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Presentation for
EWADE 2007

A Student Project of a Blended Wing Body Aircraft – From Conceptual Design to Flight Testing

Prof. Dr.-Ing. Dieter Scholz, MSME

Contents

Introduction	BWB Definition Square-Cube-Law
Projects	BWB Projects
Aero. Disciplines	**Preliminary Sizing** Aerodynamics Flight Mechanics Structures Mass Prediction System Integration
Air Transport System	Ground Handling Emergency Wake Turbulence Interior Design
AC20.30	**AC20.30:** **Test Flights** **Wind Tunnel Tests**
Summary	Summary

Acknowledgement

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Data for this presentation
was obtained from:

Internet
Literature
Diplomarbeiten / Master Thesis
Team Effort at HAW
Airbus
Personal Communication

Introduction

BWB Definition

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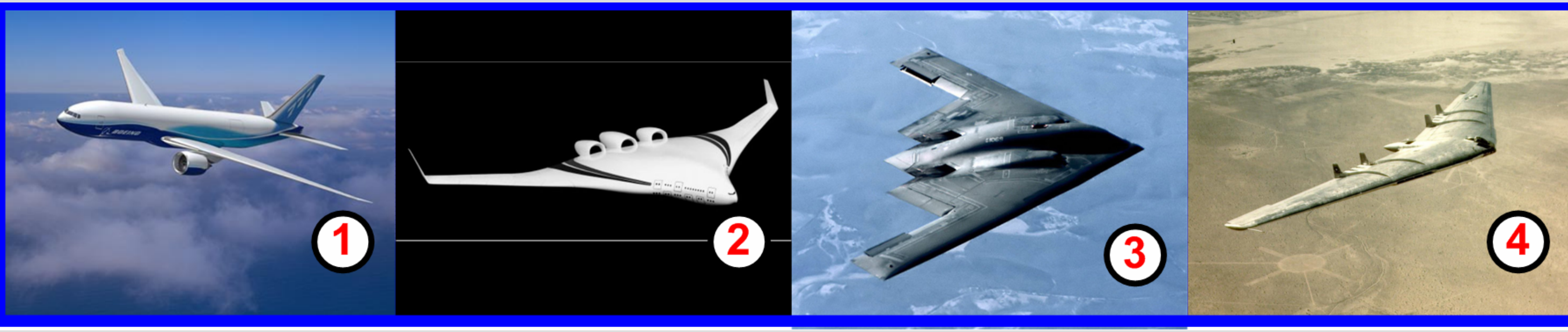

1) Conventional Configuration: "Tube and Wing" or "Tail Aft" (Drachenflugzeug)
2) Blended Wing Body (BWB)
3) Hybrid Flying Wing
4) Flying Wing

The Blended Wing Body aircraft is a blend of
the tail aft and the flying wing configurations:
A wide lift producing centre body housing the payload
blends into conventional outer wings.

Square-Cube-Law

The BWB configuration is favoured for ultra large aircraft.
Why does physics demand a BWB?

Geometric Scaling: $V \propto l^3$ $m \propto l^3$ $m_{MTO} \propto l^3$

$S_W \propto l^2$

Landing Field Length and Approach Speed is limited:

$$\Rightarrow \frac{m_{MTO}}{S_W} = const \;\wedge\; m_{MTO} \propto l^3 \;\Rightarrow\; S_W \propto l^3$$

Square-Cube-Law

Square-Cube-Law

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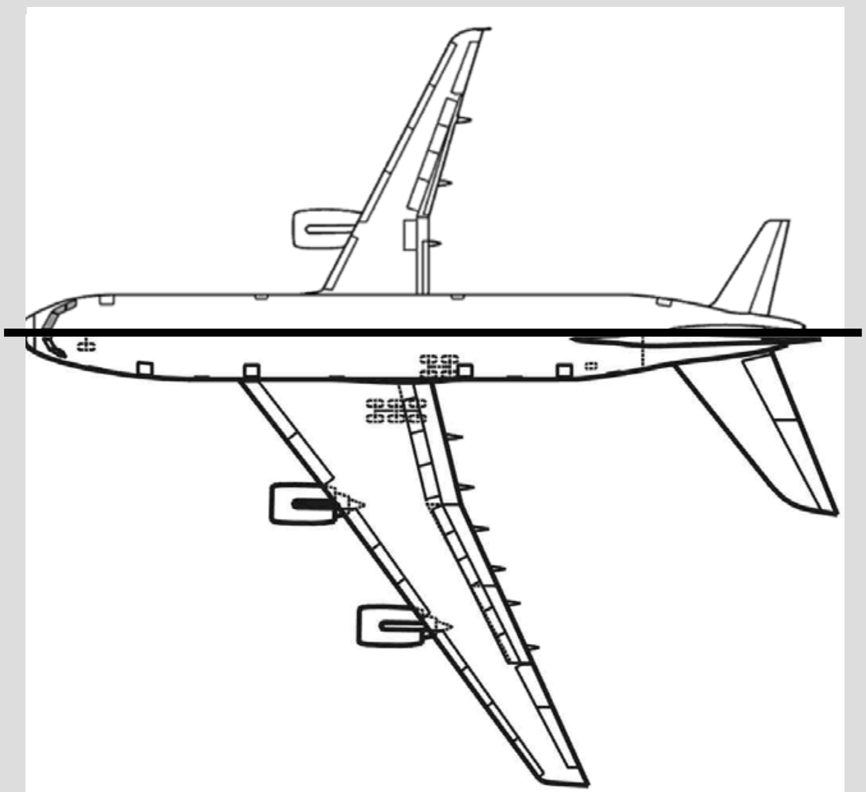
The BWB configuration is favoured for ultra large aircraft.

Why does physics demand a BWB?

$$S_W \propto l^3$$



A321 scaled to the same size as the A380.

A321: $\frac{m_{MTO}}{S_W} = 727 \text{ kg/m}^2$

A380-800F: $\frac{m_{MTO}}{S_W} = 698 \text{ kg/m}^2$

Aircraft even bigger => BWB

Selected BWB Projects

BWB Projects

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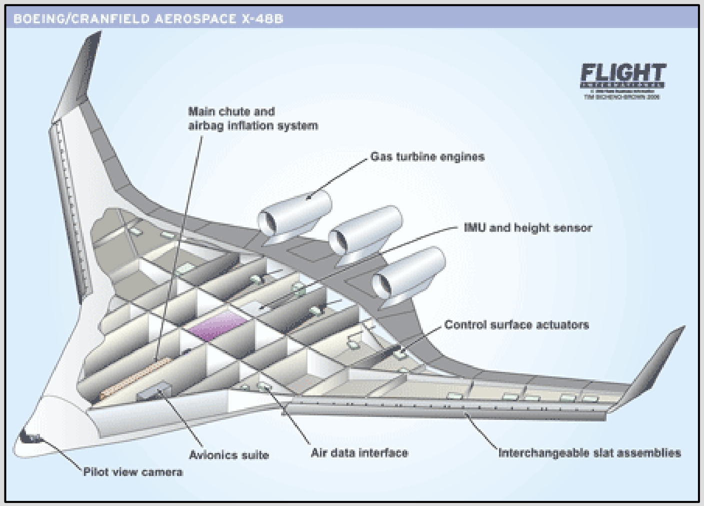
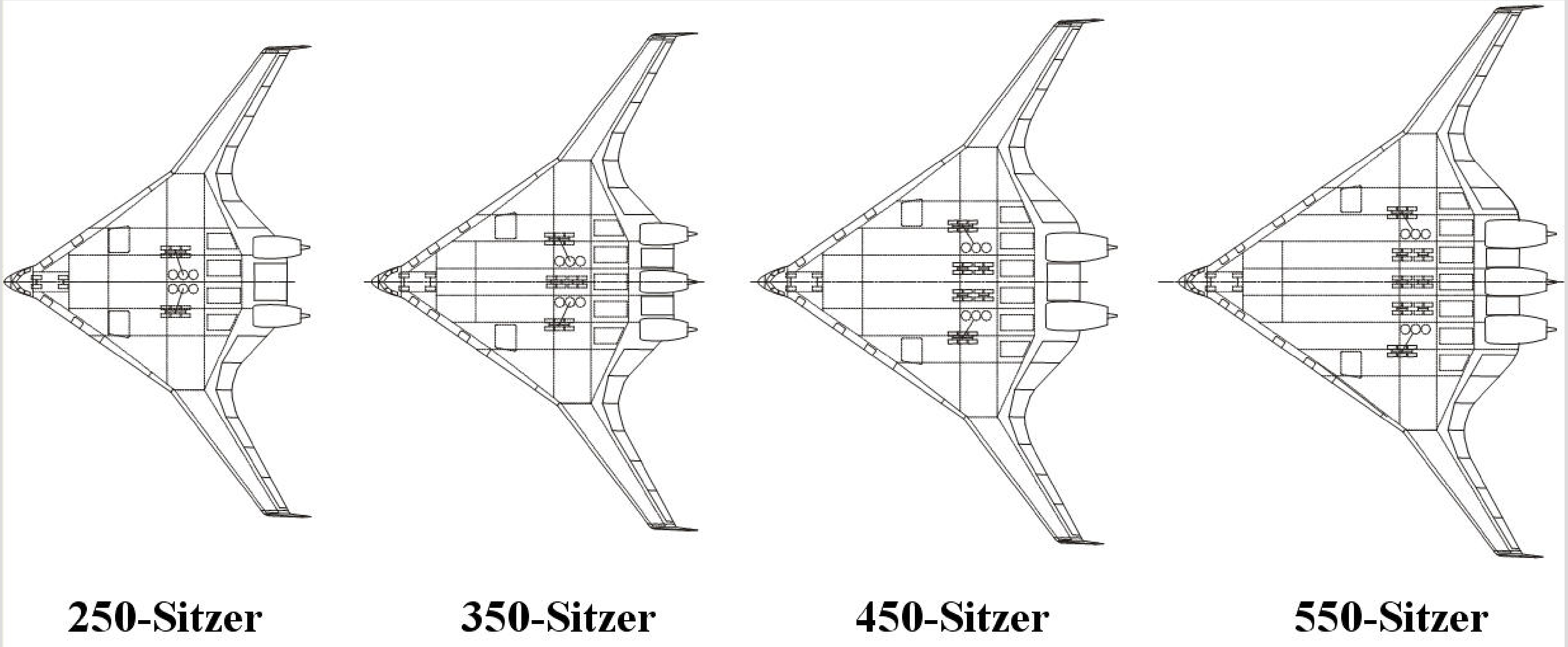
Boeing X-48B



2006: Boeing, NASA, U.S. Air Force. 21 ft span wind tunnel and flight test model. Two X-48B are built. Original: 450 seats, range 7000 NM, span 75.3 m, cruise: high subsonic.

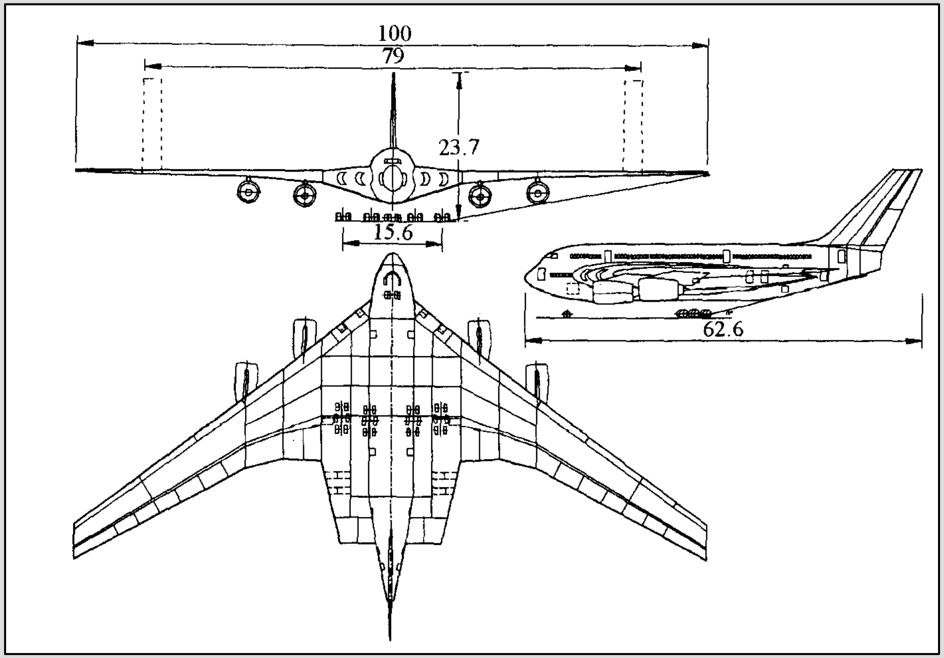
Boeing BWB-250 ... BWB-550



Boeing: study of BWB aircraft family

Today BWBs are not a topic anymore at Boeing for civil transport!

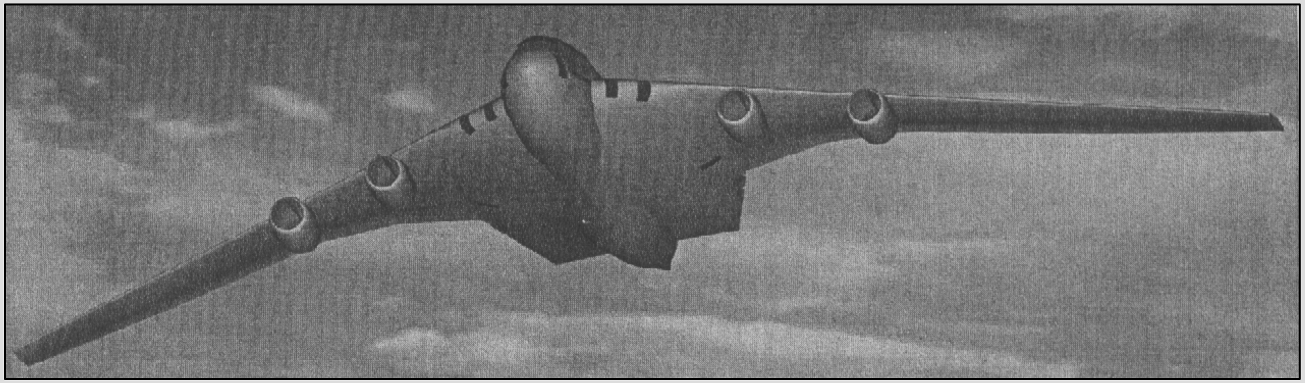
TsAGI (Russia) Integrated Wing Body (IWB)



Best configuration from comparison of four New Large Aircraft configurations based on VELA specification.

Research sponsored by AIRBUS INDUSTRIE

AIRCRAFT DESIGN, Vol 4 (2001)



5th Framework Programme of the European Commision: VELA and MOB

1999 - 2002

17 partners: D, F, UK, E, I, NL, CZ, P

Very Efficient Large Aircraft (VELA)

Two datum configurations for a flying wing (VELA 1 and VELA 2).
A first step in a long-term work plan will be followed by further research work.
Passenger-carrying aircraft.

Multidisciplinary Optimisation of a BWB (MOB)
Freighter version.

BWB Projects

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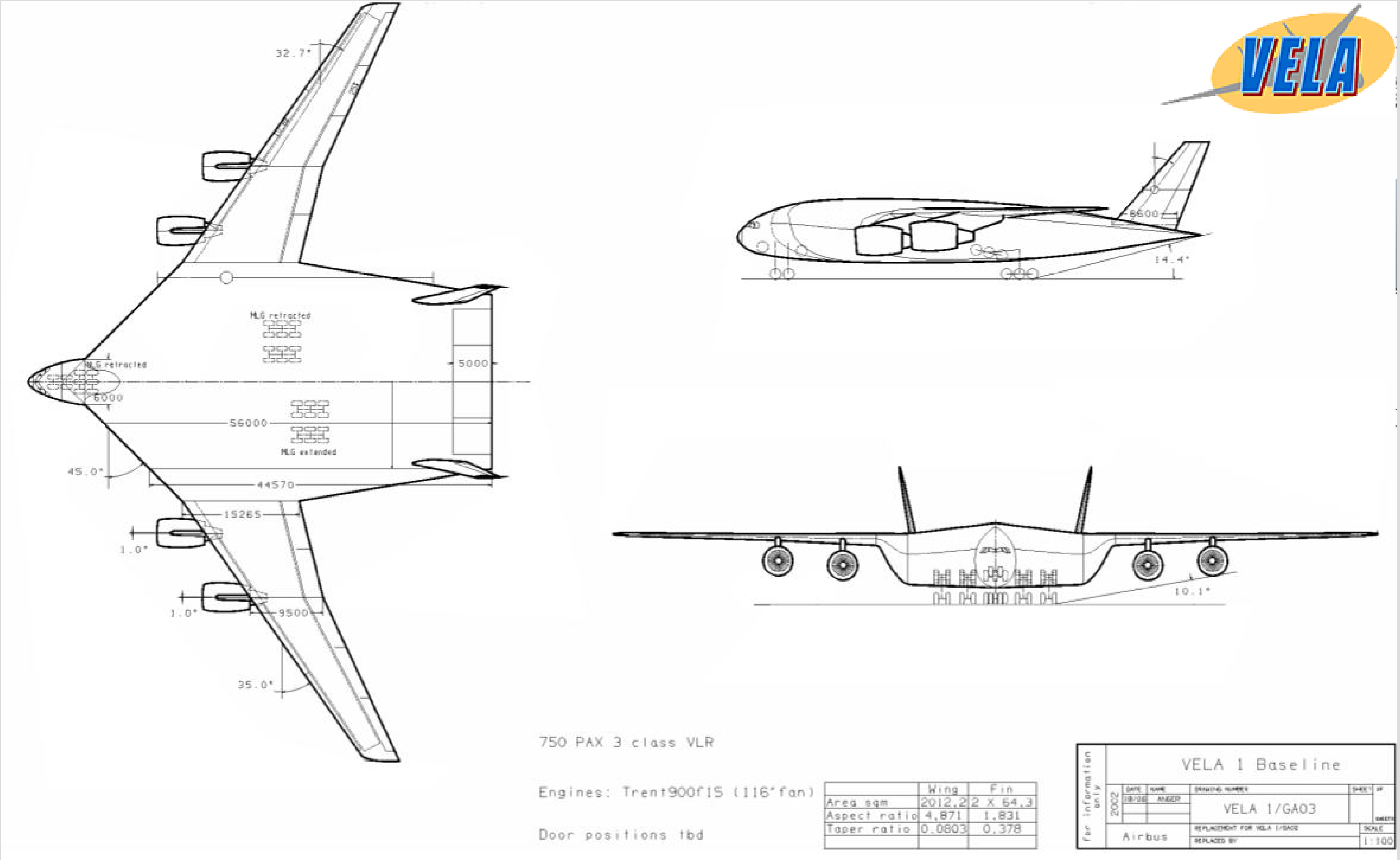
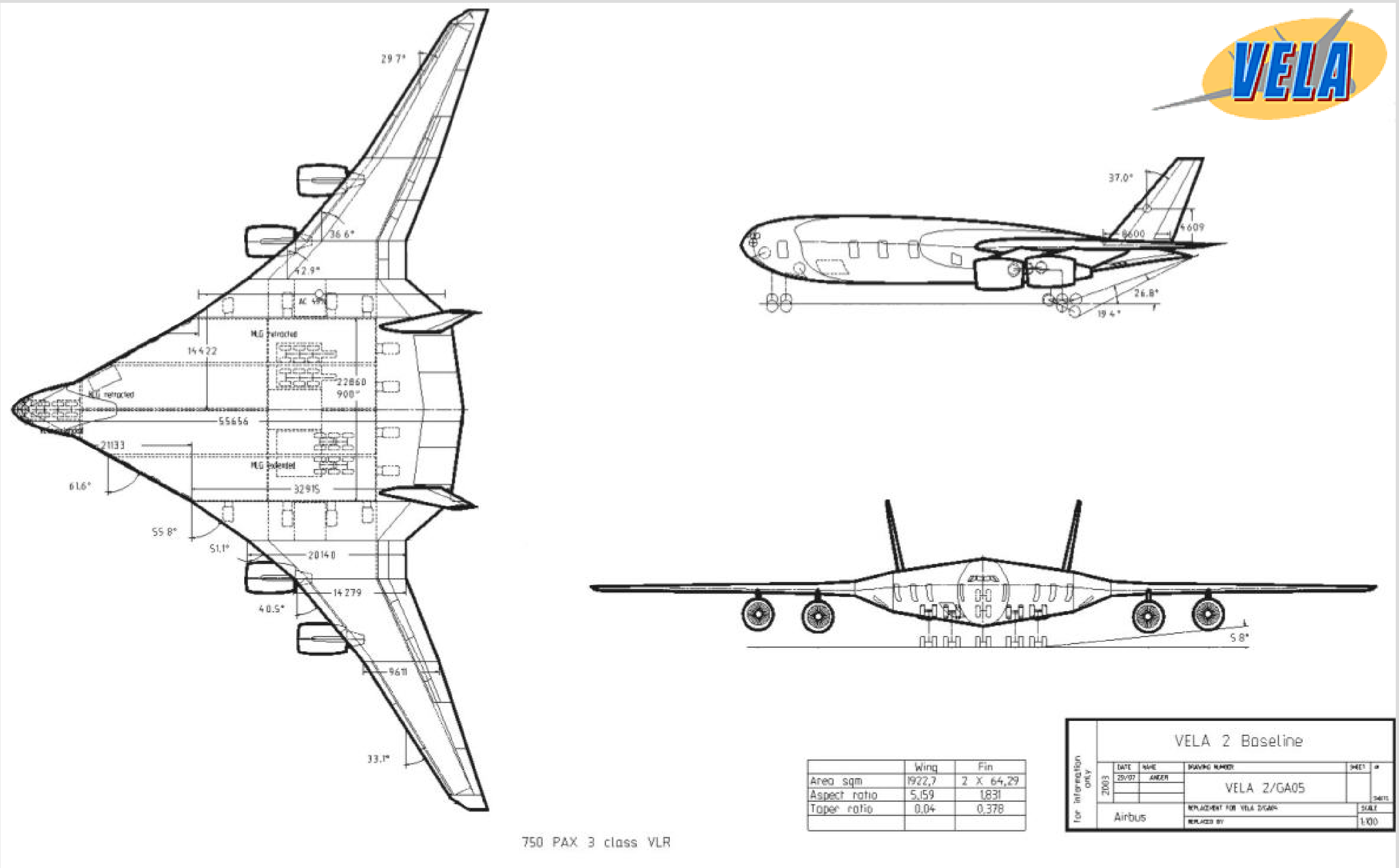
VELA 1



BWB Projects

VELA 2



	Wing	Fin
Area sqm	1922,7	2 X 64,29
Aspect ratio	5,159	1,831
Taper ratio	0,04	0,378

BWB Projects

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6th Framework Programme of the European Commision: NACRE with PDA (VELA follow on)

SIXTH FRAMEWORK PROGRAMME

2003 - 2006

WP3:	Payload Driven Aircraft (VELA 3)
WP4:	Flying scale model for novel aircraft configuration

Payload Driven Aircraft (PDA)

BWB Projects

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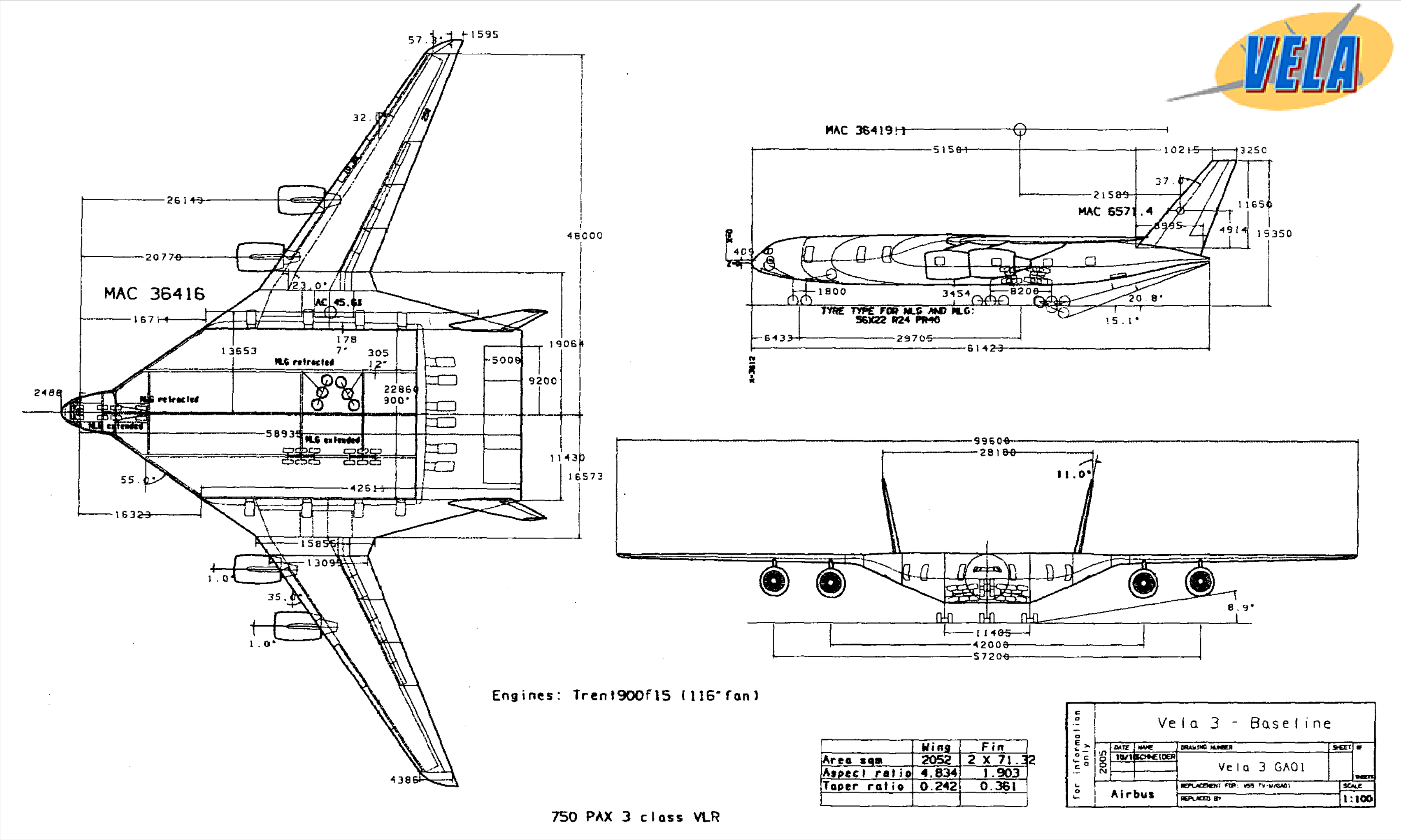
VELA 3



BWB Projects

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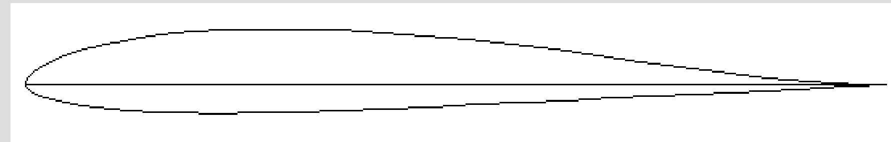
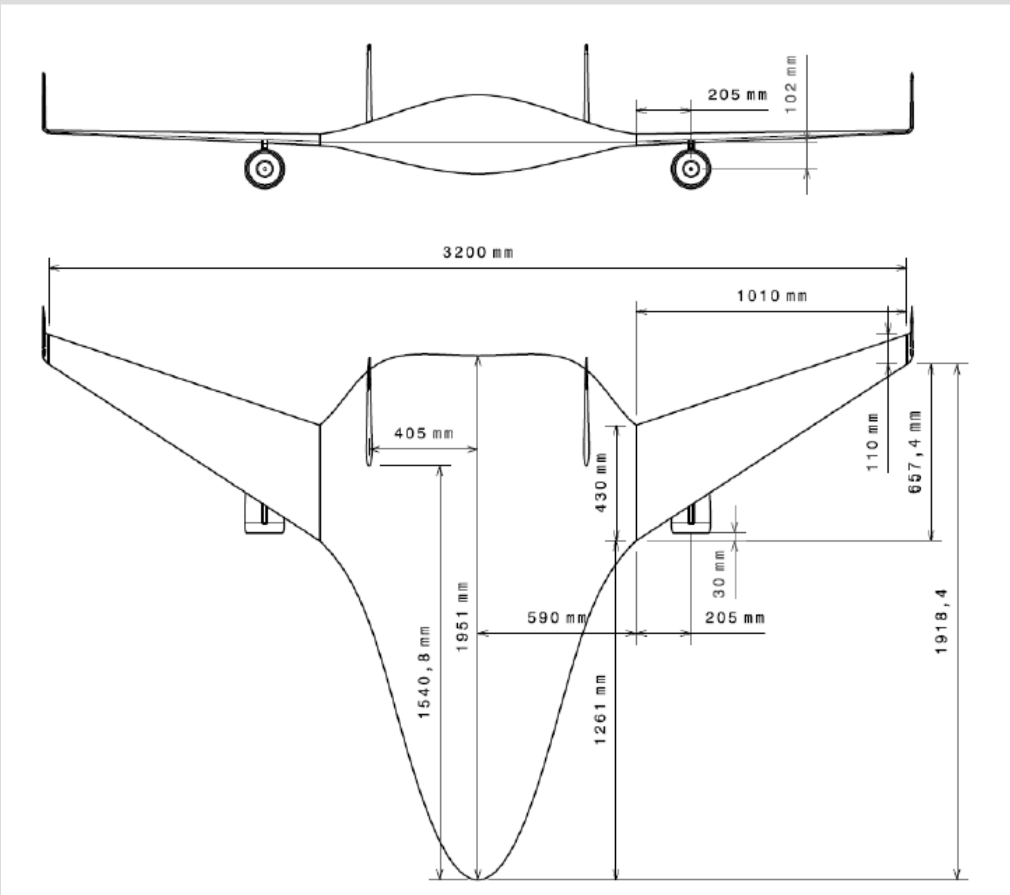
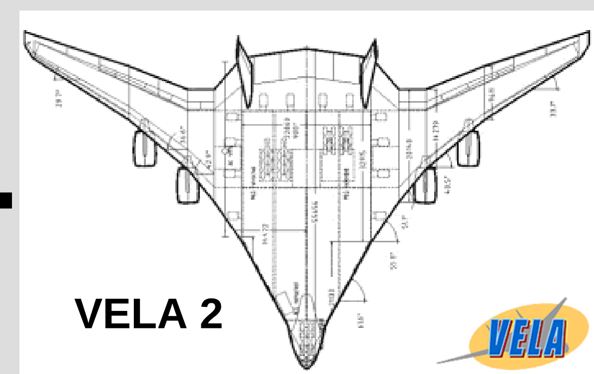
HAW Student Project: AC 20.30





Wing profile: MH-45
(Martin Hepperle)
t/c = 9.85%,
low drag, improved max. lift,
low $c_{m,\,c/4}$,
proven even at Reynolds
numbers below 200000.
Body profile: MH-91.



AC 20.30: geometry is based on VELA 2; student project; sponsor: "Förderkreis"

BWB
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preliminary sizing

VELA 2 Technical Data

Requirements:

3-class seating: 750 pax (22 / 136 / 592)

cargo capacity > 10 t

range: 7500 NM (200 NM to alternate, 30 min. holding, 5% trip fuel allowance)

high desity seating: 1040 pax

cruise Mach number: 0.85

M_{MO} : 0.89

take-off field length < 3350 m (MTOW, SL, ISA +15°C)

approach speed < 145 kt   (here: approach speed = 165 kt)

ICA (300 ft/min, max. climb) > 35000 ft

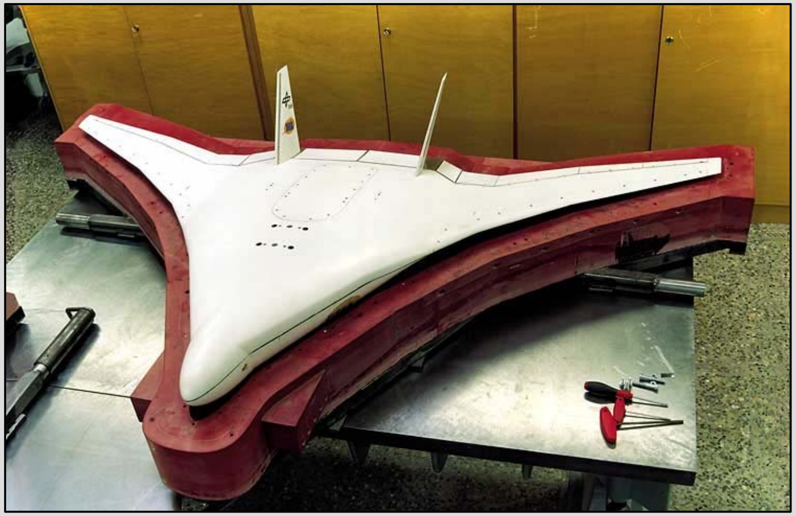
time to ICA (ISA) < 30 min.

max. operating altitude > 45000 ft (=> cabin Δp)

runway loading (ACN, Flex. B) < 70

span < 100 m

wheel spacing < 16 m



Input Parameters for Preliminary Sizing

Estimation of maximum glide ratio $E = L/D$ in normal cruise

A :	aspect ratio
S_{wet} :	wetted area
S_W :	reference area of the wing
e :	Oswald factor; passenger transports: $e \approx 0.85$

$$E_{max} = k_E \sqrt{\frac{A}{S_{wet} / S_W}}$$

from statistics: $k_E = 15,8$

$$k_E = \frac{1}{2}\sqrt{\frac{\pi\, e}{\overline{c_f}}} = 14.9$$

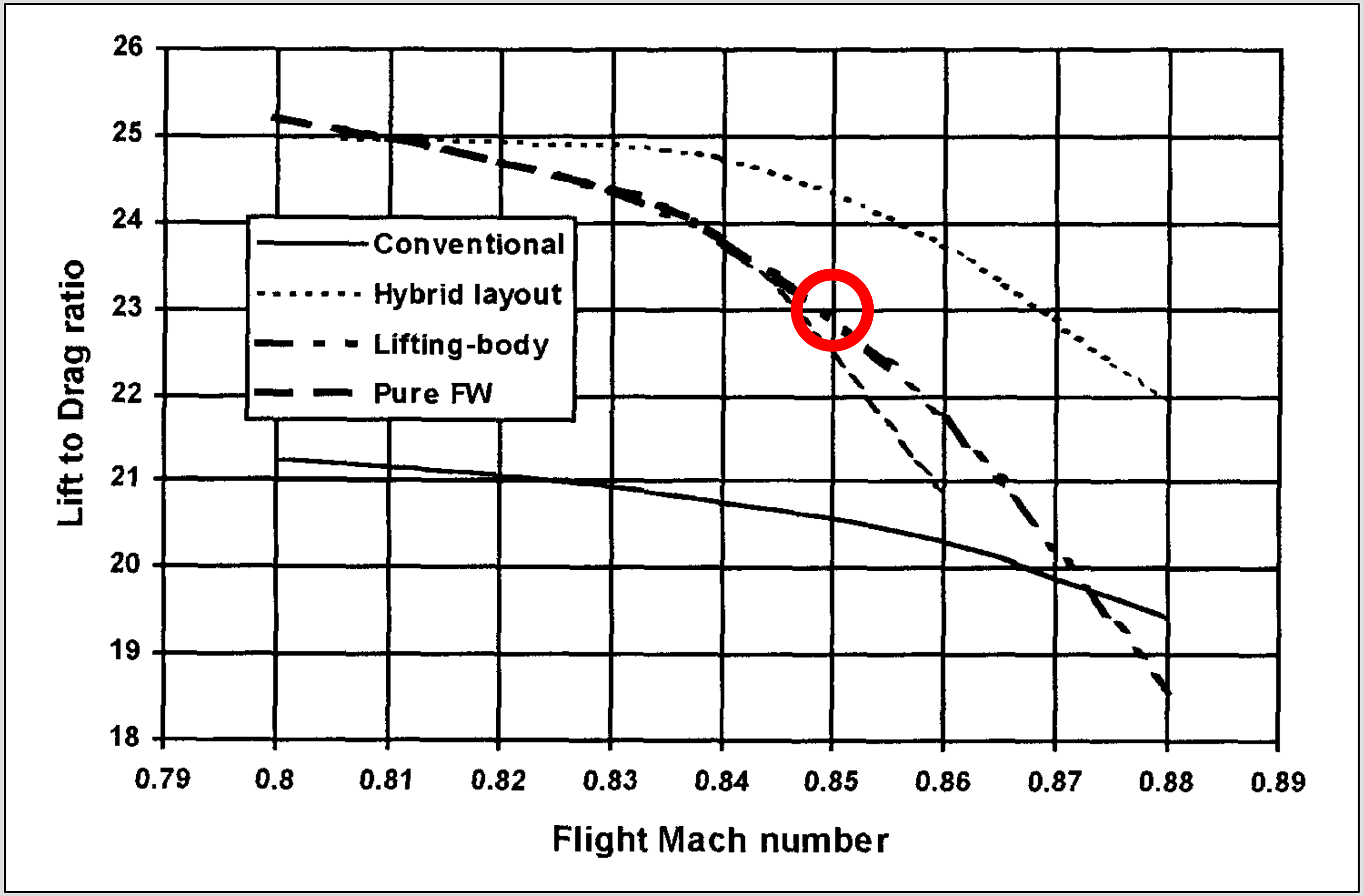
$$\overline{c_f} = 0.003$$

S_{wet} / S_W :	conv. aircraft	6.0 ... 6.2
	BWB	≈ 2.4
A :	conv. aircraft	7.0 ... 10.0
	VELA 2	5.2

$E_{max} = 23,2$

Input Parameters for Preliminary Sizing

Estimation of maximum glide ratio *E = L/D* in normal cruise



TsAGI for AIRBUS

Input Parameters for Preliminary Sizing

Estimation of maximum lift coefficient take-off and landing

$$C_{L,max} = C_{L,0} + \frac{\partial C_L}{\partial \alpha}\alpha + \frac{\partial C_L}{\partial \eta_W}\eta_W + \frac{\partial C_L}{\partial \eta_B}\eta_B$$

= 0.73

Wind tunnel measurements of AC 20.30:

$C_{L,0}$ **= 0**

$\frac{\partial C_L}{\partial \eta_W}$ **= 0.22**

$\frac{\partial C_L}{\partial \eta_B}$ **= 0.43**

$\frac{\partial C_L}{\partial \alpha}$ **= 2,5**

α **= 12 °**

η_W **= 18 °**

η_B **= 18 °**

VELA 2

Assumptions:

OEW / MTOW = 0,5	LOFTIN: 0,52 (T/W!) A380: 0,49 VELA 2: 0.55 → 0.48
SFC = 1.4 mg/(Ns)	latest technology assumed (GEnx)
approach speed = 165 kt	
mass of pax and luggage	for long distance flying: 97.5 kg per pax

Given:

Wing Area:	1923 m²

Preliminary Sizing

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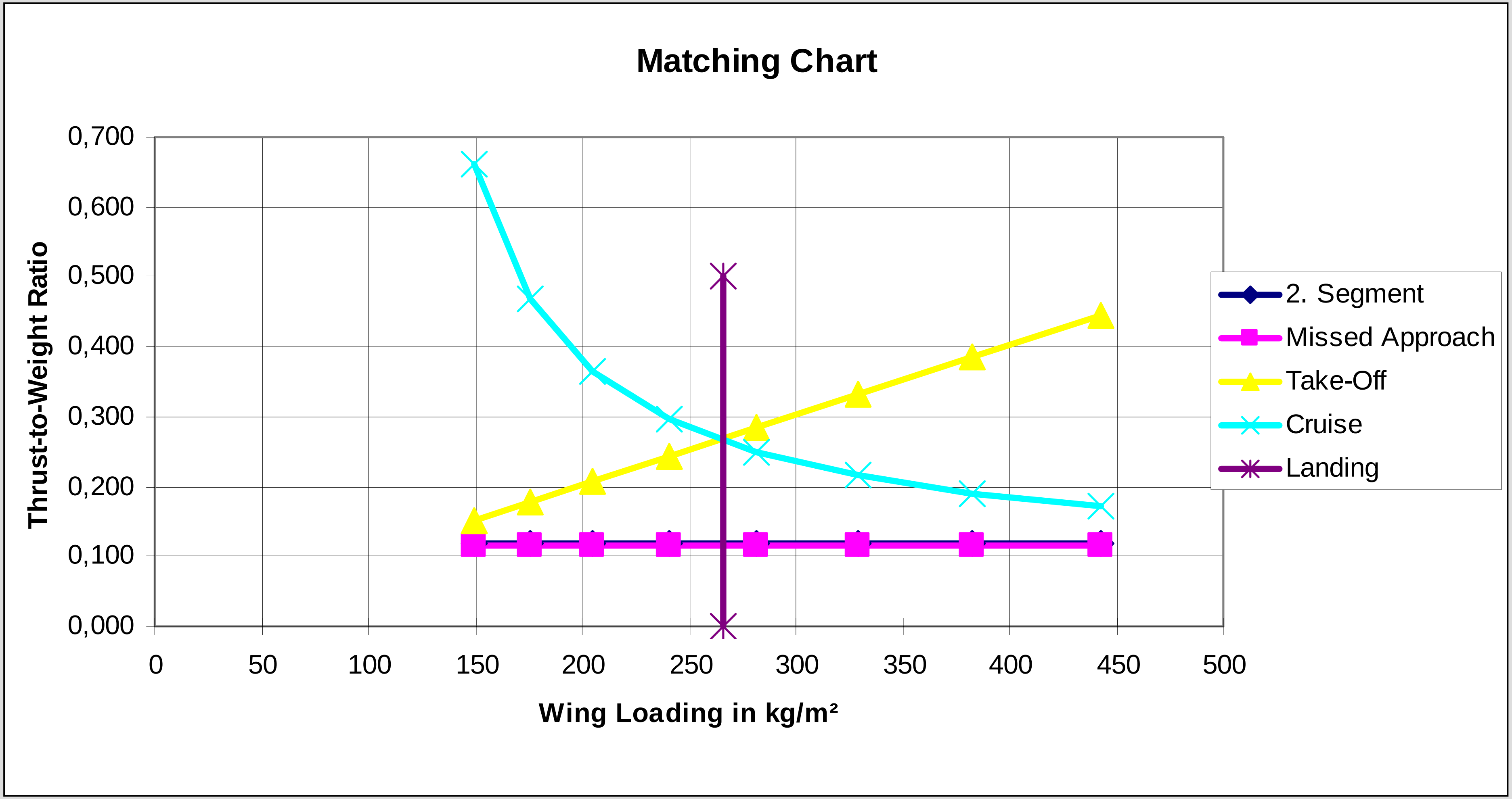
VELA 2



VELA 2

Sizing Results:

L/D during 2. segment: 17.0 (higher than conv. due to small lift coefficient and small drag).

L/D during missed approach: 11.0 (normal, because landing gear drag dominates, FAR!)

V / V_{md} = 1.09 (normal: V / V_{md} = 1.0 ... 1.316) => E = 22.8

lift coefficient cruise: 0.25

trust to weight ratio: 0.28 (value is slightly high for 4-engined A/C, reason: TOFL and C_L)

wing loading: 260 kg/m² (very low for passenger transport, due to low lift coefficient)

Initial Cruise Altitude (ICA): 38400 ft (= 11.7 km)

payload:	83000 kg	
MTOW:	501000 kg	(VELA 2: 691200 kg)
Wing Area:	1923 m²	(VELA 2: 1923 m² - forced to fit)
MLW:	366000 kg	
OEW:	251000 kg	(VELA 2: 380600 kg)
Fuel:	167000 kg	(VELA 2: 278200 kg ?)
Thrust:	344 kN	(for each of the four engines)

VELA 3

Assumptions:

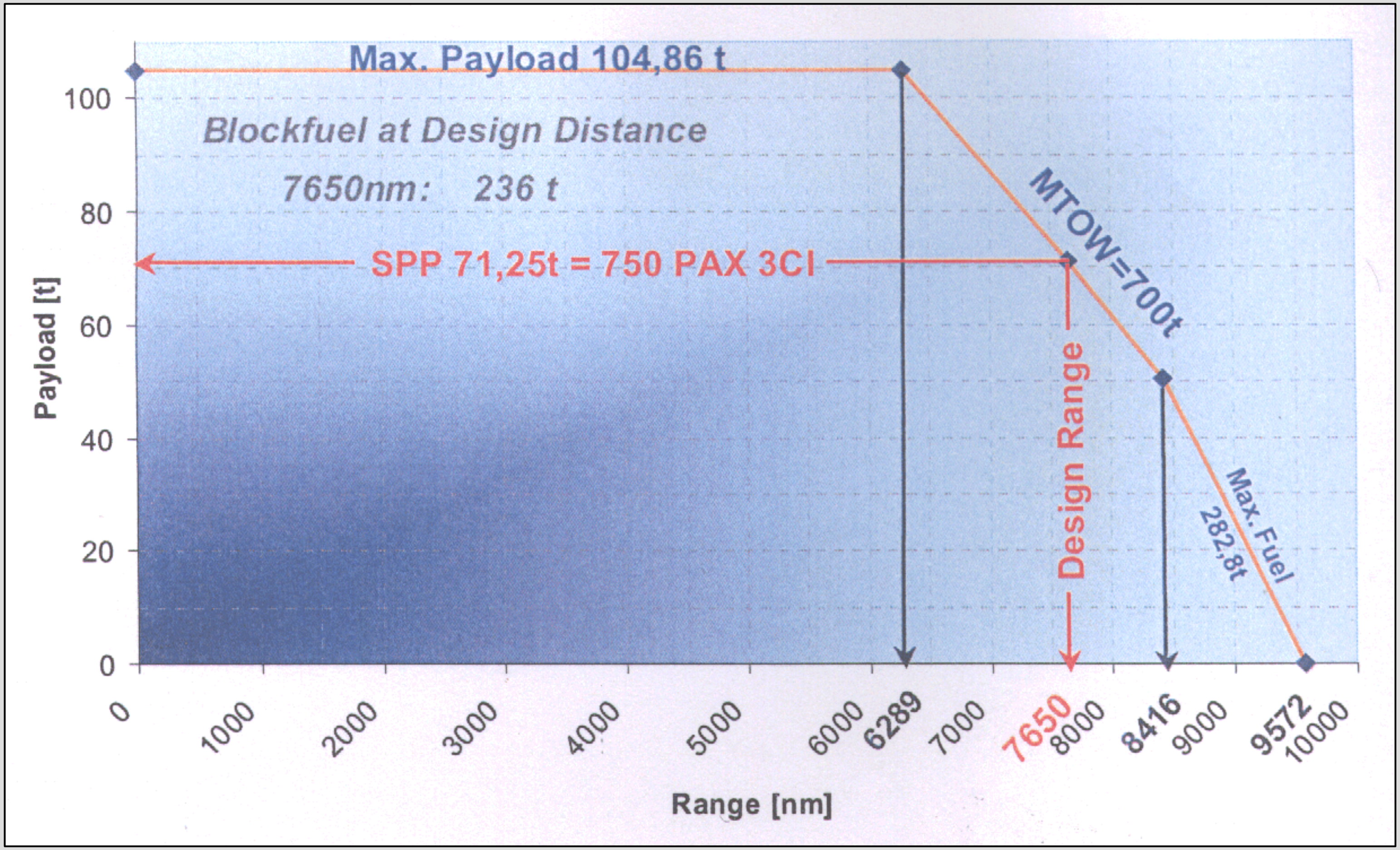
OEW / MTOW = 0,5	LOFTIN: 0,52 (T/W!) A380: 0,49 BWB structural benefits?	
SFC = 1.6 mg/(Ns)	normal technology level assumed	
approach speed = 165 kt		
Reserves:	200 NM to alternate, 30 min. holding, 5% trip fuel allowance	

Given:

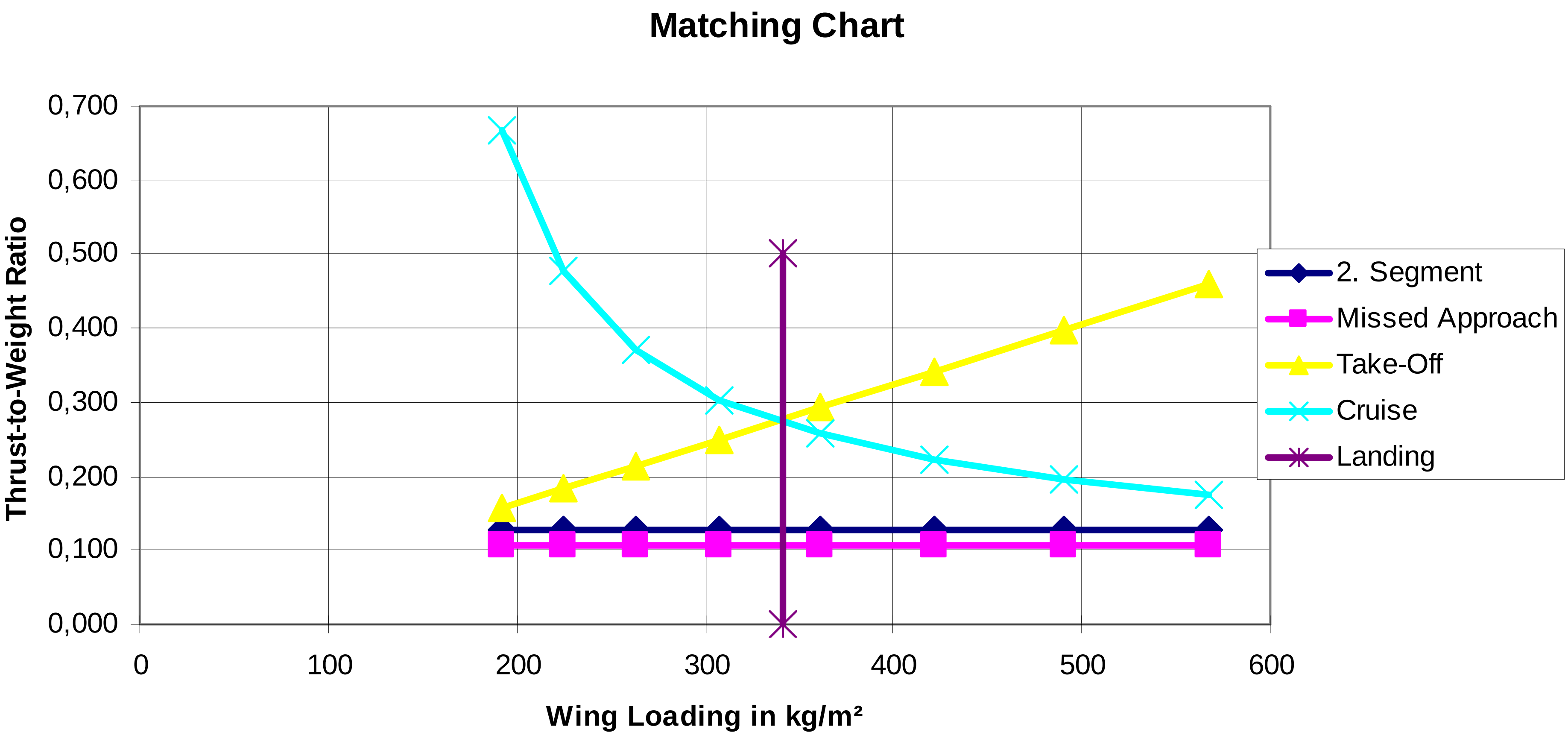
range:	7650 NM
MTOW:	700000 kg
Wing Area:	2052 m²
Wing Loading:	341 kg/m² (very low for pass. transp. due to low lift coeff.)
mass of pax and luggage:	95.0 kg per pax
payload:	71250 kg

VELA 3

Given:


Max. Payload 104,86 t
Blockfuel at Design Distance
7650nm: 236 t
SPP 71,25t = 750 PAX 3Cl
MTOW=700t
Design Range
Max. Fuel
282,8t
Payload [t]
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
6289
7000
7650
8000
8416
9000
9572
10000
Range [nm]

VELA 3


Matching Chart
Thrust-to-Weight Ratio
0,700
0,600
0,500
0,400
0,300
0,200
0,100
0,000
0
100
200
300
400
500
600
Wing Loading in kg/m²
2. Segment
Missed Approach
Take-Off
Cruise
Landing

VELA 3

Sizing Results:

lift coefficient landing: 0.86 (higher than HAW wind tunnel results)
L/D during 2. segment: 15.2 (higher than conv. due to small lift coefficient and small drag)
L/D during missed approach: 11.0 (normal, because landing gear drag dominates, FAR!)
L/D_{max} : 20.9 (lower than BWB estimate)
V / V_{md} = 1.0 => $L/D = L/D_{\mathrm{max}}$ (normal: V / V_{md} = 1.0 ... 1.316)
lift coefficient cruise: 0.31
trust to weight ratio: 0.28 (value is slightly high for 4-engined A/C, reason: TOFL and C_L)
Initial Cruise Altitude (ICA): 37800 ft (= 11.7 km)
MLW: 469000 kg
OEW: 350000 kg
Fuel: 279000 kg (VELA 3: 282800 kg)
Thrust: 481 kN (for each of the four engines)

BWB
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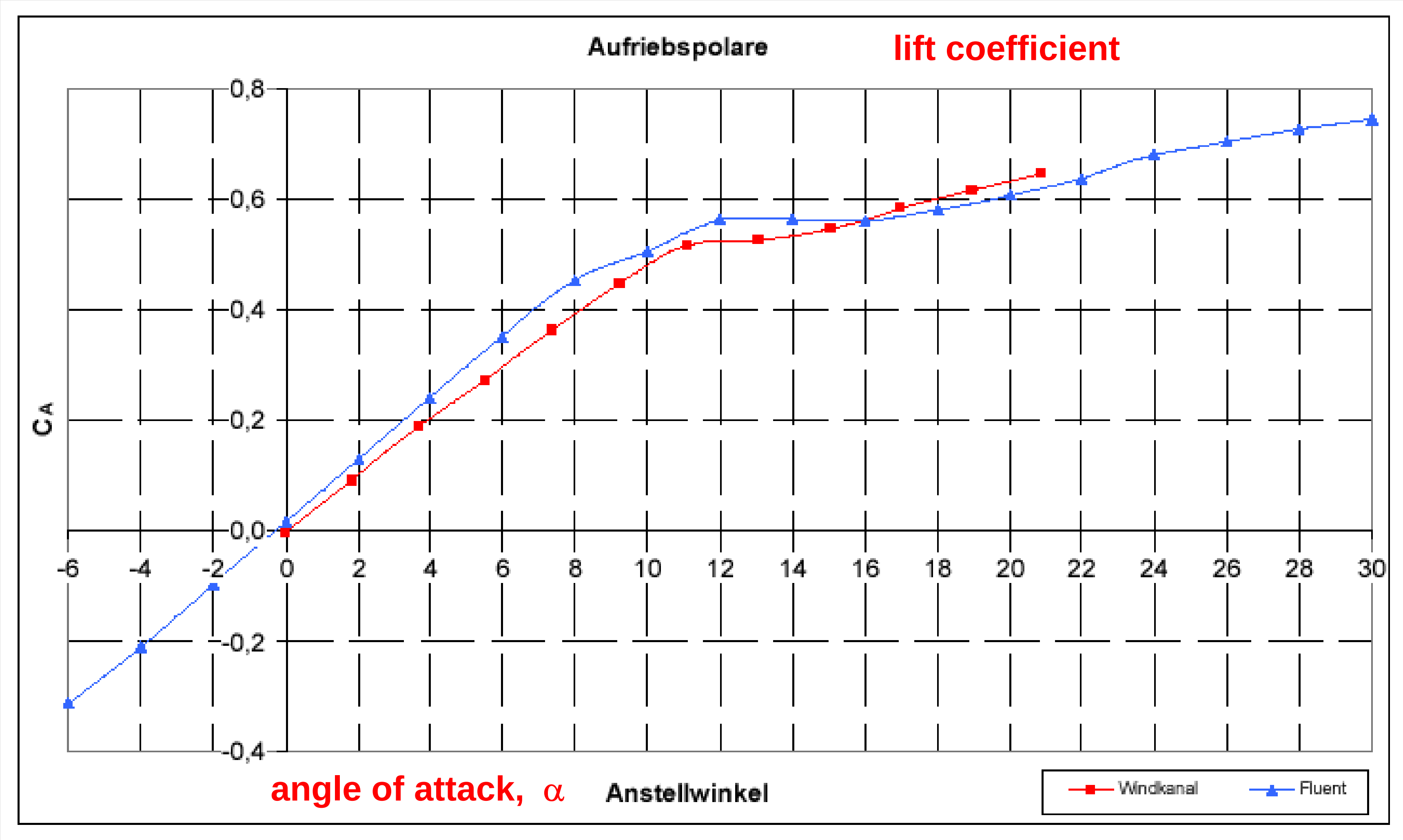
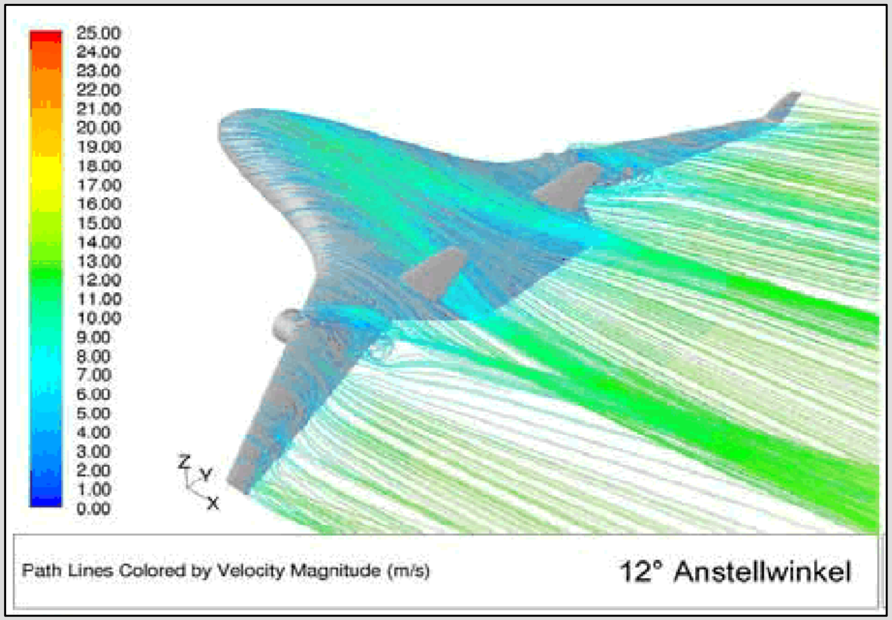
brief results from other disciplines

AC20.30: CFD with FLUENT

Diplomarbeit: H. Brunswig



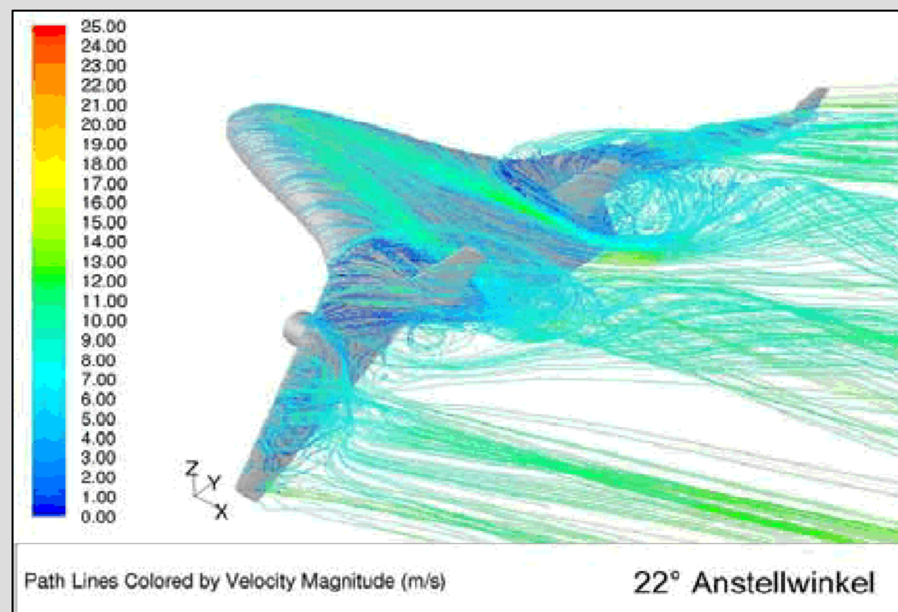
AC20.30: CFD with FLUENT



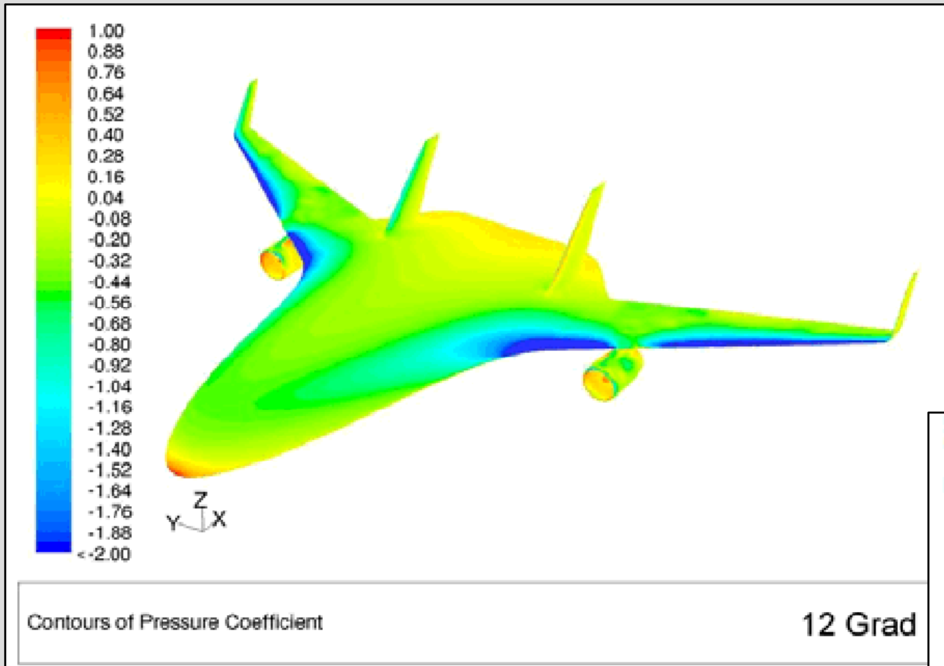
Stalls can easily be handled
Usable lift up to AOA of 12°
At 22° AOA:

wings are stalled
body continues to produce lift
but control surfaces do not
deliver control power

path lines



AC20.30: CFD with FLUENT



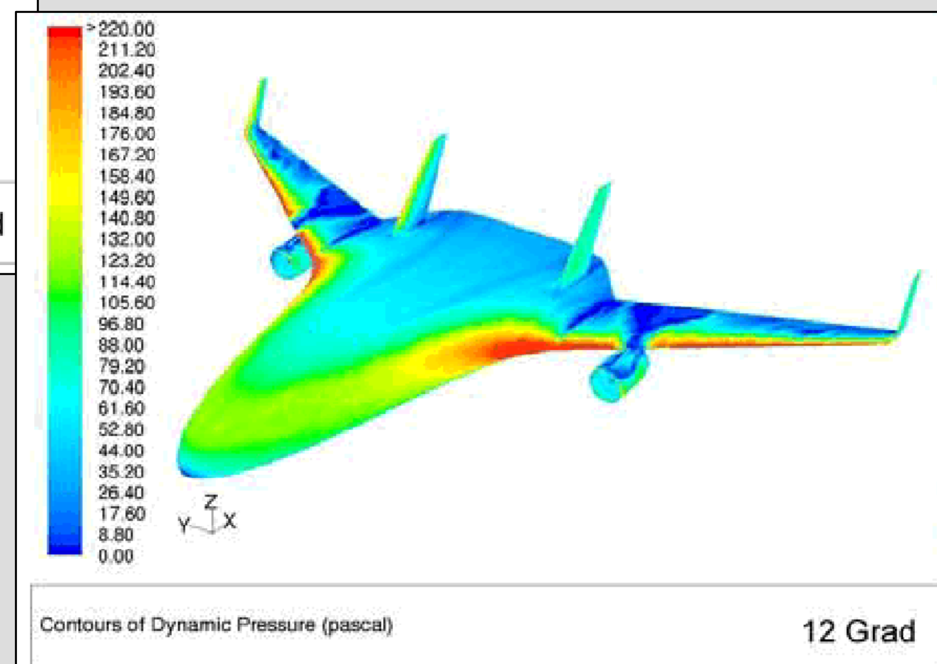
Contours of Pressure Coefficient 12 Grad

$$q = \frac{1}{2}\rho V^2$$

dynamic pressure

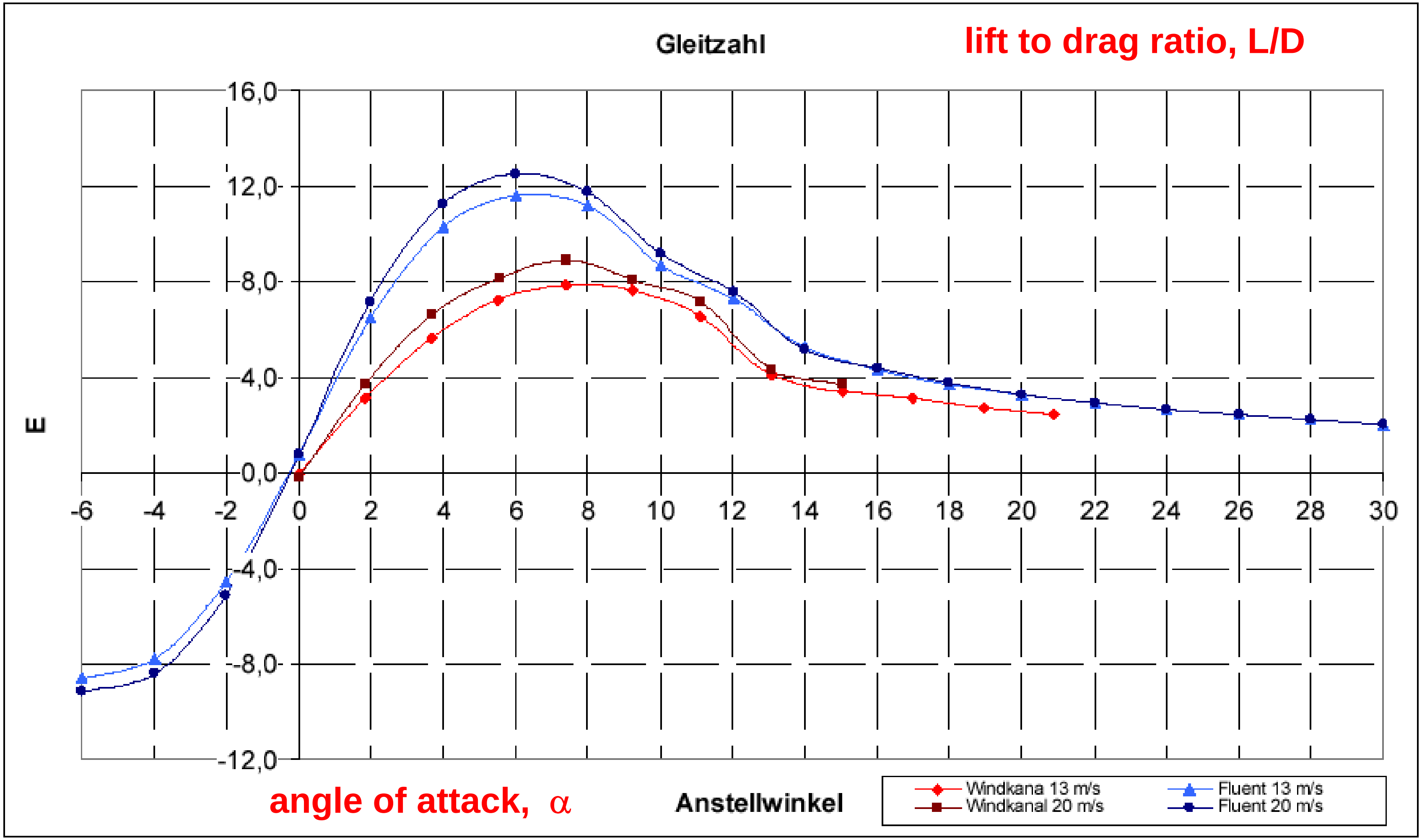
pressure coefficient

$$c_p = \frac{p - p_\infty}{q} = 1 - \left(\frac{V}{V_\infty}\right)^2$$

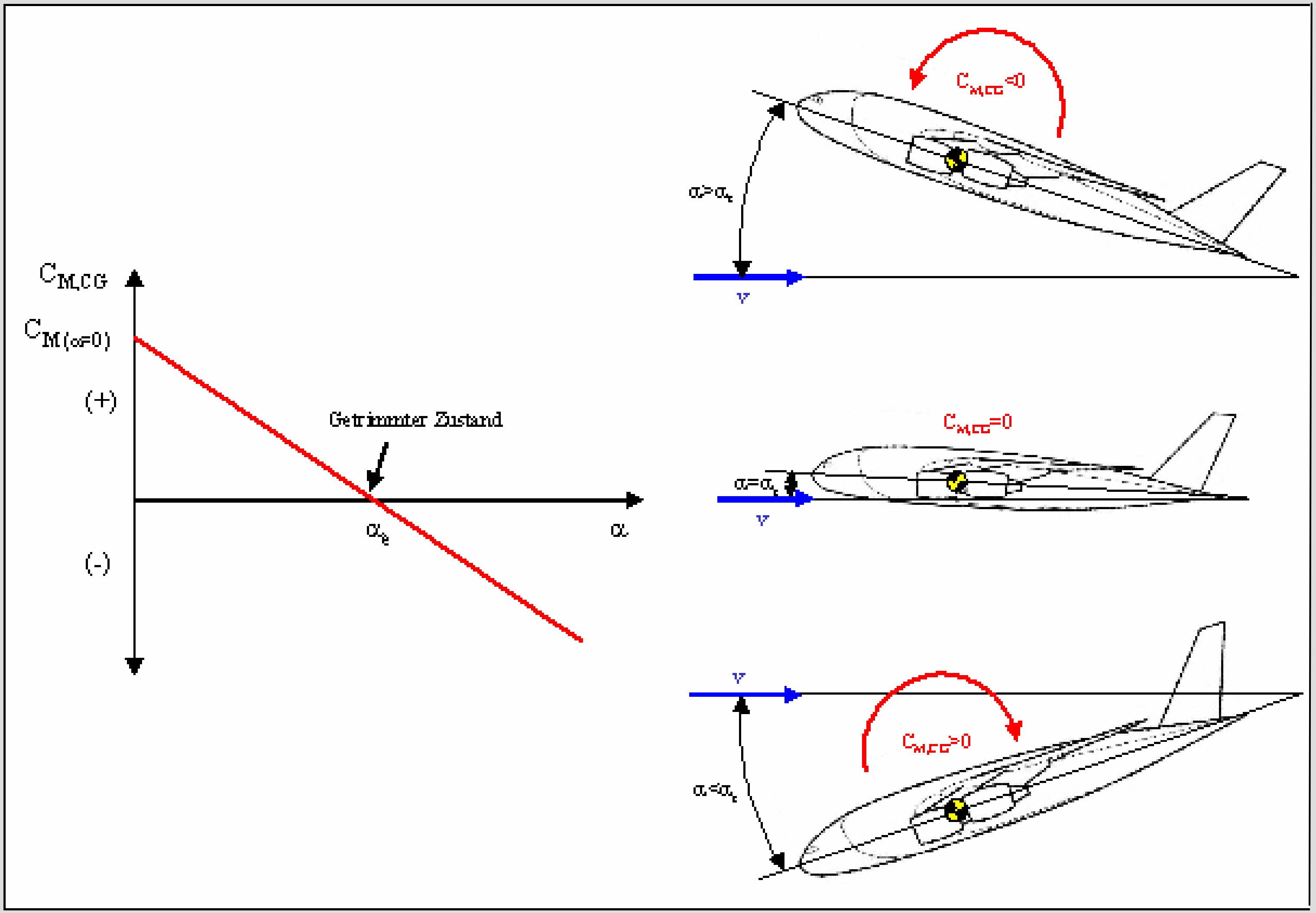


Contours of Dynamic Pressure (pascal) 12 Grad

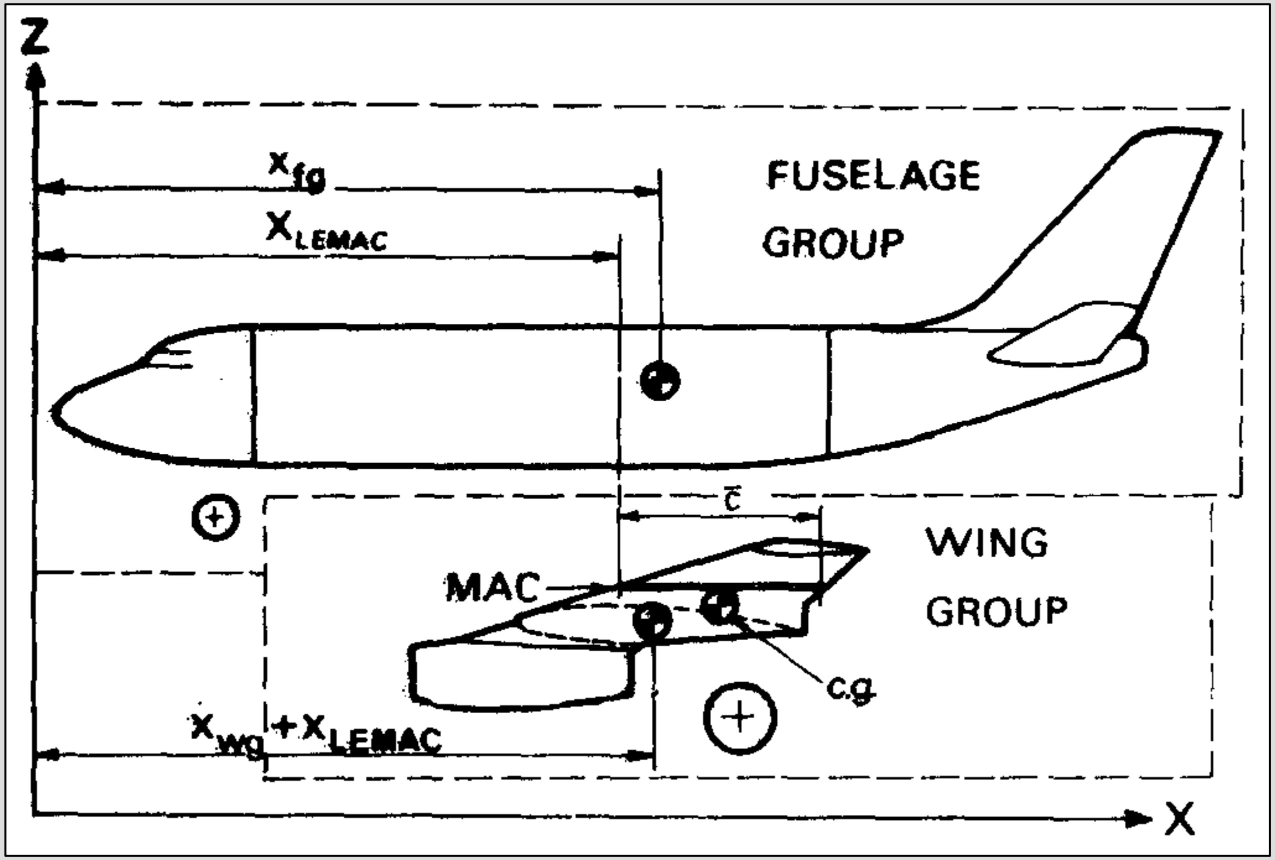
AC20.30: CFD with FLUENT



Static Longitudinal Stability Fundamentals



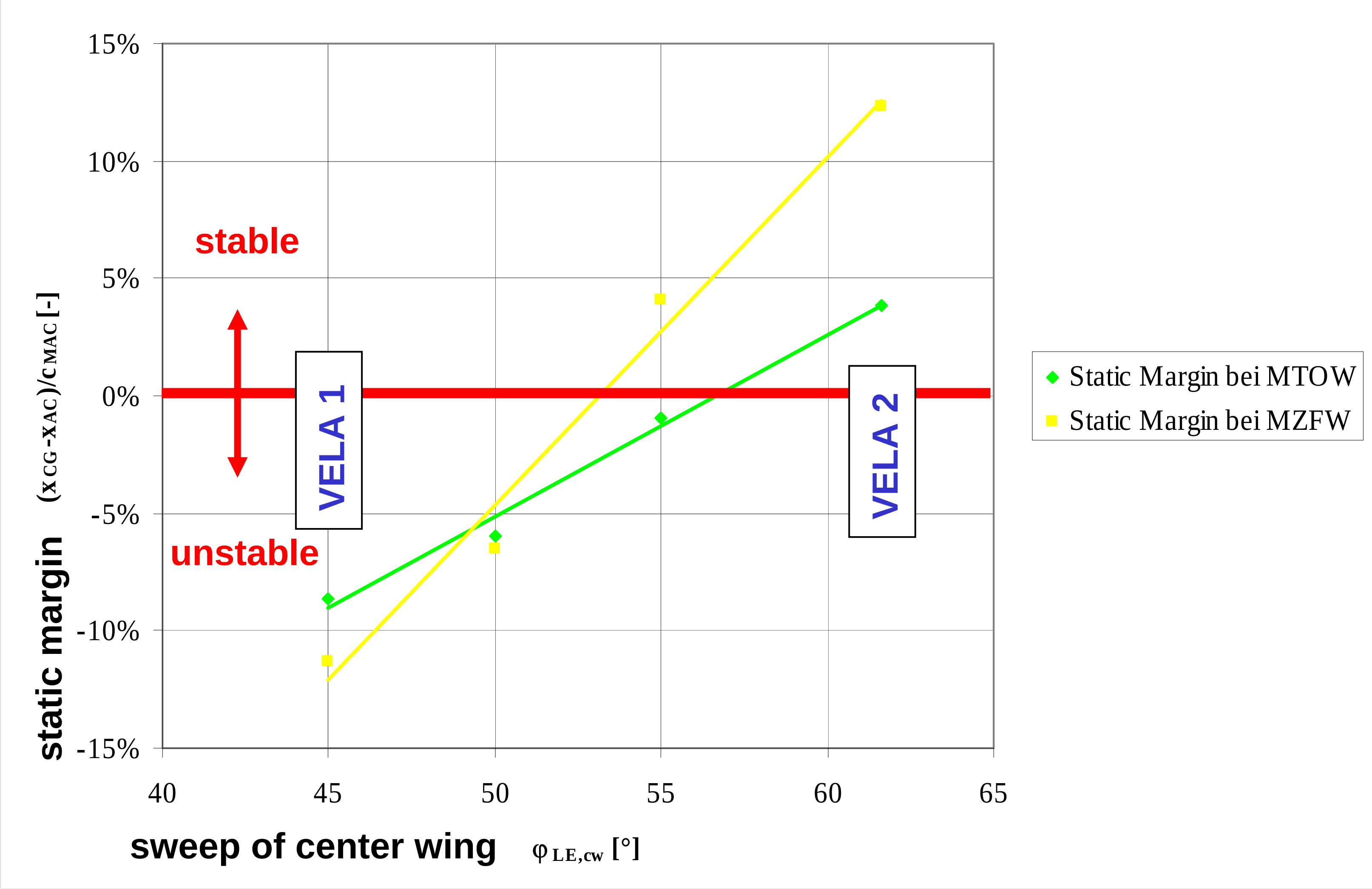
Flight Mechanics



Positioning of the CG on the Mean Aerodynamic Chord (MAC) for required *static margin* is achieved in conventional design by shifting the wing with respect to the fuselage. This approach is not possible in BWB design!

$$x_{LEMAC} = x_{fg} - x_{cg} + \frac{m_{wg}}{m_{fg}}\left(x_{wg} - x_{cg}\right)$$

Static Longitudinal Stability for VELA Configurations



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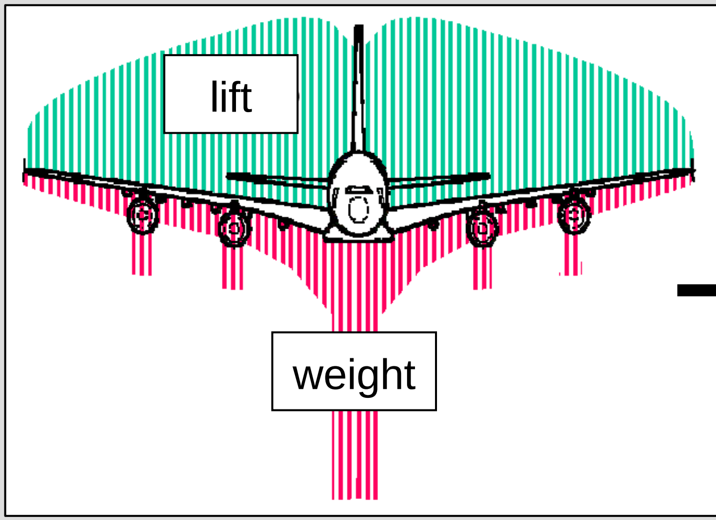
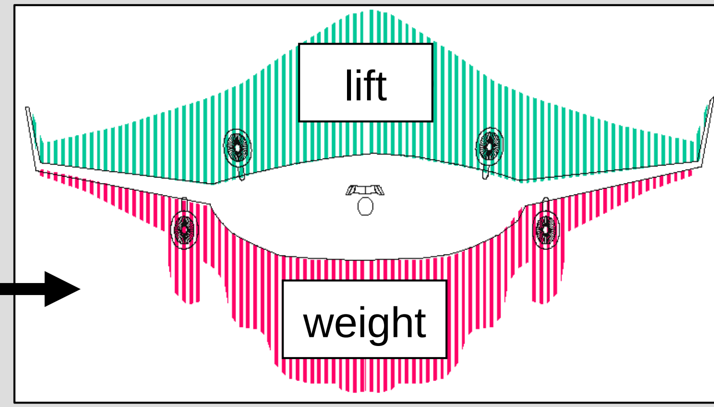
Weight Saving Potential of BWB Configurations





Less bending moments in a flying wing or BWB

BWB study with distributed propulsion (Virginia Polytechnic)

Helios - example of an extreme span loader with distributed propulsion (NASA / AeroVironment, Inc.)

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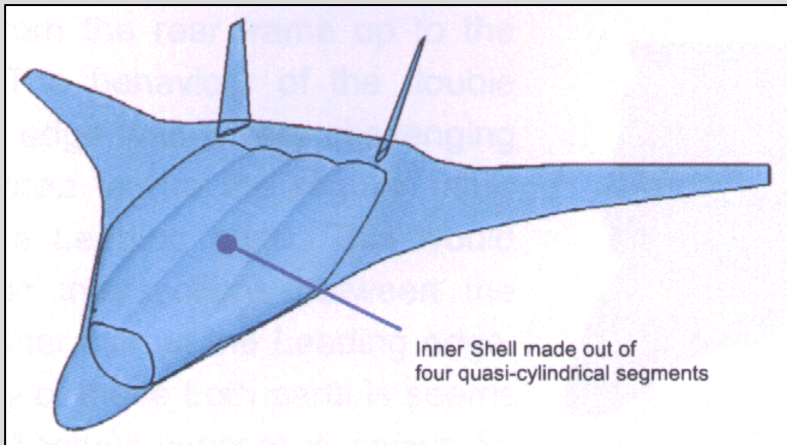
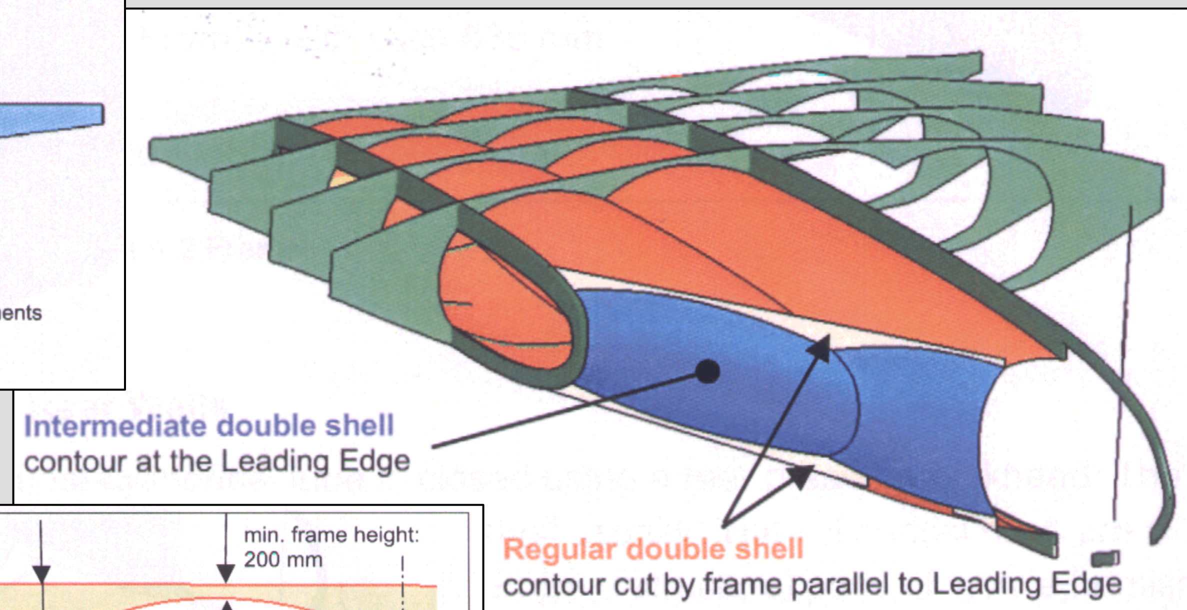
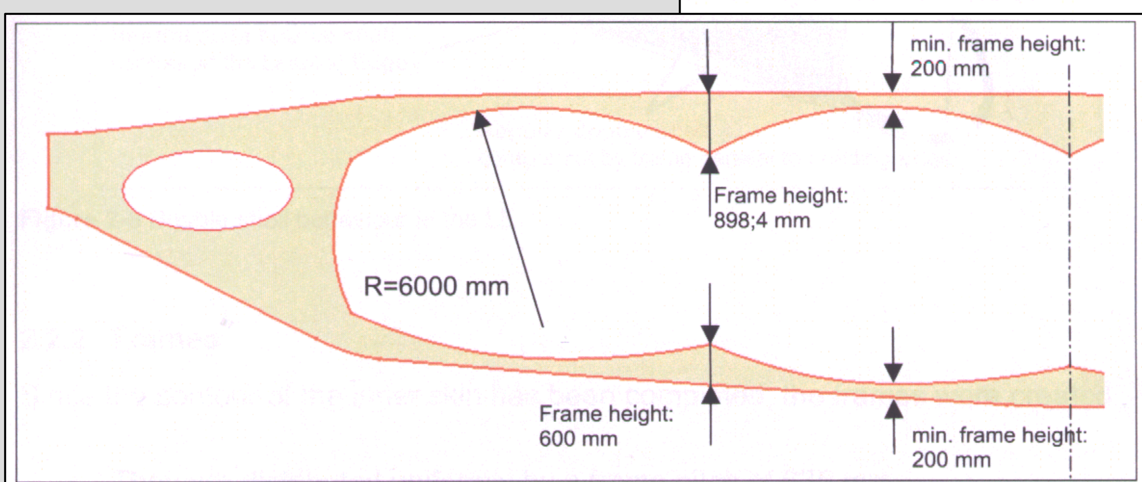
VELA 2 - Basic Structural Layout

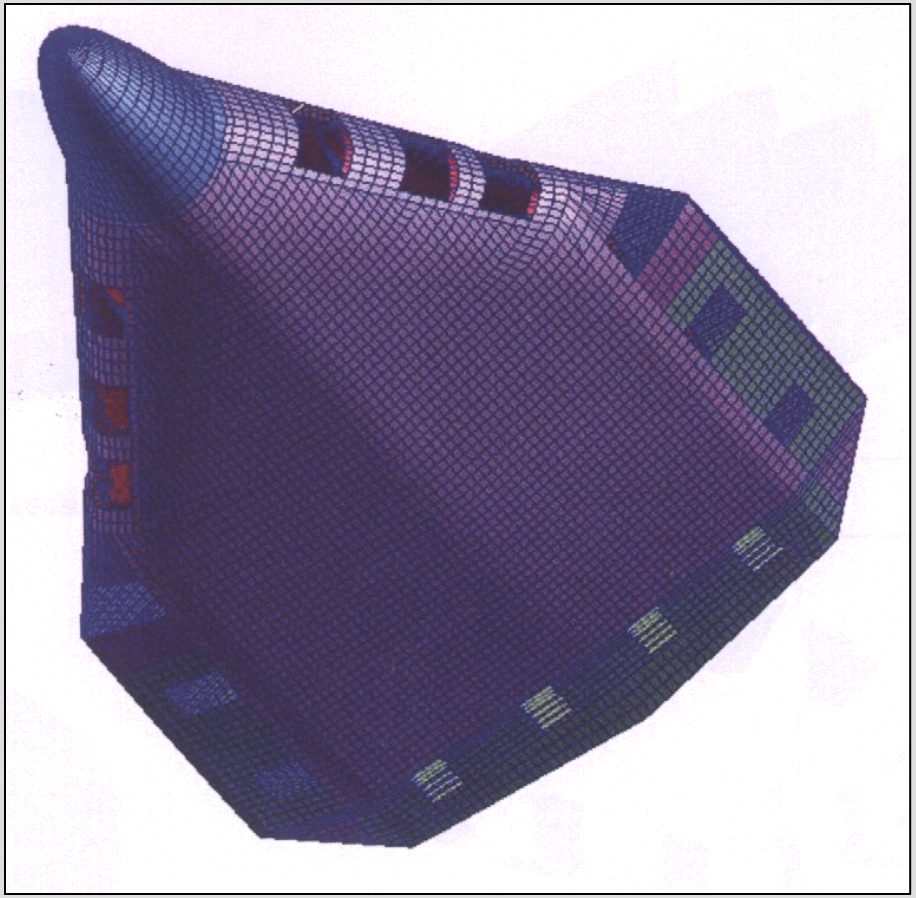
Thesis: T. Kumar Turai



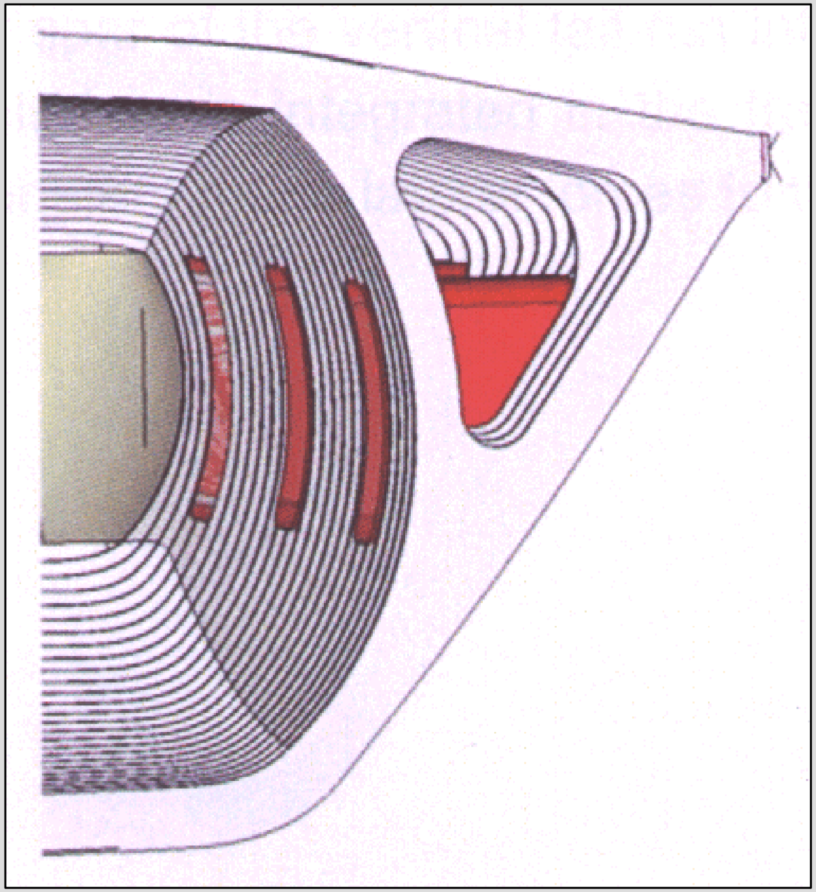




VELA 2 - Doors



Door cut-outs



Side door integration

Mass Prediction

VELA 2

Weight Chapter	F. Bansa	T. Kumar Turai	T. Kumar Turai (FEM)
10 Structure	234669 kg	253529 kg	210070 kg
20 Power Units	37731 kg	36603 kg	->
30/40 Systems	19795 kg	23302 kg	->
50 Furnishings	35313 kg	27588 kg	->
60 Operator Items	35313 kg	39578 kg	->
OWE	362820 kg	380600 kg	337141 kg
OWE/MTOW	**0.525**	**0.551**	**0.488**
Loftin	0.521		
Marckwardt	0.462		
A380-800	**0.501**		
A340-600	**0.475**		

Taken for Preliminary Sizing: **0.500**

Result: The BWB design does not significantly improve the OWE/MTOW ratio!
Latest News: One-shell layout can lead to OWE/MTWO = **0.44 ... 0.46** !

System Integration

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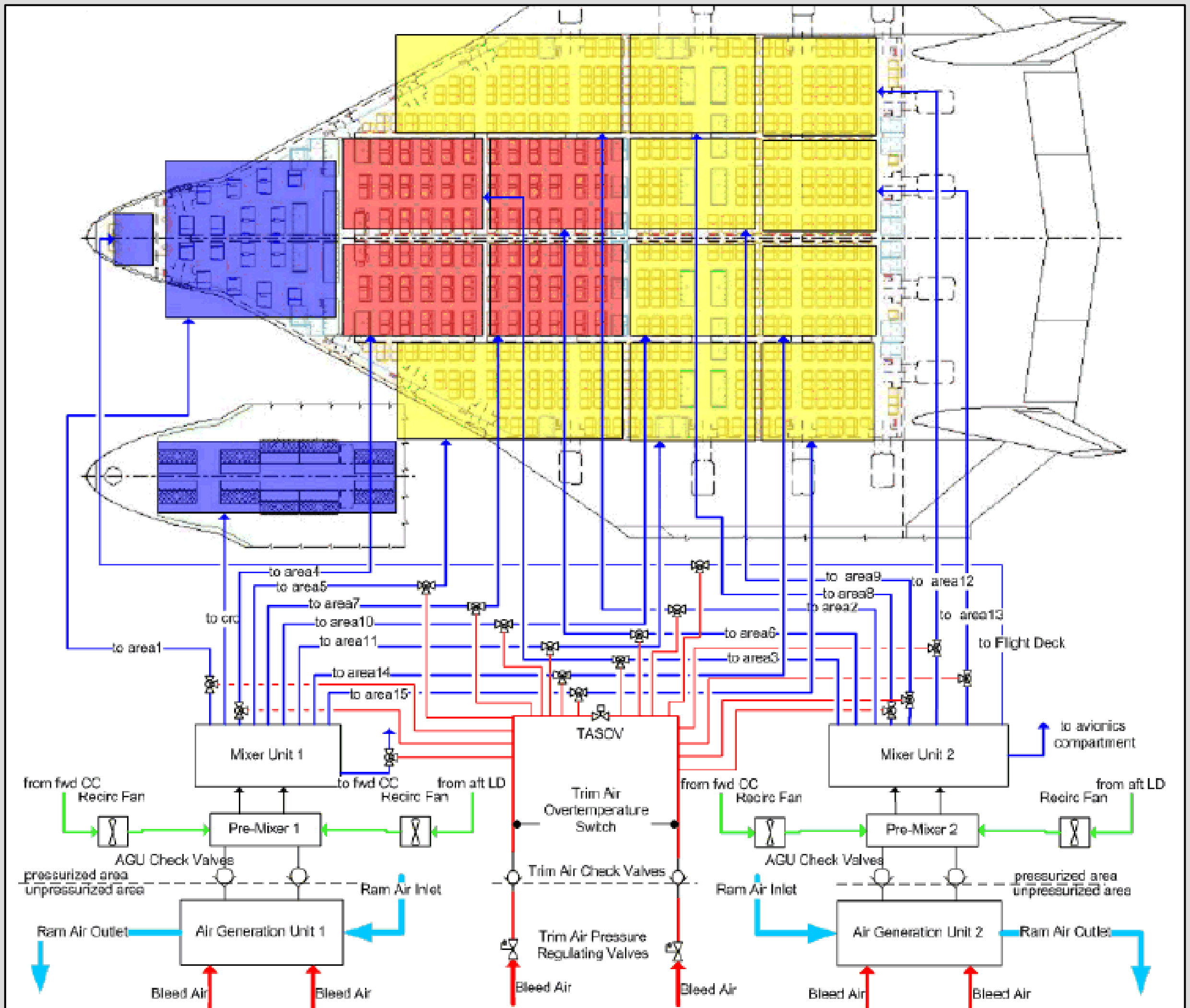
VELA 2 - ATA 21 - Temperature Control & Ventilation

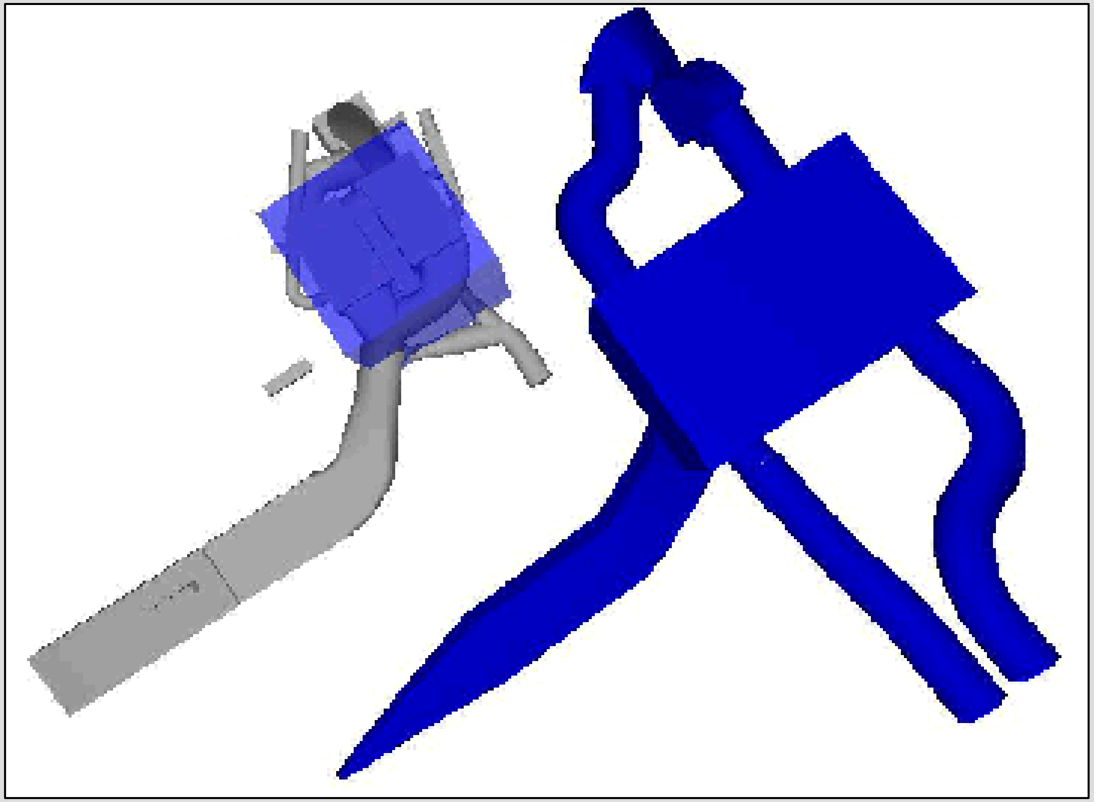


Diplomarbeit: M. Mahnken

Steps in system integration:

1.) System diagram
2.) Sizing
3.) Routing & ducting

VELA 2 - ATA 21 - Pack Sizing



Air Generation Unit (pack): A380 and VELA 2

Steps in system integration:

1.) System diagram

2.) Sizing

3.) Routing & ducting

System Integration

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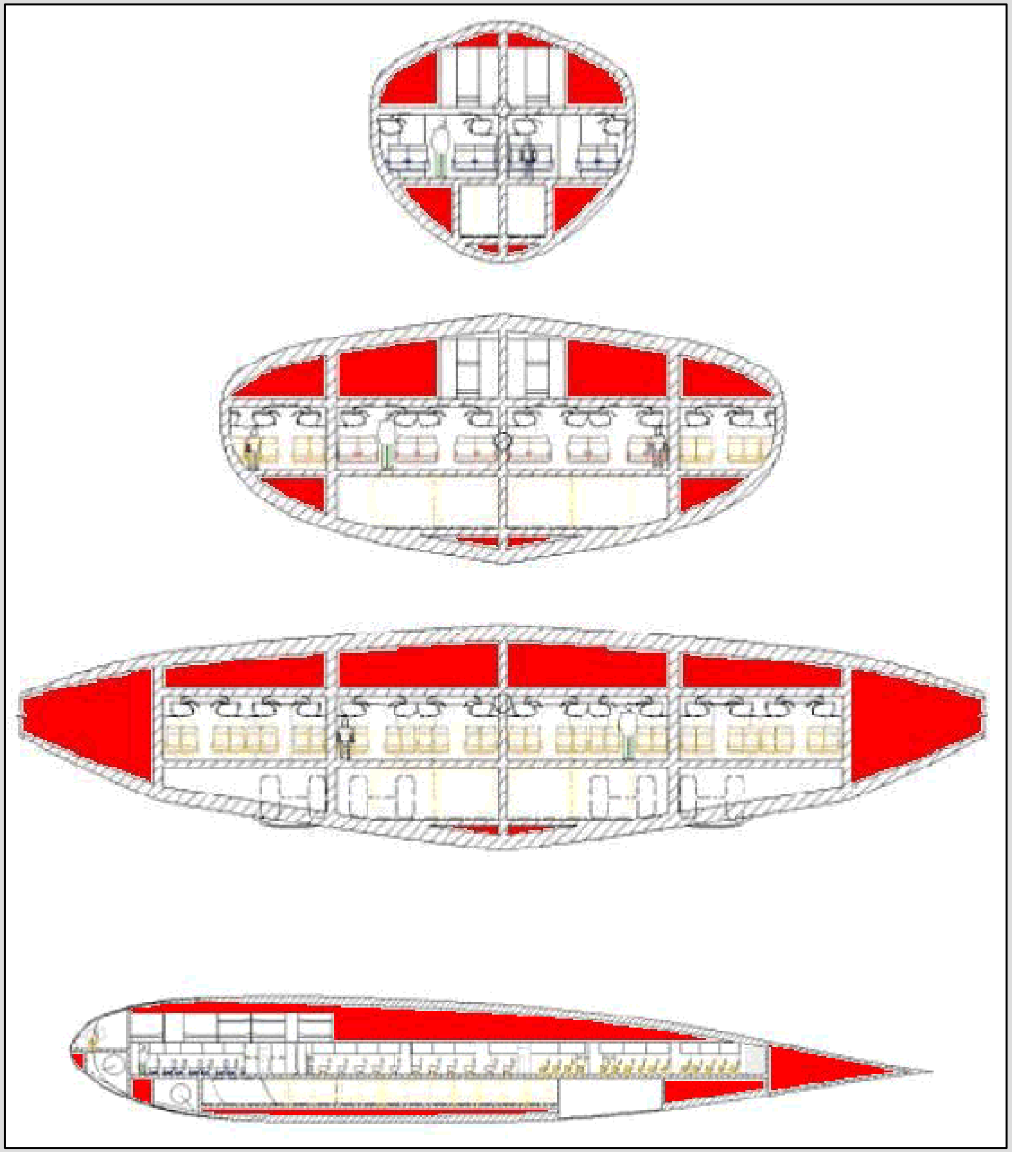


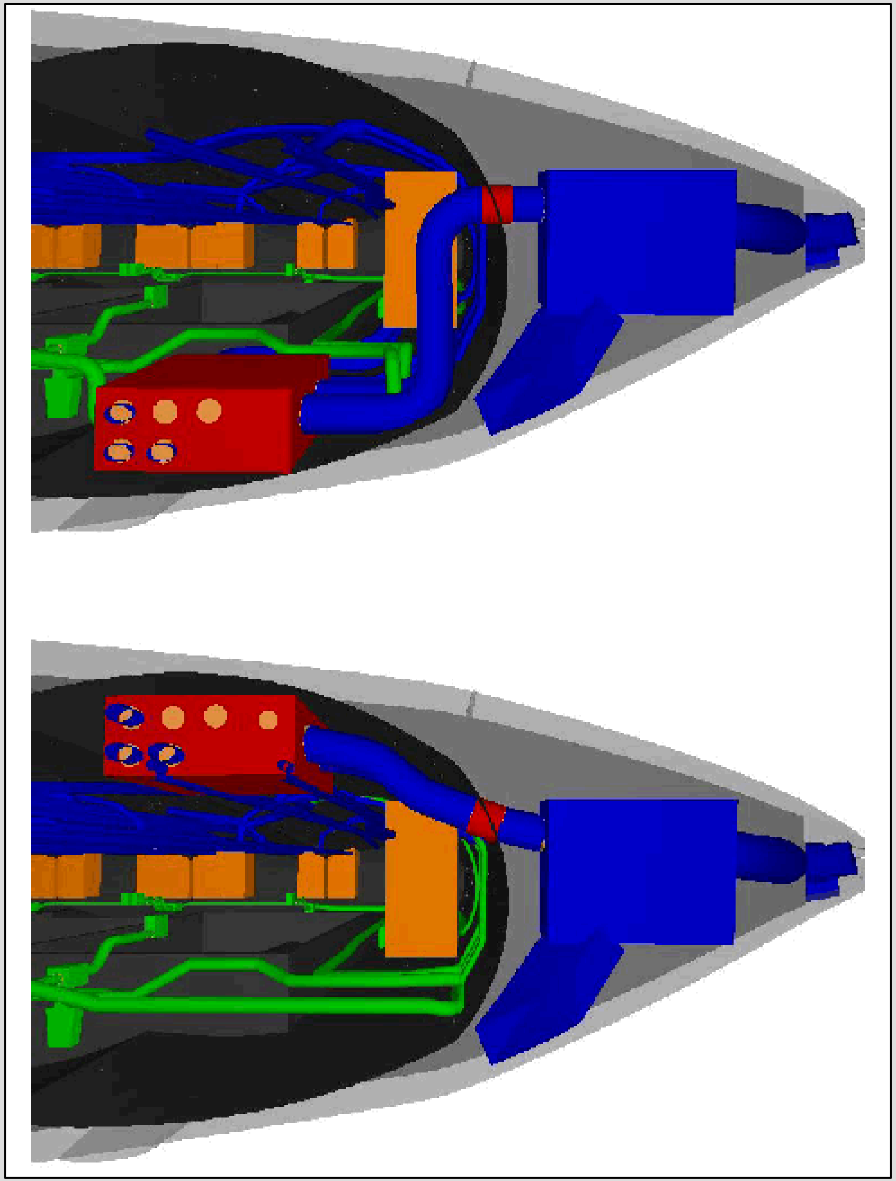
VELA 2 - System Installation Areas

Steps in system integration:

1.) System diagram

2.) Sizing

3.) Routing & ducting



VELA 2 - ATA 21 - Positioning of the Mixing Unit

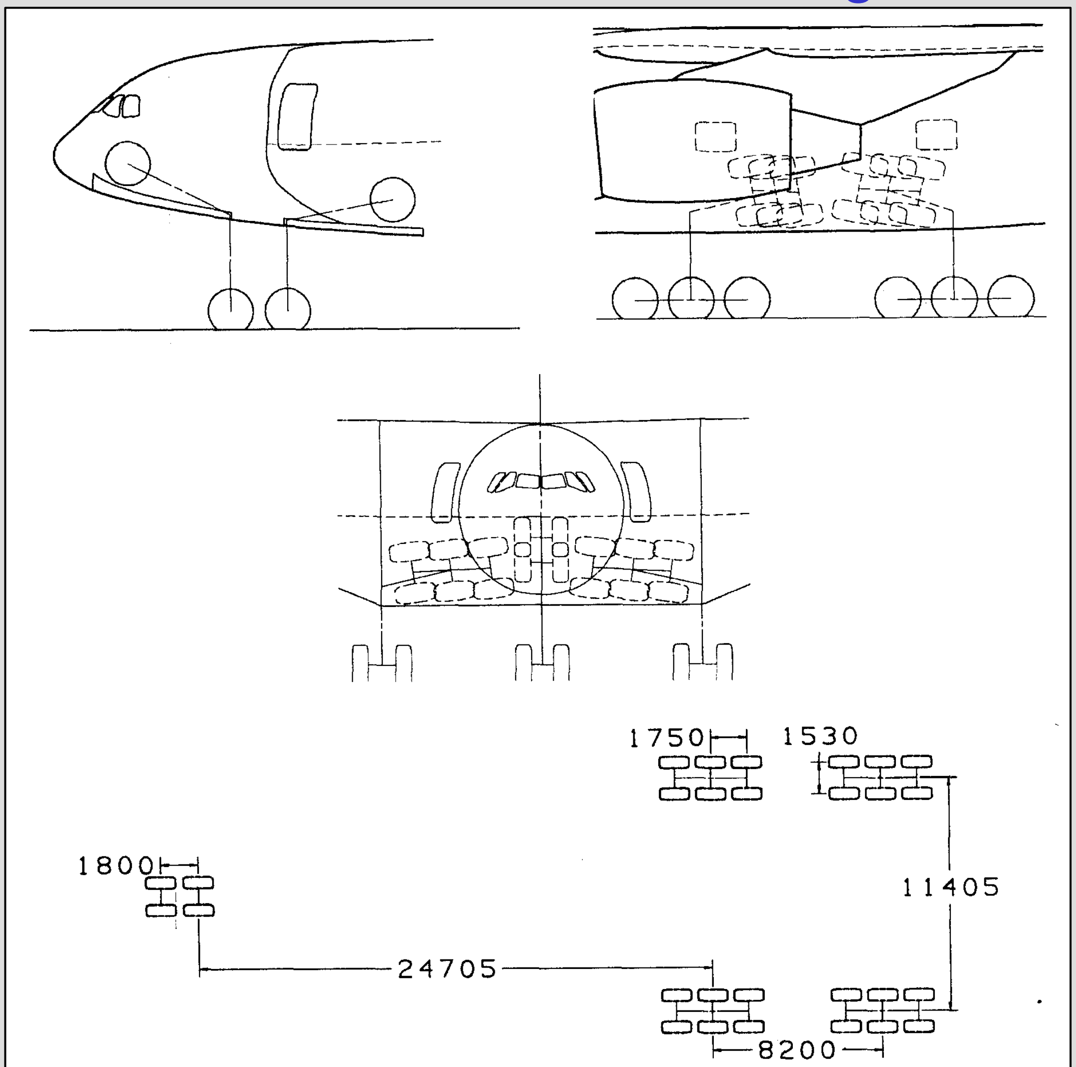
Steps in system integration:
1.) System diagram
2.) Sizing
3.) Routing & ducting

Air Generation Unit is positioned in the transition wing.

Alternative position (above cabin) of the Mixing Unit eliminates riser ducts.

Ducts for recirculation air.

VELA 3 - Landing Gear Integration



Twin tandem (Bogie) nose landing gear.
Two retraction mechanisms.

Two twin tri-tandem (6-wheel) main landing gears on each side.
Special retraction mechanism.

MLG wheel spacing only 11.4 m due to rib location (requirement:
wheel spacing < 16 m)

Rule of Thumb: 30 t / MLG wheel
=> max. MTOW: 720 t

Air Transport System

Ground Handling

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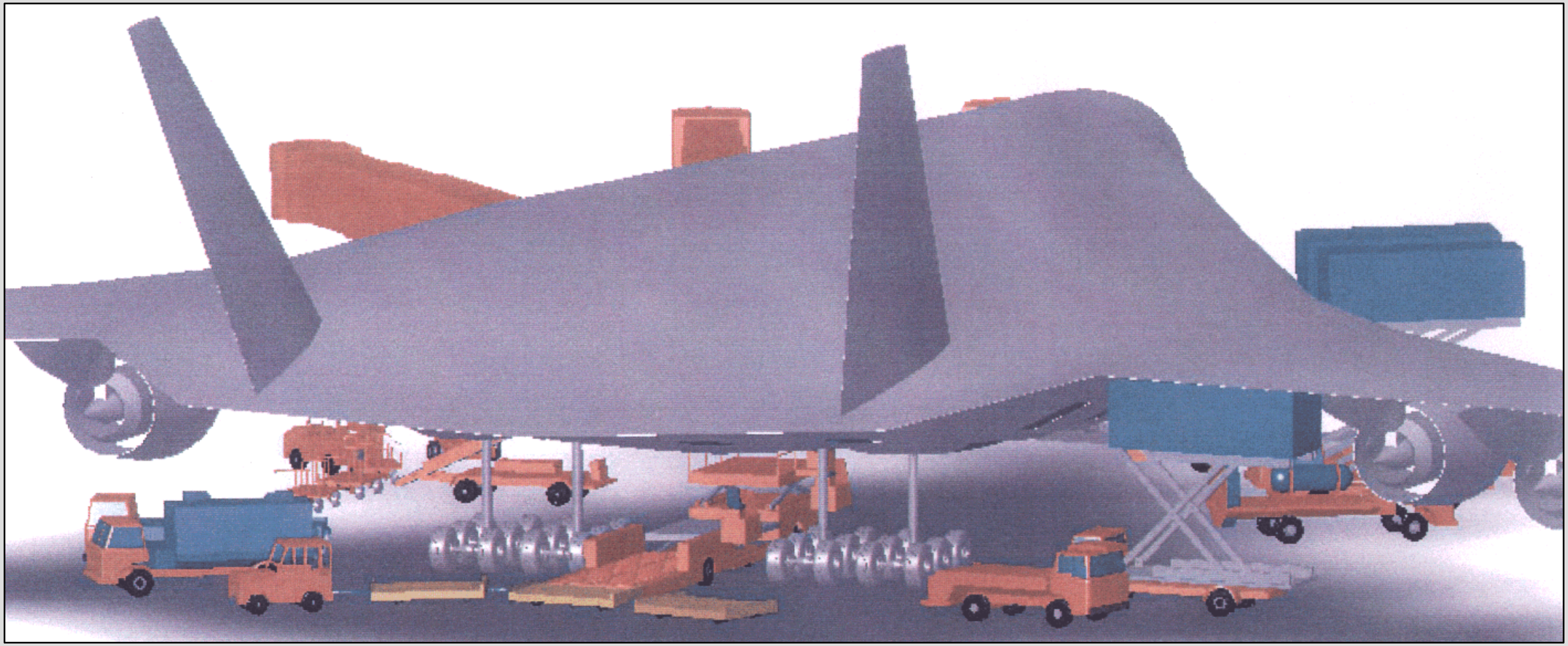
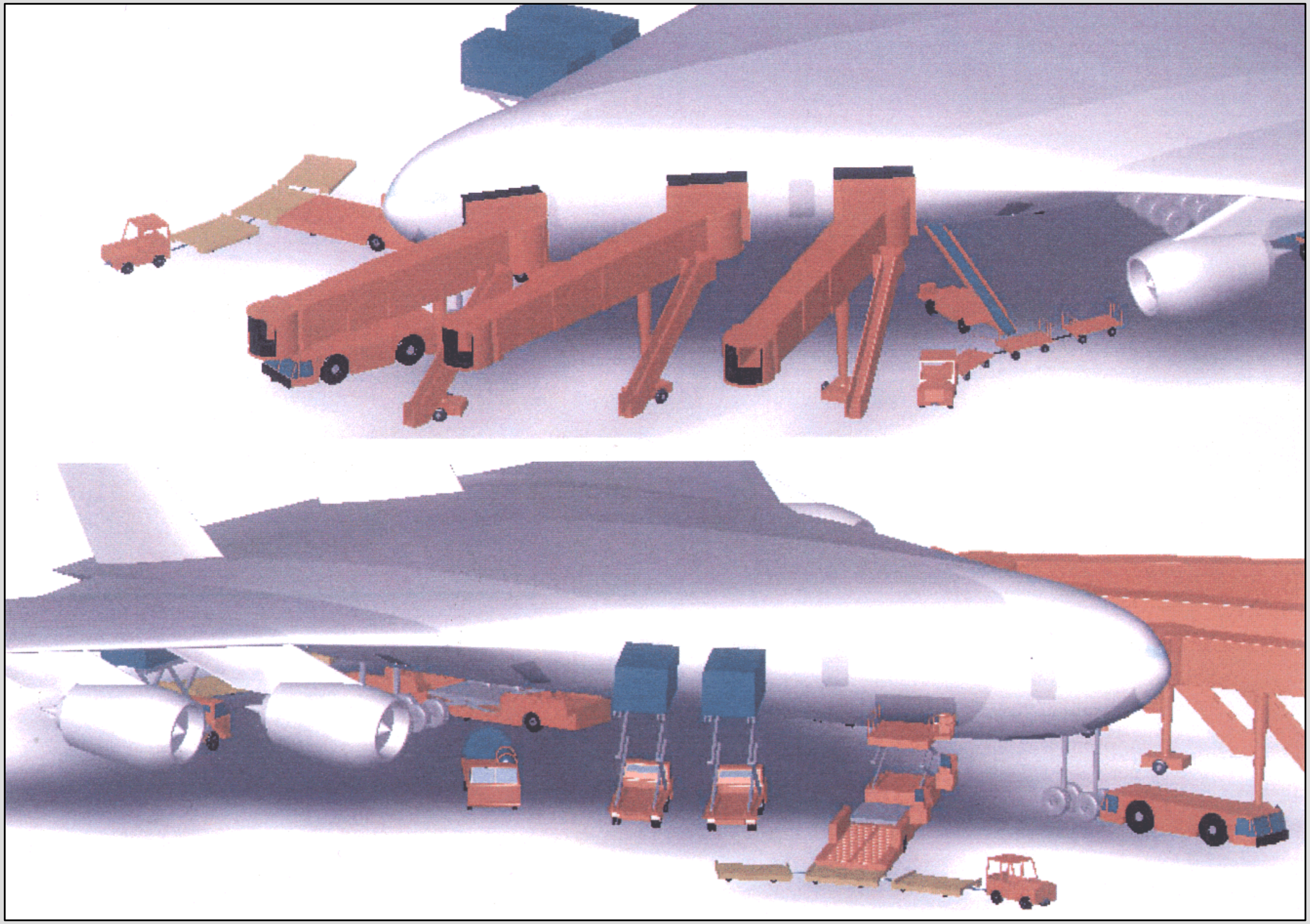
VELA 3



A cargo loading vehicle drives in between the MLGs. Cargo loading from below with lifting system.
Catering from the right.

Water / waste servicing on trailing edge left side.

VELA 2



Cargo loading from the right.

Catering from the right.

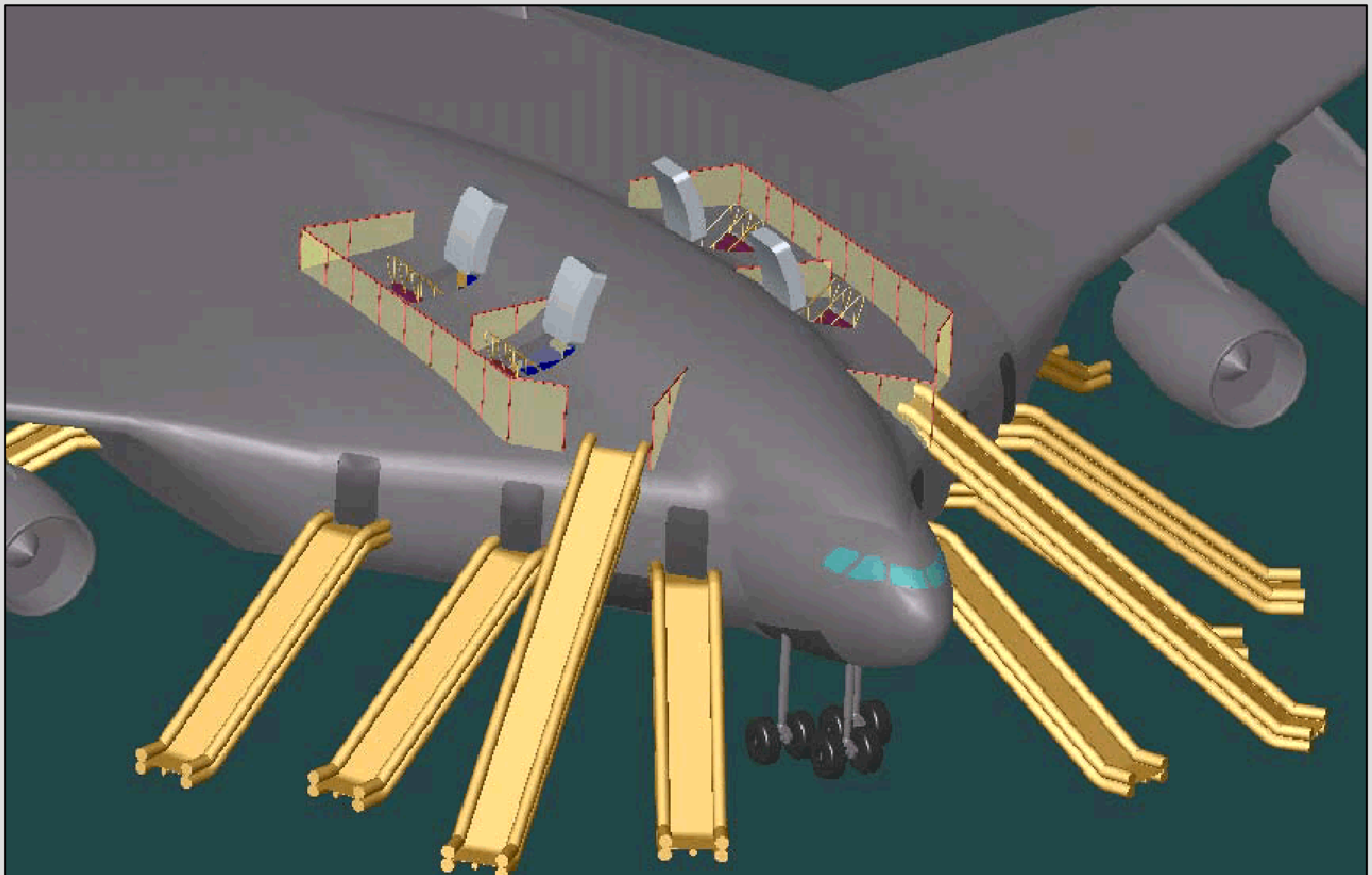
Boarding through three bridges.

Fuel truck under right wing.

Towing truck.

Not shown: Electrical ground power unit, air starting unit, air conditioning vehicle, water service truck, lavatory service truck.

VELA 1 - Emergency Evacuation - Slides - Ditching



Slides on forward doors.

This modification of VELA 1 allows also evacuation after ditching (into the water) through over wing doors.

VELA 1, 2, 3 standard configuration can not be certified, because doors will be submerged.

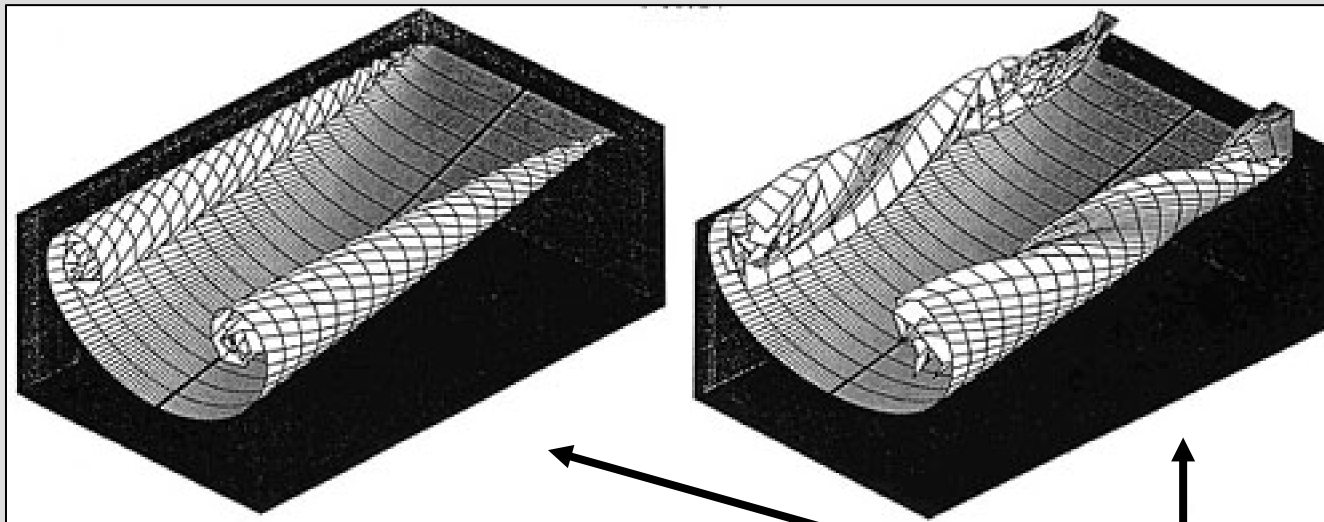
Wake Turbulence - Fundamentals

Wing tip vortices cause induced drag, D_i .

Wake turbulence cause a danger to following aircraft.

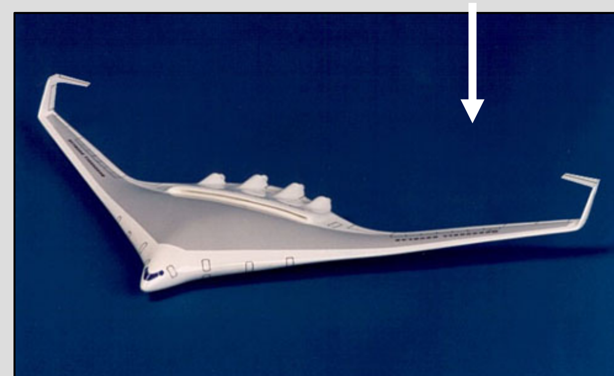
The initial strength of the wake turbulence is based on basic aircraft parameters:

$$P_{wake} = D_i V = \frac{2g^2}{\pi A e} \frac{m(m/S)}{\rho V}$$



Decay of wake turbulence from a conventional wing and a C-wing.

C-Wing-BWB:



Wake Turbulence - Comparison

$$\frac{P_{wake,BWB}}{P_{wake,A380}} \approx \frac{A_{A380}}{A_{BWB}} \cdot \frac{m_{MTO,BWB}}{m_{MTO,A380}} \cdot \frac{(m/S)_{BWB}}{(m/S)_{A380}} = \frac{7.53}{4.83} \cdot \frac{700}{560} \cdot \frac{341}{663} = 1.00$$

with BWB-Data from VELA 3. Result: no major problems expected.

Interior Design

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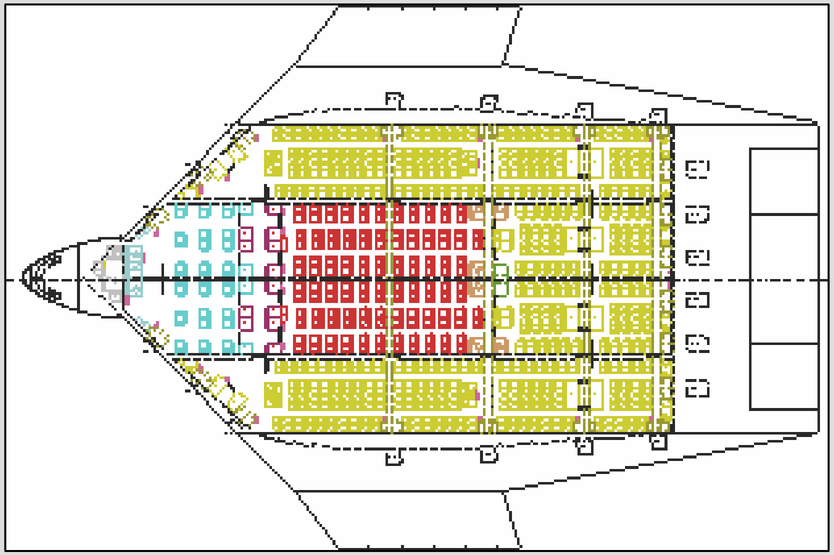
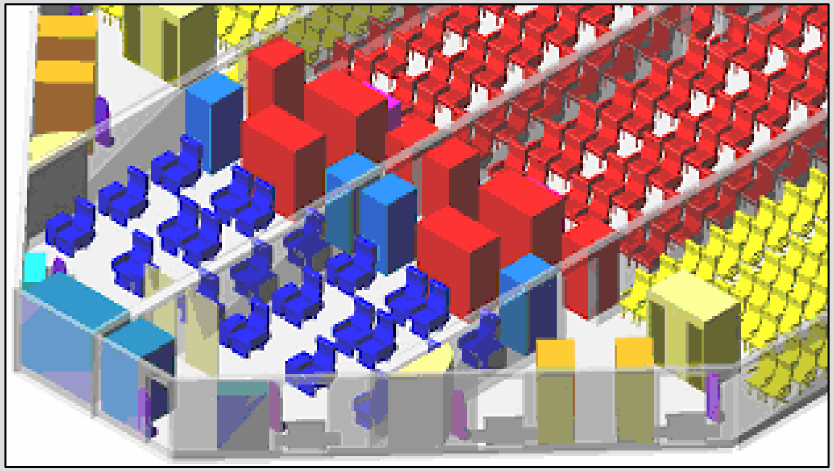
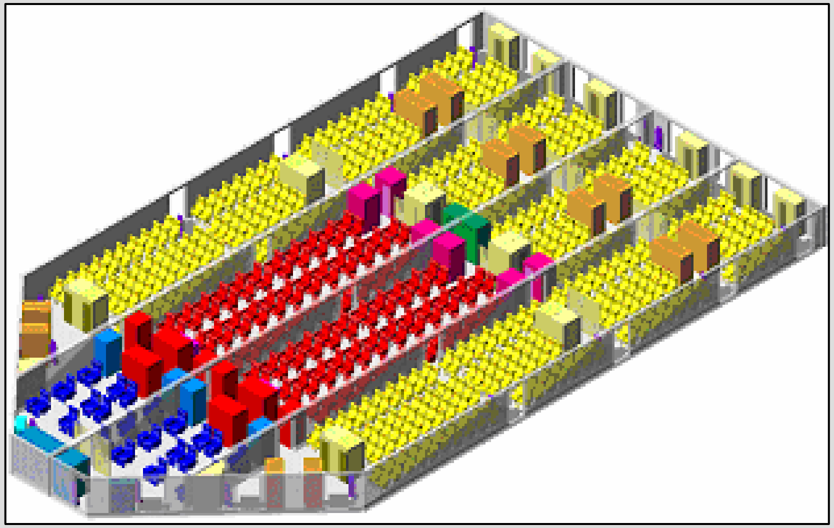
VELA 1 - Cabin Layout

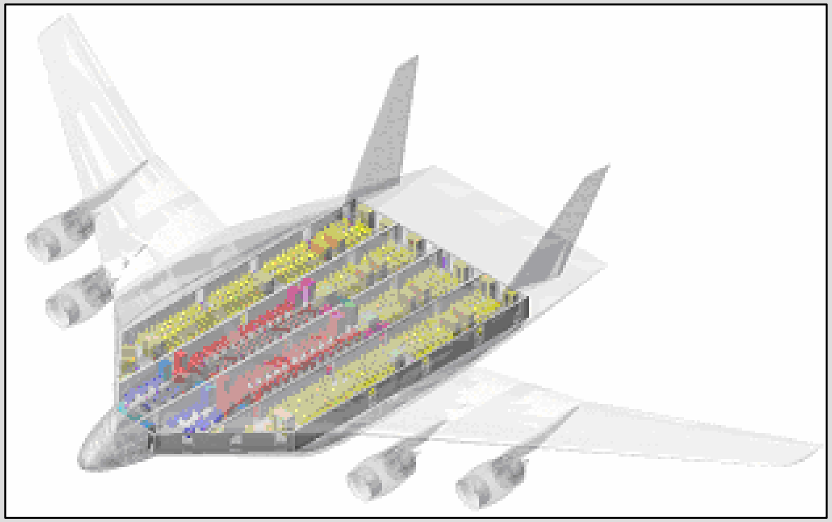
Diplomarbeit: S. Lee



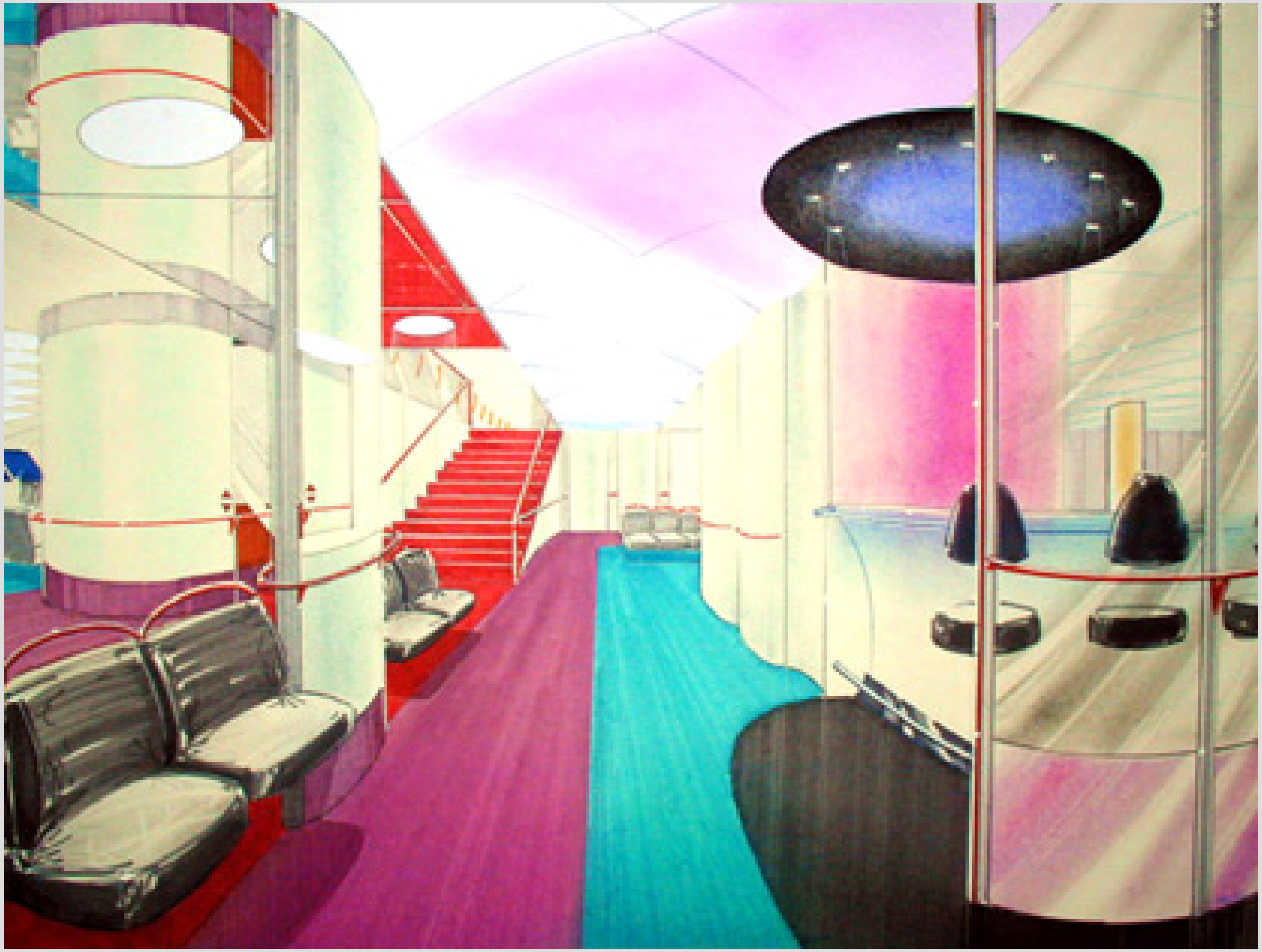
Vertical acceleration for pax on outer seats.



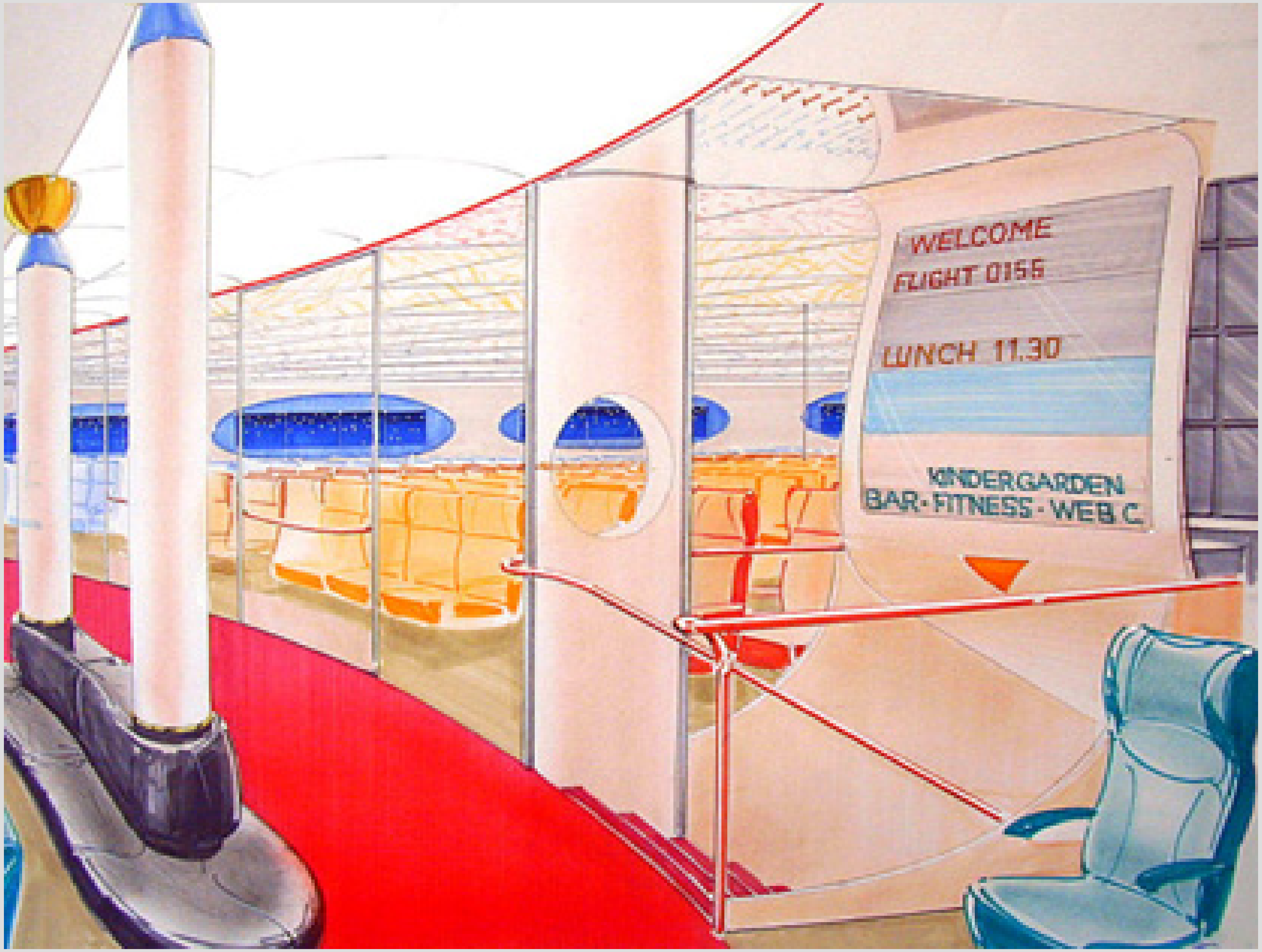




Double Deck BWB



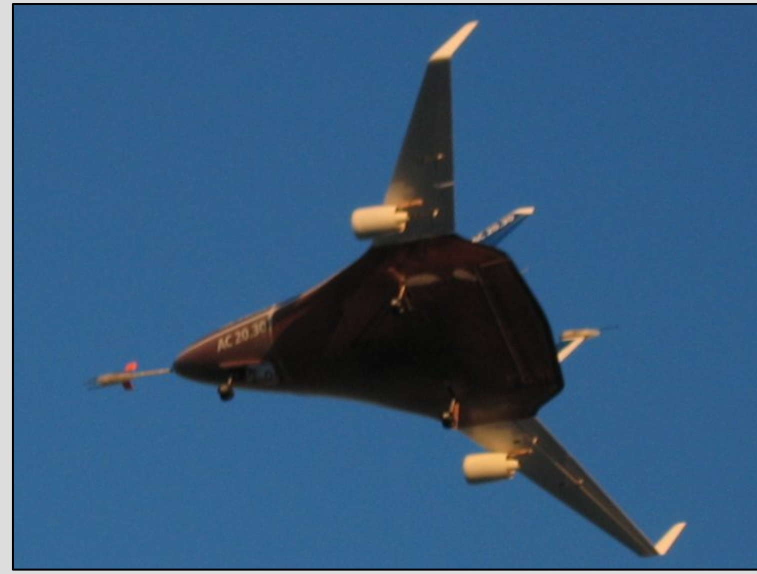
Underfloor Usage - Artificial Windows



BWB Center Wing Shapes from Inside

AC20.30

Test Flights



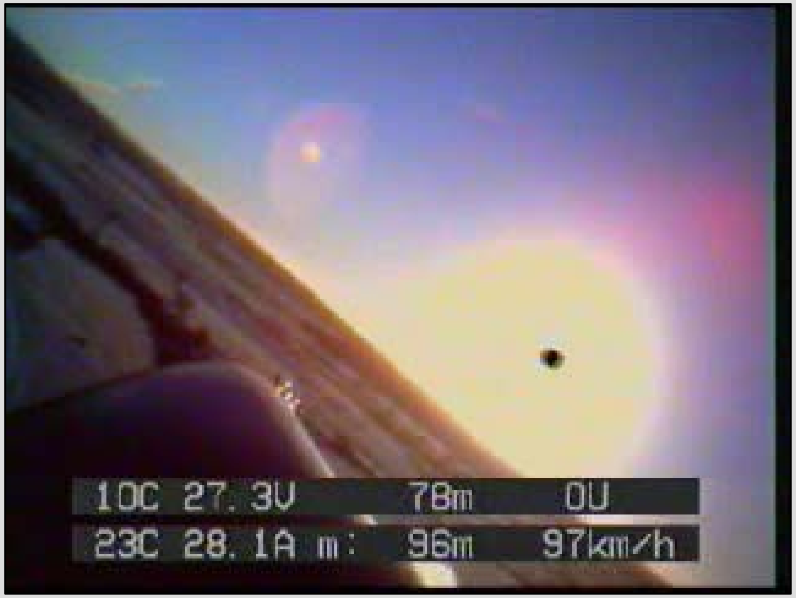
AC20.30 Parameters

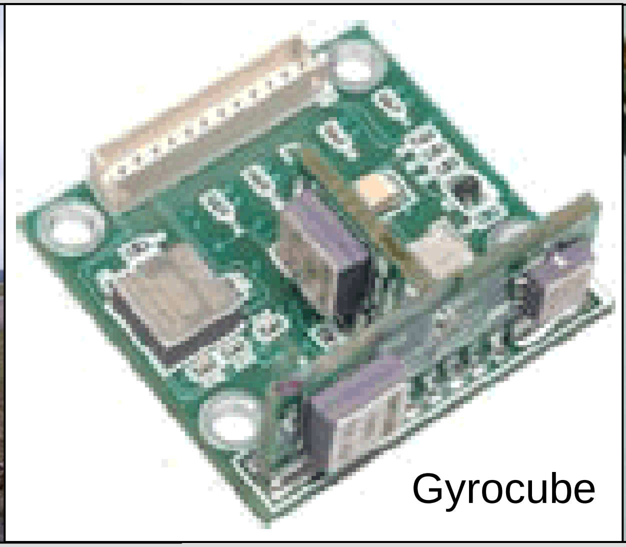
Scale	1:30
Span	3.24 m
Length	2.12 m
MTOW	12.5 kg
Engines	2 electric driven fans
Thrust	2 x 30 N
Power input	2 x 1400 W

AC20.30

Test Flights

Recorded Parameters
barometric height, two temperatures
voltage, current
air speed, engine RPM
GPS-Coordinates (=> position and ground speed)
angle of attack, side slip angle
3 accelerations, 3 rotational speeds
position of 4 control surfaces
turn coordinator, ping, aerborne camera picture




Gyrocube

AC20.30 Flight Test

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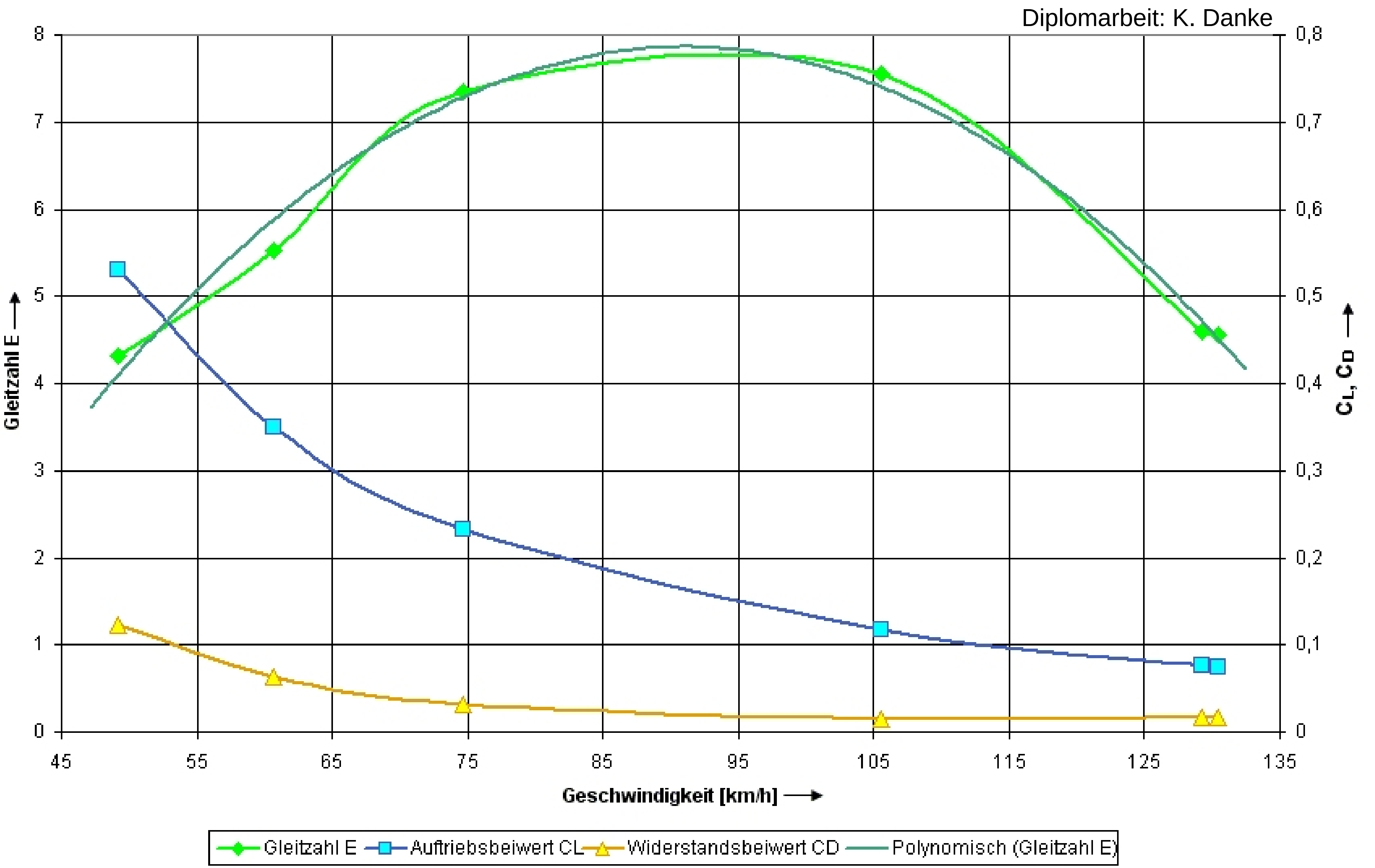

Euler Angles form Test Flights with "Gyrocube"

$$U = V_T \cos\beta \cos\alpha$$

$$V = V_T \sin\beta$$

$$W = V_T \cos\beta \sin\alpha$$

$$a_x = \dot{U} + QW - RV + g\sin\Theta$$ ← solved for pitch angle, Θ

$$a_y = \dot{V} + RU - PW - g\cos\Theta\sin\Phi$$ ← solved for roll angle, Φ

$$a_z = \dot{W} + PV - QU - g\cos\Theta\cos\Phi$$ ← check results

Experience with Measurement Technique:

Simple and inexpensive method.

Drift problems are unknown.

Good results only for manoeuvres with moderate dynamic.

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Wind Tunnel Tests

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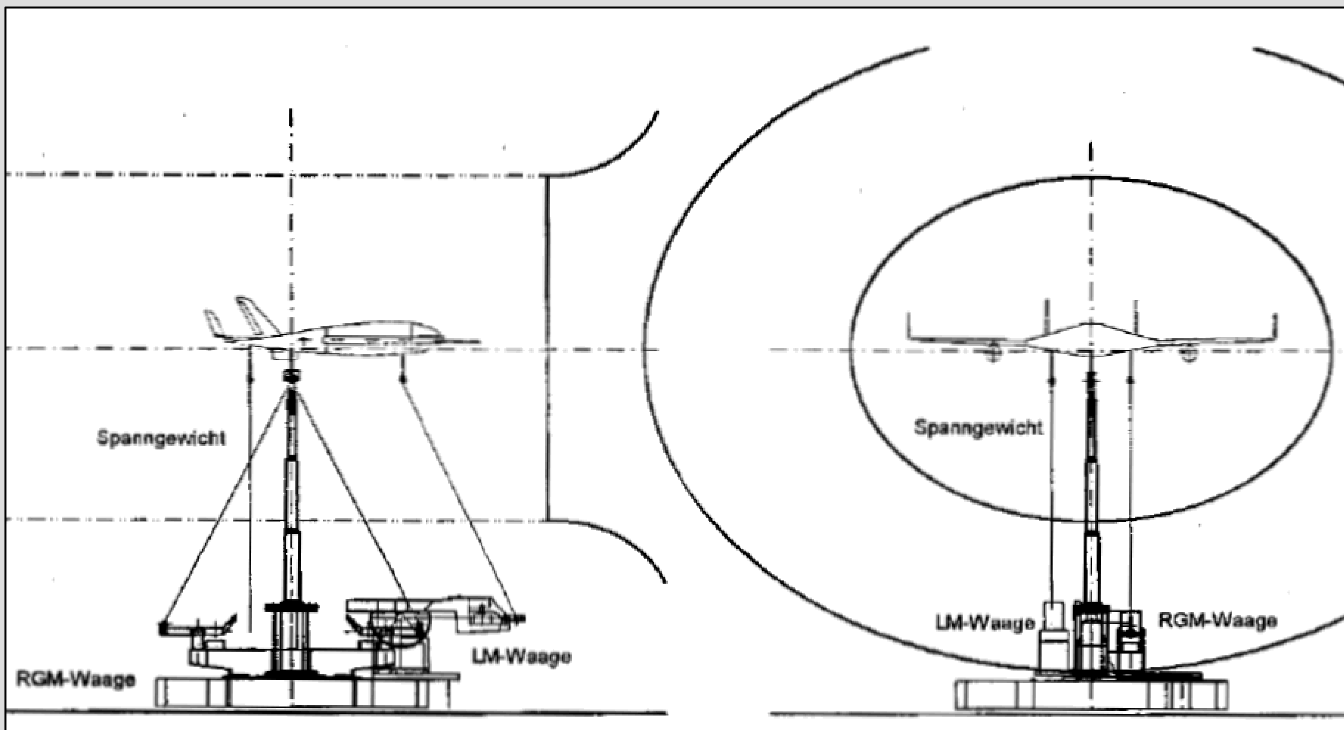

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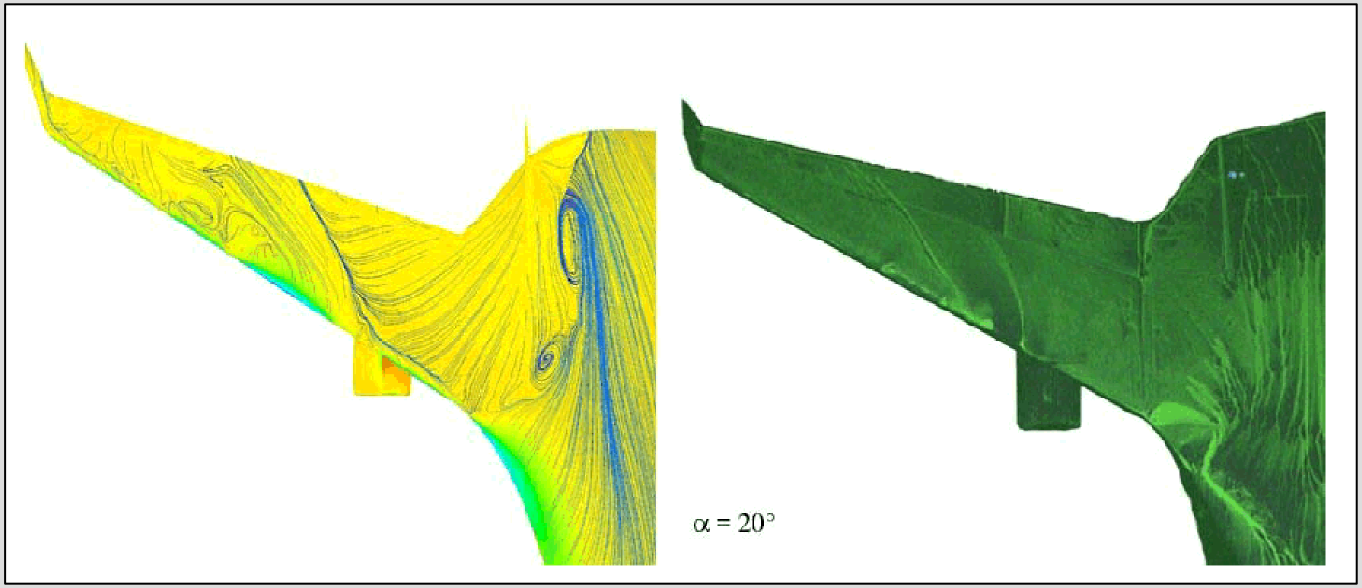
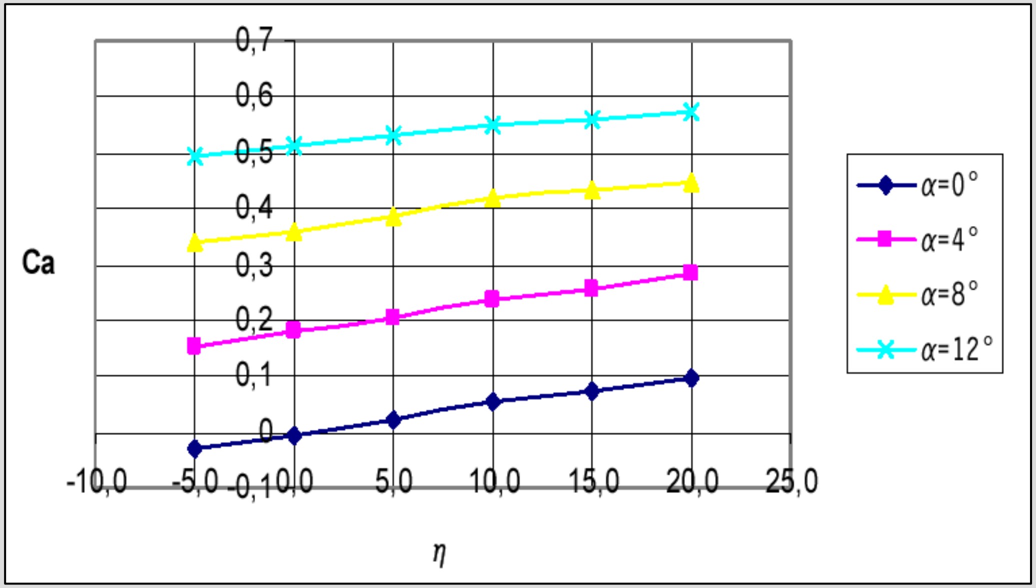


CFD surface stream lines (left)
Fluorescend paint in wind tunnel (right).



Lift coefficient dependend on flap angle (wing) and angle of attack.

Summary

Summary

BWB advantages compared to todays advanced aircraft

reduction in weight :	single shell required than: 8% better
better L/D :	10 to 15% better (not apparent from AC20.30)
reduction in fuel consumption :	yes, due to L/D
reduction in emissions :	yes
reduction in noise :	only with engines on top
increase of airport capacity :	yes, more than 750 pax per A/C (probably no problems with wake turbulence)
reduction in DOC :	down ??% (mostly due to scale effect)

But:

open certification problems :	unstable configuration (?), ditching
open design problems :	rotation on take-off, landing gear integration, ...

The End