expendable refrigerants. Both approaches can be used either directly or in conjunction with secondary heat transfer fluids. Expendable refrigerants usually find application: (1) in intermittently used apparatus, (2) where extremely high temperatures are also to be produced within the same enclosure, (3) for very small and inexpensive type chambers, (4) for producing temperatures lower than those easily obtainable with mechanical refrigeration (using liquid nitrogen), or (5) where very rapid cooling rates are required or infrequent high peak cooling capacities are experienced.

Under altitude simulation conditions, removal of heat from a test object is possible by convection up to about 100,000 ft (8.3 mm Hg abs). To accomplish this the air mover should be of the largest practical size so that the residual air in the chamber is passed at high velocity through the cooling coils and directed on and around the test object.

An envelope of cooled, rarified air, within which temperature gradients will be reasonably small, is thus produced around the test object.

Rather large gradients may occur throughout the rest of the chamber but will not affect the test results. Air flow should be reduced at low temperatures to minimize the fan brake horsepower addition to the cooling load. Cold wall construction reduces the heat load to be transferred to the cooling coils within the vacuum space, provides surface for radiant transfer, and overcomes the losses through the structure.

Evaporators should be maintained at the lowest practical temperature to provide the maximum temperature difference for both radiant and convective heat transfer. Over 100,000 ft, it is generally recommended that a radiation heat transfer system be designed into the chamber to produce the desired temperature control conditions on the test part. Treatment of the walls of the chamber to produce high emissivity is necessary in this case and close control of the entire wall surface is generally advisable. The limitation of radiant heat transfer in the low temperature range must be kept in mind because the amount of heat transferred from one surface to another is a function of the ratio of the square of the absolute temperatures. With temperatures in the −100 F range, the heat transfer rate is very small. The detailed calculation of this effect is described in the applicable Chapter 4 of the ASHRAE GUIDE AND DATA BOOK 1961 wherein the basic Stefan-Boltzmann equation is discussed.

Primary Refrigerants

Any refrigerant suitable for mechanical refrigeration could conceivably be used as the primary refrigerant. Selection requires an evaluation of equipment size or cooling load, type of evaporator, temperatures to be produced, method of condensing, hazards, lubrication, and special operating requirements.

The halocarbon group of refrigerants are most commonly employed because of their lack of toxicity or flammability and their stability at elevated temperatures, although ammonia is used in some large systems where it does not present a hazard and temperatures below −85 F are not required. In small and medium sized systems, cooling from ambient down to evaporator temperature of −65 F, common practice is to use Refrigerant 12 or Refrigerant 22 in single-stage or compound compression arrangements. Designs are similar to those used in commercial practices. In larger systems of about 20 hp and up, two- and three-stage compound systems utilizing Refrigerant 22 are still used, particularly for the low operating temperature range of −65 to −85 F. Multiple stage cascade systems use Refrigerants 12, 22, 13, 13B1, 23

Table 1 .... Selected Saturation Temperatures of Several Low Temperature Primary Refrigerants

Refrigeration No.	Saturation Temp F at Pressure Indicated		
	2 psia	14.7 psia	160 psia
12	−91	− 21.6	114
22	−105	− 41.4	80
13B1	−137	− 72.0	50
13	−170	−114.6	− 6
170 (ethane)	−182	−127.5	− 19
1150 (ethylene)	−206	−155.0	− 56
14	−239	−198.4	−116

and 14 of the halocarbon group, 170 (Ethane) or 1150 (Ethylene), and, occasionally, methane, of the hydrocarbon group. Table 1 gives data indicative of the useful operating range for each of these. Refrigerant 13 in a low stage and either Refrigerant 12 or 22 in the high stage of a two-stage cascade system can easily produce evaporating refrigerant temperatures between −115 and −135 F with reasonable compression ratios. A three-stage cascade arrangement using Refrigerants 22, 13 and 14 can, utilizing proper techniques, produce evaporating refrigerant temperatures of −200 F and lower. Because of the immiscibility of the halocarbon group refrigerants used for producing temperatures of −100 F and lower, oil return to the compressor from the evaporator is one of the more serious problems. The hydrocarbon group of refrigerants exhibit better oil carrying capabilities, therefore, are not uncommon in systems used to cool to temperatures of −150 F and below. Their flammability hazards must not be overlooked. Test chambers are frequently required to be operated at high as well as low temperatures. When using primary refrigerants in evaporators which may be subjected to temperatures above 500 F, thermal isolation and cooling of the evaporator is necessary to prevent oil decomposition or other possible deterioration of the refrigerant circuit. Refrigerant 13 is more stable than either R-12 or R-22. Pump down of an R-13 circuit, when operating up to 500 F, has proved to be reasonably satisfactory. A secondary refrigerant heat exchange fluid which is pumped out of the cooling coil at some safe predetermined temperature is another method for protection against overheating of a primary refrigerant coil. Due to the added expense of this type of system, it is more common to use expendable refrigerants for high temperature equipment even with the disadvantage of high operating costs at low temperature.

Expendable Refrigerants

Expendable refrigerants such as dry ice, liquid carbon dioxide, liquid nitrogen and helium and others discussed in Chapter 65, Cryogenics, are suitable for producing low temperatures in environmental chambers. Sublimation of dry ice within the chamber, chilling brine for circulation through heat exchangers or direct expansion of the liquids within the test space are the common methods of using expendable refrigerants. Liquid nitrogen, helium, and other cryogenic liquids are particularly useful in work below the temperature range of mechanical refrigeration systems.

The advantages due to expendable refrigerants in environmental test equipment are reduced cost, basic simplicity, reduced weight and size of the chamber and ability to produce very rapid pulldown rates to low temperatures. Results of elimination of direct expansion refrigeration coils from within the chamber are: very high operating cost at low temperature, inconvenience of providing the expendable refrigerant supply, and the disadvantage of submerging the tested product in CO_2, N_2 or He gas which are expanded directly into the test space. Indirect brine systems frequently approach the first cost of mechanical refrigeration systems. Direct expansion of expendable refrigerants in altitude chambers is impracticable.

The selection of an expendable refrigerant must often be predicated on its availability and cost in the geographical location of the test chamber. Generally, they are readily available in the missile and rocket development centers but may not be available at reasonable cost in other parts of the United States.

Satisfactory methods for temperature or capacity control of dry ice cooling systems include the use of a motorized damper to proportionally control the amount of air passing over the dry ice, or use of two fans; one constantly recirculating air in the workspace, and a second cycled as required to draw air over the dry ice. For cooling control near ambient temperatures, a small amount of heat frequently is required for supplemental control. Well-designed systems include means of thermally isolating the dry ice from the workspace and means of baffling to minimize or prevent free convection between the two compartments.

For control of direct injection liquid CO_2 systems, only *on-off* cycling is possible because of the triple point of CO_2. Solenoid actuated two-way valves or pneumatically or electrically actuated ball valves have been used with much success. If reduced capacity operation is desirable, the control valve should be either time-pulsed or more than one valve should be used with small and large size expansion orifices. Solenoid valves with built-in orifices designed for this specific application are available.

Liquid CO_2 is used at two pressures; low pressure bulk liquid is stored in refrigerated receivers at approximately 0 F and 300 psig. Its latent heat is approximately 120 Btu per lb. High pressure liquid is stored at room temperature at pressures ranging from 750 to 1000 psig depending upon ambient temperatures. Its latent heat varies from approximately 50 to 75 Btu per lb depending upon initial temperature. Because of this low latent heat and since there are only about 60 to 70 percent liquid in a high-pressure cylinder, and also because it has a considerably higher cost than low-pressure liquid, it is used only for very small or infrequent cooling loads. For increased efficiency when using high-pressure liquid CO_2, an economizer which precools incoming liquid by heat exchange to the exhaust cold vapors can be used to advantage. The CO_2 requirement can be reduced by 15 to 30 percent in this manner.

Dry ice has a latent heat of approximately 240 Btu per lb and a cost about that of low-pressure bulk liquid. Frequently, however, even with its higher latent heat the long time operating cost is about equal to that of low-pressure liquid due to handling costs and losses in storage.

Liquid nitrogen can be used either directly or indirectly to cheaply and easily produce temperatures down to its approximate −321 F boiling point (at one atmosphere). Control is accomplished by either on-off cycling of special solenoid actuated valves or by specially designed flow metering valves. The liquid is stored in Dewar flasks or vacuum-insulated tanks. Transfer is accomplished by the use of either self-pressurizing the storage vessel or by using dry air or nitrogen, properly pressure regulated, to pressurize the flask and force the liquid from a discharge tube. Piping, valves, heat exchangers, etc., should be fabricated of non-ferrous metals, stainless steel or high nickel steel. Few plastics are suitable seals in this temperature range. Although its latent heat of evaporation at one atmosphere pressure is only 85 Btu per lb, another 56 Btu per lb is available from the super-heating of gas to −100 F. Therefore, it has a greater capacity of heat absorption than does low pressure liquid CO_2 when operating at −100 F or higher control point. Suitable precautions should be taken against the low temperature hazards to operating personnel.

Other cryogenic liquids such as liquid helium and liquid hydrogen provide test temperatures close to absolute zero. These are too expensive for routine work at temperatures which can be obtained by more economical means. Special storage and control valves are required.

More detailed information on cryogenic liquids, their handling and piping will be found in Chapter 65, Cryogenics, of this volume.

Secondary Refrigerants

Low temperature heat transfer fluids are used where: (1) control flexibility is better accomplished by their use, (2) large central cooling systems have been chosen, (3) the high temperatures experienced will rule out primary refrigerants because of complex mechanical design problems, or (4) expendable refrigerants are used and direct cooling of air or a product is not possible. Halocarbons, liquid hydrocarbons, alcohol, some of the primary refrigerants, silicone fluids, and aqueous glycol solutions are used as secondary refrigerants. Table 2 gives a few important data for several of the liquids used. Thermal considerations include viscosity, specific heat, specific gravity, thermal conductivity, freezing and boiling points, and coefficient of expansion. Other important considerations are flammability, toxicity, corrosiveness, vapor pressure, and water solubility.

To minimize evaporation losses, the more volatile fluids are used in closed systems with suitable expansion tanks or accumulators and are frequently pressurized by an inert gas such as nitrogen. Certain fluids must be kept refrigerated to prevent boiling off under standby conditions.

Secondary refrigerants are cooled in insulated sublimation tanks by recirculating or spraying the liquid over dry ice or directly injecting liquid CO_2 into the refrigerant. Such systems require a pump for recirculation of the secondary refrigerant, and air-to-liquid heat exchanger, and piping. The test atmosphere remains undiluted with CO_2. By modulating or mixing the fluid flow, very close temperature control is possible. When high temperatures are produced in the test space, normal procedure is to drain the heat exchanger. Common operating difficulties in sublimation systems include cavitation in pumps due to the release of dissolved CO_2 gas, and also foaming in the sublimation tank with resultant carry-over of the secondary heat transfer liquid with the vented CO_2 gases. Positive displacement pumps and positive suction pressures are recommended. High velocity pressures within the pump should be avoided. By introducing a foreign gas such as dry air or nitrogen, the partial pressure of the CO_2 is reduced and temperatures below the normal −109.4 F sublimation temperature of CO_2 are possible.

HEATING SYSTEMS

Electric heat is most commonly used in environmental chambers. Prime or extended surface, tubular, or strip heaters are suitable for circulating air stream systems. With proper precautions, open nichrome, strip, or coil wire heaters