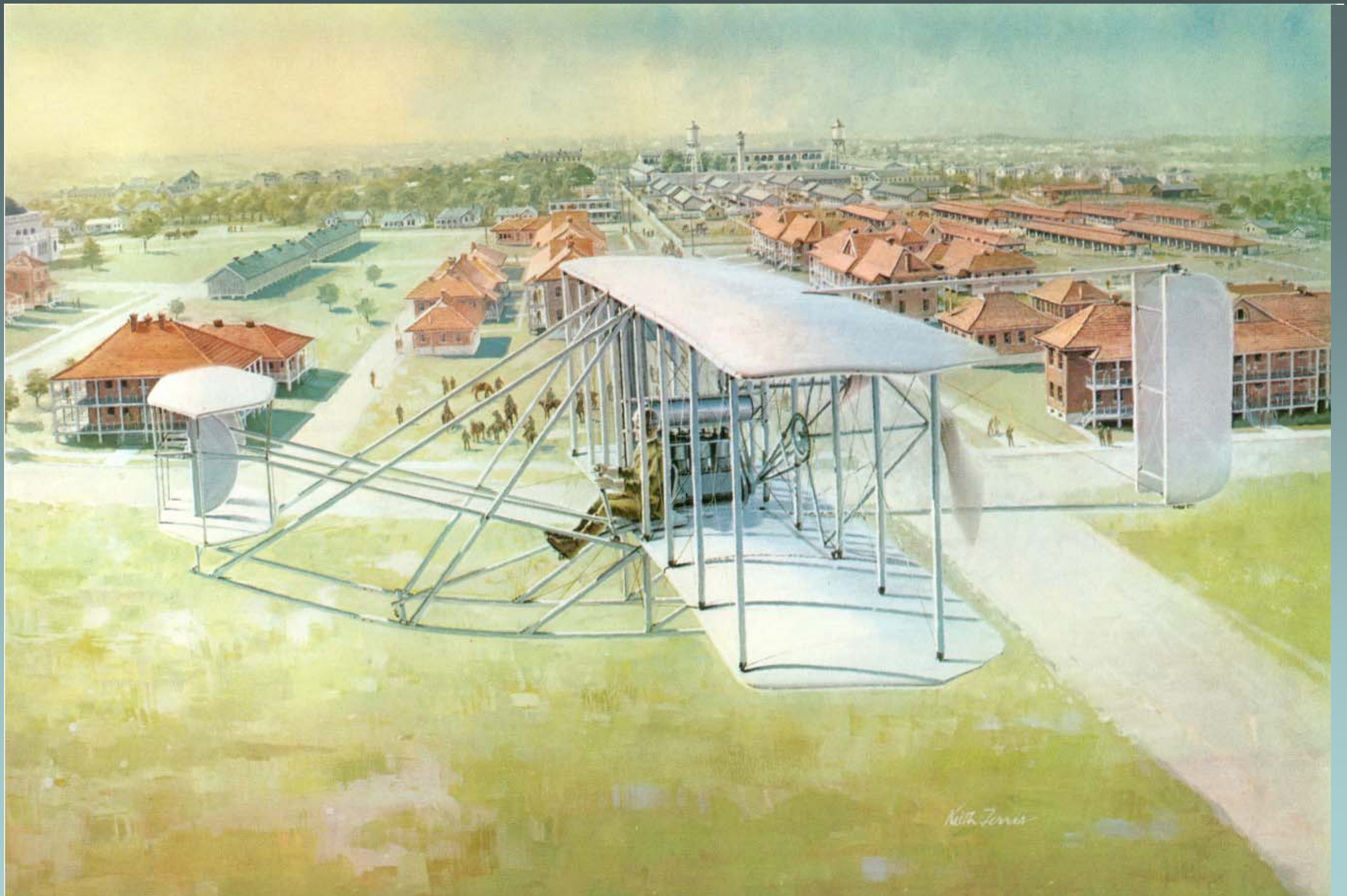
BLENDED WING BODY AND ALL-WING AIRLINERS

EGBERT TORENBEEK

European Workshop on Aircraft Design Education
(EWADE)
Samara, Russia, May/June 200

WRIGHT TYPE A (1910)



PIAGGIO P-180 AVANTI (1986)

THE DOMINANT GENERAL ARRANGEMENT

BOEING 707 (1954)

DREAMLINER

BOEING 787 (2007)

EFFICIENCY OF FUEL ENERGY CONVERSION

Seat-kilometer per liter fuel: $$\frac{H\ \eta\ L/D}{W_{to}\ /\ N}$$

H - fuel heating value per liter

η - efficiency of energy conversion

L/D - glide ratio

W_{to}/N - aircraft all-up weight per seat

MAIN CONFIGURATION CHOICES

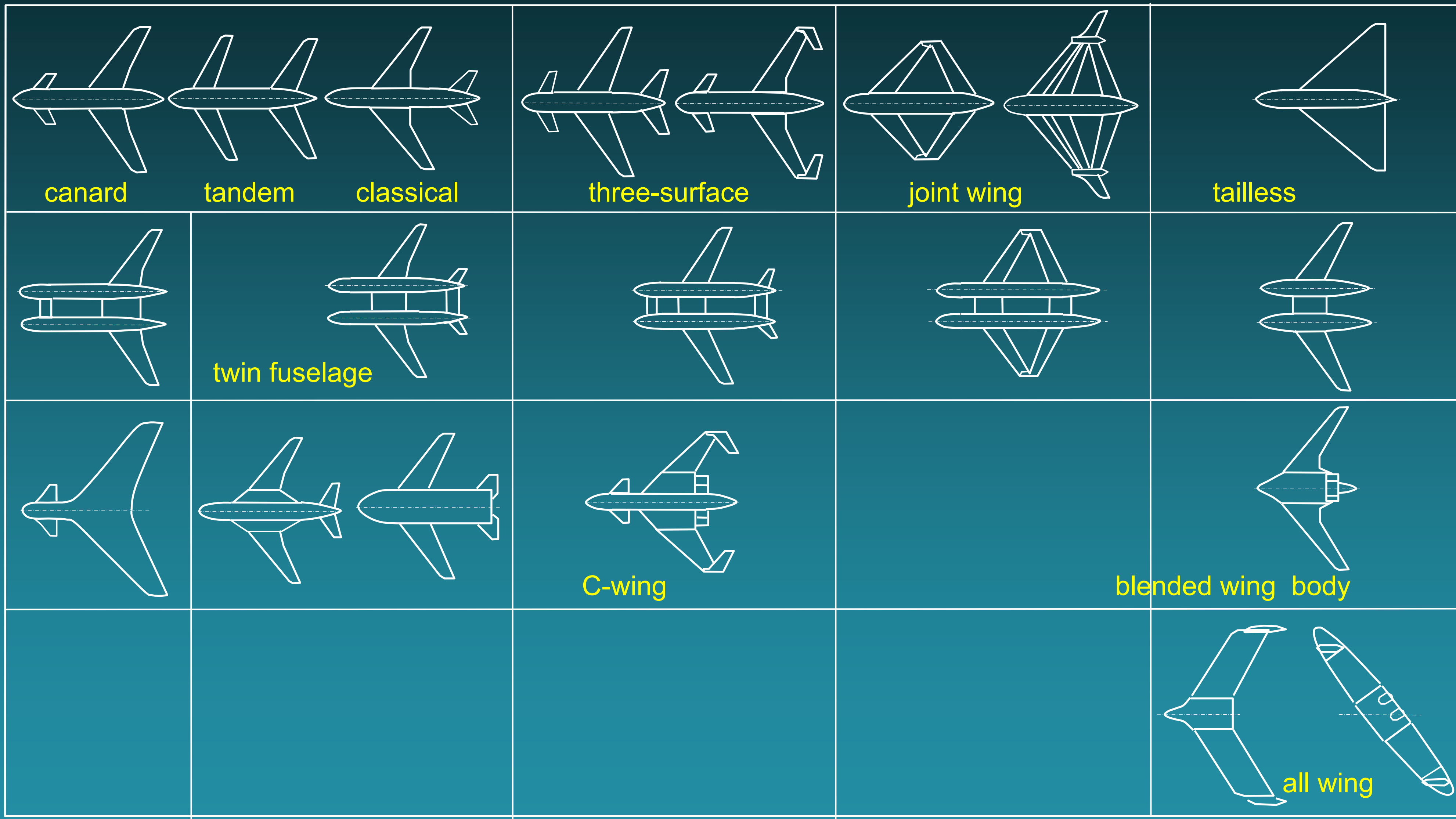
PRIMARY

- NUMBER AND LONGITUDINAL DISPOSITION OF LIFTING SURFACES
- ALLOCATION OF USEFUL VOLUME (PAYLOAD, FUEL) IN WING AND FUSELAGE(S)
- PROPULSION SYSTEM CLASS (TURBOFAN, TURBOPROP, DUCTED ROTOR)

SECONDARY

- VERTICAL DISPOSITION OF LIFTING SURFACES
- LOCATION OF ENGINES

CONFIGURATION MATRIX

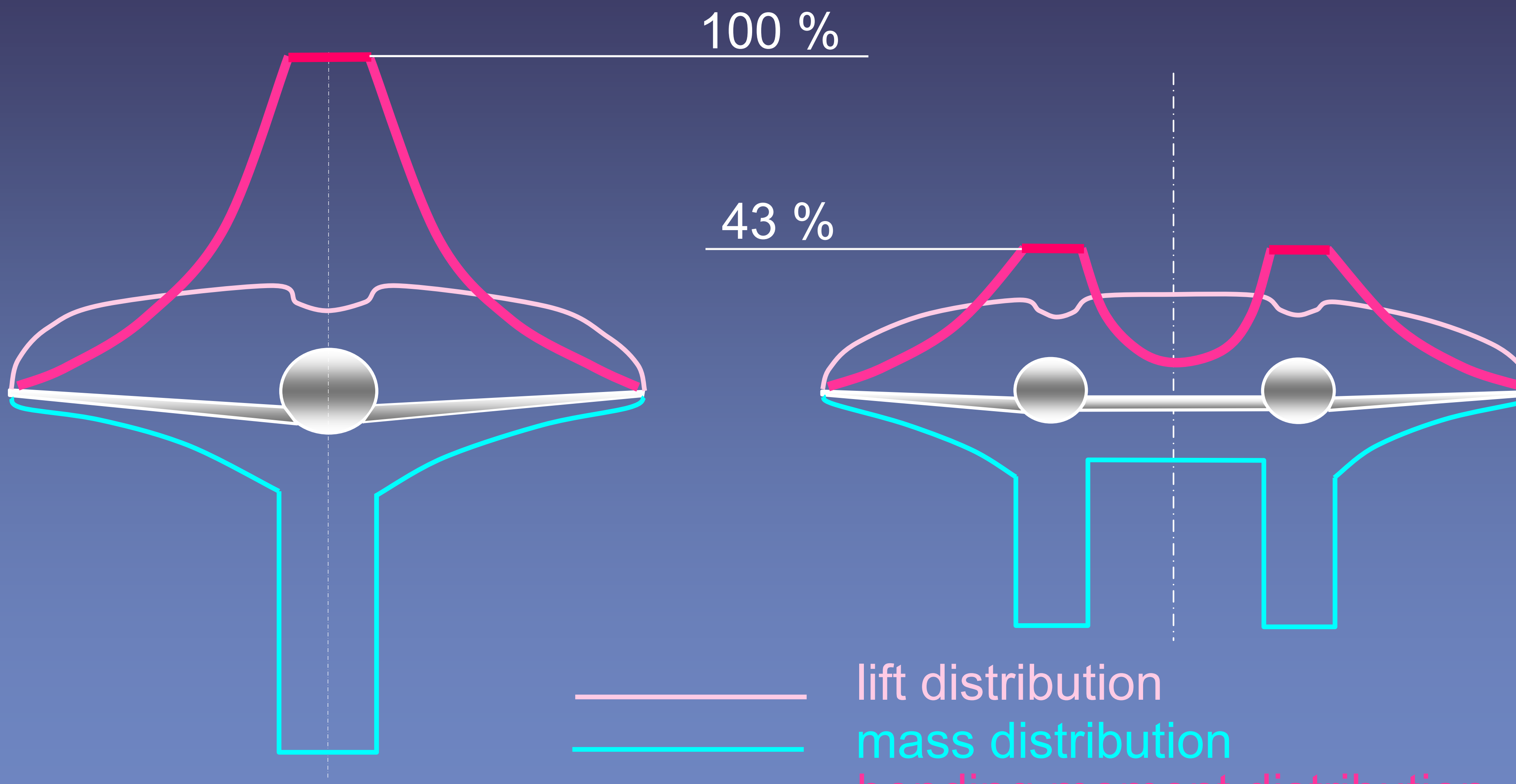


DASA (modified)

AIRBUS 350 SUCCESSOR?

ADSE/TORENBEEK (2002)

SINGLE AND TWIN FUSELAGE WING BENDING



TWIN FUSELAGE WEIGHT REDUCTIONS

Design mass, kg	conventional	twin-fuselage	Δ %
MTOW	155,000	134,000	-13.5
MLW	128,000	113,000	-11.7
MZFW	120,000	106,000	-11.7
OEW	84,000	70,000	-16.7
Payload (structural limit)	36,000	36,000	0
Block fuel for 8,000 km	40,715	34,245	-15.9
Installed thrust, kN	2x222.5	2x178.0	-20.0

AERODYNAMIC EFFICIENCY

$$(L/D)_{max} = \frac{1}{2}\frac{b}{\sqrt{S_{wet}}}\sqrt{\frac{\pi e}{C_{D_{wet}}}} = \frac{1}{2}\sqrt{\frac{\pi Ae}{(C_D S)_{wet}/S}}$$

b - wing span

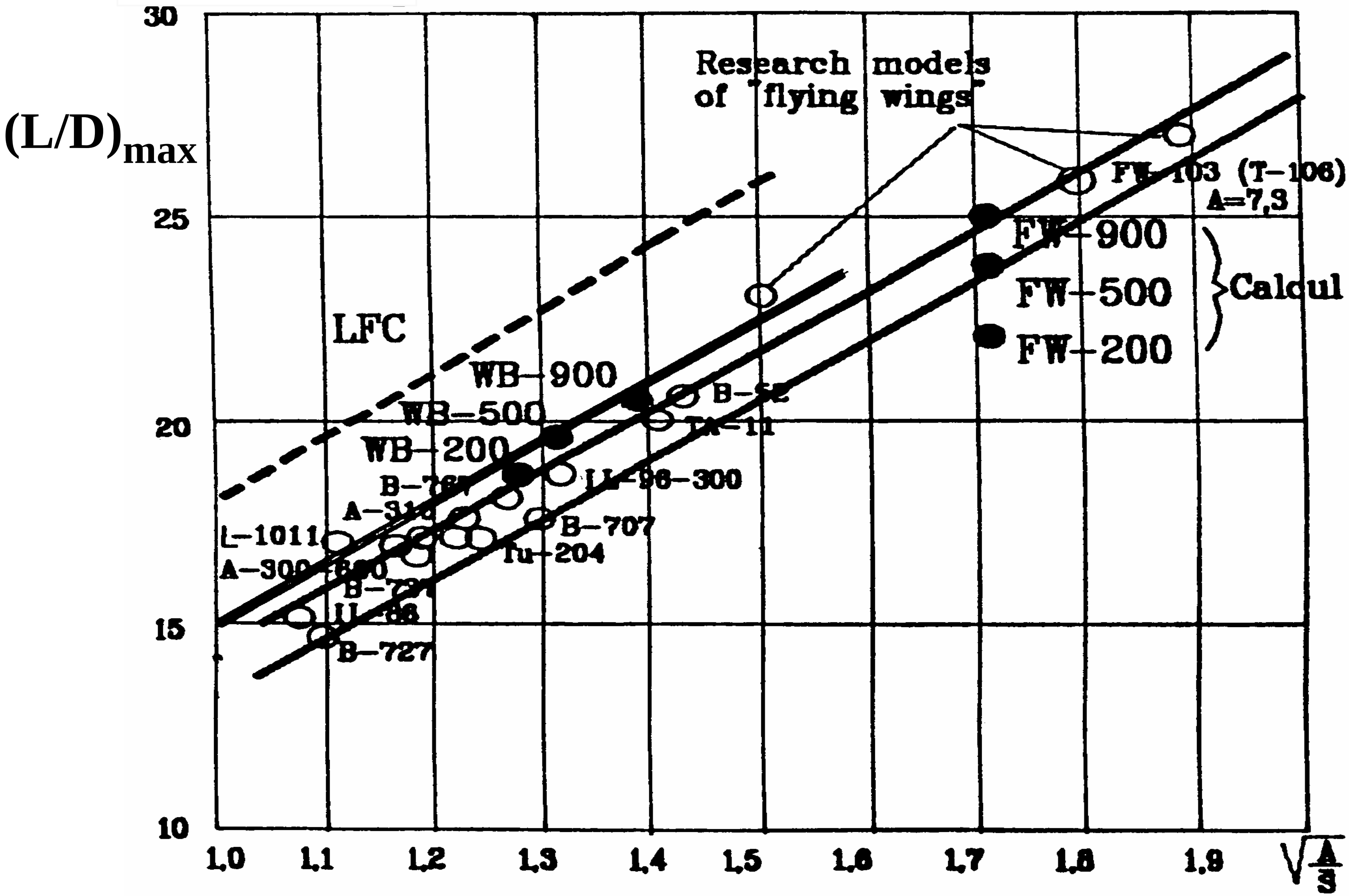
e - Oswald's span efficiency factor

S_{wet} - total surface area exposed to flow

$C_{D_{wet}}$ - profile and parasitic drag coefficient based on S_{wet}

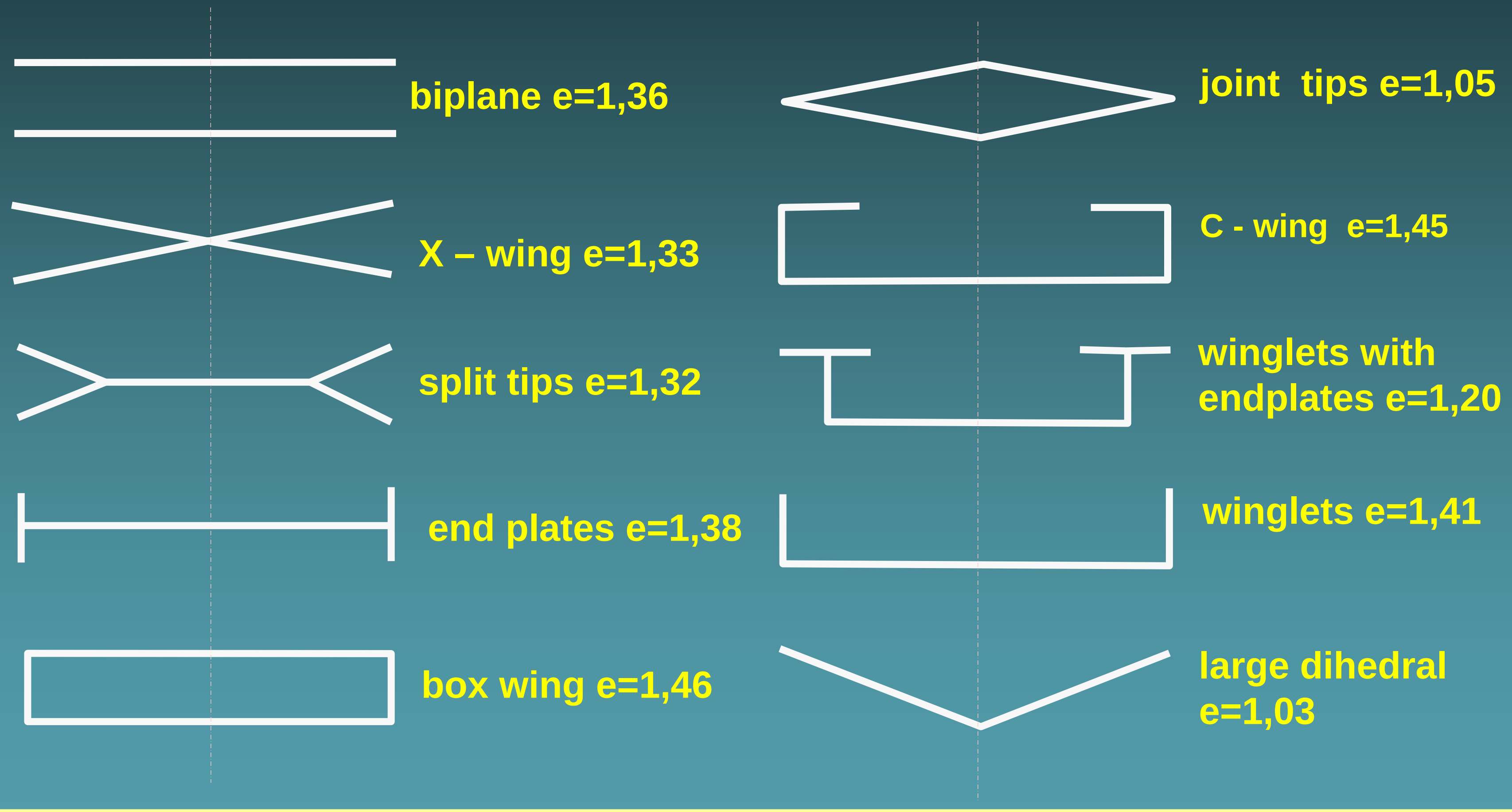
AERODYNAMIC EFFICIENCY

TsAGI INFORMATION



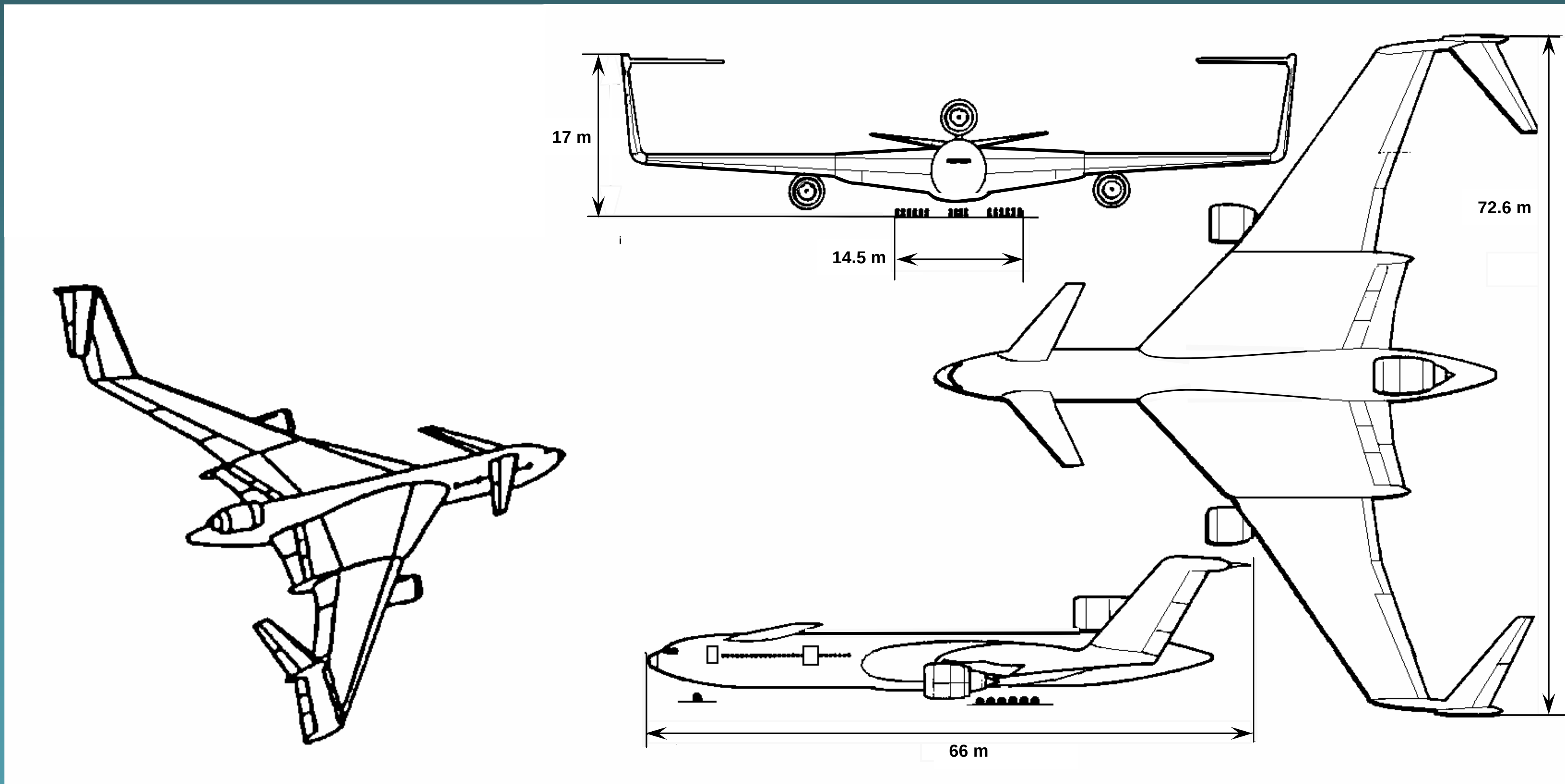
WING SHAPE AND SPAN EFFICIENCY

e $\equiv$ span efficiency factor for induced drag



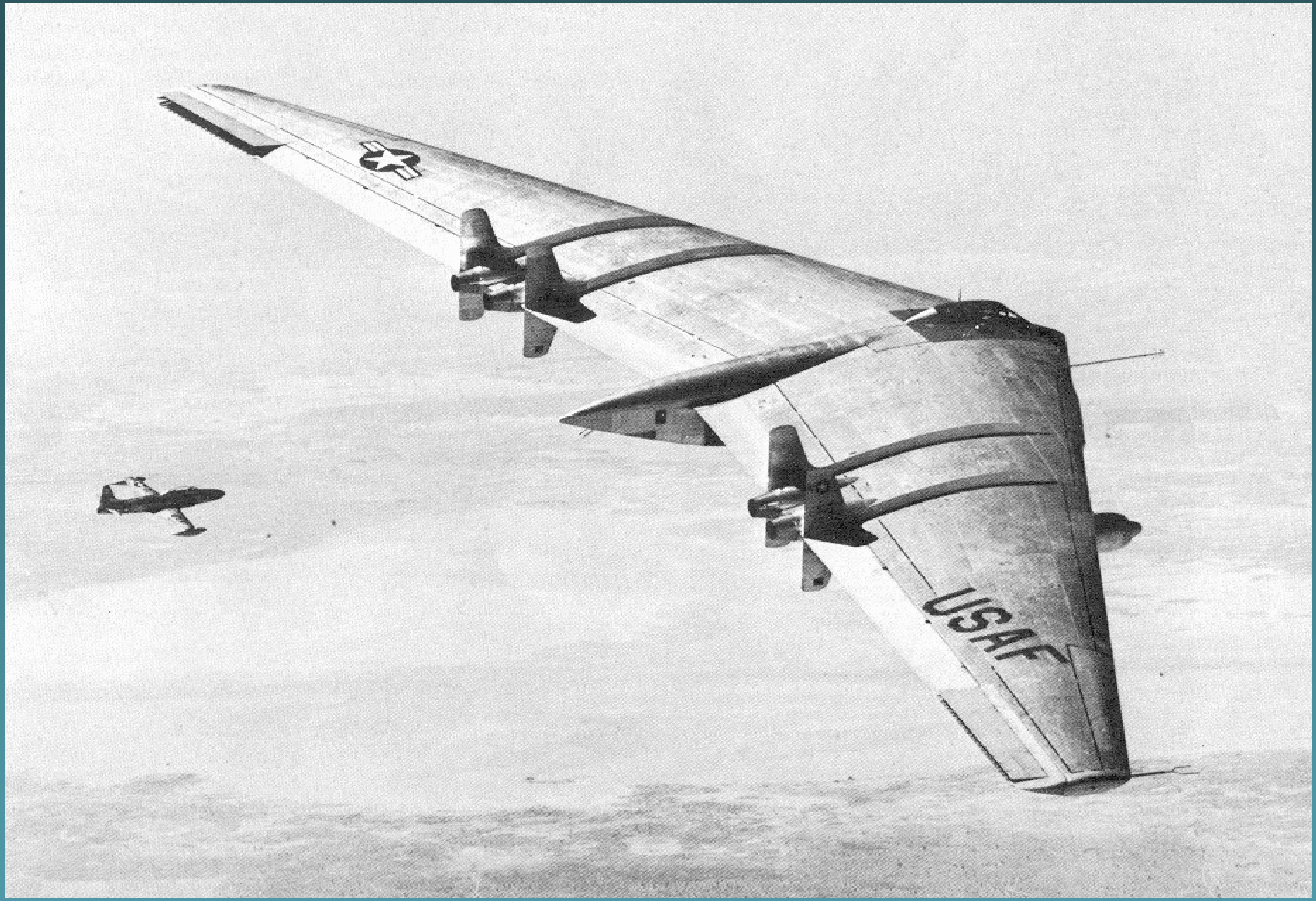
rear view

BOEING C-WING



LOCKHEED BOX WING

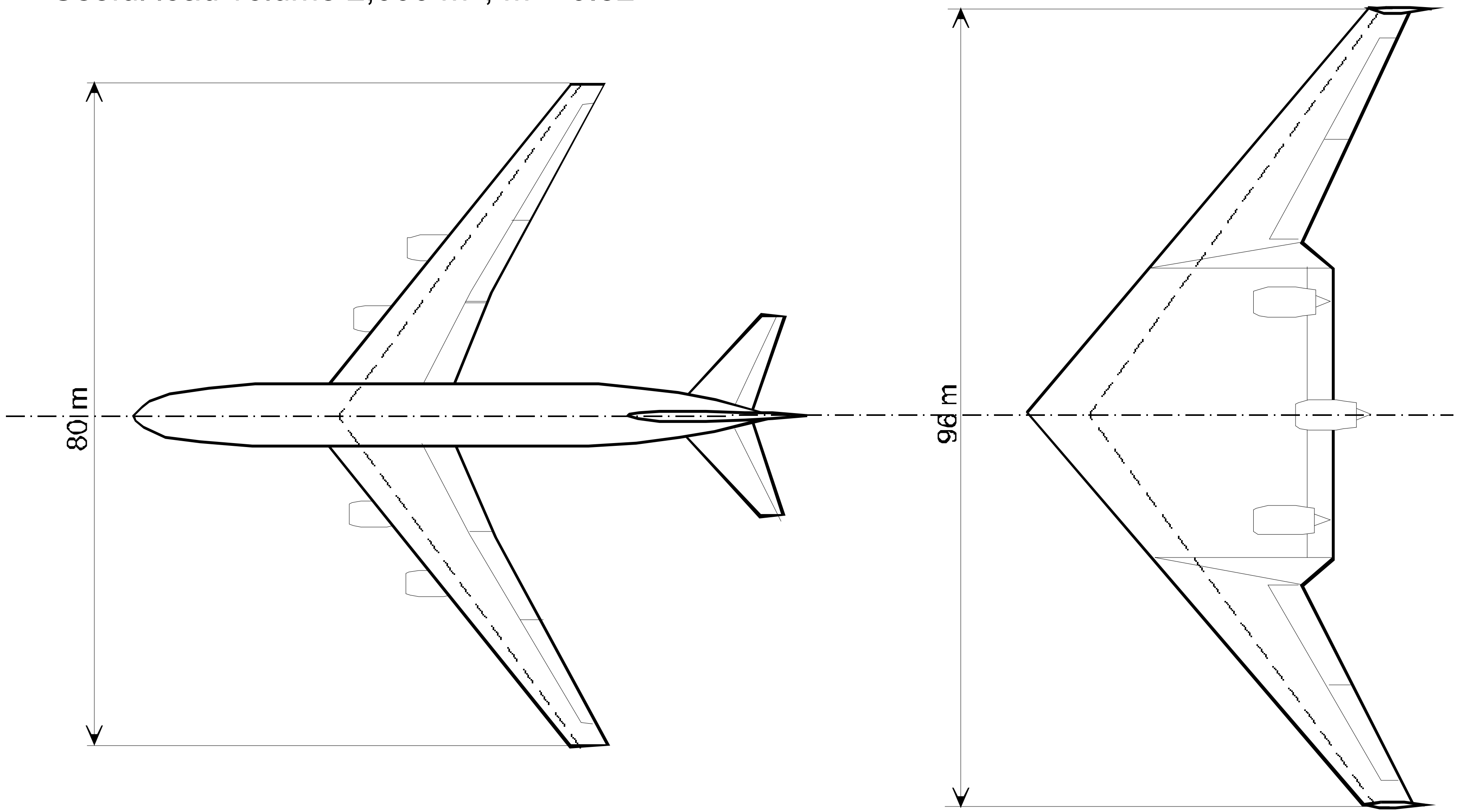
NORTRHOP YRB - 49A (1950)



It has long been recognized that the flying wing, when jet propelled, is a poor choice for an aircraft configuration intended to achieve long range (J.V.Foa 1984)

CONVENTIONAL AND FLYING WING COMPARED

Useful load volume 2,000 m^3, M = 0.82



Conventional configuration, $(L/D)_{max}$=20.6

Flying wing, $(L/D)_{max}$=25.7

WING PLUS BODY COMBINATIONS WITH THE SAME TOTAL VOLUME

WING ASPECT RATIO 8

$$\frac{\text{WING VOLUME}}{\text{TOTAL VOLUME}} \downarrow$$

0.15

0.25

0.50

0.75

0.85

BASIC ASSUMPTIONS

- WING / BODY COMBINATIONS ARE COMPARED FOR CONSTANT TOTAL USEFUL VOLUME AND WEIGHT
- AERODYNAMIC PERFORMANCE IN CRUISING FLIGHT IS USED AS FIGURE OF MERIT TO COMPARE DIFFERENT VOLUME ALLOCATIONS
- DRAG DUE TO TAILPLANES, INTERFERENCE, ROUGHNESS, AND EXCRESCENCES ARE ACCOUNTED FOR BY MULTIPLICATION FACTORS
- POWERPLANT INSTALLATION DRAG IS ACCOUNTED AS A REDUCTION OF INSTALLED THRUST

DEFINITIONS

VOLUME ALLOTMENT RATIO X

$$X = \frac{\text{USEFUL VOLUME INSIDE WING}}{\text{TOTAL USEFUL VOLUME}} = \frac{Q_w}{Q_{tot}}$$

BODY VOLUME:

$$Q_b = (1 - X)\, Q_{tot} = \left(\frac{1}{X} - 1\right) Q_w \quad ; \quad 0 < X \leq 1$$

FLYING WING, THEORETICALLY: $X = 1$

APPROXIMATION FOR "WET" WINGS:

$$X \approx \frac{\text{VOLUME WING FUEL TANKS}}{\text{VOLUME (tanks + cabin + freighthold)}}$$

TYPICAL VALUES FOR CONVENTIONAL LONG-RANGE JET TRANSPORTS:

$X = 0.15$ TO 0.20

SHAPE FACTOR k_{bw}

$$k_{bw} = \frac{\bar{C}_{D_b}}{\bar{C}_{D_w}} \left(\frac{\eta_w}{\eta_b}\right)^{2/3}$$

b = BODY

w = WING

$$\bar{C}_D = \frac{\text{ZERO-LIFT DRAG AREA}}{(\text{ENCLOSED VOLUME})^{2/3}} = \frac{C_D\, S}{Q^{2/3}}$$

$$\eta_w, \eta_b = \frac{\text{(NET) USEFUL VOLUME}}{\text{(GROSS) ENCLOSED VOLUME}}$$

TYPICAL NUMERICAL VALUE: $k_{bw} = 1/4$ TO $1/3$

PHYSICAL MEANING:

$$k_{bw} = \frac{\text{BODY (PARASITE) DRAG}}{\text{WING (PROFILE) DRAG}} \quad \text{for } Q_w = Q_b$$

A wing has three to four times the drag of a fuselage with the same useful volume. This is due to the more favorable ratio of wetted area to volume for streamline bodies of revolution, compared to the two-dimensional wing.

GLIDE RATIO

$$\frac{C_D}{C_L} = \frac{C_{D_p}}{C_L}\left[1 + k_{bw}\left(\frac{1}{X} - 1\right)^{2/3}\right] + \beta C_L$$

WHERE C_{D_p} = WING PROFILE DRAG COEFFICIENT

$\beta = d\, C_D/d(C_L{}^2)$

FOR GIVEN	* ALL-UP WEIGHT	W
	* DYNAMIC PRESSURE	$q = 1/2\gamma p M^2$
	* TOTAL VOLUME	Q_{tot}

THE LIFT COEFFICIENT IS:

$$C_L = C_{L_{X=1}}\; X^{-2/3}$$

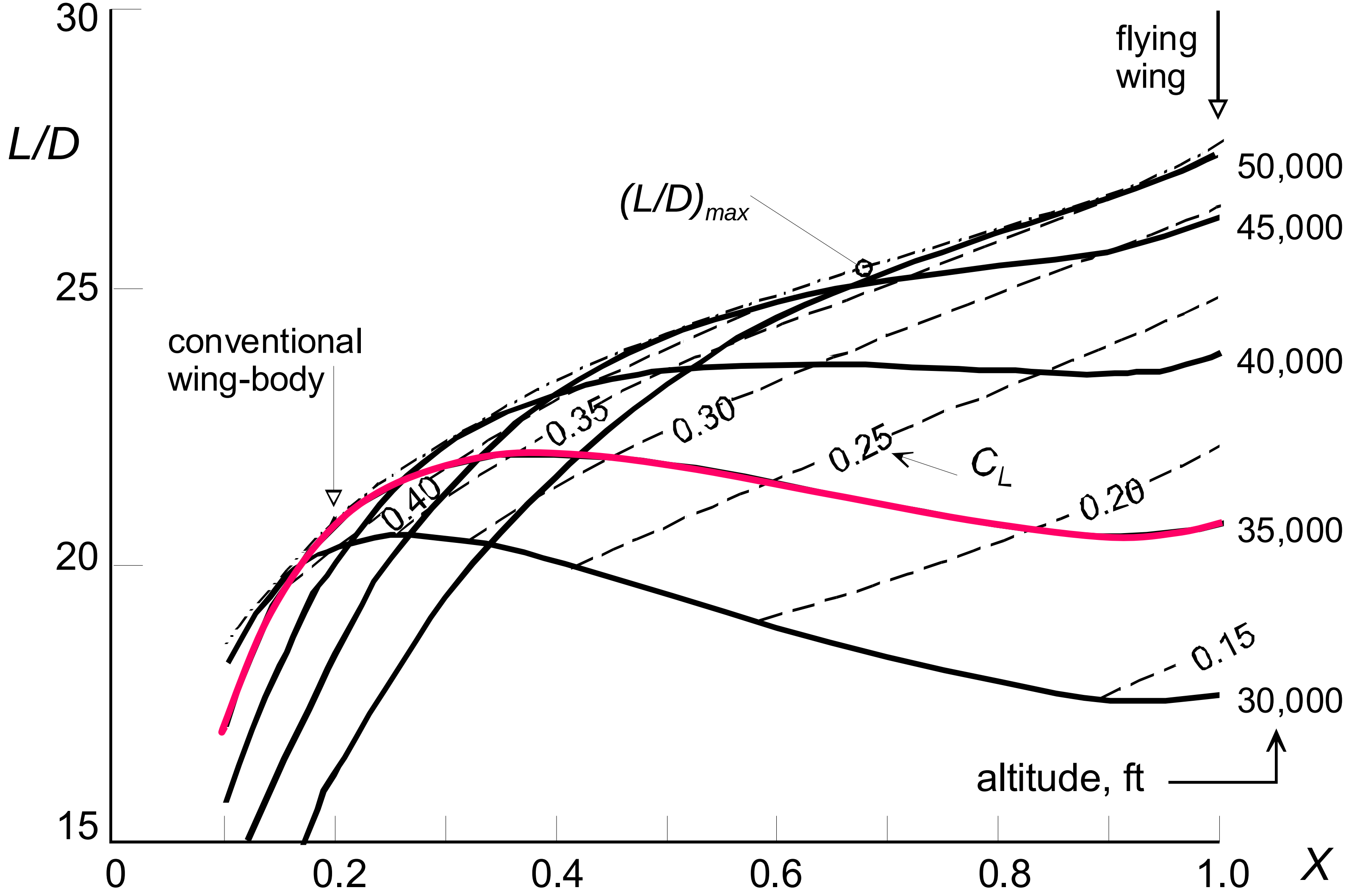
WHERE $(C_L)_{X=1}$ DENOTES THE LIFT COEFFICIENT OF A FLYING WING WITH VOLUME Q_{tot}

HENCE THE LIFT/DRAG RATIO IS OBTAINED FROM:

$$\boxed{\frac{C_D}{C_L} = \frac{C_{D_p}}{C_{L_{X=1}}}\left[X^{2/3} + k_{bw}(1 - X)^{2/3}\right] + \beta\, C_{L_{X=1}}\; X^{-2/3}}$$

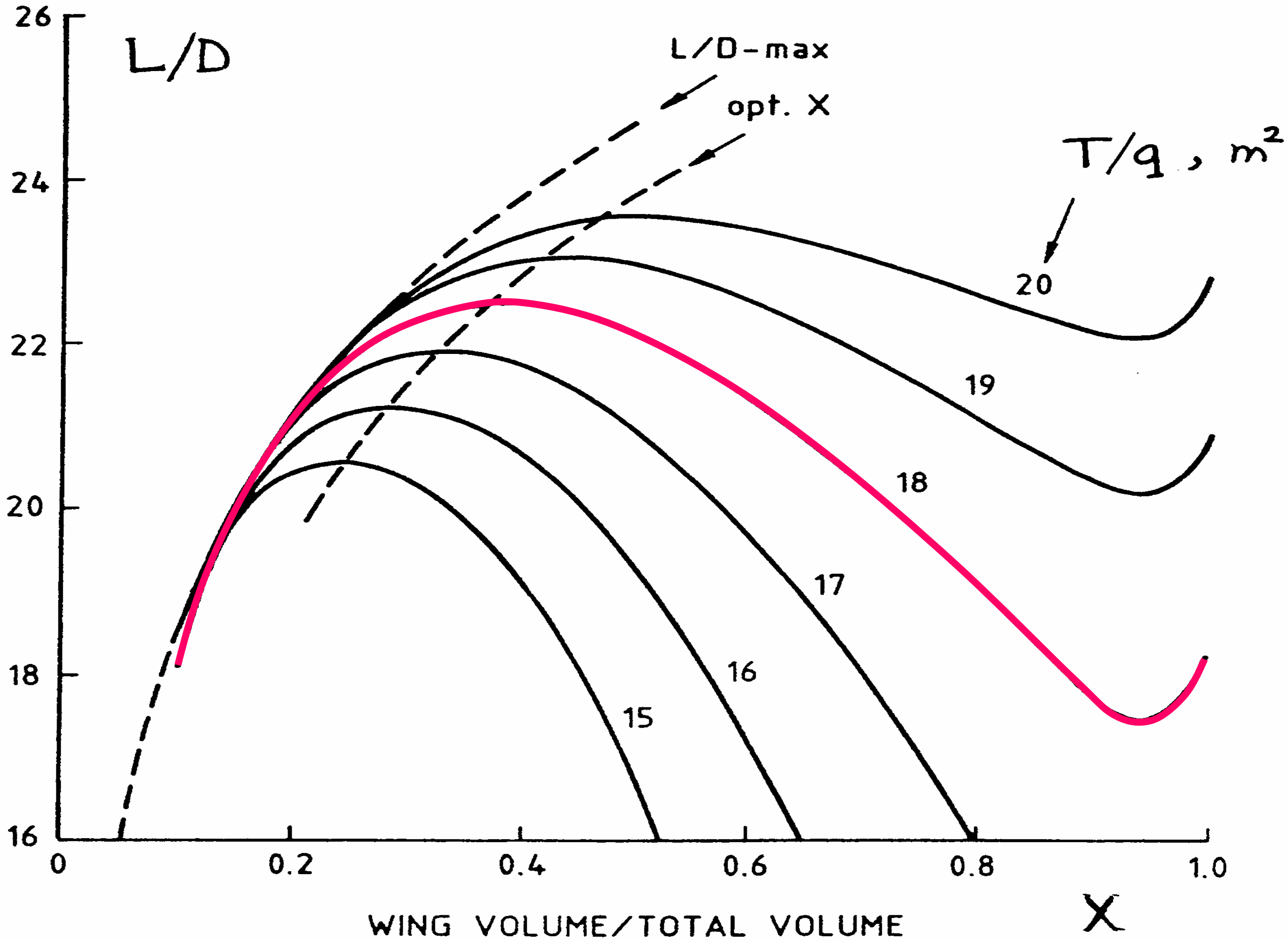
L/D AFFECTED BY ALTITUDE

AUW 4,500 kN; total gross volume 2,000 m^3; Mach 0.8; A=8



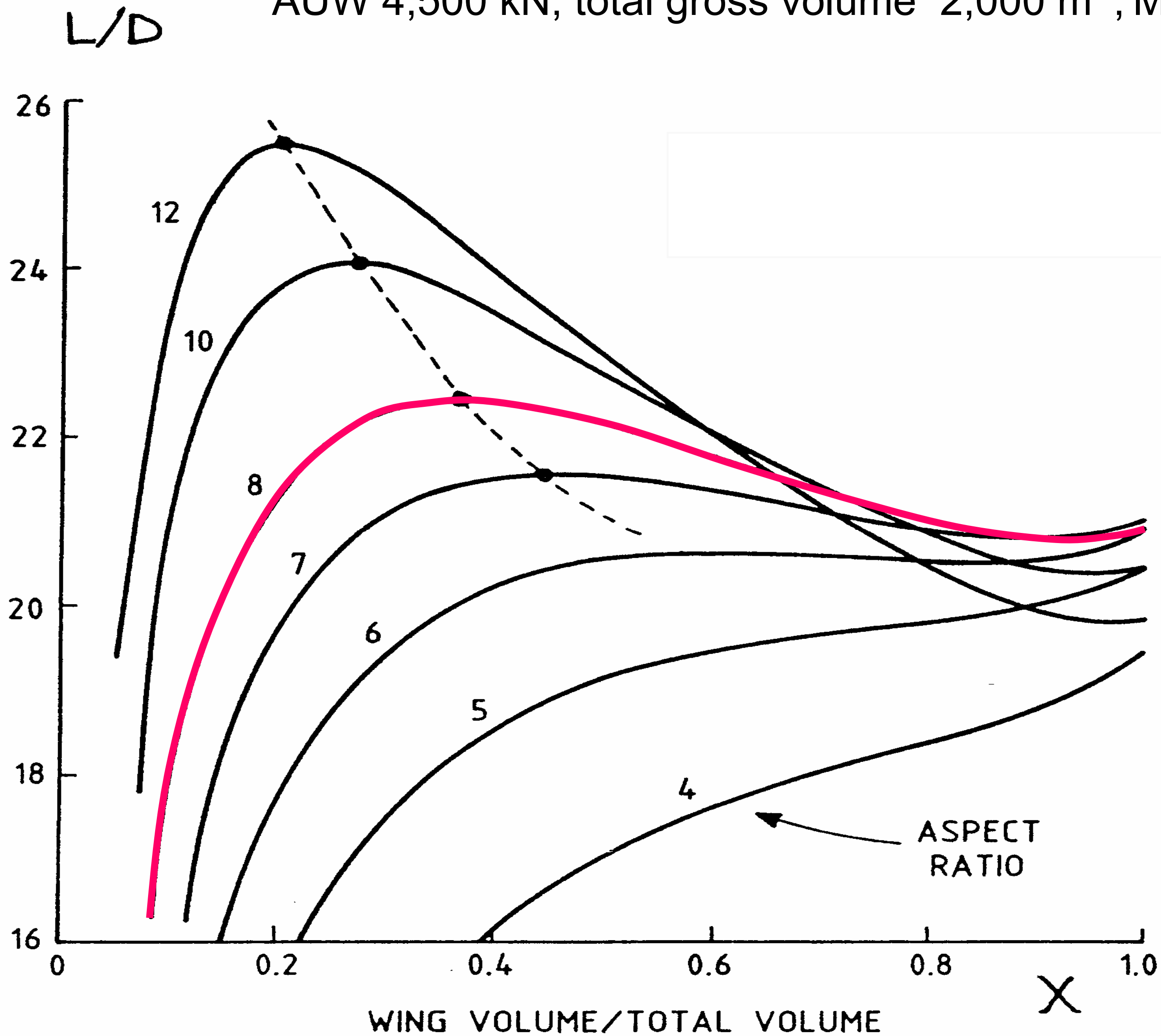
L/D AFFECTED BY AVAILABLE THRUST

AUW 4,500 kN; total gross volume 2,000 m^3; M=0.8; A=8



L/D AFFECTED BY ASPECT RATIO

AUW 4,500 kN; total gross volume 2,000 m^3; M=0.8 @ 35,000ft



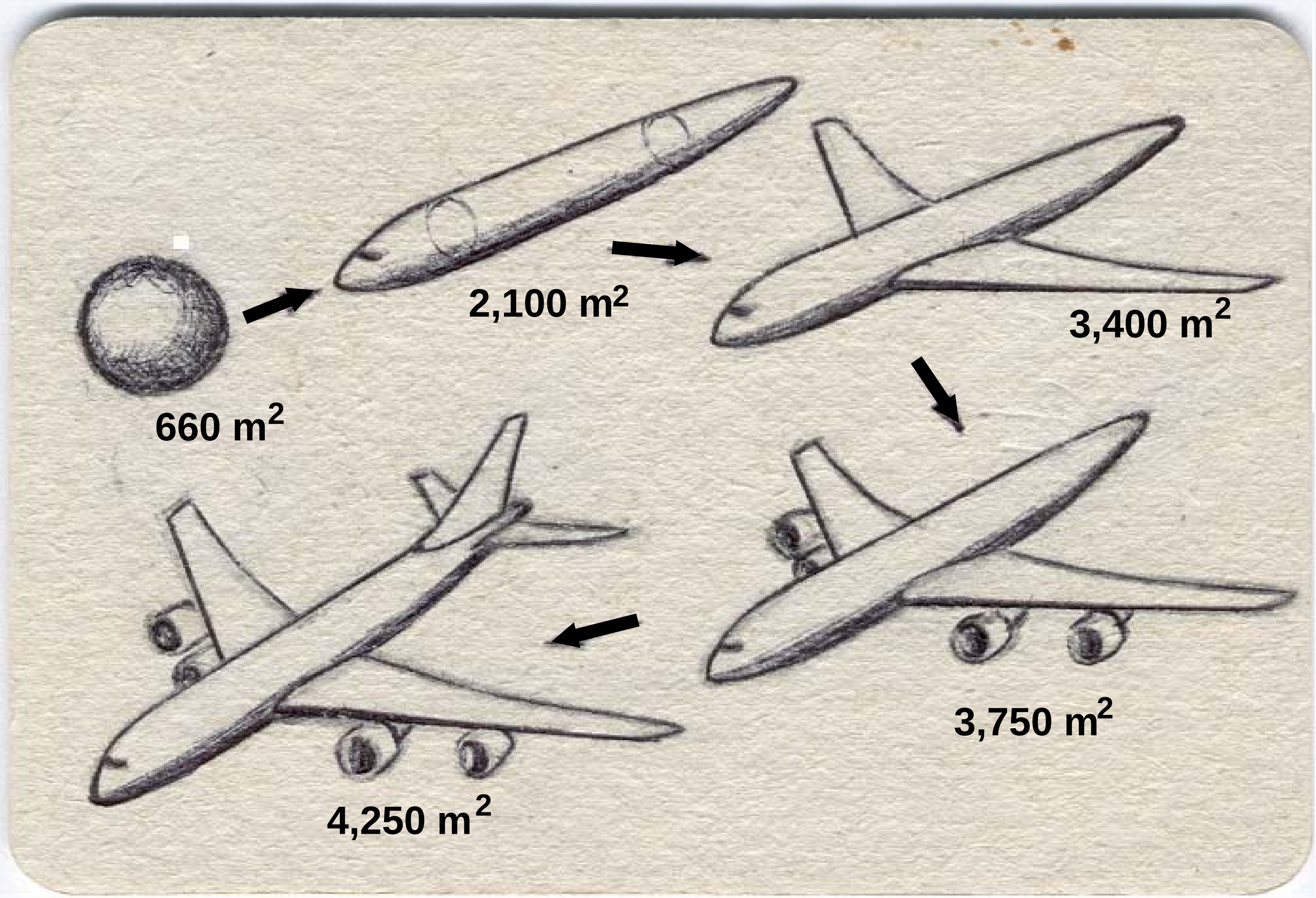
INITIAL OBSERVATIONS

- FOR GIVEN FLIGHT CONDITION THE HIGHEST L/D IS OBTAINED FOR EITHER A FLYING WING OR A DISCRETE WING/BODY CONFIGURATION
- FOR SPECIFIED INSTALLED ENGINE THRUST THE HIGHEST L/D IS GENERALLY OBTAINED FOR A WING/BODY COMBINATION
- THE ASPECT RATIO HAS A MAJOR EFFECT ON L/D FOR WING/BODY COMBINATIONS
- ALL-WING AIRCRAFT DO NOT GAIN FROM A HIGH ASPECT RATIO

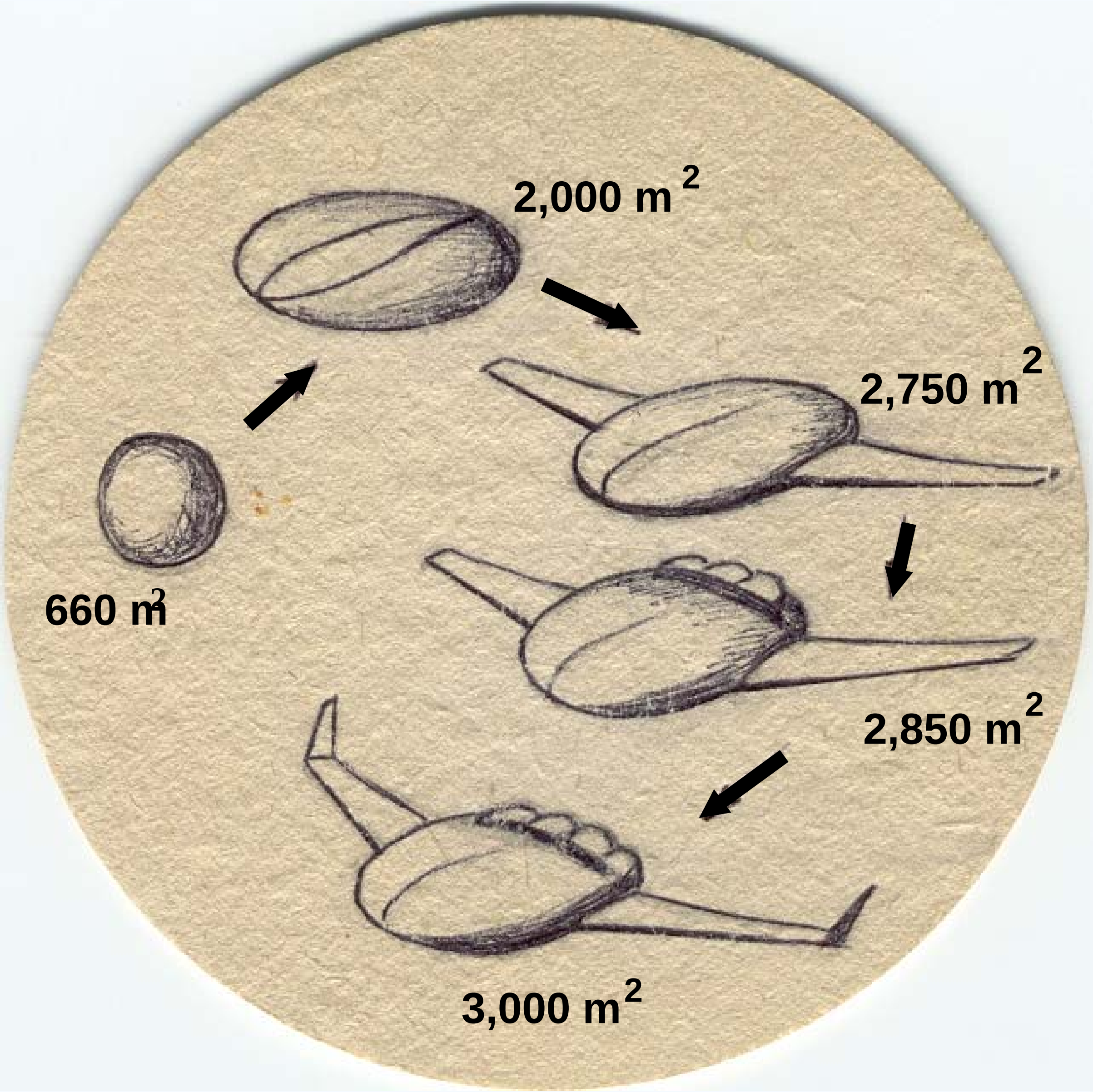
ALL-WING AIRCRAFT

- THE VOLUMETRIC CAPACITY IN RELATION TO WETTED AREA TENDS TO BE UNFAVOURABLE COMPARED TO CONVENTIONAL A/C
- FOR TYPICAL TRANSONIC CRUISE ALTITUDE AND SPEED ALL-WING A/C DO NOT ACHIEVE THE HIGHEST AERODYNAMIC PERFORMANCE
- THE BEST PERFORMANCE IS ACHIEVED FOR HIGH ALTITUDES AND LOW AIR SPEEDS
- HIGH ASPECT RATIO IS NOT HELPFUL

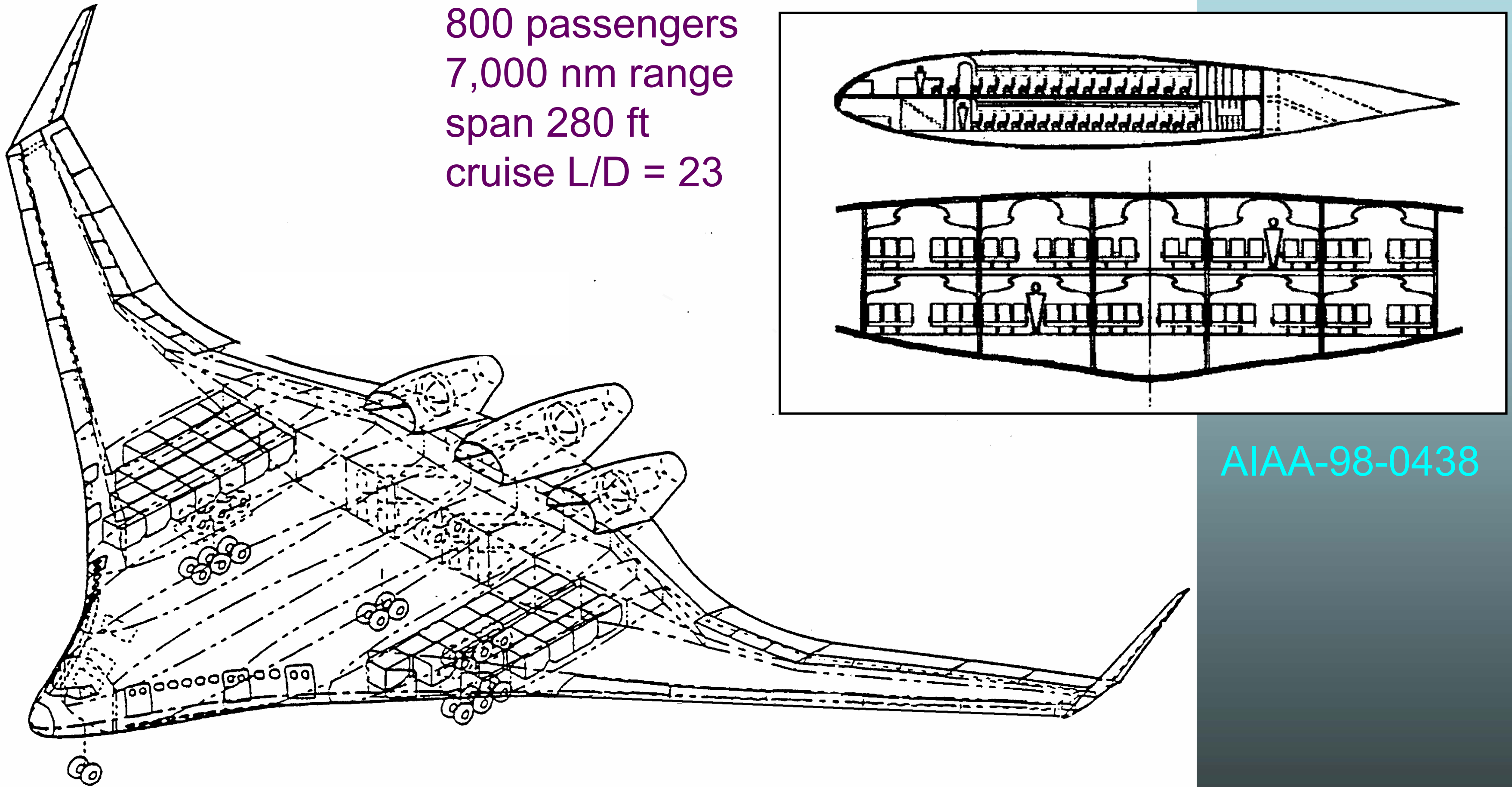
TRANSFORMATION OF A BALL INTO AN AIRCRAFT



AIRCRAFT SHAPED AS A BEERMAT



EARLY MDD/BOEING BWB DESIGN

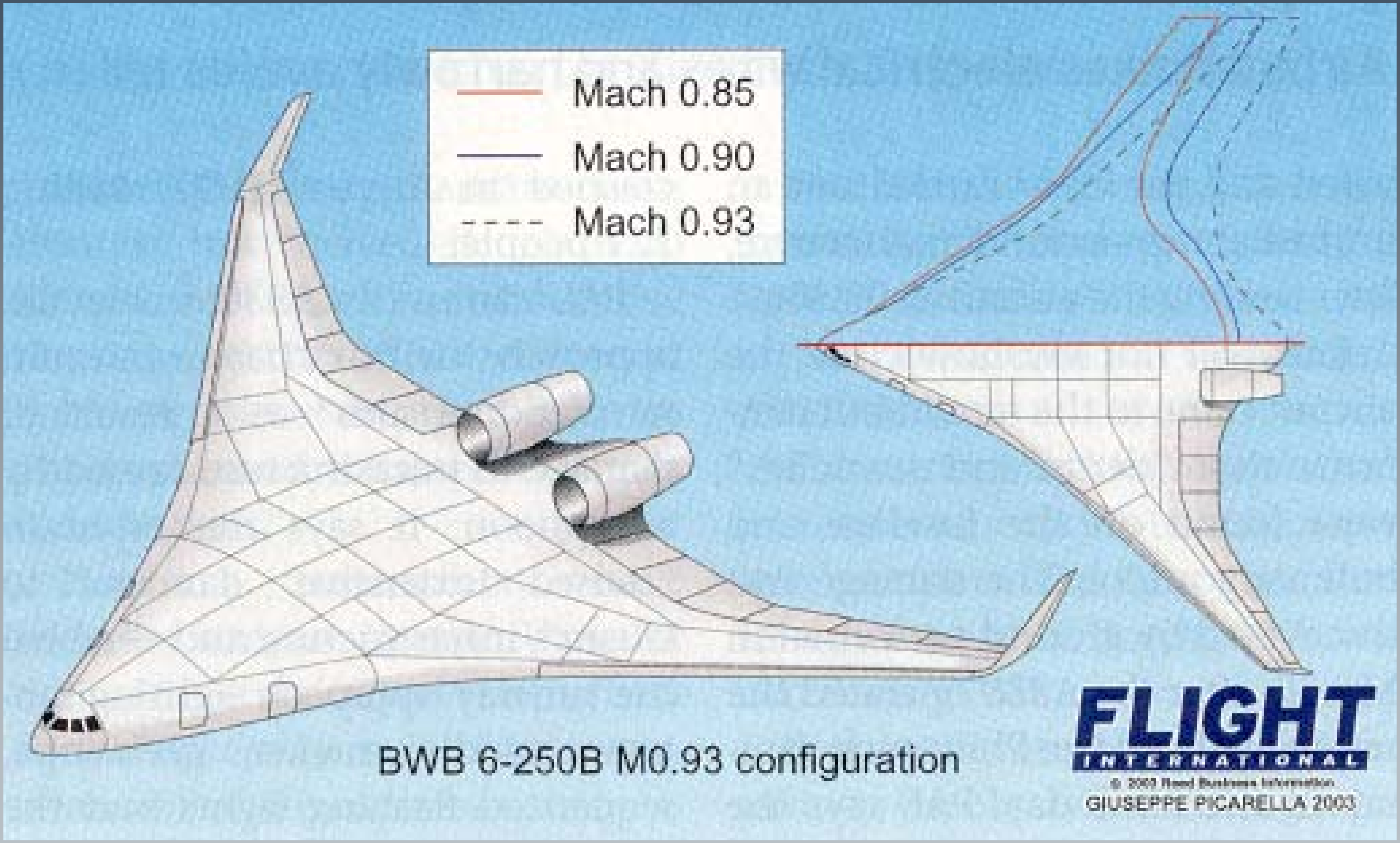


800 passengers
7,000 nm range
span 280 ft
cruise L/D = 23

AIAA-98-0438

RECENT (SMALLER) BWB DESIGN HAS THE PASSENGER CABIN ON ONE UPPER DECK

HIGH MACH NUMBER BWB CONFIGURATIONS



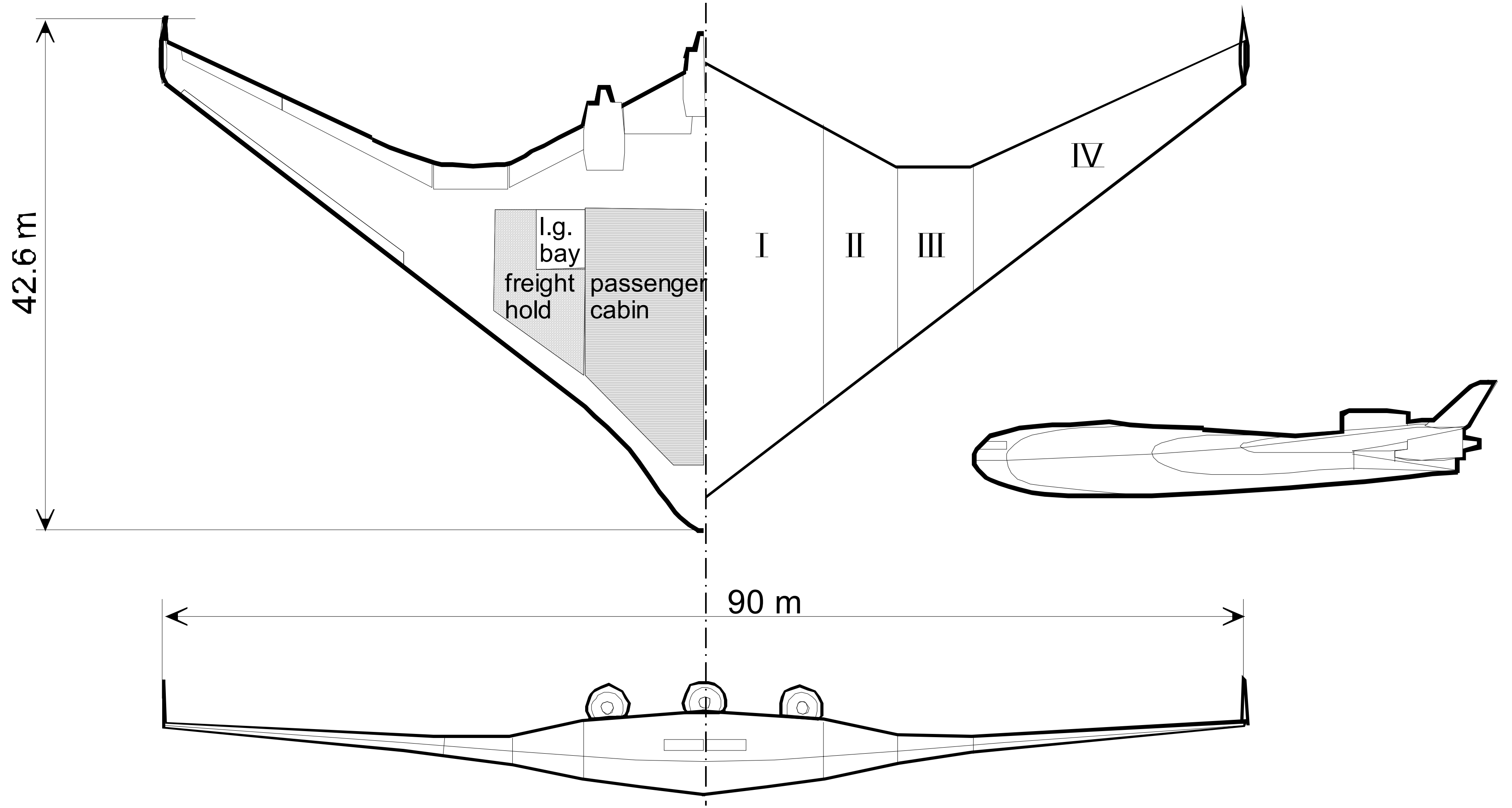
SYNERGY OF BASIC BWB COMPONENTS

- PASSENGER CABIN SHAPE, FREIGHTHOLD AND FUEL TANK ALLOCATIONS ARE STRONGLY INTERRELATED
- THE FUSELAGE IS ALSO A WING AND A PITCH CONTROL SURFACE, ENGINES MAY BE BURIED INSIDE
- VERTICAL SURFACES PROVIDE DIRECTIONAL STABILITY/CONTROL, AND ACT AS WINGLETS
- SYNERGY REDUCES TOTAL WETTED AREA BY 30%, TYPICALLY, RELATIVE TO CONVENTIONAL LAYOUT WITH THE SAME USEFUL LOAD

THE UNUSUAL BWB DESIGN PROCESS

- THE INTERACTION OF THE BASIC DISCIPLINES (AERO, STRUCTURES, WEIGHT AND BALANCE) IS UNUSUALLY STRONG
- CONVENTIONAL DESIGN INTUITION AND APPROACH ARE CHALLENGED
- A SLIGHT CHANGE IN PLANFORM LEADS TO A COMPLETE RECONFIGURING OF THE ENTIRE VEHICLE
- THE BWB MUST BE SELF-BALANCED IN ORDER TO AVOID HIGH TRIM DRAG DUE TO CONTROL DEFLECTION

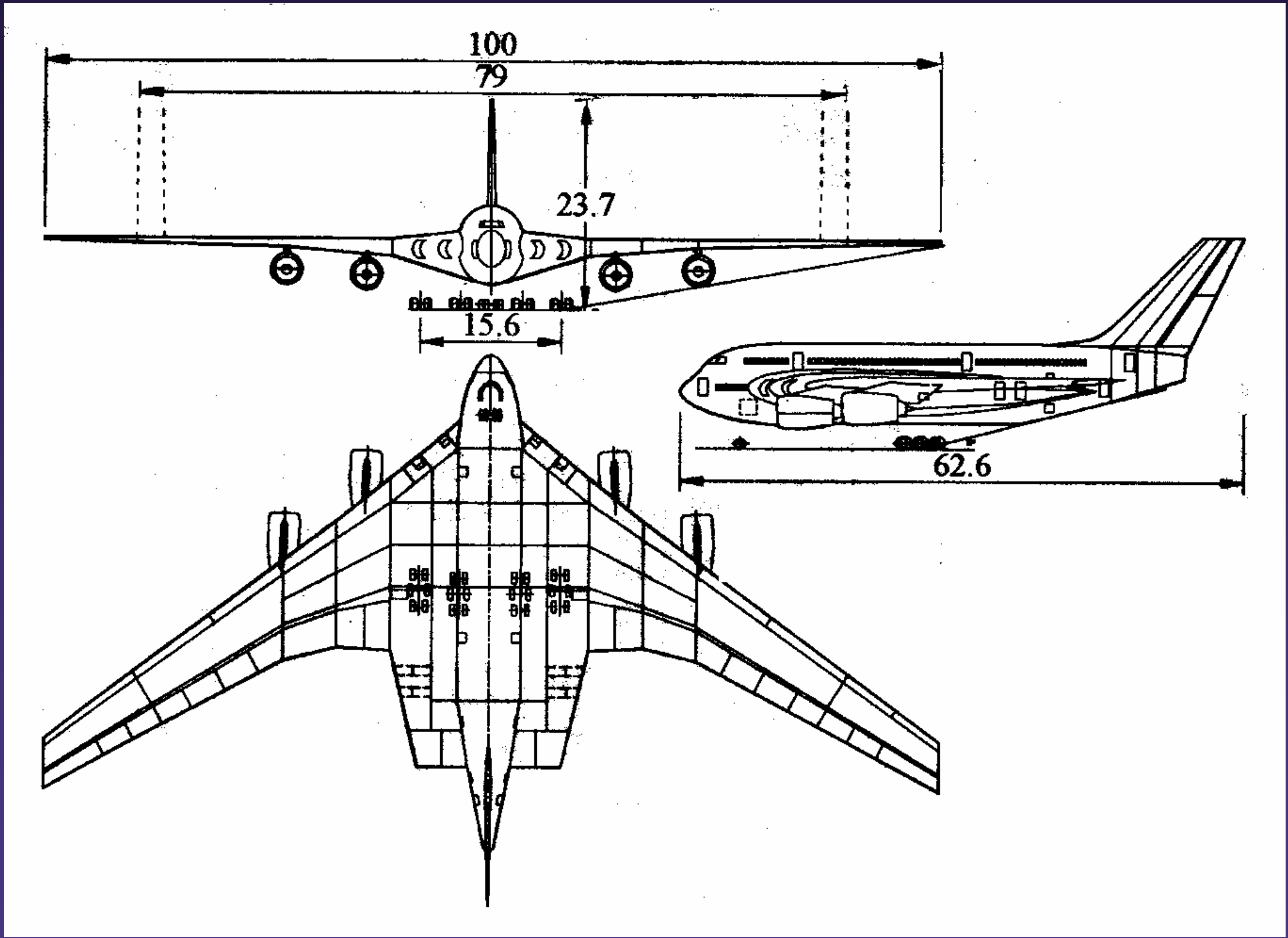
TYPICAL LARGE BLENDED WING BODY



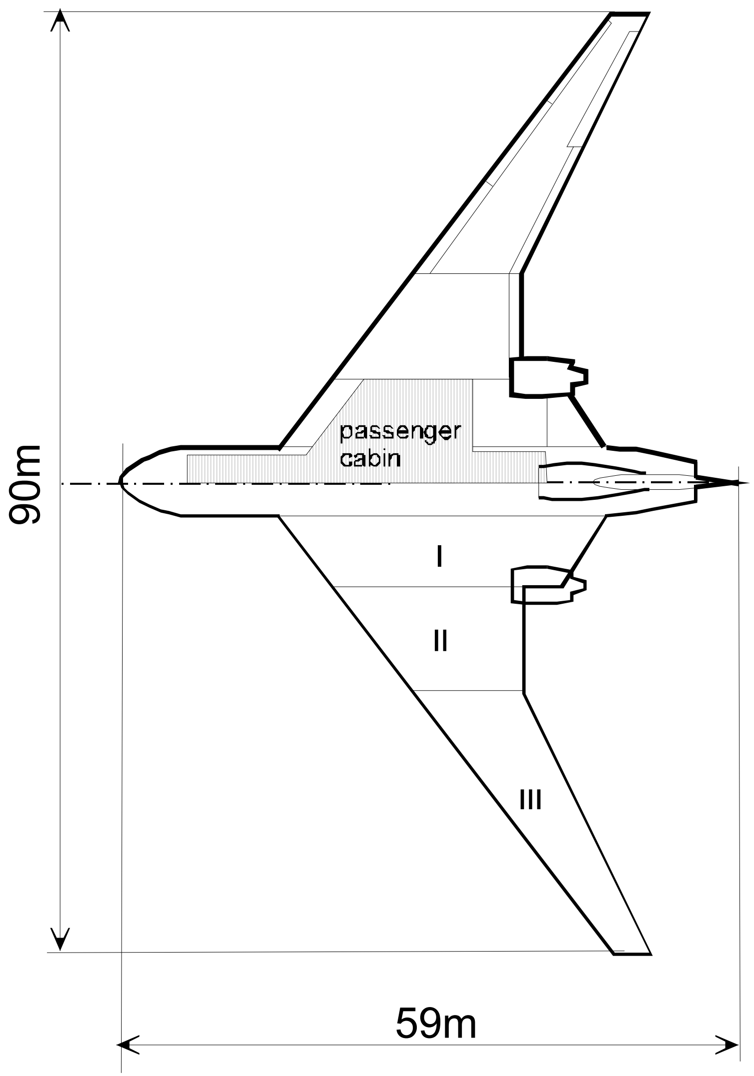
CHALLENGES FOR THE BWB CONCEPT

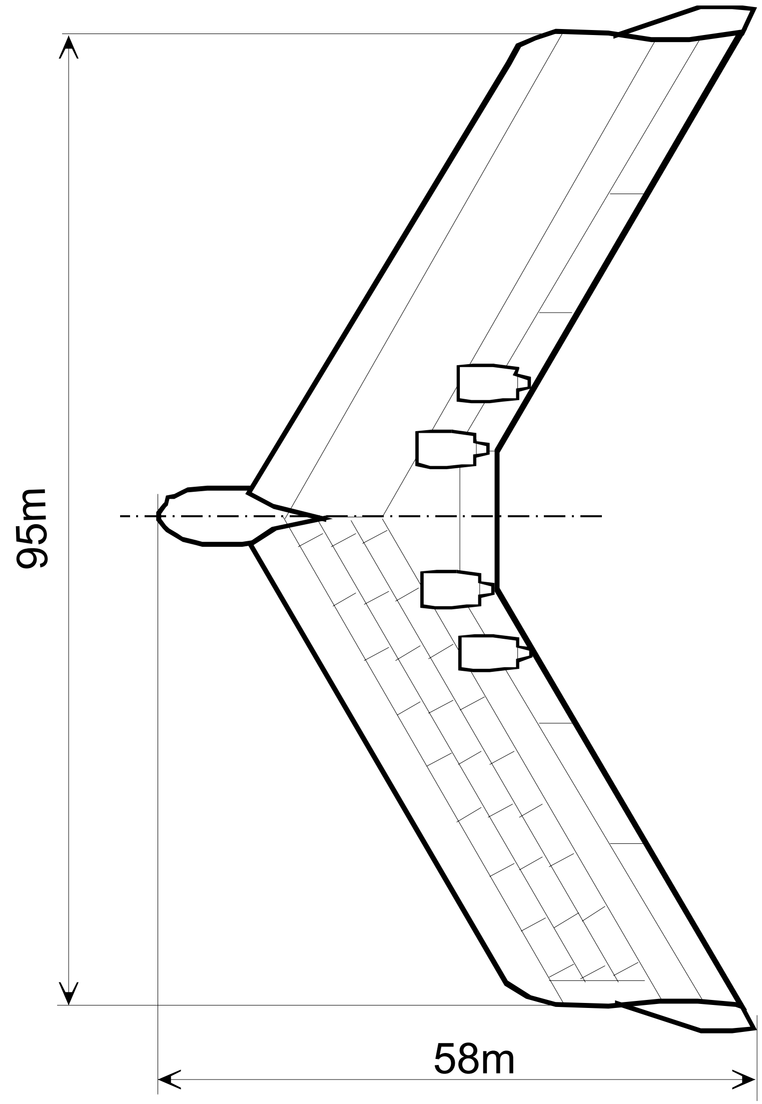
- STRUCTURAL DESIGN OF THE PRESSURE CABIN DUE TO ITS NON-OPTIMUM CROSS SECTION
- STRETCHING OR SHRINKING MUST TAKE PLACE LATERALLY (SPANWISE) IN HEAVILY LOADED AND NON-CYLINDRICAL STRUCTURE
- PASSENGER ACCEPTANCE OF WINDOWLESS CABIN AND HIGH ANGLES OF ATTACK DURING TAKE-OFF AND LANDING
- RIDE QUALITY DURING GUSTS AND MANEUVRES
- NEW EMERGENCY EVACUATION RULES REQUIRED

TsAGI HYBRID CONFIGURATION



HYBRID FLYING WING AND SPAN-LOADER





5 CONFIGURATIONS COMPARED

	Volume m^3	Wetted area m^2	$(L/D)_{max}$ subcritical	C_L cruise	L/D cruise
CONVENTIONAL	3,262	3,852	20.6	0.47	19.7
ALL-WING	3,319	3,562	25.7	0.24	23.2
BLENDED WING BODY	3,025	3,040	26.1	0.28	24.4
HYBRID FLYING WING	3,230	3,445	24.5	0.36	22.7
SPANLOADER	6,700	4,800	24.0	0.26	22.1

Approximately equal useful load, cruise speed and altitude

CONCLUSIONS – BLENDED WING BODY

- THE BWB FORMS A NEW CATEGORY BETWEEN CONVENTIONAL AND ALL-WING CONFIGURATIONS
- IT IS CHARACTERIZED BY A LOW ASPECT RATIO HIGH THICKNESS RATIO INBOARD WING, A HIGH ASPECT RATIO OUTBOARD WING, AND BASIC VERTICALS
- A BWB HAS THE POTENTIAL OF ACHIEVING THE SAME OR BETTER AERODYNAMIC QUALITY AS ALL-WING AIRCRAFT, FOR SMALLER WING SPAN
- WING LOADING AND CRUISE CONDITIONS ARE WELL TEMPERED
- CRUISE L/D RATIO IMPROVEMENTS UP TO 25% ARE POSSIBLE, FUEL AND INSTALLED THRUST SAVINGS ARE EVEN HIGHER

IS THERE A FUTURE FOR THE BWB?

- INDUSTRIAL AND OPERATIONAL REALIZATION WILL ENTAIL SIGNIFICANT CHALLENGES
- MOST DOUBTS ARE ASSOCIATED WITH PASSENGER ACCEPTANCE
- A VERY LARGE CIVIL OR MILITARY FREIGHTER SEEMS TO HAVE THE BEST CHANCE OF REALIZATION