

## ENVIRONMENTAL TEST FACILITIES

|                                                                 |      |
|-----------------------------------------------------------------|------|
| <a href="#"><i>Cooling Systems</i></a> .....                    | 37.1 |
| <a href="#"><i>Heating Systems</i></a> .....                    | 37.2 |
| <a href="#"><i>System Control and Instrumentation</i></a> ..... | 37.4 |
| <a href="#"><i>Design Calculations</i></a> .....                | 37.5 |
| <a href="#"><i>Chamber Construction</i></a> .....               | 37.6 |

**E**NVIRONMENTAL test facilities are used to simulate an environment or combination of environments under laboratory controlled conditions that duplicate or exaggerate the effects found in actual service. They assist the engineer and scientist in exploring the effects of equipment and in developing equipment for resistance to the many environmental forces.

The acceptance of and demand for environmental simulation facilities result from the following factors: (1) parallel and reproducible tests can be made, (2) equipment being tested can usually be observed and analyzed during testing, and (3) supporting equipment requirements are reduced to a minimum. Field testing and product development costs are reduced, lead time required for completion of product development is shortened, and most desirable reliability features can be incorporated in the original manufacture of the product.

Environmental test facilities are used not only to determine the performance of mechanical and electrical equipment, but for certain tests on personnel as well. Personnel testing includes (1) checking protective equipment and clothing, (2) altitude and space procedures indoctrination, and (3) studying physiological and psychological effects.

Environmental testing is usually divided into two general classifications—climatic and dynamic. The **climatic tests** of primary interest include the following:

**Temperature Chambers.** These are used for (1) temperature soaks at high and low extremes, (2) temperature shock testing in which the part is subjected to rapid high and low temperature cycling, and (3) programmed cycling in which the parts are subjected to repetitive expansion and contraction stresses and breathing.

**Humidity Chambers.** These may involve simply exposing the equipment to a constant humidity level, or **cycling**, wherein the temperature and relative humidity are varied. Cycle testing induces breathing and condensation within the parts tested. Subcooling may also be used to produce icing conditions.

**Salt Spray Chambers.** These are used for study of the corrosive action of salt vapor on components, usually at constant high-humidity test conditions.

**Fungus Chambers.** These are used to stimulate the growth of fungus on equipment, primarily electrical, being studied to ensure protection against tropical climates.

**Miscellaneous Climatic Chambers.** These include chambers for the simulation of desert sand and dust with high-velocity air movement, sunshine, snow, and rain, as well as chambers for proof testing of explosion-resistant wiring devices.

**Altitude and Space Chambers.** Altitude chambers have been used for some time in testing aircraft equipment. In recent years, space chambers have been developed for missiles, rockets, and space vehicle development work.

**Combined Environment Testing.** This type of test facility combines two or more of the above environments in one system, with all the complexity implied. Current thinking is that this type of testing is the only satisfactory means of proving that a piece of equipment will stand up in actual service.

**Dynamic or nonclimatic tests** include vibration, physical shock, acceleration, mechanical stress, nuclear radiation, cosmic radiation, micrometeorite bombardment, and many other types of stress.

The air-conditioning and refrigerating engineer may be directly concerned with designing test chambers to simulate most climatic environments. Some suggested methods of designing of test equipment for the production and control of various environments are given; the dynamic tests, however, are beyond the scope of this text. Because of the wide variety of tests that must be produced, detailed descriptions are not possible within this chapter.

Many techniques used in the design of environmental test equipment are the same as those employed for cryogenic equipment ([Chapter 38](#)), low-temperature refrigeration ([Chapter 39](#)), and biomedical applications ([Chapter 40](#)).

Many existing federal specifications outline basic environmental test specifications and the design method for some of the chambers to be used in this work.

## COOLING SYSTEMS

Temperature reduction in test chambers can be accomplished by both mechanical refrigeration systems and the use of expendable refrigerants. Both methods can be used directly or in conjunction with secondary heat transfer fluids.

## Primary Refrigerants

Any refrigerant suitable for mechanical refrigeration can be used as the primary refrigerant. See [Chapter 39](#) for information on low-temperature refrigerants and refrigeration systems. Selection requires an evaluation of equipment size, cooling load, type of evaporator, temperatures to be produced, method of condensing, hazards, lubrication, and special operating requirements. The use of chlorofluorocarbons is being eliminated. Although single-stage and cascade systems are the most common designs presently used, a two- or three-stage compound system may be selected for certain load applications.

Test chambers are frequently required to operate at high as well as low temperatures. When using primary refrigerants in evaporators that may be subjected to temperatures above 150°C, thermal isolation and cooling of the evaporator are necessary to prevent lubricant decomposition or other possible deterioration of the refrigerant circuit. Refrigerant filter cartridges should be changed frequently in systems where the evaporator is subjected to high temperatures. 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. However, it is more common to use

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expendable refrigerants for high-temperature equipment, even with the disadvantage of higher operating costs at low temperature.

### Expendable Refrigerants

Expendable refrigerants, such as dry ice, liquid carbon dioxide, liquid nitrogen, liquid helium, and others discussed in [Chapter 38](#), 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 common expendable refrigerant methods. Liquid nitrogen, liquid helium, and other cryogenic liquids work particularly well below the temperature range of mechanical refrigeration systems.

The advantages of expendable refrigerants in environmental test equipment are reduced initial cost, basic simplicity, reduced mass and size of the chamber, and the ability to produce very rapid pull-down rates to low temperatures. Disadvantages include higher operating costs, the need for a reliable source of expendable refrigerants, the potential personnel hazard resulting from the absence of oxygen when the air is displaced in the test space, and the possible detrimental effect of submerging the tested product in the gas or liquid of an expendable refrigerant which is 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.

Chambers using dry ice as the expendable refrigerant have, in most cases, been replaced with direct injection of liquid carbon dioxide or liquid nitrogen, which eliminates the need for a dry ice compartment. Also, the chamber is smaller and the temperature more easily controlled. Only on-off cycling is possible for control of direct injection liquid CO<sub>2</sub> systems because of the triple point of CO<sub>2</sub>. Solenoid-actuated two-way valves and pneumatically or electrically actuated ball valves have been used with much success. If reduced-capacity operation is desirable, the control valve should be time-pulsed or more than one valve should be used with small and large expansion orifices. Solenoid valves with built-in orifices designed for this specific application are available.

Liquid CO<sub>2</sub> is used at two pressures; low-pressure bulk liquid is stored in refrigerated receivers at approximately -20°C and 2 MPa. Its latent heat is approximately 280 kJ/kg. High-pressure liquid is stored at room temperature at pressures ranging from 5 to 7 MPa, depending on ambient temperatures. Its latent heat varies from approximately 115 to 175 kJ/kg, depending on initial temperatures. High-pressure liquid is used only for very small or infrequent cooling loads because the latent heat is low, the liquid fills only 60 to 70% of a high-pressure cylinder, and the cost is considerably higher than for low-pressure liquid. For increased efficiency when high-pressure liquid CO<sub>2</sub> is selected, an economizer that pre-cools incoming liquid by heat exchange to the exhaust cold vapors can be used to reduce the CO<sub>2</sub> requirement by 15 to 30%.

Liquid nitrogen can be applied either directly or indirectly to produce temperatures cheaply and easily down to its approximate -196°C boiling point (at 101.3 kPa). Control is accomplished either by 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 either by 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, and so forth should be fabricated of nonferrous metals, stainless steel, or high nickel steel. Few plastics are suitable seals in this temperature range. Although its latent heat of evaporation at 101.3 kPa pressure is only 198 kJ/kg, another 130 kJ/kg is available from the superheating of gas to -73°C. Therefore, it has a greater capacity of heat absorption than does low-pressure liquid CO<sub>2</sub> when operating at a -73°C or higher control point. Suitable precautions should be taken against the low-

temperature hazards to operating personnel. Oxygen monitoring systems should be located in the test cells to warn personnel if oxygen depletion occurs. Carbon dioxide and nitrogen gases should be vented to the outside atmosphere after they have been used in the test chamber.

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 that can be obtained by more economical means. Special storage and control valves are required. More detailed information on cryogenic liquids, their handling and piping, may be found in [Chapter 38](#).

### Secondary Coolants

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, (4) expendable refrigerants are used and direct cooling of air or a test specimen is not possible, (5) the wall of a temperature chamber or the shroud of a space simulator is to be conditioned and a close temperature gradient is required, or (6) thermal shock by alternately immersing the test specimen in liquids of different temperatures is required.

Halocarbons, liquid hydrocarbons, alcohol, some primary refrigerants, silicone fluids, and aqueous glycol solutions are used as secondary coolants. Thermal considerations include viscosity, specific heat, density, 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. However, some secondary refrigerants dissolve in nitrogen. In that case, other methods, such as an expansion tank with a diaphragm separator, must be used to pressurize the system. Also, certain fluids must be kept refrigerated to prevent boiling off under standby conditions.

Secondary coolants are cooled in insulated sublimation tanks by spraying the liquid over dry ice or directly injecting liquid CO<sub>2</sub> or liquid N<sub>2</sub> into the secondary coolant. Such systems require a pump for recirculation of the secondary coolant. Common operating difficulties in sublimation systems include both cavitation in pumps because of the release of dissolved CO<sub>2</sub> or liquid N<sub>2</sub> gas and foaming in the sublimation tank with resultant carryover of the secondary heat transfer liquid with the vented gases. Positive displacement pumps and positive suction pressures are recommended.

In a system with a wide temperature range, the pump and shaft seal must be carefully selected. Magnetic drive and canned pumps have no external seals, which eliminates the shaft seal problem.

Secondary coolants can also be cooled by a mechanical refrigeration system or by a heat exchanger cooled by liquid nitrogen. These systems avoid carryover, cavitation, and moisture problems. The evaporator or heat exchanger must be designed to avoid freeze-up. In [Chapter 21 of the ASHRAE Handbook—Fundamentals](#), more detail is included and additional coolants and their properties are discussed.

### HEATING SYSTEMS

Electric heat is most commonly used in environmental chambers. Prime or extended surface, tubular, or strip heaters are suitable for circulating airstream systems. This method is a conduction or convection type of heating used to duplicate conditions in storage, in transportation, and when a protective housing is provided around equipment. With proper precautions, open nichrome, strip, or coil wire heaters can be used; they offer the advantages of a rapid response because of their low thermal mass.

All types of electric heaters require proper insulation and protection against moisture. Generally speaking, temperature test chambers (dry-bulb control) may use open wire resistance heaters, although condensation at low temperatures may produce excessive moisture and corrosion on the heaters.

Some specifications prohibit direct radiation from chamber heaters to the test specimen. In this case, heater baffling may be required.

Salt-spray chambers are heated indirectly, usually by circulating heated water or air around the outside of the chamber shell outside the salt-fog atmosphere. Sand and dust chambers must use sheathed heaters that have good resistance against the erosion of high-velocity sand and dust. Explosionproof testing chambers contain an explosive fuel and air mixture. Heaters must have temperature-limiting devices on the sheath with terminals extended to the outside to prevent ignition of the mixture.

Altitude and space chambers present special heat problems. Arcing between terminals under vacuum conditions must be prevented. General practice brings the terminals to the outside of the vacuum space through a vacuum-tight fitting. The reduced convective heat transfer of a heater under vacuum must be considered in the design to prevent burnout. Thermal and mechanical bonding of sheathed heaters to the exterior wall of the vacuum structure has been successfully used to avoid some of these problems. Internal forced convection heating is usually suitable up to about 15 km of altitude, approximately 10 kPa.

Indirect heating is also suitable for environmental chambers. Hot water, steam, brines, and oils can be used in coils in various configurations. These heating systems are particularly applicable where close tolerance must be provided within the system because complete modulation is possible. Modulation control is also possible in electrical resistance heating systems by using power-proportioning equipment. Hot-water recirculating systems and steam systems can be used with relatively standard design approaches. Complete drainage of the coils and piping within the chamber must be ensured if the chamber will be operated below freezing. Proper water treatment should be provided.

Many brines and heat-exchange fluids that are not limited to the temperature ranges of water or steam are available. No one fluid for the commonly required wide ranges of environmental test equipment, such as  $-75$  to  $150^{\circ}\text{C}$ , is available at present. Most chemical brines present some problems with viscosity, toxicity, flammability, chemical reaction with the piping, and other limitations. Any heat-exchange fluid must be carefully evaluated for limitations.

Another type of heating system is the radiant type, which is required to simulate such situations as sun exposure where both the heat-flux density and the wavelength are important; more commonly, radiant sources are used in equipment exposed to radiation from some high-temperature source. Radiant sources in environmental chambers vary from exposed nichrome wire heaters to specialized equipment such as arc lamps and mercury xenon lamps used to simulate sunshine.

Because the wavelength of the source is a function of its temperature, the conditions to be simulated must be understood before a suitable radiant heat source can be designed. Where the problem is simply to produce high power density on the test specimen, bare nichrome wires, sheathed heaters, carbon and silicon carbide rod heating elements, and similar devices are available. Tubular quartz heat lamps are often suitable for very rapid heat-up conditions. Sunshine at sea level is usually simulated by the use of mercury vapor lamps or combinations of tungsten filament heat lamps to produce the proper wavelength and power density. Radiant heating systems may be required to produce heat densities in excess of  $1300\text{ kW/m}^2$ . Careful design of the chamber structure, proper support of the heating elements, and correct location of the heating elements are required to prevent mechanical and thermal stress problems resulting from large temperature differentials and rapid heat-up and cool-down cycles.

Under altitude simulation conditions, removal of heat from a test specimen is possible by convection up to about 30 km (1.1 kPa). 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 specimen. An envelope of cooled, rarefied air, within which temperature gradients will be reasonably small, is thus produced around the test specimen.

Large gradients may occur throughout the rest of the chamber but will not affect the test results. Airflow should be reduced at low temperatures to prevent fan motor overload and minimize the 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 some of the losses through the structure. A pumped secondary refrigerant to prevent high wall temperature gradients can be used.

Evaporators should be maintained at the lowest practical temperature to provide the maximum temperature difference for both radiant and convective heat transfer. In simulated altitudes over 30 km, a radiation heat transfer system should be designed into the chamber to produce the desired temperature-control conditions on the test specimen. Treating the walls of the chamber to produce high emissivity is necessary in this case; close control of the entire wall surface is generally advisable. The limitation of radiant heat transfer in the low-temperature range must be considered 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  $-75^{\circ}\text{C}$  range, the heat transfer rate is small. The detailed calculation of this effect is described in [Chapter 3 of the ASHRAE Handbook—Fundamentals](#), where the Stefan-Boltzmann equation is discussed.

## Air Movement

All types of fans and air movers are used in test chambers. Propeller, axial flow, and centrifugal fans are generally selected. Positive displacement or multistage turbine-type blowers provide the necessary total pressure for ram air simulation under altitude conditions. Drives for internally mounted fans must be located externally when extreme conditions are encountered in the airstream. To eliminate corrosion and minimize heat transmission, stainless steel shafts are commonly used. In almost all instances, a vapor seal is required to minimize or eliminate transmission to or from the ambient air. Internal bearings must withstand the full range of environmental conditions with a reasonable life expectancy. Altitude chamber fan shafts must be equipped with vacuumtight shaft seals.

Air distribution within the work space of the test equipment is important in producing both uniform gradient conditions and system response. Frequently, close temperature gradients specified for air circulation rate and distribution will complicate the control problem. Air densities may vary almost three-to-one in temperature test chambers and more than fifty-to-one in altitude test chambers. Therefore, motor sizing and speed control of fans require careful attention. The airflow for a specific gradient is directly proportional to the net heat gain or loss in the work space and inversely proportional to the permissible temperature gradient and density of the air.

Usually the air volume must be increased at elevated temperatures because of the lower density. The circuit pressure drop will be approximately proportional to the air density. Therefore, the system balance points should be determined from the fan characteristic curves for various operating range conditions in the chamber.

## Humidification

Common means of raising the relative humidity within a test chamber include directly introducing low-pressure steam, vaporizing water by electric immersion heaters in an open evaporation pan,

and directly atomizing water sprays alone or in combination with electric heaters to aid vaporization of the spray.

Steam and vapor generators are best for increasing humidity as well as temperatures, because considerable sensible heat is introduced. Control of steam may be modulating or on-off. With the latter, control set point anticipation is suggested to minimize overrun because of too rapid a rise in moisture content. When self-contained steam generators are used, they should include a low water cut-off device, suitable pressure relief valves, and other safety devices. Makeup water should be provided from a distilled or demineralized source.

Vapor generators operating at atmospheric pressure are commonly selected when it is desirable to produce test conditions of  $95 \pm 5\%$  rh at temperatures between 40 and 70°C. Protection against immersion heater burnout is mandatory for good design.

For production of high humidities at temperatures near and below ambient, some form of atomized water spray is recommended because of the adiabatic cooling effect on evaporation. Although water spray systems do not have as rapid a response as steam, this is no disadvantage at lower temperatures where the humidity ratio is low. By controlling the temperature of the sprayed water, both humidification and dehumidification can be achieved with a single system. Heating and cooling means may be located either inside the conditioning spray plenum or externally in the recirculating water circuit. Close control of humidities is possible with such a design. Distilled or demineralized water is suggested; the hardness of tap water may be corrosive or cause contamination. Recirculating spray systems should be periodically flushed out because of possible airstream contamination of equipment or test specimen. For the system to operate properly, the construction material must be considered carefully.

## Dehumidification

Low-humidity conditions with controlled dew points above freezing are usually produced by mechanical refrigeration cooling and electric reheating, because most environmental chambers require mechanical refrigeration for extended dry-bulb temperature range control. For the control of humidity conditions requiring dew points below freezing and continuous operation, either alternately defrosted dual evaporators or automatically regenerating desiccant dehumidifiers are used. If an enclosure is sufficiently vaportight and there is no internal latent load, an evaporator sufficiently large to handle the frost buildup because of initial latent load may be an acceptable solution.

Ram air coolers that simulate the cooling air supply for electronic airborne equipment at controlled temperature, humidity, and altitude conditions, present special dehumidification problems. If 100% outdoor air is required, it is best handled by a wet coil that removes a large part of the moisture just above freezing, followed by a set of parallel alternately defrosted evaporators. For ram air simulators in a closed-loop arrangement, simpler systems are possible if the cooling of air does not involve dehumidification.

When using certain liquid or solid desiccants in very high or low dry-bulb ranges, mechanical refrigeration cooling may be required for precooling or aftercooling. In such systems, a portion of the chamber air is continuously withdrawn by an auxiliary blower and passed through the drying agent and any necessary precooling or aftercooling coils.

Some tests require the conditioned air dew point to remain sufficiently low to prevent condensation within the test specimen during dry-bulb control temperature cycling. This requirement can be a problem during rapid heat pull-up and may require a desiccant dehumidifier.

## SYSTEM CONTROL AND INSTRUMENTATION

### Control Tolerances

Environmental test facilities generally require minimal control tolerances over a wider range than that required for ordinary HVAC

systems. Control of temperatures as close as  $\pm 0.3$  to 0.5 K are commonly specified. Relative humidity control tolerance is at most  $\pm 5\%$  and more often  $\pm 3\%$  or even less. To meet these requirements, the control and instrumentation system must have an even better accuracy since operating tolerances often exceed control tolerances.

When, in addition, the test chamber is designed to provide a wide range of test conditions, the HVAC equipment must be oversized for most of those conditions. The control system is then required to modulate equipment output to a small percentage of capacity, with all of the difficulties inherent in controlling oversized equipment.

For these reasons, the control devices used with test chambers must be of the highest quality. In general this will be "industrial quality," as used in process-control applications. Most systems operate in a modulating mode, using proportional plus integral (PI) or, occasionally, proportional plus integral plus derivative (PID). Proportional only control is not acceptable due to its inherent deviation from set point. For discussions of control theory, operating modes and typical systems, see [Chapter 15 of the ASHRAE Handbook—Fundamentals](#) and Haines (1987).

### Temperature Controls

Systems for temperature control are of the types discussed in [Chapter 15 of the ASHRAE Handbook—Fundamentals](#) and Haines (1987). Controllers should operate in PI mode, although PID may be needed when rapid cycling over a wide range of set points is required.

Temperature sensors may be thermocouples, thermistors, or resistance temperature detectors (RTDs). Thermistors and RTDs should be specified to have an absolute accuracy of  $\pm 0.3$  K and a sensitivity of at least 0.06 K. Most good RTD and thermistor sensors can meet these requirements. Thermistors must be specified with factory-certified performance and a guarantee of not more than 0.5 K drift per year so that they can be readily replaced. Thermistors do drift and must, therefore, be recalibrated or replaced at frequent intervals, depending on the tolerance specifications. Wound wire RTDs may be specified with no drift over time. The best-quality wound wire RTDs are platinum; these may be obtained with certified accuracies, traceable to industry standards. Platinum RTDs using solid-state deposition techniques are also available. These are accurate and have a fast response but are subject to drift over time. Sensitivity and accuracy may not be suitable for close tolerances when bulb and capillary-type sensors are used with pneumatic controllers. RTD sensors used with pneumatic controllers can greatly improve accuracy. Electronic controllers are generally preferred.

Sensors must be suitable for the temperature ranges required. Consult the sensor manufacturer for this information. Where wide ranges are required, two or more instruments may provide better accuracy over the entire range.

Recorders may be digital or of the strip or circular chart type. They may use the same sensors as are used by the controllers. If separate sensors are used they must be calibrated together. For accurate calibration, laboratory mercury thermometers should be used, depending on the range.

### Humidity Controls

Accurate humidity sensing is very difficult. Materials that vary dimensionally with changes in relative humidity are not suitable for close control because of hysteresis and drift. Electrolytes and wet-bulb/dry-bulb sensors require essentially continuous maintenance to ensure accuracy. For any system, accuracy at extremely high or below-freezing temperatures may be questionable. For reasonably close control ( $\pm 5\%$  rh), solid-state deposition sensors of the capacitance or resistance type are satisfactory and have a fast response. They must be calibrated regularly—the best have a drift of about 1% per year. For very close control, for calibration, and for continuous accurate sensing, the chilled-mirror dew-point sensor should be

used. This device is available in several packaging arrangements and, if needed, can be obtained with a certification of accuracy traceable to an agency standard. Its response is somewhat slow for use with rapidly changing conditions. In some cases, it has been used to back up and check the solid-state instruments that are actually used for control.

Controllers must operate in the PI or PID mode, and recorders may use sensors in common with the controllers.

### Pressure Controls

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 the system may be completely automatic, operated by a mechanical or electronic sensing device that actuates modulating bleed controls to automatically regulate the vacuum. A U-tube manometer can show 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 to correct for local barometric pressure variations.

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 to 60 km. They provide on-off control or proportioning output signals and can control various functions of the vacuum system. Electronic vacuum-sensing devices measure the change in interference across an air gap between two electronic devices because of the reduction in gas molecules in the space. Coupled with amplifiers, this effect initiates action in control circuits at a set point.

One instrument system has an alpha emitter and measures the amount of energy reaching the grid to determine the vacuum level. Another system uses ionization of a filament. A thermocouple measures the change in the heat exchange rate as a function of vacuum. Most electronic vacuum instruments are available with microampere or millivolt output that may be coupled to a standard potentiometer to provide both a record and an output signal for controlling the vacuum system.

The most common method of automatically controlling a vacuum system is to bleed air into the chamber through a modulating valve. This 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 measure 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.

### Valves and Dampers

Haines (1987) discusses the factors to be addressed in selecting control valves and dampers. In test chambers where a wide range of conditions must be simulated, the system gains are aggravated by the need to size the HVAC equipment for the most severe conditions, which means that it is oversized for every other condition, sometimes extremely so. Oversizing the valve or damper inevitably leads to poor control. It follows that valves and dampers should be undersized rather than oversized if close control is to be obtained. Undersizing penalizes the air or water system hydraulics but may be necessary to obtain the desired results. Use of multiple small dampers should be considered.

### Computers as Controllers

Typically, direct digital control (DDC) with computers is used. The computer simply takes over the controller function. It can be

programmed to any kind of operating and timed sequence desired. It can also provide visual and printed output of system status, either in real time or as history, including graphic and statistical presentations. The engineer should select the functions needed to satisfy the design parameters.

### Accessories

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-drier, and a surge tank; all are standard with such systems. For systems operating below freezing, nitrogen or dried compressed air should be considered as the pneumatic medium rather than compressed air if the system is to run within the chamber.

The selection of 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 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 because of low convection transfer. Often there is a temperature limit controller to prevent damage that may occur because of excessive heating or cooling of the test module.

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 variables 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 and Heating Loads

Because the rate of temperature change is usually important in the operation of test chambers, both the steady-state and transient load must be calculated to size the refrigeration and heating system. The steady-state cooling load includes heat transferred through the insulation, framing, windows, sleeves and penetrations, fan shafts and other conducting materials, and the internal live heat loads of lighting, fans, personnel, and test specimen. The sum of these loads that occur simultaneously at the lowest air temperature in the chamber is the minimum design capacity. The equipment needs to be sized to handle this design capacity, plus a factor of safety, at the refrigerant evaporating temperature required and as determined by the evaporator size.

Transmission losses must also be determined to calculate the total steady-state heating load. The live loads, such as blowers and lights, will decrease the heating load, but usually they are not deducted from the transmission losses. The heaters are then sized with the load at the high temperature and derated for low voltage and operating temperature.

For transient conditions, the thermal mass of all items, including chamber air, liner and bracing, insulation and framing, evaporators, heat exchangers, heaters, blower, brackets, shelves or other gear, and the test specimen must be determined. The product of the mean specific heat and the mass gives the average thermal mass. The product of the time rate of temperature change and the thermal mass gives the instantaneous load due to temperature transients. The total load may include transmission and live loads as well.

Under transient conditions, a gradient will exist between the room ambient and the heat source or sink. For small chambers, conservative design assumes that the temperature of all items directly contacting the chamber air changes at the same rate as the air temperature. In cases with very rapid temperature changes and high mass loads, the surface areas, air velocity, and point of temperature control must be considered in designing the necessary refrigerating

or heating system. A larger system cooling requirement may be calculated by this method rather than by one based on the total load changing with the air temperature—especially if a linear rate of change is required and the final temperature is low on the capacity curve of the refrigeration equipment. This larger capacity is also required for heating, except electric heating, where the capacity is essentially uniform at all temperatures.

### Relative Humidity

Equipment selection for relative humidity control is similar to normal air-conditioning applications, only more complex in that widely varied control conditions must be produced. A typical control range is 2 to 85°C dry-bulb temperature and from 20 to 98% rh above 2°C dew point. Very low dew points may be required for special test programs. Sensible cooling loads may be calculated in a manner similar to that for low-temperature loads, but must also account for such additional factors 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 it as required to keep it at the desired dry-bulb temperature level. If the total air volume 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.

Where large internal heat gains are present and high humidities are desired, spray-wetted surfaces producing adiabatic saturation may be used. By atomizing the spray and controlling the temperature of the recirculating spray water, systems may be used for simultaneous cooling and humidification.

The sizing of heaters for increasing dry-bulb temperature is the same as for normal chamber heating. Atmospheric pressure vapor generators and direct steam injection are alternative methods of humidification. The amount of water that 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

Inner liners of test chambers for high and low temperature and humidity are most commonly made of type 302 or 304 welded stainless steel. The outside liner is made of aluminum or mild steel, welded or sealed to provide a vaportight structure for the insulation. For walk-in rooms, prefabricated, urethane-insulated, foamed-in-place modular panels are popular. Special care must be taken in the sealing of the panel joints.

A means must be provided to prevent an excessive pressure differential between the inside and outside of the chamber during rapid changes of temperature. Even opening and closing a door, when test space conditions are different from ambient, may change the air temperature and consequent pressure enough to buckle the liner of a well-sealed chamber if it is not properly vented.

The structure must be designed to provide for the considerable expansion and contraction that take 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 moving parts are not interfered with 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 drain rapidly from the chamber. This

feature is important in programmed humidity chambers in which operation ranges from high- to low-humidity conditions.

### Altitude Chambers

Generally, a chamber that simulates altitude to 75 km (2.1 Pa) is considered an altitude chamber; above that altitude, the chamber is considered a space simulator. Interior liners of chambers that simulate altitude are usually constructed of aluminum, mild steel, or stainless steel, with exterior structural steel reinforcing designed to withstand a vacuum or 100 kPa (gage).

Depending on the desired test space configuration, chamber liners may be rectangular or cylindrical. Design of the chamber to withstand the exterior pressure should be in accordance with the latest edition of the American Society of Mechanical Engineers' (ASME) *Boiler and Pressure Vessel Code*.

Altitude chambers that control temperature or humidity or both, in combination with altitude simulation, are built with the pressure liner on the inside or outside of the insulation space. The inside liner, whether or not it is the pressure liner, should be made of a corrosion-resistant material such as stainless steel. The outside liner may be mild steel. If the outside liner is the pressure liner, it must be of sufficient thickness or reinforced to withstand a vacuum or 100 kPa pressure differential. It must also be treated for corrosion resistance due to equalization with the test space, which will introduce various combinations of temperature and (high) humidity into the liner surfaces and insulation.

If the inner liner is the pressure liner, it must be stressed for the temperature range involved as well as the pressure. The inner liner should be the pressure liner if high-altitude use is a major consideration, because the insulation space is not exposed to the vacuum. However, because of the liner and reinforcing mass, the cooling and heating load during temperature transition is greater than with an outside pressure liner. With an outside pressure liner, the insulation space must be equalized with the test space to prevent inner liner collapse. Achieving high vacuum on the insulation and insulation space is very difficult unless it is dry; therefore, this fact must be considered during temperature or temperature-humidity runs, or when diving the chamber to atmospheric pressure after an altitude test.

Seam welds of the vacuum vessel should be on the vacuum side and should be of one continuous pass with skip welding, if required, on the outside. This method of welding virtually prevents leaks and allows for leak checking.

### Insulation

[Chapters 23, 24, and 25 of the ASHRAE Handbook—Fundamentals](#) discuss insulation fundamentals and applications in detail.

### Doors

Both overlap and plug-type doors are used, the latter most frequently on both high-humidity chambers (because of internal condensation) and high-temperature chambers, to prevent or minimize warping. They must be rugged and well fitted, particularly for altitude chambers. Vapor sealing with multiple gaskets is important, particularly on smaller chambers, since defrosting means are seldom provided. Suitable gasket materials would be natural rubber, synthetic rubber, and silicone. Plastics or light-gage stainless steel are recommended for thermal breaker strips; pressed wood hardboard materials generally have insufficient resistance to physical damage, high temperatures, or high humidities. Low-wattage heater cables, installed under the breaker strip, prevent larger doors from freezing closed. Safety measures, including doors easily opened from inside, are essential for walk-in freezers.

For altitude chambers, the door assembly must register against a gasket that will easily vacuum seal. Vacuum gaskets must be properly retained to prevent their being drawn into the chamber.

### Windows

Special hermetically sealed multilight window assemblies are manufactured for special conditions. They are suitable for wide-range temperature and humidity tests and, if provided with an inner pane of sufficient strength, for altitude tests as well. Tempered plate is required for the inner panes so that temperature shocks will not cause failure. Because of the pressures that build up, sealed assemblies for higher temperatures require careful design. For temperatures up to 500°C, windows of tempered glass are required and hermetic sealing is difficult, but research indicates a possible range of -180 to 500°C. The number of panes and design for a given task are usually specified by the window manufacturer. A typical -75 to 150°C window contains six lights of glass enclosing dry gas spaces.

### Accessories

**Interior lighting** is mostly incandescent, in vaportight and sometimes explosionproof fixtures. Ample illumination will be given usually by 60 to 100 W/m<sup>2</sup> of floor space. Lamps are not recommended for use inside chambers above 300°C.

**Power leads** may handle normal alternating current or special aircraft voltages and frequencies.

**Thermocouples** in almost any number may be called for. Bare iron-constantan should not be installed in a high-humidity chamber. For the operator's convenience, thermocouples are frequently connected to plugs and outlets.

**Turning shafts**, if small and manually operated, may be coupled to adjustable devices on the test specimen. These shafts should be stainless steel tubes. O rings on the outside of the chamber may be used for pressure sealing.

**Power shafts**, provided for driving rotating equipment, must have vacuumtight shaft seals for vacuum chambers.

**Sleeves and plugs** are required for general-purpose testing. Holes of various sizes may be specified. On altitude chambers, threaded or flanged caps must be provided.

**Special lines** for pneumatically or hydraulically operated equipment may require pressure pipes with special connections at the ends.

**Protective panels** are used to prevent damage to the chamber if an internal explosion or sudden release of pressure occurs.

**Window wipers** are installed on windows to remove condensation if vision is required when temperature adjustments are made within the chamber.

**Reach-in ports**, with or without gauntlets, may be provided for minor work within a test space without opening doors or disturbing internal conditions.

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