AEROSPACE RECOMMENDED PRACTICE

ARP85™	REV. G

Issued 1943-01
Revised 2019-09
Reaffirmed 2024-10

Superseding ARP85F

Air Conditioning Systems for Subsonic Airplanes

RATIONALE

The purpose of this revision is to update references that have changed since the previous publication of ARP85.

ARP85G has been reaffirmed to comply with the SAE Five-Year Review policy.

TABLE OF CONTENTS

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) contains guidelines and recommendations for subsonic airplane air conditioning systems and components, including requirements, design philosophy, testing, and ambient conditions.

The airplane air conditioning system comprises that arrangement of equipment, controls, and indicators that supply and distribute air to the occupied compartments for ventilation, pressurization, and temperature and moisture control. The principal features of the system are:

a. A supply of outside air with independent control valve(s).

b. A means for heating.

c. A means for cooling (air or vapor cycle units and heat exchangers).

d. A means for removing excess moisture from the air supply.

e. A ventilation subsystem.

f. A temperature control subsystem.

g. A pressure control subsystem.

Other system components for treating cabin air, such as filtration and humidification, are included, as are the ancillary functions of equipment cooling and cargo compartment conditioning.

The interface with the major associated system, the pneumatic system (Chapter 36 of ATA 100) is at the inlet of the air conditioning shutoff valves. This boundary definition aligns with that in the ATA 100 Specification.

1.1 Purpose

The purpose of this ARP is to provide guidance for the design, installation, and analysis of subsonic airplane air conditioning systems.

1.2 Field of Application

This ARP applies to subsonic airplane air conditioning systems within the ATA 100 Specification, Chapter 21. ATA Chapter 21 covers the air conditioning system that maintains passenger and crew environment, and ATA 21 also encompasses cabin pressure control systems. This ARP does contain cabin pressurization control guidelines; however, the focus is on air conditioning systems. Refer to ARP1270 for detailed recommendations on cabin pressure control systems.

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2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR860	Aircraft Electrical Heating Systems
AIR910	Ozone in High Altitude Aircraft
ARP986	Guide for Qualification Testing of Aircraft Air Valves
AIR1168/3	Aerothermodynamic Systems Engineering and Design
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning
AIR1204	Control of Water Carryover from the Environmental Control System and Condensation on the Structure
AIR1539	Environmental Control System Contamination
AIR1600	Animal Environment in Cargo Compartments
AIR1609	Aircraft Humidification
AIR1826	Acoustical Considerations for Aircraft Environmental Control System Design
AIR4766	Air Quality for Commercial Aircraft Cabins
AIR4766/1	Air Quality for Commercial Aircraft Cabin Particulate Contaminants
AIR4766/2	Airborne Chemicals in Aircraft Cabins
ARP86	Heater, Airplane, Engine Exhaust Gas to Air Heat Exchanger Type
ARP89	Aircraft Compartment Automatic Temperature Control Systems
ARP147	Environmental Control Systems Terminology
ARP699	High Temperature Pneumatic Duct Systems for Aircraft
ARP731	General Requirements for Application of Vapor Cycle Refrigeration Systems for Aircraft
ARP1270	Aircraft Cabin Pressurization Criteria
ARP1796	Engine Bleed Air Systems for Aircraft
AS8040	Heater, Aircraft Internal Combustion Heat Exchanger Type

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2.1.2 U.S. Government Publications

2.1.2.1 U.S. Department of Defense Publications

Available from the Document Automation and Production Service (DAPS), Building 4D, 700 Robbins Avenue, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

JSSG-2009	Department of Defense Joint Services Specification Guide, Air Vehicle Subsystems
MIL-HDBK-310	Department of Defense Handbook, Global Climatic Data for Developing Military Products
MIL-STD-1472	Department of Defense Design Criteria Standard, Human Engineering
MS33562	Detail Specification Sheet, Connection, Aircraft Ground Air Conditioning, 8 Inch

2.1.2.2 Code of Federal Regulations (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

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14 CFR Part 23	Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes
14 CFR Part 25	Airworthiness Standards: Transport Category Airplanes
14 CFR Part 27	Airworthiness Standards: Normal Category Rotorcraft
14 CFR Part 29	Airworthiness Standards: Transport Category Rotorcraft
14 CFR Part 33	Airworthiness Standards: Aircraft Engines
14 CFR Part 121	Certification and Operations: Domestic, Flag and Supplemental Air Carriers and Commercial Operators of Large Aircraft
14 CFR Part 135	Operating Requirements: Commuter and on Demand Operations and Rules Governing Persons Onboard Such Aircraft
AC 25-20	Advisory Circular: Pressurization, Ventilation and Oxygen Systems Assessment for Subsonic Flight including High Altitude Operation

2.1.3 Airlines for America (A4A) Publications

Available from Airlines for America (A4A), 1301 Pennsylvania Avenue, NW, Suite 1100, Washington, DC 20004, Tel: 202-626-4000, www.airlines.org.

Specification 100	Manufacturers' Technical Data.
MSG-3	Operator/Manufacturer Scheduled Maintenance Development, Volume 1 - Fixed Wing Aircraft

2.1.4 EASA Publications

Available from European Aviation Safety Agency, Ottoplatz, 1, D-50679 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu.

CS-25	Certification Specifications for Large Aeroplanes
CS-APU	Auxiliary Power Units
CS-E	Certification Specifications and Acceptable Means of Compliance for Engines

2.1.5 AIA Publications

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928, Tel: 703-358-1000, www.aia-aerospace.org.

Airline Industry Standard: World Airlines Technical Operations Glossary (WATOG) - 14th Edition, 1992.

2.1.6 ICAO Publications

Available from International Civil Aviation Organization, 999 University Street, Montreal, Quebec H3C 5H7, Canada, Tel: +1 514-954-8219, http://www.icao.int/.

Annex 16, Vol. 1 Environmental Protection, Volume I - Aircraft Noise. Fifth Edition.

2.1.7 Other Applicable References

W. W. Thayer, "Tobacco Smoke Dilution Recommendations for Comfortable Ventilation," presented at ASHRAE 1982 annual meeting, Toronto, Canada, 27 June to 1 July, 1982.

P. F. Halfpenny and P. S. Starrett, "Control of Odor and Irritation Due to Cigarette Smoking Aboard Aircraft," ASHRAE Journal, March 1961, p. 39-44.

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AS4073 Air Cycle Air Conditioning Systems for Military Air Vehicles

2.2.2 ASHRAE Publications

Available from ASHRAE Headquarters, 1791 Tullie Circle, NE, Atlanta GA 30329, Tel: 800-527-4723 (U.S. and Canada only) or 404-636-8400, www.ashrae.org.

ASHRAE Std 161-2018 Air Quality for Aircraft Cabins

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2.3 Definitions

APU: Auxiliary power unit.

cfm: Cubic feet per minute.

CFR: Code of Federal Regulations.

CS: Certification specification.

ECS: Environmental control system.

HEPA: High-efficiency particulate air (refers to a high-efficiency air filter).

ppmV: Parts per million, by volume.

RH: Relative humidity.

TRI-HUB BURST: A failure condition whereby a high-speed rotating part disintegrates into three major pieces, each of which transmit about 1/3 of the total energy to the containment vessel.

VOC: Volatile organic compound (refers to a vaporous substance found in the airstream).

For other definitions, refer to ARP147.

3. SYSTEM DESIGN RECOMMENDATIONS

The major elements of air conditioning system design are as follows:

1. Ensure safety of airplane occupants, ground crews, and maintenance personnel.

2. Provide comfortable environment for passengers and crew.

3. Provide cockpit interfaces that minimize workload for flight crews.

4. Be cost effective to operate and maintain.

5. Be compatible with the environment.

The following is an overview description of an airplane air conditioning system:

The air conditioning system may accept high-pressure, high-temperature fresh air from the main engines, from separate compressors, from an APU, from ground carts, or from a fixed ground supply. The flow of supply air should be controlled and the air conditioned to control temperature and remove excess moisture. Sufficiently redundant air supplies should be provided to ensure continuity of ventilation, control of temperature, and pressurization following reasonable probable failures. Conditioned air may be distributed to both occupied and unoccupied areas. This requires control of supply and exhaust air for each of these areas. Venting requirements for lavatories, galleys, cargo compartments, etc., should be considered. Each of the air conditioning system functions should include monitors to the extent necessary to permit efficient crew control and problem diagnosis.

Other documents covering aspects of cabin air conditioning are ARP1270, which deals with pressurization controls; AIR1609, which covers added moisture; AIR1204, which deals with control of free water in the cabin air supply; AIR4766/1, which deals with particulate contamination; AIR1600, which covers animal environments; AIR1826, which covers the acoustic environment; and ASHRAE Standard 161-2018, which covers aircraft cabin air quality design parameters

This section provides applicable safety requirements for air conditioning systems.

3.1.1 Requirements Imposed Via Regulations

The air conditioning system shall comply with airworthiness requirements, the scope of which should be defined in the airplane specification. Design should also be regulated by the airplane specification. In the event of conflict, airworthiness requirements should prevail.

Regulatory bodies include the United States Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA). The FAA regulates the design of airplanes by 14 CFR Part 25. The EASA regulates design by CS-25, which represents the combined requirements of the Airworthiness Authorities of the participating European nations. The 14 CFR Part 25 and CS-25 applicable requirements include the following paragraphs:

a. 25.561 Emergency Landing Conditions - General

b. 25.831 Ventilation

c. 25.832 Cabin Ozone Concentration

d. 25.833 Heating Systems

e. 25.841 Pressurized Cabins

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f. 25.843 Tests for Pressurized Cabins

g. 25.853 Compartment Interiors

h. 25.855 Cargo and Baggage Compartments

i. 25.856 Thermal/Acoustic Insulation

j. 25.863 Flammable Fluid Fire Protection

k. 25.1163 Powerplant Accessories

l. 25.1301 Equipment, Function and Installation

m. 25.1309 Equipment, Systems and Installations

n. 25.1322 Warning, Caution and Advisory lights

o. 25.1438 Pressurization and Pneumatic Systems

p. 25.1461 Equipment Containing High-Energy Rotors

(14 CFR Parts 23, 27, and 29 have equivalent requirements to those listed in 14 CFR Part 25 for rotorcraft and small airplanes.)

In addition, sections of Subpart D of 14 CFR Part 25 and CS25 are applicable to air conditioning system components.

Operating rules based on FAA or EASA regulations are applied individually by the nation of registry. Adequate provision shall be made in systems design to ensure that it is possible for the airplane operators to meet their relevant requirements. These requirements are established by regulations such as 14 CFR Part 121 and Civil Aviation Authority - Air Navigation Order.

Departure from convention in design or in operating environment may result in special airworthiness requirements being imposed. The requirements may be identified as special conditions until they are incorporated into the U.S. Code of Federal Regulations, EASA, and other regulations. The existence and interpretation of such special conditions should be established at the outset.

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3.1.2 System Design Recommendations for Safety

All aspects of the air conditioning system design should consider the safety of the passengers and crew. The safety considerations include the following:

a. All parts of rotating components containing very high amounts of energy should be contained in the event of failure.

b. Noxious or toxic substances should be prevented from entering the cabin or flight deck either through the primary air conditioning system or the recirculation system. Special attention should be given to hydraulic fluids, fluorocarbon fluids, fuel vapors, and lubricants.

c. Any combination of reasonably probable failures should not result in excessively high or low temperatures in the cockpit or cabin.

d. For all components located in an area where flammable fluids or vapors might leak, there should be means to minimize the probability of fluid or vapor ignition in accordance with 14 CFR 25.863.

e. Select nonmetallic materials that have the lowest practicable smoke density and toxicity rating.

f. Mount equipment installed in the cockpit or cabin strongly enough to prevent serious injury to occupants in the event of a minor (wheels up) crash landing. Use design load factors per 14 CFR 25.561.

g. Ensure that fans do not start fires in the event of motor protector failure.

h. Ensure that carbon dioxide released from dry ice used in galleys or in cargo compartments does not cause a hazard.

i. Filter galley exhaust air to prevent the accumulation of flammable oils in the exhaust ducts. The filters should not burn and should not permit a fire to pass through them into the ducts.

j. Provide protective devices for all electric heaters where failures can cause fires or unacceptable temperatures.

k. Adequate instrumentation/indication should be provided to ensure that significant failures do not go undetected.

l. The design should require a minimum use of flight crew operating procedures, especially where incorrect use of procedures can cause a subsequent failure or potentially hazardous operating condition.

m. All electrical equipment located in a zone potentially subjected to (combustible) flammable vapors should meet explosion proof criteria.

n. Air flow sufficient to maintain cabin pressure should be maintained under any combination of reasonably probable failures.

o. Air supplied to the cabin shall be free from substances that can impair safe operation of the aircraft (refer to CS-E, CS-APU, and 14 CFR Part 33.75.)

The design of inlets and surface insulation should be such that no metallic surface which can be touched by occupants for prolonged periods exceeds 120 °F (49 °C) when the air conditioning system has reached its stabilized operating condition, or 140 °F (60 °C) during transient operation. For plastic or wood surfaces, 156 °F (69 °C) and 185 °F (85 °C) apply, respectively (MIL-STD-1472, paragraph 5.13.4.6).

3.1.3 Failure Considerations

A fault and failure analysis should be conducted to determine the need for safety devices such as overpressure and over temperature protective features and pressure relief functions, etc. Included in the analysis should be complete loss of electrical power, loss of one or more packs in multiple pack systems, loss of pressure regulation, loss of temperature control at both inlet and outlet, and any other failures or faults which may have adverse effects.

The air conditioning system inevitably requires electrical power. It is important that the following functions are maintained in the event of the loss of electrical power.

a. Air supply for ventilation, pressurization, and smoke removal.

b. Control of cabin pressure.

It is in the above context that the functional difference between a normally open, normally closed, or latching solenoid valve and a motorized valve is most evident. This is especially important when considering electrical system failures that leave only essential or battery power available.

Additional reliability considerations are found in 4.1.2.

3.2 Comfort

The aspects of air conditioning system design that contribute to occupant comfort are:

a. Ventilation.

b. Air distribution.

c. Compartment temperature.

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d. Compartment humidity.

e. Cabin noise.

f. Air quality.

3.2.1 Ventilation

For the purposes of this document, ventilation shall refer to outside (fresh) air ventilation. The ventilation rate refers to the air change rate: the rate at which cabin air is exchanged with outside (fresh) air.

3.2.1.1 Ventilation Requirements

The occupied compartments shall be ventilated whenever the airplane is in operational service. The minimum outside air ventilation rate required by various regulatory bodies is as shown in Table 1:

Table 1 - Outside air requirements

FAA	EASA
0.55 lb/min/occupant (= 10 CFM at 8000 feet) (14 CFR 25.831)	10 CFM/crew in crew compartment (CS 25.831)
0.4 lb/min/occ for failure conditions exceeding 5 minutes (AC 25-20)	0.4 lb/min/passenger with loss of an air source for periods exceeding 5 minutes (= 7.26 CFM at 8000 feet) (AMC 25.831)

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Ventilation rates affect CO and CO_2 concentrations in the cabin. Ozone concentration is influenced by ventilation rate as well (and, on some airplanes, may be controlled by a dedicated ozone converter); Table 2 gives the requirements applicable to CO and CO_2, as well as O_3:

Table 2 - Airborne contaminants requirements

	FAA	EASA
CO_2*	0.5% Vol	0.5% Vol
CO*	50 ppmV	50 ppmV
O_3	0.25 ppmV, sea level equivalent above FL320 Plus 0.1 ppmV, sea level equivalent, time-weighted average during any 3-hour interval above FL270**	

* Source of CO and CO_2 requirements: CS and 14 CFR 25.831.
** Refer to AIR910 for complete ozone maximum requirements.

3.2.1.2 Ventilation Recommendations

To minimize energy consumption, the air conditioning system should operate to provide the minimum required ventilation rate, except when it is desirable to increase the ventilation rate to accomplish the following:

a. Meet compartment temperature demand; it may not be possible to cool or heat the compartment to the desired temperature with the system supplying conditioned air at the minimum ventilation rate.

b. Clear smoke from the compartment.

To meet the ventilation requirement, the air conditioning system should operate from the normally available on-board air sources (e.g., main engine, auxiliary, or APU compressor bleed). It should also be possible to operate on the ground from external sources. AIR4766 provides information on cabin air quality; AIR4766/1 and AIR4766/2 provide information regarding particulate and gaseous air contamination, respectively.

A ram air or auxiliary ventilation source should be considered if, under minimum equipment dispatch conditions, reasonably probable failures can result in the loss of all ventilation. This auxiliary ventilation may consist of a ram circuit supplying the normal distribution system, or provisions for manipulating cabin pressure control valves to draw ambient air through the cabin and flight deck, through door seals, negative relief valves, hatches, etc.

Other ventilation recommendations are to provide a draft-free environment with uniform air distribution and temperatures and good air mixing (see 3.2.2).

3.2.1.2.1 Air Quality and Quantity

The quality of air in the cabin depends on the quantity and quality of outside air supplied, contamination generated within the cabin, and the contamination removal efficiency of the air conditioning system.

The quality of outside air is dependent on the source. On the ground, air from adjacent aircraft engine exhaust or nearby ground vehicles can be ingested into the air conditioning system. Turbine engine air sources may also contain contaminants; refer to AIR1539. CS-E, CS-APU, and 14 CFR 33.75 also provide guidance on main engine and APU contamination of air conditioning air.

AIR4766 provides information on cabin air quality; AIR4766/1, AIR4766/2, and AIR1539 provide information regarding particulate and gaseous air contamination, respectively.

Contaminant sources within the aircraft include occupants, cargo, and non-metallic cabin furnishings such as carpets or plastics. In some circumstances, insecticide and cleaning agents may also be present.

Finally, air conditioning systems may be configured to remove contaminants. Systems that employ recirculation of cabin air should use particulate filters. HEPA-type filters are capable of removing certain microbial contaminants. It is also possible to remove gases, VOC, bioaerosols, and other contaminants through the use of adsorbents or catalytic reactors.

3.2.1.2.2 Smoking

Smoking is banned on virtually all commercial flights, so the applicability of this section may be limited to certain business or other private aircraft. In general, this section is no longer applicable to commercial aircraft.

The most challenging ventilation function in many applications is to dilute tobacco smoke to acceptable levels[1].

A number of tests have been run (Thayer, 1982) in which smoker and nonsmoker response to various dilution indices was obtained. The dilution index (D.I.) is defined as the liters of fresh air per milligrams of tobacco burned. Figure 1 shows how irritation varies with dilution index, and Figure 2 shows the percentage of smokers and nonsmokers who reported the irritation levels as acceptable.

In the tests of Halfpenny and Starrett (1961), the mean smoking rate was found to be 13.4 mg/min per smoker; unless other specific smoking data are available, it is recommended that the mean plus one standard deviation (3.6 mg/min) be used for design purposes. The recommended design rate is then 17 mg/min per smoker.

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[1] 14 CFR 121.317(c) [change 75, Amendment 121-213, effective Feb. 25, 1990] defines FAA requirements applicable to domestic, flag, and supplemental air carriers and commercial operators of large aircraft

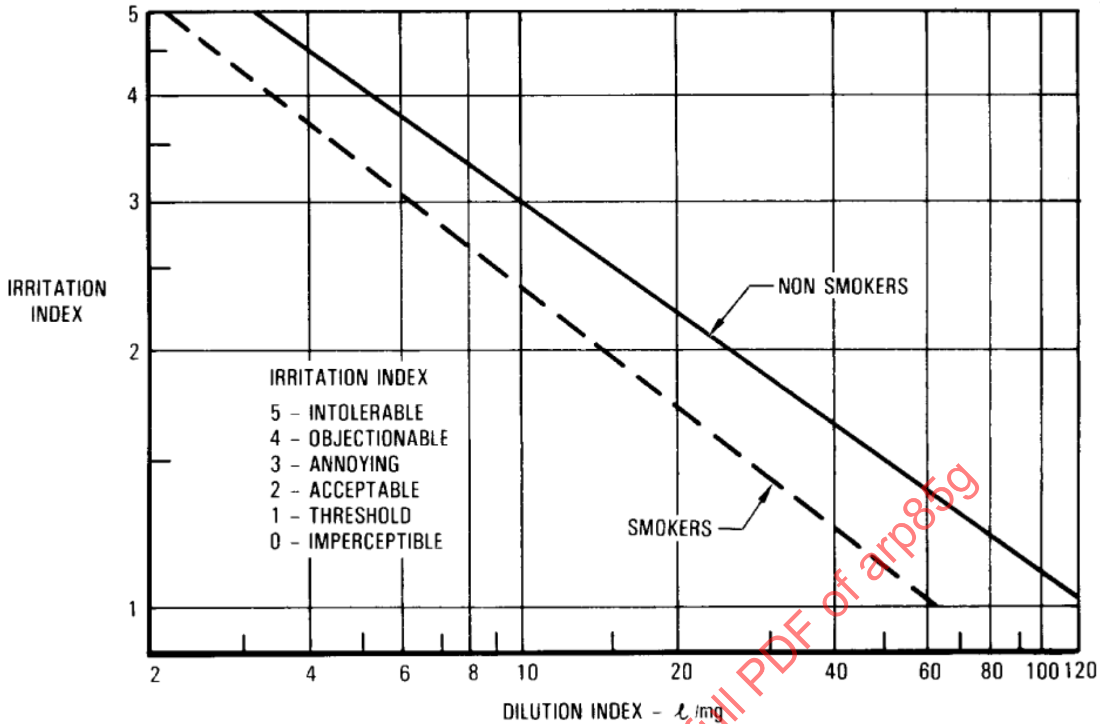

Figure 1 - Irritation versus dilution

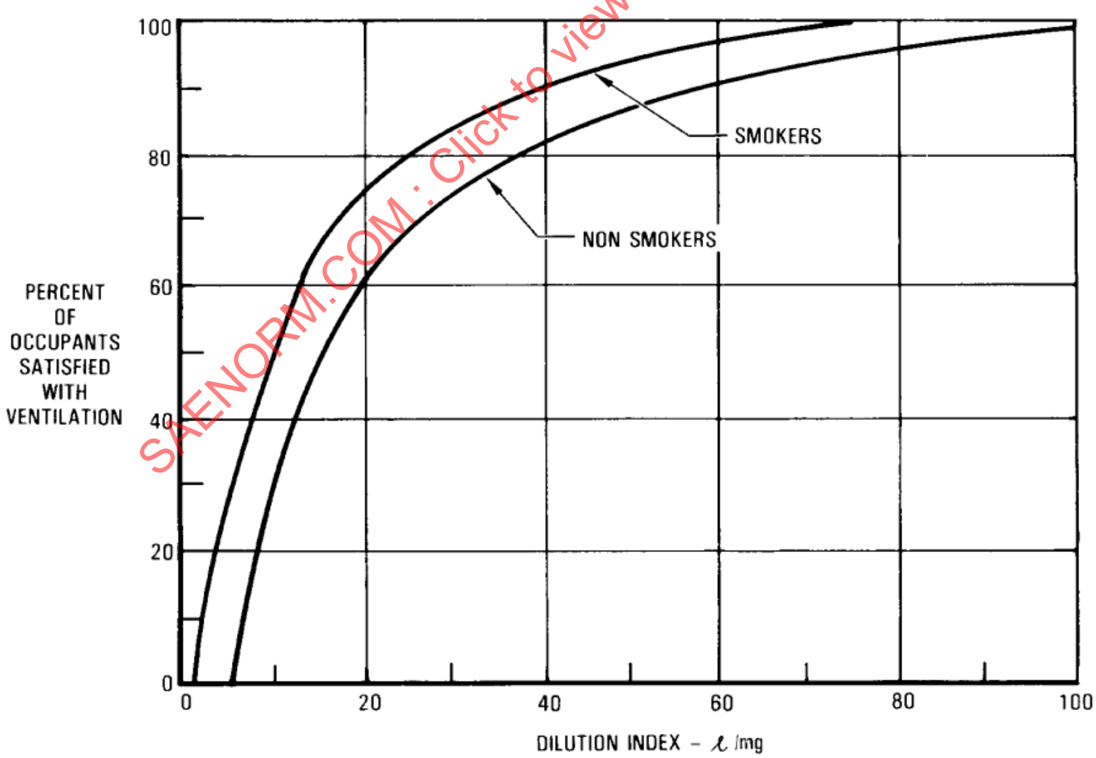

Figure 2 - Effect of dilution index on occupant satisfaction

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3.2.1.2.2.1 Smoking Zones

The data of Figure 2 may be used, along with an estimated smoking rate of 17 mg/min per smoker, to calculate the ventilation necessary to obtain any desired acceptance rate in a smoking zone.

Ventilation should be at a level so that at least 80% acceptance by smokers is achieved in the smoking zone. To achieve an 80% acceptance level, the D.I. should be 24 ℓ/mg (Figure 2). At a smoking rate of 17 mg/min, per smoker, the ventilation rate is 408 ℓ/m (14.4 cfm) per smoker.

The size and location of smoking zones vary with airlines and routes. There may be as many as three different smoking zones on a large wide-bodied airplane, and as many as 45% of the total seats assigned to smoking zones on long flights. Some airlines flying shorter legs assign as few as 23% of the seats to smoking zones.

3.2.1.2.2.2 Minimum Fresh Air Ventilation Rate

The minimum fresh air ventilation rate specified in 3.2.1.1 is generally established to meet CO_2 levels and control odors. Temperature control and distribution needs may establish higher ventilation rates than is required for CO_2 and odor control. In addition, if air is recirculated from smoking zones into nonsmoking zones, it should be filtered to remove gaseous contaminants and aerosols, or it should be diluted with enough fresh air to achieve a D.I. of 60 ℓ/mg, which is acceptable to 90% of the nonsmokers. Equation 1 shows how the recirculation and fresh air quantities may be established in a nonsmoking zone.

$$\text{Fresh Air} = \text{Recirculated Air}\left\{\frac{\text{D.I. Required}}{\text{D.I. Smoking Zone}}\right\} - 1 \qquad \text{(Eq. 1)}$$

Thus, if a 60 ℓ/mg D.I. is required, and the smoking zone D.I. is 24 ℓ/mg, then the minimum ratio of fresh to recirculated air is 1.5:1.

Smaller airplanes, such as business and executive aircraft, commuters, and small and large military transports, may allow smoking zones. The D.I. for these airplanes is based on the total smoke generated and total fresh air supplied. To achieve a 90% acceptance of the ventilation by nonsmokers, a 60 ℓ/mg D.I. is required for the entire cabin. Based on a smoking ratio of 17 mg/min per smoker and 1/3 smokers, the fresh airflow is 60 x 17 x 1/3 = 340 ℓ/mg (12 cfm) per passenger. The air distribution system for these types of airplanes should ensure good mixing to achieve a uniform D.I.

3.2.1.2.3 Ventilation Flow Control

The air conditioning system should contain a means to control airflow to satisfy one or more of the following:

a. Maintain a specified ventilation rate to the cabin.

b. Provide an adequate supply of fresh air.

c. Provide sufficient cabin inflow to be compatible with the cabin pressure and temperature requirements.

d. Limit the amount of airflow in the cabin to keep noise and drafts to an acceptable level.

e. Limit the amount of engine bleed airflow to conserve engine fuel.

f. Control air flow for smoke clearance.

The flow control device or system includes a means for sensing downstream pressure or the airflow rate and the required valving to modulate the airflow to meet a prescribed airflow schedule. ASHRAE Standard 161 provides information for verifying flow rates throughout an aircraft cabin.

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3.2.1.2.3.1 Flow Sensing

The method of airflow sensing should be selected based on an evaluation of the accuracy required to meet the flow schedule and limits desired and the ease of interfacing with the modulating valve. Some techniques for flow sensing include the following:

a. Venturi: The pneumatic duct is constricted in a smooth venturi section, usually with a gradual taper on the outlet for pressure recovery. The differential pressure is measured between inlet and throat. This differential pressure can be used as a signal pressure for a mechanical servo controller. Or, the differential pressure can be converted to an electrical signal through the use of a pressure sensor. An electronic controller can then calculate flow. An air inlet temperature can be used in the calculation to enhance accuracy. The venturi can be a constriction of the duct flow area, or as an alternative a boosted-pitot can be used. This is a smaller venturi placed inside the duct with pneumatic sense lines connecting with the sensing elements located outside the duct. The boosted pitot must be positioned in the duct to get a representative flow signal.

b. Heated-element: Sometimes referred to as a hot-wire anemometer, this is a device with a heated probe that is placed in the air stream to measure the cooling effect of airflow going past the probe. The air flow rate is a function of the cooling effect. Since the cooling effect is also a function of the air temperature, this must be factored into the flow calculation. The calculation can be done by electronics onboard the sensor or in a remotely mounted controller.

c. Flow scheduling: Discussed in 3.2.1.2.3.4.

3.2.1.2.3.2 Flow Modulation

A valve to modulate air flow to achieve the desired flow is placed upstream of the other air conditioning system components. The valve to modulate airflow should be designed in conjunction with the flow-sensing device and sized to handle the airflows required by the air conditioning system. If other airplane systems require airflow, such as avionics cooling, that additional airflow should be considered when sizing the valve. Other features that should be considered for the airflow modulation valve are as follows:

a. A remote means to open and close the valve to modulate or shut off system airflow.

b. A method to mechanically override the airflow modulation device to allow manual operation to open and close the valve and lock it in the closed position.

c. Flow scheduling: Discussed in 3.2.1.2.3.4.

d. A means to modulate the valve towards closed should an over temperature be sensed in the system.

3.2.1.2.3.3 Inlet/Outlet Flow Control Variables

For the normal operating range, the flow control device or system upstream of the air conditioning pack may see the following range of variables for subsonic airplane air conditioning systems:

a. Inlet pressure from 10 to 60 psig (69 to 414 kPa gage).

b. Inlet temperature from 100 to 500 °F (37.8 to 260 °C).

c. Uncontrolled inlet pressure rate of change 40 psi/s (276 kPa/s).

d. Variable downstream restriction resulting in a 5 to 40 psig (34 to 276 kPa gage) pressure demand.

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3.2.1.2.3.4 Flow Control Scheduling

Various types of flow scheduling may be desired or required and should be evaluated for the specific airplane and mission. These are:

a. Flow schedule reset as a function of altitude.

b. Constant volumetric airflow scheduling reset as a function of passenger loading.

c. Flow scheduling reset as a function of the amount of cabin recirculation flow.

d. Flow scheduling reset as a function of cabin pressure.

e. Flow scheduling reset to compensate for a failure of one of the supply channels.

f. Flow scheduling reset to ensure adequate bleed air supply to other system without exceeding engine bleed limits.

3.2.2 Air Distribution Recommendations

The following is a list of recommendations for distribution of air within the pressurized cabin:

a. The design should ensure air supply to, and exhaust from, the occupied compartments. The location of inlets is usually selected based on prior proven designs and confirmed by quantified and subjective testing outlined in ASHRAE Standard 161. Generally, passenger compartment air is introduced at high level and exhausted at floor level. The design of air exhausts should preclude the possibility of blockage by luggage, clothing, or litter.

b. The overall flow pattern should preclude the possibility of contaminated air generated; for example, by systems failures under the floor or behind furnishings, entering occupied compartments.

c. Flight crew should have means to direct and vary airflow. Such adjustment should not significantly affect the overall balance of air distribution nor allow complete shutoff of air supply to the flight compartment.

d. Air from lavatories and galleys should not be exhausted into other occupied areas.

e. Air from cargo compartments should be able to be isolated and never be exhausted into occupied areas.

f. Where individual air supplies are provided, the flow should be adjustable. The jet velocity at seated head level should be at least 200 ft/min (1 m/s).

g. With individual air supplies closed and the air conditioning system operating normally, the air velocity, in the vicinity of seated occupants, should not exceed 60 ft/min (0.3 m/s) and should, for optimum comfort, be between 20 ft/min and 40 ft/min (0.1 m/s and 0.2 m/s). To avoid sensation of stagnation, air velocities should not be less than 10 ft/min (0.05 m/s) at seated head height.

h. Compartment air distribution should be such that with stabilized conditions the variation in temperature in a cabin zone should not exceed 5 °F (2.8 °C), measured in a vertical plane from 2 inches (5 cm) above floor level to seated head height.

i. Cabin distribution ducting and air inlets should be sized to limit air velocities so as not to generate air noise levels objectionable to occupants.

j. The temperature of air entering occupied compartments should, in normal operation, be not less than 35 °F (2 °C), nor more than 160 °F (71 °C).

k. Where cabin air supplies combine, or where cold or hot air is added for temperature control, the various supplies should be effectively mixed to achieve uniform temperature distribution, prior to distribution in occupied compartments.

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l. Free water present in the air supply system should not be discharged onto passengers or equipment. Any drainage facilities should ensure that the water presents no hazards to equipment or airplane structure.

m. Distribution ducting should be insulated in accordance with 3.2.3.2.2.

3.2.3 Compartment Temperature Recommendations

The air conditioning system should have the requisite heating and cooling capacity to achieve the desired compartment temperature. The system should also provide a temperature control system to maintain the desired compartment temperature over the expected range of ambient conditions, flight conditions, and payloads.

3.2.3.1 System Capacity

The required air conditioning system capacity is that which can balance the airplane heat loads at the desired cabin temperature in a steady-state thermal analysis. The following typical subsonic airplane heat loads should be considered:

a. Occupant latent and metabolic: Note that different values typically are used for crew and passengers.

b. Electrical equipment: Any devices that reject heat into the compartment, including lights, flight deck displays, in-flight entertainment, galley ovens, and chillers.

c. Recirculation or gasper fans: Any devices that add heat to the conditioned air stream.

d. Conducted (also called UA loads): The heat path from the compartment to outside ambient.

e. Solar: Radiation through compartment windows.

The heat load of the airplane can be determined by referring to AIR1168/3, Equations 3A-49 and 3A-50. Using that heat load, the following performance should be achievable on the respective hot and cold reference days defined in 7.1.

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3.2.3.1.1 Cooling Capacity

The system should provide sufficient cooling capacity to maintain the desired compartment temperature on a hot day as defined in 7.1.1.

During cruise, the system should be capable of maintaining an average compartment temperature of 75 °F (24 °C) with full passenger load.

During ground operations, the system should be capable of maintaining an average compartment no higher than 80 °F (27 °C) with full passenger load and all external doors closed.

The system should be capable of cooling the compartment on the ground to an average temperature of 80 °F (27 °C) within 30 minutes, starting with a compartment temperature of 115 °F (46 °C), no passengers or other internal heat loads, and with all external doors closed.

3.2.3.1.2 Heating Capacity

During cruise, the system should be capable of maintaining an average temperature of 75 °F (24 °C) with 20% passenger load.

During ground operations, the system should be capable of heating the compartment on the ground to an average temperature of 70 °F (21 °C) within 30 minutes, starting with a cold soaked airplane at a temperature of -25 °F (-32 °C), with no passengers or other internal heat loads, and with all external doors closed.

The system should maintain the cargo compartment bulk air temperature above 40 °F (4.4 °C). Cargo floor temperatures should be above 32 °F (0 °C) to prevent freezing of cargo. These temperatures should be attainable during all cruise conditions.

These requirements should apply with a cold day as defined in 7.1.2.

3.2.3.1.3 Average Temperature Definition

As the compartment temperature is subject to a gradient in between the blow-in temperature and the exit temperature, the average temperature depends on the air distribution in the compartment. For small compartment volumes, it is difficult to distribute the air adequately to obtain reasonable minimal temperature gradients while at the same time obtaining the desired temperatures. Therefore, the average compartment temperature is usually defined as:

$$T_{average} = a * (T_{out} - T_{in}) + T_{in}, \text{ with "a" between 0.75 and 1}$$

For large volume airplanes, the factor "a" is usually equal to one, which defines the average temperature as the outlet temperature.

For small volume airplanes, the factor usually used is between 0.85 (fighter) and 0.8 (regional airplane). More detailed information is given in U.S. Air Force Specification Guide JSSG-2009.

3.2.3.1.4 Degraded System Performance

The following recommendations apply for system failures:

a. With the loss of an air conditioning pack or bleed source, on a hot day the compartment temperature requirement may be relaxed by 5 °F (3 °C).

b. With total loss of inflow, the system should comply with compartment temperature requirements in 14 CFR 25 Amendment 25-87.

3.2.3.2 Compartment Temperature Controls

Independent, automatic temperature controls should be provided for the flight crew and passenger compartments. An exception to this practice is made where the volume of the flight deck and other compartments are less than 800 ft^3 (23 m^3) or the aircraft design is arranged such that the flight deck and other compartments can be maintained within 5 °F (3 °C) of each other (14 CFR 25.831(e)).

In large airplanes, additional temperature controls should be provided, on a zonal basis, to cater for uneven thermal loading due, for example, to mixed cargo/passenger configuration, or non-uniform occupancy.

For each zone, including the flight deck, an adjustable temperature selector shall be provided to establish the set point for the temperature control system. For large passenger airplanes, temperature selectors for the cabin zones may be placed at flight attendant work stations. This relieves the flight crew of the task of making selector adjustments to satisfy passenger requests. These selectors for the main cabin zones should not affect temperature control of the flight deck.

Consideration should be given to providing a manual override for control of flight deck temperature in the event of control system failures.

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3.2.3.2.1 Compartment Temperature

Each compartment or zone air temperature should be adjustable within the range 65 to 85 °F (18 to 29 °C) for human occupied compartments. For air conditioned cargo compartments, the selectable range should be 40 to 80 °F (4 to 27 °C).

Within limitations of system capacity, the temperature indicated by the sensor should be maintained within 2 °F (±1.1 °C) at the compartment sensor after stabilization following startup or temperature reselection. Means should be provided for the temperature sensor to sample compartment air at a rate compatible with control sensitivity requirements. The air sample should be taken from a location representative of average compartment temperature.

Following reselection, compartment temperature indicated by the sensor should not overshoot or undershoot the newly selected value by more than 3 °F (1.7 °C). The rate of change of the zone temperature should not exceed 0.5 °F (0.3 °C) per minute within the temperature range of 70 to 81 °F (21 to 27 °C).

Compartment supply temperature should be controlled within limits appropriate to required heating and cooling rates and with consideration to occupant safety. This latter consideration should preclude the possibility of smoke or fumes generated by ducting materials at high temperature. In the event of a system failure, the mean compartment temperature should not exceed 140 °F (46 °C) for any period. During transient conditions leading to a mean compartment temperature rise above 100 °F (38 °C), the elapsed time that the mean compartment temperature exceeds 100 °F (38 °C) must be less than or equal to the crew and passenger exposure time (14 CFR 25.831(a) as further defined in AC-25.20, paragraph 5e).

3.2.3.2.2 Insulation - Compartment Surfaces and Ducts

In occupied areas, insulation should be provided so that wall and floor temperatures should be within 10 °F (6 °C) of the compartment temperature (MIL-STD-1472F, paragraph 5.8.1.5).

Insulation should be provided to maintain outside surface temperatures of air conditioning distribution ducting above the maximum expected dew point in the area. If this cannot be accommodated, appropriate drip trays should be utilized to collect and drain the condensate in accordance with AIR1204.

3.2.4 Cabin Humidity

A primary function of the air conditioning system is to reduce cabin humidity during ground operations on hot humid days. Depending on the cycle, there are several methods of removing moisture from the conditioned air being supplied to the cabin. With air cycle refrigeration, high-pressure water collectors or low-pressure water separators are used to remove moisture from the conditioned outside (fresh) air. With vapor cycles, water from both the outside and recirc air streams is condensed at the evaporator

Due to the very dry air at altitude, moisture is not removed by the air conditioning system during cruise. The only source of moisture during high altitude flight is from the occupants. Air conditioning systems which use recirculated air tend to have slightly higher RH levels than systems using all-outside (fresh) air.

In effort to improve comfort, some airplanes have been fitted with humidifiers to provide supplemental humidity (see 4.2.6).

3.2.5 Compartment Noise Recommendations

The effect of the air conditioning system on noise levels in the occupied compartment should be evaluated during the component and system design. Specific requirements are generally defined by the airplane design specification. Detailed recommendations for acoustic design are provided in AIR1826. Ramp noise is discussed in 3.5.1.

Sources of air conditioning system compartment noise are typically component case radiated noise, component noise transmitted through pneumatic ducting, airflow noise generated at valves, component self-induced vibration transmitted to the airplane structure, and air distribution system duct noise associated with inlets, exhaust ports, turns, and restrictions. The criticality of noise levels generated is dependent on the proximity of the equipment to the compartment or the location of inlet and exhaust ports within the compartment, the spectrum shape of the generated noise, and the background noise level.

Noise generated by the air conditioning during flight should be masked by the combined engine and aerodynamic noise in each octave band. During other modes of operation, when the air conditioning system is the main source of noise in the occupied areas, there should be a smooth balanced noise spectrum with no audible pure tones. Levels during these conditions should allow easy communication between crew members in the flight station and between a window seat passenger and a cabin attendant standing in the aisle.

To reduce the air conditioning noise in the airplane interior, two approaches are possible: source reductions and transmission path attenuation. To reduce noise at the source, it is necessary to identify the components or parts of the system generating the noise and to determine the mechanism of the sound generation process. Generally, it is advantageous to take all available steps to reduce noise at the source. Any further improvement may come from the addition of insulation, absorption, or other treatments into the path between source and compartment.

This necessitates that the dominant sound transmission path be determined; i.e., either structure-borne or airborne.

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3.2.5.1 Duct Velocity Criteria

The air velocity in the system should be kept to a minimum and preferably not to exceed 50 ft/s; 3000 ft/min (15 m/s).

Current design rule applied for a narrow body airplane is to size the air distribution ducting to limit air velocities:

a. To a maximum of 2000 ft/min (10 m/s) above floor level.

b. To a maximum of 3000 ft/min (15 m/s) for ducting below floor.

NOTE 1: The recommended maximum velocity in the air distribution system for wide body airplanes could be increased by a factor of 1.5 when necessary.

NOTE 2: The recommended maximum velocity in the air distribution ducts for buildings is less than 800 ft/min (4 m/s).

NOTE 3: Consideration can be given to exceeding these guidelines for non-normal flow schedule operation if noise is deemed to be less important for those conditions.

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In addition, the following guidelines apply:

a. The air velocity in the distribution system should be kept as close to being the same as possible.

b. There should be no element producing a discrete disturbance within eight diameters of an outlet (for example, flow balance orifices should be located at least eight diameters upstream of the outlet).

c. There should be a minimum number of elements producing a discrete disturbance in a distribution system.

d. As a result of the above recommendations, sharp bends, sharp edges, sudden expansion and contraction, as well as ducting of aspect ratio above six shall be avoided.

3.2.5.2 ΔP Across Temp Control Bypass Valves

Delta-pressure across air conditioning system valves, such as temperature control bypass valves, should be minimized. In airplanes with multiple cabin temperature zones, a zone trim pressure regulating valve upstream of the zone trim valves is recommended. The zone trim manifold pressure should be set to a pressure level just high enough to deliver sufficient trim flow to provide adequate temperature control authority under maximum demand conditions.

3.2.5.3 Tones from Rotating Equipment

Rotating equipment such as recirculation fans or air cycle machine turbines can emit tones that can enter occupied compartments, either via ducting or via structure. In some cases, mufflers or isolators must be used to satisfy compartment noise requirements.

3.3 Cockpit Interface

The air conditioning system shall have controls, indication, and a degree of automation that is consistent with the overall flight crew/cockpit interface approach of the airplane.

Control policy is decided by the cockpit (or flight compartment) configuration and the operational role of the flight crew. The crew workload imposed by systems management is an increasingly important factor in systems design. Consideration shall be given to the number of flight crew persons, whether the airplane has conventional or flat-panel “glass” displays, and to the presence or absence of centralized crew alerting and indication systems. For all airplanes, air conditioning system design shall strive to minimize crew workload by providing the appropriate amount of system indication; too much indication may be distracting, especially status information that is not needed by the crew to make decisions.

For airplanes with a three-person flight crew that includes a flight engineer, cockpit controls and indication should provide the flight engineer with information and manual means to carry out fault isolation and system reconfiguration to optimize performance under abnormal or failure conditions.

Airplanes having a two-person flight crew should be provided with more automation and less indication and manual control than provided for the three-person crew. The scarcity of panel space and possible absence of a designated flight engineer have to be countered by stricter discipline in layout and further automation in control and fault rectification. Account should also be taken of the capability of electronic displays and data processors to present relevant information only when it is needed to monitor system health and to facilitate maintenance troubleshooting. This philosophy is intended to present the flight crew with less workload associated with the operation of the air conditioning system. Reducing crew workload is of particular importance during emergency conditions where crew stress levels may be elevated. For example, the air conditioning system response to loss of electrical power should minimize any compensating actions or adjustments by the flight crew.

The objectives of system control design should be to minimize crew actions in normal operation, crew intervention after a single failure, and crew indications not requiring corrective action. These objectives imply a fail-passive design approach and increased redundancy.

3.3.1 Operating Controls

Some basic controls are necessary for airplane certification. For example, the flight crew should be able to control its environment separately from the passenger cabin, and controls should be available to shut off potential sources of smoke or toxic or noxious gasses. Bleed air systems from the engine or APU should have shutoff controls and air conditioning packs, and recirculation fans (if utilized) should also be capable of being shut off.

Other operating controls include the ability to select cabin zone temperatures, usually within a range of 65 to 85 °F (18 to 29 °C).

In some passenger airplanes, a cabin attendant panel is provided so that attendants can adjust and monitor cabin zone temperature.

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3.3.2 Operating Indications

Indications are necessary to show an abnormal state of crew controls or to indicate an abnormal state of system operation. Examples are lights to show that air conditioning packs have been switched off and lights to show that systems have self-detected critical faults.

The levels of indication should be prioritized, as listed below, and also prioritized by different methods of annunciation.

a. Warning: Immediate crew corrective or compensating action required.

b. Caution: Immediate crew awareness and future compensating action required.

c. Advisory: Crew awareness and possible future crew action required.

Warnings and cautions should have attention-getting means to satisfy the need for immediate recognition.

In addition to the use of lights and mechanical indications, great emphasis is now placed on the use of flat-panel or cathode ray tube displays. These displays can give analog or digital information or give discrete messages, arranged in order of priority. The displays can utilize automatic or manually selected storage and data retrieval systems.

The use of gauges should be avoided due to the time required for monitoring and interpreting.

3.3.3 Dispatch Indications

The status of air conditioning systems can impact the dispatchability of the airplane. The status of these systems can be displayed in order for the crew to recognize any airplane operating limitation that might exist. It is a common practice for the crew to interrogate the dispatch limitations prior to flight.

3.4 Economics

Three aspects of air conditioning system economics are as follows:

a. Acquisition.

b. Operation.

c. Support.

Often, a system design attribute may impact these economic factors differently. For example, a feature that allows for easier (and hence less costly) maintenance may result in increased acquiring cost. If said design feature happens to increase weight or power consumption, then operating cost may increase as well. To the design choices that provide the most optimum overall economics, the use of financial tools such as net present value models are suggested. These tools can help understand the overall financial impact of various design approaches.

3.4.1 Acquisition

In general, the designer should strive to reach the lowest-cost design solution that meets all the system requirements.

3.4.2 Operation

Fuel costs are a significant portion of airplane operating expense. The cost penalty assessable to the airplane air conditioning system should be considered in the system design. System architecture definition and system sizing requires a balancing between several cost elements which influences the direct operating cost (DOC) of the aircraft. These cost elements are mainly:

a. Fuel costs.

b. Direct maintenance cost.

c. Delay and cancellation costs.

The direct maintenance cost and the rate for delays and cancellation are linked together via the system reliability and operational reliability, which are influenced by the system architecture. However, a high operational reliability achieved by a high redundancy level results usually in an increase weight, which in turn results in higher fuel costs. The weight again can be varied by changing ram air, etc. This demonstrates the need for a balance analysis between fuel consumption, operational reliability, and system reliability.

The fuel consumption can be determined analyzing the penalties for fixed mass, ram air drag, bleed air off takes, and mechanical power off takes.

To be able to assess a design architecture against the cost effects, some clues are given below. A calculation method is given in AIR1168/8. The penalties depend on the mission profile of the A/C (speed, altitude, flight duration), lift/drag ratio, specific fuel consumption of the engine, bleed stage, etc. The type of A/C (military, commercial), the type of engine, and the system architecture all play very important roles in determining such figures. Taking into account this wide variety, the penalty ranges shown in Table 3 are given as a guideline.

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Table 3 - Fuel burn penalties

Cost Element	Penalty [1]	Unit	Comment
Bleed off-take[2]	Approx 2.7	$kg_{fuel}/(kg/min_{air}*h)$	Military (F-15) three-phase mission
	1 to 1.4		Passenger A/C
Shaft power	0.2 to 0.4	$kg_{fuel}/(kWh)$	
Ram air	Approx 0.6	$kg_{fuel}/(kg/min_{air}*h)$	Military (F-15) three-phase mission
	Approx 0.35		Passenger A/C
Weight	0.3	$kg_{fuel}/(kg*h)$	Military (F-15) three-phase mission
	0.03 to 0.05		Passenger A/C

1 Penalties for carrying the fuel included.

2 The bleed off-take penalty will vary widely depending on where on the engine the bleed air is extracted; i.e., fan circuit, low-pressure bleed port, high-pressure bleed port.

AIR1168/8 provides a means for relating power consumption and drag with weight. This can be used as a tool for design trade studies aimed at producing a system that has the lowest penalty to the airplane.

3.4.3 Support

Support is a large part of airplane economics. Support includes the people, equipment, and facilities needed to enable an airplane to perform its requisite mission. The following factors must be considered in the total cost of ownership of an airplane system:

a. Ground support equipment.

b. Ground power utilities.

c. Fault isolation time and accuracy.

d. Component reliability.

e. Component remove and replace times.

f. Component remove and replace personnel requirements.

g. Component repair or replacement costs.

h. Maintenance crew training requirements.

i. Spares inventory requirements.

j. Cost of airplane dispatch delay, schedule interruption, or failure to achieve intended flight mission.

3.4.3.1 Maintenance Indications

The previous discussions have been associated with actual ground or flight operation of the systems by the flight crew. In addition, there is a need, especially with today's more complex systems, to provide maintenance information to a convenient location such as the flight deck. The display systems, previously discussed, may be used by the maintenance crew to recall system information so that problems may be isolated to specific line replaceable units (LRUs), and to direct action to specific built-in test (BIT).

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3.4.3.2 BIT

Systems should provide an automatic BIT function which checks proper operation of the system. This function should include the following design considerations:

a. In general, the system should not include dedicated BIT equipment; rather, the BIT function should utilize sensors and monitoring devices needed for system control and indication.

b. Multiple LRU failures should not be summed into one operating indication.

c. Automatically stored information should be stored so that fault information from the last several flights is obtainable. This information should be separately obtainable if it aids in fault isolation. Oldest information should be automatically dropped from memory.

3.4.3.3 Reliability and Maintainability

The systems specifications should explain the maintenance philosophy to be applied to that airplane and set design targets for equipment reliability and maintainability. The various maintenance philosophies are defined in the Airline Industry Standard WATOG. The recent general change to "on condition" maintenance emphasizes the need to design for reliability and for equipment life to match that of the airplane. A formal maintenance analysis technique has evolved (refer to MSG-3) and this is widely adopted in commercial airplane operations.

Systems design is a process influenced by failure analyses, the objectives of minimum maintenance burden, and practical configuration deviation list (CDL) and minimum equipment lists (MEL) for airplane dispatch. Specific considerations for air conditioning are:

a. Relative flight-time and flight-cycle sensitivity of the diverse equipment.

b. Accessibility of individual items on packaged assemblies.

c. Redundancy in critical equipment.

d. Manual positioning of control valves and actuators for dispatch.

e. Design to eliminate routine servicing.

Reliability targets should be determined from consideration of the system failure analysis. The generalized requirements for airplane systems are specified in 14 CFR and CS 25.1309, and detailed in AMC 25.1309.

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3.5 Emissions

3.5.1 Ramp Noise

Although the major problems arising from ECS noise concern the passenger cabin and flight station, efforts should be made to protect ground crews working around the airplane. Air exhausting from air cycle machine fans or other overboard bleed flows can generate unacceptably high noise levels. ICAO specifies a ramp noise requirement that applies to air condition systems. Note that an APU is also a significant ramp noise source. Ground servicing locations should be identified in relation to noise sources.

3.5.2 Air Exhaust Temperature

The temperature of air discharging the airplane should be considered:

a. The design and material selection of any adjacent equipment should be considered in any area on which exhaust air impinges.

b. For ground operation, the proximity of maintenance personnel should be considered; appropriate safeguards should be taken.

c. For low-observable military applications, the temperature and flow rates of exhaust streams are of interest.

In some cases, it may be required to limit overboard exhaust air temperature, which will impact design of the air conditioning system.

4. COMPONENT DESIGN RECOMMENDATIONS

This section provides recommendations and guidelines for air conditioning component design.

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4.1 General Component Design Recommendations

General design recommendations encompass considerations that apply to most components, such as materials used, material strength (including factors related to internal pressures in components), leakage allowable, and electrical specifications. General recommendations about any rotating components also are presented.

4.1.1 Materials and Processes

Component parts of the air conditioning equipment should be constructed of materials which are considered acceptable for the particular use and should be made and furnished with the degree, uniformity, and grade of workmanship required to meet the reliability, performance, and safety goals. Attention should be given to corrosion prevention; e.g., avoid the use of dissimilar metals in contact.

4.1.2 Component Failure Concept

Any failure within a given component should not cause failure of another component. Default positions of components, i.e., fail open, closed, or last position, shall be selected so that safe operation with minimum loss of function results.

The considerations of 3.1.2 should be included.

4.1.3 Rotating Equipment Containment

The housing and scrolls of all rotating equipment should contain all hazardous high-energy fragments from:

a. Fused (designed with a minimum section to fail at a selected speed) drive rotor failures (including tri-hub burst) at the maximum fuse speed and at the pressure and temperature associated with this speed.

b. Non-fused drive rotor failures (including tri-hub burst) at the containment speed. The containment speed is defined by either one of two ways:

    1. 125% of the maximum speed resulting from normal operating condition, at the pressure and temperature associated with the speed.

    2. The maximum speed resulting from any operating or multiple failure condition associated with a probability that is greater than 1×10^{-9}.

NOTE: JSSG-2009 considers 135% as appropriate for fans and simple cycle ACMs, and accepts lower values for the bootstrap and other non-simple cycle machines. For non-simple cycle ACMs where JSSG-2009 is specified, it is recommended to design the machine to 135% maximum speed and to use this value as the upper tolerance band of the speed range 125 to 135% for containment testing.

c. Driven rotor failures (including tri-hub burst) at the maximum speed that can result from (a) or (b) at the pressure and temperature associated with this speed. Driven rotors should not burst at speeds lower than the drive rotor's burst.

d. Driven rotor failures when powered by electric or hydraulic motors at the maximum speed that can result from any failure inducing condition or 135% of the maximum normal speed, whichever is greater.

Particles or parts resulting from a failure and passing through inlet or outlet ports of the assembly should be contained by the adjoining duct.

Witness shields may be used in containment tests to demonstrate that any fragments escaping the containing housing are sufficiently low in energy. Witness shields are normally constructed of soft aluminum.

4.1.4 Rotating Equipment Overspeed Spin

All rotating equipment should be designed so that operation at the speed resulting from the worst case single failure or up to 120% of normal maximum operating speed for a period of 5 minutes is possible without rubbing or other adverse effects on the equipment. Freewheeling of all rotating equipment should be prevented or limited.

4.1.5 Contamination

Component design should anticipate ingestion of foreign material from all potential sources. Types and sources of contamination typically encountered by air conditioning systems are discussed in AIR1539. Components should operate satisfactorily under these conditions.

Components should not add harmful concentrations of any toxic, combustible, or objectionable materials to the cabin air supply or equipment compartment. Refer to 14 CFR 33.75 for regulatory requirements of bleed air purity. Also, CS-E and CS-APU mandate that the engine and APU manufacturer provide contaminant generation rates to the airframe manufacturers for design purposes.

4.1.6 Strength

Components, including attachments, should be designed to meet structural acceleration, shock, vibration, and fatigue loads, as well as pressure loads coming from ducting interfaces occurring during the life of the airplane.

4.1.7 Proof Pressure

Components of the air conditioning system shall be structurally adequate to resist without permanent deformation a proof pressure equal to the greater of the following:

a. Proof pressure 1.5 times the gage pressure, with the component at the associated temperature for the most adverse pressure and temperature condition that occurs during normal operation. This complies with the requirements of 14 CFR Part 25 paragraph 25.1438.

b. Proof pressure 1.1 times the gage pressure, with the component at the associated temperature for the most adverse pressure and temperature condition that occurs in the event of failure of a pressure or temperature control device (JSSG-2009).

Note that the above factors may be increased for ducting to allow for installation variables and additional requirements may be required to deal with thermal deflections. Also note that different values of the above factors are defined in military specifications and in European regulation CS- 25 paragraph 25.1438 and associated ACJ (Advisory Compliant, Joint):

a. Proof pressure of 1.5 times any normal maximum $<10^{-3}$ probable event or failure condition.

b. Proof pressure of 1.33 times the operating pressure resulting from a remote failure condition between 10^{-3} to 10^{-5} per flight hour.

c. Proof pressure of one times the pressure condition resulting from an improbable failure with a probability $<10^{-5}$ per flight hour.

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4.1.8 Burst Pressure

Components of the air conditioning system should be structurally adequate to resist without rupture a burst pressure equal to the greater of the following:

a. Burst pressure three times the gage pressure, with the component at the associated temperature for the most adverse pressure and temperature condition that occurs during normal operation. This complies with the requirements of 14 CFR Part 25 paragraph 25.1438.

b. Burst pressure 1.5 times the gage pressure, with the component at the associated temperature for the most adverse pressure and temperature condition that occurs in the event of failure of an upstream pressure or temperature control device (JSSG-2009).

Note that the above factors may be increased for ducting to allow for installation variables and additional requirements may be required to deal with thermal deflections. Also note that different values of the above factors are defined in military specifications and in European regulation CS-25 paragraph 25.1438, associated ACJ and ARP699:

a. Burst pressure of three times any normal maximum and down to 10^{-3} probable event or failure condition.

b. Burst pressure of 2.66 times the operating pressure resulting from a remote failure condition between 10^{-3} to 10^{-5} probability per flight hour.

c. Burst pressure of two times the pressure condition resulting from an improbable failure with a probability between 10^{-5} and 10^{-7} per flight hour.

d. Burst pressure of one times the pressure condition resulting from a failure rate $<10^{-7}$ per flight hour.

4.1.9 Fluid Leakage

Leakage for the entire system should be reviewed, and limits on component leakage should be consistent with safety and system economy.

Internal and external leakage rates for all subsystem components should not exceed values specified in the equipment detail specification.

Leakage should be specified for operating conditions; however, initial or "cold" conditions should also be considered.

4.1.10 Bonding and Grounding

All electrical and electronic equipment should be electrically bonded in accordance with the equipment design specification. The bonding should not be degraded by corrosion preventive measures or by any other finish or process.

The criteria for establishing the bonding and grounding requirement shall include:

a. Prevention of personnel hazard due to electrical shock when the component is powered.

b. Prevention of generation of electrical sparks in case of short circuit in electrical components installed in flammable zones.

c. Meeting EMI and lightning requirements.

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4.2 Specific Component Design Recommendations

These recommendations cover only the major components in the air conditioning system.

4.2.1 Heat Exchangers

Heat exchangers for airplane air conditioning systems are primarily of the plate-fin type because of the generally favorable ratio of total heat transfer-to-volume as compared with tubular construction. Heat exchanger configurations vary widely according to installation, types of hot and cold fluids, pressure drop, effectiveness, and flow rate requirements. The uniqueness of each set of these requirements usually requires a new design for each different heat exchanger application.

a. Materials: Heat exchangers should be constructed of corrosion-resistant materials suitable for the temperatures and pressures encountered. They are fabricated primarily of aluminum, stainless steel, or nickel alloy, depending on operating temperature. The ultimate selection of materials should be based on allowable stresses, environmental conditions, and minimum possible weight.

b. Cyclic stress: Heat exchangers should be designed to withstand the cyclic thermal stresses accumulated during their specified service life. The cyclic thermal stresses result from transient operating conditions experienced during normal airplane operations. Actual airplane service conditions can be reasonably represented by pressure and temperature cycling consisting of initial hot and cold side conditions (pressure, temperature, and flow) representative of minimum (engine idle) conditions, and final hot and cold side conditions representative of maximum (takeoff) conditions. One cycle consists of changing from minimum-to-maximum conditions at a rate equivalent to operational conditions, remaining there until the heat exchanger outlet temperatures are stabilized, and returning to minimum conditions at a rate equivalent to operational conditions and allowing heat exchanger outlet temperatures to stabilize.

c. Cyclic testing: The minimum number of pressure-temperature cycles should be equal to the service life of the heat exchanger divided by the average flight time, depending on type of service and maintenance schedule. Accelerated life cycle testing using higher pressure/temperature excursions over fewer cycles is acceptable. The heat exchanger should not exhibit structural failure or leakage in excess of detailed specification values after being subjected to the specified temperature-pressure cycles. Repair of the unit is permissible after completion of the number of cycles corresponding to the established overhaul period.

d. Installation: Ram air heat exchangers and associated inlets should be located to avoid operational problems due to hail, icing of both the inlet and heat exchanger face, and ingestion of runway debris. Special fins designed to resist foreign object damage (FOD) should be provided where the heat exchanger is subjected to ingested hail and debris. For airplanes that may operate from unprepared runways, the increased exposure to sand and dirt should be considered. Plate fin heat exchangers usually are more susceptible to blockage of the ram flow circuits than tube type heat exchangers. Fin geometry can be selected for improved tolerance to FOD. It is desirable to be able to inspect and clean the ram core without removing the heat exchanger from the airplane.

e. Liquid cooled heat exchangers: Heat exchangers which dissipate heat from the bleed air into fuel or other liquid coolants should be designed to minimize the possibility of a single structural failure that could result in leakage of fuel or coolant into the supply air sufficient to create the possibility of fire or explosion, or result in excessive toxicity levels or noxious odors in occupied compartments.

f. Maintenance costs: Heat exchanger designs should facilitate low-cost methods for removal of contaminants which degrade thermal performance and permit low cost methods for repair of internal leaks with minimum core performance loss.

4.2.2 Air Cycle Machines

The air cycle machine is the most widely used means of providing cooling for airplane air conditioning systems. Compressed air extracted from one or more stages of the engine compressor expands through a turbine with the power extracted used to drive a fan (simple cycle), a compressor (bootstrap cycle), or both (simple/bootstrap cycle). Air cycle machines may also utilize two turbines (condensing cycle).

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The power extraction and expansion across the turbine(s) results in an air temperature decrease. This air is then used as a cooling media for the air conditioning system and also as a means for cabin pressurization.

a. Housings: Each housing or scroll should be designed so that it can be readily replaced at the time of overhaul in the event of erosion or damage.

b. Nozzles: The turbine inlet nozzle material should be resistant to erosion and corrosion and non-toxic. Erosion of the nozzle material during the operational life can decrease cooling performance to below acceptable levels. The material should also be non-toxic as the dust from normal or abnormal erosion or wear can enter the breathing air. The use of cadmium and beryllium should be avoided. The turbine nozzle should be replaceable as a single unit and should not be part of the torus of any other major part.

c. Balancing: Air cycle machines should have provisions to permit initial balancing and re-balancing. The degree of balance should be such that the air cycle machine does not transmit excessive vibration to the airplane structure.

d. Bearings: Air cycle machines may use either precision angular contact ball bearings, air bearings, or magnetic bearings. Ball bearing design should have self-contained oil supply systems with provisions to facilitate the in-place checking and replenishment of oil. Oil seals should be selected and installed to prevent leakage due to oil coking or wear. Machines using air bearings should be designed to minimize contaminants in the bearing cooling air and minimize wear during rotation start and stop. A minimum air flow requirement should be coordinated with the system designer to minimize start-stop cycles. Magnetic bearing designs typically need an external electric power supply to levitate the shaft during operation. Backup bearings should be included which are suitable for the installation with considerations for electric power reliability and time of operation in the event of electric power loss.

e. Reverse thrust load: The air cycle machine should satisfactorily withstand reverse thrust loads that may result from the normal back-pressure load on the fan or compressor wheel and the transient back-pressure loads on the turbine wheel resulting from such things as a valve closing or freezing of the water separator. During maximum reverse thrust load conditions, there should be no rubbing of the turbine, fan, or compressor wheel against the housing or mating parts.

f. Free moisture: The air cycle machine should be designed so that free moisture in the air entering the turbine does not cause nozzle erosion, does not build as ice in the exducer or enter the oil sump and cause loss of lubrication.

g. Noise: The air cycle machine and the cooling fan installation should be designed to minimize the noise level associated with high speed rotating equipment. This should include consideration of ramp noise from ram air inlet and ram air outlet, turbine discharge noise and radiated noise as installed in the aircraft.

4.2.3 Moisture Control

Two basic types of water separators are used in airplane air conditioning systems to remove free moisture from the cooling air supplied to the cabin. The first type is a low-pressure water separator, which removes free moisture downstream of the cooling turbine. The second type is a high-pressure water collector, which removes free moisture upstream of the cooling turbine.

Whereas the low-pressure water separator is limited by icing considerations to inlet temperatures of 32 °F (0 °C), and removal of only 80 to 90% of the total moisture, the high-pressure water collector permits delivery of air at temperatures and dew points well below freezing. The use of recirculated cabin air in conjunction sub-freezing turbine discharge temperatures is recommended to increase the delivery temperature of the air to avoid ice and snow buildup in downstream ducting and equipment.

In both types of water removal approaches, a moisture drain line should be provided which is of adequate size to assure no accumulation of water at the maximum moisture removal conditions. The drain line design should consider obstruction by debris or freezing of the removed moisture. Consideration should be given to using the removed moisture to cool the heat exchanger, thus increasing cooling capacity.

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Consideration should be given to installing drains in the downstream ducting to remove any residual moisture.

a. Low-pressure water separators: Low-pressure water separators consist of a coalescer section which agglomerates the finely dispersed water particles, a vortex section which imparts rotation to the air stream, and a collector/drain section which collects and drains the water droplets which have been centrifuged from the air stream.

   An integral bypass valve, which will allow passage of airflow around the coalescer section, should be incorporated if blockage of the normal flow path by dirt or ice is possible. The bypass valve should be so located and designed that its operation and function is not impaired by ice build-up. The bypass should be sized to pass sufficient flow to maintain required ventilation and pressurization.

   The coalescer should be positively retained and designed such that incorrect installation is unlikely. The water separator coalescer should not disintegrate in normal use and should be washable or cleanable. The water separator should be designed for quick and easy removal and replacement of the coalescer, preferably without disconnecting the water separator inlet or outlet.

b. High-pressure water collectors: High-pressure water collectors consist of a heat exchanger which condenses the free moisture in the high-pressure air upstream of the cooling turbine and a collector and drain section which collects and drains the water droplets; a vortex section may be required, depending on the installation and collector configuration.

   The heat exchanger may be a regenerative type using cooling turbine discharge air as the cold side fluid or may use other sources of cooling air or transport liquid as a heat sink.

   The collector and drain section may be integral with the heat exchanger high-pressure outlet header, or may be remotely located downstream.

   The heat exchanger surface should be maintained above water freezing temperature to prevent ice accretion. Surface cross-stream temperature gradients should be considered, particularly for single-pass cross-flow heat exchangers.

4.2.4 Valves and Controls

Airplane air conditioning systems include a wide variety of valves and their actuators and controls that govern pressure, temperature, and flow of bleed and ram air, as well as liquids that may form part of the loop. The valves may be actuated pneumatically, electrically, or hydraulically, and the controls may be pneumatic, electronic, or electro-pneumatic. Pneumatic actuators are powered by deep-convolution diaphragms or pistons. Electric actuators usually consist of servo motors coupled with a gear train.

Several different valve configurations are used (e.g., poppet, gate, plug, louver, and butterfly) depending on the desired flow, pressure drop characteristics, and leakage requirements. The butterfly is the most commonly used valve where a relatively high flow with low pressure drop is needed.

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4.2.4.1 General Valve Design

The following general valve design guidelines apply to all types of valves:

a. All valves should have an external position indicator visible in the installed position, except that check valves and pneumatic valves without actuator springs do not require external position indication.

b. All valves except insert-type check valves without flow bodies should have a flow direction arrow visible in the installed position.

c. All valves except insert-type check valves should be designed such that no part of the valve (butterfly disc, poppet, or flapper) projects beyond the end of the valve body, regardless of whether the valve is closed or open.

d. Valves should incorporate external manual override and locking features if appropriate to permit inoperative dispatch; these features should not require the use of special tools.

e. The requirement for filters in the servo section of pneumatically actuated valves should be avoided where possible. Where necessary, filters other than mainstream filters should be used. Filters should be readily removable without removing the valve; and filters should not require scheduled maintenance. In severe environments, self-cleaning filters should be considered.

f. Aerodynamic forces or vibration environment should not affect the performance of the valve within the specified operating range.

g. All valve switches should be hermetically sealed if operation could cause an explosion hazard and, as a minimum, be environmentally resistant. Switch replacement should require only minimal disassembly of the valve.

h. Valves should be designed to prevent accumulation of water at the valve or be located such that water does not accumulate in the valve.

i. Valves should meet the test requirements of ARP986.

4.2.4.2 Flow and Pressure-Regulating Valves

Airplane air conditioning systems utilize a valve upstream of each air conditioning pack to control the bleed airflow or pressure supplied to the pack. The pack valve is typically a pneumatically controlled and actuated butterfly valve with a solenoid-actuated override shutoff function. The valve may be a downstream pressure regulator or a flow control. In some environmental control systems, the pack flow or pressure regulator valve is part of ATA 36-10 (PNEUMATIC-Distribution); more commonly, it is part of ATA 21-10 (AIR CONDITIONING-Compression).

The quantity of APU or engine bleed flow to each air conditioning pack should be controlled by the pack valve. The flow control or pressure-regulating schedule should satisfy cooling, heating, pressurization, and fresh air ventilation requirements. Bleed airflow in excess of that necessary to meet these requirements should be held to a minimum. Dual range or continuously variable flow controls can be used to minimize bleed flow and yet meet single pack flow schedule criteria.

Provisions should be made to shut off bleed flow to each air conditioning pack. The shutoff valve may incorporate a solenoid to enable actuation of the valve to the fully closed position in response to an electrical signal. The maximum time required to close the valve from any degree of opening, including the full open position, should be 2 seconds. The shutoff provisions may be part of the pack (flow control or pressure regulating) valve assembly.

4.2.4.3 Temperature-Control Valves

Add-heat modulating valves are used in airplane air conditioning systems to control the pack discharge temperature, prevent icing within the system, and provide warming trim air for individual multi-zone systems. These functions are accomplished by mixing bleed air and refrigerated air in response to a sensed mixed air temperature. Butterfly valves are most commonly used as add-heat valves; both electric-motor actuators and pneumatic actuators are commonly used to drive these valves.

Failure modes of add-heat temperature control valves should be considered. If the valve does not fail in the closed position, the resulting temperature should not propagate subsequent failures or cause an unsafe condition.

The valve should fully close in response to an electrical signal. The maximum time required to close the valve from any degree of opening, including the full open position, should be considered in the system design.

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4.2.4.4 Check Valves

Check valves are utilized in airplane air conditioning system bleed and ram air duct systems to prevent reverse flow under certain normal operating modes and, under failure conditions such as a burst duct, to prevent loss of cabin pressurization. The most common type of check valve used is the flapper-type, lightly spring-loaded to the closed position; poppet-type check valves are also used. The following general guidelines are provided for check valves:

a. Care should be exercised in locating flapper-type check valves in the duct system to minimize the effects of pressure and flow distribution that may cause unstable flapper operation. If possible, the check valve should be located at least ten diameters downstream of a control valve, a sharp bend, or a mixing tee.

b. Check valves should be designed to minimize wear resulting from flapper flutter, impact against the valve seat or stop, and vibration.

c. Check valves should be designed to withstand the pneumatic and aerodynamic forces that occur when the check valve closes and stops a high-velocity stream of air, for both normal and failure conditions.

d. Check valves should be designed so that they cannot be installed backwards in the duct system.

e. Check valves can be orientation sensitive and should be installed in a manner that allows the flappers or poppet to function properly. It is recommended that gravity be used to set a default flapper position; this helps avoid impact to the check valve when the system is pressurized.

f. Specialized check valve designs are used for sub-freezing moisture-laden air so that ice does not accumulate and cause the valve to freeze in position. This type of valve is often used as a bulkhead check valve for chilled-recirculated air conditioning systems.

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4.2.5 Sensors and Controls

Temperature control systems are used to modulate the quantity and temperature of the ventilating air entering an airplane cabin. The temperature control system accepts information from the appropriate temperature sensors and translates it to valve command signals. Each temperature sensor should be a temperature sensitive device so located that, when air is circulated over it, either an electrical signal or pressure signal is generated. The sensor should not be affected or damaged by ice particles, aerodynamic forces, or vibration. Thermistor type sensors should be used in a manner to preclude adverse self-heating conditions. The operating characteristics of the sensor should not change over its specified operating life. Pneumatic and electrical temperature sensor and control design considerations and criteria are discussed in detail in ARP89.

Consider the example of the temperature control scheme shown in the accompanying Figure 3. Air extracted downstream of the primary heat exchanger or precooler is usually controlled at 350 to 400 °F (176 to 204 °C), and is used as the source of warm air. The cabin temperature control valve modulates the quantity of the warm manifold air that mixes with the refrigerated air supply emanating from the air cycle machine (ACM) turbine or vapor cycle evaporator. The cabin temperature sensor provides feedback to the cabin temperature controller, which signals the cabin temperature control valve to modulate. The duct high-temperature limit sensor provides an override signal to the controller to limit the opening of the cabin temperature control valve to prevent the supply air temperature from exceeding a predetermined amount. A value of 160 °F (71 °C) is typically used. The controller minimizes the overshoot of the cabin temperature control by comparing the selected cabin temperature, the actual cabin temperature, and the duct supply temperature. An algorithm is incorporated into the controller to readjust the output gain of the controller, which establishes the rate of movement of the temperature control valve.

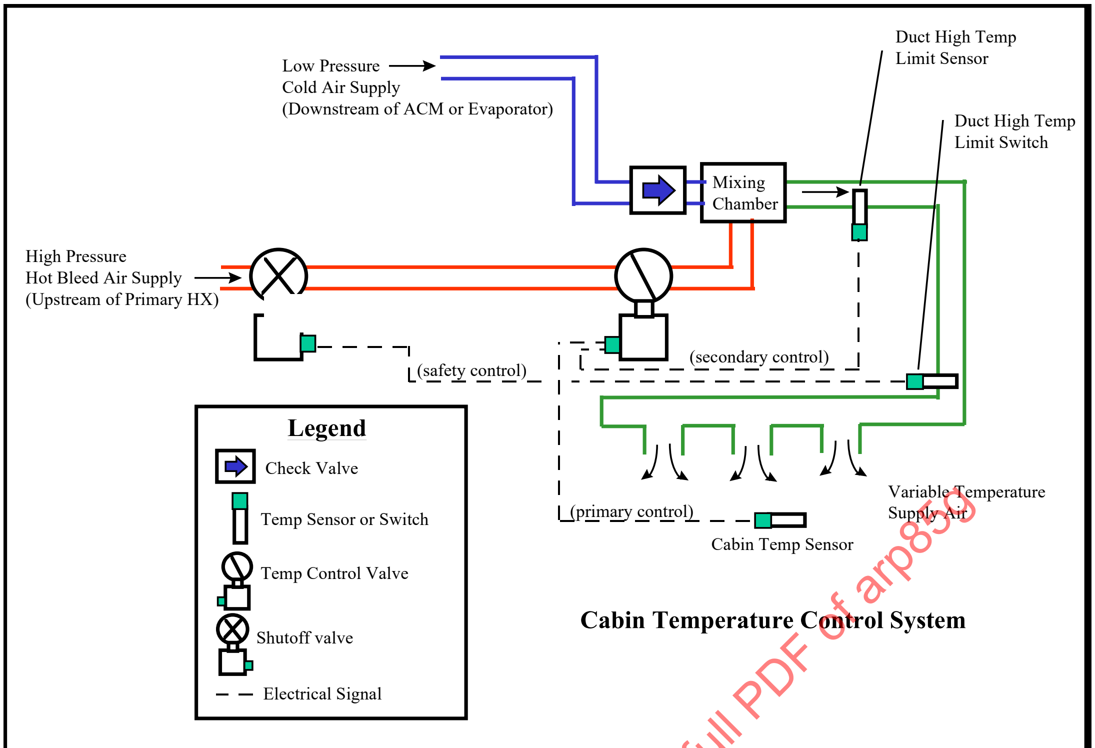

Figure 3 - Example of a temperature control system

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A duct high-temperature limit switch is incorporated to close the shutoff valve and secure the bleed air supply in the event of a failure of the temperature control valve. A value of 190 to 220 °F (88 to 104 °C) is typically used. In normal operation, the cabin temperature control valve will modulate accordingly to provide the desired temperature to the cabin, as directed by the cabin temperature selector. Cabin temperature selectors provide the ability to control the cabin zone(s) usually within a range of 65 to 85 °F (18 to 29 °C).

4.2.5.1 Zone Control

Multiple temperature control circuits are required when the heat loads of the airplane do not increase or decrease uniformly throughout the pressurized areas. A single temperature control circuit will suffice with small military airplanes with one, two, or even up to four crewmembers, provided that the electronic heat loads dissipated into the cockpit and the overhead canopy area is approximately the same at all crewmember stations. However, in business jet and transport-type airplanes where the flight deck is partitioned from the remaining passenger area (cabin), multiple zones may be required to prevent temperature gradients from one zone to another. The flight deck requires a dedicated temperature control circuit, in part due to the large solar loads associated with the front windscreen. The remaining pressurized cabin will require at least one dedicated control circuit. Since the fuselage is basically a constant cross section aft of the flight deck, aerodynamic heat flux is constant. If the metabolic, electronic, and solar heat fluxes of this area are also constant, then only one control circuit is required. Depending on the placement of the internal electronic heat loads, the existence of partitions, and the location of the side windows, additional zones may be required. It is most common for the cabin of a transport aircraft to incorporate at least two zones. Exceptions may be taken providing that the requirements of 14 CFR 25.831(f) are maintained.

4.2.5.2 Cabin Temperature Controller

The cabin temperature controller, along with the selector panel, should accommodate both automatic and manual mode of operation.

In the automatic mode, the temperature selector sets the desired cabin temperature, and the controller will modulate the temperature control valve to maintain the selected temperature, usually within 1 °F (±0.5 °C). When maximum heating is demanded, the duct temperature sensor should signal the controller to prevent the temperature control valve from opening too far, thus avoiding potential crew injury or damage to ducting.

While in the manual mode, the temperature selector directly controls the position of the temperature control valve. The lowest temperature position will correspond to a fully closed temperature control valve, while the highest temperature position will correspond to a fully open temperature control valve. The duct temperature sensor is not active during manual mode, so the duct temperature high limit switch will shut the cabin temperature control valve in the event of an over temperature condition.

4.2.5.3 Temperature Control Valves

The temperature control valves and ducting should be sized at operation during the lowest available bleed air temperatures and pressures, which normally occurs with engines at idle power. Sufficient capacity must exist to provide enough warm air to heat the cabin during the coldest operating environment. In addition, the components must permit sufficient warm air flow during cold soak conditions during transient heating (pull up).

4.2.6 Humidifiers

Control of cabin humidity is discussed in 3.2.4. Refer to AIR1609 for specific recommendations on humidifiers.

4.2.7 Fans and Ejectors

Fans and/or ejectors are used in airplane air conditioning systems for one or more of the following functions:

a. Provide cooling airflow for the heat exchanger of a bootstrap air cycle air conditioning system.

b. Provide cooling airflow for the condenser of a vapor cycle air conditioning system.

c. Provide cabin recirculation airflow for air cycle or vapor cycle air conditioning systems.

d. Provide cooling airflow for equipment cooling.

e. Provide airflow over compartment temperature sensors for proper response.

Fans are usually electrically driven from the airplane's AC or DC power supply. Hydraulically and pneumatically driven fans are also used. Fans should use permanently lubricated bearings and additional lubrication should not be required except at overhaul. A screen or inherent design configuration should prevent injury to personnel and protect the fan from foreign object damage.

Air-to-air ejectors are sometimes used where the penalties of its noise and low efficiency can be favorably traded against the weight, cost, and complexity of a fan. Air-to-water ejectors (aspirators) are commonly used to spray the water drained from a low-pressure water separator into the cooling air side of the air conditioning pack heat exchanger.

4.2.8 Ground Cart Connections

For ground operation, a conditioned air ground cart may be used in lieu of operating the aircraft air conditioning system. To enable the use of a conditioned air ground cart, a tapoff is provided on the conditioned air supply duct leading to the cabin. The tapoff terminates at a point on the aircraft that is easily accessed from the ground. It is recommended to use a standard connection per MS33562 that is compatible with most ground carts.

4.2.9 Vapor Cycle Components

Component design recommendations for vapor cycle refrigerant compressors, evaporators, condensers, and controls are covered in ARP731.

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4.3 Component Equipment Installation

Accessibility of the installation should be optimized to enable:

a. Individual component identities to be seen.

b. Component changes to be made without disturbance of adjacent parts.

c. Operating functions to be checked in place.

d. Equipment servicing actions to be accomplished.

Equipment and structure in the vicinity of ducts handling air at high temperatures or pressures should either be protected by barriers or other means or be inherently capable of withstanding the air blast and heat that may be released by a complete duct rupture or connector failure for the time required to detect the failure and complete corrective action.

In locations where there is a possibility of contamination of equipment by fluid mist (e.g., hydraulic, fuel, or toilet waste) protection should be provided.

Positive means to prevent component reverse installation is recommended; e.g., check valves, flow control valves to be polarized with different end connections, or with mounting brackets that prevent reverse installation.

Valves should be permanently marked to show direction of flow, if flow direction affects performance. Ducting adjacent to the valve should be permanently marked showing the direction of flow.

Stringent design control should be exercised to avoid the use of left- and right-handed components or subassemblies.

Protective devices should be provided with integral means of checking their serviceability by plug-in test equipment without requiring disturbance from their operating positions, e.g., warm-up circuits for overheat sensors.

The noise levels of continuous and intermittently operating equipment should be below annoyance levels within passenger compartments; see 3.2.5.

5. SYSTEM ARCHITECTURE CONSIDERATIONS:

Designs and features, which can be used to minimize bleed and ram air penalties and optimize performance for specific applications, are considered in this section.

5.1 Candidate Systems

Typical air conditioning systems for airplanes include vapor cycle systems, conventional air cycle systems, and integral recirculation air cycle systems.

Typical vapor cycle system configurations are shown schematically in Figures 4A and 4B. Vapor cycle systems provide cabin cooling using fresh air and/or recirculated cabin air refrigerated to about 50 °F (10 °C) in the refrigerant evaporator. The major vapor cycle components include the compressor, condenser, evaporator, expansion valve, and fans for the condenser ambient air heat sink supply and evaporator fresh/recirculated air supplies. Two or more stages of compression may be required to provide the required temperature lift between the evaporator and condenser phase change temperatures. In systems requiring two-stage compressors, an economizer can be used to conserve power at off-design conditions; the reduction in power consumption is realized by subcooling the evaporator inlet refrigerant. The economizer also allows the specific speeds of the compressor stages to be matched. The refrigerant compressor and air supply fans are typically electric motor driven, but may also be driven by geared shafts, hydraulic motors, or air motors. Compartment supply air moisture condensed in the evaporator is normally drained overboard. A separate means is required to provide compartment heating; engine bleed air, electric heaters (AIR860), exhaust gas heaters (ARP86), or internal combustion heaters (AS8040) can be used for this purpose.

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Air cycle systems cool the compressed fresh air supply with heat exchanger(s) using ambient air as the heat sink, and refrigerate this air supply with an expansion turbine (air cycle machine); the turbine power is absorbed by an ambient air fan and/or a supply air compressor. These air cycle machine (ACM) configurations include simple cycle (turbine-fan), bootstrap (turbine-compressor) and three-wheel (turbine-compressor-fan); shown schematically in Figures 5A, 5B, and 5C.

The simple cycle was the first air cycle system developed and operated at high pressures obtained by bleeding the final compression stage of the aircraft jet engines. The simple cycle was used for early turbojet fighter aircraft and helicopters where high bleed pressures at relatively low flows are available. The simple cycle has the advantage of providing the heat exchanger ambient airflow during ground operation, hover, or low-speed flight where ram airflow is insufficient.

The bootstrap cycle provides a significant increase in cycle efficiency over the simple cycle system at the expense of additional system complexity. It does this by providing an additional stage of compression of the bleed air supply by replacing the ACM fan with a compressor rotor. This increases the inlet pressure at the cooling turbine resulting in increased turbine power. However, this necessitates an additional heat exchanger (intercooler) to remove the added heat of compression, and a separate fan or ejector to provide heat exchanger cooling air during ground operation and possibly during low-speed flight conditions.

The three-wheel or simple/bootstrap cycle combines the simplicity of the simple cycle with the performance advantage of the bootstrap cycle by incorporating both the simple cycle fan and the bootstrap compressor on the same shaft as the cooling turbine (three-wheel air cycle machine). The simple cycle fan precludes the need for a separate fan or ejector, and the bootstrap compressor enhances cycle efficiency. Bootstrap cycle efficiency is approached since most of the turbine power (~85%) is absorbed by the compressor while the heat exchanger cooling airflow requirement is satisfied by the fan, using the remaining turbine power.

The air cycle system cabin supply air temperature is controlled by mixing hot bleed air with the refrigerated air to satisfy the full range of heating and cooling requirements.

Air cycle systems include low-pressure water separators (see Figure 6A) or high-pressure water separators to remove the free moisture condensed during the refrigeration cycle; shown schematically in Figures 6B and 6C.

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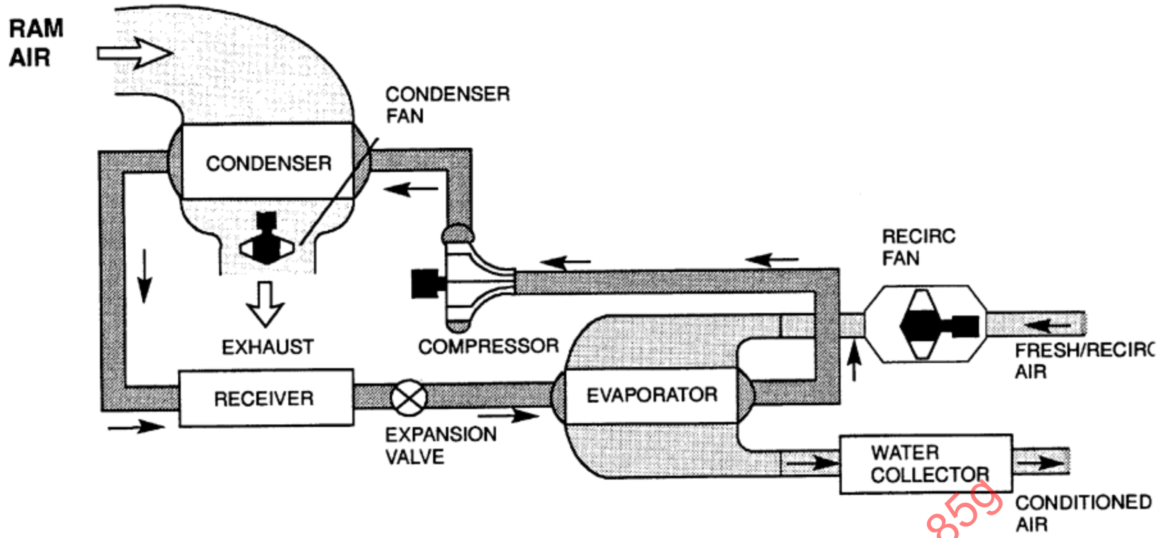

Figure 4A - Basic vapor cycle

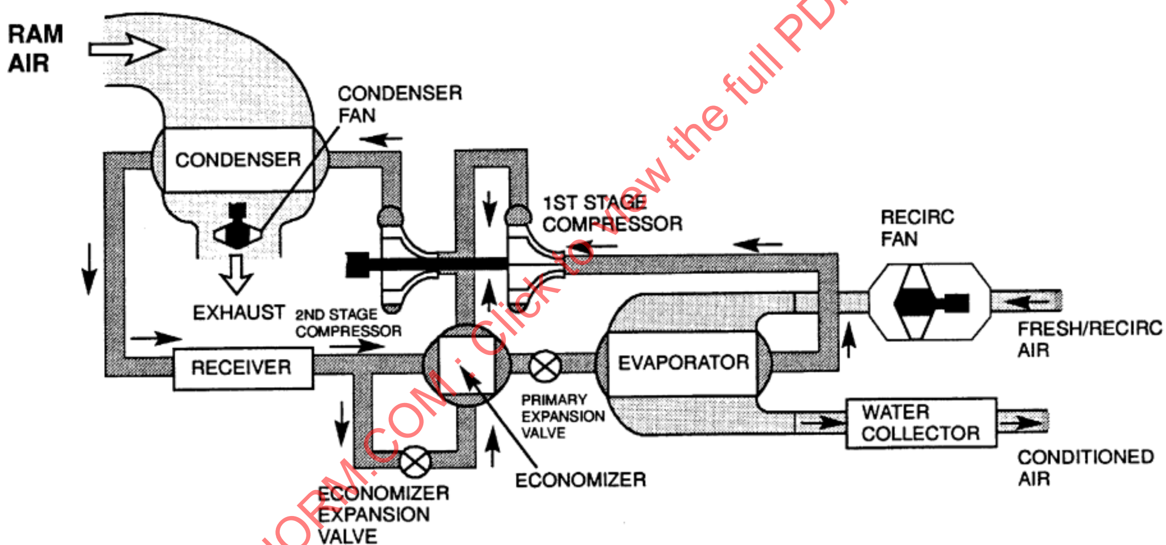

Figure 4B - Enhanced vapor cycle (two-stage compressor and economizer)

Figure 4 - Examples of vapor cycle

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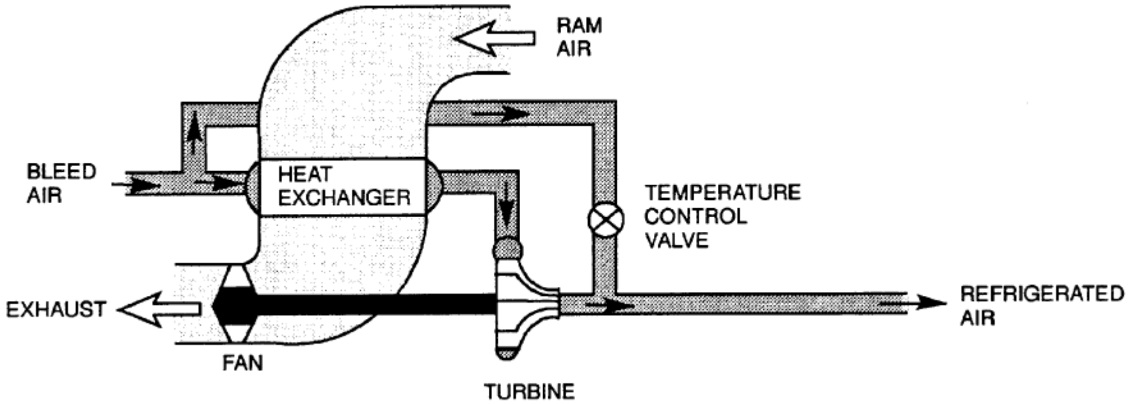

Figure 5A - Simple cycle (turbine fan)

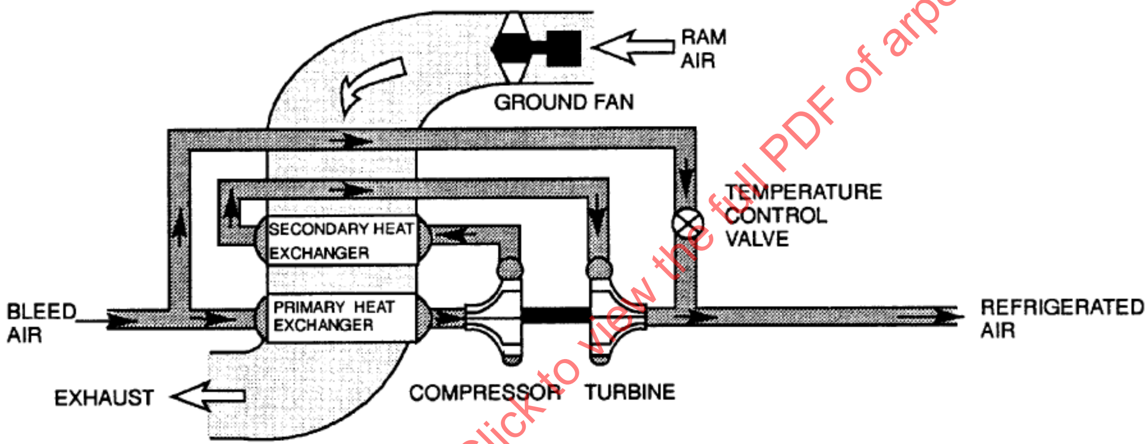

Figure 5B - Bootstrap cycle (turbine compressor)

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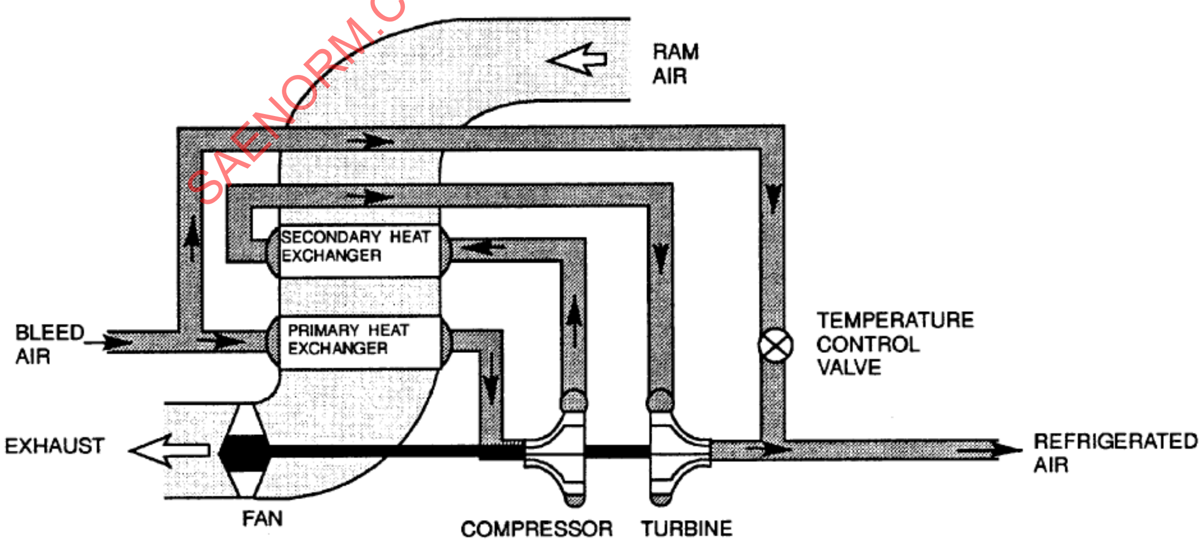

Figure 5C - Simple/bootstrap cycle (three-wheel ACM)

Figure 5 - ACM cycle examples

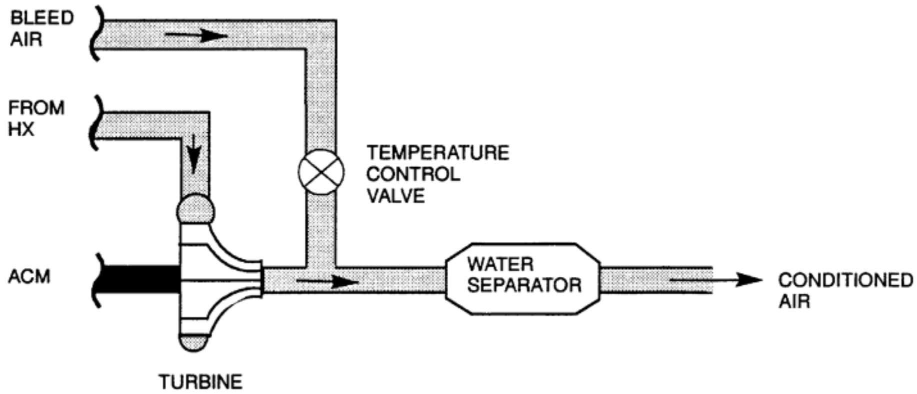

Figure 6A - Low-pressure water separator

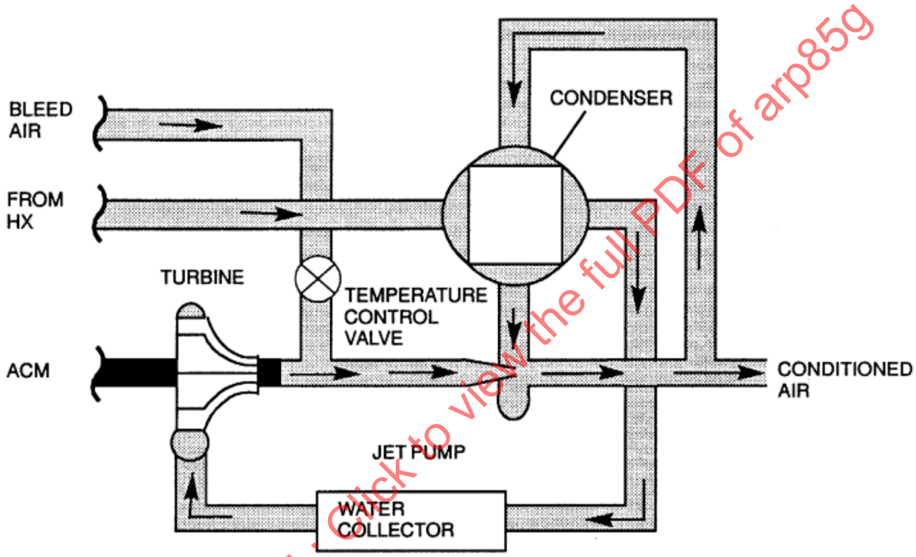

Figure 6B - High-pressure water separation (partial flow)

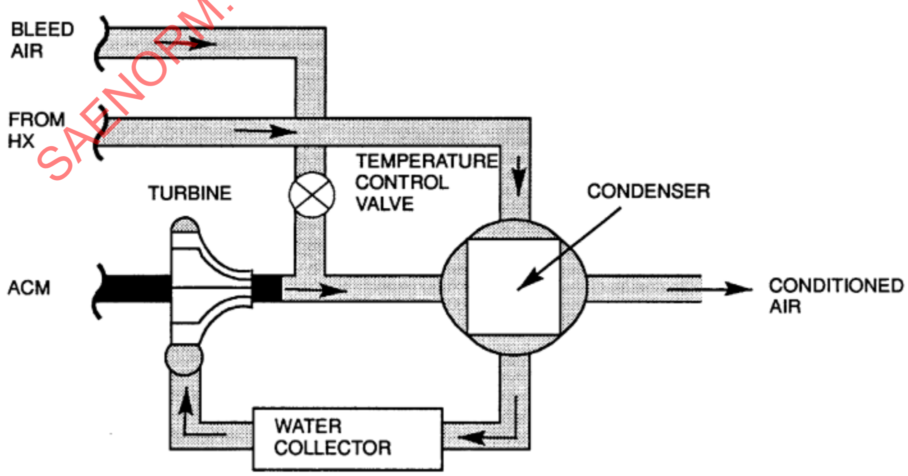

Figure 6C - High-pressure water separation

Figure 6 - Examples of water separators

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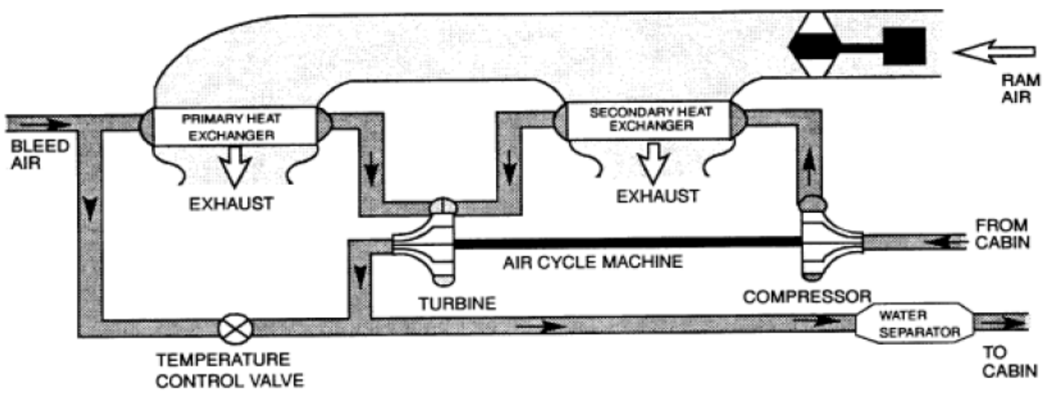

Figure 7A - Compressor recirculation (shoestring) cycle

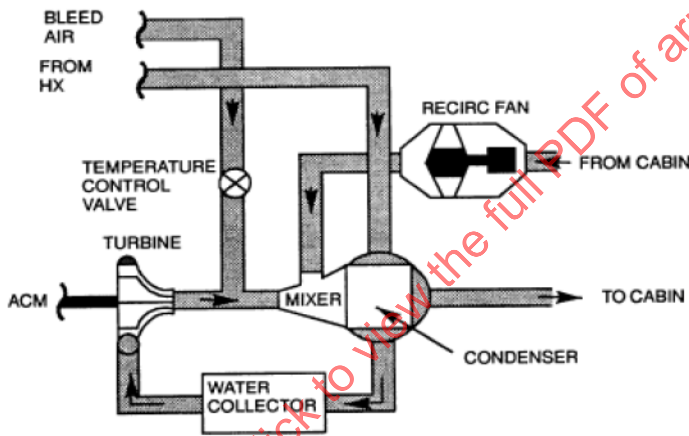

Figure 7B - Chilled recirculation cycle (upstream recirc)

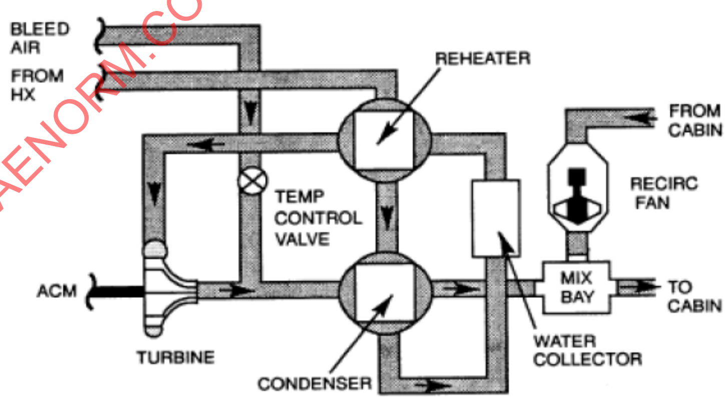

Figure 7C - Chilled recirculation cycle (downstream recirc)

Figure 7 - Integrated recirculation ACM

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