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DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
Master of Science in Aerospace Engineering

MASTER DEGREE THESIS

Design of Innovative Environmental Control Systems for high-speed commercial aviation

Candidate:
Luca DE GIORGI
254977

Supervisor:
Eng. **Roberta Fusaro**

Co-Supervisors:
Prof. **Nicole Viola**
Eng. **Davide Ferretto**

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Alla mia amata nonna Lucia,
Fonte inesauribile di forza, coraggio e dedizione...
Sei andata via prima che potessi saperlo,
spero di renderti sempre orgoglioso di me.
Mi manchi.

"...Vien dietro a me, e lascia dir le genti:
sta come torre ferma, che non crolla
già mai la cima per soffiar di venti.."
Alighieri Dante, Divina Commedia, Purgatoio, Canto V, vv13-15.

Ringraziamenti

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Grazie a tutti voi,

Luca.

Abstract

The Environmental Control System, ECS, represents a constant power demand over the complete flight envelope, regardless of engine project that study the feasibility of a Hypersonic civil passenger transport aircraft concept, STRATOFLY MR3, that shall be able to cruise at 30 km altitude and Mach 8 flight speed with the primary goal to reduce flight time, noise and emissions. It is about an innovative way of conceiving air transport and, so, it is an interesting challenge for scientists which will probably change the aerospace industry from the field of high-speed propulsion to high-temperature resistant materials. This is the challenge that awaits the years to come and it will radically change the way of conceiving the Earth and humanity itself.

This Thesis focuses on the definition, design, sizing and simulation of the Environmental Control System for hypersonic civil aviation. It is about an innovative way to conceive this subsystem, never experienced before. At subsonic and supersonic speed, until Mach 3, open - loop ECS is assumed, in line with traditional commercial aviation systems to meet entry-into-service requirements, adopting technical solutions that are technologically ready. From Mach 3 to Mach 4 there is a transitional phase in which open and closed Loop coexist: in this step an air tank is refilled in order to compensate air leakage during closed loop phase. At hypersonic speed full closed-loop system is the optimal solution given present data. Carbon Dioxide Removal Assembly (CDRA) and Trace Contaminants Control Subassembly (TCCS) are responsible TO remove CO_2 and contaminants in order to provide clean air to passengers.

The target of the work is to define a proper architecture for the subsystem and verify its compliance to the mission. First of all, stating from the information of cruise speed and using the zero-dimensional steady-state analysis based upon a convective-radiative-conductive heat transfer balance, skin temperature and heat penetrating across the hot insulation layer, are computed. After computing the heat loads that the ECS shall withstand in operation, the necessary airflow to cool down the cabin into $+18^oC$ to $+25^oC$ temperature range is obtained and then it is compared with the mass flow rate required for breathing. After that architecture design is hypothesized and open to future development, for example using CO_2 from CDRA to create oxygen exploiting Sabatier reaction or exploiting electrolysis to use water condensed in Air Cycle Machine (ACM) in order to produce oxygen to enrich the air in the cabin. In this case, hydrogen could be sent to liquid hydrogen tanks for improving range autonomy.

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List of Abbreviations

ACM Air Cycle Machine

ACS Atmosphere Control and Supply

AEA All Electric Aircraft

AoA Angle of Attack

ARS Atmosphere Revitalization Section

ATR Air Turbo Rocket

CAU Cold Air Unit

CAV's Cruise and Acceleration Vehicles

CDRA Carbon Dioxide Removal Assembly

CFD Computational Fluid Dynamics

CoG Center of Gravity

DMR Dual Mode Ramjet

DRM Design Reference Mission

ECLSS Environmental Control and Life Support System

ECS Environmental Control System

EPS Electrical Power Subsystem

EVA Extra Vehicular Activities

FCS Flight Control System

HEPA High Efficiency Particulate Air filter

HTS Heat Transport Section

ISS International Space Station

MEA More Electric Aircraft

MELiSSA Micro Ecological Life Support System Alternative

MSOC Molecular Sieve Oxygen Concentrators

OGA Oxygen Generator Assembly

OSCPCS Oxygen Supply and Cabin Pressure Control Section

PLSS Primary Life Support System

RV-NW's Non-Winged Re-entry Vehicles

RV-W's Winged Re-entry Vehicles

SIM Surface Impact Method

STRATOFLY STRATOspheric FLYing opportunities for high-speed propulsion concepts

STS Space Transportation System

TCCS Trace Contaminants Control Subassembly

TCS Thermal Control System

TEMS Thermal and Energy Management Subsystem

THC Temperature and Humidity Control

TPS Thermal Protection System

UPA Urine Processor Assembly

WMS Water Management System

WPA Water Processor Assembly

Chapter 1

Introduzione

L'uomo ha da sempre cercato un modo per potersi elevare a Dio, quella sensazione di immortalità che lo consegnasse alla storia come l'essere più magnificente che potesse essere concepito. La scoperta del fuoco ha dato l'incipit a tutto questo: forniva calore durante l'inverno e luce nel corso delle ore più buie, ma soprattutto ebbe conseguenze devastanti sulla quotidianità dei primi ominidi, con ricadute dirette sull'evoluzione dell'intero genere umano, sino ai giorni nostri.

Sebbene l'evoluzione sia una costante che accompagna il genere homo sin dalla sua prima comparsa sul pianeta, è negli ultimi trecento anni, ma soprattutto nell'ultimo secolo, che si è assistito ad un'incredibile escalation di successi tecnologici tali da poter essere considerati, dai nostri antenati, come delle divinità. Facciamo affidamento su complesse macchine in grado di solcare i cieli come gli uccelli, attraversare le immense distese d'acqua degli oceani, comunicare attraverso raggi invisibili e persino di oltrepassare i limiti della nostra culla, il Sistema Solare, alla ricerca di risposte alle domande più ancestrali. Da sempre l'uomo si chiede quale sia il senso del proprio essere ed ha cercato di comprendere e decodificare il mondo che lo circonda, guidato da un'arma infallibile e con lui connaturata: il desiderio di conoscenza. **Aristotele** era certo che tutti gli uomini tendono per natura alla conoscenza e **Kant**, con la sua gnoseologia, fece della natura umana la base della conoscenza, ed allo stesso tempo mise in risalto quanto l'uomo cerchi sempre più di spingersi al di là delle proprie possibilità, desiderio insito nel suo stesso intelletto.

La storia ci insegna che Kant aveva ragione: l'uomo ha sempre provato a conoscere quel noumeno, a sfidare l'ignoto sospinto dalla fiamma perenne della sua *cupiditas sciendi* e la letteratura fornisce delle prove schiaccianti. Il simbolo universale di quest'anelito verso la conoscenza è Odisseo, emblema e simbolo di quella passione travolgente per la conoscenza che porta l'uomo a sacrificare anche ciò che ha di più caro, trovando la sua massima espressione nelle parole che Dante gli fa pronunciare nel Canto XXVI dell'Inferno, Considerate la vostra semenza: ***fatti non foste a viver come bruti*** *ma per seguir virtute e canoscenza.*

In quest'ottica, l'Illuminismo ha consentito di compiere passi da gigante alla civiltà umana, presentandosi come un impegno ad avvalersi della ragione in modo libero e pubblico ai fini di un miglioramento effettivo del vivere, rappresenta l'*uscita dall'uomo dallo stato di minorità che egli deve imputare a sé stesso. Minorità è l'incapacità di valersi del proprio intelletto senza la guida di un altro. Imputabile a se stesso è questa minorità, se la causa di essa non dipende da difetto di intelligenza, ma dalla mancanza di decisione e del coraggio di far uso del proprio intelletto senza essere guidati da un altro. Sapere aude! Abbi il coraggio di servirti della tua propria intelligenza!*

È dunque con l'Illuminismo che la scienza si candida con fervore al primo posto nella gerarchia delle attività conoscitive, anzi esso può essere visto come il punto d'arrivo della rivoluzione scientifica, interpretata a sua volta come punto di partenza dell'Illuminismo stesso. Il sogno baconiano di una civiltà scientifica in grado di padroneggiare la natura si manifesta nella realizzazione dell'uomo tramite un sapere vero e utile al contempo, estendendo naturalmente il concetto di *Tantum possumus quantum scimus* (sapere è potere), dalla natura alla società andando alla ricerca di una scienza dell'uomo *in grado di comprendere e dominare a proprio vantaggio i meccanismi economici, politici e morali.*

Il progresso scientifico cui si assiste nel XVIII secolo portò inevitabilmente alle rivoluzioni industriali, caratterizzate dall'applicazione sempre più su larga scala delle scoperte ai vari rami dell'industria, sino a che, nella seconda metà dell'Ottocento, si abbrevia la percezione della distanza, consentendo a persone e merci di viaggiare rapidamente come non era mai successo prima. Inizia in questo periodo il processo di internazionalizzazione, i collegamenti tra le varie parti del mondo diventano più intensi. Oggi questo processo quotidiano costruisce una rete intorno al mondo realizzando la globalizzazione.

Il trasporto aereo è motore essenziale per lo sviluppo dell'intera economia di una regione, soprattutto in un contesto fortemente improntato a logiche di globalizzazione dei mercati e di integrazione delle economie nazionali. In tale scenario è naturale che si faccia sempre più pressione sul settore aeronautico affinché vengano sfruttate le più recenti ricerche inerenti lo sviluppo di velivoli estremamente veloci.

Queste tipologie di velivolo hanno gli impieghi più vari quali voli cargo suborbitali e stratosferici, business travel, trasporto urgente di beni, turismo suborbitale, servizi spaziali e voli di linea stratosferici/suborbitali atti al trasporto passeggeri. È proprio in queste ultime categorie che s'inserisce il lavoro svolto all'interno della presente tesi. In particolare si va a studiare un innovativo Environmental Control System in grado di garantire la sopravvivenza di passeggeri a bordo di un velivolo ipersonico.

1.1 Purpose of the work and Thesis baseline

During the aviation history several solutions were investigated in order to develop winged bodies able to fly in the atmosphere at a very high speed. After that commercial Supersonic Transport has been experimented thanks to the *Concorde* (retired in 2003 due to high operational costs and high noise and emissions), the next step is to investigate Hypersonic Transport opportunities that will allow people to move at hypersonic speed from one point to another one of the Earth surface. A six-fold increase in passengers is predicted by 2050 [1] and the exploitation of new air space thanks to the development of technologies in the fields of high-speed flight and high-temperature resistant solutions shall be explored.

Modern passenger aircraft look similar to their decade-old counterparts. However fuel efficiency has doubled since 1960, although at a demising rate. This is obtained replacing classical turbojets engine with high-bypass-ratio turbofans.

Also the topology of Environmental Control Systems (ECSs) has been stable since '60s, with some exceptions as Boeing 787 and advanced More Electric Aircraft (MEA) solutions, still standing on an academic level. Moreover ECSs still suffer some problems:

- Non uniform temperature regulation inside the cabin that degrades passengers comfort;
- Stability issues in the engine bleed air system lead to longer development times.

This Thesis was developed within the frame of Stratospheric Flying Opportunities for high-speed Propulsion Concepts (STRATOFLY) Project, coordinated by *Politecnico di Torino* with the aim of developing innovative ECSs for high-speed commercial aviation capable of guaranteeing survival of civil passenger inside an aircraft flying at Mach 8.

The present work is organized in order to convey the analysis from the input data available in literature up to the results of the simulations. It is important to observe that there is a lack of bibliography and dedicated studies, apart from those developed by NASA for Apollo missions or by ESA for International Space Station (ISS). Because of this, a design perspective is followed: starting from the classical idea of ECSs, a new architecture has been developed. Last but not the least, this is the first stage of the project, in fact there are no much pieces of information about the whole vehicle and systems, therefore a first sizing will be provided, being subjected to refinements in an iterative process.

Below a general overview of Thesis organization is provided:

- **Chapter 1**: Purpose of the work, rationale of the research and description of the Thesis structure.
- **Chapter 2**: Environmental Control System, literary review: typical functions and architectures
  - ECS for aeronautical applications: architectures, main aspects and applications;
  - ECLSS for Space applications: architectures, main aspects and applications.
- **Chapter 3**: Sizing of the ECS system for hypersonic aircraft
  - - ECS architectures suggested for high-speed aviation;
  - - Preliminary sizing model of the ECS system for high-speed transport.
- **Chapter 4**: Case of study presentation; overview on the STRATOFLY MR3 aircraft, general information, characteristics and typical mission;
- **Chapter 5**: ECS integration into the cabin of the case of study STRATOFLY MR3, sizing example for the case of study;

- **Chapter 6**: Conclusions, summary of the main results obtained and identification of possible further developments.

The Thesis contributes at giving further information about the possible solutions to be implemented in order to guarantee the feasibility of future missions at hypersonic speeds with civil passengers on board.

Nothing left to say, just sit and have a good read and I hope you will find the content of this Thesis useful and delightful.

Chapter 2

EC(L)S(S) Literature review

"Engineering discipline dealing with the physical, chemical and biological functions to provide humans and other life forms with suitable environmental conditions."

Environmental Control (and Life Support) System (EC(L)S(S)) refers to equipment that is able to maintain a comfortable close environment for a given payload (goods, living matter, and people), i.e. keeping temperature, pressure, and air composition, within acceptable limits. This is possible thanks to a circulation of a fluid for thermal control and for life-support.

The ECS is necessary for every vehicle that operates in hostile environments as submarines, aircraft and spacecraft.

Focusing on aeronautical/space systems, it emerges that they need not only to provide a comfortable environment but also to support the lives of the astronauts, without whom the mission would fail miserably.

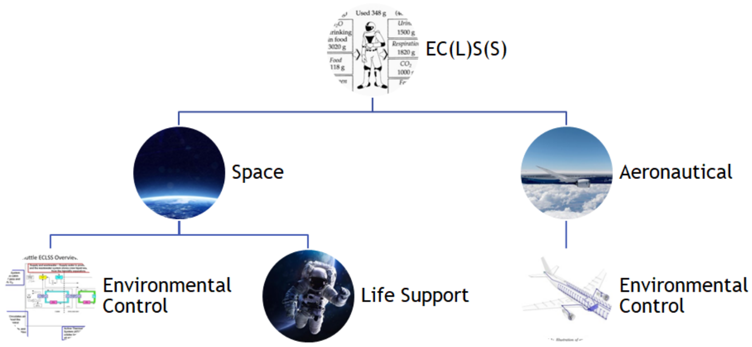


Figure 2.1 – EC(L)S(S)

2.1 Objectives

The objective is to create a suitable environment by controlling the environmental parameters, providing resources, and managing waste products.

EC(L)S(S) systems are responsible for:

- Pressurization
- Ventilation
- Temperature
- Humidity levels
- Anti-Icing and De-Misting
- Fire Suppression

It must also support special operations such as Extra Vehicular Activities (EVA), respond to environmental contingencies and provide health related services.

2.2 Essentials of human physiology

Breathing is a vital physiological process that allows the human body to take in oxygen and return carbon dioxide; in order to extract oxygen from the air, an appropriate pressure shall be guaranteed in lungs: by osmosis, oxygen passes into the blood through the surfaces of the alveoli, attaching itself to the hemoglobin.

People are open systems: they exchange matter and energy with their environment. They consume matter to provide the building blocks for biosynthesis and the fuel and oxidant required to run their biological "engines". The engines produce energy for growth, mobility, and maintenance of internal human systems. This "combustion" process produces thermal and chemical by-products. People need mainly food, water, and oxygen, and their main outputs are heat and metabolic products such as sweat, urine, feces, and carbon dioxide.

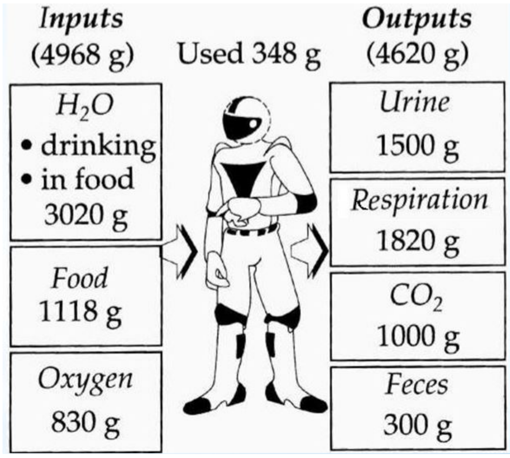


Figure 2.2 – Input/Output - Human body [2]

2.2.1 O_2 Partial Pressure

The partial pressure of O_2 is important. If the oxygen supply to the tissues falls below a certain limit, **hypoxia** occurs, which manifests itself first of all with **weakness and poor concentration** and, subsequently, **loss of consciousness**. The percentage of O_2 in the atmosphere is about 20% (and it is practically constant when the altitude changes), therefore the atmospheric pressure of $400mmHg$ is required, corresponding to an altitude of $15000ft$ ($4500m$); above $6000m$ the risk of loss of consciousness is high. Alternatively, it is possible to increase the partial pressure of the O2 by enriching the air, breathed by special dispensing masks (as military use).

It is necessary to re-establish a correct value of the partial pressure of oxygen, and this is possible in two ways:

- By increasing the atmospheric pressure of the air to the same percentage of oxygen;
- By increasing the percentage of oxygen in the air with the same atmospheric pressure.

The wellness condition maintained in the cabin is, for civil passenger transport aircraft, within the equivalent altitude of $8000ft$, with gradients increasing ($<$ of $500ft/min$) and decreasing ($<$ of $250ft/min$) since **there is greater ease of compensation with pressure gradients going up**. Higher pressure gradients can cause damage due to the natural slowness of physiological compensation.

People need a $pO2$ of about $19kPa$ to be productive and comfortable, though they can withstand lower values. Two-hour emergency $pO2$ specification is established: $13.4kPa$.

Condition	PB [kPa]	PO_2 [kPa]	PCO_2 [kPa]	Comments
Sea level std	101.3	21.3	0.04	Nominal conditions; pH_2O = 0.4
NASA 1995b	99.9 - 102.7	19.5 - 23.1	< 0.4	25%-70% RH (pH_2O < 3, f(T))

Figure 2.3 – Oxygen Partial pressure [2]

In resting conditions, human beings require about 6/7 liters/minute of air at atmospheric pressure to meet their oxygen requirements. The environment must allow the elimination of carbon dioxide produced by breathing and ensure an adequate and stable temperature.

2.2.2 Temperature Control

Temperature control is also crucial not only in flight to compensate for heat loss to the outside, but also on the ground during handling phases where ambient temperatures can be very far from the ideal value required by the human body, both in terms of "too hot", in summer with a full aircraft, and "too cold".

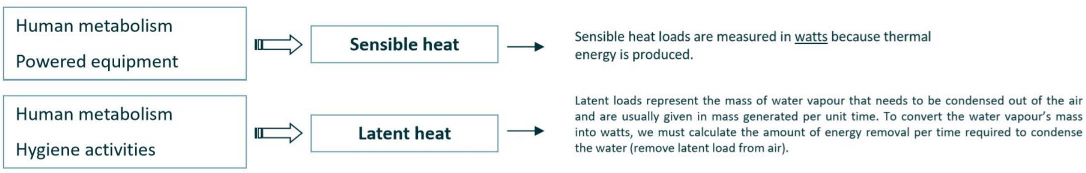


Figure 2.4 – Sensible and latent heat [2]

In addition, the human being is a source of heat ($80/100W/h$ in resting conditions).

Temperature stability must be considered in relation to the size of the fuselage, since from the moment a change is required in a certain area of the cabin to the time the temperature stabilizes, it may take several minutes as it is related to the capacity of the air conditioning system. The wellness conditions related to temperature and humidity are more difficult to define.

The temperature is considered acceptable for values between $20 - 24^oC$ in summer and $18 - 22^oC$ in winter, with relative humidity levels around $30 - 70\%$ and a sufficient amount of air for effective ventilation.

These conditions must be maintained in the aircraft in any condition: they must be ensured with the aircraft stationary in the Sun on a runway in the equatorial zone, such as in flight at cruising altitude or on the ground in the polar zone.

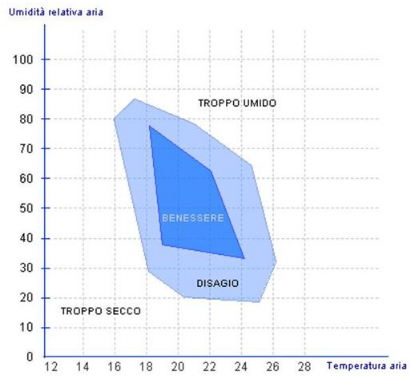


Figure 2.5 – Thermohygrometric wellness

Moreover, surface temperature should prevent condensation, as well as discomfort or injury for crewmembers. Maximum and minimum temperatures for contact with bare skin are fixed around 45^oC and 4^oC respectively, for continuous contact.

2.3 Air Purity and Ozone

The purity of the air plays a fundamental role: bacteria, dusts or various impurities, ozone are to be controlled for the passenger's well-being. Finally, the human organism is sensitive to the gradient of change in the air pressure, and this will have to be taken into account by the system.

Controlling humidity in a space habitat's atmosphere is particularly important because condensation on electronic parts may affect their performance or make them unsafe. The air taken on cruises by the engines comes from the outside environment and is therefore dry; it can also be reused for long periods of time and can cause dehydration phenomena, to which correspond annoyances to the nose, throat, etc. In this respect, some aircraft have been fitted with air-damping devices, but this solution has been abandoned and therefore the only way to combat dehydration is to offer drinks during the flight.

The standard air is composed of 78% nitrogen and 21% oxygen as well as carbon dioxide and other inert gases, but during the flight it undergoes alterations for various reasons including:

- The percentage of carbon dioxide increases with the breathing of passengers.
- - The presence of particles in suspension due to dust, clothing fibres, etc.
- - The dispersion of odors due to perspiration, galley operation, etc...

These factors determine the need for a change of air and this is done by introducing new air (hot or cold) to stabilize the temperature.

2.4 Air recirculation

The air conditioning system takes air under pressure and at high temperature from the pneumatic system, which in turn removes a quantity of air with high enthalpy content from the engines.

Picking up air out of engines absorbs power and therefore leads to fuel consumption increases of up to 3/4%, which is significant both for the weight of the fuel transported and for its cost. Keep in mind that modern aircraft, in order to optimize fuel consumption and reduce noise and exhaust pollution, are more and more double-flow engines with a high By - Pass ratio that are the most sensitive to efficiency losses (fuel consumption) due to the effect of the pneumatic spillers. In the latest generation aircraft, cabin air recirculation has taken on an important function in pursuing the reduction of fuel consumption, and the systems have been equipped with cabin air recovery systems by means of intake fans, filters and delivery to manifolds where it mixes with fresh air.

In the latest generation aircraft (B787), the solution of thrusters that does not allow the pneumatic system to be taken out, anticipating the solutions of the All Electric Aircraft (AEA).

2.5 State of the Art - Aeronautics

Modern aircraft, in order to perform best, must fly at the maximum altitude compatible with the weight, aerodynamics and power of the engines and therefore in an external environment characterized by dry air, low pressure and low temperature. The environment conditions, at the common flight height, are incompatible with the requirements of common passengers with regard to all environmental parameters as temperature, pressure, humidity, ozone and so on.

The theoretical condition to ensure comfort on board would be to offer throughout the flight, at any altitude and at any maneuvering stage, an adequate and stable pressure and temperature over time, an acceptable level of humidity and adequate air replacement. In order to ensure these conditions during flight, the passenger cabin must therefore have a pressure and temperature very different from that of the outside environment:

- At cruise height $(40.000ft)$ the external pressure can be a fifth of that on the ground, far from the ideal value required by the human body.
- During the flight, the external temperature at the same altitude could be -55^oC, while the desired internal temperature is $20/25^oC$; this gradient generates strong heat dispersion from the passenger cabin.

It is therefore clear that the passenger compartment must in some way be kept under pressure by sending air at a pressure/temperature greater than that outside for the duration of the flight. In addition, the oxygen consumption by passengers, the inevitable loss of seals and the loss of heat through the fuselage make it necessary to constantly change the air in order to recover the two comfort conditions indicated. This operation is conceptually simple to do, but is strongly conditioned by two technical-economic factors, which require intervention to be limited:

- A differential pressure between the interior and the exterior of the cabin would lead to high structural stresses both static and operative. Therefore, in order to limit the weight/management cost, the differential pressure must be limited.
- Replacement of air, with other hot and pure, would absorb too much power from the engines with consequent impact on fuel consumption.

Civil transport aircraft, in order to fully carry out their mission, must also welcome passengers with adequate comfort when the aircraft is on the ground, where environmental conditions may change depending both on the airport of transit and the seasons and weather conditions in general, as well as on the number of passengers on board and the length of time the aircraft is on the ground for Air Traffic Control purposes. It follows that on

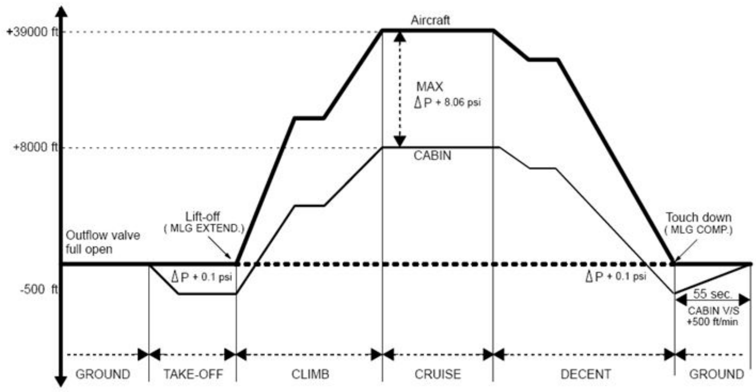


Figure 2.6 – Differential Pressure between the interior and the exterior of the cabin [3]

the ground the aircraft may have an ambient temperature that extends from minus 30^oC in some areas of the planet to plus 40^oC in others, at the limit even between the airport of departure and arrival. It should be remembered that temperature is not the only parameter to be controlled for adequate comfort of passengers and crew.

The operating conditions in which comfort and health have to be guaranteed are quite variable and the installations for this purpose (e. g. the air conditioning and pressurization plant and partly the oxygen plant) must take account of these situations.

For example:

- Environmental conditions on the ground (during the handling phases) may vary considerably as they are related to climatic conditions, which in turn are related to the geographical location of the airport, and to seasonal effects.
- Between airports of departure and arrival of the same flight the weather conditions could be very different, also for seasonal reasons (think of flights crossing the equator) and in any case change during the execution of the same route.
- The variability in the number of passengers on board affects the purity of the air and the thermal balance of the cabin.
- The purity of air in the passenger cabin must also be seen in terms of bacteria, galley odors and toilets.

- High altitude air may have percentage of ozone that is not acceptable to the human body.
- For the same number of aircraft and passengers, the length of the routes varies with the type of network operated.
- The fuselage disperses a lot of heat in the air due to the differences in temperature, the large exchange surface and the relative velocity of the air.
- To give comfort, it is necessary to control relative humidity and the air replacement, in turn influenced by the height and the number of passengers.
- The human body would require that all operational phases of air temperature, pressure, purity and humidity be close to the ideal conditions as well as maintained stable both on the ground and during flight.
- Changes in aircraft altitude during maneuvers are rapid and are not necessarily followed by changes in cabin altitude.
- The human body does not like too sudden changes in external pressure to grow or rise.
- The level of comfort should, as far as possible, also take individual requirements into account.
- The cabin ambient pressure, which determines the partial oxygen pressure, for structural reasons cannot always be equal to that at sea level.

This combination of operating conditions requires a complex and continuous management of the cabin environment and this is the mission of the Environmental Control System.

2.6 ECS Philosophy

The most common technical solution used in large passenger transport aircraft is to take air from the pneumatic system and subject it to a continuous thermodynamic process using special devices. This allows to have - in all operating conditions - a mass of air to be sent in the cabin with adequate pressure and temperature, regardless of changes in altitude, number of passengers, external environmental conditions, and in all operating conditions. This sequence of interventions is also made complex by the fact that the air supplied by the pneumatic system cannot have optimal values only for air conditioning, as it is intended for various types of users (see the case of the de-icing system) who intervene in the operating phases with significant demands both in terms of temperature and pressure.

A generalized functional tree is shown below:

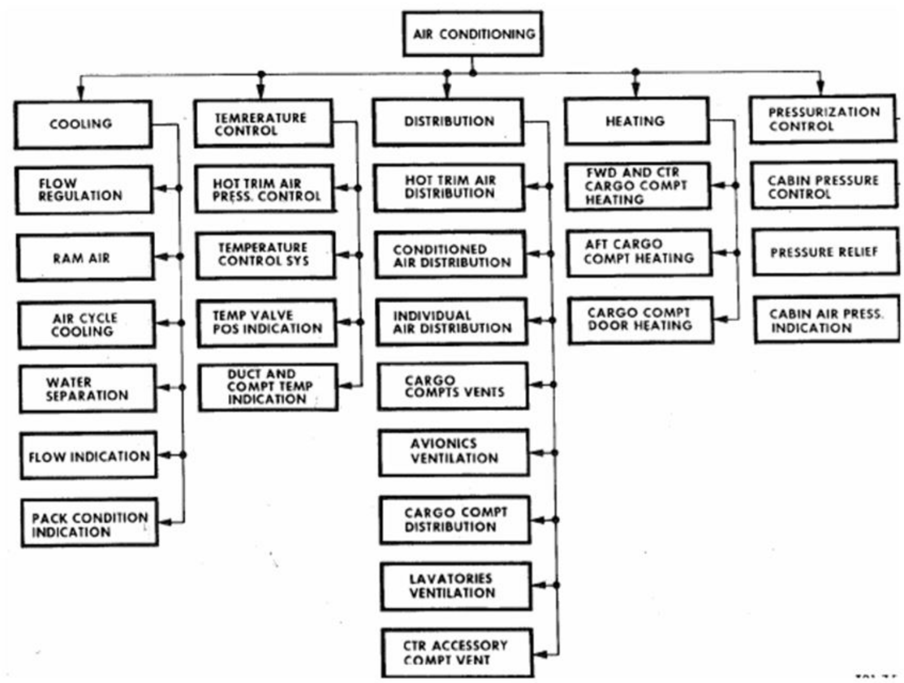


Figure 2.7 – Functional tree ECS

From functional tree is clear that:

- Pilots and passenger compartments have similar needs.
- The general baggage area receives air at the same pressure, but with less controlled temperatures and with less control of the percentage of oxygen.

- Some baggages where animals are transported have devices for temperature control.
- The toilet and galley area, in addition to the theme of air conditioning, have forced suction systems by means of extraction fans.
- The area of the electronic compartments, to protect the equipment from high temperatures, are ventilated to dispose of heat especially with aircraft on the ground.

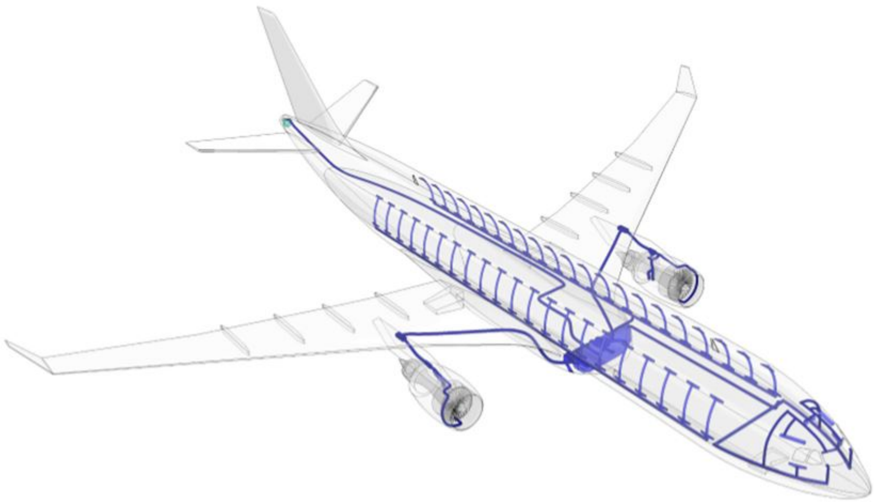


Figure 2.8 – Illustration of an aircraft ECS [4]

By temporarily excluding air replacement, ECS is characterized by two fundamental aspects:

2.6.1 Heating System

Solutions of increasing complexity are used following the history of aeronautical technology the mission of aircraft:

- **Exhaust heating system**: it is the simplest system of all and uses heat exchangers between dynamic intake external air passing through a coaxial ring duct at the discharge of a piston engine (typically). The system is used in small general aviation aircraft.
- **Heating with burners**: air passes through, without an air/gas exchanger in which the heat is transferred by a second flow of dynamic

intake air in which fuel is injected which by burning generates the heating of the air to be sent into the fuselage. The system is more powerful and faster to meet the needs of the necessary comfort and simple at the same time.

- **Electric heating system**: This system is sometimes used when the aircraft is on the ground and the engines are off. Usually the air from the cabin itself is heated by passing it over hot electrical resistors and then recirculated into the cabin. This method is sometimes used on small aircraft with turbo-powered propulsion.

- **Heating with compressed and hot air extracted from the turbo-propelled compressor (bleed air heating system)**: the air extracted by means of special valves from a very hot area of the compressor is sent to a mixing chamber with other cold air and/or recirculated from the cabin itself and mixed in such proportions as to adapt to the specific needs of the air-conditioning area time. Where computerized control systems are available, a high degree of responsiveness to varying operational and environmental situations is achieved.

2.6.2 Cooling System

There are two possible solutions:

- **Closed - Loop refrigeration cycle with freon type gas**: this is a traditional closed-circuit refrigeration cycle where a gas, which has been previously compressed, expands, giving a strong absorption of heat for the evaporation of the fluid, and the heat through an exchanger is taken away from the environment to be cooled. The system is identical to that used in normal homes, cars and is also used on some aircraft with piston engines or small turboprop.

- **Open Refrigeration Cycle with Air Cycle Cooling Machine**. It is an open-circuit refrigeration cycle, very sophisticated but also very powerful. It is commonly used in transport aircraft of a certain size and equipped with large turbojet engines.

2.7 ECS Approaches

2.7.1 Open Loop Systems

The life support systems of mostly short past missions have provided oxygen, food, and water by carrying them on board the spacecraft. Waste was stored and returned to Earth. This type of system relies completely on an external supply of resources. The matter is continuously flowing into and out of it. Open-loop systems tend to be simple and highly reliable, but their big disadvantage is that a mission's required resources increase linearly as duration and crew size increase. Cost-effectiveness of open-loop systems depends on transportation costs and the value of a spacecraft's storage volume.

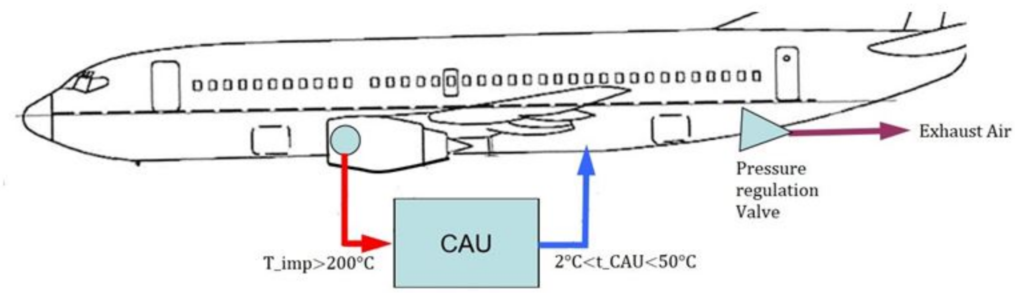


Figure 2.9 – Illustration of an open-loop system CAU [5]

It is necessary to use the air source taken from the compressed pneumatic system. This flow rate is very hot: it is necessary to cool it and then adjust its pressure.

This task is assigned to the Cold Air Unit (CAU): air drive a compressor by flowing through a turbine that extracts heat energy and pressure form the flow. The air emerges from the turbine at a low temperature since the turbine expands it. The Open Loop system evolves by introducing partial air recirculation in the cabin, to reduce the flow rate tapped to the engine compressor ("bleed") and therefore the fuel consumption. The reduction of the tapped flow rate is possible under two conditions:

- By Reducing T_{CAU} below 0^oC (after dehumidifying the air);
- By recycling the air in the cabin: in this way the supply air is at $T \approx 0^oC$; it is necessary a recycling fan.

In the first case, it should be noted that reducing T_{CAU} it is reduced the mass flow rate proportionally. This makes the CAU smaller and lighter. The following diagram shows the components and stages of the process that is able to extract air from the pneumatic system and bring it to the various areas of the aircraft after mixing it in such a way as to achieve the required conditions locally:

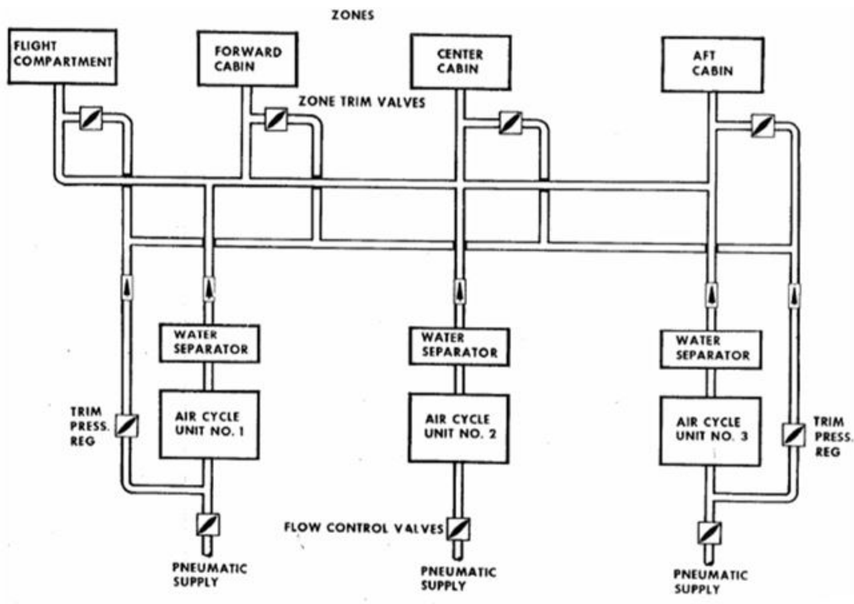


Figure 2.10 – Air Cycle cooling distribution diagram

The cold flow is obtained by means of a refrigeration cycle made by a special component called Air Cycle Machine (ACM), being the most complex unit of the air conditioning system. Ultimately, the humidity control is carried out by means of a water separator.

The main component of a CAU, is the Air Cycle Machine, which according to the components as it is constituted, may be of different types. The main ones are:

- **Simple Air Cycle Machine**: the hot, compressed air coming from the pneumatic system undergoes cooling at constant pressure in an air-air exchanger and then passes through a turbine that moves a fan mounted on its own shaft, which in turn forces the external flow that feeds the heat exchangers. This makes the system capable of operating even when the aircraft is stationary or at low speed.

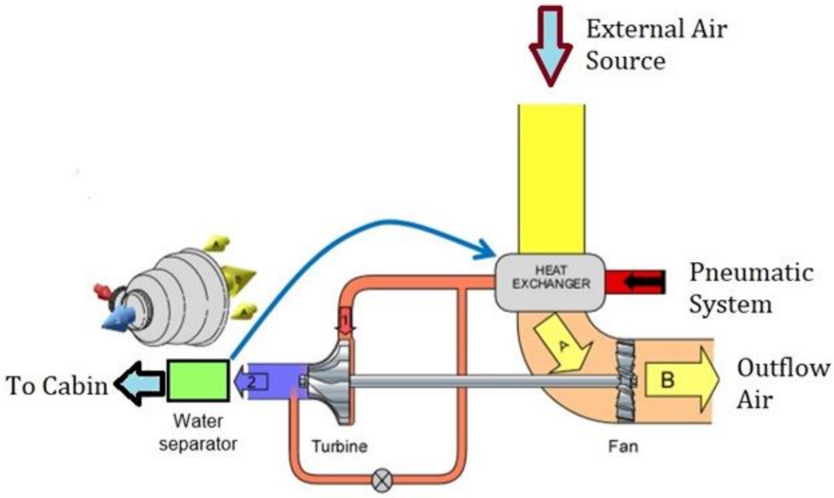


Figure 2.11 – Simple Air Cycle Machine Scheme [5]

- **Two wheels Air Cycle Machine Bootstrap**: The compressor is driven by the turbine and any fan is powered by an electric motor. there is an extra heat exchanger that allows greater refrigeration capacity, and with the same final pressure compared to the previous solution, lower temperatures are obtained.

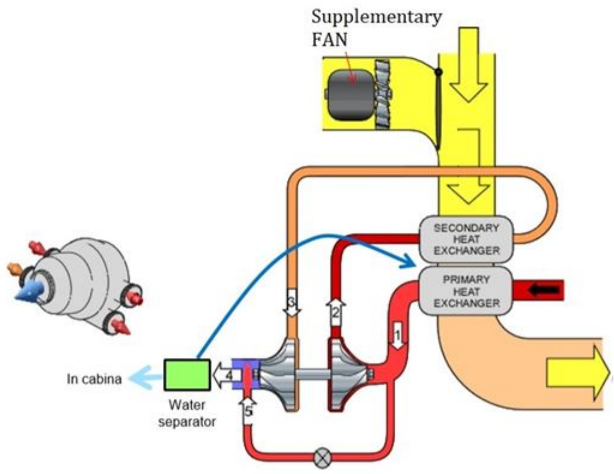


Figure 2.12 – Two Wheels Air Cycle Machine [5]

- **Three wheels Air Cycle Machine Bootstrap**: On the same compressor and turbine shaft a fan is added, in this way the turbine supplies energy to both the compressor and the fan.

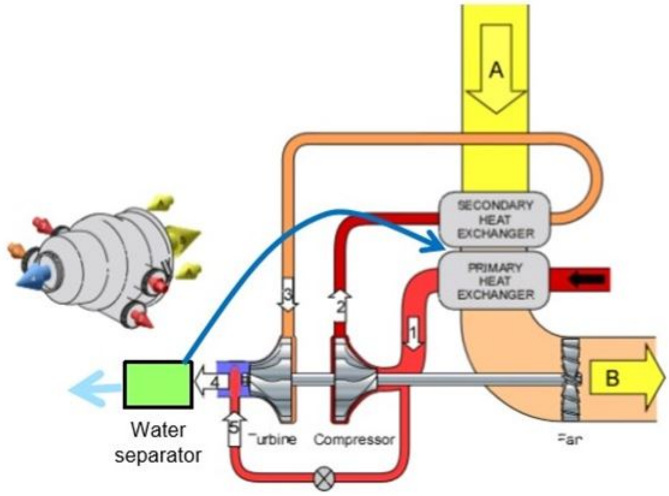


Figure 2.13 – Three Wheels Air Cycle Machine [5]

There are two different types of the latter:

- **Low Pressure Water Separation System**: the air spilled by the engine passes through a primary heat exchanger where it is cooled and then passed into the compressor, where it is heated and compressed, sent to the main heat exchanger and cooled again. Then reach the turbine, where it expands and decreases the temperature and pressure values. It then reaches the water extractor where the water vapor is separated from the pneumatic flow.

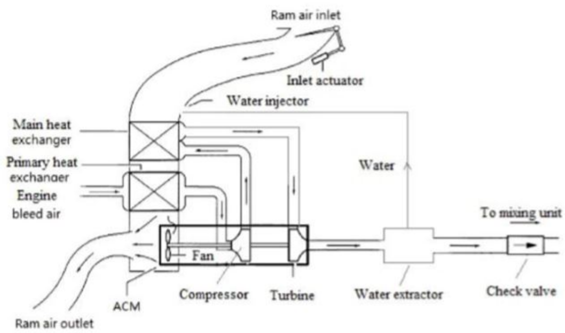


Figure 2.14 – Low Pressure Water Separation System scheme

The extracted water vapour is sprayed upstream of the main heat exchanger in order to maximize its efficiency and cooling. The turbine generates the mechanical work used for about 85% to move the compressor, and 15% to move the fan capable of forcing the external cooling flow into the exchangers. The output temperature from the CAU is around $2-3^oC$ to prevent water from forming on the turbine's pallets and damaging its operation.

- **High Pressure Water Separation System**: In this type of ACM, the air has to reach temperatures of tens of degrees below zero, so it is necessary to water from the air flow before entering in turbine. In this way, the problem of ice formation on the bleeds is solved. After

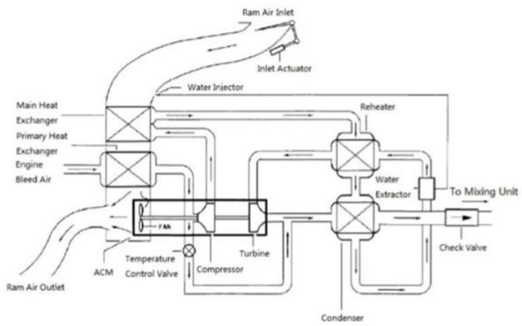


Figure 2.15 – High Pressure Water Separation System scheme

cooling the air in the main exchanger, the flow passes through an additional exchanger, Reheater, where it is further cooled by the cold and dehumidified air coming out of the water extractor. Then is flow into a condenser powered by already air conditioned and finally into the steam extractor which removes moisture and makes the flow dry and ready for its entry into the turbine.

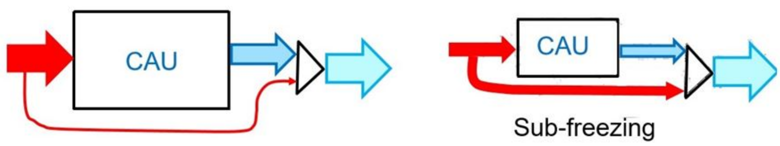


Figure 2.16 – CAU Subfreezing [5]

Here the flow expands and cools further reaching tens of degrees below zero, feeds the condenser and mixes with the air coming from the cabin recirculation and the air that has bypassed the ACM and then enters the latter. This architecture is also known as CAU Sub Freezing.

The method allows savings in weight installed on board and increased efficiency.

The reasons for implementing air recirculation rather than introducing totally fresh air in addition to the aforementioned benefit of reducing the air flow to the engine and thus reducing fuel consumption, are many:

- Air from recirculation helps to meet the requirements imposed by the regulations in terms of optimum humidity percentage for the well-being of passengers.

- The use of recirculation air allows to reduce the temperature difference between that already present in the cabin and that introduced through the air conditioning vents, thus allowing to maximize passenger comfort.

The air is recirculated from the cabin to the mixing unit where it meets the fresh air coming from the CAU through fans and passed through chemical purification filters to eliminate any viruses and bacteria present in the cabin. The air is then distributed in the fuselage through a distribution system that culminates with nozzles arranged dividing the cabin into several zones according to the size of the aircraft.

Their arrangement is designed to ensure the required flow rate in the cabin, but also to ensure proper internal fluid dynamics to prevent passengers from experiencing temperature changes inside the cabin, noise or other nuisances. It is necessary to control the temperature also of the compartments in which the avionics and electronic equipment in general are present in order to avoid overheating during their operation, and to provide ventilation of the cargo area where live animals are boarded.

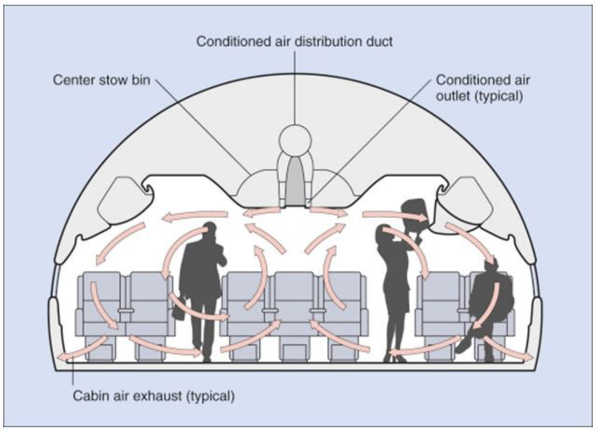


Figure 2.17 – Air distribution in cabin [6]

2.7.2 Open system with Recirculation

It is necessary to evaluate what is the most convenient "mix" between the recirculation flow rate and the new air from the CAU. This is done to avoid excessive air pollution and to save energy, limiting the flow rate processed by the CAU. In general, the recirculation flow rate can increase up to about 50% of the total flow rate.

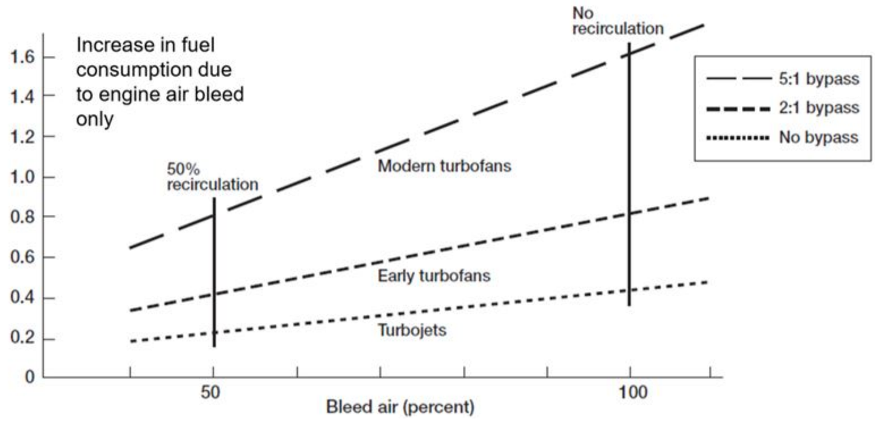


Figure 2.18 – Comparison between recirculation and no recirculation engine's performance

Figures below represent concepts of the ECS in classical aviation

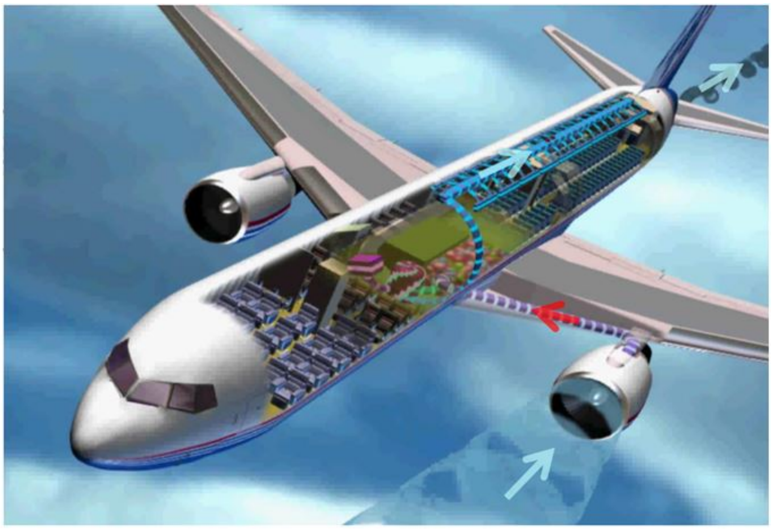


Figure 2.19 – Classical Aviation ECS

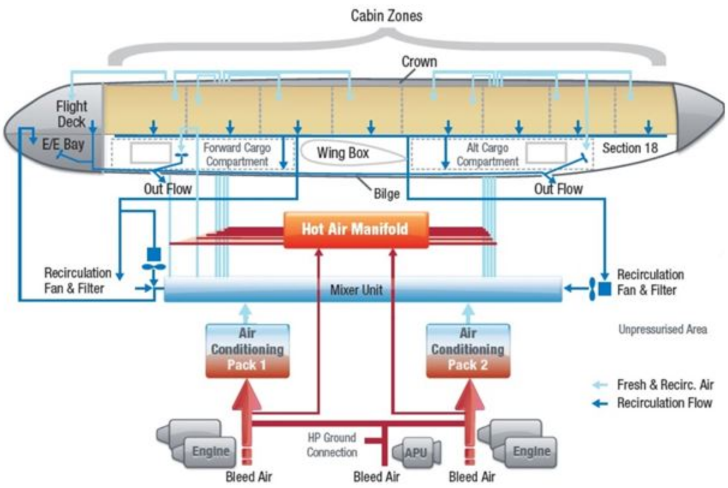


Figure 2.20 – Air distribution in Classical Aviation ECS [5]

2.7.3 Closed-Loop Systems

It is necessary to bring a supply of resources from Earth and then to process waste products and recover useful resources. These types of systems recycle materials instead of getting them from an external source. It is possible to define the closure level of a life support system as the percentage of the total resources recycling provides. Higher closure means less re-supply, and full closure implies autonomous operations. The disadvantages are high costs to develop technology, demands for more power, and increased heat loads, as well as complexity and therefore reliability and maintainability concerns.

It is necessary to equip the system with chemical purification filters, since the flow rate lost through external leakage is small. This solution is adopted in modern "more electric" aircraft as in the case of the B-787 aircraft.

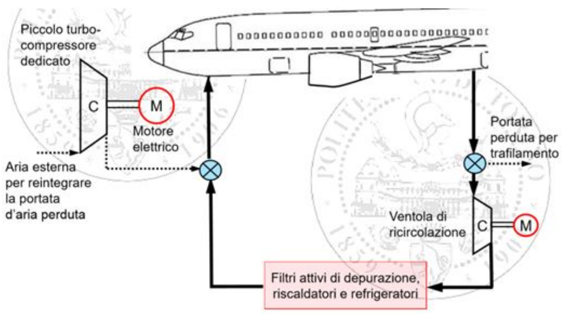


Figure 2.21 – Closed Loop System - civil aviation [5]

2.8 ECS Summary Approaches

It is clear that in case of pressurizing cabin with an open-loop ECSs it have to be connected with the pneumatic system, while if the pressurization is made by closed – loop ECSs it in not necessary to be connected with the pneumatic system as in non – pressurized cabin.

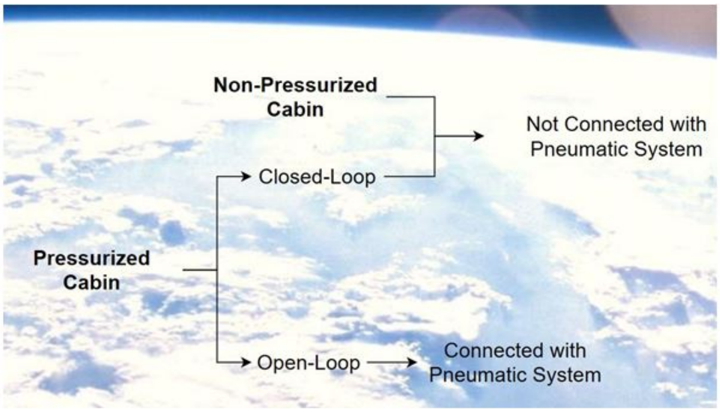


Figure 2.22 – ECSs Summary Approaches

2.9 Modern ECSs - Future Trends

2.9.1 Boeing 747-8

The $747-8$ air-conditioning pack has several key features that allow it to be classified as a true subfreezing pack, which will operate to temperatures below the freezing point of water at all altitudes. While earlier air-conditioning packs can drive subfreezing during all conditions, there are limitations that need to be placed upon the system due to the operating environment and the technology implemented within the system. As a result, below $25000 feet$ ($7620 meters$), where environmental icing is a factor, the pack turbine discharge is limited to approximately 1.67^oC prior to mixing of recirculated air in the main distribution plenum. At cruise, where icing concerns are not a critical issue for operation, many packs do drive subfreezing as conditions warrant.

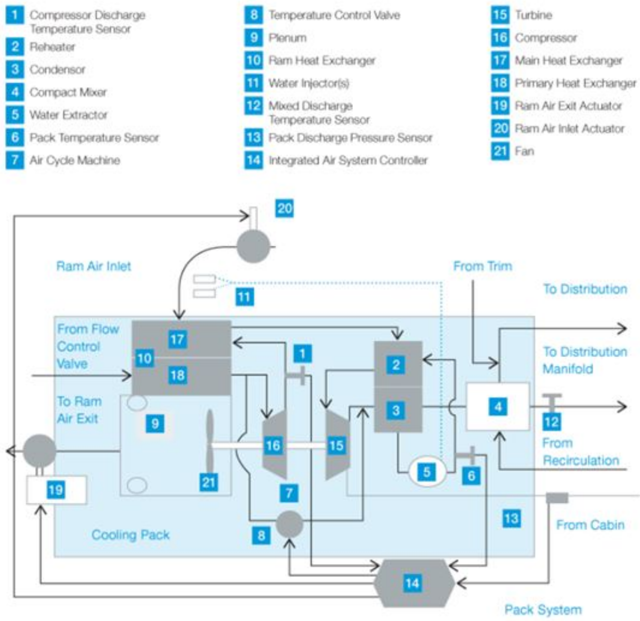


Figure 2.23 – 747-8 Air Conditioning Pack [7]

2.9.2 More Electric/All Electric Aircraft (MEA/AEA)

AEA/MEA architectures allow the reduction of the size of the engine core, an increase in the by-pass ratio and in the compression ratio and turbine inlet temperature without worsening the consumption, increasing the performance and efficiency of the engine, as the global power extraction from the thrust one goes down. Moreover, it is also necessary to consider the weight loss due to the elimination of traditional systems as opposed to the increase in weight of the electrical system and, finally, thanks to the use of innovative systems, we want to try to meet the delicate problem of CO_2 emissions and try to lower their emissions. This technology is implemented in the Boeing B-787 Dreamliner.

This AE-ECS adds some $200kg$ *on airliners (and some maintenance costs), but saves some* 5% *fuel (may be* $5000kg$*). Higher humidity in the passenger cabin is possible because of the use of composites (which do not corrode). Ozone is removed from outside air; HEPA filters remove bacteria, viruses and fungi; and a gaseous filtration system removes odours, irritants and gaseous contaminants.*

The problem of taking air necessary to ensure a minimum flow rate sufficient for breathing, survival and well-being on board is solved differently depending on the technology used on board:

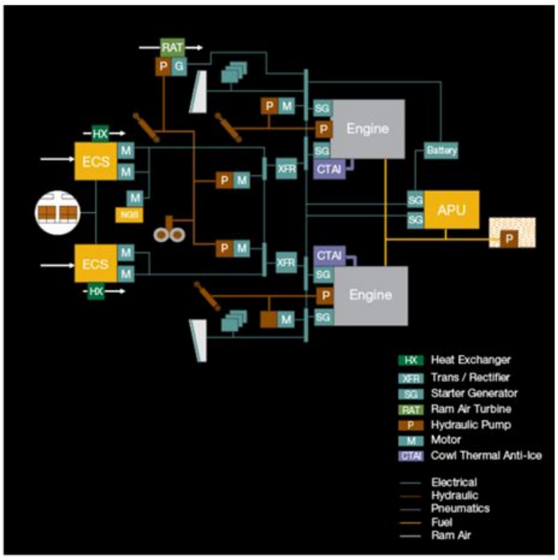


Figure 2.24 – 787 Dreamliner ECS Scheme [8]

- **Air Cycle Machine** uses air taken from outside through special air intakes, compressed by means of dedicated compressors.
- **Vapour Cycle Machine and Heat Pump Machine** uses only the air present in the cabin which is then recirculated completely, going to condition it cycle after cycle in terms of temperature and physical-chemical composition. The first solution is simpler to implement and has a TLR equal to the current one, but having to take air from outside requires the arrangement of air intakes whose size can become important, resulting in increased resistance and an impossibility of use for hypersonic aircraft.

2.10 Supersonic flight

In order to reach higher speeds it is necessary to fly at higher altitudes, necessarily reaching the ozone layer. Ozone is present above the tropopause, at an approximate altitude of 11km in the middle latitudes in summer. It enters the cabin through engines and its concentration inside is a function of the outside concentration, the use of absorber, design of air distribution and total airflow. It is important to identify a cabin ozone retention factor that is the ratio of the ozone concentration in the cabin to the ozone concentration outside the cabin. Retention ratio goes to 0.75 to 1 without recirculation and goes to 0.4 to 1 with recirculation. [9]

Composition of outside air does not change in the compression cycle. Some particles can be removed by centrifuging in the port through which air is extracted from the engine. But Ozone can be affected by the heat of compression. In supersonic flight the compressed-air temperatures are so high that nearly all the ozone is destroyed in the engine, and no further treatment are so high that nearly all the ozone is destroyed in the engine, and no further treatment is needed. This happened, for example, in Concorde, but in commercial aircraft, the temperature of the compressed air taken from the engine for air-conditioning is not adequate to reduce the free ozone concentration.

2.10.1 *Concorde*

Concorde [10] was the first and only commercial jet to exceed the speed of sound in aviation history. So it was the first technological challenge that allowed civil passenger to go beyond the speed of sound.

Figure 2.25 – Concorde [11]

Concorde's ECS comprised of four independent subsystem. In each these, air passes through a primary ram-air heat exchanger to an air cycle cold-air unit and then through secondary air/air and air/fuel heat exchangers. The air was then mixed with hot air and fed to the cabins.

These groups are identical and installed in pairs on each side of the aircraft. Compressed air is bled by each group from the last stage of the high pressure compressor of the associated engine. There is a cross bleed system between each pair of groups which is located on one side of the aircraft and makes it possible to have either group supplied with air from the engine associated with the other groups or from an air supply unit if the engines are shut down on the ground.

- Group No.1 – Supplies flight compartment in priority
- Group No.2 – Supplies the forward cabin
- Groups No.3 & No.4 – Supplies the aft cabin

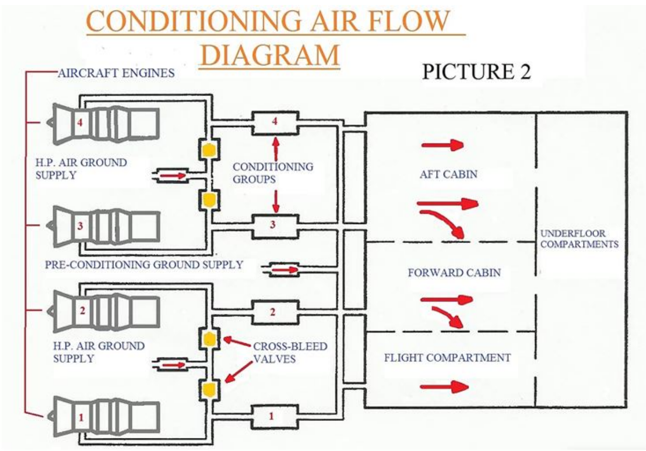


Figure 2.26 – *Concorde* Conditioning air flow diagram

Primary Cooling System

This system consists mainly of the following:

- Air conditioning valve: it is an electro-magnetic valve that cuts off or admits airflow at determined rates.
- Mass flow control valve: It is an electro pneumatic valve. It limits the airflow to 45 Lb. /min. in normal operation.

- - Primary heat exchanger: it limits the Cold Air Unit compressor inlet temperature to 200^oC.
- Ram air control valve: operates to control the airflow through the primary heat exchanger in order to keep the system performances at cold temperature.

Secondary Cooling System

This system consists mainly of the following:

- Cold air unit (Bootstrap): it consists of a centrifugal compressor and an expansion turbine mounted on the same shaft. The cold air unit is provided with a three position turbine nozzle corresponding to three different outlet areas.
- Secondary Heat exchanger: it lower the fuel heat exchanger inlet air temperature to 190^oC.
- Fuel Heat Exchanger: reduce the conditioning air temperature at the turbine inlet to the lowest value compatible with its volume and permissible inflow.
- Intercooler Water Drain Swirler: its function is to remove condensation water from the conditioning air in order to prevent turbine erosion.
- CAU By pass system: controls the air temperature at the cold air unit outlet in accordance with the value selected on corresponding temperature control. selector

Ice sensor and Water Separator

The ice sensor transmits an electrical signal to the temperature controller in order to prevent icing downstream of the system. Under 30000 feet, water separator removes 80% of water in suspension, while above 30000 feet, water separator is by-passed because layers of atmospheric air are dry.

Warning and sasfety systems

Each air conditioning system has a safety system to prevent overheat, overpressure, leaks and dust ingestion.

- High temperature safety: In the event of fuel heat exchanger over-temperature (95^oC), the fuel control valve opens. The distribution duct overheat (210^oC) causes the shut off valve, cabin isolations valve and two adjacent cross-bleed valves to close. In this case the group is no longer operative.

- Overheat test and air conditioning valves: it is a switch that enables checking overheat detection devices.

- Overpressure safety: When the over-pressure switch operates (85 psi) the shut off valve closes.

- Leak detection of cold air unit double wall: ducts are provided with double walls in order to prevent air leaks in the wing compartment.

- Dust: A dust centrifuge provided with a dust outlet is mounted on the system.

- Smoke detection: Four high sensibility smoke detectors installed downstream of the water separators monitor the air blown from the air conditioning groups, the airflow speed being very high.

Ventilation distribution

There are two axial flow fans, one on each side of the under-floor bay. They extract air from the passenger compartment and supply it to the forward equipment racks. There are also three axial flow fans at a junction of the extraction ducting that extract air from cabin and discharge it overboard. System has also three mixed flow fans that extract air from rear equipment racks and discharge it into the under-floor space.

The forward hydraulic chassis is shrouded and ventilated to contain risk from hydraulic oil mist. Aircraft batteries are vented to atmosphere through two inter-connected pipes that incorporate relief valves and drain valves. These are attached to the drain outlets of the relief valves and allow that excess pressure is released by the relief valve.

Moreover there are three fuel tank system that are sealed, ventilated and drained to eliminate hazard from fuel leakage. Fuel leaking into the vapor seal air space is passed overboard by gravity feed through the drain pipes.

2.10.2 XB-70

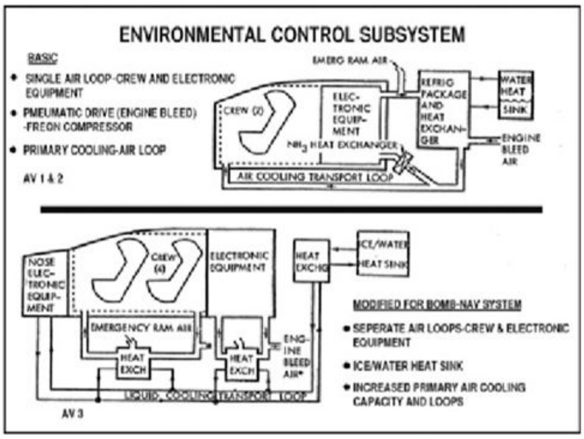
The North American Aviation XB-70 Valkyrie was the prototype version of the planned B-70 nuclear-armed, deep-penetration strategic bomber for the United States Air Force Strategic Air Command. Designed in the late 1950s by North American Aviation (NAA), the six-engined Valkyrie was capable of cruising for thousands of miles at Mach 3+ while flying at 70000 *feet (*21000 *m).*

At these speeds, it was expected that the B-70 would be practically immune to interceptor aircraft, the only effective weapon against bomber aircraft at the time. The bomber would spend only a brief time over a particular radar station, flying out of its range before the controllers could position their fighters in a suitable location for an interception. High speed also made the aircraft difficult to see on radar displays and its high-altitude and high-speed capacity could not be matched by any contemporaneous Soviet interceptor or fighter aircraft. [12]

Figure 2.27 – XB-70 [13]

Before XB-70 Confortable environment at the flight speed and altitude that it marked was a concept unheard. This confortable environment was obtained by using a high-pressure bleed air system, supported by two Freon refrigeration units that helped cool the crew cabin and the equipment bays. In this way pressure cabin were maintained at 8000 feet.

Refrigeration units used high-pressure bleed air to run the Freon compressor turbines: air entered at 850^oF and reduced to 45^oF (cabin's temperature was regulated between 40^oF and 160^oF) thanks to additional bleed air that left the Freon exchangers. After that air was circulated into a glass-lined plenum cell at the end of the porous wall and ducted back to the heat exchangers after passing through a water vaporizer.



The cockpit environmental system varied between AV 1 and AV 2 and 3 as seen in this schematic shown in the B-70 Study. *(North American Rockwell)*

Figure 2.28 – ECS - XB-70 [13]

Cooling air was forced through each chassis from a self-contained ECS which employed liquid nitrogen for cooling and pressurization. Pressure was maintained so that it was never less than that corresponding to 8000 feet altitude. Environmental control provisions were dual, providing back-up operation in the event of an in-flight failure of the system. The instrumentation package was entirely independent of any air vehicle system with the exception of electrical power.

2.11 Space Application of ECS: ECLSS

A life – support system allows surviving in an environment that does not support life. It is necessary to use it in situations where the outside environment is hostile. When this environment is “Space” the system that allows survival is called Environmental Control and life – support System (ECLSS).

Throughout the history of crewed space exploration, the NASA has developed and implemented a variety of spacecraft life support systems. As the duration and complexity of missions increased from minutes or hours for a single astronaut during Project Mercury to days and ultimately months for crews of 3 or more during the Apollo, Skylab, Shuttle, and ISS programs, these systems have become more sophisticated. Maintaining a safe, comfortable environment for the crew requires significant resources. As mission duration and crew size have increased [14], Figure makes it readily apparent that life support systems on board spacecraft such as the ISS must balance many competing factors. Primarily, their design must provide long-term environmental control and life support for a small mass, volume, and power penalty while maximizing their safety, reliability, and performance. [15]

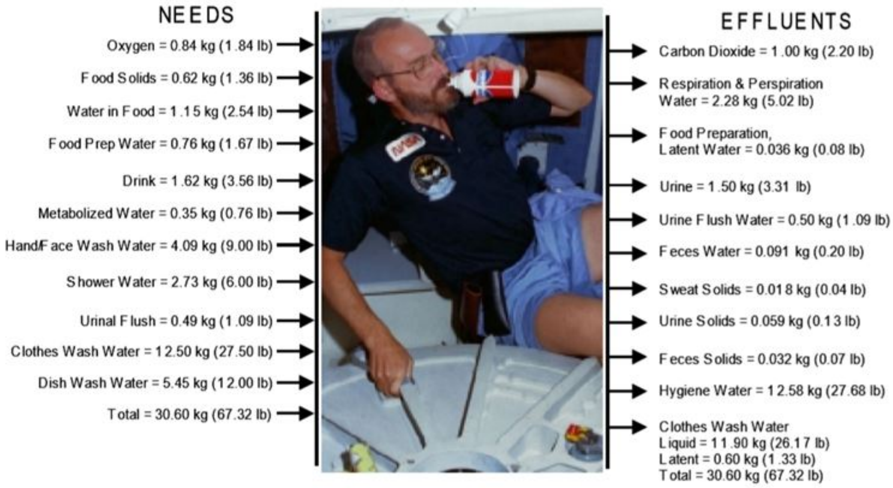


Figure 2.29 – Crew needs and byproducts [15]

ECLSS systems are responsible for:

- Pressurization
- Ventilation
- Temperature

- Humidity levels
- Anti-icing and De-Misting
- Fire Suppression

It must also support special operations such as Extra Vehicular Activities (EVA), respond to environmental contingencies and provide health related services. None of these systems operate alone.

2.11.1 ECLSS Functions

Atmosphere Management

Atmosphere Management System is composed by Atmosphere Control and Supply System (ACS) and Temperature and Humidity Control (THC).

Managing the atmosphere function of the ECLSS means continuously monitoring and controlling the space habitat's environment to maintain and/or provide:

- Partial and total pressure
- Cabin temperature and humidity
- Contaminants at ssafe level
- Adequate ventilation

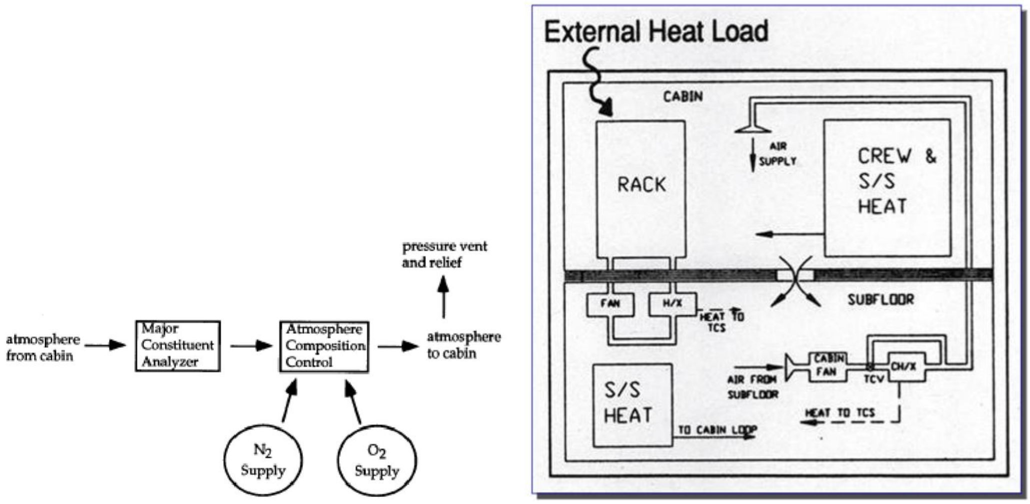
Figure below summarize the typical cabin air quality parameters for a crewed spacecraft.

Atmosphere mngt requirements	ISS nominal values
Total pressure	99.9-102.7 kPa
Oxygen, partial pressure (O2)	19.5-23.1 kPa
Nitrogen, partial pressure (N2)	79 kPa
Carbon dioxide, partial pressure (CO2)	0.4 kPa
Temperature	18.3-23.9 °C
Relative humidity	30-70%
Concentration of trace gases	< SMAC* levels
Ventilation	0.08-0.2 m/s

*Spacecraft Maximum Allowable Concentrations

Figure 2.30 – Cabin Air Quality parameters [2]

It is important to observe that the elimination of diluent gases increases fire risks, especially in ground operations when total pressure inside the cabin exceed the external pressure (Apollo 1).



(a) *ACSs* (b) *THC*

It is advisable to use a mixture of nitrogen/oxygen because oxygen toxicity becomes a risk factor at high concentration. Pure oxygen is actually used only in pressure suits during EVA.

The equipment should be able to continuously sense and display carbon monoxide and dioxide.

Figure shows the interactions between factors that influence cabin air quality.

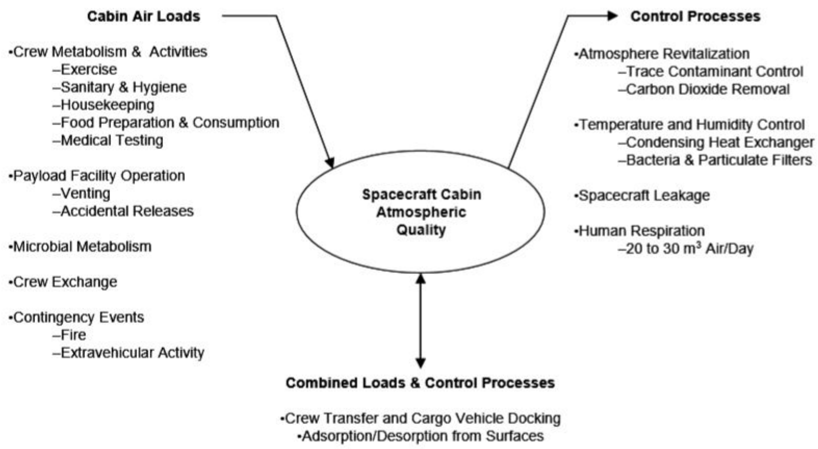


Figure 2.31 – Factors influencing spacecraft cabin air quality [15]

Ventilation reduces or eliminates density gradient air movement and it affects coefficients of heat transfer, moreover keep crews safe and comfortable by preventing stagnation and thoroughly mixing air within and between modules.

It is necessary to consider the need for removing Carbone Dioxide from the atmosphere. In fact high concentration levels of it can build up in a short time. Finally, to make atmosphere totally breathable, it is necessary to remove particulates as hair, lint and trace contaminants produced by humans and equipment Table below provides a summary of the air purification technologies used on NASA spacecraft.

PROJECT	MISSION DURATION	CABIN VOLUME (m^3)	CREW SIZE	AIR QUALITY TECHNOLOGIES
Mercury	34 hours	1.56	1	CO_2 removal: LiOH Trace contaminants: activated carbon
Gemini	14 days	2.26	2	CO_2 removal: LiOH Trace contaminants: activated carbon
Apollo	14 days	5.9	3	CO_2 removal: LiOH Trace contaminants: activated carbon
Skylab	84 days	361	3	CO_2 removal: Type 13X and 5A molecular sieves regenerated by pressure swing Trace contaminants: activated carbon
Shuttle	14 days	74	7	CO_2 removal: LiOH Trace contaminants: activated carbon with ambient temperature CO catalytic oxidation
Space Station	180 days	Up to 600	3 to 6	CO_2 removal: Silica gel with type 13X and 5A molecular sieves regenerated by combined pressure/thermal swing Trace contaminants: activated carbon with thermal catalytic oxidation

Figure 2.32 – Air purification technologies - NASA [15]

Water Management System (WMS)

The Water Management System provides water for the crew to drink and use for hygiene and to carry out other activities. Water quality may vary widely for different uses at a space habitat.

In Space it is needed:

- Potable water for drinking, preparing food and EVA cooling;
- Hygiene's water for shower, hand wash, laundry, dishwashing and urinal flushing;
- Medical water for special needs.

This system is responsible for storing and distributing water to users. These processes are very difficult, in fact storing and distributing process are complex because of the micro-gravity condition. Particularly, water quality must be maintained over extended period and, last but not the least, since puddles do not occur in microgravity environment, the system shall also be responsible of detecting leakages.

Water Management System monitors and maintains water quality, in particular it has to monitor the pH, ammonia content, organic carbon, electrical conductivity and microbial concentration.

Finally, WMS processes waste water (cabin's humidity, hygiene waste water and so on..) and collected at its point of production, then stored locally or plumbed to a central location.

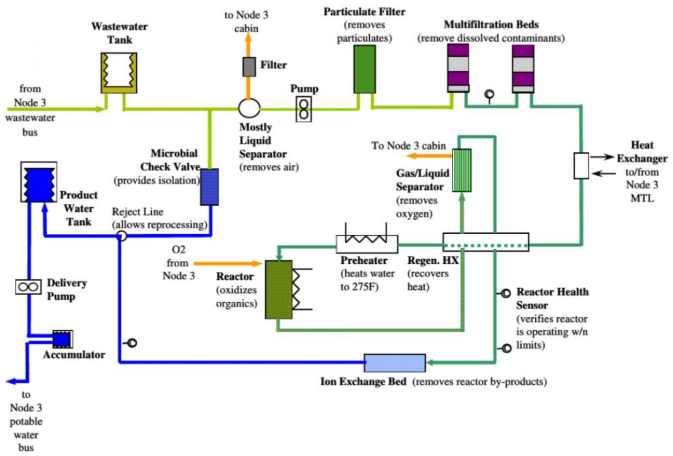


Figure 2.33 – WPA - Water Processor Assembly [16]

Urines can be used to produce water thanks to the Urine Processor Assembly (UPA).

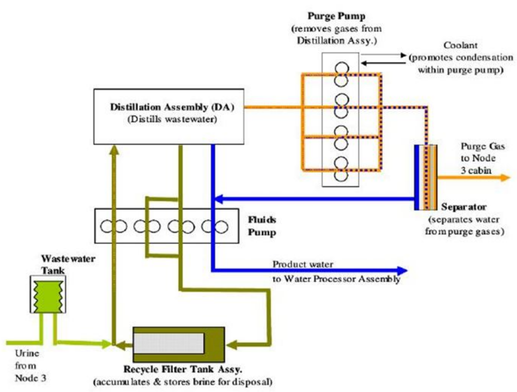


Figure 2.34 – UPA - Urine Processor Assembly [16]

Urine is pretreated in the place of collection by adding chromium trioxide and sulfuric acid in order to control microbial growth and the degradation of urea into ammonia. Subsequently, it is collected in the Wastewater Storage Tank Assembly from which it is redirected by a peristaltic pump to the Distillation Assembly, where the actual distillation takes place. The water obtained from here is sent to the WPA while the waste products are transferred to the Recycle Filter Tank Assembly. The heart of the structure is, therefore, the Distillation Assembly which is composed of a centrifuge where the water is evaporated from the urine stream at an extremely low pressure and the steam thus obtained is collected by a new peristaltic pump and sent to the Separator Plumbing Assembly, where the water is recondensed and separated from other unwanted gases. This system is nominally able to recover 85% of the water from the urine stream.

However, the estimates have been heavily revised due to the large quantities of calcium sulphate precipitates present in the pretreated urine, due to the reaction between the calcium excreted in the urine and sulfuric acid. This concentration is higher than expected due to the greater amount of calcium expelled by the astronauts in conditions of microgravity, to the point of saturating the solution and precipitating with the increase in temperature that is found in the distillation chamber. Furthermore, the precipitation of calcium sulphate is also facilitated by an anomaly in the pH value of the pretreated urine, expected between 1.5 and 1.8 and found between 1.7 and 2.5, which appears to be related to high values of dissolved phosphates. [16]

Waste Management System

The way waste materials are treated depend on its nature and the mission. Short missions do not require recycling, in fact waste are collected, stabilized and stored. Medium-duration missions and near Earth missions do not need much recycling. Problems arrive when missions start becoming longer since storage may become prohibitive because of the associated weight and volume penalties and because biological and chemical waste degrades potentially contaminating the habitat. At the end, if humans want to be an interplanetary species, they need to build permanent planetary bases that need that all consumables should be directly regenerable or suitable for recycling into the water and food loops.

Food Management

Food can be launched from Earth and stored on the spacecraft until needed or produced and stored in the space habitat. There are three categories of food products:

- Little or no processing.
- Primary processing.
- Secondary processing.

The first category includes food that is edible in its natural form, such as fresh fruit and some vegetables. Minor processing might consist of washing and cutting, but with little hardware support. The second one comprises food products that require hardware support, such as juice presses, grain mills. This hardware has to adapt to the limited requirement on power, mass and volume in space environment. The latter category includes biological products that are not edible in raw but contain potentially digestible and nutritious food, such as cellulose can be converted into glucose.

2.11.2 ECLSS Relationship

The figure below diagrams the four main subsystems descripted before as well as how they relate to crews.

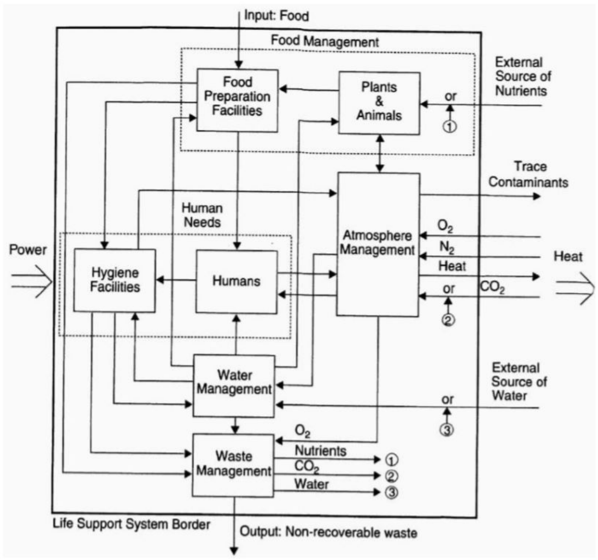


Figure 2.35 – ECLSS Relationship [2]

Leakage and processing will always keep some open loops, so it is expected continuous input from external sources. With the right waste-processing procedure, however, it is possible to nearly close the loops for nutrients, oxygen, and water, thus minimizing re-supply.

The interfaces, which the schematic shows as simple input-output arrows, represent material flow across functional boundaries. These interfaces are relatively predictable.

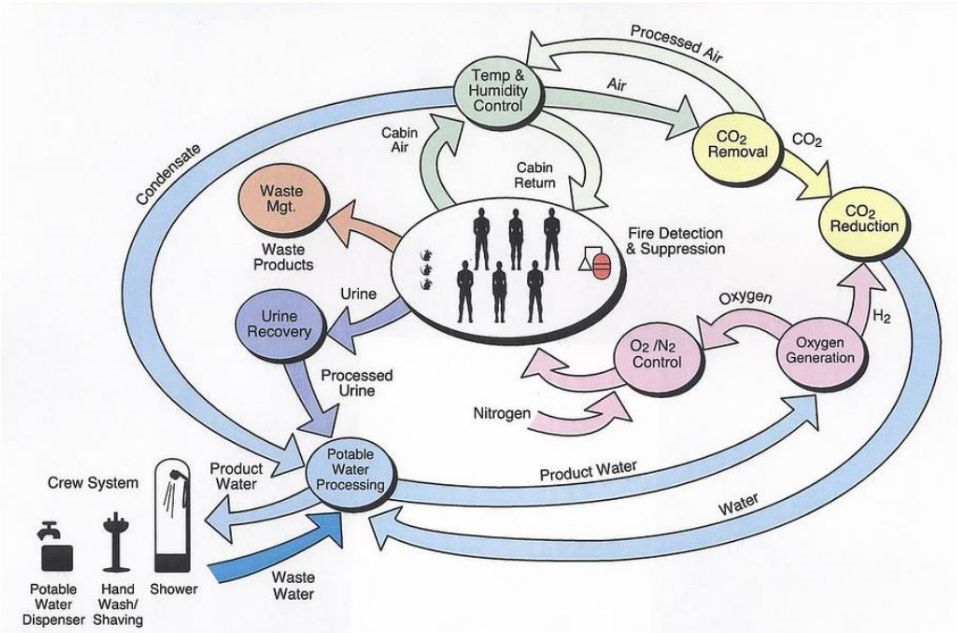


Figure 2.36 – ECLSS on International Space Station [17]

2.11.3 Technology Options and Future trends

Actually Physical-Chemical solutions are used. They use fans, filters, physical and chemical separation, concentration processes and so on. These solutions are compact, easy to maintain but above all our technology level is mature for it. Nevertheless they cannot replenish food stocks and this must not be underestimated. We are planning to build settlements on Moon and Mars but actually we do not have the technology to close the loop.

Micro Ecological Life Support System Alternative (MELiSSA)

To colonize new planets, it is necessary to leave behind the chemical-mechanical systems, which are too expensive and prone to failures, and focus on the use of bio-regenerative solutions that means Closed-Loop.

In the 1980's, several European visionaries wanted to learn how to recycle waste and carbon dioxide on spacecraft using bacteria. Under the impetus of them – Claude Chipaux and Daniel Kaplan of Matra Espace, Professor Max Mergeay of SCK, Professor Willy Verstraete of the University of Ghent and Professors Marcelle Lefor Tran and Guy Dubertret of CNRS - a group of European organisations sharing common interests decided to pool their efforts in the MELiSSA consortium. [18]

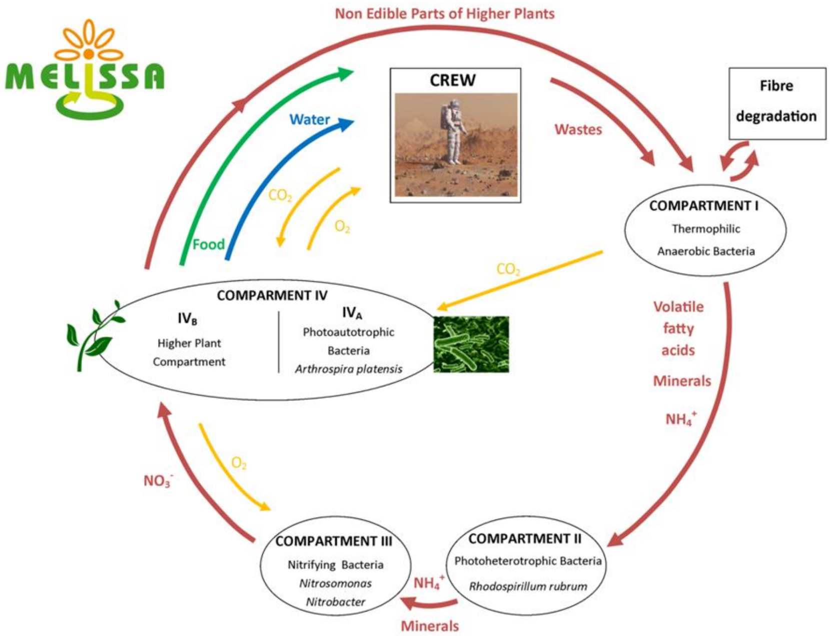


Figure 2.37 – MELiSSA Closed-Loop

It is based on the principle of an "aquatic" lake ecosystem where waste products are processed using the metabolism of plants and algae which in return provide food, air revitalization and water purification.

Melissa Loop has been structured as an assembly of unit-processes called compartments that are created to simplify the behavior of an artificial ecosystem.

Each compartment has specific functions assigned. The liquefying compartment, Compartment I, determines the fraction of organic wastes that will be recycled in the loop. Actually, physical/chemical treatment are under research in order to improve the biodegradability.

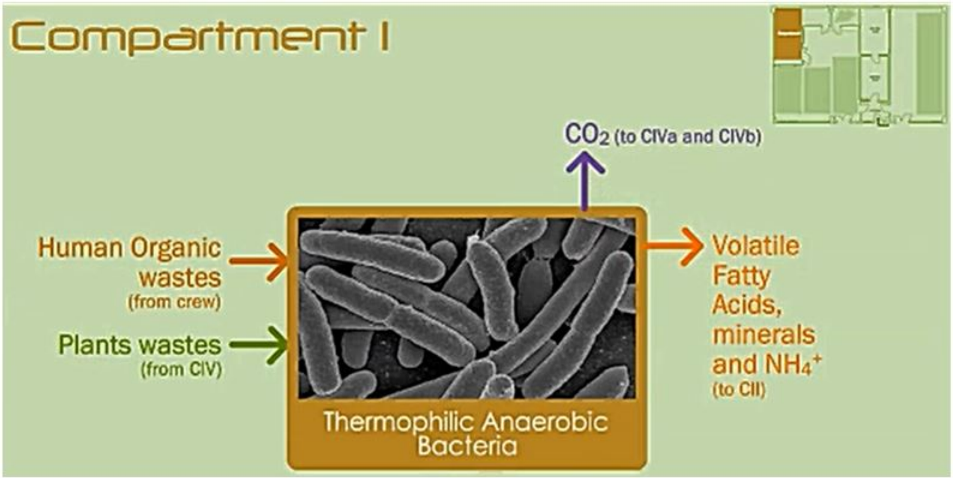


Figure 2.38 – Organic waste degradation and solubilisation

Carbon Dioxide produced in Compartment I is supplied to Compartment IV, where photosynthesis happened. The ammonia produced during the anaerobic process is fed to the photoheterotrophic anoxygenic compartment, also known as Compartment II, where organic carbon is transformed into inorganic carbon source.

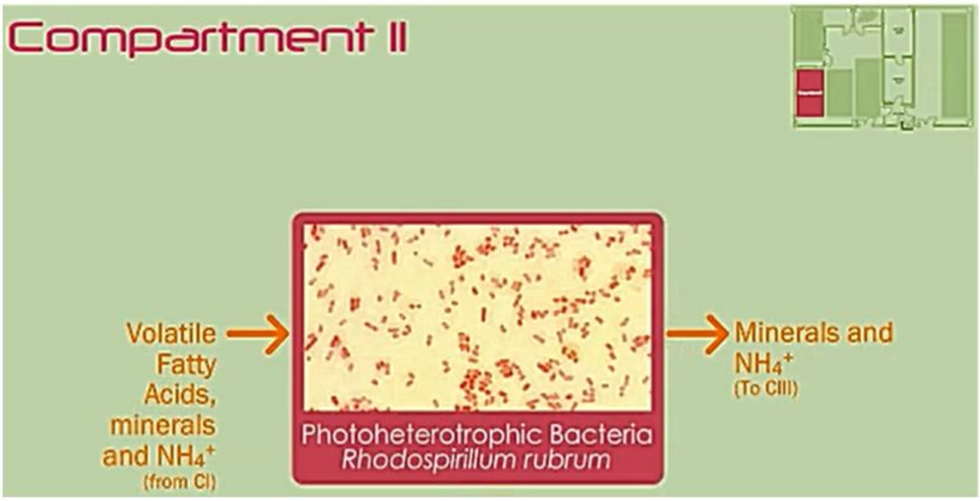


Figure 2.39 – Carbon Compounds Removal

The nitrifying compartment (Compartment III) converts ammonia into nitrates that are source of nitrogen for Compartment IVb (Higher Plant).

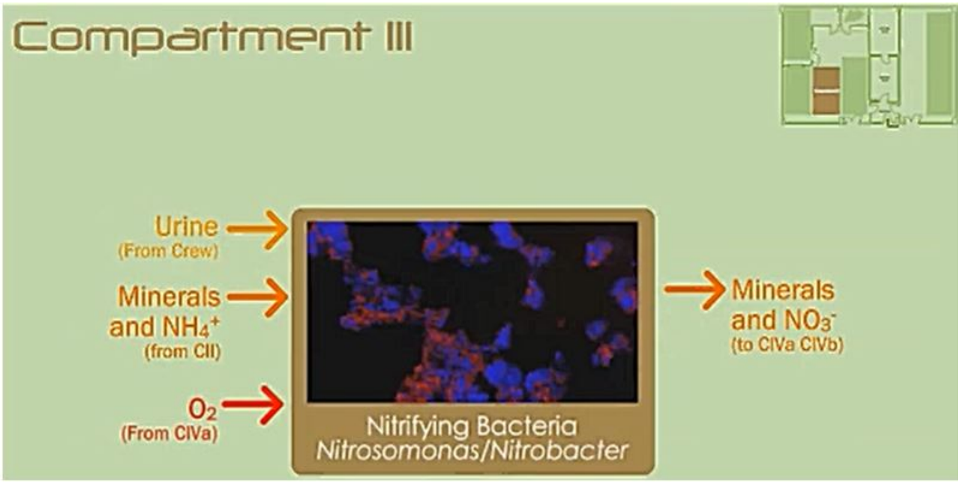


Figure 2.40 – Nitrogen transformation: Nitrification

Compartment IV, also known as photoautotrophic compartment, remove CO2, generate edible biomass as food supply, recover water and regenerate oxygen for the crew.

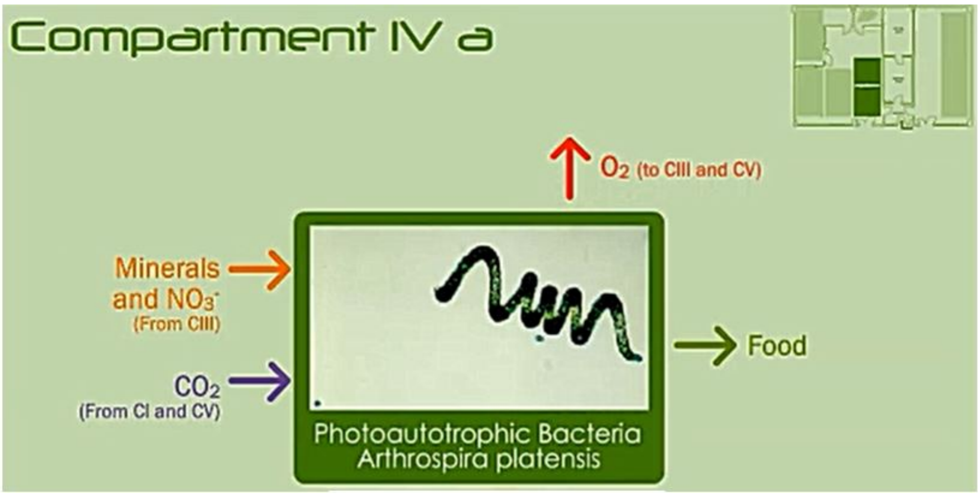


Figure 2.41 – Food and Oxygen Production

The following tables contain the reactions that take place in the various chambers and the species of bacteria considered in the project.

Table 1
Chemical conversions, describing the general C, O, N and S cycles in the bacterial compartments of the life support system MELiSSA

BC[a]	Element	Chemical equation[b]	Acting organism
I	C	$\underbrace{CH_{1.67}O_{0.83}}_{\text{sugar polymer}} + H_2O \rightarrow \underbrace{CH_2O}_{\text{sugar monomer}} + \text{energy}$	Fermentative bacteria
		$\underbrace{CH_2O}_{\text{sugars}} \rightarrow CO_2 + H_2 + \underbrace{CH_2O_{0.52}}_{\text{volatile fatty acids}} + \text{energy}$	Acidogenic/acetogenic bacteria
	N, S	$\underbrace{C_{4.18}H_{7.36}ON}_{\text{proteins}} + H_2O \rightarrow \underbrace{C_{4.18}H_{9.37}O_2NS_{0.06}}_{\text{amino acids}} + \text{energy}$	Fermentative bacteria
		$\underbrace{C_{4.18}H_{9.37}O_2NS_{0.06}}_{\text{amino acids}} + H_2O \rightarrow NH_3 + CO_2 + \underbrace{CH_2O_{0.52}}_{\text{volatile fatty acids}} + H_2S + \text{energy}$	Acidogenic/acetogenic bacteria
II	C	$\underbrace{CH_2O_{0.52}}_{\text{volatile fatty acids}} + NH_3 + H_3PO_4 + H_2SO_4 + CO_2 \xrightarrow{\text{light}} \underbrace{CH_{1.60}O_{0.36}N_{0.22}P_{0.02}}_{\text{biomass}} + H_2O$	*R. rubrum*
		$\underbrace{CH_2O}_{\text{sugars}} + H_2O \xrightarrow{\text{light}} CO_2 + H_2$	
	N, S	$\underbrace{C_{4.184}H_{9.372}O_2NS_{0.06}}_{\text{amino acids}} + H_2O \rightarrow NH_3 + CO_2 + \underbrace{CH_2O_{0.52}}_{\text{volatile fatty acids}} + H_2S + \text{energy}$	
		$CO_2 + 2H_2S + NH_3 + H_3PO_4 \xrightarrow{\text{light}} \underbrace{CH_{1.60}O_{0.36}N_{0.22}P_{0.02}}_{\text{biomass}} + H_2O + 2S$	
		$CO_2 + S + H_2O + NH_3 + H_3PO_4 \xrightarrow{\text{light}} \underbrace{CH_{1.60}O_{0.36}N_{0.22}P_{0.02}}_{\text{biomass}} + H_2SO_4$	
III	C	$CO_2 + H_2O + NH_3 + H_3PO_4 + H_2SO_4 + \text{energy} \rightarrow \underbrace{CH_{1.60}O_{0.36}N_{0.22}P_{0.02}}_{\text{biomass}} + H_2O$	*N. europaea* and *N. winogradskyi*
	N, O	$NH_3 + \frac{3}{2}O_2 \rightarrow HNO_2 + H_2O + \text{energy}$	*N. europaea*
		$HNO_2 + O \rightarrow HNO_3 + \text{energy}$	*N. winogradskyi*
IVa	C, O	$CO_2 + H_2O \xrightarrow{\text{light}} \underbrace{CH_{1.60}O_{0.36}N_{0.22}P_{0.02}}_{\text{biomass}} + H_2O + O_2$	*Arthrospira* sp.
	N, S	$NO_3^- + 2H^+ + \text{energy} \rightarrow NO_2^- + H_2O$	
		$NO_2^- + 8H^+ + \text{energy} \rightarrow NH_4^+ + 2H_2O$	
		$NH_4^+ + H_2SO_4 + \text{energy} \rightarrow \underbrace{C_{4.184}H_{9.372}O_2NS_{0.06}}_{\text{amino acids}} + H_2O$	

[a] Bacterial compartment in the MELiSSA loop.
[b] The chemical equations that reflect general conversions have not been adapted stoichiometrically.

Figure 2.42 – Reactions in each chamber

Table 2
List of genome characteristics of the principle MELiSSA strains and other relevant strains

Comp.[a]	Organism	Strain	Family[b]	Status	Mb	ORFs	GC%	Center[c]	Ref.
II	*Rhodospirillum rubrum*	ATCC 25903	Rhodospirillaceae	No data	–	–	–	–	NA
	Rhodospirillum rubrum	ATCC 11170	Rhodospirillaceae	Complete	4.40	3829	65.4	DOE/JGI	Unpub.
	Rhodobacter capsulatus	SB1003	Rhodobacteraceae	Complete	3.70	3709	66.8	IG	Unpub.
	Rhodobacter sphaeroides	2.4.1	Rhodobacteraceae	Complete	4.10	3980	69.0	DOE/JGI	Unpub.
III	*Nitrosomonas europaea*	ATCC 19718	Nitrosomonadaceae	Complete	2.81	2461	51.6	DOE/JGI	[12]
	Nitrosomonas sp.	(Unknown)	Nitrosomonadaceae	No data	–	–	–	TIGR	NA
	Nitrosomonas sp.	17	Nitrosomonadaceae	No data	–	–	–	CVI	NA
	Nitrosomonas eutropha	C71	Nitrosomonadaceae	No data	–	–	–	DOE/JGI	NA
	Nitrosospira multiformis	Surinam	Nitrosomonadaceae	7 contigs	3.20	2794	53.9	DOE/JGI	Unpub.
	Nitrospira marina	Nb-295	Nitrosomonadaceae	No data	–	–	–	CVI	NA
	Nitrosococcus oceani	ATCC 19707	Chromatiaceae	26 contigs	3.50	3160	50.3	DOE/JGI	Unpub.
	Nitrosococcus oceani	C27	Chromatiaceae	No data	–	–	–	CVI	NA
	Nitrosococcus sp.	(Unknown)	Chromatiaceae	No data	–	–	–	TIGR	Unpub.
	Nitrospina gracilis	Nb-211	Desulfoarculaceae	No data	–	–	–	CVI	NA
	Nitrococcus mobilis	Nb-231	Ectothiorhodospiraceae	No data	–	–	–	CVI	NA
III	*Nitrobacter winogradskyi*	ATCC 25391	Bradyrhizobiaceae	42 contigs	3.40	3258	62.0	DOE/JGI	Unpub.
	Nitrobacter winogradskyi	ATCC 14123	Bradyrhizobiaceae	No data	–	–	–	–	NA
	Nitrobacter sp.	Nb-311A	Bradyrhizobiaceae	No data	–	–	–	CVI	NA
	Nitrobacter hamburgensis	(Unknown)	Bradyrhizobiaceae	15 contigs	4.60	4669	61.6	DOE/JGI	Unpub.
	Rhodospseudomonas palustris	CGA009	Bradyrhizobiaceae	Complete	5.46	4836	65.5	DOE/JGI	[42]
IVb	*Arthrospira* sp.	PCC8005	Oscillatoriaceae	No data	–	–	–	–	NA
	Arthrospira platensis	(Unknown)	Oscillatoriaceae	1282 contigs[d]	5.20	7213[e]	44.0	BGC	NA

Abbreviations: Mb, megabase; ORF, open reading frame; GC%, molar guanine-cytosine of DNA content in percentiles; NA, not applicable; unpub., unpublished. Principle strains used in the MELiSSA loop are indicated in gray.
[a] Comp.: compartment of the MELiSSA loop.
[b] Family name according to the NCBI taxonomy browser (http://www.ncbi.nlm.nih.gov/Taxonomy/).
[c] Joint Genome Institute (DOE/JGI), Integrated Genomics (IG), The Institute for Genomics Research (TIGR), Craig Venter Institute (CVI), Bejing Genome Center (BGC).
[d] C.-C. Zhang, pers. communication.
[e] This is likely an overestimate based on preliminary gene modeling.

Figure 2.43 – Bacteria in each chamber

MELissa's Challenges

One of the main challenges of the project is maintaining stability within the system population.

Although it has been shown that extremely dynamic and differentiated communities of bacteria are very efficient in maintaining functional stability, dynamism is an undesirable aspect in a controlled artificial ecosystem such as that proposed by MELiSSA.

The environment of microgravity, prolonged exposure to ionizing radiation as well as contact with human waste, which can introduce pollutants (hormones, heavy metals and metabolic waste in general) could strongly affect the stability of the system and lead to potentially destructive consequences. Continuous quality controls and strong compartmentalization are required to reduce the interconnection of the system and, consequently, its complexity.

The problems solved to develop the current generation of the ECLSS have had a positive technological impact on Earth. For example, they have contributed to the creation of very efficient and low cost water purification systems of which some examples are found in the most remote areas of the planet, while the development of the next generations could also reserve small revolutions, from microbial control to food production and biofuels to reduce carbon dioxide emissions.

2.11.4 APOLLO Program

Project Apollo was the most important human spaceflight program achieved by National Aeronautics and Space Administration which leaded successfully humans on the Moon.

Figure 2.44 – Apollo program's Logo [19]

The most important challenge of the Apollo program was to bring three astronauts “to the Moon and back”. In order to succeed in this enterprise, it was necessary to create an adequate ECLSS system that could guarantee the survival of all crew members, both on the Space Shuttle and in the Lunar Lander. In the following paragraphs some aspects and technological challenges faced by the scientists of the time will be analyzed, thanks to some block diagram.

Apollo 11 ECS Introduction

The Environmental Control Subsystem (ECS) enables pressurization of the cabin and space suits, controls the temperature of electronic equipment, and provides breathable oxygen for the astronauts. It also provides water for drinking, cooling, fire extinguishing, and food preparation and supplies oxygen and water to the portable life support system.

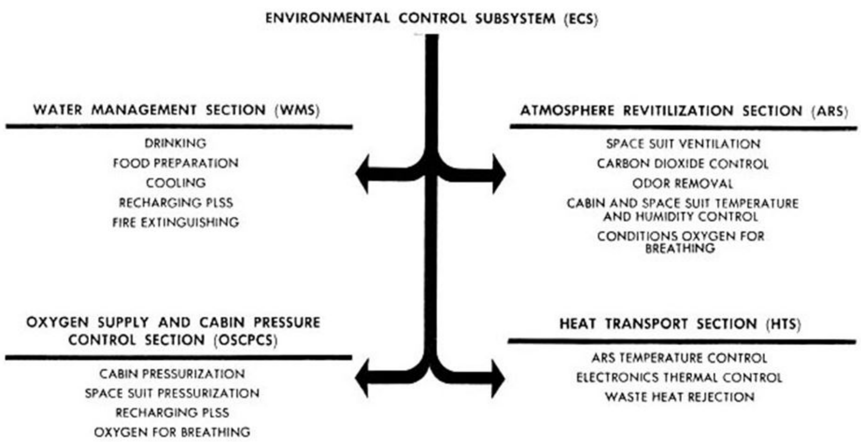


Figure 2.45 – ECS - Apollo Program [20]

The most important part of ECS is in the cabin, while other equipment such as oxygen and water tank are located outside the cabin. Environmental Control System is composed by:

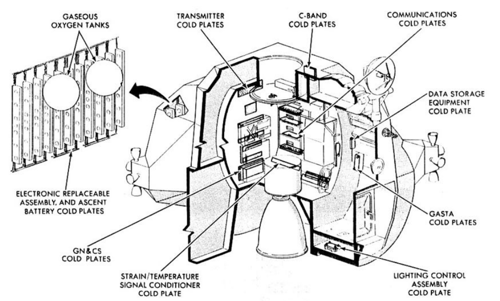
- Atmosphere revitalization Section (ARS);
- Oxygen supply and cabin pressure Control Section (OSCPCS);
- Water Management Section (WMS);
- Heat transport Section (HTS).

ARS purifies oxygen from carbon dioxide, excess water vapor and odors for cabin and space suits.

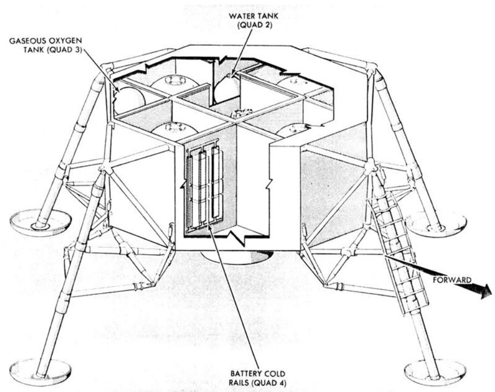
OSCPCS stores gaseous oxygen and supply it to the ARS in order to compensate crew metabolic consumption and leakage. There is one oxygen tank in the descent stage to provide oxygen during the descent stage and two oxygen tanks in the ascent stage used for rendezvous.

WMS supplies water for drinking, food preparation and cooling. Moreover it delivers water from ARS water separators to HTS sublimators.

HTS consists of a primary coolant loop and a secondary coolant loop. The latter is used as a backup loop, so it functions only if the primary loop fails. Primary Loop provides temperature control for batteries and electronic equipment other than maintain oxygen in a range of temperature adequate for human respiration.



(a) *Component Locations – Outside the Cabin in the Ascent Stage*



(b) *Component Locations – In the Descent Stage*

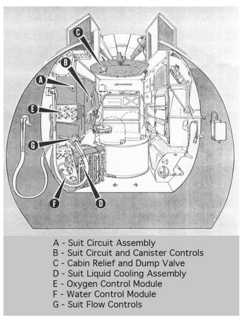


Figure 2.46 – Components Location - In the cabin

Functional description of each systems is supported by a functional flow diagram.

Atmosphere Revitalization Section

Oxygen flows to the space suits and then is discharged to the suit circuit. The latter is in relationship with the oxygen regulators that control pressure by supplying makeup oxygen to the suit circuit.

Metabolic heat is removed by suit liquid cooling assembly by circulating cool water through the liquid cooled garment. Leakage and volumetric changes are compensated by an accumulator.

The quantity of water that flows through the heat exchanger is controlled by a bypass valve.

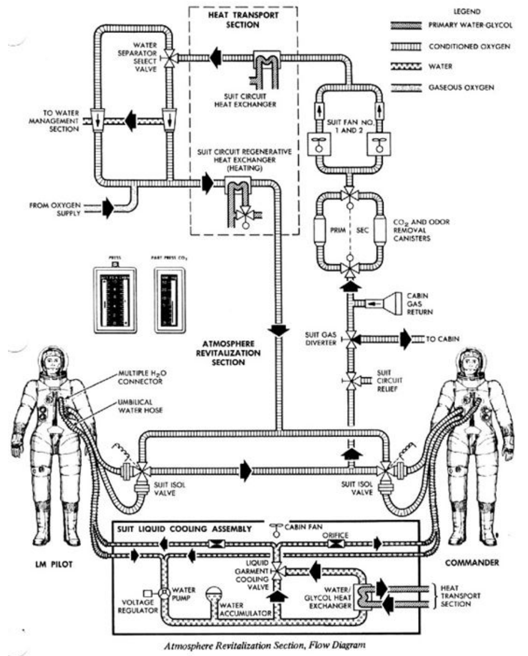


Figure 2.47 – ARS Functional description diagram

Oxygen Supply and Cabin Pressure Control Section

The ECS descent stage hardware consists of a descent oxygen tank, high-pressure fill coupling, high-pressure oxygen control assembly, an interstage flex line and a descent stage disconnect.

While the ascent stage hardware consists of an ascent stage disconnect, interstage flex line, oxygen module, two ascent oxygen tank and cabin pressure switch. OSCPCS has the task of storing gaseous oxygen, replenish ARS with oxygen and refill PLSS oxygen tank.

It is important to underline that before staging, descent stage oxygen tank supply oxygen. After that, the oxygen control module is supplied by ascent stage oxygen tanks. In order to control oxygen in the OSCPCS there are valves in the descent stage for high-pressure assembly and in the ascent stage for oxygen control module.

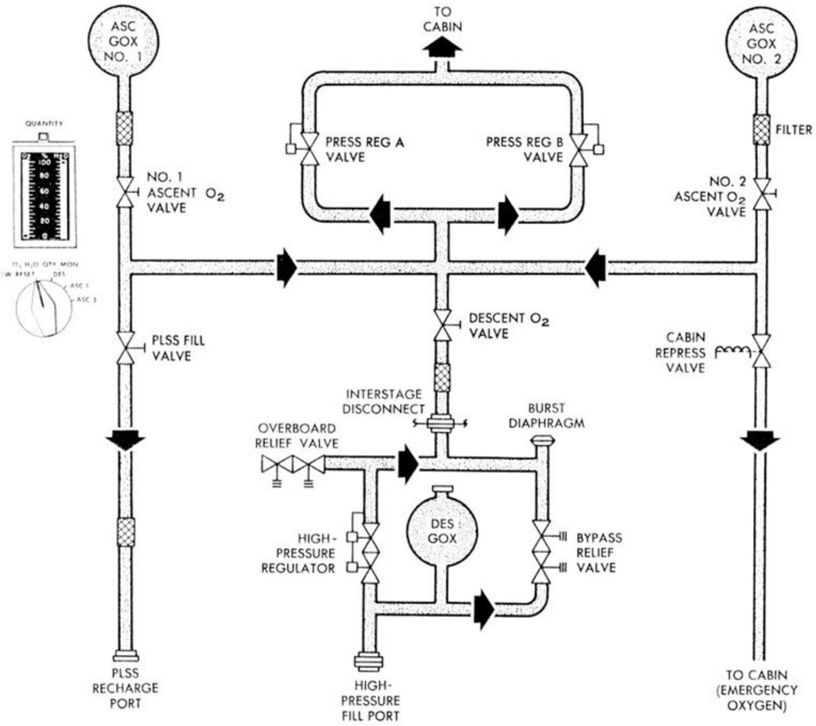


Figure 2.48 – OSCPCS Functional description diagram

Water Management Section

This section stores water for metabolic consumption, evaporative cooling, fire extinguishing and PLSS water tank refill. Moreover it is responsible to control the distribution of stored water and to control required water from the ARS for water separators.

There are three tanks: the biggest one is in the descent stage, while the others are in the upper midsection of the ascent stage. Each tank is pressurized with nitrogen before launch. In case there is the failure of the primary HTS loop, water from the ascent tank is directed to the secondary sublimator, where arrives the discharge water from water separators too.

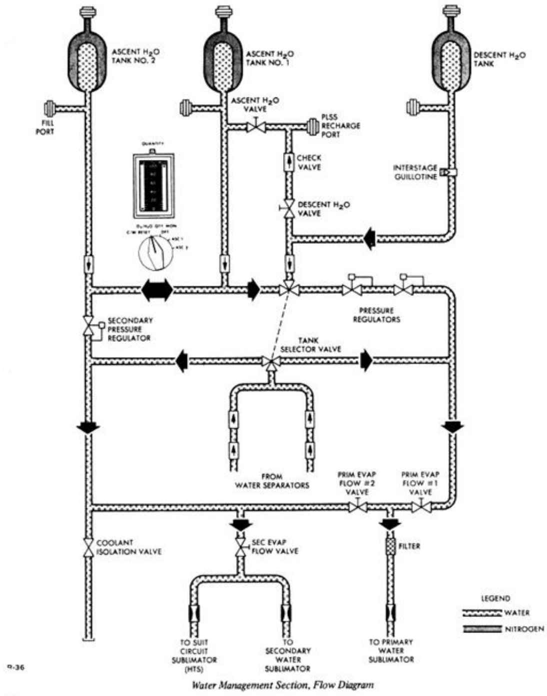


Figure 2.49 – WMS Functional description diagram

Heat Transport Section

This section consists of a primary and a secondary closed loops trough which a water-glycol solution is circulated to cool the suit circuits, electronic equipment and atmosphere in cabin. Primary closed loop is the most important; in fact it can be used as a heat source for cabin's atmosphere.

Heat removal takes place by absorption and thanks to sublimation heat is rejected to Space.

When coolant leaves the recirculation assembly, part of this flows to the suit circuit heat exchanger to cool the suit circuit gas of the ARS. Warmer cool flow can be diverted to suit circuit regenerative heat exchanger in order to increase suit inlet gas temperature.

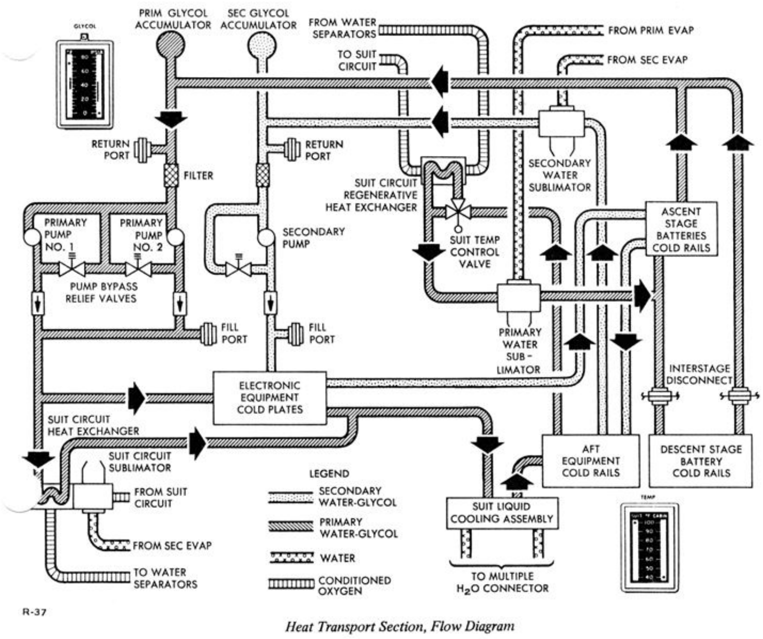


Figure 2.50 – HTS Functional description diagram

Apollo 11 Equipments

It is possible to identify equipment that belong to each section. These equipments are schematized in four different diagram below.

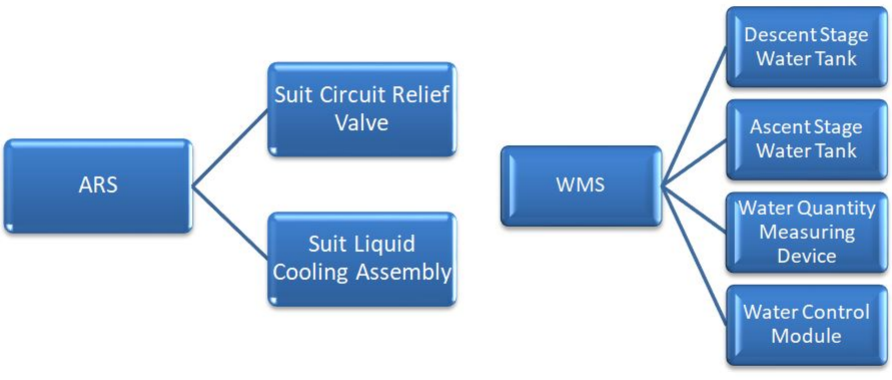


Figure 2.51 – ARS and WMS Equipments

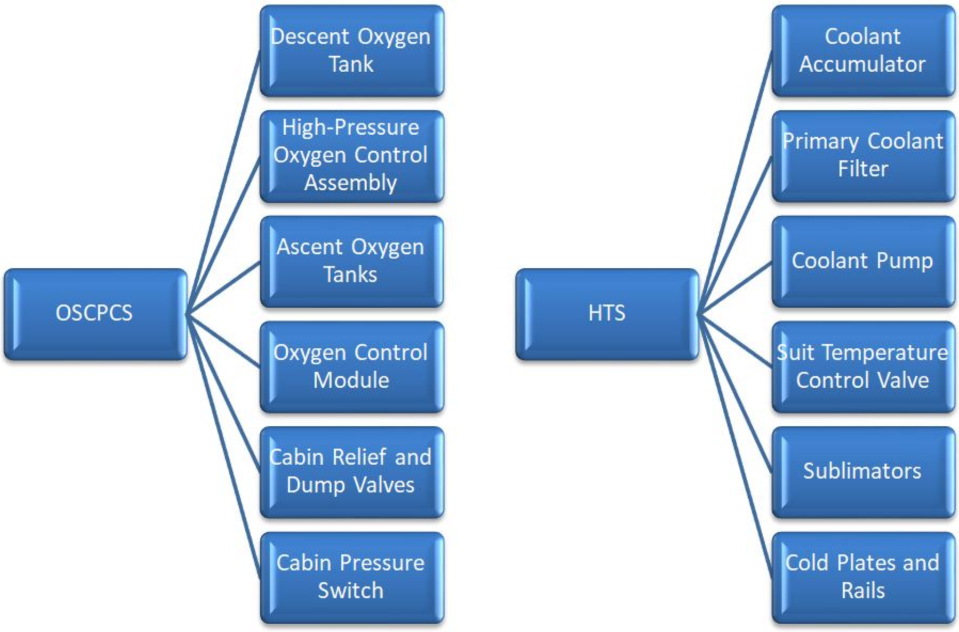


Figure 2.52 – OSCPCS and HTS Equipments

2.11.5 Space Shuttle

Space Shuttle was the spacecraft that gave a ride from Eath to Low Lunar Orbit. Consequently human were inside and so also Space Shuttle, known as Space Transportation System (STS), needed Environmental Control System.

In this paragraph this system will not be described but only illustrated using block diagram. This choice is due to the fact that we do not want to further bore the reader with the historiography of Environmental Control Systems in space.

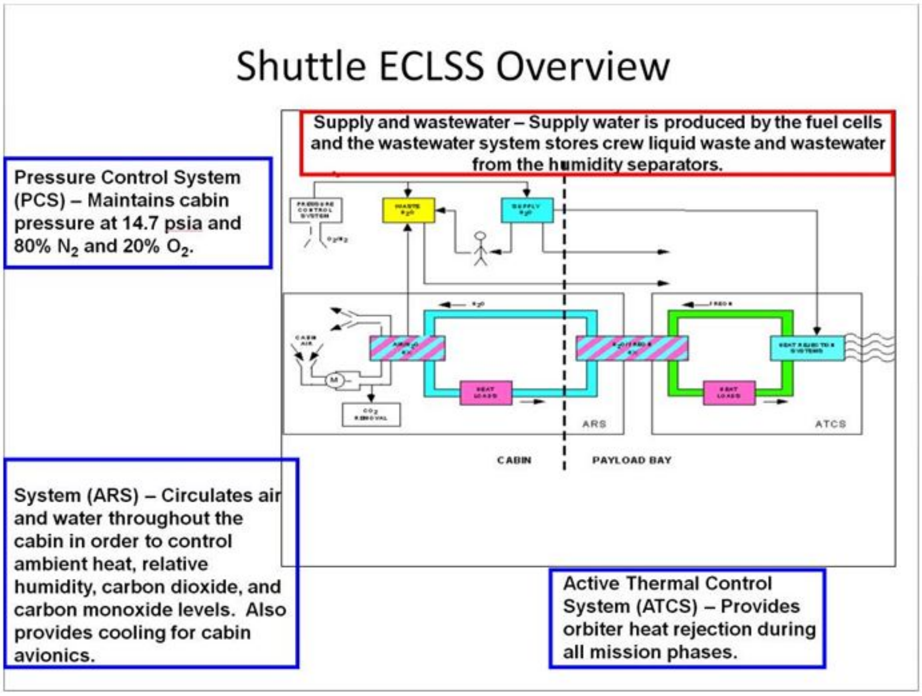


Figure 2.53 – Shuttle ECLSS Overview [21]

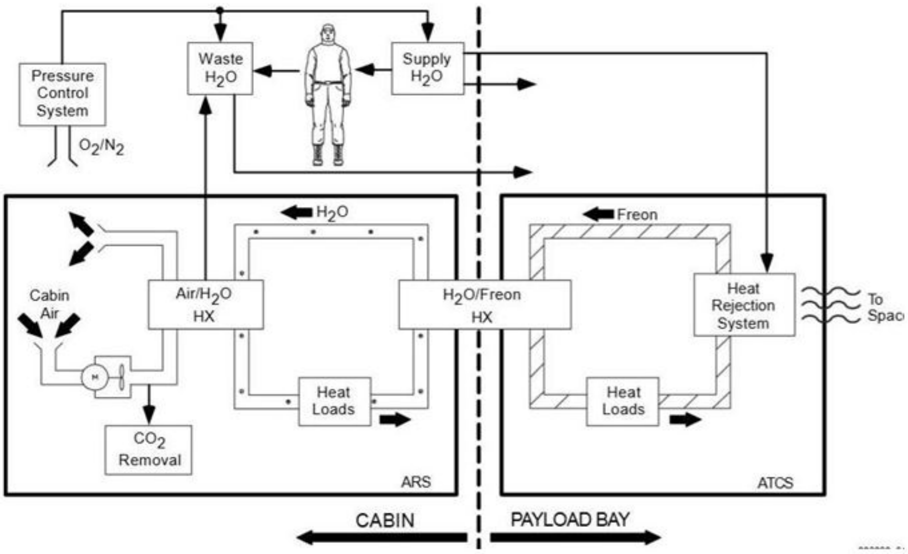


Figure 2.54 – Shuttle ECLSS Interfaces [21]

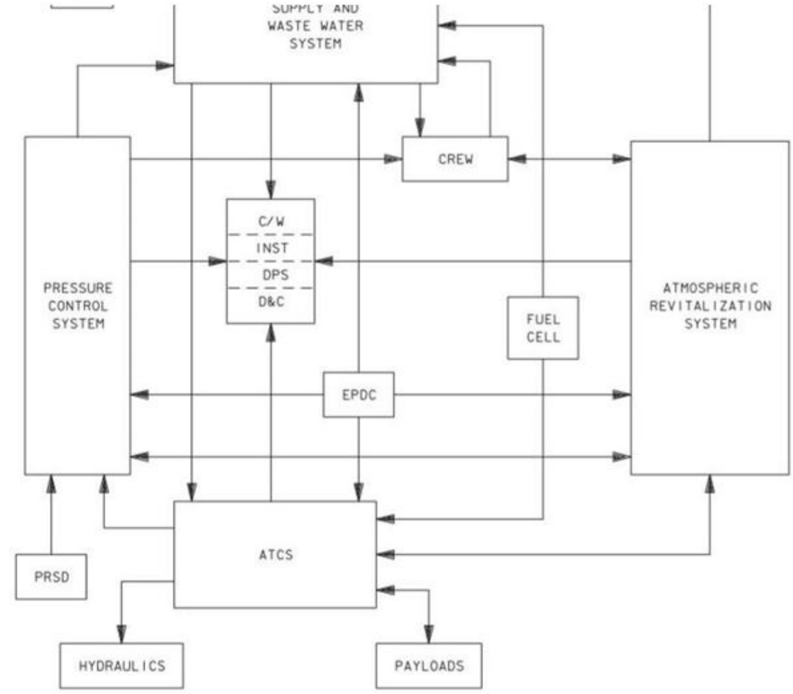


Figure 2.55 – Pressure Control System Interfaces [21]

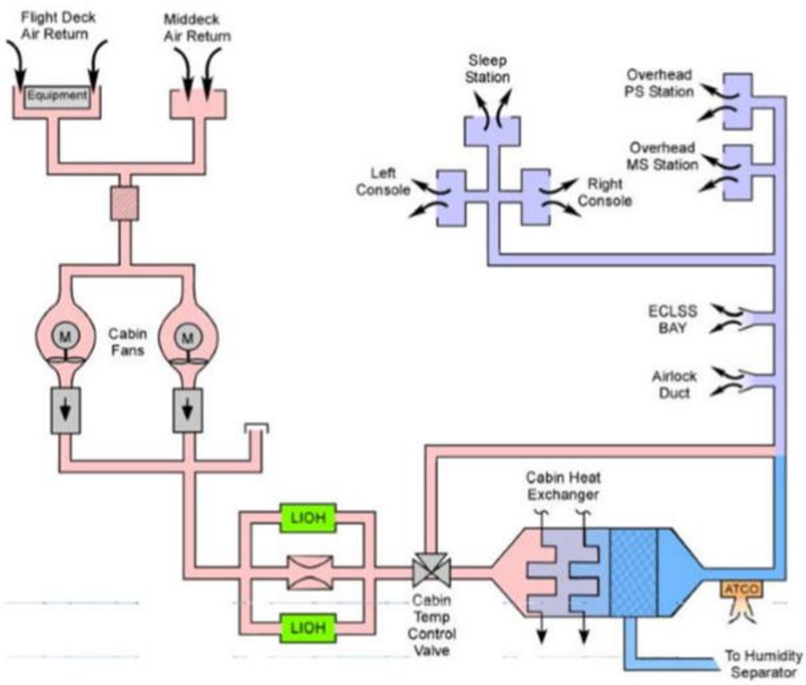


Figure 2.56 – Cabin Air System diagram [21]

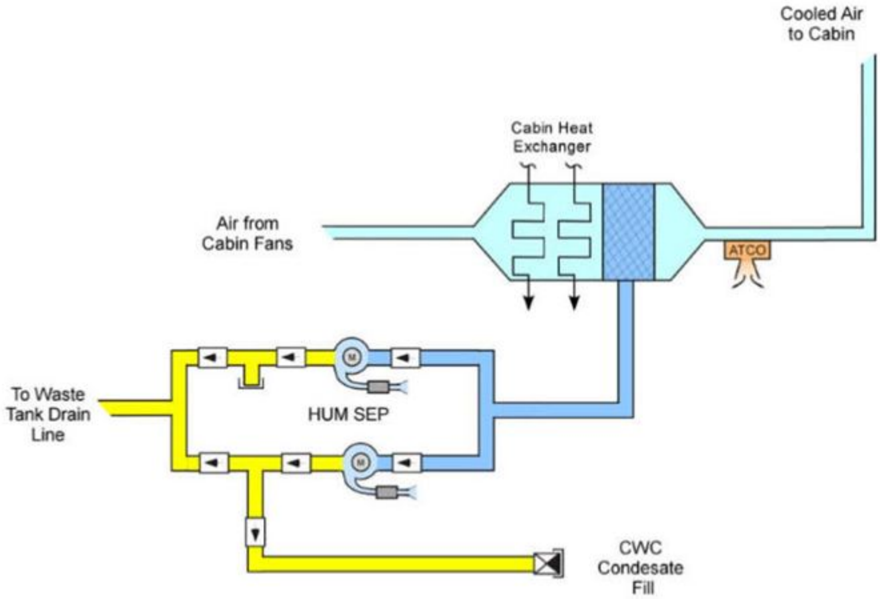


Figure 2.57 – Humidity Separator diagram. [21]

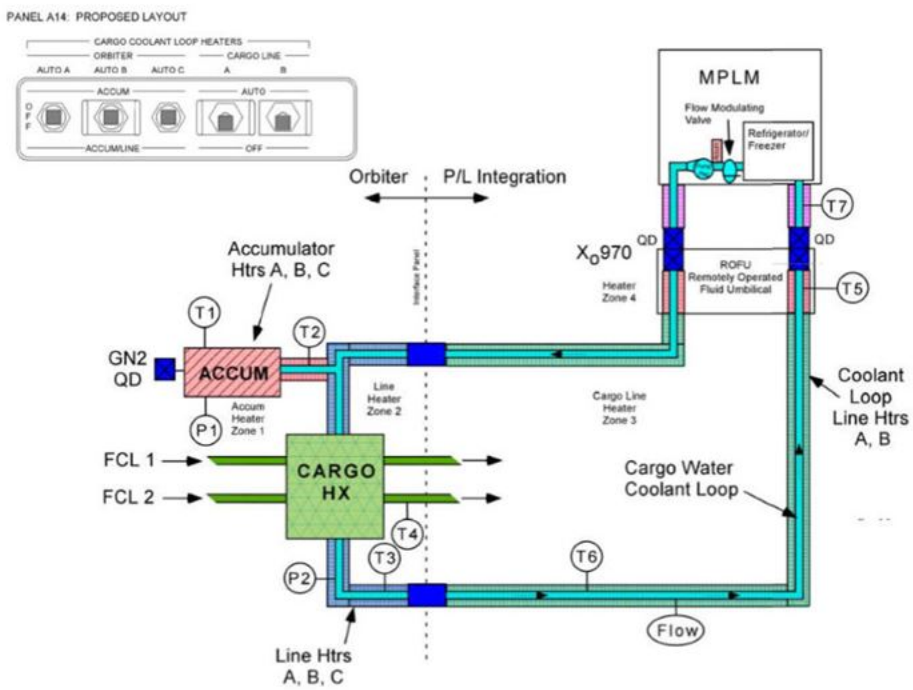


Figure 2.58 – Cargo Heat Exchanger diagram [21]

Chapter 3

ECS sizing for Hypersonic Aircraft

In the following paragraphs basis of aerothermodynamics are briefly treated, which are of importance for aerodynamic and structural characterization of hypersonic vehicles. It is necessary to distinguish between hypersonic flight and hypersonic flow: winged re-entry vehicle flies at hypersonic speed, but the flow in shock layer is in the subsonic to low supersonic domain. While an airbreathing flight vehicle flies at hypersonic speed but the flow past the vehicle is a hypersonic flow. It is clear that it is necessary to identify from the begin classes of hypersonic vehicles, since Aerothermodynamic phenomena have different importance for different vehicle class, especially for *heat loads.*

Different hypersonic vehicles pose different Aerothermodynamic design problems [22]:

- Winged re-entry vehicles (**RV-W's**) are launched by means of rocket boosters, but also as rocket-propelled upper stages of two-stage-to-orbit (TSTO) space transportation system. In this class there are Space Shuttle Orbiter, HERMES, HOPE-X, X-34, X-38 and HOPPER/PHOENIX.

- Cruise and acceleration vehicles with airbreathing propulsion (**CAV's**), such as the lower stage of the TSTO system SÄNGER, STAR-H, RADIANCE.

- Non-winged re-entry vehicles (**RV-NW's**), such as HUYGENS, BEAGLE2, OREX, APOLLO, ARD, SOYUZ, VIKING and others.

Aerodynamic features are summarized in figure below:

Item	Winged re-entry vehicles (RV-W's)	Cruise and acceleration vehicles (CAV's)	Non-winged re-entry vehicles (RV-NW's)
Mach number range	30–0	0–7(12)	30–0
Configuration	blunt	slender	very blunt, blunt
Flight time	short	long	short
Angle of attack	large	small	head on
Drag	large	small	large
Aerodynamic lift/drag ratio	small	large	small, zero
Flow field	compressibility-effects dominated	viscosity-effects dominated	compressibility-effects dominated
Thermal surface effects: 'viscous'	not important/ locally important	very important	not important
Thermal surface effects: 'thermo-chemical'	very important	important	very important

Figure 3.1 – Comparative consideration of Aerothermodynamic features of the three reference classes of hypersonic vehicles [22]

It is clear that for CAV's viscosity effects, notably laminar-turbulent transition and turbulence play a major role, while high temperature gas effects are important for RV-W's and RV-NW's. In consequence of this, an airbreathing hypersonic flight vehicle, such as the STRATOFLY MR3, poses different problems from that of a RV-W. If CAV's are considered as hypersonic passenger transport aircraft, a high acceleration capability is not necessarily the driving factor since a problem can be the degradation of passenger comfort due the acceleration. From now on, there will be an overview of Aerothermodynamic issues of CAV's. It is considered only the external flow path around the vehicle usually flying at small angle of attack.

The external flow path around the vehicle flying at small angle of attack is considered to study the Aerothermodynamic phenomena. The lower side of the aircraft must have a positive inclination angle against the free-stream in order to allow for pre-compression, while the upper side should have an inclination angle close to zero in order to keep wave drag increments small.

Summarizing , the external flow path of CAV's [23]:

- is viscous effects dominated,
- is governed especially by viscous thermal surface effect,
- is strongly affected by laminar-turbulent transition because the flight altitudes are in general lower than $40 - 60km$,
- has Mach number and surface properties effects on laminar – turbulent transition and on turbulent flow phenomena,
- has radiation cooled,
- includes weak high temperature real gas effects,
- contains strong interaction phenomena (shock/shock and shock/boundary layer interaction, corner flow, boundary layer separation),
- has gap flow at trim and control surfaces,
- includes hypersonic viscous interaction and low-density effects.

The thermal state of the surface is defined by:

- the actual temperature of the gas at the wall surface, T_{g_w}, and the temperature of the wall, T_w, with $T_{g_w} = T_w$ if low density effects are not present,
- the temperature gradient in the gas at the wall, $\partial T/\partial n|_w$, in the direction normal to the surface, respectively the heat flux in the gas at the wall, q_{g_w}, if the gas is a perfect gas or in thermo-chemical equilibrium.

Once that the mission is preliminarily characterized in terms of profile and phases, the heat loads coming from both internal and external sources can be identified. What is Heat?

All matter is made up of molecules and atoms. These atoms are always in different types of motion (translation, rotational, vibrational). The motion of atoms and molecules creates heat or thermal energy. All matter has this thermal energy. The more motion the atoms or molecules have the more heat or thermal energy they will have.

Heat can travel from one place to another in three ways:

- Conduction
- Convection
- Radiation

Both conduction and convection require matter to transfer heat. It is important to underline that if there is a temperature difference between two systems, heat will always find a way to transfer from the higher temperature system to lower temperature system.

3.1 Heat transfer

3.1.1 Conduction

Conduction is the heat transfer that happens between two substances in direct contact each other. This kind of heat transfer occurs when a substance is heated: its molecules gain energy and start vibrating. These molecules collide with adjacent molecules transferring them part of their energy. Conduction occurs in solids, liquids and gases. In solids it is due to molecular vibrations within the crystal lattice, while in liquids and gases it occurs due to collisions between molecules. In high speed Earth atmospheric environment this phenomenon allows heat exchange from external skin to internal compartment.

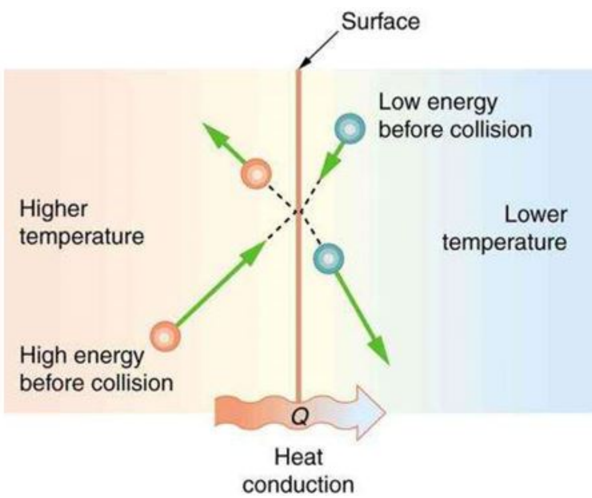


Figure 3.2 – Conduction

The amount of heat that propagates by conduction depends on the geometry and characteristics of the body, as well as on the difference in temperature. The Fourier postulate allows the determination of the heat flux transmitted by conduction:

$$\dot{Q} = -\lambda A \frac{dT}{dx} \tag{3.1}$$

From the relationship it clearly emerges that the thermal power transmitted by conduction is proportional to the temperature gradient. The negative sign is linked to the fact that heat is transmitted spontaneously (second law of thermodynamics) in the direction of decreasing temperatures, therefore moving along x the temperature gradient would become negative if the temperature decreases moving in that direction. Area A of the heat exchange surface is always normal to the direction of heat transmission.

3.1.2 Convection

Convection is the heat transfer that occurs when warmer areas of liquid or gas rise to cooler areas in the liquid or gas. Sun warm Earth's surface so the warm air in contact with the ground rises and cool air moves in. The heat transmitted by convection increases with the velocity of the fluid. If the fluid is forced by the wind or a fan to flow over a surface, this is called forced convection. Otherwise we speak of natural convection if the motion of the fluid is caused by upward forces induced by density differences linked to temperature variations in the fluid. Although the phenomenon is somewhat complex to study, Newton's law states that the thermal power transmitted by convection is directly proportional to the temperature difference:

$$\dot{Q} = hA(T_w - T_\infty) \tag{3.2}$$

where:

- h is the convection transmission coefficient, in $W/(mK)$
- A is the area through which the heat transmission take place
- T_w is the wall temperature
- T_∞ is the temperature outside the boundary layer

It is observed that the heat transfer coefficient by convection is not a property of the fluid. It is an experimental parameter dependent on geometry, type of motion, properties and fluid's speed. In high speed Earth atmospheric environment this phenomenon is responsible of the heating of aircraft

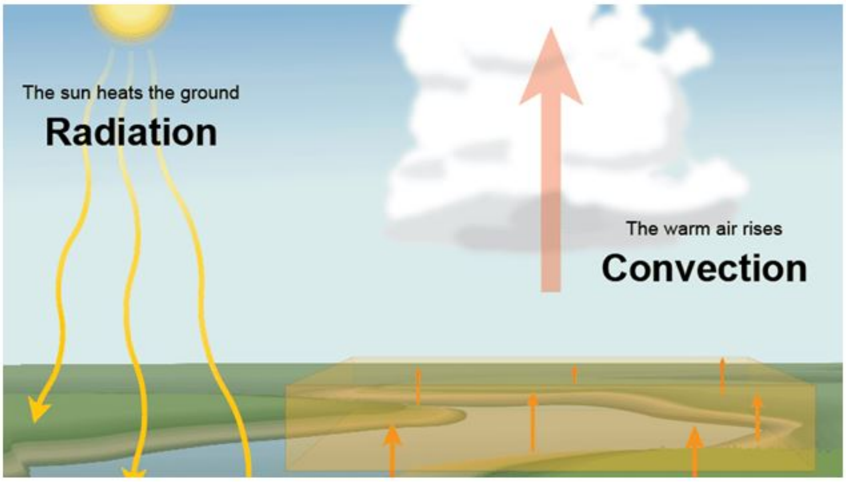


Figure 3.3 – Convection

produced by its high- speed passage through air, therefore its kinetic energy is converted to heat by adiabatic heating and skin friction. This phenomenon is called Aerodynamic heating.

3.1.3 Radiation's heat transfer

Radiation's heat transfer does not rely on any contact between heat source and warmed object as happen in conduction and convection. Heat is transmitted through empty space by infrared radiation, thanks to changes in electronic configurations in atoms and molecules. In radiation process medium is no required and there is not mass exchange.

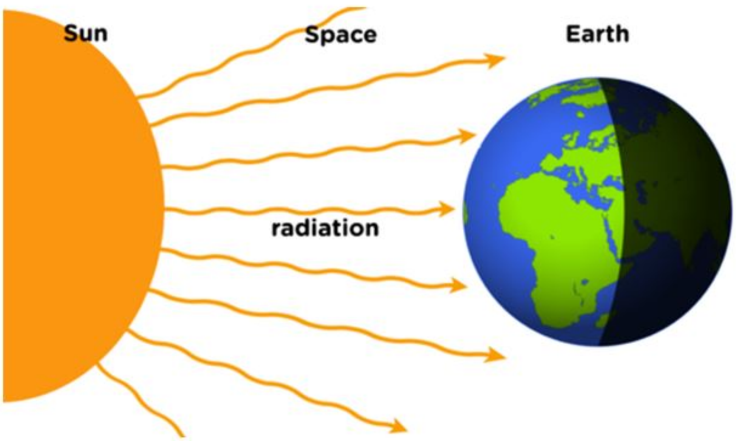


Figure 3.4 – Radiation

Studies concerning the transmission of heat by radiation are associated to thermal radiation, i.e. the radiation emitted by all bodies due to their temperature. As a consequence of this, all bodies whose temperature is above absolute zero emit thermal radiation, evaluated through the Stefan-Boltzman law:

$$\dot{q} = \sigma T_s^4 \tag{3.3}$$

The ideal surface that emits this maximum power is called the black body. However, real surfaces emit less heat at the same temperature:

$$\dot{q} = \epsilon \sigma T_s^4 \tag{3.4}$$

Where ϵ is the emissivity of the surface and is a value between $0 \leq \epsilon \leq 1$ which indicates how much a body behaves like a black choir having $\epsilon = 1$.

Each body emits energy but also absorbs it, so it is necessary to determine the net thermal power transmitted by radiation. In general, if the radiant power absorbed is greater than the emitted ones, the surface gain energy by radiation, vice versa it loses it.

The study of this phenomenon is somewhat complicated, since the net thermal power exchanged by radiation depends on the properties of the surfaces and their relative orientation, as well as on the characteristics of the medium present between the irradiating surfaces.

In summary, flying in Earth's atmospheric environment we encounter the following heat sources:

Heat flux	$[W/m^2]$
Incoming solar radiation	342
Reflected solar radiation	102
Surface Radiation	380
Outgoing Infrared Radiation	238.5

Table 3.1 – Atmospheric Environment Data

Figure 3.5 well represents what has been said up to now.

The sources of external thermal loads affecting the mission of aeronautical and space vehicles are highly dependent on the mission, which can be identified in a preliminary way by defining:

- Altitude

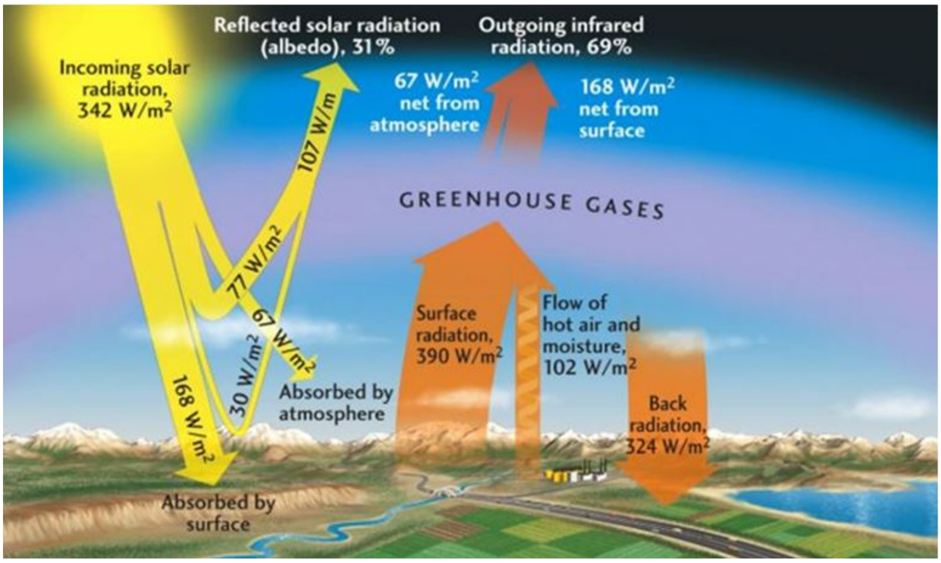


Figure 3.5 – Atmospheric Environment

- Speed
- Atmospheric flight segment

Speed flight is important because it determines the structure of Environmental Control System. In fact for Atmospheric Low Speed Flight it is necessary to control temperature levels of payload cabin and subsystem/propulsion, moreover:

- ECS accomplishes both environmental and temperature control for payload and subsystems,
- Subsystems and propulsion may have their own cooling means,
- External skin temperature is not a problem.

In this case heat transfer occurs through conduction and convection.

While in Atmospheric High-Speed Flight not also controls temperature levels of payload cabin and subsystem is needed but is also needed additional requirements for external skin temperature:

- ECS and Thermal Control System (TCS) are used,
- Thermal Protection System (TPS) may be required.

In this case heat transfer occurs through conduction, convection and radiation.

3.1.4 Internal Heat Source

Also internal heat loads coming from the vehicle itself shall be taken into account for the global thermal balance. These contributions are strictly dependent on vehicle architecture and on the payload/subsystems which are hosted on board:

- Heat produced/required by payload,
- Heat produced/required by subsystems,
- Heat produced/required by propulsion.

3.2 Thermal conductivity and insulating materials

It is the measure of a material's ability to conduct heat. By exploiting the Fourier postulate previously formulated, thermal conductivity can be defined as the thermal power that is transmitted through a unit thickness of the material per unit of surface area and per unit temperature difference. High conductivity values indicate that the material is a good conductor of heat, otherwise it enters the category of insulators.

The latter are used to oppose thermal flow resistance. Generally they consist of heterogeneous materials with low thermal conductivity and air cavities. Obviously, the energy savings obtained with insulation are not limited to hot surfaces, but also with cold surfaces, i.e. surfaces whose temperature is lower than the ambient temperature: in the absence of insulation, the heat would transfer from the environment to the cold surfaces and this would entail a heavier work for the refrigeration machine.

Research in the field of insulating materials had a strong development around the 70s, when the energy crisis increased awareness of the importance of energy saving.

3.3 Thermal Evaluation

In order to determine the service life of a hypersonic aircraft is necessary to determine the mechanical loads and the heat fluxes on the aeroshell during the mission. It is known that heat flux increase with the cubic power of the free-stream velocity:

$$\dot{Q} \propto q_{din} v_\infty = \frac{1}{2}\rho v_\infty^2 v_\infty \propto v_\infty^3 \tag{3.5}$$

Nevertheless, simplified zero-dimensional analysis shows that this approximation is not adequate for hypersonic aircraft. Experiments show that heat flux during Mach 8 flight is from 25% to 35% higher than heat flux at Mach 5 flight. Moreover at Mach 8 the flight time is reduced than at Mach 5 and so there is up to 25% lower heat accumulated during cruise. This is what scientists call *Thermal Paradox*.

Zero-dimensional steady-state analysis is based upon a convective-radiative-conductive heat transfer balance. The external geometry of the vehicle is simulated by inclined flat plates. The internal side of panels has an insulation layer that is in contact with cryogenic tank at 20 K. The external temperature is set at 250 K in order to simulate the atmosphere layer in which hypersonic vehicles cruise. [24]

Heat transfer balance consists in an equilibrium equation, in which several phenomena is necessary to take into account:

- Convective heat exchange in boundary layer,
- Radiation from the aircraft outer layer in which Stephan-Boltzmann radiation equation of grey body is considered,
- Conduction of heat through outer layer and insulation towards the inside of the aircraft.

Based on what has been said, the resulting equilibrium equation is:

$$h_{conv} \cdot (T_{rec} - T_w) = \epsilon \cdot \sigma \cdot T_w^4 + \frac{k}{t} \cdot (T_w - T_{LH_2}) \tag{3.6}$$

in which:

- h_{conv} is the convective heat transfer coefficient:

$$h_{conv} = St \cdot \rho_\infty \cdot v_\infty \cdot c_p \tag{3.7}$$

where St is the Stanton number:

$$St = \frac{c_f}{2 \cdot 0.95} \tag{3.8}$$

The turbulent skin friction and the reference temperature are given by:

$$c_f = \frac{0.0583}{Re_x^0.2} \left(\frac{T_\infty}{T_{ref}}\right)^{0.8} \left(\frac{\mu_{ref}}{\mu_\infty}\right)^{0.2} \tag{3.9}$$

$$\frac{T_{ref}}{T_\infty} = 0.5\left(1 + \frac{T_w}{T_\infty}\right) + 0.22\left(\frac{T_{rec}}{T_\infty} - 1\right) \tag{3.10}$$

for viscosity, Sutherland's law is used.

- c_p is the specific heat at a constant pressure,
- T_{rec} is the wall recovery temperature,
- T_w is the wall temperature,
- ϵ is the emissivity,
- σ is the Stephan-Boltzmann constant, $5.67 \cdot 10^{-8} W/(m^2K^4)$
- k is the insulation layer thermal conduction,
- t is the insulation layer thickness.

With this data we want to determine wall temperature varying the emissivity of the body in exam.

Three emissivity values were chosen: $\epsilon = 0.3; 0.8; 1$.

In order to determine T_{rec} is necessary to study what happen after the oblique shock wave. The oblique shock wave originates as a result of the deflection of the wall which "brings to approach" the deflected current towards the direction of the upstream current.

Current properties after the oblique shock wave are studied thanks to an algorithm, in which input data is the upstream current Mach and output is the inclination angle of the shockwave, β.
This algorithm exploits the so-called $\theta - \beta - Mach$ relationship (Fig. 3.7).

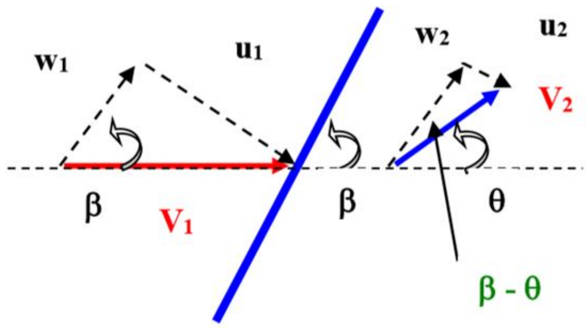


Figure 3.6 – Physical quantities before/after a shock wave [25]

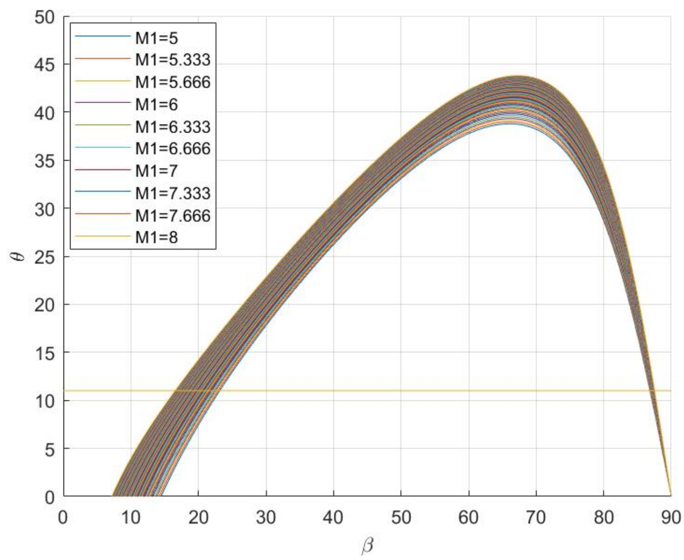


Figure 3.7 – Graphical representation: $\theta - \beta - Mach$ relationship

T_{rec} is obtained considering adiabatic flux with $\frac{dp_e}{dx} \neq 0; Pr \neq 1$.

In this condition there is not a rigorous solution of equation energy:

$$\rho u \frac{\partial H}{\partial x} + \rho v \frac{\partial H}{\partial y} = \frac{\partial}{\partial y}\left[\frac{\mu}{Pr}\left(\frac{\partial}{\partial y}\left(Pr\frac{u^2}{2} + h\right)\right)\right] \tag{3.11}$$

In the case of boundary layer flow, the solution of the equation sees the following binomial conserved with an excellent approximation.

$$h + R\frac{u^2}{2} = cost = H_{rec} = c_p T_{rec} \tag{3.12}$$

where R is the recovery factor for $Pr < 1$ results $R < 1$.

The recovery factor takes into account the fact that in the case $Pr < 1$ the wall reaches temperature lower than the stagnation temperature.

$$R = \begin{cases} Pr & Couette \\ Pr^{0.5} & LaminarBoundaryLayer \\ Pr^{1/3} & TurbulentBoundaryLayer \end{cases} \tag{3.13}$$

From enthalpy the recovery temperature is obtained:

$$T_{rec} = T_{\infty}\left(1 + R\frac{\gamma - 1}{2}M_{\infty}^2\right) \tag{3.14}$$

In order to solve the equilibrium equation is necessary to determine the convection coefficient. The value of the heat transfer coefficient depends on several parameters: air velocity, air temperature, geometry of the surface in contact with the air, etc. Following relationships are implemented in an algorithm that calculate the coefficient.

If flight altitude is between 20000 meters and 25000 meters:

$$T = 273.15 - 56.45 \tag{3.15}$$

$$p = 2.65 \cdot 10^3 \cdot e^{1.73 - 0.000157 \cdot h} \tag{3.16}$$

$$\rho = \frac{p}{287 \cdot T} \tag{3.17}$$

$$c = \sqrt{\gamma R T} \tag{3.18}$$

While if flight altitude is over 25000 meters:

$$T = 273.15 - 131.21 + 0.00299 \cdot h \tag{3.19}$$

$$p = 2.488 \cdot 10^3 \cdot \left(\frac{T}{216.6}\right)^{-11.388} \tag{3.20}$$

$$\rho = \frac{p}{287 \cdot T} \tag{3.21}$$

$$c = \sqrt{\gamma R T} \tag{3.22}$$

After that, values of speed, Reynolds number, friction coefficient and Stunton number are obtained:

$$v = c \cdot M \tag{3.23}$$

$$Re = \frac{\rho \cdot v \cdot L}{\mu} \tag{3.24}$$

$$\frac{0.455}{[log(0.06 \cdot Re)]^2} \tag{3.25}$$

Finally the conduction coefficient h_{conv} is calculated as written previously.

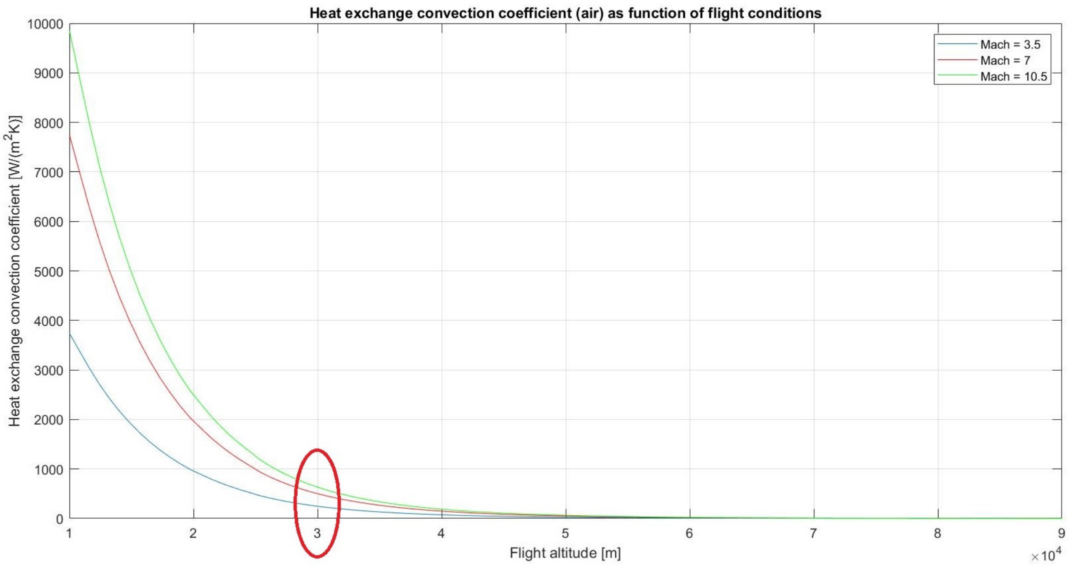


Figure 3.8 – Conduction coefficient

As the figure shows, with good approximation, an acceptable value is around $450W/(m^2K)$ for aircraft that cruise at Mach 8.

The equilibrium equation is solved giving the following figure (Fig. 3.9) that give wall temperature in function of Mach number for three different emissivity values.

Ceramix matrix composite materials (CMC) with $\epsilon = 0.8$ has $T_w < 1200K$ for all Mach numbers.

Using all of these information, the heat flux at esternal surface is calculated.

$$q_{in} = h_{conv}(T_{rec} - T_{wall}) \tag{3.26}$$

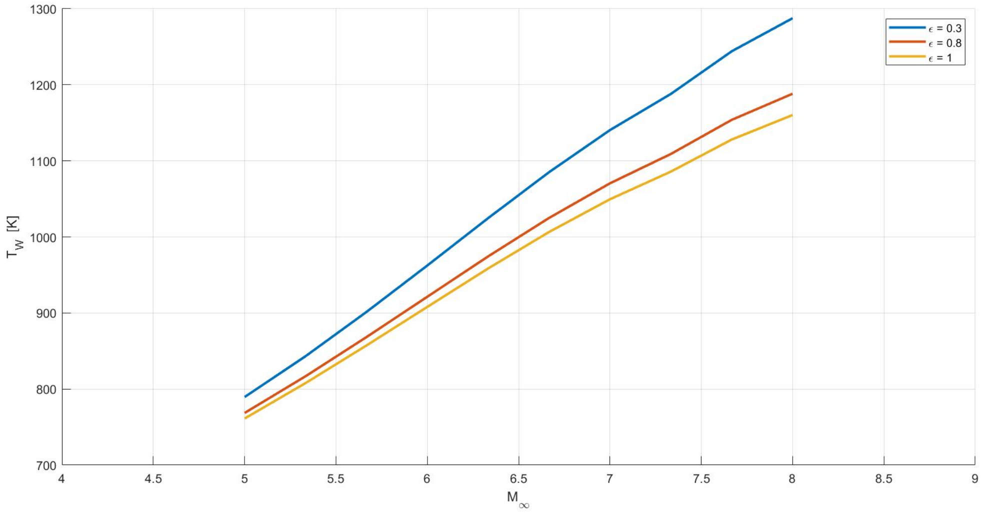


Figure 3.9 – Wall temperature in function of Mach

3.4 Model characterization

The cabin is modeled as a cylinder with internal radius r1 and length L which exchanges heat with the external environment via the side surface.

The transverse surfaces are considered adiabatic and therefore there is no heat exchange.

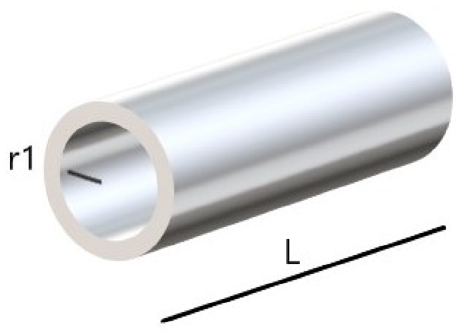


Figure 3.10 – Cabin model section

The cabin wall comprises an inner and an outer insulation layers separated by LH2 channel. Aeroshell is made in carbon matrix composite.

The following table report propertied of the cabin insulation materials.

Layer		Material	Thickness mm	Axial Length m	k W/m/K	C kJ/kg/K	ρ kg/m^3
Insulation	P2	Glass Fiber	50	6.3	0.1	1	48
	P8						
	P5			19.1			
Shell	S2, S8	CMC	1	6.3	15	1.4	2000
	S6	Aluminum Alloy		6.6	100	0.9	2700

Figure 3.11 – Properties of the cabin insulation materials [26]

From the external to internal surface there are four layers:

- P5 is the first insulation layer
- LH2 layer separate external from internal insulation layer
- P8 is the second insulation layer
- S8 is the shell inside the cabin

Figure 3.12 – Layer layout

Using data reported in Tab. It is possible to determine the temperature inside the cabin.

3.4.1 Thermal Resistance - Analogy to Electric Resistance

Considering the thermal conduction through the wall of a tubular section, it is intuitively understood that the heat transmission occurs in the radial direction without significant exchanges in the other directions. Moreover, if the temperatures inside and outside the duct remain constant, the heat transmission can be considered not only one-dimensional but also stationary. In this situation, the temperature of the duct is independent of the azimuth angle and the axial distance and can be expressed as $T = T(r)$.

Assuming stationary conditions, the thermal power transmitted through the duct must be constant.

$$\dot{Q}_{cond} = cost \tag{3.27}$$

Consider the generic case of a cylindrical layer with internal radius r_1, external radius r_2, length Land average thermal conductivity k, whose internal and external surfaces are kept at constant temperatures T_1 and T_2.

Applying Fourier's law of thermal conduction to the transmission of heat through the cylindrical layer we obtain:

$$\dot{Q}_{cond} = -\lambda A \frac{dT}{dr} \quad [W] \tag{3.28}$$

Where $A = 2\pi r L$ is the area of the generic surface through which heat is transmitted.

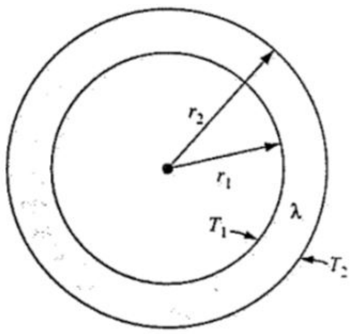


Figure 3.13 – Cylindrical duct section

By separating the variables and integrating between the internal and external surfaces we obtain:

$$\int_{r_1}^{r_2} \frac{\dot{Q}}{A} dr = - \int_{T_1}^{T_2} \lambda dT \tag{3.29}$$

and so:

$$\dot{Q} = 2\pi L \lambda \frac{T_1 - T_2}{ln\left(\frac{r_2}{r_1}\right)} \tag{3.30}$$

Here we can identify the conductive thermal resistance:

$$R = \frac{ln(r_2/r_1)}{2\pi L\lambda} \tag{3.31}$$

Having to simulate the behavior of a cylindrical cabin, it is good to remember that it will consist of a series of layers and insulating layers that protect it from the external environment. It is therefore necessary to discuss the steady-state heat transfer for multilayer cylinders.

An additional series resistance is added for each layer.

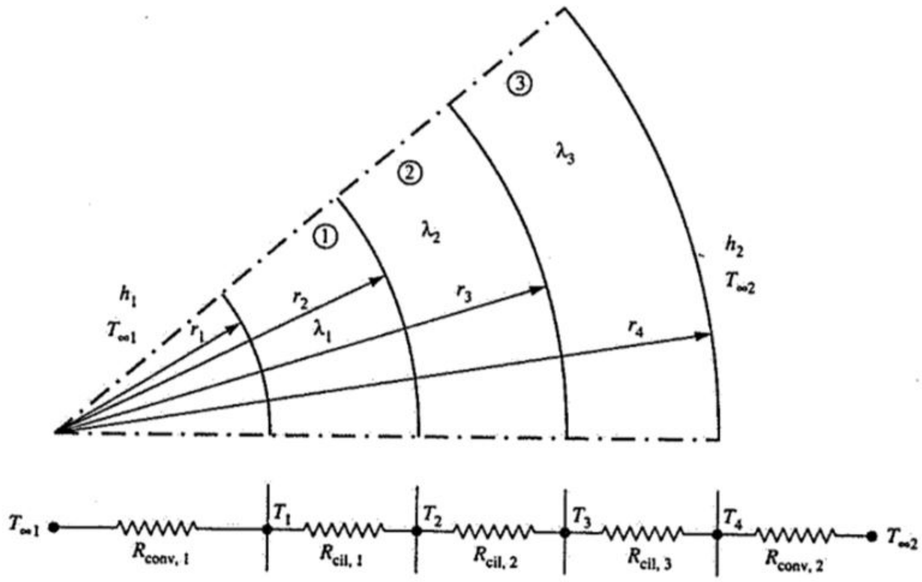


Figure 3.14 – Thermal resistance network for heat exchange through a cylinder consisting of three layers and subject to convection on both sides

The stationary thermal power transmitted is:

$$\dot{Q} = \frac{T_{\infty_1} - T_{\infty_2}}{R_{tot}} \tag{3.32}$$

Where:

$$R = \frac{1}{h_1 A_1} + \frac{ln(r_2/r_1)}{2\pi L\lambda_1} + \frac{ln(r_3/r_2)}{2\pi L\lambda_2} + \frac{ln(r_4/r_3)}{2\pi L\lambda_3} + \frac{1}{h_2 A_4} \tag{3.33}$$

Within the model, the thermal contact resistance is neglected. It is assumed, in fact, that at the interface between two layers there is a "perfect" contact, i.e. without temperature variation. The reality is quite different, as the surfaces coming from mechanical processing turn out to be rough with numerous peaks and cavities. What happens is that the peaks ensure good contact, while the cavities generate voids filled with air. These act as insulators due to the low conductivity of the air and therefore also the interface offers a certain resistance to heat transmission.

The values of the thermal contact resistance are experimentally determined and vary in the range between 0.00001 and 0.001 m^2K/W. It decreases as the surface roughness decreases and as the pressure at the interface increases.

Knowing the relationships to be used and having determined the overall thermal resistance, we proceed with the determination of the temperature variation between the interior and exterior of the cabin and, using the electrical analogy:

$$\Delta T = q_{in} \cdot R = T_w - T_{int} \tag{3.34}$$

where T_{int} is the temperature inside the cabin.

3.4.2 Estimating internal heat sources

In each aircraft that flies in Earth atmosphere, there are different heat sources:

- Heat produced by payload:
  - Metabolism
  - Human thermoregulation
  - Working activity (pc's work - crew members)
  - Evaporative power
  - Thermal power exchanged by radiation, convection, conduction.
- Heat produced by subsystems

- Heat produced by propulsion

First of all, the thermal load deriving from the presence of human beings on board is determined. It is the basal metabolic rate of passengers and the average heat produced by crew members during their activities [27].

The relationship that allows us to determine the basal metabolic rate is:

$$q_{met} = q_{rest} \cdot n_{pax} + q_{work} \cdot n_{crew} \tag{3.35}$$

This represents the heat produced by human beings metabolism inside the aircraft, which is function of:

- q_{rest} is the heat produced by human body in rest condition ($100W$)
- q_{work} is the heat produced by human body during light working conditions ($300W$)
- n_{pax} is the number of passengers
- n_{crew} is the number of crew members (cockpit and cabin crew)

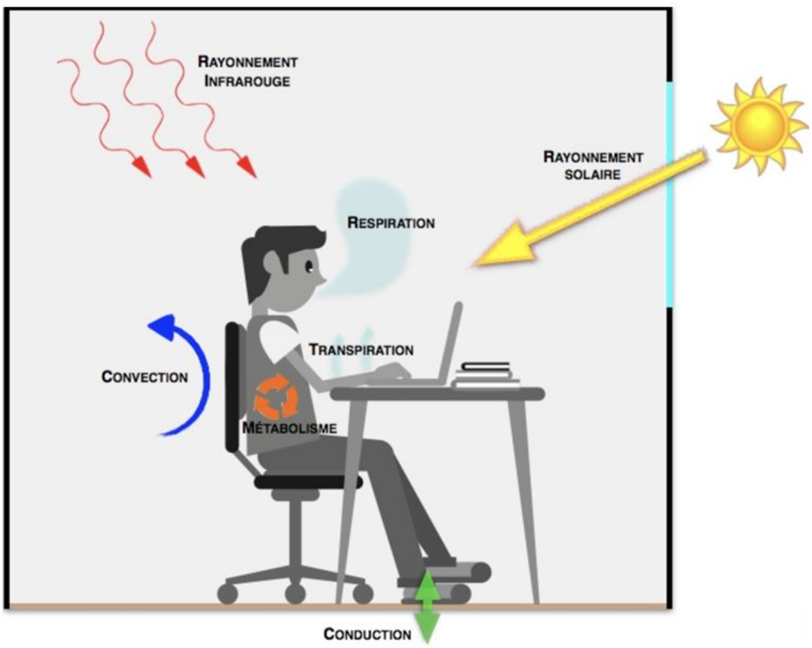


Figure 3.15 – Human's Heat transfer

Next step is the determination of the heat produced by the on-board systems.

On-board systems are electronic systems with powers, per unit of surfaces, ranging from a minimum of $1W/cm^2$ to over $100W/cm^2$. In any resistive element, heat is generated inside it for as long as the current flows through it. This causes an accumulation of thermal energy and consequently an increase in temperature both inside the component and around it. If, therefore, this heat is not subtracted, the temperature would continue to increase until the component itself is destroyed.

This is a useful operation not only for the survival of the human beings on board, but also necessary for the proper functioning of on-board systems.

Most electronic equipment remains in operation for a long period of time, so the cooling system must be designed for stationary operation.

However, since this is a *phase A* project, it will not be possible to determine the actual thermal loads of each individual component, therefore a semi-empirical formulation is used that takes into account some factors:

$$q_{sys} = \left(q_{eq} + q_{pax_{eq}}\right) K_{eq} \tag{3.36}$$

Where:

- $$q_{eq}\ [W] = \begin{cases} 6000 & - \quad \textit{up to } 100 \textit{ passengers} \\ 10000 & - \quad \textit{up to } 200 \textit{ passengers} \\ 15000 & - \quad \textit{up to } 300 \textit{ passengers} \\ 20000 & - \quad \textit{more than } 300 \textit{ passengers} \end{cases} \tag{3.37}$$

  is the heat produced by on-board systems scaled with the size of the aircraft.

- $q_{pax_{eq}}\ [W] = 1000 + 50 \cdot n_{pax}$ is the heat produced by cabin equipment as in-flight entertainment, galleys,..

- $$K_{eq} = \begin{cases} 1 & - \quad \textit{in flight} \\ 0.11 & - \quad \textit{on ground} \end{cases} \tag{3.38}$$

  is the systems and equipment utilization coefficient.

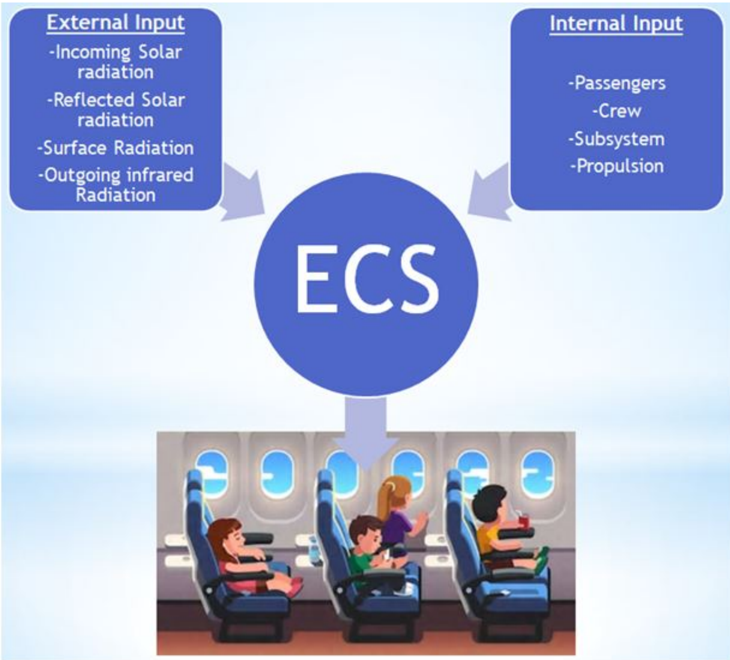


Figure 3.16 – Environmental Control System Input

3.4.3 Necessary air flow determination

Once the individual thermal loads acting on the aircraft have been calculated, the net heat flow is determined.

This step is essential as it determines the air flow that the ECS system must be able to manage.

$$q_{tot} = q_{in} + q_{met} + q_{sys} \tag{3.39}$$

Depending on the environment conditions outside the aircraft it is possible to define different scenarios [27]:

- The environment is cold and so it is necessary to warm up the cabin,
- The environment is hot and so it is necessary to cool down the cabin.

Since this project is in phase A, the worst scenario is cruising at maximum speed during the night.

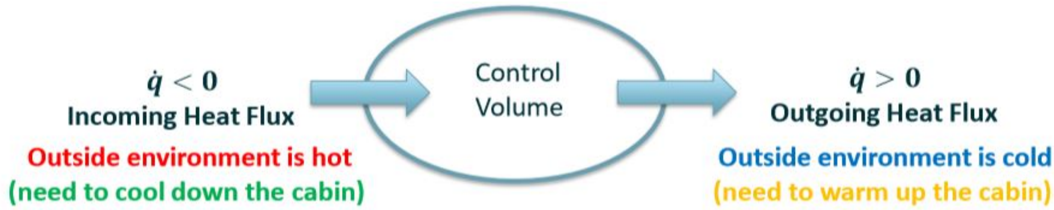


Figure 3.17 – Relations between incoming/outgoing Heat Flux and cabin's needs

The necessary air flow is:

$$\dot{m}_{ECS} = \frac{\dot{q}_{tot}}{c_{p_{air}} \cdot (T_{imm} - T_{int})} \tag{3.40}$$

Where:

- $\dot{q}_{tot}$ is the incoming/outgoing heat flux,
- T_{imm} is the cabin inlet temperature,
- T_{int} is the internal temperature

Cabin inlet temperature can range from a minimum of 6^oC, in case you want to cool the environment, to a maximum of 50^oC, in case you want to heat the environment. Consequently, the inlet temperature in the cabin is a function of the heat flow:

- Incoming Heat flux: cooling;
- Outgoing Heat flux: heating.

The flow rate to be bleeded from the engine is equal to that previously determined to which a certain percentage of flow rate is subtracted and recirculated in the cabin itself:

$$\dot{m}_{ECS_{bleed}} = \dot{m}_{ECS} - \dot{m}_{ECS_{rec}} \tag{3.41}$$

In Chapter 5, once the number of Air Cycle Machines has been hypothesized, the flow rate that will actually feed ACM can be determined:

$$\dot{m}_{ECS_{ACM}} = \frac{\dot{m}_{ECS}}{N_{ECS}} \tag{3.42}$$

Finally, the results obtained are compared with the minimum capacity to be provided to each passenger by law.

Although there is still no legislation regarding hypersonic aircraft, FAR25 provides minimum air flow rate of $0.25 kg/min$ per passenger.

3.5 Architecture

Low hypersonic and high supersonic flights have same problems related to heat transfer and the ways to manage it are similar too.

In the hypersonic regime, specific phenomena inherent in aerothermodynamics arise, such as the origin of the thermal boundary layer coupled to the kinematic one, and Aerothermochemistry, such as the dissociation and ionization of chemical species. The laws governing this field of motion are described by Newtonian theory, whose hypotheses include:

- Fluid consists of equal, non-interacting and equidistant particles;
- Negligible molecular agitation motion.

This implies that the pressure force on each element of the surface depends only on the orientation of the front surface with respect to the local incidence of the particles.

Another aspect that should not be underestimated is that in this regime, the ramjet engines are unable to produce thrust and, consequently, it would not be possible to bleed the air flow necessary for the correct operation of the ECS system.

The problem is solved by using a closed-loop architecture. The proposal is to use a conventional Open-Loop up to Mach 3 and then close the cycle in order to be perfectly operational in the high supersonic / hypersonic regime.

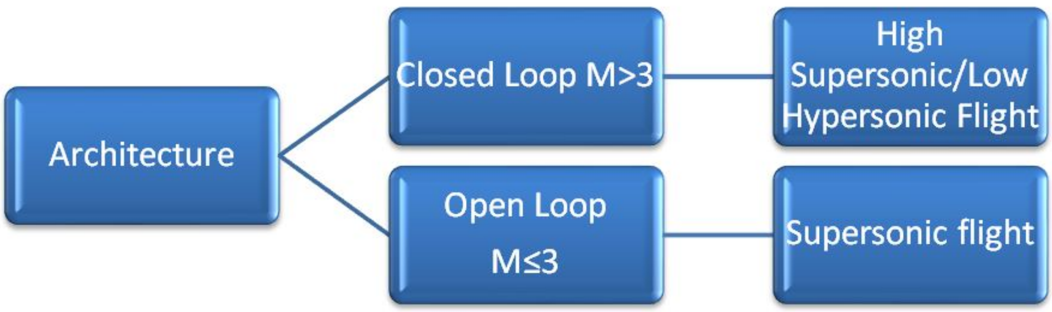


Figure 3.18 – Proposed Architecture

Chapter 4

The STRATOFLY Project

The STRATOFLY Project (STRATOspheric FLYing opportunities for high-speed propulsion concepts) has received funding from the European Union's Horizon 2020 research and innovation programme [28]. The project gains relevant knowledge from previous European projects in the field of high-speed transportation, in particular, it can be considered as a follow-up of the LAPCAT II project [29]. STRATOFLY MR3 is actually designed under the STRATOFLY Project.

This Chapter aims at giving an overview on project objectives and participants institutions. Moreover, the STRATOFLY MR3 vehicle design will be described in terms of configuration, aerodynamics and main subsystems, according to the current state of the design activities.

4.1 Project Objectives

The STRATOFLY Project investigates the feasibility of high-speed civil passenger stratospheric flight opportunities. The Project aims at studying new possible stratospheric routes in order to reduce transfer time but, at the same time, guaranteeing high safety levels and reducing noise and emissions.

STRATOFLY Project relies on the fact that the number of civil aviation passengers is predicted to globally increase of six times in 2050 [1].Consequently, continuing to think about air transport in the current way is not sustainable from an economic and environmental point of view: the Project may represent the keystone of future civil aviation.

Figure 4.1 – STRATOFLY Project logo

The main objectives and requirements are summarized below:

- To perform civil passenger transport mission, flying at Mach 8 above 30km of altitude
- To decrease transfer time of long range civil flights
- To evaluate economical and environmental sustainability of the operability of hypersonic vehicles
- To investigate new trajectories in the stratosphere

Last but not least, the Project wants to reach a Technology Readiness Level (TRL) – 6 of key enabling technologies by 2035 and to increase the maturity level of technologies that will be useful for reusable space transportation systems.

4.2 STRATOFLY Project Participants

The collaboration of 10 partners institutions from 7 different European countries is actually realizing the STRATOFLY Project which started in June 2018 and will end in November 2020.

The project participants are listed in the following:

- *POLITECNICO DI TORINO*, Italy. Project Coordinator
- *CENTRO ITALIANO RICERCHE AEROSPAZIALI (CIRA)*, Italy

- *DEUTSCHES ZENTRUM FUER LUFT – UND RAUMFAHRT EV (DLR)*, Germany
- *TECHNISCHE UNIVERSITAT HAMBURG*, Germany
- *INSTITUT VON KARMAN DE DYNAMIQUE DES FLUIDES*, Belgium
- *CENTRE NATIONALE DE LA RECHERCHE SCIENTIFIQUE CNRS*, France
- *OFFICE NATIONAL D'ETUDES ET DES RECHERCHES AEROSPATIALES*, France
- *STICHTING NATIONAAL LUCHT – EN RUIMTEVAARTLABORATORIUM*, Netherlands
- *TOTALFORSVARETS FORSKNINGINSTITUT*, Sweden
- *FUNDACION DE LA INGENIERIA CIVIL DE GALICIA*, Spain

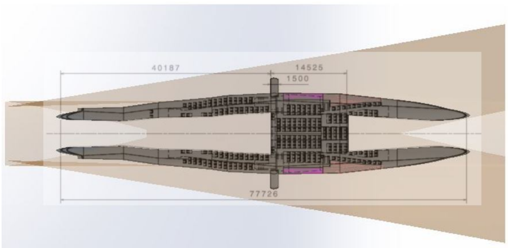
4.3 STRATOFLY MR3 Vehicle Design

The STRATOFLY MR3 has a waverider configuration and a bubble-structure approach with a dorsal engine located on top of the vehicle, multi-lobe tanks structure and an integrated passenger cabin located in the ventral part of the vehicle.

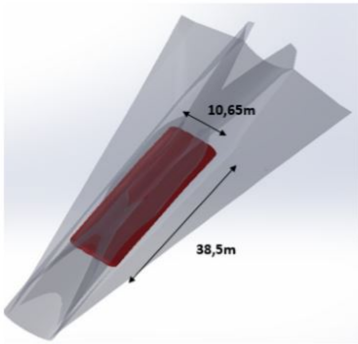
Figure 4.2 – STRATOFLY MR3 Vehicle concept

The STRATOFLY MR3 vehicle design can be considered as a refinement of the LAPCAT MR2 concept. The main characteristics are the same for both vehicles, but there are some differences concerning external configuration and internal layout.

One of these is related to the internal layout of passenger cabin configuration as figure below shows.



(a) *LAPCAT MR2 passenger cabin design*



(b) *STRATOFLY MR3 passenger cabin design*

Both vehicles can host a maximum of 300 passengers, but the cabin design is totally different for different reasons:

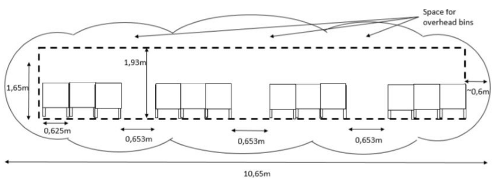
- Better compartment location boarding procedures and cabin escape thanks to the better location of doors, improving safety.
- A unique environment is the better solution for passenger comfort (more volume available) and thermal insulation.
- A unique environment for passenger cabin ensures a better weight balance and so the CoG position during the mission is always located at about the center of the vehicle.

Following figures illustrate details of the STRATOFLY MR3 cabin design.

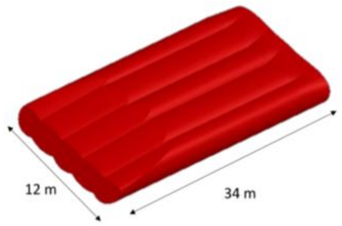
The following subsystems compose the vehicle:

- Propulsive and Propellant Subsystems
- Environmental Control System (ECS)
- Thermal and Energy Management Subsystem (TEMS)
- Thermal Protection Subsystem (TPS)

- Flight Control System (FCS)
- Avionic Subsystem
- Electrical Power Subsystem (EPS)
- Landing Gear



(a) *STRATOFLY MR3 passenger cabin*



(b) *STRATOFLY MR3 cabin configuration*

Actually not all the subsystems have reached the same level of design detail. Hereafter Aerodynamics Characteristics, Propulsive Subsystem, TEMS and TPS are briefly described, since they deeply affect ECS behavior.

4.3.1 Aerodynamic Characteristics

The overall aerodynamic performances of a high-speed transport vehicle depends mainly in the L/D ratio, therefore intake performance and integration between internal and external flow paths have to be designed to avoid the generation of additional drag [29].

The aerodynamic coefficients have been computed by CIRA using both non viscous CFD, combined with semi-empirical formulation for the derivation of missing viscous contribution, and Surface Impact Method (SIM) for supersonic and hypersonic range. The coefficients have been provided as a function of Mach numbers from $M = 0.3$ to $M = 8$, and different angles of attack.

Fig. 4.3 shows that both C_L and C_D increase in subsonic regime until reaching a maximum in subsonic-supersonic transition and progressively decreasing towards hypersonic regime. It is also observed that both C_L and C_D are lower for lower Angle of Attack (AoA).

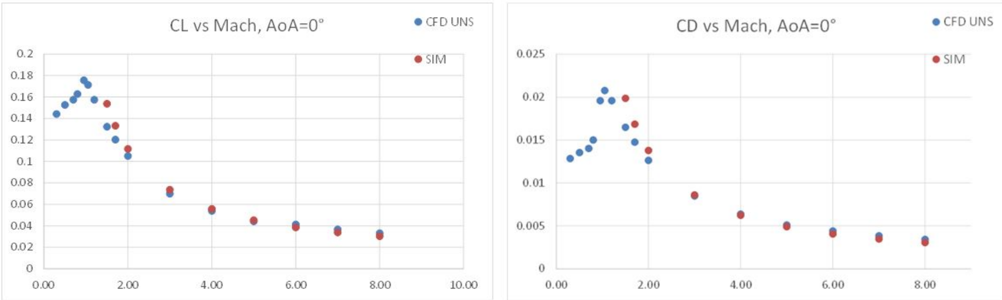


Figure 4.3 – Aerodynamic coefficients of STRATOFLY MR3 as function of Mach number for AoA equal to 0^o.

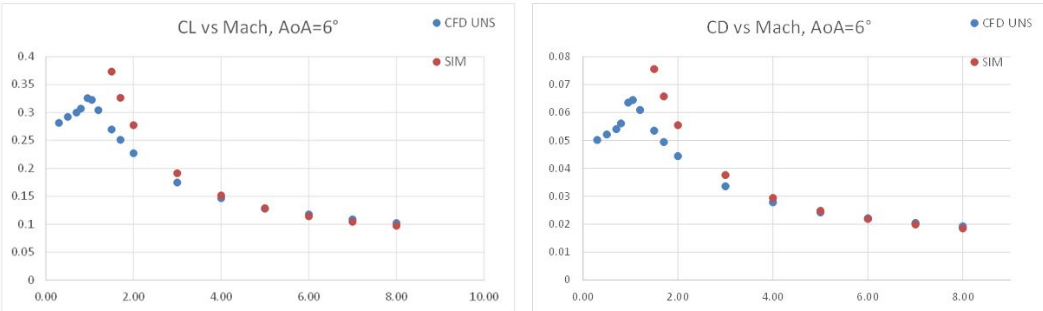


Figure 4.4 – Aerodynamic coefficients for STRATOFLY MR3 as function of Mach number for AoA equal to 6^o.

4.3.2 Propulsive Subsystem

This subsystem is located on top of the vehicle and it is composed by two main power plants composed by 6 Air Turbo Rockets (ATR), located on two sides, and one Dual Mode Ramjet (DMR) located at the center. Both engine units operate with liquid Hydrogen (LH2).

The ATR operates from Mach 0 up to Mach 4, so comprises different phases:

- Take-off
- Subsonic acceleration
- Supersonic acceleration
- Final Approach
- Landing

The original LAPCAT MR2.4 concept was designed to perform unpowered approach and landing but, for the purpose of this work, also considering regulation requirements concerning critical near-ground phases, ATR are supposed to be re-activated as soon as bottom of descent is reached.

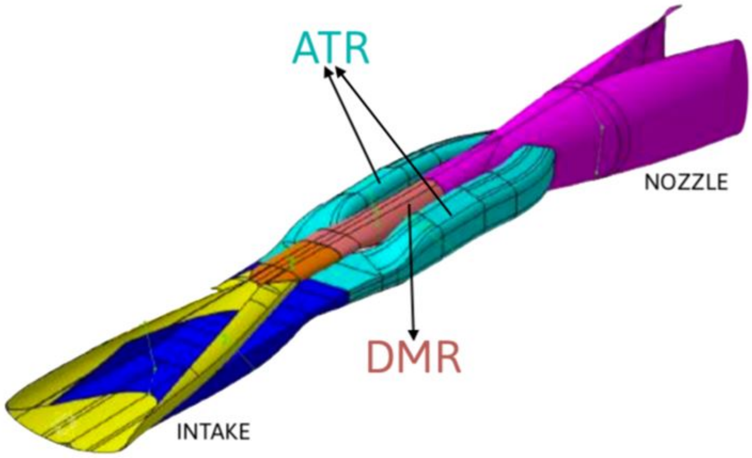


Figure 4.5 – Propulsive Subsystem concept

DMR operates for all hypersonic flight conditions (from Mach 4 up to Mach 8) giving to the aircraft the necessary thrust for hypersonic acceleration and cruise. The intake and the duct are designed to drive the airflow towards one or the other engine unit on the basis of the flight condition [31], while the exhaust gases produced by the ATR or DMR at a different regimes are expelled by a common nozzle [32].

Hereafter, the performances of ATR and DMR are shown as a function of altitude and Mach number with Equivalence Ratio (ER), the ratio between real injected fuel mass flow and stoichiometric fuel mass flow, equal fo 1 for ATR. This parameter is necessary to control the ratio of effective net thrust to the maximum thrust potentially generated by the engine at stoichiometric conditions. ATR thrust requirement has been re-evaluated in STRATOFLY, and some differences in the thrust profile can be appreciated with respect to the results obtained during LAPCAT Project.

$$ER = \frac{\dot{m}_{LH2}}{\dot{m}_{LH2_{stoich}}} \tag{4.1}$$

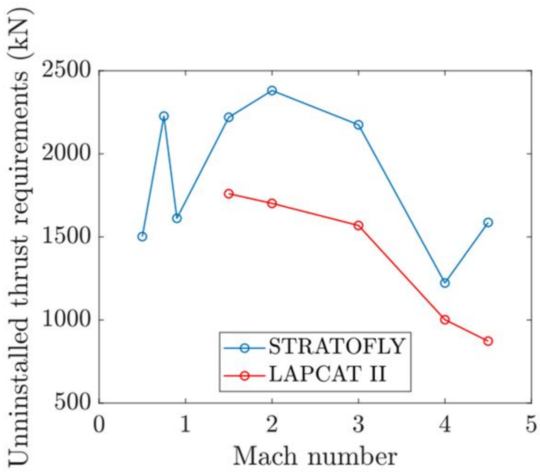


Figure 4.6 – ATR performances requirements (total thrust) as function of Mach number

DMR performances have not been addressed in STRATOFLY Project, so the results obtained during LAPCAT are shown.

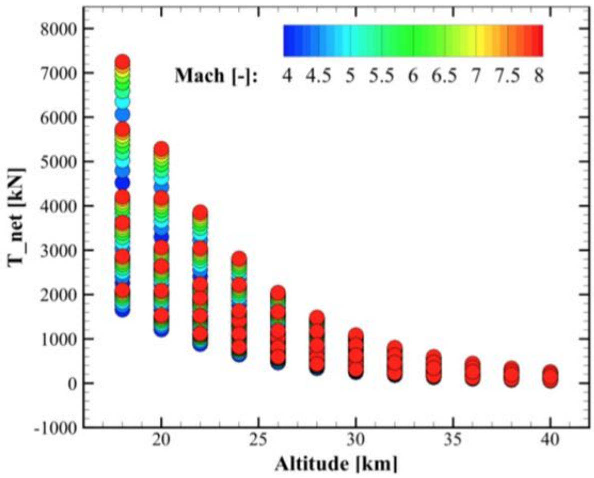


Figure 4.7 – ADMR performances as a function of altitude and Mach number at different sets of ER. [30]

4.3.3 Thermal and Energy Management Subsystem

This subsystem protects aircrafts and, in general, reentry vehicles from high heat fluxes, in order to manage internal and external temperatures. The analysis show that temperature on external vehicle skin can reach average values of about $1200K$ on bottom aircraft skin, as the model illustrated in Chapter 3 confirms, whilst stagnation temperature may reach up to $2000K$.

TEMS wants to take advantage of high-temperatures experienced during hypersonic flight and to integrate Thermal Protection System (TPS), Environmental Control System (ECS) and propellant subsystem. Consequently TEMS is totally interfaced with these subsystems in order to accomplish their goals.
Hereafter the working principle as well as the main schematic are shown: aerodynamic heating produces LH2 boil-off which within the tanks, which is used for three purposes:

- Cool down passenger cabin;
- Cooling the air pack of ECS;
- Engines cooling and exploitation of regenerative cycle within the propulsion plant.

After that, LH2 is pumped in combustion chamber and gaseous H2 is there injected.

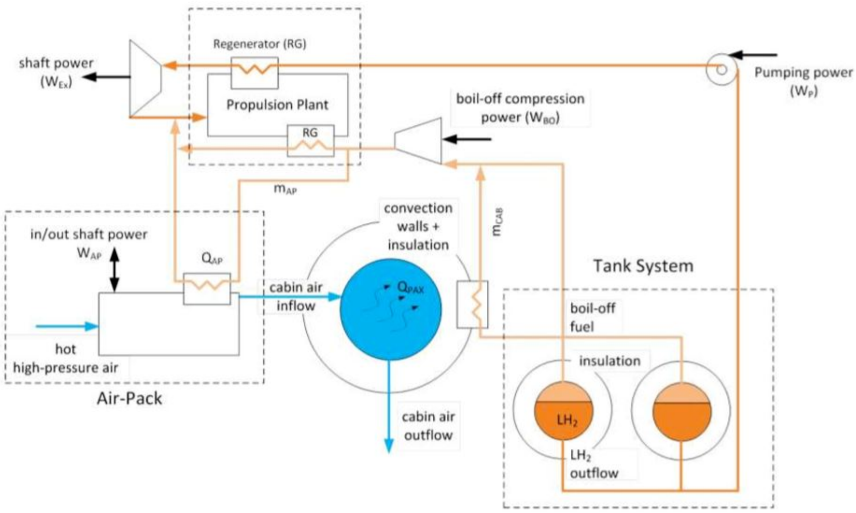


Figure 4.8 – TEMS configuration. [33]

4.3.4 Thermal Protection Subsystem

TPS has the task of protecting aircraft from the external heat flux. It works in two different ways:

- Passive System: Ceramic materials are installed on the skin to protect the aeroshell;
- Active System: heat pipes located under the aeroshell allow heat conduction from outside environment to tanks in order to boil-off LH2 that TEMS needs.

Following figure illustrate the latter operational mode.

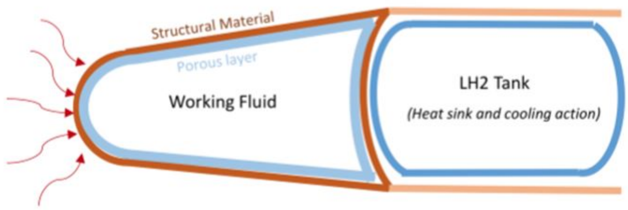


Figure 4.9 – TPS - Active System concept. [33]

It is clear that all the systems described above are intrinsically linked to each other and above all they influence and are influenced by the Environmental Control System.

4.4 Design Reference Mission (DRM) Summary

STRATOFLY MR3 Design Reference Mission (DRM) inherits the reference mission trajectory of LAPCAT MR2. The main route that has been considered is Brussels-Sidney, represented in figure below:

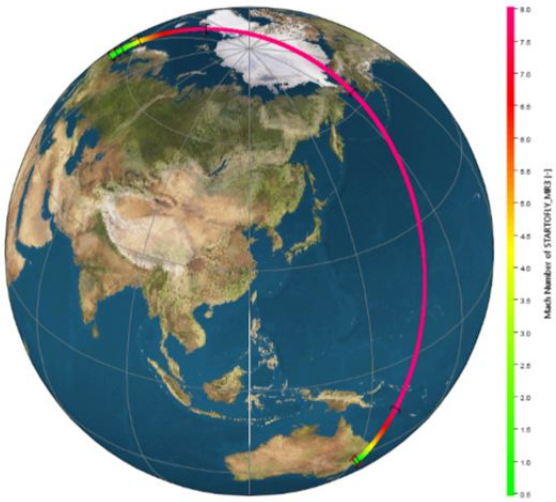


Figure 4.10 – Illustration of Brussels - Sidney trajectory. [30]

The reference mission is a step climb trajectory, since the climb and the descent are divided in different steps as figure below shows:

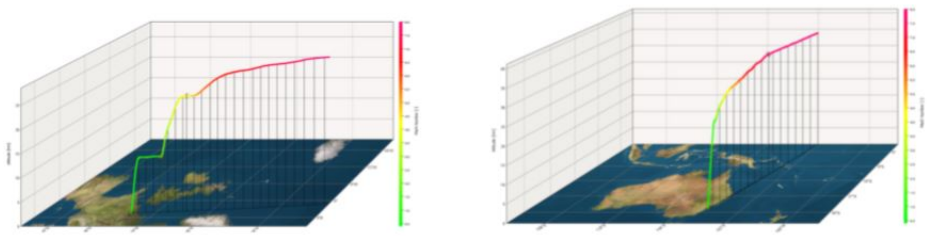


Figure 4.11 – Take-off, from Brussels, and landing (to Sydney) trajectory. [30]

The entire mission can be divided into 11 different phases:

- Pre-departure
- Taxi out
- Take-off
- Subsonic Climb

- Subsonic Cruise
- Supersonic Climb
- Supersonic Cruise (propulsion plant transition)
- Hypersonic Climb
- Hypersonic Cruise
- Descent
- Final Approach
- Landing
- Taki-in
- Ramp cool-down and parking

Relation between Mach number and flight altitude versus time during the DRM is represented in the figure below:

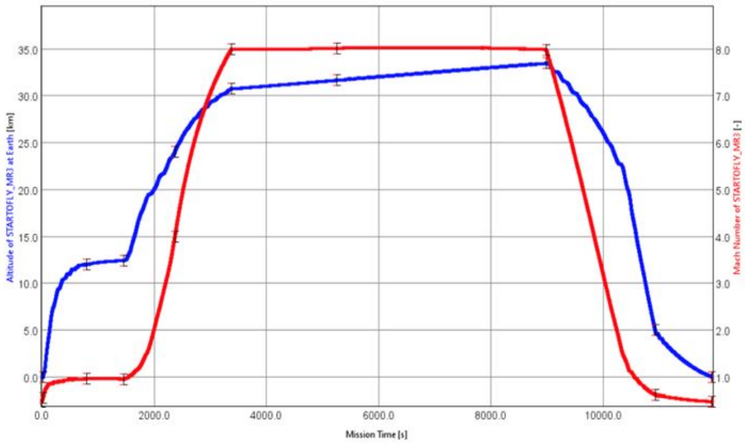


Figure 4.12 – Mach number and flight altitude vs Mission time - Brussels/Sidney.

The need of a subsonic cruise lies in the fact that regulation put limits on the noise that an aircraft can produce, consequently supersonic flight are banned over inhabited areas because of sonic boom.

After the take-off from Brussels, an altitude of about $12km$ is reached. Here the subsonic cruise phase starts. Later there is a supersonic ascent until an altitude of about $22km$ is reached at Mach 4. Here, after a short supersonic cruise needed to perform transition from ATR to DMR propulsion plant, hypersonic flight starts and aircraft continues to increase altitude and speed until a speed of Mach 8 and an altitude of $35km$ are reached. Here start the hypersonic cruise. When a distance of $15200km$ from the Brussels airport has been reached, the descent phase begins: engines are shut-off and the aircraft decelerates thanks to the atmospheric drag that allows decreasing altitude too. Finally, engines are reactivated for final approach and landing.

Chapter 5

ECS sizing and Architecture

As already discussed, this system is something between a classical aircraft's Environmental Control System (ECS) and a space-oriented Environmental Control and Life Support System (ECLSS).

In this chapter we will exploit the mathematical modeling described in Chapter 3 in order to apply the hypersonic scenario to the specific case study [34]. The transition from the model to the case study was by no means immediate, in fact, while the first started from the generic hypothesis of a circular monobloc cabin that exchanges heat with the outside exclusively through the lateral surfaces, here we are dealing with a geometry called "Bubble" made up of several compartments. Furthermore, each single compartment behaves autonomously, since it is necessary to take into account the presence of the engine duct and the wing tanks, in addition to the heat generated by the hypersonic speed.

5.1 Cabin layout

As mentioned above, the STRATOFLY MR3 cabin has been completely redesigned with respect to the one conceived for its predecessor, LAPCAT MR2.4, in order to:

- Increase passengers' comfort (Volume optimization, floor inclination during the mission profile)
- Increase passengers' safety (new boarding strategy, new emergency procedure and location of subsystems improved)
- Balance the weight (CoG position control in different flight phases)

The cabin is located around the middle of the vehicle, specifically between section B and F (see Fig. below). Its length is approximately of $38.35m$ and its width around $10.65m$, with a total volume of $1220m^3$ in order to be capable of boarding 300 passengers.

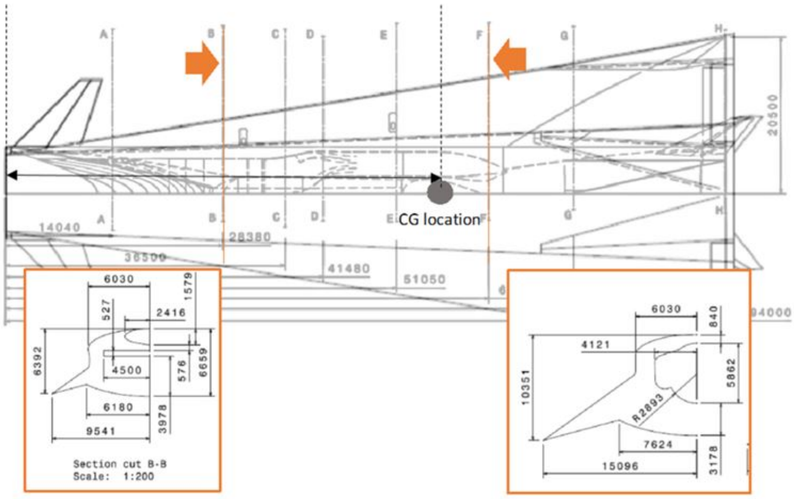


Figure 5.1 – Cabin location. [34]

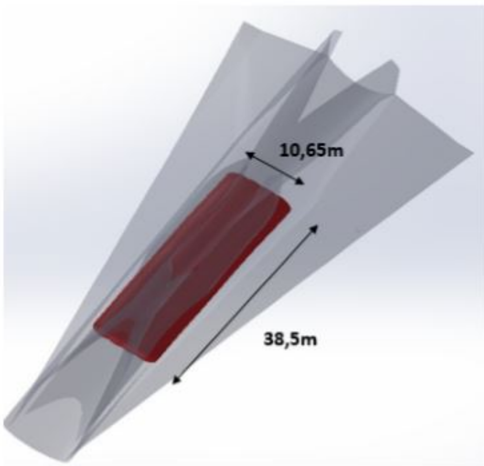


Figure 5.2 – Cabin main dimension. [34]

The following figure shows the consecutive aisles and floors; in this way the internal volume optimization is guaranteed and it allows improving the subsystems' positioning.

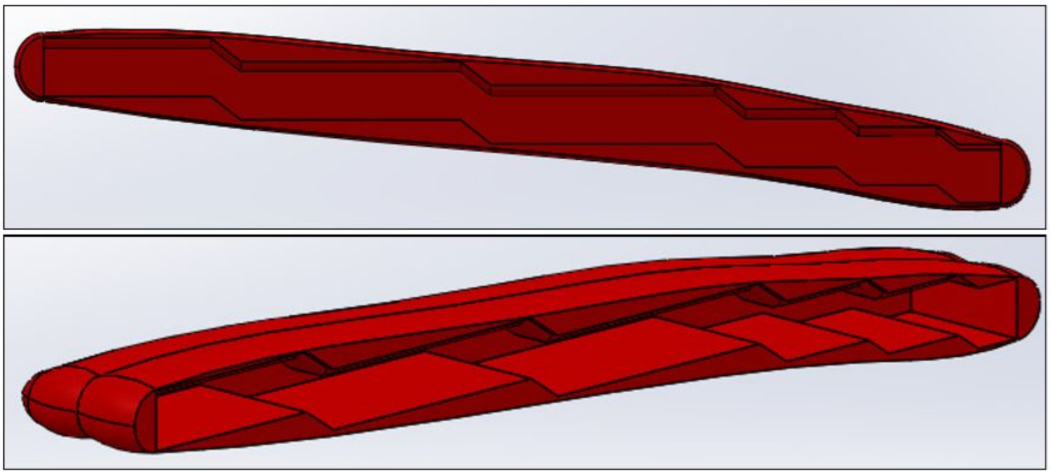


Figure 5.3 – Cabin floors (side view and isometric view). [34]

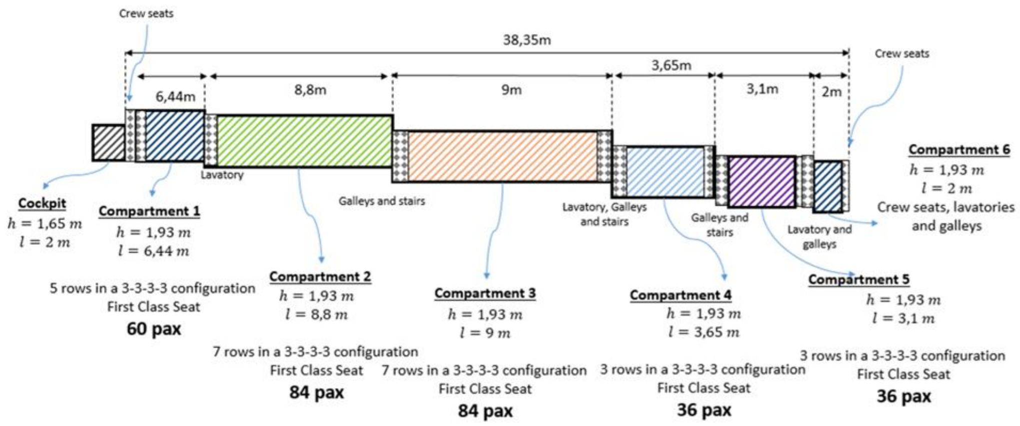


Figure 5.4 – Sketch of the internal configuration. [34]

The internal configuration consists of:

- 6 passengers' compartment at a different floor levels and with different passengers' capacity
- 1 cockpit with 2 pilots
- Stairs

- Lavatories
- Galleys

Passengers are distributed as follows. There are 300 First Class seat.

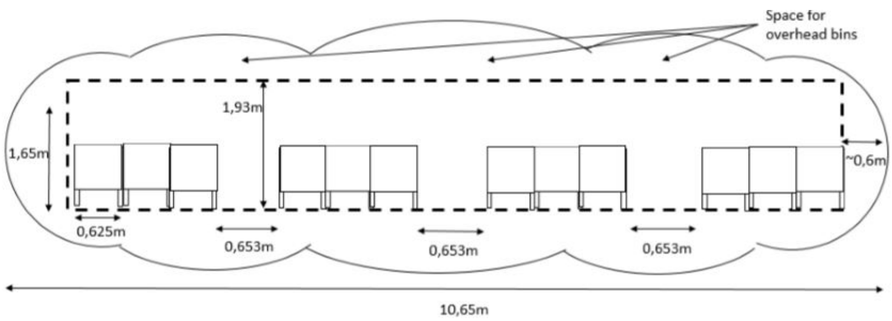


Figure 5.5 – First Class Seat Layout and dimensions. [34]

Note the structure and positioning of the cabin inside the aircraft, it is necessary to proceed by studying the elements with which it is in contact, in order to obtain the interface temperature data and related heat flow.

5.2 Passenger cabin interfaces

The passenger cabin, given its position in the aircraft system, is interfaced with the following compartments on the different limits:

- Roof Side → Engine Compartment
- Deck Side → Aeroshell (outer Skin of the aircraft)
- Port&Starboard Sides → Hydrogen tanks
- Front&Rear Sides → Hydrogen tanks

5.2.1 Roof Side - Engine compartment interface

The upper side of the cab interfaces with the engine compartment along its entire length. The interface surface is therefore obtained from the heights of the different internal compartments of the cabin, summarized in Tab. [5.2].

The cabin is linked to the engine compartment with an aluminum reticular metal structure with thermal conductivity equal to $k = 56,1 W/mK$. The

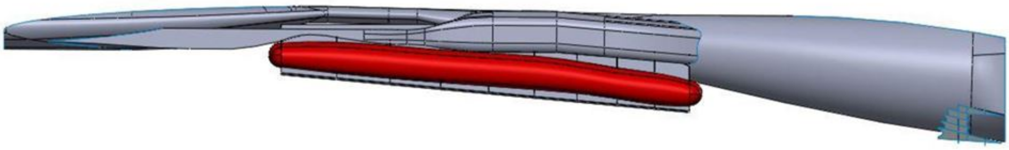


Figure 5.6 – Cabin positioning in reference to engine duct. [35]

function of this structural system is to distance the cabin from the engine compartment by about $1m$.

The temperature of the external skin of the engine, in contact with the aluminum structure, is set at $1000K$, while the maximum temperature allowed by the primary structure is $473K$. From a thermo-kinetic point of view, what happens is that the heat flow exiting the engine duct propagates through the metal structure, reaching the external casing of the cabin, consisting of several layers as already described in Chapter 3. It is necessary to take into account the fact that there is no convective cooling chamber, therefore it will be necessary to appropriately size the thicknesses of the individual layers and the material to be used [26].

5.2.2 Deck Side - Interface with external aircraft skin

The deck side of the cabin interfaces directly with the ventral skin of the aircraft along its entire length. The interface surface is therefore obtained from the heights of the different internal compartments of the cabin, summarized in Tab. [5.2].

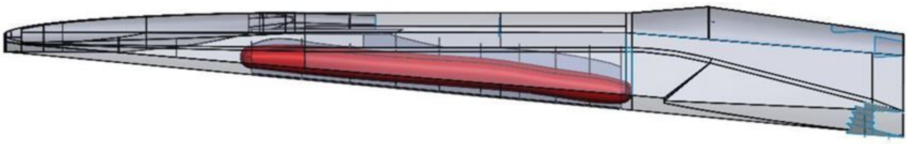


Figure 5.7 – Cabin positioning in reference to external Aeroshell. [35]

The incoming heat flow is therefore given by the aerothermal contribution from the outside. Also in this area, the cabin is not protected by the liquid hydrogen tanks and the configuration of the different insulating layers is the same as reported in Chapter 3.

5.2.3 Port&Starboard Sides - Partial interface with wing tanks

The port and starboard sides of the cabin are partially in contact with the inner end of the wing fuel tanks. There are, in fact, areas, in correspondence with the bays of the trolley and the exits, where the tanks are absent.

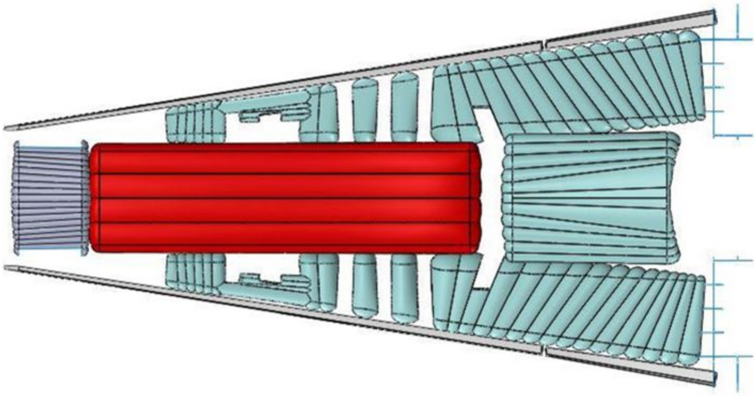


Figure 5.8 – Cabin positioning in reference to side/front tanks. [35]

Initially, according to what is represented in the previous figure, the section directly in contact with the hydrogen tanks was supposed equal to half the side surface of the cabin, obtainable thanks to the data summarized in Tab. [5.2]. The average thickness of the hydrogen tanks considered for the thermal calculation is approximately 1m, while the remaining surface was supposed to be in contact with the outer skin of the aircraft, especially in the wing-fuselage junction.

However, this first study hypothesis, affected by large simplifications, presented several problems. In particular, the one that led to the definitive exclusion is related to the fact that the liquid hydrogen tanks, given their size and parameterization, were able to completely absorb the external heat flow, causing a complete phase change of the hydrogen from liquid to gaseous, with detrimental effect on propulsion.

Furthermore, it is necessary to remember that the cryogenic tanks are designed in such a way as to avoid any transmission of thermal energy from the external wall to the liquid, therefore they are all equipped with a double coating which is vacuumed inside, in order to prevent the passage of heat. by convection and radiation. Consequently, the heat exchange that may occur will be minimal compared to that entering from the outside.

The hypothesized solution thus involves bleeding a certain amount of liquid hydrogen from tanks and inserting it into the gap between the layer of insulation P5 and P8, as shown in fig. (chapter 3). In this way a thin layer is created with very low conductivity having a temperature of 20K. As it will be possible to see from the results obtained, this layout allows to significantly reduce the cabin temperature, lowering the workload which ECS will have to carry out.

From what can be deduced, this study phase was the most critical, so, apart from thermal model tuning, it was also necessary to identify the compartments affected by contact with the wing tanks. Given the position of the cabin in reference to the wing tanks and given the size of the cabin itself, it emerged that the compartments in direct contact with the wing tanks are:

Compartment	**Tanks Interface**
Cockpit	-
Compartment 1	-
Compartment 2	✓
Compartment 3	-
Compartment 4	✓
Compartment 5	✓
Galleys	-

Table 5.1 – Tanks interface with cabin compartments

There seems to be an inconsistency: from the image emerges that Cockpit and Galleys are also in contact with the LH2 tanks. However, the following paragraph describes the reasons why it is possible to exclude these two compartments from the thermal evaluation.

5.2.4 Front&Rear Sides – Full interface with fuselage tanks

The front and rear sides of the cab are completely in contact with the hydrogen tanks Fig. (Above). The rear is actually separated due to the presence of the landing gear retraction bay but this contribution can be neglected. In fact, given the large size of the tanks themselves, the heat exchange through these interface surfaces is negligible, looking at the heat flow from the outside. The cabin walls in these areas can therefore supposed to to be isolated from the external environment and their contribution is not considered for the computation of the total incoming heat flow.

5.2.5 Summary interface

For the study, the "bubble" shape of the structure will be neglected and a box structure will be considered. This structure consists of 7 hypothetical isolated compartments, characterized by the dimensions shown in Fig. (The one with the colored sections) and by a length, in section, obtained from the figure above, equals to:

$$L = 9.45m \tag{5.1}$$

The cabin is modeled as a structure made up of 7 single adjacent compartments between which the heat exchange is considered null. Each compartment has a regular prismatic structure with a rectangular base. The flat walls that make up the structure are characterized by their own thickness and thermal conductivity.

The figure below represents a generic section of a compartment equipped with an insulating cavity containing LH2.

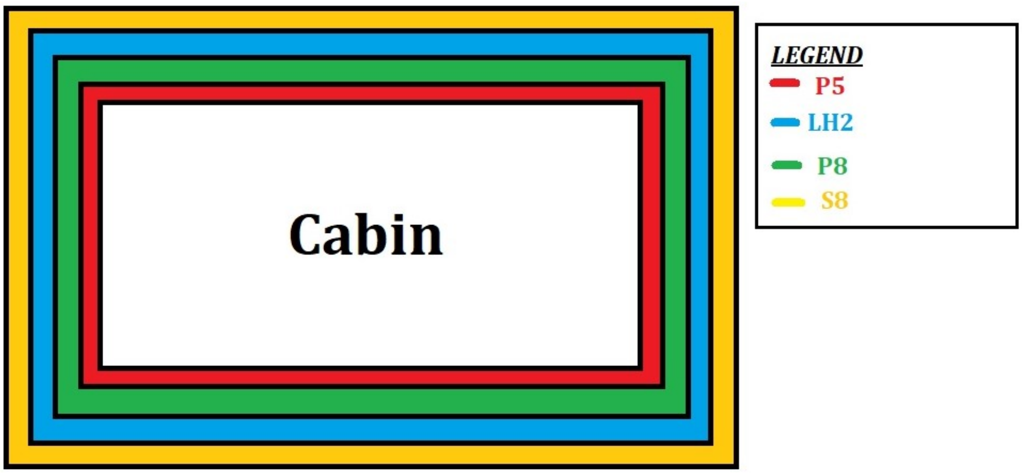


Figure 5.9 – Cabin Section

In summary, the geometric dimensions are:

Compartment	h $[m]$	l $[m]$	L $[m]$
Cockpit	1.65	2	9.45
Compartment 1	1.93	6.44	9.45
Compartment 2	1.93	8.8	9.45
Compartment 3	1.93	9	9.45
Compartment 4	1.93	3.65	9.45
Compartment 5	1.93	3.1	9.45
Galleys	1.93	2	9.45

Table 5.2 – Cabin compartments geometric dimensions

The thicknesses and thermal conductivities have been chosen after an iteration process for the creation of the model in $MatLab$:

	S_8 $[mm]$	P_8 $[mm]$	P_5 $[mm]$	k_{S_8} $[\frac{W}{mK}]$	k_{P_8} $[\frac{W}{mK}]$	k_{P_5} $[\frac{W}{mK}]$
Cockpit	1	10	10	15	0.55	0.55
Compartment 1	1	1	1.5	15	0.2	0.7
Compartment 2	1	3	1	15	0.8	0.3

Table 5.3 – Thermal conductivities and thicknesses

Based on what emerged from the Table (tank interfaces), compartments 2, 4, 5 will have an additional cavity containing liquid hydrogen with a thickness and thermal conductivity equal to:

$$s_{LH2} = 0.5\ mm \quad ; \quad K_{LH2} = 0.1\ W/mK \tag{5.2}$$

5.3 MatLab Model

As anticipated in the previous paragraphs, the study was carried out by creating a cabin model in a MatLab environment capable of simulating, as closely as possible to reality, the internal temperature trend and the evolution of the necessary air flow. The model is conceived to determine the design point and, thus, to show the correct functioning of the Environmental Control System (ECS) in high supersonic/low hypersonic conditions, i.e.

from Mach 4 to cruising speed, Mach 8. The ECS is actually designed for these flight regimes, even if it performs its duties over the entire flight profile (including also subsonic and low supersonic phases).

The model, created using the mathematical model illustrated in Chapter 3 and the geometric model illustrated in the previous paragraphs, was developed in such a way as to be flexible to possible future changes in the cabin configuration. It is possible, for example, to change:

- Number of compartments with relative spatial dimensions
- Interfaces with the various environments presented in paragraph 5.2
- Engine skin temperature
- Material of the metal lattice structure
- Thicknesses of the insulation layers
- Material of the insulation layers
- LH2 cavity tickness
- Number of passengers and crew members
- Maximum/minimum acceptable temperature in cabin

While for what concerns the thermodynamic model, it will be possible to modify:

- Isentropic compression efficiency
- Compression ratio
- Turbine isentropic efficiency
- Expansion ratio
- Mechanical compressore/turbine efficiency

	Mach				
	4	**5**	**6**	**7**	**8**
T_{rec}	625.03	819.91	1019.29	1226.22	1429.86
T_{wall}	595.71	761.14	912.21	1050.10	1169.01

Table 5.4 – Recovery and wall temperature vs Mach.

5.3.1 Current configuration results

Heat fluxes and necessary flow rate

Considering, as input, those data previously described in the tables, the algorithm first calculates the wall temperature and the recovery temperature for each Mach of the hypersonic field:

The temperature trend as a function of Mach is shown in the following figure:

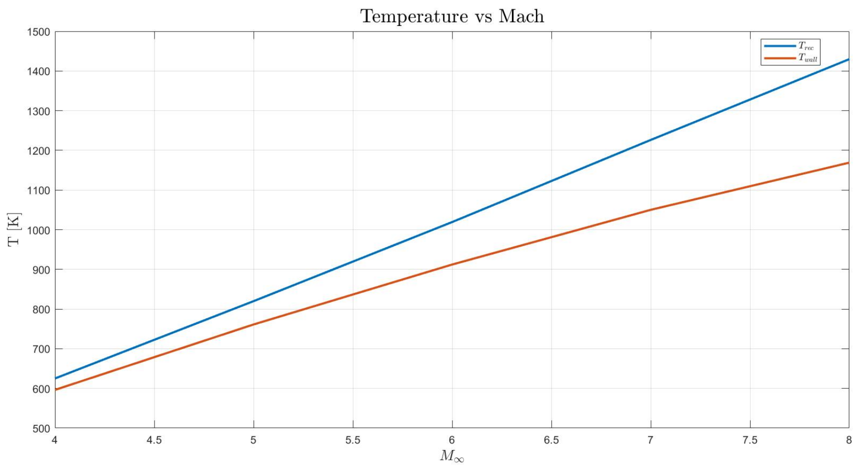


Figure 5.10 – Temperature vs Mach.

Figure demonstrates what we expected: recovery temperature of a flow increases with the speed of the flow and is greater at high speeds.

The surfaces and volumes of each single compartment are then determined.

	V $[m3]$	$S_{roof}[m^2]$	$S_{deck}[m^3]$	$S_{lat}[m^2]$
Cockpit	31.19	18.90	18.90	6.60
Compartment 1	117.46	60.86	60.86	24.86
Compartment 2	160.50	83.16	83.16	33.97
Compartment 3	164.15	85.05	85.05	34.74
Compartment 4	66.57	34.49	34.49	14.09
Compartment 5	56.54	29.30	29.30	11.97
Galleys	36.47	18.90	18.90	7.72
Total	632.88	330.66	330.66	133.95

Table 5.5 – Geometric data – Current configuration.

As described in the dedicated paragraph, in the current aircraft configuration, the engine duct is in direct contact with the entire upper surface of the cabin. This will be the only thermal contribution to be taken into consideration on this interface.

The heat flux is obtained by exploiting Fourier's law (Chap. 3) on convection. The values relating to the surface wetted by the flow, the convection coefficient and the cabin-engine distance are those indicated above.

	$q_{eng}[MW]$
Cockpit	0.35
Compartment 1	1.12
Compartment 2	1.54
Compartment 3	1.57
Compartment 4	0.64
Compartment 5	0.54
Galleys	0.35

Table 5.6 – Engine heat flow

As for the temperatures involved, it has been assumed that the entire engine duct has an external temperature of 1000 K and that the maximum permissible external temperature from the cabin is the temperature to which the outermost layer of each single compartment is brought. This hypothesis is made as being still in the preliminary design and first sizing phase, it was preferred to stress the system as much as possible, in order to have an over-sized estimate of the values involved.

By exploiting the electrical analogy it is possible to obtain how the temperature varies along the layers of insulation and, ultimately, the internal temperature in the cabin, which is equal to 326.84 K in each compartment. Below is the temperature trend between the various layers.

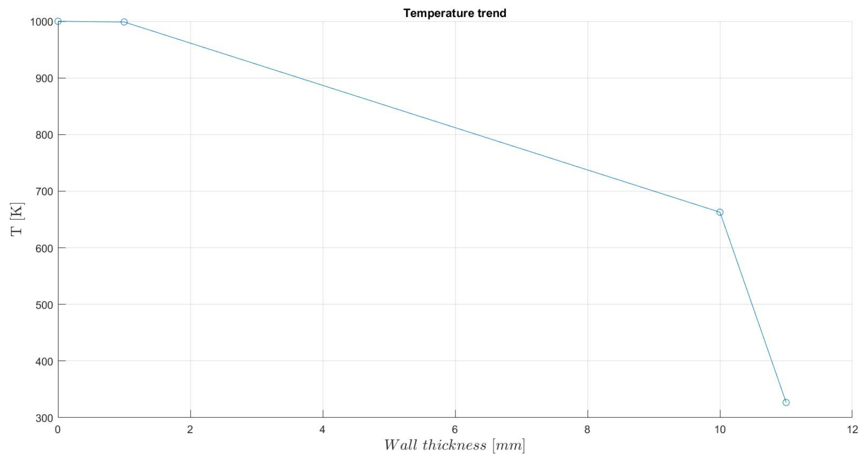


Figure 5.11 – Temperature trend – Roof side.

The study concerning the interface with the external skin of the aircraft is completely similar to the one just introduced.

The difference lies in the fact that the incoming heat flow is not due to the engine duct, but to the high speeds reached.

Consequently Newton's law on thermal convection in forced regime will be exploited. In this case, the heat flow is strictly dependent on the flight speed, in fact:

	Mach				
	4	**5**	**6**	**7**	**8**
	$q_{deck}[MW]$				
Cockpit	0.24	0.50	0.91	1.50	2.22
Compartment 1	0.79	1.61	2.93	4.82	7.14
Compartment 2	1.08	2.20	4.00	6.59	9.76
Compartment 3	1.10	2.25	4.10	6.74	9.98
Compartment 4	0.45	0.91	1.66	2.73	4.05
Compartment 5	0.38	0.77	1.41	2.32	3.44
Galleys	0.24	0.50	0.91	1.50	2.22

Table 5.7 – Deck heat flow

Below is the trend of the incoming heat flow - Deck side as a function of the flight Mach is reported. As expected, as the speed increases, the heat flow increases too.

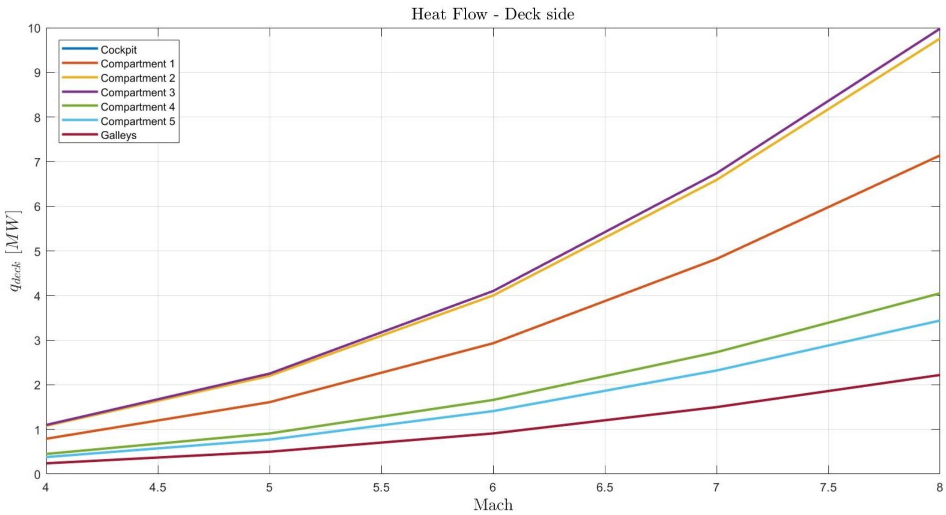


Figure 5.12 – Heat Flow - Deck side vs Mach.

Also in this case, using the electrical analogy it is possible to obtain the internal temperature in each compartment. Obviously, the internal temperature will also be a function of the flight Mach.

Finally, the heat flow entering the cabin is obtained from the side surfaces. The speech is analogous to the previous one, so it could be wrongly assumed that the flow is the same. However, by analyzing Newton's relation for convection, it is observed that the incoming heat flow is directly proportional to the wetted surface which is obviously different from the deck side.

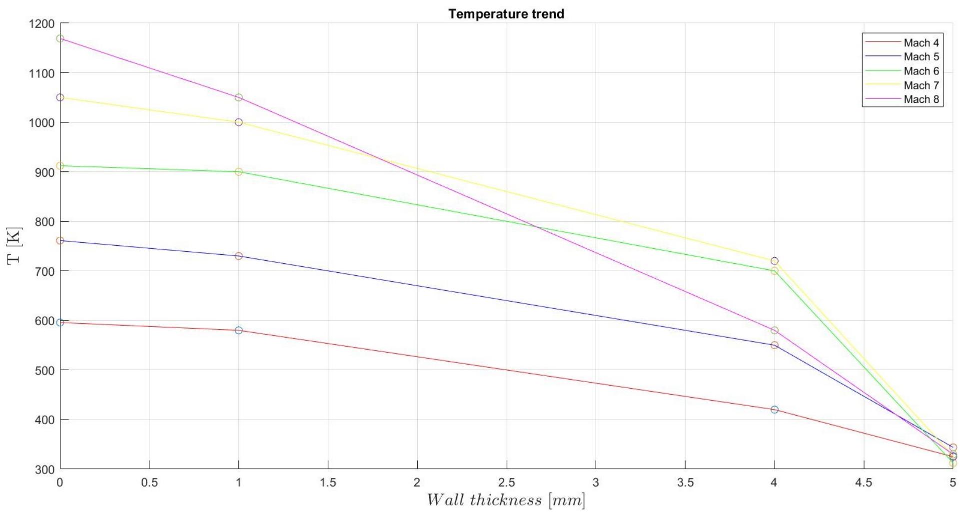


Figure 5.13 – Temperature trend - Deck side.

Furthermore, it must be considered that the air flow does not directly touch the side surfaces of the cabin but undergoes deviations due to the wing conformation of the aircraft itself.

Since no suitable software was provided and it was required to create an appropriate model in MatLab, we proceeded to make this side area as a parametric smooth wall, made up of the same layers discussed in Chapter 3, lapped by the current external.

The heat flow entering the wall is calculated in the same way as in the previous case, obtaining the following results:

	Mach				
	4	**5**	**6**	**7**	**8**
	$q_{LH2}[MW]$				
Cockpit	0.085	0.175	0.318	0.523	0.774
Compartment 1	0.321	0.657	1.198	1.970	2.918
Compartment 2	0.439	0.898	1.637	2.692	3.987
Compartment 3	0.449	0.919	1.674	2.753	4.078
Compartment 4	0.182	0.373	0.679	1.117	1.654
Compartment 5	0.155	0.316	0.577	0.948	1.405
Galleys	0.099	0.204	0.372	0.612	0.906

Table 5.8 – Port & Starboard sides Heat Flow

The trend of the incoming heat flow is reported:

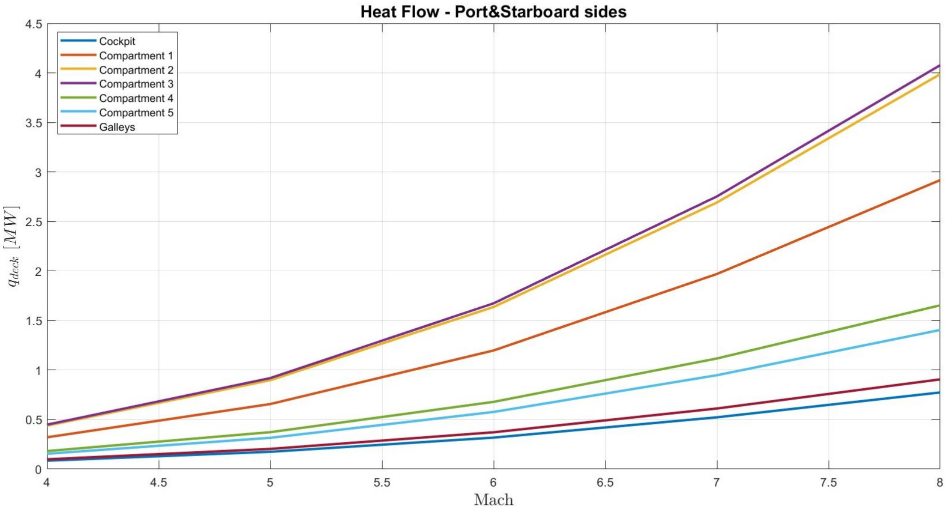


Figure 5.14 – Heat Flow – Port&Starboard sides.

Once again, using the electrical analogy, the temperature profile is obtained through the wall and therefore the internal temperature in each compartment. However, it is necessary to take into account the presence of the liquid hydrogen interspace which contributes to the modeling of the walls of compartments 2, 4 and 5. As a result, different graphs will be obtained:

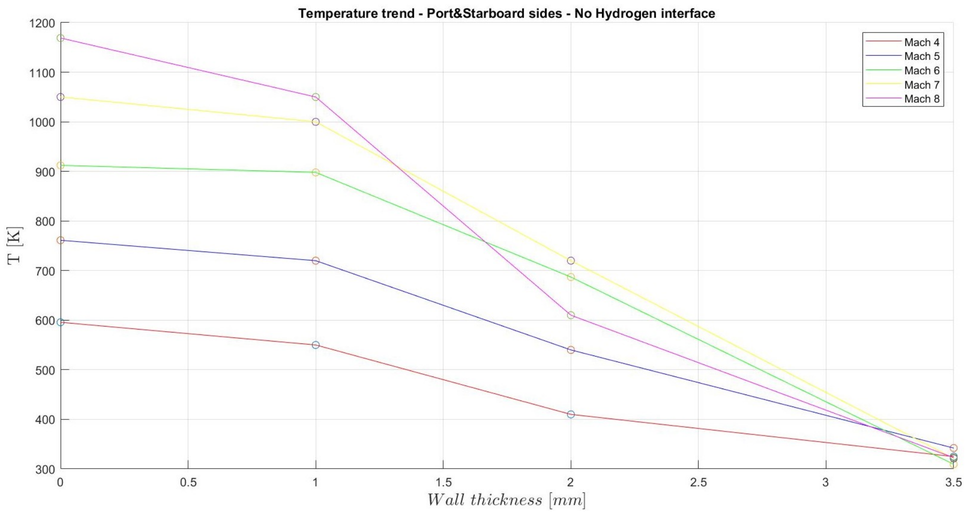


Figure 5.15 – Temperature trend – Port&Starboard sides – no Hydrogen interface.

Known the internal temperatures of each compartment, determined as if the various flows were applied one at a time, to determine the actual internal temperature it is necessary to identify the equilibrium temperature.

In general:

$$T_e = \frac{\sum_{i=1}^{n} m_i c_i T_i}{\sum_{i=1}^{n} m_i c_i} \tag{5.3}$$

Since the mass of air in each compartment is always the same, the equilibrium temperature coincides with the arithmetic mean of the initial temperatures:

	Mach				
	4	**5**	**6**	**7**	**8**
	$T_e[^oC]$				
Cockpit	52.32	64.58	43.16	51.66	53.43
Compartment 1	52.32	64.58	43.16	51.66	53.43
Compartment 2	51.64	63.19	40.64	47.27	47.27
Compartment 3	52.32	64.58	43.16	51.66	53.43
Compartment 4	51.64	63.19	40.64	47.27	47.27
Compartment 5	51.64	63.19	40.64	47.27	47.27
Galleys	52.32	64.58	43.16	51.66	53.43

Table 5.9 – Compartment temperatures

Having determined the incoming heat flows and the temperatures present inside each compartment, we continue, using the relationships introduced in chapter 3 (Eq. [3.35-3.36]), With the determination of the thermal load due to the presence of humans on board:

$$q_{met} = 33600[W] \tag{5.4}$$

and electronic systems:

$$q_{sys} = 31000[W] \tag{5.5}$$

Therefore the heat produced inside the aircraft turns out to be:

$$q_{int} = 64600[W] \tag{5.6}$$

The latter results must be divided in a weighted manner to the individual compartments obtaining:

	$q_{int}[kW]$
Cockpit	3.18
Compartment 1	11.93
Compartment 2	16.40
Compartment 3	16.80
Compartment 4	6.80
Compartment 5	5.77
Galleys	3.72

Table 5.10 – Distribution of the Heat produced in the aircraft.

Considering each single compartment as a control volume, it must be added to the incoming heat flow, thus determining the net incoming heat flow. It is clear that we are in the second scenario described in Chapter 3:

The environment is hot and so it is necessary to **cool down the cabin**.

Assuming to enter air at 6^oC and to want keeping the environment in a temperature range between $18^oC \leq T_{int} \leq 25^oC$, the necessary air flow in supersonic and hypersonic high flight conditions is obtained.

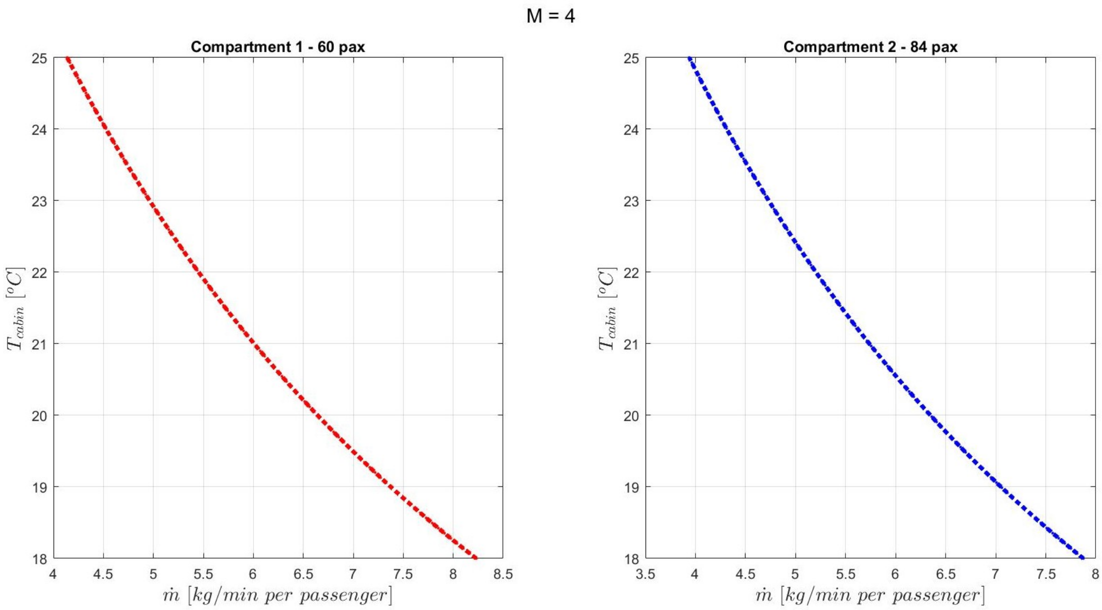


Figure 5.16 – Airflow in Compartments 1 – 2 at Mach 4 .

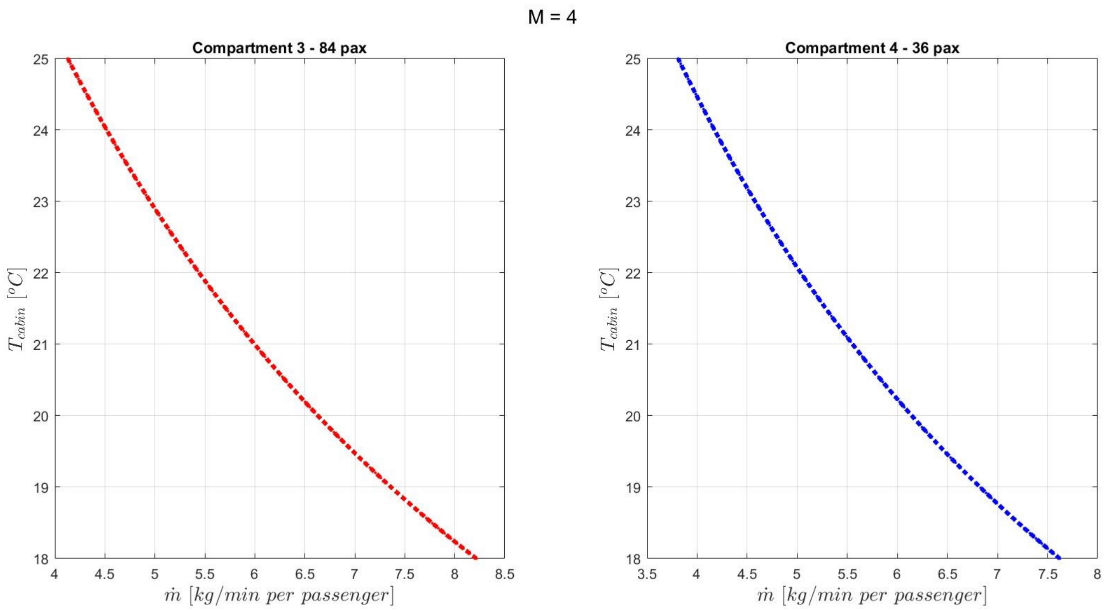


Figure 5.17 – Airflow in Compartments 3 – 4 at Mach 4.

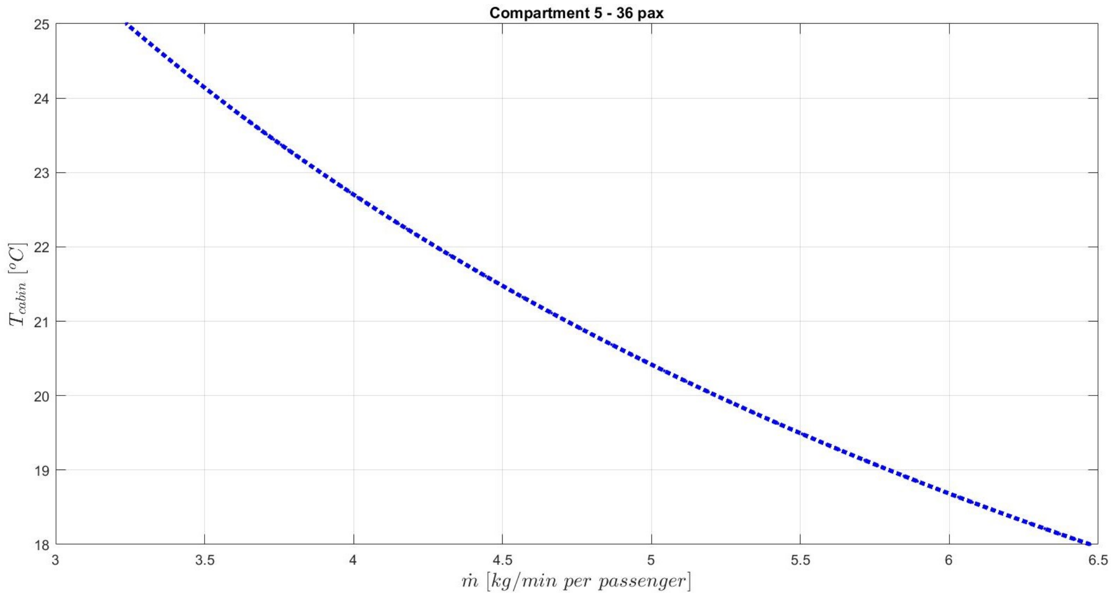


Figure 5.18 – Airflow in Compartments 5 at Mach 4.

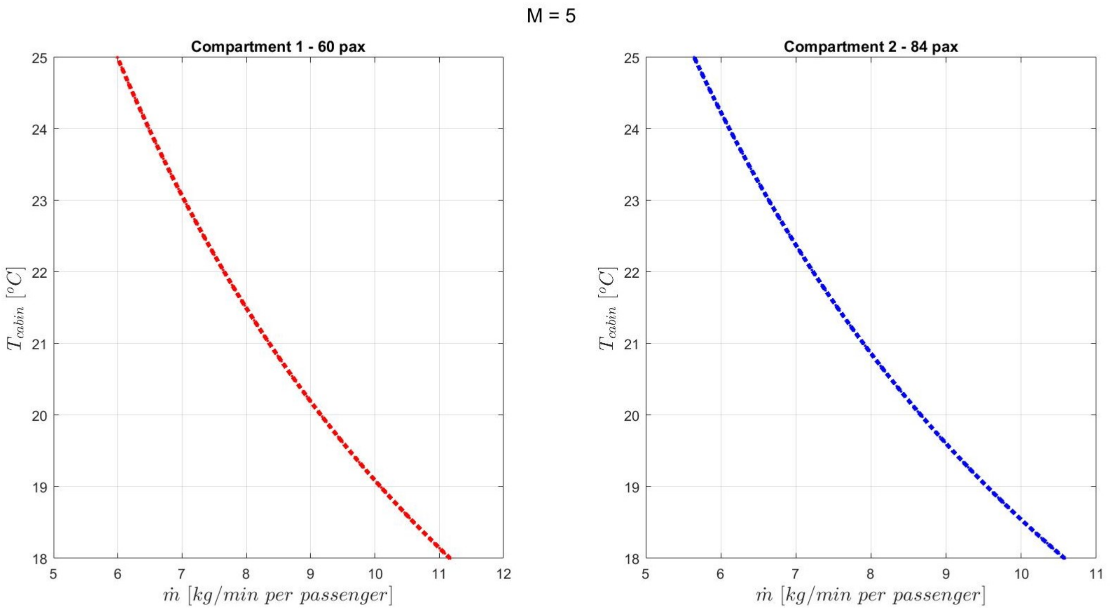


Figure 5.19 – Airflow in Compartments 1 – 2 at Mach 5.

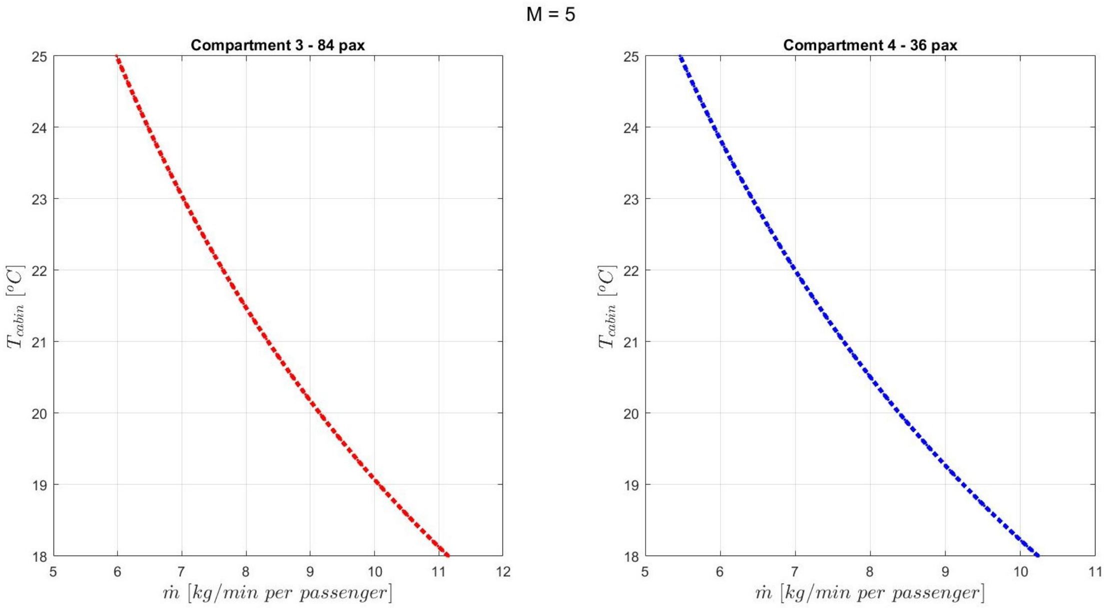


Figure 5.20 – Airflow in Compartments 3 – 4 at Mach 5.

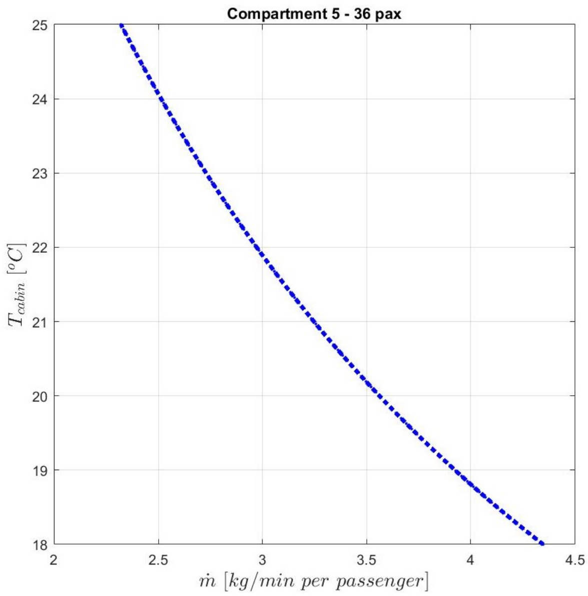


Figure 5.21 – Airflow in Compartments 5 at Mach 5.

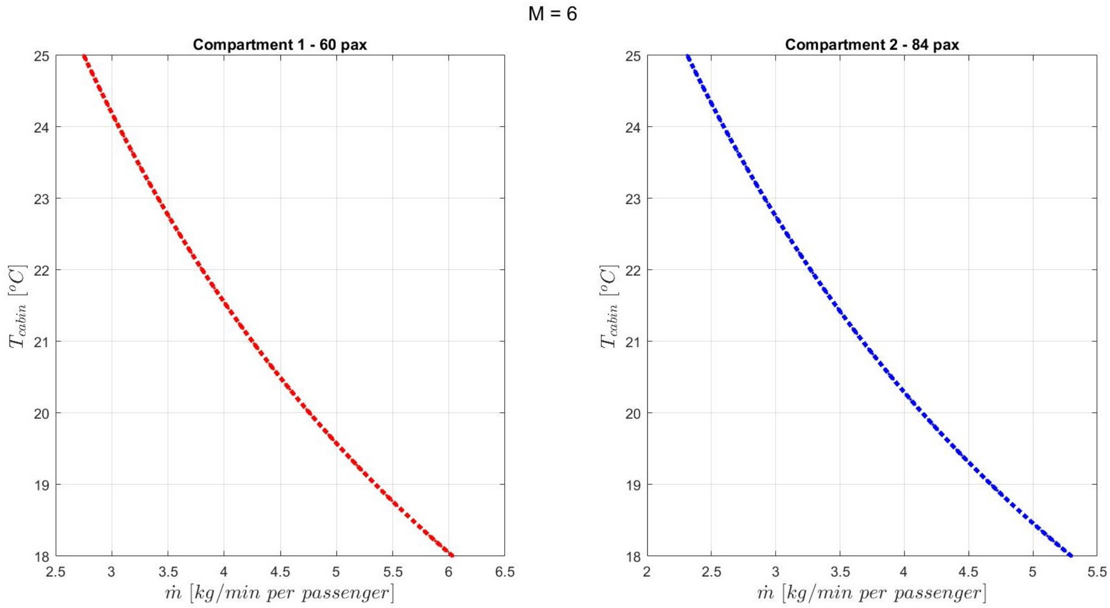


Figure 5.22 – Airflow in Compartments 1 – 2 at Mach 6.

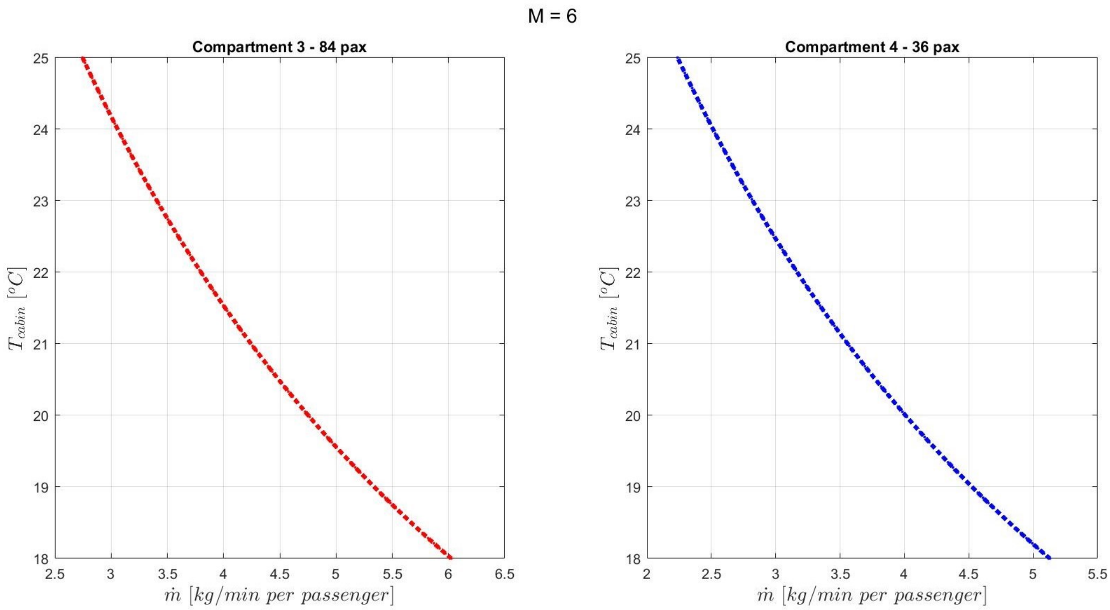


Figure 5.23 – Airflow in Compartments 3 – 4 at Mach 6.

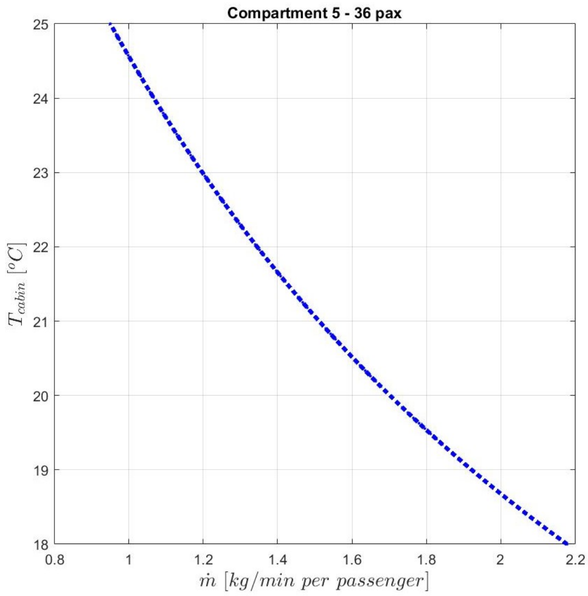


Figure 5.24 – Airflow in Compartments 5 at Mach 6.

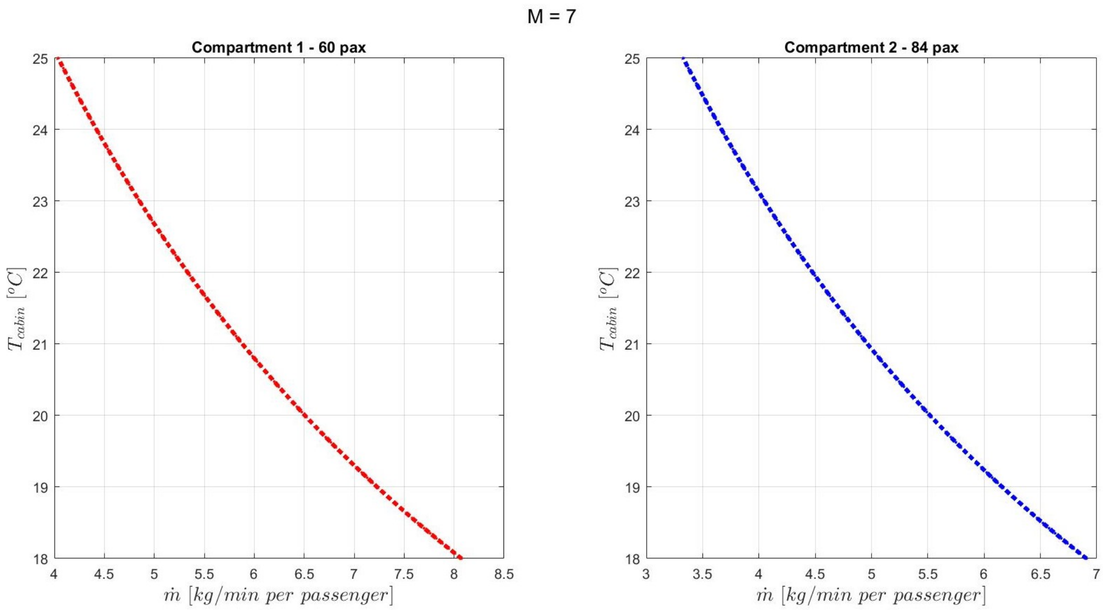


Figure 5.25 – Airflow in Compartments 1 – 2 at Mach 7.

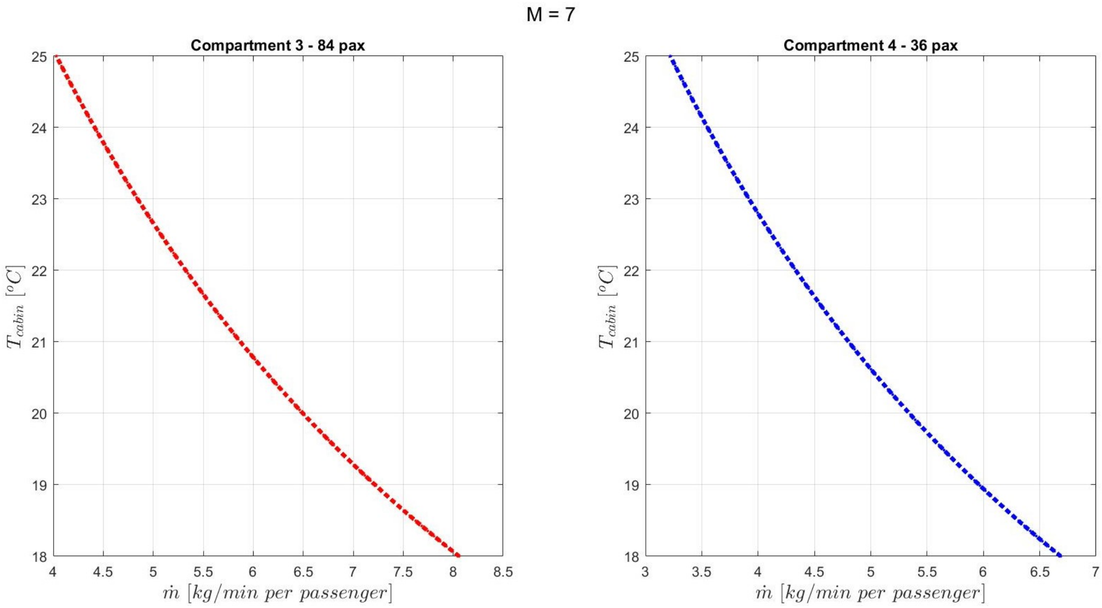


Figure 5.26 – Airflow in Compartments 3 – 4 at Mach 7.

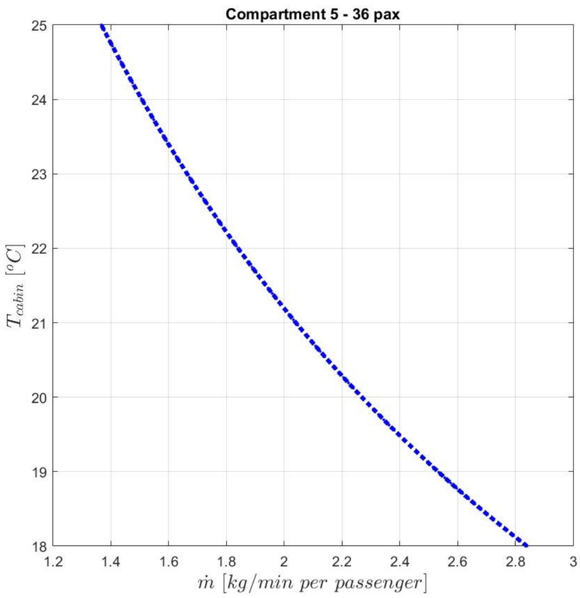


Figure 5.27 – Airflow in Compartments 5 at Mach 7.

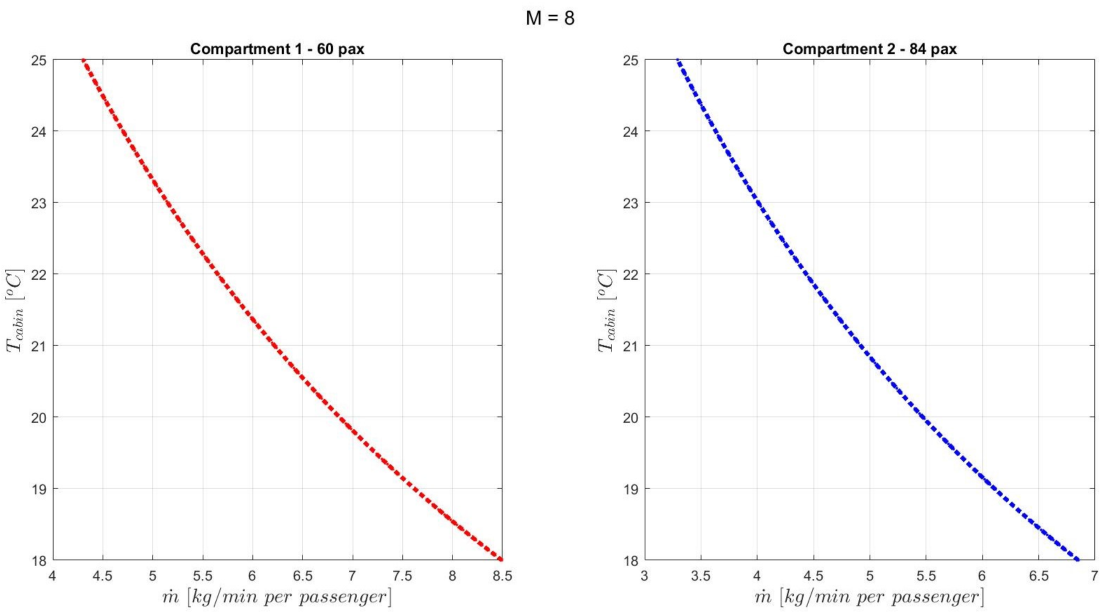


Figure 5.28 – Airflow in Compartments 1 – 2 at Mach 8.

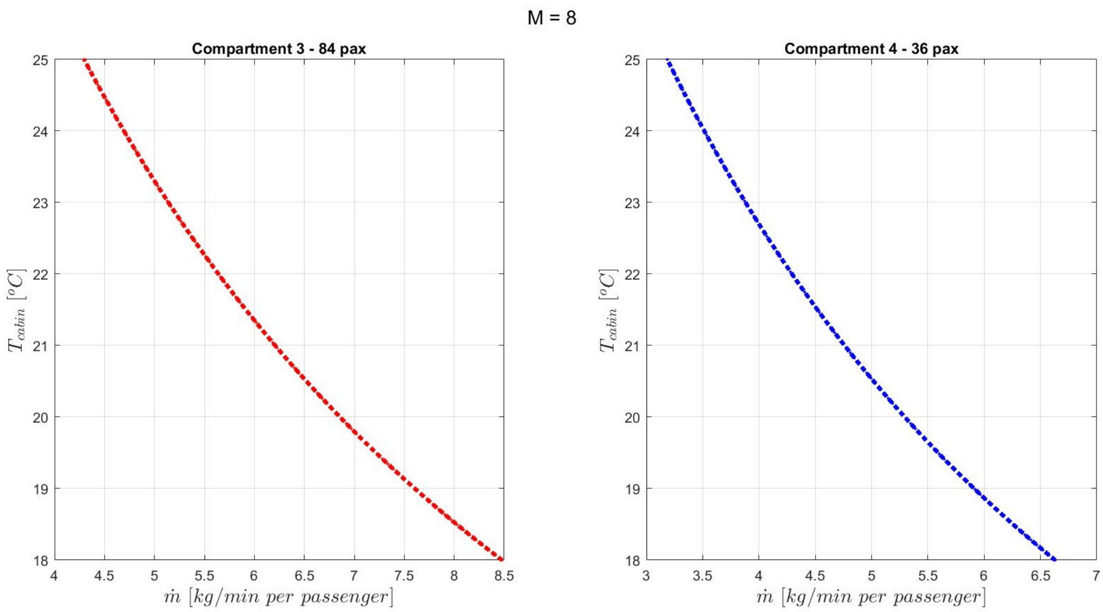


Figure 5.29 – Airflow in Compartments 3 – 4 at Mach 8.

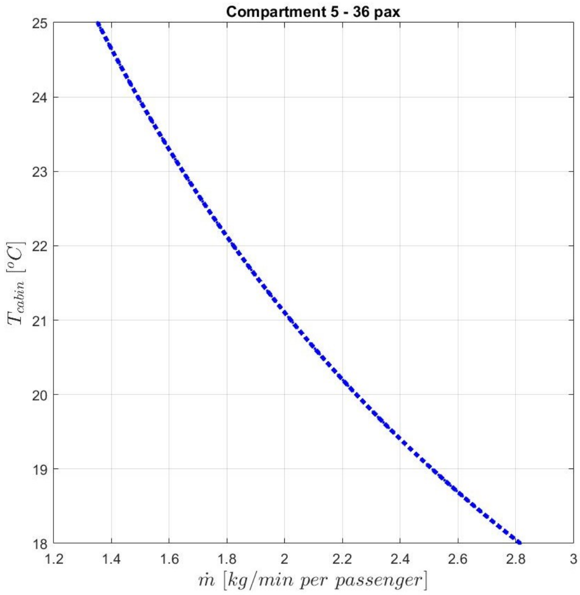


Figure 5.30 – Airflow in Compartments 5 at Mach 8.

The graphs show how the hydrogen gap effectively contributes at reducing the flow rate required to maintain the temperature in the cabin within the identified range. However, it is also observed that the net advantage of this solution is obtained starting from Mach 7, i.e. in the vicinity of the cruising conditions. This is no coincidence, in fact the thicknesses and materials have been optimized in such a way as to obtain the best performance in the cruising phase, i.e. in the most critical phase from the aerothermal point of view (high incoming heat flow).

In this way it is possible to use the same Environmental Control System not only in missions that involve a cruise at Mach 8 but also for shorter missions that require a maximum cruising speed of Mach 5.

Ultimately, it is noted that the mass flow rate of air obtained in the various configurations is higher than the minimum quantity envisaged by $FAR25$, that is $\dot{m} \geq 0.25$ kg/min per passenger.

Characterization of the thermodinamic cycle

As already discussed in the previous chapters, the optimal solution reached consists in using an open cycle in the subsonic / supersonic phase and a closed cycle for the hypersonic phase.

The air flow required for closed cycle operation has just been determined.

To determine that required by the open loop, rather than repeating the same procedure, we assume:

- The flow rate required by the open cycle in the subsonic phase is equal to the average of the minimum values of the flow rates required in cruising conditions and the most advantageous flight condition (in terms of flow to be tapped to the engine), in this case Mach 6;
- The flow rate required by the open cycle in the supersonic phase is equal to the average of the flow rates required in cruise conditions and in the most advantageous flight conditions.

With these assumptions it is obtained:

- Subsonic phase:
$$G_{sub} = 14.86 kg/s \tag{5.7}$$
- Supersonic phase:
$$G_{sup} = 21.37 kg/s \tag{5.8}$$

To determine the operating temperatures and pressures within the cycle, the information provided by the *Von Karman Institute for Fluid Dynamics* was used, in particular the pressure and temperature trend in the area of the air flow extraction motor is reported, *Air Pre-Combustion*, as the flight Mach varies.

Mach Number	0.3	0.44	0.5	0.75	0.82	1.5	2	3
Air pre-combustion pressure [Pa]	190000	240000	251219	258375	157987	135842	156319	176102
Air pre-combustion temperature [K]	363.407	390.19	395.35	406.616	368.138	442.518	519.707	825.92

Figure 5.31 – Characterization of flows in the engine duct.

The air bleeded under the conditions indicated in the table passes through an air-air type heat exchanger (primary heat exchanger) in which the fluid, in addition to lowering its temperature, undergoes a pressure drop due to distributed and concentrated pressure drops due to the component ducts.

Then the air passes through the compressor, driven by the turbine, in which the flow undergoes a supposed isentropic compression. This condition implies that all the energy produced by the compressor is used to compress the fluid:

$$pV^{\gamma} = cost \tag{5.9}$$

Where:

- p is fluid pressure
- V is fluid volume
- γ is the ratio between specific heat at constant pressure and constant volume

Considering air as an ideal gas having the following properties:

- Point molecules with negligible volume
- Presente og only elastic collisions
- Non-interacting molecules

The following relationship can be used:

$$pV = nRT \tag{5.10}$$

Which combined with the previous one allows to obtain the relationship that links pressure and temperature in the isentropic case:

$$\frac{T_{2_{is}}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{5.11}$$

Where:

- $T_{2_{is}}$ compressor outlet temperature in the isentropic process
- T_1 compressor inlet temperature
- p_2 compressor outlet pressure
- p_1 compressor inlet pressure

The actual compressor outlet temperature is higher than that calculated with the previous relationship, this is because it is necessary to consider the isentropic efficiency of the compressor:

$$\eta_c = \frac{h_{2_{is}} - h_1}{h_2 - h_1} = \frac{T_{2_{is}} - T_1}{T_2 - T_1} \tag{5.12}$$

From which the compressor outlet temperature is obtained:

$$T_2 = T_1 \left\{ 1 + \frac{1}{\eta_c} \left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \right\} \tag{5.13}$$

Hence the power needed to compress the fluid:

$$P_c = \eta_{m_c} G_1 c_p (T_2 - T_1) \tag{5.14}$$

Once out of the compressor, the flow passes through a second heat exchanger (main heat exchanger) whose function is to cool the flow rate before entering the turbine where it undergoes an expansion thanks to which mechanical energy is produced to move the compressor and the fans connected.

The relationship between the turbine outlet and inlet temperature is completely similar to that of the compressor and is obtained in the same way:

$$T_4 = T_3 \left\{ 1 - \eta_t \left[\left(\frac{p_4}{p_3} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \right\} \tag{5.15}$$

Similarly, the isentropic turbine efficiency:

$$\eta_t = \frac{h_3 - h_{4_{is}}}{h_3 - h_4} = \frac{T_3 - T_{4_{is}}}{T_3 - T_4} \tag{5.16}$$

From which the power generated in turbine is obtained:

$$P_t = \eta_{m_t} G_1 c_p (T_3 - T_4) \tag{5.17}$$

Then the flow passes through a condenser, used to condense the moisture in the condenser and store it in a suitable tank that will be used for the closed cycle.

With data available and having assumed:

- $\eta_c = 0.8$
- $\beta_c = p_2/p_1 = 1.5$
- $\eta_t = 0.9$
- $\beta_t = p_4/p_3 = 3$ $\eta_{m_c} = \eta_{m_t} = 0.8$

It was possible to obtain the thermodynamic evolution of the flow in the various flight conditions that characterize the open cycle:

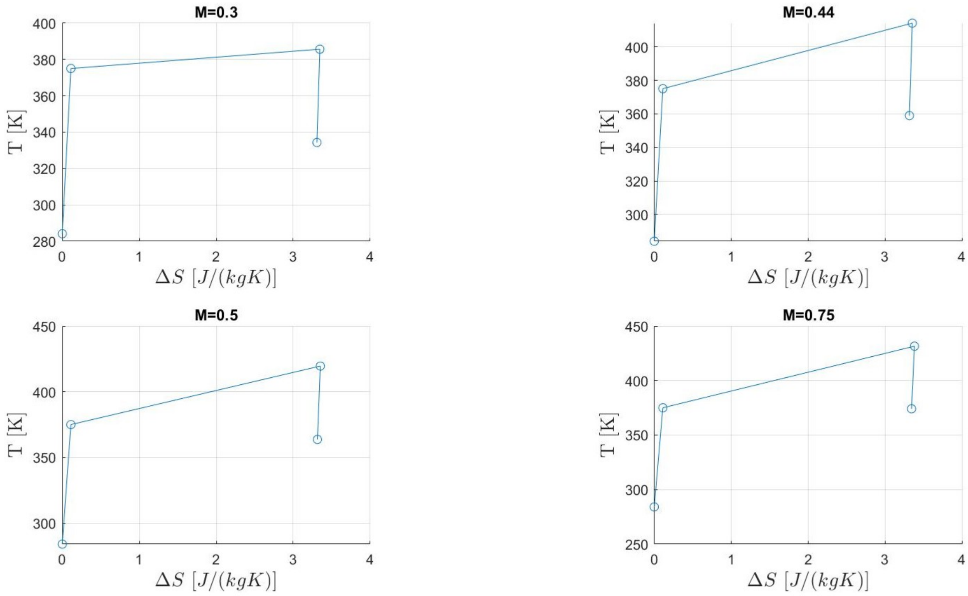


Figure 5.32 – Thermodynamic cycle – subsonic flight conditions.

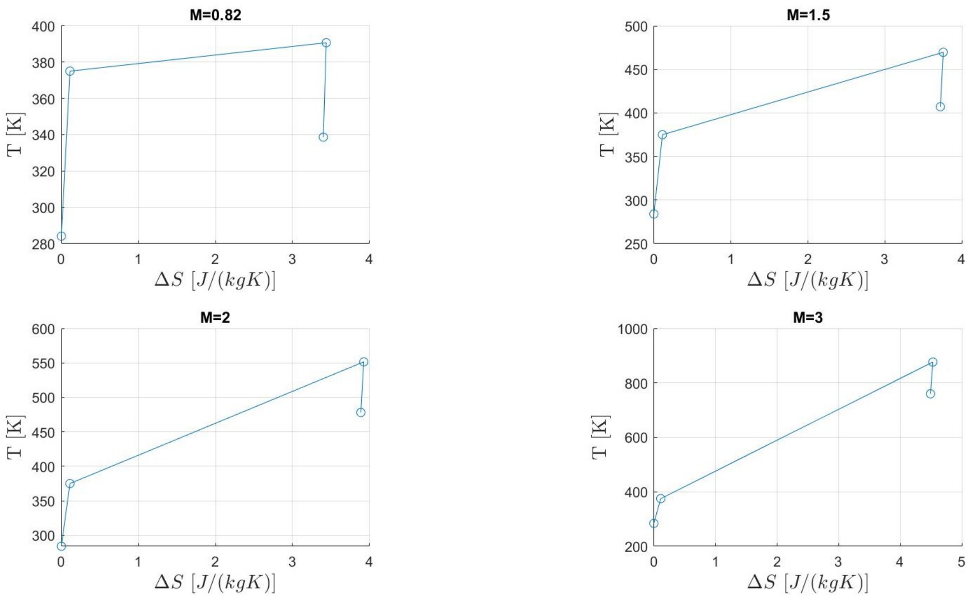


Figure 5.33 – Thermodynamic cycle – Transonic and supersonic flight conditions.

The powers supplied by the turbine and required by the compressor are shown below.

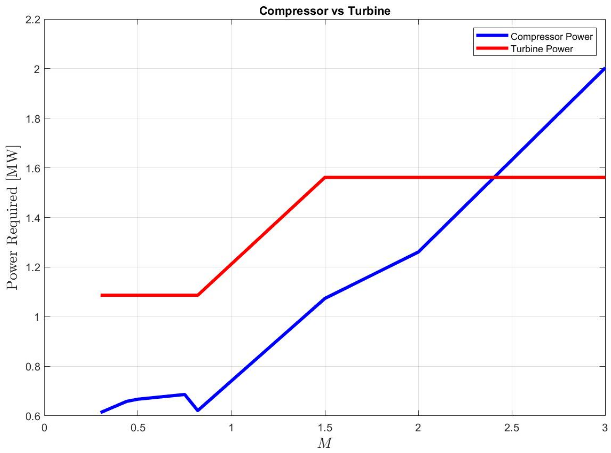


Figure 5.34 – Power Required – Compressor vs Turbine.

The graph clearly shows how the turbine is able to generate sufficient power to move the compressor up to Mach 2. However, in the last supersonic phase, i.e. the one that goes from Mach 2 to Mach 3, the power delivered by the turbine is not able to move the compressor. It therefore seems that there is a need to integrate the power margin.

This is true if is supposed to use a single ACM unit capable of generating the required powers, which would require the development of aeronautical technology that is able to meet particular requirements, namely the delivery of a good 2MW of power.

In conventional aircraft there are 2 ACMs with a typical power of 0.5MW each. Therefore, rather than using a single unit to be invented from scratch with a useless waste of money, it is possible to use 4 ACM units connected in parallel to be able to develop a total of 2MW.

In this way two problems at the same time are solved:

- It is not necessary to develop new technology;
- The turbine is able to move the compressor up to Mach 3.

The following is the operating diagram of the open cycle-

The elements present in the loop have been described previously, except for:

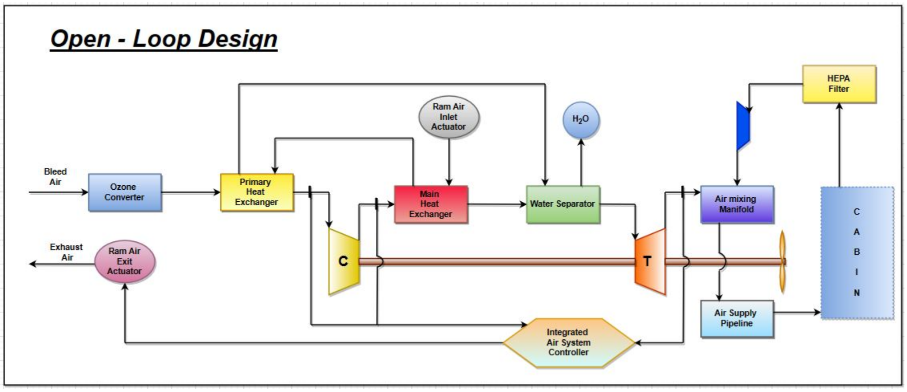


Figure 5.35 – Open-Loop Design.

- Ozone Converter
- HEPA filter

The ozone converter is used to remove ozone from the bleed air system. While High-efficiency particulate air (Hepa) filter [36] is composed of microfiber filter sheets (generally in borosilicate) assembled in several layers, separated by aluminum septa. The microfiber filter sheets have the task of blocking the polluting solid particles (or particulates) present in the fluid stream to be treated. [36] In summary, they eliminate the impurities present in suspension in the air taken from the cabin.

In summary, the characterization of the Open-Loop cycle does not differ much from the ECS operating system for conventional aircraft, except that, in order to guarantee the necessary power margin in the supersonic, it is necessary to have 4 ACMs. In conventional aircraft, only 2 are used, one of which is redundant.

This obviously entails an increase in the weight of the ECS system but above all the abortion of the mission in case one of the 4 does not work, as 3 of them would guarantee correct functioning only up to Mach 2. One solution may be to use another ACM, but this would significantly affect the cost and weight of the overall system. Another solution, certainly simpler to implement, is to adjust the input parameters of the air flow within the open cycle.

Going to reduce the temperature and pressure of withdrawal from the engine area by 80%, it is possible to obtain a reduction in the maximum power required of about 20%. This brings undisputed advantages in terms of costs and above all in terms of inertia at stake. First of all, there is no longer a need to integrate power margin, as the turbine is able to move the compressor up to Mach 3 (Fig. 5.36) And above all, there is additional margin to continue moving the recirculation fans installed in the cabin. As a consequence of the above, it is possible to think of using 4 ACMs, with the substantial difference that, in this case, there would be a redundancy necessary to guarantee the correct functioning of the system and therefore the success of the mission.

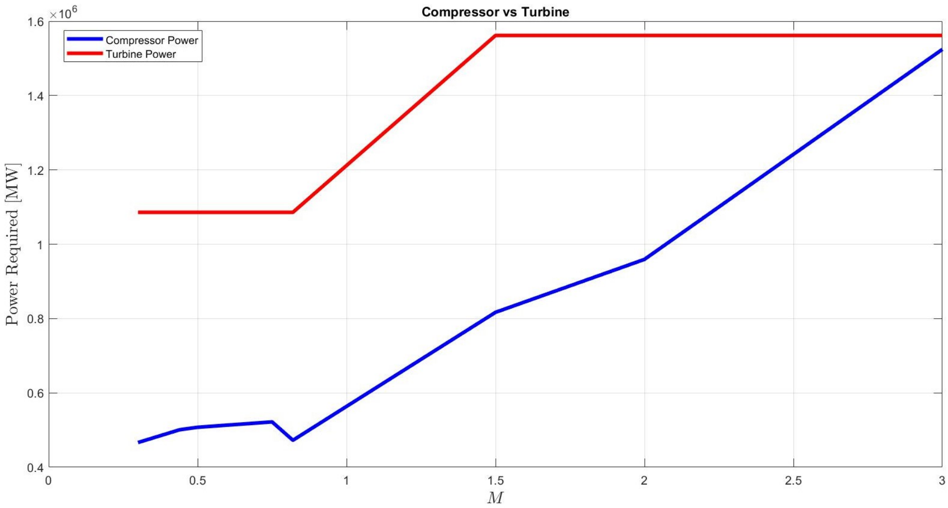


Figure 5.36 – Compressor vs Turbine after adjustment.

The transitional phase from Open Loop cycle to Closed Loop cycle, i.e. the one that goes from Mach 3 to Mach 4, allows to store a certain amount of air that will compensate for any internal losses of the closed cycle, but above all it allows to keep the oxygen content circulating in the system, since, as already mentioned, it is not possible to drop below 18% of the oxygen concentration.

The possibility of using oxygen tanks was discarded first of all for safety reasons for passengers on board and secondly for costs.

Safety is linked to the high oxidizing power of oxygen: a small trigger is enough to immediately ignite the entire tank and consequently the interior of the aircraft. In the literature there are cases of space disasters due to the use of pure oxygen. The first documented case concerns Apollo 1. This is the first manned mission of the Apollo program, planned to be the first Low Earth Orbit test of the command module. However it never flew due to a fire in the cabin. The board was not able to determine the specific initiator for fire, but it identified the conditions that lead to the disaster [37]:

- A sealed cabin, pressurized with an oxygen atmosphere
- An extensive distribution of combustible materials in the cabin
- Vulnerable wiring carrying spacecraft power
- Vulnerable plumbing carrying a combustible and corrosive coolant
- Inadequate provisions for the crew to escape
- Inadequate provisions for rescue or medical assistance

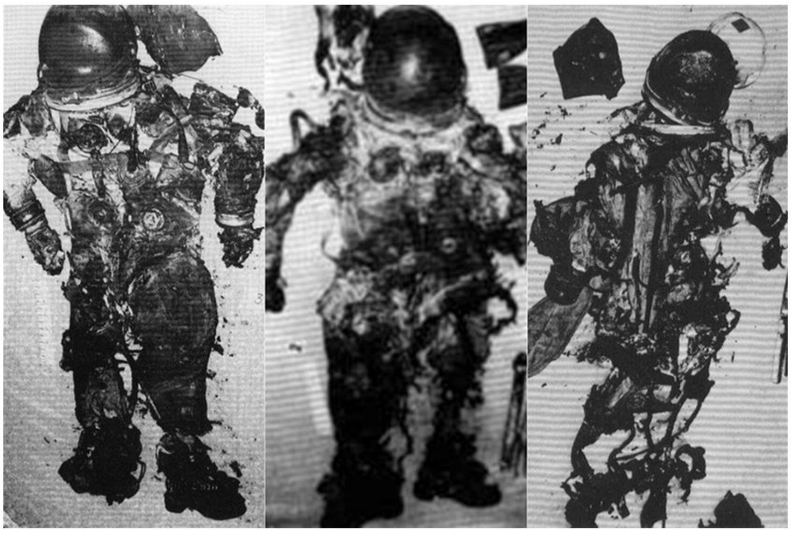


Figure 5.37 – Remains of the charred bodies of the Apollo 1 crew.

NASA could have taken the risk, being a military crew, however it is too high and unacceptable for a civilian crew to take.

Another excessive risk is that which the airline would incur should a disaster arise: the purchase of a plane ticket establishes a contract between the airline and the passenger which establishes that the latter must arrive at their destination alive. According to the Montreal Convention, the agreement on the rules of international air transport provides, in the unfortunate hypothesis that a plane crashes causing the death of its passengers, that the airline is obliged to proceed with compensation of approximately 126 thousand euros per victim [38] . Which, in the case of the STRATOFLY MR3 aircraft, amounts to approximately 37 million and 800 thousand euros. Not to mention that, being a hypersonic transport aircraft, the expense per passenger, in the event of a disaster, will probably increase as a result of higher insurance costs.

For these reasons it was therefore preferred to use a supply tank with inert mixture air directly taken in the flight phase between Mach 3 and Mach 4.

In the closed loop there are some elements to analyze.

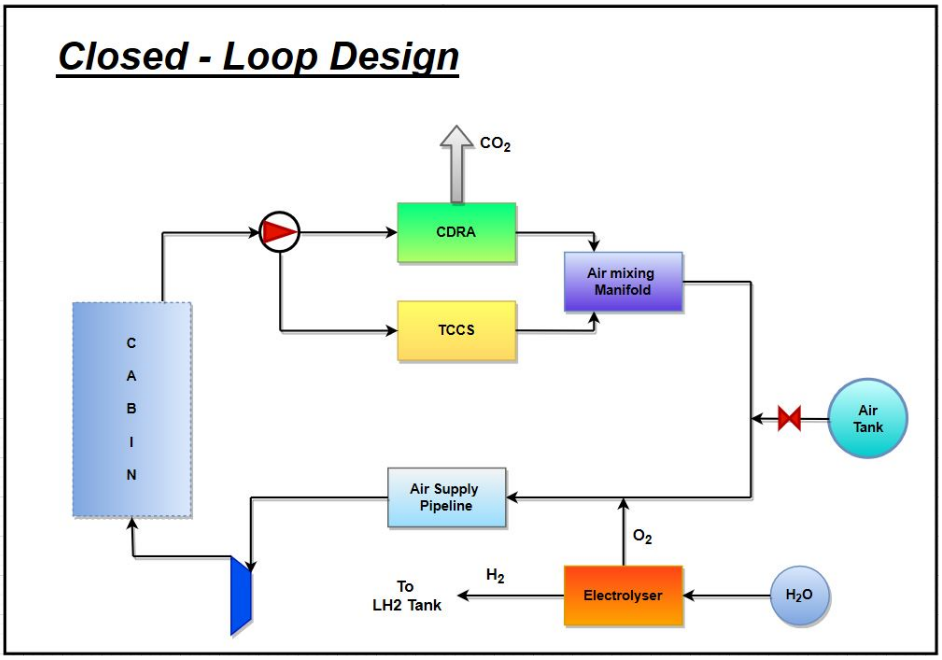


Figure 5.38 – Closed-Loop Design.

First of all the presence of an Air Tank. It is a tank with a capacity equal to 20% of the internal volume of the cabin that is completely filled with air in the transient acceleration phase ranging from Mach 3 to Mach 4, that is, when the Open-Loop starts to close.

This solution is linked to the fact of making up for any losses that may exist in the closed loop ducts and to introduce air with a certain oxygen content (about 20%) The need to introduce clean air is also linked to the presence of *Carbon Dioxide removal Assembly* (CDRA).

It maintains the cabin's carbon dioxide partial pressure within the allowable range in order to maintain passengers and crew health. Its primary component include 4 adsorbent beds, a blower, an air save pump, and 6 selector valves. Cabin air enters the CDRA in the range of $19.5 - 40.8 kg/h$ and after the process the carbon dioxide adsorbent bed is evacuated by a pump, heated to 204^oC, and exposed to external atmosphere. [15]

Consequently, expelling carbon dioxide expels the oxygen present in the air and therefore during the performance of the mission there is a risk of going below the percentage of O_2 allowed. CDRA requires nearly $1kW$ of power.

Hereafter is shown schematically the CDRA process diagram

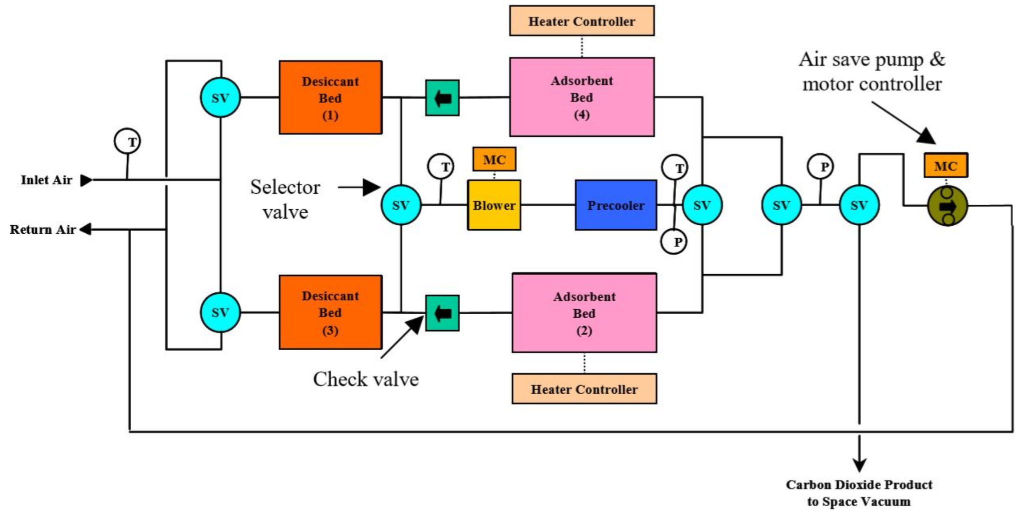


Figure 5.39 – Simplified CDRA assembly process diagram [15].

To make up for the lack of O2, as proposed by *Concordia University*, a *Molecular Sieve Oxygen Concentrators* (MSOC) can be used. This is a military technology which produces O2 from bleed air.

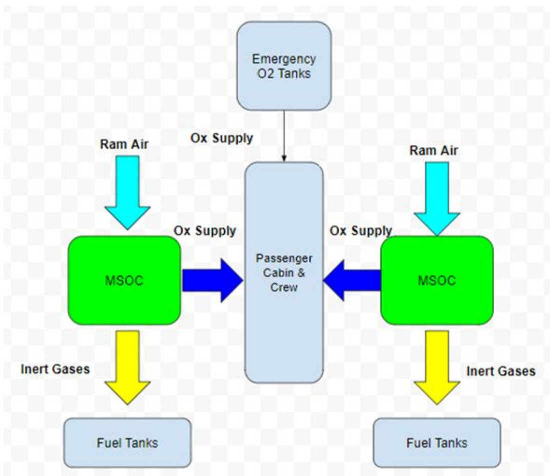


Figure 5.40 – Closed-Loop with MSOC [39].

The problem is that this system involves the use of O2 tanks. This solution was discarded for a simple reason, namely that bringing on board pure oxygen tanks enormously increases the risk associated to a critical failure: minimal leaks inside the ducts or malfunctions lead to instant oxygen combustion, causing the end of the mission and the lives of passengers. This would, ultimately, lead to an extreme increase in the airline's insurance costs.

Therefore, since this is a mission with civilian passengers on board, we prefer to avoid the presence of pure oxygen, preferring a more stable gaseous mixture.

The last element to be analyzed is the Trace Contaminant Control Subassembly (TCCS). It consists of a fixed bed containing granular activated carbon, a thermal catalytic oxidation reactor assembly and a fixed bed containing granular lithium hydroxide. It removes acid gaseous oxidation products from the process air stream. [15]

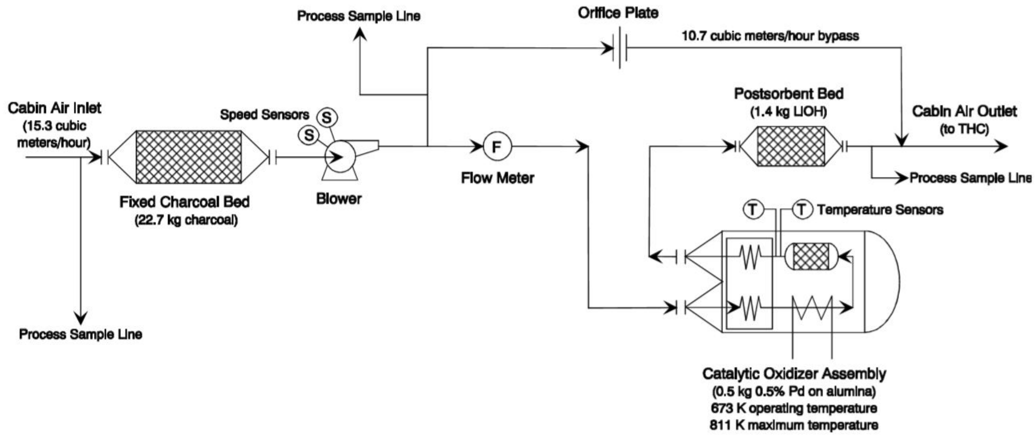


Figure 5.41 – Simplified TCCS process diagram [15].

TCCS requires approximately 167 Watts of power at 100% duty and an average of $120 Watts$ of power under normal operation. [15]

Chapter 6

Conclusion and future developments

This work was carried out in order to identify one of the possible innovative solutions capable of guaranteeing the survival of a crew on an aircraft flying at hypersonic speeds. The need is due to the world trend: traditional air routes are starting to be more and more saturated, as a result we are looking towards layers of the atmosphere hitherto unseen by civil aviation, in particular the stratosphere. The stratosphere is the second of the five layers that make up the atmosphere and extends from $15km$ to $50km$ of altitude. Consequently, the STRATOFLY MR3 aircraft will fly, in its hypersonic phase, entirely in this area. Unlike the troposphere, in the stratosphere, around $20km$ of altitude there is a sub-layer known as the ozonosphere, therefore, unlike conventional aircraft, it is necessary to equip the ECS system with an Ozone Converter.

Altough it is made up of 3 Oxygen atoms, O_3, it has been found to cause various types of effects on the respiratory tract, in particular:

- Irritates the respiratory system
- Reduces lung function
- Aggravates asthma and other respiratory diseas
- Causes inflammation of cells' layer that lines the respiratory tract
- Reduces the immune system's ability to fight infections of the respiratory tree

It is therefore clear that it is not acceptable to allow ozone to enter the cabin, especially if the passengers include infants, the elderly and immunosuppressed. Despite this, we must not demonize this substance, as the absorption of ultraviolet radiation by the zone is essential for life on Earth, as it is a biologically harmful radiation that breaks the bonds of DNA.

Atmospheric pressure, as well as temperature, decreases with altitude. Temperatures in the cabin that are too low affect the normal thermoregulation of the human body, leading to a reduction in body temperature below 35^oC. This leads to hypothermia. It presents with intense chills and alterations of the state of consciousness (drowsiness, hallucinations and coma) and a reduction in the respiratory rate and heart rate, until cessation. For these reasons it is necessary that the environment in the cabin has a comfortable temperature for humans and, according to their physiology, settles at a temperature between $18 - 25^oC$.

A large reduction in pressure, such as that which the human body undergoes, which passes from $101300Pa$ on the ground, to about $11000Pa$ at hypersonic altitudes, causes pathological syndromes called hypobarotropies. The effects include a decrease in the partial pressure of oxygen and an increase in the volume of gases contained in the body's cavities. This latter effect hinders the pressure compensation between the external and internal walls of the tympanic membrane, which undergoes an outward bending until it breaks. While the decrease in the partial pressure of oxygen causes anoxia, insufficient oxygenation of the tissues due to poor oxygen supply and therefore, death.

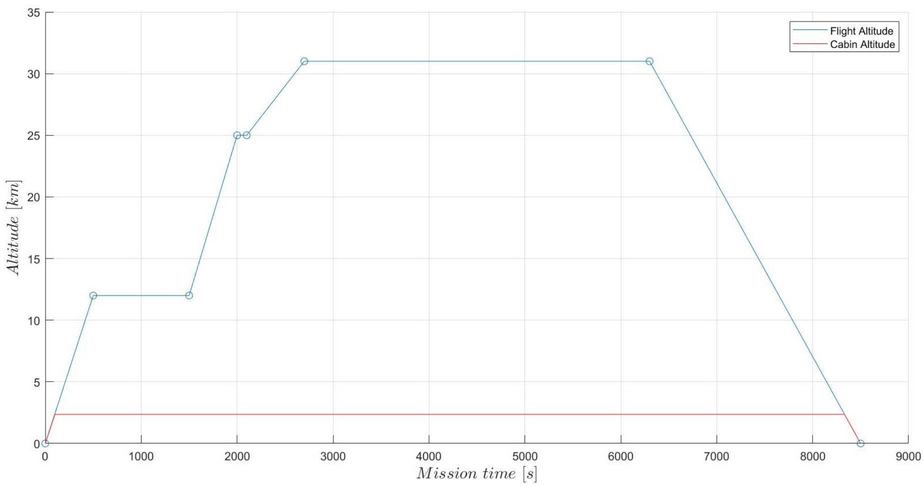


Figure 6.1 – Cabin Altitude compared to flight altitude.

Therefore, in order to guarantee the success of the mission, a pressurization of the cabin is required. Pressurization involves the generation of forces normal to the internal surface of the booth that strain the material. These forces are all the higher the more marked the pressure gradient between the inside of the cabin and the outside is marked. A compromise must therefore be found between human and structural needs. For this reason it was decided to pressurize the cabin to $75000Pa$. This implies that the aircraft flies at its cruising altitude, while the cabin is as if it were at about $2.36km$ of altitude.

Therefore, the Air Cycle Machine (ACM) must be able to process the air in such a way as to guarantee the mentioned pressure and temperature levels.

Considering the flight regimes in which the closed-loop system operates, a maximum heat flow at deck side has been identified equal to $9.98MW$ in cruising conditions, Mach 8. The most critical values occur upon entry into the hypersonic phase, i.e. Mach 5, in which the temperature values are approximately 64.5^oC, which requires a maximum flow rate of $11.2kg/min$ per passenger to be disposed of. The presence of the liquid hydrogen layer as an insulator, in the walls of compartments 3, 5 and 6, causes the temperature reduction inside by 13% which leads to a lower demand for air flow equal to about 21%.

The considerations on the open cycle are carried out by taking into consideration the minimum average values of flow rate for subsonic flight and the average values for supersonic flight, thus obtaining in one case $14.86kg/s$ and in the other case $21.37kg/s$. Through this information it is possible to determine the powers involved, in particular the compressor group can require, in the most critical condition at Mach 3, about$1.5MW$, while the turbine is capable of delivering about $1.58MW$, which is sufficient for handling the compressor and the recirculation fans in the cabin.

As far as the closed cycle is concerned, it is good to discuss future development possibilities. At present, the carbon dioxide extracted from the CDRA is released into the atmosphere, helping to increase chlorofluorocarbon pollution. The problem lies not so much in the journey itself, but rather in the future possibility that the air traffic of the STRATOFLY MR3 could increase so much as to make this additional CO2 pollution unsustainable.

Thanks to the studies carried out by NASA about the utilization of CO2 to produce life support consumables, such as O2 and H2O. This is crucial for deep exploration of space where re-supply options are nonexistent. The concept of Closed-Loop cabin Atmosphere Revitalization System (ARS) in the Space Shuttle, which includes the CDRA, Oxygen Generator Assembly

(OGA), Carbon Dioxide Reduction Assembly (CDRA), has become an integral part of NASA mission architectures for future long-duration human space exploration. [40] In ISS the CO2 is removed and vented into space, resulting in a net loss of O2. The idea to solve this problem is to store CO2 and use it into the Sabatier reactor for the methanation process, where CO2 reacts with hydrogen to produce methane and water:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \Delta H^o = -165kJ/mol \tag{6.1}$$

Here it is important to avoid the CO_2 reduction via the reverse water gas shift (RWGS) reaction, :

$$CO_2 + 2H_2 \rightarrow C_{(s)} + 2H_2O \tag{6.2}$$

Where solid carbon is produced, reducing the selectivity towards methane formation. Moreover Bosch reaction must be avoided for the same reason.

$$CO_2 + H_2 \rightarrow CO + H_2O \tag{6.3}$$

The water produced by Sabatier reaction can be collected and electrolyzed in order to form O_2 and H_2:

$$2H_2O_{(aq)} \rightarrow 2H_{2g} + O_{2_g} \tag{6.4}$$

Hydrogen can be recycled back to the Sabatier reactor for carrying out more CO_2 reduction, while methane can be stored and once the aircraft lands it can be used for domestic heating, electricity generation and so on. It is important to underline the impact of hundreds STRATOFLY MR3 that could sail the skies in the next future and so the amount of methane which could be produced.

It is feasible even now. The Sabatier reaction is exothermic and it is demonstrated that lower operating temperatures, around $250 - 400^oC$, are desirable for higher CO_2 conversion. These temperatures are available on board, so it is possible to use engine's heat in order to support the reaction. NASA has demonstrated that zeolites and molecular sieves coated on *Microlith* metal mesh elements can adsorb contaminants and so this is the future of DRA. The Microlith substrate consists of a series of ultra-short-channel-length, catalytically coated metal meshes with very small channel diameters.

In catalytic reactors involving exothermic reactions, such as the Sabatier process, enhanced heat transfer properties are necessary to eliminate local hot spots and temperature excursions at the catalyst surface, and to prevent catalyst deactivation due to metal sintering. [40]

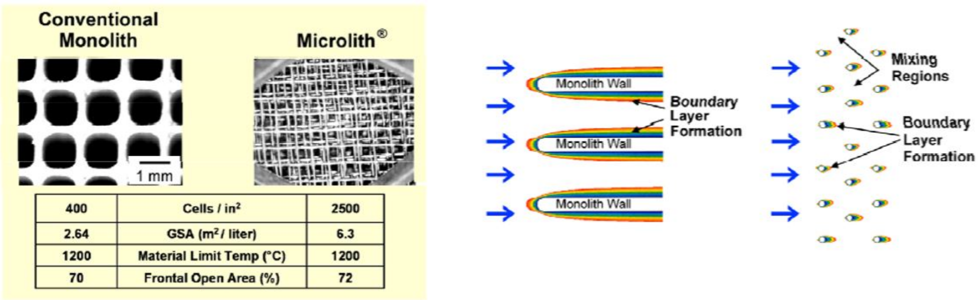


Figure 6.2 – Physical characteristics of conventional, long honeycomb and Microlith substrates. [40]

This process require about $1kW$ of power, while electrolysis about $18.5kWh$. Actually is not possible to say if these powers are available on board for these process. The discussion about it could be reopened when there will be a clearer idea of all the subsystems.

However it can be said that the technology to carry out a cycle of this type exists and is therefore achievable today. In light of this, the future Closed-Loop could be like this:

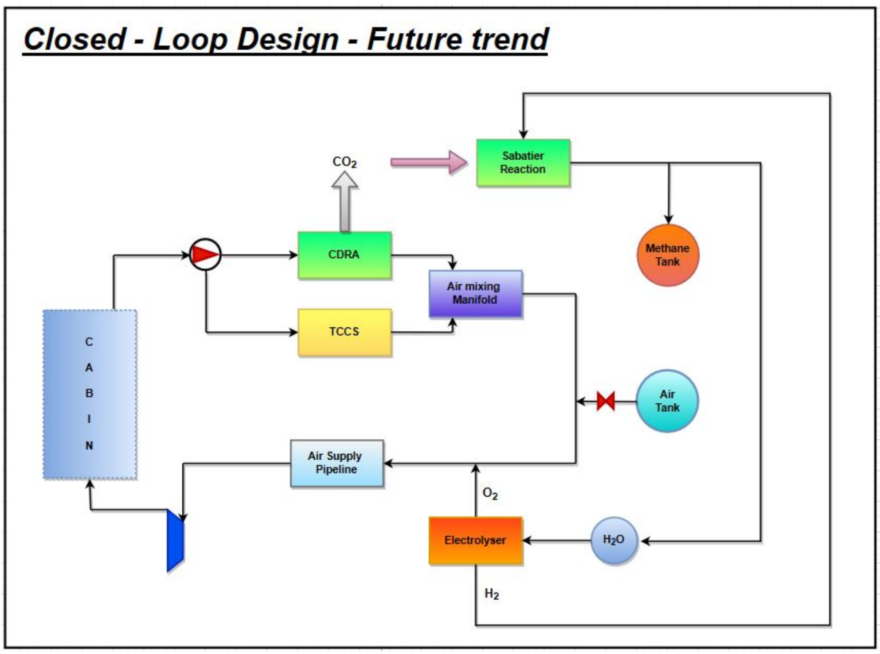


Figure 6.3 – Future ECS Closed-Loop

As soon as the MELiSSA Project will be able to definitively close the cycle, it will be possible to think of using bio-regenerative system that require less energy and have a much higher efficiency than the mechanical ones.

The tools developed and the results achieved in this Thesis could be used to further developments and assessment to be carried out within the STRATOFLY Project, such as the thermal evaluation on the fuselage, taking into account the possible aircraft's trajectories. The mathematical models can be further improved in order to simulate a wide range of real phenomena occurring in interaction between the winged body and the airflow, in order to analyze entirely the physical complexity.

In conclusion, the project STRATOFLY is an interesting and fascinating challenge to be faced especially considering that any small contribution from students, such as this Thesis would like to be, can be useful to the various engineers and researchers who spend their lives improving that of humanity.

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