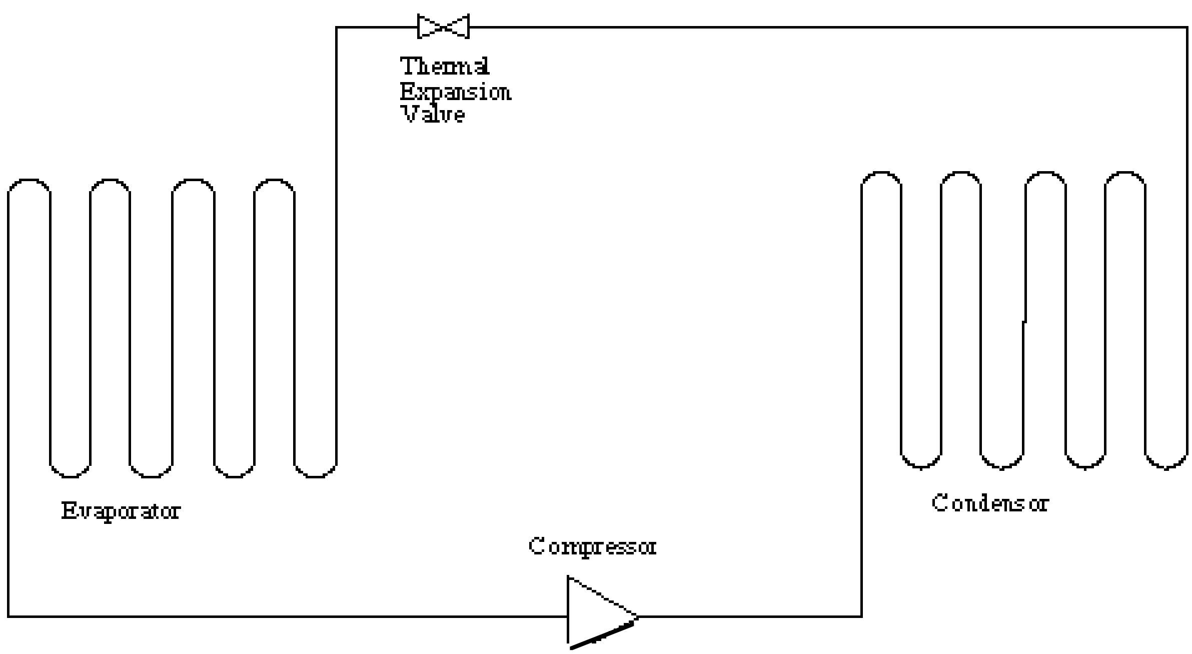
# REFRIGERATION CYCLE

The refrigeration cycle shown here is a typical R-22 system. The compressor and thermal expansion valve are the boundaries for the high and low sides.

It's important to understand that a refrigerator is a heat engine that operates in reverse. Energy is transferred from a low level to high level, which is contrary to the spontaneous processes that occur in nature. To accomplish this transfer, an amount of work must be supplied dependent on the temperatures involved. Energy must be added to this workload to compensate for the inefficiencies inherent in heat transfer, inefficiencies that arise from heat exchange equipment and the irreversible behavior of compression or expansion equipment.

Some of the same principles used in this basic system apply to normal cryogenic refrigeration systems as well.

***A BASIC SYSTEM***




## COMPRESSOR

The **compressor** takes low pressure, low temperature gas and compresses it into a high pressure, high temperature gas.

### CONDENSOR

The **condenser** accepts the gas from the compressor and, through some cooling medium, condenses it to a high pressure, cool temperature liquid.

### THERMAL EXPANSION VALVE

The liquid line feeds the **thermal expansion valve** or device where the liquid expands and flashes to a gas and cools.

### EVAPORATOR

The **evaporator** is a heat exchanger where the expanded cold gas exchanges heat with the area being cooled. (This area may be a refrigerator, your living room, or a meat locker. The fluid generally is just normal air.)

## *CARNOT CYCLE*

All refrigerators work on a combination of processes, cycles, which achieve cooling, and thereby liquefaction, through expansion. The Carnot cycle is a combination of isentropic and isothermal processes.

**Isentropic Expansion**, is where a fluid does work and expands keeping its entropy constant. This is an adiabatic process; no heat is allowed to enter or leave the system. It is also a reversible process since the work can be returned to the fluid through compression. This is the best method of expansion because it produces the largest temperature change over a given pressure. (Van Sciver 273, Sears 348)

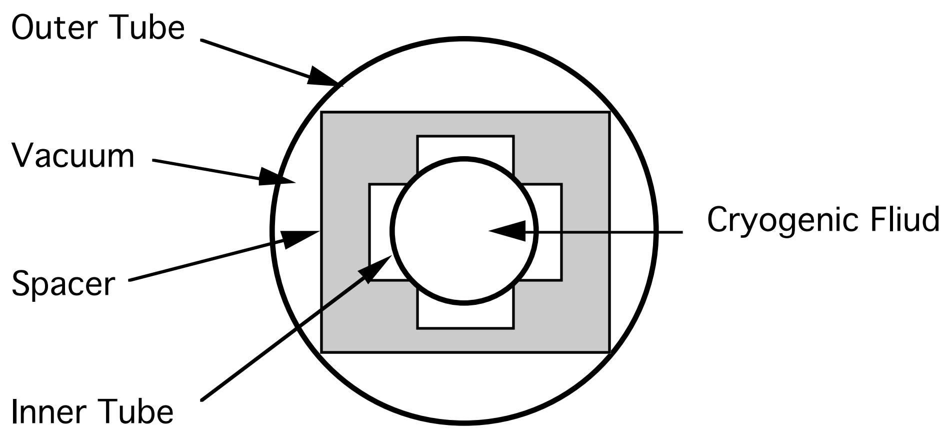
**Isenthalpic Expansion**, is where a fluid undergoes a pressure change without heat transfer. This method is in common application in practical refrigeration systems for its ease of use. However, it is of lower thermodynamic efficiency because it is an irreversible process leading to non-idealities.

Sadi Carnot, (1796-1832) a French physicist and engineer, developed, in 1824, a hypothetical heat engine with a 100% efficiency. (As we learned earlier, this is contrary to the second law.) He examined this hypothetical engine and discovered that the perfect engine must avoid all irreversible processes. Every heat transfer, in his idealized cycle, must be isothermal or adiabatic.

His formula $K = T_C / T_H - T_C$, represents an ideal efficiency that can never be attained.

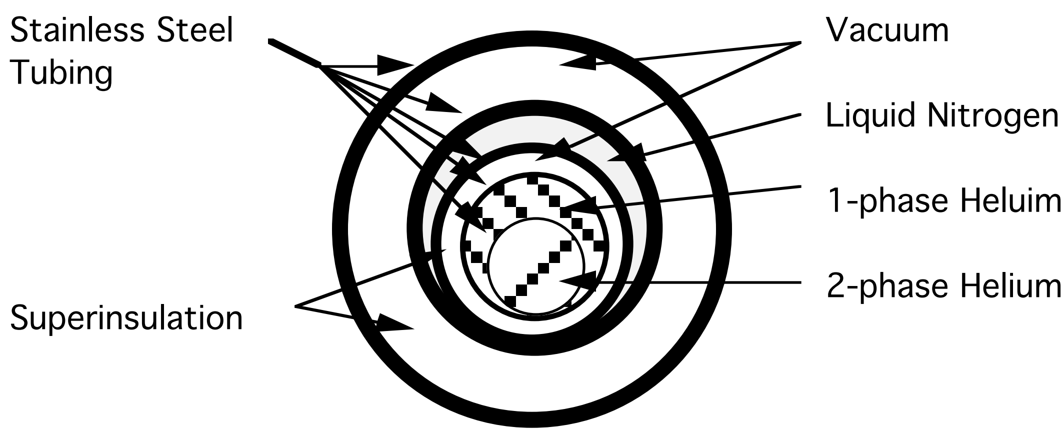
### *TRANSFER LINES*

The efficient transfer of liquid helium, or even nitrogen, requires a vacuum-insulated line. This is because transfer lines suffer all the heat transfer problems of conduction, convection, and radiation expressed earlier. A liquid helium transfer line is vacuum jacketed and usually shielded with liquid nitrogen.




Simple Transfer Line

This simple transfer line shows how many of these problems are solved. The center tube would carry the cryogenic fluid. It is held in place by a spacer made of materials that are poor conductors of heat. The outer tube holds a vacuum to protect the inner tube.




Proton Transfer Line

This is a diagram of the Proton transfer line, but all fixed target transfer lines are constructed similarly. The transfer line consists of five stainless steel tubes that hold vacuum and superinsulation, spacers (not shown), liquid nitrogen, two-phase helium, and single-phase helium. The vacuum, insulation (wrapped at 60 layers per inch), and liquid nitrogen all act as a shield for the supply and return helium.

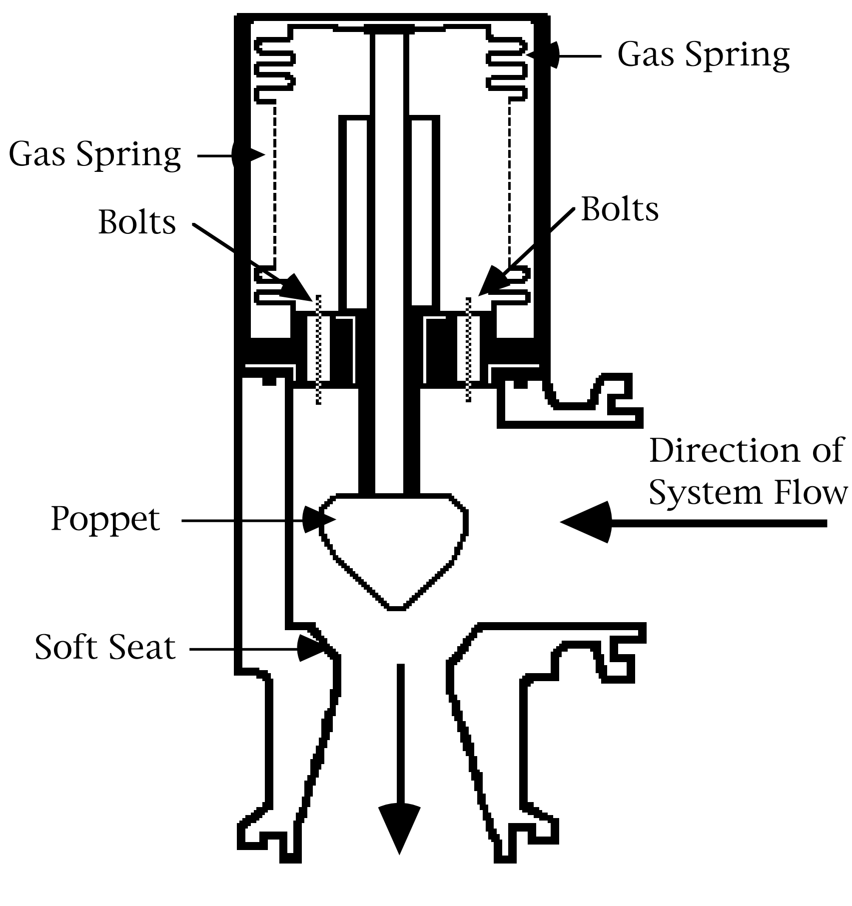
The innermost tube handles the two-phase return from the magnet string. The next outer tube supplies the magnet string with liquid helium . You may think it odd that we have a gas and a liquid in contact, by conduction, with each other, but please note that these two tubes do not act as a heat exchanger in the way you might think. The returning two-phase gas, flowing through the center tube, is expanded after leaving the magnet string. The affect of this expansion is that the two-phase return gas becomes slightly colder than the single-phase supply, thus the two-phase return gas acts as a precooler for the supply line.

### *CRYO VALVES*

Cryogenic valves are necessary to control the flow of both gas and liquid phases flowing through the refrigerator. The best valves offer the following characteristics: low heat leak, reliable operation, small heat capacity, small resistance to flow, simplicity and economy of construction, and adaptability of insertion into ordinary vacuum-insulated lines. The following information on Kautzky valves describes one of Fermilab's important developments.

### THE KAUTZKY VALVE

The development of Fermilab's cryogenic system required new components, one of which was a relief valve that could reseal itself after venting. The Kautzky valve is a pressure relief valve used on every superconducting magnet. The valve vents helium in the event that internal pressure raises too high, as from a quench, and then reseats itself.

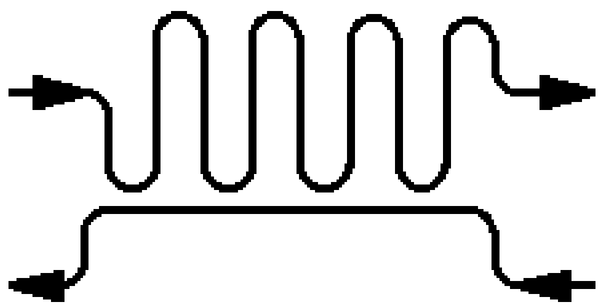


The most important aspect of the Kautzky valve is its chatter free ability to open and reseal. It's able to do this because the poppet moves counter to the flow when opening. During a quench, the seating force is reduced by the high cryostat pressure acting on the inner surface of the actuator, which opposes the "gas spring." When the force holding the poppet on its seat is reduced to zero, the poppet begins to open. The force of this flow pushes the poppet fully open. Even as the flow past the poppet equalizes, the poppet remains open down to a few psi less than the pressure that caused it to open. If the pressure continues to drop, the remotely supplied pressure of the "gas spring" will close the valve.

### *HEAT EXCHANGER (HEX)*

Heat transfer occurs when objects, gasses, or fluids of different temperatures encounter each other. The modes of heat transfer are through **conduction**, **convection**, or **radiation**.

Heat Exchanger

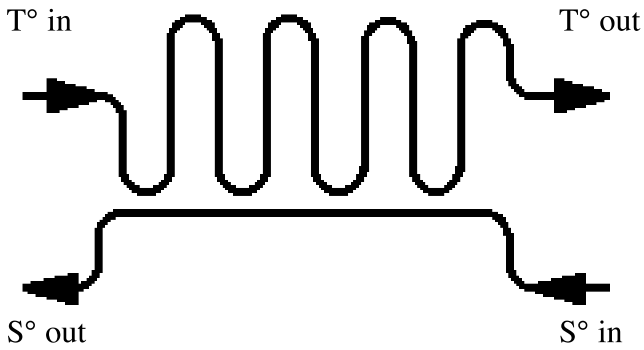


There are many types of heat exchangers used in cryogenic systems. This discussion will limit itself to the types of heat exchangers used by the Main Ring and the Research Division in their satellite refrigerators. The construction of these heat exchangers is commonly referred to as tube and shell exchangers.

### TUBE & SHELL HEAT EXCHANGERS

The tube portion is a finned copper tubing, which is wound around a mandrel in a spiral configuration like a spring. The return shell path is an annular space surrounding this tube bundle. Heat exchange is accomplished by **convection** from the fluid over the surface of the copper tubing and by **conduction** through the tubing wall. The entire assembly is enclosed in a vacuum vessel and super insulated to reduce heat loss to the ambient environmental temperature.

COUNTER FLOW

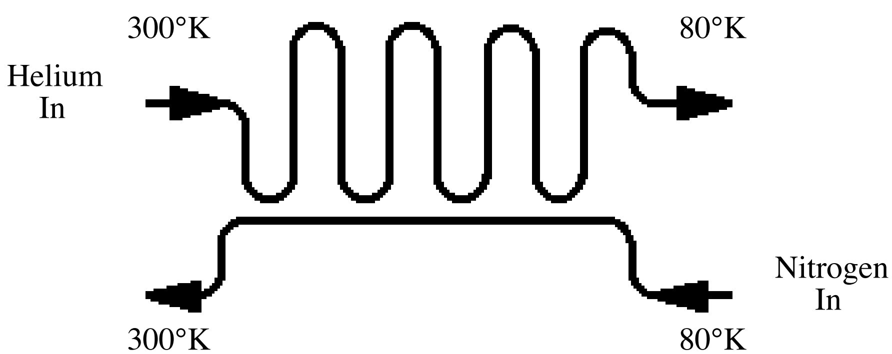



T° in = S° out and T° out = S° in

In a perfect heat exchanger, the counter flow streams exchange heat with 100% efficiency. The supply side outlet temperature would be equal to the return side inlet temperature and the supply side inlet temperature would equal the return side outlet temperature. Unfortunately, there are no perfect heat exchangers. There are always losses due to inefficient insulation, poor vacuum and heat transfer through materials such as copper.

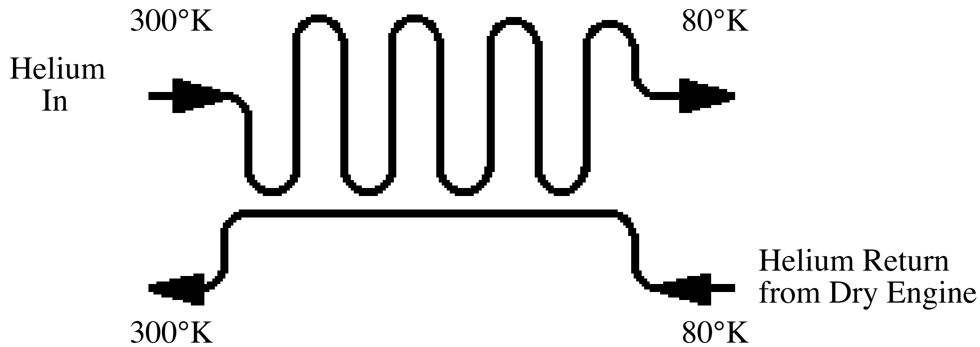
Even though this is not a perfect heat transfer, it is very important to understand these temperature relationships. So let's follow a cascade of heat exchangers and see the temperature ranges.

HEX I




Heat exchanger I, in a satellite refrigerator system, uses liquid nitrogen on the "shell" side as the cooling medium. The "tube" side, which contains the hot helium gas, is totally immersed in a bath of liquid nitrogen. This is probably the most efficient heat exchanger in the entire refrigerator. The helium stream is cooled to nitrogen temperature as it winds its way through the tube bundle. The nitrogen enters the heat exchanger as a liquid at 80°K and leaves as a gas at about 265°K.

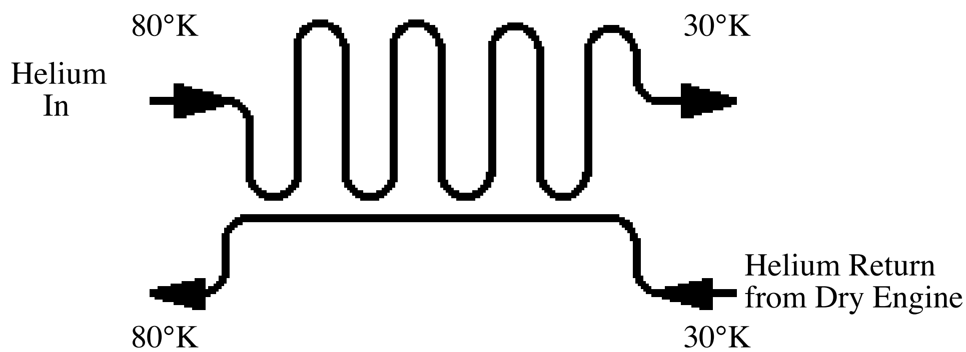
HEX II




Heat exchanger II exchanges heat from the supply helium to the returning helium stream. HEX 2 is only put on line once the dry expander is running and cooling. (A system such this is called a non-star refrigerator.)

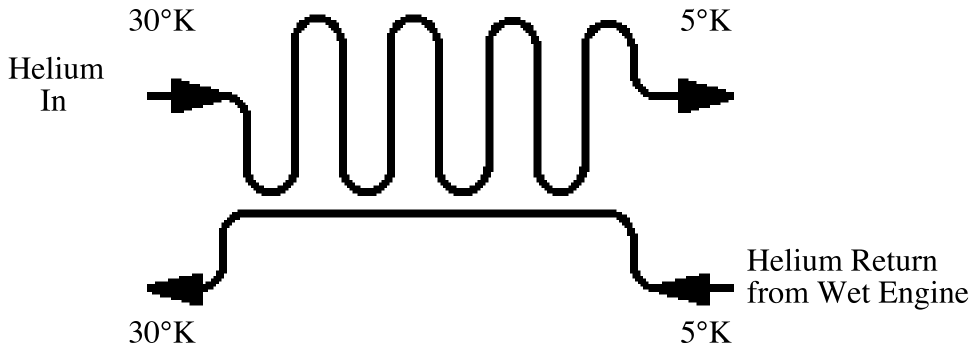
In a star refrigerator system, HEX II is actually two heat exchangers, which are labeled II and IIa here at Fermilab. HEX II works like a non-star refrigerator in that it takes the return supply of helium from the dry engine to cool the incoming gas, but it also has HEX IIa which exchanges heat with the in coming liquid nitrogen supply to HEX I. (The flow path is illustrated in the Star system diagram.)

HEX III



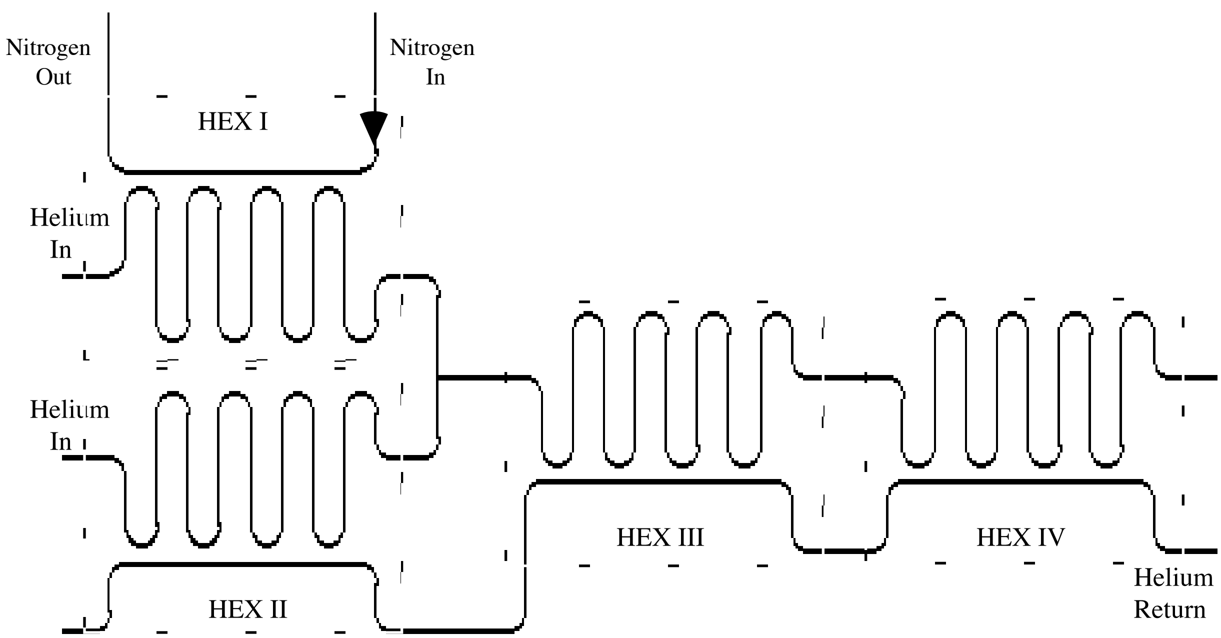

HEX III is a straightforward counter flow helium-to-helium heat exchanger in the bootstrap chain. (A bootstrap operation is one that operates without outside help.) Its purpose is to reduce the temperature of the supply stream prior to expansion by the dry expander. This heat exchanger's operating temperature is achieved because of the dry expander.

HEX IV

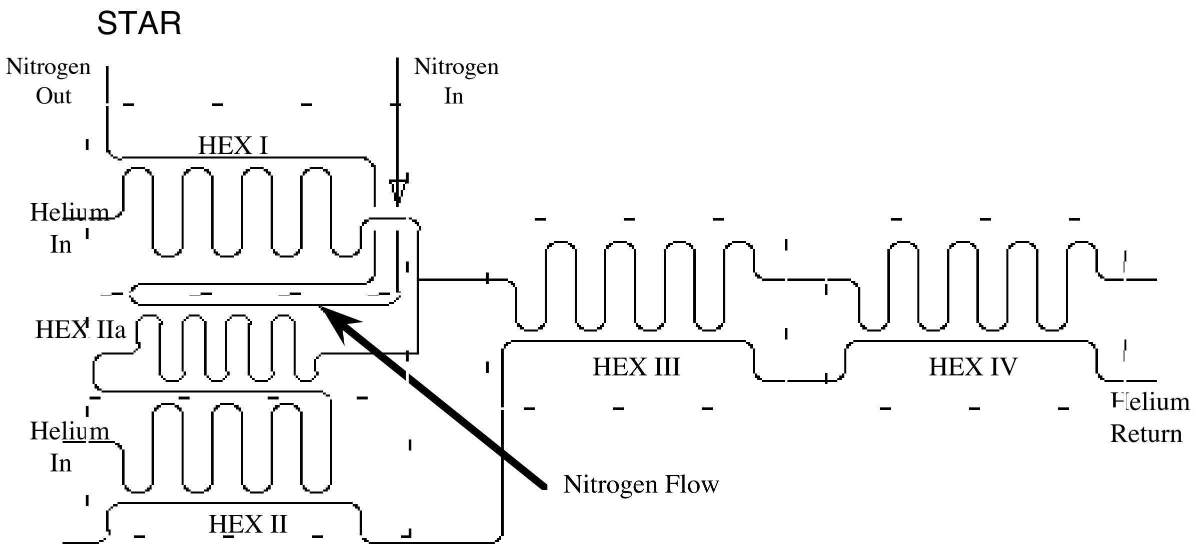



HEX IV is cooled as a combined effort of the dry expander and wet expander outlet, and from the return flow from the system.

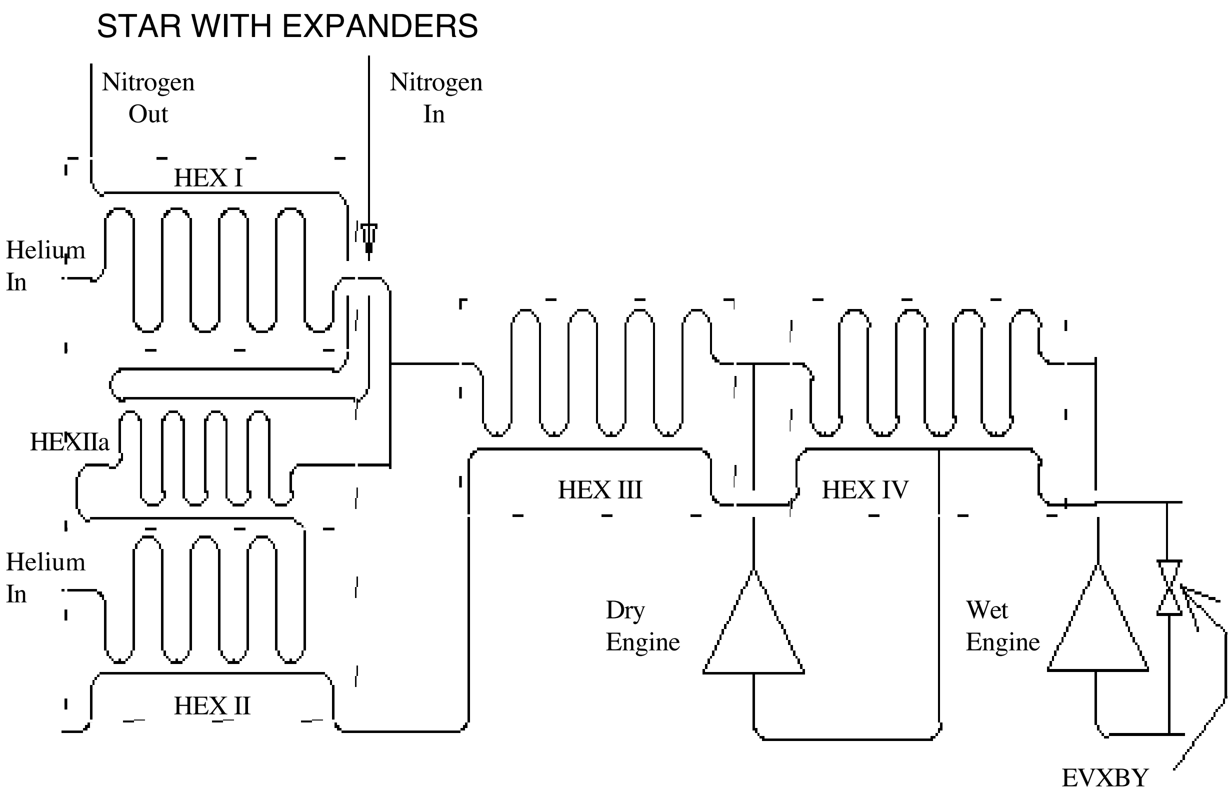
NON STAR




This flow diagram shows a non-star flow path without expansion engines. This configuration is used at PS1. (Note the lack of HEX IIa.)



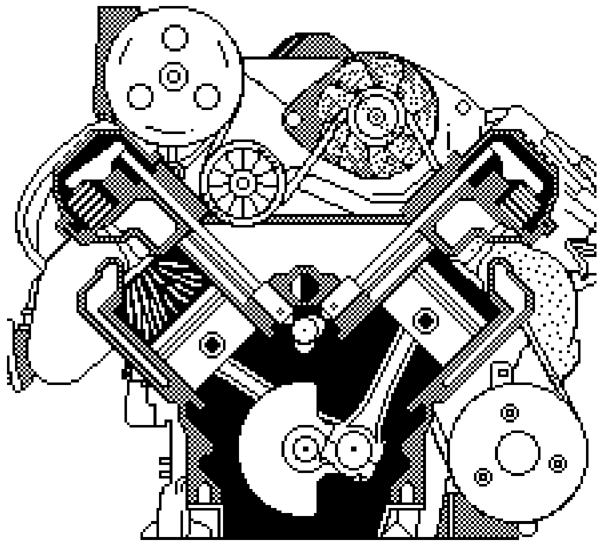

This is the flow path of a star HEX without the expansion engines. Follow the path of Liquid nitrogen and how it relates to HEX IIa. This configuration is used at Meson and PS4.




This diagram includes the expansion engines and shows, approximately, where each engine receives gas and thereby aids in cooling. Note the valve that would allow the Wet expander flow to enter the return flow path. This valve would be EVXBY.

### ***ENGINES***

According to the Random House Dictionary, engine is defined as "a machine for converting thermal energy or power to produce force and motion."



The engine pictured here is one of the most commonly found types in the world, a combustion engine, and follows the dictionary definition to the letter.

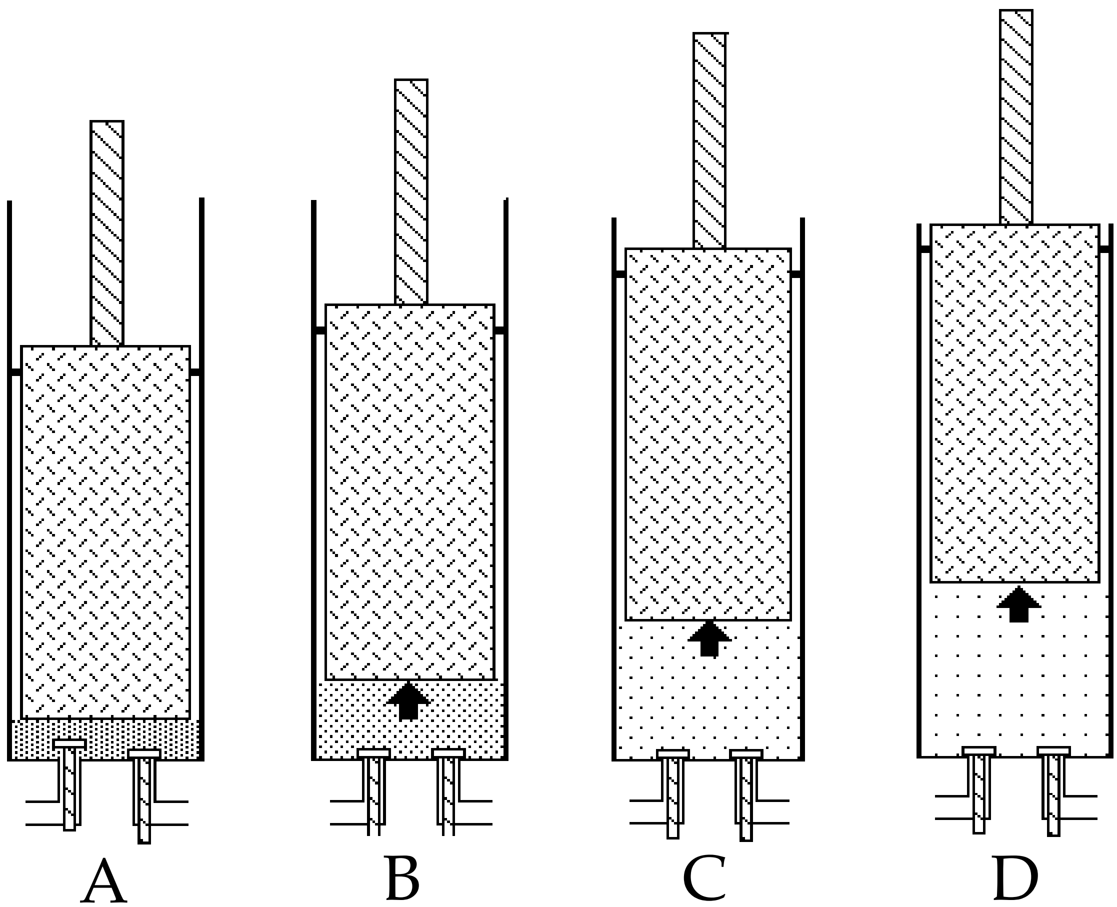
Our cryogenic systems in the External Beamlines use engines in a slightly different way — to cool and liquefy helium gas.

The French engineer Georges Claude introduced the reciprocating expansion-engine refrigerator in 1902. In principle, it was simply a reciprocating piston-and-cylinder engine similar to the steam engine that had been in use for over a century.

The thermal energy in the high-pressure helium stream, is used to create force and motion by the expansion of the gas that in turn drives the flywheel and motor generator. Unlike a combustion engine, the desired result is not the motion created but the temperature drop caused by the expenditure of energy in the form of sensible heat. To see how this happens, let's examine a cryogenic expansion cycle.

EXPANSION ENGINE CYCLE

A The <u>inlet valve</u> opens allowing high pressure (250 to 300psig) helium gas to enter the cylinder resulting in driving the piston in an upward motion.

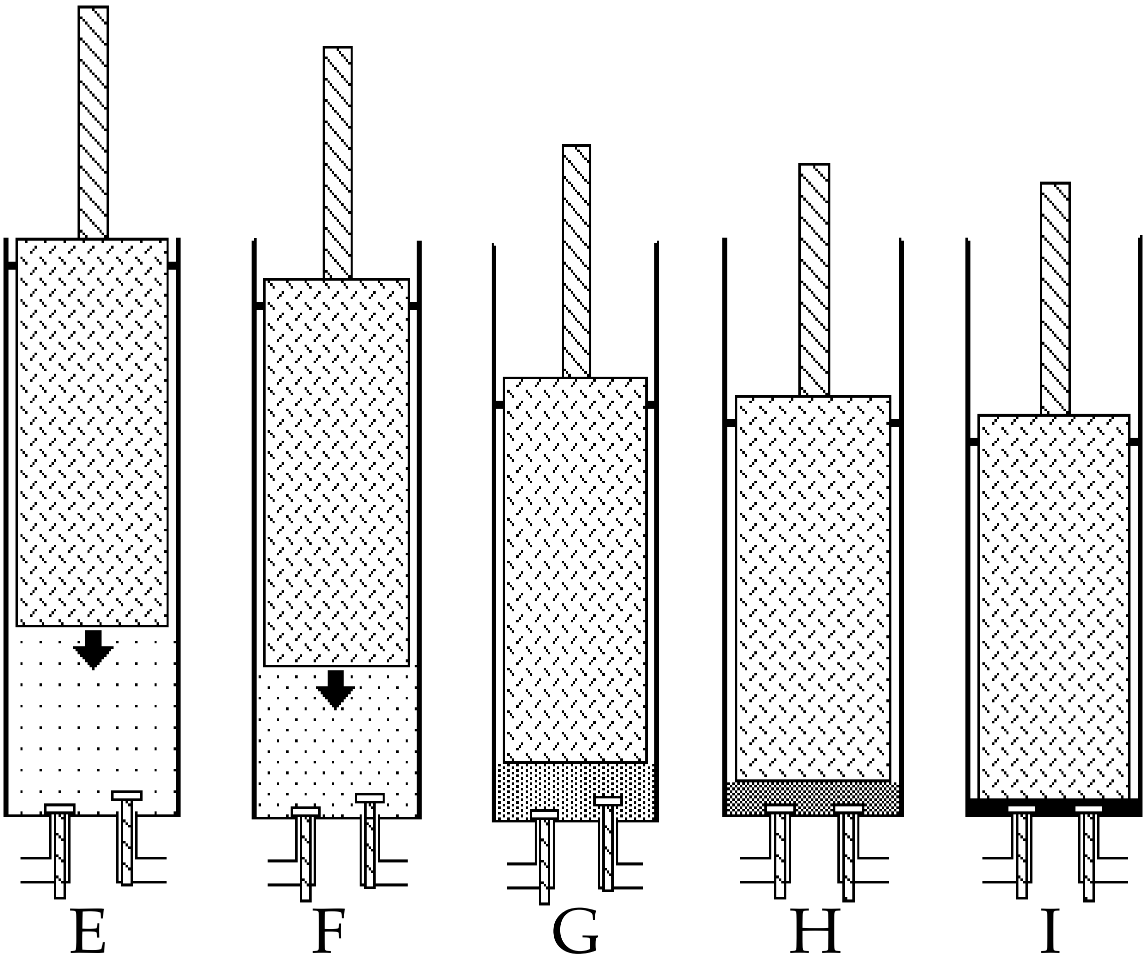


B The <u>intake valve</u> closes while the piston continues to move up. The gas expands and cools.

C The expansion cycle continues. The gas expands and cools.

D The piston reaches top dead center (TDC).

E Once the piston passes top dead center the exhaust valve opens. The motion of the flywheel along with the second piston keeps the cycle going. Now the piston pushes the low pressure cold helium gas (or liquid) out of the cylinder.




F The piston continues downward and is being driven by the other piston and flywheel .

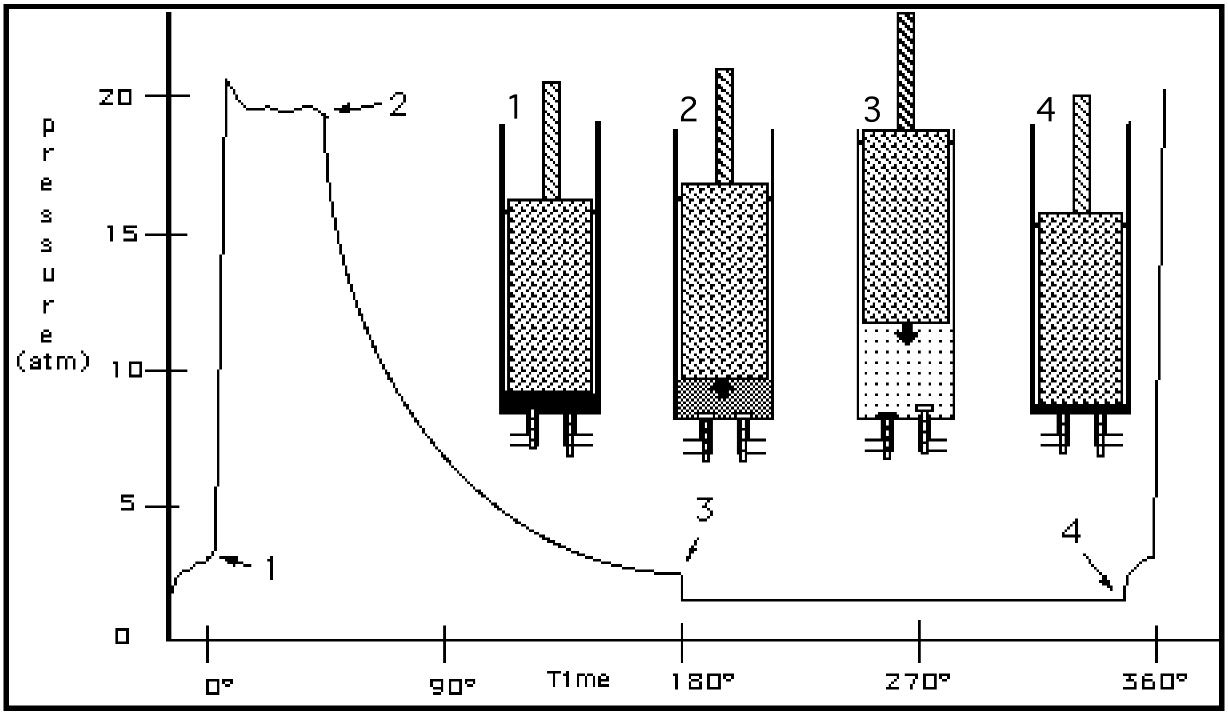
G As the piston nears bottom dead center, (BDC) the exhaust valve closes.

H The exhaust valve closes and for a short time both valves remain closed as the piston continues its downward travel . The gas in the cylinder is then compressed. This is called recompression.

I BDC and recompression.

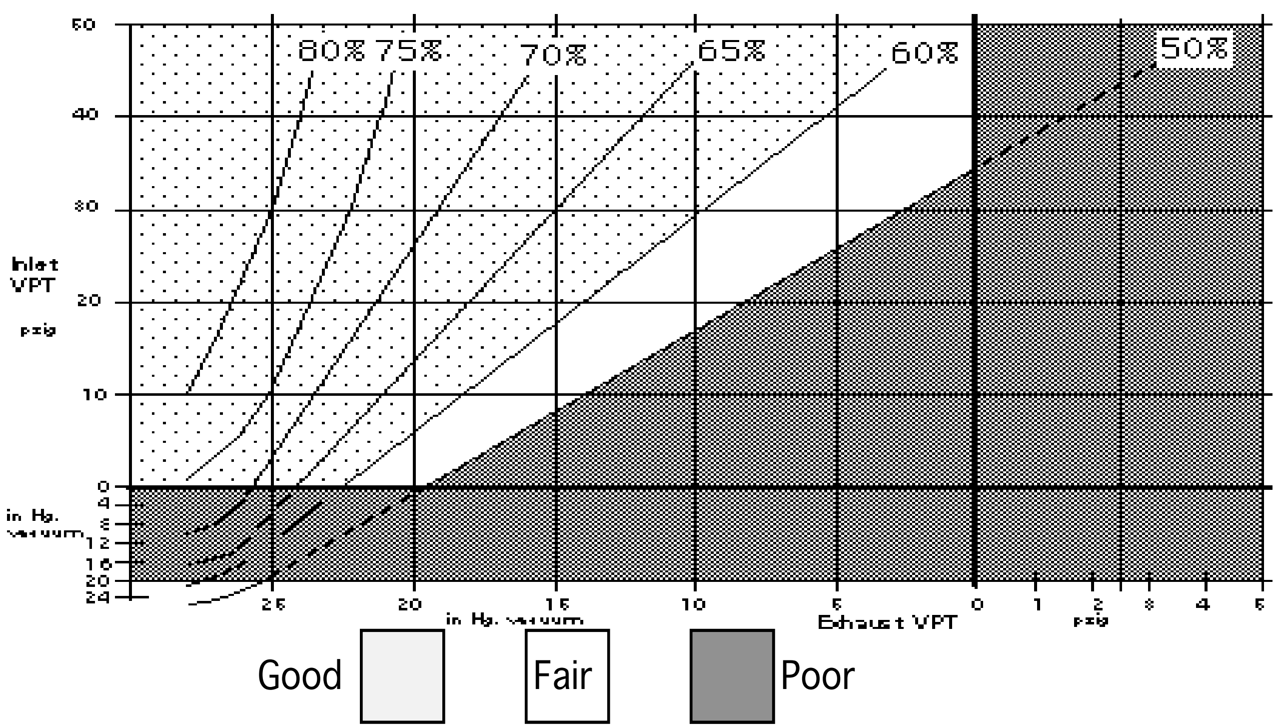
## ENGINE TRACE

1. Inlet valve opens and pressure goes up.
2. Inlet closes and pressure drops off. Point 2 to 3 is the expansion cycle.
3. Exhaust valve opens and pressure abruptly drops.
4. Exhaust closes causing slight recompression of gas.




This illustration is a plot of the cylinder pressure vs. time. The degree increments indicate approximate piston position.

ENGINE EFFECIENCY PLOT




This efficiency plot functions as a ratio of the inlet pressure to the outlet pressure.

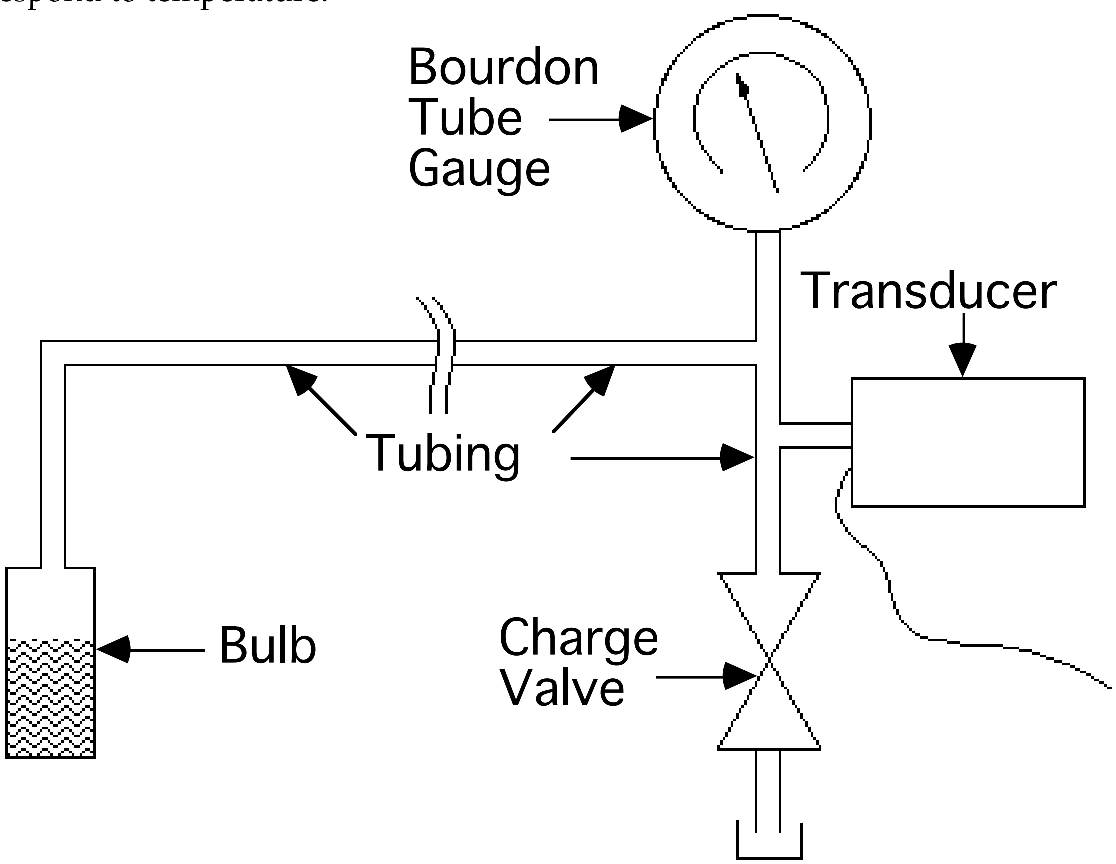
The inefficiencies of Fermilab's expansion engines are usually due to valve leaks caused by poor lifter clearance, or valve damage caused by dirty valves.

### *TEMPERATURE MEASURING DEVICES*

#### VPT

A vapor-pressure thermometer consists of a bulb filled partly with a liquid or solid and partly with vapor in equilibrium with the condensed phase. The bulb is connected by a pressure-transmitting line to a pressure-measuring instrument. The VPT can be an extremely precise instrument; this is especially true when the lower-boiling elements are used(Scott 115), such as helium.

A VPT operates on the principle that in a closed system, which is at equilibrium, the pressure will remain constant as long as the temperature remains constant. If the temperature in the VPT's bulb drops through conduction, part of its bulb's liquid will condense and change the system's volume; thus, pressure will correspond to temperature.




Bourdon Tube Gauge: Compound gauges are used on certain VPTs since some vapor pressures can be sub-atmospheric.

Bulb: The bulb itself is small and should contain some liquid when in the proper temperature range. The bulb should be filled partly with liquid and vapor in equilibrium with the condensed phase connected via tubing to a pressure-measuring device. (It's the condensation of gas that reduces the pressure contained in the bulb and tubing, and it's this lowering of pressure that corresponds to a lowering of temperature.)

Transducer: An optional transducer is used when computer controls or read back are needed.

Charge Valve: The charge valve is used to correct the gas pressure. A typical pressure in a VPT is 100 psig at ambient temperature. This valve is capped when not in use to help eliminate leakage.

Tubing: The volume of the VPT system is crucial for proper performance. The tubing Inner Diameter (ID) needs to be small if long runs are made.

Types of Gases: Nitrogen, Argon, Neon, Hydrogen, and Helium VPTs are commonly found in the Research Division Systems. These gases are selected for their liquid temperature range.

Some Temperature Ranges

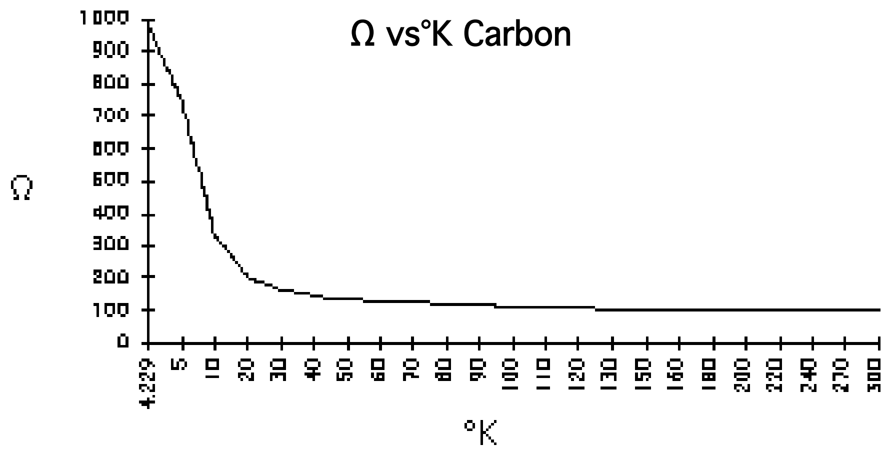
| | | | |
|---|---|---|---|
| Helium | 2.27°K | - | 4.5°K |
| Neon | 21.1°K | - | 27.7°K |
| Hydrogen | 13.°K | - | 21.1°K |
| Nitrogen | 62.7°K | - | 80°K |

## RESISTORS

The resistivity of a pure metal near room temperature is approximately proportional to its absolute temperature. This property of pure metal is applied in a very successful temperature-measuring instrument, the *resistance thermometer*(Scott 128).

## CARBON RESISTORS

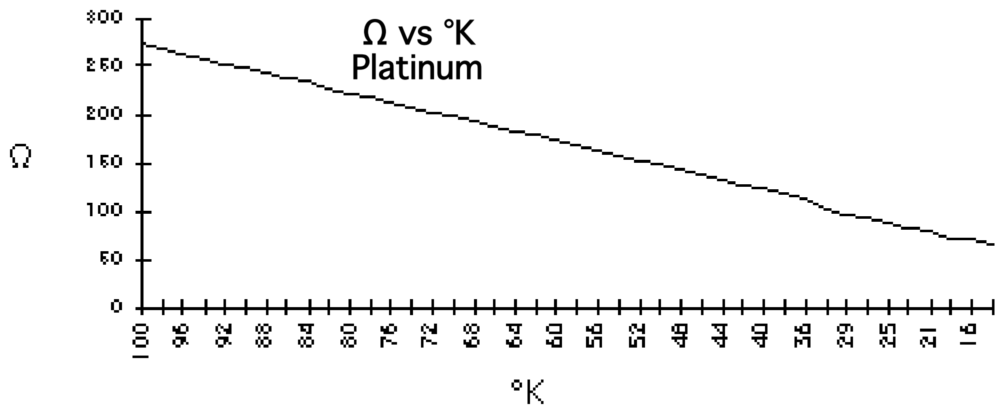
Carbon resistors are used to read low temperatures because they're sensitive at lower temperatures such as 80°K and lower.




As the plot indicates, the relationship between ohms and temperature with carbon resistors is not linear.

## PLATINUM

Platinum resistors are used to read low temperatures because they're sensitive at temperatures down to approximately 30°K. In lower temperature ranges the sensitivity of platinum resistors suffer.




The plot indicates that the relationship between ohms and temperature is linear with platinum resistors. They are used where liquid nitrogen or argon temperatures are expected, up to or above ambient.