller than that of any other element. The only binding forces in the liquid are van der Waals forces, which arise from the fluctuating polarization charges induced in the electron shells of adjacent atoms. These weak attractive forces between electrically neutral atoms and molecules are weaker in helium than in all other substances, so the critical and boiling points of helium are the lowest of all(Wilkes 1).

There exists two isotopic forms of liquid helium used in most cryogenic research projects, liquid ^{3}He and ^{4}He. Both types of helium remain liquid to the lowest temperatures as long as they remain under their saturated vapor pressures(Wilkes 1).

Fermilab doesn't extract helium from the atmosphere. A contractor supplies the lab with tube trailers of ^{4}He.

For those interested, Fermilab uses a satellite refrigerator modeled after the CTI 1400 liquefier.