Model & Sizing Air Systems

Overall Air System Functions, Requirements and Physiological Thresholds

February, 2023

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Air Systems Course Syllabus

- 1st of February : 4h Introduction + Environmental Control System + Exercise
- 7th of February : 4h Wing Ice Protection System + Exercise
  Bleed Air System + Exercise
- 9th of February : 4h Vapour Cycle System + Exercise
  Cabin Pressure Control System + Exercise

Sizing

- 15th of February : 4h Model of Air Systems – Dymola Exercise
- 28th of February : 3h Model of Air Systems – Dymola Exercice

Model

Exam MCQ => 7th of March

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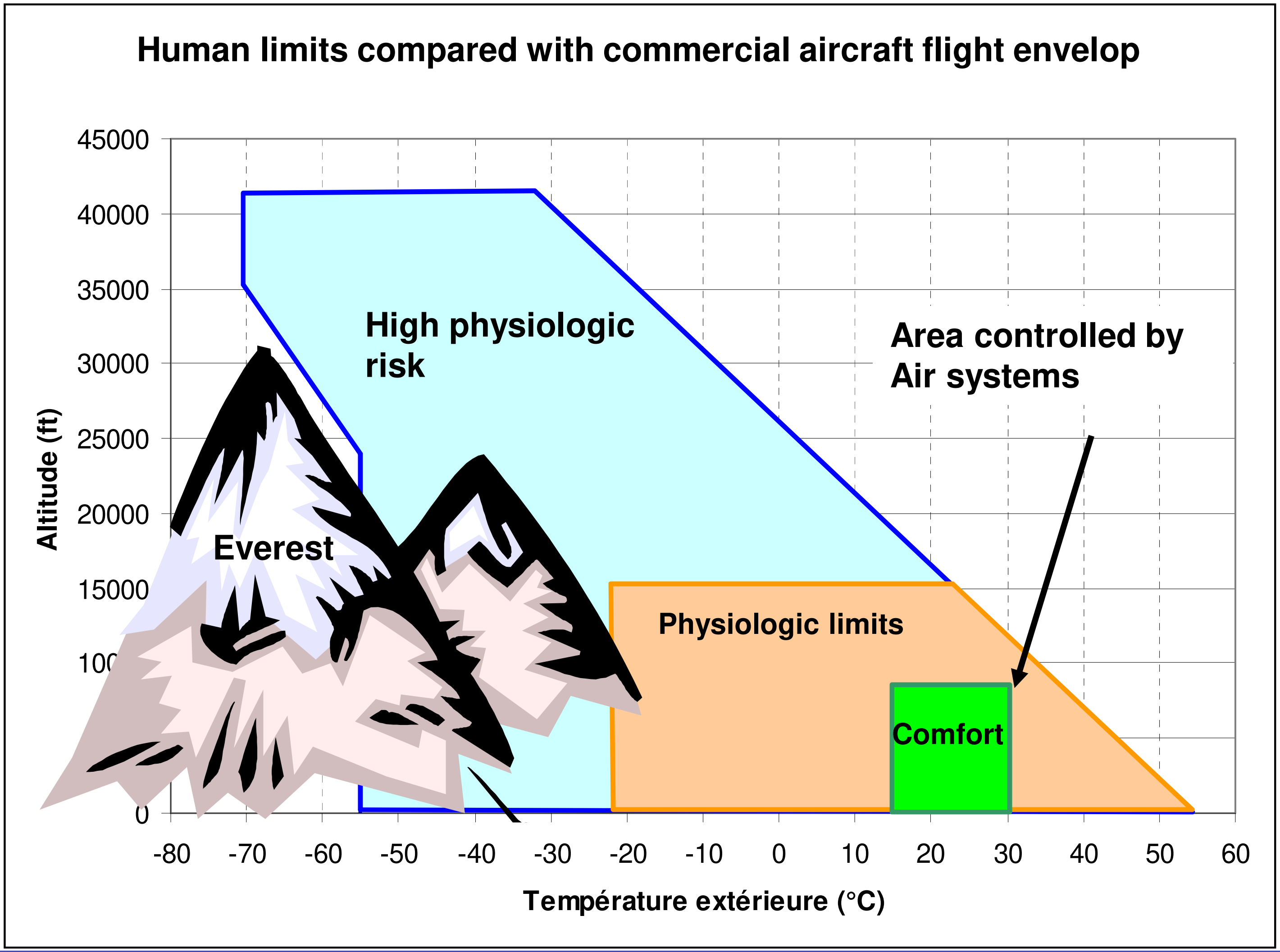
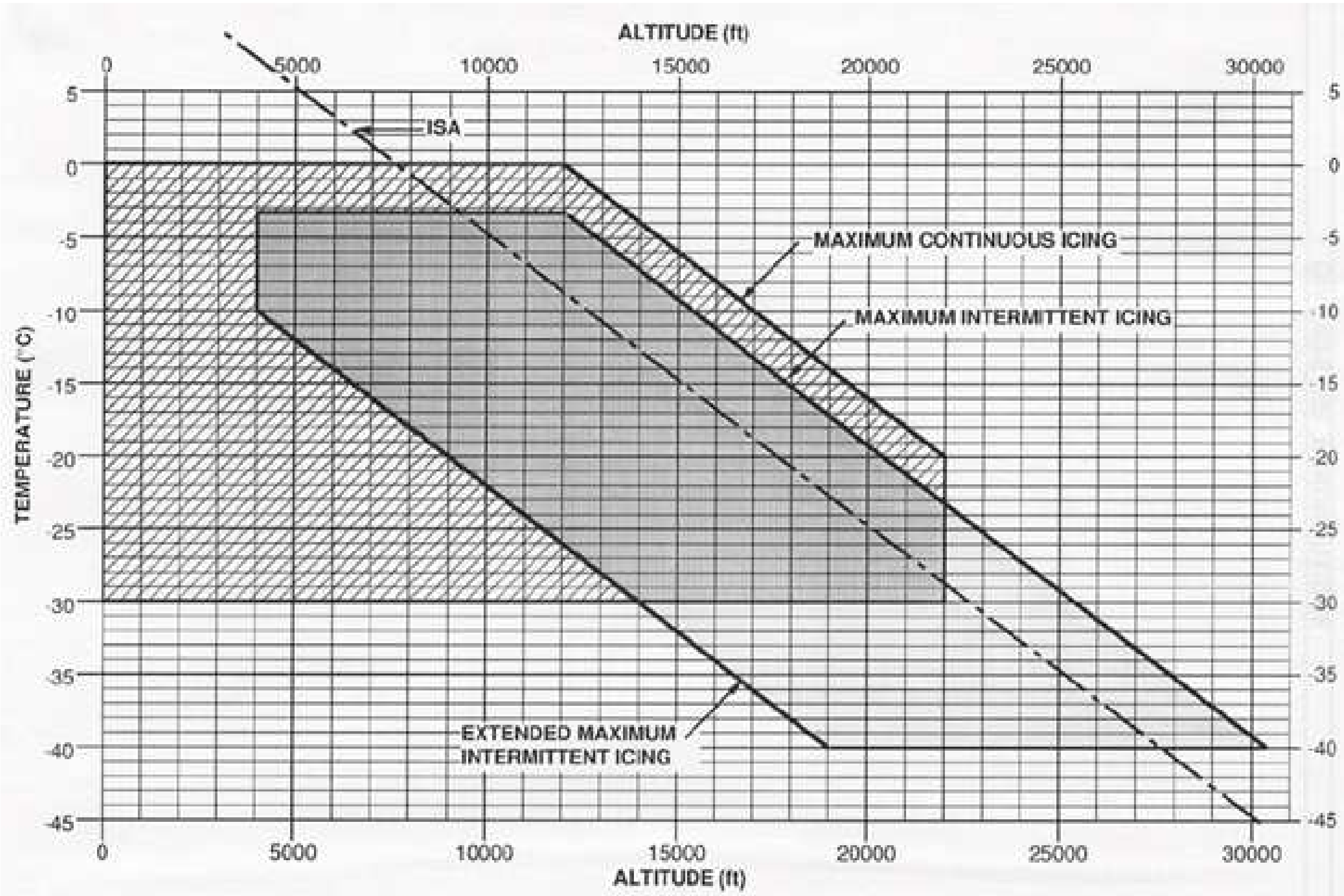
Air Systems : What is the point?



Air Systems : What is the point?



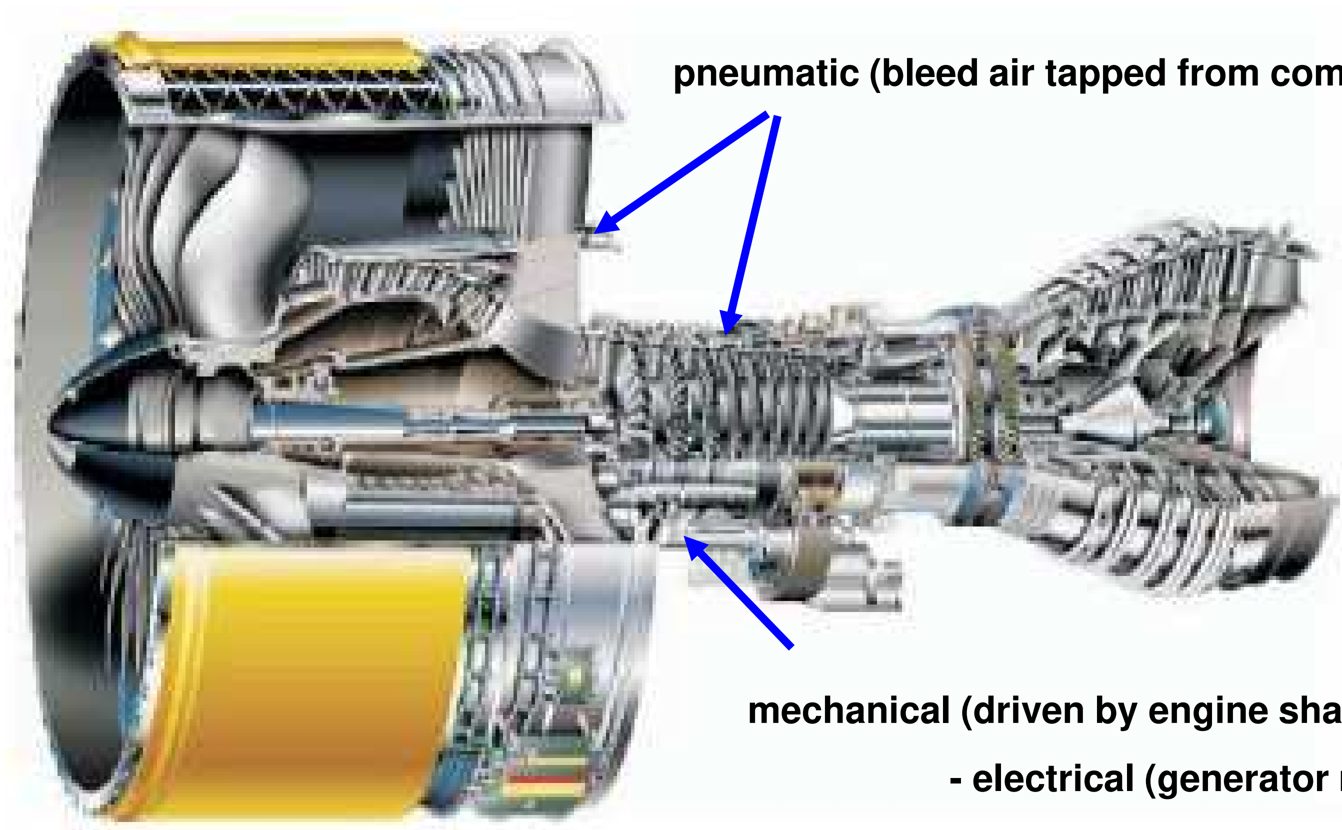
Air Systems : What is the point?

- Two primary functions:
  - Ensure a viable environment to occupants (passengers and crew members)
    - Pressurize cabin in order to keep cabin altitude below 8000ft (2400m)
    - Maintain a constant cabin temperature around 24°C (cooling/heating)
    - Ventilate occupants with fresh air to avoid high concentration of hazardous gas (CO, CO_2) : 0.55ppm* per passenger
    - Cool down Electronics equipments
  - Protect wings and nacelles from icing conditions

* ppm = pound per minute   1kg = 2.2046 pounds

Air Systems : Which energy?

The primary source of energy on aircraft is fuel. This source of energy can be transformed through the engines and Auxiliary Power Unit into other forms of energy:



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Air Systems : Quick history

First civilian aircraft with pressurized cabin : Boeing Model 307 Stratoliner (1938)

Circular shape to sustain stress due to pressure difference

Mechanically driven cabin air compressor

Cruise altitude : 20 kft

First civilian aircraft with pressurized cabin with direct bleed air : Sud Aviation Caravelle (1955)

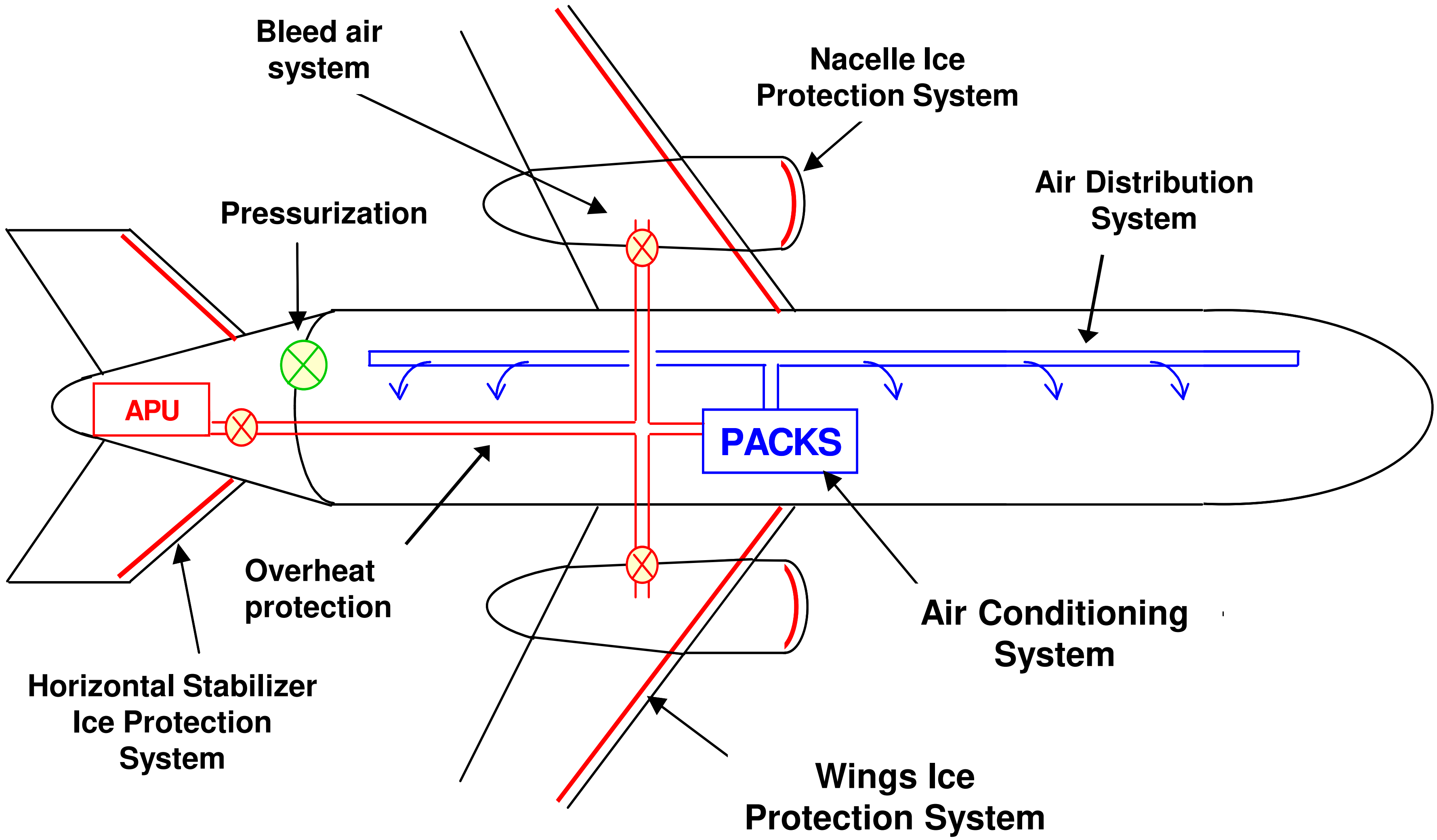
First civilian aircraft with pressurized cabin with electric compressor : Boeing 787 (2009)

Boeing Stratocruiser (1947) !

By choosing pneumatic power, other systems are needed:

- Bleed Air system (Engine and APU)
- Overheat Detection System
- Pneumatic Engine start

Air Systems : Global architecture



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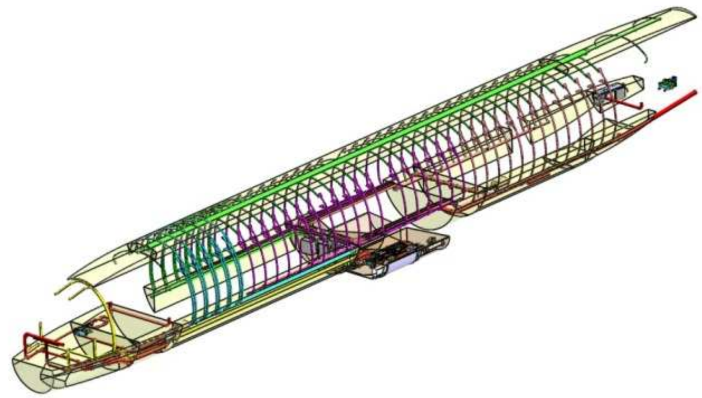
Air Systems – Impacts on aircraft

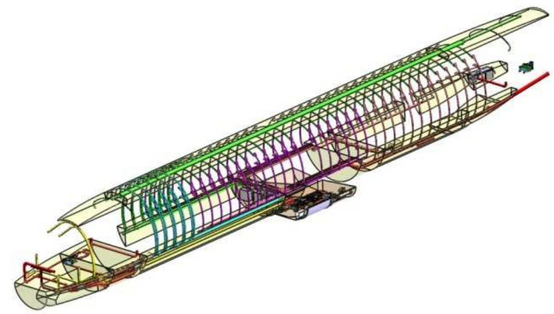
- **Some numbers**
  - Approximate value 1% - 2% of aircraft cost
  - 3 to 10% of the aircraft fuel consumption
  - 1,5 to 4% of the aircraft maintenance cost
  - 5kg per passenger



- **Taking bleed air from engine leads to:**
  - Increase the aircraft Specific Fuel Consumption (SFC)
  - Reduce take-off thrust (increase T/O runway length and obstacle clearance for climb)
  - Increase the engine idle thrust (in order to supply sufficient air for the cabin & anti-ice),
    - Increase landing distances
    - Reduce descent rate without spoilers
    - Increase brake system usage/heat in taxi
  - Oversize the engine compressor (lead to weight + size and drag increase)
- **RAM air :**
  - Increases aircraft drag, thus aircraft SFC

Air Systems – Conclusions

- **Air systems protect occupants and aircraft**
- **They are installed everywhere**
  - In fuselage from cockpit to tail cone and belly fairing
  - In wings
  - In engines



- **They are by far the biggest fuel consumers on the plane (after propulsion!)**
  - Typical single aisle systems power at take off:

Propulsion :	20000 kW	
Air conditioning:	520 kW	
Wings ice protection:	240 kW	940 kW
Nacelles ice protection:	180 kW	
Commercial loads (ovens, lights, In Flight Entertainment) :	60 kW	
Hydraulic pumps :	30 kW	
Fuel pumps:	15 kW	
Avionics :	10 kW	

- **Thus Air systems have to be very optimized in order to minimize their impact.**

Thermodynamics reminder

- **Air speed calculation within ducts**
- $\dot{m} = \rho.V.S$
  - With density $\rho = \frac{P}{R.T}$ for incompressible perfect gas
  - Thus air speed $V = \frac{4R.T.\dot{m}}{\pi.D^2.P}$
    - With :
      - R = 287J.kg^{-1}. K^{-1} for air
      - γ = 1.4 for air
      - T air temperature in K
      - $\dot{m}$ mass air flow in kg.s^{-1}
      - D duct diameter in m
      - P air absolute total pression in Pa
  - $Mach = \frac{V}{c}$ with $c = \sqrt{\gamma.R.T}$

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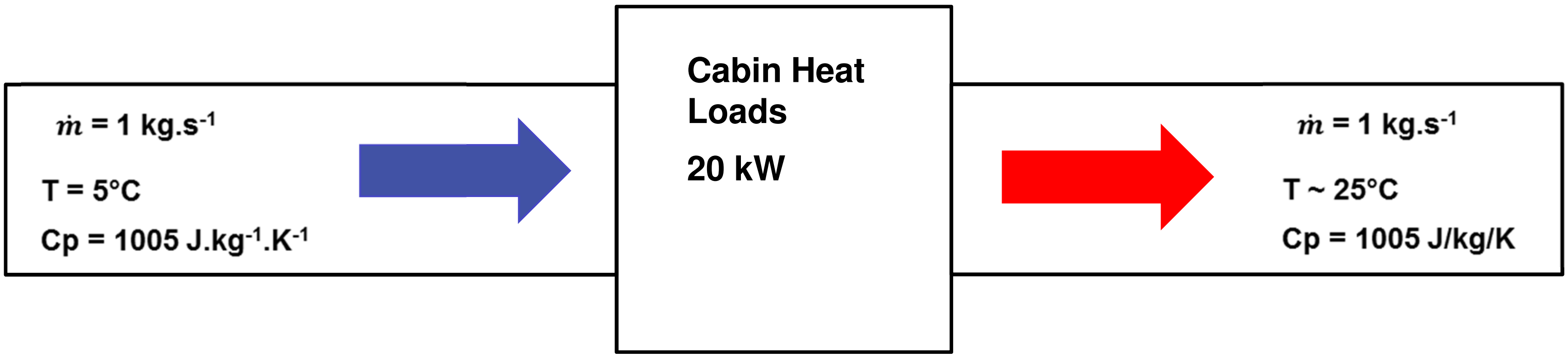
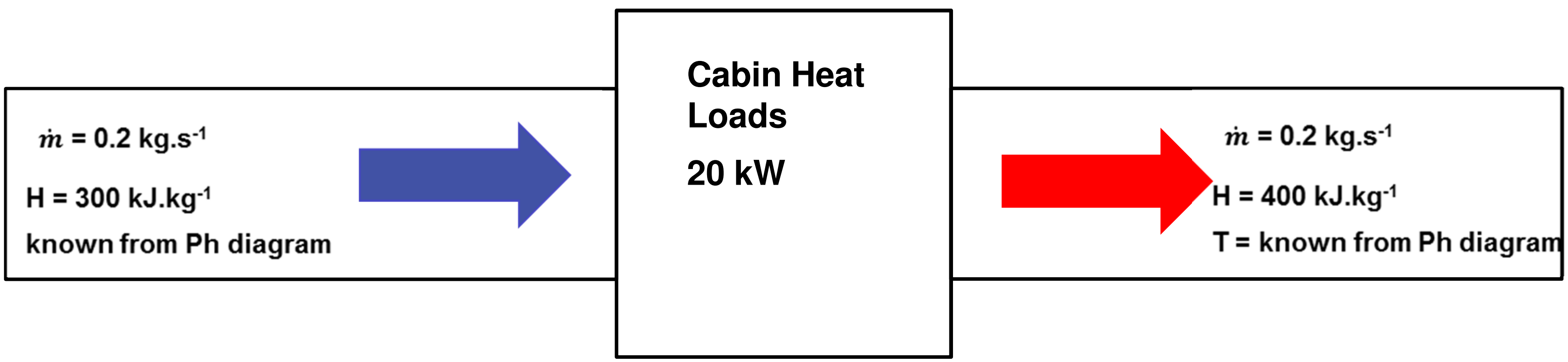
Thermodynamics reminder

Heat Power balance:

- $P = \dot{m}\,.\,Cp.\Delta T$ for monophasic fluid (dry air)



- $P = \dot{m}\,.\,\Delta H$ for diphasic fluid (evaporation/condensation of refrigerant)



Model & Sizing Air Systems

Air Conditioning and ECS Systems

February 2023

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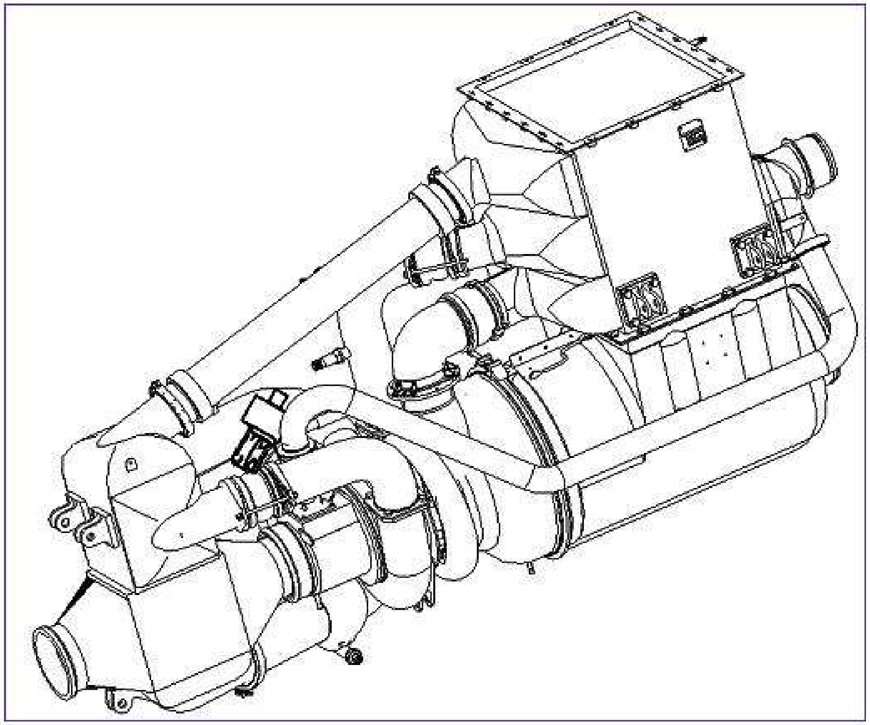
Course syllabus

- **Environmental Control System**
  - **System Functions and Requirements**
  - Basic principles and technology evolution
  - System Architecture & Sizing
  - Components Description



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All System Functions & Requirements

Cockpit and Cabin Air System

- **Ensure correct temperature:**
  - **Cooling** when **outside air is hot** (ground cases, flight with high thermal loads)
  - **Heating** when **outside air is cold** (ground cases, flight with low thermal loads)
- **Ensure minimum certification ventilation flow**
- **Ensure pressurization and repressurization**
  - Pressurization flow : maintain a constant pressure within the cabin => counterbalance air leakages
  - Re-pressurization flow : increase cabin pressure during descent => counterbalance air leakages + additional flow to increase cabin air density

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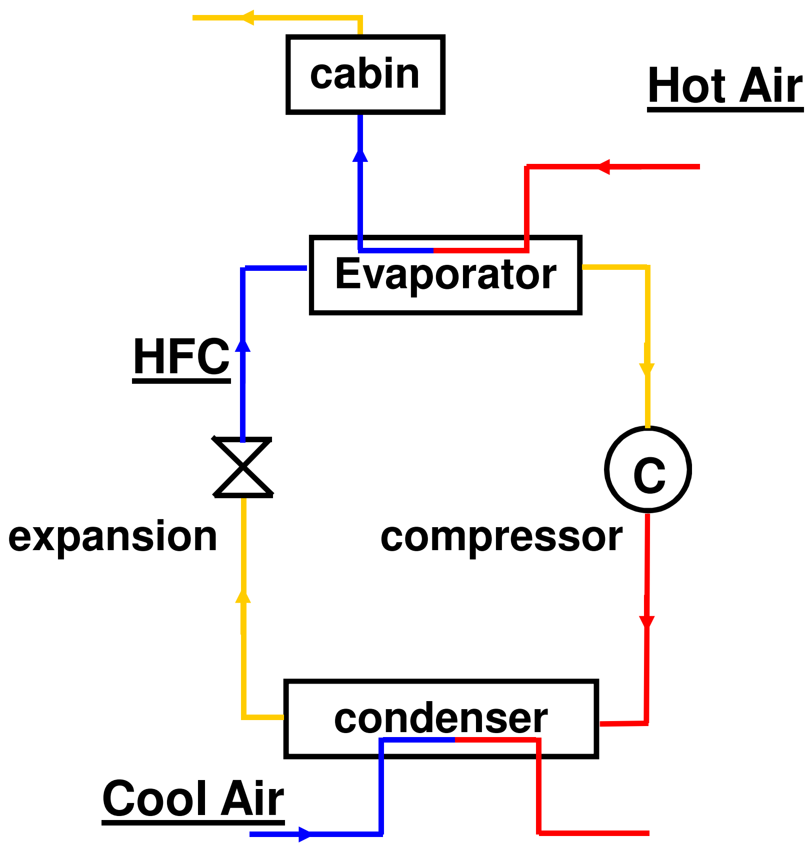
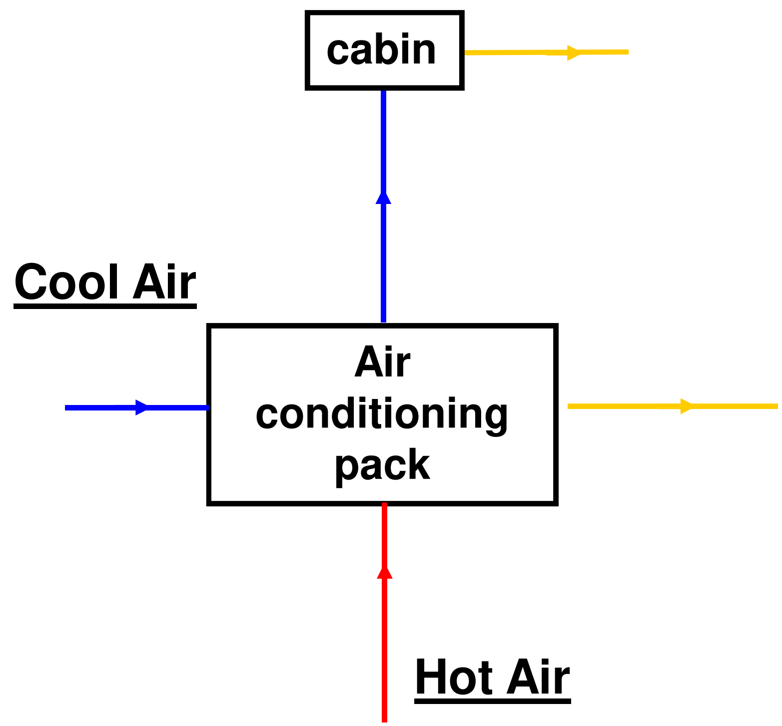
Primary Technology - Different Approaches

- VAPOR CYCLE



- AIR CYCLE



Primary Technology - Different Approaches

VAPOR CYCLE

- Closed loop
- Cooling Fluid = refrigerant fluid
- Good Energetic coefficient > 2
- Efficient load for small cabin volume
- Limited performances in heating mode
- Heavy maintenance (fluid leaks)
- Applications :
  - Helicopters
  - POD Cooling
  - Supplemental Cooling (Galley)

AIR CYCLE

- Open loop
- Cooling Fluid = air
- Average Energetic coefficient < 1
- Reduced weight for large cabin volume
- Easy modulation Cold/Hot
- Reduced maintenance
- Applications :
  - Airplanes
  - Trains

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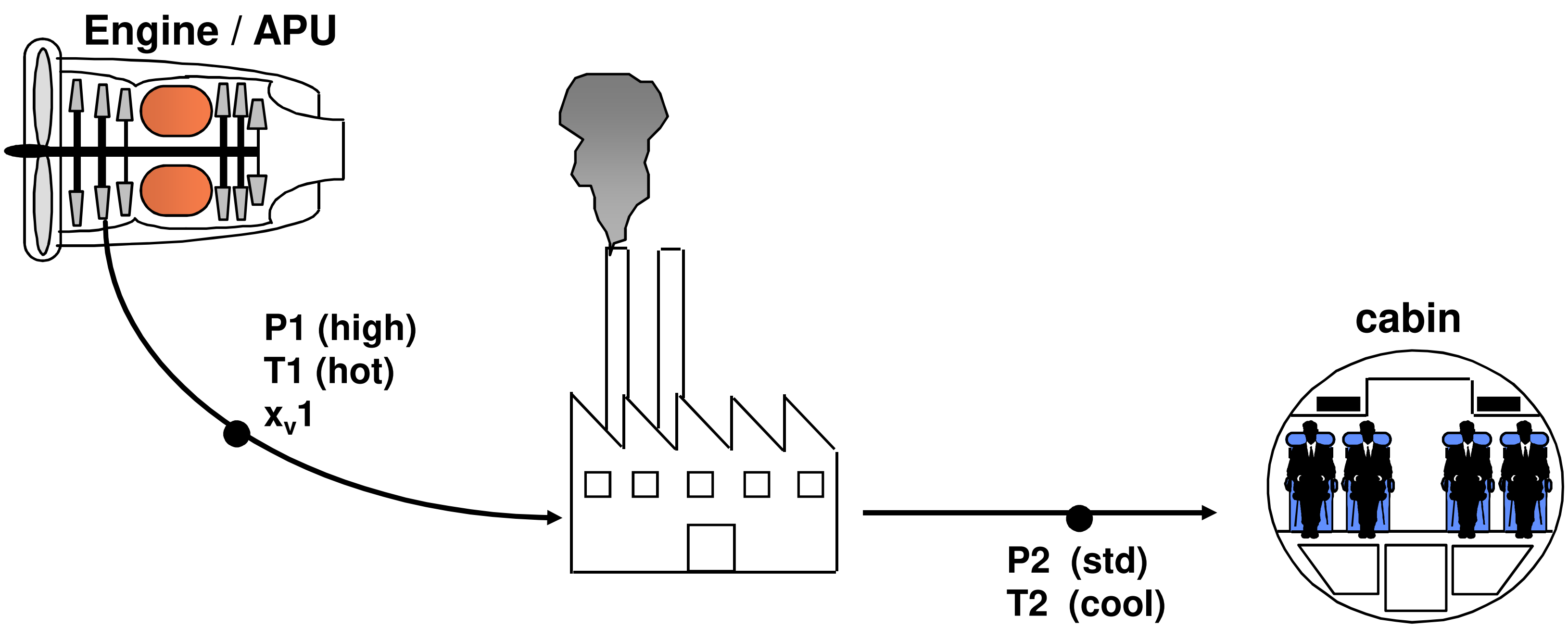
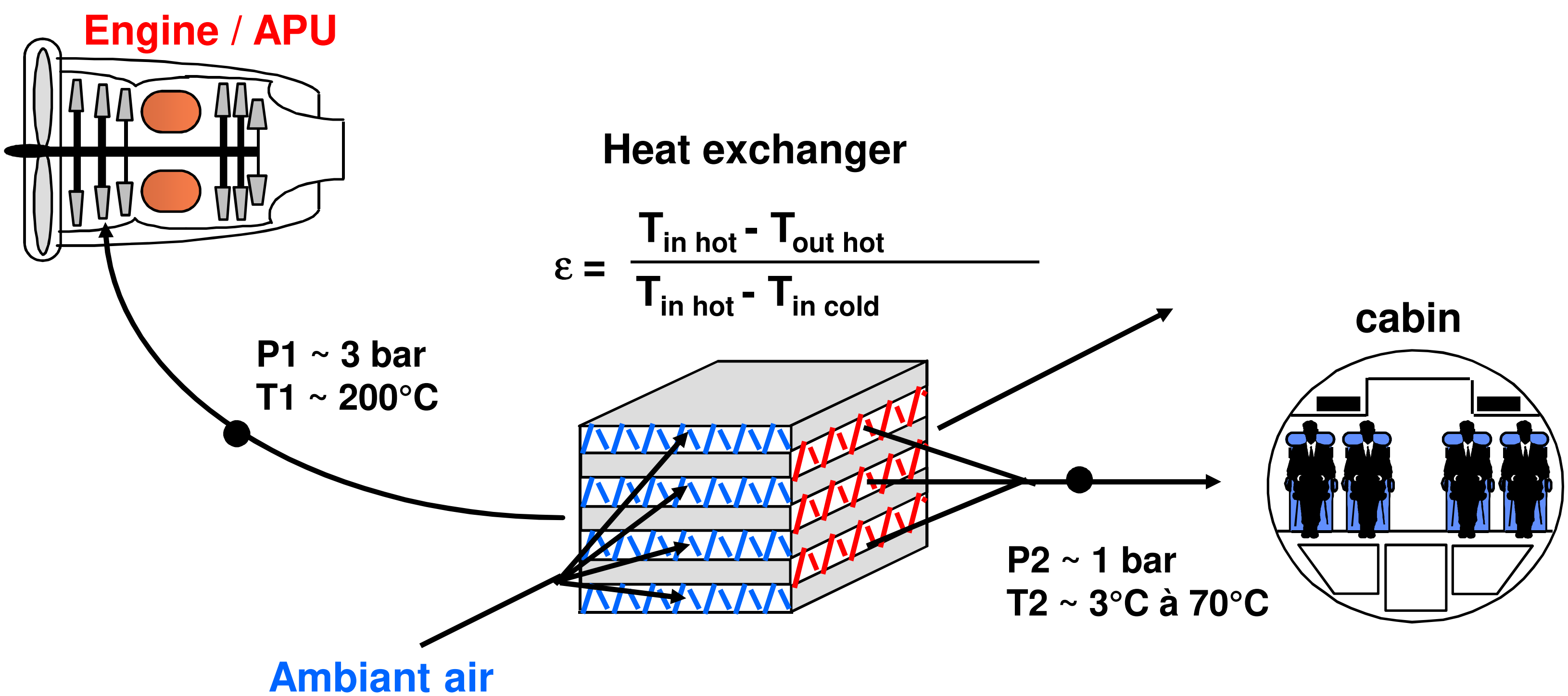
Air Cycle Systems - Operating Principles



Air conditioning pack :

- ⇒ pressure
- ⇒ temperature
- ⇒ humidity

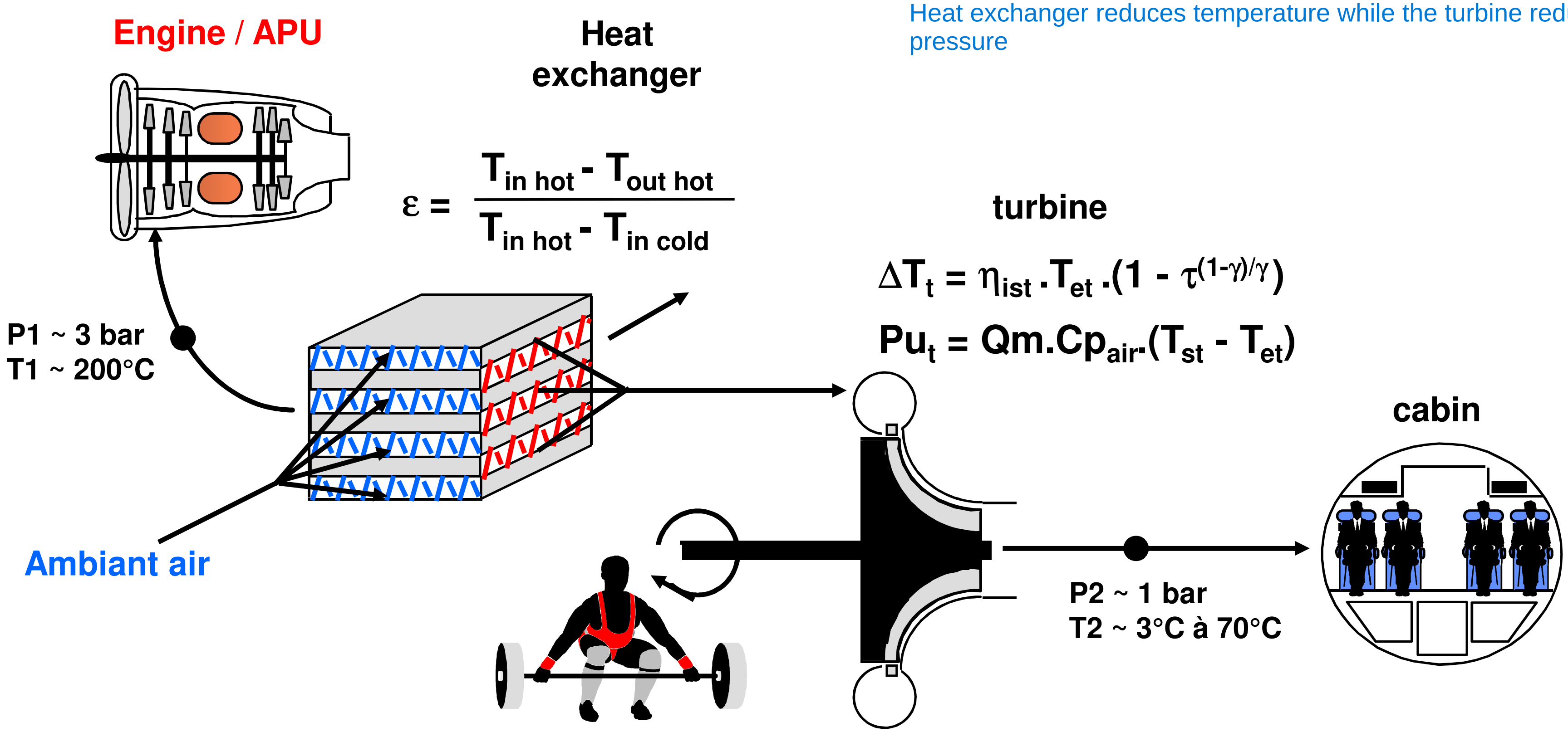
Air Cycle Machines - technology evolution



- Distribution Temperature > Outside Air Temperature
- Expansion potential P1 / P2 not fully used

Air Cycle Machines - technology evolution

Heat exchanger reduces temperature while the turbine reduces pressure



⇨ **Mechanical air power available**

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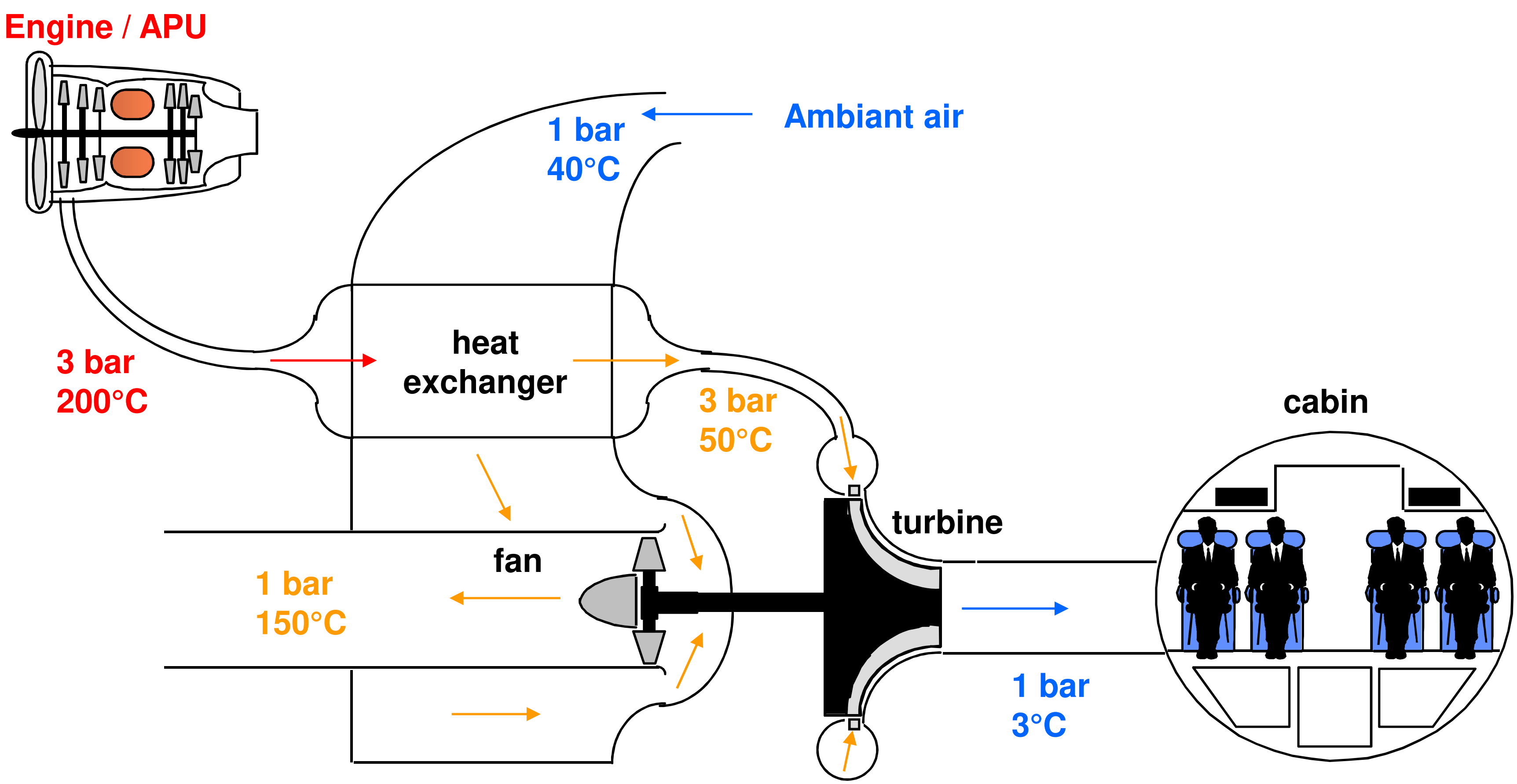
Air Cycle Machines - Turbo-fan



$$Pu_v = - (Pu_t - Pu_{\text{pertes mécaniques}})$$

$$Pu_v = \rho_{air}.Qv.Cp_{air}.(T_{sv} - T_{ev})$$

$$\Delta T_v = T_{ev}.(\tau^{(\gamma - 1)/\gamma} - 1) / \eta_{isv}$$

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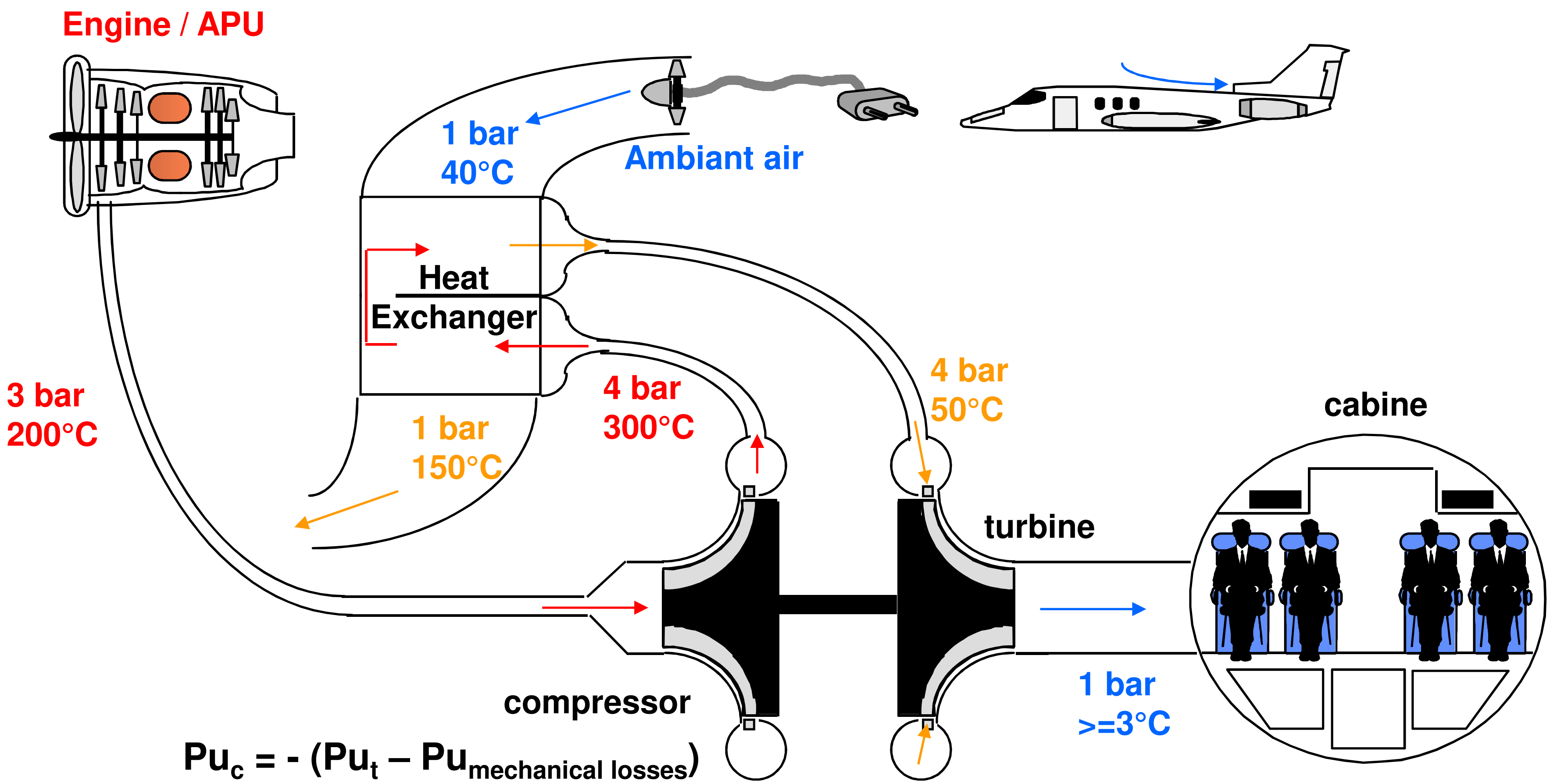
The compressor increases the pressure of the air as well as the temperature. This increases the effectiveness of the heat exchanger and allows to reduce the size of the heat exchanger. A final lower temperature is also possible

Air Cycle Machines - Turbo-compressor



$$Pu_c = -(Pu_t - Pu_{mechanical\ losses})$$

$$Pu_c = Qm.Cp_{air}.(T_{sc} - T_{ec})$$

$$\Delta T_c = T_{ec}.(\tau^{(\gamma-1)/\gamma} - 1) / \eta_{isc}$$

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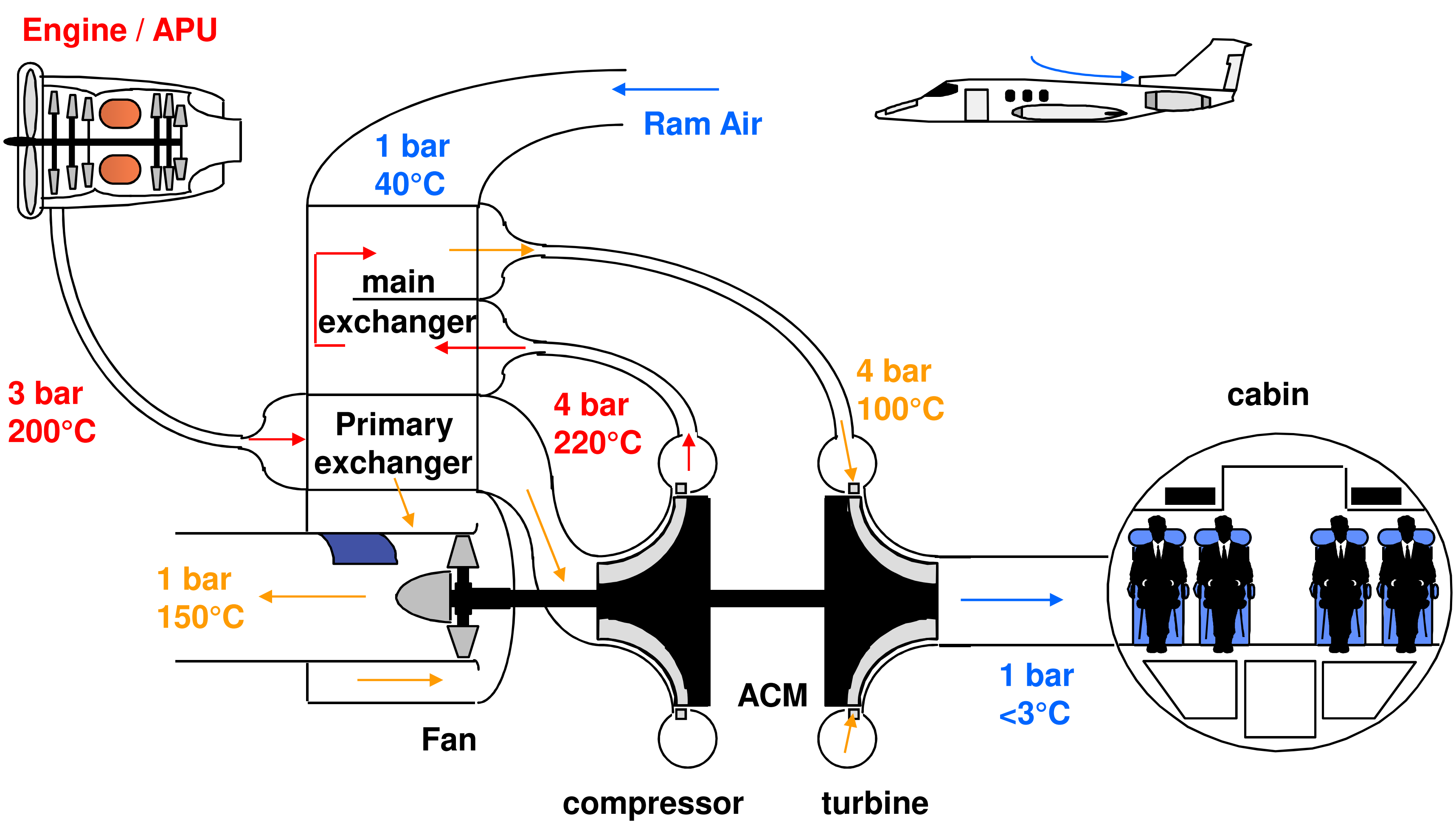
The fan allows a steady flow of ambiant air. The primary exchanger reduces the temperature a bit to be able to compress it more and also heat it more

Air Cycle Machines - Modern Bootstrap 3 Wheel Design



Modern ACMs drive fan wheel on the same shaft and use air bearings to obtain low friction, very high RPMs and high reliability.

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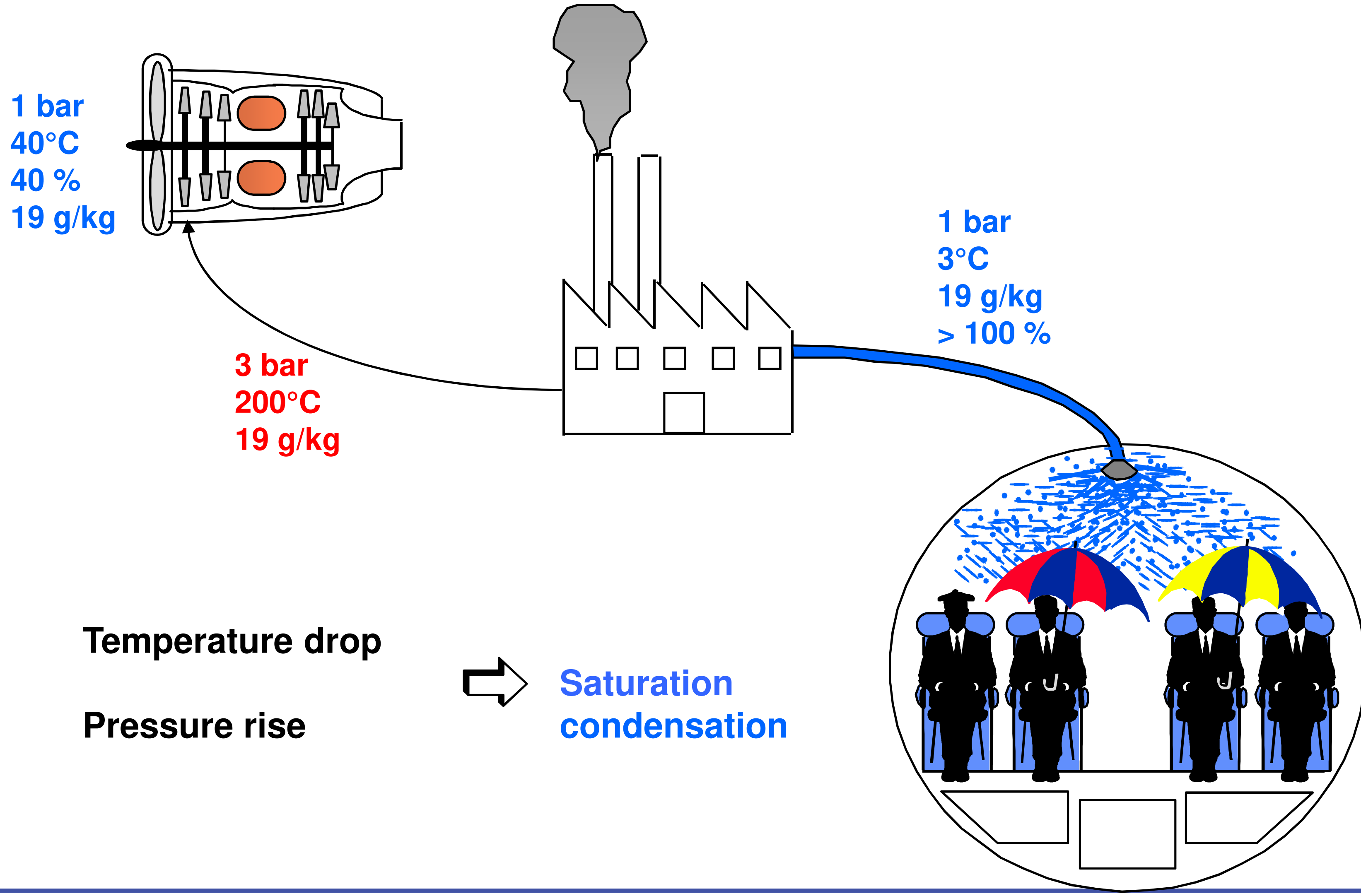
Air Cycle Machines- Water Extraction



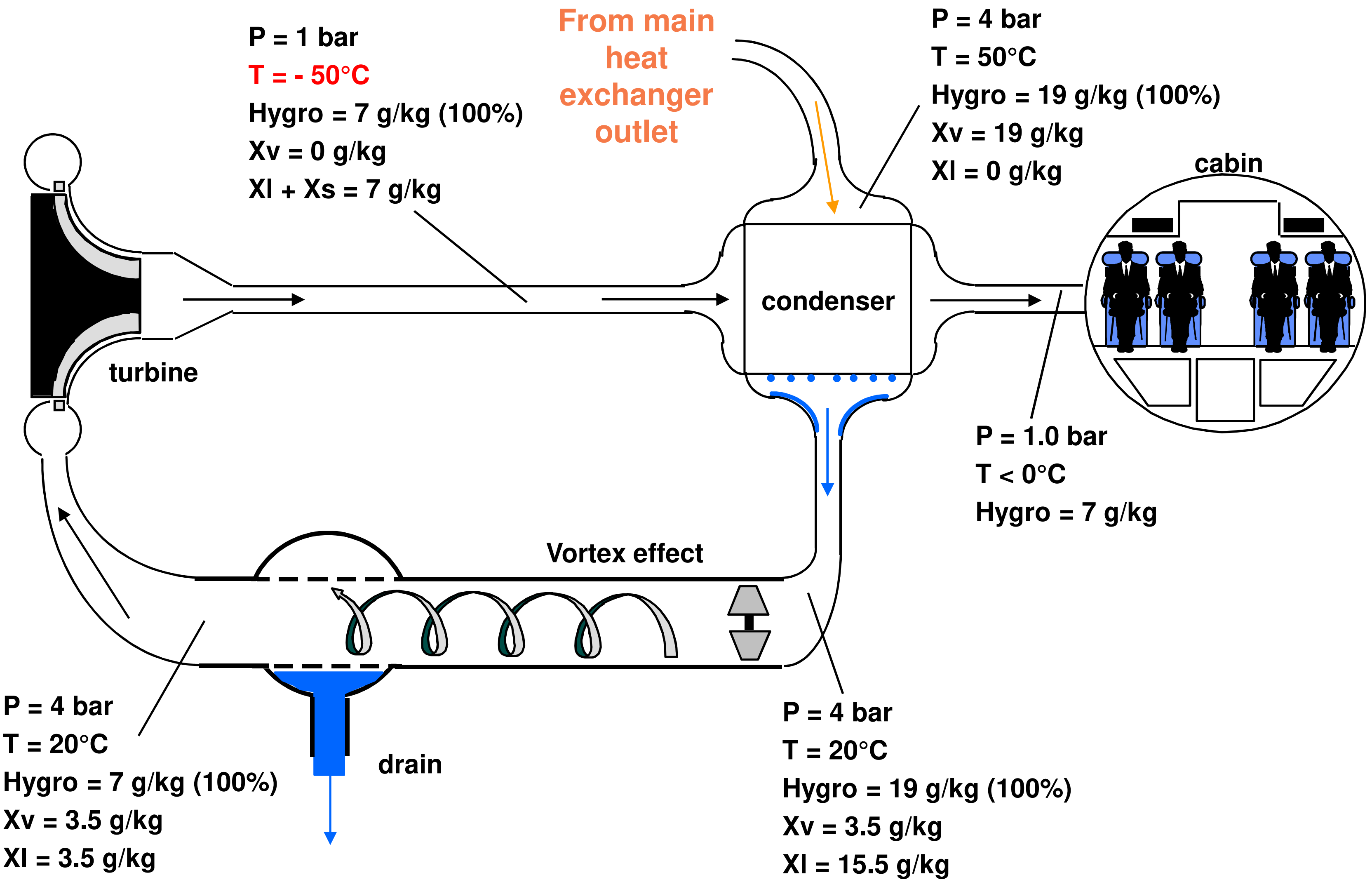
Temperature drop

Pressure rise

⇨ Saturation condensation

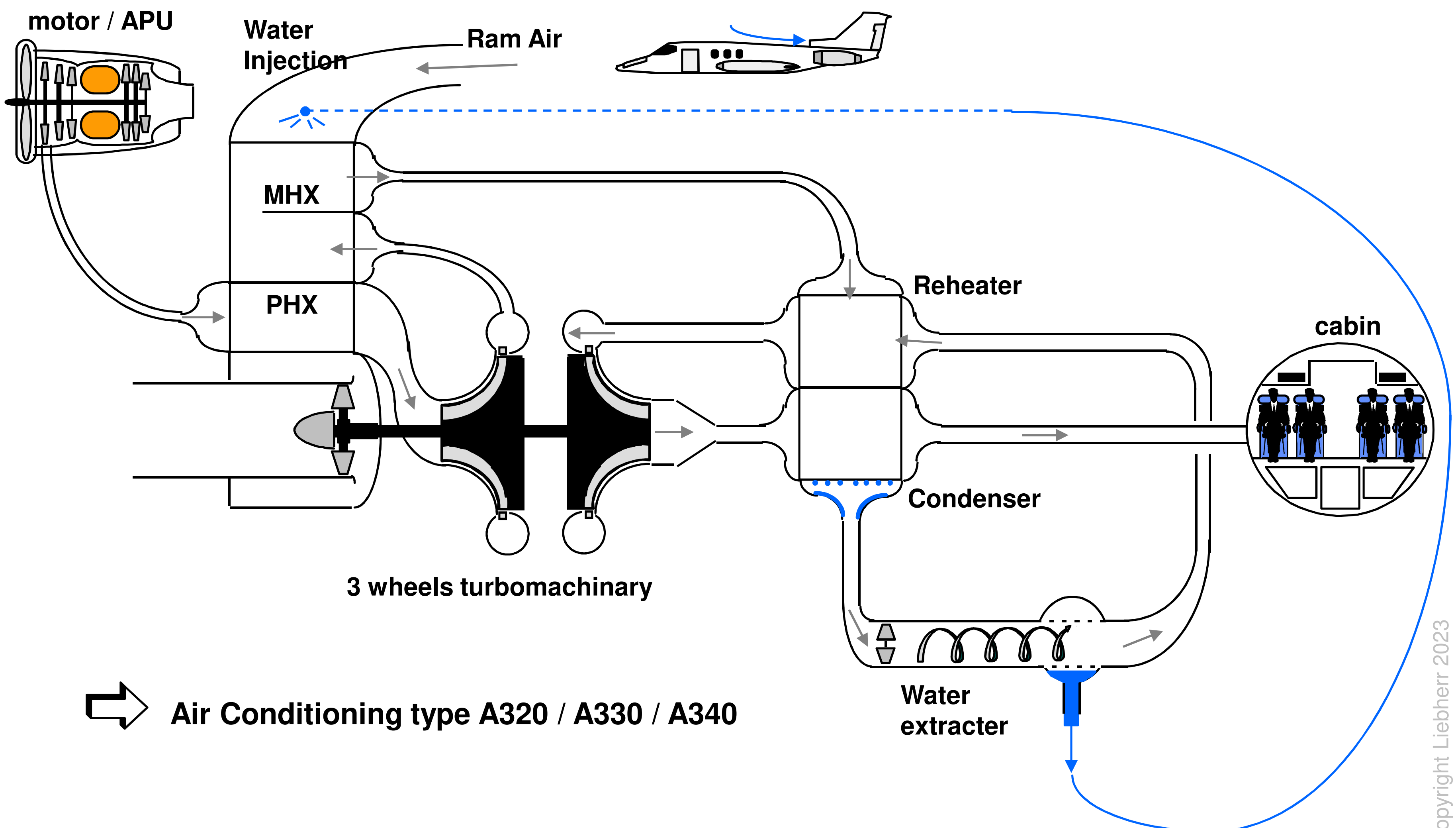
The condenser is a heat exchanger that cools down air to the point where a lot of it condenses. Then, the liquid part is drained out by the vortex effect and the rest is expanded by the turbine. This results in mostly liquid and solid composition which is fed into the condenser.

Air Cycle Machines- Water Extraction



The reheater is another heat exchanger that heats the air a little before it enters the turbine. This results in a slightly higher temperature of the air after expansion which prevents the pipes from freezing (-50deg is too less).
The drained water is used to further reduce the temperature of the ambiant air to make the MHX more effective

Air Cycle Machines- Water Extraction



Air Conditioning type A320 / A330 / A340

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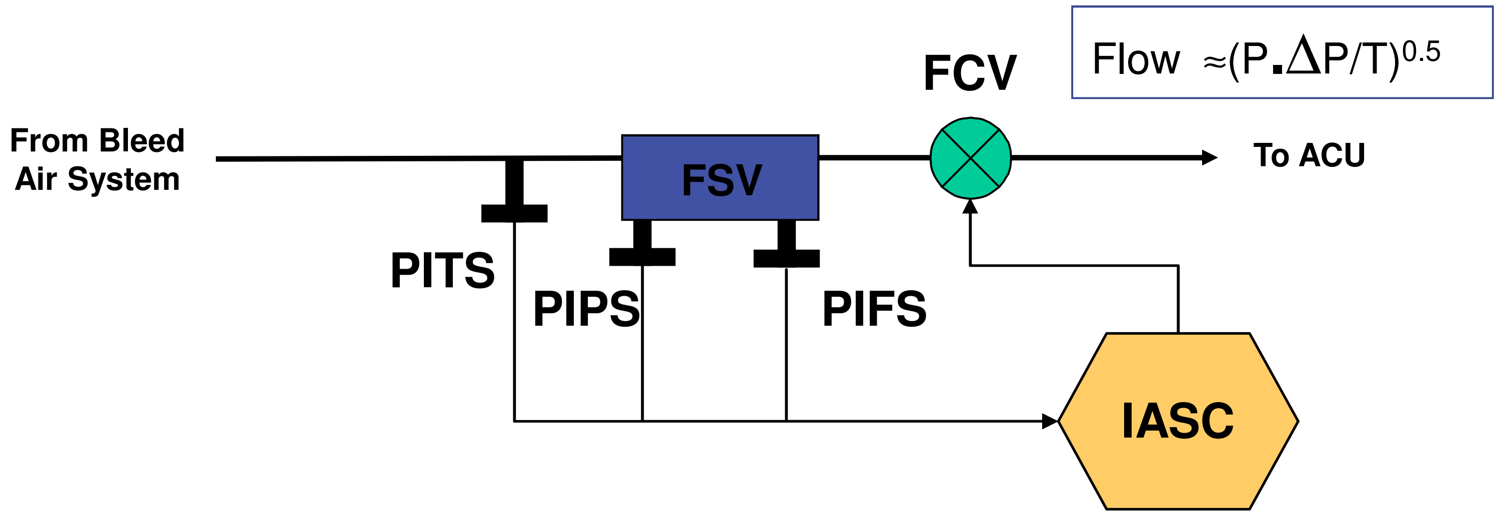
Flow Control sub–system



- PITS - Pack Inlet Temp Sensor (T)
- PIPS - Pressure Senor (P)
- PIFS – Flow Sensor (ΔP)
- FCV – Flow control Valve - manages mass flow into Air Cycle Unit
- FSV – Flow Sensor Venturi
- IASC – Integrated Air System Controller

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Air Conditioning Units and Ram Air

- The AIR CONDITIONING UNITS **perform the following functions**
  - Temperature & Humidity conditioning of the bleed air
  - Temperature control of the cabin zones & cockpit
  - Protection of the system against extreme temperature and against effects of freezing.

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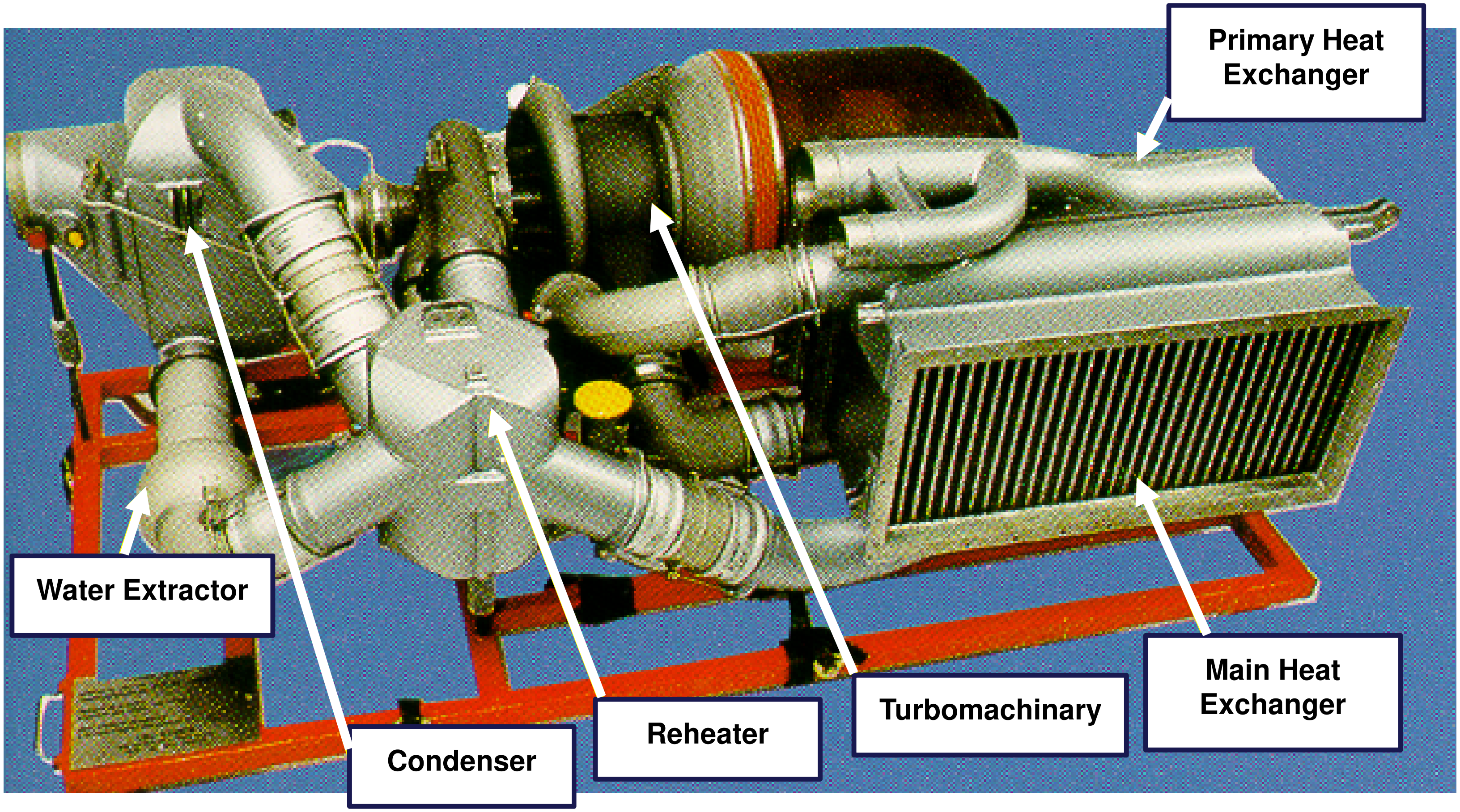
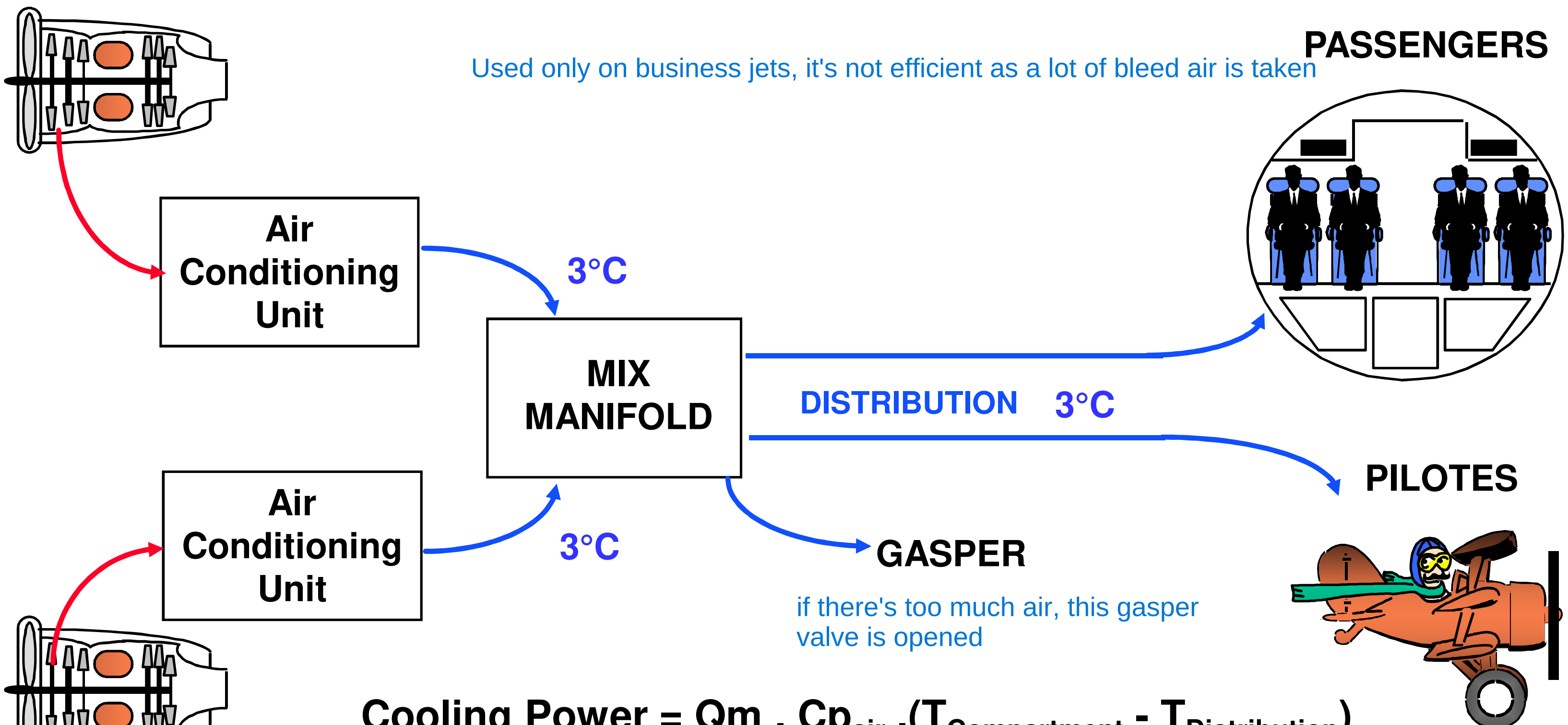
Air Conditioning Units and Ram Air



Air Distribution – without Recirculation



$$\text{Cooling Power} = Qm \,.\, Cp_{air} \,.(T_{Compartment} - T_{Distribution})$$

$$T_{Distribution} = T_{Pack\ Outlet}$$

$$T_{Distribution} > 3°C \Longrightarrow T_{Pack\ Outlet} > 3°C$$

In order to maintain acceptable cabin temp supply & ventilation, full potential of ACM not used. Engine flow is equal to distribution flow.

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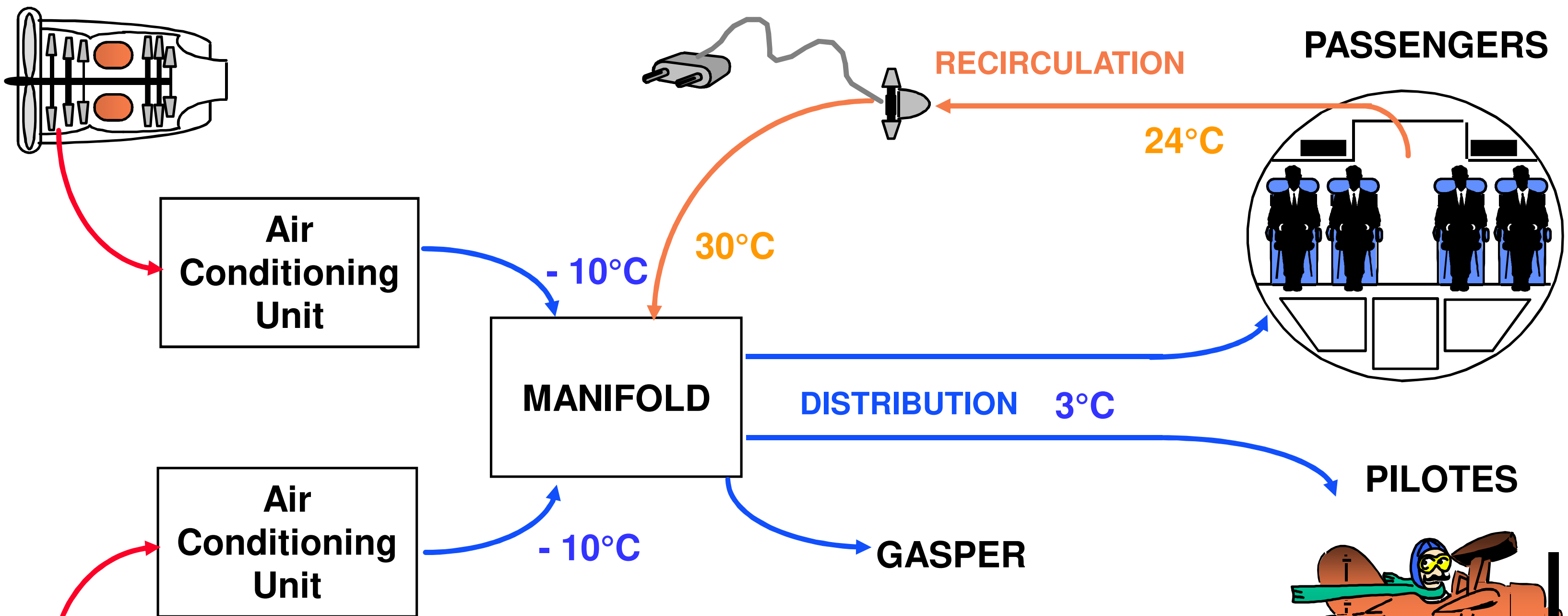
Air Distribution – with Recirculation

what every other aircraft uses



$$\text{Cooling Power} = Qm \cdot Cp_{air} \cdot (T_{Compartment} - T_{Distribution})$$

$$T_{Distribution} = T_{Mixmanifold\ Outlet}$$

$$T_{recirculation} > 24°C \Rightarrow T_{Pack\ Outlet} < 0°C$$

Permits reduced engine demand- increased fuel efficiency whilst maintaining better cabin circulation, and clean air. Engine flow is about half distribution flow.

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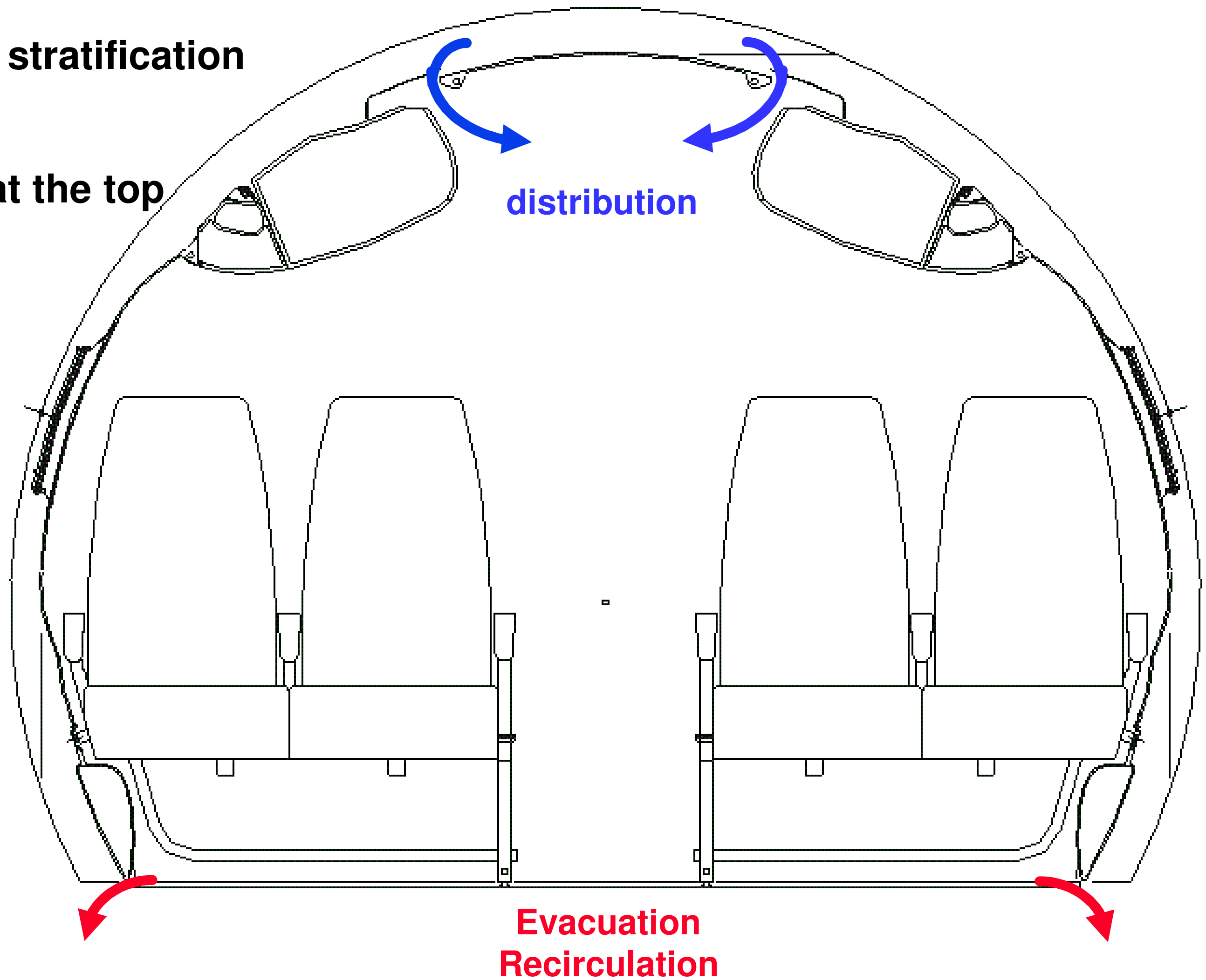
Cabin Air Distribution

Must be designed for :

- **Avoid temperature stratification**
- **Avoid Cold Feet**
- **Avoid all the heat at the top**
- **Low noise**



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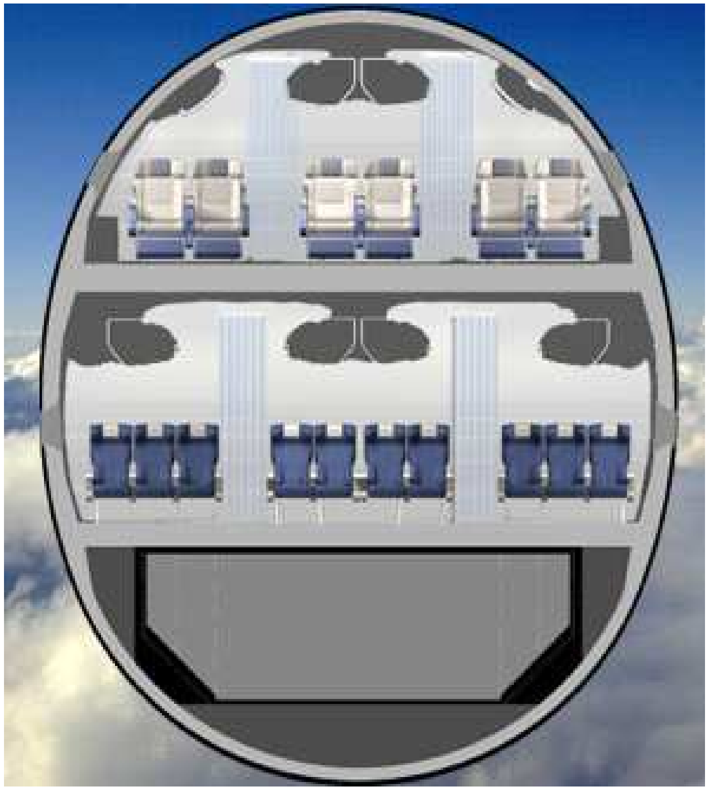
Most Complex Systems!



2 Level Cabin type A380 or 747-800 with 2 Recirc circuits to improve exchanges between zones, avoid cold zones (stairways etc)

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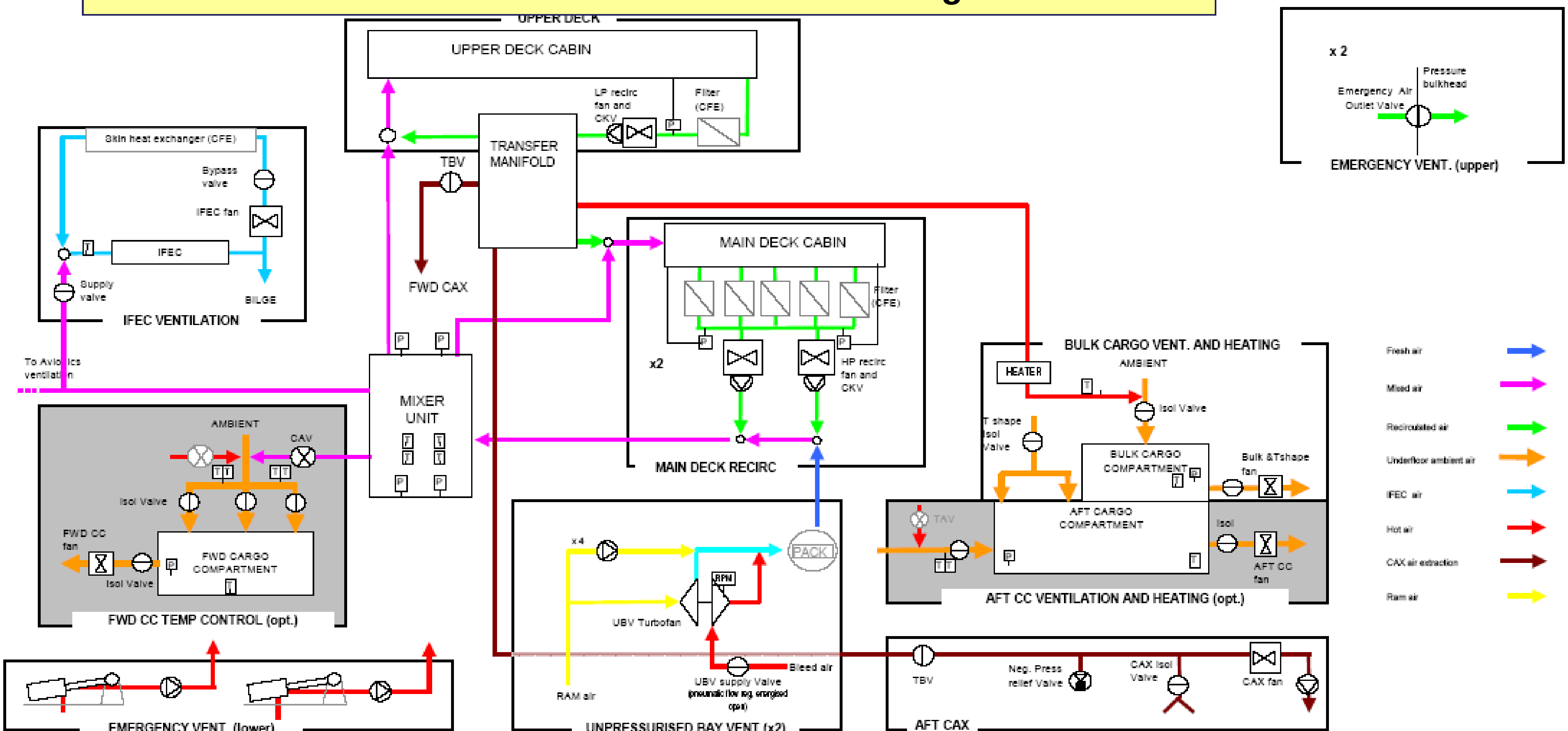
Result in extremely complex distribution/ventilation…

Thermal cabin simulation and control modeling is a critical element in successful cabin ECS design



Modeling, system and system control architecture must permit solutions for all aircraft customer delivery configurations

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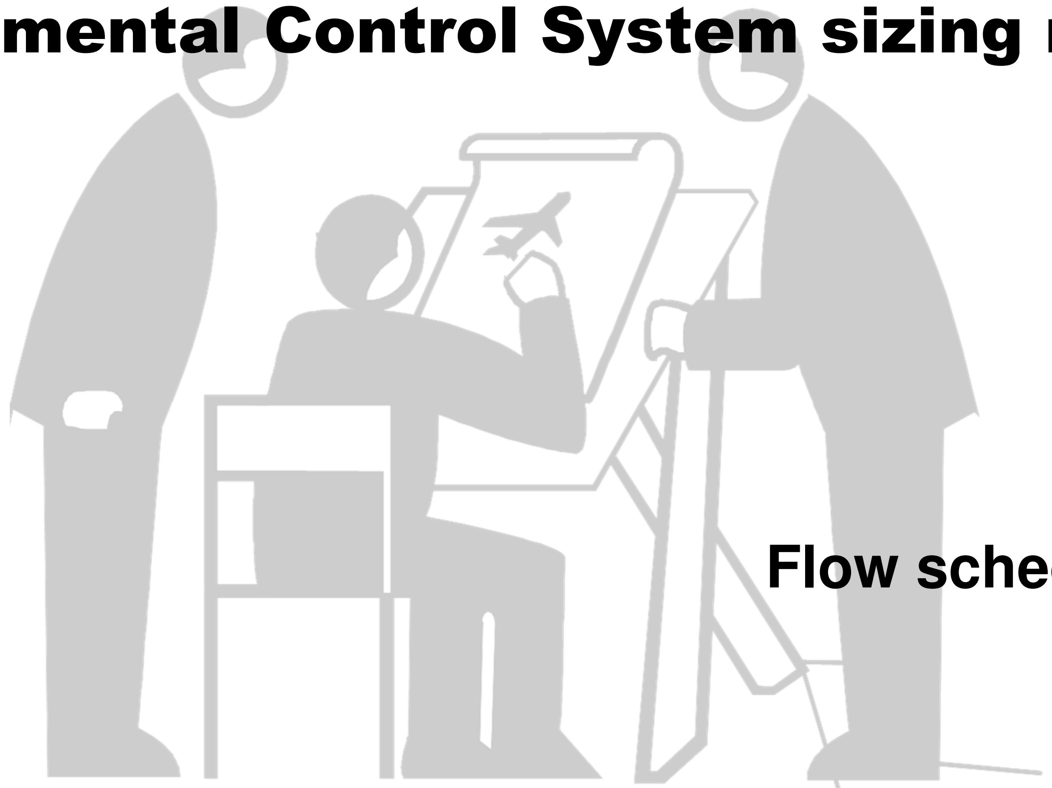
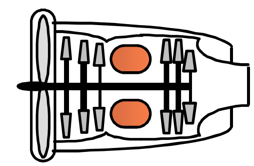
Environmental Control System sizing method



Flow schedule

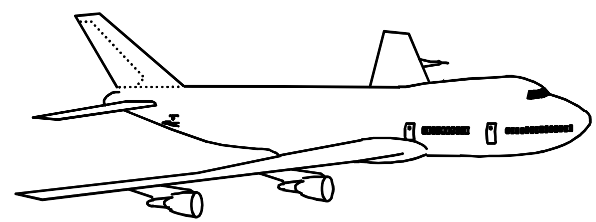
Environmental Control System sizing method

- Evaluate cabin heat loads

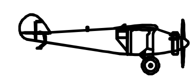


- Calculate flow schedule taken on engine

- Size cooling packs (air cycle or vapour cycle)



- Optimize the system



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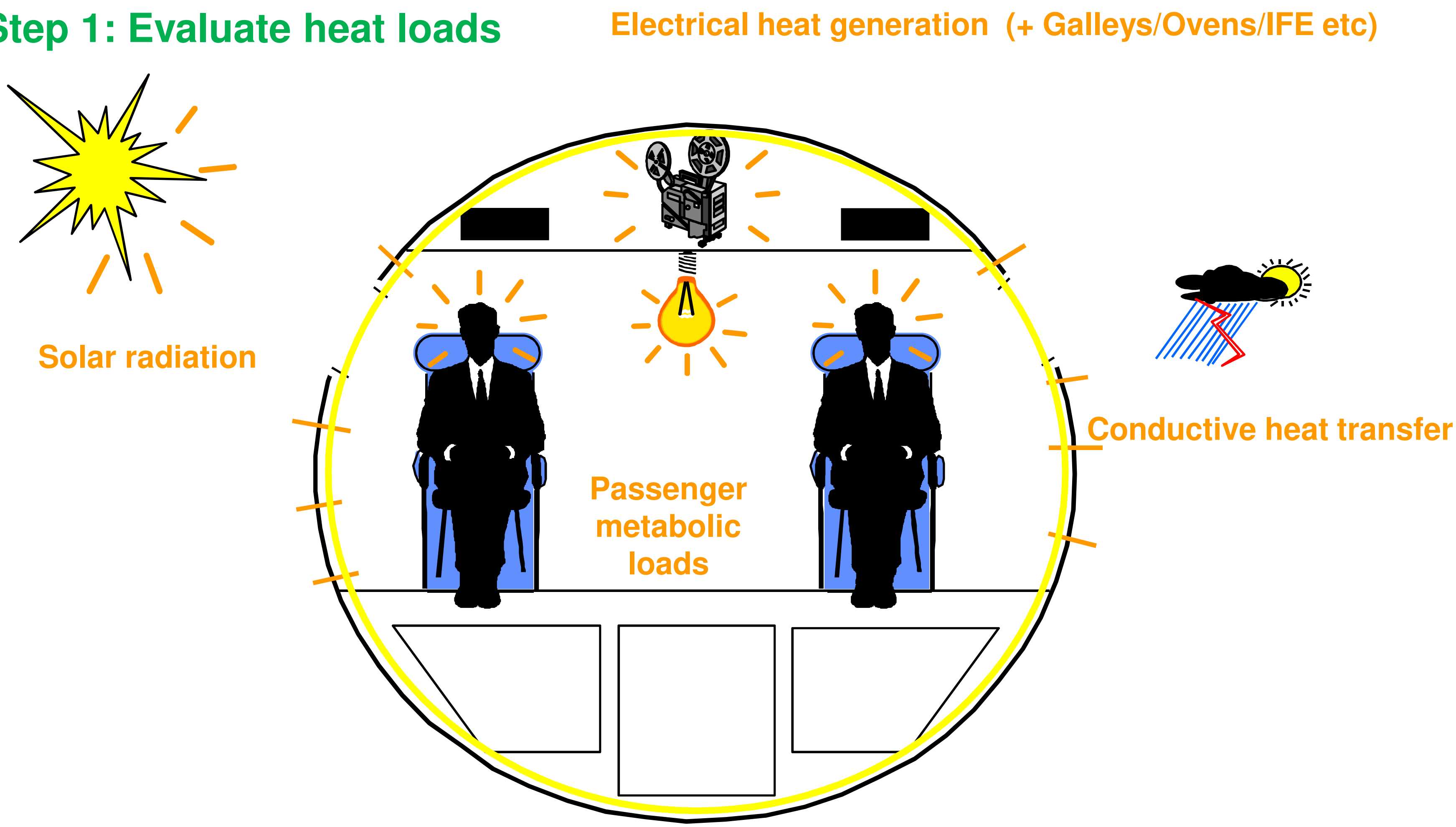
ECS sizing method : Heat loads calculation

Step 1: Evaluate heat loads



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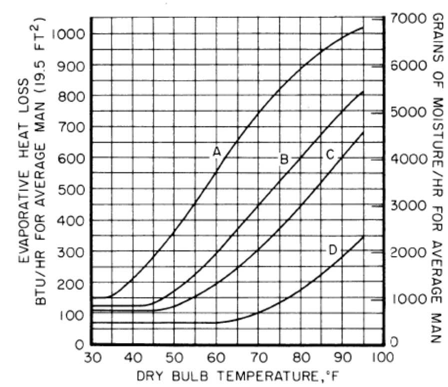
ECS sizing method : Heat loads calculation

Metabolic loads

- Number of occupants (passengers + crew members)
- 1 seated passenger ~75W + 1g/min exhaled water at 24°C
- 1 working crew member ~150W + 2.5g/min exhaled water at 24°C
- Exhaled water is only taken into account in heat loads if there is a recirculation
- This water will condensate (so release heat) within:
  - Evaporator (Vapour cycle)
  - Mixmanifold (Air cycle pack with cabin air recirculation)

$$Heat\ Loads_{metabolic}\,(W) = \mathbf{188 - 4.7\,T_{cab}}\ (°C)$$



SAE AIR 1168/3

Electric components heat dissipation

- Lights
- Galley components (ovens)
- Avionics depending on installation and ventilation of it
- IFE (In Flight entertainment)
- If no value given by aircraft manufacturer consider

$$Heat\ Loads_{electric}(W) = \mathbf{800 + 60\,.\,N_{pax}}$$

Solar Heat Loads

- Projected windows area = 0.5 x Total windows area (only one side can be heated by the sun!)
- Windows transmissivity ~0.7
- Effective projected windows area = 0.7 x 0.5 x Total windows area
- Solar flux : 1135W/m² on ground (higher solar flux at higher altitude)

ECS sizing method : Heat loads calculation

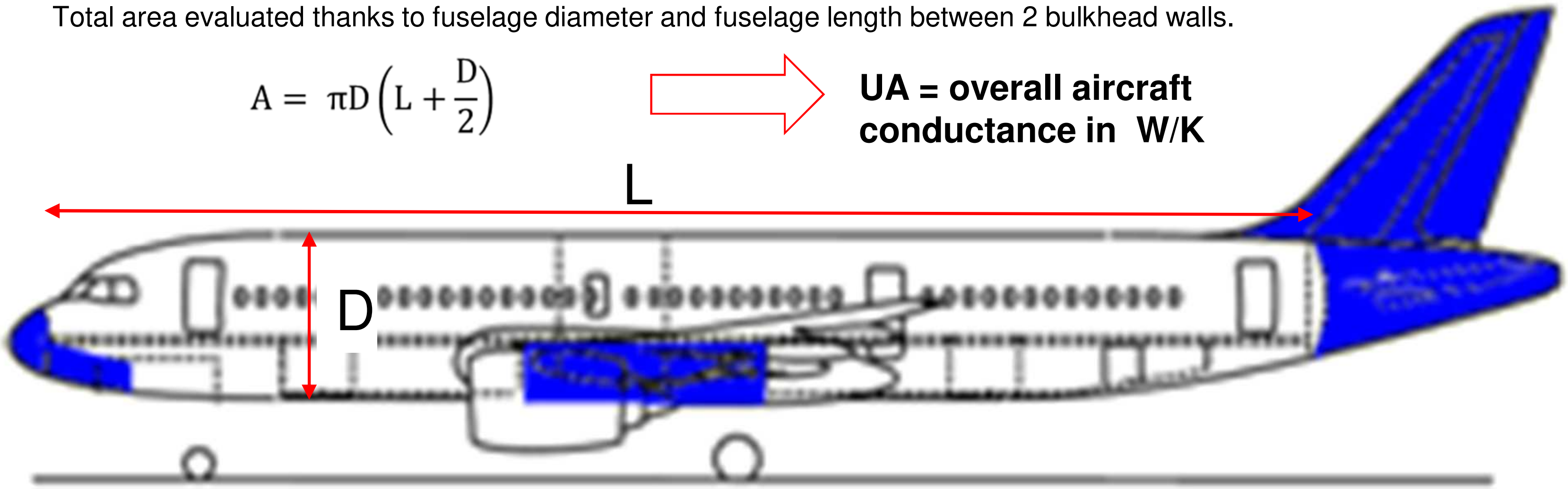
External Heat Loads

- Heat transfer coefficient between aircraft skin and cabin air (internal convection + conduction)
  - Helicopter/military aircraft — U = 5 W/m²/K
  - General Aviation — U = 2.4 W/m²/K
  - Business Jet — U = 1.5 W/m²/K
  - Regional Jet — U = 1 W/m²/K
  - Single aisle, Widebody — U = 0.7 W/m²/K

  Total area evaluated thanks to fuselage diameter and fuselage length between 2 bulkhead walls.

$$A = \pi D \left(L + \frac{D}{2}\right)$$

UA = overall aircraft conductance in W/K



- **Skin temperature Ts**
  - **Ground hot day** — **Ts (°C) = 1.2368 x OAT (°C)**
  - **Ground cold day** — **Ts = OAT**
  - **Flight** — **Ts(K) = OAT (K) x (1+0.18M²)**

$$P_{ext} = UA.(T_s - T_{cab})$$

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ECS sizing method : Heat loads calculation

- Hot day / Cold day assumptions – Normal case/failure case

	Normal case	Failure case
Hot Day	■ Maximum number of occupents (passengers, crew member) ■ Solar loads ■ Maximum aircraft speed ■ OAT max (performance not operational !) ■ Maximum electric loads ■ Cabin air temperature ~24°C	■ Maximum number of occupents (passengers, crew member) ■ Solar loads ■ Maximum aircraft speed ■ OAT max (performance not operational !) ■ 50% Maximum electric loads ■ Cabin air temperature between 27 and 32°C
Cold Day	■ 20% of maximum number of occupents (passengers, crew member) ■ No solar loads ■ Minimum aircraft speed ■ OAT min (performance not operational !) ■ 20% of max electric loads (50% for cockpit) ■ Cabin air temperature ~24°C	■ 20% of maximum number of occupents (passengers, crew member) ■ No solar loads ■ Minimum aircraft speed ■ OAT min (performance not operational !) ■ 20% of max electric loads (50% for cockpit) ■ Cabin air temperature between 15 and 21°C

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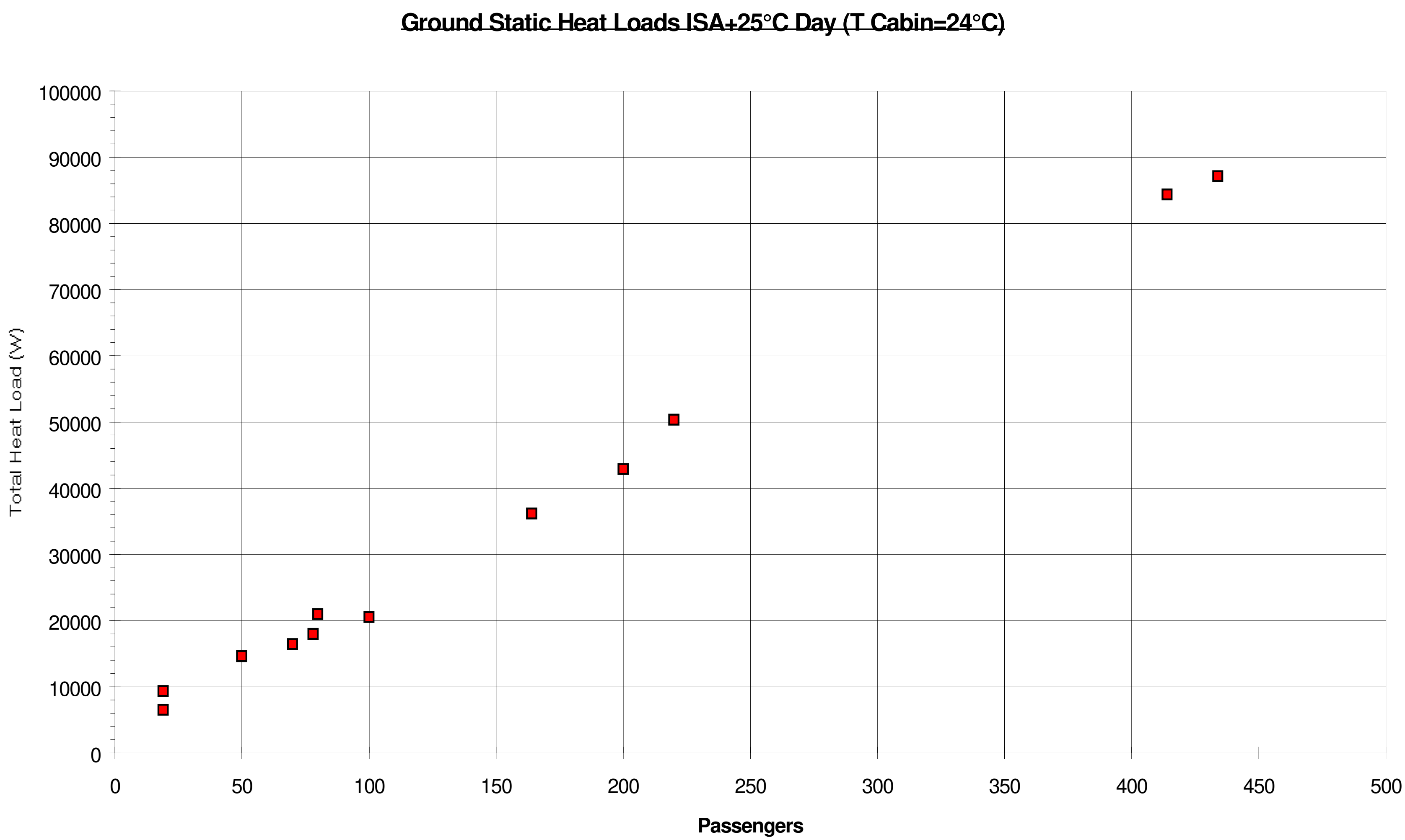
ECS sizing method : Heat loads calculation

Validate your calculations, compare to existing aircrafts



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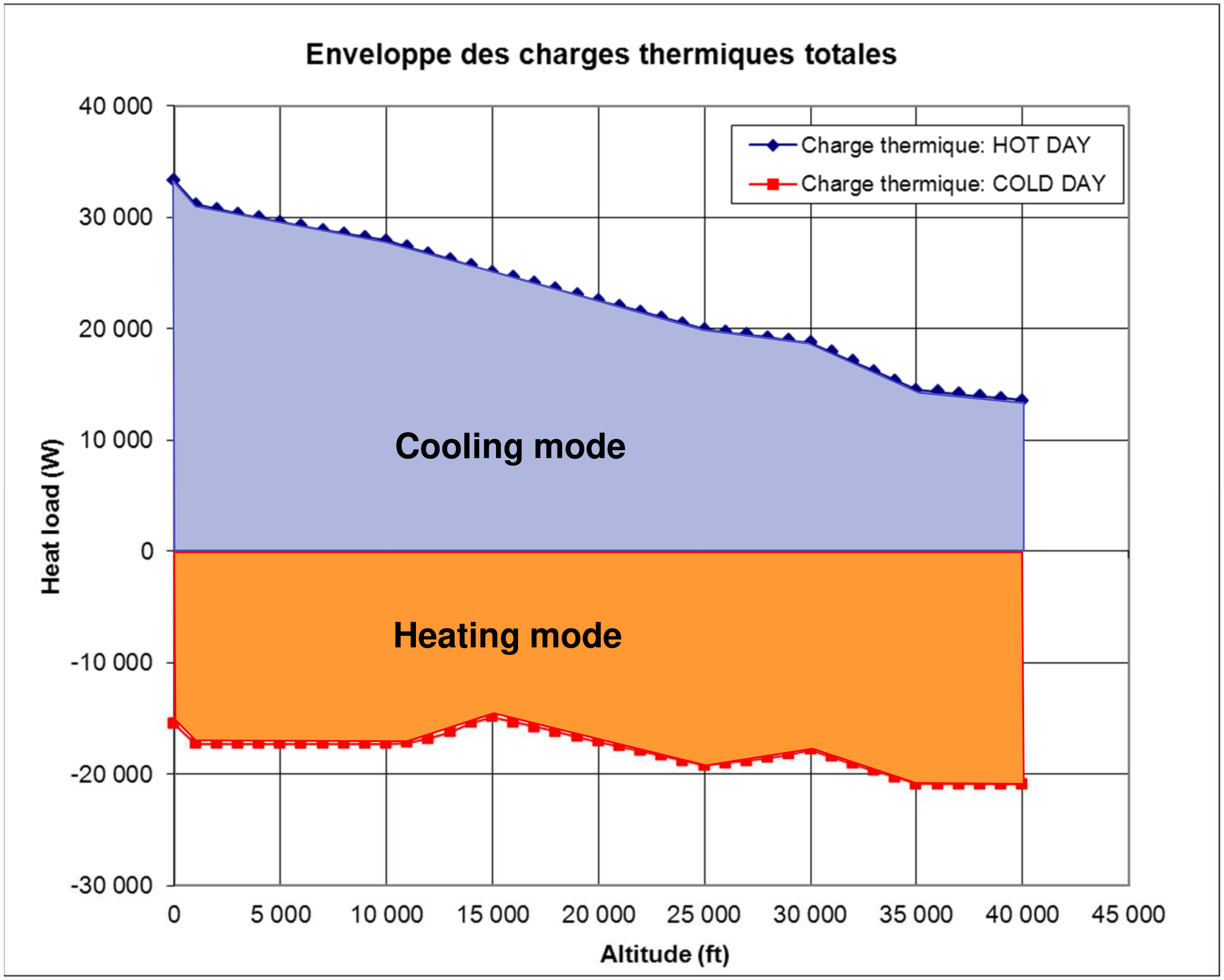
ECS sizing method : Heat loads calculation

- Example of cabin heat loads for a single aisle aircraft



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ECS sizing method : Flows calculation

Step 2: Evaluate minimum flow to cover all the functions

- **Minimum flow for thermal comfort : cooling and heating**

  Based on heat loads calculated in step 1 and following assumptions on blowing air :

  - Temperature in cabin:
    - Without passenger : ~3°C minimum, ~70°C maximum
    - With passengers : ~8°C et ~50°C
  - Liquid water in cabin (will evaporate partially in distribution ducts)

    ≈1 to 2 g/kg dry air maximum

- **Fresh air flow : certification rules**
  - 0.55 lb/mn/passenger minimum in normal case
  - 0.40 lb/mn/passenger minimum in failure case (it is authorized to be during few minutes under this value if CO_2 analysis demonstrate CO_2 concentration is under 5000ppm)
  - 10 ft3/mn (cfm) minimum per crew member in normal and failure case (0.8ppm on ground, 0.55ppm at 8000ft cabin altitude)

    => to simplify we provide twice passenger flow to crew member

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ECS sizing method : Flows calculation

Step 2: Evaluate minimum flow to cover all the functions

- **Pressurization and re-pressurization flow**

Pressurization flow is calculated based on sum of all equivalent leakage area:

- end of life aircraft equivalent leakage area

- OFV (Outflow Valve) on its minimum regulation position. In predesign we consider half the aircraft leakage equivalent area.

- electronics cooling valves

Flow (Q) between 2 volumes is linked to equivalent area (A) between those volumes.

Assuming the higher pressure is in volume 0 (noted P0) we get :

For a subsonic flow between 0 and 1 ($\frac{P_0}{P_1} \leq 1{,}893$) :

$$Q = P_0 . A\, 0{,}1562 \sqrt{\frac{\left(\frac{P_0}{P_1}\right)^{-1{,}429} - \left(\frac{P_0}{P_1}\right)^{-1{,}714}}{T}}$$

For a sonic flow between 0 and 1 ($\frac{P_0}{P_1} > 1{,}893$) :

$$Q = \frac{P_0 . A\, 0{,}04045}{\sqrt{T}}$$

With :

Q: flow in kg/s

P0, P1 : pressure in Pa

A : efficient leakage area in m²

T : air temperature in K

Re-pressurization flow is calculated based on pressurized volume and re-pressurization rate (+22 mbar/min = twice normal threshold)

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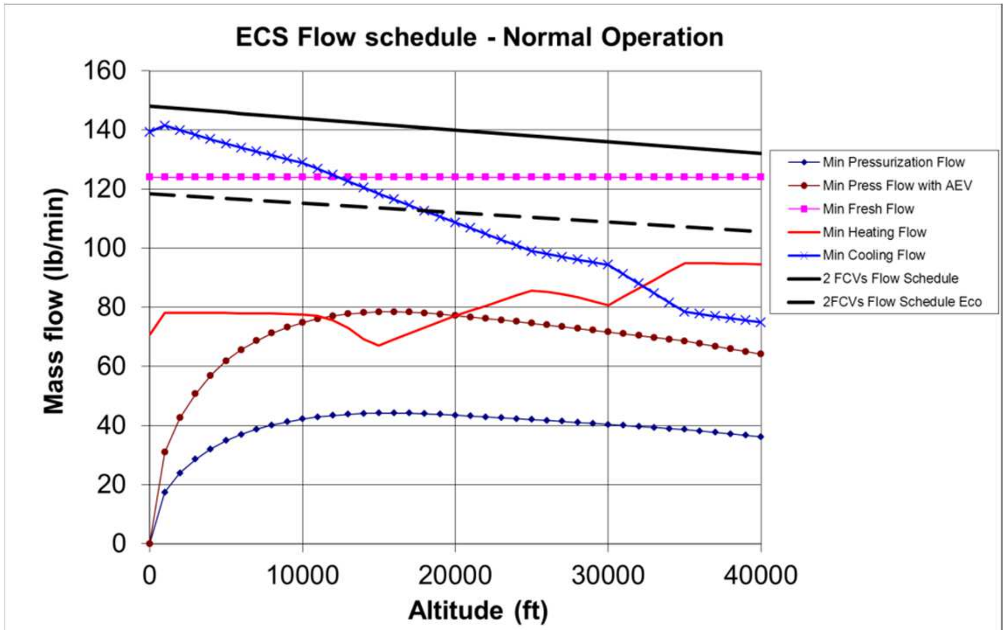
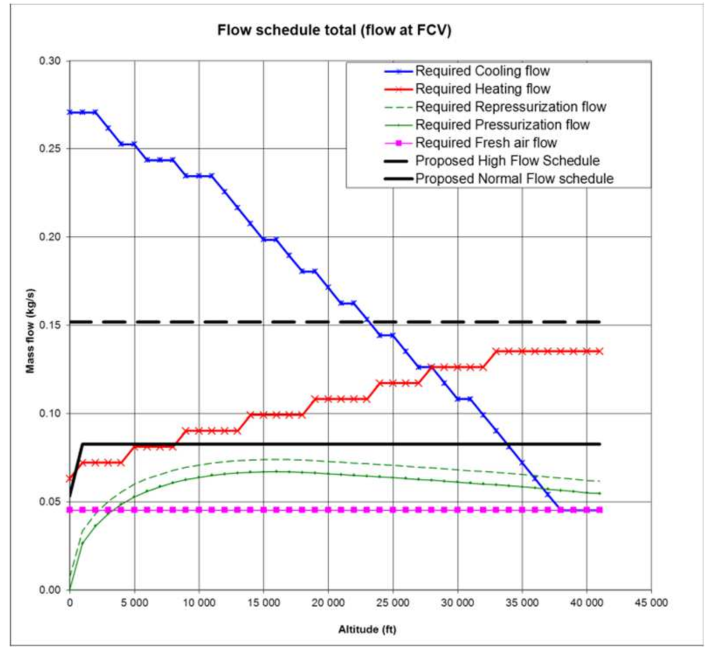
ECS Flow schedules

Step 3: Define global architecture





ECS functions :

- Fresh air
- Cabin Heating
- Pressurization
- Cabin cooling

can be ensured by bleed air without recirculation Air cycle packs

ECS functions :

- Fresh air
- Cabin Heating
- Pressurization

Bleed air

- Cabin cooling

Vapour cycle system

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Course syllabus

Environmental Control System

- System Function and Requirements
- Basic principles and technology evolution
- System Architectures & Sizing
- **Components Description**

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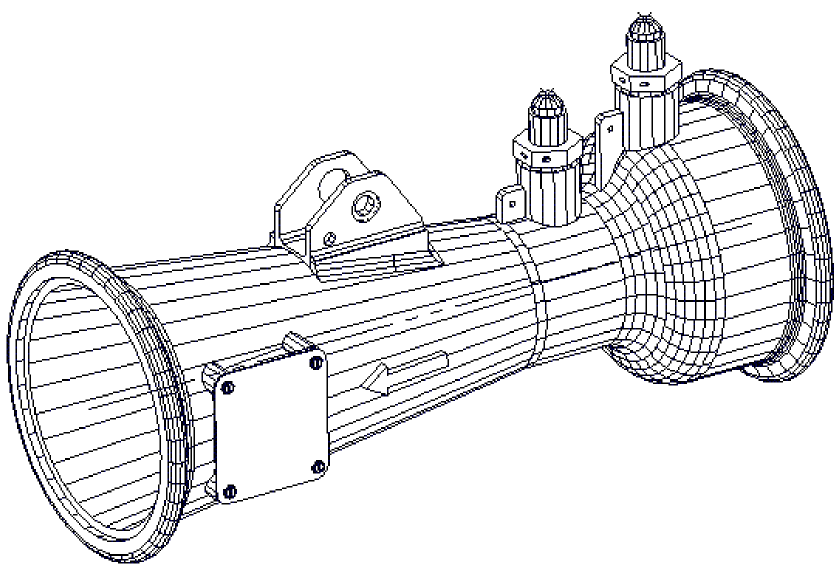
Components Description – Flow Control

- FLOW SENSOR VENTURI

Venturi throat body with two static pressure tappings. 3 inches diameter. Body constructed of light alloy.

Permits calculation of flow velocity – mass rate.



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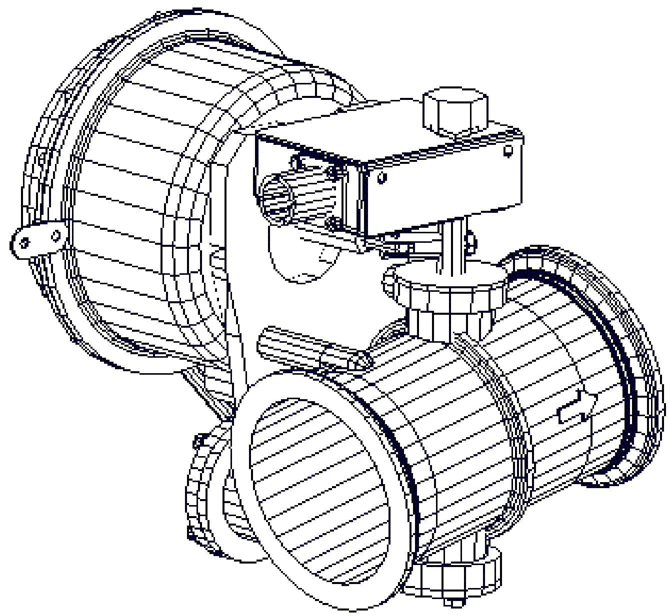
Components Description – Flow Control

- FLOW CONTROL VALVE (FCV) – Cont'd



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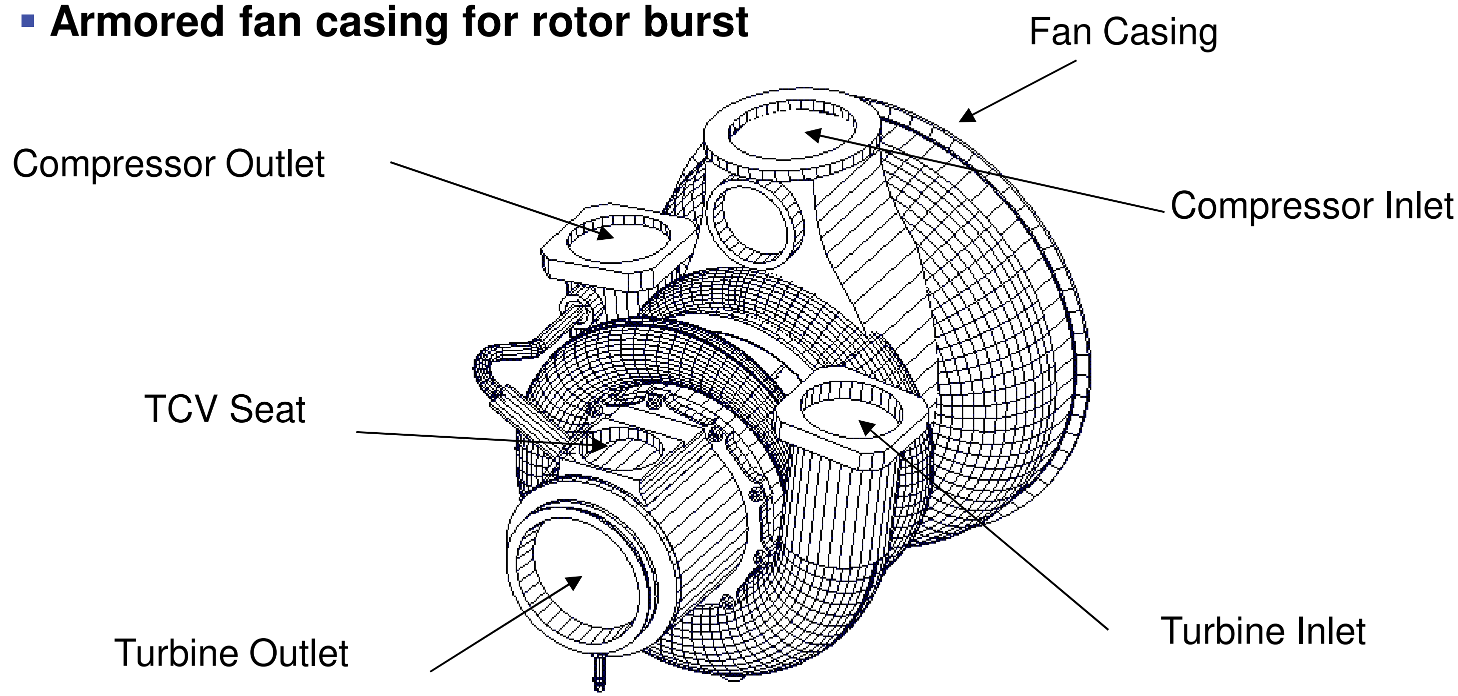
Components Description – ACM

- **AIR CYCLE MACHINE (ACM)**

- **Three Wheels, Air Bearings**
- **Armored fan casing for rotor burst**



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- **Air bearings : (efficiency = 95%)**

Wheel	PERFORMANCES	MATERIAL
Turbine	efficiency = 90%	light Alu alloy (alu)
Compressor	efficiency = 85%	stainless steel
Fan	efficiency = 75%	light Alu alloy (alu)

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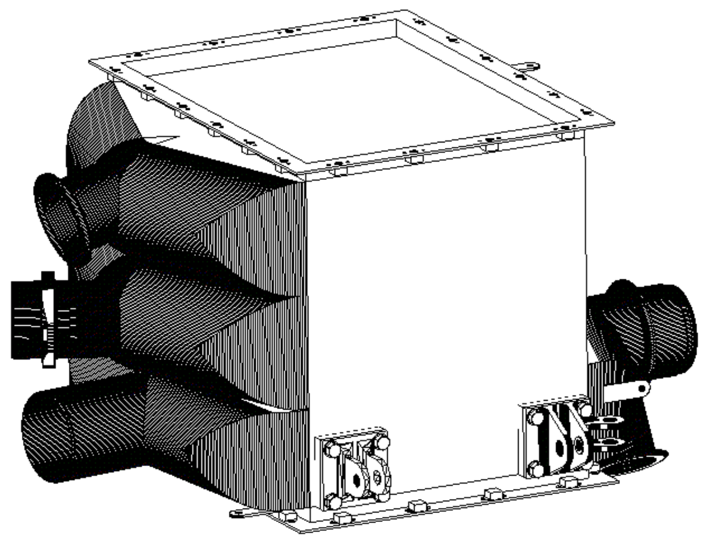
Components Description – Pack

- DUAL HEAT EXCHANGER (DHX)

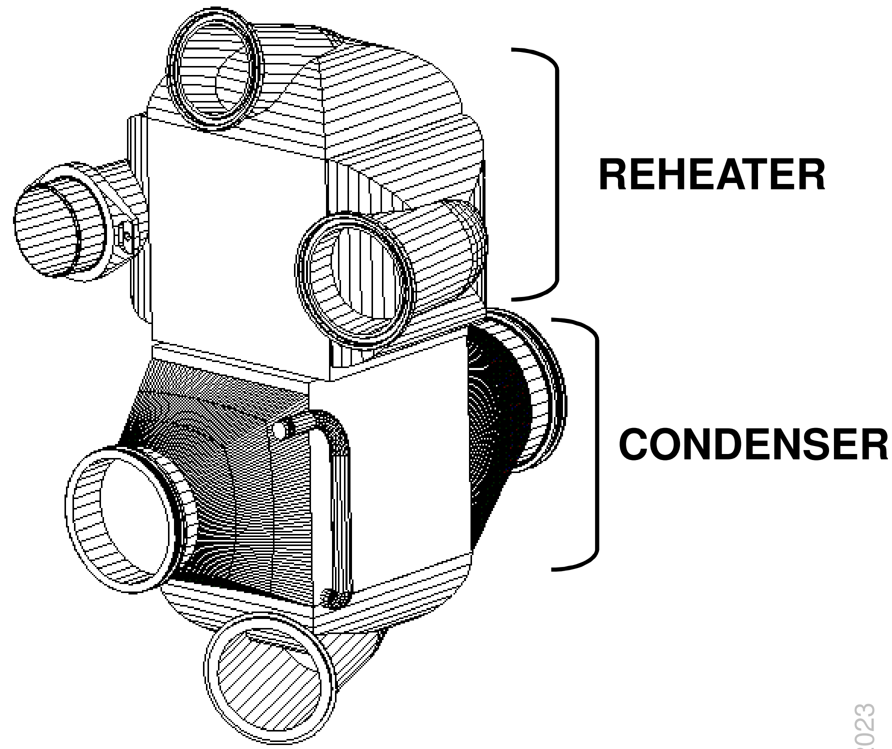
- **Made of aluminum alloy. Integrates Main and Primary Exchangers.**



Components Description – Pack

- REHEATER / CONDENSER (REH/CON)

⇨ **Made of aluminum alloy. Single pass exchanger, designed to cool down air temperature in order to extract water and heat air entering turbine inlet.**



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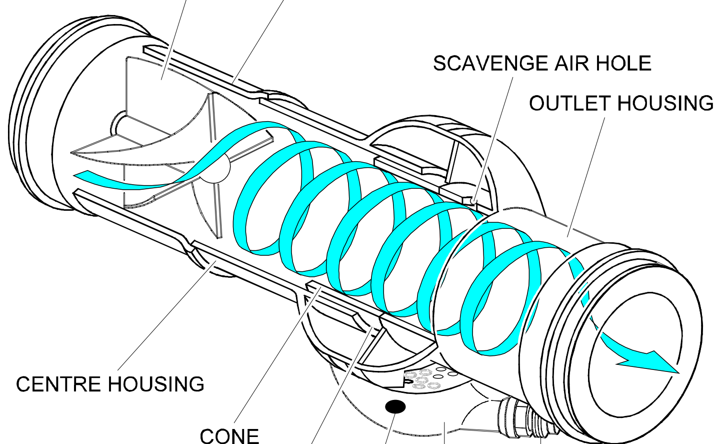
Components Description – Pack

- **WATER EXTRACTOR (WE)**

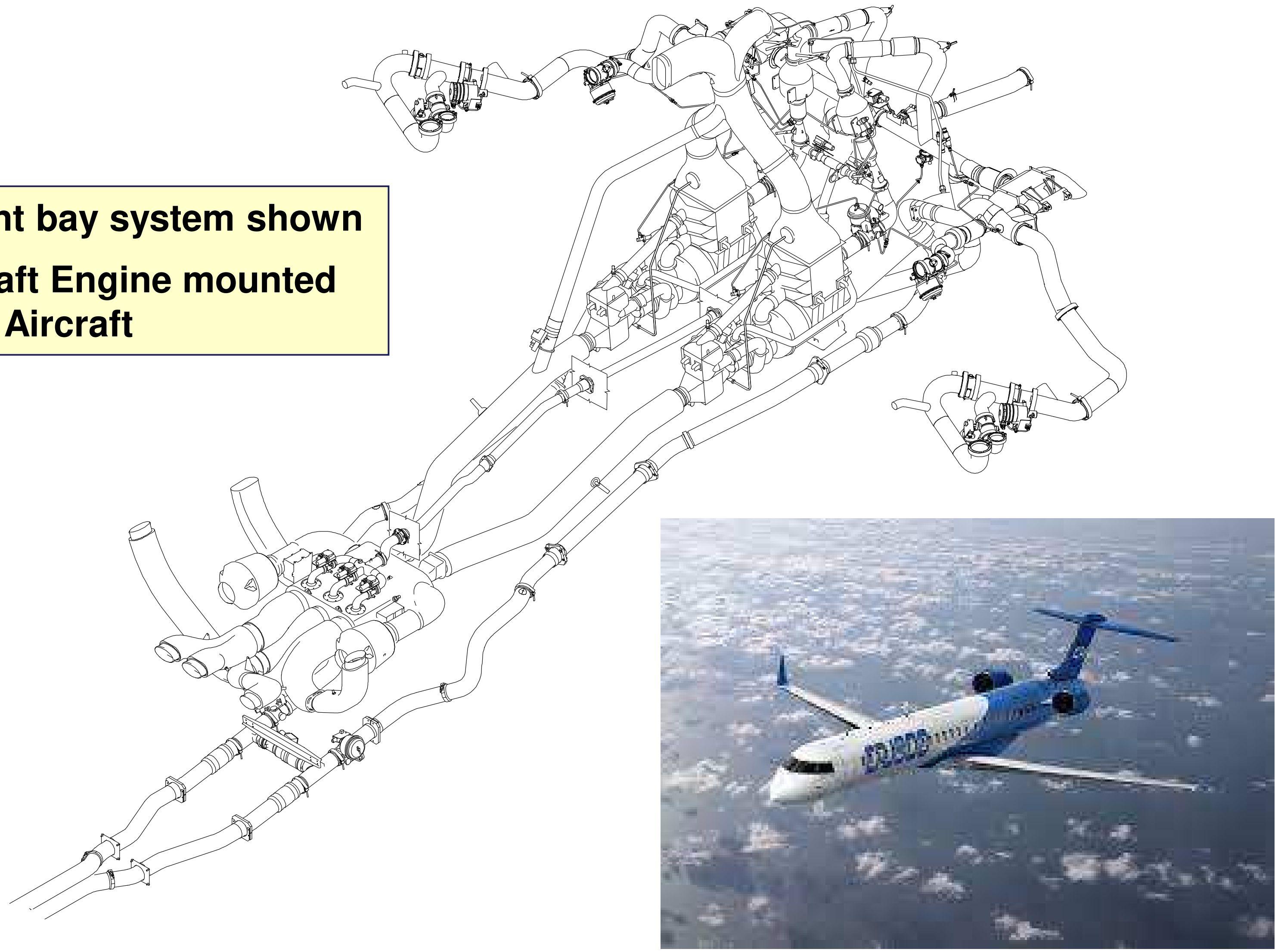
- **Made of four swirl vanes into an aluminum body. Reduces water quantity in bleed air.**



Overall All Integrated ECS System

Aft Equipment bay system shown

Typical for aft Engine mounted Aircraft



Integrated Air Management System

Wing Ice Protection System

WIPS

February, 2023

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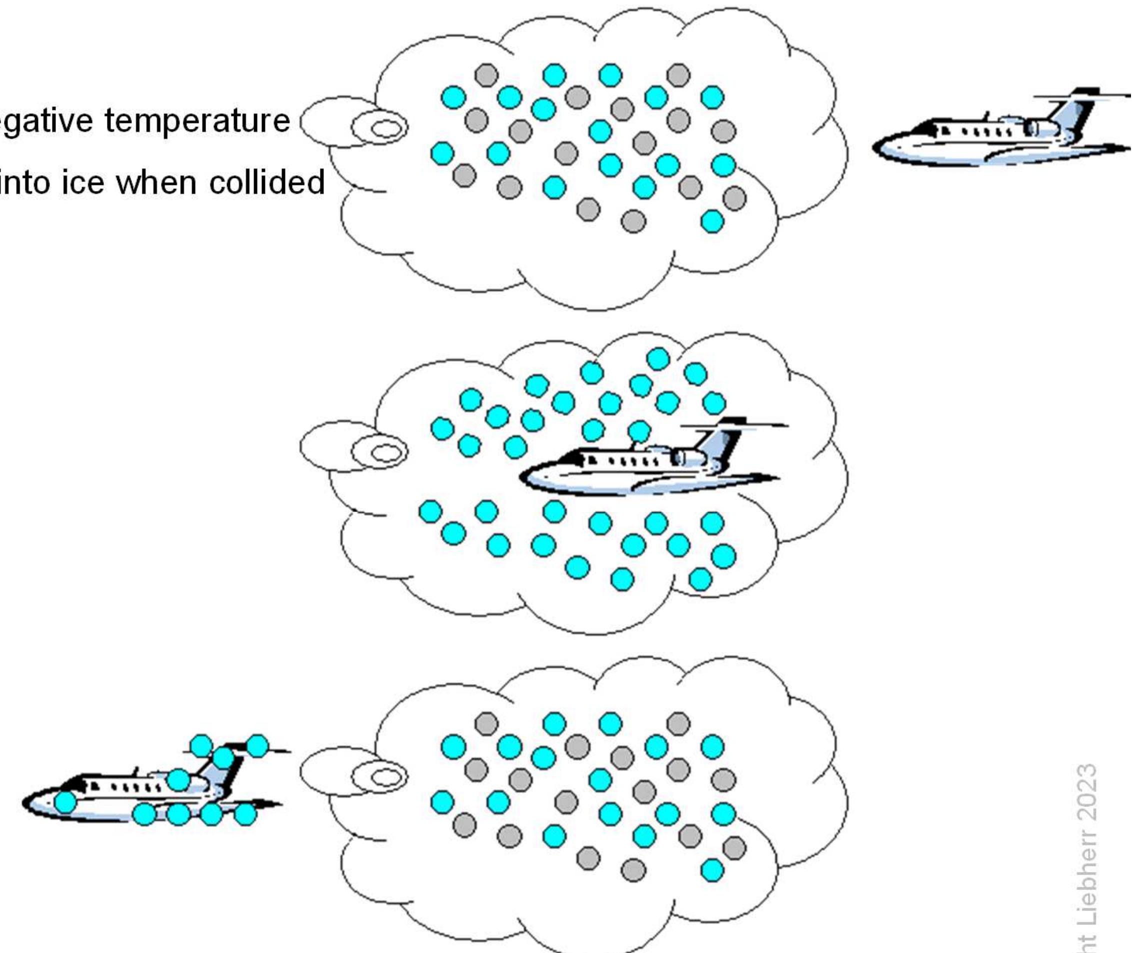
Course syllabus

Wing Ice Protection System

- **Icing Conditions**
- System Functions and Requirements
- System Architecture, Sizing and Operation
- Components Description

Icing conditions

- **Icing conditions**
  - Supercooled droplet = liquid water at negative temperature
  - Unstable equilibrium => transformation into ice when collided
  - 3 mains condition types:
    - CM: Continuous Maximum
    - IM: Intermittent Maximum
    - SLD: Supercooled Large Droplet



- **Main parameters:**
  - OAT (Outside Air Temperature) <0°C
  - MVD (Median Volume Diameter):
    - CM and IM: 15-50µm
    - SLD: >250µm
  - LWC (Liquid Water Content): g/m³
    - CM: from 0.2 to 0.8 g/m³
    - IM - SLD: from 0.2 to 3 g/m³

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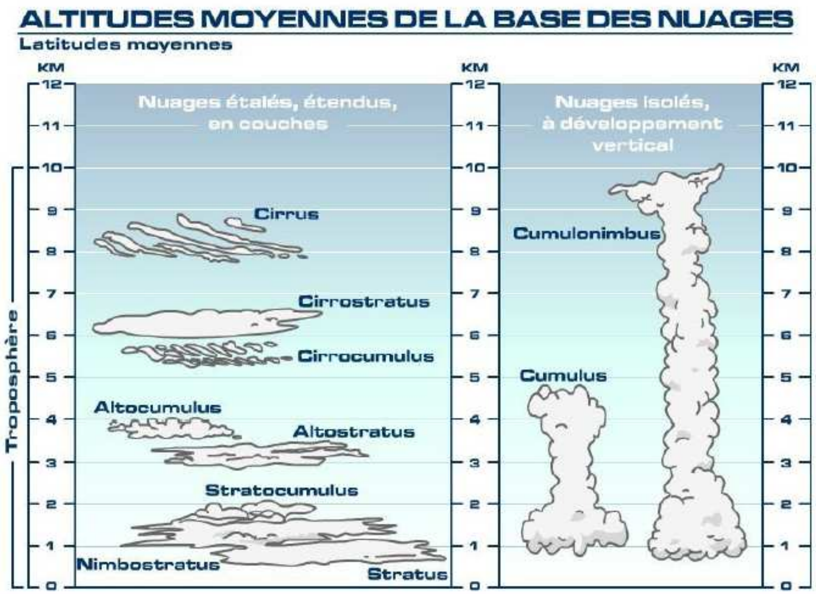
Icing conditions : clouds shapes

Stratus clouds

Low water content

High horizontal dimension

⇒ Continuous Max



Cumuliform clouds

High water content

High vertical dimension (but limited horizontal dimension)

⇒ Intermittent Max

Wing Ice Protection System

- Icing Conditions
- **System Functions and Requirements**
- System Architecture, Sizing and Operation
- Components Description

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Ice Protection – Functions

- **To prevent or limit ice formation on certain surfaces, for which this ice formation is deemed unacceptable**
  - Either because it compromises the flight characteristics
  - Or because blocks of ice can damage other parts of the aircraft if they fall off

- **Usually, the surfaces in question are:**
  - Part or all of the wing leading edges
  - Engine air intakes
  - Stabilizers
  - Other air inlets
  - Windshield, sensors

- **Safety impact**
  - The criticality of ice protection depends a lot on the type of aircraft
  - It may imply scenarios of aircraft loss : **Catastrophic Event 10^{-9} FH**
    - Asymmetrical icing protection
    - Non-signalled loss of the protective function

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Course syllabus

- # Wing Ice Protection System
  - Icing Conditions
  - System Functions and Requirements
  - **System Architecture, Sizing and Operation**
  - Components Description

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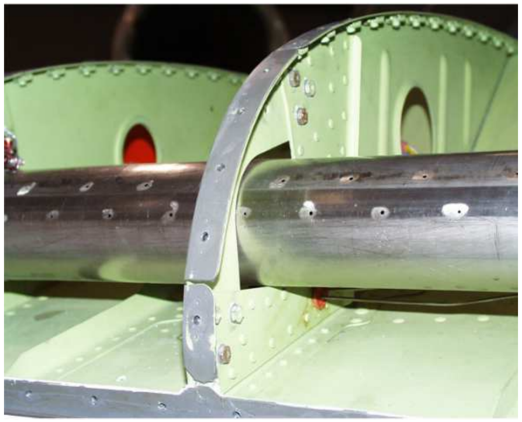
Ice Protection : system types

- **DE-ICING**
- **Permits some accumulation of ice within acceptable limits**



- **ANTI-ICING**
- **Does not allow ice to form around the leading edge**

Comment: icing conditions are encountered on average on less than 10% of flights and for a period of a few minutes.

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Ice Protection : system types

Means of action / Power source	Mechanical	Thermic
	De-icing only	
Pneumatic	Low pressure boot (ATR) High pressure boot	Hot air systems (90% large civil aircraft)
Electric	Electro-impulsion Electro-expulsion	Heat mattress (B787)

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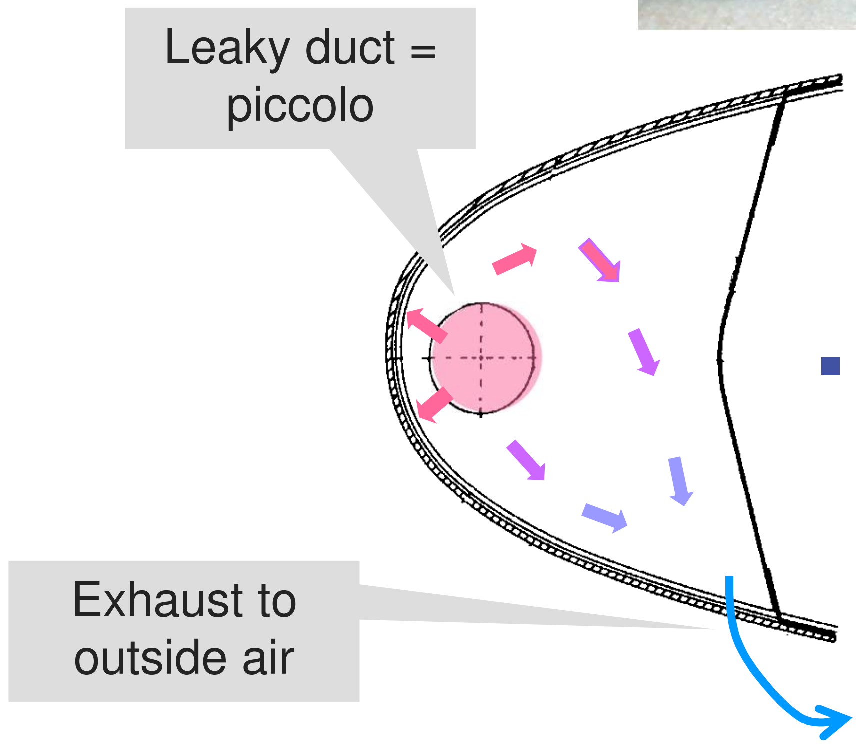
Basic principle of hot air systems

The impact of air jets inside the leading edge increases heat exchange



- **Leading edge thermal efficiency:**

$$\varepsilon = \frac{T_{Piccolo} - T_{Exhaust}}{T_{Piccolo} - TAT}$$

TAT = Total Air Temperature (K) = $OAT(K) \times (1 + 0.2M^2)$

- **Leading edge internal thermal power:**

$$P_{int} = Q_{bleed}.Cp.(T_{piccolo} - T_{exhaust})$$

$$P_{int} = Q_{bleed}.Cp.\varepsilon.(T_{piccolo} - TAT)$$

Q_{bleed} = Hot air mass flow (kg/s)

Cp = air specific heat ~1010 J/kg/K @200°C

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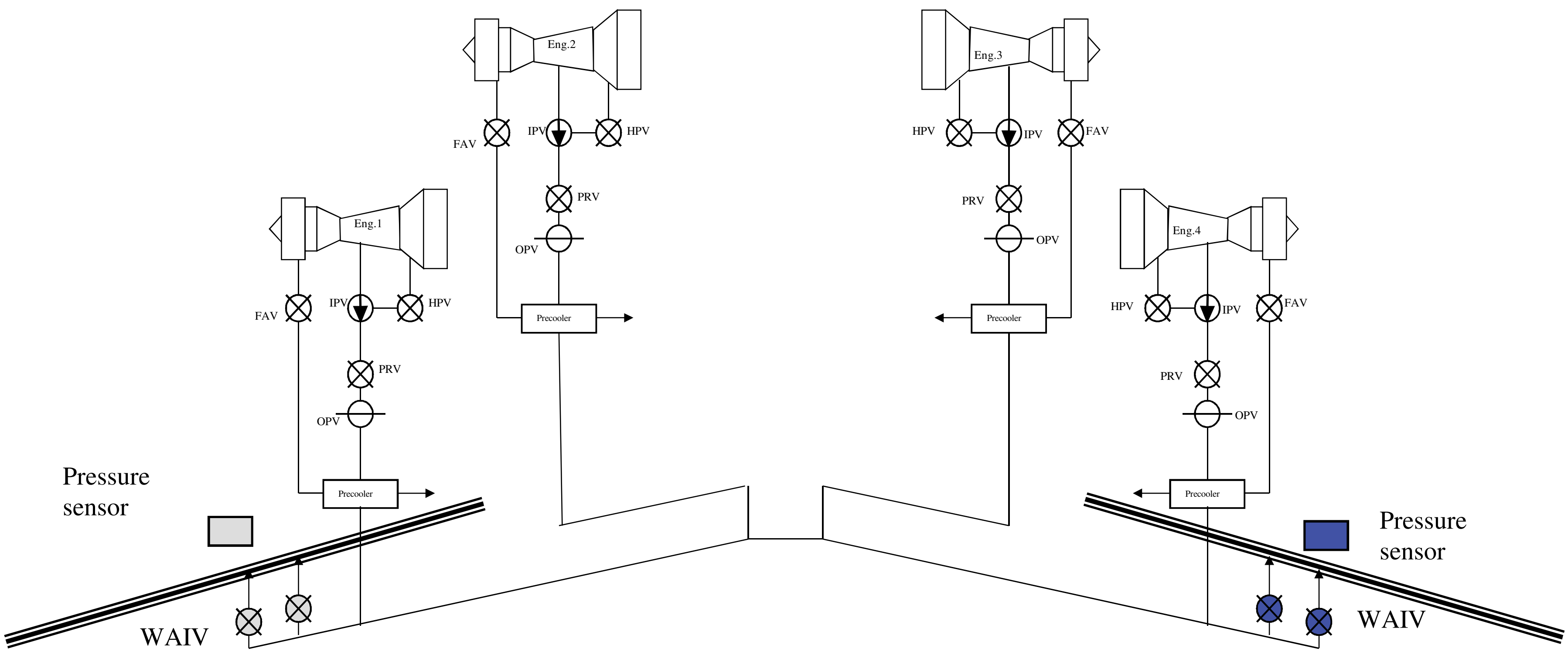
Ice Protection : 2 architectures

FIXED FLOW

Why? Extremely simple and robust

How?

- Relative pressure control
- Monitoring by pressure sensor



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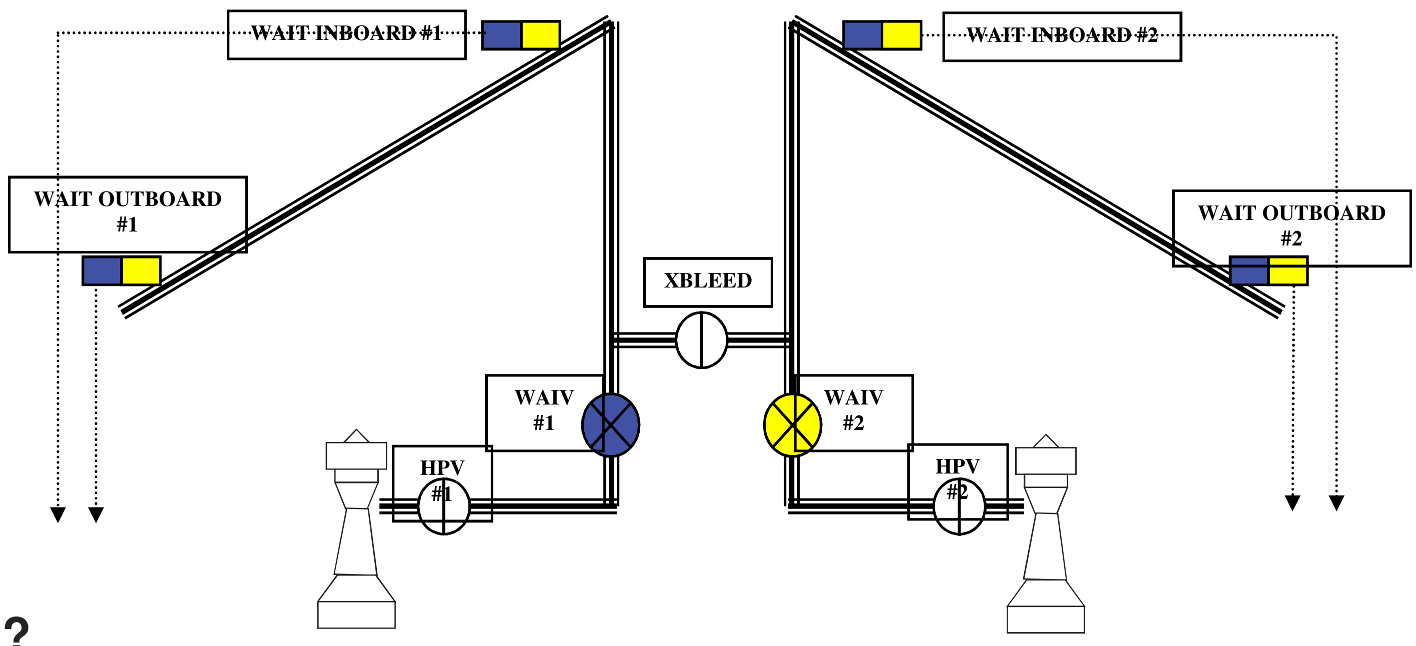
Ice Protection : 2 architectures (cont.)

VARIABLE FLOW

Why? Limits leading edge temperature, reduces SFC (Specific Fuel Consumption)



How?

- temperature control of leading edge skin in closed loop
- monitoring by wing tip sensors

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Key parameters

- **Pressure and temperature conditions for the engine air bleed**
- **Aircraft manufacturer requirements**
  - Identification of the areas requiring protection
  - Acceptable quantity of residual ice, run-back ice
  - β-curves (quantity of water captured along the aerofoil for a given condition)
  - Selection of flight points affecting design
  - External and internal geometry of the leading edges

The design of ice protection systems implies close cooperation with the aircraft manufacturer

The borderline between the responsibility of the aircraft manu-facturer and the systems manufacturer is very hard to gauge!!!

Design method: What needs to be done...

- **Build the architecture:**
  - Fixed or variable flow system?
  - Number of valves, intercom valve, number of sensors, number of ice detectors, number of computers, duct network
    - According to the safety requirements and availability

- **Work out roughly the flows in normal operation conditions and problem scenarios**
  - Use predesign equations
  - Determine the diameters of the supply ducts and piccolos

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Design method: What needs to be done…

■ Evaluate flow :

- Step 1 :
  - External thermal power is sum of:
    - Thermal power to evaporate water impacting leading edge
    - Thermal power to maintain LE skin temperature above freezing point (~40°C)

$$P_{ext} = L_{wings}.\left[WCR.L_{vap} + h_{ext}.L_{LE}.(T_{skin} - TAT)\right]$$

L_{wings} = Wings length to protect(m)

WCR = Water Catch Rate (CM ~2.5 g/s/m; IM ~15g/s/m)

L_{vap} = Latent heat of vaporization (~2500 kJ/kg)

h_{ext} = Convection heat transfer coefficient (~150 W/m²/K)

L_{LE} = Leading edge length(~0.3m)

T_{skin} = Average skin temperature(~40°C)

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Design method: What needs to be done…

Evaluate flow :

- Step 2 :
  - Flow is based on:
    - External power
    - Leading edge efficiency
    - Average piccolo air temperature (= bleed system air outlet temperature – 20°C for heat losses)

$$P_{ext} = 0.9\, P_{int}$$

0.9 to take into account heat losses behind leading edge

$$Q_{bleed} = \frac{P_{ext}}{0.9\, Cp\,.\,\varepsilon.\,(\,T_{piccolo} - TAT)}$$

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ICE DETECTION

PRIMARY / ADVISORY detection

- Notion of airworthiness
- Primary: Detectors are an acknowledged, sufficient means of detecting icing conditions.
  Detection responsibility falls to the system.
- Advisory: Detectors are a tool for the crew to detect icing conditions.
  The responsibility of detection falls to the pilot.

MANUAL / AUTOMATIC activation

- Manual: Once icing conditions have been detected, the ice protection system is activated manually by the crew
- Automatic: Once icing conditions have been detected, the ice protection system is automatically activated.

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Course syllabus

Wing Ice Protection System

- Icing Conditions
- System Functions and Requirements
- System Architecture, Sizing and Operation
- **Components Description**

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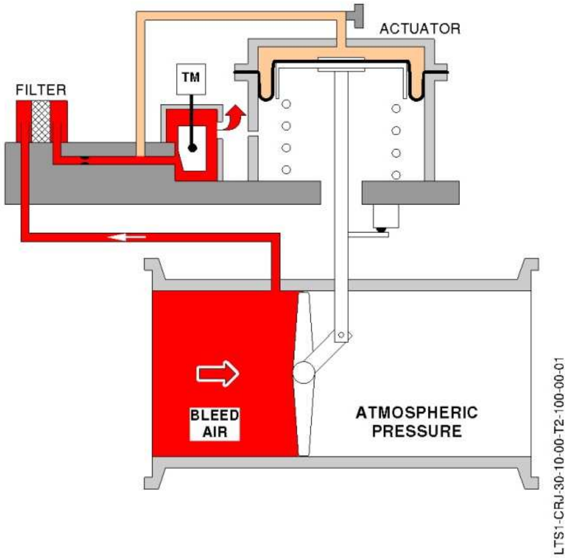
Components Description

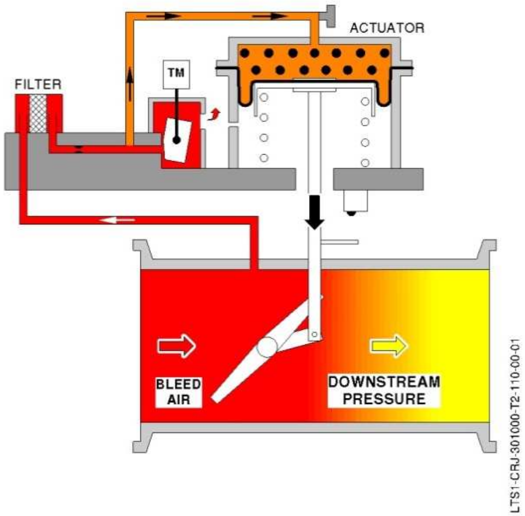
- **Wing Anti-Ice Valve**

  - Electro-Pneumatic: Driven by bleed air and commanded electrically by torque motor

Closed position



Regulation position



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Components Description

- **Ice detector**
  - Based on vibration fequency change due to ice accretion on sensing element

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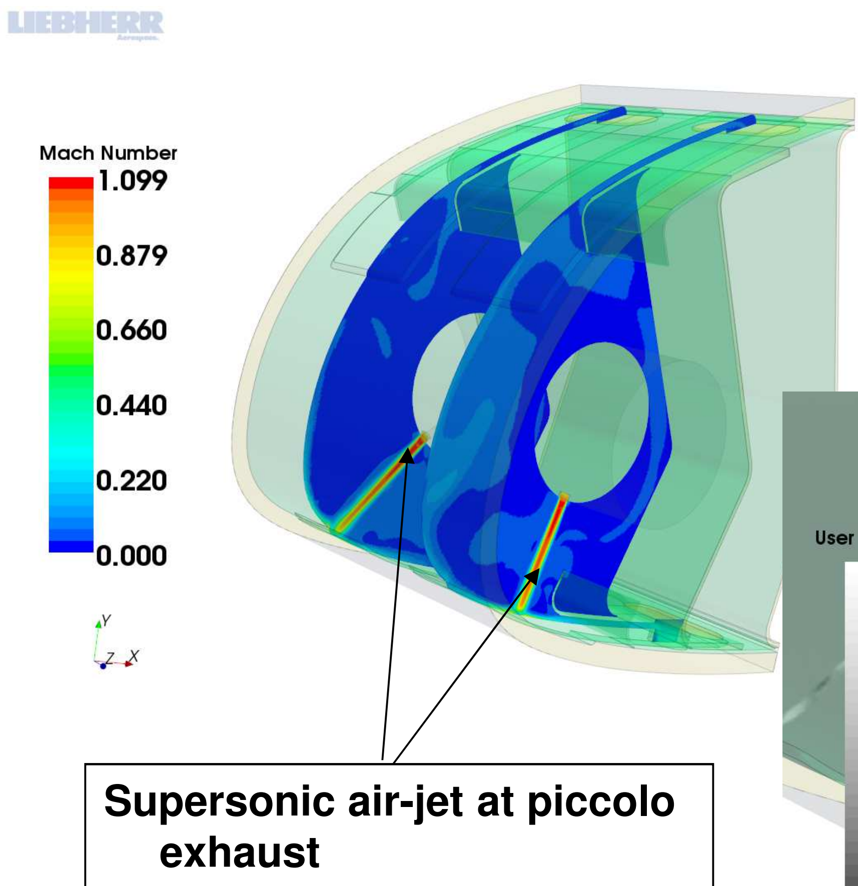
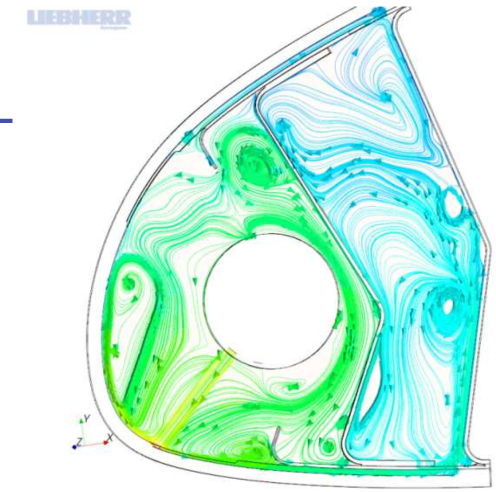
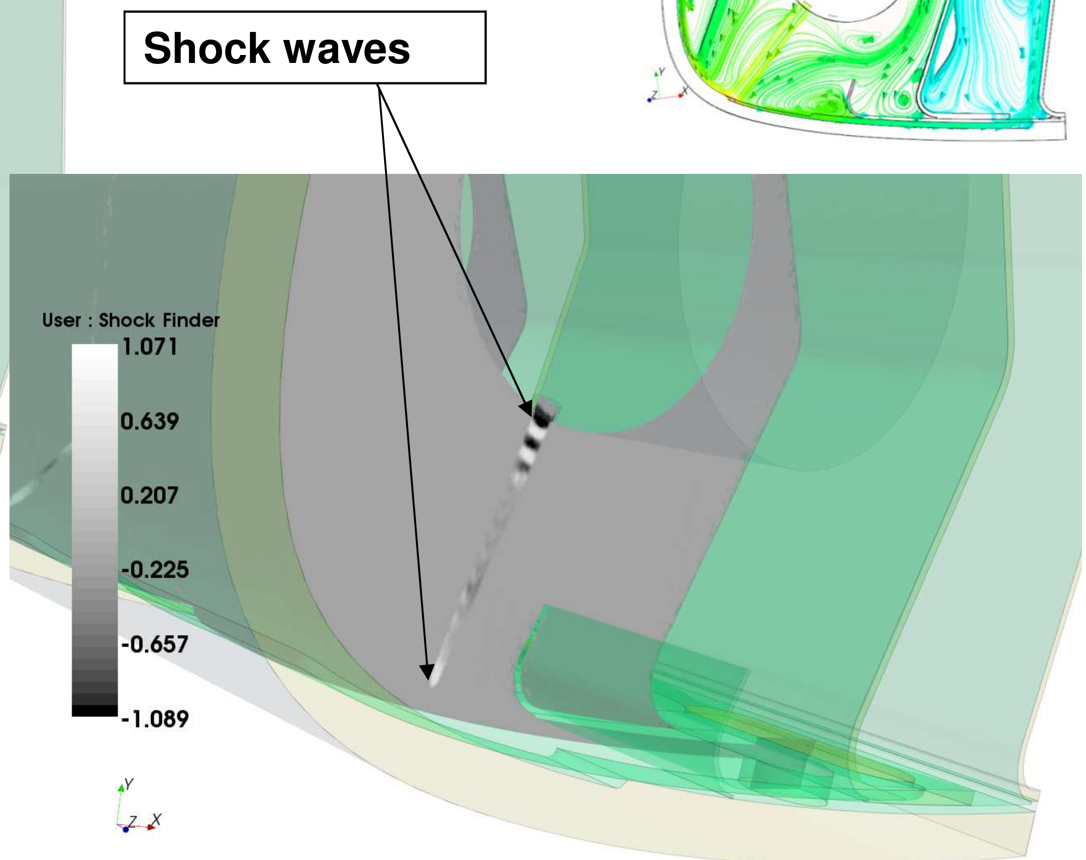
Leading edge air stream calculations







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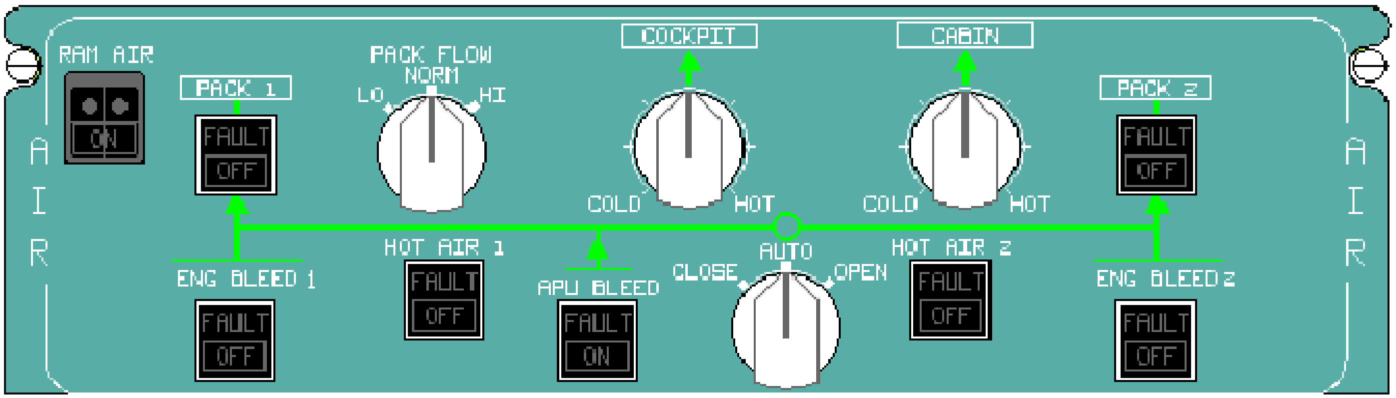
Integrated Air Management System

Pneumatic Systems



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Course syllabus

- **Pneumatic Systems**
  - **BLEED AIR SYSTEM**
  - Leak Detection System
  - Components Description

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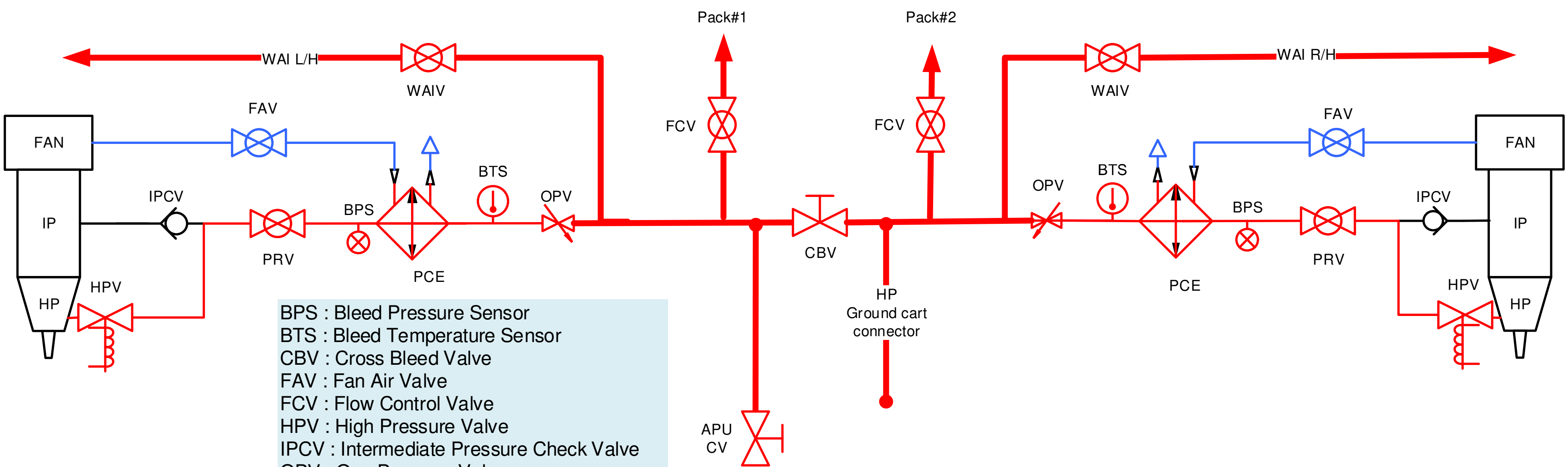
Bleed Air System – Provide power for ECS & WIPS

Bleed Air System architecture



- BPS : Bleed Pressure Sensor
- BTS : Bleed Temperature Sensor
- CBV : Cross Bleed Valve
- FAV : Fan Air Valve
- FCV : Flow Control Valve
- HPV : High Pressure Valve
- IPCV : Intermediate Pressure Check Valve
- OPV : OverPressure Valve
- PCE : Precooler
- PRV : Pressure Regulating Valve
- WAIV : Wing Anti-Ice Valve

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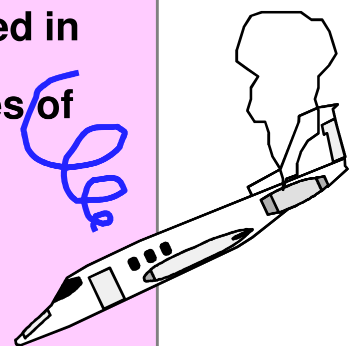
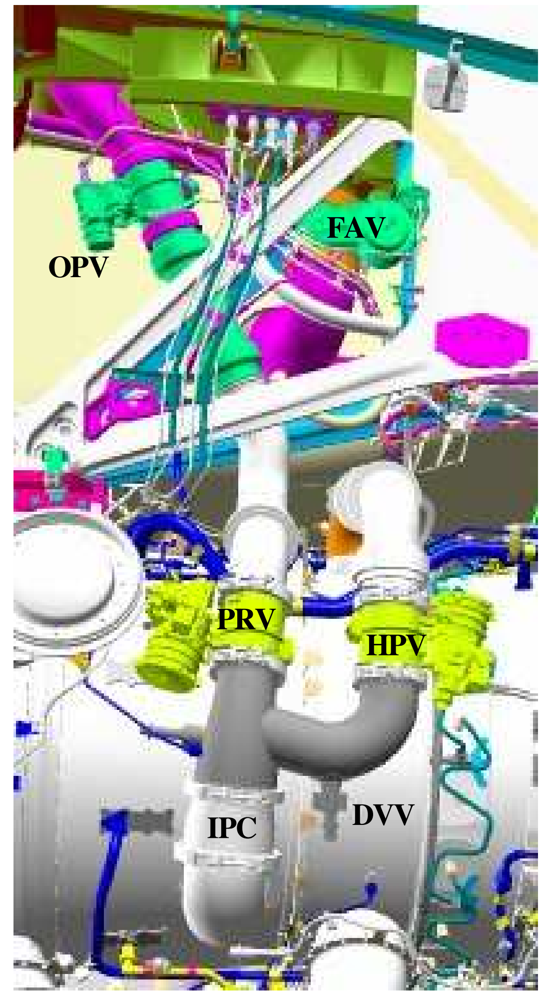
Design Requirements

- **Safety:** **bleed air system is implied in scenarios which jeopardise the lives of passengers**
  - Non-isolated engine fire
  - Non-isolated hot air leakage





- **Environment:** **installation of equipment in the engine leads to high ambient temperatures (up to 300°C) and high vibration levels (> 40 g)**

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Design requirements (cont.)

- **Availability:** The plane must be able to fly even if in the case of certain equipment failure
- **Reliability:** to reduce maintenance
- **Capacity to isolate equipment causing the failure:**
  to reduce maintenance time
- **Weight:** as low as possible
- **Cost:** as low as possible

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Key Parameters (parameters dictating design)

- **Bleed flow required by users in normal operating conditions and problem scenarios**
  - ➡ Valve diameters, size of exchanger
- **Needs and limitations in terms of pressure and temperature for users**
  - ➡ Amount of equipment (OPV), choice of points on HP or IP port
- **Safety/availability analysis**
  - ➡ Dictates level of redundancy
- **Installation**
  - ➡ The location of the equipment dictates the choice of materials to withstand the environment
  - ➡ Space available for the precooler

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Bleed Air System– FUNCTIONS

- Isolation – Selection of air source
- Engine bleed air stage transfer
- Regulating, limiting pressure
- Temperature regulation
- Balancing flow
- Reverse flow protection
- Signalling and monitoring

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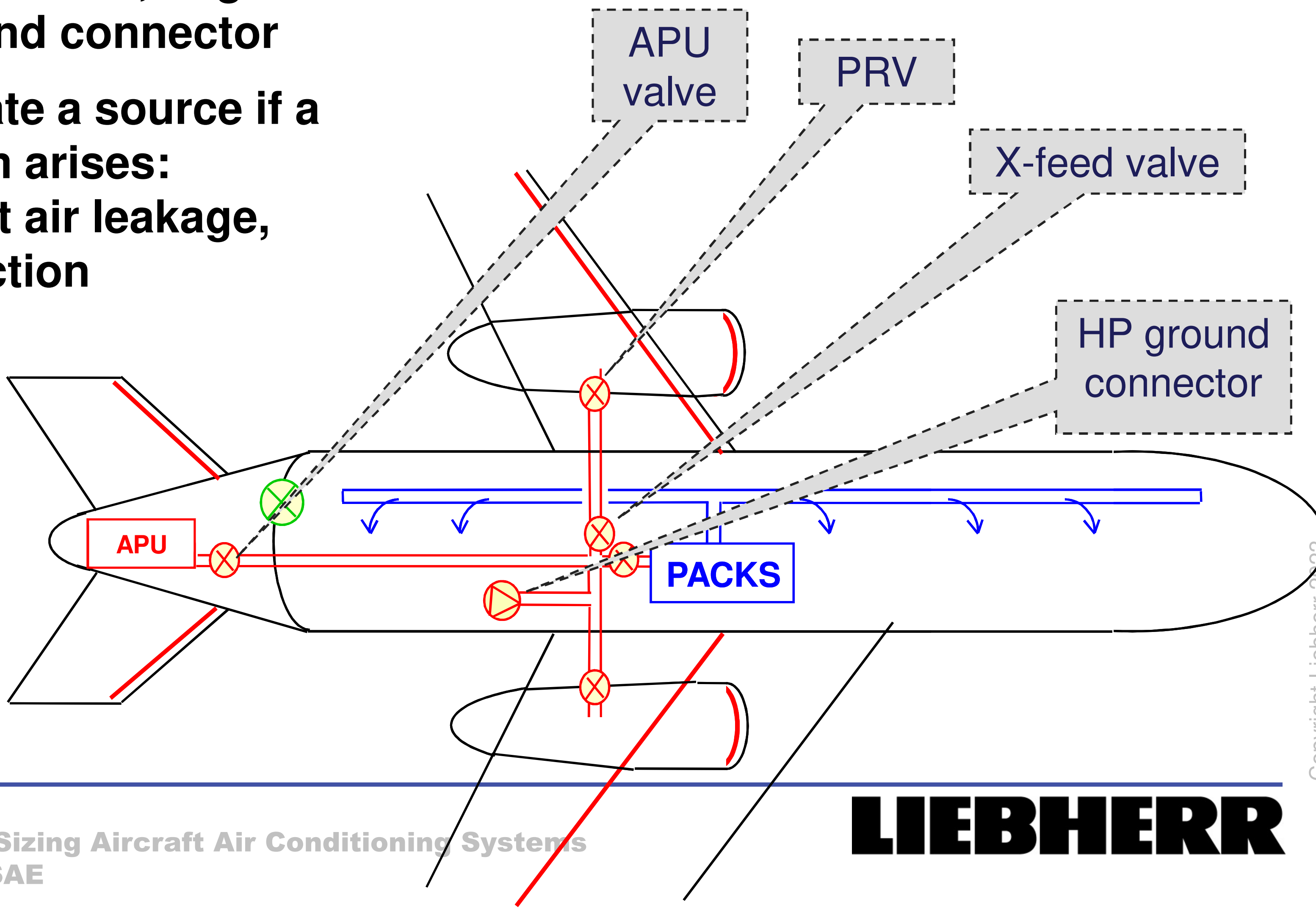
Isolation – Selection of air source

- **Why ?**
  - **To select APU, engine or ground connector**
  - **To isolate a source if a problem arises: Fire, hot air leakage, malfunction**

How ?



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Engine bleed air stage transfer

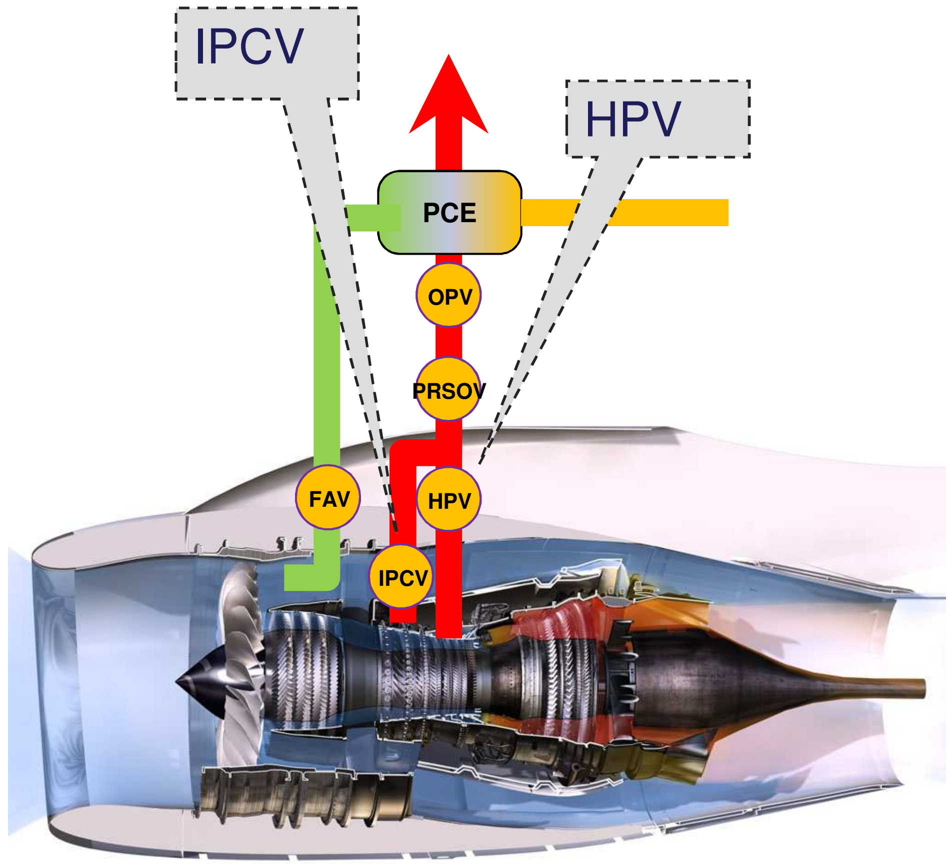
Why?

- To supply required pressure and/or temperature in all flight configurations
- High power rating (take-off, climbing, cruising): IP Intermediate pressure
- Low power rating (ground roll, descent): HP High pressure.

Standard values

Air bleed on HP, up to 15 rel bar, 450°C

How?



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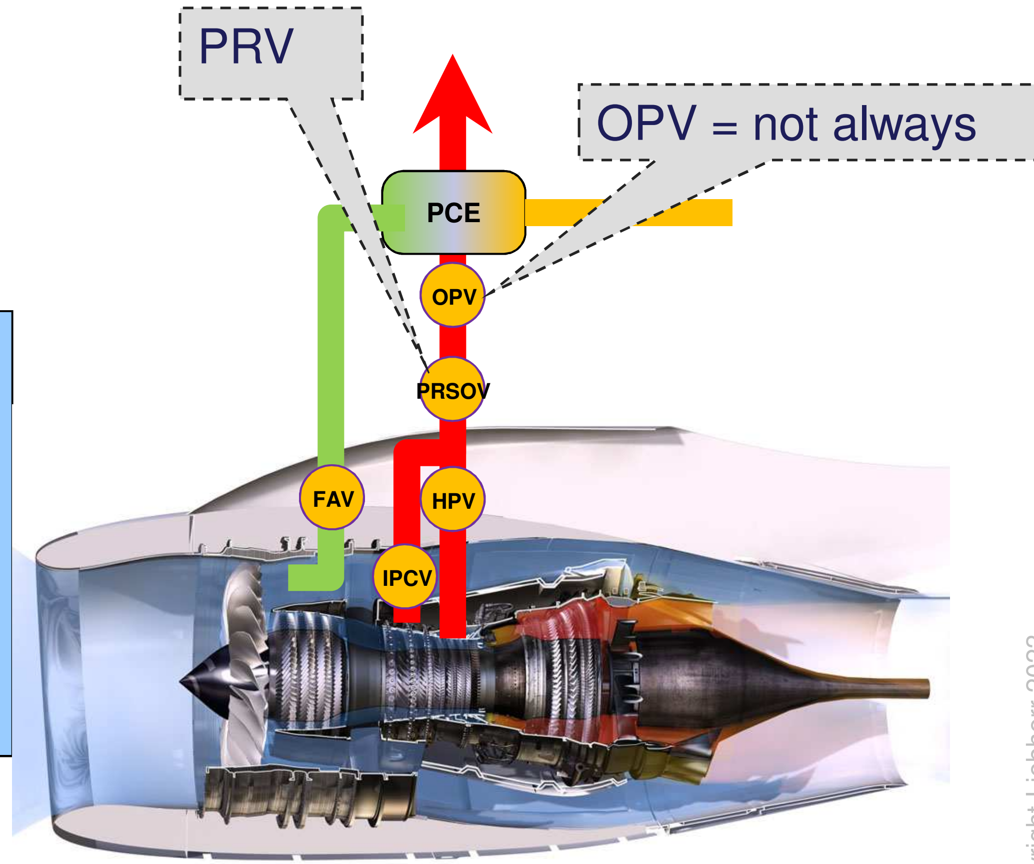
Regulating, limiting pressure

- **Why?**
- **To reduce stress generated by pressure in the downstream circuits**

How?



Standard values
- **PRV regulates 3.2 rel bar**
- **PRV shuts of at 4.1 rel bar**
- **OPV shuts of at 6 rel bar**
- **No OPV if max IP<6.2 rel bar**

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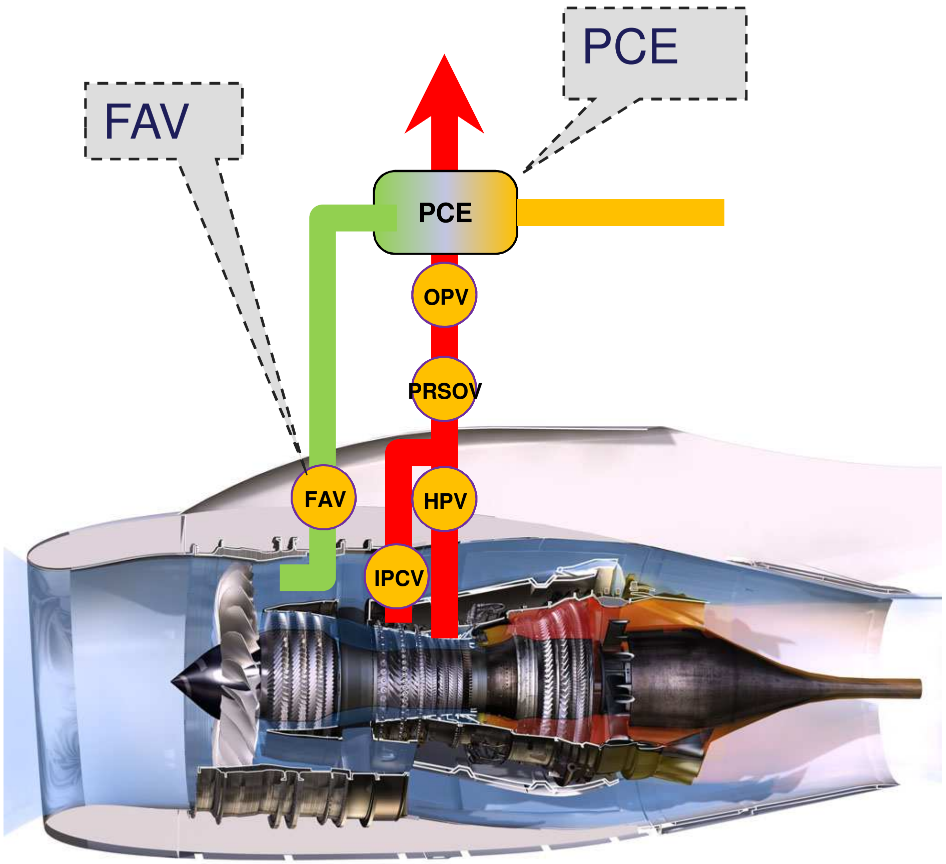
Temperature regulation

Why?

- To reduce the stress generated by pressure in the downstream circuits

How?



- **Standard values**
- **150 °C – 230°C**
- **System shuts down at 260°C**

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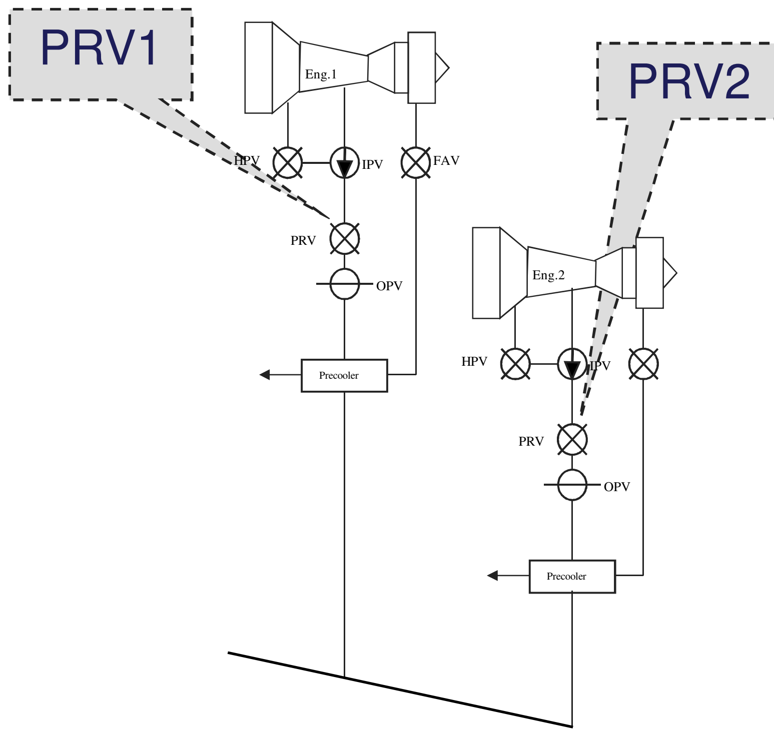
Balancing the flow

- **Why?**
- **If 2 circuits flow in the same pipe, the circuit with the highest pressure determines the flow**
- **Requires constant control of the PRVs to balance out the flows of adjacent systems**

How?



> **Standard values**
>
> **Balancing ± 10% of nominal flow**
>
> **Used on 4-engined aircraft**

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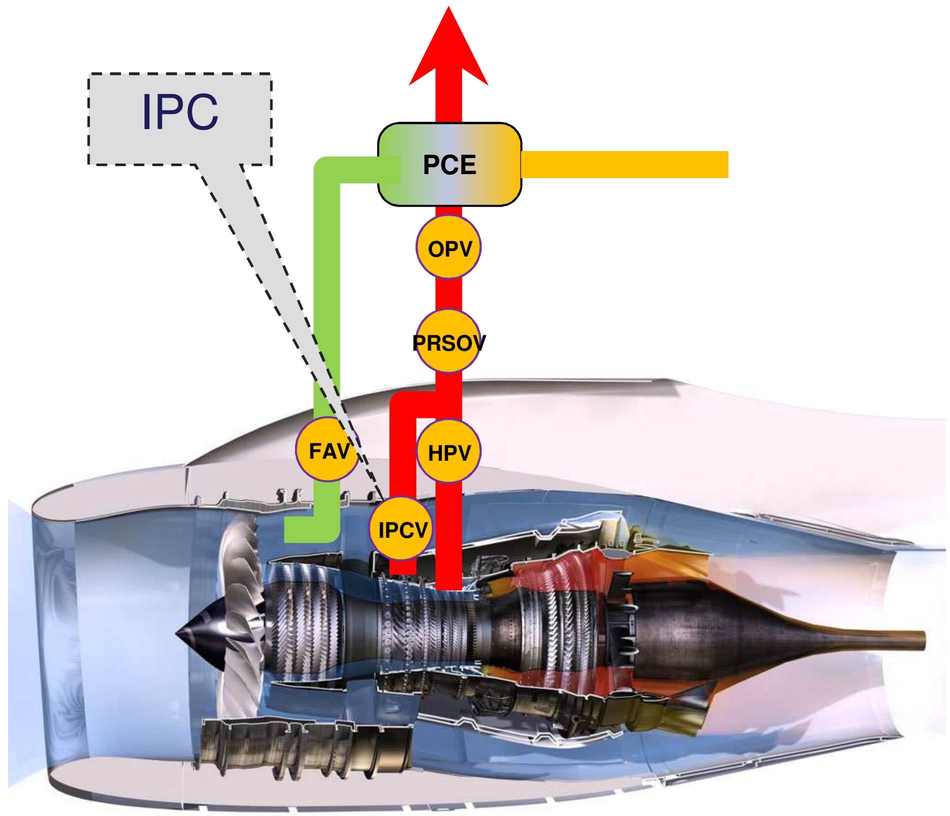
Reverse flow protection

- **Why?**
- Flow ingested in compressor (APU or engine) may cause it to shut down

- **2 levels need protecting**
- HP air backflow in IP outlet
- APU backflow to an engine or from an engine to another

- **How?**
- HP backflow in IP



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Reverse flow protection (cont.)

- ## How? (cont.)
- **Backflow from downstream**
- **Several solutions**
  - **Cross-feed valve : prevents cross-over of air sources**
  - **Droopy HPV : function integrated pneumatically in the valve**
  - **Shut-off activated when reverse flow detected : function controlled pneumatically with sensor between upstream PRV and downstream precooler**

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Engine start-up

- Ancillary function using pneumatic power
  - Either of the APU:
    - By reverse back-tracking through the precooler and the distribution line upstream of the PRV, possibly through the cross feed valve
  - Or an adjacent engine:
    - By blowing though its precooler and cross feed valve and back-tracking through the precooler of the starting motor

N.B.: This function is usually a design factor for the APU flow

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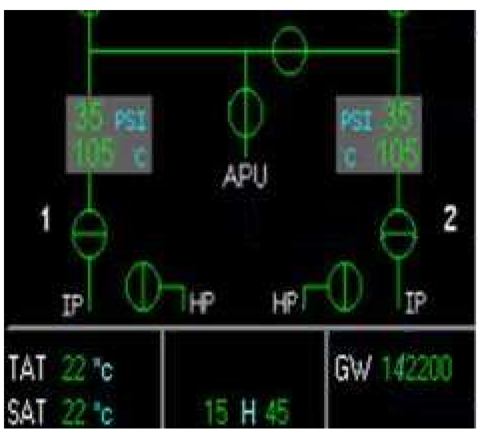
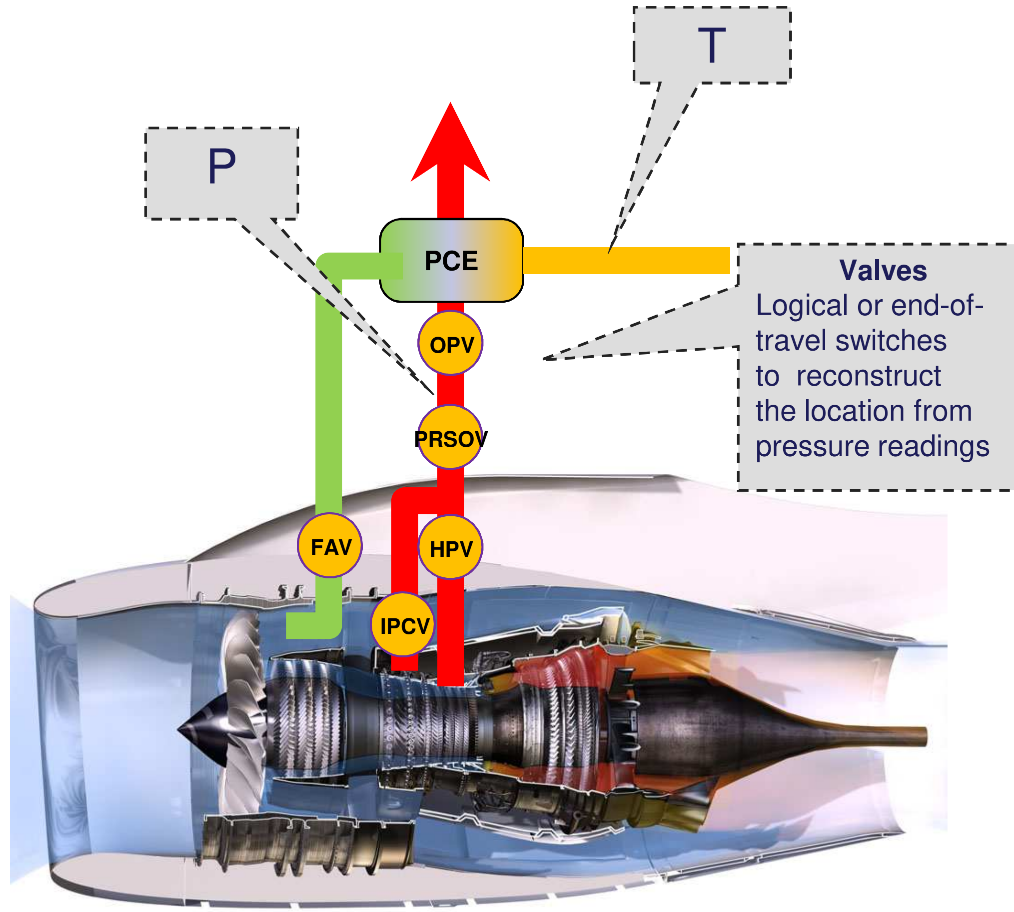
Signalling and monitoring

- **Why?**
- **Signalling: need to signal to the cockpit**
  - The bleed port ⇒ HPV position
  - System status (open/closed) ⇒ PRV position
  - Status of cross-feed valves
  - User pressure and temperature



How?



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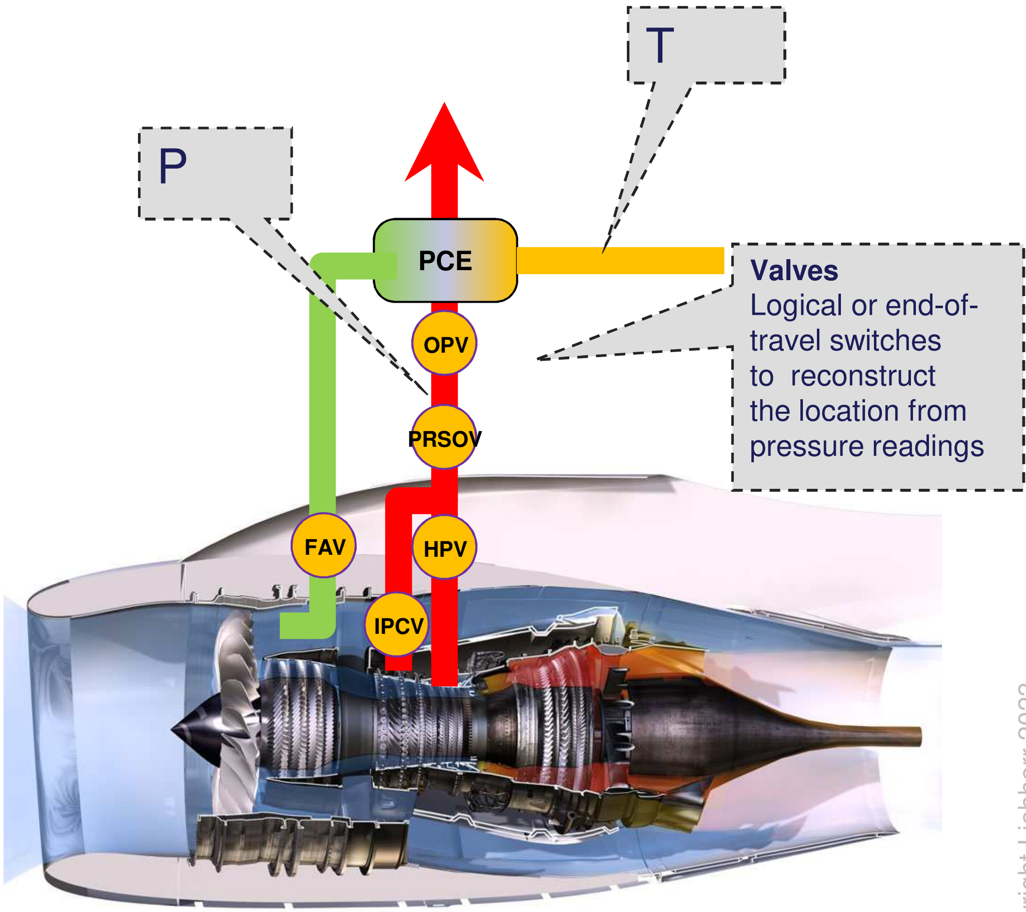
Signalling and monitoring (cont.)

- **Why?**
- **Monitoring**
- **To identify the following conditions**
  - Overpressure
  - Low pressure
  - Overheating
  - Low temperature
  - Refusal to shut
- **To identify the source of the problem**

How?



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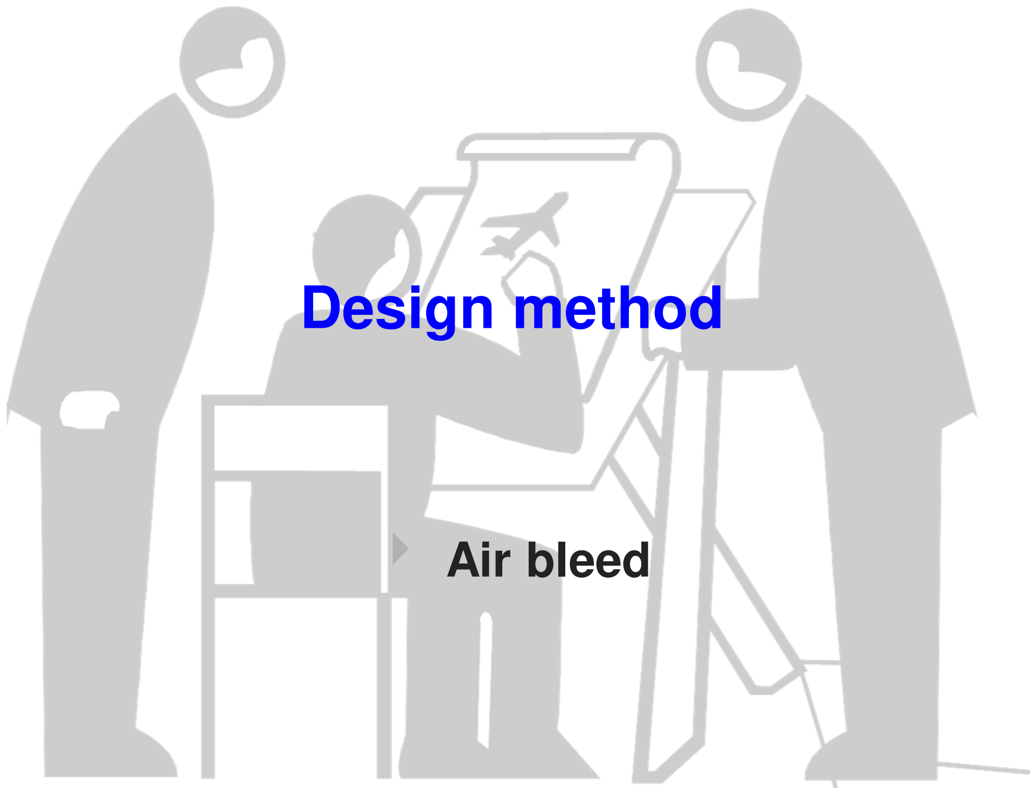

Design method

- Air bleed

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Design method: what needs to be done

Determine the system **flows**

- Select the right diameters to respect a Mach number < 0.25 in the nacelle
- This criteria is the optimum between:
  - Space constraint
  - Pressure drop

$\Rightarrow$ **Incompressible fluid formula**

REFERENCE DOCUMENTS

- **SAE ARP 1796: Engine Bleed Air Systems for Aircraft**
- **SAE ARP 699: High temperature pneumatic duct systems for aircraft**

Determine the **min. / max. P and T** in all configurations

- Check the diameters are OK by calculating the pressure loss
- Check need for OPV
  - The max. pressure must not exceed the max. value tolerated by the downstream circuits
- Lay down the performance level required of the exchanger (heat, pressure loss)

Lay down the **general operating conditions**

- P and T in each section with associated probability
- Will dictate the requirements in terms of endurance, stress and bursting

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Design method: what needs to be done (cont.)

- **Select the default positions of the valves**
  - Taking into account: fire, pneumatic and electrical power consumption and availability
    - Without any pressure
    - Without any electrical supply

- **If ducts: conduct motion analysis**
  - Tolerance + thermal expansion
  - Select moving unions and fixture points

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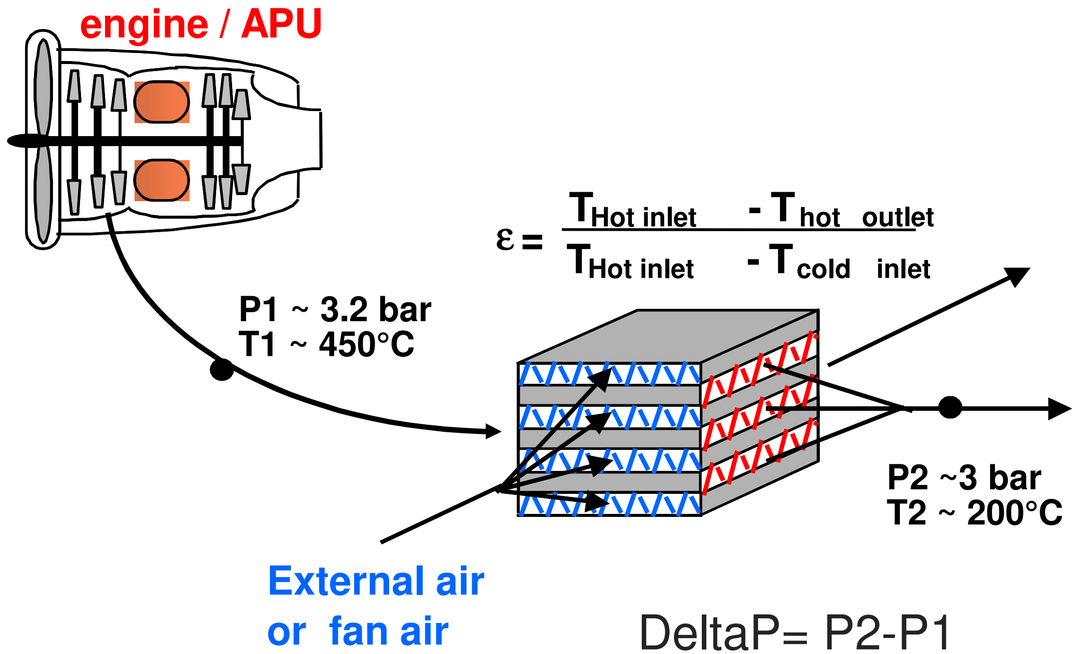
Designing the precooler

- Use the efficiency formula for precooler calculations:



$$\varepsilon = \frac{T_{Hot\ inlet} - T_{hot\ outlet}}{T_{Hot\ inlet} - T_{cold\ inlet}}$$

- **The efficiency of the exchanger depends on the ratio between the hot air flow and the cold air flow**
- **The energy transferred for the hot-air pass is equal to that for the cold-air pass**

DeltaP= P2-P1

Pm/Tm*DeltaP=KQ$^{\alpha}$

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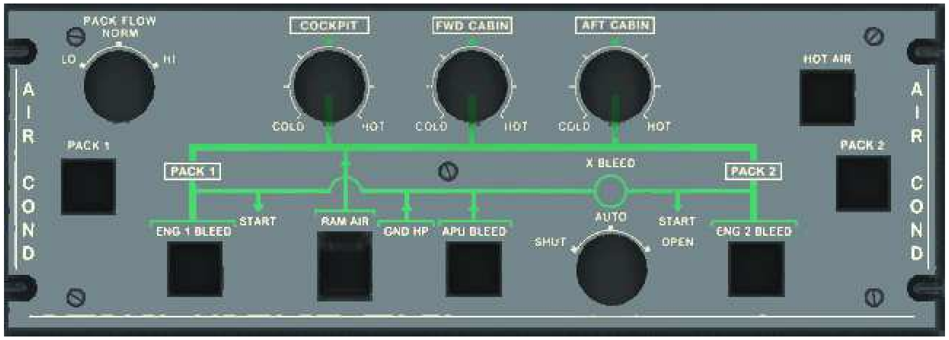
Control and monitoring strategies

ECS Overhead Control Panel A320



- **Two (2) critical functions**
  - CLOSING
  - MONITORING

- **All the other functions have a lower criticality rating. they can be conducted pneumatically or electronically:**
  - balancing the flow
  - regulating the pressure
  - HP / IP transfer

- **Generally speaking, controlling the bleed air consists in**
  - Plenty of logic
  - Few adjustments

Control and monitoring strategies

- **STANDARD REGULATIONS**
- **Pressure regulation: a (very rapid) pneumatic control loop, with an electro-pneumatic adjustment (possibly) of the procedure**
- **Flow balancing (for 4-engined aircraft): variation in the pressure regulation procedure to equalize the P deltas on the precooler terminals (pneumatically or electro-pneumatically)**
  - In the case of a 4-engined aircraft, finding the balance between the two engines on the same wing
  - On a twin-engined aircraft, balancing the flow between the two engines to prevent one of them being bled more than the acceptable rate (admissible % of main flow to avoid overheating at turbine intake)
- **Temperature regulation: variation in the FAV handling pressure**
  - Pneumatically (with pneumatic thermostat)
  - Electro-pneumatically
  - FAV muscle pressure is adjusted pneumatically by a pressure reducing valve

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LOGIC – standard

- Management of the engine start-up sequences
- Automation of the choice of bleed air source
- Automation of reconfigurations in the case of a failure
- HP/IP transfer
- Isolation of failures
- Bleed without switch

MONITORING

Basic principle

- **Monitoring protects the aircraft against malfunctions in the system**

  but is not used to check the performance of the on-board system

  - Select the thresholds according to the admissible values acceptable by the users and not with reference to the control values

Standard values

- Temperature: 260°C
- Pressure: 60 psig

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Course syllabus

- **Pneumatic Systems**
  - Bleed System
  - **LEAK DETECTION SYSTEM**
  - Components Description

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Leak Detection System

- Detection: For what purpose?

- **FAR/CS 25 "NO DUCT BURST SHALL HAZARD THE AIRCRAFT"**
- **Hot air may**
  - Damage the structures or systems located near the ducts
  - Cause some fluids to burst into flame when the temperature exceeds 250°C (approx.)
- **One way of avoiding damage due to hot air leakage is to detect it and cut off the air supply**
- **According to where it is and the temperature of the leaking air, hot air leakage can have repercussions ranging from "minor" to "catastrophic" (aircraft loss)**

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Leak Detection System

- Location: For what purpose?
- It takes a long time to locate a leak during maintenance: different areas possible linked to different access panels, difficulty in reconstructing the event on the ground etc.
- At the time the "leakage" event occurs, location means the area can be identified with some accuracy and the event stored in memory for the maintenance teams.

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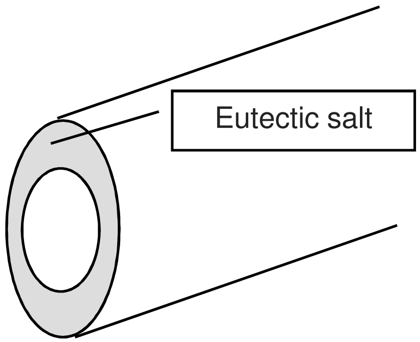
Leak Detection System

Working principle - detection



- Coaxial cable
- The 2 conductors are separated by an insulating salt
- At a pre-set temperature, this salt becomes a conductor $\Rightarrow$ short-circuit
- The phenomenon is reversible

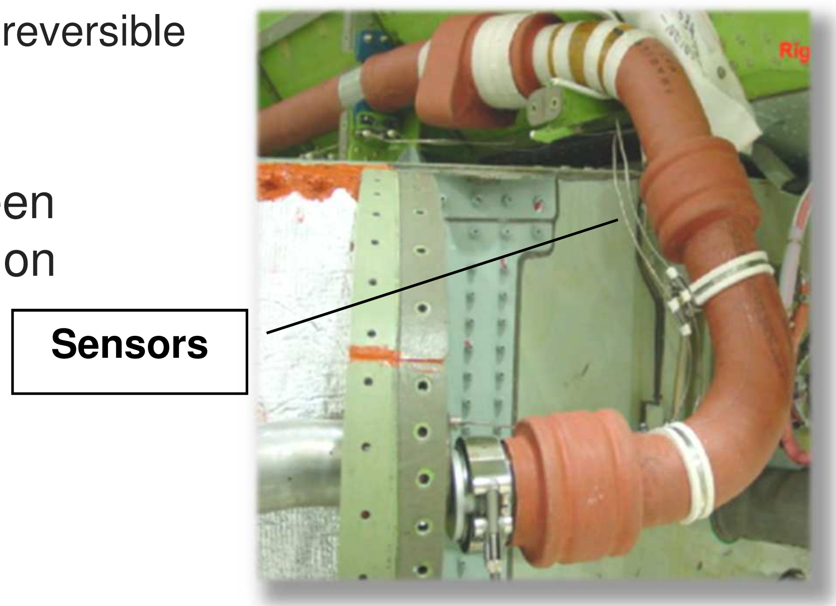
The cable is laid near the duct or between the duct & an element requiring protection

3 advantages

discrete phenomenon

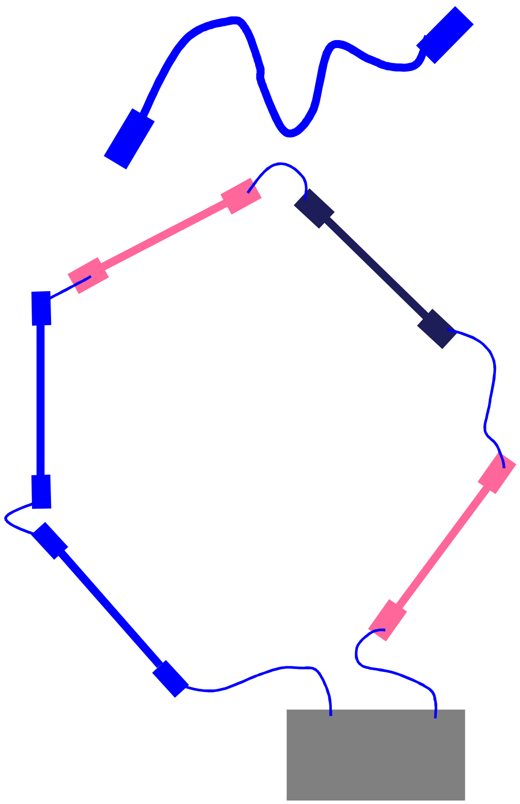
continuous in terms of space

reversible



Leak Detection System

Working principle – detection (cont.)



1 cable = 1 sensitive element

There are different activation temperatures

The cables are linked up to each other with electrical wiring

The loop is closed on a computer which measure the insulation resistance between the 2 conductors

Different activation temperatures can be set in series

The cables developed and marketed by Fenwal haven't changed for 50 years!

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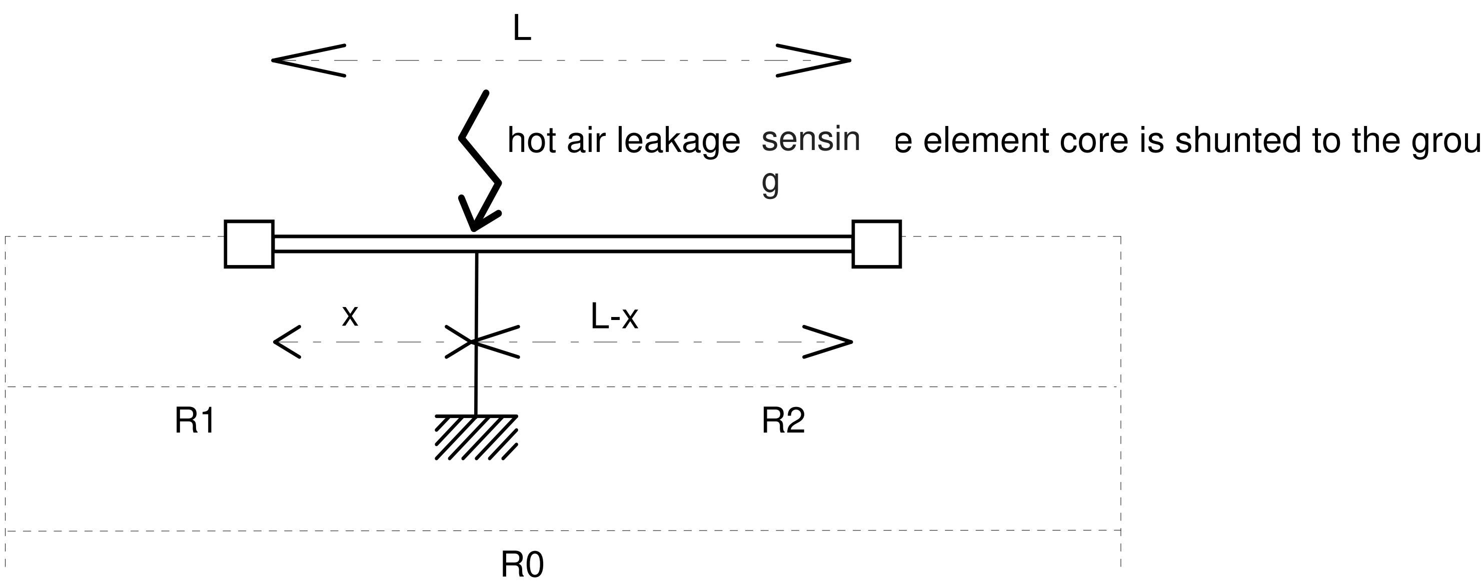
Leak Detection System

Working principle – location



$$\frac{x}{L} = \frac{R0 + R1 - R2}{2.R0}$$

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Key parameters

- **Safety**
  - Determine the need to protect a section according to what is in the area - structures, systems, flammable fluids
- **Availability**
  - A faulty loop takes a long time to repair
  - The loops can be doubled up so as not to detract from availability
- **Maximum admissible temperatures in the various areas housing the ducts**
  - Will help select the activation temperatures (limited number of temperatures available)
- **Installation: where should the cables run and how should they be fixed?**

Few rules, but a lot of good engineering judgement!!!

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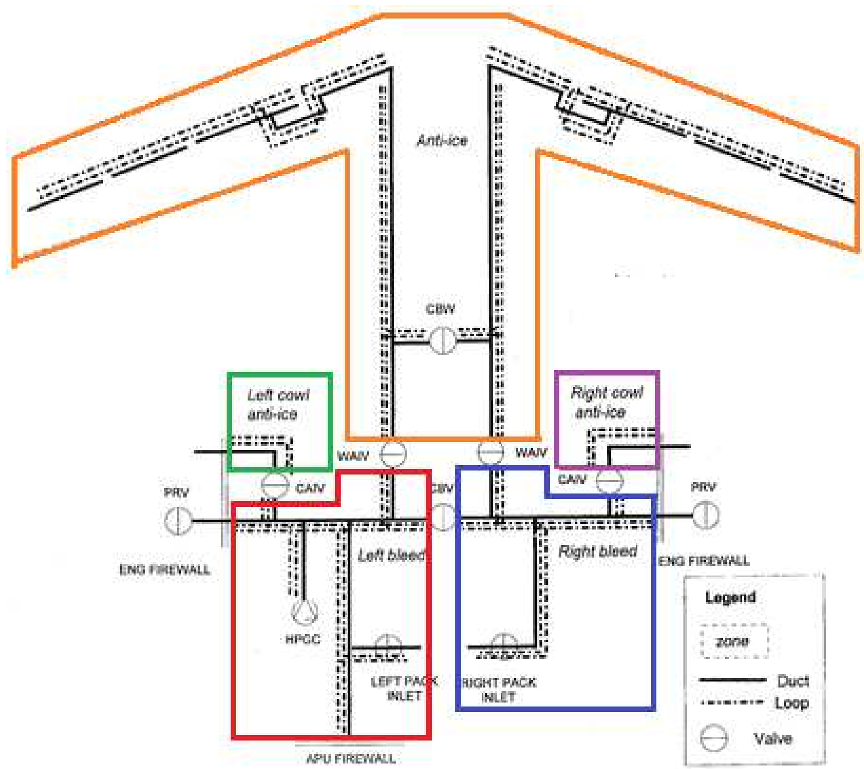
Design method: What needs to be done…

- **Place the ducts requiring monitoring in isolatable areas**
  - An isolatable area is one where the air supply can be cut off by one or more valves
  - A loop (or several loops if the area is very large) is allocated to each isolatable area



- **Setting up the architecture**
  - Determine whether the loops should be single or doubled up (combination of safety and availability)
  - Select the coherent architecture of the computers: in a double loop (A & B), loop A must be acquired independently of loop B
- **Select the activation temperatures**
  - Lower than the temperature of blown air
  - Higher than the max. temperature for the area by about 100°F (55°C)

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Control strategies

General

- Detection is a critical function
- Location is a "comfort" function (facilitates maintenance)

On-going

- Monitor the isolation resistance of the loops (detection)
- Locate
- Identify untimely detection in the case of double loops (one loop detects and the other doesn't)

When the computer is activated

- Check the continuity of the internal conductors (loop cut-off detection)

Control strategies (cont.)

- **Normal operation / problem scenarios**
- **In a double loop,**
  - If both loops function,
    leakage detected when loop A **AND** loop B signal the leakage

  ➡ Untimely detection is therefore avoided

  - if one loop is seen to be faulty (loop cut off),
    leakage detected when loop A **OR** loop B signals the leakage

- **Actions associated with leakage detection**
  - Signal in cockpit
  - Possible automatic valve closing: automation may reduce the time between the occurrence of the leakage and the closing of the valves concerned

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Course syllabus

- **Pneumatic Systems**
  - Bleed Air System
  - Leak Detection System
  - **COMPONENTS DESCRIPTION**

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Components Description - Air Valves

3 typical valve types

- Pneumatic: driven and commanded by bleed air
  - Implies numerous air sense lines for control

- Electrical: driven and controlled electrically
  - Implies power lines, harness installations and local electrical motor

- Electro-Pneumatic: Driven by bleed air and commanded electrically by electrovalves or torque motors

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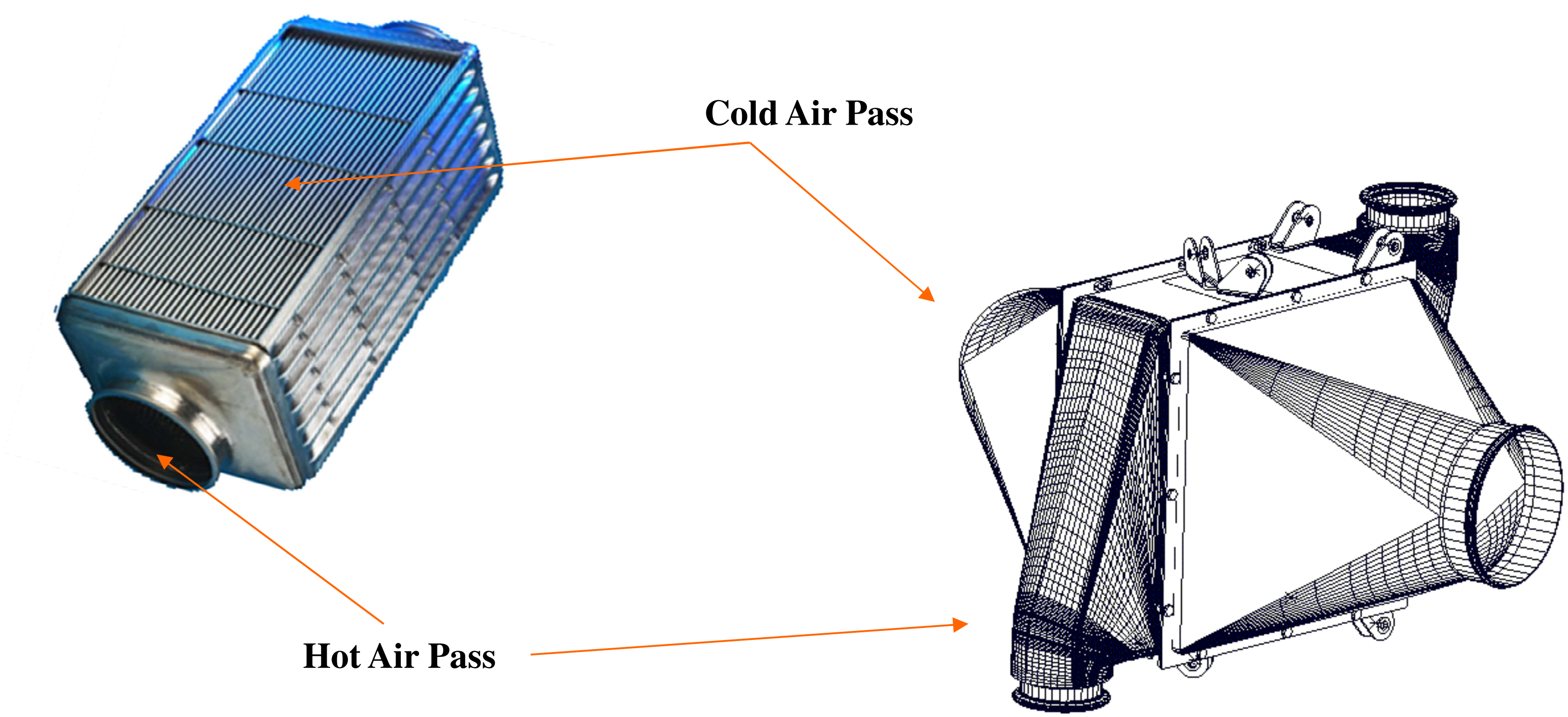
Components Description - Precooler

- PRECOOLER ASSY
  - ⇨ **Designed to nominally limit the pack inlet temperature to 450°F/ 230 °C.**
  - ⇨ **Two design types, plates & fins, or tubes & fins**



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Integrated Air Management System

Vapour Cycle System

VCS

February 2023

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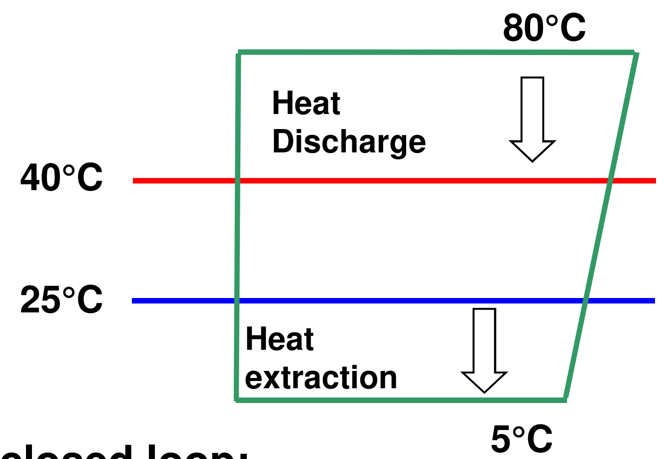
Vapour cycle : Principle

: Use changing phase properties of fluids to :

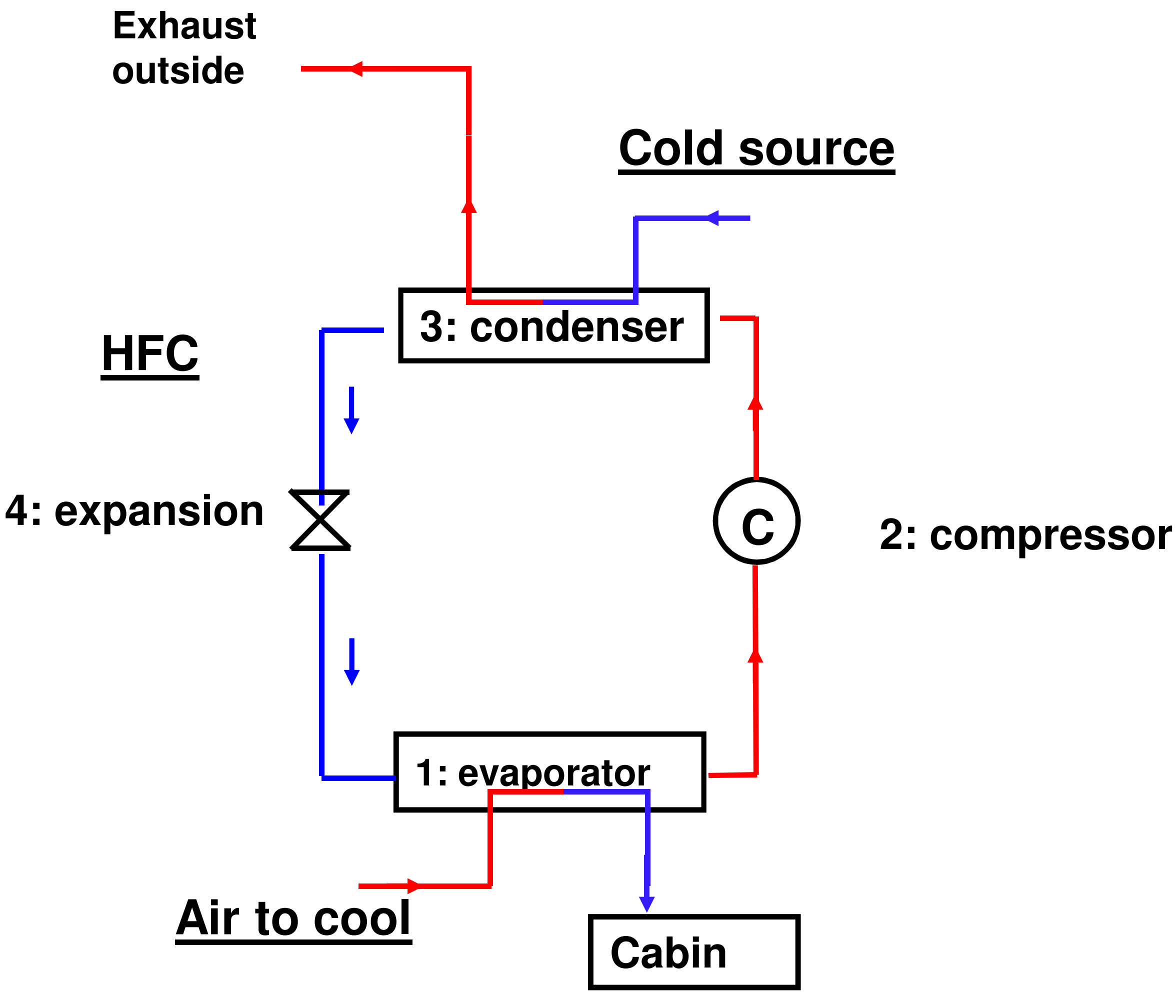
- Extract heat from cabin (hot source)
- Transport calories to higher pressure
- Discharge this heat to cold source



- **Vapour cycle uses frigorigen fluid properties in a closed loop:**
  - By evaporating : fluid can extract heat at low temperature (and low pressure)
  - By condensing : fluid will discharge heat at high temperature (and high pressure)

Limitation : cooling power capacity is linked to temperature difference between evaporation and condensation.

Vapour cycle : Principle



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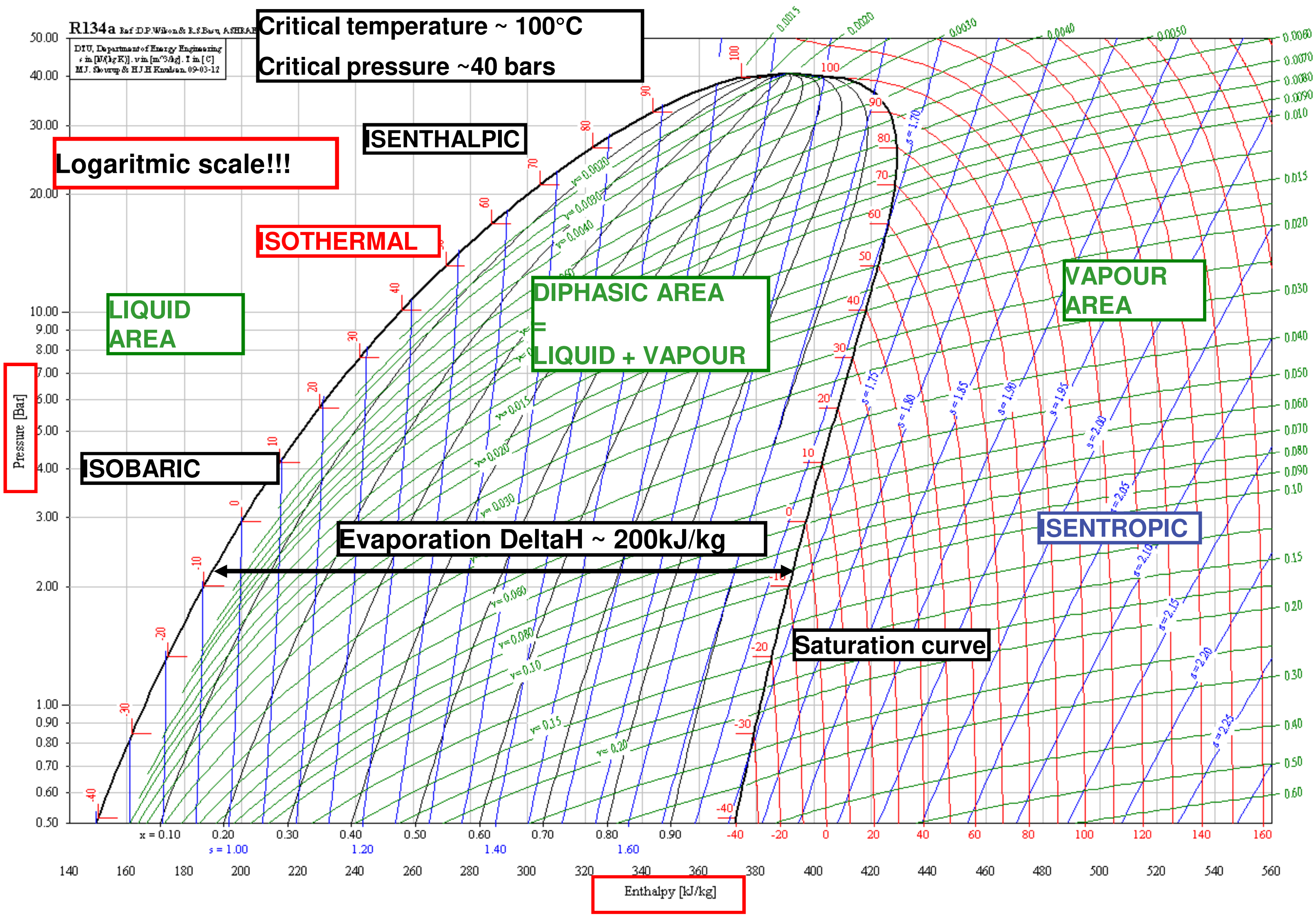
Vapour cycle: Thermodynamic diagram



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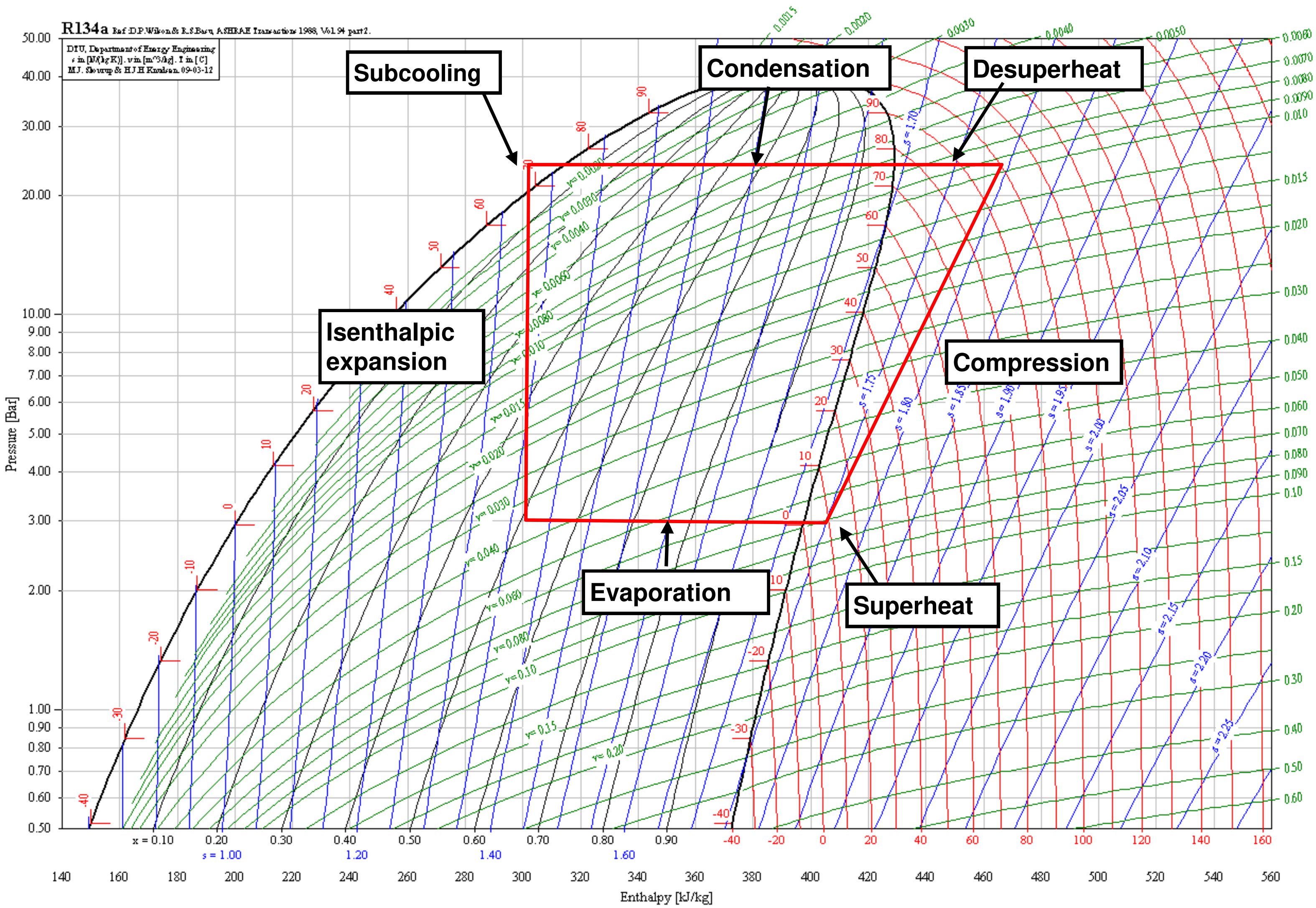
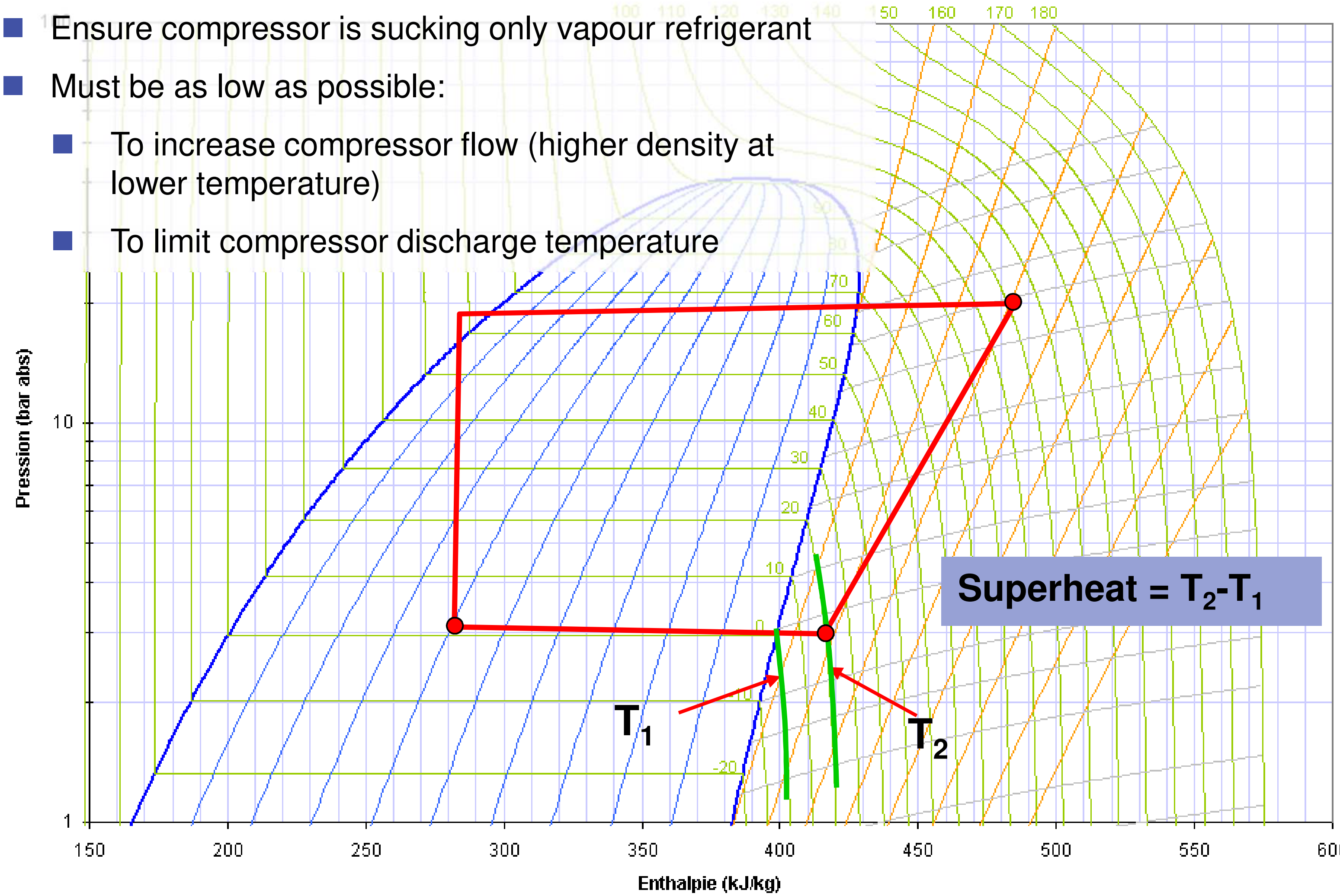
Vapour cycle: Thermodynamic diagram



Vapour cycle: Thermodynamic diagram

Superheat

- Ensure compressor is sucking only vapour refrigerant
- Must be as low as possible:
  - To increase compressor flow (higher density at lower temperature)
  - To limit compressor discharge temperature



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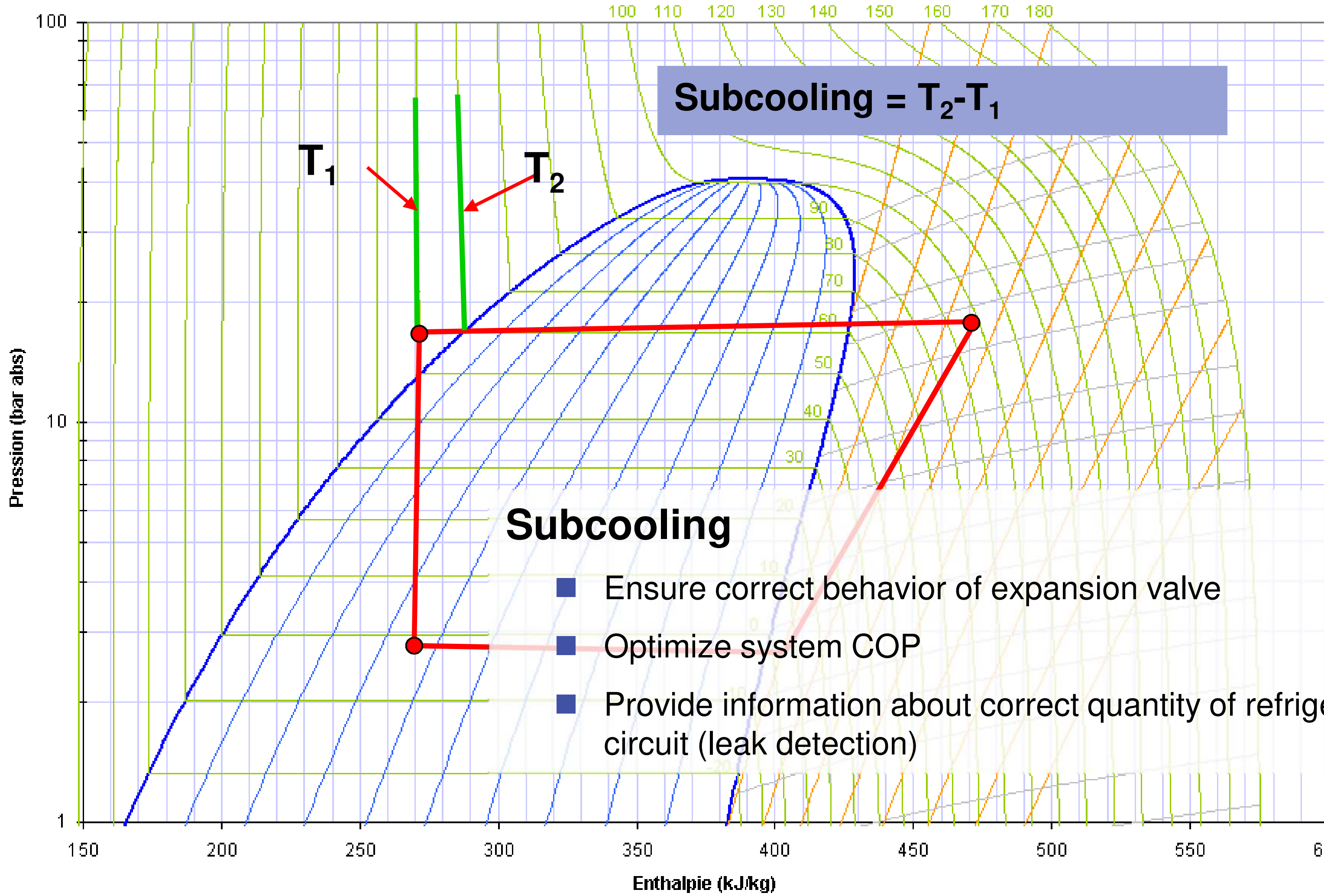
Vapour cycle: Thermodynamic diagram



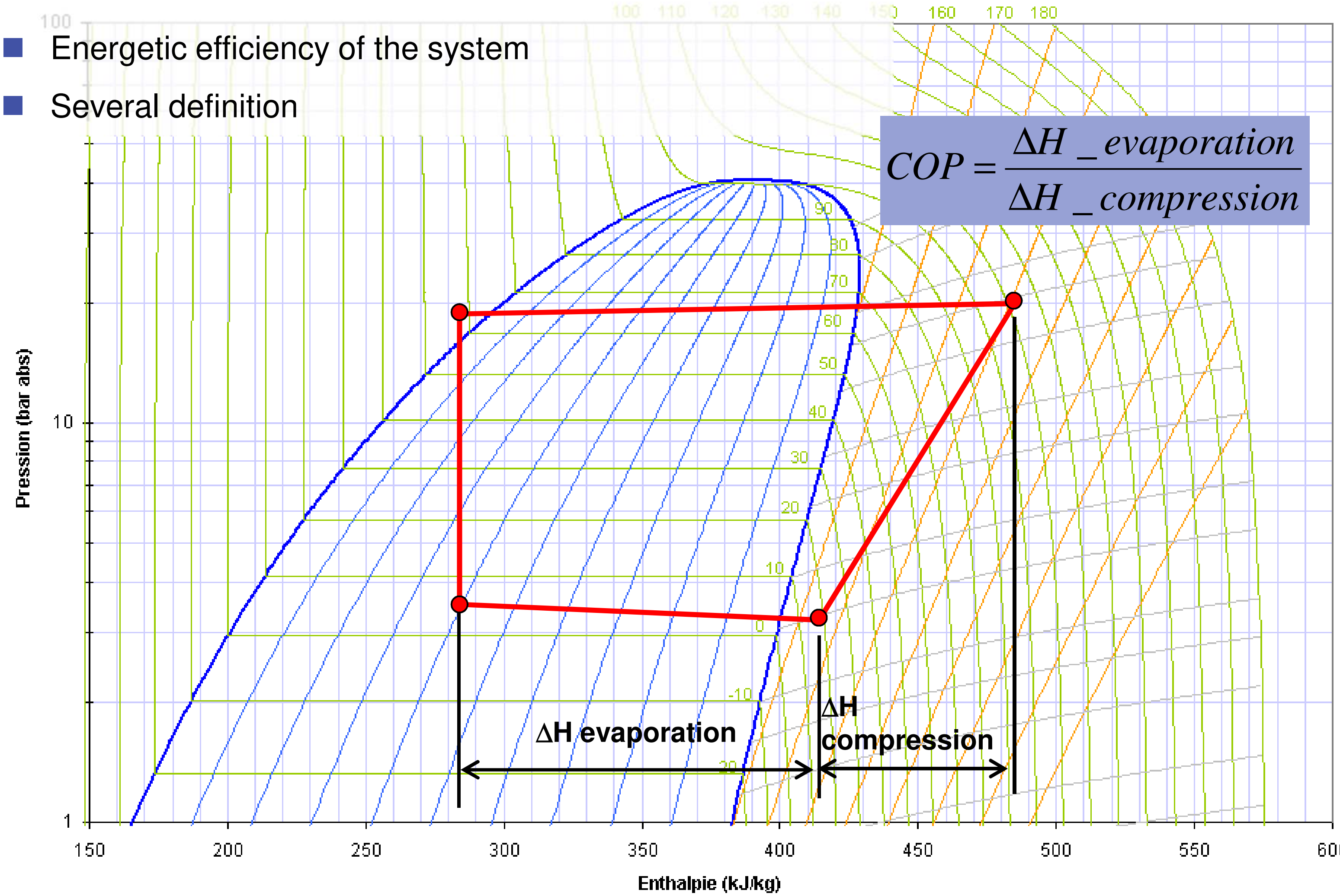
Subcooling

- Ensure correct behavior of expansion valve
- Optimize system COP
- Provide information about correct quantity of refrigerant in the circuit (leak detection)

Vapour cycle: Thermodynamic diagram

Coefficient Of Performance (COP)

- Energetic efficiency of the system
- Several definition



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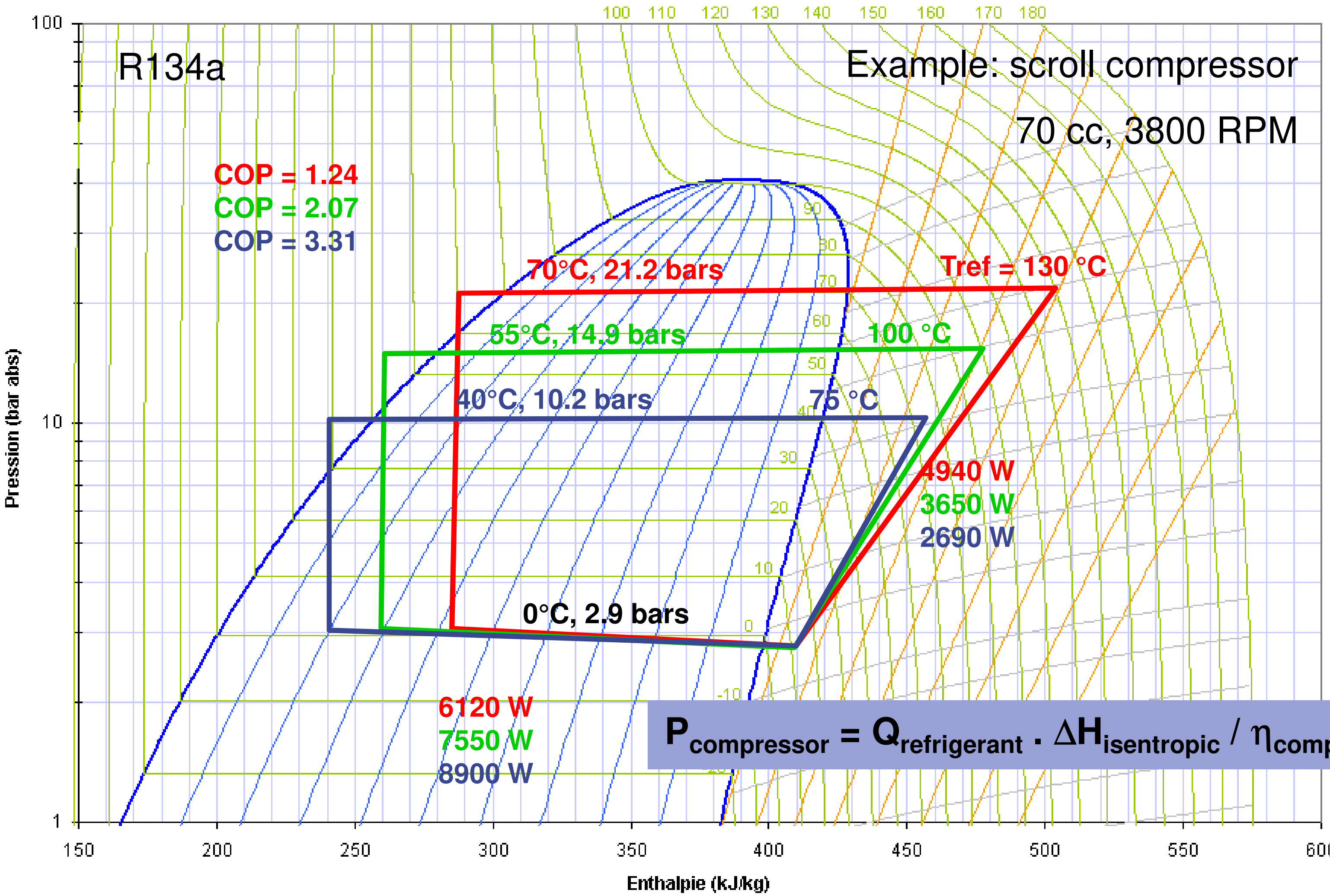
Vapour cycle: Thermodynamic diagram

Impact of condensation temperature



$$P_{compressor} = Q_{refrigerant} \cdot \Delta H_{isentropic} / \eta_{compressor}$$

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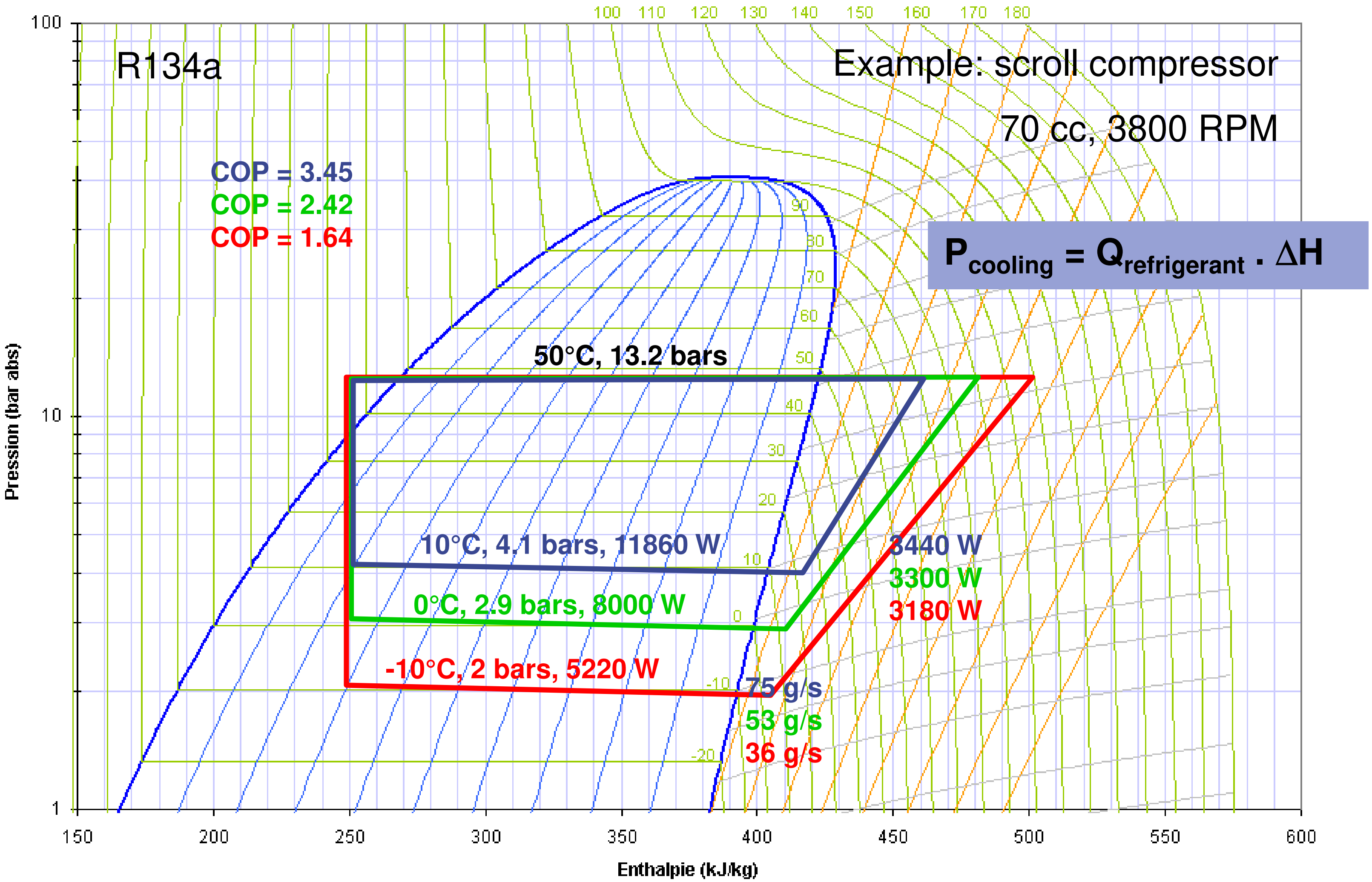
Vapour cycle: Thermodynamic diagram

Impact of evaporation temperature



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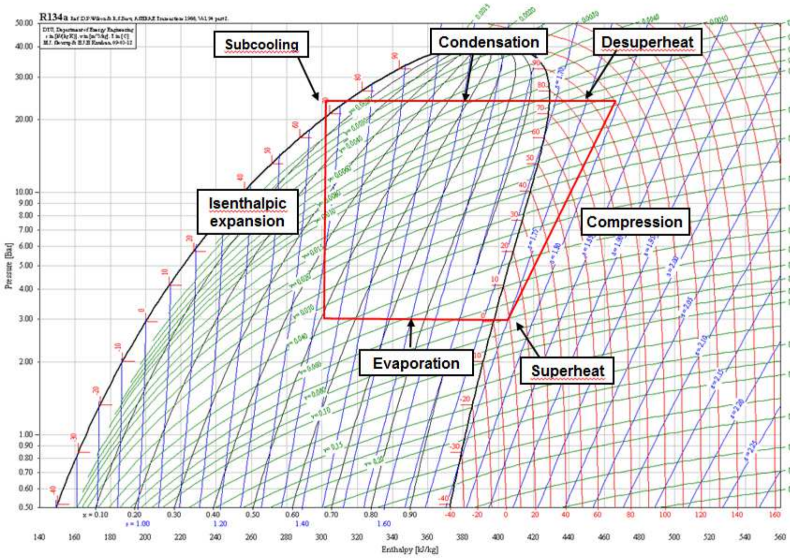
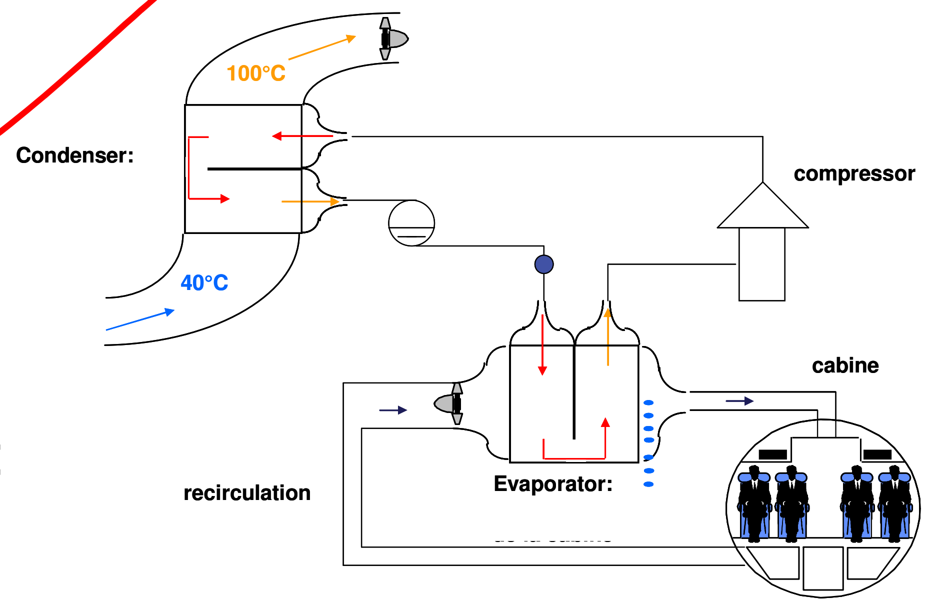
Vapour cycle: From theory to real product



Theory

Real product



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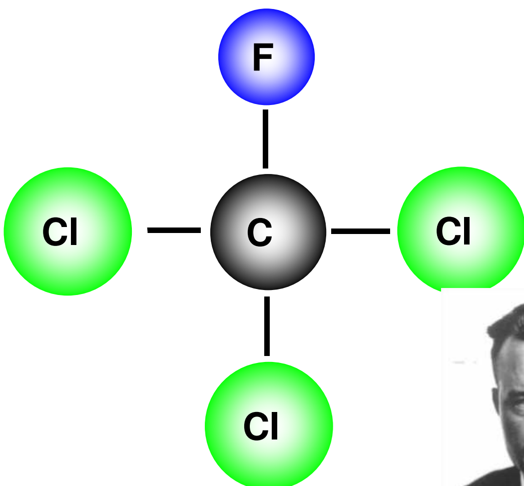
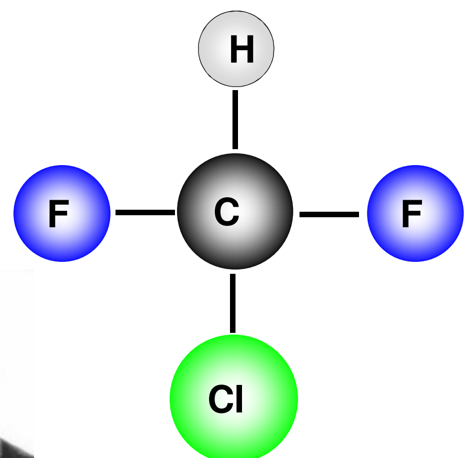
Vapour cycle : refrigerant fluid

- Produced from hydrocarbons (methane, ethane, propane)
- Part of Hydrogen is replaced by Fluorine or Chlorine
- Chimical formulae : $C_mH_nCl_pF_q$
- R-HZE with H = m-1, Z = n+1, E = q

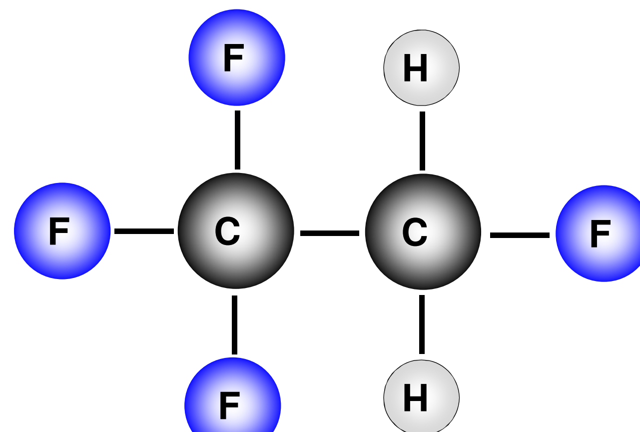


CFC
R11

Thomas Midgley Jr
CFC & Leaded gasoline



HCFC
R22



HFC
R134a

Vapour cycle : refrigerant fluid

Impact on environment

- CFC, HCFC, HFC …
- Ozone depletion potential (ODP) R11
- Global warming potential (GWP) CO2

Type	CFC, HCFC	HFC	CO_2, HFO1234yf
ODP	☹	☺	☺
GWP	☹	☹	☺

  - GWP of R134a: 1300 => 1kg of R134a released in atmosphere is equivalent to 1300kg CO2 released in atmosphere (~10 000 km car drive)
- Total Equivalent Warming Impact (TEWI)
  - Sum of two effects:
    - Direct GWP
    - Indirect : CO2 emission due to energy consumption to drive the VCS during its life (20 years)

- **France 58g CO2 per kwh**
- **Germany 560g CO2 per kwh**

2019 data from RTE and Franhofer

- Rules:
  - CFC forbidden
  - HCFC progressively forbidden
  - HFC used in majority today
  - HFC ban for new car since 2014

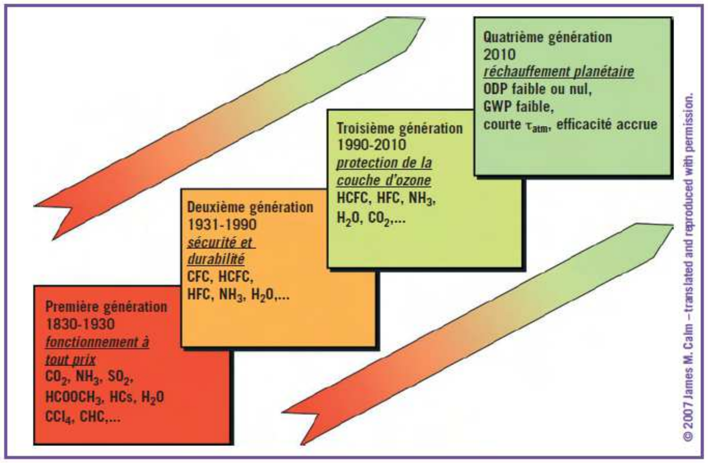


Figure 1. Progression des frigorigènes à travers quatre générations.

Vapour cycle : key components

Compressors : different types

1 BTU/min = 17.6 W

- **Scroll** : high efficiency compressor but limited in power due to low rotational speed (~4000 RPM). Limited reliability.

- **Screw** : Good efficiency compressor that can reach high cooling power thanks to higher speed (~10000RPM) compared to scroll compressor. High reliability.

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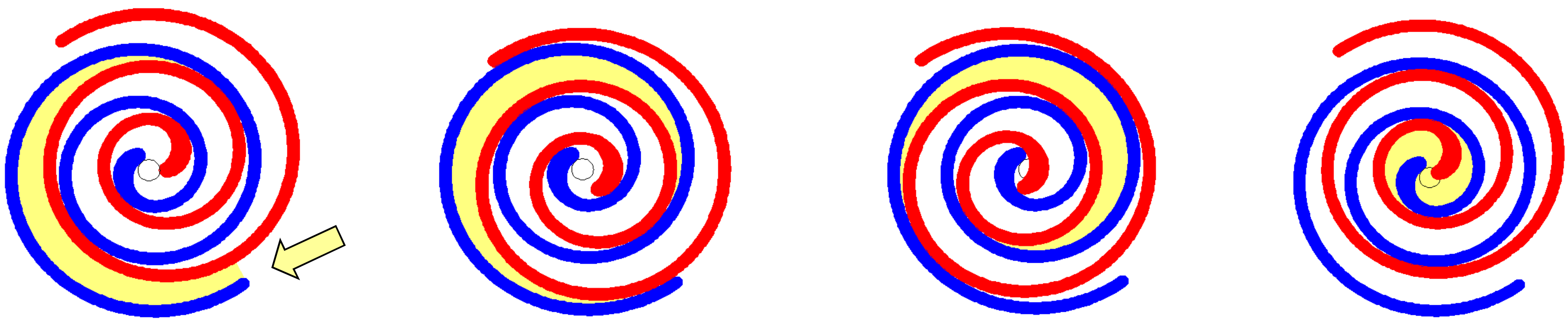
Vapour cycle : key components

Scroll compressor :

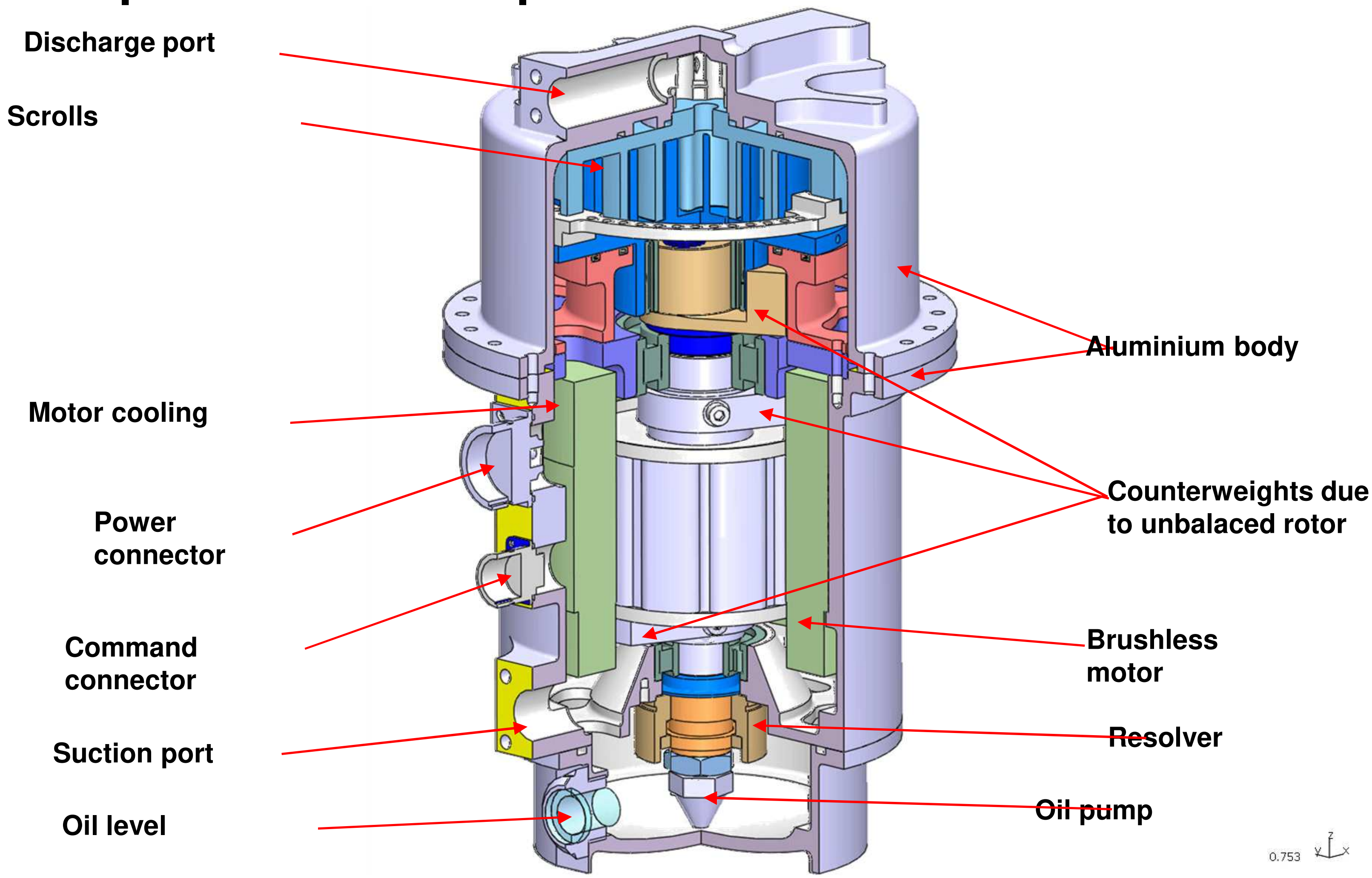
- Low friction speed
- Orbite radius : from 3 to 7 mm
- Limited rotational speed (~4000 tr/min)



① Suction ② Pockets sealed ③ Compression ④ Discharge

Vapour cycle : key components

Exemple of scroll compressor



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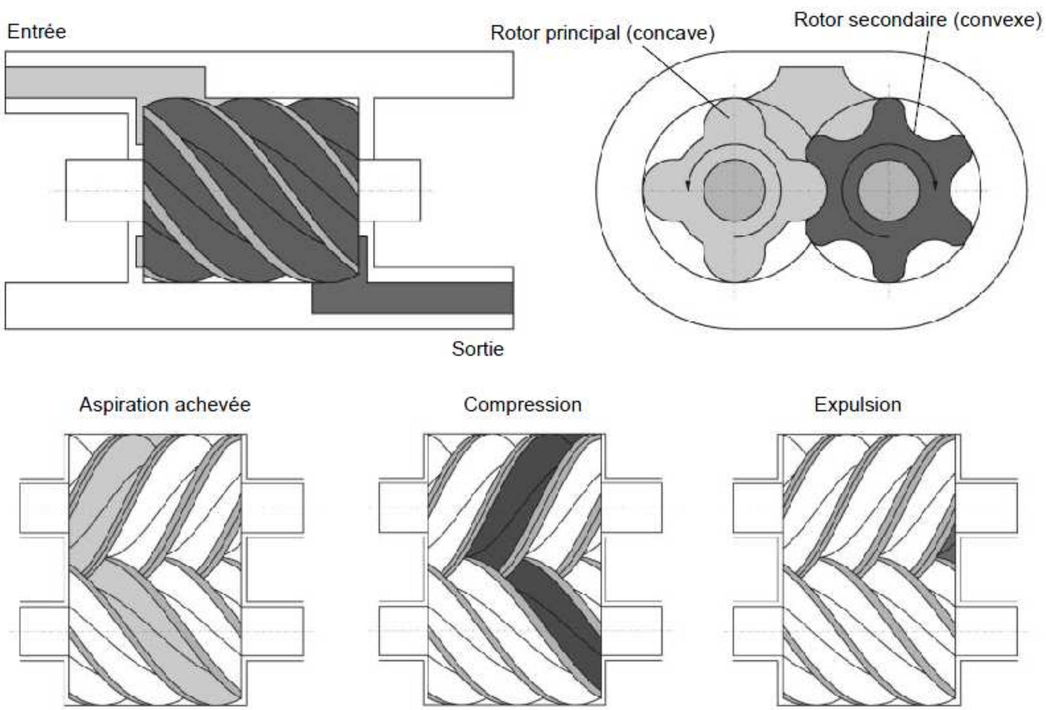
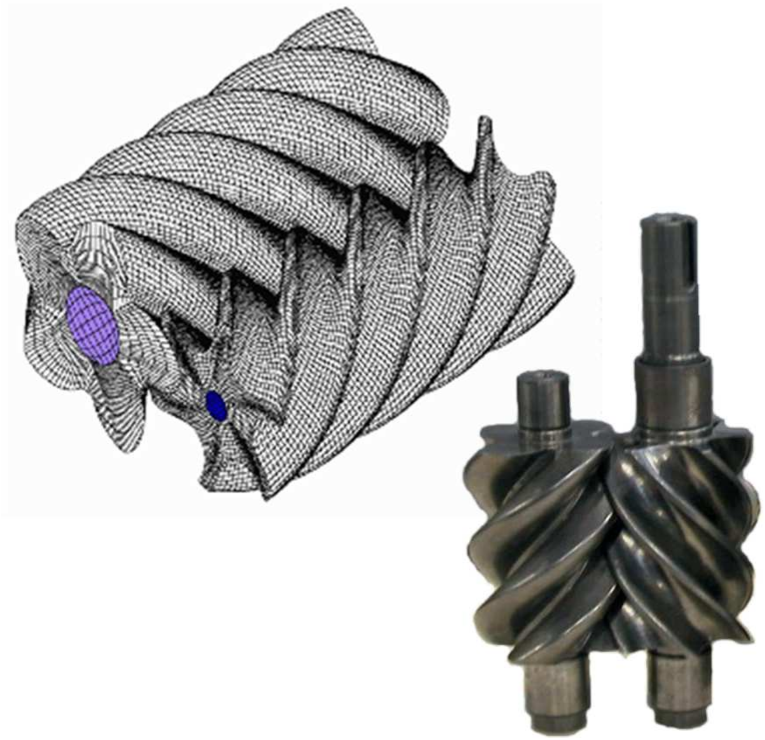
Screw compressor: principle

- Balanced rotor => high rotational speed (10000 tr/min)
- Need a high quantity of oil to lubricate rotors

  => Oil separator required





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Vapour cycle : key components

Volumetric compressors: volumetric efficiency

- Definition:

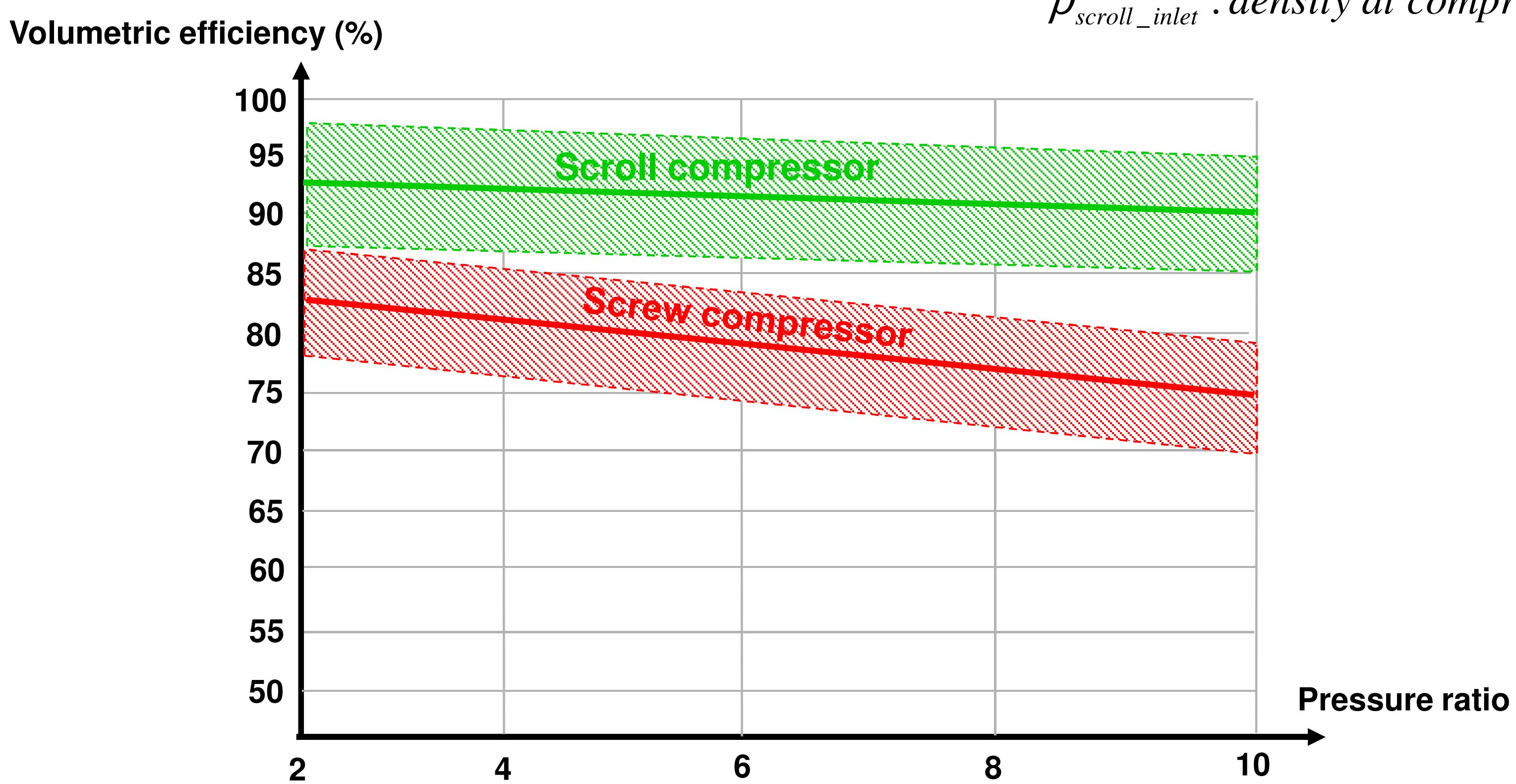
$$\eta_{volumetric} = \frac{Q}{N \times Cyl \times \rho_{scroll\_inlet}}$$

Q : refrigerant flow

N : rotational speed

Cyl : positive displacement

ρ_{scroll_inlet} : density at compressor inlet



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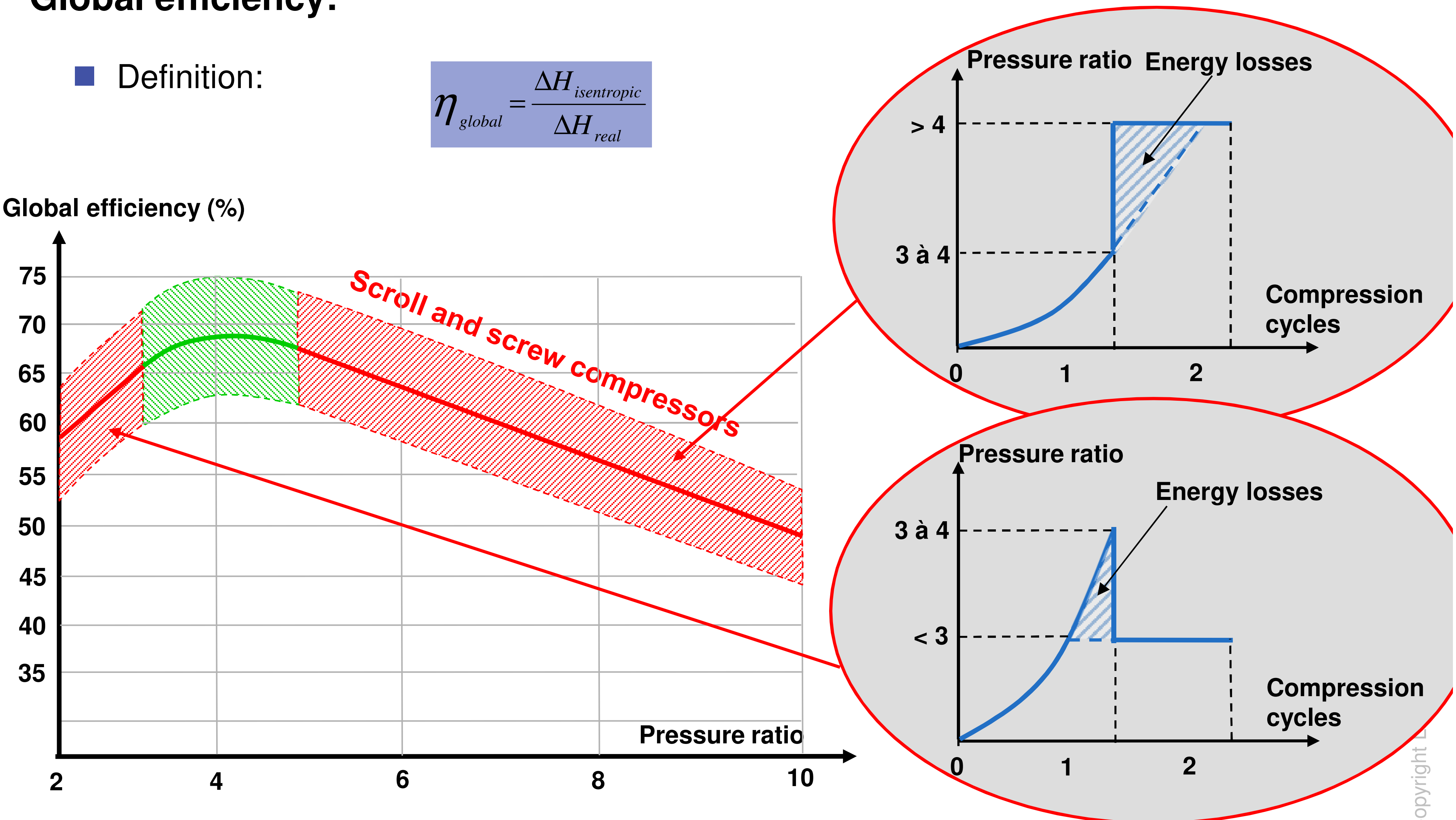
Vapour cycle : key components

Global efficiency:

- Definition:

$$\eta_{global} = \frac{\Delta H_{isentropic}}{\Delta H_{real}}$$



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Vapour cycle : key components

Evaporator

- Cools down air or liquid
- Good evaporator efficiency is needed to optimize compressor pressure ratio and cooling power

Evaporator efficicency = $\varepsilon = \dfrac{T_{air\_inlet} - T_{air\_outlet}}{T_{air\_inlet} - T_{evaporation}}$

Power (kW) = $Q_{refrigerant}$ (kg/s)x ΔH (kJ/kg)

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Vapour cycle : key components

Condenser

- Releases heat absorbed by evaporator and injected by compressor on the cold source
- Good condenser efficiency is needed to optimize compressor pressure ratio and cooling power

Condenser efficicency $\varepsilon = \dfrac{T_{sortie\_air} - T_{entrée\_air}}{T_{condensation} - T_{entrée\_air}}$

Power$_{condenser}$ = Power$_{evaporator}$ + Power$_{compressor}$

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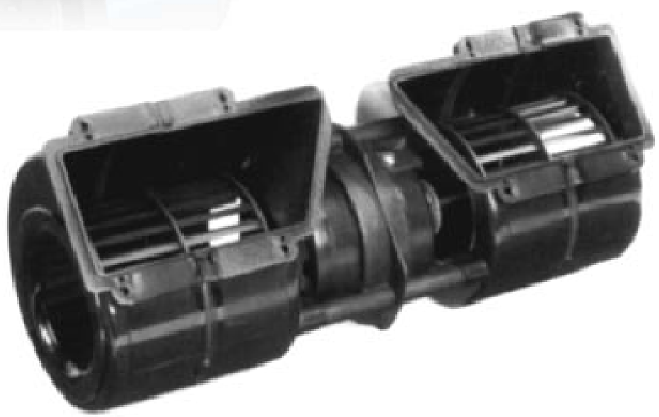
Vapour cycle : key components

Fans (evaporator & condenser)

- Axial fan
  - Low deltaP
  - Surge
  - Noisy
  - But high efficiency

Axial fan

- Radial fan :
  - High delta P
  - No surge
  - Low noise
  - But low efficiency



Radial fan

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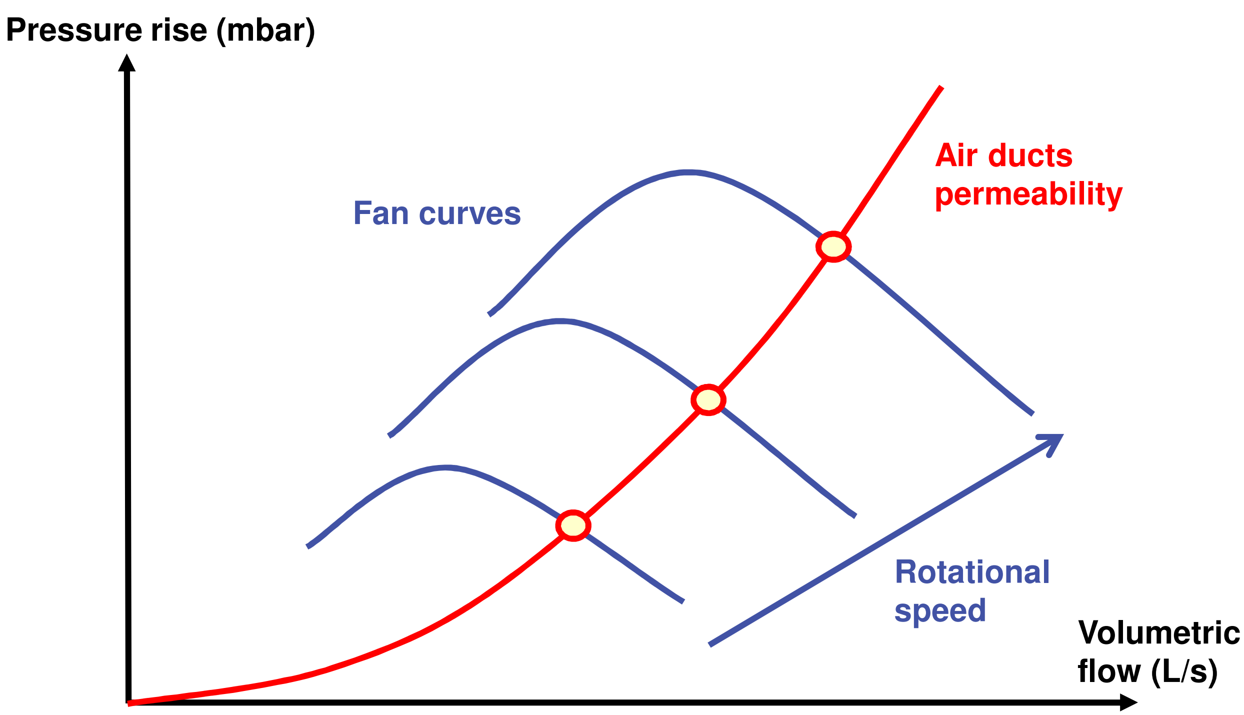
Vapour cycle : key components

Fan sizing

- Fan size is driven by required flow and air ducts permeability.
- Axial fan are sensible to surge conditions !



$$P_{fan}(W) = \frac{Q_{v\_air}(l/s) \times \Delta P_{air}(mbar)}{10.\eta_{fan}}$$

$$\eta_{axial\ fan} = 0.4 \text{ à } 0.62$$

$$\eta_{radial\ fan} = 0.25 \text{ à } 0.35$$

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VCS Sizing Method

Step 1: Refrigerant fluid choice

- High COP (high DeltaH + isentropic curves in vapour area vertical)
- High Delta H evap => low flow => smaller compressor
- Max air temperature on condenser

Fluid characteristics comparison

Fluid	CO_2		R134a		R236fa	
Critical temperature	31°C		101°C		125°C	
Temperature	Pressure	Density	Pressure	Density	Pressure	Density
0°C	34.8 bars	97.3 kg/m3	2.9 bars	14.4 kg/m3	1.1 bars	7.6 kg/m3
50°C	-	-	13.2 bars	66.2	5.8 bars	39.2
75°C	-	-	23.6 bars	133.5	11.1 bars	78.0
100°C	-	-	39.7 bars	373.0	19.4 bars	157.1
Utilization	Low GWP		Up to 70°C OAT		For military applications	

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VCS Sizing Method

- **Step 2: Define evaporation and condensation temperatures**

  Generally:

  $$T_{condensation} = T_{cds\ inlet} + 20°C$$
  $$T_{evaporation} = T_{evap\ outlet} - 5°C$$

  - Usually, evaporator outlet temperature is equal to cabin air blowing temperature so blowing air temperature limitations shall apply (5 - 8°C with passengers).

- **Step 3: Set 10°C of superheat and 2°C of subcooling**
  - Outlet condenser, Inlet and outlet evaporator enthalpy can be read on diagram.

- **Step 4: Assess pressure losses between:**
  - Evaporator and compressor inlet : suction pressure losses
  - Compressor outlet and condenser : discharge pressure losses
  - Suction and discharge pressures are known as well suction enthalpy.

- **Step 5: Define global efficiency depending on pressure ratio (Slide 138)**
  - Discharge enthalpy can be calculated

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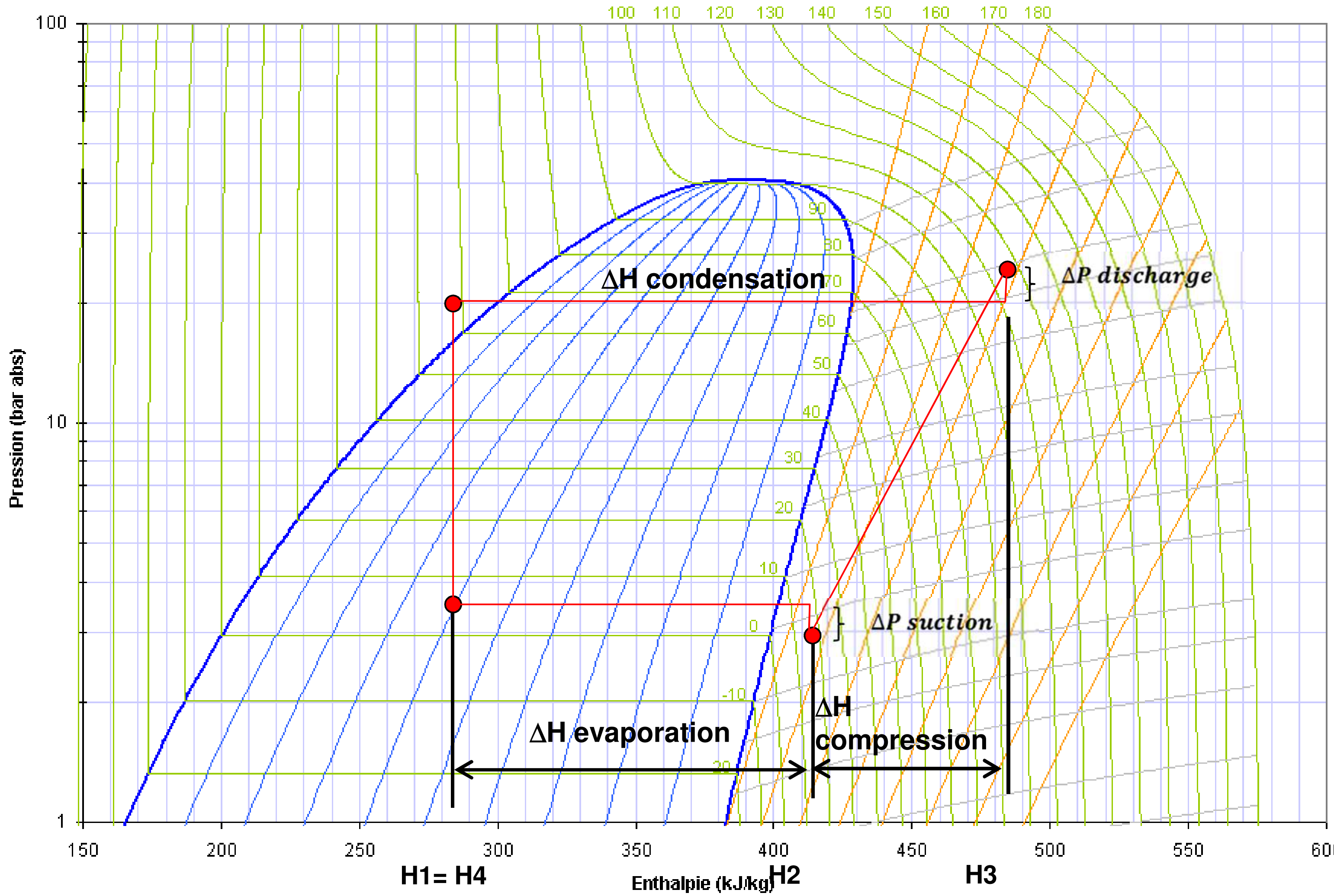
VCS Sizing Method

After step 5, all system points are defined :



VCS Sizing Method

Step 6: Determine flows (air and refrigerant) based on cooling power :

- Evaporator cooling power is equal to:
  - Cabin heat loads
  - Evaporator fan power
  - Thermal losses in distribution ducts
  - Expired passenger humidity condensation in evaporator
  - Fresh air flow cooling (sensible and latent heat loads)

$$Q_{Evap\ fan} = \frac{1.1 P_{HL}}{Cp_{air} \times \Delta T_{air}}$$

P_{HL} = Cabin heat loads

1.1 to take into account distribution thermal losses

ΔT_{air} = Cabin temperature – Blowing air temperature

(for vapour cycle free water=0, so T_{db} = T_{dar})

$$P_{fan}(W) = \frac{Q_{v\_air}(l/s) \times \Delta P_{air}(mbar)}{10.\eta_{fan}}$$

$$Q_{v\_air}(l/s) = \frac{1000 \times Q_{Evap\ fanair}(kg/s)}{\rho(kg/m^3)}$$

$$\eta_{axial\ fan} = 0.4 \text{ à } 0.62$$

$$\eta_{radial\ fan} = 0.25 \text{ à } 0.35$$

$$P_{evap} = P_{HL} + P_{Evap\ \ fan} + P_{cds\ eau} + P_{fresh\ \ air\ cooling}$$

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VCS Sizing Method

Refrigerant flow calculation:

$$Q_{refrigerant}(kg.s^{-1}) = \frac{P_{evapo}\ (kW)}{DeltaH\ (kJ.kg^{-1})}$$

$$Q_{refrigerant}(g.s^{-1}) = \frac{P_{evapo}\ (W)}{DeltaH\ (kJ.kg^{-1})}$$

Compressor power calculation:

$$DeltaH_{comp}(kJ.kg^{-1}) = \frac{DeltaH_{isentropic}\ (kJ.kg^{-1})}{\eta_{global}}$$

$$P_{mech\ comp}(W) = Q_{refrigerant}(g.s^{-1}) \times DeltaH_{comp}(kJ.kg^{-1})$$

$$P_{elec\ comp}(W) = \frac{P_{mech\ comp}(W)}{\eta_{elec}}$$

Condenser power :

$$P_{condenser}(W) = P_{avap}(W) + P_{comp}(W)$$

$P_{comp} = P_{mech\ comp}$ if mechanically driven
$P_{comp} = P_{elec\ comp}$ if electrically driven

$$Q_{Fan\ condenser} = \frac{P_{condenser}}{Cp_{air} \times \Delta T_{air\ cds}}$$

$\Delta T_{air\ cds}$ = 15°C generally

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VCS Sizing Method

Compressor sizing:

For a given technology (scroll or screw), required positive displacement is given by:

$$Cyl(cm^3) = 60000.\frac{Q_{refrigerant}(g/s)}{\eta_{volumetric}.N(tr/\min).\rho_{compressor\_inlet}(kg/m^3)}$$

Usually, compressor is selected from existing off-the-shelf components. Correct existing compressor is selected based on rotational speed calculation:

$$N(tr/\min) = 60000.\frac{Q_{refrigerant}(g/s)}{\eta_{volumetric}.Cyl(cm^3).\rho_{compressor\_inlet}(kg/m^3)}$$

Scroll : correct speed between 3000 and 6000RPM

Screw : correct speed between 6000 and 10000RPM

Slide 134 for $\eta_{volumetric}$

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Integrated Air Management System

Cabin Pressure Control System

CPCS

February, 2023

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Course syllabus

- **Cabin Pressure Control System**
  - System Function and Requirements
    - Cabin Altitude, Relative pressures and Cabin rate
  - General Operating Principles
  - System Architectures and sizing
  - Components Description / Installation

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CPCS Functions & Requirements

Cabin Pressure Control System

- Maintain correct cabin pressure for necessary occupant oxygen levels
- Maintain pressure requirements for structural integrity
- Adjust cabin altitude change rates to ensure safe and comfortable rate of depressurization
- Adjust cabin pressure « altitude » to match airport landing pressure « altitude »
- Ensure cabin pressure “dump” for emergency evacuation
- Appropiate annunciations

- Maintain 8000 ft (not to exceed) pressure altitude in cabin at 41000 ft at min weight/power cruise settings or idle
- Ensure protection against overpressure for structural integrity
- Typical Max Diff pressure 8.3 +/- 0.1 psid
- Typical Relief settings
  - Overpressure:+ 8.6 $^{\pm 0.1}$ psid (593$^{\pm 7}$ mbar)
  - Under-pressure - 0.5 psid (-34 mbar)

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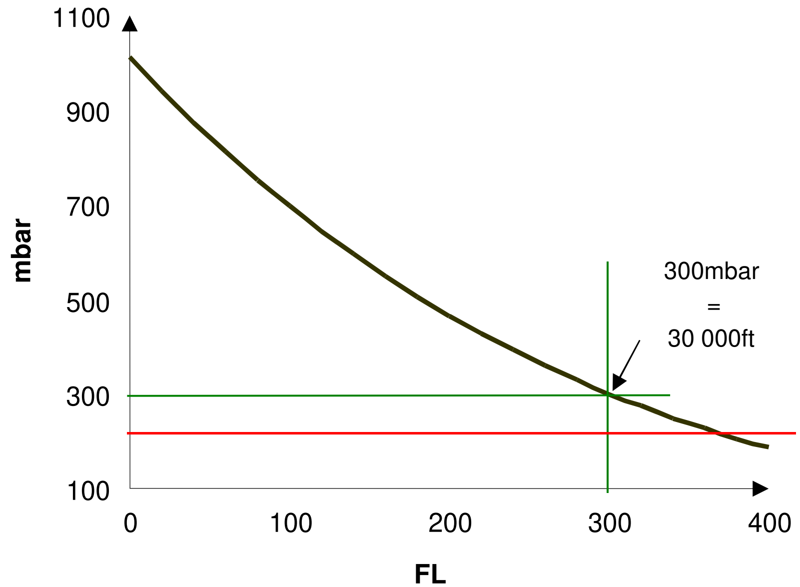
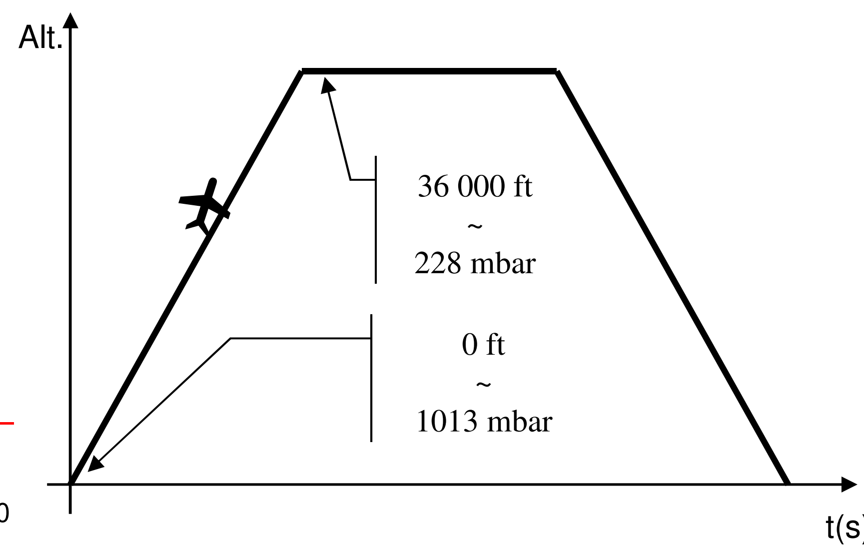
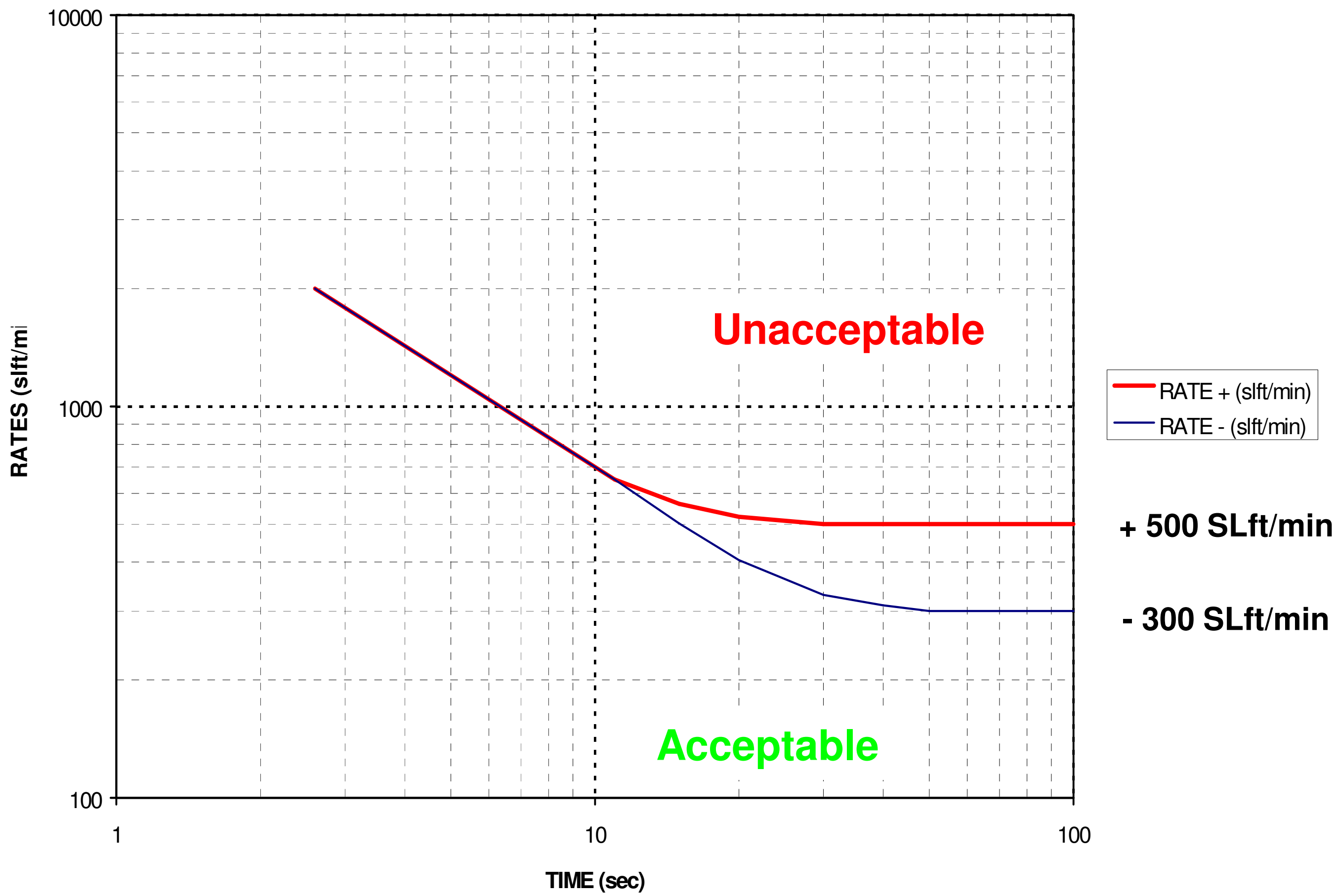
CPCS Functions & Requirements

- PRESSURE vs. ALTITUDE
  - The ambient pressure (static pressure) is a function of the altitude. This variation is not linear.
  - A standard atmosphere pressure corresponds to an altitude value.





Acceptable rates of change for passenger comfort



Note: Typical a/c Climb/ descent rates 2000 – 3000 ft/min

CPCS Functions & Requirements

- **Critical system : involved in many catastrophic safety events**
- **Passangers are very sensitive to CPCS performance : high impact on passangers comfort**
- **Antinomic constraints:**
  - Comfort and physiology => high cabine pressure
  - Aircraft structural weight => Sizing for structure
    - Low pressure difference with ambiant pressure => Low cabin pressure
    - Pressurization cycle => ageing of structure
  - Thus cabin pressure is set to maximum authorized 753mbar (8 000 ft).
    - For long range aircrafts and business jets cabin pressure is higher 812mbar (6 000ft) .

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CPCS Functions & Requirements

- Loss of pressurization (CAT)
  - Cabin altitude must be maintained under 8 000 ft
  - In some failures cases cabin altitude may reach 10 000 ft
  - If aircraft ceiling is above 25kft, CPCS must be equiped with independent mean to limit cabin altitude to 15kft in case of simple failure.
  - System design must ensure better than 10^{-9} that:
    - Cabin altitude will not be over 25kft during more than 2 minutes
    - Cabin altitude will never exceed 40kft

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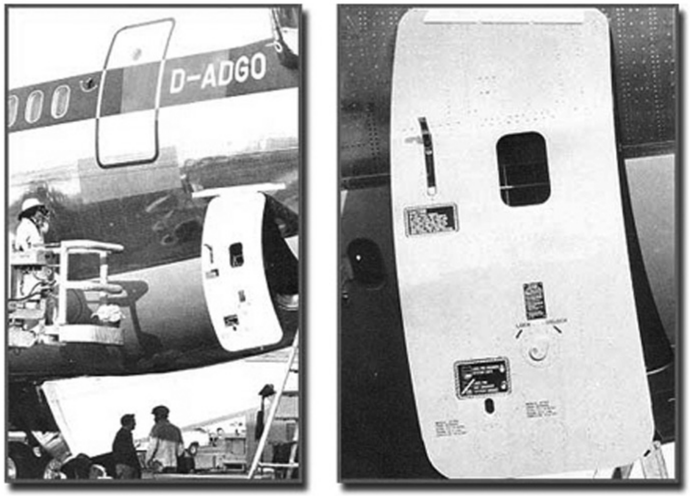
CPCS Functions & Requirements

- Excessive positive differential pressure (CAT)
  - CPCS must get 2 valves protecting aircraft from excessive positive differential pressure.
- Excessive negative differential pressure (CAT)
  - CPCS must get 2 valves protecting aircraft from excessive negative differential pressure.

CPCS Functions & Requirements

- Loss of pressurization inhibition (CAT)
  - If doors are not properly locked closed, CPCS must not pressurize cabin
- Loss of residual pressure protection (CAT)
  - CPCS must ensure pressure equalization on ground in order to open safely doors



- DC10 / TK981

03/03/1974

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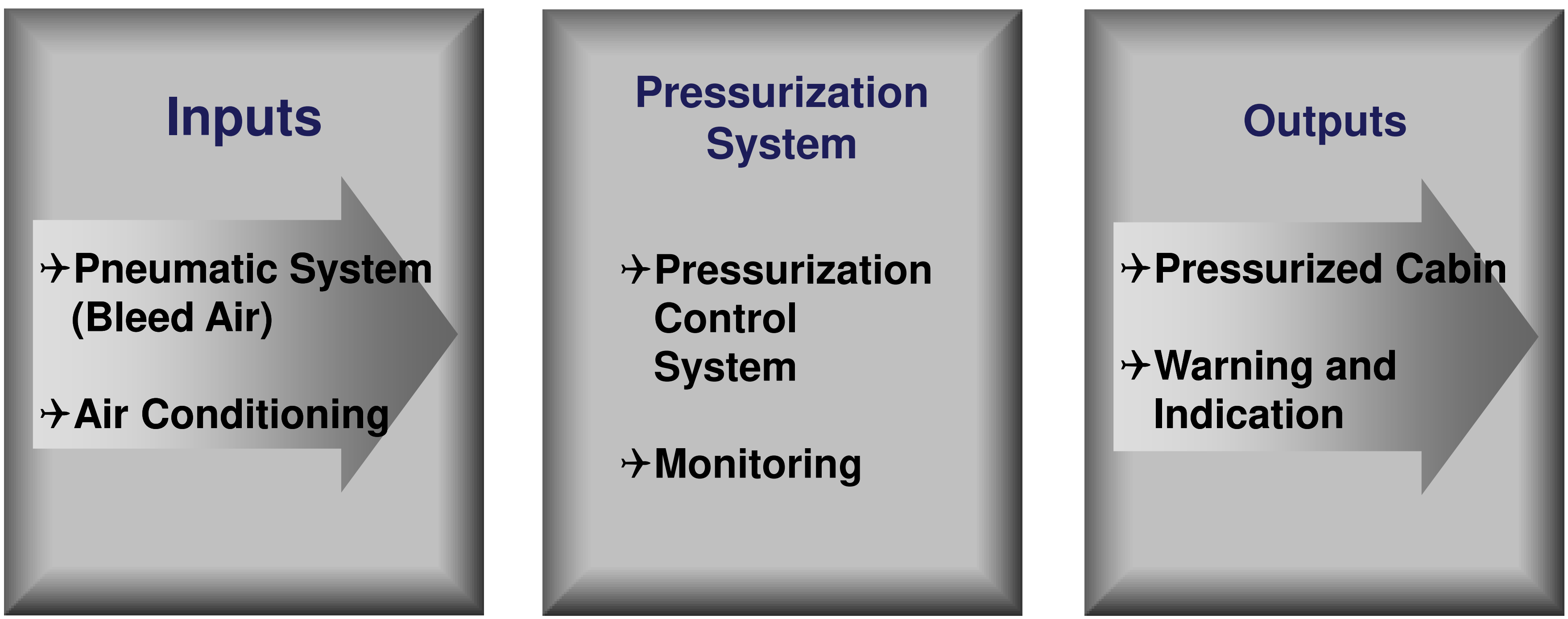
CPCS General Operating principles

System Interfaces

- In order to properly function , the following elements are involved:



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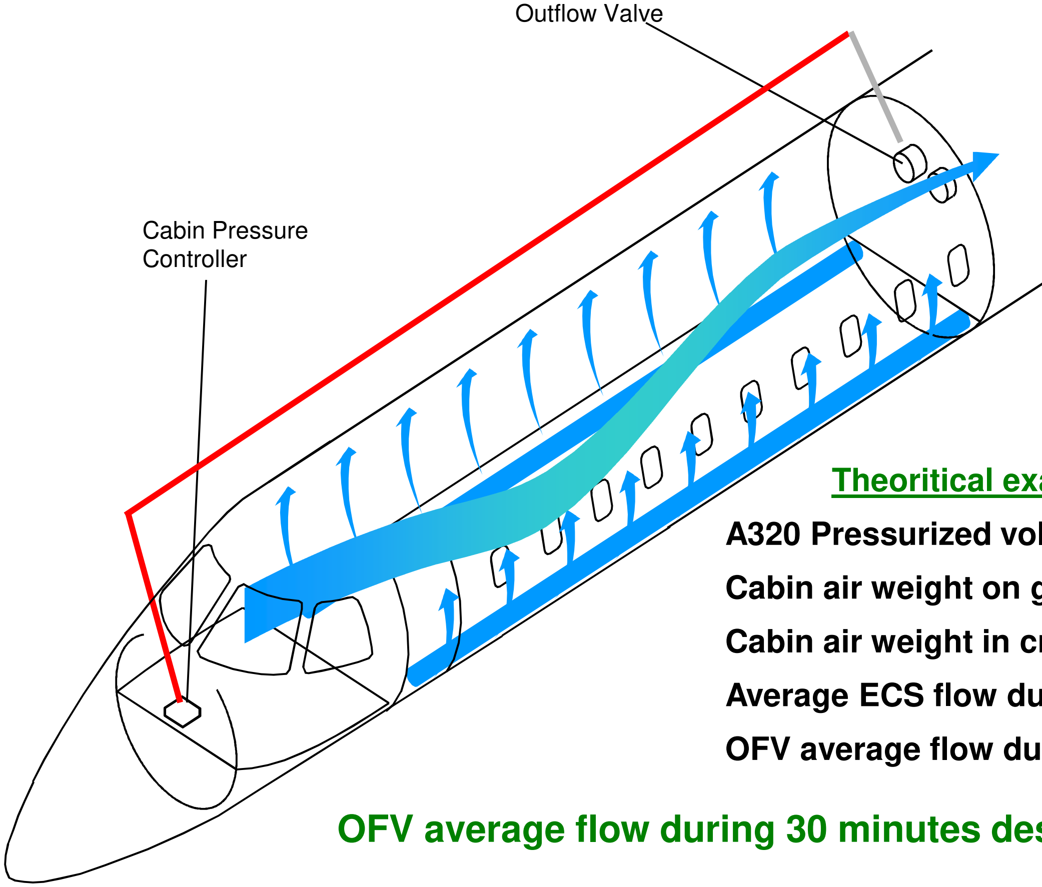
CPCS General Operating principles

CPCS Principle



1- Incoming air from pack.

2- Distribution of air and pressure build-up.

3- Cabin Pressure Controller (CPC) sends a command to the Outflow Valve (OFV).

4- Outflow Valve evacuates the air out of the cabin to regulate the pressure.

Theoritical example (No A/C structure leakage):

A320 Pressurized volume : ~400m3

Cabin air weight on ground : 480kg (density 1.2kg/m3)

Cabin air weight in cruise : 352kg (density 0.88kg/m3)

Average ECS flow during climb : 1kg/s

OFV average flow during 30 minutes climb = $\frac{480-352}{30*60}+1=1.07kg.s^{-1}$

OFV average flow during 30 minutes descent?

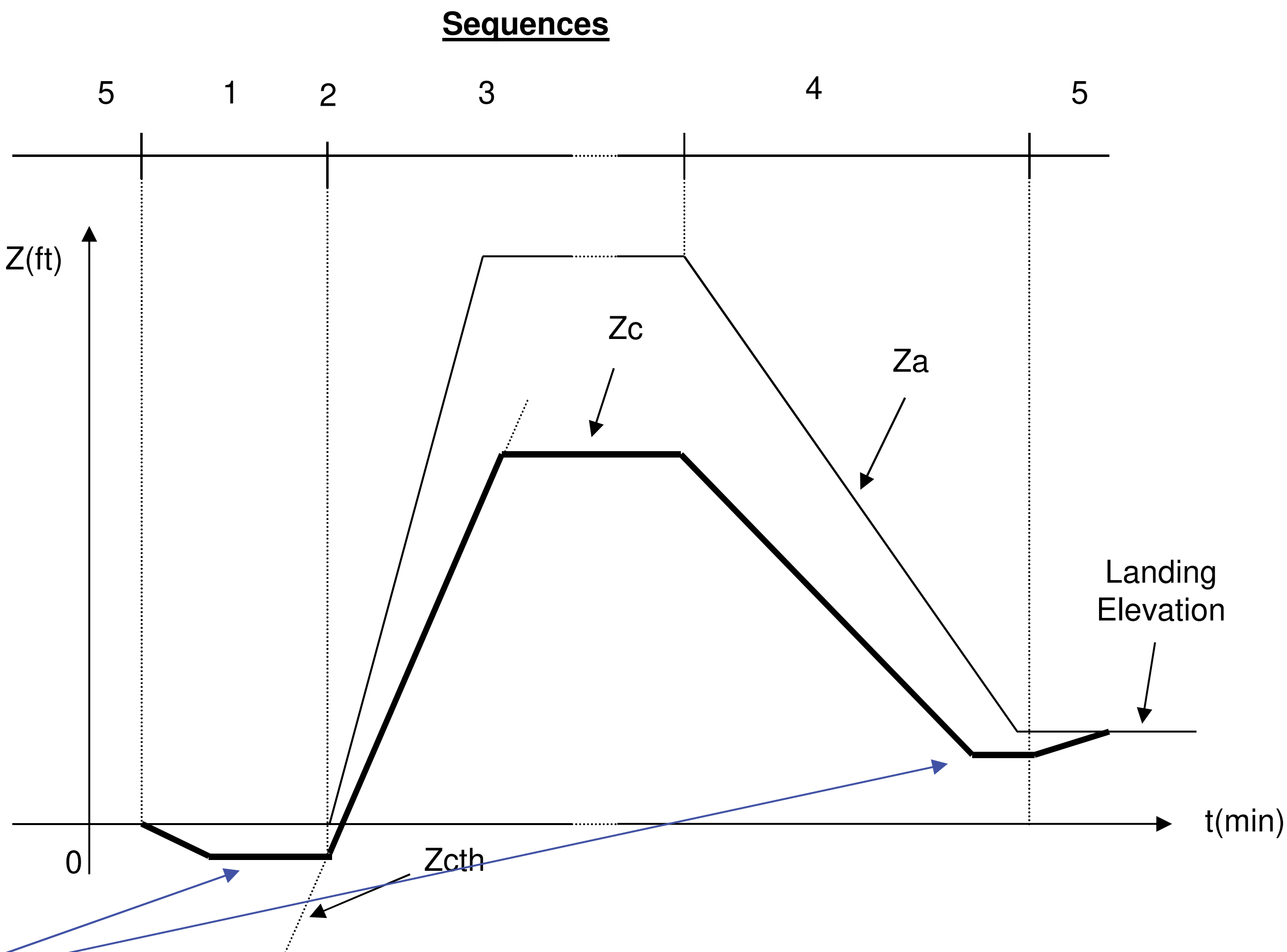
Pressurization flight profile

Lexicon:

1: pre-pressurization
2: take-off
3: flight
4: descent
5: depressurization

Za =actual aircraft pressure altitude

Zc = Cabin altitude



Pre-Pressurization avoids a cabin pressure “bump” due to the overpressure below the fuselage during the A/C rotation at take-off & landing

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System Architecture : Electric CPCS

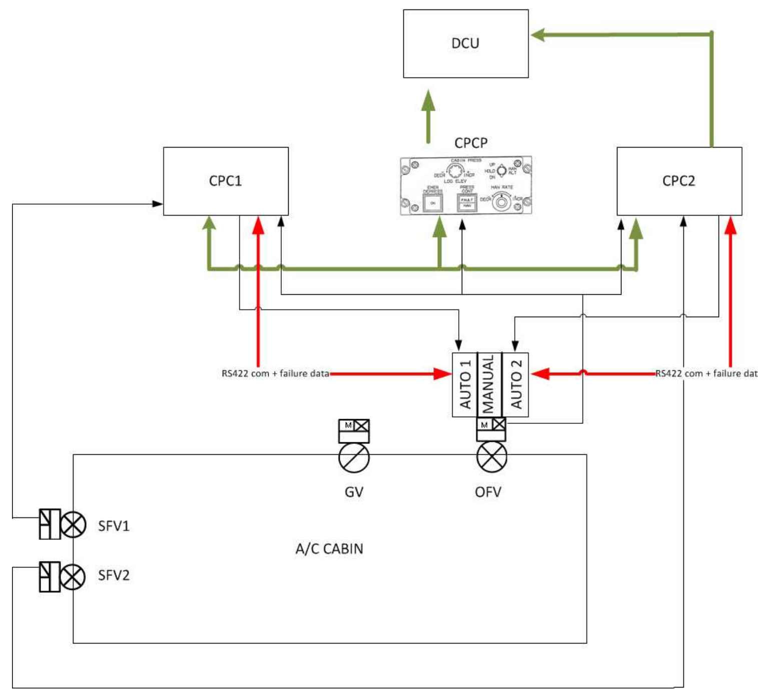
- 2 Cabin Pressure Controller (CPC)

  Each CPC contains:

  - 1 Automatic channel (chip's board)
  - 1 Manual channel (having cabin altitude limitation function)

- 1 Electric OutFlow Valve (OFV)
  - 2 identical and independent AUTOMATIC modes
  - 1 MANUAL mode (controlled by pilots)

- 1 Ground Valve (GV)
- 2 Safety Valves (SFV)
- 1 Cabin Pressure Control Panel (CPCP)



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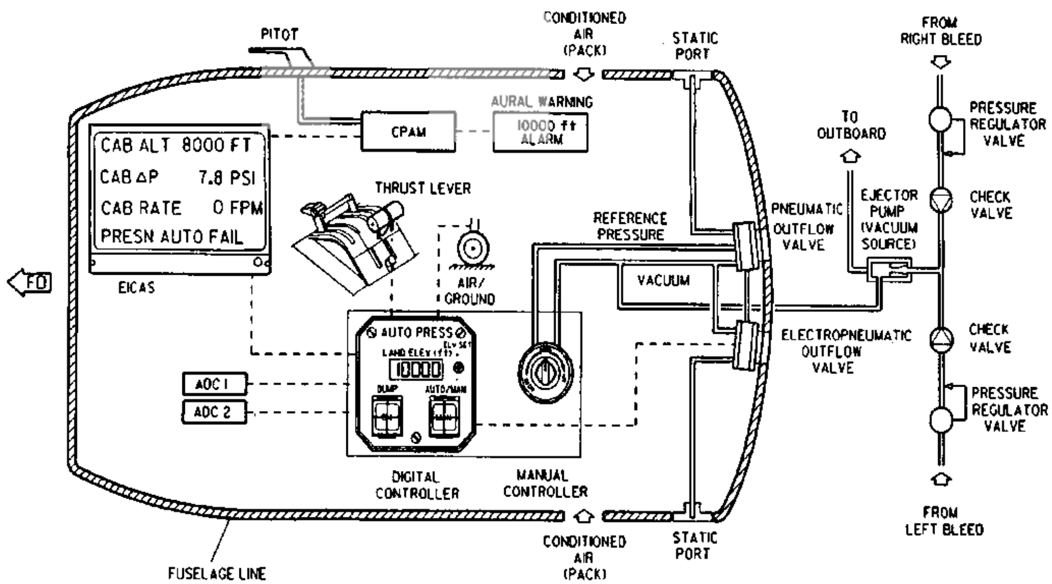
System Architecture : Pneumatic CPCS

- **This system architecture requires :**
  - Pneumatic Outflow valves, with overpress function
  - The vacuum source
  - Reference pressure line, vacuum lines and static port lines
  - The manual pressure controller
  - A digital controller



Key parameters to size CPCS

- Max ECS flow to exhaust (Environmental Control System)
- Max residual pressure on ground
- Cabin leakage
- Pressurized cabin volume (min and max)
- Aircraft performances :
  - Max climb rate (max thrust and light aircraft)
  - Max descent rate (emergency descent)
- Max aircraft cruise altitude
- Max cabin altitude
  - Lead to max positive delta P
- Max negative delta P

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Pressurization valve sizing (OFV)

- **OFV size is driven by residual pressure acceptable on ground. (between 1 and 5 mbar: 5mbar on 2m² door => 100kg)**

- **Parameters needed to calculte OFV size:**
  - Residual pressure specified by aircraft manufacturer
  - Max ECS flow
  - Number of OFVs

Based on those data, minimum efficient area can be calculated.

- This calculation is done taking into account no aircraft leakage
- Warning : efficient area ≠ geometric area => discharge coefficient

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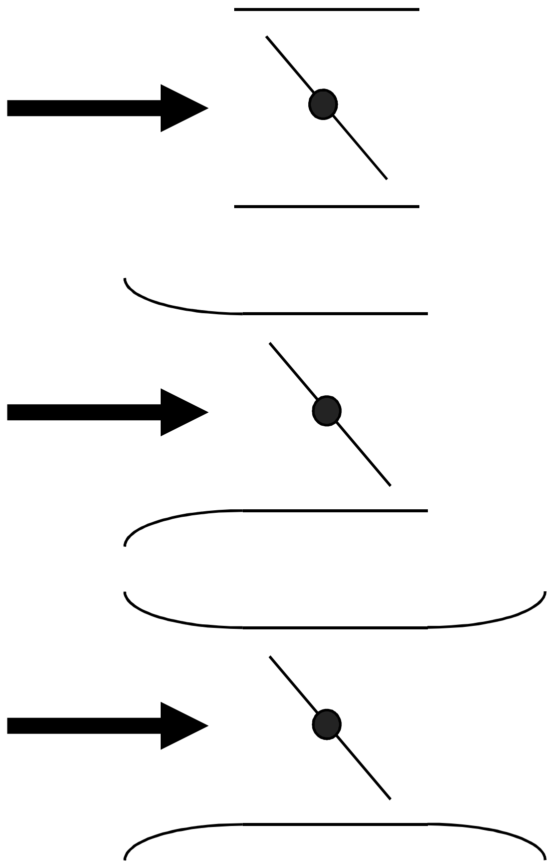
Pressurization valve sizing (OFV)

- OFV efficient area can be improved by using convergent / divergent
  - Smaller hole in aircraft structure for the same efficient area
  - Weight benefit



- **Simple valve body:**
  - Discharge coefficient ~0.7
- **Valve body with convergent :**
  - Discharge coefficient ~0.8
- **Valve body with convergent + divergent:**
  - Discharge coefficient ~0.85

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Pressurization valve sizing (OFV)

- **OFV size can be limited by depressurization analysis:**
  - ***Case to analyse:***
    - Aircraft is flying at its max cruise altitude
    - Max aircraft leakage (end of life)
    - Total OFV opening (failure case)
    - 17 secondes after warning signal « EXCESSIVE CABINE ALTITUDE » pilot starts ''emergency descent ''
  - ***If cabin altitude is over:***
    - 25000 ft during more than 2 minutes
    - Or reach 40000 ft
  - ***Then OFV size is too big:***
    - OFV size has to be reduced and a ground valve must be added to ensure max residual pressure on ground.

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Flow calculation

Flow between 2 volumes is function of efficient area between them and pressure ratio.

If pressure (P0) in volume 0 is higher than pressure (P1) in volume 1:

Subsonic flow ($\frac{P_0}{P_1} \leq 1{,}893$) :

$$Q = P_0 \,.\, A \,0{,}1562 \,.\, \sqrt{\frac{\left(\frac{P_0}{P_1}\right)^{-1{,}429} - \left(\frac{P_0}{P_1}\right)^{-1{,}714}}{T}}$$

Sonic flow ($\frac{P_0}{P_1} > 1{,}893$) :

$$Q = \frac{P_0 \,.\, A \; 0{,}04045}{\sqrt{T}}$$

With

Q: flow in kg/s

P0, P1 : pressure in Pa

A : efficient area in m²

T : temperature in K

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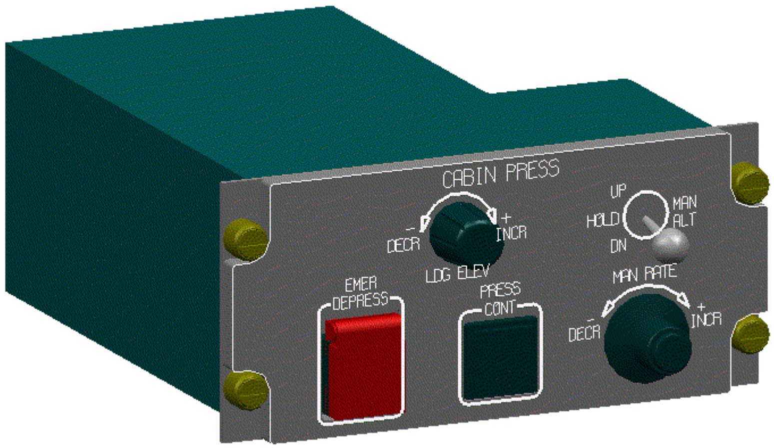
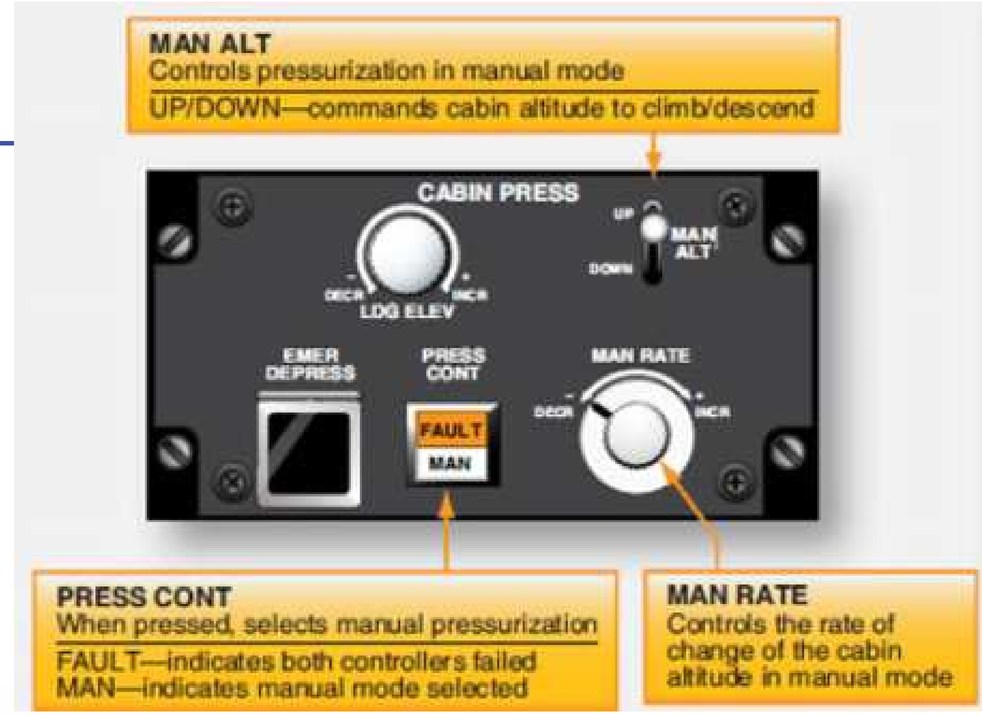
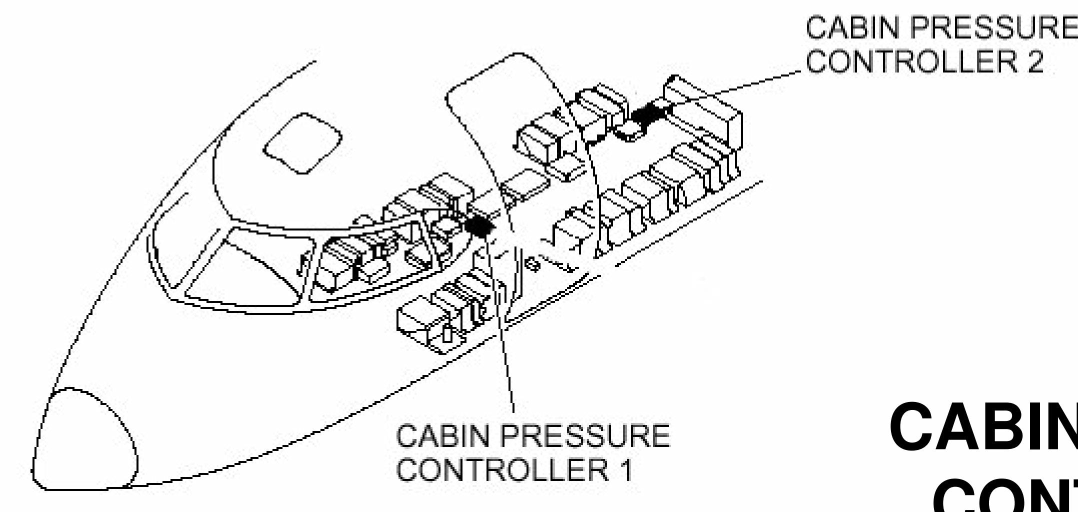
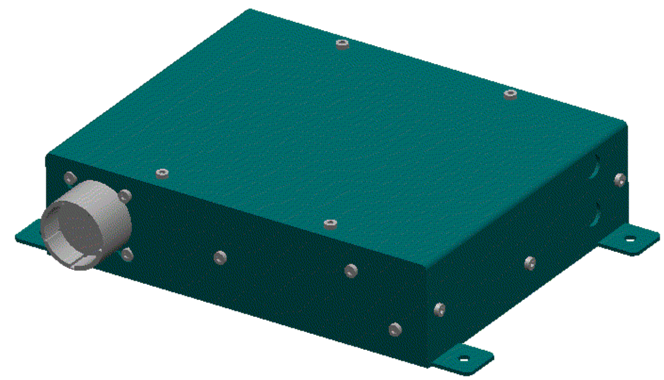
Installation



CPC Panel







CABIN PRESSURE CONTROLLERS

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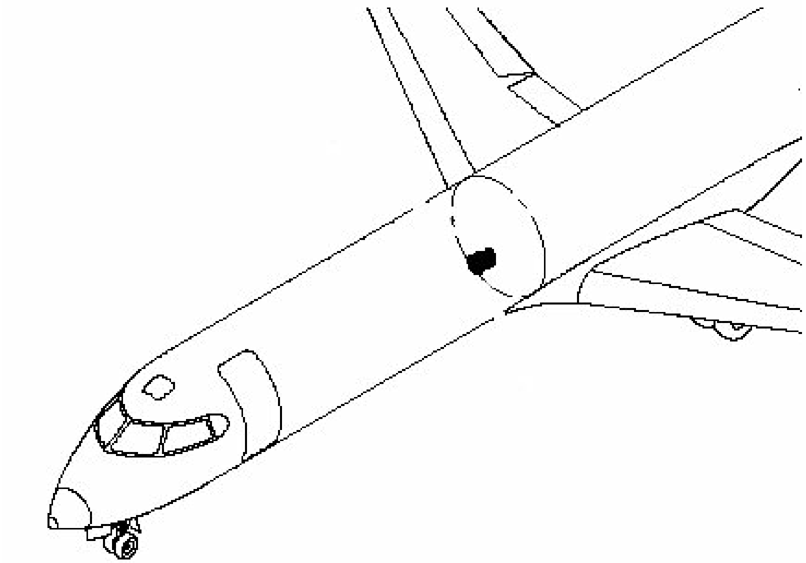
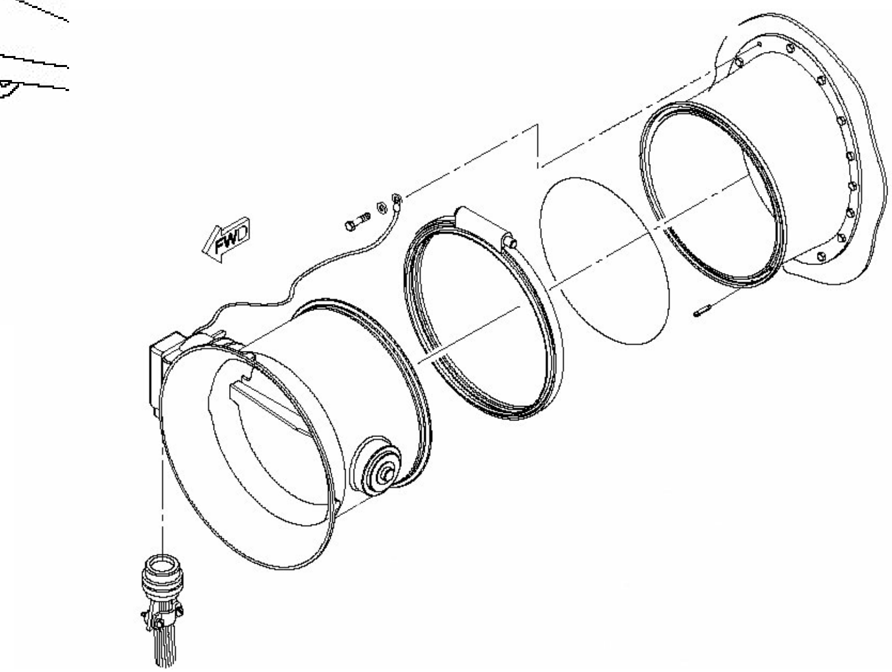
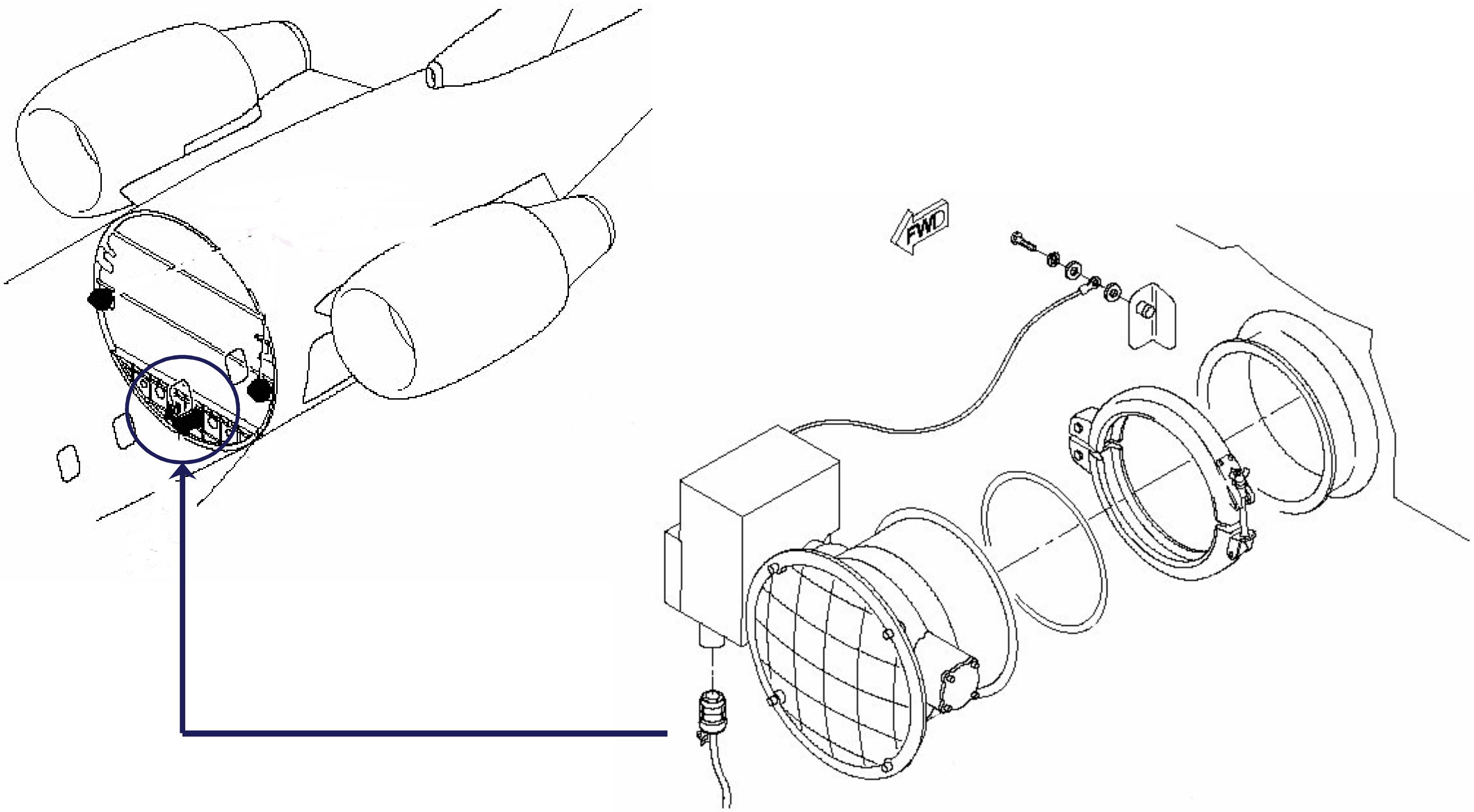
GROUND VALVE

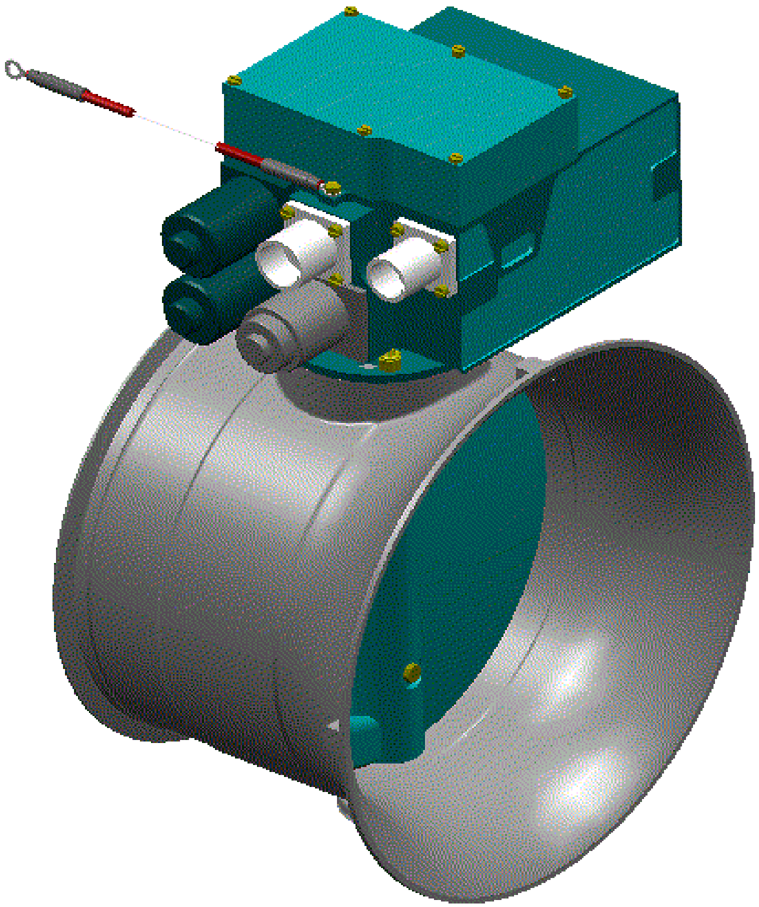




OUTFLOW VALVE



OFV – Outflow Valve



- **Function:**

  Pressure regulation on ground and in flight, depending on the flight sequence

- 7'' valve body
- Actuator: 3 independent modes (2 AUTO and 1 MANUAL)

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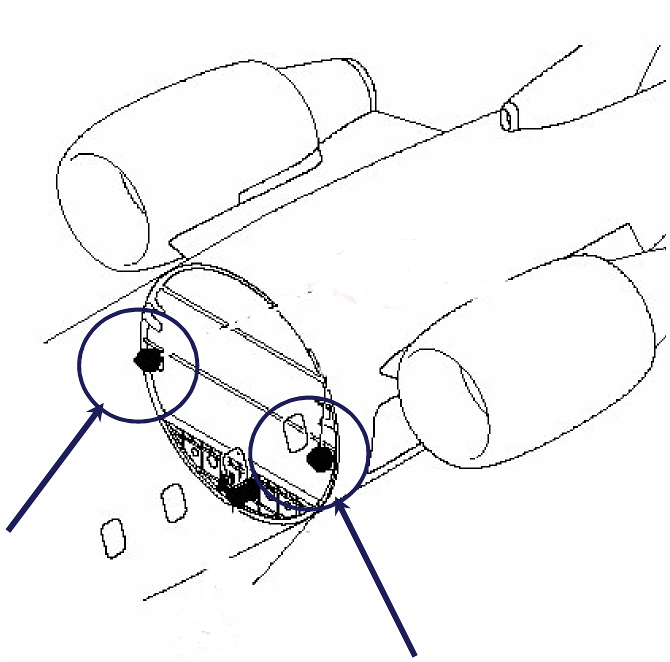
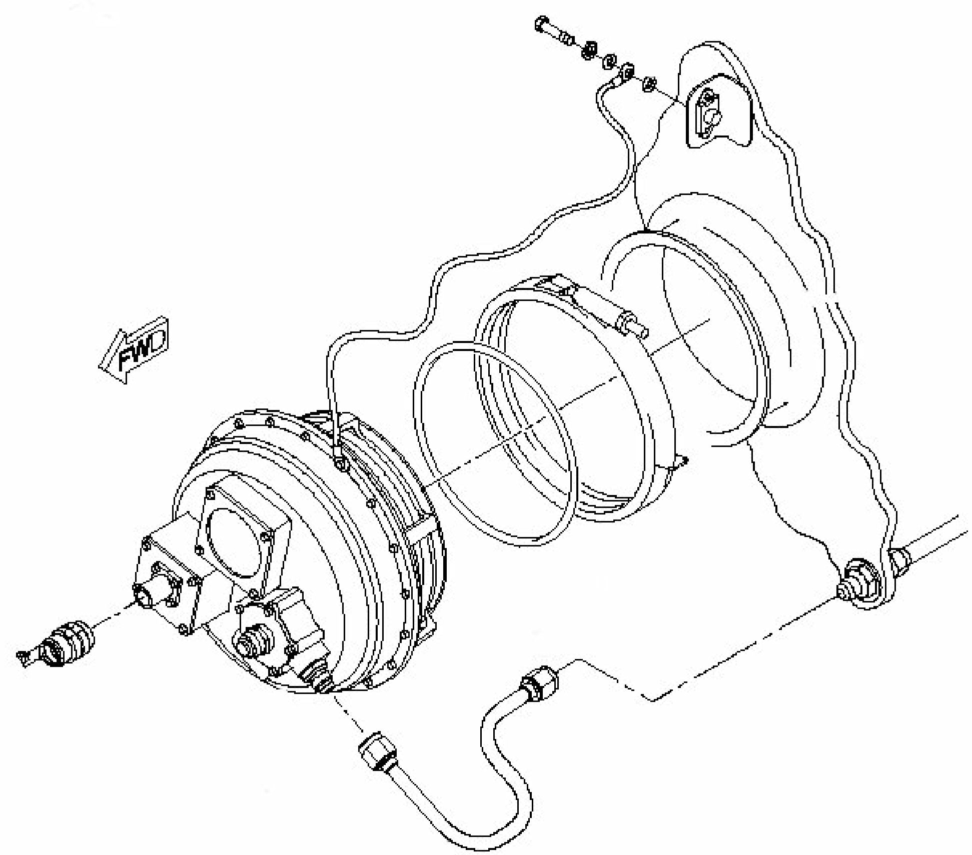
Installation

SAFETY VALVES





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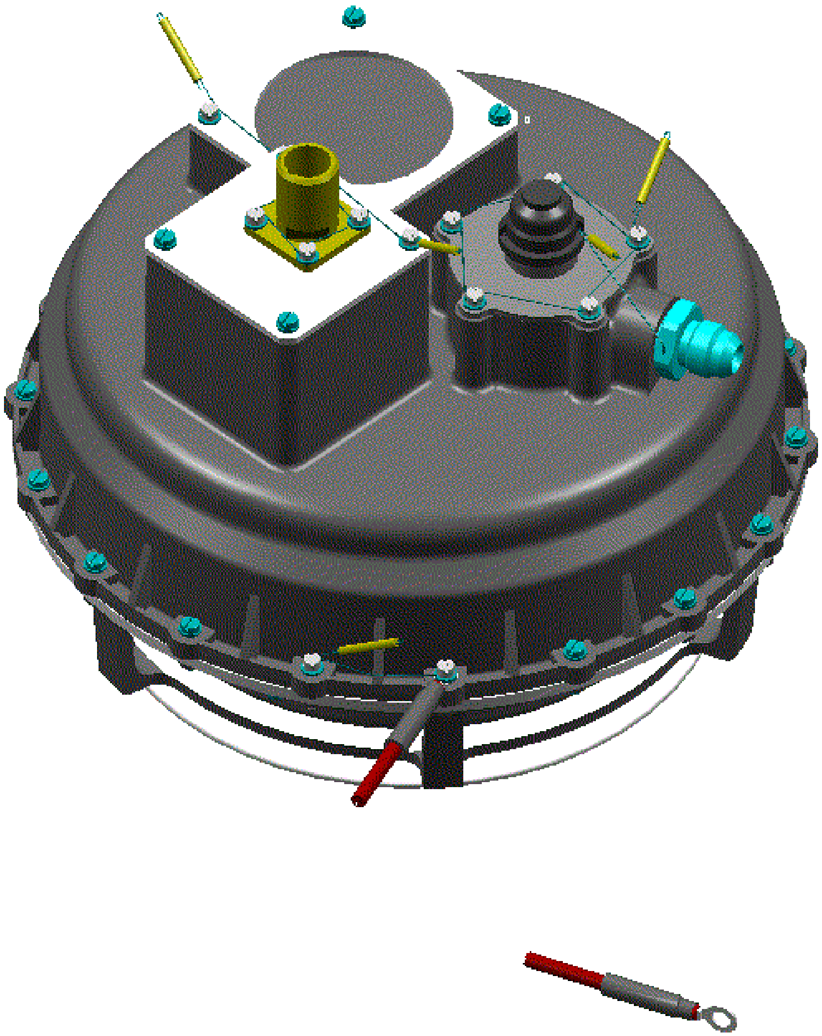
SFV – Safety Valve



- **Function:**
  - Overpressure relief
  - Negative pressure relief

- 5.5'' valve body
- Both SFV are fully pneumatic and independent
- One SFV is enough to ensure overpressure and negative pressure relief capabilities

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