CHAPTER 10

AIRCRAFT

ENVIRONMENTAL control system (ECS) is a generic term used in the aircraft industry for the systems and equipment associated with ventilation, heating, cooling, humidity/contamination control, and pressurization in the occupied compartments, cargo compartments, and electronic equipment bays. The term ECS often encompasses other functions such as windshield defog, airfoil anti-ice, oxygen systems, and other pneumatic demands. The regulatory or design requirements of these related functions are not covered in this chapter.

Environmental control systems of various types and complexity are used in military and civil airplane, helicopter, and spacecraft applications. This chapter applies to commercial transport aircraft that predominantly use air-cycle air conditioning for the ECS.

Commercial users categorize their ECS equipment in accordance with the Air Transport Association of America (ATAA) *Specification* No. 100, Specification for Manufacturers' Technical Data. The following ATAA 100 chapters define ECS functions and components:

- **Chapter 21**, Air Conditioning, includes heating, cooling, moisture/contaminant control, temperature control, distribution, and cabin pressure control. Common system names are the air-conditioning system (ACS) and the cabin pressure control system (CPCS).
- **Chapter 30**, Ice and Rain Protection, includes airfoil ice protection; engine cowl ice protection; and windshield ice, frost, or rain protection.
- **Chapter 35**, Oxygen, includes components that store, regulate, and deliver oxygen to the passengers and crew.
- **Chapter 36**, Pneumatic, covers ducts and components that deliver compressed air (bleed air) from a power source (main engine or auxiliary power unit) to connecting points for the using systems (Chapters 21, 30, and Chapter 80, Starting). The pneumatic system is also commonly called the engine bleed air system (EBAS).

REGULATIONS

The Federal Aviation Administration (FAA) regulates the design of transport category aircraft for operation in the United States under Federal Aviation Regulations (FAR) Part 25. ECS equipment and systems must meet these requirements, which are primarily related to health and safety of the occupants. Certification and operation of these aircraft in the United States is regulated by the FAA in FAR Part 121. Similar regulations are applied to European nations by the European Joint Aviation Authorities (JAA), which represents the combined requirements of the airworthiness authorities of the participating nations; the equivalent design regulation is JAR Part 25. Operating rules based on FAA or JAA regulations are applied individually by the nation of registry. Regulatory agencies may impose special conditions on the design, and compliance is mandatory.

Several FAR and JAR Part 25 paragraphs apply directly to transport category aircraft ECSs; those most germane to the ECS design requirements are as follows:

FAR/JAR 25.831	Ventilation
FAR 25.832	Cabin ozone concentration
FAR/JAR 25.841	Pressurized cabins
FAR/JAR 25.1309	Equipment, systems, and installations
FAR/JAR 25.1438	Pressurization and pneumatic systems
FAR/JAR 25.1461	Equipment containing high energy rotors

These regulatory requirements are summarized in the following sections; however, the applicable FAR and JAR paragraphs, amendments, and advisory circulars should be consulted for the latest revisions and full extent of the rules.

Ventilation

FAR/JAR *Paragraph* 25.831:

- Each passenger and crew compartment must be ventilated.
- Each crew member must have enough fresh air to perform their duties without undue fatigue or discomfort (minimum of 10 cfm).
- Crew and passenger compartment air must be free from hazardous concentration of gases and vapors:
  - Carbon monoxide limit is 1 part in 20,000 parts of air
  - Carbon dioxide limit is 0.5% by volume, sea level equivalent
  - Conditions must be met after reasonably probable failures
- Smoke evacuation from the cockpit must be readily accomplished without depressurization.
- The occupants of the flight deck, crew rest area, and other areas must be able to control the temperature and quantity of ventilating air to their compartments independently.

FAR *Amendment* No. 25-87:

- Under normal operating conditions and in the event of any probable failure, the ventilation system must be designed to provide each occupant with airflow containing at least 0.55 lb of fresh air per minute (or about 10 cfm at 8000 ft).
- The maximum exposure at any given temperature is specified as a function of the temperature exposure.

JAR ACJ (*Advisory Circular-Joint*) 25.831:

- The supply of fresh air in the event of loss of one source should not be less than 0.4 lb/min per person for any period exceeding 5 min. However, reductions below this flow rate may be accepted provided that the compartment environment can be maintained at a level that is not hazardous to the occupant.
- Where the air supply is supplemented by a recirculating system, it should be possible to stop the recirculating system.

Cabin Ozone Concentration

FAR 25.832 specifies the cabin ozone concentration during flight must be shown not to exceed

The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.

- 0.25 ppm by volume, sea level equivalent, at any time above flight level 320 (32,000 ft)
- 0.10 ppm by volume, sea level equivalent, time-weighted average during any 3 h interval above flight level 270 (27,000 ft)

At present, JAR 25 has no requirement for cabin ozone concentration.

Pressurized Cabins

FAR/JAR 25.841:

- Limits the maximum cabin pressure altitude to 8000 ft at the maximum aircraft operating altitude under normal operating conditions.
- For operation above 25,000 ft, a cabin pressure altitude of not more than 15,000 ft must be maintained in the event of any reasonably probable failure or malfunction in the pressurization system.
- The makeup of cabin pressure control components, instruments, and warning indication is specified to ensure the necessary redundancy and flight crew information.

FAR *Amendment* No. 25-87 imposes additional rules for high-altitude operation.

Equipment, Systems, and Installations

FAR/JAR 25.1309:

- Systems and associated components must be designed such that occurrence of any failure that would prevent continued safe flight and landing is extremely improbable.
- The occurrence of any other failure that reduces the capability of the aircraft or the ability of the crew to cope with adverse operating conditions is improbable.
- Warning information must be provided to alert the crew to unsafe system operating conditions to enable them to take corrective action.
- Analysis in compliance with these requirements must consider possible failure modes, probability of multiple failures, undetected failures, current operating condition, crew warning, and fault detection.

FAR *Advisory Circular* AC 25.1309-1A and JAR ACJ No. 1 to JAR 25.1309 define the required failure probabilities for the various failure classifications: probable, improbable, and extremely improbable for the FAR requirements; and frequent, reasonably probable, remote, and extremely remote for the JAR requirements.

Pressurization and Pneumatic Systems

FAR 25.1438 specifies the proof and burst pressure factors for pressurization and pneumatic systems as follows:

- Pressurization system elements (air conditioning)
  - Burst pressure: 2.0 times maximum normal pressure
  - Proof pressure: 1.5 times max normal pressure
- Pneumatic system elements (bleed)
  - Burst pressure: 3.0 times maximum normal pressure
  - Proof pressure: 1.5 times maximum normal pressure

JAR 25.1438 and ACJ 25.1438 specify the proof and burst pressure factors for pressurization and pneumatic systems as follows:

- Proof pressure
  - 1.5 times worst normal operation
  - 1.33 times worst reasonable probable failure
  - 1.0 times worst remote failure
- Burst pressure
  - 3.0 times worst normal operation
  - 2.66 times worst reasonably probable failure
  - 2.0 times worst remote failure
  - 1.0 times worst extremely remote failure

Equipment Containing High-Energy Rotors

FAR/JAR 25.1461:

Equipment must comply with at least one of the following three requirements:

- High-energy rotors contained in equipment must be able to withstand damage caused by malfunctions, vibration, and abnormal temperatures.
  - Auxiliary rotor cases must be able to contain damage caused by high-energy rotor blades.
  - Equipment control devices must reasonably ensure that no operating limitations affecting the integrity of high-energy rotors will be exceeded in service.
- Testing must show that equipment containing high-energy rotors can contain any failure that occurs at the highest speed attainable with normal speed control devices inoperative.
- Equipment containing high-energy rotors must be located where rotor failure will neither endanger the occupants nor adversely affect continued safe flight.

DESIGN CONDITIONS

Design conditions for aircraft applications differ in several ways from other HVAC applications. Commercial transport aircraft operate in a physical environment that is not survivable by unprotected humans. This requires a complex ECS to provide passengers and crew with safety and comfort without health risks.

Aircraft ECSs operate under unique conditions. Outside air at altitude is extremely cold, dry, and can contain high levels of ozone. On the ground outside air can be hot, humid, and contain many pollutants such as particulate matter, aerosols, and hydrocarbons. These ambient conditions change quickly from ground operations to flight. The hot-day, high-humidity ground condition usually dictates the size of air-conditioning equipment, and high-altitude flight conditions determine the impedance necessary to overcome in order to provide adequate ventilation and pressurization bleed airflow. Maximum heating requirements can be determined by either cold-day ground or flight operations.

In addition to essential safety requirements, the ECS should provide a comfortable environment for the passengers and crew. This presents a unique challenge because of the high-density seating of the passengers and the changes in cabin pressure and the outside environment during flight. Also, aircraft systems must be lightweight, accessible for quick inspection and servicing, highly reliable, tolerant of a wide range of environmental conditions, able to withstand aircraft vibratory and maneuver loads, and able to accommodate failures occurring during flight.

Ambient Temperature, Humidity, and Pressure

Figure 1 shows typical design ambient temperature profiles for hot, standard, and cold days. The ambient temperatures used for the design of a particular aircraft may be higher or lower than those shown inFigure 1, depending on the regions in which the aircraft is to be operated. The design ambient moisture content at various altitudes that is recommended for commercial aircraft is shown in Figure 2. However, operation at moisture levels exceeding 200 grains per pound of dry air is possible in some regions. The variation in ambient pressure with altitude is shown in Figure 3.

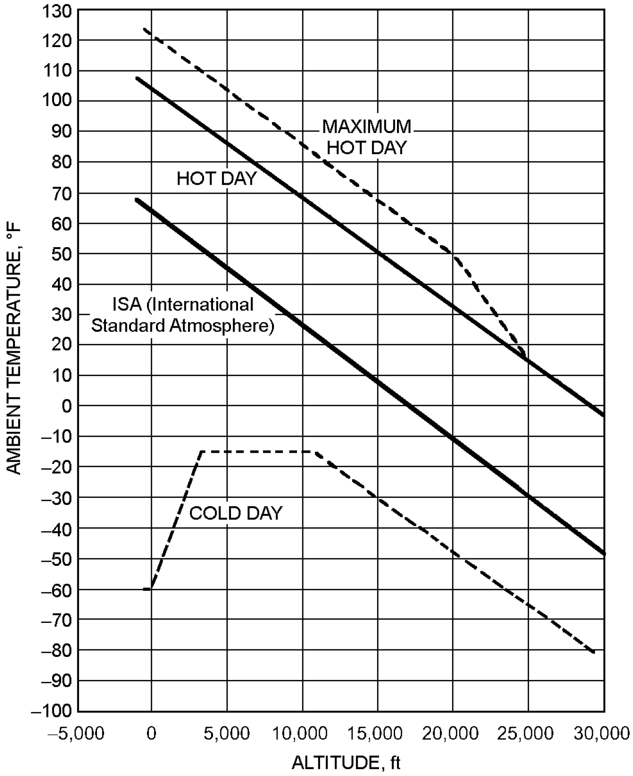

Fig. 1 Typical Ambient Temperature Profiles

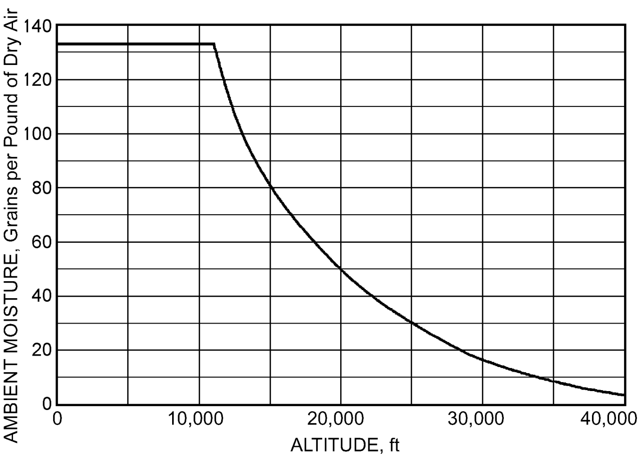

Fig. 2 Design Moisture for Equipment Performance

ECS Performance

The ECS is designed to provide a comfortable cabin temperature, acceptable ventilation, good airflow distribution across the cabin width, and sufficient bleed airflow to maintain cabin pressurization and repressurization during descent, while accounting for certain failure conditions. The ECS also includes provisions to dehumidify the cabin supply during cooling operations.

Load Determination. The steady-state cooling and heating loads for a particular aircraft model are determined by a heat transfer study of the several elements that comprise the air-conditioning load. The heat transfer involves the following factors:

- Convection between the boundary layer and the outer aircraft skin
- Radiation between the outer aircraft skin and the external environment

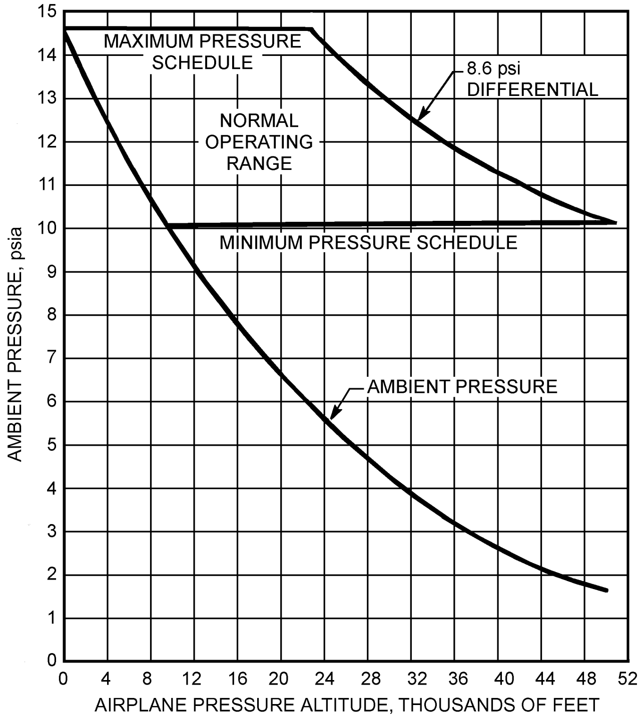

Fig. 3 Variation of Ambient Pressure with Altitude

- Solar radiation through transparent areas
- Conduction through cabin walls and the aircraft structure
- Convection between the interior cabin surface and cabin air
- Convection between the cabin air and occupants or equipment
- Convection and radiation from internal sources of heat such as electrical equipment

The heat transfer analysis should include all possible flow paths through the complex aircraft structure. Air film coefficients vary with altitude and should be considered. During flight, the increase in air temperature and pressure due to ram effects is appreciable and may be calculated from the following equations:

$$\Delta t_r = 0.2M^2 T_a F_r$$

$$\Delta p_r = (1 + 0.2M^2)^{3.5} p_a - p_a$$

where

F_r = recovery factor, dimensionless
Δt_r = increase in temperature due to ram effect, °F
M = Mach number, dimensionless
T_a = absolute static temperature of ambient air, °R
Δp_r = increase in pressure due to ram effect, psi
p_a = absolute static pressure of ambient air, psi

The average increase in aircraft skin temperature for subsonic flight is generally based on a recovery factor F_r of 0.9.

Ground and flight requirements may be quite different. For an aircraft sitting on the ground in bright sunlight, surfaces that have high absorptivity and are perpendicular to the sun's rays may have much higher temperatures than ambient. This skin temperature is reduced considerably if a breeze blows across the aircraft. Other considerations for ground operations include cooldown or warm-up requirements, and the time that doors are open for passenger and galley servicing.

Cooling. The sizing criteria for the air conditioning are usually ground operation on a hot, humid day with the aircraft fully loaded and the doors closed. A second consideration is cooldown of a empty, heat-soaked aircraft prior to passenger loading; a cooldown time of less than 30 minutes is usually specified. A cabin temperature of between between 75 and 80°F is usually specified for these hot day ground design conditions. During cruise, the system should maintain a cabin temperature of 75°F with a full passenger load.

Heating. Heating requirements are based on a partially loaded aircraft on a very cold day; cabin temperature warm-up within 30 minutes for a cold-soaked aircraft is also considered. A cabin temperature of 70°F is usually specified for these cold day ground operating conditions. During cruise, the system should maintain a cabin temperature of 75°F with a 20% passenger load, a cargo compartment temperature above 40°F, and cargo floor temperatures above 32°F to prevent the freezing of cargo.

Temperature Control. Commercial aircraft (over 19 passengers) can have as few as two zones (cockpit and cabin) and as many as seven. These crew and passenger zones are individually temperature controlled to a crew-selected temperature for each zone ranging from 65 to 85°F. Some systems have limited authority bias selectors in the passenger zones that can be adjusted by the flight attendants. The selected zone temperature is controlled to within 2°F and the temperature uniformity within the zone should be within 5°F. Separate temperature controls can be provided for cargo compartments.

Ventilation. Aircraft cabin ventilation systems can use all bleed air or a mixture of bleed and recirculated air. The bleed air source is engine compressor air that powers the air-cycle air-conditioning equipment and pressurizes the aircraft cabin. A typical ventilation system supplies 10 cfm of bleed air per occupant, which satisfies regulatory (FAA/JAA) requirements for ventilation and concentrations of carbon monoxide and carbon dioxide.

An equal amount of filtered, recirculated cabin air can be provided for improved distribution and circulation. The use of filtered, recirculated air reduces the bleed air penalty and increases cabin humidity. Most systems have no filtration of the engine bleed air supply, although bleed air centrifugal cleaners are sometimes offered as optional equipment. Some aircraft that fly where high ambient ozone levels can be expected require catalytic ozone converters.

Particulate filters are used to filter the recirculated cabin air. High-efficiency particulate air (HEPA) filters are preferred. Charcoal filters are sometimes offered as optional equipment, and are installed in series with the particulate filters. The demand for charcoal filters is low for domestic carriers because of the smoking ban on domestic flights. Their use worldwide is also limited by cost, frequency of maintenance (replacement), and disposal requirements.

Pressurization. Cabin pressurization achieves the required partial pressures of oxygen for the crew and passengers during high-altitude flight. While the aircraft operates at altitudes above 40,000 ft, the occupied cabin must be pressurized to an equivalent altitude of 8000 ft or less to permit normal physiological functions without supplemental oxygen. The maximum pressure difference between the cabin and the outside environment is limited by aircraft structural design limits. The differential pressure control provides a cabin pressure based on the flight altitude of the aircraft. A typical cabin altitude schedule is shown in Figure 4. The cabin pressure control must also limit the normal maximum rates of change of cabin pressure; the recommended limits are 500 fpm for increasing altitude (ascent) and 300 fpm for decreasing altitude (descent). Provisions separate from the normal cabin pressure controls must be provided for positive and negative pressure relief to protect the aircraft structure.

SYSTEM DESCRIPTION

The outside air supplied to the airplane cabin is provided by the engine compressors (or auxiliary power unit in the aircraft tailcone), cooled by **air-conditioning packs** located under the wing center section, and mixed with an equal quantity of filtered, recirculated air. An air-conditioning pack uses the compressed outside air passing through it and into the airplane as the refrigerant in an air-cycle refrigeration cycle.

Air is supplied and exhausted from the cabin on a continuous basis. As shown in Figure 5, air enters the passenger cabin from overhead distribution outlets that run the length of the cabin. The exhaust air leaves the cabin through return air grilles located in the sidewalls near the floor, and running the length of the cabin on both sides. The exhaust air is continuously extracted from below the cabin floor by recirculation fans that return part of the air to the distribution system and to an outflow valve that purges the remaining exhaust air overboard. The cabin ventilation system is designed and balanced so that air supplied at one seat row leaves at approximately the same seat row, thus minimizing airflow in the fore and aft directions.

The following basic systems comprise the typical aircraft ECS.

Pneumatic System

The pneumatic system or engine bleed air system extracts a small amount of the gas turbine engine compressor air to ventilate and

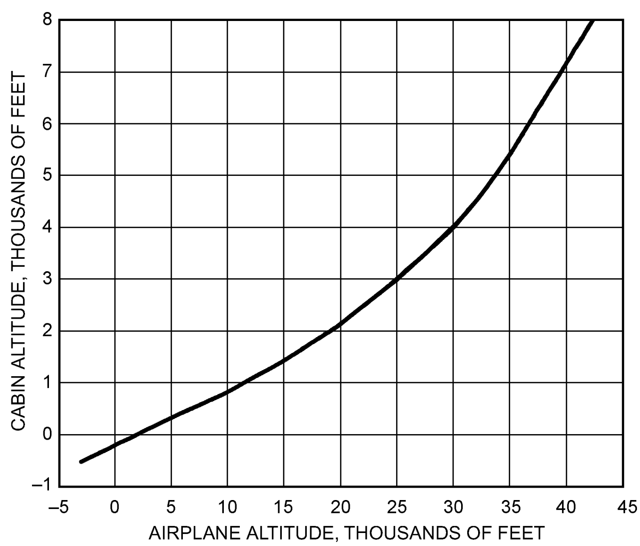

Fig. 4 Typical Cabin Altitude Schedule

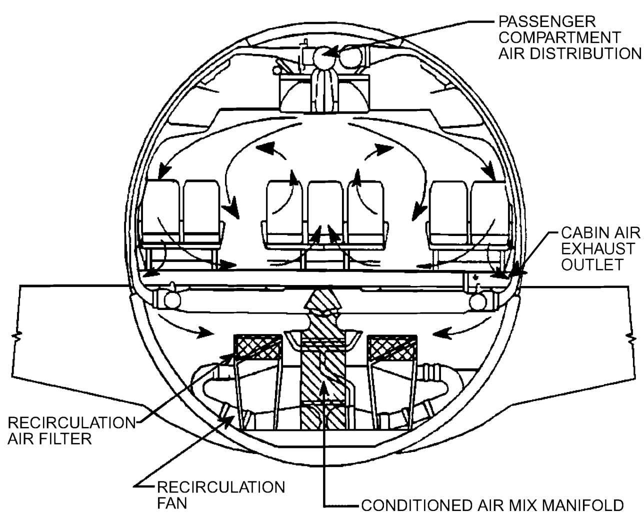

Fig. 5 Cabin Airflow Patterns
(Hunt et al. 1995)

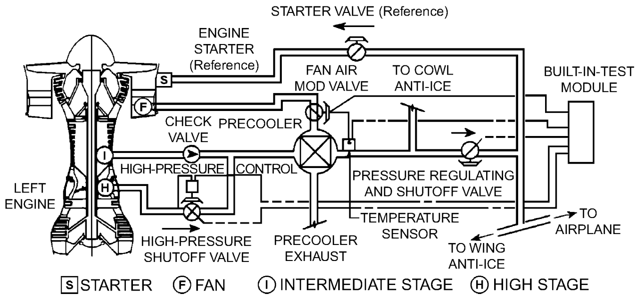

Fig. 6 Typical Engine Bleed Air System Schematic
(Hunt et al. 1995)

pressurize the aircraft compartments. A schematic of a typical engine bleed air system is shown in Figure 6. During climb and cruise the bleed air is usually taken from the midstage engine bleed port for minimum bleed penalty. During idle descent it is taken from the high-stage engine bleed port where maximum available pressure is required to maintain cabin pressure and ventilation. The bleed air is pressure controlled to meet the requirements of the using system, and is usually cooled to limit bleed manifold temperatures to be compatible with fuel safety requirements. In fan jets, the fan air is used as the heat sink for the bleed air heat exchanger (precooler); for turboprop engines, ram air is used, which usually requires an ejector or fan for static operation. Other components include bleed-shutoff and modulating valves, fan-air modulating valve, sensors, controllers, and ozone converters. The pneumatic system is also used intermittently for airfoil and engine cowl anti-icing, engine start, and several other pneumatic functions.

Each engine has an identical bleed air system for redundancy and to equalize the compressor air bled from the engines. The equipment is sized to provide the necessary temperature and airflow for airfoil and cowl anti-icing, or cabin pressurization and air conditioning with one system or engine inoperative. The bleed air used for airfoil anti-icing is controlled by valves feeding piccolo tubes extending along the wing leading edge. Similar arrangements are used for anti-icing the engine cowl and tail section.

Air Conditioning

Air-cycle refrigeration is the predominant means of air conditioning for commercial and military aircraft. The reverse-Brayton cycle or Brayton refrigeration cycle is used, as opposed to the Brayton power cycle that is used in gas turbine engines. The difference between the two cycles is that in the power cycle fuel in a combustion chamber adds heat, and in the refrigeration cycle a ram-air heat exchanger removes heat. The familiar Rankine vapor cycle, which is used in building and automotive air conditioning and in domestic and commercial refrigeration, has limited use for aircraft air conditioning. The Rankine cycle is used mostly in unpressurized helicopters and general aviation applications.

In an air cycle, compression of the ambient air by the gas turbine engine compressor provides the power input. The heat of compression is removed in a heat exchanger using ambient air as the heat sink. This cooled air is refrigerated by expansion across a turbine powered by the compressed bleed air. The turbine energy resulting from the isentropic expansion is absorbed by a second rotor, which is either a ram air fan, bleed air compressor, or both. This assembly is called an **air-cycle machine** (ACM). Moisture condensed during the refrigeration process is removed by a water separator.

The compartment supply temperature is controlled by mixing hot bleed air with the refrigerated air to satisfy the range of heating and cooling. Other, more sophisticated means of temperature control are often used, such as ram air modulation, various bypass schemes in the air-conditioning pack, and downstream controls that add heat for individual zone temperature control.

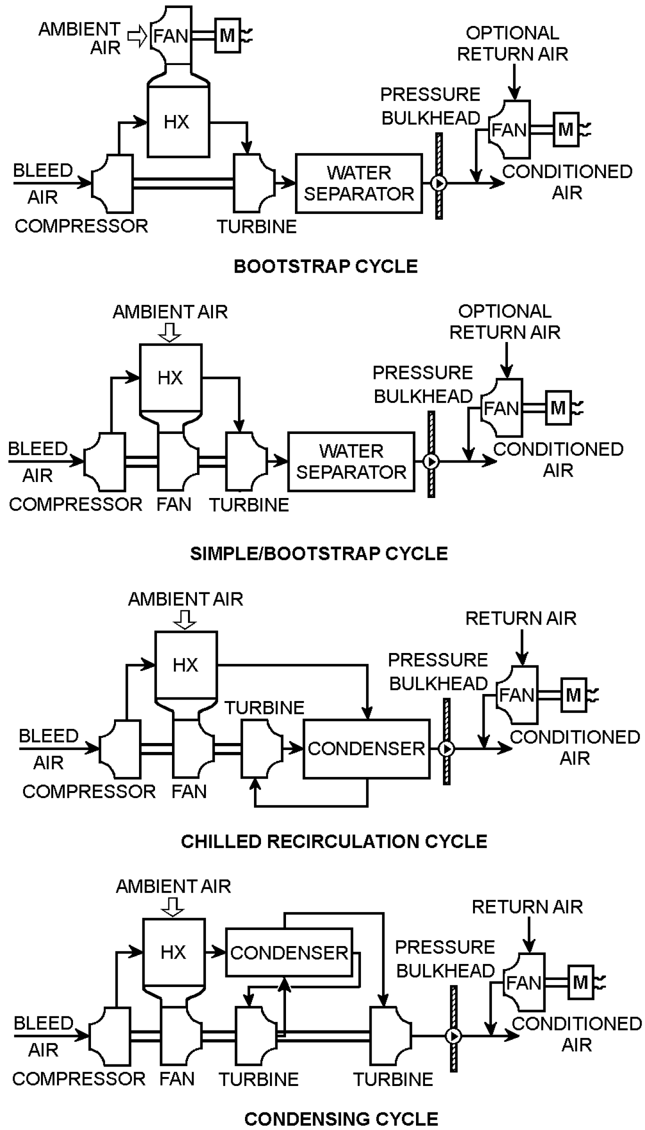

Fig. 7 Air-Conditioning Air-Cycle Configurations

The bleed airflow is controlled by a flow-control or pressure-regulating valve at the inlet of the air-conditioning pack. This valve controls bleed air used to minimize engine bleed penalties while satisfying the aircraft outside air ventilation requirements.

Most aircraft use two or three air-cycle packs operating in parallel to compensate for failures during flight and to allow the aircraft to be dispatched with certain failures. However, many business and commuter aircraft use a single-pack air conditioner; high-altitude aircraft that have single packs also have emergency pressurization equipment that uses precooled bleed air.

The most common types of air-conditioning cycles in use on commercial transport aircraft are shown in Figure 7. All equipment in common use on commercial and military aircraft is open loop, although many commercial aircraft systems include various means of recirculating cabin air to minimize engine bleed air use without sacrificing cabin comfort. The basic differences between the systems are the type of air-cycle machine used and its means of water separation.

The most common air-cycle machines in use are the bootstrap ACM, consisting of a turbine and compressor; the three-wheel ACM, consisting of a turbine, compressor, and fan; and the four-wheel ACM, consisting of a two turbines, a compressor, and a fan.

The bootstrap ACM is most commonly used for military applications, although many older commercial aircraft models use the bootstrap cycle. The three-wheel ACM (simple bootstrap cycle) is used on most of the newer commercial aircraft, including commuter aircraft and business aircraft. The four-wheel ACM (condensing cycle) is also in use in newer entries in the commercial fleet.

Both low- and high-pressure water separation are used. A **low-pressure water separator**, located downstream from the cooling turbine, has a coalescer cloth that agglomerates fine water particles entrained in the turbine discharge air into droplets. The droplets are collected, drained, and sprayed into the ram airstream using a bleed-air-powered ejector; this process increases pack cooling capacity by depressing the ram-air heat-sink temperature.

The **high-pressure water separator** condenses and removes moisture at high pressure upstream of the cooling turbine. A heat exchanger uses turbine discharge air to cool the high-pressure air sufficiently to condense most of the moisture present in the bleed air supply. The moisture is collected and sprayed into the ram airstream.

In the condensing cycle one turbine removes the high-pressure water and the second turbine does the final expansion to subfreezing-temperature air that is to be mixed with filtered, recirculated cabin air. Separating these functions recovers the heat of condensation, which results in a higher cycle efficiency. It also eliminates condenser freezing problems because the condensing heat exchanger is operated above freezing conditions.

The air-conditioning packs are located in unpressurized areas of the aircraft to minimize structural requirements of the ram air circuit that provides the necessary heat sink for the air-conditioning cycle. This location also provides protection against cabin depressurization in the event of a bleed or ram air duct rupture. The most common areas for the air-conditioning packs are the underwing/wheel well area and the tailcone area aft of the rear pressure bulkhead. Other areas include the areas adjacent to the nose wheel and overwing fairing. The temperature control components and recirculating fans are located throughout the distribution system in the pressurized compartments. The electronic pack and zone temperature controllers are located in the electrical/electronics (E/E) bay. The air-conditioning control panel is located in the flight deck. A schematic diagram of a typical air-conditioning system is shown in Figure 8.

Cabin Pressure Control

Cabin pressure is controlled by modulating the airflow discharged from the pressurized cabin through one or more cabin outflow valves. The cabin pressure control includes the outflow valves, controller, selector panel, and redundant positive-pressure relief valves. Provisions for negative-pressure relief are incorporated in the relief valves and/or included in the aircraft structure (door). The system controls the cabin ascent and descent rates to acceptable comfort levels, and maintains cabin pressure altitude in accordance with cabin-to-ambient differential pressure schedules. Modern controls usually set landing field altitude if not available from the flight management system (FMS), and monitor aircraft flight via the FMS and the air data computer (ADC) to minimize the cabin pressure altitude and rate of change.

The cabin pressure modulating valves and safety valves (positive-pressure relief valves) are located either on the aircraft skin in the case of large commercial aircraft, or on the fuselage pressure bulkhead in the case of commuter, business, and military aircraft. Locating the outflow valves on the aircraft skin precludes the handling of large airflows in the unpressurized tailcone or nose areas and provides some thrust recovery; however, these double gate valves are more complex than the butterfly valves or poppet valves used for bulkhead installations. The safety valves are poppet valves for either installation. Most commercial aircraft have electronic controllers located in the E/E bay. The cabin pressure selector panel is located in the flight deck.

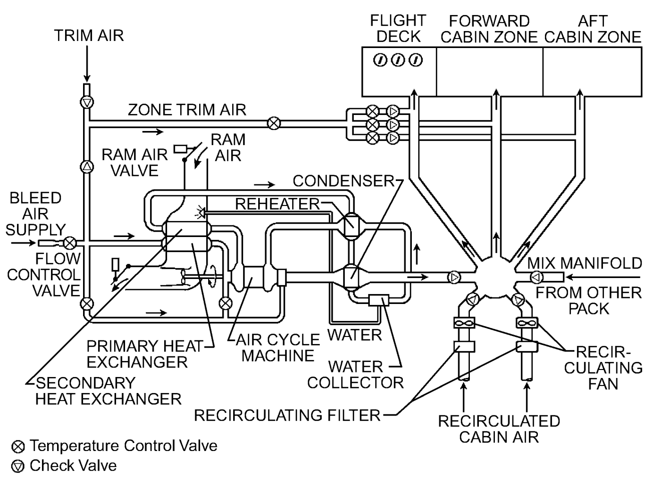

Fig. 8 Typical Aircraft Air-Conditioning Schematic

TYPICAL FLIGHT

A typical flight scenario from London's Heathrow Airport to Los Angeles International Airport would be as follows:

While the aircraft is at the gate, the ECS can be powered by bleed air supplied by the auxiliary power unit (APU), bleed air from a ground cart, or bleed air from the main engines after engine start. The APU or ground-cart bleed air is ducted directly to the bleed air manifold upstream of the air-conditioning packs. Engine bleed air is preconditioned by the engine bleed air system prior to being ducted to the air-conditioning packs. The air-conditioning packs are normally switched to operation using engine bleed air after the engines are started.

Taxiing from the gate at Heathrow, the outside air temperature is 59°F with an atmospheric pressure of 14.7 psia. The aircraft engines are at low thrust, pushing the aircraft slowly along the taxiway.

Engine Bleed Air Control

As outside air enters the compressor stages of the engine, it is compressed to 32 psia and a temperature of 330°F. Some of this air is then extracted from the engine core through one of two bleed port openings in the side of the engine. Which bleed port extracts the air depends on the positioning of valves that control the ports. One bleed port is at the engine's fifteenth compressor stage, commonly called high stage. The second is at the eighth compressor stage, commonly called low stage or intermediate stage. The exact stage varies depending on engine type. The high stage is the highest air pressure available from the engine compressor. At low engine power, the high stage is the only source of air at sufficient pressure to meet the needs of the bleed system. The bleed system is totally automatic, except for a shutoff selection available to the pilots on the overhead panel in the flight deck.

As the aircraft turns onto the runway, the pilots advance the engine thrust to takeoff power. The engine's high stage compresses the air to 1200°F and 430 psia. This energy level exceeds the requirements for the air-conditioning packs and other pneumatic services—approximately 50% of the total energy available at the high-stage port cannot be used. However, the bleed system automatically switches to the low-stage port, which conserves energy.

Because the engine must cope with widely varying conditions from ground level to flight at an altitude of up to 43,100 ft, during all seasons and throughout the world, the air at the high or low stage of the engine compressor will seldom exactly match the needs of the pneumatic systems. Excess energy must be discarded as waste heat. The bleed system constantly monitors engine conditions and selects

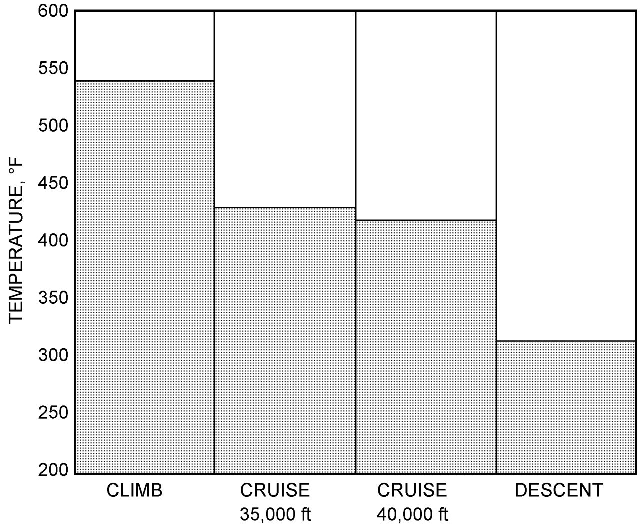

Fig. 9 Typical Air Temperature Supplied to Bleed System During Flight
(Hunt et al. 1995)

the least wasteful port. Even so, bleed temperatures often exceed safe levels at which fuel will not auto-ignite. The precooler automatically discharges excess energy to the atmosphere to ensure that the temperature of the pneumatic manifold is well below that which could ignite fuel. The precooler is particularly important in the event of a fuel leak.

The aircraft climbs to a cruise altitude of 39,000 ft, where the outside air temperature is −70°F at an atmospheric pressure of 2.9 psia, and the partial pressure of oxygen is 0.5 psi. Until the start of descent to Los Angeles, the low compressor stage is able to compress the low-pressure cold outside air to more than 30 psia and a temperature above 400°F. This conditioning of the air is all accomplished through the heat of compression—fuel is added only after the air has passed through the compressor stages of the engine core.

Figure 9 shows the temperature of the air being extracted from the engine compressor to the bleed system from the time of departure at London to the time of arrival at Los Angeles. The temperature of the air supplied to the bleed system far exceeds that required to destroy any microorganisms present in the outside air during any point of the trip. At cruising altitudes, outside air contains very few biological particles (a few dark fungal spores per cubic metre of air), although there are higher concentrations at lower altitudes. Because of the high air temperatures from the engine compressor, the air supplied to the air-conditioning packs is sterile.

Air leaving the bleed system while in cruise enters the pneumatic manifold at 400°F and 30 psia. The air then passes through an ozone converter on its way to the air-conditioning packs located under the wing at the center of the aircraft.

Ozone Protection

While flying at 39,000 ft, several ozone plumes are encountered. Some have ozone concentrations as high as 0.8 parts per million (ppm) or 0.62 ppm sea level equivalent (SLE). This assumes a worst-case flight during the month of April, when ozone concentrations are highest. If this concentration of ozone were introduced into the cabin, passengers and crew could experience some chest pain, coughing, shortness of breath, fatigue, headache, nasal congestion, and eye irritation.

Atmospheric ozone dissociation occurs when the ozone goes through the compressor stages of the engine, the ozone catalytic converter (which is on aircraft with a route structure that can encounter high ozone concentrations), and the air-conditioning packs. The ozone further dissociates when contacting airplane ducts, interior surfaces, and the airplane recirculation system. The ozone converter dissociates ozone to oxygen molecules by the catalyzing action of a noble catalyst such as palladium. A new converter dissociates approximately 95% of the ozone entering the converter to oxygen. It has a useful life of about 12,000 flight hours.

As the air leaves the ozone converter, it is still at 400°F and a pressure of 30 psia. Assuming a worst case when the converter is approaching the end of its useful life with an ozone conversion efficiency of 60%, the ozone concentration leaving the converter is about 0.25 ppm SLE. This air goes through the air-conditioning packs and enters the cabin. The ozone concentration in the cabin is about 0.09 ppm. As mentioned in the section on Regulations, the FAA sets a three-hour time-weighted average ozone concentration limit in the cabin of 0.1 ppm and a peak ozone concentration limit of 0.25 ppm.

Air-Conditioning and Temperature Control

The air next enters the air-conditioning packs, which provide essentially dry, sterile, and dust-free conditioned air to the airplane cabin at the proper temperature, flow rate, and pressure to satisfy pressurization and temperature control requirements. For most aircraft, this is approximately 5 cfm per passenger. To ensure redundancy, two air-conditioning packs (two are typical, some aircraft have more) provide a total of about 10 cfm of conditioned air per passenger. An equal quantity of filtered, recirculated air is mixed with the air from the air-conditioning packs for a total of approximately 20 cfm per passenger. This quantity of supply air results in a complete cabin air exchange about every 2.5 min, or about 25 air changes per hour. The high air exchange rate is necessary to control temperature gradients, prevent stagnant cold areas, maintain air quality, and dissipate smoke and odors in the cabin. Temperature control is the predominant driver of outside airflow requirements.

The automatic control for the air-conditioning packs constantly monitors airplane flight parameters, the flight crew's selection for the temperature zones, the cabin zone temperature, and the mixed distribution air temperature. The control automatically adjusts the various valves for a comfortable environment under normal conditions. The pilot's controls are located on the overhead panel in the flight deck along with the bleed system controls. Normally, pilots are required only to periodically monitor the compartment temperatures from the overhead panel. Temperatures can be adjusted based on flight attendant reports of passengers being too hot or too cold. Various selections are available to the pilots to accommodate abnormal operational situations.

Air Recirculation

The air has now been cooled and leaves the air-conditioning packs. It leaves the packs at 60°F and 11.8 psi. The relative humidity is less than 5% and ozone concentration is less than 0.25 ppm. The carbon dioxide concentration remains unchanged from that of the outside air at about 350 ppm. As this air enters a mixing chamber, it is combined with an equal quantity of filtered recirculated air.

The recirculated air entering the mix manifold is essentially sterile. Over 99.9% of the bacteria and viruses produced by the passengers are removed by HEPA filters, which are used on most modern aircraft. The filters cannot be bypassed and become more efficient with increased service life. They do, however, require replacement at periodic maintenance intervals. Gases, which are not removed by the filters, are diluted to low levels with outside air at a high exchange rate of about 12.5 times per hour.

Air Distribution

The air flows from the mix manifold into duct risers dedicated to each seating zone. The risers direct the air from below the floor to the overhead cabin ventilation system. Trim air (hot bleed air from the pneumatic manifold) is added in the risers to increase the air temperature, if needed. The supply air temperature per seating zone can vary due to differences in seating densities between seating zones.

The overhead air distribution network runs the length of the cabin. The air is dust free and sterile with a relative humidity of 10 to 20%. The temperature is 65 to 85°F, depending on the seating zone the air is being supplied to, and the carbon dioxide concentration is about 1050 ppm. The carbon dioxide is generated by passenger respiration.

Because of the large quantity of air entering the relatively small volume of the cabin, as compared to a building, control of the airflow patterns is required to give comfort without draftiness. Air enters the passenger cabin from overhead distribution outlets that run the length of the cabin. These outlets create circular airflow patterns in the cabin (Figure 5). Air leaves the outlets at a velocity of more than 500 fpm, becomes entrained with cabin air, and maintains sufficient momentum to sweep the cabin walls and floor and to wash out any cold pockets of air in the cabin. The air direction is oriented to avoid exposed portions of a seated passenger, such as the arms, hand, face, neck, and legs, yet it is of sufficient velocity to avoid the sensation of stagnant air. This requires seated passenger impingement velocities between 20 and 70 fpm.

The air volume circulates in the cabin while continuously mixing with cabin air for 2 to 3 min before it enters the return air grilles that are located in the sidewalls near the floor and run the length of the cabin along both sides. While this air is in the cabin, about 0.33% of the oxygen is consumed by human metabolism. The oxygen is replaced by an equal quantity of carbon dioxide from passenger respiration. In addition, the return air entrains microorganisms or other contaminants from passengers or the cabin itself. Approximately one-half of the return air is exhausted overboard and the other half recirculated to sterile conditions through HEPA filters.

In the aft section, exhaust air is extracted by the cabin pressure outflow valve and exhausted overboard. In the forward section, it is continuously extracted from below the floor by recirculation fans, filtered, and then mixed with the outside air being supplied by the air-conditioning packs.

The cabin ventilation is balanced so that air supplied at one seat row leaves at approximately the same seat row. This minimizes airflow in the fore and aft directions, to minimize the spread of passenger-generated contaminants.

Cabin Pressure Control

The cabin pressure control continuously monitors ground and flight modes, including altitude, climb, cruise or descent modes, as well as the airplane's holding patterns at various altitudes. It uses this information to position the cabin pressure outflow valve to maintain cabin pressure as close to sea level as practical, without exceeding a cabin-to-outside pressure differential of 8.60 psi. At a 39,000 ft cruise altitude, the cabin pressure is equivalent to 6900 ft, or a pressure of 11.5 psia. In addition, the outflow valve repositions itself to allow more or less air to escape as the airplane changes altitude. The resulting cabin altitude is consistent with airplane altitude within the constraints of keeping pressure changes comfortable for passengers. Normal pressure change rates are 0.26 psi per minute ascending and 0.16 psi per minute descending.

The cabin pressure control system panel is located in the pilot's overhead panel near the other air-conditioning controls. Normally, the cabin pressure control system is totally automatic, requiring no attention from the pilots.

AIR QUALITY

Aircraft cabin air quality is a complex function of many variables including ambient air quality, the design of the cabin volume, the design of the ventilation and pressurization systems, the way the systems are operated and maintained, the presence of sources of contaminants, and the strength of such sources. The following factors can individually or collectively affect aircraft cabin air quality.

Airflow

The total volume of air is exchanged approximately every 2.5 to 3 min in a wide-body aircraft, and every 2 to 3 min on a standard-body aircraft. The airflow per unit length of the airplane is similar for all sections. However, economy class has a lower airflow per passenger because of its greater seating density as compared to first class and business class. A high air exchange rate and sufficient quantity of outside air is supplied to each cabin zone to maintain air quality, control temperature gradients, prevent stagnant cold areas, and dissipate smoke and odors in the cabin.

The flight deck is provided with a higher airflow per person than the cabin in order to maintain a positive pressure in the cockpit (1) to prevent smoke ingress from adjacent areas (abnormal condition), (2) to provide cooling for electrical equipment, (3) to account for increased solar loads and night heat loss through the airplane skin and windows, and (4) to minimize temperature gradients.

Typical commercial transport aircraft provide approximately 50% conditioned (outside) and 50% filtered recirculated air to the passenger cabin on a continuous basis. Increasing the quantity of outside air beyond 50% to the cabin would lower the cabin CO_2 concentration slightly, but it would also increase the potential cabin ozone concentration and lower the cabin relative humidity.

The recirculated air is cleaned by drawing it through HEPA filters that cannot be bypassed. The air distribution system is designed to provide approximately 10 cfm outside air and 10 cfm filtered, recirculated air per passenger. A fully loaded, all-tourist-class passenger aircraft, which has the maximum seating density throughout the airplane, provides an outside airflow per passenger of 6.5 (standard-body) to 8 cfm (wide-body).

The outside air quantity supplied on some aircraft models can be lowered by shutting off one air-conditioning pack. The flight crew has control of these packs to provide flexibility in case of a system failure or for special use of the aircraft. Packs should be in full operation whenever passengers are on board.

Environmental Tobacco Smoke (ETS)

Currently, there are no governmental, occupational, or ambient standards for environmental tobacco smoke (ETS). However, in 1986, the National Academy of Sciences recommended banning smoking on U.S. domestic flights to eliminate the possibility of fires caused by cigarettes, to lessen irritation and discomfort to passengers and crew, and to reduce potential health hazards.

On flights where smoking is allowed, ETS in the cabin is controlled indirectly by controlling the concentration of carbon monoxide (CO) and respirable suspended particulates (RSP). CO and RSP are tracer constituents of ETS and several standards do list acceptable maximum levels for these constituents. Table 4 in Chapter 9 of the 2001 *ASHRAE Handbook—Fundamentals* summarizes these standards. This method of control does not consider other constituents present in ETS.

Measured CO levels in aircraft smoking section(s) during peak smoking are within acceptable limits. RSP concentrations in smoking sections can exceed recommended levels during peak smoking, which is also true of most heavy-smoking areas (e.g. restaurants, bowling alleys, etc.). Of 92 airplanes tested in a DOT-sponsored study, average RSP values of 40 $\mu g/m^3$ and 175 $\mu g/m^3$ were measured in nonsmoking and smoking sections, respectively.

Ozone

Ozone is present in the atmosphere as a consequence of the photochemical conversion of oxygen by solar ultraviolet radiation. Ozone levels vary with season, altitude, latitude, and weather systems. A marked and progressive increase in ozone concentration occurs with an increase in the flight altitude of commercial aircraft. The mean ambient ozone concentration increases with increasing latitude, is maximal during the spring (fall season for southern hemisphere), and often varies when weather causes high ozone plumes to descend.

Residual cabin ozone concentration is a function of the ambient concentration, the design of the air distribution system and how it is operated and maintained, and whether catalytic ozone converters are installed.

Cabin ozone limits are set by FAR 121.578 and FAR 25.832. The use of catalytic ozone converters is generally required on airplanes flying mission profiles where the cabin ozone levels are predicted to exceed these FAR limits (refer to the FAA Code of Federal Regulations for other compliance methods).

Microbial Aerosols

Biologically derived particles that become airborne include viruses, bacteria, actinomycetes, fungal spores and hyphae, arthropod fragments and droppings, and animal and human dander. Only one study has documented the occurrence of an outbreak of infectious disease related to airplane use. In 1977, because of an engine malfunction, an airliner with 54 persons onboard was delayed on the ground for 3 h, during which the airplane ventilation system was reportedly turned off. Within 3 days of the incident, 72% of the passengers became ill with influenza. One passenger (the index case) was ill while the airplane was delayed.

With the ventilation system shut off, no fresh air was introduced into the cabin to displace microbial aerosols and CO_2 or to control cabin temperatures. It is believed that, had the ventilation system been operating during the delay, the possibility of other passengers becoming ill would have been minimal.

The airplane ventilation system should never be shut off when passengers are on board; an exception to this recommendation is during no-pack takeoffs when the air packs (but not the recirculation fans) are shut off for the short time only on takeoff.

To remove particulates and biological particles from the recirculated air, filter assemblies that contain a HEPA filter with a minimum efficiency of 94 to 99.97% DOP as measured by MIL-STD-282 should be used. A HEPA filter is rated using 0.3 μm size particles. A filter's efficiency increases over time as particulates become trapped by the filter. Due to the overlap of capture mechanisms in a filter, the efficiency also increases for particles smaller and larger than the most penetrating particle size (MPPS). For an airplane filter, the MPPS is about 0.1 to 0.2 μm.

The efficiency of a filter that can remove 0.003 μm particles from the air is in excess of 99.9+%. Most bacteria (99%) are larger than 1 μm. Viruses are approximately 0.003 to 0.05 μm in size. Test results in a DOT study conducted on 92 randomly selected flights showed that bacteria and fungi levels measured in the airplane cabin are similar to or lower than those found in the home. These low microbial contaminant levels are due to the large quantity of outside airflow and high filtration of the recirculation system.

Volatile Organic Compounds

Volatile organic compounds (VOCs) can be emitted by material used in furnishings, pesticides, disinfectants, cleaning fluids, and food and beverages. In-flight air quality testing on revenue flights sponsored by The Boeing Company and the Air Transport Association of America (ATAA 1994) detected trace VOC quantities that were considered well below levels that could result in adverse health effects.

Carbon Dioxide

Carbon dioxide is the product of normal human metabolism, which is the predominant source in aircraft cabins. The CO_2 concentration in the cabin varies with outside air rate, the number of people present, and their individual rates of CO_2 production, which vary with activity and (to a smaller degree) with diet and health. Carbon dioxide has been widely used as an indicator of indoor air quality, typically serving the function of a surrogate. Per a DOT-sponsored study, measured cabin CO_2 values of 92 randomly selected smoking and nonsmoking flights average 1500 ppm.

The Environmental Exposure Limit adopted by the American Conference of Governmental Industrial Hygienists (ACGIH) is 5000 ppm as the time-weighted average (TWA) limit for CO_2; this value corresponds to a fresh air ventilation rate of 2.3 cfm per person. The TWA is the concentration, for a normal 8 h workday and a 40 h workweek, to which nearly all workers can be repeatedly exposed, day after day, without adverse effects. As mentioned in the Regulations section under Ventilation, a FAR also limits CO_2 to 5000 ppm (0.5%). Aircraft cabin CO_2 concentrations are below this limit.

ASHRAE *Standard* 62, which does not apply to aircraft per se, states, "Comfort (odor) criteria are likely to be satisfied if the ventilation rate is set so that 1000 ppm CO_2 is not exceeded." It further states, "This level is not considered a health risk but is a surrogate for human comfort (odor)." An interpretation of this standard noted that 1000 ppm CO_2 is not a requirement of the standard, but it can be considered a target concentration level.

Humidity

The relative humidity in airplanes tested in a DOT-sponsored study ranged from approximately 5 to 35% with an average of 15 to 20%. The humidity is made up mainly of moisture from passengers and will increase with more passengers and decrease with increased outside airflow. A major benefit of filtered, recirculated air supplied to the passenger cabin is an increase in cabin humidity compared to airplanes with only outside supply air.

After three or four hours of exposure to relative humidity in the 5 to 10% range, some passengers may experience dryness of the eyes, nose, and throat. However, no serious adverse health effects of low relative humidity on the flying population have been documented.

Cabin Pressure/Oxygen

At a normal airplane cruise altitude, aircraft cabins are pressurized to a maximum cabin altitude of 8000 ft (to compress ambient air to a physiologically acceptable form). A DOT-sponsored National Academy of Sciences study concluded that current pressurization criteria and regulations are generally adequate to protect the traveling public. The Academy also noted that the normal maximum rates of change of cabin pressure (approximately 500 ft/min in increasing altitude and 300 ft/min in decreasing altitude) are such that they do not pose a problem for the typical passenger.

However, pressurization of the cabin to equivalent altitudes of up to 8000 ft, as well as changes in the normal rates of pressure during climb and descent, may create discomfort for people suffering from upper respiratory or sinus infections, obstructive pulmonary diseases, anemias, or certain cardiovascular conditions. In those cases, supplemental oxygen may be recommended. Children and infants sometimes experience discomfort or pain because of pressure changes during climb and descent. Injury to the middle ear has occurred to susceptible people, but is rare.

Some articles and reports state that substandard conditions exist in airplane cabins due to a lack of oxygen, attributed in some reports to reduced fresh air ventilation rates or the use of recirculated air. These arguments imply that the oxygen content of cabin air is depleted through consumption by occupants. Humans at rest breathe at a rate of approximately 0.32 cfm, while consuming oxygen at a rate of 0.015 cfm. The percent oxygen makeup of the supply air remains at approximately 21% at cruise altitude. A person receiving 10 cfm of outside air and 10 cfm of recirculation air would therefore receive approximately 4.2 cfm of oxygen. Consequently, the content of oxygen in cabin air is little affected by breathing as it is replaced in sufficient quantities compared to the human consumption rate.

Although the percentage of oxygen in cabin air remains virtually unchanged (21%) at all flight altitudes, the partial pressure of oxygen decreases with increasing altitude, which decreases the amount of oxygen available to the blood's hemoglobin. The increase in cabin altitude may cause low-grade hypoxia (reduced tissue oxygen levels) in some people. The National Academy of Sciences concluded that pressurization of the cabin to an equivalent altitude of 5000 to 8000 ft is physiologically safe for healthy individuals—no supplemental oxygen is needed to maintain sufficient arterial oxygen saturation. However, people with chronic pulmonary disease, cardiovascular disease, and anemia could be at risk at these cabin altitudes.

Multiple Factors

Multiple factors can influence comfort, and cabin air quality is a function of several parameters. These cabin environmental parameters, in combination with maintenance, operations, and individual and job-related factors, collectively influence the cabin crew and passenger perceptions of the cabin environment. The collective influence of these factors is acknowledged by the Aerospace Medical Association (AsMA) in a Special Committee report on Cabin Air Quality (Thibeault 1997), which cites factors such as hypoxia, decreased barometric pressure, crowding, inactivity, temperature control, jet lag, noise, three-dimensional motion, fear, stress, individual health, alcohol consumption, etc.

Figure 10 shows the three groups that can influence cabin environmental comfort: manufacturers, airlines, and the occupants themselves. Airplane manufacturers influence the physical environment by the design of the environmental control system integrated with the rest of the systems on the airplane. Airlines affect the environmental conditions in the cabin by seating configuration, amenities offered, and procedures for maintaining and operating the aircraft. Finally, cabin environmental comfort is influenced by the individual and job-related activities of the cabin crew and passengers.

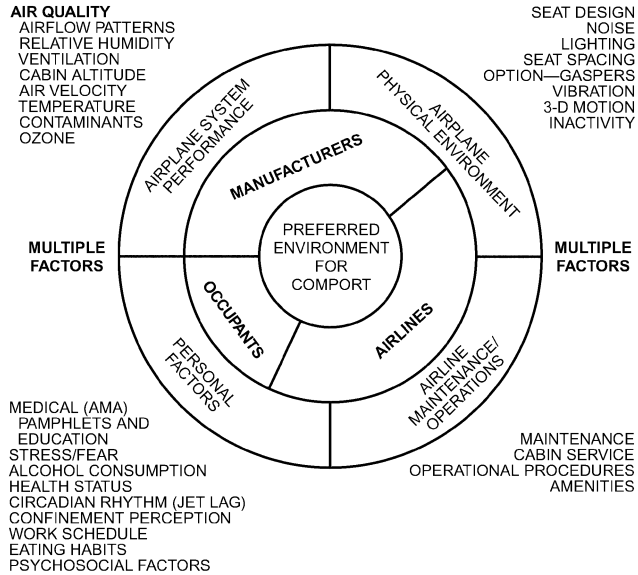

Fig. 10 Airplane Cabin Environment Wheel
(Adapted, with permission, from STP 1393—Air Quality and Comfort in Airliner Cabins, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428)

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