CRANFIELD UNIVERSITY

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Cabin Environment and Air Quality in Civil Transport Aircraft

SCHOOL OF ENGINEERING

MSc. Research Thesis

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Academic Year: 2011 - 2012

Supervisor: Dr. Craig Lawson

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ABSTRACT

The cabin environment of a commercial aircraft, including cabin layout and the quality of air supply, is crucial to the airline operators. These aspects directly affect the passengers' experience and willing to travel. This aim of this thesis is to design the cabin layout for flying wing aircraft as part of cabin environment work, followed by the air quality work, which is to understand what effect the ECS can have in terms of cabin air contamination.

The project, initially, focuses on the cabin layout, including passenger cabin configuration, seat arrangement and its own size due to the top requirements, of a conventional aircraft and further into that of a flying wing aircraft. The cabin work in respect of aircraft conceptual design is discussed and conducted by comparing different design approaches. Before the evaluation of cabin air quality, an overall examination of the main ECS components involved in the contaminants access will be carried on and, therefore, attempt to discover how these components influence the property of the concerned contaminants. By case study in the B767 ECS, there are some comments and discussions regarding the relationship between the cabin air contaminations and the passing by ambient environment. The thesis ends up with a conclusion explaining whether or not the contaminated air enters the occupants' compartments on aircraft and proposing some approaches and engineering solutions to the continue research.

Keywords:

Cabin layout, flying-wing aircraft, cabin air contamination, contaminants, ECS(environmental control system)，air conditioning pack

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

A340	Airbus model 340
B777	Boeing model 777
B787	Boeing model 787
GDP	Group Design Project
AVIC	Aviation Industry Corporation of China
ECS	Environmental Control System
B767	Boeing model 767
IATA	International Air Transport Association
FAR	Federal Aviation Airworthiness Regulation
in	Inch or inches
ft	feet(foot)
A330	Airbus model 330
MTOW	Maximum Design Take-off Weight
OEW	Operating Empty Weight
L/D	Lift to Drag ratio
BWB	Blended Wing Body
EASA	European Aviation Safety Agency
CS	Certification Specifications
APU	Auxiliary Power Unit
HEPA	High Efficiency Particulate Air Filter
MSL	Mean Sea Level
VOC	volatile organic compound
TCP	Tri-Cresyl Phosphate
DfT	Department for Transport
SVOC	Semi-Volatile Organic Compound
CO	Carbon Monoxide
TOCP	Tri-ortho cresyl phosphate
TBP	Tri-butyl phosphate
TCE	Tetrachloroethylene
TWA	Time-weighted average
VC10	Vickers model VC10
FWD	Forward

AFT	aft
M_{tow}	Maximum Design Take-off Weight
pax	passenger
nm	nautical mile(s)
CO_2	Carbon Dioxide
cfpm	cubic feet per minute
ppm	part(s) per million
ACP	Air Conditioning Pack
CFD	Computational Fluid Dynamics

1 Introduction

1.1 Background

The current volume of travelling by commercial aircraft is rapidly increasing, making civil transport a global industry, which provides safe, fast, efficient and economical services, beyond the boundary of the country, nation and culture. There has also been increasing the cost of fuel in flight, from the energy crisis, by which drives the aircraft manufacturer to design a more economical airliner.

The initial consideration for operators to reduce costs is to request a economical jet airliner with more efficient performance. As we know, several kinds of general layout less fuel-consumption aircraft have been in service now, such as A340 and B777, and B787 will be put into operation soon. Compared to general layout aircraft, a flying wing aircraft has unparalleled advantages in fuel savings and noise reduction, although a significant increase in stability control complexity. So, it is very worthwhile to design a flying wing passenger aircraft in today's scarce oil resources. In China, rapid economic development brings great market demand for air transportation and civil aircraft, and the Chinese government tries to develop its own commercial aircraft. From ARJ21 to C919, the government has been trying to manufacture advanced aircraft to meet the huge domestic demand.

Both of those determine on the Group Design Project (GDP) program for 4th cohort Aviation Industry Corporation of China (AVIC) students, which is to design a concept Flying Wing aircraft, considered as a new concept 200-seat airliner. The GDP program aims to design a long range flying wing passenger aircraft to meet the increasing global aircraft demand. As a part of AVIC MSc course, the new Flying Wing project consists of three-phase program: conceptual design, preliminary design, and detail design. It should be answered in conceptual design, which has an overall coverage of configuration arrangement and cabin layout, size and weight, performance as well.

Another factor that is of interest to airline operators is the cabin environment, in that passengers are exposed in a mixed of conditions, such as seat density, travel comfort, the inhalable air for occupants and the need for pressurization. The crew and passengers of a commercial aircraft must be supplied with air to breathe, whether on the ground or in the air. This is part of what the Environmental Control System (ECS) does. Clean air is the most important condition to enable passengers and crew to live in the cabin. There have been reports from pilots and cabin crew worldwide who believe that they have been adversely suffered from breathing contaminated cabin air, specifically by toxic products in engine oil or lubricants leaking into the bleed air which is used for cabin pressurization and air conditioning. The recent occurrences of aircrew affected by the contaminated air in the commercial airliners have been investigated for a decade or more.

Contaminated air fumes primarily occur because normally most of the commercial jet aircraft take air directly from the compression section of the engines, which is called bleed air or pneumatics, and deliver this unfiltered air, after pressurization and cooling, into the aircraft cabin. When this air becomes contaminated with the materials used to lubricate the engine or hydraulic fluids used in various aircraft systems, passengers and crew will be exposed.

Suspected exposure to contaminated air has led to flight crew and cabin crew being retired early with chronic ill-health including severe neurological, neuropsychological and respiratory disorders. In addition to the risk to the long term health of aircrew there is also a risk to flight safety as a result of in flight impairment due to decreased cognitive performance, irritancy and toxicity adverse effects.

There could be so many questions about the cabin air contamination: e.g. how often contaminated air exposures occur exactly; what is the source of contaminants and what the contaminants are composed of. Unfortunately, limited works had been carried out to investigate which contaminants existed in the aircraft cabin environment during a contaminated cabin air event. This led to some consequent results: there are no detecting and warning devices onboard an airliner as well as no effective recording system. The aviation industry and some operators may intend to ignore the responsibility and legal liability to protect the crew members, passengers and other maintenance and servicing staff by the excuse mentioned.

1.2 Aims and Objectives

The research project focuses on two aspects of cabin environment, the first stage is the cabin layout and the other is the quality of cabin air. The initial main work aims to design the cabin layout for the flying wing aircraft and a baseline conventional airliner with the same seat capacity as a comparison. Both for the conventional aircraft and for the flying wing concept, actions should be conducted in this stage as follows:

1. Cabin size and capacity(due to the requirements, to accommodate those passengers)
2. Seat arrangement(mixed class and single class, seat pitch, width of aisles, abreast seat number and so on)
3. Other facilities arrangement (attendants seats, lavatory, galley , closet, etc)
4. Evacuation consideration(number of doors and emergency exit, their locations)
5. Cargo layout(cargo size, type of containers and pallets)

The purpose of the second stage, namely the cabin air quality, is to understand what effect the ECS can have in terms of cabin air contamination. This may include contaminants sourced from the ECS components, or upstream at the engine. The mechanism for contamination of bleed air at the engine is not considered in detail here, in order to limit the scope of the study to the ECS component only.

Thus, it should have a general examination of all components involved in the ECS primarily, and therefore find out the possible route by which the contaminants come through.

The following work can be divided into several parts, as follows:

1. Understand the ECS and focus on the individual components of it.

2. According to the track of the contaminations from the bleed air, ECS to cabin, find out the functionality of those components, the temperature and the pressure at the key points.
3. By case study in the B767 ECS, give a corresponding discussion on the contamination transfer and transformation.

1.3 Structure

This research work is organised as follows. Previous research and related literature review are discussed in chapter 2. After carrying out the cabin layout for the flying wing and baseline aircraft in chapter 3, details for the ECS and air conditioning pack are analyzing at chapter 4. Furthermore, chapter 5 presents the case study in the B767 and a discussion on the contaminants transference and fume events. At the end of thesis, chapter 6 concludes all of research project and fulfils with recommendations for the future research.

1.4 Methodology

1.4.1 GDP Work

The methodology applied for flying wing aircraft cabin layout is described below. The cabin layout starts with a derivation of the passenger cabin requirements, which comes after the analysis of strategy and marketing work. Based on the requirement, a survey of the civil jet airliners will be taken and a prototype that has the same cabin capacity under same configuration will be selected. Also, factors that specify the passenger cabin can be summarized through the literature review. The cabin layout of the conventional aircraft, which need a multi-disciplinary examine, probably can be completed as well as the cargo and exits consideration. However, that is the first step from existing concept to flying wing aircraft. Besides compromise between its huge superiority and its drawbacks, iterations must be one of essentials so that the new aircraft can achieve the aim of a satisfied performance. Some particular aspects like security and evacuation is suggested to be studied in the process.

1.4.2 IRP Work

The research method for the cabin air quality can be described as follows: As I specialize in aircraft system engineering, firstly I would like to study the ECS deeply and from a detailed direction, which means to check the main components of ECS, so as to make sure what are the relationships with the instruments of air conditioning system and by what route the contaminants enter the system.

Following this, a case study will be introduced, which will consider the ECS of a certain aircraft, particularly the B767. In the case study, several works will be planned to inspect and assess the outcome acquired from the first step, which comes from a theoretical analysis process.

By the case study, it will be discussed what changes could occur while the contaminants passing by those components with the bleed air, from ECS to cabin.

Finally, the technical relationships between the contaminants and the main ECS components will be concluded to provide any support for the improvement of the airframe systems design. Moreover, further recommended work or aspects will be provided.

2 Literature Review

2.1 Passenger Aircraft Cabin Layout for Conventional Design

2.1.1 Cabin Layout in Conceptual Design

As mentioned above, the first stage of the cabin layout to design is a baseline conventional airliner which has major similarities in the conceptual design with the commercial airliner currently operated. To start a civil transport aircraft, the first main component parts considered is the fuselage, as its inner size and shape, which is depended on the seats number and its allowable load related to the passengers, namely, the cabin capacity. Lloyd R. Jenkinson, the author of the book “Civil Jet Aircraft Design”, previewed like that.

There will be an initial discussion of the overall criteria and regulations for the cabin layout, such as airworthiness, crashworthiness and other specifications, in order that all of the occupiers are under safe travelling consideration and they can be evacuated from the aircraft in an emergency circumstance. Before describing the parameters related to the passenger cabin capacity, some decisions must be done firstly, involving the cabin geometry at the cross section and the distribution of passenger seats between each seating classes. Additionally, other factors must be taken into account for the cabin layout. These contain the crew accommodation, housing and freight facilities like galley, lavatory, standard containers and pallets. [1]

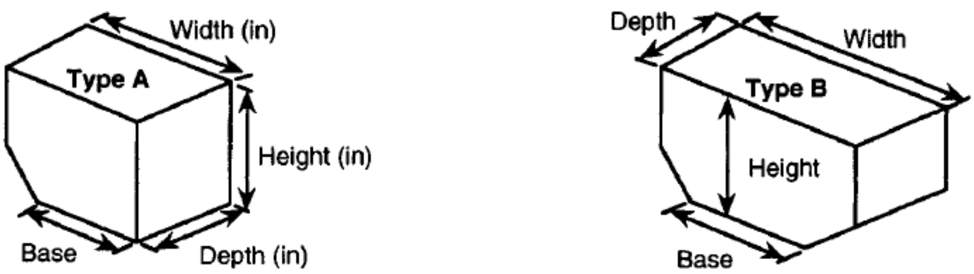
Two of those geometrical parameters that define the passenger cabin are the cabin diameter and length, while the cabin diameter is the most elementary as the cross-section of cabin is determined with it. Another requirement that influence the shape of the cabin cross-section, as we can see, is the pressure inside the cabin. Passenger cabin cannot accommodate people unless it is pressurized to a proper cabin height. The ideal distribution of the loads resulting from the pressurization is uniform if the cabin has a circular shell structure. This makes the circular shell efficient so that the weight of the structure is the lowest. Cabin cross-section and size is usually determined in the initial design study to be undertaken for a new project. The size must be considered to be smaller to reduce the structure weight and fuselage drag, while the shape must provide a flexible cabin interior and a comfortable environment. Thus, the solution to be carried is how to arrange the number of seats across the cabin and the consequent aisle width. Once the number of passengers is specified, the seats abreast will affect the number of rows and therefore the length of the cabin. The length-to-diameter ratio (or called fuselage fineness ratio) is a crucial parameter for the cabin layout.

To decide the fuselage diameter, the seat classes is the further consideration for the sectional layout of the cabin is a vital configuration. As in a civil transport aircraft, normally there should be different ticket classes provided in order to maximise the market for airliner operators. Once the cabin section is selected the operational layout options available for the airlines within the cabin are determined. Before freezing the cabin cross-sectional shape, aircraft manufacturers should have to take advices of the operational layout from potential customers by reason that it is an inconvenient means for an alternative layout.

From the existing cross-sectional shapes of aircraft, the space below the cabin floor is used to hold cargo containers. Containers and pallets are used to package the freight and passengers' luggage into by the major airlines, which are designed for their own airliners and ground handling facilities. The sizes of the containers have been specified by the IATA (International Air Transport Association) to allow use on different type of commercial aircraft. Table 2-1 shows specifications of some frequently used LD-designations. [1]

The quantities and type of containers should contribute to the payload specification for the aircraft, which correspond to the luggage allowance for the passengers. It is of necessity to provide a volume of 0.125 m^3 per seat, which is equivalent to the minimum 20kg luggage allowance for the economy class. Since the airlines always want to use the aircraft to carry cargo besides passengers, it must be taken into account to handle the provision of enough spaces in accordance with the cargo requirements for potential customers. [1]

Table 2-1 Standard sizes for freight containers [1]



Designation	Width	Height	Depth	Base	Maximum load (lb)	Notes
LD-1	92.0	64.0	60.4	61.5	3500	Type A
LD-2	61.5	64.0	60.4	47.0	2700	Type A
LD-3	79.0	64.0	60.4	61.5	3500	Type A
LD-4	96.0	64.0	60.4	–	5400	Rectangular
LD-5	125.0	64.0	60.4	–	7000	Rectangular
LD-6	160.0	64.0	60.4	125.0	7000	Type B
LD-7	125.0	64.0	80.0	–	13 300	Rect/Contoured
LD-8	125.0	64.0	60.4	96.0	5400	Type B
LD-9	125.0	64.0	80.0	–	13 300	Rect/Contoured
LD-10	125.0	64.0	60.4	–	7000	Contoured
LD-11	125.0	64.0	60.4	–	7000	Rectangular
LD-29	186.0	64.0	88.0	125.0	13 300	Type B

The size of passenger seats mounted in the aircraft is usually determined by the individual operators. Some recommended data of the widths are demonstrated in Table 2-2. [1]

Table 2-2 Typical seat widths [1]

Class	Seat width (mm)	Seat width (in)
Charter	400–420	16–17
Economy	475–525	19–21
Business	575–625	23–25
First	625–700	25–28

Terms from airworthiness regulations specify the minimum passenger aisle width for commercial airliners, seen in FAR 25.815. [4] Quotes: the minimum passenger aisle width is 15 in and 20 in respectively less and more than a reference height of 25 in above the floor due to the cabin seating capacity.

However, most airlines prefer to choose aisle width greater than this standard so as to enable the flight attendants to move smoothly inside the cabin. Flexibility in the seat options of cabin design makes the aisle widths diverse, for instance, some airways arrange seats that is configured to be adjustable from double first/business class to triple layout for economy. These requirements come from the seasonal feature of the market, which force the airlines to change the proportions of seat in each class to suit the variations. Another aspect related to the aisle width is the adequate headroom of passengers sitting at the window. While referring to the headroom in the cabin design, the designers must have to be aware to the cabin profile and how far it is away from the side of the outer seats, especially for the upper floor of a double deck layout.

Once the cabin cross-section has been decided, the number of seats across the cabin will be fixed. Dividing this number into the total number of seats in each class gives the average number of rows of seats to be installed. The required cabin length will be related to the leg-room provided for each class. For well designed seats this is related to the seat pitch. The perception of comfort is directly linked to the seat pitch and the number of seats in a unit (a single seat requires less leg length than a double). It is obviously impractical to make the seat pitch variable with the actual seat unit as airlines prefer straight rows across the cabin to simplify servicing (passenger management, serving food, cleaning, etc.). The seat pitch is chosen by the operator within the ranges as shown in Table 2-3. [1]

Table 2-3 Typical seat pitches [1]

Class	Seat pitch (mm)	Seat pitch (in)
Charter	700–775	28–31
Economy	775–850	31–34
Business	900–950	36–38
First	950–1050+	38–42+

The number of seats to be provided in each class is dependent on the type of operation and the demand for tickets in each class. The type of operation may vary due to seasonal demand for air travel. In the summer months there will be more demand for the cheaper seats from the holiday market, while in the winter the total demand may fall but the business demand will not reduce proportionately. This means that the allocation of seats between the various classes changes throughout the year. Airlines may need to reconfigure the cabin layout to suit the demand pattern according to the winter and summer operations. Seats and internal partitions must be easily moved to avoid long change-over times. Rails running along the length of the cabin floor are used to hold the seat and partitions with sufficient security to meet the crash load conditions specified in the airworthiness regulations. All the various seating arrangements must be consistent with the lateral position of these rails. The total number of passengers that can be accommodated in the cabin will be limited by the aircraft maximum take-off weight limit. This is set by structural, aerodynamic and performance criteria and not relate to the interior arrangement. Also, the cabin capacity may be limited by the type and number of emergency exits provided (see FAR 25.807 for reference). This may also restrict the maximum number of seats in the high-density charter role. [1][4]

In order to fix the initial layout, an estimate of the proportion of passengers in each class has to be made. Evidence should be collected from aircraft of the same type and operated on similar routes as the proposed design, typically for a three-class layout there will be 8% first, 13% business and 79% economy seats. [1] Different arrangements of seats will be possible within a fixed cabin length. It is important for the project designers to identify the special requirements for each airline to satisfy the overall layout. Besides, how the fixed cabin facilities like toilets and galleys in the design have been cleverly positioned to act as partitions between the different compartments. More space is needed for the business and first class accommodation and this will reduce the total number of seats that can be fit into the fuselage. In turn this will affect the revenue potential of the flight although the first and business class seats will attract a premium on the ticket price. The layout options will be carefully studied by the airlines to find a match for their market variations. Extra seats must be provided for the cabin attendants. The number of attendants is left to discretion of the airline but must be sufficient to control passenger evacuation in an emergency and satisfy the airworthiness licensing authority. The number of stewards is set by the airline to provide prompt service for safe evacuation to the passengers. Typically, one attendant per 30-40 passengers is chosen for the economy class, one for 20-25 in business and one for 10-15 in first class. The attendants will be provided with flip-up seats for use during the take-off and landing phases. These are generally positioned in the vicinity of the emergency exits and on other doors. [1]

Service facilities (including galleys, lavatories and wardrobes) must be provided in the cabin layout. These must be positioned to suit the proposed seating layouts. The galley and toilet units need so called built-in modules as the function of electricity supply, water and waste management. These facilities also should have to be serviced for the duration of the aircraft turn-round time. This will dictate the position of external access (doors and panels). It is not possible to quickly alter the position of galley and toilet facilities although some units may be interchangeable. The provision of galley and toilet facilities is left to the operator. The number of each type is matched to the passenger capacity, for example, short-haul flights will require less galley service than long-haul flights. For an aircraft used for both long-haul and short-haul operations there will be more seats in the short-haul configuration and this will set the requirement for toilets and possibly galleys. The number of passengers for each facility is related to the ticket class with typically between 10 and 60 passengers for each galley and 15-40 passengers for each toilet (that is also the lower numbers for first class accommodation).[1] The position of those units must not interfere with movement of passengers during loading or disembarkation. From Boeing and Airbus aircraft user manuals, typical size of the galley and toilet assembly is 30×36 in and 36×36 in respectively. [1]

Although the accommodation of passengers is the principal concern of the fuselage designer, it is also important to provide sufficient and convenient cargo space. In some configurations a mixture of freight and passengers is accommodated in the main cabin in separate sections. Such kind of layout requires a large freight door to access the cargo area. In most designs, freight loads will be assigned to the space beneath the floor of the passenger's cabin. A complete specification will include the disposition of cargo in the front and rear holds. Large access doors will be needed to get the freight luggage containers into the holds. For short-haul types the aircraft turn-round time must be minimised to reduce block time and improve direct operating costs. The overall arrangement of the various panels and access doors around the fuselage must be considered in relation to the airport services and the management of aircraft turn-round. The size and positioning of doors must suit airport ground equipment geometry. It is usual to provide passenger doors on the left side of the aircraft which leaves access on the right side for aircraft servicing, catering, toilet cleaning and luggage handling, etc.

For commercial operation, most of the airworthiness regulations are aimed at preventing accidents. However, even with the best efforts of aeronautical engineers and operators the aircraft may crash. In such an event it is the responsibility of the fuselage designers to ensure that the passengers are given protection during and immediately after the accident and that they can quickly and safely evacuate the fuselage. The designers have often more than one option for the design of the aircraft. Airworthiness and evacuation criteria must be considered when making decisions on cabin layout. Emergency evacuation of the cabin plays an important part in deciding the fuselage layout. Before a certificate of airworthiness is granted to the type, the manufacturer will be expected to demonstrate to the airworthiness authorities that all occupants can vacate the aircraft in 90 seconds or less using the emergency equipment normally carried. [4]

The airworthiness regulations state precisely the minimum quantity and type of those emergency exits to be provided in the cabin. These must be positioned each side of the fuselage. Doors used for services could be ranged to the emergency exits use, in order to ensure unobstructed access during emergency circumstances. The position of these doors for emergency evacuation may fix the location of the service units in the cabin. Exits not used for passenger loading or service will also require extra space to avoid congestion during evacuation. Cabin windows are often placed in emergency exit structures. The need to make more space available in these areas conflicts with equal seat spacing in the cabin. Doors and emergency exits are heavy and complicated structures. Designers will specify the number, position and sizes of these exits at the initial stage of the project. As mentioned earlier, the cabin layout options may be limited to match the number and type of emergency exits provided (e.g. see FAR 25.807 for full details). [4] The minimum number of exits to be provided is related to the maximum number of seats. The airworthiness regulations set out the precise requirements. In these regulations the type of exit is specified according to the size of the opening or hatch, which can be seen in the Table 2-4. [4]

Table 2-4 Types of emergency exit [4]

Types of exits	Definition
Type I	A floor-level exit with a rectangular opening of not less than 24 inches wide by 48 inches high, with corner radii not greater than eight inches.
Type II	A rectangular opening of not less than 20 inches wide by 44 inches high, with corner radii not greater than seven inches. Type II exits must be floor-level exits unless located over the wing, in which case they must not have a step-up inside the airplane of more than 10 inches nor a step-down outside the airplane of more than 17 inches.
Type III	A rectangular opening of not less than 20 inches wide by 36 inches high with corner radii not greater than seven inches, and with a step-up inside the airplane of not more than 20 inches.
Type IV	A rectangular opening of not less than 19 inches wide by 26 inches high, with corner radii not greater than 6.3 inches, located over the wing, with a step-up inside the airplane of not more than 29 inches and a step-down outside the airplane of not more than 36 inches.
Type A	A floor-level exit with a rectangular opening of not less than 42 inches wide by 72 inches high, with corner radii not greater than seven inches.
Type B	A floor-level exit with a rectangular opening of not less than 32 inches wide by 72 inches high, with corner radii not greater than six inches.
Type C	A floor-level exit with a rectangular opening of not less than 30 inches wide by 48 inches high, with corner radii not greater than 10 inches.

Another Table 2-5 [4] from airworthiness regulations specified the minimum number and type of exits to be provided on each side of the fuselage. For capacities greater than 179, a pair of additional Type A exits will allow an extra 110 seats, a pair of Type I exits will allow an extra 45 seats. Above 300 seat capacity all exits must be of Type A, for instance, a new large aircraft with 600 seats will require 6 Type A exits on each side of the fuselage. As mentioned above, to give uncongested access to these doors in an emergency, the internal cabin layout near these exits must provide more space than in other parts of the cabin. [2]

Table 2-5 Type and number required [4]

Type A	110
Type B	75
Type C	55
Type I	45
Type II	40
Type III	35
Type IV	9

The maximum number of passenger seats depends on the type and quantity of exits set on both sides of the fuselage. Except as above restricted for some special circumstances, the maximum number of passenger seats permitted for each exit of a specific type is as the above table, according to the type.

2.1.2 Reference prototype

Here is a prototype and a reference civil airliner for the conventional aircraft. Airbus A330 could be proposed as the current aircraft operated successfully, whose performance and specification match the design requirements of the conventional project.

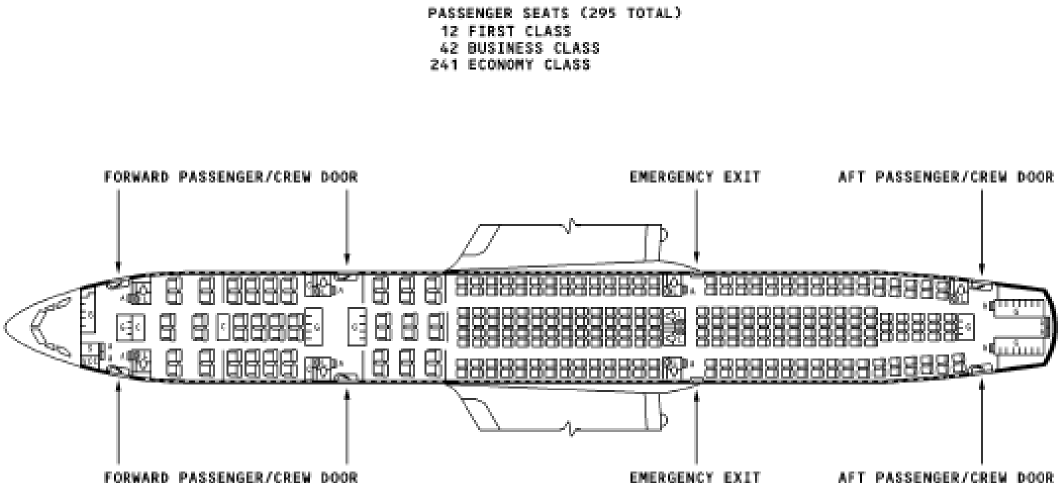
There are two basic versions of commercial aircraft in A330 family: A330-200 and A330-300, which have the same wing but altered with their seating capacity.

Table 2-6 shows the airplane description, including general dimensional and other basic aircraft data of A330 from Airbus. [5]

Table 2-6 A330 general airplane characteristics data [5]

Items	Units	A330 model 200	A330 model 300
MTOW (Maximum design take-off weight)	kg	230000	212000
	lb	507062	467479
OEW (Operating empty weight) estimated	kg	116840	120000
	lb	257588	264400
Standard seating capacity	Single class	303	335
Passenger cabin volume	m^3	335	372
	ft^3	11830	13137
Cockpit volume	m^3	12	12
	ft^3	424	424
Cargo compartments volume	m^3	178.4	215.4
	ft^3	6300	7606.7

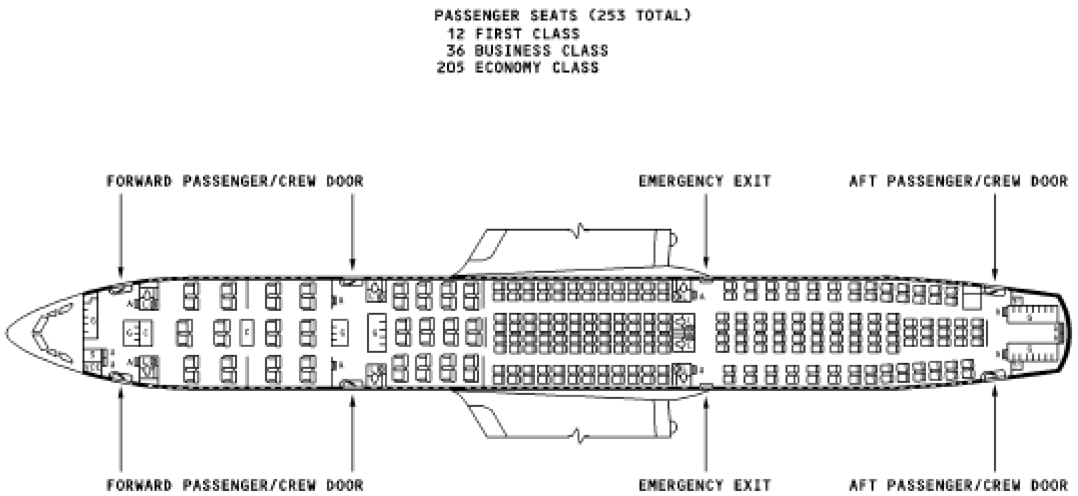
Interior arrangements under several typical layouts have been introduced as the following Figure 2-1 and Figure 2-2. [5]



NOTE : FOR DOOR SIZES
SEE CHAPTER 2-7

ITEM	DESIGNATION
A	ATTENDANTS SEAT (12)
C	COAT STOWAGE (4)
G	GALLEY (7)
L	LAVATORY (9)
S	STOWAGE (1)

Figure 2-1 A330-300 interior arrangement for typical layout [5]



NOTE : FOR DOOR SIZES SEE CHAPTER 2-7

ITEM	DESIGNATION
A	ATTENDANTS SEAT (12)
C	COAT STOWAGE (2)
G	GALLEY (6)
L	LAVATORY (8)
S	STOWAGE (1)
Tr	TROLLEY (2)

Figure 2-2 A330-200 interior arrangement for typical layout [5]

As a successful solution to family issue, A330-200 and A330-300 they have been considered to keep the same wing design and the same cabin arrangement, except the length of the fuselage due to different payload and range. Thus they have the same cross-section at the cabin compartments, shown in the Figure 2-3.

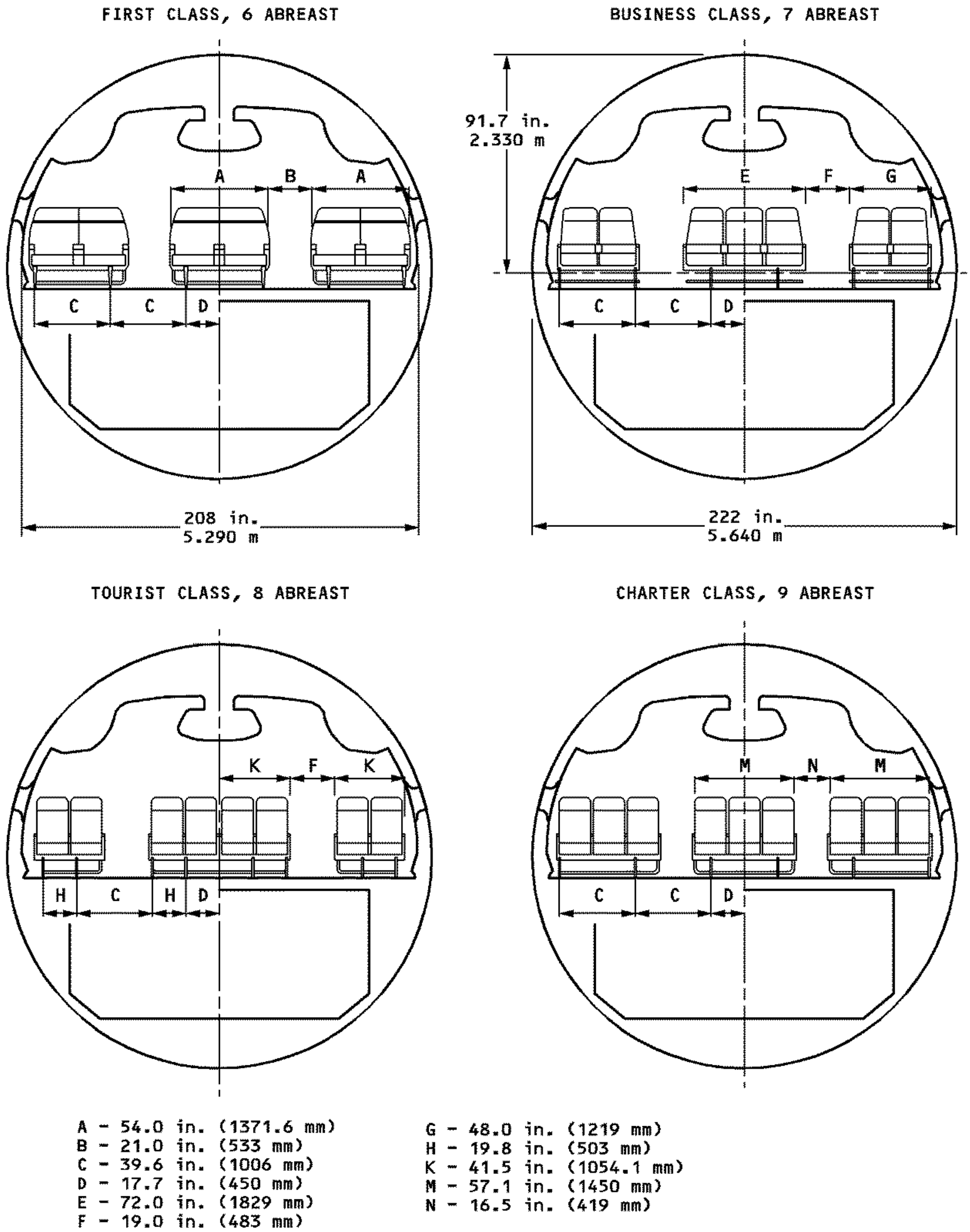


Figure 2-3 A330 passenger cabin cross-section [5]

In addition, there are 8 doors and exits for passenger evacuation in an emergency on A330, illustrated in Figure 2-1 and 2-2. The forward and middle passenger/crew doors are Type A exits, as well as the aft passenger/crew doors, while the two emergency exits are of Type C. Regarding the maximum seating capacity, passengers and crew must have sufficient time to evacuate the airplane using half of the exits in a urgent circumstance, ending up within 90 seconds.

2.2 Passenger Aircraft Cabin Layout for Flying Wing

The project of designing the flying wing aircraft is expectedly a challenging task, even though the cabin layout for flying wing has been quite similar with that of the conventional design. At first, what is a flying wing aircraft? “A flying wing is a type of airplane in which all of the functions of a satisfactory flying vehicle are disposed and accommodated within the outline of the airfoil itself,” defined by Jack Northrop, the founder of Northrop Corporation in the USA. [7] Significant challenges have been faced during the process. For instance, on the one hand, the inner part of the wing should be sufficiently thick to arrange the crew, passengers, cargo and tanks; on the other hand, outer part should be thin to achieve high cruise speed and L/D ratio. In addition, the issue of stability and control should be considered. To some extent, the compromise in aerodynamic performance is necessary to meet the different aspects of the requirements.

In the stage of conceptual design, normally it could not necessarily define the detailed flight deck elements, like the actual pilot’s eye point, the location of controls and instruments. Nevertheless, the approximate volume must be checked so that in the following stage, it will not revise the overall aircraft due to the detail flight deck design and payload integration work. Probably the actual cabin layout for a commercial airliner is determined much more by the marketing than by the regulations. Thus, pitch, width and headroom would be redefined for a flying wing aircraft according to its new concept in the airfoil and its entirely different fuselage structure. [2]

The configuration of a flying-wing passenger cabin has several unique features as compared with that of conventional aircraft. There is an extension in width at the flying wing cabin which is significantly varied concerning the cabin proportion. As a new concept, there are fewer windows in the flying wing cabin than a traditional cylindrical fuselage aircraft or might be no windows at all, which would result in experiencing unpleasant journey for passengers. An acceptable flying wing must be certificated by the airworthiness authorities (e.g.

FAR, EASA CS), depending on its capability of emergency evacuation. The emergency exits should be set sufficiently respecting their size, position, access in all possible location and configuration of the aircraft. It is said in the FAR 25 about the demonstration of emergency evacuation that the ground evacuation requests only half of the exits to be used. Therefore it is reasonable to take the exits arranged along one side of the aircraft, but the cabin of flying wing is obviously wider and this may increase the distance from passenger seats to the half of exits. Whilst considering other kinds of situation, either the forward exits or the aft exits might be used only, which can make this worse. The solution can be found by enabling the airworthiness to have a further consideration on the new concept design. [3]

Another new concept is the BWB (Blended Wing Body), which is regarded as a kind of hybrid flying wing. The seat areas within the BWB cabin can be determined due to the ration of the absolute seat area and total cabin area of modern service aircraft, which is typically up to 55%. Subsequently， with the given fuselage and unaffected by the need to scale the aircraft for a dedicated number of passengers, aisles, galleys and other remaining area are derived in accordance with the requirements. Also door and exits positions, sizes and evacuation paths are considered as part of the total cabin concept. With aisle widths orientating at conventional dimensions, cabin layout has to be designed attractively to achieve a high perception from the passenger. Emergency exits are provided all round the cabin area with wing and aft exits according to FAR 25.807 of type B dimensions; two type A doors per side in the leading edge of the wing, as shown in Figure 2-4. [9]

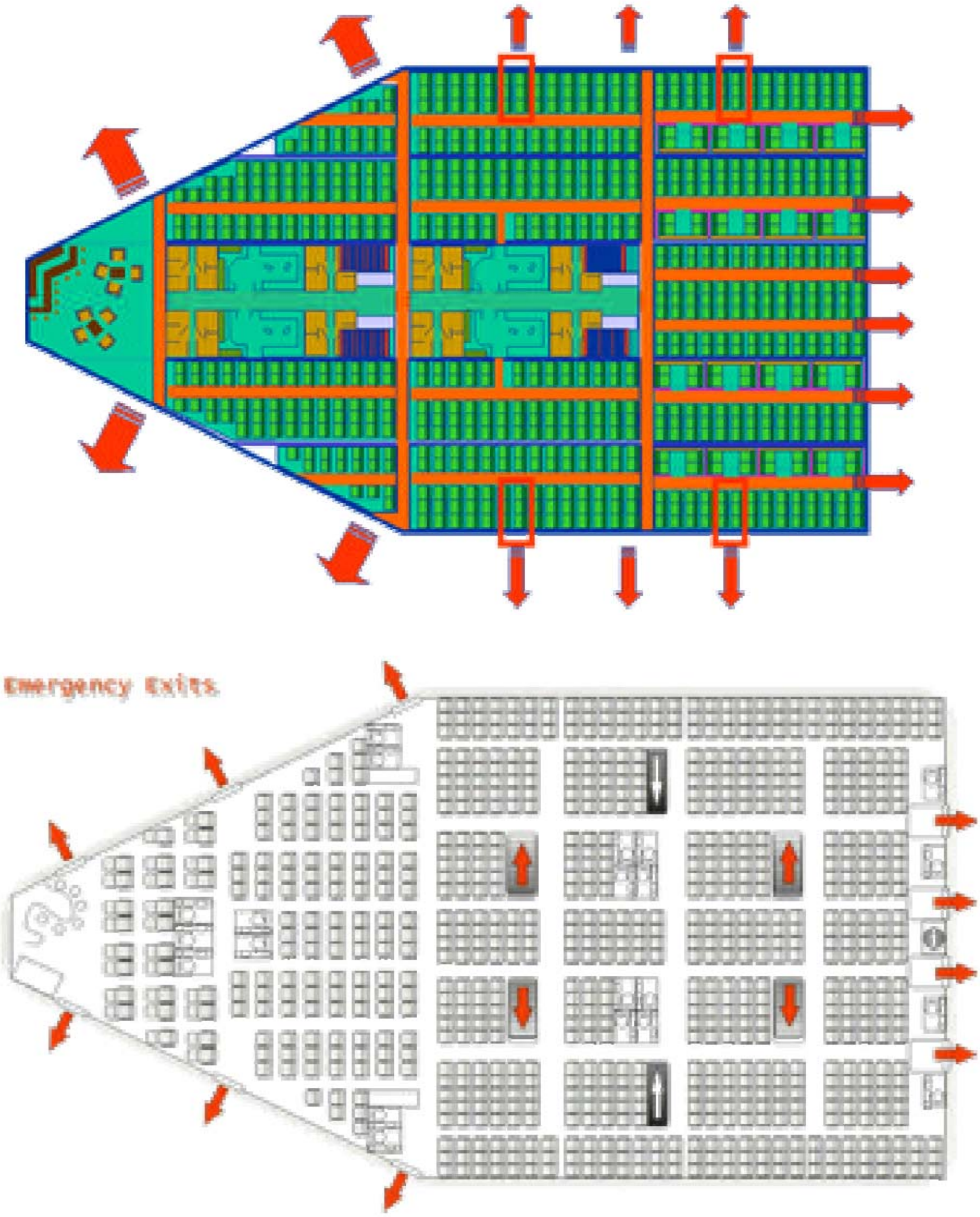


Figure 2-4 BWB 2D cabin layout options with emergency exits [9]

Either for a flying wing or the BWB, the shape of cross section through the cabin and its sizing parameters should be determined primarily. One example of the cabin layout for BWB passenger transport from a university's journal has selected the multi-bubble architecture, which is a favourite commonly used. As mentioned in the context of the cabin layout for the conventional design, an estimate of the proportion of passengers in each class has to be made in order to fix the initial layout. Evidence has been collected from aircraft of the same type and operated on similar routes as the proposed design, typically for a three-class layout there will be 8% first, 13% business and 79% economy seats. [2] With a 250-seat example, there would be 20 seats for the first class, 32 seats for the business class and 198 economy class seats. Before the required size of the cabin has been decided, the cross section of the cabin should be selected, mainly according to the quantity of passenger seat abreast and the width of aisle. However, as using a multi-bubble architecture, it is important to consider how many cabin compartments are schemed in the cabin and how many seats are set for one single row. It is simply estimated that choosing a 6-seat abreast for a single-aisle compartment could be appropriate for the economy class. While for a mixed-class cabin layout, a 4-seat or 5-seat abreast setting can be flexible in the first class and business class, but with different seat pitches, as shown in Figure 2-5. [8][9]

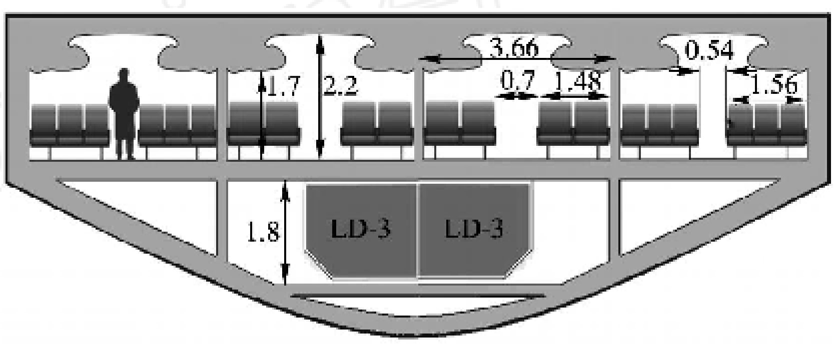


Figure 2-5 A 250-seat BWB Cabin cross-section view (unit: metre)

In respect of passenger evacuation in an emergency, there are two passenger and service doors arranged in each side of the leading edge, two ventral exits respectively in each side of the rear body. The access to every exit is strictly conformed to the regulation of airworthiness. In addition, service facilities including galleys lavatories and closets must be provided in the cabin layout, which also must be positioned near to the service doors due to the limit within the airliner turn-around time, by reason that these facilities will need to be serviced during the flight intervals. Those are illustrated in Figure 2-6, and the 3D model of passenger cabin for the 250-seat BWB has been displayed in Figure 2-7.

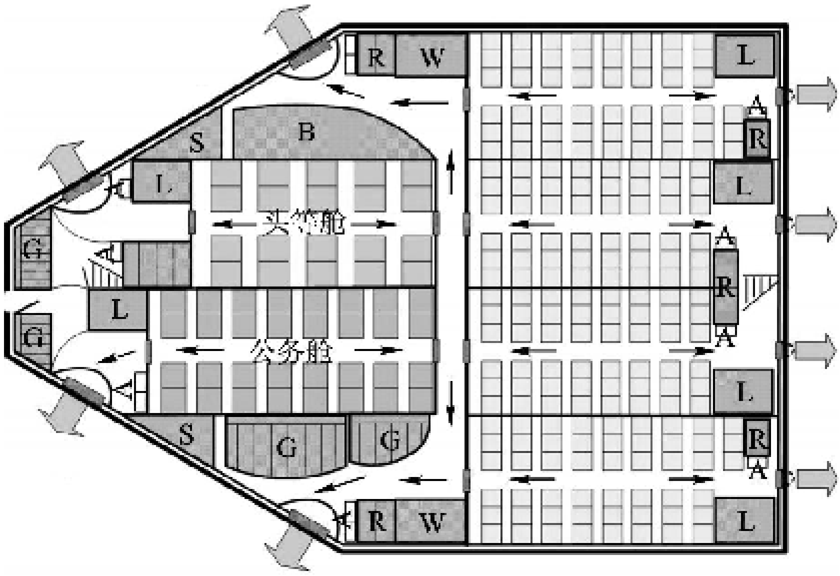


Figure 2-6 A 250-seat BWB Cabin layout and evacuation routes [10]

(L-lavatory, S-storage, A-attendant's seat, G-galley, R-restroom, W-wardrobe, B-bar)

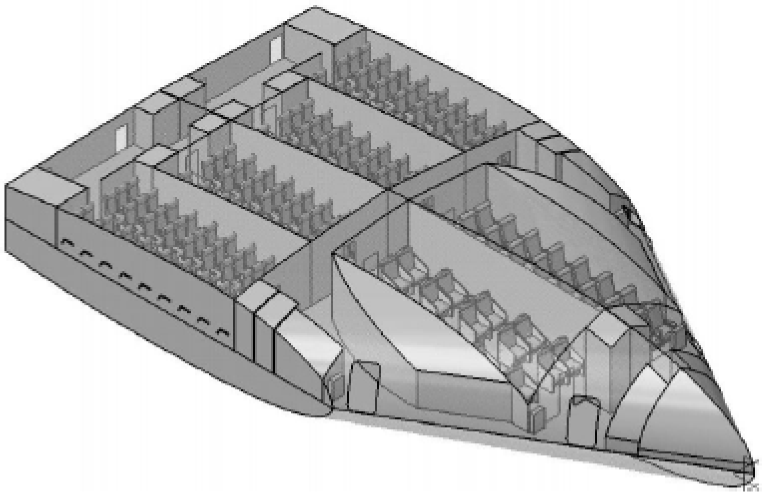


Figure 2-7 A 250-seat BWB cabin 3D model [10]

2.3 Air Quality in the Passenger Cabin

2.3.1 Thesis on Contaminated Air in Aircraft

As mentioned above, suspected exposure to contaminated air has led to flight crew and cabin crew being retired early with chronic ill-health. This issue is discussed comprehensively in a PhD thesis named Health and flight safety implications from exposure to contaminated air in aircraft, which is accomplished by Susan Michaelis. This thesis aims to investigate diverse aspects of exposure to contaminated air supply onboard commercial aircraft.

From the author's review and analysis of air detecting studies, the contamination sources can be recognized. These include: engine oils, hydraulic fluids, fuel, de-icing fluids, exhaust fumes, ozone, solvents, pesticides, anti-corrosion spray, paints and electrical odours within others. It is suggested that contaminants contain: oxides, esters; methylated, fluorinated, chlorinated, phosphate or nitrogen compounds; aliphatic hydrocarbons; aromatic hydrocarbons and aldehydes. Jet engine oils have been tested to have an appreciable hazard due to toxic ingredients, but are safe in use while provided appropriate safety precautions and the oil stays in the engine. However, the oils and other contaminants could get their way into the air supply area where passengers and crews are located, through incidents such as engine or APU oil leaks, seal failures and fluid ingestion by the engines or APUs. [11]

Since the contamination issue had a severe consequence for the health and safety of the person onboard a commercial transport aircraft, what should the regulations and standards regarding the cabin air be adhered to? The international airworthiness standards for transport aircraft like US FAR, EASA CS and other airworthiness regulations have been continuously amended as well as the standards for aircraft ventilation, in which those certain substances such as fuel vapours, ozone and carbon monoxide cannot be above certain limits, but the levels of any other contaminants are not included. Many in the industry including regulators, manufacturers and operators incorrectly assume that only the listed contaminants are covered. When questioned about the airworthiness in respect of the ongoing fume events, many are quick to say that the aircraft have been certificated and meet all the certification requirements. In addition to these aviation regulations, there are also occupational regulations and guidelines in most countries to protect the employees in their working environment. These standards and codes cover almost all of the areas relating to the workers and their workplaces. But the reality is that there is a major conflict between the occupational health and flight safety regulations, with the result that neither is effectively enforced. As far as the issue was raised with the airworthiness regulations, a certain amount of the regulators have taken effort to address this issue and made those regulations more specific to protect the crew and passengers regarding to the cabin air contamination.

The aircraft is pressurized and has an environmental control system therefore when a commercial jet aircraft reaches its maximum design cruise altitude, the cabin altitude or the equivalent altitude related to the sea level, would be about 8000 feet or 2438 m, [11] which is to support the passengers living in the flight environment. Currently for majority of the transport airliner, it is designed to use bleed air from the specific compression section of the jet engine, after cooling and depressurizing, the ECS distributes the air to supply the pilots and passengers for breathing and to pressurize the flight deck and the cabin. The bleed air systems or called pneumatic systems varied on the type of engine and APU. In most jet engine configuration the bleed air is taken out far forward on the engine where the compressor air is not too hot and the fuel leakage may not get into the bleed air ducting, while in some other engine constructions the air is bled further aft in the compressor, which subsequently result in an increased risk that the leaking oils can be present in the bleed air with both much higher temperature and pressure as like the BAe 146. [11] When the bleed air leaves the engine compression section into the ECS, it is reported that the temperature can be from 300°C up to 650°C, yet in the intermediate compressor, it will be considerably lower between 50°C and 300°C. The bleed air used on the BAe 146 is said to range between 100°C and 400°C. Therefore, the air must be cooled firstly before entering the passenger cabin or the cockpit. Cooling is done initially by a heat exchanger such as a pre-cooler located in the engine struts cooling the air down to around 200°C and then, after flowing through ducting in the wing, enters the air conditioning packs. [11]

There had been awareness of cabin air contamination for many years, as authorities published regulations and textbooks stated smoke fumes and ventilation air in the crew and passenger compartments as well as the toxicological test information involving the thermal decomposition of the synthetic jet oils, lubricants and hydraulic fluids. Contaminants and its sources also had been considered in the design and maintenance of the aircraft ECS, which could be suspected of synthetic engine lubricants, hydraulic and de-icing fluids. As an alternative source of bleed air, the APU is used only on the ground or for taking off and landing, it can provide air for air conditioning besides the air source for starting the engine and electrical power generators. Either for the engine or the APU, seals are commonly used as precautions against oil leakage from the bearing chambers, also as means to lead and control the air flow to expectant positions. Citing the bleed air as an example, the design goal for system engineer to set various different seals is to ensure the compression bleed air not contaminate. However, the inherent design flaw of the bleed air in relation to the seals had been acknowledged due to the design, practices and maintenance issues of the seals. It seems impossible to design a mechanical seal which throughout its life will always assure no engine oils to contaminate the air supply, neither from its principles nor its materials. Consequently, the current oil seal design could be prone to failure or malfunction. When a seal fails or leaks, there are even no fail-safe systems present to prevent the air supply becoming contaminated with the decomposed engine oils as the bleed air is not filtered on the commercial air transport.

Re-circulated air is another different source of the cabin air supply except the bleed air, coming from the consideration of cutting operating costs. This can be accomplished by using recirculation system mounted with HEPA (High Efficiency Particulate Air) filters to eliminate the concentration of particulate contaminations. However HEPA filter cannot remove gases and vapours accordingly due to the small molecular sizes, which can be only dealt by dilution with further incoming high quantities of outside air. The HEPA filtration system is usually positioned just beside the mix manifold so that the cabin air used to be re-circulated passes through the filtration system before it enters the mix manifold, where it is mixed with the unfiltered bleed air. A simplified flow chart (see Figure 2-8) shows a typical air supply system used today on commercial jet aircraft. Only the re-circulated air is filtered by HEPA filters, the bleed air is not filtered and it is through bleed air that contaminated air enters the cabin.

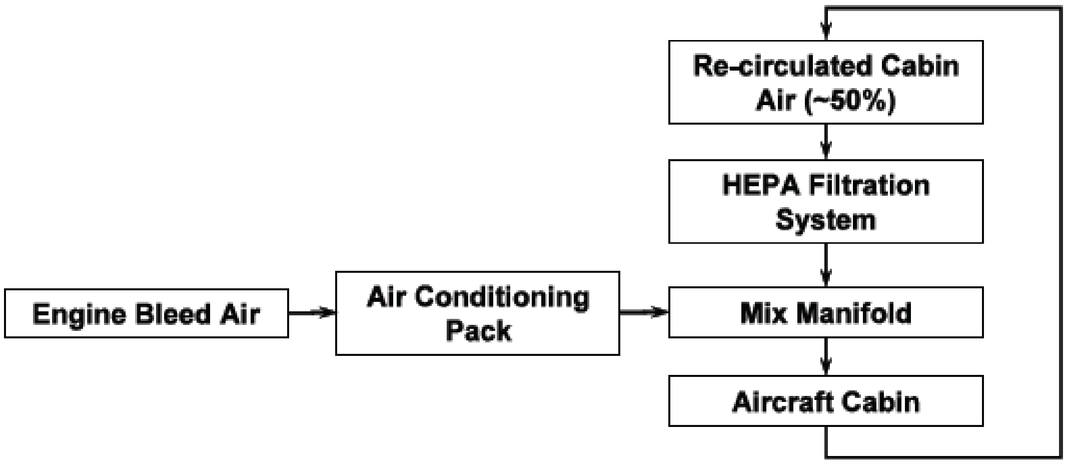


Figure 2-8 Re-circulated Air flow [11]

Relatively for the outside air to be bled from engine, the gaseous contaminants within the air are controlled by dilution assuming the source of the air is cleaner than the air presented or where ozone converters are used by chemical conversion. Some aircraft are fitted with combined ozone and odour reduction converters, which in addition to removing ozone plus odours entering the cabin via the bleed air during ground stages. Since acknowledging those particulates may enter via the mix manifold, some manufacturers have utilized both low temperature applications and chemical absorption filter methods due to technical issues and temperature limitations. In the high temperature section of ECS, new technologies on filtration of the pneumatic bleed air are under consideration from several aspects: filter media, performance, type of contaminants and so forth. In order to afford a safe, healthy and pleasant environment for the travel of passengers and crews, consideration for adequate filtration of the outside air is required for both existing and future aircraft.

The new Boeing 787 has been designed with a different system whose air supply to the passenger cabin and flight deck, really do not depend on bleed air. In the Boeing 787 conventional bleed air is replaced by electrically driven pneumatic systems, which will be more efficient than bleed air and making the aircraft more fuel saving. The Bleed Free philosophy applied on the Boeing 787 introduces no-bleed architecture that lets the outside air supply to the cabin. As the Figure 2-9 shown, this architecture prevents the risk of engine oil decomposition products from being led into the cabin air supply. Current and future filtration technology can never be designed to be completely effective and reliable throughout its service life. Consequently, the only effective long term solution to settle the problem of bleed air contamination by hydraulic fluids, engine oils and their by-products is the introduction of bleed free architecture in all future aircraft designs as is used on the Boeing 787. [11]

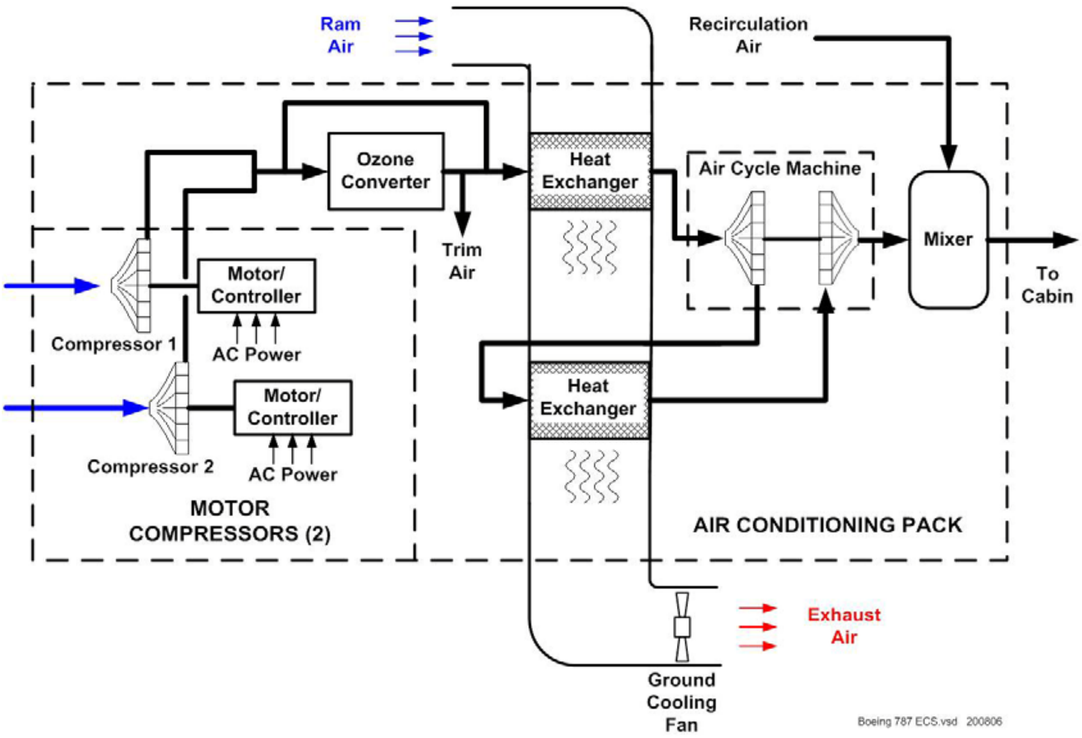


Figure 2-9 Re-circulated Air flow [22]

The BAe 146 provides a case study of an aircraft that was allowed to leak oil into the air supply from its beginning. The aircraft and engine manufacturers along with airlines in the 1980s were well aware of this and took a large number of limited steps that did not adequately address the source of the problem. The problems were passed on to other operators of the BAe 146. Considerable but ineffective action was taken, however it was inappropriate as the actions failed to address the whole problem at the source, were not made mandatory or overseen. The problem was shifted from an engineering and design problem to one that then sought to blame and marginalize those who complained. This likely change of emphasis likely resulted from the realization that the design flaw would never be corrected during the life of the aircraft and therefore a campaign of misinformation and denial had to be introduced to accompany the aircraft to its natural end of service life. The continuation of allowing contaminated air to routinely pass into the air supply and limited actions undertaken were resulted by regulators and passed from one airline customer to the next. The extensive official documentation and company actions clearly demonstrate that they were able to operate outside the legal framework under the attitude of product improvement and keeping aircraft flying.

The use of the bleed air system was initially considered unacceptable because of the inherent problems in the design of oil seals. However, as the desirability to use bleed air from more advanced engines took over it was assumed actions taken by engine, aircraft and seal manufacturers had reduced oil leakage and to acceptable levels. The military has remained almost silent despite clear awareness of the toxicity issues. The commercial market has failed to check the data and effectively ignored all evidence which indicates that contamination is not disappeared, far more frequent than desired, and is not a ground based workplace to which industrial safe levels can be applied, a design issue and anything beyond a motivation. To recognize such issues would require real and major change.

Many in the airline industry have suggested this is a problem for one or two aircraft types only. Unfortunately, current available evidence shows that all aircraft using bleed air can and may allow contaminated air to contaminate the air supply. Throughout all of the evidence and data acquired so far, a variety of recommended researches should be taken. To establish standards and control measures for all contaminants suitable for the cabin air environment and the heated mixture of contaminants, rather than individual ground based standards is a urgent challenge for the aviation authorities. Meanwhile, it will be an effective way of exploring suitable bio-monitoring methods and other related techniques able to identify whether exposure to contaminated bleed air. As an retrieval action, development and introduction of effective bleed air filtration or bleed air cleaning systems should be introduced on current aircraft fitted with bleed air system. In addition, the attempt of effective bleed air detection (might be real time monitoring) systems whose function is to detect contaminated air should be expected in each bleed supply line and duct. This will alert crew prior to the concentration of the harmful contaminants is approaching to the warning level and help engineering with the post-flight fault diagnosis.

2.3.2 Systems Perspective on Aircraft Travel and Health

Aircraft operate at altitudes from mean sea level (MSL) to above 50,000 ft, [12] spending pretty long durations in flight and also on the ground being serviced, cleaned and boarded by passengers. The external environment around aircraft varies considerably and this has an effect on the internal cabin environment in which the crew and passengers are accommodated, which in flight is of high altitudes with lower partial pressure of oxygen.

Passengers travel by air now expect not just comfortable seats, entertainment and plentiful food and drink, but a comfortable environment for the cabin air. Accordingly, designers of aircraft ECSs contend to provide an environment with clean air, appropriate temperatures and pressures, as well as right level of humidity. Although the cabin air is conditioned after it has been obtained from the engines, it is still possible for it to be contaminated by oil vapour, anti-icing fluid and so forth, whose quality and supply is determined by the filtration and the air distribution system of ECS. The risk is that contaminants in the atmosphere will not be filtered completely, or may even be present in the system lines and ducts as a result of cleaning fluid residue and other toxic material entering the system.

Discussing the sources of contamination, the internal cabin environment only is to be considered. The engine compressor seals prevent contaminated air being fed into the ECS, but there is a possibility that these seals may fail during their service life. The APU seals should also prevent the bleed air being contaminated, yet while the APU operates on the ground, at a busy airport, its intake air will be polluted by other aircraft exhaust, ground vehicle exhausts and vapours from spilled fluids on the tarmac. It may also be subject to re-ingestion of air from its own exhaust or from the aircraft engine exhaust depending on the wind conditions or heat rising from the tarmac.

The commercial aircraft takes a number of passengers and crew for the duration of the flight, which means that the cabin should be kept at certain altitude equivalent to a comfortable pressure and should be supplied with air circulation for the passengers. The aircraft ECS obtains air from the engine, the APU and the outside and then distributes it to the flight deck and cabin at the appropriate temperature, pressure, humidity and cleanliness to support the occupants. Bleed air is usually tapped off from the intermediate-pressure or the high-pressure stages of the engine where it has a very high temperature, and then it is cooled through heat exchangers before entering the cabin. Bleed air is also need for anti-icing and pressurization as well. The aircraft may well be parked for long time on the ground without the engine running, when the air is bled from the APU and fed into the cooling and distribution system. To enable the cabin conditions to be comfortable and controlled, the cabin is divided into sections and temperature control is provided for each section by the cabin crew. Air enters the cabin roof level and is extracted at floor level, flowing downwards to prevent cross contamination between passengers. Modern ECS of civil transport aircraft re-circulates up to half of the cabin air, while the fresh bleed air is treated to remove ozone and the recycled air is filtered for many contaminants including bacteria, dust, odours, and volatile organic compounds (VOCs). Such filtration module is accomplished by a high-efficiency particulate air filter (HEPA), conforming to European Standard 1822-1. This standard defines efficiencies from 85% to 99.995%, and it is supposed filters on transport aircraft conduct at the upper end of this scale with efficiencies of at least 99.95%. [12] A typical HEPA filter has the performance to ensure that the re-circulated air can be as clean as the fresh outside air.

There have been reports and events of smoke and fumes in the cabin air resulting from the oils leakage or hydraulic fluids entering the bleed air or pollutions left in the air distribution ducting during ground service. This may have a hazardous effect on the human respiratory system, particularly for the pilots. Recent research found high level of tri-cresyl phosphate (TCP). Exposure to it can lead to severe symptoms of respiratory illness and neurologic problems. Passengers often complain of feeling unwell after long-haul travel, but some aircrew are suffering illness that has the risk to cause them early retired from flying, which they claim is a result of air contamination.

Designers need to keep an awareness of the implications of their system on passengers and crew in a technical environment in which changes in one system may have a severe impact on other. Thus changes to engine oil additives may have produced contamination which is not being filtered out by current HEFA filters. New contaminants contained in the bleed air from new compounds used for the engine lubrication are thought to be a challenge as they enter the cabin air. But before it is possible to design a new filter to remove the contamination, sampling work is needed to identify the compounds in the cabin air. Aircraft such as the Boeing 787 are leading the concept of designing a completely new conditioning system that uses ram air to feed the ECS, rather than bleed air from the engine. The benefits to air quality is not primary, the main advantage of the new system came from a desire to isolate the engine from external bleeds to provide consistent operating conditions. Nevertheless it does provide air for the majority of the aircraft flight free from any form of combustion products. However, this does not mean that the APU if used to provide conditioning on the ground, will not provide contaminated bleed air. [12]

The conventional system is shown to draw air from the engines at high pressure and high temperature. In comparison, the Boeing 787 obtains its air from the external environment at relatively low pressure and temperature, the air being compressed by electrically driven turbo-compressors prior to entering the cooling cycles. This puts a high demand on the electrical system.

2.3.3 Cranfield report: Aircraft Cabin Air Sampling Study

This report describes the methodology and results of a sampling study for aircraft cabin air quality undertaken by Cranfield University and two contracted analytical laboratories on behalf of the Department for Transport (DfT). This study was set up because of concerns about possible adverse effects on the health and well-being of air crew resulting from exposure to toxic substances in the cabin air.

The principal objectives were to analyze the samples of the cabin air for volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), particles and carbon monoxide (CO) in normal routine operations during all phases of each flight (taxi, climb, cruise and descent), and to detect and characterize any abnormal increase of VOC, SVOC and particle concentrations during any fume events or air quality events in which bad smells or similar occurrences were reported. [14] Total sampling studies on 100 flights in 5 different aircraft were monitored in this way. The first part of the study involved monitoring on Boeing 757 cargo aircraft and included all necessary preparatory work for these operations, including equipment purchase, questionnaire design and protocol development. Subsequently Parts 2 to 5 of the study utilized the equipment and methods of Part 1 to carry out monitoring on Boeing 757, Airbus A320/1, BAe 146 and Airbus A319 passenger aircraft respectively. Aircrew and cabin crew were asked to carry out a post-flight questionnaire for all flights. This included questions regarding any fumes or smokes that occurred during the flight. It was also completed by the scientist conducting the air quality measurements. The flight staff were informed that the questionnaire was to be used in addition to normal fume event reporting procedures and that it did not replace them. No fume event occurred during this study to trigger the airline's formal reporting procedures. Sorbent tube samples were analyzed for the following target compounds: Tri-ortho cresyl phosphate (TOCP), one of a number of TCP isomers; Other tri-cresyl phosphate (TCP) isomers, applications include a minor component of engine oil; Tri-butyl phosphate (TBP), applications include a component of hydraulic fluid; Toluene, m+p-xylenes, Limonene, Tetrachloroethylene (TCE), undecane. [14]

This study successfully completed a range of air quality measurements during the course of 100 flights. No fume events occurred during these flights that could conform to the airline's protocols for the formal reporting of incidents.

Flight and cabin crew, as well as the investigating scientists reported a number of fume and smell events in a post-flight questionnaire. The monitoring results indicate that levels of carbon monoxide and toluene did not exceed safety, health or comfort limits described in the European standard “Aircraft internal air quality standards, criteria and determination methods”. Concentrations of carbon monoxide recorded during nine flights were equivalent to the 8h TWA health limit, [14] but this is supposed to be instrument malfunction rather than actual ascending levels of carbon monoxide. Samples specifically taken during recorded air quality events did not have obvious rising concentrations of any of the measured objects. Therefore, with respect to the conditions of flight that were experienced during this study, there was no evidence for target pollutants occurring in the cabin air at levels exceeding available health and safety standards and guidelines.

2.3.4 Workshop on Inhalable Toxic Chemicals in Cabin Air

A workshop "Inhalable Toxic Chemicals in Aircraft Cabin Air", held on 11th, October 2011 at Cranfield University, was organized in order to respond to the disinformation that has increasingly aimed and surrounded the issue of whether the aircraft cabin air is contaminated with the organophosphate chemicals, and whether those substances had already caused ill-health for the pilots and cabin crew. [16]

The issue has recently been brought into public focus by the publication earlier this year, of the "Aircraft Cabin Air Sampling Study", whose reporting work was carried out by the Institute of Environment and Health at Cranfield University on behalf of the UK Department of Transport. This report actually found significant concentrations of organophosphate and other toxic substances appeared in the cabin air even under normal flying conditions. Unfortunately, the final conclusion of the report is the statement: "With respect to the conditions of flight that were experienced during the study, there was no evidence for target pollutants occurring in the cabin at levels exceeding available health and safety standards and guidelines." The first phrase emphasizes the fact that the study failed to achieve measurement of a fume event, even though that was one of its principal objectives. Even if for normal flying conditions the claimed conclusion is irrelevant because no standards are available for some of the most problematic substances and chemicals. Nevertheless, despite the fact that this conclusion is neither reasonable nor justified by the sampling work already carried out, it has been carelessly and uncritically cited, and widely used to conclude that there is no safety and health problem.

It is widely recognized that, as not every possible experiment and observation has been carried out, there is already a great deal of data available regarding the problem. What might be lacking are an adequate critical analysis of the data and a consequential plan of actions.

The key initial hypothesis is "oil breakdown products from the engine are present in cabin air in concentration known to damage health". It should be the aim of the workshop to promote considered acceptance or rejection of this hypothesis and then to make it more precise. The primary focus should be definitely on the tri-cresyl phosphates present in jet engine oil as anti-wear additives. [15] Careful laboratory studies in animals have demonstrated their severe neurotoxicity. They can leak into the cabin via the oil seals in the engines and, as noted above, measurements have confirmed they did. There is, therefore, truly a health risk, increasing with the extent of exposure. There must also be a flight safety risk since the pilots are breathing the same air, even before inhalation is sufficient to cause complete ineligible state.

If there is proven evidence in favour of the hypothesis, the focus should move to possible technical solutions. [16] One is to stop bleeding air. The Vickers VC10 from the early 1960s was, apparently, the last jet airliner to have a separate compressor until the Boeing 787, which enters regular services in the recent time. But it will take many years before the world's existing bleed air jetliners is replaced, hence other ways must still be sought. Another is to reformulate the oil to eliminate tri-cresyl phosphate. Steps are being taken in this direction but it is proving hard to find substitutes with the same mechanical properties. Yet another is to decontaminate the air before it reaches the cabin, using adsorbent material. Again, work is being carried out without a satisfactory system having been developed yet. This remedy will, in any case, only work in conjunction with technology to continuously monitor the air composition. The development of an improved monitoring system should be given a high priority. It will alert pilots to any failure of the air supply leading to chemical contamination and enable an accurate decision on what actions to take in response to the reported level of contamination.

2.3.5 Summary

From such relevant literatures, the source of contamination in the cabin air could be involved in engine oils, hydraulic fluids, fuel, de-icing fluids, exhaust fumes, etc. The work of cabin air sampling undertaken by Cranfield University had been carried out by detecting and analyzing all the exposure substances, characterizing elevations and particle concentration during any fume events. The study had obtained air samples on a total of 100 flights from 5 types of commercial aircraft respectively. The result of the sampling study showed that the levels of the target compounds did not exceed the standards or guidelines in any available health and safety regulations, even though the existence and concentrations of the organophosphate and some other chemicals were found actually. It is considered that there are no specific standards and regulations for most of the contaminants for the cabin air, except two of the aimed pollutants, although some other standards and guidelines set for domestic and working environments had been regarded as references. Therefore, there are no regulations that can be enforced to the ECS systems and other related systems. Accordingly, the cabin air quality might never come into the system designer’s initial schedule. Furthermore, it is supposed that the limits to some substances levels within the current regulations and standards could be inconsequence, in which there is not an obvious illustration whether the level of those pollutants induce acute or chronic ill health.

Even if the bleed free architecture for air supply to the cabin, as completely cutting off the route by which contaminants from the engine come into, absence of contamination in the cabin air cannot be assured. The APU has been already used to provide air on the ground. The hydraulic system still requires pneumatic air to pressurize the hydraulic fluid tank. If this module fails then the fluid may enter the pneumatic system and hence find its way through the ECS into the cabin. The de-icing fluid can enter the ram air system as well. The solution to the cabin air contamination would be an integrated and multidisciplinary solution, concerned with other functional system related to the ECS, like the fuel system, the hydraulic system, the anti-icing system and so forth.

3 Cabin Layout

3.1 Cabin Layout for Conventional Aircraft

At the beginning of the GDP work, a conventional airliner was designed as a baseline by us so that every member can get an overview of conceptual design. Another purpose is to make a comparison between flying wing concept and conventional aircraft. According to the requirement based on the Chinese domestic market, the baseline airliner has been suggested to a family series, a medium range and large capacity as well as a long range and medium capacity, to meet different route and area of the domestic market.

After an consideration of the requirements and overall criteria for the conceptual design, the fuselage parameters that size the passenger cabin should be described.[2] This includes instructions on the fuselage cross-sectional geometry and the longitudinal layout of the seat rows, as well as the distribution of the seats between different classes. Meanwhile, airworthiness regulations must be involved into in order that passengers should be evacuated from the cabin in an emergency circumstance.

3.1.1 Cabin of Medium-range Airliner

Maximum seating capacity：320 in all-economy class

Typical configuration： 230 in mixed classes

External fuselage width： 5.64m

Internal cabin width： 5.30m

Seating abreast： 8(2-4-2) for economy class

Mixed classes layout

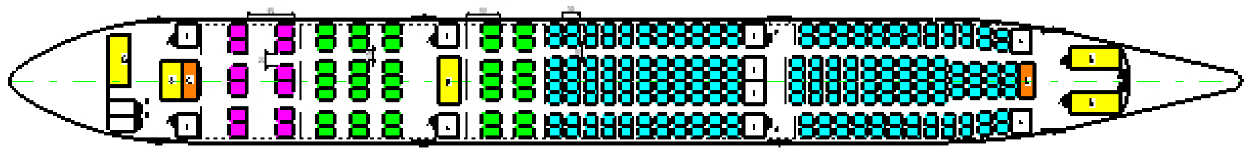


Figure 3-1 Three-class cabin configuration

First class seats: 12

First class pitch: 85 in

Seat width: 27 in

Business seats: 35

Business pitch: 60 in

Seat width: 24 in

Economy seats: 184

Economy pitch: 32 in

Seat width: 20.7 in

Two-class layout

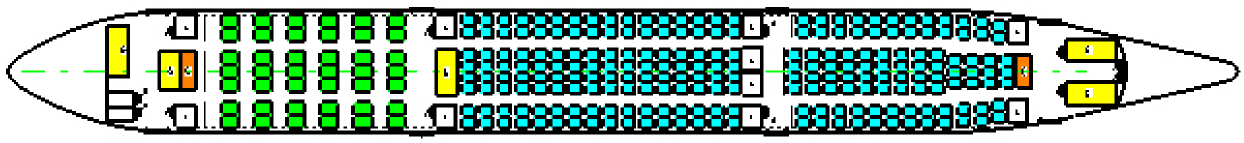


Figure 3-2 Two-class cabin configuration

Business seats: 42

Business pitch: 60 in

Seat width: 24 in

Economy seats: 224

Economy pitch: 32 in

Seat width: 20.7 in

Single class layout

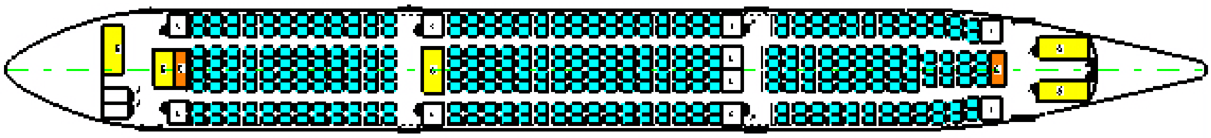


Figure 3-3 Single class cabin configuration

Economy seats: 320

Economy pitch: 32 in

Seat width: 20.7 in

3.1.2 Cabin of Long-range Airliner

Maximum seating capacity232 in all-economy class and high density configuration

Typical configuration： 196 in mixed classes

External fuselage width： 5.64m

Internal cabin width： 5.30m

Seating abreast：   8(2-4-2) for economy class

Mixed classes layout

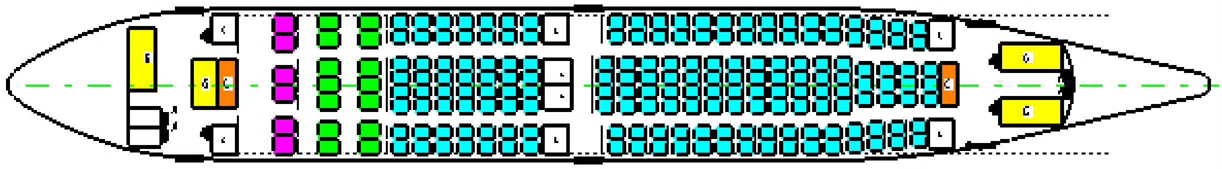


Figure 3-4 Three-class cabin configuration

First class seats: 6

First class pitch: 85 in

Seat width: 27 in

Business seats: 14

Business pitch: 60 in

Seat width: 24 in

Economy seats: 176

Economy pitch: 32 in

Seat width: 20.7 in

Two-class layout

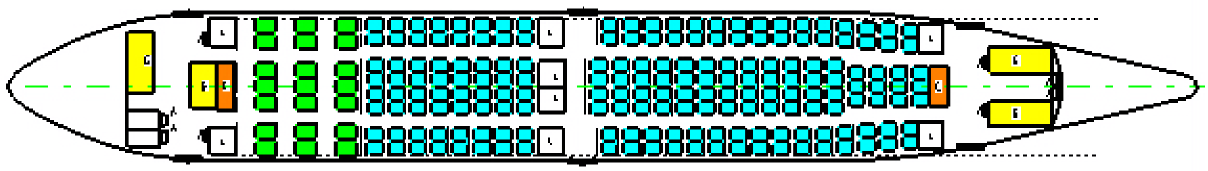


Figure 3-5 Two-class cabin configuration

Business seats: 21

Business pitch: 60 in

Seat width: 24 in

Economy seats: 184

Economy pitch: 32 in

Seat width: 20.7 in

Single class layout

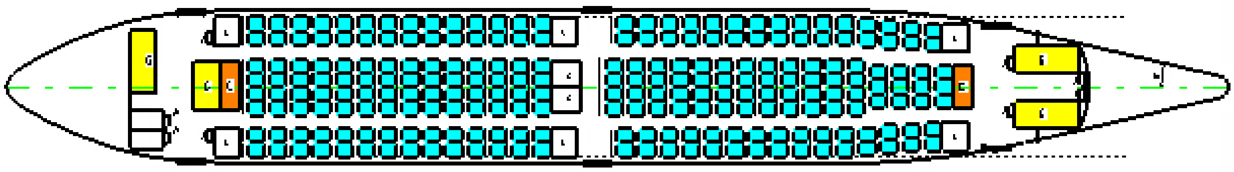


Figure 3-6 Single class cabin configuration

Economy seats: 232

Economy pitch: 32 in

Seat width: 20.7 in

3.1.3 Cross section of the cabin

First class (2-2-2)

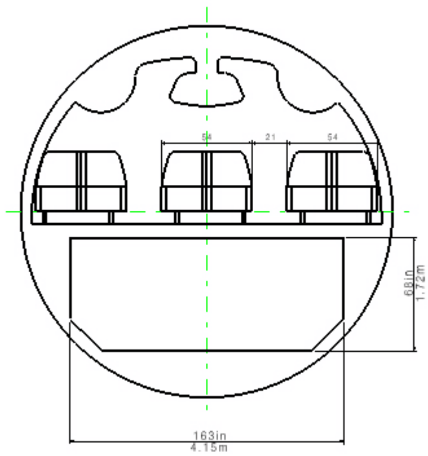


Figure 3-7 First class cross-section (unit: mm)

Business class (2-3-2)

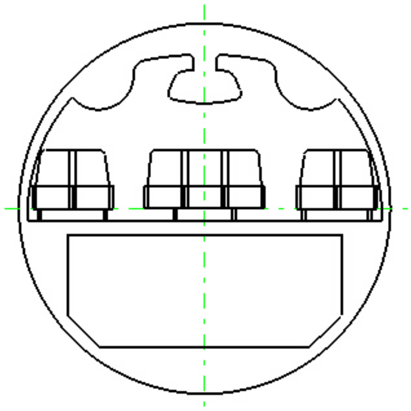


Figure 3-8 Business class cross-section (unit: mm)

Economy class (2-4-2)

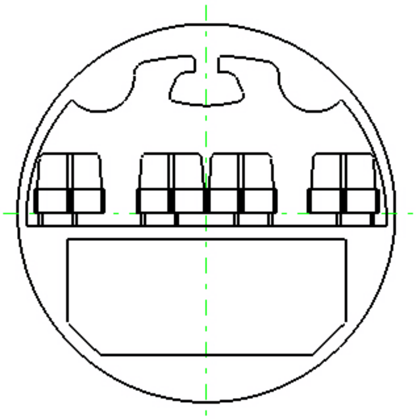


Figure 3-9 Economy class cross-section (unit: mm)

3.1.4 Cargo Arrangement

Table 3-1 Cargo capacity

	Long range 232-seats		Medium range320-seats	
Cargo area	FWD	AFT	FWD	AFT
LD3 Containers(No.)	12	6	18	14
Container cargo(m^3)	81		144	
Bulk cargo(m^3)	9.85		9.85	
Overall cargo volume(m^3)	90.85		153.85	
Cargo/passenger (m^3)	0.39		0.48	

3.1.5 Doors and Exits

Table 3-2 Doors and exits

	Long range 230-seats		Medium range 320-seats	
	Type	Quantity	Type	Quantity
Passenger/crew doors	A	4	A	6
Emergency exits	I	2	I	2
Cargo doors	N/A	2	N/A	2

Dimensions for all of the doors and exits (height by width):

Passenger/crew doors: 1930mm×1070mm,

Emergency exits: 1660mm×1070mm,

Cargo doors: 1700mm×2700mm

3.2 Cabin Layout for Flying Wing

The practice of designing the flying wing aircraft is expectedly a challenging task. Significant challenges have been faced during the process. For instance, on the one hand, the inner part of the wing should be sufficiently thick to arrange the crew, passengers, cargo and tanks; on the other hand, outer part should be thin to achieve high cruise speed and L/D ratio. In addition, the issue of stability and control should be considered. To some extent, the compromise in aerodynamic performance is necessary to meet the different aspects of the requirements.

In the stage of conceptual design, normally it is not necessary to define the detailed flight deck elements, like the actual pilot's eye point, the location of controls and instruments. Nevertheless, the approximate volume must be checked so that in the following stage, it will not revise the overall aircraft due to the detail flight deck design and payload integration work. [3] Probably the actual cabin layout for a commercial aircraft is determined much more by the marketing the by the regulations. Thus, pitch, width and headroom would be redefined for a flying wing aircraft according to its new concept in the airfoil and its entirely different fuselage structure.

Maximum seating capacity：248 in all-economy class

Typical configuration： 208 in mixed classes

Internal cabin width： 11.6 m (4 compartments)

Seating abreast： 4(2-2) seats in economy classes

Mixed classes layout

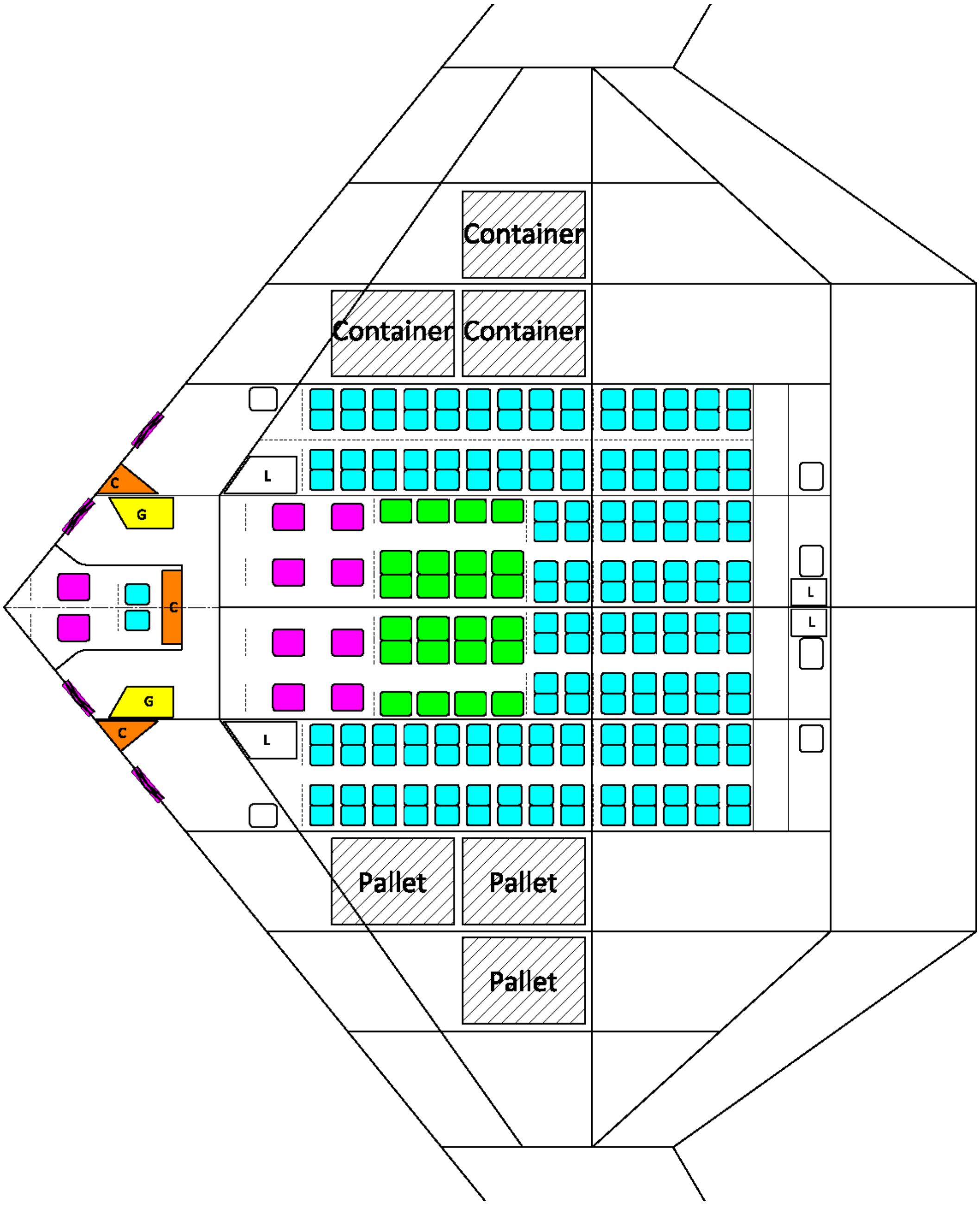


Figure 3-10 Three-class cabin configuration

First class seats: 8

First class pitch: 60 in

Seat width: 27 in

Business seats: 24

Business pitch: 38 in

Seat width: 24 in

Economy seats: 176

Economy pitch: 32 in

Seat width: 20.7 in

Single class layout

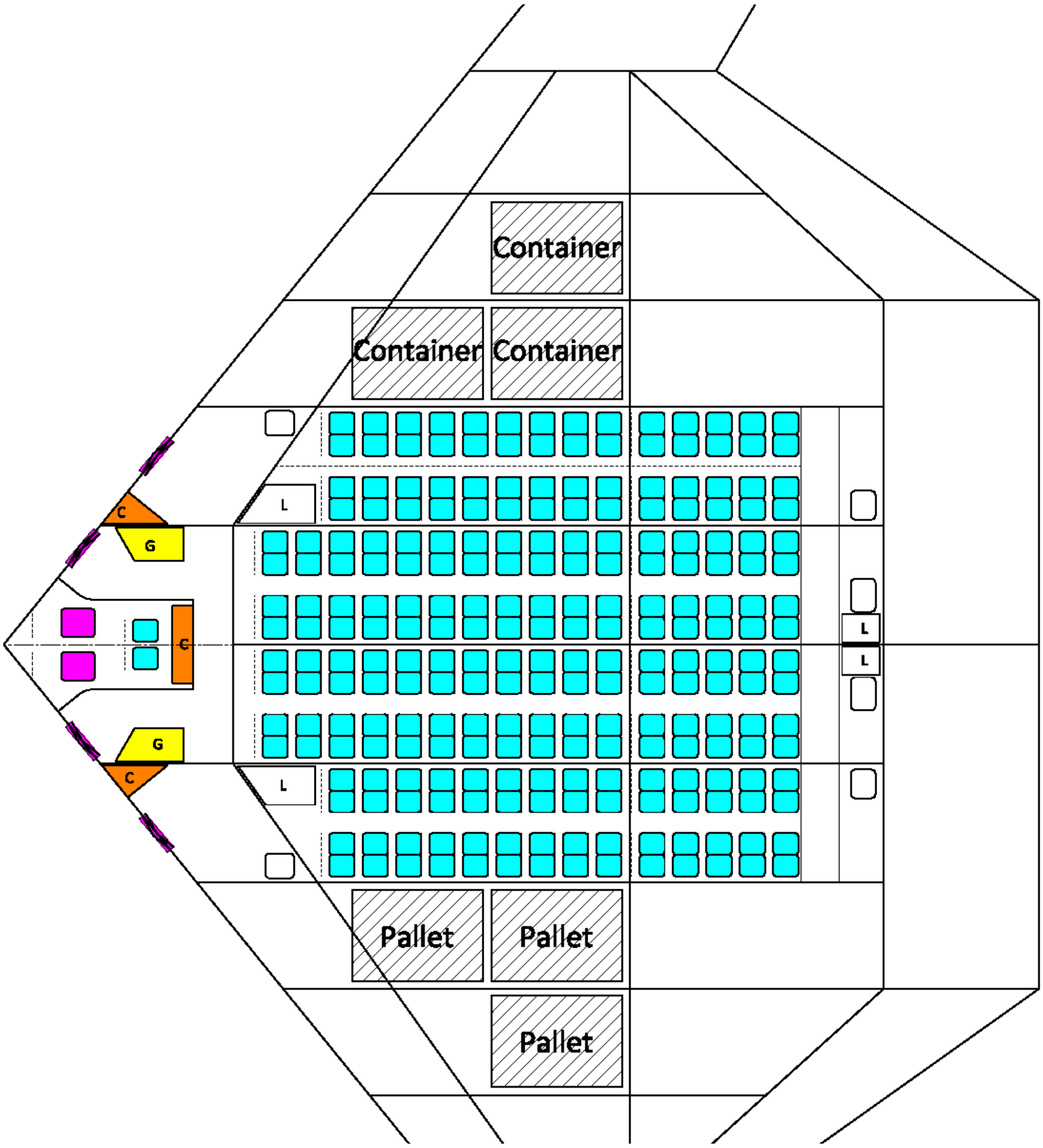


Figure 3-11 Single class cabin configuration

Economy seats: 248

Economy pitch: 32 in

Seat width: 20.7 in

Cross section

Business class (2-1)

Economy class (2-2)

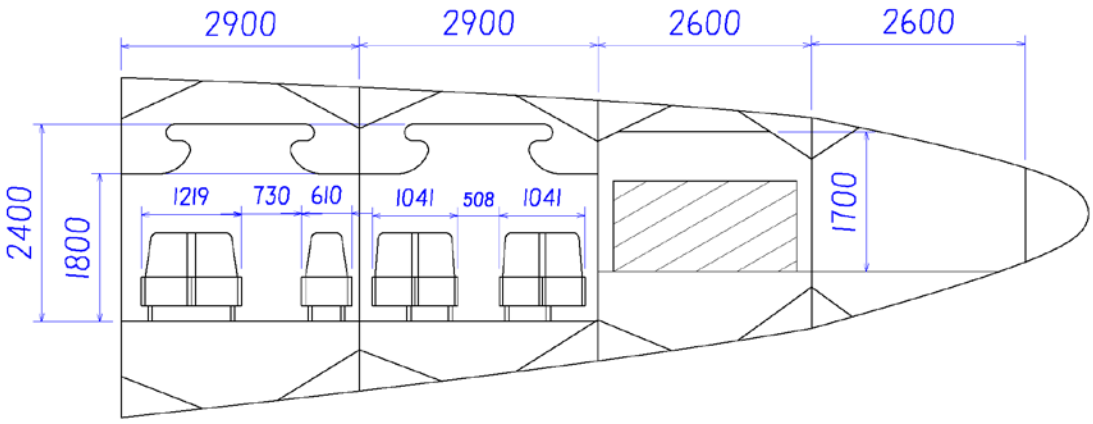


Figure 3-12 Business class and economy class cross section (unit: mm)

Doors and Exits

Table 3-3 Doors and exits

	Type	Quantity
Passenger/crew doors	A	4
Emergency exits	N/A	6
Cargo doors	N/A	2

Dimensions for all of the doors and exits (height by width):

Passenger/crew doors: 1900mm×1070mm,

Emergency exits: 800mm×600mm, 700mm×600mm, (length by width)

Cargo doors: 1100mm×2400mm

Cargo

Non-standard container dimension: 88 in(width)×125 in(length)×43 in(height)

Standard pallets with limited height: 88 in(width)×125 in(length)×42 in(height)

No. of containers (pallets): 6

Overall cargo volume (m3): 44.4

Cargo/passenger (m3): 0.176

3.3 Performance

The performance specified here includes field performance, cruise performance and payload range characteristics.

Field Performance [17]

Maximum certificated runway for maximum Take-off at ISA sea level conditions: 1,670 m

Factored FAR Landing distance at maximum landing weight: 1,852 m

Cruise Performance [17]

Design cruise speed: M 0.82

Minimum Cruise ceiling from M_{tow} take-off: 35,000 ft

Payload Range Characteristics

The payload-range diagram is shown in Figure 3-13 and Table 3-4.

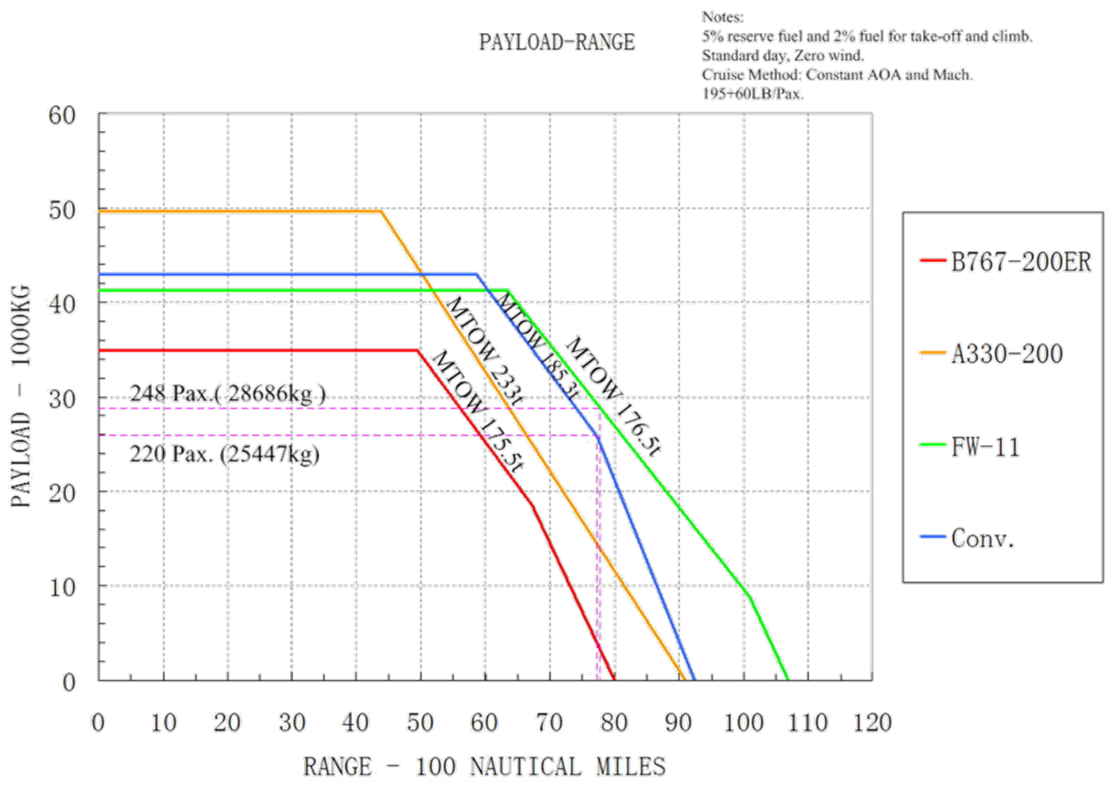


Figure 3-13 Diagram of payload-range [17]

Table 3-4 Fuel efficiency data [17]

seats	248
weight/pax(kg)	115.7
MTOW(kg)	176469
OEW(kg)	75044
payload(kg)	28686
Payload & OEW(kg)	103730
Payload Range(nm)	7772
fuel capacity(kg)	72739
Fuel used(kg)	67647
Fuel/pax/nm(kg)	0.035

3.4 Conclusion

From the performance comparison especially the payload range characteristics (Figure 3-13), it can be illustrated that the flying wing aircraft would be more fuel efficient, about 29% less fuel consumption averagely than A330-200, [17] which can be significantly attributed to improved L/D ratio and decreased wing load. Another reasonable advantage is the reduction of manufacturing and maintenance costs, since the flying wing aircraft is assembled by fewer products than a conventional one.

However, some drawbacks are aware of along with the project. As we know, cabin arrangement directly affects the passenger comfort. The flying wing aircraft could not support so many windows for passenger view in the air. Besides the windows, the pressurization for the cabin is an obstacle to this kind of irregular compartment, which could lead to reinforcing the structure and weight rising.

4 ECS Components Related to the Air Quality

4.1 Introduction

Civil transport aircraft are designed to deliver passengers securely and comfortably, through long durations in air, from departure to destination. The external environment of the aircraft, during all the flying stages, varies considerably in outside temperature, pressure and humidity. As for jet aircraft to carry passengers in the extremely rigorous environment, environmental control systems (ECS) are designed for the purpose of maintaining a perfect internal cabin environment. As referred to the context, cabin air contamination can be sourced from the engine oils through the ECS. Therefore, in this chapter, each component or subsystem that is considered to be part of the ECS or that is integral to providing essential environmental conditions for the aircraft cabin would be then described and examined, following by an overview the main functions of the ECS.

As nearly all current commercial passenger aircraft in service use engine bleed air for the air source of the ECS, so the emphasis is on ECS systems with bleed air architecture. Consequently, it should have a definite understanding of each ECS components, although the descriptions presented are for typical aircraft and some may not apply to specific aircraft models and their systems.

4.2 Current ECSs in Commercial Airliner

All commercial passenger aircraft manufactured recently and such aircraft in service use ECSs usually based on engine bleed air. Figure 4-1 presents an overview of the bleed-air-based ECS and equipment, temperatures and pressures listed are typical examples of some aircraft in the cruise conditions. Bleed air is extracted from the engine compressors and supplied to those air conditioning packs, where it is further cooled, compressed, and then transferred into the passenger cabin. The conditioned air out of the packs is supplied to a mixing manifold that distributes it to the separated zones in the cabin. Recirculation fans extract air from the cabin, pass it through filters, and deliver it to the mixing manifold, where it is mixed with the conditioned air from the air conditioning packs. Trim air is part of hot bleed air that bypasses the air conditioning packs. Small amounts of trim air are mixed with the air supplied to the cabin from the mixing manifold to provide independent fine temperature control in each zone. The bleed air from the engines is at a pressure sufficient to operate the air conditioning packs and pressurize the cabin. Accurate cabin pressure is maintained by several outflow valves that automatically regulate the flow of air out of the aircraft pressure hull to the ambient environment to maintain the expected cabin pressure.

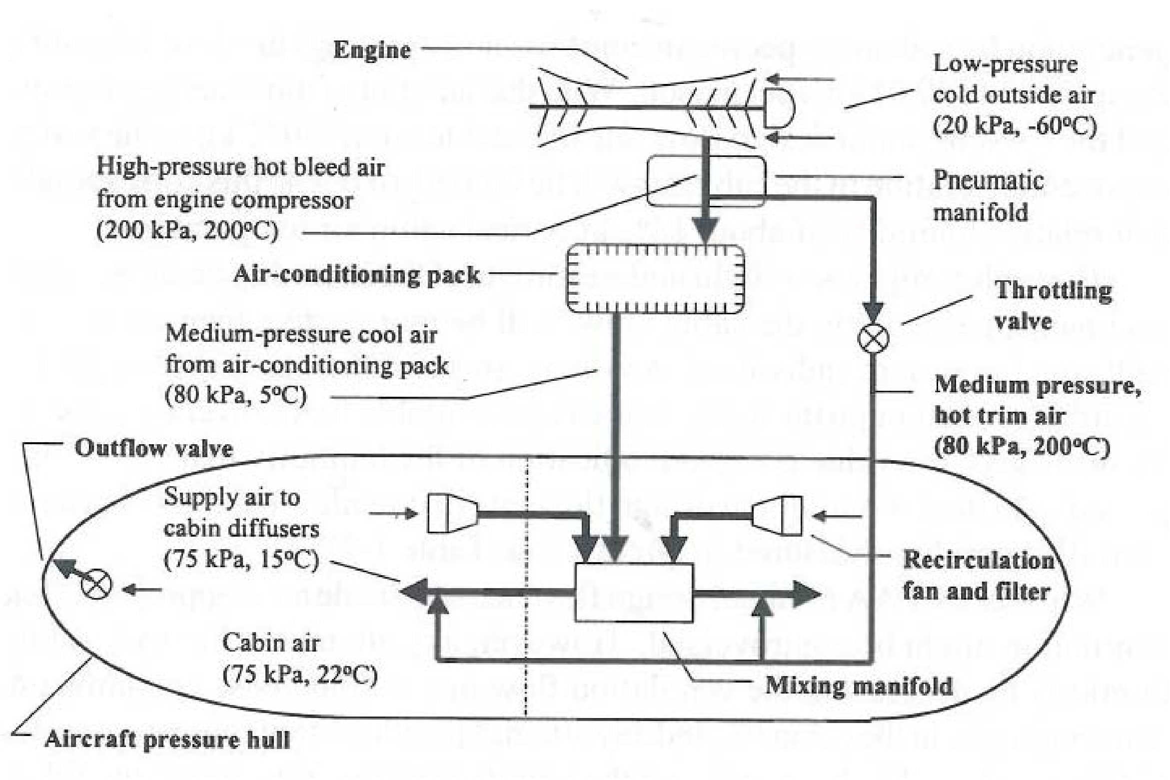


Figure 4-1 Simplified illustration of aircraft ECS [20]

Another typical example is the air conditioning system of Boeing 757, which represents a typical airliner ECS, as shown in Figure 4-2. Bleed air coming from twin engines, APU, or high pressure air from ground facility is conditioned by the two identical air conditioning packs, after removing ozone through the ozone converters. Conditioned air from the packs runs into the mix chamber where it mixes with the recirculation air. Recirculation fans maintain overall cabin air circulation while allowing a reduction of cabin air ventilation, permitting the packs to be operating at a reduce flow. Then the mixed air is ducted into the passenger cabin. The flight deck receives absolute fresh conditioned air from the left pack only and is assured at a slightly higher pressure than the passenger cabin, which prevents smoke from entering the flight deck. When the left pack is invalid, the flight deck can receive air from the mix manifold.

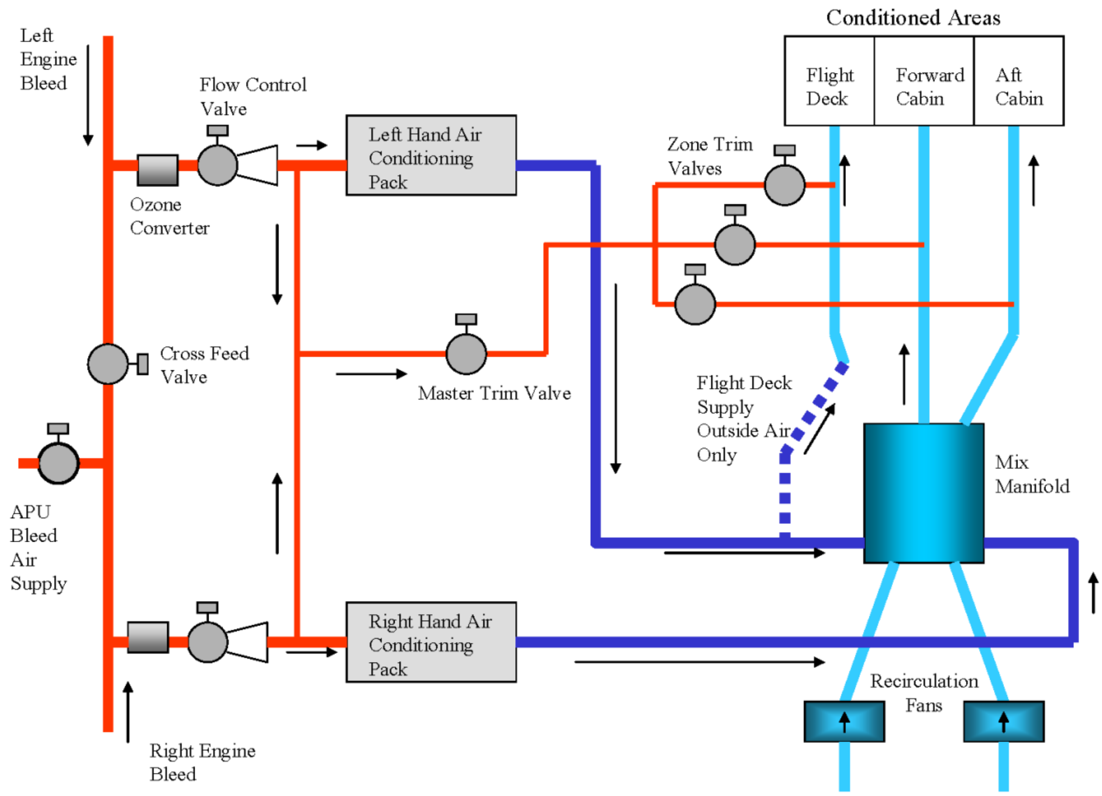


Figure 4-2 Boeing 757 air conditioning system schematic diagram [28]

The main ECS components and subsystems are discussed below. Before the effect each component have as regards the cabin air contamination, the potential contaminants sources such as engine oils, lubricants, hydraulic fluids and de-icing fluids should be understood. All of the analyses and comments are on a basis of the assumption that there are engine oils leaking into bleed air in consequence of engine seals failure or any other reason.

4.2.1 Contaminants Sources

Contaminants from the engines and APU may enter the bleed air system that supplies air for the air conditioning packs. As the routes from engine to their first destination-ECS pack has already been fixed, the physical properties of those contaminants and their source compounds should be understood initially. After that, examinations and analyses would be carried out accurately and effectively.

Bleed air is extracted from the engine compressors section, upstream stage of the combustion chambers, as used most of the commercial aircraft. From many reports and investigations, it can be recognized that the intake of synthetic jet engine oils, hydraulic fluids and de-icing fluids causes the bleed air to become contaminated, primarily due to various incidents such as oil leaks or inoperative sealing at the engine or APU. Those oil or fluid leaks from the engine may be in the form of unchanged state, thermal degraded, combusted or pyrolised into the form of gases, vapours, mists and particulate matter. A range of other toxic substances or chemicals formed of those compounds may be produced, through oil breakdown under the high pressure and temperature. Pyrolysis studies showed that two jet engine oil heated to 525 ºC resulted in the release of CO_2 and CO, besides a large number of volatiles with TCP found both in oils as well as in the air. It is also showed that the Grade 1 oil MIL-L-7808 will decompose at temperatures above 400 ºF (204 ºC) with the formation of various vapours. [11] Further pyrolysis studies of two hydraulic fluids and jet engine oil showed that volatiles and organophosphate were released in all kind of situations, with engine oils being an important source of carbon monoxide.

However, what are those chemicals and substances and which kind of form are those in the aircraft ECS? An oil leak from an engine at high temperature or pressure may burn or pyrolyze before it enters the cabin air supply. There are few studies about the actual chemicals that enter the aircraft ventilation systems from the APU or the engines when the lubricating oils or other aircraft fluids have been heated in excess of 500 ºC. At such high temperatures, pyrolysis of the contamination compounds can be expected accordingly, the result of which is a thermal breakdown of the products that could have unexpected effects. [11]

The cabin air contaminants will be in the gas, vapour, mist and particulate form and such a complex cannot be neglected without consideration. Mists and aerosol particulates would usually decrease under the force of gravity and when they adhere to the surfaces of the piping or components even be eliminated, hence the concentration of the mist in the air would drop dramatically, only low consistency of vapour left, with only low levels of measurable chemicals. Therefore specific analysis of the air could be reduced by orders of importance. Concerning the extremely high temperature and pressure at the inlet of bleed air system, any reaction or degradation cannot exclude of consideration yet.

4.2.2 Bleed Air Supply

As Figure 4-3 shows, the essential features of a modern jet engine that is used on most commercial passenger aircraft are listed. Bleed air is the compressed air that is extracted from the engine compressor, where there are mostly two extraction ports located at the high stage and the intermediate stage of the compressor respectively. Figure 4-4 shows a typical bleed air system. When the bleed air comes off the engine, it is at a high temperature and pressure, exactly depended on the mode of the engine setting.

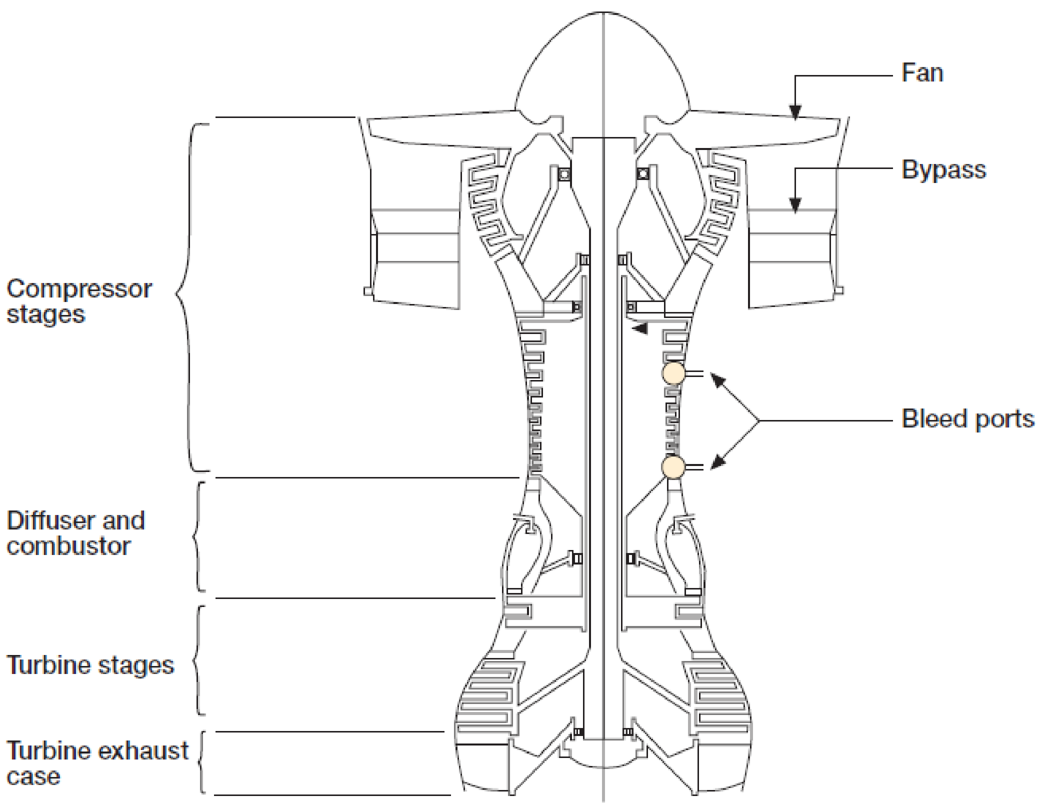


Figure 4-3 Basic Components of a jet engine [20]

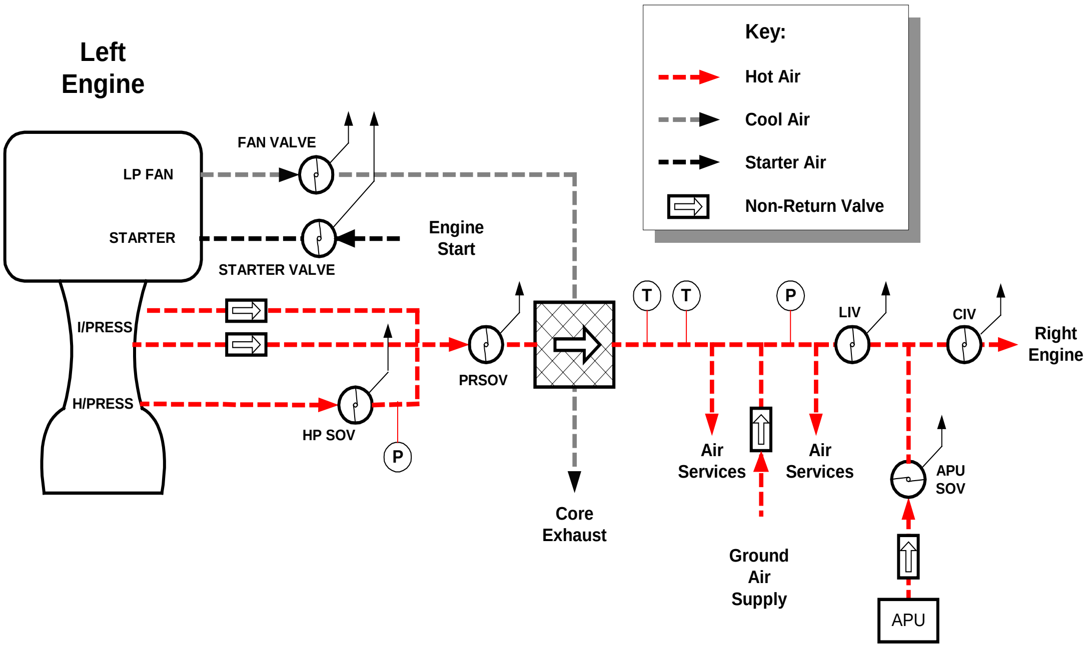


Figure 4-4 Bleed air supply from engine [22]

However, the bleed air can be too hot to directly supply to the air conditioning packs unless it passes through a pre-cooler, which regulates the temperature of the bleed air to about 175 ºC (350 ºF). High pressure bleed air is tapped off to the leading edge of the engine for the purpose of de-icing and engine starting. Then pressure regulators reduce the pressure to 310 kPa (45 psi) in order to meet the inlet pressure of the air conditioning pack. [18] [19]

At cruise altitudes, the ambient air may contain excessive ozone. Some aircraft may be equipped with ozone converters to trim down the ozone in the bleed air to an acceptable level before supplying to the ECS. It can be noted from the Figure 4-3 that some bleed air systems may have an ozone converter bypass feature that permits bleed air to enter the cabin immediately. The bypass is to allow air to the ECS up to 20000 ft, the ozone converter is only required above this altitude where ozone concentration increases and becomes a to humans. This bypass feature can be taken as a safe configuration that prevents contaminating the converter catalyst when the outside air might be polluted at low altitude or the takeoff stage.

From the above introduction on bleed air supply, it can be seen that the temperature and pressure of the air for air conditioning is regulated to meet the inlet level of the pack. [20] Nevertheless, the pressure of the bleed air can be as high as 1170 kPa (170 psi) and the temperature can be up to 350 ºC (660 ºF) when it comes out of the engine. Such high pressure and temperature could make the polluted oils degrade. Both the two high elements can keep those misted or vapour chemicals active and make their molecular movement more strongly. Later, when crossing a pre-cooler and some pressure reducing valves, the contaminations could slow down but still probably spread to the air conditioning packs.

4.2.3 Air conditioning Packs

Air conditioning packs are used to cool, dehumidify the bleed air from the engines or APU before it enters the passenger cabin. Commercial passenger aircraft typically have at least two air conditioning packs. Figure 4-5 shows a typical air conditioning system, which is for an aircraft with two engines and two packs but the basic principles are the same as others.

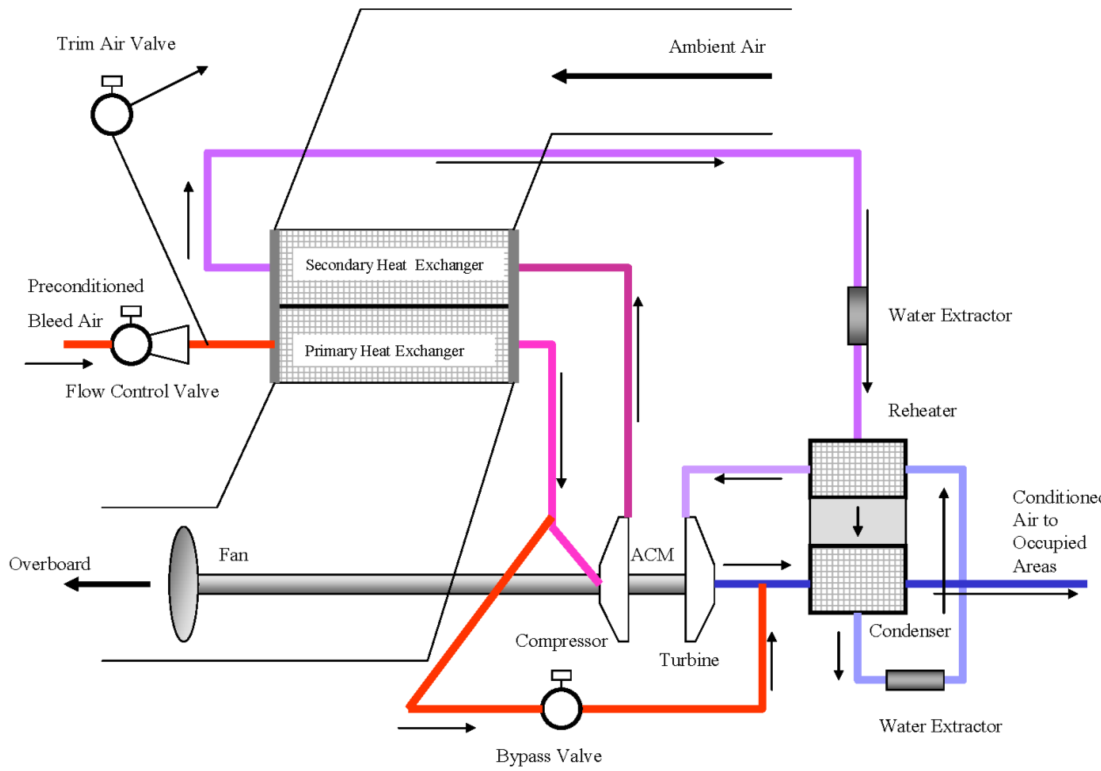


Figure 4-5 Configuration of air conditioning packs

The air conditioning pack includes two heat exchangers cooled by ram air, a compressor, and a turbine. The inlet for the ram air duct faces the airflow over the aircraft, thereby pressurizing the ram air to flow through the heat exchanger when the aircraft is in flight. When the aircraft is on the ground, however, a fan is required to drive the cooling air through the heat exchanger. The functions of the compressor and turbine in the pack are different from those in the engine. The air conditioning pack has no fuel or combustion and the power to operate the pack is derived from the pressure of the conditioned air stream. Also, the pack compressor and turbine can use air bearings to eliminate the need for lubricants. [18]

Bleed air from the aircraft engines or APU enters a pneumatic manifold and is supplied to the air conditioning pack. It passes through the primary heat exchanger where it is cooled, and then is compressed to a higher pressure in the compressor, increasing its temperature. The hot, high pressure air is cooled again in the secondary heat exchanger. The air is then expanded, and its pressure is reduced in the turbine. Sufficient energy to operate the compressor is extracted from the pressurized air by the turbine. As a result, the temperature of the air drops distinctly and is cold enough to provide cooling for the cabin even in hot environments.

In typical cruise conditions, the ram air is cold enough to cool the bleed air, and the bleed air is sufficiently dry so that no moisture has to be removed. If so, a bypass valve is opened to let the bleed air go from the primary heat exchanger in the pack to the cabin without further conditioning.

When the aircraft is on or near the ground in a humid environment, moisture will condense from the air when it expands in the turbine. The moisture is removed from the air by a water separator downstream of the turbine. The water separator cannot be allowed to freeze, and this requirement often ensures the lower temperature limit for the air from the pack. The need to prevent freezing in the water separator is an important limitation on the system described in Figure 4-5.

In conclusion, the air conditioning pack continues to cool the air supply and remove the moisture from the air after the bleed air pre-cooling. The temperature can be less than 10 ºC after mixing with recirculation air. As for the contaminants following by the air supply, the vapour and mist substances inside of the air can be easily put off. Thus, the pack would decrease the consistency of the contaminants in the air supply, even though it is difficult to measure. [20]

5 Boeing 767 ECS effect on contamination

Current civil transport aircraft usually use bleed air as the air supply and power source for the ECS. What we discuss above is to look over the main components through which the bleed air enters the passenger cabin. If contamination occurred in the sources of bleed air, what effects could be given by each of the components located across the routes that bleed air invades into. Therefore, this chapter presents a case study of the Boeing 767 (B767) ECS, in order to find out any relations of the contaminants delivery and the variables in each cabin air supply components.

The B767 is a wide-body jet airliner manufactured by Boeing Commercial Airplanes, mounted with twin engines, of which the ECS mixes conditioned outside air and filtered recirculation air at an appropriate temperature. As Figure 5-1 shows, there are two identical air conditioning packs cooling the bleed air from the engines or APU. Conditioned air from the packs enters a mix manifold where it is mixed with air from two recirculation fans. After that, the mixed air is transmitted into the different temperature controlled areas of the aircraft cabin.

The B767 case study follows with a sequential explanation of each component involving with the cabin air supply, following by some comments and analyses about the effects that ECS components have in terms of any variables such as temperature, pressure and humidity. After those studies, there is a discussion on the overall consequences on the cabin air contamination transference. [30]

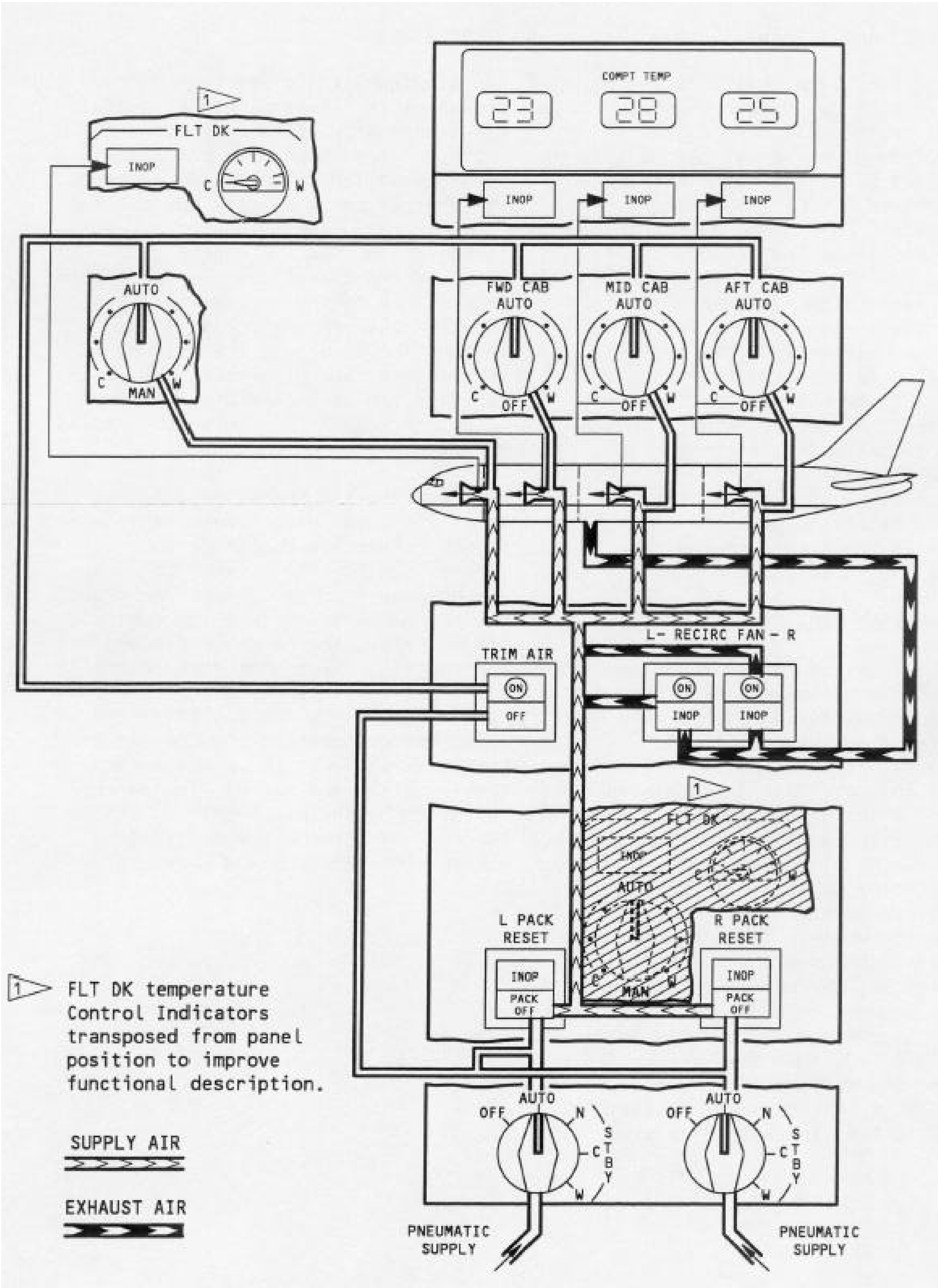


Figure 5-1 Boeing 767 air conditioning system schematic diagram [30]

5.1 Introduction

The B767 ECS consists of separate subsystems that provide control and conditioning of airflow into the cabin areas. Preconditioned air from the pneumatic system is supplied to the two air conditioning packs. The conditioning pack constitutes of a three-wheel air cycle machine, four heat exchangers, control valves, protective devices and all necessary ducting and accessories. A microprocessor provides automatic control for each pack. The conditioned air from each pack is mixed with recirculated cabin air in a conditioned air mixing manifold. The conditioned air from the mix manifold is then distributed to the three temperature controlled zones in the aircraft. A zone trim air subsystem provides a means to mix warm bleed air with mixing manifold conditioned air for temperature control purposes. A microprocessor provides automatic zone temperature control. Fibreglass ducting distributes conditioned air to the three zones. A gasper system consisting of a fan and associated ducting provides gasper air distribution to each passenger seat position. A ventilation system consists of ducting, fans and check valves that provide ventilation of the lavatories and galleys. [31]

The cargo compartment heating system consists of aluminium ducting, valves, and thermal switches. The system controls the flow of the warm air from the bleed air system into the floor area of the cargo compartments. Automatic control and overheat protection is provided for each compartment.

A pressurization outflow valve provides passenger cabin pressure control. Microprocessors provide automatic system control. Relief valves provide positive pressure relief and vent doors provide negative pressure relief. System control, indication and warning are provided on the overhead control panel in the flight deck. The cabin pressurization system will be covered as a separate instructional segment after the air conditioning system.

The equipment cooling system consists of fibreglass ducting, fans, valves and sensors that provide forced air cooling for the electrical and electronic equipment installed in the equipment bays and flight compartment. A microprocessor provides automatic control for the system. An analogue controller provides temperature control for the system. The ventilation system provides draw-thru cooling for the aft equipment centre.

5.2 Study of ECS Components

5.2.1 Pneumatic system

The pneumatic system, namely bleed air system, is the air source of the ECS. After ambient air enters the compression stages of the engine, it is compressed to 220 kPa and heated to 166 ºC (330 ºF). [36]Amount of the hot air is then extracted from the engine through the high stage and the intermediate stage of the engine compressor, which can be different due to the engine type. Figure 5-2 illustrates a simplified schematic including the mains components of the P&W 4000 engine.

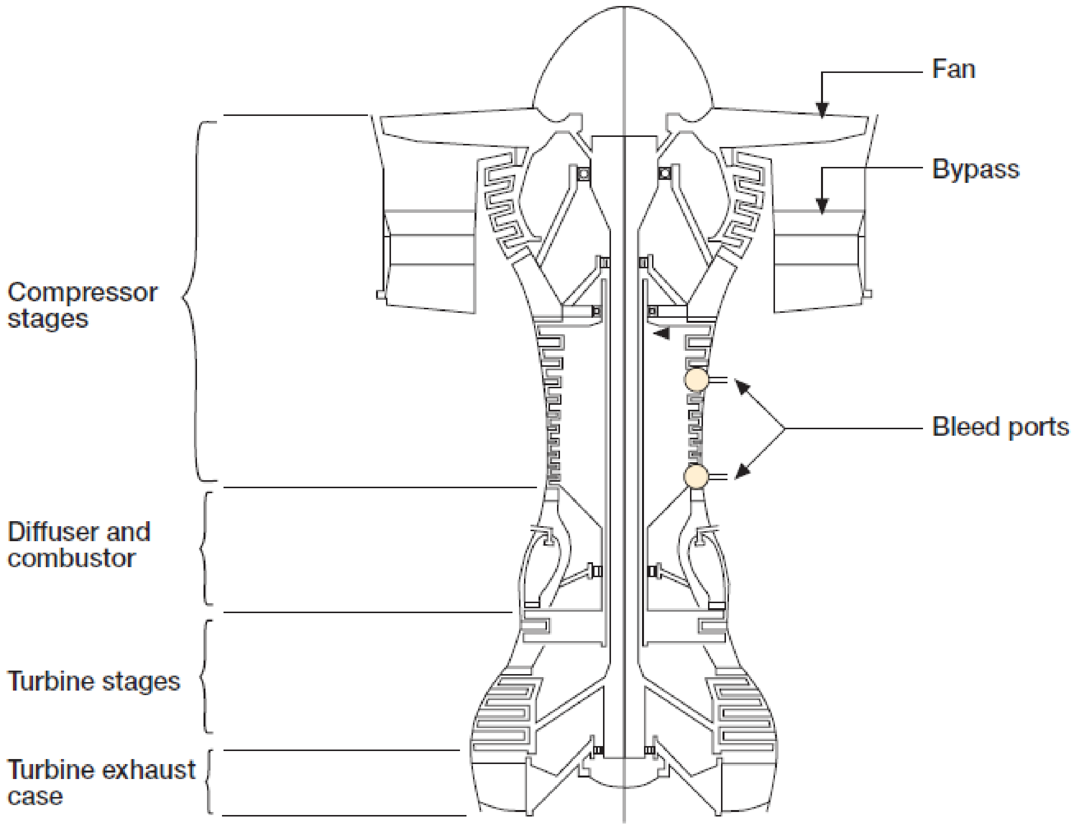


Figure 5-2 P&W 4000 engine architecture [36]

The high stage is that air inside which has a higher pressure available from the engine compressor. With a low engine throttle setting, the high stage can be the only source of air at sufficient pressure to meet the needs of the bleed air system. The bleed air system consists of a number of valves and a heat exchanger. It automatically provides air at the proper temperature and pressure required to meet the needs of all pneumatic services on the aircraft. A schematic of B767 bleed air system is presented in Figure 5-3.

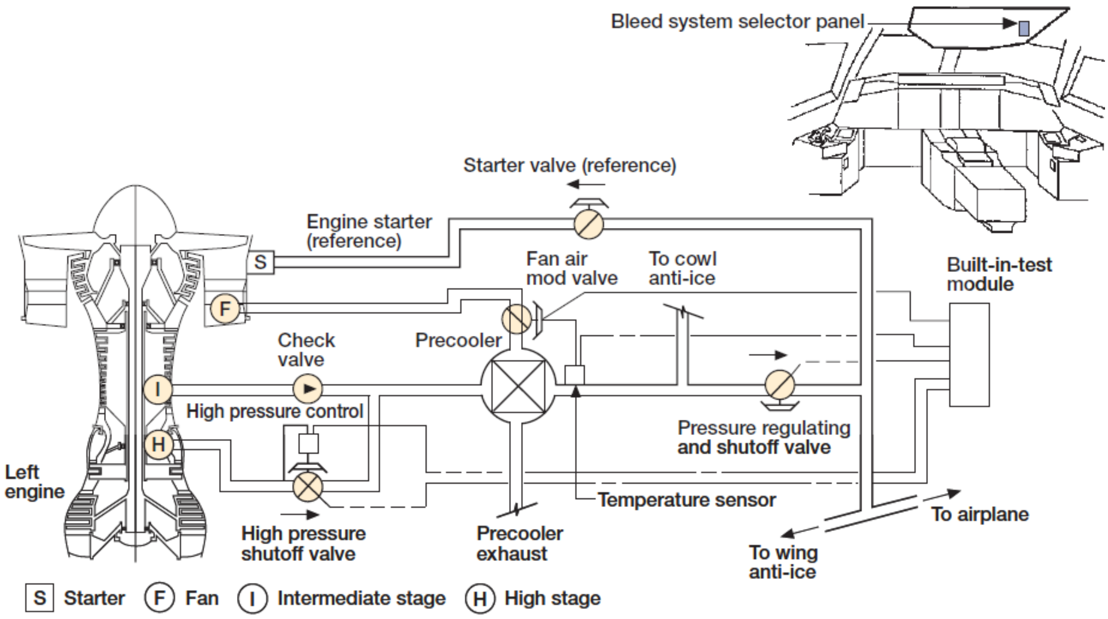


Figure 5-3 Boeing 767 bleed air system [36]

As the aircraft taxis onto the runway, the engine thrust is raised to takeoff power gradually, while the high stage air can be compressed to 650 ºC (1200 ºF) and 2960 kPa. [36] This level exceeds the requirements for the air conditioning pack and other pneumatic uses. However, the bleed air system automatically switches to the intermediate stage port. The function of the precooler is to discharge the excess energy back into the atmosphere, which ensures the temperature of the pneumatic manifold is always well below the ignition point. This is important in the event of a fuel leaking.

Once the aircraft climbing to a cruise altitude of 40,000 ft, the outside condition changes dramatically. The outside air temperature is at a pressure of 20 kPa. The partial pressure of oxygen is 3.4 kPa. Under the above conditions, it cannot survivable for unprotected human beings. The low or intermediate port can supply compressed air with temperature above 205 ºC (400 ºF) and pressure of more than 206 kPa. Figure 5-4 shows the temperature of air being extracted from the engine compressor to the bleed air system during flight. The airflow leaves the pneumatic system at a temperature of 205 ºC (400 ºF) and a pressure of 206 kPa while in cruise. Then the air passes through an ozone converter to the air conditioning packs. [36]

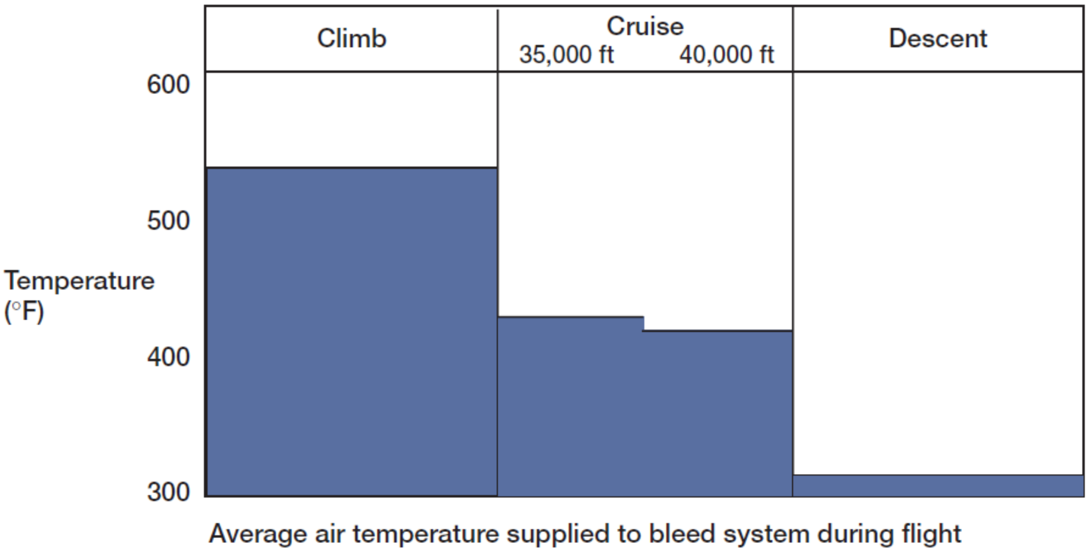


Figure 5-4 Air temperature at the engine bleeding port [36]

If the leaking events occur at the bleed air system, there could be any of the engine oils, lubricants or other fluids that enters into the compressed air at the upstream of the bleeding ports. Under those rigour conditions of the bleed air system, of which the temperature can be 166 ºC to 350 ºC and pressure can up to 2960 kPa, [31] the contaminants will keep a unsteady state , might in the form of gases, vapours, mists and particulate matter due to thermal degradation, combustion and pyrolysis. A range of other toxic substances or chemicals formed of those compounds may be produced, through oils and lubricants breakdown. The next destination of those substances might be to enter the air conditioning packs following with the bleed air.

5.2.2 Air Conditioning Packs

The air conditioning pack of B767 is an air cycle refrigeration system that uses the air passing through and into the aircraft as the coolant. This is accomplished by a combined turbine and compressor machine, valves for temperature and flow control, and heat exchangers using outside air to reject the unnecessary heat.

The air conditioning pack provides essentially dry, clean and dust free conditioned air to the aircraft cabin at proper temperature, flow rate and pressure to satisfy pressure and temperature control requirements. For the B767, this is approximately 5 cubic ft per minute (cfpm). To ensure redundancy, two air conditioning packs provide a total of about 10 cfpm of conditioned air per passenger, whereas an equal quantity of filtered recirculation air is mixed with it for a total of approximately 20 cfpm per passenger. [36] This high quantity of supply air results in a complete cabin air exchange about every two and a half minutes. The high air exchange rate is important to control temperature gradients, maintain air quality and prevent smoke and odours in the cabin. Temperature control is the predominant driver of outside airflow requirements.

From the temperature and pressure at the outlet of the air conditioning pack, the contaminated air have had a procedure of cooling and pressure reduction as well as the contaminants. As from the reference, the outlet is at a temperature of 15 ºC (60 ºF) and pressure of 80 kPa. [31]Hence the vapour and mist substances inside of the air could decrease as these can easily adhere to the solid components and ducts. Other chemicals of contamination would still exist and be delivered to the next component of ECS with the air supply.

5.2.3 Mix Manifold

The airflow has been cooled through the air conditioning packs, before it comes into the mixing manifold at a temperature of 15 ºC (60 ºF) and pressure of 80 kPa. The relative humidity is less than 5% and ozone concentration is less than 0.25 ppm. [36]The carbon dioxide concentration remains the same as that of the outside air. As this air enters a mixing chamber, it is combined with an almost equal quantity of filtered re-circulated air. The mixing manifold of the B767 is shown in Figure 5-5.

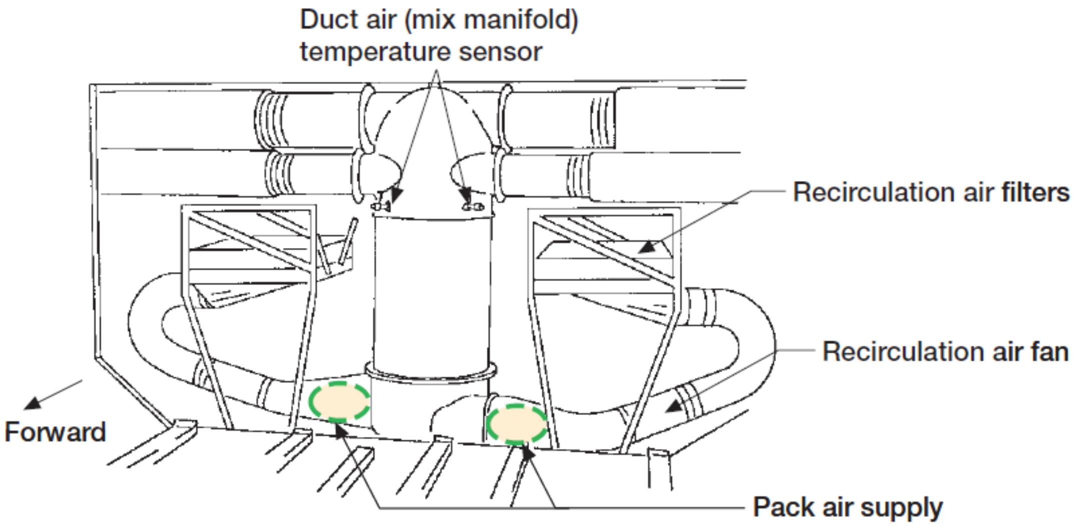


Figure 5-5 Mix Manifold of the Boeing 767 [36]

It seems that the contaminated air cannot change their composition through the mix manifold, even if it is mixed with the cabin recirculation air. The recirculation air cannot be filtered to be as completely clean as fresh air. If the recirculation air from the passenger cabin was polluted, the HEPA filters also could not to reject those chemicals whose forms are vapour and gases.

5.2.4 Air Distribution System

The air supplied from the mix manifold is separated into ducting system which can deliver the air to the cabin ventilation. It is then supplied to each zone of cabin. Trim air directly from the pneumatic manifold is mixed in the ducting to increase the air temperature, if needed, in order to meet the required air temperature for various control requests. The air supply temperature to the divided zones can vary due to differences in seating density of each independent controlling area.

The air now is entering the cabin distribution system. This overhead air distribution network runs the length of the cabin. The air is dust free and sterile with a relative humidity of 10% to 20%, and the temperature is 18 ºC to 29 ºC, according to the different controlling zones. [36]

The trim air may contain some contaminants and volatile organic compounds, such as TCP, TBP and toluene. Although the amount of trim air is much less than the cabin ventilation requirements, this can make the air contamination worse in the cabin. Accordingly, it can be find out that the inhalable contaminants and other substances must exist in the cabin to some extent. However the concentration of these chemicals also should be sampled and measured during the fume event of civil transport aircraft.

5.3 Discussion

As from the last chapter and the case study, it can be learnt that the cause of contamination events is the failure and malfunction of the bearing seals at the engine or APU. Those seals design can be damaged by normal wear and tear. Thus the contaminant compounds such as engine oils or lubricants, hydraulic fluids and de-icing fluids could find ways to enter the bleed air.

The bleed air is extracted from the compressor stage of engine. Its physical conditions and the ambient conditions would both make those oily or liquid substances breakdown, pyrolysis and thermal decomposition due to so high temperature and pressure. Even though there are some components like pre-cooler and pressure reducing valve, the various forms of chemicals may mostly exist and transmit in the bleed air ducting system.

As the polluted air reaches the air conditioning packs, it will be a complex procedure for both temperature and pressure. Table 5-1 presents several performance data [38] from a typical air condition pack of a conventional airliner when the pack works at a steady state. Both the temperature and pressure have varied according the request of cooling, heating, evaporating and condensing in order to condition the air to a proper temperature, humidity and pressure. The temperature changing can affect the substances that are at forms of vapour and mist, though the temperature might also dedicate. However, these should not have prevented the transfer of the gases and particle matters inside the contaminated air, besides the trim air directly introduced from the pneumatic system. In conclusion, the contaminants can arrive at the passenger cabin and flight deck of a civil aircraft.

Table 5-1 Performance data of a typical conditioning pack at steady state

Cases / parameters	Hot ground	Hot cruise	Normal ground	Normal cruise
ACP inlet temperature(℃)	182	126.8	118.6	106.9
ACP inlet pressure(kPa)	288	100	258	100
compressor inlet temperature(℃)	76.3	46	35.6	44
Compressor inlet pressure(kPa)	278	95	248	95
Turbine inlet temperature(℃)	65.9	14.5	59.6	14.7
Turbine inlet pressure(kPa)	499.8	96.9	457	97.1
Turbine outlet temperature(℃)	-21.2	7.4	-20.9	7.4
Turbine outlet pressure(kPa)	120	86.2	120	86.2
ACP outlet temperature(℃)	6.9	7.4	6.9	7.4

6 Conclusions and Recommendations

6.1 Conclusions

The cabin air supply in the modern civil transport aircraft has been transferred from the engine bleed air, after being conditioned and distributed by the environmental control system, to the different areas of the aircraft. If the bleed air is contaminated by the engine oils due to the failure of bearing seals, the toxic substances or chemicals released by oils pyrolysis and degradation, then it may cause severe effects, temporary or permanent chronic or acute ill health, to the passengers or the crews. Contaminants are ducted by passing the bleed air system, air conditioning pack and air distribution system, to the cabin and flight deck. By analyzing and examining the main components related to the air contamination, including the case study on Boeing 767, it can be concluded that the contaminants could find its way into the passenger cabin and flight deck. However, there are still some problems left, such as what is the safe level of these substances, whether or not the contaminants encounter any reaction under so high pressure and high temperature, if so, which kind of reaction will occur. The restriction is that the studies have been done focus on the pressure, temperature and humidity, and from the aeronautical engineer's point of view, this issue seems an interdisciplinary work, involving petro-chemistry, aerospace, medicine and other airframe systems like the fuel system.

During the analysis of the ECS components and the B767 case study, the important variables such as temperature, pressure and humidity of the air supply are considered as the key factors that could affect the concentration of the substances. Therefore, there are some benefits from the research. Firstly, in the design stage of ECS, some design flaws can be avoided according to the requirement of the air quality. Secondly, because there are not definite guidelines and terms in the aviation regulations, the system designers do not pay much attention to the air quality. It is an urgent action to consider about this with respect to the safety of the crew, passengers and other employees. Thirdly, which symptoms are caused by those contaminants and what is the safe level of them, both of them need accurate and direct proofs. This should attribute to the area of the sampling study, which contains the monitoring and detecting functions. Moreover, it can provide some guidelines for the strategy and methodology of the sampling work.

6.2 Recommendations and Future Work

This research has conducted the analysis and examinations on the principles and some key variables of the ECS components. There are still many studies and works to do for the further understanding. The recommendations and future work are listed below:

- From the systems perspective, a reliable proof to the contamination issue should be by calculation work or laboratory test. For the calculation, an ECS model can be built by the simulation software and methods like CFD can be applied to support the calculation work on the substances movement, concentration and reactions.
- The aviation regulations and standards should be revised and considered by the authorities. This must be undertaken by the experts from each related fields, physiology, medicine and airframe systems engineering.
- A bleed free architecture ECS could be a good solution to the contamination event. However, it can increase the weight of the whole system. This need find a compromise among the air quality, fuel penalty and the performance. Also it is not simple to retrofit this solution to existing aircraft because of the need to provide ram air ducts, turbo compressors and their AC power, and need to match to existing air cycle machines. So, if there is a risk, it cannot be resolved for current aircraft types which have a long operational life ahead of them.

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