# Introduction to Aerospace Engineering

## Lecture slides

# Introduction Aerospace Engineering

## Flight Mechanics

Dr. ir. Mark Voskuijl

15-12-2012

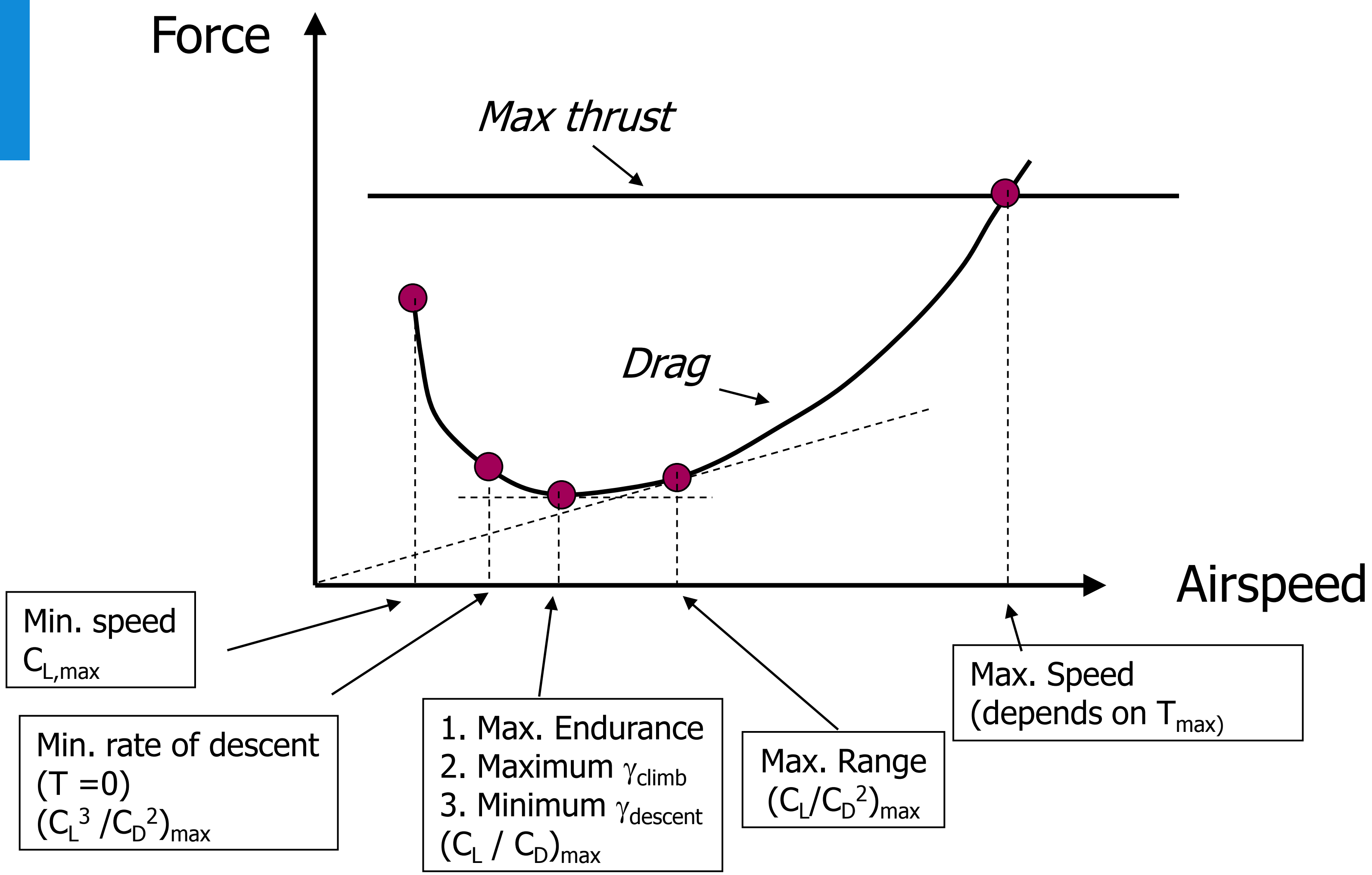
# 7&8.

*Flight envelope*

# Contents

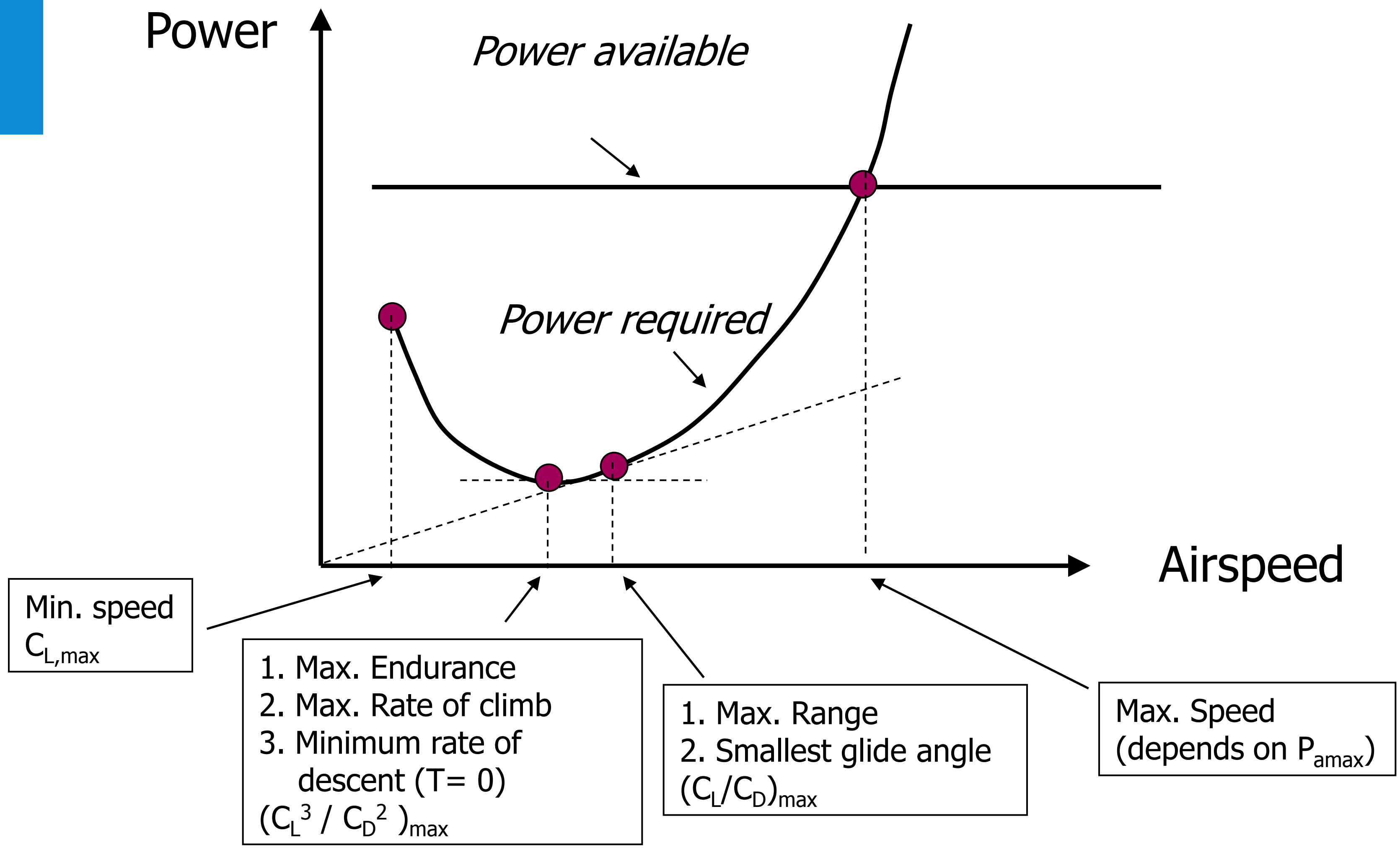
# Contents

# Summary - Jet



Force
Max thrust
Drag
Airspeed
Min. speed
$C_{L,max}$
Min. rate of descent
(T =0)
$(C_L^3 / C_D^2)_{max}$
1. Max. Endurance
2. Maximum $\gamma_{climb}$
3. Minimum $\gamma_{descent}$
$(C_L / C_D)_{max}$
Max. Range
$(C_L/C_D^2)_{max}$
Max. Speed
(depends on $T_{max}$)

# Summary – Propeller Aircraft



# Contents

1. Summary previous lectures
2. **Introduction**
3. Altitude effects on performance diagram
4. Performance limits
5. Operational limits
6. Flight envelope
7. Flight instruments
8. Example calculations

# Introduction

- So far we considered the aircraft performance at one given altitude
- How is aircraft performance influenced by altitude effects?


*Lockheed U-2: High altitude jet aircraft for weather and radiation research and also reconnaissance missions*

*Question:*
*How high can this aircraft fly?*

# What do you need to learn

**The lecture sheets are most important!!!**

Background material:
Anderson, Introduction to flight, Par. 6.7, 6.10

**Not everything is treated in the book!!!**

# Contents

# Altitude effects on aerodynamic drag

## Consider a constant angle of attack

- Drag (one particular $\alpha$):

$$D_{H_1} = \frac{C_D}{C_L} W \rightarrow D_{H_2} = \frac{C_D}{C_L} W$$

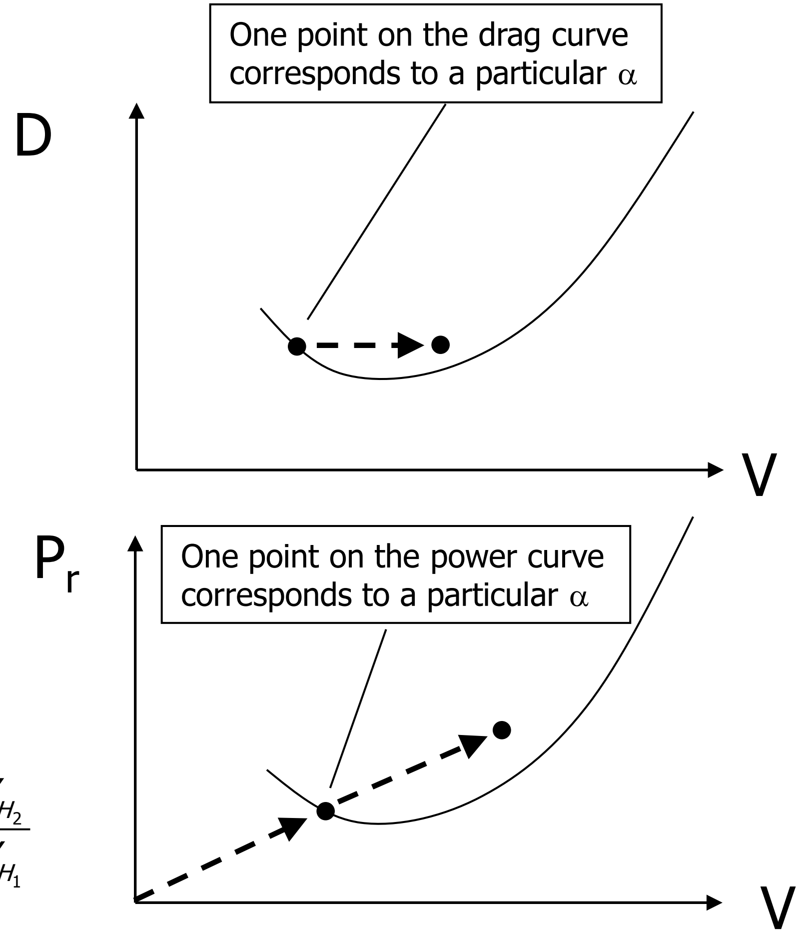
- Airspeed (one particular $\alpha$):

$$V_{H_1} = \sqrt{\frac{W}{S} \frac{2}{\rho_{H_1}} \frac{1}{C_L}}$$

$$V_{H_2} = \sqrt{\frac{W}{S} \frac{2}{\rho_{H_2}} \frac{1}{C_L}}$$

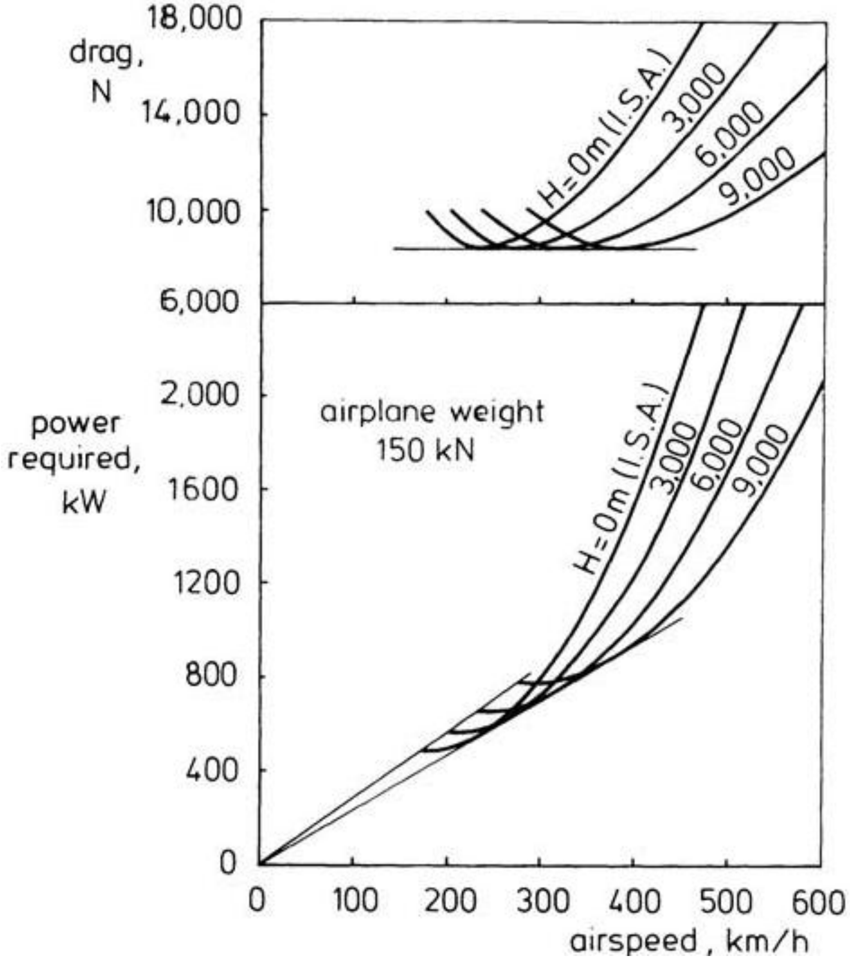
- Power required (one particular $\alpha$)

$$\left. \begin{aligned} P_{r,H_1} &= D_{H_1} V_{H_1} \\ P_{r,H_2} &= D_{H_2} V_{H_2} \end{aligned} \right\} \Rightarrow P_{r,H_2} = P_{r,H_1} \sqrt{\frac{\rho_{H_1}}{\rho_{H_2}}} \Rightarrow \frac{P_{r,H_2}}{P_{r,H_1}} = \frac{V_{H_2}}{V_{H_1}}$$



# Altitude effects on aerodynamic drag

## Overview




For increasing altitude:

- Drag curve shifts to the right
- Power curve shifts up and to the right

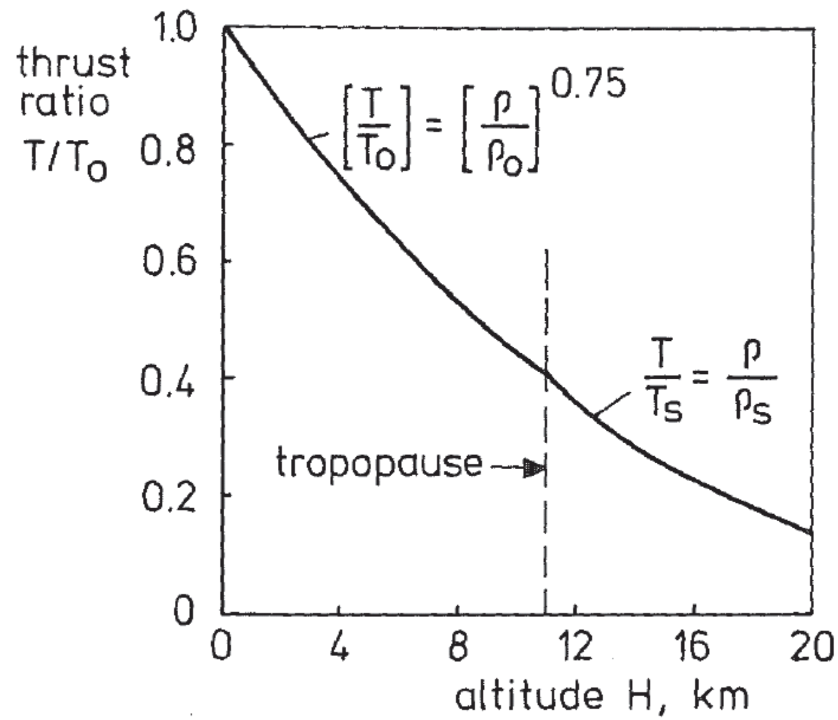
# Altitude effects on engine thrust

## Jet aircraft

Two effects:

- Air density decreases
- Temperature decreases (up to tropopause)

1. Performance is limited by maximum turbine temperature. Lower air temperature allows more heat added to the gas
2. Decrease in density reduces mass flow and thus engine thrust




$$T(V) = \text{constant}$$

$$\frac{T}{T_0} = \left(\frac{\rho}{\rho_0}\right)^{0.75} \quad \text{(in troposphere)}$$

# Altitude effects on power available

## Propeller aircraft

- Turboprop airplanes show similar behaviour as turbojet airplanes

$$P_a(V) = \text{constant}$$

$$\frac{P_a}{P_{a,0}} = \left(\frac{\rho}{\rho_0}\right)^{0.75} \quad \text{(in troposphere)}$$


- For supercharged piston engines, power available is fairly constant up to the critical altitude

# Performance diagram

## How does it change with altitude?

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

# Contents

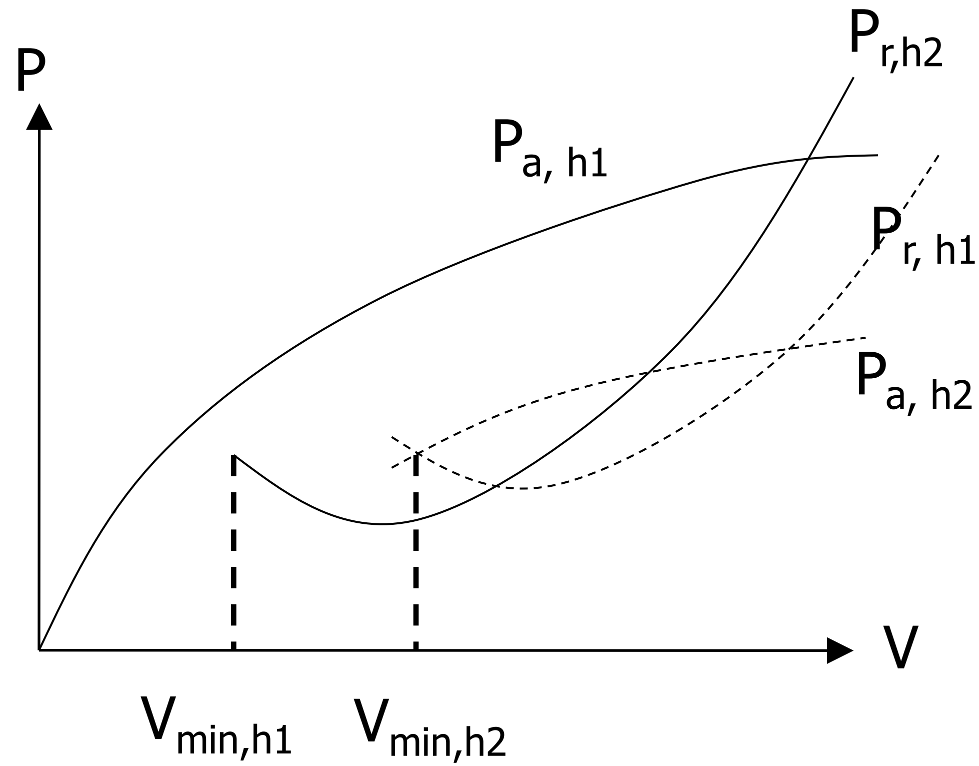
1. Summary previous lectures
2. Introduction
3. Altitude effects on performance diagram
4. **Performance limits**
5. Operational limits
6. Flight envelope
7. Flight instruments
8. Example calculations

# Minimum airspeed

## How does it change with altitude?

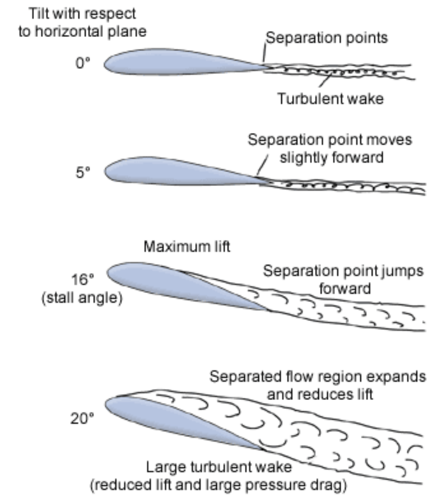
- Aerodynamic limit (stall)
- Power limit

- Minimum airspeed increases with altitude!

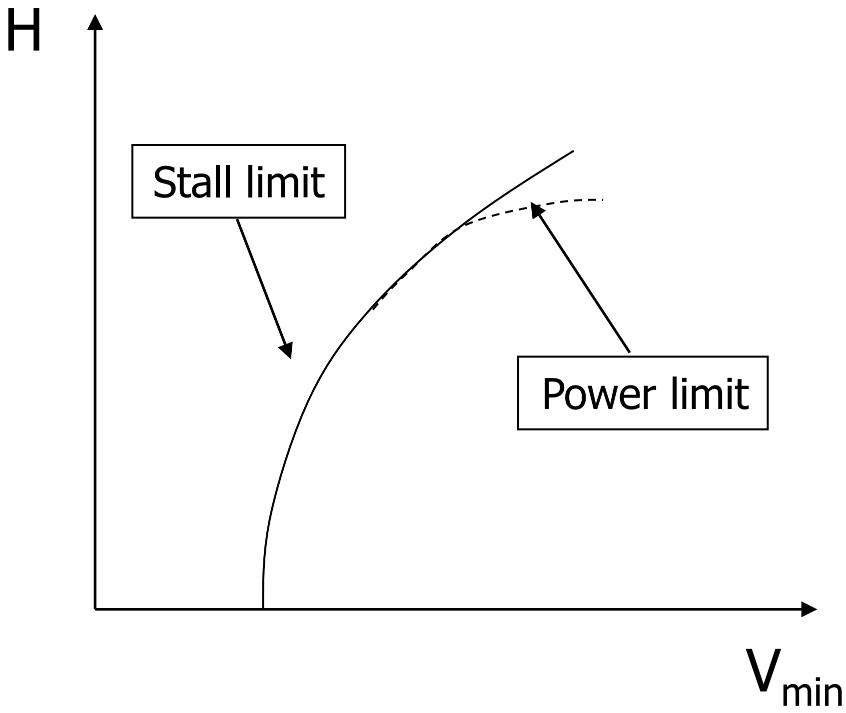


# Minimum airspeed

## As function of altitude




Up to a certain altitude, the minimum airspeed is determined by the stall. At higher altitudes it depends on the engine power

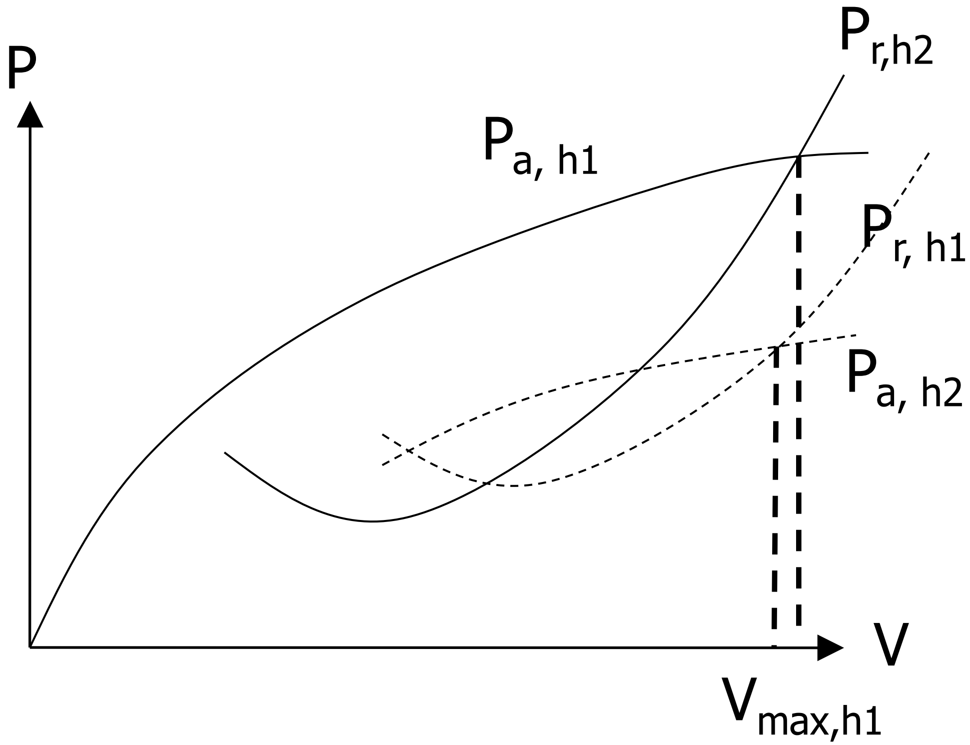



# Maximum airspeed

## How does it change with altitude?

- Power available shifts down
- Power required shifts up and to the right

- Depending on the engine characteristics and altitude, $V_{max}$ will increase or decrease

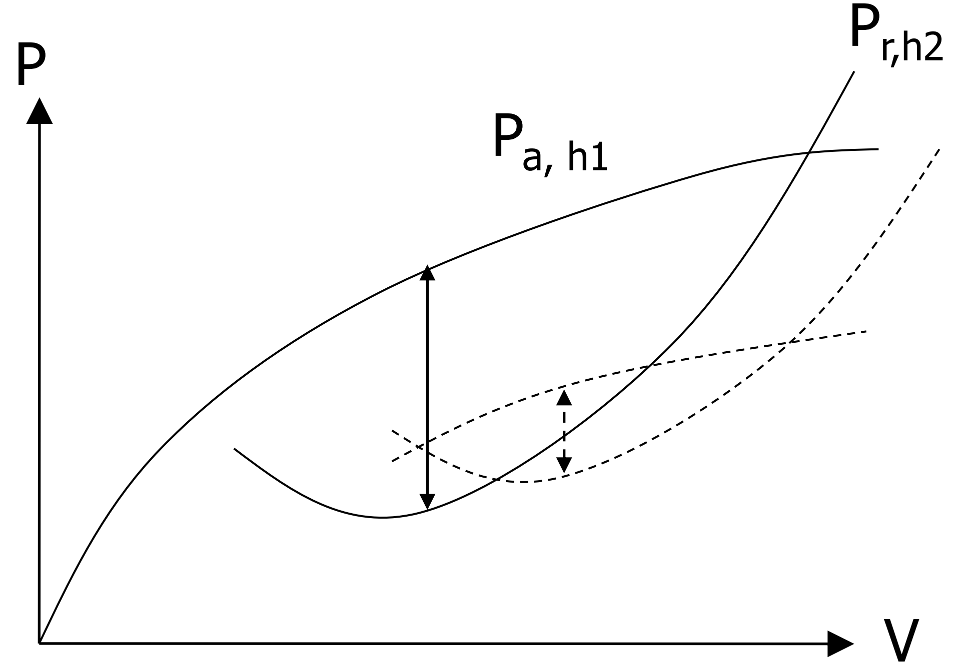


# Maximum rate of climb

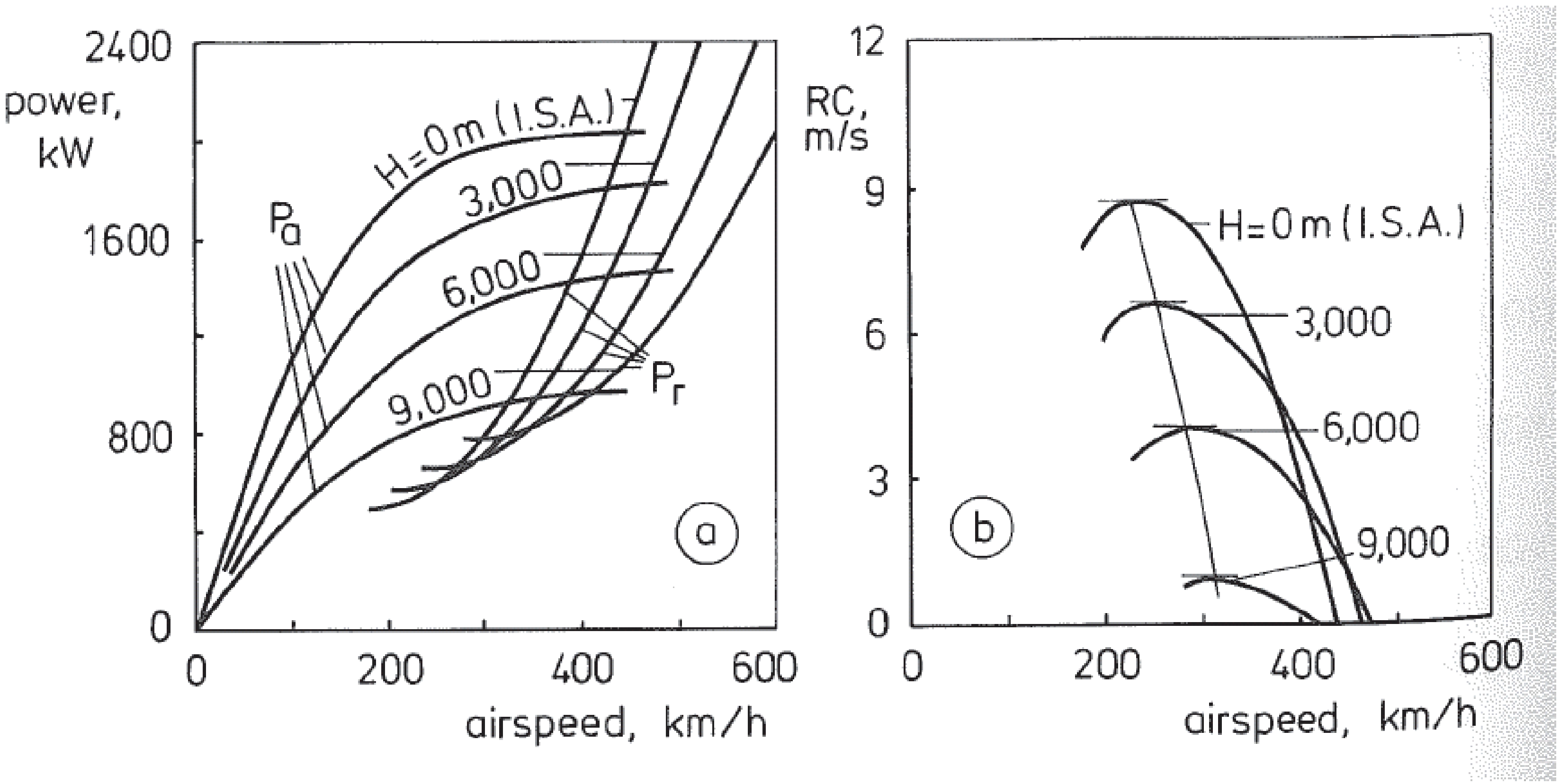
## How does it change with altitude?

$$\boxed{\frac{P_a - P_r}{W} = RC}$$

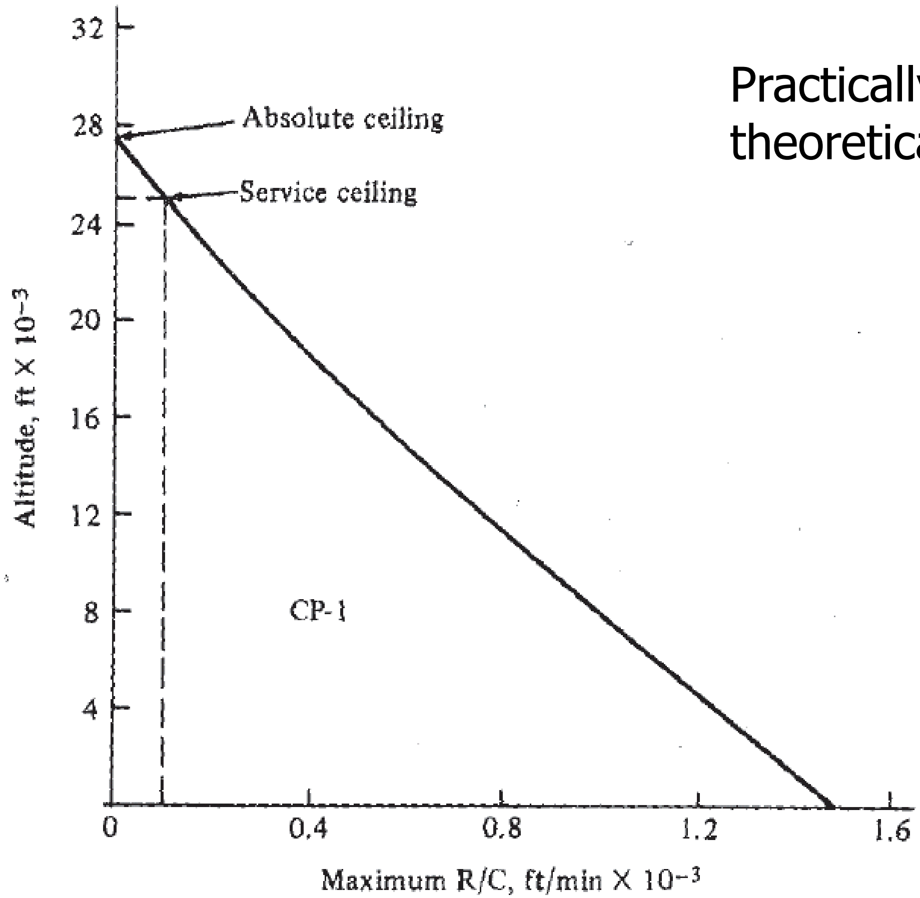
- $RC_{max}$ decreases with altitude



# Maximum altitude



# Maximum altitude

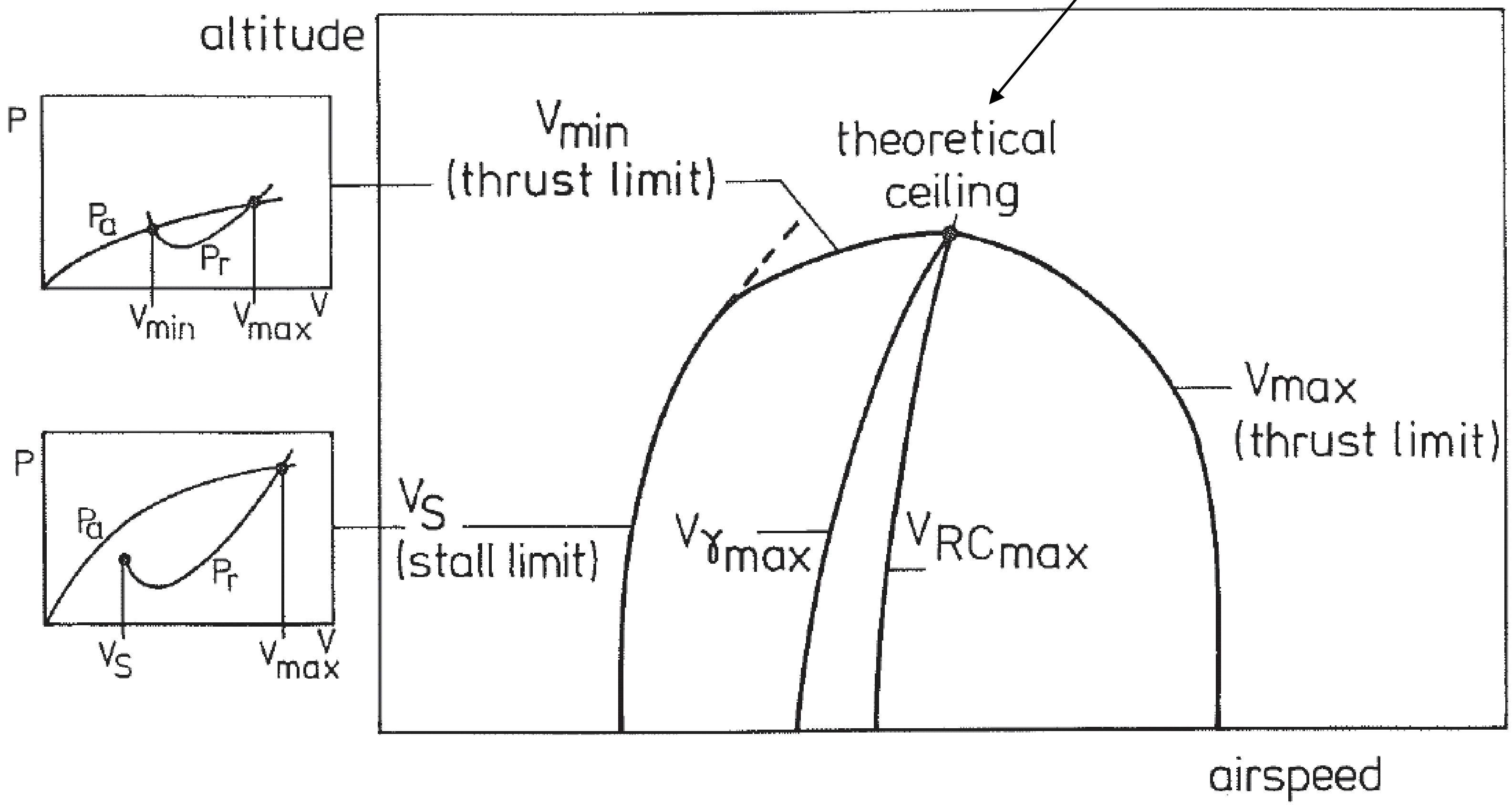



Practically it is impossible to reach the theoretical (absolute) ceiling in steady flight

# Story U2

# Performance limits combined

At the theoretical ceiling: $V_{min} = V_{max} = V_{RCmax} = V_{\gamma max}$

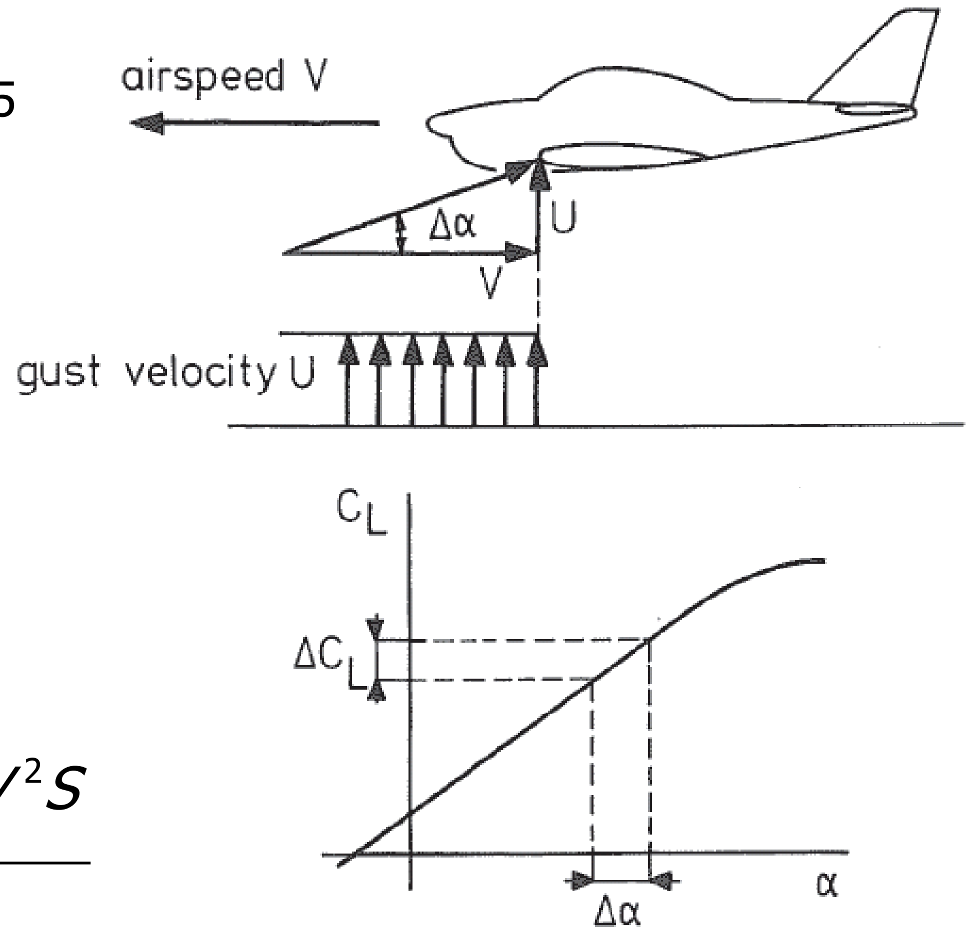


# Contents

# $V_{ed}$ (design diving speed)

## Structural aircraft limit

- Positive and negative gusts of 25 ft/s must be considered at the design diving speed




$$\Delta\alpha = \tan\frac{U}{V} \approx \frac{U}{V}$$

$$\Delta C_L = \frac{dC_L}{d\alpha}\Delta\alpha = \frac{dC_L}{d\alpha}\frac{U}{V}$$

$$n \equiv \frac{L}{W} \Rightarrow \Delta n = \frac{\frac{dC_L}{d\alpha}\frac{U}{V}\frac{1}{2}\rho V^2 S}{W}$$

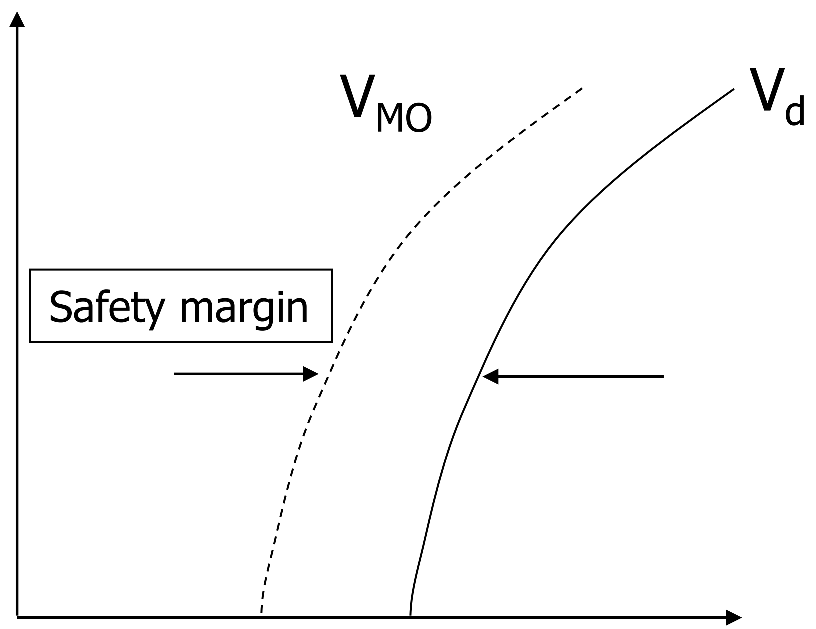
# $V_{ed}$ (design diving speed)

## Structural aircraft limit

- The aircraft is designed to withstand a certain load factor *n*
- The design diving speed **increases** with **increasing** altitude

$$\Delta n = \frac{\frac{dC_L}{d\alpha}\frac{U}{V}\frac{1}{2}\rho V^2 S}{W}$$

constant



# Maximum Mach number

## Sound Barrier

**Bell X-1**
First supersonic flight
Chuck Yeager, 1947
Four rocket engines
Thin wings, small aspect ratio

M = 0.88 – 0.90:
Buffet / Tuck under

M = 0.94
Total **loss of elevator effectiveness**

M = 0.98
Normal behavior

**Bell X-1**

**De Havilland Swallow**

# Maximum Mach number

## Operational limit

- Undesirable flying qualities associated with buffeting effects

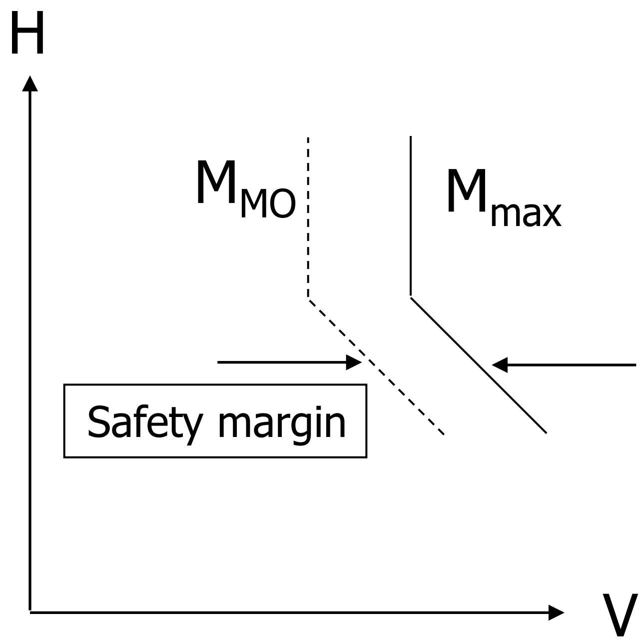
$$V = M \cdot a = M\sqrt{\gamma R T}$$

Troposphere (<11km):

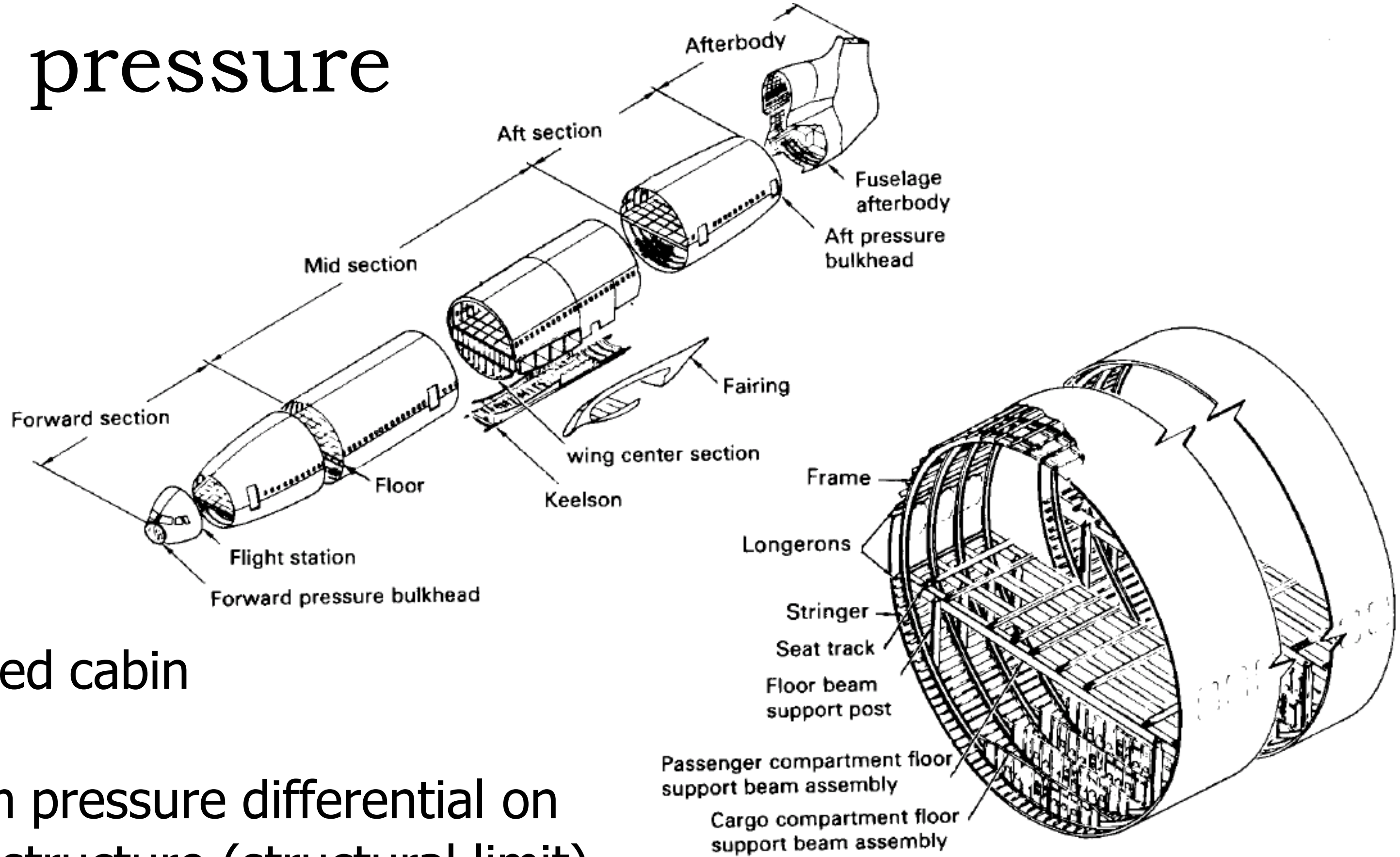
$$T = T_0 + \lambda H = 288.15 - 0.0065H$$

Stratosphere (>11km)

$$T = \text{constant}$$



# Cabin pressure



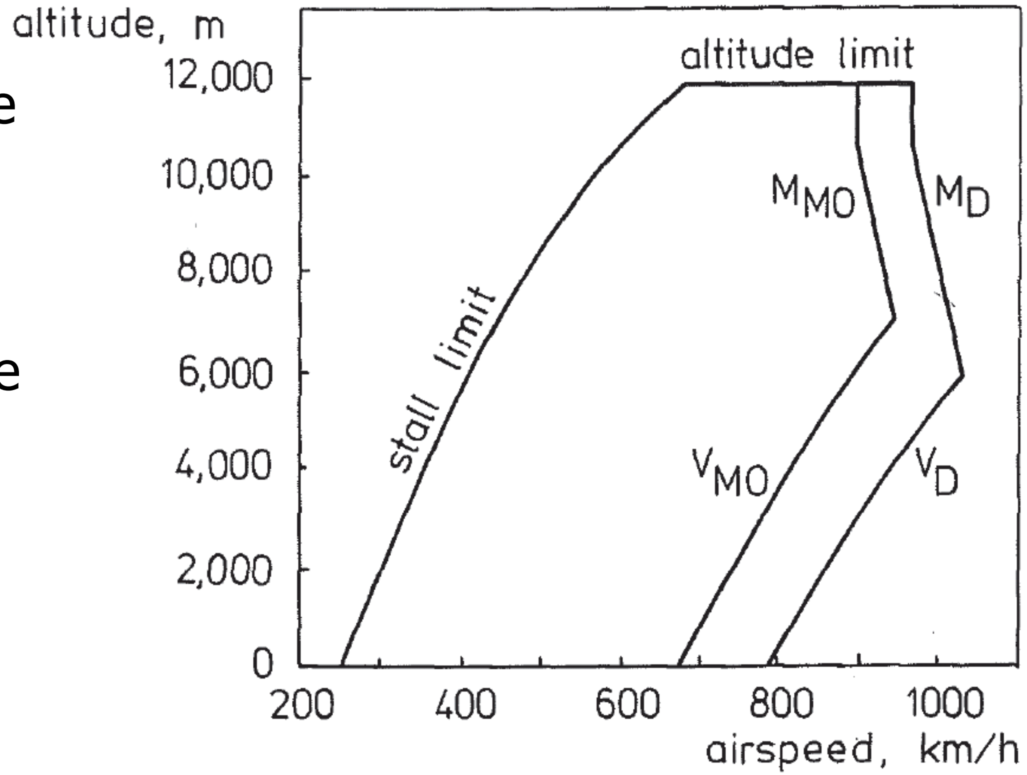

- Pressurized cabin
- Maximum pressure differential on fuselage structure (structural limit)
- Maximum flight altitude

# Contents

# Flight envelope

## Altitude and airspeed to which aircraft is constrained

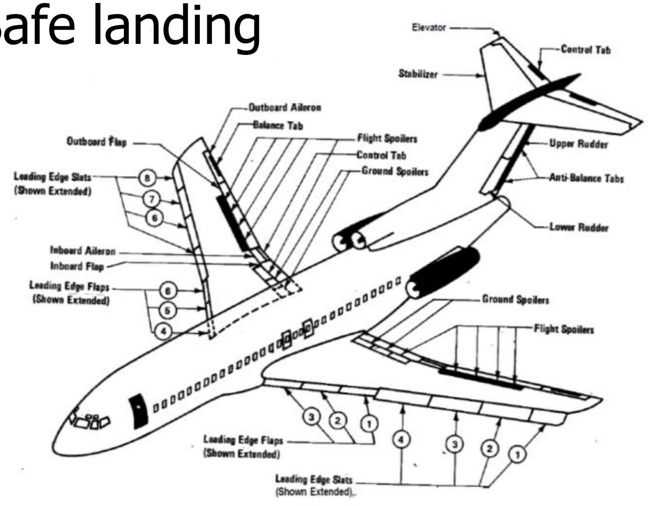
- Note that these limits are fixed
- Performance limits can exceed or lie within these boundaries
- The performance limits depend on the aircraft weight as well

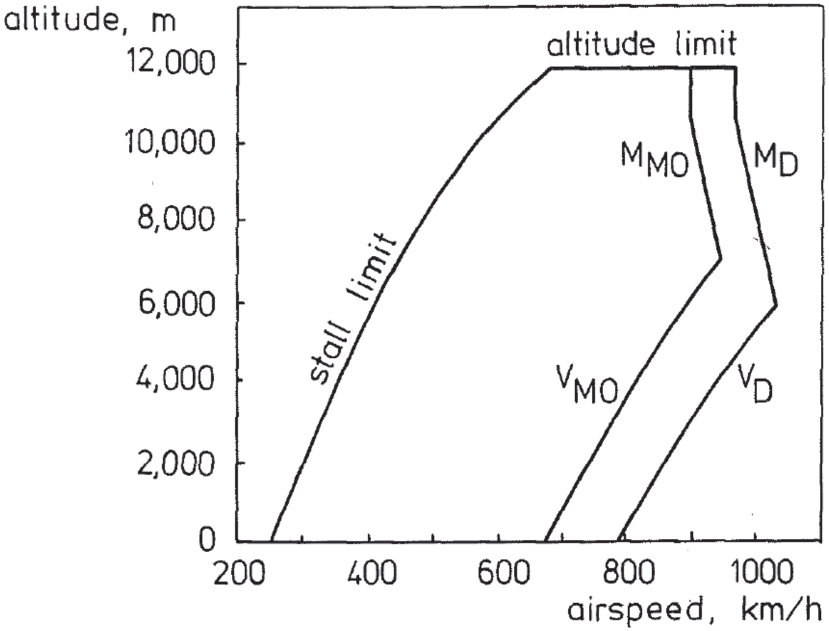


# TWA Flight 841

- 1979 New York – Minneapolis
- High altitude holding (39,000 ft)
- Failure with slat nr. 7

- 34,000 ft dive in 64 seconds
- Landing gears deployed
- 6 ‘g’  pullup
- Safe landing

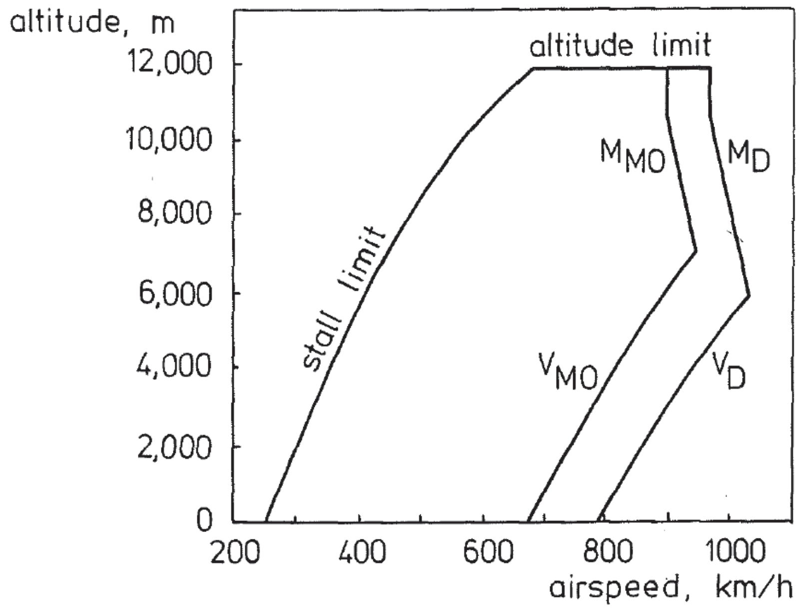



# Problem!

## Stall limit is variable with altitude

How does the pilot know where the stall limit is???

The airspeed indicator solves this problem!



# Contents

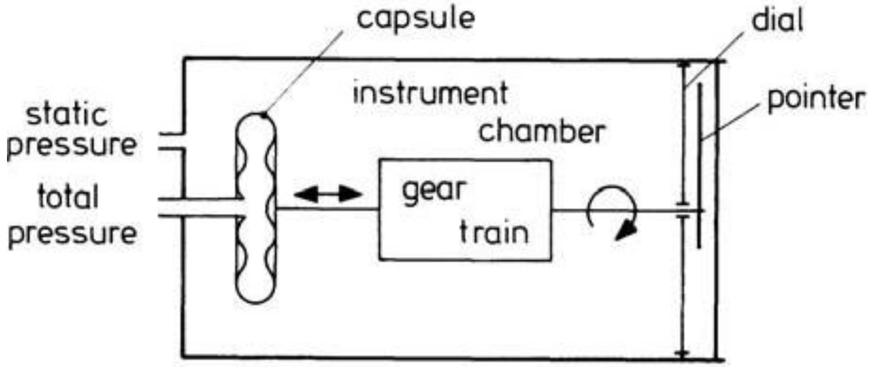
# Airspeed indication

## Basic six

# Pneumatic instruments

# Pitot tube / static port

# Airspeed indication





Displacement is measure of pressure difference $p_t - p = \frac{1}{2} \rho V^2$ (M<<1)

**1 equation**
**2 unknowns**

# Airspeed indication

Solution:

$$\boxed{\begin{gathered}\tfrac{1}{2}\rho V^2 = \tfrac{1}{2}\rho_0 V_e^2 \\ V_e \overset{def}{=} V\sqrt{\frac{\rho}{\rho_0}}\end{gathered}}$$

So, the airspeed indicator does not show the true airspeed!

$$V_{\min} = \sqrt{\frac{W}{S}\frac{2}{\rho}\frac{1}{C_{L,\max}}} \quad \text{(TAS)}$$

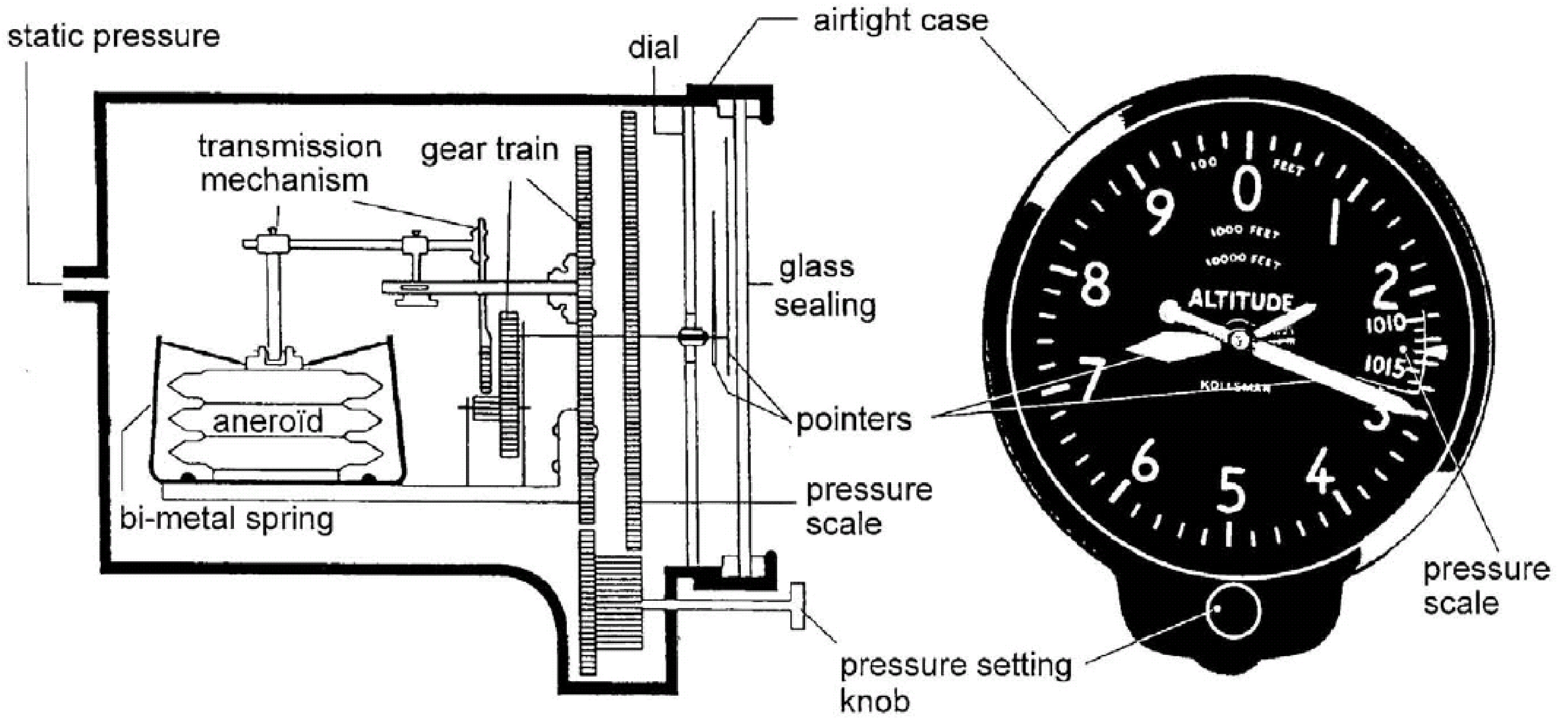
$$V_{e,\min} = V_{\min}\sqrt{\frac{\rho}{\rho_0}} \quad \text{(EAS)}$$

$$V_{e,\min} = \sqrt{\frac{W}{S}\frac{2}{\rho_0}\frac{1}{C_{L,\max}}} \quad \text{(EAS)}$$

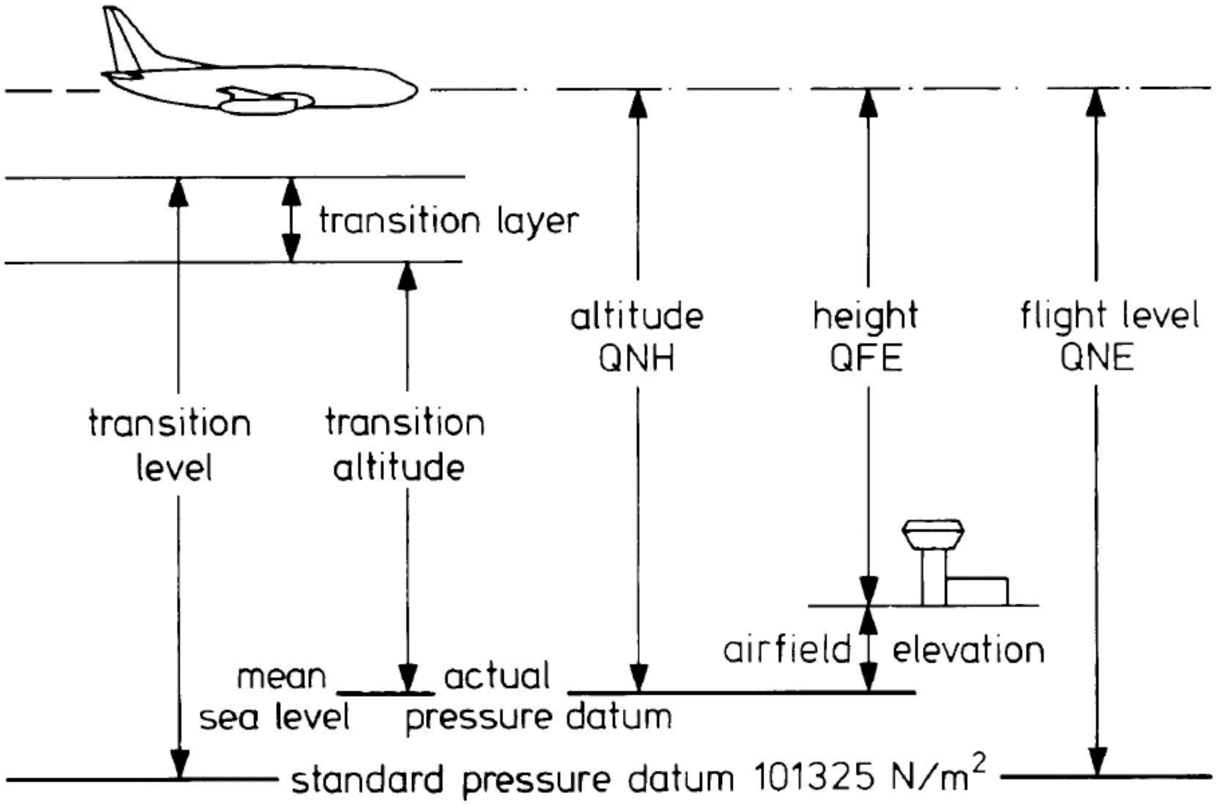
Minimum equivalent airspeed is independent of altitude!

*Note, compressibility effects are neglected for now. This will be explained later. (The basic principle is the same; sea level conditions are assumed by the airspeed indicator)*

# Altimeter


static pressure
dial
airtight case
transmission mechanism
gear train
glass sealing
aneroïd
pointers
bi-metal spring
pressure scale
pressure setting knob
pressure scale
ALTITUDE
100 FEET
1000 FEET
10000 FEET
0
1
2
3
4
5
6
7
8
9
1010
1015

# Height altitude or level?



$p_0$ is set at
1013.25 mbar

Transition altitude 3000 ft

$p_0$ at actual pressure
QNH

Sea level

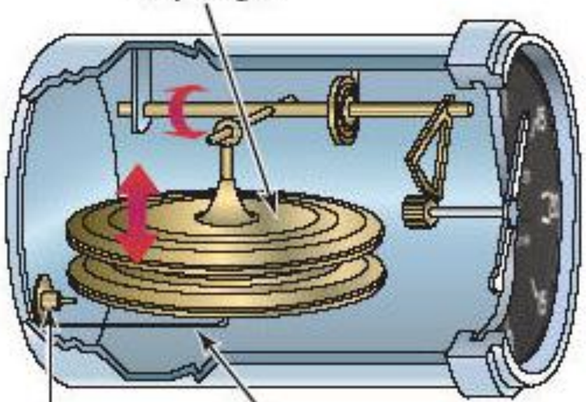
$p_0$ is set at
1013.25 mbar

Transition level FL 40

$p_0$ at actual pressure
QNH

Sea level

# Vertical speed indicator

# Contents

# Example Question

## Climbing performance of the Beach King Air

Two engine propeller aircraft

$C_D = C_{D0} + kC_L^2$
$C_{D0} = 0.02$
$k = 0.04$
$W = 60$ [kN]
$S = 28.2$ [$m^2$]

Power available can be assumed independent of airspeed
Maximum power available at sealevel is 741 kW
Aircraft is performing a steady symmetrical climb

$$P_a = P_{a,\max,sealevel}\left(\frac{\rho}{\rho_0}\right)^{0.75}$$ (in troposphere)

**Question a**: *What is the maximum rate of climb of this aircraft at sea-level ($\rho$ = 1.225 [kg/$m^3$] and what is the corresponding airspeed?*

**Question b**: *What is the maximum rate of climb at 1000 m ($\rho$ = 1.1117 [kg/$m^3$]) and the corresponding airspeed. Explain why your results are different than for question a*