THE HONG KONG POLYTECHNIC UNIVERSITY
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Department of Aeronautical and Aviation Engineering
航空及民航工程學系

# Introduction to Aircraft Systems

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# Environmental control system (ECS)/環境控制系統

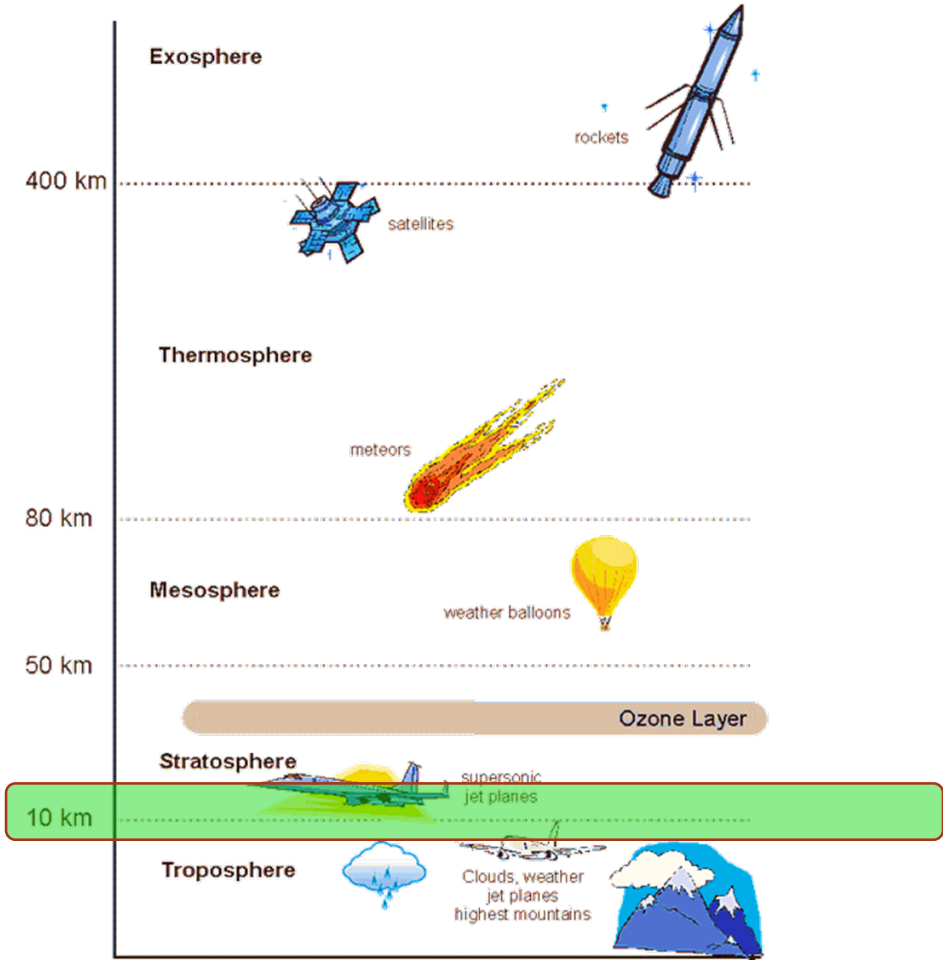
- Introduction
- Air conditioning
  - Heating system, cooling system, humidity control
- Pressurization
- Anti-g system
- Anti-icing and de-icing systems
- Anti-misting and de-misting systems
- Rain dispersal systems
- Summary

Packard-Le Père LUSAC-11, (1920, a modified French design, not actually pressurized but with an enclosed, oxygen enriched cockpit)

# Introduction

# The need for a controlled environment

- Commercial aircraft operate primarily in the **troposphere** and lower **stratosphere**.
- At such high altitude, the environment is quite **hostile** to life.




Typical operational height of commercial aircraft:

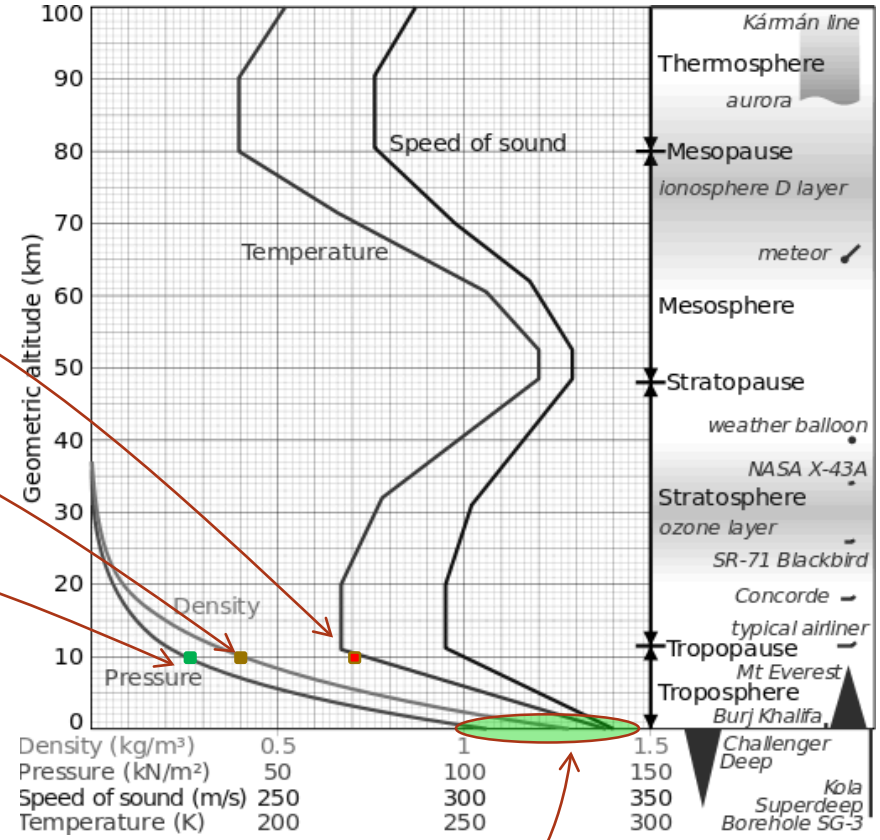
- Atmospheric property
- Number of aircraft…

# The need for a controlled environment

- Factors that are hostile for life due the high-altitude flight include:
  - Extreme environment conditions
  - Aerodynamic kinetic heating
  - Solar heating
  - Avionics heating load

# The need for a controlled environment

- Example of the atmospheric conditions
  - Outside temperature can be below -50°C
  - Density less than 16% of that at sea level
  - Ambient pressure can be less than 20 KPa
  - Air is very dry

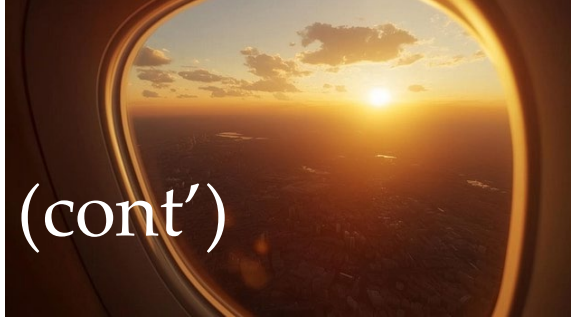



Common atmospheric condition for life

# The need for a controlled environment (cont')

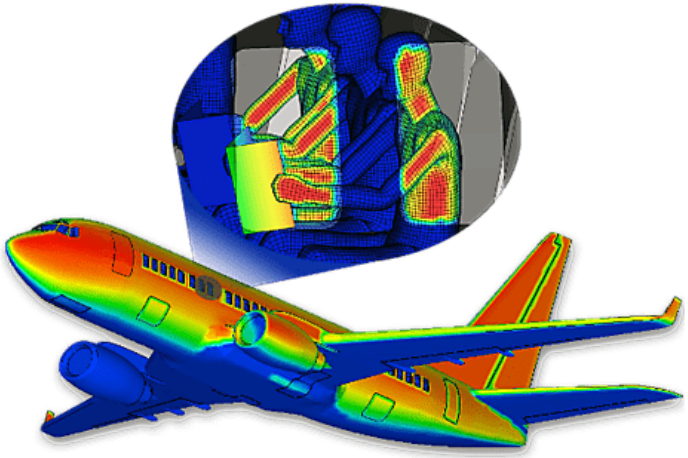
- Kinetic heating: the aircraft skin heats up due to the friction with surrounding air.
- It is also called the aerodynamic heating
- The skin temperature can raise up to 100°C or above at transonic speeds.
- The temperature can be higher with the increase of the flight speed
- The leading edge of the aircraft experiences the highest kinetic heating.

A schematic showing the aerodynamic heating of at the leading of the hypersonic vehicle



# The need for a controlled environment (cont')

- Solar heating: it can affect the thermal comfort for the passengers
- For military aircraft, solar heating can affect the cockpit directly through windscreen and canopy.
  - The aircraft is often designed to provide large transparent canopy to give the pilot good vision.
  - The solar heating can raise the internal temperature by 20°C



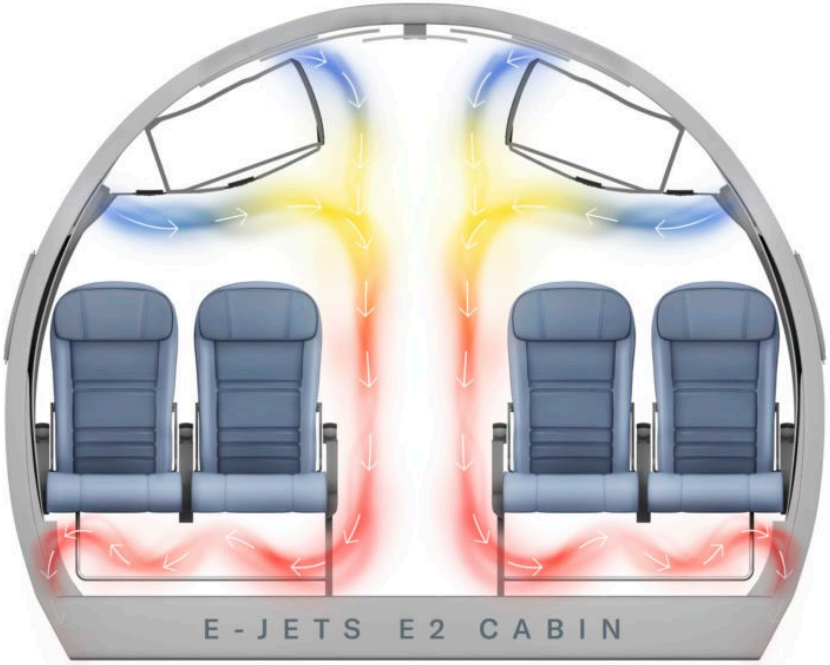
# The need for a controlled environment (cont')

- Avionics heat loads: the avionics system can generate heat continuously.
  - They should be cooled down to ensure the performance, and thus safety.
- Other aircraft systems, including the hydraulic systems, electrical generators, engines, and fuel systems also produce heat.
  - To maintain the efficiency and safety, the working conditions for these systems should also be maintained.

Cooling fans for the avionics systems

# The need for a controlled environment (cont')

- Cabin conditioning:
  - For civil aircraft, conditioning is provided to maintain comfortable environment for passengers and crew.
  - The air is ingested from overhead of the cabin and is extracted at floor level to reduce the risk of air flowing between passengers.
  - Filtration is required to remove the viral and bacterial contamination.



# The need for a controlled environment (cont')

- Equipment conditioning:
- Usually, equipment can be operated at a more tolerable environment than human.
  - Air conditioning systems typically provide maximum conditioned bay temperature of 70°C and minimal temperature of -30°C.
  - The equipment is often designed to work in a wider temperature range to avoid being damaged, e.g., from -40°C to 90°C
- But the long-time operation in such conditions can affect the reliability. Therefore, equipment conditioning is also needed.

# Introduction

- Through the aircraft operation, people in the cabin should be kept in a safe and comfortable condition.
- The environmental control system (ECS) deals with the requirements in the cabin
  - Ventilation, temperature, humidity, pressure

Air conditioning pressurization

- ECS also provides **cooling** for avionics bays, heat transfer from hydraulic and fuel systems.
- ECS also contributes to **de-misting**, **anti-icing**, **anti-g** and **rain dispersal** services, etc.

# Air conditioning/空調系統

# Air conditioning

- Air conditioning system covers to the requirements in **ventilation/通風**, **temperature/溫度**, and **humidity/濕度**.
- At low flight attitude, e.g., below 10,000 ft, air conditioning alone is enough for the environmental control.
- At high light attitude (above 10,000 ft), pressurization is required to ensure the needed **pressure** and **oxygen** for breathing.

We will introduce pressurization later

# Humidity control

- Humidity control is related to:
  - Passenger comfort.
  - Prevent damage to electrical and electronic equipment
  - Reduce the need for windscreen de-misting.
- Fine mist of water droplets in cold cabin inlet supply should be coalesced into large droplets that can be trapped/drained away.
- Water separators are in common use to remove the waters.
- Sometimes, water collection devices can be used in vapor cycle refrigeration systems to reduce humidity levels

# Ventilation

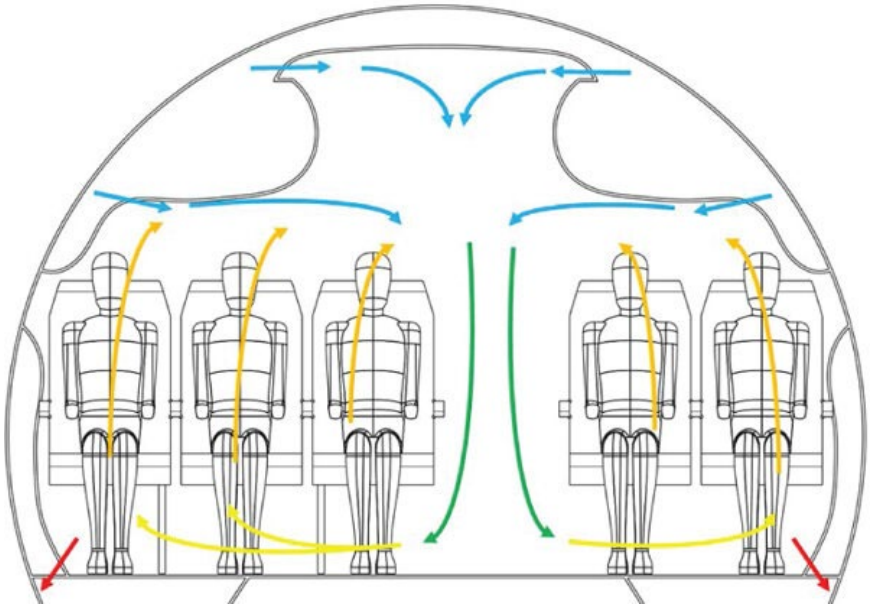
- Ensure breathable air for passenger or crew
  - Prevents hypoxia/缺氧: ventilation mixes fresh air with recirculated cabin air to main a safe oxygen level
  - Removes $CO_2$ buildup: FAA requirements (below 5000 ppm-parts per million)
- Controls humidity & prevents discomfort
  - Prevents dry air issue
  - Reduces contaminants
- Control temperature & heat load
  - Dissipates the heat from avionics, solar heating and aerodynamic heating

Exhaled $CO_2$ :
- Drowsiness
- Headaches
- Loss of consciousness

- Dusts
- Microbes
- Volatile organic compounds

# Ventilation

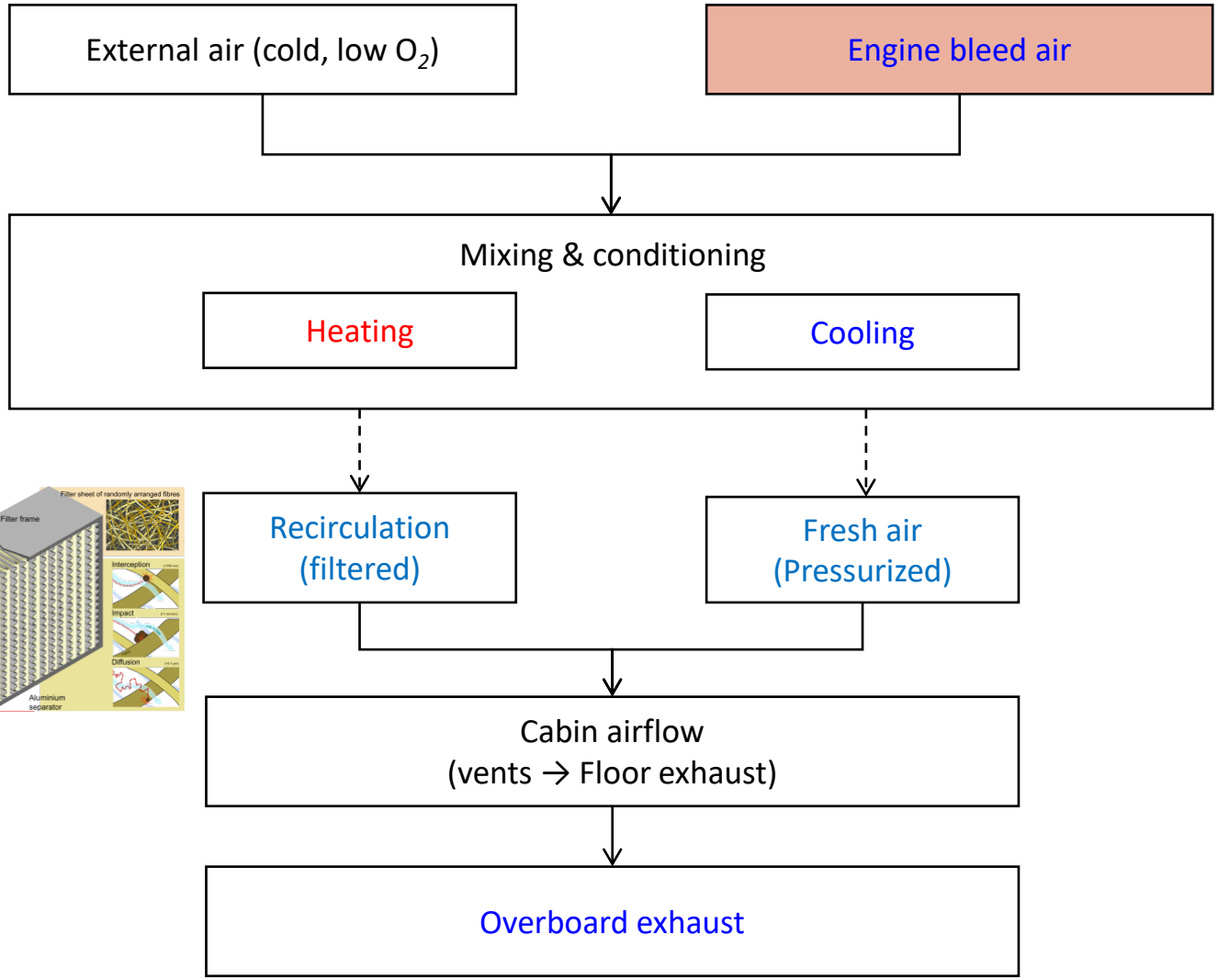
- Prevents fogging & condensation
  - The airflow can prevents fogging on window and avoid electrical short circuits
- Mitigates smoke and hazardous gases
  - In case of fire, remove smokes to maintain visibility and remove toxicity
  - Filters out the fuel vapors
- Reduces spread of airborne pathogens
  - Removes bacteria/viruses

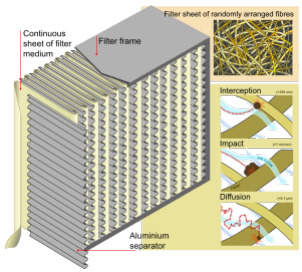


# Sources of air used for conditioning

What are the sources of air to achieved this functions?

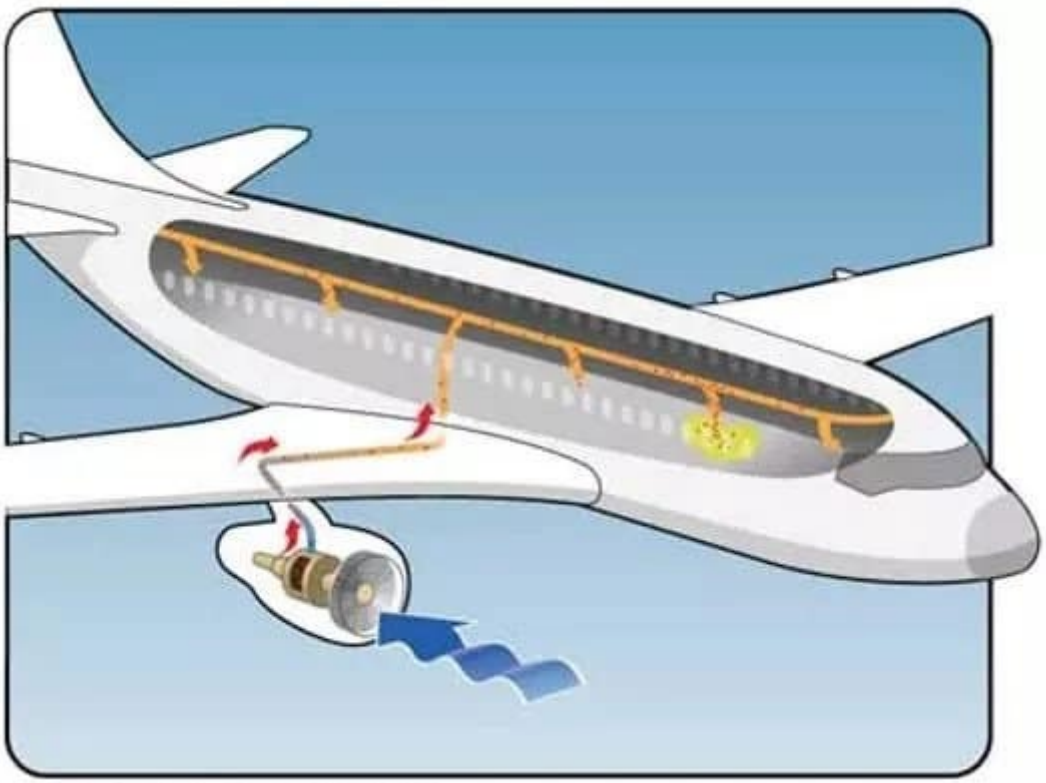
# Air in the conditioning system: schematic



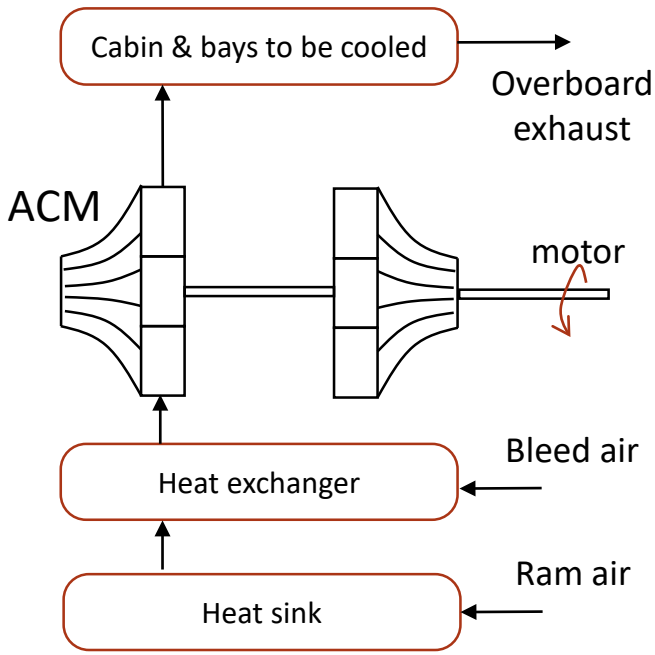
# Engine bleed air

- The major source of conditioning air is engine bleed from high-pressure compressor.
  - It is also used for cabin pressurization.

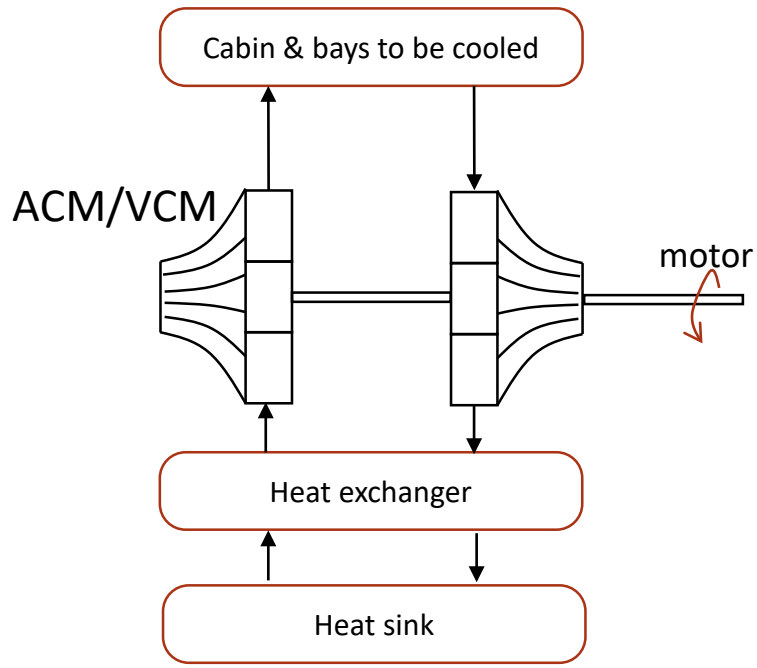


# Engine bleed air

- The bleed air system can be classified to two types:
  - Open system: it provides large amount of air from engines, refrigerate it and then use it in the cabin.
  - Close system: it collect the air that has been used for cabin conditioning. The collected air is refrigerated and recycle to the cabin.




Open system



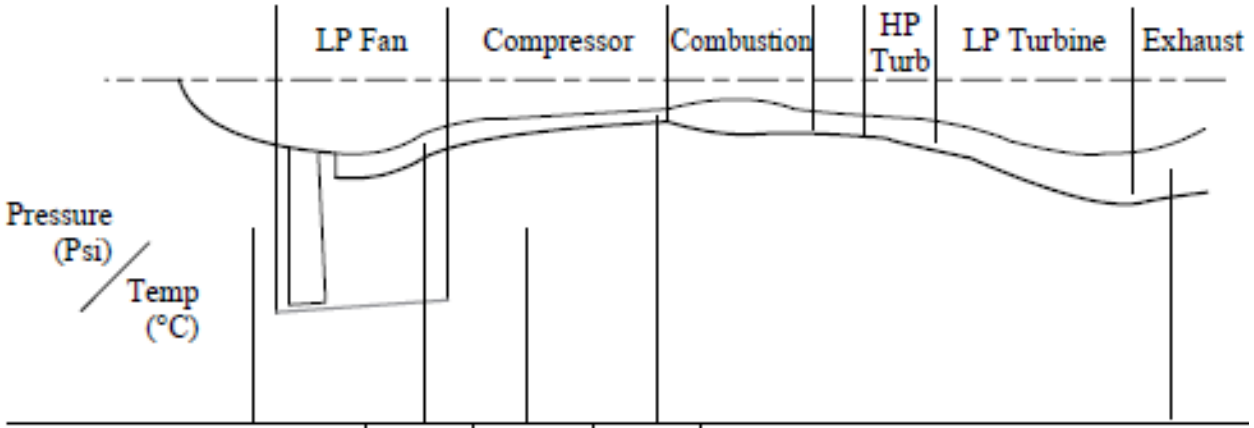

Close system

# Engine bleed air

- For close system, less bleed air from the engine is needed, and the engine thrust performance will be higher.
- However, the application is still limited
- The recycle process requires sealing and pressurization.
- Extra fans will still be needed to realize the recirculation.
- Heavier and more expensive than open systems.

# Air source in aircraft: engines

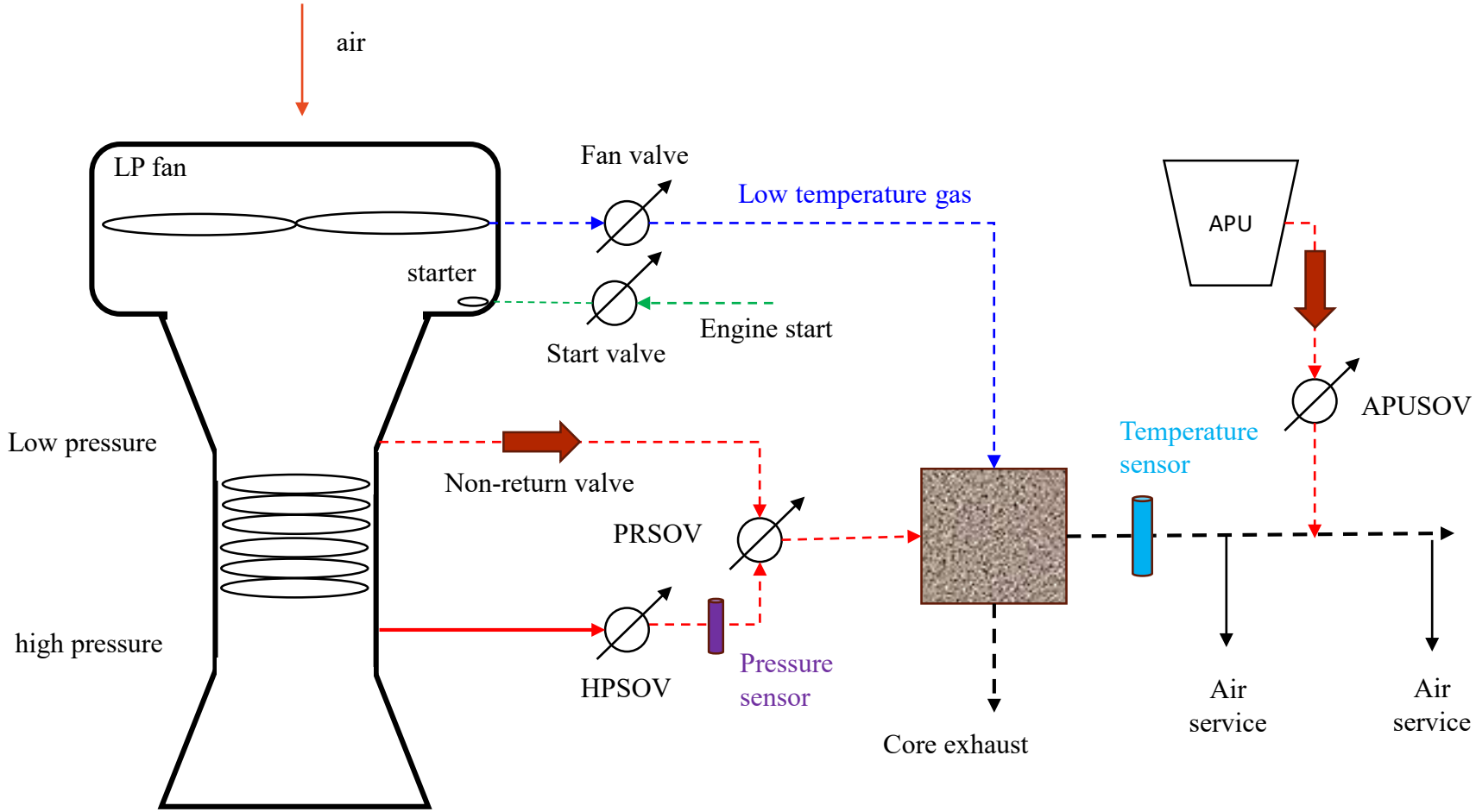
- The engine provides the high-pressure, high-temperature air.




| | | | | | |
|---|---|---|---|---|---|
| Idle | 14.7/15 | 16/20 | 15/16 | 50/180 | 14.8/340 |
| Take-Off | 14.7/15 | 39/115 | 25/65 | 410/540 | 23.0/510 |
| Cruise | 5.3/–25 | 14/60 | 8.5/15 | 150/400 | 6.8/340 |

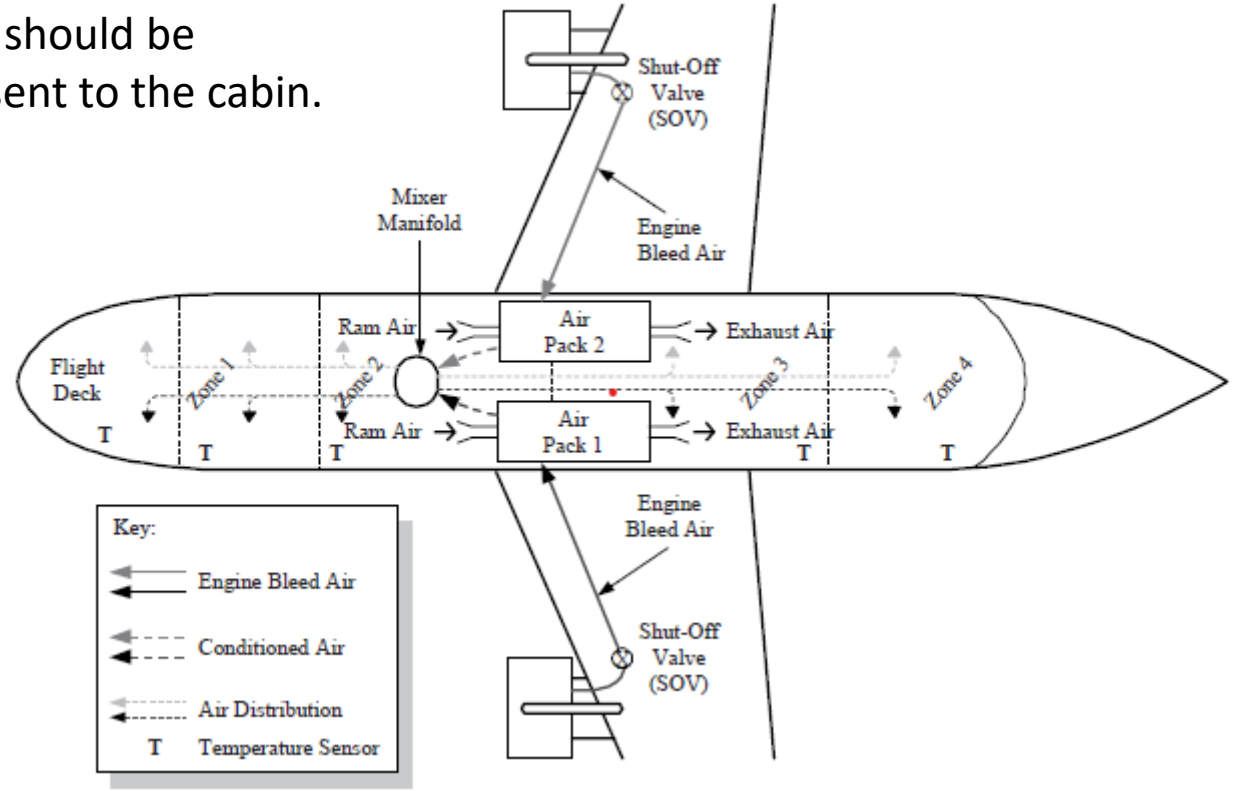
Typical air property in a modern turbofan engine

# Engine bleed air control



# Cabin temperature control system

Once the pressure of the bleed air is reduced & modulated by the pressure valves, the temperature should be regulated before being sent to the cabin.



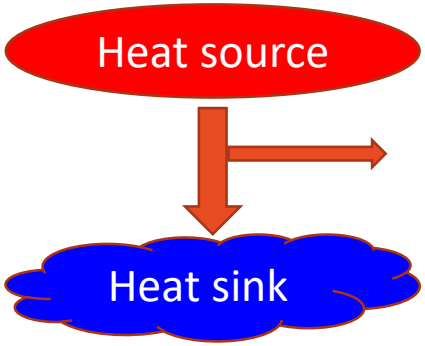
Note: Typical (relative) humidity level in cabin is around 10-20%, being lower than in buildings. (U.K. Civil Aviation Authority)

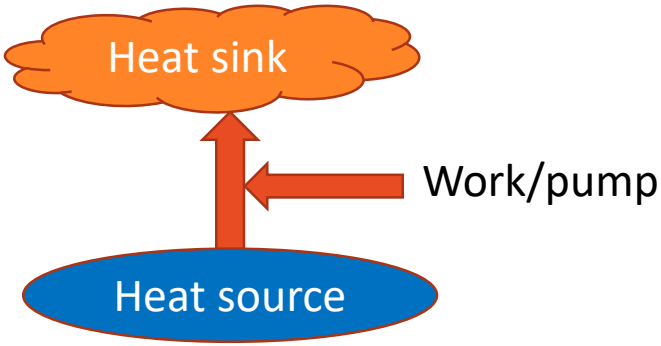
# Air conditioning

- Representative range for a comfortable environment:
  - Ventilation rate: about 0.45kg air per person per minute
  - Temperature: 18-24°C
  - Relatively humidity: 40-70%
- As the aircraft is operated different levels, the air conditioning system should:
  - Warm up the extreme cold air to an acceptable level: heating system
  - Cool the hot humid air to an acceptable level: cooling system

# Cooling & heating system

- The cooling problem is to remove heat from (high-temperature) sources to heat sinks and eventually reject them from the aircraft.
- Heat sinks could be:
  - Ambient cold air:
    - it can be used directly as ram air;
    - or indirectly as the air bled from the engines.
  - Internal fuel
- Sometimes, heat pumps are needed if the heat sinks have higher temperature: refrigeration



# Cooling & heating system

- Heat is taken from the heat source, the temperature is reduced.
  - The heat source will be cooled
- Heat is rejected to the heat sink, the temperature is increased.
  - The heat sink will be heated

Both processes are necessary. For example, for the air supply to the cabin, the temperature should be adjusted.

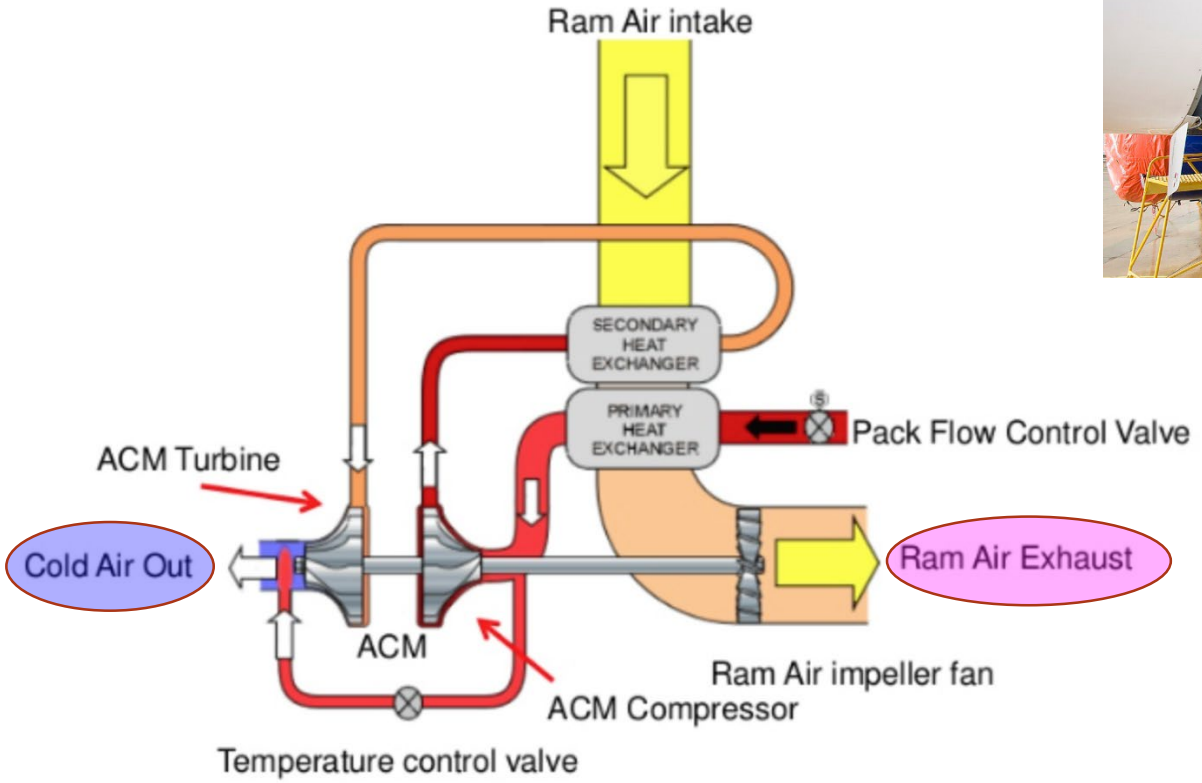
- Very cold ram air should be heated
- Very hot engine bleed air should be cooled

# Heating system

- Heating is relatively straightforward.
- For light aircraft with only ventilation and ram air heating systems, the hot air is supplied by the exhaust gas from engines.
- For aircraft at higher altitude, the ambient air is heated up by gases from turbine compressors or other devices, depending on the design.
- The moderated air is distributed to the cabin.

# Heating the ram air

ACM (air cycle machine) is a refrigeration unit of the ECS in an aircraft. The cooled air is often used for cabin ventilation or electronic equipment cooling.



ACM aboard a Sukhoi superjet 100

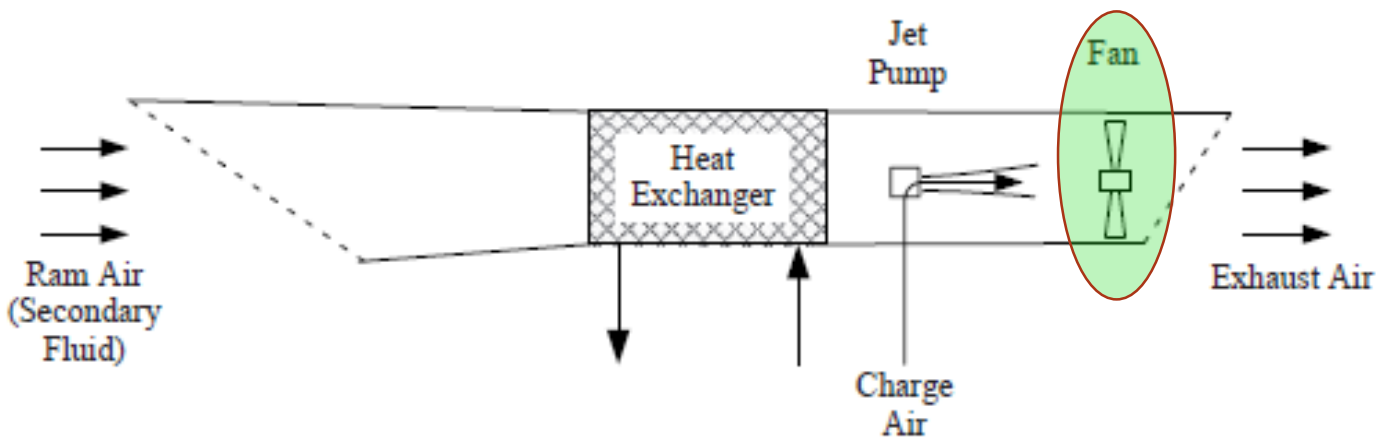
Hot engine bleed air

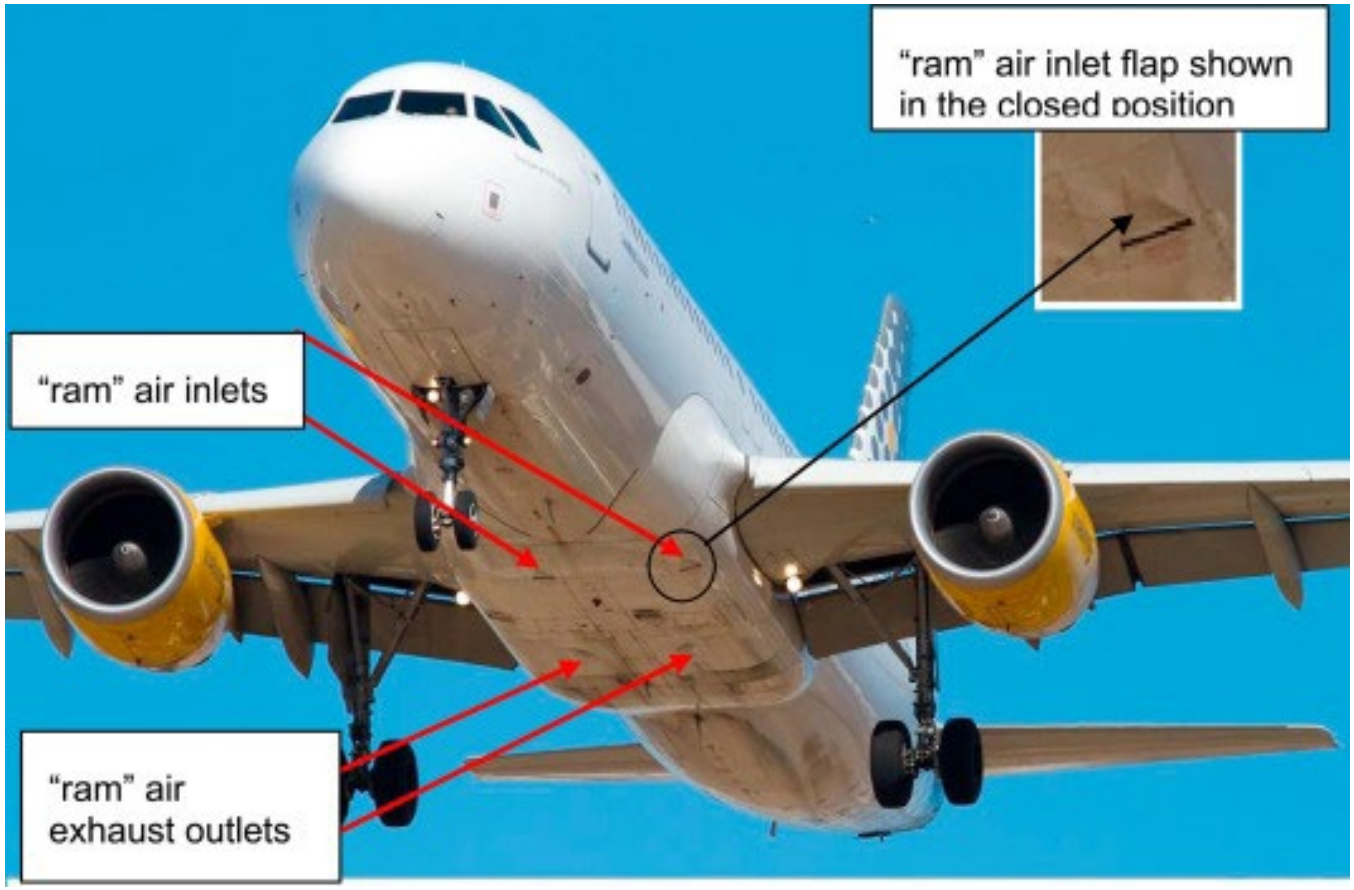
Ram air as heat sink

# Ram air cooling

- Ram air cooling is to remove the aircraft heat to the (ram) air around it.
- Factors that can affect the ram air cooling:
  - The drag could be increased.
  - The ram air temperature increases with flight speed, i.e., kinetic heating
  - At high altitude, the air density decreases, making the heat capacity low
- In practical designs, fans are induced to enhance ram air flow

e.g., at Mach 0.8 at sea level, the ram air temperature can reach 80 °C



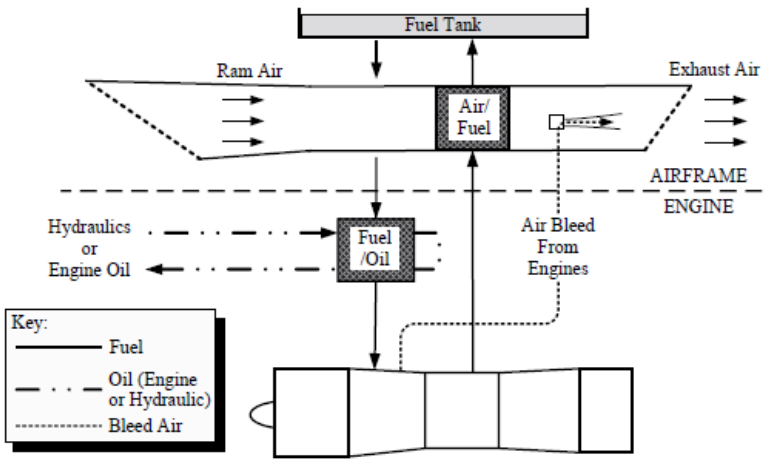



S. Wright et al., Thermal Sci. Eng. Prog., vol. 7, p. 184-202, 2018

Fuel as heat sink

# Fuel cooling

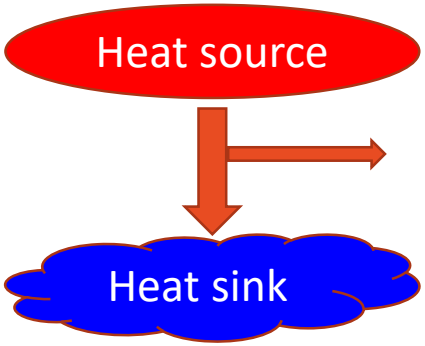
- Fuel is another possible heat sink in aircraft.
  - It has higher heat capacity than air
- But in practice, the applications is limited since:
  - Fuel amount varies during the flight
- It is mainly used to cool:
  - Engine oil
  - Hydraulic oil
  - Gearbox oil



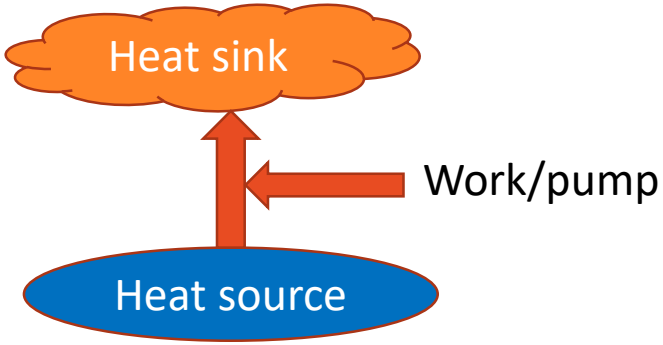

When the fuel flow is low, the fuel temperature will rise significantly, so the return lines are used to pipe the hot fuel back into the fuel tank. Ram air cooled fuel coolers often need to be introduced into the return flow lines to prevent a rapid increase in fuel temperatures in the tank when fuel level is low.

# Cooling of air

- In aircraft application, approaches based on ram air cooling or fuel cooling are not sufficient.
- We need not only to reduce the temperature of hot bleed air or remove the heat during operation. We also need to control the temperature of the cabin air.

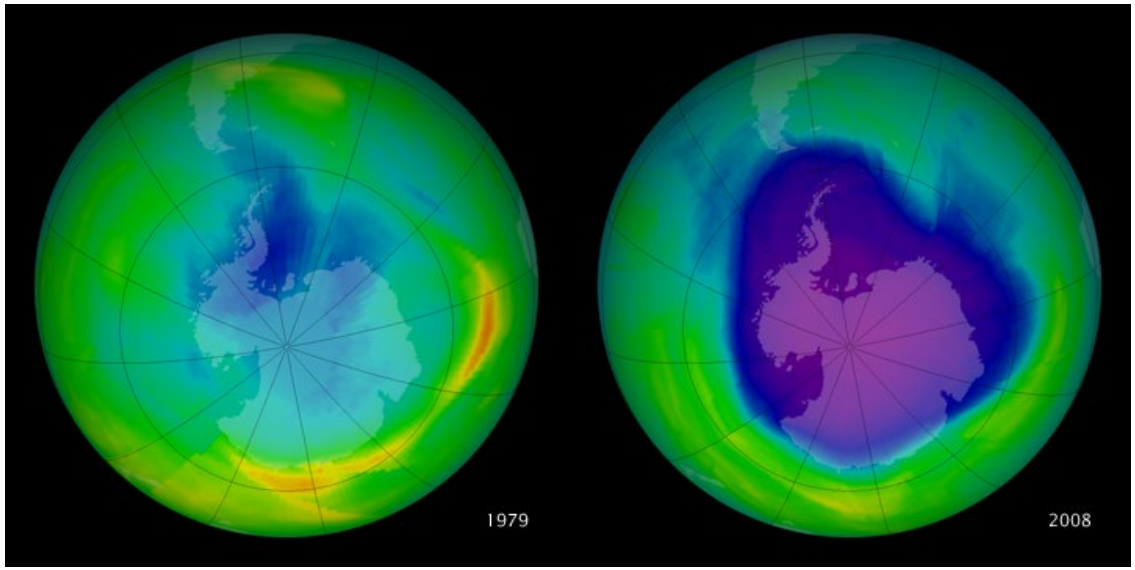



- Cooling of air can also be achieved by the refrigeration process. Two types of refrigeration:
  - Air cycle refrigeration or Air cycle machine (ACM)
  - Vapor cycle refrigeration or Vapor cycle machine (VCM)



# Cooling of air: VCM

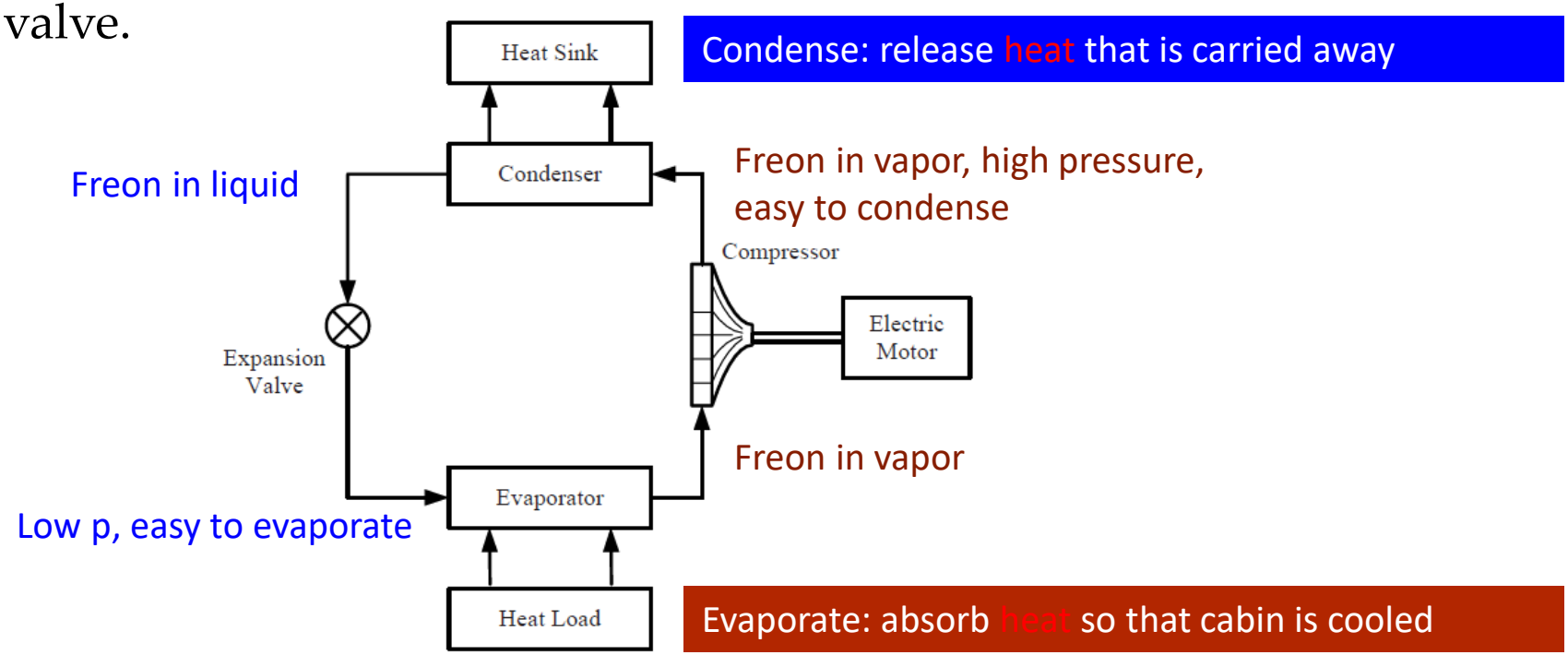
- A vapor cycle refrigeration system is a closed system where the heat is absorbed by the evaporation of a liquid refrigerant/製冷劑, e.g., Freon/氟利昂
- It should be noted that chlorofluorocarbons (CFC) endanger the ozone layer and are the subject of much debate calling for a limitation in their use



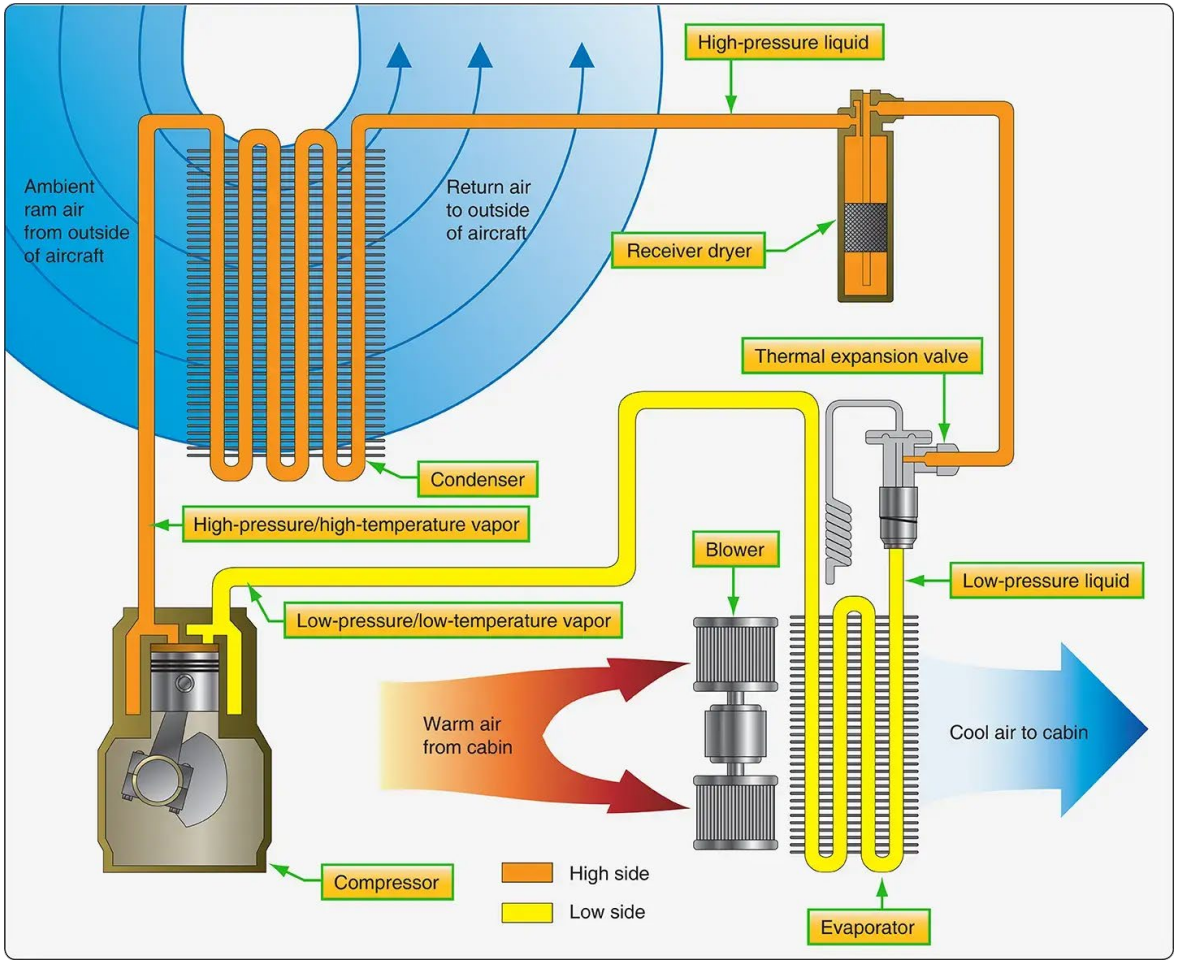

Ozone hole increased

# Cooling of air: VCM

- The refrigerant, e.g. Freon, passes through a compressor where pressure and temperature are increased.
- Then it is cooled down in a condenser where the heat is rejected to a heat sink.
- The refrigerant flows back to the evaporator via an expansion valve.



# Cooling of air: VCM



Thomson-Joule effect: the temperature change due to the gas expansion

# Cooling of air: ACM

- In air cycle refrigeration systems:
  - Heat is removed by a heat exchanger from compressed air, which performs work by passing through a turbine that drives the compressor.
  - Air passing the turbine expanses, reducing the temperature
  - Energy is transferred from internal energy to mechanical energy, i.e., turbine motion
- An air cycle refrigeration system is also called a Cold Air Unit (CAU). Several common CAU types are:
  - Turbofan
  - Bootstrap
  - Brake turbine

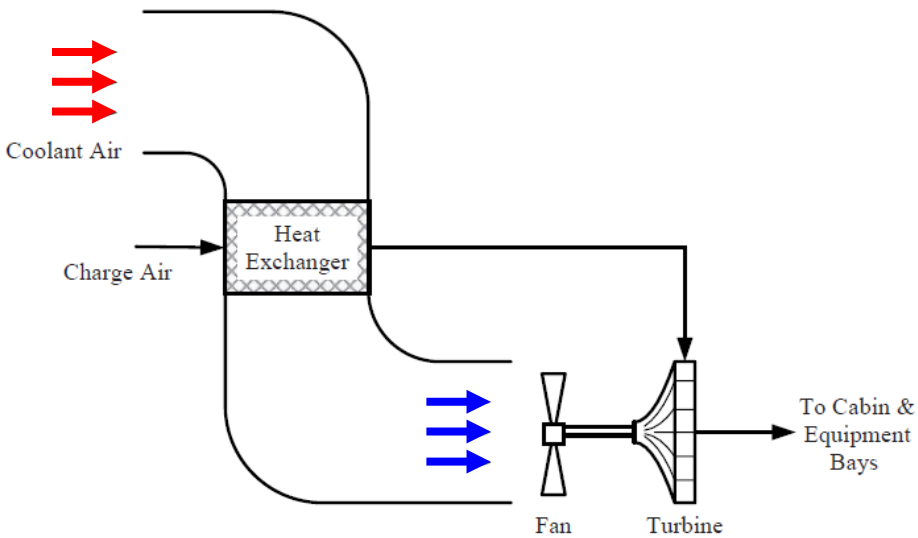
ACM is the simplest solution to cool the engine bleed air down the temperature required for cabin.

# Cooling of air: ACM

The air cycle machine aboard a Sukhoi Superjet 100

# Turbofan cooling system

- The turbofan cooling system is typically used in low-speed civil aircraft where the temperature is not very high.

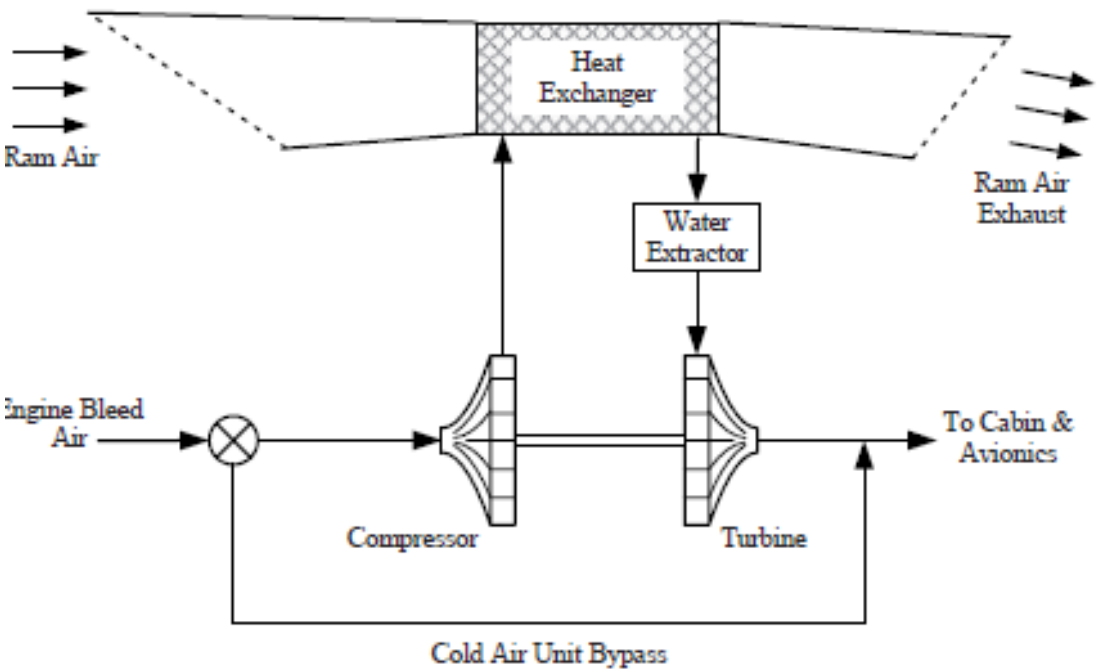



Heat → mechanical energy

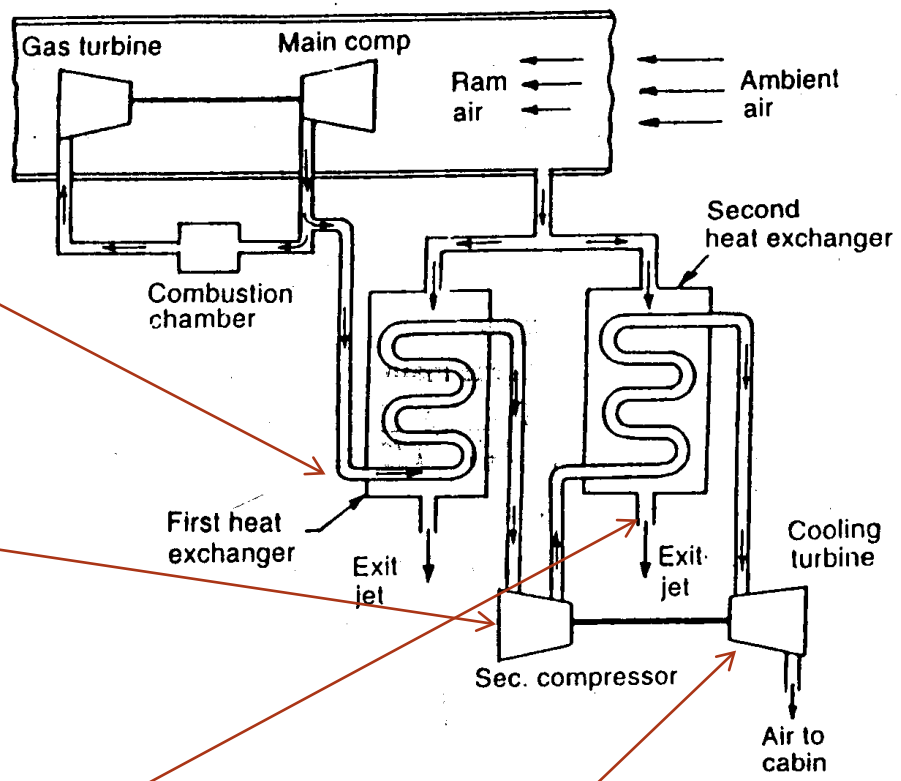
This system employs turbofan to compress the coolant air. It should not be confused with the cooling of the turbofan blades.

# Bootstrap cooling system/升压式制冷系统

- The system consists of a cold air unit and 2 heat exchangers.
- The turbine of the CAU drives the compressor, both of which are mounted on a shaft.
- It is used to provide adequate cooling for high ram temperature conditions, e.g., for high-performance fighters



# Bootstrap cooling system/升压式制冷系统




Cool the bleed air by ram air

Increase pressure & temperature increases

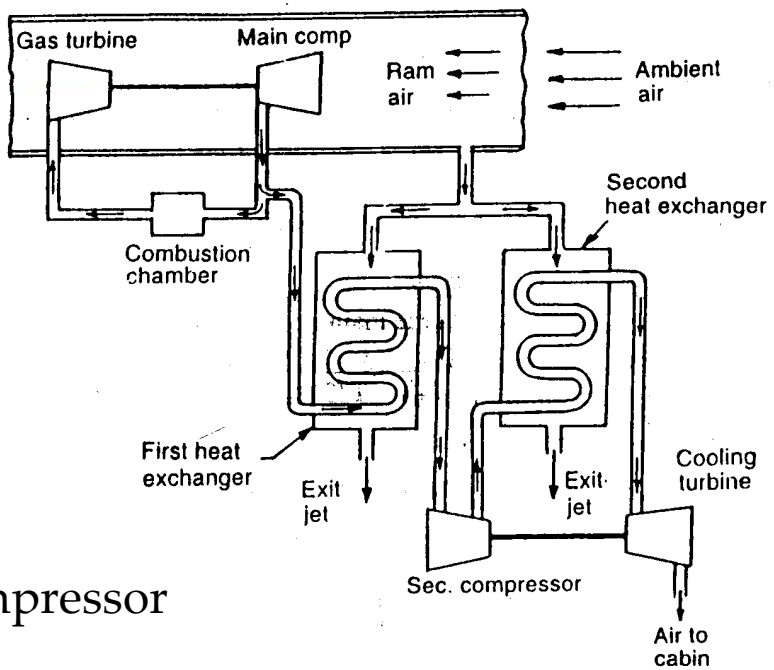
Cool the high-pressure air by ram air

Sometimes, water separators are also needed

Expansion through turbine, reducing temperature. It also drives the compressor

Can drop below 0°C at some working conditions

# Bootstrap cooling system

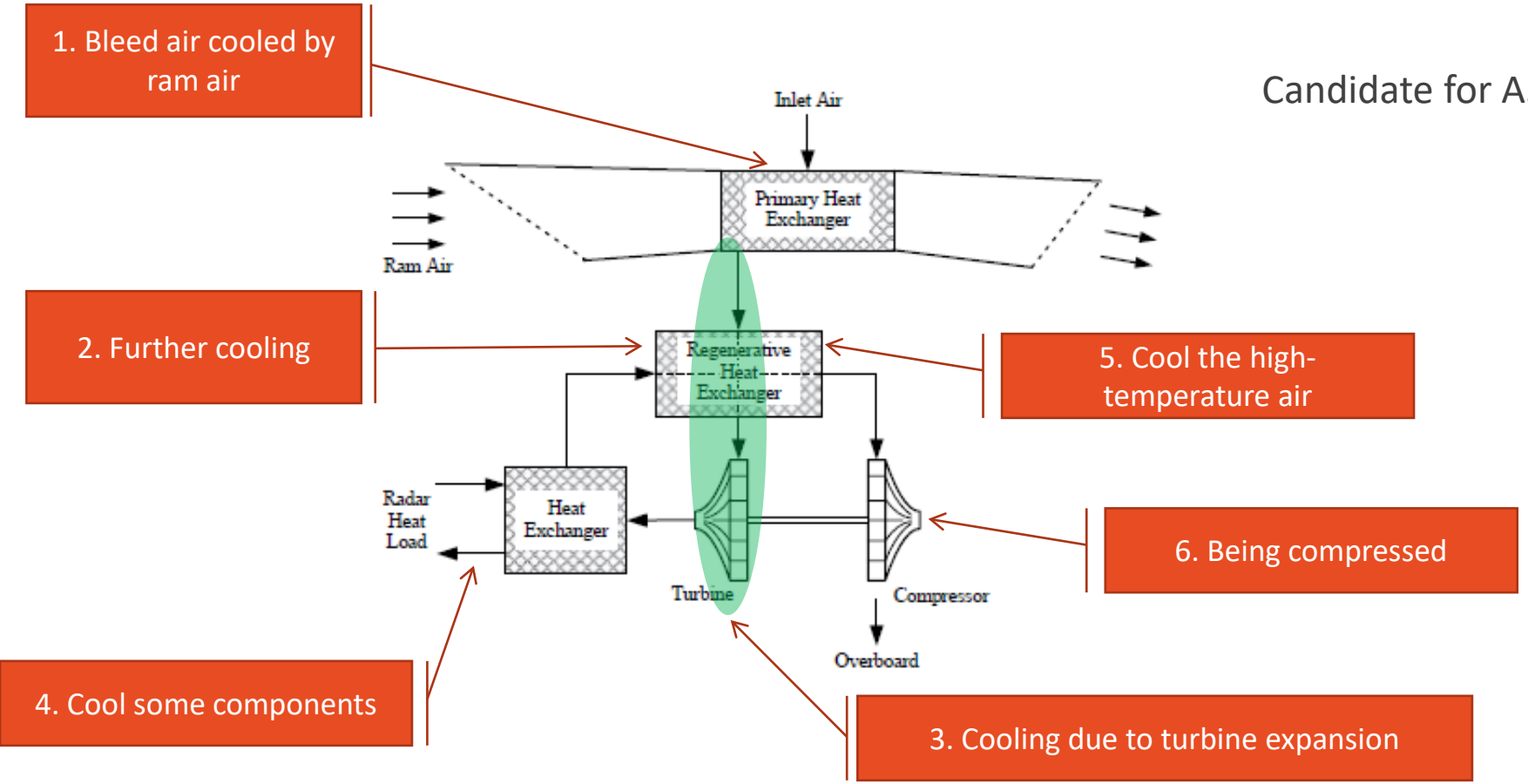



- A bootstrap cooling system contains:
  - Heat exchangers
  - Compressor
  - Turbine, which is linked together with compressor
- The system can self start:
  - When air flows across the turbine, it start rotating and then compress the air.
- The output air from the compressor is passed through secondary heat exchanger before supplied to the turbine.
- The air is then expanded in the turbine, which is cold.

# Reversed bootstrap cooling system/逆升压式制冷系统

- In comparison to bootstrap cooling system, it changes the sequence of air passages through compressor and turbine.

Candidate for A320neo



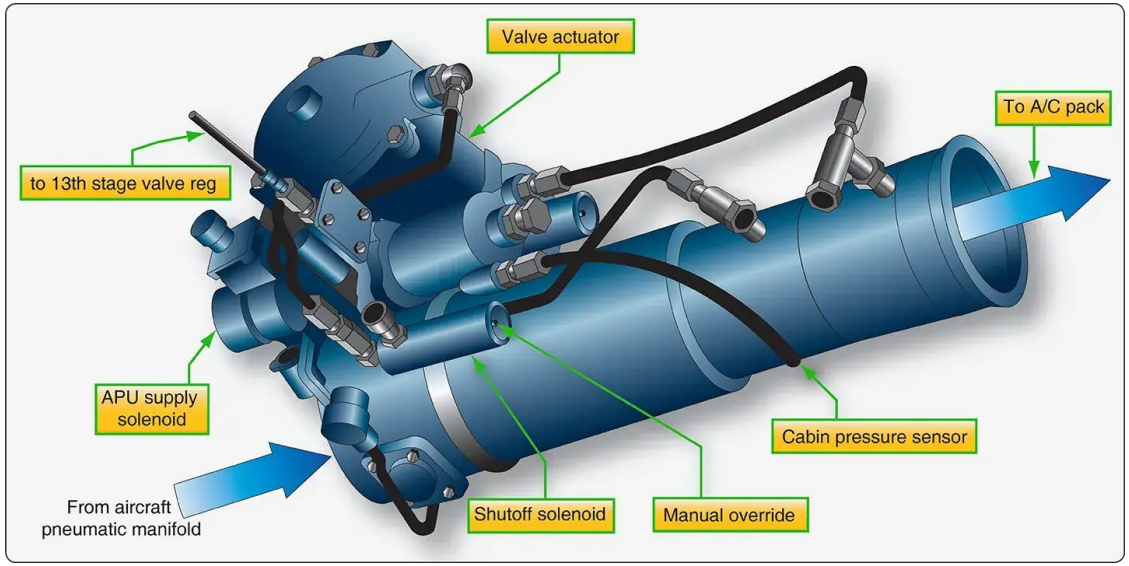
# Charge air in the cooling systems

- In bootstrap (and reversed bootstrap) cooling system, the hot charge air is generated by engine bleed air.
  - The hot air is also at high pressure.
- The air passes:
  - flow control valve: to control the flow amount from engine bleed
  - bypass valve: controls the amount of air goes into the heat exchanger
  - primary heat exchanger: the air is cooled by the ram air
- The cold air is then mixed with hot air to supply to cabin.

It is necessary we briefly introduce the key components related to charge air control

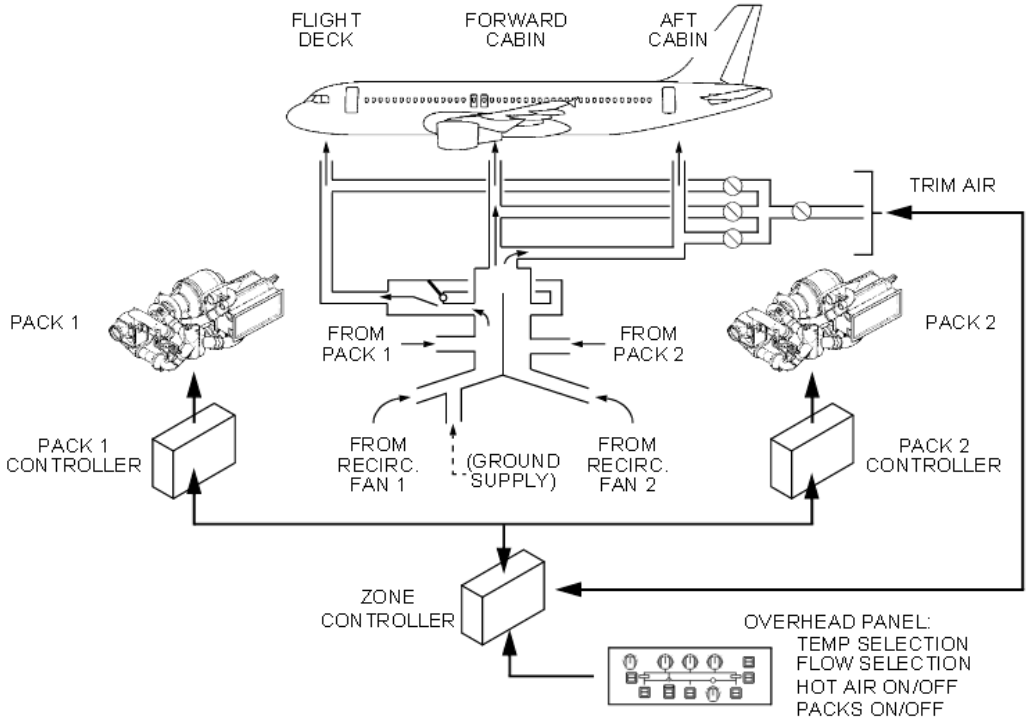
# Component operation: pack valve

- The pack valve (supply shutoff valve) is used to regulate bleed air goes into the ACM
- It is controlled with a switch from the air conditioning panel in the cockpit.
- The pack valve opens, closes, and modulates to allow the air conditioning system to be supplied with a designed volume of hot, pressurized air.



# Component operation: bleed air bypass

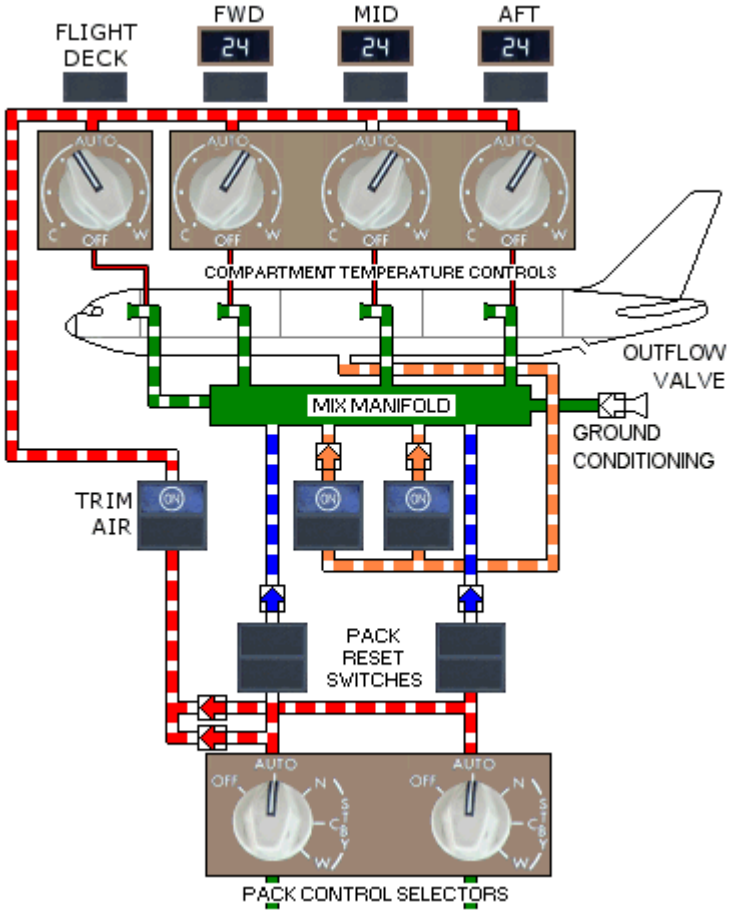
- It is used to bypass some pneumatic air to the surrounding of ACM. It does not go into ACM!
- The warm bypass air is mixed with cold air to provide comfortable mixed air to the cabin.




Use of trim air on the Airbus A320 family

# Component operation: bleed air bypass

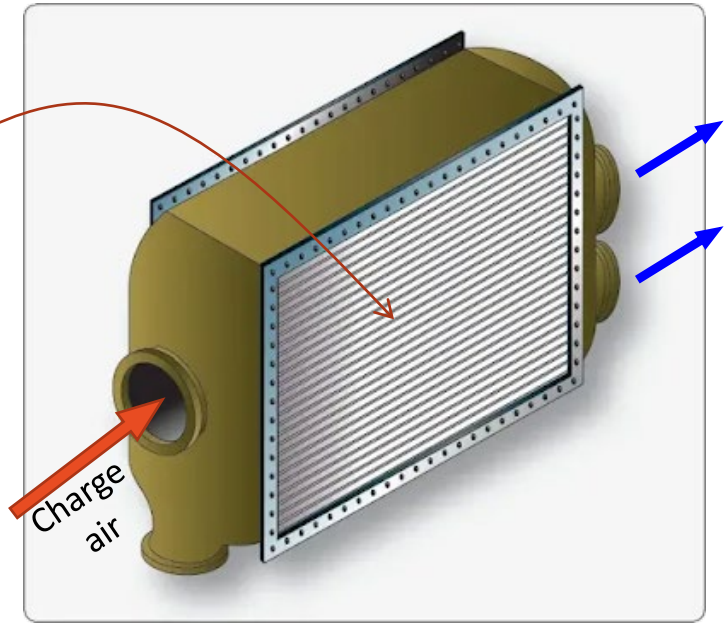
- Sometimes, the bleed air bypass is also called trim air
- There is a trend of adopting on-demand heating to realize the multi-zone independent control
  - Cockpit
  - Individual passenger seat
- Temperature sensors and rapid responses are needed




http://hibdz.skydiving.co.uk/757/767_tech/air_systems/air_conditioning.htm

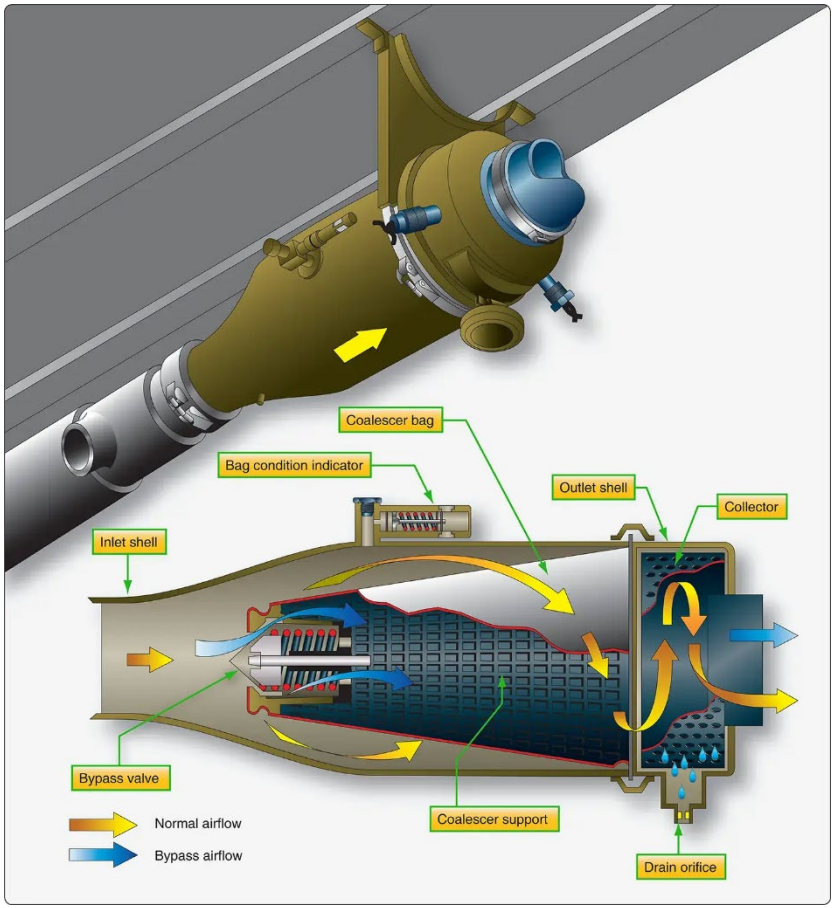
# Component operation: primary heat exchanger

- The warm air crossing the ACM passes the primary heat exchanger.
- A controlled flow of the ram air is ducted over the exchanger, reducing the air temperature inside it.
- The ram air is modulated to realize the target heat change rate.



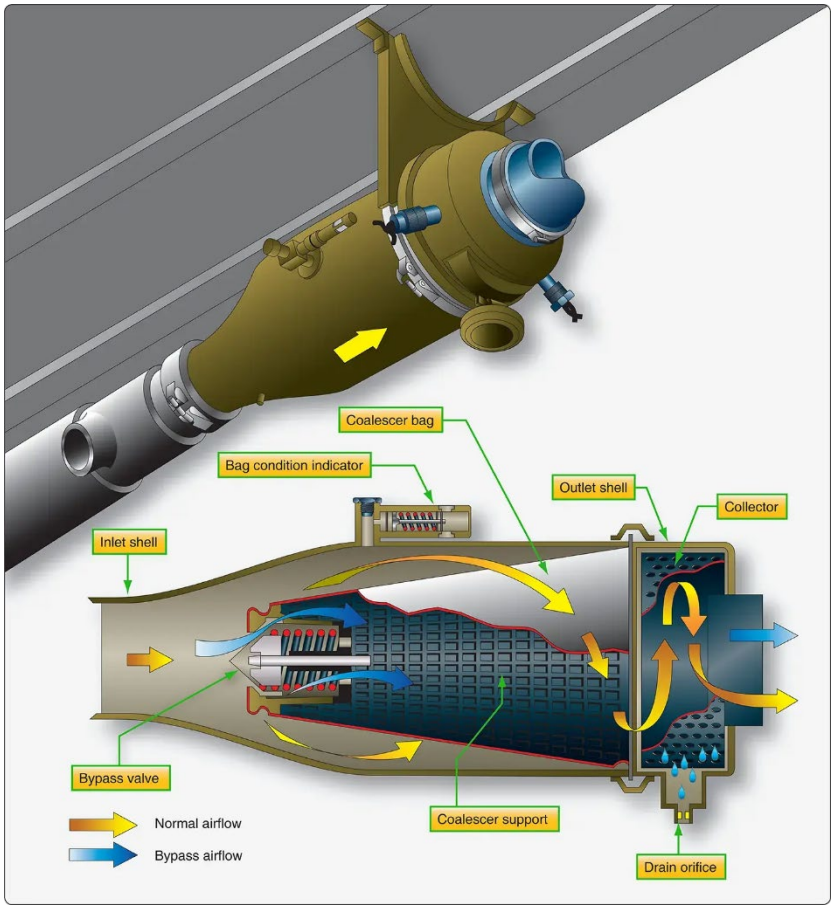
# Component operation: water separator

- The cool air from the ACM cannot hold the quantity of water when it was warm.
- A water separator is used to remove the water from the saturated air before it is sent to the aircraft cabin.

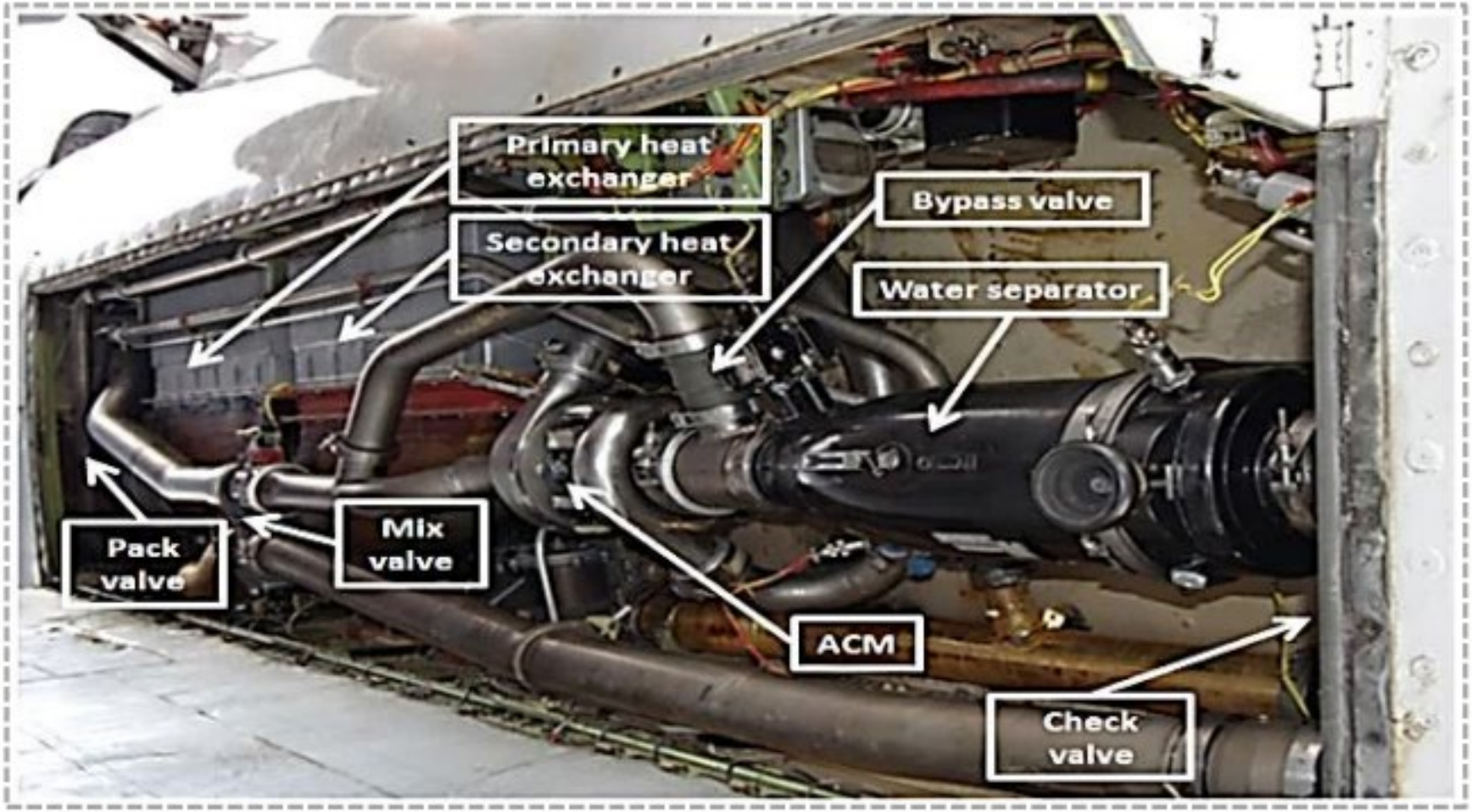


# Component operation: water separator

- Foggy air from the ACM enters and is forced through a fiberglass sock that condenses and mixes with mist into larger water drops.
- The interior structure of the separator swirls the air and water.
  - The water collects on the sides of the separator and drains down and out of the unit
  - The dry air passes through.



# Example of the Boeing B737-200 ECS



# The inefficiency of current systems

- Currently, the hot bleed air is cooled down to the temperature that can be used in the cabin. A large amount heat, which is potential useful energy, is rejected into atmosphere

$$\frac{P_E}{P_C} \approx 10$$

Power provided by engine for cooling

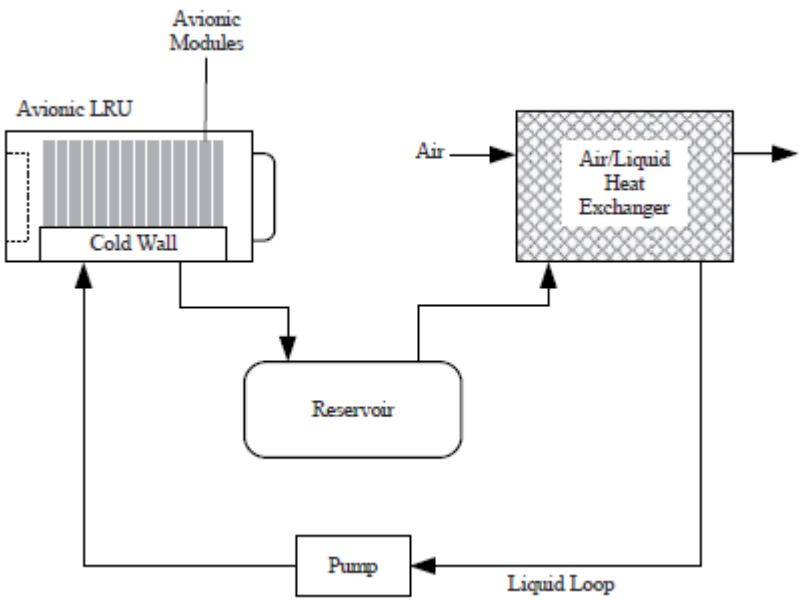
Power of the cooling

- Some engine power is used to overcome drag of the ram air exchanger.
- With the increase of the avionics systems, more heat will be produced. The aircraft weight will be increased because of the increase of the ECS.
- To use the closed loop systems can be helpful the increase the reliability and efficiency.

# Other cooling systems

# Liquid cooled systems

- For an aircraft, the devices and avionics system also require cooling
- Liquid cooled systems are often used to remove heat from the avionics systems.
- To replace air as the heat transport medium through heat exchanger



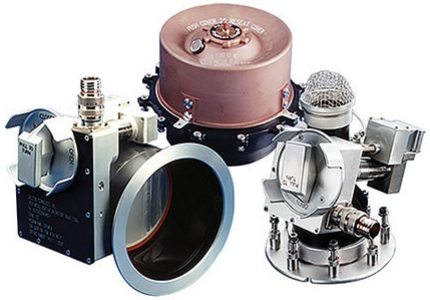

Advantages:
- Efficient
- Compact

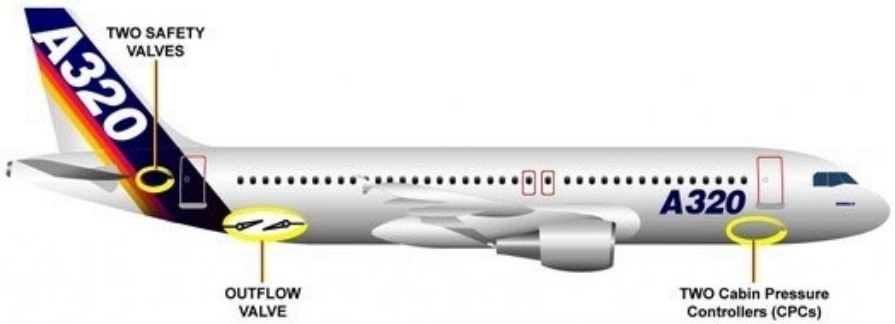
Disadvantages:
- Expensive
- The medium is often toxic

# Pressurization

# Cabin pressurization/加压

- Cabin pressurization is achieved by cabin pressure control valves installed in the cabin wall.





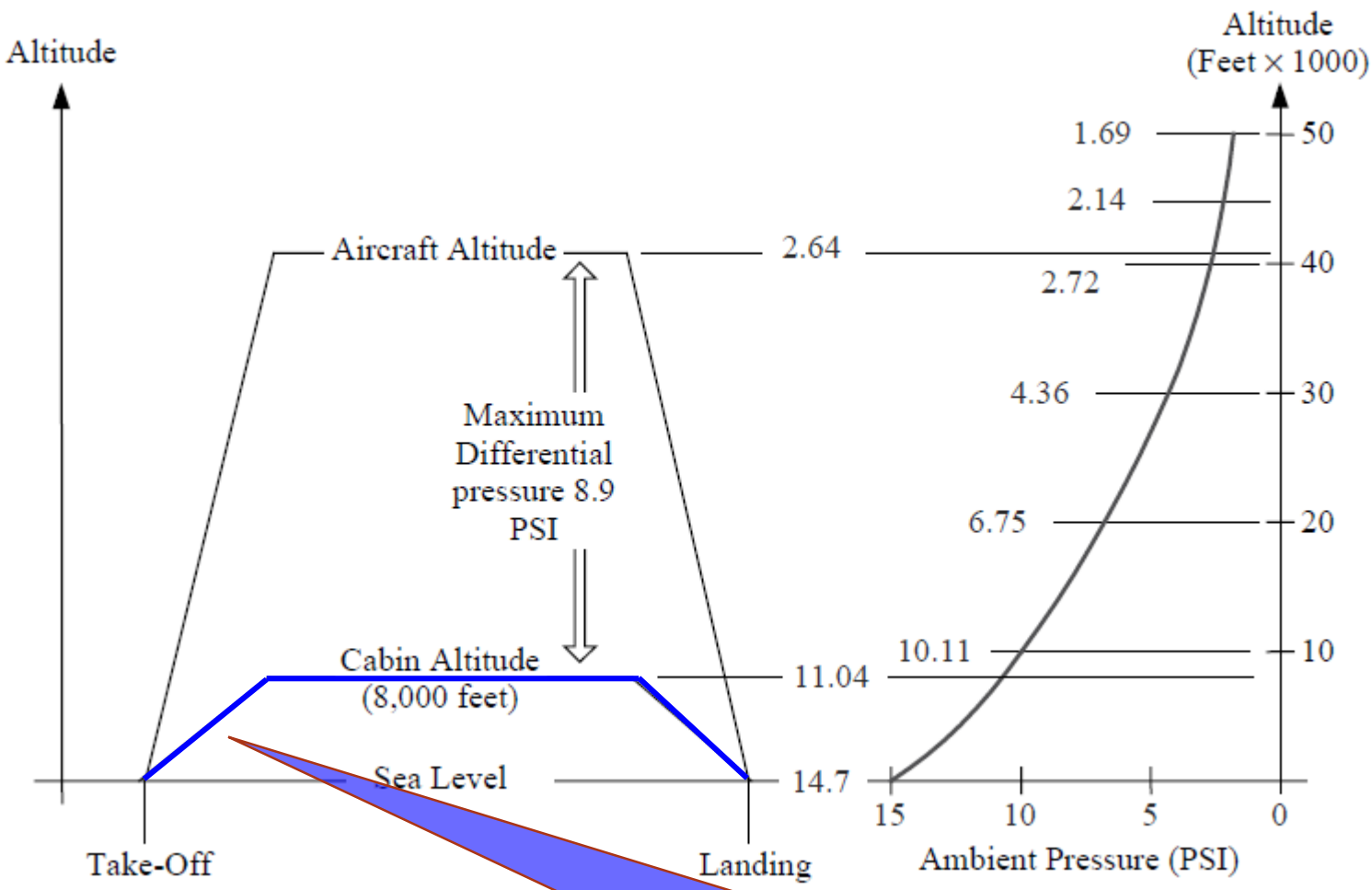
*Outflow valve*

# Cabin pressurization/加压

- The pressure is controlled by regulating the air flow based on the aircraft altitude.
- As a balance between physiological needs of passengers and crew and structural limitations.
- For commercial aircraft, he cabin will be pressurized to the cabin altitude is about 8000 ft.
  - The cruise altitude is often about 35,000 ft, leading to a pressure difference of 50 kPa across the cabin wall.
- For aircraft that uses oxygen routinely, e.g., military aircraft, the pressurization system is usually designed with a cabin altitude less than 20,000 ft.

This cabin altitude refers to the pressure altitude!

# Cabin pressurization

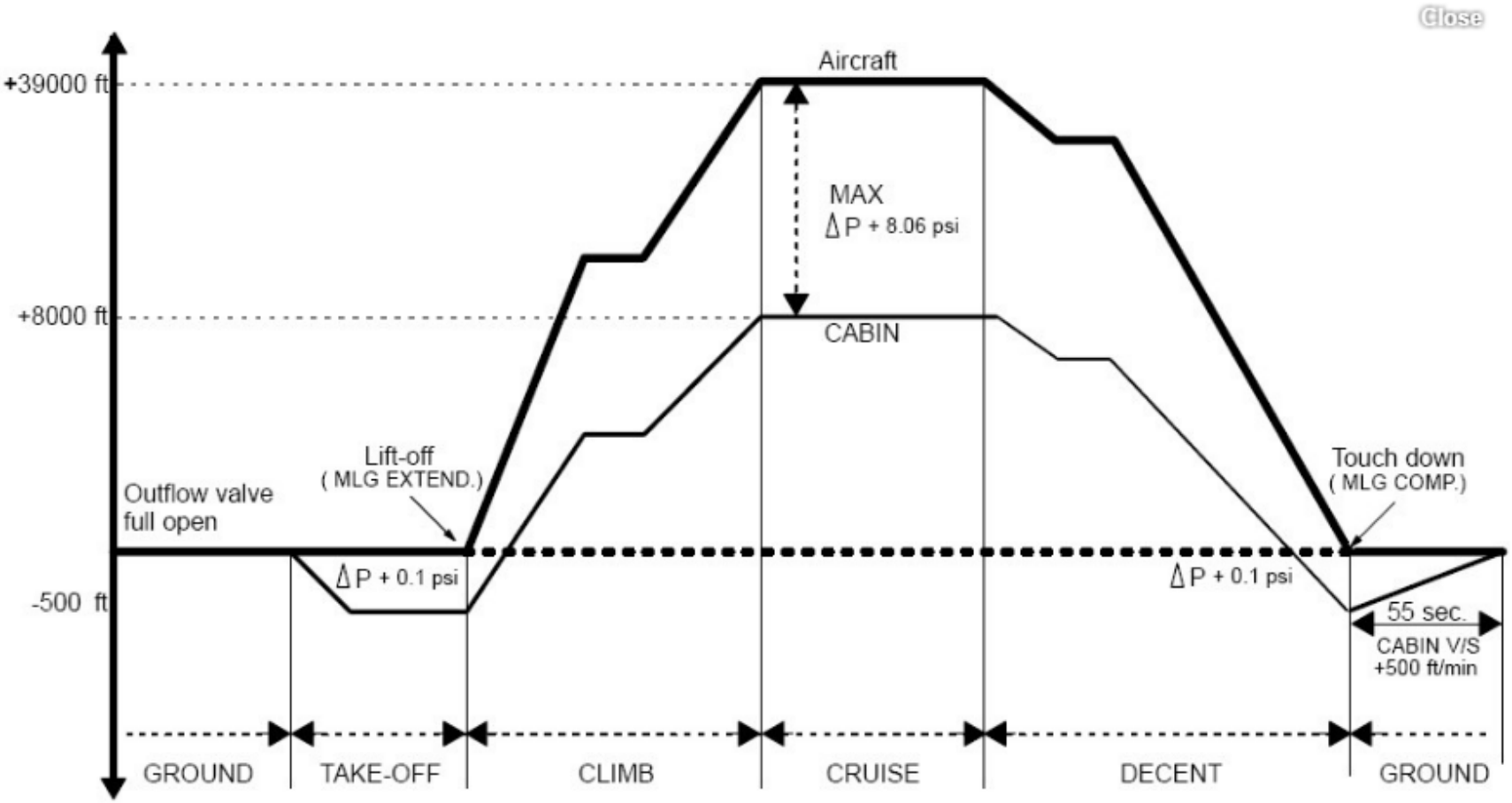



Adjust the cabin pressure based on the ISA at these cabin altitude levels

# Pressurization modes

- Aircraft cabin pressurization can be controlled via different modes of operation.
  - Isobaric mode: works to maintain cabin altitude at a single pressure despite the changing altitude of the aircraft. For example, the flight crew may select to maintain a cabin altitude of 8,000 feet (10.92 psi).
  - Constant differential mode: which controls cabin pressure to maintain a constant pressure difference between the air pressure inside the cabin and the ambient air pressure, regardless of aircraft altitude changes.

# Typical design pressure altitudes in different phases

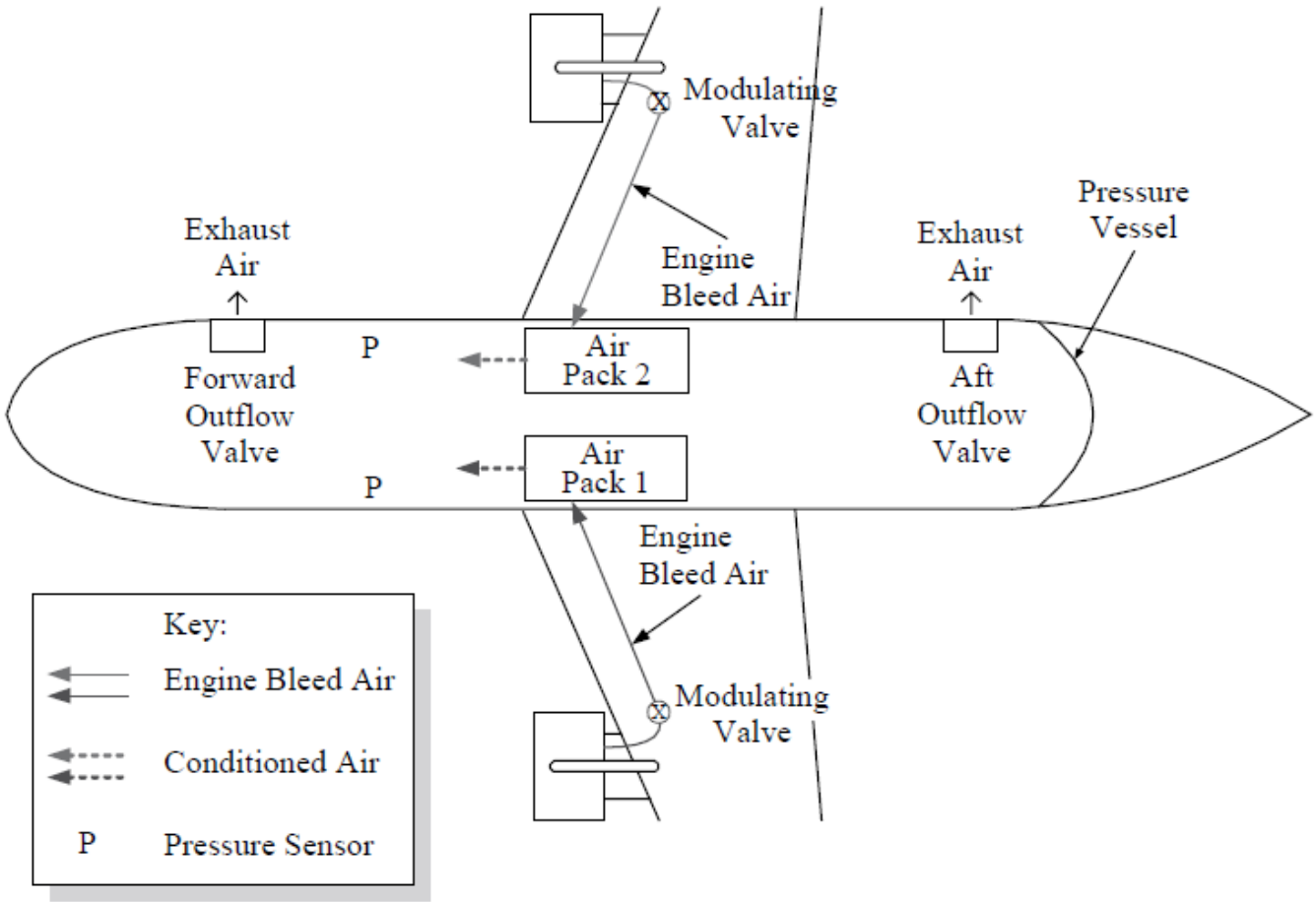



Cabin of passenger airliner is designed to operate at a differential pressure is 8 – 9 psi, e.g., around 50 kPa

# Cabin pressurization

- During the flight, the differential pressure is maintained high enough to ensure that there is sufficient time for pilot to descent when pressurization fails.
- The cabin should be designed as a pressure vessel with minimal leakage.
  - No-return valves are installed in air distribution pipes cross cabin wall
  - Safety valves are installed in the cabin wall to relieve internal pressure

# Cabin pressurization



# Unplanned decompression

- Unplanned loss of cabin pressure at altitude is rare but has caused accidents. It could be caused by: airframe integrity loss, slow leaks or equipment malfunctions.
- Any failure of cabin pressurization above 10,000 ft (3,048 m) requires an emergency descent to 8,000 ft (2,438 m), and the deployment of an oxygen mask for each seat.
  - Without emergency oxygen, hypoxia may lead to loss of consciousness and subsequent loss of control of the aircraft
  - The amount of oxygen should be sufficient during the descent to 8,000 ft.
- An alternative method is to increase the concentration of oxygen in cabin atmosphere.

# Hypoxia/缺氧

- Breathing air at reduced atmospheric pressure will result in reduction in alveolar oxygen pressure which in turn cause oxygen supply deficiency to the body and brain tissues.
- Effect of hypoxia:
  - Up to 10,000 ft cabin altitude, no significant impact on body
  - To 15,000 ft cabin altitude, markedly difficult to perform physical tasks
  - At 20,000 ft cabin altitude, performance of physical tasks will be grossly impaired, thinking becomes slow.
  - Above 20,000 ft, likely there will be loss of consciousness.

# Oxygen supply

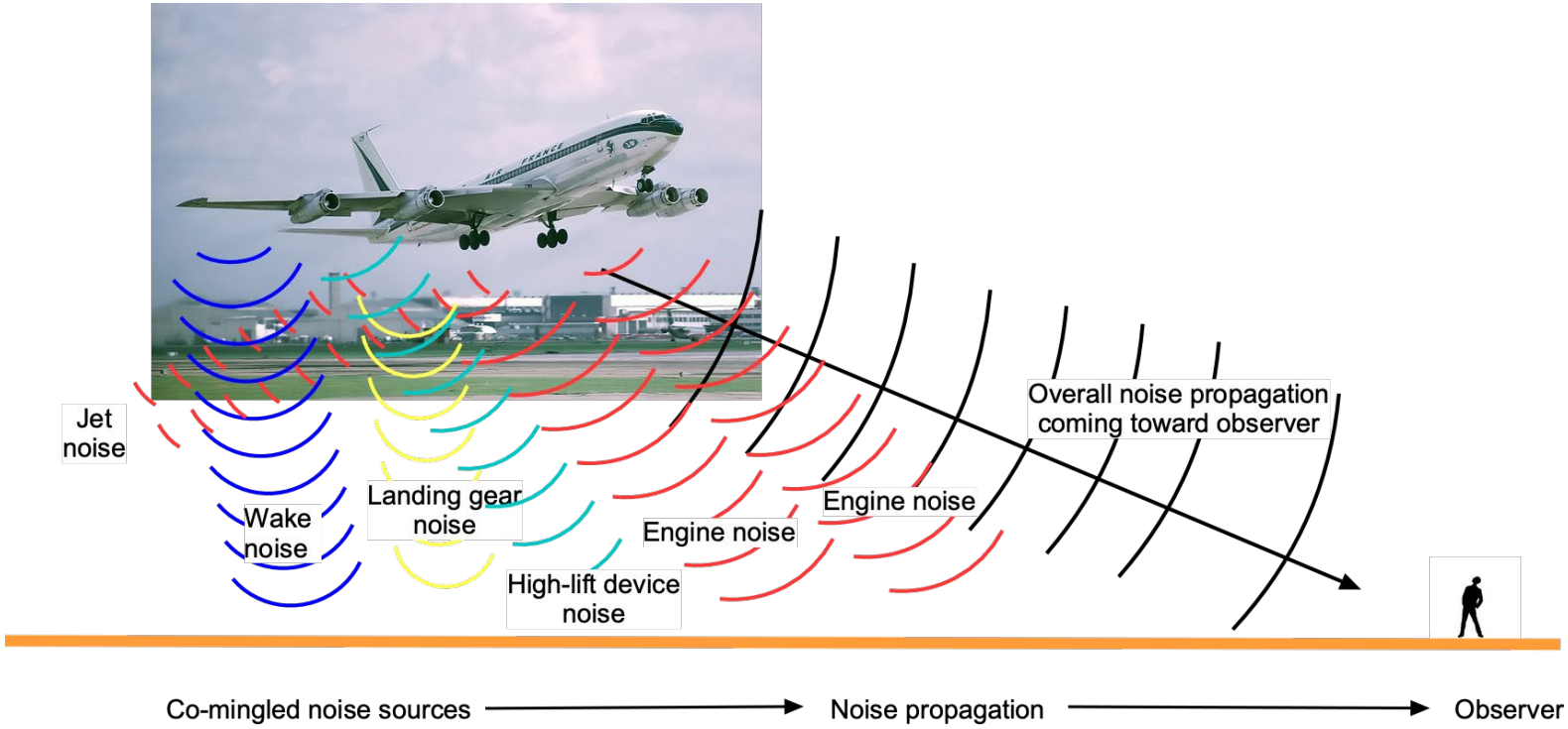
- For commercial aircraft, oxygen is only supplied in case of fast cabin depressurisation or contamination of cabin air
  - Emergency procedures are taken by crew and pilot
  - Mask is connected by hoses and the oxygen regulator output
- Currently, the oxygen is mainly provided by pre-charged or liquid oxygen bottles
- The Molecular Sieve Oxygen Concentrator (MSOC) is being developed by producing oxygen from engine bleed air

- B787 (optional)
- A350XWB

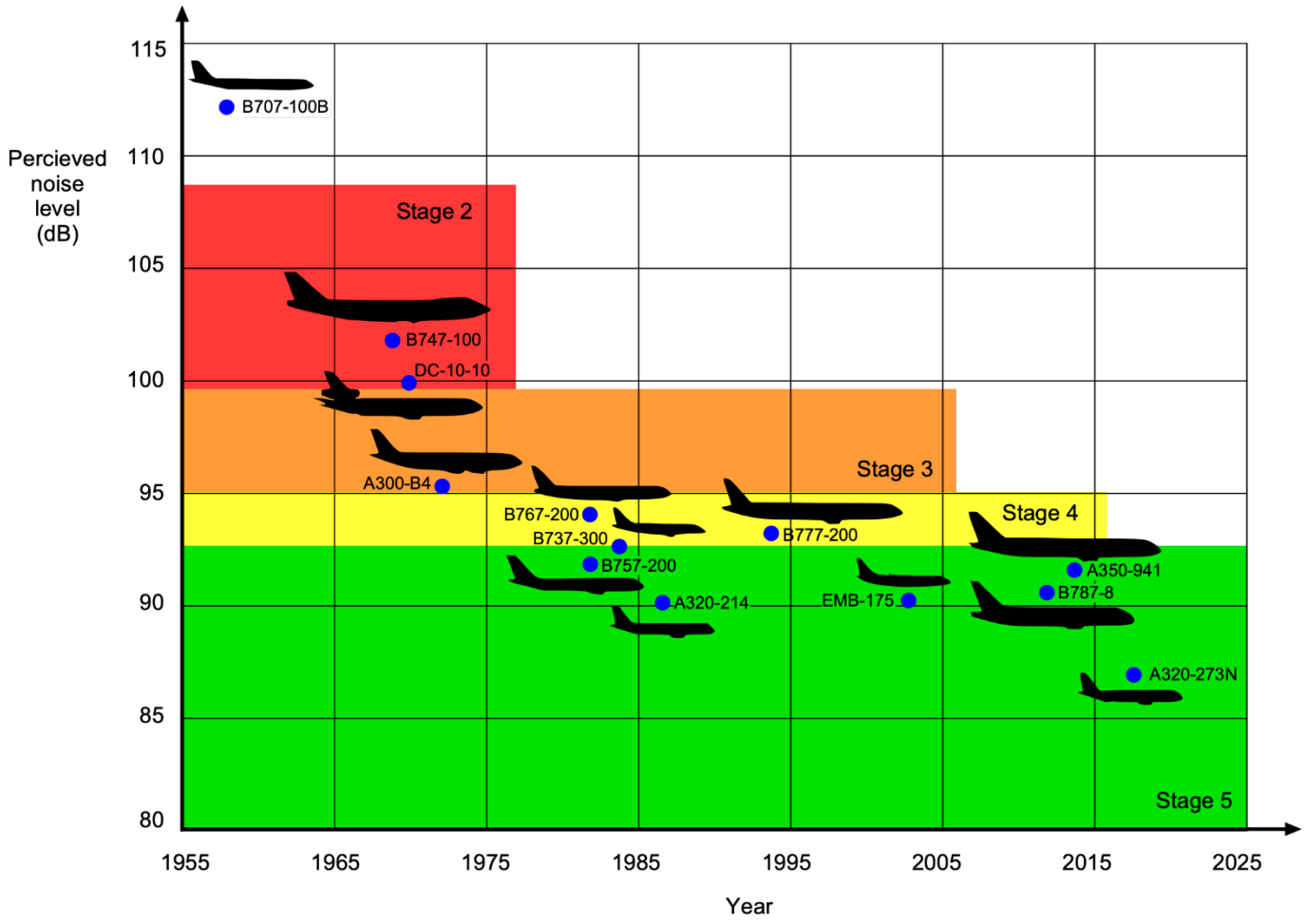
# Cabin noise

# Aircraft noise impact

- Noise requirements for aircraft are mainly applied to regulate the influence on the surrounding environment



# Aircraft noise requirement



# Cabin noise

- However, reducing the cabin noise is necessary to increase the completeness of the aircraft in the market.
- Also, legislations is gradually lowering the threshold for people at work
- Aircraft are designed aerodynamically or structurally to keep externally generated noise levels to a minimum.
  - Crew: are able to communicate satisfactorily over a radio or intercom, or to operate direct voice input avionics systems
  - Passengers: reduce the damage to hearing and reduce annoyance

# Anti-g system

# Anti-g system

- In military aircraft in maneuverer flight, or civil aircraft in extreme weather conditions, e.g., Typhoon, the flight acceleration can be very high
- The acceleration can be measured in *g*.
  - 1 *g* is the acceleration due to gravity, e.g., 9.81 $m/s^2$
- A typical pilot can bear 3-4*g* to perform the maundered flight.
- At high "g" levels, heart becomes unable to supply enough oxygenated blood to the brain, leading to a black out/黑視.

# Anti-*g* system

- If the acceleration onset is gradual, the blood supply of the eyes is the first to reduce sufficiently to work
- Anti-*g* trousers are used to partially to alleviate the effect of excessive g on the body:
  - It consists of **inflatable air bladders**/充氣氣囊 with ECS air.
  - Control valves are used to restrict the blood flow away from brain.
- With anti-g trousers, pilots can perform flight up to 8*g*.

# Anti-icing system and de-icing system

# Aircraft icing

- Icing is caused by:
  - Freezing on the aircraft surfaces of some from of precipitation, this usually happens on the ground;
  - Supercooled liquid water droplet found in clouds impacting with aircraft structure.
- It happens near the stagnation points, e.g., wing leading edge, engine intakes, etc.
- Icing is affected by temperature on the aircraft, temperature of water droplet, aircraft altitude, etc.

Aircraft icing is an extremely important factor in the world of aviation and despite the best efforts of the industry there are still continuing accidents resulting from inadequate protection against the impact of icing on aircraftcontrollability.

# Anti-icing system and de-icing system

- Anti-icing: the ice-creation is prevent.
- Anti-icing systems can use:
  - Hot bleed air is introduced to the location where icing may occur, e.g., wing leading edge
  - Electrical heating the location where elements are embedded in structure that is prone to icing.
  - Liquid ice protection where a freezing point depressant liquid is deposited on the surface

- De-icing: limited amount of ice creation is allowed, and technology is used to take it
- De-icing systems can use:
  - Pneumatic boots/除冰罩 where a reinforced synthetic rubber is overlaid on susceptible surface
  - Electrical heating
  - Electro-expulsive system to use magnetic fields to break the ice

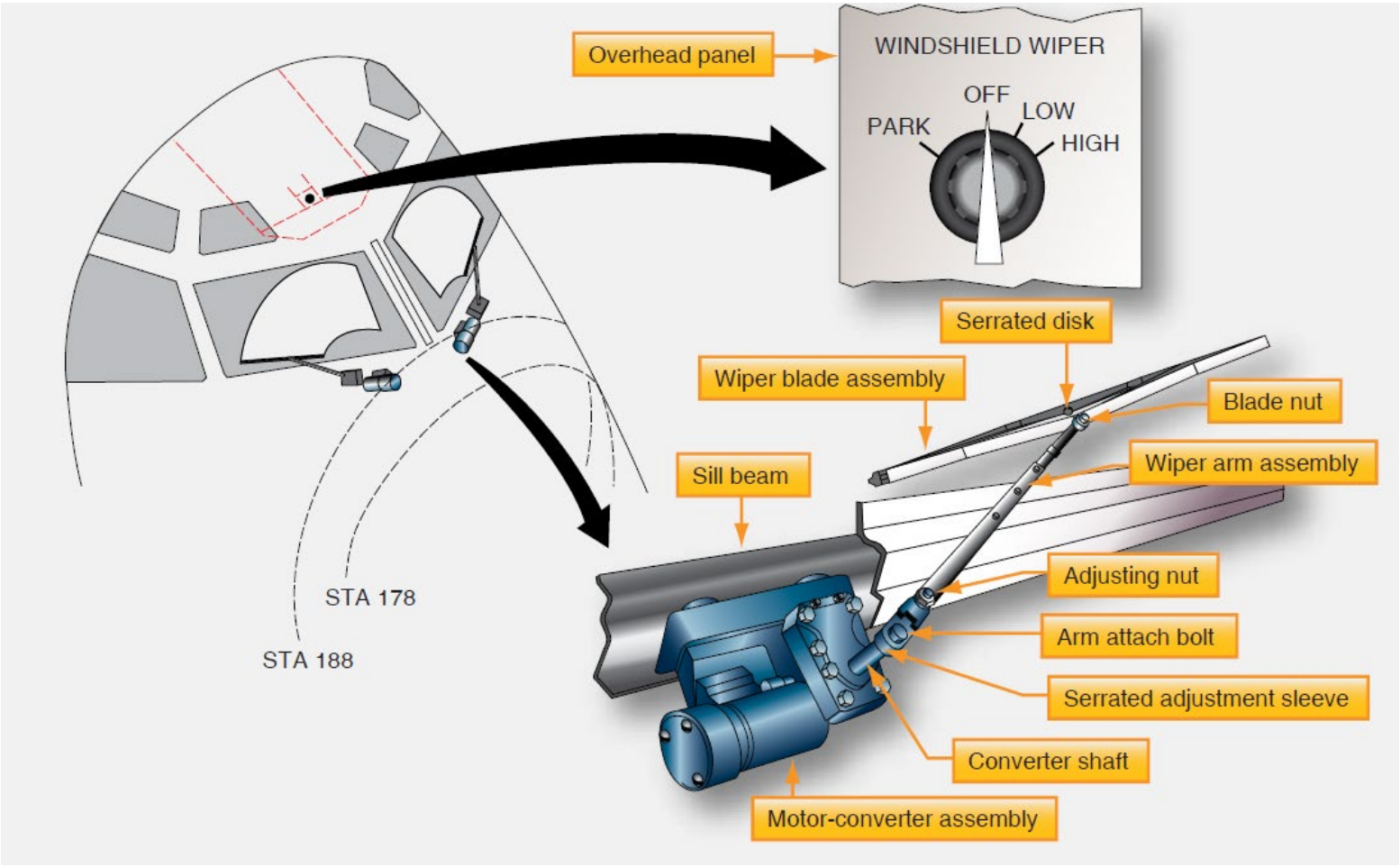
# Rain dispersal

# Rain dispersal

- A pilot must have clear vision through the windscreen under all weather conditions, particularly on approach to landing.
- The use of windscreen wipers/雨刷 can be effective up to high subsonic speeds, particularly on large screens.
- Wipers are used in conjunction with washing fluid to clean the screen of insect debris, dust, dirt and salt spray etc.
- However, wipers are not suitable for use with plastic windscreens since they tend to scratch the surface.
- They also have the disadvantage of increasing drag.

# Rain dispersal

- Hot air jets for rain dispersal can be used up to much higher speeds than wipers and are suitable for use on glass and plastic.
- The air is discharged at high velocity over the outside surface of the screen from a row of nozzles at the base.
- The air discharged from the nozzles is supplied from the ECS at temperatures of at least 100 °C. Such high temperatures are required to evaporate the water.
- However, the nozzles must be designed so that the windscreen surface temperature is not increased to such an extent that damage occurs. This is particularly a problem with stretched acrylic windscreens which begin to shrink back to the cast acrylic state at temperatures above 120 °C.


Overhead panel
WINDSHIELD WIPER
OFF
PARK
LOW
HIGH
Serrated disk
Wiper blade assembly
Blade nut
Wiper arm assembly
Sill beam
Adjusting nut
Arm attach bolt
Serrated adjustment sleeve
Converter shaft
Motor-converter assembly
STA 178
STA 188

# Anti-Misting and De-Misting

# Aircraft misting

- Misting will occur when the surface temperature of the transparency falls below the dew point of the surrounding air.
- Misting typically occurs when an aircraft which has been cruising at an altitude where air is cold and relatively dry.
- When the aircraft descends into a warmer and more humid atmosphere, misting will occur on the surfaces which have not had enough time to warm up to a temperature above the dew point of the air.

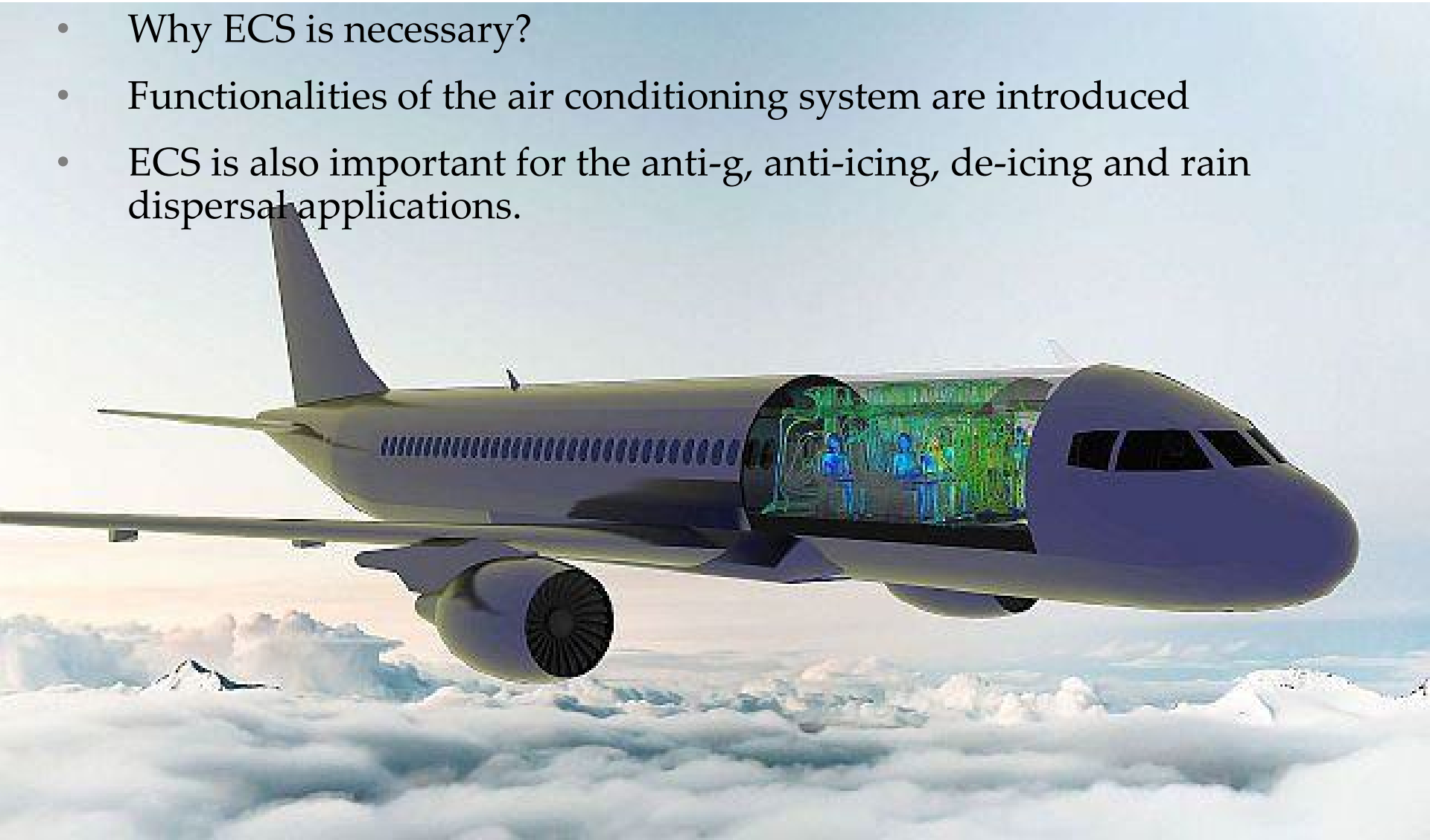
# Anti-misting system

- An anti-misting system can be provided to keep the surface temperature of the transparency above the dew point and thus prevent misting.
- A system of nozzles blowing air at about 100 °C over the canopy from its base can be used, or alternatively an electrically heated gold or metal oxide film can be deposited on the transparency surface or placed between laminations.

# De-misting system

- A transparency de-mist system can be provided to clear the transparency of mist should misting occur suddenly, or if the anti-mist system fails.
- This is particularly important on landing for aircraft where the pilot is tightly strapped into his seat and cannot clear the screen with his hand.
- The de-mist system consists of nozzles blowing environmental control system air at high flow rates across the transparency.

# Summary

# Summary

- Why ECS is necessary?
- Functionalities of the air conditioning system are introduced
- ECS is also important for the anti-g, anti-icing, de-icing and rain dispersal applications.