wick in order to prevent the evaporation at the wet bulb from raising the internal vapor pressure and relative humidity of the chamber. Multi-range instruments may be desirable in certain applications such as the temperature-humidity chamber which operates from −100 F to +500 F with humidity control in the +35 to 180 F range. If the dry-bulb controller has the full 600 deg range, it will provide relatively poor control during a humidity test. Therefore, multi-range instruments are frequently used so that the range can be expanded for the humidity section of the test (usually between 0 and 200 F).

Many of the more elaborate instruments can be obtained with a variety of control forms to provide whatever action is required for the system. Auxiliary switches, actuated at any point in the range, can be provided to perform auxiliary functions such as draining and filling a humidifier pan near the freezing point, draining and filling a secondary refrigeration coil at required temperatures, and performing many staging functions. In addition, many controllers can be equipped with programming systems with which predetermined cycles can be set up for automatic operation without manual readjustment of the controller set point. These are particularly useful for many of the 24 hour humidity cycling tests which may be run as long as 30 days.

An altitude measurement and control system may consist of a simple manometer, for indicating pressure, and a hand-throttling or bleed valve to control the level; or it may be a completely automatic system operated by a mechanical or electronic sensing device which operates modulating bleed controls to automatically regulate the vacuum. The U-tube manometer shows relative pressure between the site barometric pressure and the internal vacuum of the chamber. Absolute vacuum measuring manometers are recommended for altitude chambers to avoid the need for correction due to local barometric pressure variation.

Opposed-bellows absolute pressure controllers and electrical instruments using strain gage pressure transducers with bridge circuit electronic controllers are available. These instruments are suitable for altitudes up to 200,000 ft (0.5 mm Hg). They provide on-off control or proportioning output signals and can be used to control various functions of the vacuum system. Electronic vacuum-sensing devices measure the change in interference across an air gap between two electronic devices due to the reduction in gas molecules in the space. Coupled with amplifiers, this effect is used to initiate action in control circuits at a set point. One system uses an alpha emitter and measures the amount of energy reaching the grid to determine the vacuum level. Another uses ionization of a filament. A thermocouple is used to measure the change in heat exchange rate as a function of vacuum. Most electronic vacuum instruments are available with millivolt output which may be coupled to a standard potentiometer controlling device to provide a record and an output signal for controlling the vacuum system.

The most common way of automatically controlling a vacuum system is to bleed air into the chamber through a modulating valve. This merely floods the pump to the desired capacity so that good control can be maintained with the proper size bleed valve. Frequently two or more valves are required to control the pressure in the chamber over a wide range.

Altitude chambers can be controlled by cycling a solenoid valve in the pump suction line or simply turning the pump on and off. The latter system is not recommended because of the excessive strain on the motor and the drive mechanism. These two methods are not practical for diffusion pumping systems.

## Accessories

In order to provide satisfactory operation, a control system must include other accessories besides sensing elements and controllers. A pneumatic system should include a pressure reducing valve, a filter-dryer, and a surge tank which are standard with such systems.

Pressure switches, operated by the control air-pressure signal, may be used to switch off banks of heaters as progress is made toward the control point and thereby provide step modulation near the control point. Thus one controller can modulate the flow of brine to a cooling coil and also provide on-off control of electric heaters to decrease the number of heaters in circuits or modulate a vacuum bleed valve, or also switch pumps in and out of the system. Pressure switches are also used on time-pattern transmitter and pneumatic controller combinations. The transmitted air pressure is proportional to the value of the variable set on the controller; the action of these pressure switches can put into operation the equipment required to achieve this value. For example, the object may be the selection of either one- or two-stage operation of the refrigeration system depending on how low a temperature is called for by the controller. The use of other accessories will occur to the designer.

Safety, and other interlock relays and switches, should be carefully considered not only to provide safe operation but to control the system and reduce the number of switch settings that are to be made by the operator. Vacuum switches are frequently used to cut out the heaters or switch them to series wiring whenever an altitude chamber is under vacuum, thus preventing burnout due to low convection transfer.

Damage of test parts from exposure to too high (or too low) a temperature is an important consideration. Test packages that are placed in environmental chambers frequently have a very high monetary value; a malfunction of the control system may represent considerable loss. It is therefore becoming common to require an adjustable independent safety device to prevent over-heating in case of malfunction of the basic temperature control system.

In addition to the conventional control systems for temperature, humidity and vacuum, the designer may encounter requirements for measuring or controlling many other variables. These may include hydrogen ion concentration (pH); fluid velocity and pressure, dust and smoke density; explosive fuel and air mixtures; ozone, oxygen, and carbon dioxide levels; and others.

# DESIGN CALCULATIONS

## Cooling Loads

Steady state cooling loads are calculated in a manner similar to normal low temperature walk-in freezers. Loads must be accurately determined because refrigeration system capacities are relatively low within the temperature ranges of environmental test chambers. When internal live loads are specified at several operating temperature levels, the load for each set of conditions must be calculated to determine which requires the larger cooling system.

Transmission heat gains include transfer through insulation, framing, windows, sleeves and penetrations, and fan shafts or other through conducting materials. Internal live heat loads include lighting, product electrical loads, flow to and from the workspace of fluids warmer than the test space



temperature, etc. A safe approach is to include as load the heat equivalent of the total maximum kilowatt input to all electrical equipment including lights, motors, and other electrical apparatus. The heat equivalent of the fan brake horsepower input should be used including addition for internal bearings and correction for the higher density of the cold air.

If personnel are inside the chamber at low temperatures, the higher metabolism rate and the electrical input to protective clothing, when used, should be taken into account.

The load due to door openings or other infiltration can be calculated by assuming conservative air changes and adding the difference in specific and latent heat content between ambient and inside air.

Systems utilizing pumps or secondary refrigerants introduce additional load such as the full electrical input to pump motors, piping insulation transmission gains, conduction through shafts, etc.

In the calculation of transient condition cooling loads, all steady state heat loads are part of the load. For small chambers, wherein the transmission heat gain is a small portion of the total load, its maximum value may be used as the assumed load. For larger chambers, the Schmidt method as applied to mechanical refrigeration systems by Threlkeld and Kusuda[8] is recommended.

A commonly used approach is to estimate the thermal mass of all items which will change temperature as the chamber temperature is pulled up or down and predict the rate of temperature change of these items. The product of time rate of temperature change of these items and their thermal mass will give the instantaneous load due to temperature change at the point under consideration. The total load includes these dead loads, the transmission, and the live loads. The items for which the thermal mass must be calculated may include chamber air, interior liner and bracing, insulation and framing, evaporators, heat exchangers, heaters, blowers, brackets, shelves, or other internal gear as well as the test specimen.

Under transient temperature conditions there will be a gradient between the room ambient and the heat source or heat sink. For smaller chambers, conservative design will result if it is assumed that all of the items in direct contact with the chamber air change at the same rate as the air. For larger chambers changing at a fairly rapid rate, the required capacity of the conditioning equipment may be reduced by taking into account the slower temperature change of those items more thermally remote from the heat source or sink.

In order to simplify the calculations, it is possible to use some rule-of-thumb values from performance data of typical chambers. Such empirical data may be used to arrive at a pull down or pull up factor which remains reasonably constant for temperature changes within certain limits and for conditioning systems of a fairly constant capacity.

## Heating Loads

Steady state heating loads are calculated in a manner similar to those for cooling adjusted for the uniform capacity of electric heaters. Internal live loads may be neglected or credited in the computation. Transient heating may be approached in the same manner as transient cooling but using uniform capacity as a function of temperature.

## Relative Humidity

Equipment selection for relative humidity control is similar to normal air conditioning applications and yet more complex in that widely varied control conditions must be produced. A typical control range is 35 to 185 F dry-bulb temperature and from 20 to 98 percent relative humidity above 35 F dew point. Very low dew points may be required for special test programs. Sensible cooling loads may be calculated in a similar manner to low temperature loads, but must also account for additional factors such as the sensible heat of steam when used for humidification. Since dehumidification is normally accomplished by mechanically cooling and reheating the air, the most common approach is to take a portion of the total recirculating air, cool it to the required dew point, then reheat as required to control at the desired dry-bulb temperature level. If the total air flow were cooled and then reheated, rather large dehumidification and reheat capacities would result. When long term tests are required at controlled dew points near freezing, heat transfer cooling surfaces must be amply sized to operate without freezing. Generally, finned cooling coils at least ten rows deep and four fins per inch are indicated as well as means to maintain refrigerant evaporating levels to prevent icing. Care should be taken in calculating the amount of dehumidification coil surface required.

Where rather large internal heat gains are present, and when it is desirable to control at high humidities, spray contactors producing adiabatic saturation are desirable. By controlling the temperature of the recirculating spray, such systems may be used for simultaneous cooling and humidification. These systems can easily humidify at elevated temperatures with very little heat added to the water because there is rapid evaporation due to great vapor pressure differences. The sizing of heaters for increasing dry-bulb temperature is the same as for normal chamber heating. For humidification in systems not employing adiabatic saturators, either atmospheric pressure vapor generators or direct steam injection is used. The amount of water which must be added to achieve the desired increase in absolute humidity for the known volume of air within the chamber determines the rate of moisture addition. Both of these methods add sensible heat as well as latent heat, which must be added to the cooling load to obtain the total load.

# CHAMBER CONSTRUCTION

Environmental testing chambers for high and low temperature and humidity work are most commonly constructed of type 302 or 304 stainless steel inside and of mild steel outside to provide a vapor tight structure for the insulation. Vapor pervasion of the insulation will cause considerable loss of thermal efficiency and also cause corrosion of any mild steel structure. Aluminum and metallized mild steel interior liners are limited in their high temperature range and have not proved satisfactory for a long-range investment. Aluminum becomes embrittled from the extreme temperature cycling. Sprayed-on coatings provide only temporary protection for the mild steel.

The structure must be designed to provide for the considerable expansion and contraction that takes place during wide range temperature cycling. Doors are a particularly difficult problem. Any fan baffles, coil mountings, or other accessories must be carefully planned so that interference does not occur with moving parts during temperature cycling runs. Shock loads induced by liquid nitrogen and other refrigerants can cause violent stress concentrations. Humidity chambers must be designed so that any condensate formed on the coils, walls, or floor will be rapidly drained from the chamber. This is particularly important in programmed