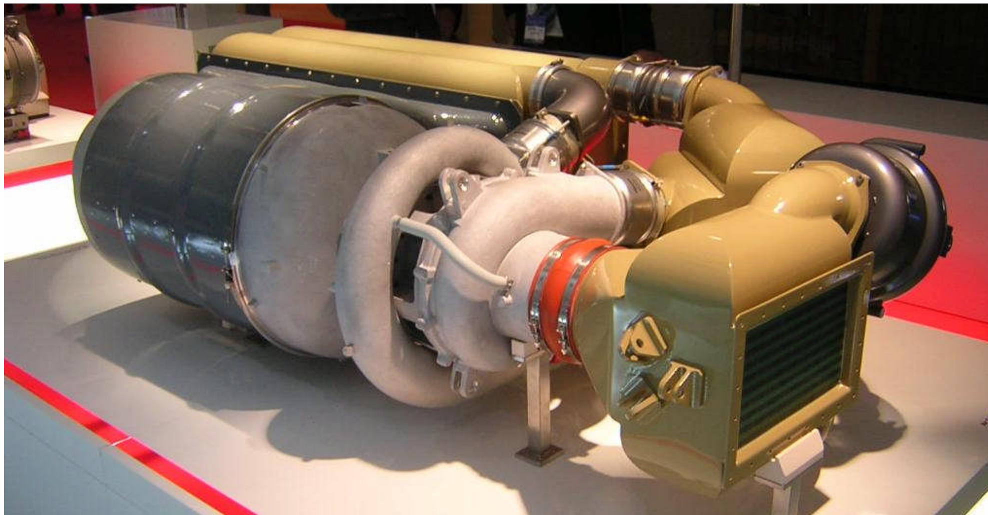
Aircraft Environmental Control Systems
A Presentation of Current Systems and New Developments




Carleton University AERO 4003 Lecture – November 9th, 2010
Omer Majeed, P.Eng.

Outline

Today's lecture is an introduction to aircraft Environmental Control Systems (ECS). The objective is to present a top level view of the systems, from regulatory requirements to the architecture and function of the individual systems. Some requirements and components will be addressed in more detail as examples.

- Summary of my education and career
- ECS definition and main applicable regulations
- Role of safety analysis in system design
- Bleed Air (Pneumatic) System functions and architecture
- Bleed Leak Detection System function
- Air Conditioning System functions and architecture
- Cabin Pressurization Control System functions and architecture
- New technology developments in ECS: Boeing 787 Dreamliner
- Questions?

Education & Career Summary

Education:

Bachelor of Aerospace Engineering, Carleton University, 1992. First graduating class.

Masters of Aerospace Engineering, Carleton University, 1995. Thesis topic was numerical modeling of transverse impact on composite coupons.

Transport Canada Commercial Pilot Licence and Multi-Engine Rating (2001).

Career:

Ingenia Communications (1995-1997).

National Research Council's Centre for Surface Transportation Technology (1997-1998).

Liebherr-Aerospace (1999-2008) as air systems engineer in Toronto (GX, Q400), Wichita (CL300) and Toulouse (A380).

Founded Specific Range Solutions Ltd. (2008) specializing in flight optimization solutions, as well as air systems analysis and design (www.srs.aero).

Professional Affiliations:

Member of PEO since November 10th, 2000.

Past member of AIAA (Wichita) and RAeS (Toulouse).

Current member of executive of CASI Ottawa Branch.

ECS Definition and Regulations

Environmental Control Systems control the temperature, pressure and air flow into the aircraft pressure vessel which includes the cockpit (flight deck), cabin and interior compartments. Safety monitoring is also performed e.g. cabin altitude (ZC), cabin ΔP.

On transport-category aircraft, ECS comprises various systems performing the following functions: bleed air supply, bleed leak detection, air conditioning, distribution, avionics cooling, cabin pressurization control, oxygen supply. The trend today is towards increasing integration of all air systems, including wing anti-ice/de-ice functions via a common controller architecture. Two system control modes are typically provided on modern aircraft systems: automatic (1 active + 1 stand-by) and manual (back-up).

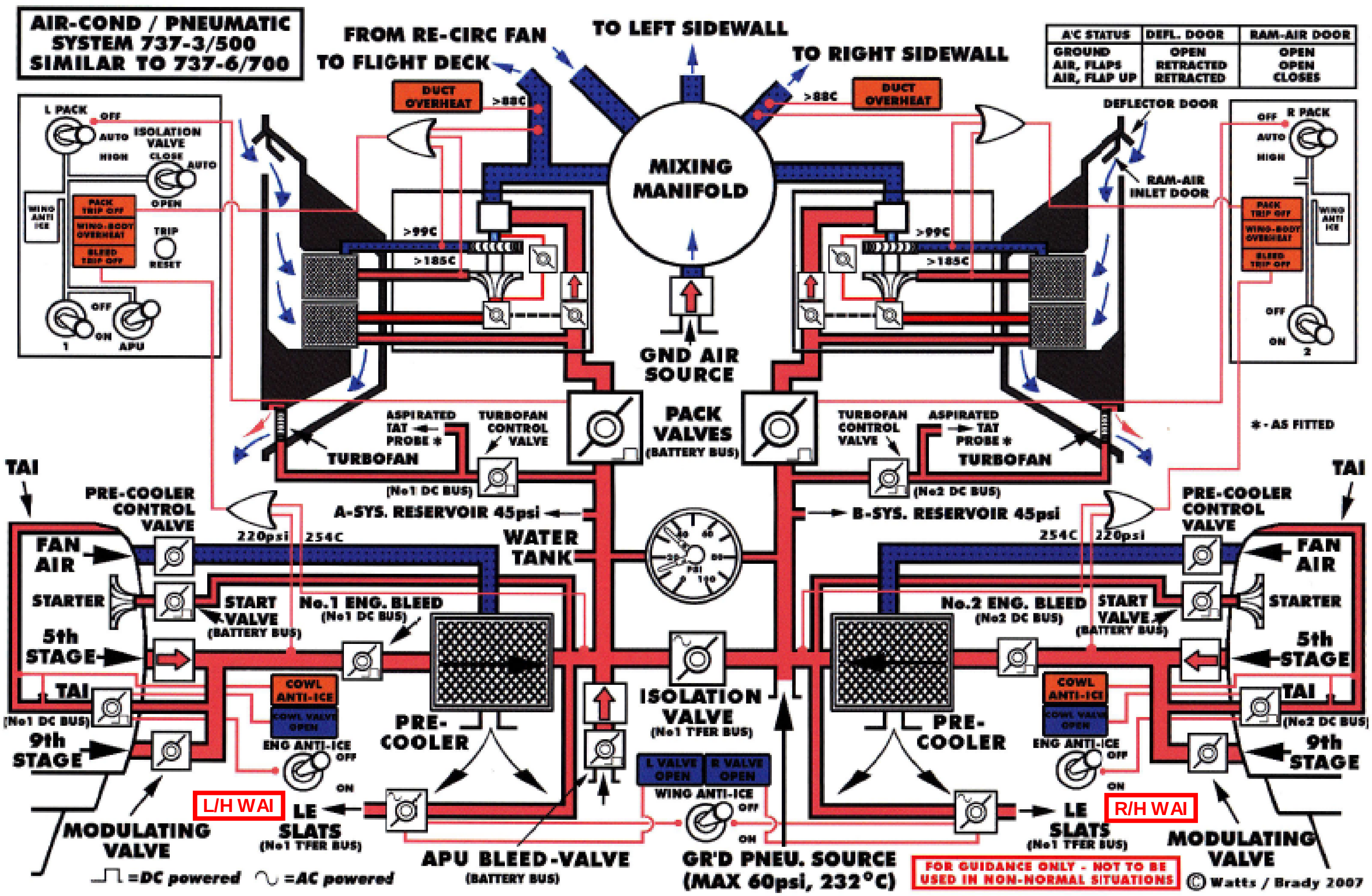
Some of the main applicable regulations for ECS are per Transport Canada's Airworthiness Manual Chapter 525:

- 525.831 Ventilation
- 525.832 Cabin Ozone Concentration
- 525.841 Pressurised Cabins
- 525.1438 Pressurisation and Pneumatic Systems

All aircraft systems must perform their intended function under any foreseeable operating condition and permit safe continuation of the flight after any failure i.e. fail-safe concept.

- 525.1309 Equipment, Systems, and Installations

Boeing 737-300/500 ECS Schematic*



* The Boeing 737 Technical Guide, Chris Brady, Tech Pilot Services © 2006

System Safety Analysis / Functional Hazard Assessment

Hazard (Risk) = Severity * Probability

Severity (Failure Condition)	**Definition**	**FAA Reference**	**EASA Reference**
None	Normal operation	N/A	AMC 25.1309 (No Safety Effect)
Minor	Failure conditions which would not significantly reduce airplane safety, and which involve crew actions that are well within their capability.	AC 25.1309-1A	AMC 25.1309 (Minor)
Major (i)	Failure conditions which would reduce the capability of the airplane or crew to cope with the adverse operating conditions to the extent that there are significant reductions in safety margins or functional capabilities.	AC 25.1309-1A	AMC 25.1309 (Major)
Major (ii)	Failure conditions which would reduce the capability of the airplane or crew to cope with the adverse operating conditions to the extent that there are large reductions in safety margins or functional capabilities.	AC 25.1309-1A	AMC 25.1309 (Hazardous)
Catastrophic	Failure conditions which would prevent continued safe flight and landing.	AC 25.1309-1A	AMC 25.1309 (Catastrophic)

Probability (Failure Rate/Flight Hour)	**Definition**	**FAA Reference**	**EASA Reference**
None	Normal operation	N/A	AMC 25.1309 (No Safety Effect)
Probable	Failure > 10E-5	AC 25.1309-1A	AMC 25.1309 (Probable)
Improbable (i)	10E-5/FH > Failure > 10E-7/FH	AC 25.1309-1A	AMC 25.1309 (Remote)
Improbable (ii)	10E-7/FH > Failure > 10E-9/FH	AC 25.1309-1A	AMC 25.1309 (Extremely Remote)
Extremely Improbable	Failure < 10E-9	AC 25.1309-1A	AMC 25.1309 (Extremely Improbable)

Bleed Air System Functions

The Bleed Air System also known as the Pneumatic System supplies the air required by the downstream consumers while regulating the pressure and temperature of the air from the engines to values of 45 psig and 200ºC, respectively. The system also selects the engine port from which to bleed.

Bleed air is supplied by the engines or the Auxiliary Power Unit (APU). Air is drawn from the compressor stage, upstream of the combustor.

- Engine bleed is typically used in flight. At take-off and ISA conditions, representative values are 85 psig and 280ºC for an engine LP (Low Pressure) port and 200 psig and 420ºC for the HP (High Pressure) port. Bleed temperatures can exceed 540ºC.
- APU bleed is typically used on the ground and permitted in flight up to a certain altitude. On a cold day (-40ºC), APU supplies air at 60 psig and 160ºC on the ground. On a hot day (+40ºC), it supplies air at 40 psig and 240ºC.

Engine bleed reduces thrust and increased fuel burn (SFC), the impact is a function of supply port (LP/IP or HP) and mass flow. Use of LP/IP bleed is preferred because of reduced impact on fuel burn.

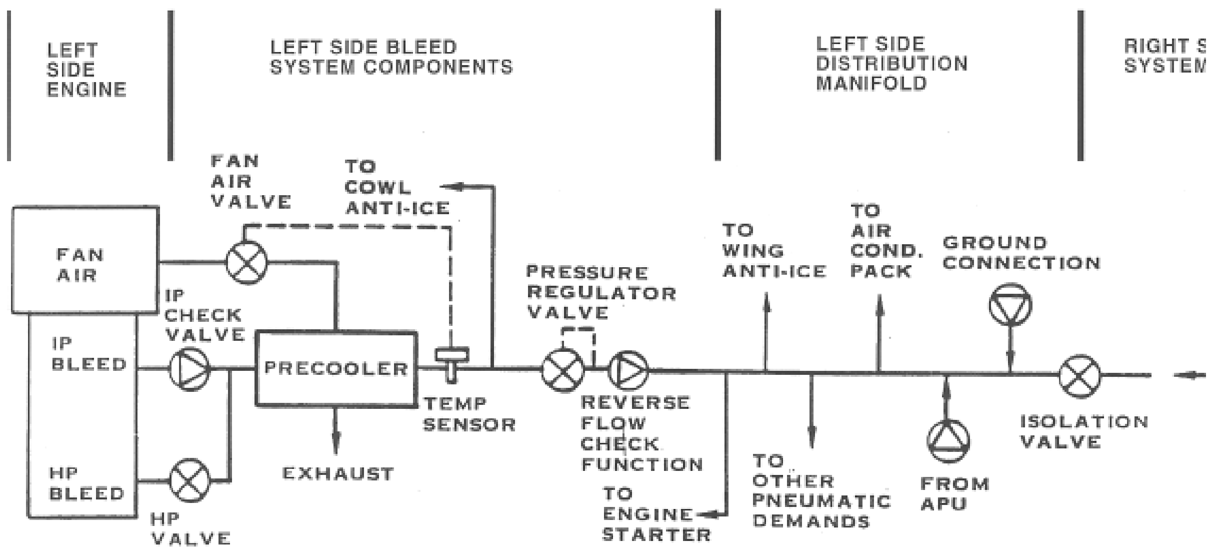
Minimum pack pressure is in the range of 15 to 20 psig which requires a minimum port pressure of 23 psig. If LP port pressure is lower than minimum value, then HP port is selected via High Pressure Valve (HPV). A check valve prevents reverse flow into LP port.

Bleed is extracted evenly from around the compressor to minimize downstream disturbance of the core flow.

Bleed Air System Functions and Architecture

Bleed pressure is controlled via a Pressure Regulating Valve (PRV) which typically includes reverse flow protection. Older systems feature pneumatic control via a downstream pressure tap, while more recent systems use electro-pneumatic control with reference to a downstream pressure sensor.

Bleed temperature is controlled via a Fan Air Valve (FAV) which modulates the fan (cold) air flow through the Precooler, an air-to-air heat exchanger. Legacy systems feature pneumatic control via a thermostat. Current system design uses electro-pneumatic control with reference to a downstream temperature sensor.



IP BLEED ~ INTERMEDIATE PRESSURE COMPRESSOR BLEED PORT
HP BLEED ~ HIGH PRESSURE COMPRESSOR BLEED PORT

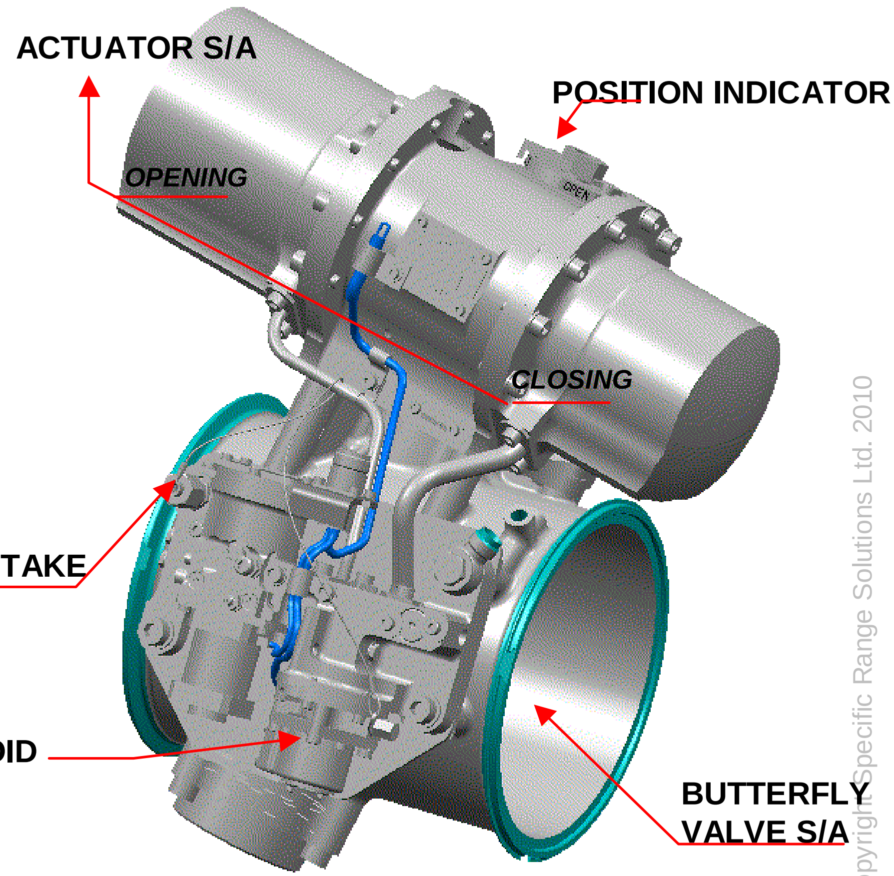
A380 Pressure Regulating Valve Functions and Design

DESCRIPTION:

6” diameter butterfly valve, pneumatically actuated, electrically controlled via solenoid & torque motor, commanded by the controller.

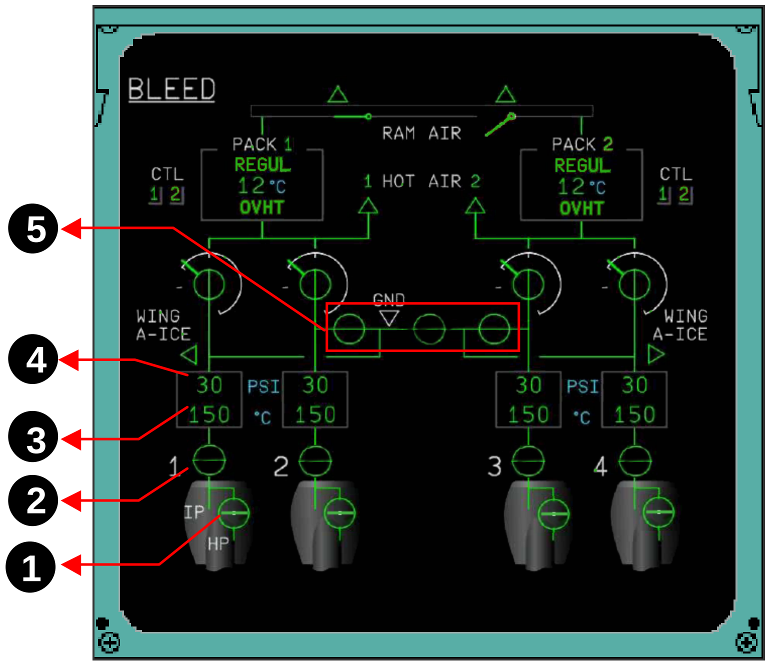
FUNCTIONS:

- To control pressure delivered to downstream users per system requirements.
- To balance the flow between adjacent Engine Bleed Air Systems when Cross Bleed Valves are open.
- To ensure shut-off function of the Engine Bleed Air System e.g. in case of fire.



KEY COMPONENT OF BLEED SYSTEM

A380 Bleed Air System Synoptic Page



1 HP VALVE POSITION

- Open
- Closed position disagree
- Closed
- Position Data not Available

2 PR VALVE POSITION

- Open
- Closed position disagree
- Closed
- Position Data not Available

3 Engine Bleed Temperature

- 30 Normal
- 110 300 Bleed Temperature Low / High
- XX Temperature data not available

4 Engine Bleed Pressure

- 40 Normal
- 110 300 Bleed Pressure Low / High
- XX Pressure data not available

5 Pneumatic Air Distribution System ATA36-12

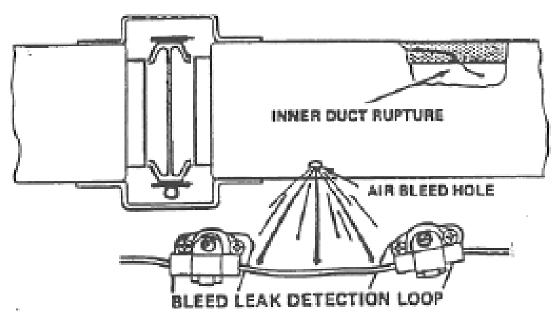
Bleed Leak Detection Function

A bleed air leak is a fire risk e.g. max. allowable surface temperature to avoid fuel auto-ignition is 204ºC per FAA AC 25.981-C. Bleed leak is also a risk to aluminum and especially composite primary structure. Leak detection required via thermal switches (zonal sensors) or via continuous elements which are routed along bleed ducts.

Continuous elements are preferred due to coverage, integrity monitoring and they function after being cut (post-PBIT). They allow for the location of the event along the circuit. Dual loops are used in critical areas for redundancy and to minimize false leak warnings.

Leak detection loops are 1/8" dia. coaxial wires (inner conductor and outer shell) separated by a high resistance eutectic salt calibrated to a specific melting temperature. When the loop is locally heated, the salt melts and a short results which changes the loop coaxial resistance. <u>Resulting voltage change = Leak detection</u>

Bleed leaks can also result in overpressure in compartments, so provision for blowout panels may also be required.



Air Conditioning System Functions

The Air Conditioning System (ACS) conditions the fresh air from the Bleed Air System and supplies it to the cockpit and cabin zones at the requested mass flow rate. Conditioning refers to the regulation of temperature and the removal of humidity. The system may have provision to recirculate a portion of the cabin air.

System requirements:

- Supply adequate fresh air i.e. sufficient oxygen and remove odours.
- Temperature control within a comfortable range in each cabin zone [15^{o}C - 35^{o}C].
- Supply air for cabin pressurization i.e. sufficient outlet pressure.

The standard dynamic sizing case is a "pull-down" or cabin cooling case on the ground on a hot day with APU bleed:

- 40^{o}C and 45% relative humidity (RH) at Sea Level.
- Interior temperature after heat soak is assumed to be 46^{o}C.
- The requirement is to pull-down the cockpit and cabin temperature to 24^{o}C in 30 min, with no passengers on board (minimum crew), and doors closed.
- 3^{o}C is the normal minimum allowed (duct) temperature supplied to occupied zones.

525.831(a) Ventilation (CAR)

Per Transport Canada's Airworthiness Manual Chapter 525:

525.831 (a)

(a) Under normal operating conditions and in the event of any probable failure conditions of any system which would adversely affect the ventilating air, the ventilation system must be designed to provide a sufficient amount of uncontaminated air to enable the crew-members to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort. For normal operating conditions, the ventilation system must be designed to provide each occupant with an airflow containing at least 0.55 pounds of fresh air per minute.

This is equivalent to 7.5 cfm at cabin altitude (ZC) of 0 ft and 10 cfm at ZC = 8,000 ft.

Cockpit flow is proportionately higher per occupant due to additional heat loads (avionics, displays, solar through windshield).

Compartment	**Challenger (19 pax)**	**CRJ100/200 (50 pax)**	**CRJ700 (70 pax)**
Flow to cockpit (%)	47	21	15
Flow to cabin (%)	53	79	85

For the Bombardier Challenger 605 which is certified for 19 passengers and a crew of 3, the required normal airflow is 19.7 lb/min.

525.832 Cabin Ozone Concentration (CAR)

Per Transport Canada's Airworthiness Manual Chapter 525:

525.832 Cabin Ozone Concentration

(a) The aeroplane cabin ozone concentration during flight must be shown not to exceed:

(1) 0.25 parts per million by volume, sea level equivalent, at any time above flight level 320; and

(2) 0.1 parts per million by volume, sea level equivalent, time-weighted average during any 3-hour interval above flight level 270.

(b) For the purpose of this section, "sea level equivalent" refers to conditions of 25°C and 760 millimetres of mercury pressure.

(c) Compliance with this section must be shown by analysis or tests based on aeroplane operational procedures and performance limitation, that demonstrate that either:

(1) The aeroplane cannot be operated at an altitude which would result in cabin ozone concentrations exceeding the limits prescribed by paragraph (a) of this section; or

(2) The aeroplane ventilation system, including any ozone control equipment, will maintain cabin ozone concentrations at or below the limits prescribed by paragraph (a) of this section.

Why is there a regulation specifically for ozone? O_3 can cause dryness of nose and throat, and itching of eyes. Long-range transports often install ozone converters (O_3 -> O_2)

ACS Steady-State Performance Requirements

Steady-state performance requirements are based on the sum of the various heat loads.
List of heat loads:

- Sensible heat emission by occupants Q_{sens} is heat emitted by a person through convection and radiation and is dependent on compartment temperature and activity level. For a person at rest in 24ºC surroundings = 73 W.
- Latent heat emission by occupants Q_{lat} is due to evaporated moisture (perspiration). Even if air is fully recirculated and Q_{lat} does not enter into heat load, it influences relative humidity of the compartment. With recirculation, some of the moisture condenses in the cooling system and is part of the heat load. For a person at rest in 24ºC surroundings = 41 W.
- Internal electrical loads Q_e is the heat generated by avionics, lights, galley equipment, etc. These loads can be quite high; for example in the CRJ700 they are approximately 3 kW. Reduction is possible if cooling air is ducted around the equipment and is discharged overboard.
- Solar heat load Q_{sol} is transmitted through the windshield and windows.
- Conductive heat load Q_c is due to heat transfer from outside the aircraft to the inside, by conduction and convection through structure, insulation, and airspaces.

Total heat load for a CRJ700 in pull-down would be 26.3 kW.

ACS Steady-State Performance Requirements & Pack Design

Per the following equation, the system must remove or supply the required thermal power:

$$\mathbf{Q = W * C_{p\_air} * (T_c - T_s)}$$

W = Mass flow in kg/s

$C_{p\_dry\_air}$ = 1.005 kW/[kg/s – K]

T_c = Cockpit/cabin target temperature in ^oC

T_s = Supply temperature in ^oC

Air Conditioning Unit / Cooling Pack Design:

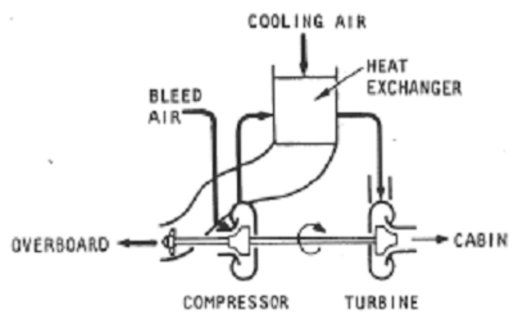
ACU's are based on vapour cycle or air cycle. Early transport aircraft used vapour cycle which absorbs heat using a refrigerant. It is still used in some GA and business aircraft, as well as helicopters. Also used in galley chillers and for military avionics cooling.

Today all large transport aircraft use air cycle architecture where bleed air is expanded (cooled), pumped into the cabin and then dumped overboard.

Advantages of air cycle systems are the refrigerant (air) is free, the compressor is already part of the engine and APU though there is an SFC impact, air is directly used for cooling or heating therefore no evaporator required, efficient heat transfer, minor leakage is not a problem and mechanically simple system. Therefore, lighter system weight, safer and more reliable.

Air Conditioning System Pack Design

There are three main types of air cycle machines: simple cycle (fan + turbine), two wheel bootstrap (compressor + turbine) and three wheel bootstrap (fan + compressor + turbine), the latter is the current industry standard.



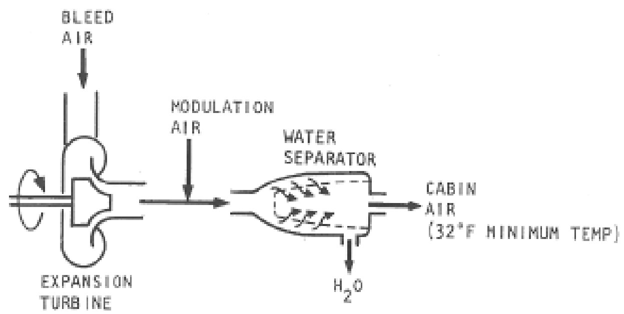
Three-Wheel Bootstrap Cycle

Three Wheel "Bootstrap" Cooling Pack (ACU):

Bleed air from the APU (unprecooled) or from the engines (precooled) is boosted in pressure and temperature by the compressor. This increases the efficiency of the heat exchange though the pack heat exchanger (HX). On the ground, the fan draws ram air to cool the bleed air while in flight, ram air does the pack cooling. The bleed air then passes through the turbine where it is expanded and flows into the cabin. The work extracted by the turbine drives the shaft and thus the compressor and fan.

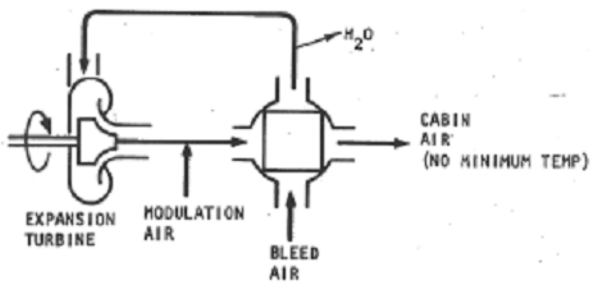
Air Conditioning System Pack Design

There is a need to extract water from the ACU to prevent condensation in the cabin (fog and water droplets) and in the case of a high-performance pack, icing at the turbine outlet. There are two means to extract water: low-pressure separation and high-pressure separation. This effectively reduces the humidity in the cabin.



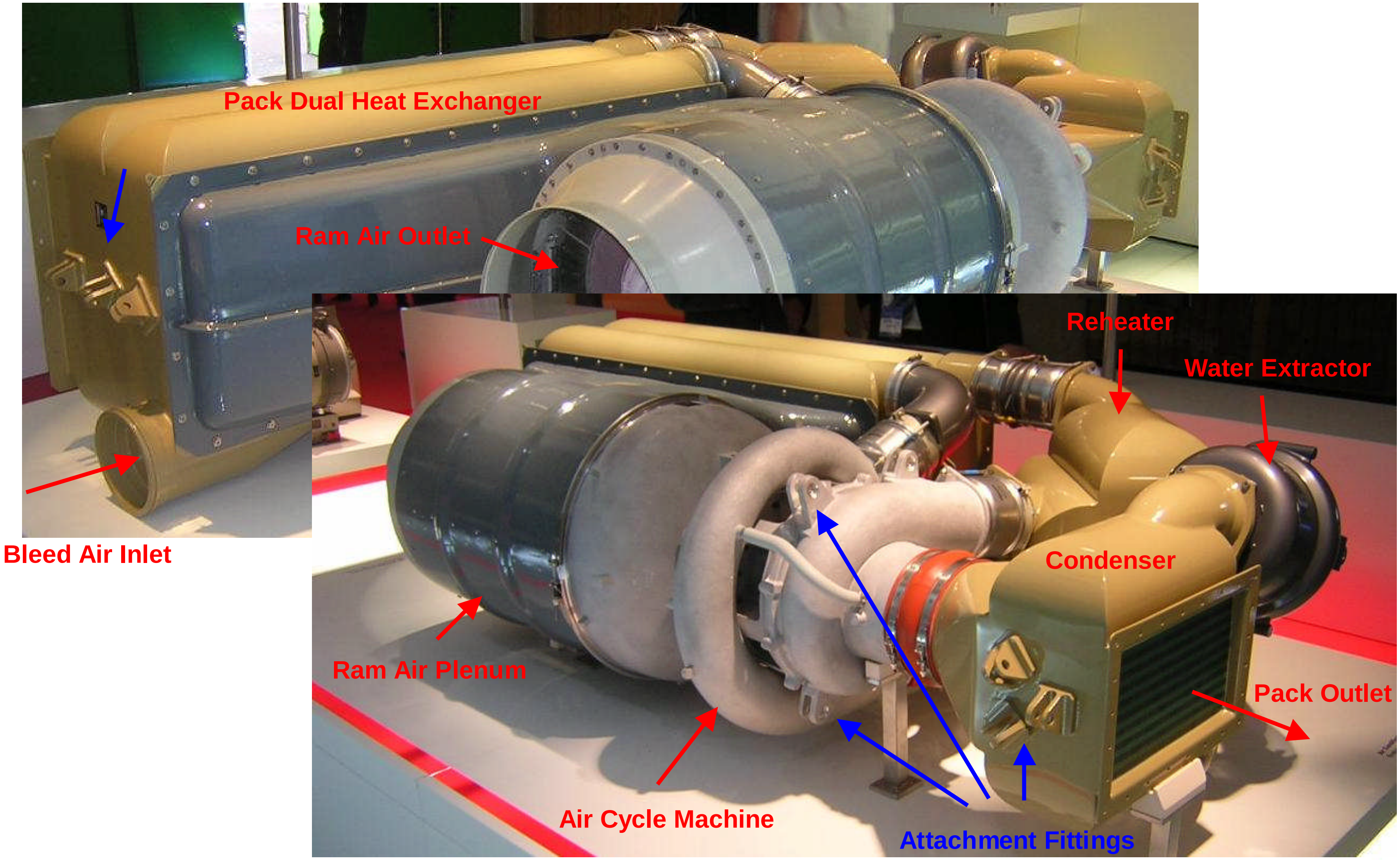
<u>Low pressure separation</u> is a simple system located downstream of the turbine outlet:

- Consists of a shell, fabric coalescer, baffles and a drain port
- Low weight and initial cost
- Disadvantages: coalescer must be periodically cleaned or replaced, and this system cannot be operated at temperatures below freezing.



<u>High pressure separation</u> requires a condenser HEX in the turbine discharge duct to cabin. The air from turbine cools the bleed air (at high-pressure and temperature) and this enables much of the bleed air moisture to condense. The droplets are extracted via swirling motion imparted to air. System is heavier and more costly, but more efficient and less maintenance is needed. Also, less turbine erosion.

Boeing 747-8 Air Conditioning Pack

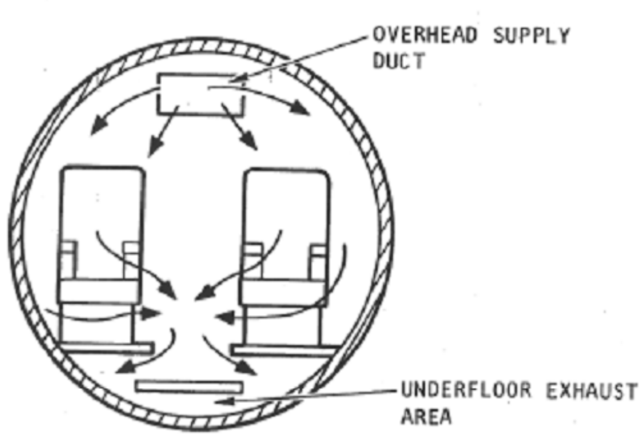


Air Conditioning System Recirculation & Distribution

Recirculation:

Many transport aircraft use recirculation: 50/50 (% fresh air / % recirculated air) or 60/40. Enables colder air from pack (down to –29^{o}C "Dry Air Rated") to be mixed with warmer air from the cabin which results in a mix manifold temperature colder than cabin temperature. This reduced bleed demand and therefore fuel burn. Recirculation also promotes more efficient cabin air extraction, thus circulation.

There are concerns regarding the transmission of viruses and bacteria in aircraft using recirculation. Recirculation systems typically have filters to clean the cabin air: HEPA, activated charcoal, cold plasma, etc.



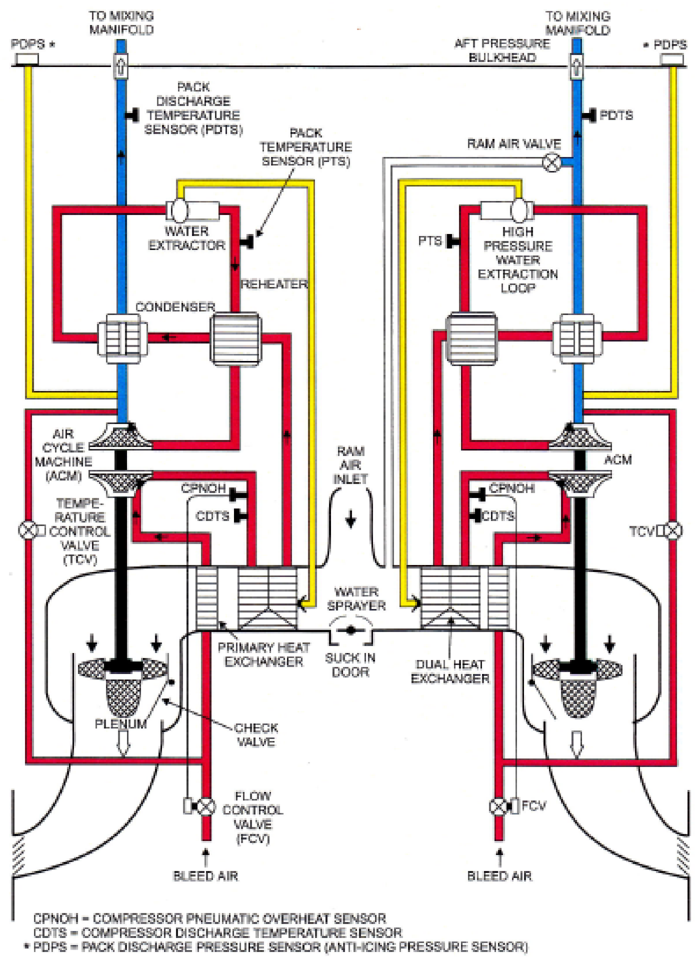
Distribution:

Objective is to evenly distribute air throughout the cabin to minimize stratification and excessive temperature variations in a zone.

- Low Pressure (LP) ducting is insulated to minimize heat loss (either way), thermal mass and pressure drop. Fuselage skin and floor are also insulated.
- Air should enter and leave the cabin uniformly.

Global Express Air Conditioning System Architecture*

Below is ACS architecture for the Global Express long-range business jet from the Flow Control Valves (FCV) to the aft cabin bulkhead Check Valves.



* Global Express IAMS Maintenance Training Guide

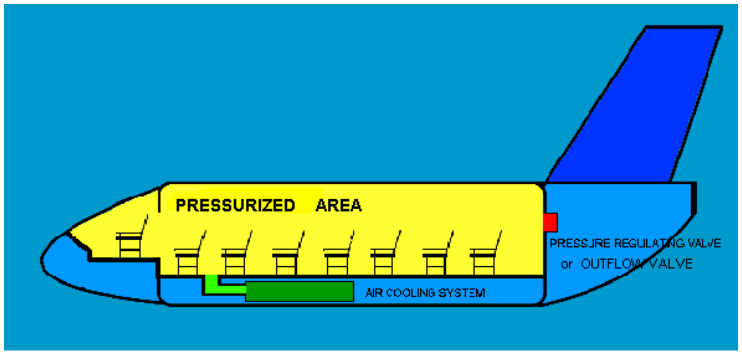
Cabin Pressure Control System Functions

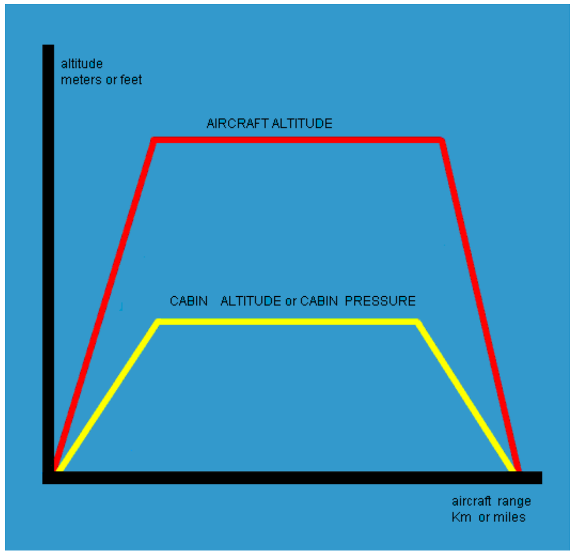
The Cabin Pressure Control System regulates the pressure within the cabin by controlling the outflow of air supplied by the ACS. This is done via one or more Outflow Valves and redundant controllers. The pressure level and rate of change are controlled to provide satisfactory pressure values for comfort and safety for all the passengers and crew.

The controllers measure the outside pressure at the altitude where the aircraft flies, the current pressure inside the fuselage and then drive the opening or closing of the Outflow Valves according to programmed laws that ensure the correct pressure inside the fuselage.

These laws take account of the flight phase : take-off, climb, cruise, descent, landing, taxiing. The general system behaviour is per the curves below.

The CPCS has independent safety functions to monitor cabin altitude and cabin ΔP. Structural protection (positive & negative ΔP) is provided via dual Safety Valves.





Cabin Pressure Control System Functions

Cabin pressure should theoretically be maintained at ground level pressure for maximum pax comfort (14.7 psia at SL), but the pressure differential at altitude would result in a heavy airframe. Therefore, the maximum permissible pressure altitude is 8,000 ft, which equals to cabin pressure of 10.92 psia. At an aircraft altitude of 41,000 ft (pressure 2.6 psia) this provides a pressure differential of 8.3 psi. This pressure results in a lighter structure.

Some aircraft such as the Gulfstream G550 use 6,000 ft cabin altitude at 51,000 ft to provide better passenger comfort. The Global Express is designed for ZC = 4,500 ft at ZA = 45,000 ft.

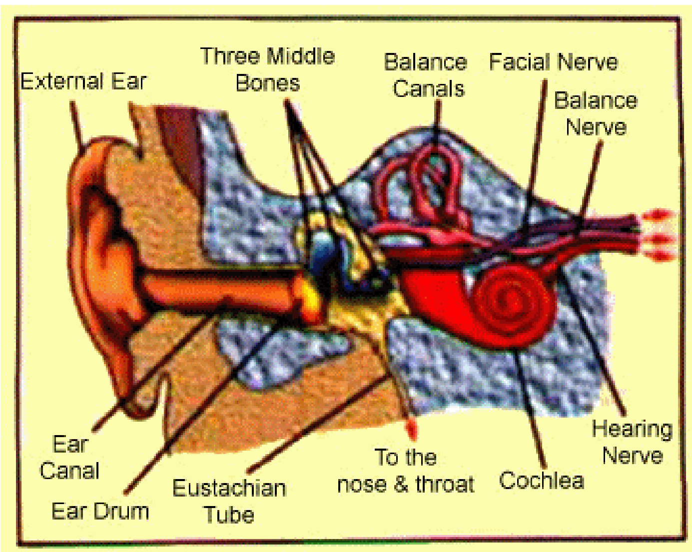
HYPOXIA

Altitude, ft	Symptom	Conscious time, min
SL	Normal	
10,000	Fatigue, headache (long exposure)	
14,000	Sleepiness, impaired vision, judgment, co-ordination	
18,000	Above symptoms, more marked	
22,000	Convulsion, collapse and coma	About 10
25,000	Collapse and coma	5
30,000		1.5
35,000		30 to 60 sec
40,000		15 sec
48,000+		0

At 63,000 ft, blood will boil and lungs will fill with water.

Physiology of the Ear

The ear is the organ that usually suffers the most due to changes in air pressure. The ear is made up of the outer, middle and inner ear. The outer ear funnels sound down the ear canal to the eardrum, the middle ear contains three bones which amplify vibrations from the eardrum to the oval window and the Eustachian tube linking the middle ear to the throat. The inner ear contains three semicircular canals used for balance and motion (“human gyros”) and the cochlea which converts vibrations into electrical signals.

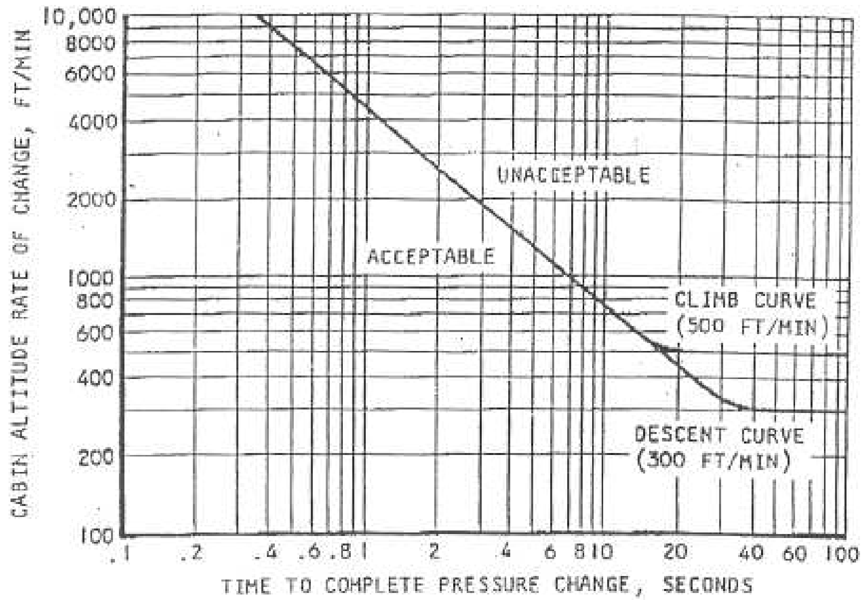


The Eustachian tube allows the ear to equalize pressure due to changes in air pressure. When cabin altitude is increasing (pressure decreasing), air easily moves down the tube. However, when cabin altitude is decreasing (pressure increasing), it is harder to equalize the pressure. In fact the Eustachian tube can collapse, causing discomfort and pain in the ear. Swallowing helps to equalize the pressure. Sinus congestion makes equalization harder yet. Infants younger than 6 months have not yet developed the swallowing reflex which why is pediatricians recommend that newborns don’t fly.

CPCS Design Guidelines

As a result of human physiology, design guidelines have been developed for CPCS based on time and rate of change. These criteria are much easier to implement in a fully automatic CPCS. Per SAE ARP1270 B Aircraft Cabin Pressurization Criteria:

- Acceptable rates for cabin altitude climb are +500 ft/min @ > 20 sec.
- Acceptable rates for cabin altitude descent are -300 ft/min @ > 40 sec.



Design Limits for Short Duration Cabin Pressure Changes, Based on Threshold of Detection by Humans

New Developments in ECS

Traditionally, ECS has been supplied with engine and APU bleed air. Boeing has developed its 787 Dreamliner with a more electric architecture, dispensing with bleed except for Cowl Thermal Anti-Ice (CTAI) and pressurising hydraulic reservoirs. Boeing believes that up to 35% in energy is saved (not dumped overboard) with this architecture and there is a 1% to 2% fuel burn savings in cruise and 3% overall. Main features of the “no-bleed system” are:

- Electric Starter/Generators
- Electric ECS Compressors
- Electric Wing Anti-Ice
- Electric Hydraulic Pumps

For system schematic (Figure 1) from “787 No-Bleed Systems” by Mike Sinnett, Boeing Aero Quarterly, QTR_04 / 07, please refer to:

http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_07/AERO_Q407_article2.pdf

New Developments in ECS

On current aircraft (767), engine mounted generators are 120 kVA capacity while the 787 features 2 x 250 kVA starter-generators. APU has 2 x 225 kVA starter-generators, therefore 6 x SG.

Electrical system has become more integrated and complex. Current aircraft have 115 VAC and 28 VDC, 787 adds 235 VAC and ±270 VDC.

Hydraulics feature classic Engine-Driven Pumps (EDP) and Electric-Motor-Driven Pumps (EMDP).

Boeing saw advantages with power electronics in terms of weight (1,000 – 2,000 lb in ECS weight savings) and fuel burn. Engine suppliers RR and GE say that in terms of engine cycle impact, no-bleed is similar to bleed. System reliability and maintenance costs are TBC.

Airbus has decided to use a bleed system on A350XWB. Similar aircraft specification, but different system solution. Bombardier CSeries ECS uses bleed air.

<u>Regulatory Developments/Impacts</u>:

525.981 Fuel Tank Explosion Prevention. The inerting of fuel tanks has a potential impact on the Bleed Air System sizing via On-Board Inert Gas Generating System (OBIGGS)

525.863 Flammable Fluid Fire Protection. The need to minimize fuel flammability hazard is driving Bleed Air System design towards 100% precooled air.

Thank you for your time and attention.

Any questions?

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