JOHN McMASTERS
COLLECTED WORKS

THE ORIGINS AND FUTURE OF FLIGHT
(A Paleoecological Perspective)

July 1993

A scientist discovers that which exists. An engineer creates that which never was.

Th. von Kārmān

To prove that a pig cannot fly is not to devise a machine that does so.

D. Küchemann

Dr. John H. McMasters

Principal Engineer
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and

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AIAA Distinguished Lecturer 1992-94

THE ORIGINS AND FUTURE OF FLIGHT

(A Paleological Perspective)

John H. McMasters
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This presentation is an eclectic overview of the technical history of aviation encompassing the earliest origins and evolution of flight in insects through the prospects for future developments in commercial transport aircraft. The volume of material available for this lecture is large [see attached outline] and may be condensed and tailored to the interests and level of technical background of a particular audience. Versions of the lecture have been successfully presented to groups ranging from elementary school students through engineering specialists in government research laboratories and universities.

The basic premises of this lecture are:

- The conventional view of aviation history is backward. In large measure, we owe much of our understanding of biological (animal and botanical) flight to experience and inspiration gained in the course of designing and developing flying machines of various types, rather than the other way around. Very few modern aircraft either fly like, or physically resemble, biological flying devices--although arguments can be advanced to support the view that an increasing number of airplane types probably should.

- The engineer, working with those from other scientific disciplines, has much to contribute to increasing our knowledge of flight in nature. The reverse of this proposition has yet to be properly exploited--and should be in the future.

- Rather than being separate disconnected topics, technological and biological flight reprsent the end of continuous, very broad, and utterly fascinating spectrum. A huge range of diverse devices and configurations are all tied together by the underlying requirement that each individual element of the full spectrum must obey the same basic laws of physics. To understand the apparent differences in devices as dissimilar as a dragonfly, a sea gull and a jet transport one must understand both the underlying physics and the context within which each must operate. This context is spacial, temporal (covering 300 million years) and economic and thus an ecological (or more properly, a paleoecological) perspective should be adopted.

Much of the material for this lecture comes from my avocational interest and subsequent writings on the region of overlap between the ranges of biological and technological flying devices beginning with small (microscopic) insects and terminating with aircraft substantially larger than the current Boeing 747 jet transport. Thus, my attention has been drawn to the equivalence between large soaring birds (condors and teratorns) and sailplanes; pterosaurs, hang gliders and ultralight sailplanes; and human powered airplanes. When my exploration of all these topics began almost thirty years ago it was considered mildly interesting and largely frivolous by the vast majority of my professional colleagues. While the view that there is little commercial value in designing better butterflies is still widespread, the topics covered in this lecture are now more respectable in the engineering community, thanks to the work of people like Sir James Lighthill. It also has become clear in retrospect that many areas of extreme interest in current aeronautical research and development are already fully and elegantly embodied in various animal fliers. Some examples are shown in the specific case of the California condor (*Gymnogyps californianus*).

Dr. John H. McMasters has been an aeordynamicist in the Boeing Commercial Airplane Group since 1976. He is currently the Lead Engineer of the Advanced Concepts group in the Central Preliminary Design organization. He has taught airplane design at Purdue and Arizona State University and is now an Affiliate Professor in the Department of Aeronautics and Astronautics at the University of Washington. He has authored over 70 technical papers, reports and articles on low-speed flight, design and engineering education. McMasters is a graduate of the University of Colorado and received his Ph.D. from Purdue University. He is an Associate Fellow of the AIAA and was a 1992-94 AIAA Distinguished Lecturer.

THE ORIGINS AND FUTURE OF FLIGHT

(A Paleoecological Perspective)

By John H. McMasters

INTRODUCTION

- The airplane design process
- A (very) general historical overview
- Why does any of this matter to us?

A THEORETICAL FRAMEWORK

- Optimal locomotion
- Optimal size

INTERDISCIPLINARY SYNERGISM (INSECTS)

- Can the bumble bee fly?
- * - Insect architecture and aerodynamics
- The supersonic deerfly

NATURAL AND HUMAN FLIGHT

- * - The origins of animal flight (birds, bats and pterosaurs)
- * - The aerodynamics and architecture of birds and bats
- * - Sailplane and soaring
- * - Pterosaurs (pterodactyls) and hang gliders
- How big can a flying animal get? [birds and pterosaurs]
- * - Human powered flight (history and technology)

EXAMPLES OF "TECHNOLOGY TRANSFER"

- Winglets and pfeathers
- * - Vortex generators
    - Wind turbines
    - 767/737 vortex control devices (VCDs)
    - Alula leading edge devices

COMMERCIAL AIRPLANE (AND RELATED TECHNOLOGY) DEVELOPMENT

- * - The history of commercial airplane development
- The future of aerodynamics at Boeing
    - Laminar flow control
    - * - The complementary role of CFD and testing
    - * - High Reynolds number technology
    - Future product development
        - NLA (747-X, XL)
        - HSCT

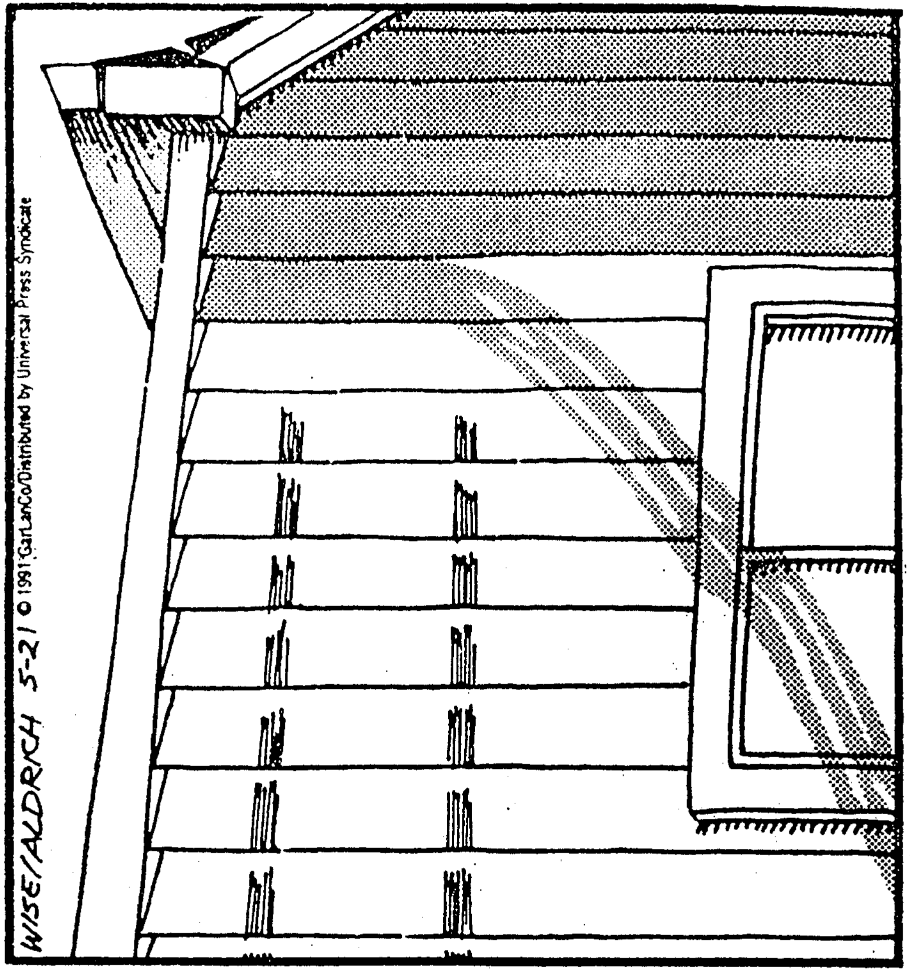
CONCLUSIONS

ADDENDA

- * - Fluid dynamic scale effects (dynamic similarity)
- * - The Airplane Design Professor as Sheepherder
- * - Paradigms Lost, Paradigms Regained: Paradigm Shifts in Engineering Education

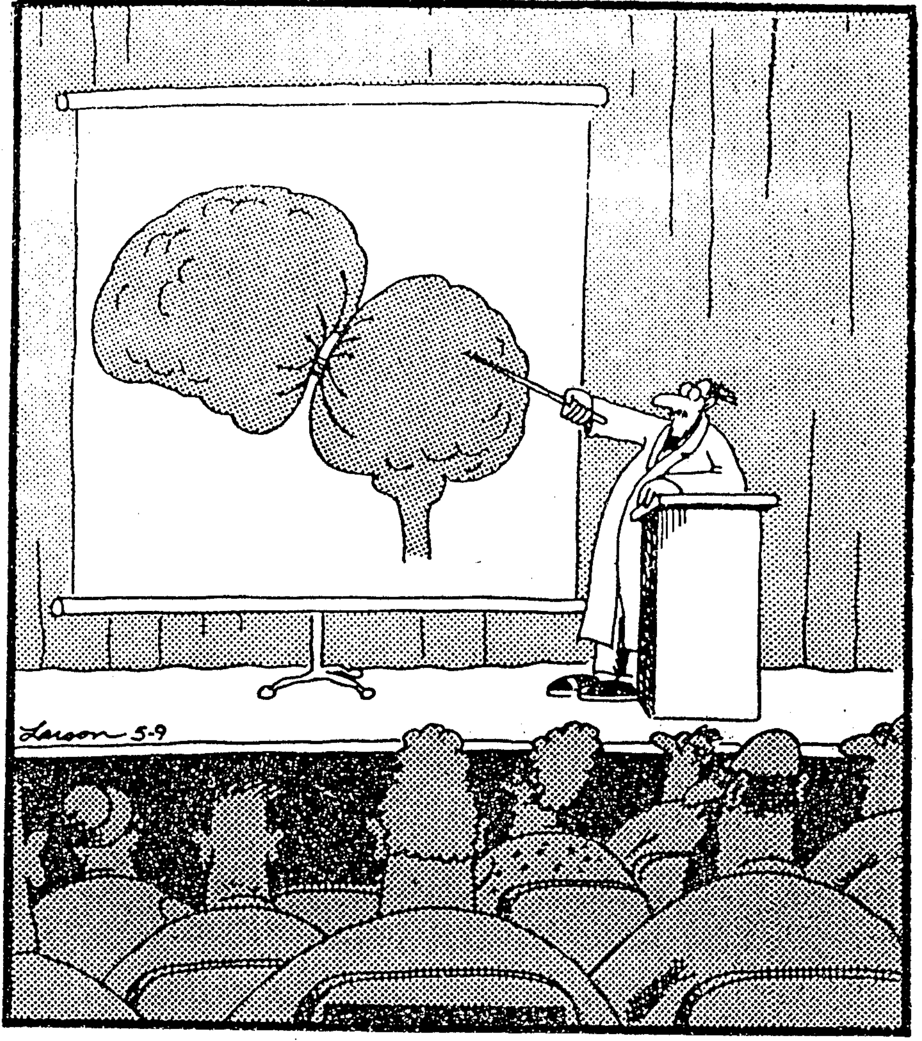
* Denotes 30-45 min. sub-lectures

REAL LIFE ADVENTURES / G WISE & L ALDRICH



Looking back on your education, perhaps Ladder Safety 101 would have been more useful than Philosophy AA410.

THE FAR SIDE / GARY LARSON



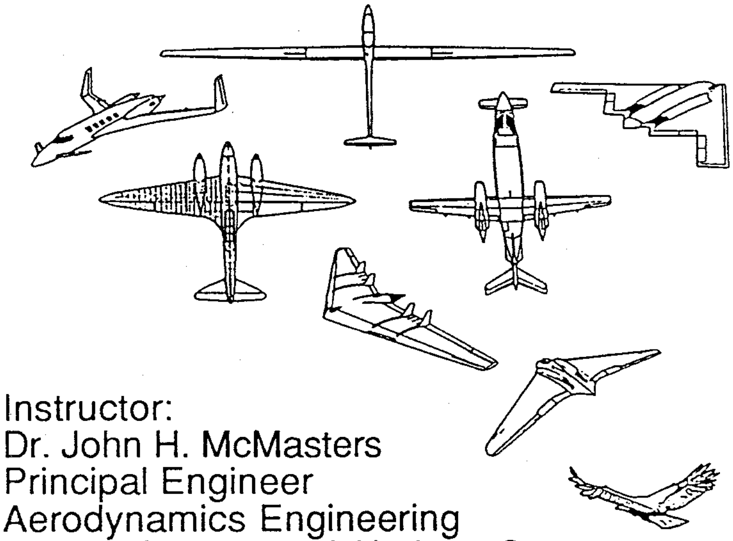
Professor McMasters **, in a seminar on compulsive thinkers, illustrates his brain-stapling technique.**

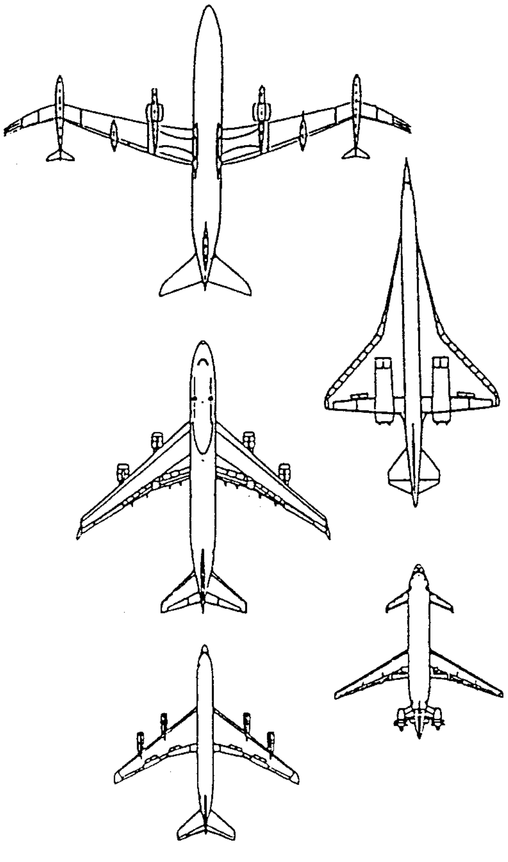
COURSE ANNOUNCEMENT

WINTER QUARTER 1992
Department of Aeronautics and Astronautics

University of Washington
Seattle, WA

AA410 Aircraft Design (4)W Conceptual design of a modern airplane to satisfy a given set of requirements. Estimation of size, selection of configuration, weight and balance, and performance. Satisfaction of stability, control and handling qualities requirements. Economic and manufacturing considerations.





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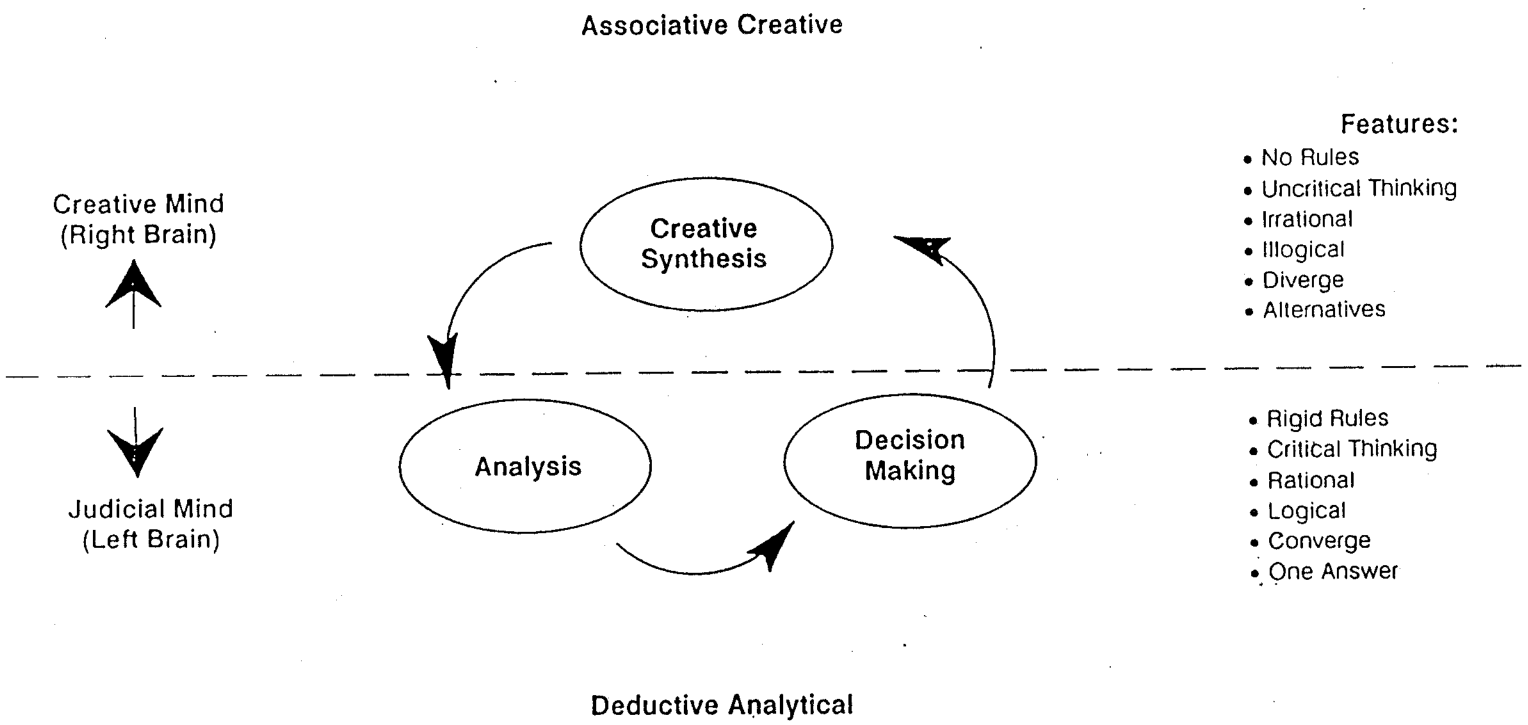
Background

Koen (1985):

"...it is the engineering method or design process, rather than the artifacts designed, that bind all engineering disciplines together and defines the engineer.

Koen, B. V., Definition of the Engineering Method, American Society of Engineering Education, Washington, DC, 1985.

The Engineering (Design) Process



Associative Creative

Creative Mind
(Right Brain)

Judicial Mind
(Left Brain)

Creative Synthesis

Analysis

Decision Making

Deductive Analytical

Features:

- No Rules
- Uncritical Thinking
- Irrational
- Illogical
- Diverge
- Alternatives

- Rigid Rules
- Critical Thinking
- Rational
- Logical
- Converge
- One Answer

Engineers (Designers/Synthesizers) ≠ Engineering Science Technicians (Analysts)

• Industry needs both •

The Book of Genesis

~from~

The Aerospace System Designers Bible

By W. Gillette & J.H. McMasters

And on the first day there was gravity and the spirit of Newton said:

$$F = K \frac{m1m2}{r^2}$$

and Matters became weighty.

And then there was boundless energy and it was consolidated and Einstein quoth:

$$E = m c^2$$

and there was Motion, but it was merely transverse.

And on the third day, from the heavens, a voice cried out:

$$C_L = \iint_{xy} \left(C_{P_L} - C_{P_U} \right) dx\, dy$$

and there was Lift.

But on the fourth day, the Devil said:

$$C_D = C_{DP_{min}} + C_L^2/\pi R \quad e + \Delta C_{DP} + \Delta C_{DM} + \Delta C_{DP\ bugs}$$
$$+ \left(\Delta C_{D_{BOUYANCY}}\right) + C_L \sin \alpha \quad \text{UPFLOW}$$
$$+ Q_3 \int (erf)^{nerf} dz - 2/3\,(\text{Management Requirement})$$
$$+ \Delta C_{D_{TRIM}} - C_{D_{BLOCKAGE}} - C_{D_{TRIP}} + C_{D_{BASE}} + 2\sigma + H.O.T. + C$$

and there was Drag.

On the fifth day a tiny voice from the wilderness cried out:

"... don't forget stability and control."

And this was echoed by various multitudes crying:

"... environmental control systems, ground support equiptment, and etc." far into the night of the sixth day.

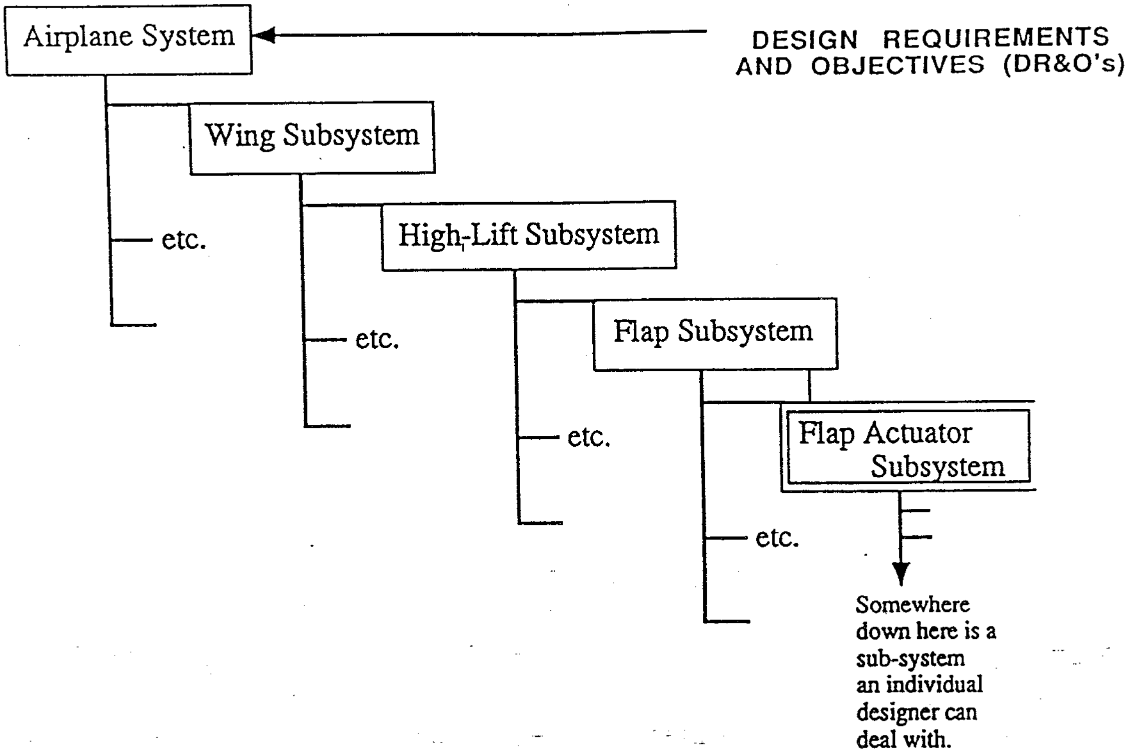
And on the last day, the spirit of Maynard Keynes proclaimed:

"He who controls the purse strings control the policy."

and there was Economic Reality.

Caveat Emptor. Amen...

The Conventional View of Airplane (System) Design


Airplane System

DESIGN REQUIREMENTS AND OBJECTIVES (DR&O's)

Wing Subsystem

etc.

High-Lift Subsystem

etc.

Flap Subsystem

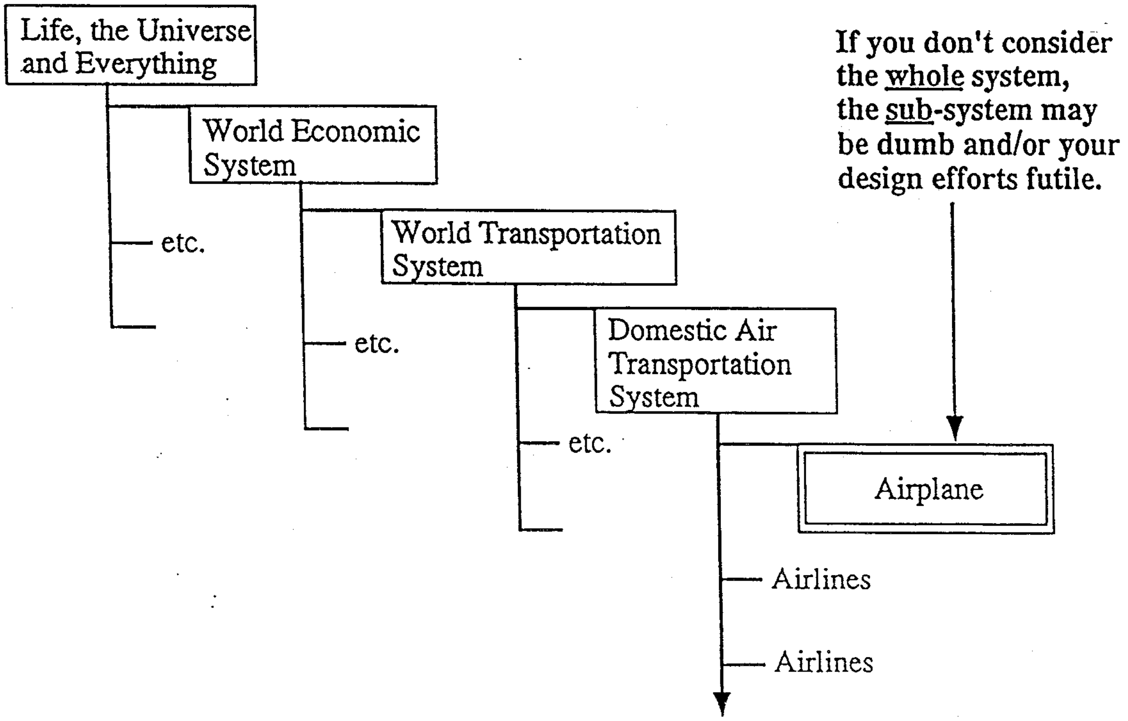
etc.

Flap Actuator Subsystem

etc.

Somewhere
down here is a
sub-system
an individual
designer can
deal with.

An Alternate View of Airplane (System) Design


Life, the Universe and Everything

World Economic System

etc.

World Transportation System

etc.

Domestic Air Transportation System

etc.

Airplane

Airlines

Airlines

**If you don't consider
the whole system,
the sub-system may
be dumb and/or your
design efforts futile.**

BASIC LAWS of AIRPLANE DESIGN

- You never get something for nothing--someone, somewhere, always pays for lunch.
- We live in a closed thermodynamic system in a largely Newtonian universe.

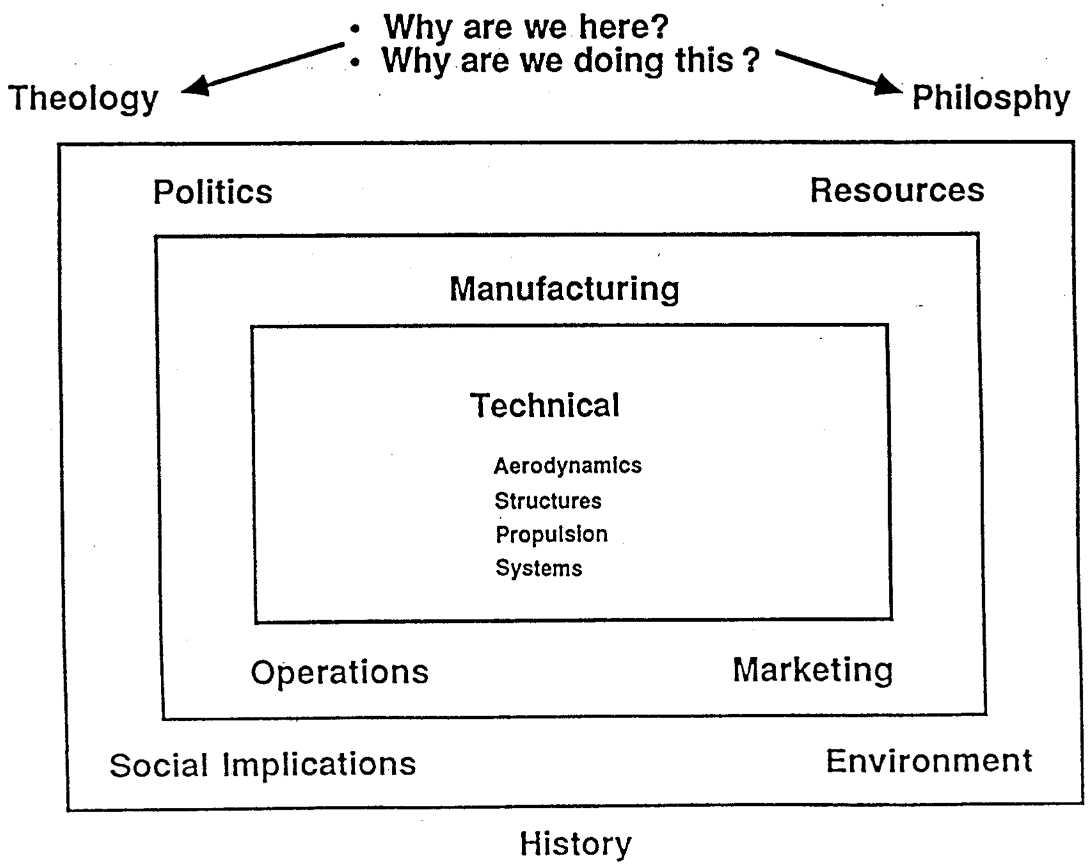
Thus:

- Weight = Lift = 1/2 $\rho V^2 C_L S$
- Thrust = Drag = 1/2 $\rho V^2 C_D S$
- The summation of the moments equals the time-rate-of-change of angular momentum (in a vector sense).

$C_L = \iint_{xy} \left(C_{p_L} - C_{p_U}\right) dx\, dy \ldots$

$C_D = C_{D_{P_{min}}} + C_L^2/\pi R\ e + \Delta C_{D_P} + \Delta C_{D_{TI}} + \Delta C_{D_{P_{bugs}}}$
$+ \left(\Delta C_{D_{boundary}}\right) + C_L \sin \alpha$ upflow
$+ Q_s \int (erf)^{nerf} dz - \%$ (Management Requirement)
$+ \Delta C_{D_{trim}} + C_{D_{blockage}} + C_{D_{wave}} + C_{D_{base}} + 2\sigma +$ H.O.T. $+ C$

- Simplicity is the essence of true elegance--it can also save weight and/or reduce cost.
- If you can't build it, you can't sell it.
- They who control the purse strings control the policy.



- Why are we here?
- Why are we doing this ?

Theology

Philosphy

Politics

Resources

Manufacturing

Technical

Aerodynamics
Structures
Propulsion
Systems

Operations

Marketing

Social Implications

Environment

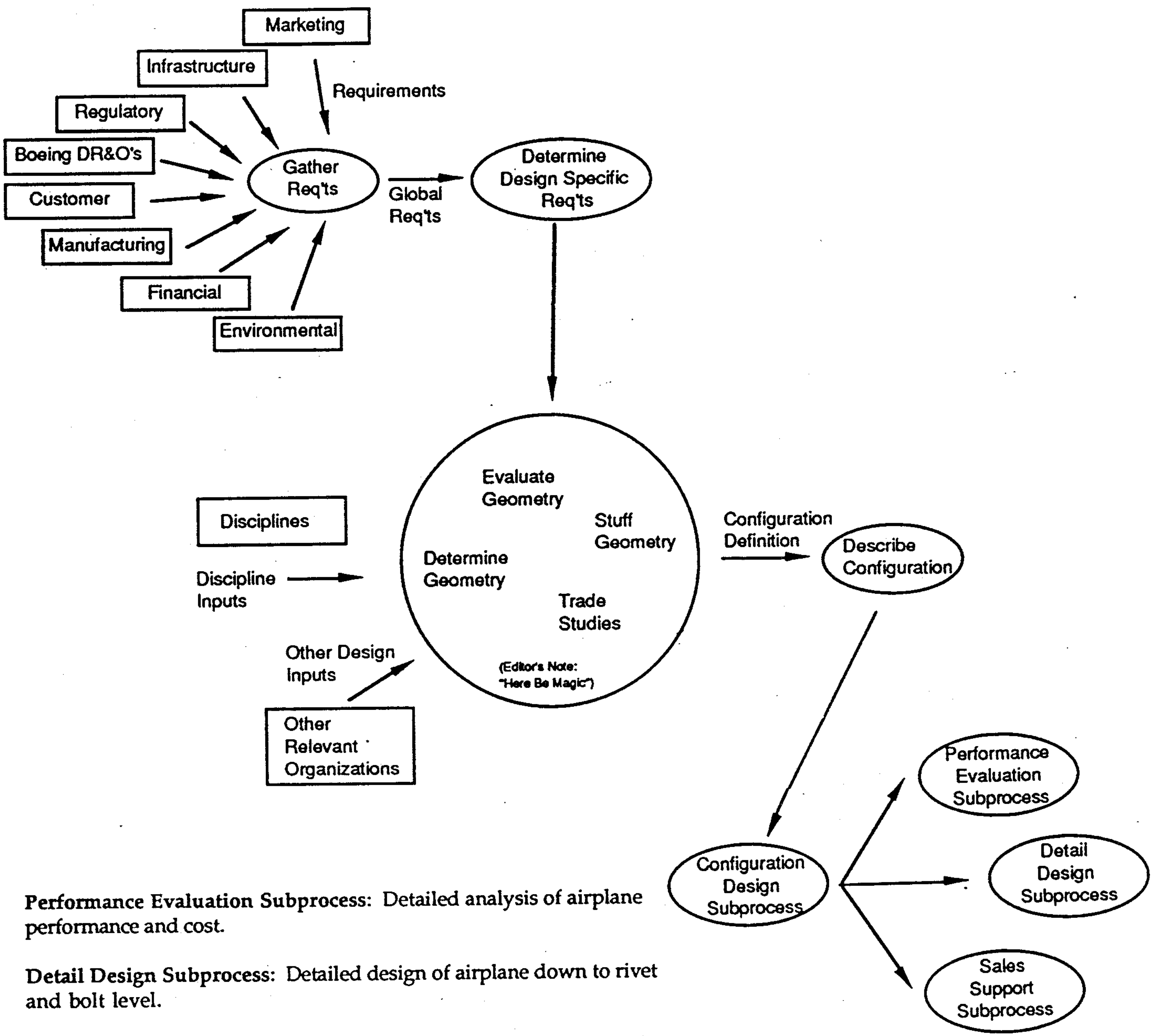
History

THE DESIGN ONION

A DESIGN VOCABULARY

SYSTEM	-	A group of elements that interact and function as a whole.
DESIGN	-	To contrive a plan [for an object or system], artistic invention.
SYNTHESIS	-	The combining of often diverse conceptions into a coherent whole.
ENGINEERING	-	Synthesis and/or design.
ANALYSIS	-	A breaking up of a whole into its parts to discover their nature (= science).
SYNERGISM	-	Cooperative action of discrete agencies such that the total effect is greater than the sum of the effects taken independently [i.e. when 1 + 1 = 3].
HERMENEUTICS	-	The study of the methodological principles of interpretation. (A biblical scholar's term expressing the concept that little which is written or done makes logical sense unless understood in the full context of its time and place in history).
HEURISTIC	-	Providing aid or direction in the solution of a problem but otherwise unjustified or incapable of justification.
COMPROMISE	-	Settlement of differences by consent reached by mutual concession.
TRADE-OFF	-	A balancing of factors, all of which are not attainable at the same time.
INTERFACE	-	The place at which independent systems meet, act on, or communicate with each other.

The Airplane Design Process

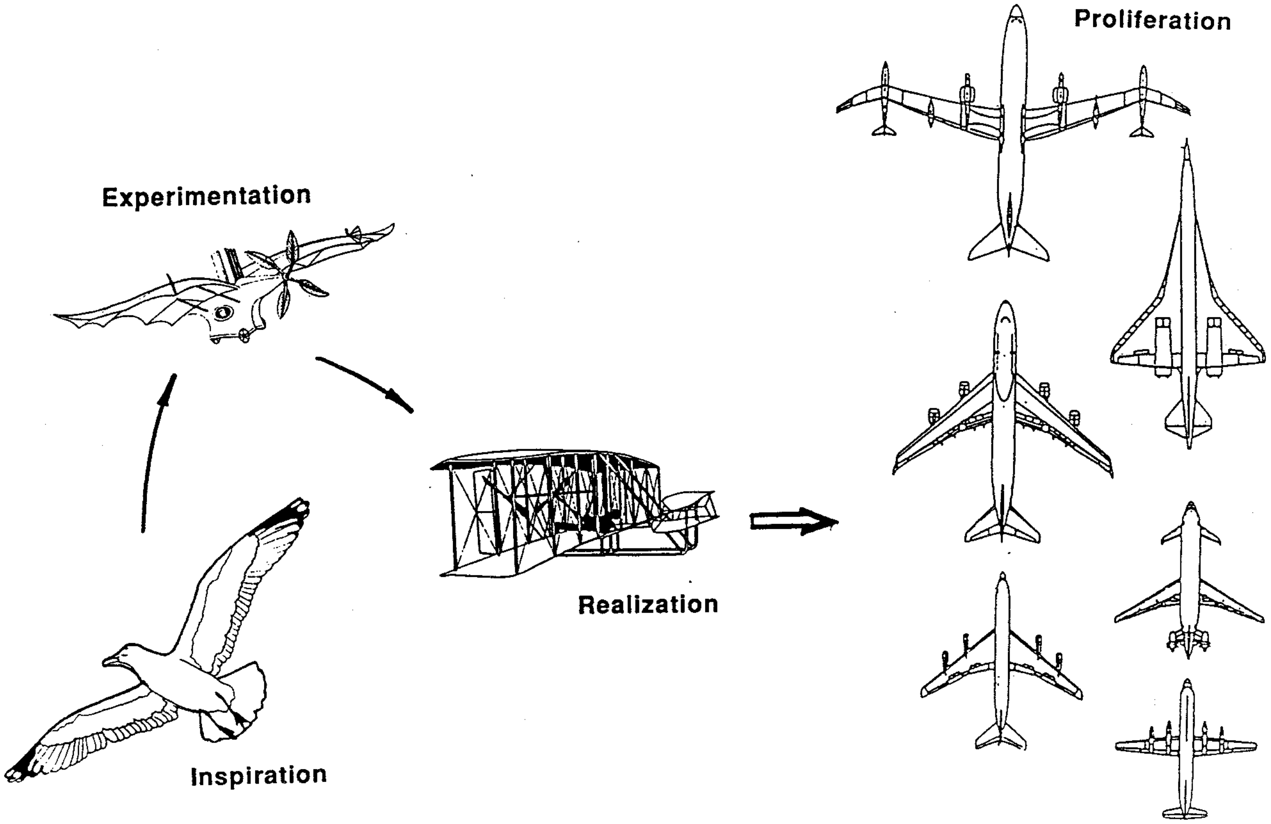


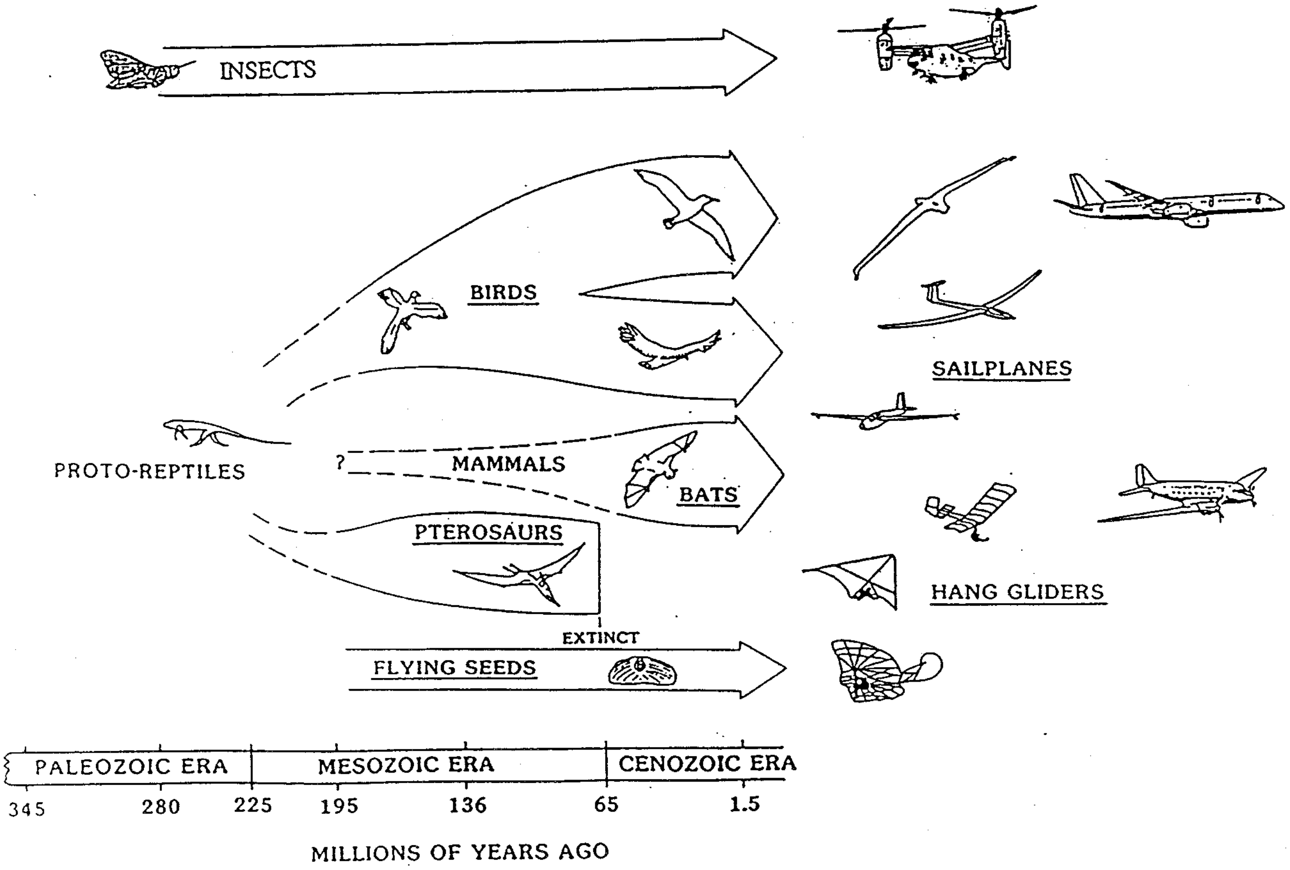
Performance Evaluation Subprocess: Detailed analysis of airplane performance and cost.

Detail Design Subprocess: Detailed design of airplane down to rivet and bolt level.

Sales Support Subprocess: Preparation of engineering information for use in marketing.

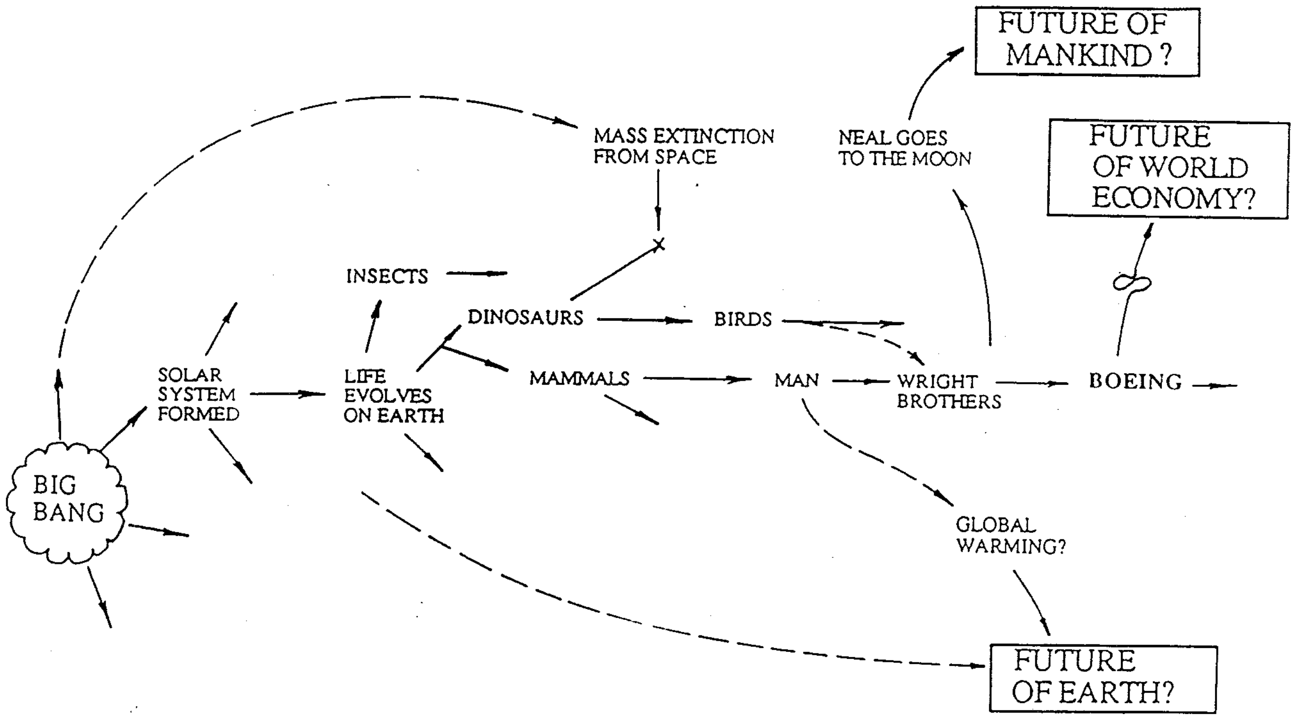
THE HISTORY OF AVIATION
(THE TRADITIONAL VIEW)



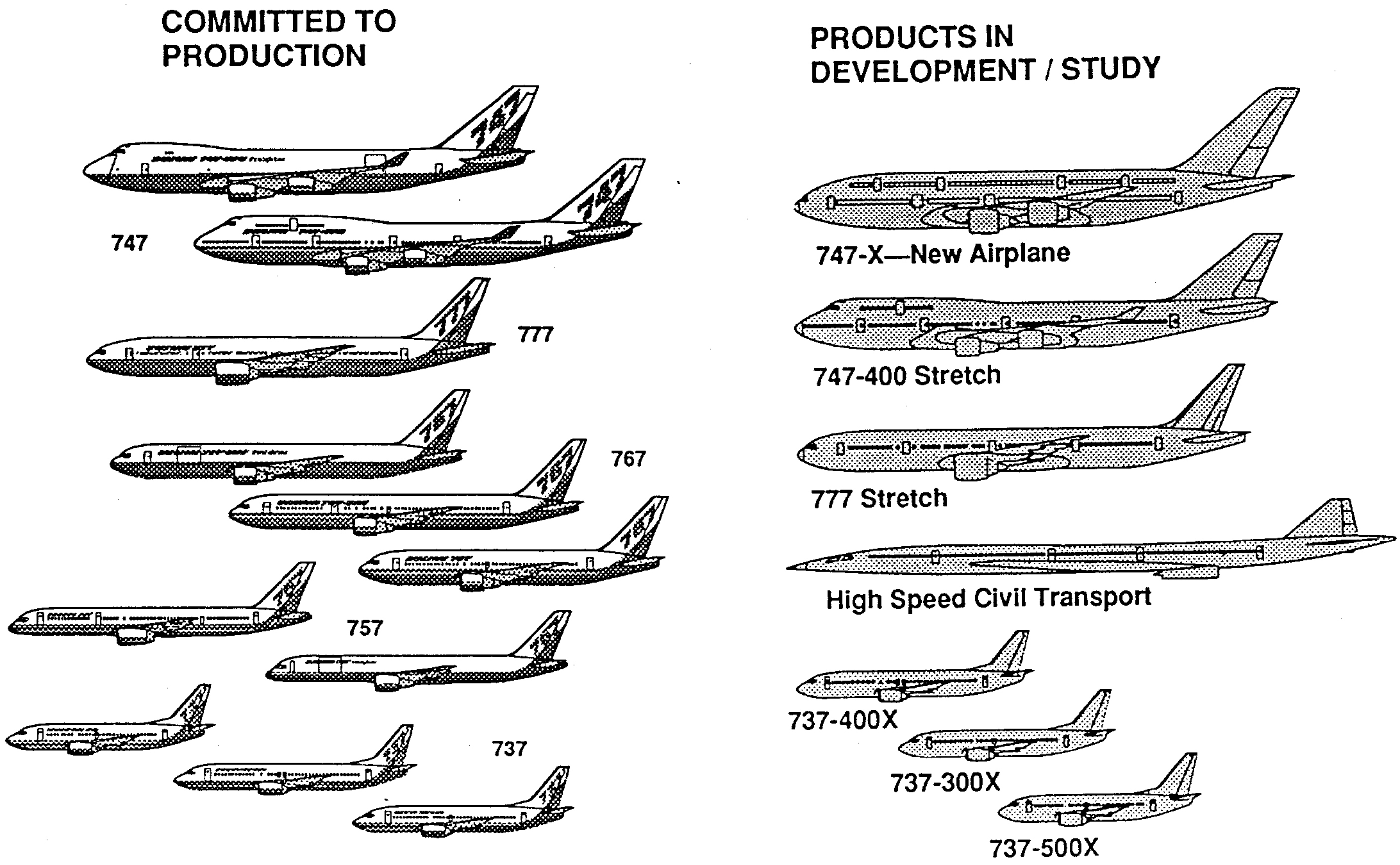


A MORE COMPLETE HISTORY of AVIATION

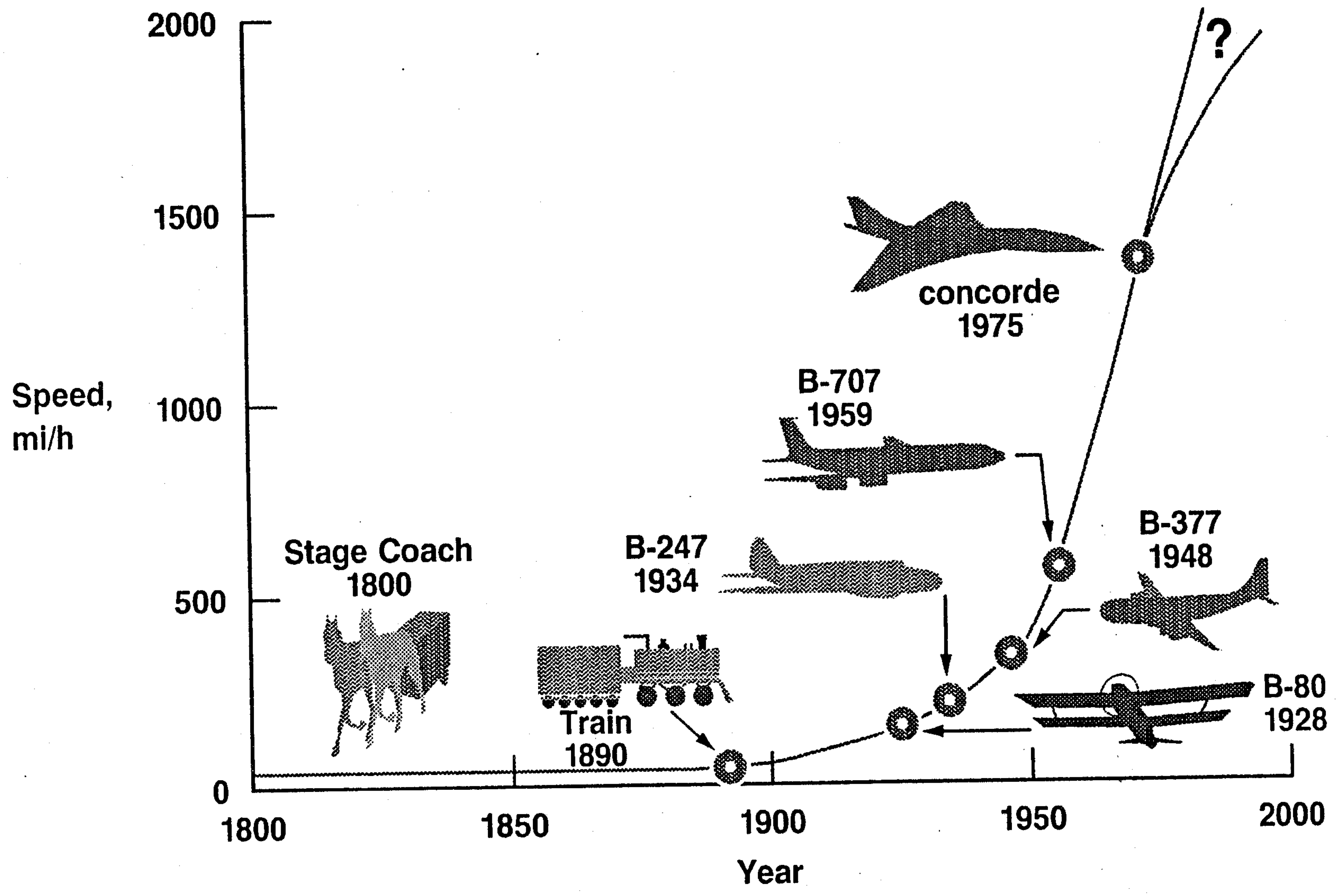
A COSMIC VIEW OF THE ORIGINS AND FUTURE OF FLIGHT



'Possibles' could enlarge Boeing family of airplanes



Commercial Travel Speeds, 1800 A.D. - 2000 A.D.



PERSPECTIVES IN BIOLOGY AND MEDICINE
Volume 29 · Number 3, Part 1 · Spring 1986

Toward a General Theory of Optimal Locomotion

a = speed of sound (speed at which a pressure disturbance is propagated)
AR = aspect ratio, b^2/S
b = wingspan
c = wing or airfoil chord
$\bar{c}$ = average wing chord, S/b
C_D, C_L = three-dimensional-configuration drag and lift coefficients, force/qS
D = drag (fluid-resistance) force
E = energy consumption
F = force
g = acceleration due to gravity
L = lift force
L, l = characteristic length
M, m = mass
M = Mach number (V/a)
P = power
q = dynamic pressure ($\rho V^2/2$)
R = range (distance traveled)
Re = Reynolds number ($V\bar{c}/\nu$)
S = wing area
T = thrust
t = time
U = payload weight
V = speed
W = weight
x, y, z = Longitudinal, lateral, and vertical coordinates
$\dot{z}$ = vertical velocity (sink rate)
α = angle of attack
ν = kinematic viscosity
ρ = air density
Φ = objective function or index of performance

- Direct Operating Cost $= \dfrac{\text{Trip Cost}}{\text{Passengers x Range}} = \$/\text{SEAT - MILE}$
- Productivity Index $= \dfrac{\text{Useful Load}}{\text{Gross Weight}} \text{ x Speed} = \dfrac{U}{W} \text{ x } V$
- Transport Economy Index $= \dfrac{\text{Power}}{\text{Weight x Speed}} = \dfrac{P}{WV}$

$$= \frac{\text{Energy Consumed}}{\text{Weight x Distance Traveled}}$$

Let us proceed with the present inquiry by defining the *purpose* of any system capable of locomotion to be to transport some "load" from one point in space to another. Such a "load" may be only the device itself (e.g., an animal in search of food) or the device plus its payload, as in the case of a commercial vehicle such as a truck. One may further hypothesize that to be viable, the system must operate "economically," whatever that may mean. The object now is to derive quantitative indices that describe this transportation process, and a very simple way to do this is to use dimensional analysis.

Assume that at least the technological portion of the transportation problem can be described by combinations of the following quantities (expressible in turn by the fundamental units of mass $[m]$, length $[l]$, and time $[t]$): W = the total operating weight of the system (this is also one measure of "size")—$[W] = (m{\cdot}l)/t^2$; U = the "useful" load to be transported—$[U] = (m{\cdot}l)/t^2$; P = the power required to move the system—$[P] = (m{\cdot}l)^2/t^3$; V = the speed at which the system travels—$[V] = l/t$; and R = the distance to be traveled—$[R] = l$.

So far each of these quantities has a clear intuitive meaning in the context of the transportation problem. The set is incomplete, however, because it does not contain a quantity explicitly describing the economics of the transportation process. One can easily argue that economics are included implicitly in these basic parameters. For example, it is known that there is a strong correlation between a vehicle's cost and its weight. As the author's strength-of-materials professor used to say (at least once a day), "You buy steel by the pound." Whatever you do to the steel in making the product, the cost is still proportional to the weight of the basic raw material. Likewise, "time is money" goes the cliché, and if one is transporting perishable goods the combination of speed and distance traveled yields time that may be convertible to profit or loss in dollars. And for a given propulsion scheme the power required is proportional to the fuel consumed, and the fuel cost can be computed directly in dollars. All of this is far too circuitous, however, and to complete the set, let us select an easily quantifiable economic parameter—the energy consumption $[E]$, where $[E] = m{\cdot}l^2/t^2$.

We now have a set of six parameters (W, U, P, R, V, and E) in three basic dimensions (m, l, and t). According to dimensional analysis (Buckingham's Pi-theorem) it is possible to form three nondimensional groups of the six parameters—yielding, it is hoped, the equivalent of the Mach or Reynolds numbers of the transportation process. By inspection, a possible set is

$$\begin{aligned} \Phi_1 &= P/WV \\ \Phi_2 &= E/WR \\ \Phi_3 &= U/W \end{aligned} \qquad (1)$$

Having performed this little exercise, one asks, so what? A little thought and a review of the literature show that several investigators have had a good time with these parameter groups, that they have interesting physical meanings, and that one even has a name. The first group (P/WV) is usually referred to as the "transport-economy index." To clarify its meaning, consider the following further manipulations:

Assume that in the transportation process the motion is steady—that is, that V is constant. In this case the "tractive force" (T) producing the motion is equal to the sum of the forces (F) resisting the motion. For flying devices the tractive force, T, is the thrust (T) and the resisting force, F, is the drag (D). Now we observe that

$$R = Vt, \text{ and } P = E/t = E\ V/R = TV = FV. \tag{2}$$

Thus we find that

$$\Phi_1 = P/WV = EV/WRV = E/WR = \Phi_2, \tag{3}$$

and that the transport-economy index (P/WV) is the energy consumed per unit weight per unit distance traveled in the transportation process. Furthermore, if one confines one's attention to flying devices (and assumes either that the power required is that delivered directly to the air or that there is no aeromechanical loss in the system), then

$$\Phi_1 = P/WV = TV/WV = T/W = (L/D)^{-1}, \tag{4}$$

where L = lift = W, and we find that the transport-economy index is merely the reciprocal of the flight vehicle's lift-to-drag ratio. For subsonic flying devices it can further be shown (using relations from the following section on variations in vehicle size with weight) that

$$\Phi_1 = P/WV \sim V^2/W^{1/3}, \tag{5}$$

since $P = TV = DV, D \sim V^2S$, and $S \sim W^{2/3}$, and (Φ_1 decreasing → good). But again, so what? What new clarifications of the overall transportation problem—and of its "optimization"—does this bit of arithmetic provide?

Two examples, one due to engineers and the other due to a biologist, are of interest. The first example is from a classic paper entitled "What Price Speed," written in 1950 by Gabrielli and von Karman [1]. Having discovered the transport-economy index, the authors set about collecting, from standard references, power, weight, and speed data for a wide variety of transportation devices. An immediate difficulty in such a search is that standard references seldom list the optimum values of such variables—rather, they generally list merely extremes. Thus these authors based their analysis on values of maximum speed, maximum uninstalled power, and maximum gross weight. Thus, in their paper $P/WV = P\text{max}/W\text{max}\cdot V\text{max} \neq 1/(L/D)\text{max}$.

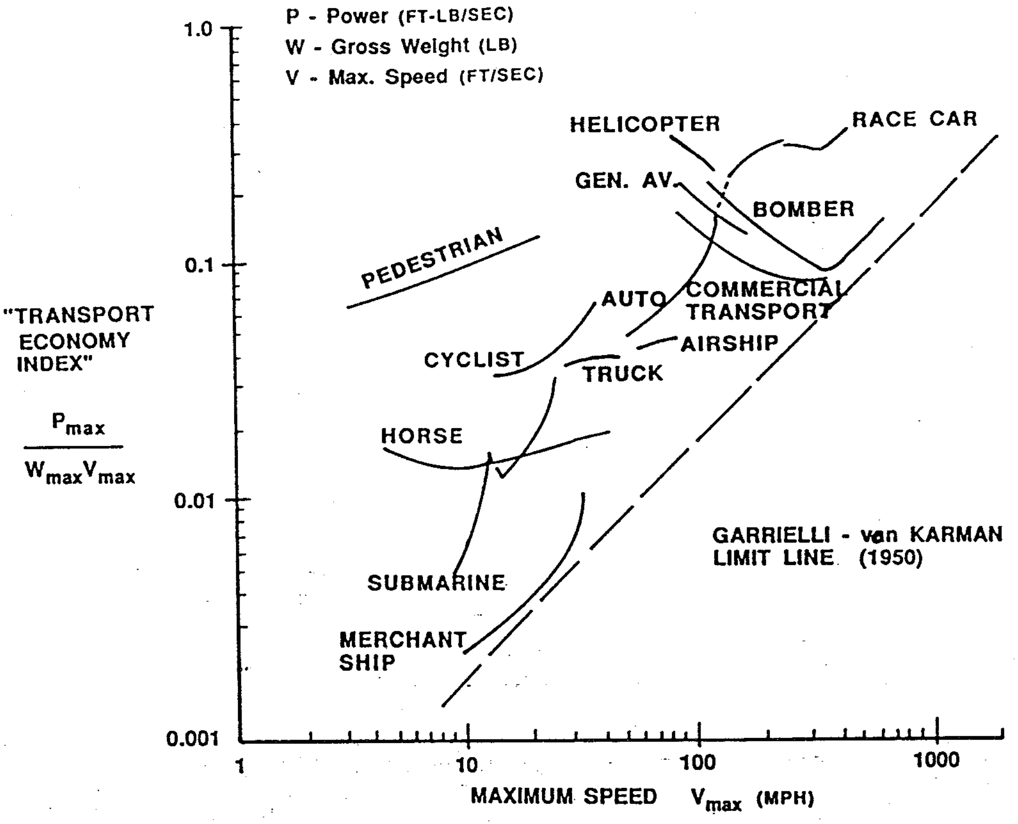


Fig. 2 VARIATION IN "MAXIMUM TRANSPORT ECONOMY INDEX" WITH MAXIMUM SPEED (SINGLE UNIT VEHICLES)

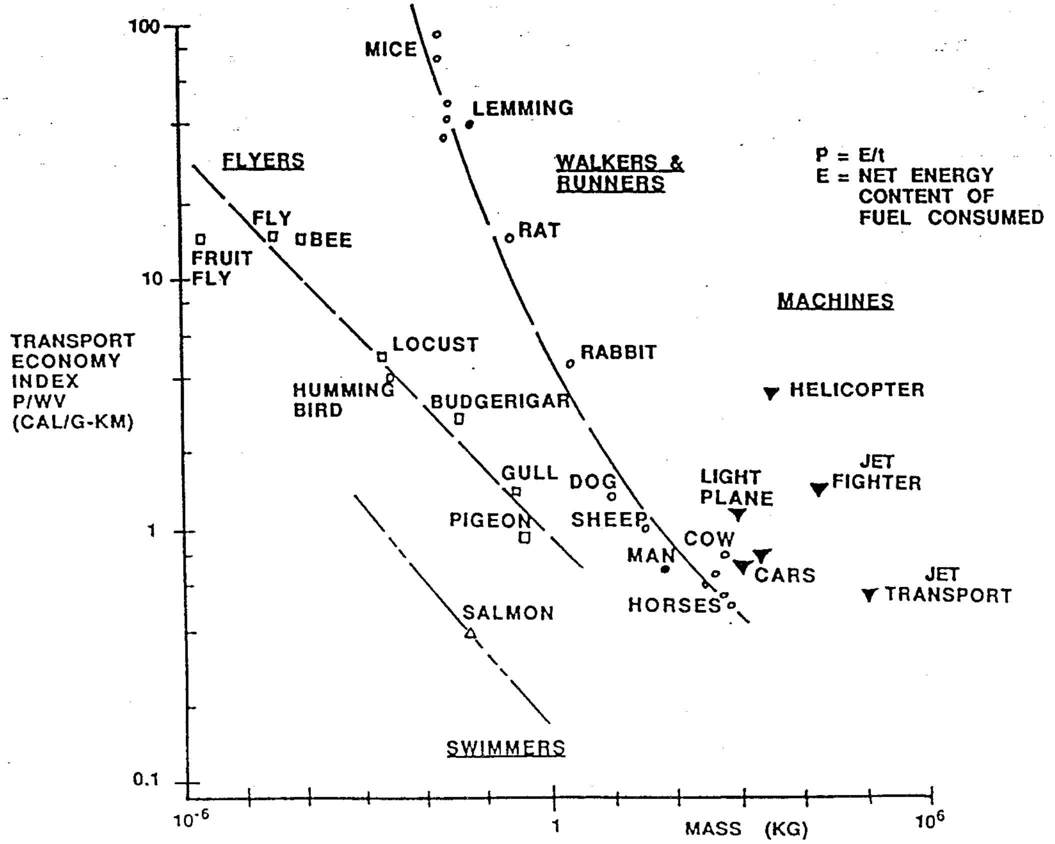


Fig.3 VARIATION IN MINIMUM TRANSPORT ECONOMY INDEX WITH MASS (TUCKER, 1971)

With large samples of data for each type of vehicle considered, Gabrielli and von Karman plotted the value of *P*max/*W*max · *V*max = *T*max/*W*max (calling *T*/*W* the "specific tractive force") versus speed (*V*). Next they observed that if only data for "single-unit" vehicles (i.e., excluding multiunit trains, tractor-trailer trucks, etc.) were considered, there appeared to be a limiting-line relation in speed beyond which the values of maximum transport economy or specific tractive force resulted in "uneconomical" vehicles. Stated another way, if one wished to produce a specific type of vehicle (an automobile, transport airplane, etc.) capable of traveling at a certain speed, one had to pay an appropriate minimum price in terms of energy consumed per unit weight per unit distance traveled. The basic Gabrielli–von Karman plot demonstrating this result is shown in figure 2. Periodically, subsequent investigators have updated the analysis and made attempts to derive this limiting-line relationship theoretically. While attempts at theoretical prediction have been unsuccessful, later statistical analyses indicate that the limit-line relation shown by the original authors still exists—but that it is technology dependent, moving parallel to itself to the right by a small increment each decade.

The second interesting study employing the transport-economy index was done by the biologist Vance Tucker at Duke University. In this case Tucker [2] was interested in the relative energetic requirements of various biological systems and used data from experiments on the "optimum" energy consumption of such systems. Dividing his (limited) data into those for swimming, flying, and walking/running systems, he plotted (*P*/*WV*)min versus weight to produce figure 3.

What one observes from figure 3 is that if one wants to transport something in the most economical way possible, making it swim or float would be the choice. Flying is the next best way to go, and walking is a poor third choice for devices of equal weight. The second trend shown in figure 3 is that for the biological devices considered, there is a dramatic improvement in economy with increasing size. For example, considering the category of walker/runners, one sees that mice at the upper end of the line should not attempt to migrate, since they are nearly two orders of magnitude less economical than horses and elephants, which are at the other end of the line.

Finally, we observe the apparently poor relative energy economy of man-made devices, compared to that of their biological counterparts. Ignoring the fact that the man-made vehicles are "commercial" (i.e., that they carry some discrete *pay*load) versus the fact that the biological devices merely travel professionally (they move about to find food and thus make a living), the discrepancy between the two is due to the trade that has been made between absolute economy, in the biological systems, and speed (which determines productivity), in the man-made commercial vehicles.

Before moving on to the question of productivity versus energy economy, it is interesting to further examine the aerodynamic efficiency

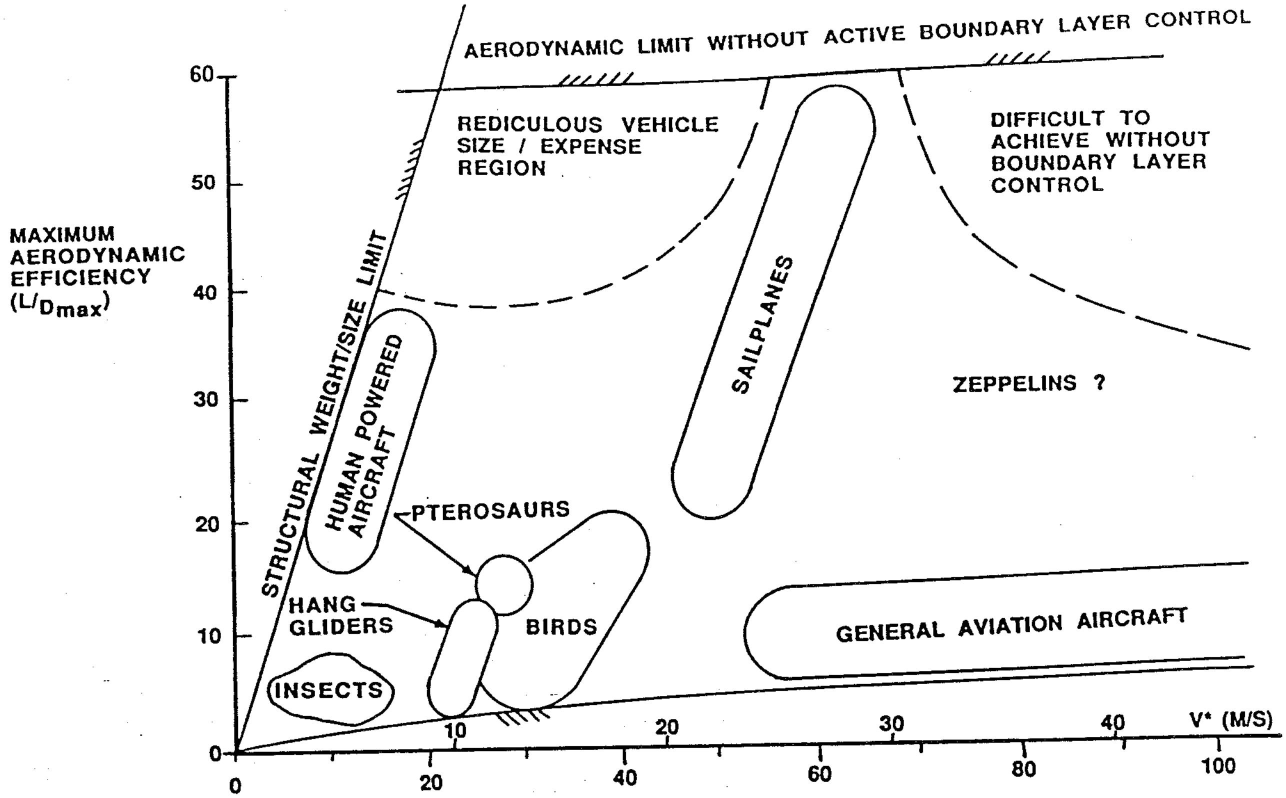


Fig.4 APPROXIMATE BOUNDARIES of the FEASIBLE LOW-SPEED SPECTRUM

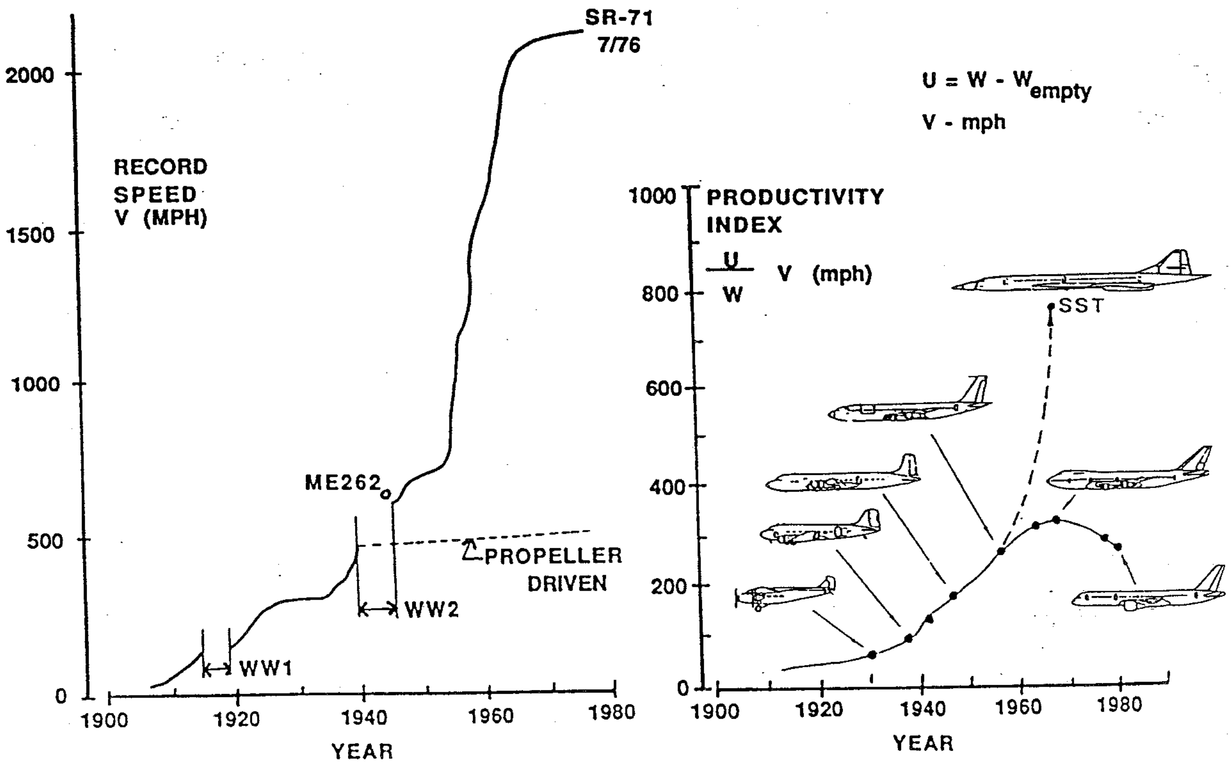


Fig.5 TRENDS IN WORLD SPEED RECORD and COMMERCIAL AIRPLANE PRODUCTIVITY INDEX WITH HISTORICAL TIME

(maximum lift-to-drag ratio) of a variety of low-speed flying devices (fig. 4). From the information in figures 3 and 4 one might conclude that, if one were prepared to redesign the wing to reduce the cruise speed of a Boeing 747 to the value for a large bird, a machine of unprecedented economy (compared to any natural counterpart) might be produced. On the other hand, no natural device is capable of flying at the speed of the actual 747. Lest one become arrogant about man's ability to excel nature, however, it should be observed that the 747 remains incapable of laying eggs and reproducing itself.

To complete the present (admittedly simplistic) outline story of transportation, it should be noted that the notion of absolute transport economy, as reflected by equations (3) and (5), has played little if any part in aviation over the first 70 years of its development. If one doubts this, one need only examine figure 5, which shows the trend in absolute world speed records since 1906 (when such records were first recognized). The auxiliary plot in figure 5 shows the corresponding trend in the measure that has driven commercial aviation, the so-called productivity index.

$$\Phi = \frac{U}{W} V \text{ (the productivity index, which is a dimensional quantity).} \quad (6)$$

Note that Φ increasing → good.

Here we see dramatic progress, and it will remain of interest to see how the inherent conflict between transport economy (eq. [5]) and productivity (eq. [6]) is reconciled as fuel costs rise and fossil-fuel resources decline in the decades to come. The flattening in the trend in the productivity index in commercial aviation development during the last decade is already clearly reflective of a realization that neither the world in which we live nor the supply of natural resources readily available to us is any longer to be considered infinite. Thus the productivity imperative, which leads naturally and inexorably from DC-3 to Boeing 707 to supersonic transport (SST) (based on 10¢/gal jet fuel), has been dramatically arrested by the rise of OPEC and a far-reaching questioning of many of the assumptions on which past technological progress had been based.

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On Being the Correct Size

Having examined in broad outline the energy-consumption-versus-productivity relations in a generalized transportation or locomotion process, we can now examine in the same spirit such interesting questions as, How big (or small) can an animal be? and, Are there general relations between size and weight for all the things that fly?

In the investigation of the first of these questions, a useful organizing principle is provided by the simple square-cube law (see fig. 6). The size-weight arguments to be advanced here on the basis of the simple square-cube law must be considered to be first-order preliminary only. An excellent critique of the square-cube law applied to biological systems, together with a more sophisticated analysis, is presented by McMahon [3]. The author also acknowledges his debt to J. B. S. Haldane and his wonderful little essay "On Being the Right Size."

The square-cube law says that the dimensions (size) of homogeneous, geometrically similar objects can be described by some characteristic length (L). This done, all surface or cross-sectional areas are proportional to the characteristic length squared (L^2), and the weight is proportional to the volume or the characteristic dimension cubed (L^3).

With these notions in hand let us begin by applying them to the geometry of a class of grazing animals—specifically, consider a spherical cow (fig. 6). Assume that the basic materials from which we wish to construct a family of such cows have common properties of yield or ultimate stress and so on. The first of our cows (A) will not be ambitious in scale, and its conservative body and head are easily supported by the nimble "slender-column" legs of an antelope or gazelle.

Our second attempt at cow design (B) is bolder, involving doubling the size (L) of the first prototype. If we attempt to maintain strict geometric similarity between our first and second designs, however, we run into

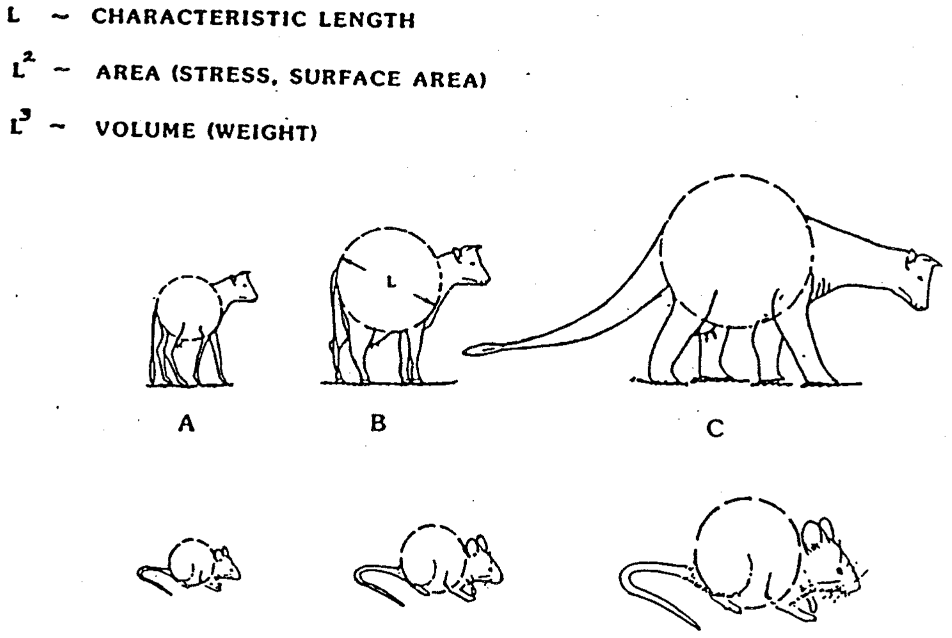

FIG. 6.—The square-cube law

trouble. Cow *B*, according to the square-cube law, must weigh eight times as much as cow *A*, but the cross-sectional area of the supporting legs has only increased fourfold. Assuming that the structure of cow *A* had been properly optimized and that the stress levels in the legs had been established such that no excess bone material beyond that necessary to support the weight was used, then the stress level in cow *B*'s legs would exceed the stress level in the legs of cow *A* by a factor of two—and cow *B* would collapse. To avoid this difficulty, we must abandon strict geometric similarity (at least in the leg structure) and thicken the legs of the *B*-model cow, with a consequent loss in agility.

Playing this game on to absurdity, we eventually arrive at the absolute cow, wherein the legs necessary to support the weight become equal to the dimensions of the brute's body, locomotion is no longer possible, and, unless grass grows very rapidly under its mouth, it will die. Somewhere between this extreme and cow *C* lie the elephant and the now extinct brontosaurus, representing practical extremes in giantism in "spherical" grazing animals.

Smallness may also be investigated using square-cube law arguments. In this case consider the giant spherical mouse. Our family of mice are warm-blooded and thus must maintain some level of internal temperature. To do so the job of these mice is to eat foods of high caloric content. In this process about 20 percent of the energy content of the food consumed can be converted by the mouse's muscles into useful work (e.g., moving about in search of more food, finding a mate, fleeing from predators). The remaining 80 percent goes into heat, which maintains internal temperature, and any excess is transferred from the body surface (which is proportional to the square of the characteristic dimension of the mouse).

In this case, as our mouse shrinks, its heat-conserving mass decreases more rapidly than its surface area, and at some point the poor creature must become truly voracious, eating continuously 24 hours a day, merely to balance its caloric intake with its heat loss—regardless of how much insulating fur it grows. In practice the smallest warm-blooded animal is a species of pygmy shrew about the size of one's thumbnail (see Schmidt-Nielsen [4, p. 187]).

Our interest in this dissertation, however, is in neither cows nor mice but in things that fly. It is thus of interest to evaluate the consequences of the square-cube law vis-à-vis birds, insects, and airplanes, the geometric similarity of which is tenuous at best. Undaunted by this detail, Greenwalt [5] and Hartmann [6] have made the task much easier with their massive compilations of data relating geometric size (wingspan and area, aspect ratio, tail area, etc.) and weights (total wing, muscle, and internal organ) for nearly the entire range of animal and insect fliers. From these sources, supplemented by data from standard aeronautical references (e.g., *Jane's All the World's Aircraft*), it is possible to construct table 1 and figure 7, which relate wing area to vehicle weight and cover 12 orders of magnitude in the latter variable. Also shown are the author's square-cube law curve fits to the entire ranges of both presentations of data.

TABLE 1 REPRESENTATIVE FLYING-DEVICE CHARACTERISTICS

TYPE OF FLYING DEVICE	CHARACTERISTICS						
	Wing Span (b) (m)	Wing Area (S) (m^2)	Aspect Ratio (AR)	Loaded Mass (M) (kg)	Optimum Speed (V) (m/sec)	Maximum Lift-Drag Ratio (L/D_{max})	Wing Loading (M/S) (kg/m^2)
Housefly (*Musca*)	.013	3×10^{-5}	5.6	1.2×10^{-5}	2		.4
Butterfly (*Papillio*)	.082	3.6×10^{-3}	1.87	3×10^{-4}	3.5		.83
Locust (*Schistocerca*)	.10	2×10^{-3}	5.0	2×10^{-3}	4.15	2.2	1.0
Dragonfly (*Aeschna*)	.10	1.85×10^{-3}	5.4	1.5×10^{-3}	10		.85
Pigeon (*Columba*)	.65	.063	6.7	.4	12.4	5.4*	6.35
Fulmar petrel (*Fulmaris*)	1.09	.102	11.7	.725	12.2	8.3*	7.11
Black vulture (*Coragyps*)	1.32	.323	5.4	1.79	12.5	~12*	5.54
	1.44	.364	5.7	2.3	15	~12*	6.32
White-backed vulture (*Gyps*)	2.2	.69	7.0	5.4	13	~14*	7.83
Ruppel's griffon vulture (*Gyps*)	2.5	.83	7.55	7.5	14.5	~15*	9.04
Wandering albatross (*Diomedae*)	3.5	.60	20.4	9.2	20	~20*	15.3
	3.45	.725	16.5	9.8	16	~19*	13.5
Dog-faced bat (*Rousettus*)	.554	.057	5.42	.119	8	6.4	2.09
Pterosaur (*Pteronodon*)	7.0	4.2	11.5	16	9	~14*	3.81
	7.6	4.6	12.5	11.3	8	~14*	2.46
Flying seed (*Zinnonia*)	.15	6.2×10^{-3}	3.63	3×10^{-4}			.05
	.115	5×10^{-3}	2.65	1.75×10^{-4}			.04
Rogallo hang glider	6.58	18.4	2.36	81.5	10	4	4.4
"Quicksilver" hang glider	9.15	10.75	7.8	118	9.8	7	11.0
"Icarus V" hang glider	9.75	14.9	6.4	100	10	8	6.7
VJ-24 hang glider	11.1	15.15	8.15	141	9	9	9.3
"Puffin II" HPA	28.4	36.3	22.2	132	8	36†	3.64
"Toucan" HPA	37.5	55.8	25.2	240	8.25	40†	4.3
"Dumbo" HPA	36.7	44.6	30.2	127	7.45	43.5†	2.85
SF-27M motor glider	15.0	12.1	18.6	370	34.2	31.5	30.6
Schweizer 1-26 sailplane	12.2	14.9	10.0	270	21.6	21.6	18.1
"Standard Cirrus" sailplane	15.0	10.0	22.5	333	26.2	37.9	26.2
ASE-12 sailplane	18.3	13.0	25.8	412	24.6	43.3	31.7
"Nimbus 3" sailplane	24.5	16.8	35.7	703	22.2	~60	41.8
Piper PA-18 "Super Cub"	10.76	16.58	7.0	794	32	10	47.9
Beechcraft "Bonanza"	10.2	16.8	6.2	1417	48	12	84.4
Cessna 310F	10.9	16.3	7.3	2190	56	12	134.4
DC-9-30 jet transport	28.4	93.0	8.7	4.9×10^4	190	17	479.5‡
Boeing 707-320	44.4	283.4	7.2	1.5×10^5	210	18	444.6‡
Boeing 747-200	59.6	511	6.95	3.56×10^5	240	18	584.7‡

*Power-off glide.

†Flight in ground effect (3 m height).

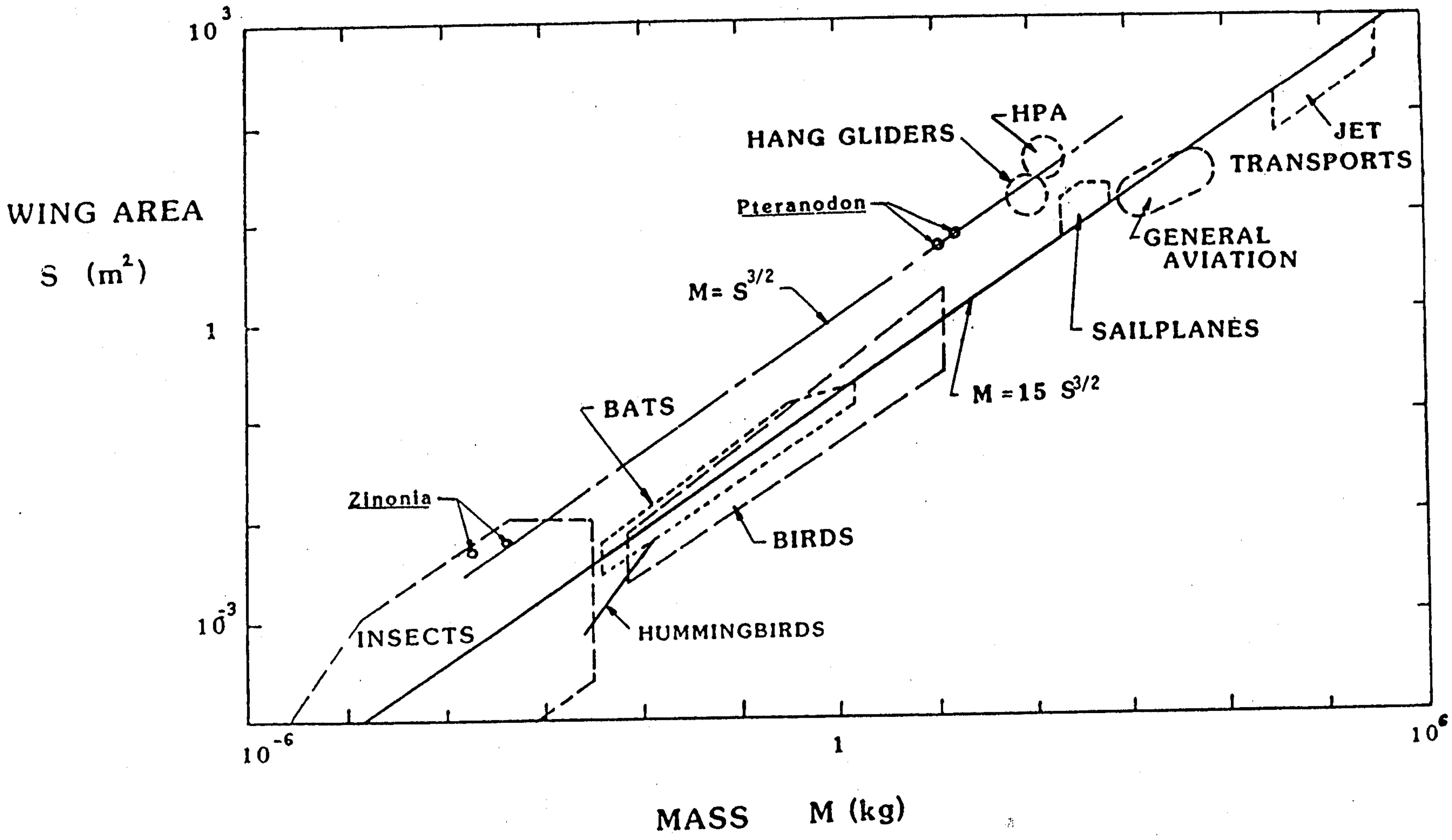

FIG. 7.—Variation in wing area with loaded mass

A casual perusal of the data presented in figure 7 shows that while there is substantial scatter about the global square-cube law mean, particularly in the insect range, basic square-cube law lines do seem to capture the trends over the full range (again, 12 orders of magnitude in mass variation) of all the different types of flying device—with a few noteworthy exceptions. Principal among these exceptions are hummingbirds [5], human-powered airplanes [7], and model airplanes (not demonstrated here). (Note that it can be argued that devices such as human-powered and model airplanes are anomalous because they are "recreational" rather than professional or commercial fliers; thus they are driven by no economic imperative, with size established merely by the basic laws of aerophysics and structural mechanics.)

One can go through a lengthy discussion of the detailed trends in weight versus wing area given in figure 7 for the variety of fliers shown, but for purposes of the present discussion it is only necessary to note the following points: (1) Again, while a single square-cube law line ($M = 15\ S^{3/2}$) captures the trend in most conventional fliers, the deviations from this mean even within a given category (e.g., insects) may be large. (2) If one takes a closer (but not *too* close) look at the data, now basing the assessment on the *way* in which different devices fly, one sees interesting further support for a simple square-cube law variation of mass with wing area. Specifically, if one considers "light gliders" (e.g., the *Zinnonia* seed, butterflies, pterosaurs, and hang gliders), all of these types display the trend $M = S^{3/2}$. Likewise, beetles, turkeys, and general-aviation aircraft can all be connected by another square-cube law trend line, and soaring birds and sailplanes are seen to be roughly equivalent in a square-cube law sense.

Despite the lack of strict geometric similarity of the devices considered in figure 7, there does appear to be a strong pattern in size-weight relations between them, particularly when they are viewed from the proper perspective of their diverse modes of flight. Further discussions of these matters have been published by Cleveland [8].

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The Flight of the Bumblebee and Related Myths of Entomological Engineering

John H. McMasters

Once upon a time, with the inspiration and enthusiasm which seem to come only to the neophyte graduate student, I began the study of the general topic of locomotion, covering the entire range of both natural and man-made devices traveling through the air, on land, and in or on water. I hoped that eventually I could derive some general relations between speed, size, shape, and energy consumption for a variety of locomotion schemes based on the laws of fluid and thermal physics, structural mechanics, and material properties.

It rapidly became apparent, however, that such a comprehensive study would be a ridiculously complex task, requiring a thorough knowledge of a wide range of engineering disciplines, the biological sciences, economics, and history, not to mention the vehicular technologies involved. The topic remained fascinating, however, and the thought occurred to me that by considering the problem in the simplest fundamental terms, I might still find some elementary way of rationally comparing the relative effectiveness of "transportation" devices as dissimilar as horses, submarines, sea gulls, and airplanes. Deriving some simple index or indices, I might then use them to study the parameters of size, weight, and shape which would lead to optimal values for a particular class of transportation device: low-speed flying machines, which were and remain the center of my interest in all this.

"To prove that a pig cannot fly is not to devise a machine that does so"
—Dietrich Küchemann

The results of my initial explorations, completed while I was employed as a designer of expedition tents, were modestly encouraging (McMasters 1974). I have continued ever since on an occasional basis to attempt to demonstrate that rather than being separate, disconnected topics, natural and human flight represent the two halves of a continuous, very broad, and fascinating spectrum. The many configurations of animal, botanical, and man-made flying devices are, in fact, subtly tied together by the underlying requirement that all must obey the same basic laws of chemistry and physics. Further, the range of viable flying devices is restricted by the requirements of the environment (both physical and economic) in which they must operate. Within these constraints, however, the variety of shapes and sizes of fliers is astonishing. It is a territory that, at the time my inquiries began, seemed to be poorly studied in interdisciplinary generality.

I have learned several things from my own studies (McMasters 1986):

—From a purely mechanical point of view, the most efficient way (in terms of energy consumption per unit weight) to get from here to there is to float—very slowly. The next best way to go is flying, and the worst way is running or commuting by automobile.

—It is demonstrable that, with the same expenditure of energy, one can travel faster on a bicycle on a smooth road than one can pedal a human-powered airplane. The advantage of flying becomes apparent, however, when one attempts to ride a bicycle on soft sand or beyond where the road ends at a cliff.

—The faster one attempts to travel in a given mode, the more it costs in terms of pure consumption of energy, and if one wishes to do something out of the ordinary—for example, hover or take-off or land vertically—it costs a lot more.

—The bigger a given transportation device is within a given category, the more economical it is, until it passes a certain point at which it ceases to function as intended. As one of several corollaries to this, small terrestrial mammals should not attempt to migrate unless, like lemmings, they have some ulterior motive.

—The observed differences between and within various categories of traveling devices can be attributed to the fundamental imperatives of physics (e.g., fluid mechanics and the mechanics of materials) and economics. Here it is to be emphasized that all natural devices travel first and foremost professionally, while man-made counterparts may be commercial or recreational, but seldom both. This factor, together with the materials available for manufacture and the range of fluid-dynamic conditions under which they operate, has a profound effect in creating the apparent dissimilarity between jet transports, dragonflies, and hang gliders.

—Man has far outstripped nature in the size and speed of transportation vehicles he has contrived. Lest we become arrogant regarding our ability to excel nature, however, it should be noted that we have yet to devise a

Figure 1. Attempts to bridge the gap between science and engineering in the study of things that fly have been regrettably rare. A notorious example of the occasional outright opposition of scientists and engineers is the apocryphal story of an aerodynamicist who allegedly proved that bumblebees should not be able to fly. It is easy to see how the bumblebee's appearance could have given rise to such a story. How could such flimsy wings support such a large body? (Animals Animals/Stephen Dalton.)

AERODYNAMICIST PROVES BUMBLEBEES CAN'T FLY!

Sun

Guru remains in a trance for 20 years

...without food or drink

Psychic Sarah tells how...

CRYSTALS

CAN BRING YOU GLOWING HEALTH

DINOSAUR SHOCKER!

The jungles are full of them, says famed explorer

Woman claims she gave birth to a slimy mudfish

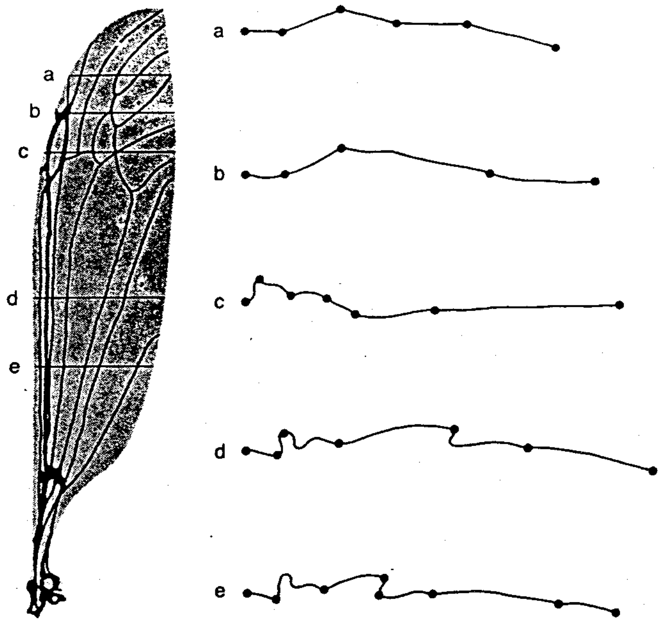
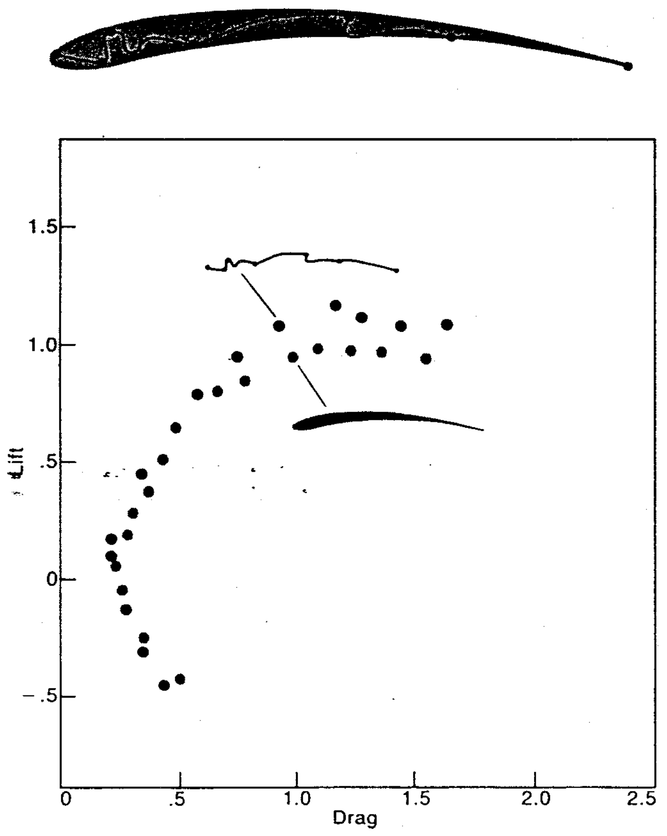


Figure 2. The work of numerous biologists and aerodynamicists during the past fifty years—sometimes in collaboration—has solved some of the mysteries of flight, including the problem of the bumblebee. Microscopic examinations of insect wings, like the crane fly wing shown above, reveal that the cross sections are highly irregular. Directly below, a smooth envelope contour resembling a conventional airplane airfoil has been superimposed on one of the irregular cross sections. As shown in the graph at the bottom, the insect wing cross section generates lift and drag characteristics similar to those generated by the airplane airfoil. (After Rees 1975a, 1975b.)



flying machine that can reproduce itself simply by laying eggs.

—Historians of technology have romanticized the inspiration natural models have provided the inventors of devices such as flying machines. The insights provided by natural models are either deviously arcane (the Wright brothers' recognition that a practical airplane, as well as being capable of merely "flying," must be stable and controllable) or seriously misleading (Leonardo's ornithopter).

While all these observations are arguably simplistic or overstated, they do (when supported with appropriate data) begin to provide a framework for investigating the myriad details in a very complicated and frequently confusing overall pattern. From this base one can make any number of forays into particular topics, such as the old story that bumblebees shouldn't be able to fly (Fig. 1).

Bumblebee aerodynamics

At present there are about 800,000 named species of insects, and it is estimated that there are as many more that have not yet been formally classified. A very large percentage of these insects fly, ranging in size from the nearly microscopic thrips to tropical butterflies with wing spans of 10 to 12 cm. Far more dramatic are fossil remains of dragonflies with wings spanning up to 70 cm (Callahan 1962). The basic design has been successful enough to survive for 300 million years, and insects in general exhibit a marvelous array of ingenious solutions to very difficult design and manufacturing problems. Despite this, my various attempts to interest the students in my airplane design classes in bug design usually elicit the response, "Well, that's all very interesting, we suppose, but they're not in our product line and we'd really rather not hear about it." So much for creativity and expanded horizons in the engineering sciences.

To understand fully the diverse forms of flying insects, it is necessary to study a number of equally diverse topics, from very low Reynolds number unsteady aerodynamics and mechanical systems design to thermodynamics and physiology. Even before such studies begin, however, one hears the antitechnology jibe aimed at engineers in general and aerodynamicists in particular: "Didn't an aerodynamicist prove that bumblebees can't fly?" Whoever this notorious individual was, he has left his legacy for all of us aerodynamicists who follow to wear about our necks like an albatross. Discovery of who this individual was and how the myth originated has provided a sometimes frustrating diversion from my more serious inquiries.

It is known that the bumblebee story was already

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circulating in German technical universities in the early 1930s, apparently beginning in the circle of students surrounding our "founding father" Ludwig Prandtl at Göttingen. The identity of the specific aerodynamicist continued to elude me until recently, when I learned from a reliable source that a possible candidate may be a Swiss professor (now deceased) who became famous for his pioneering work in supersonic gas dynamics in the 1930s and 1940s.

The aerodynamicist himself later discovered part of his error by examining a bee's wing under a microscope—but not, alas, before the myth was born in the hands of overeager journalists

In the received story, the aerodynamicist was engaged one evening in light dinner-table conversation with a biologist, who asked in passing for enlightenment about the aerodynamic capabilities of the wings of bees and wasps. Intrigued by the question, the aerodynamicist did some preliminary calculations based on the assumption that the wings were more-or-less smooth, flat plates. Because of the very low Reynolds numbers involved, he further assumed that the flow over the wings would be that associated with ordinary laminar boundary layers and thus prone to easy separation (or wing stalling)—a situation similar to that which leads sporting goods manufacturers to make golf balls with dimpled surfaces (Davies 1949; Wegener 1986). The resulting calculations "proved" the bee to be incapable of flight.

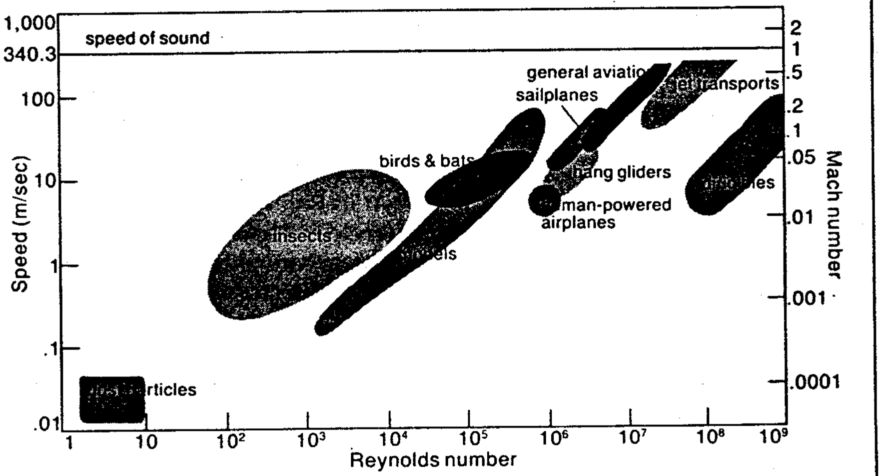
As we will see presently, the assumptions were almost wildly wrong, and the aerodynamicist himself later discovered part of his error by examining a bee's wing under a microscope—but not, alas, before the myth was born in the hands of overeager journalists. Pringle (1957) has provided a good critique of early analyses of insect flight, naming a number of individuals who may have contributed to or reinforced the bumblebee myth. In the end, however, we seem to have no better explanation for the origin of the myth than the story offered above, although we now have a fascinating book by Heinrich (1979) which shows the reality of the bumblebee to be far more interesting than apocryphal proofs that it cannot fly.

The design of insect wings

Our understanding of the details of insect flight has greatly increased over the past fifty years, owing to advances in experimental techniques (particularly high-speed photography) and computational capabilities (Ellington 1984), and to a general improvement in both aerodynamic and biological knowledge. Much of this improved understanding has been contributed by the sort of rare collaboration between biologists and aerodynamicists that is reflected in the work of Von Holst and Küchemann (1942), Weis-Fogh and Jensen (1956) and Lighthill (1975). Indeed, the monumental work of Torkel Weis-Fogh and Martin Jensen (see also Jensen 1956), intended in part to discover the inherent migratory capability of one of the biblical plagues, shed a great deal of light on the complex problem of insect flight and, more importantly perhaps, served as a model for interdisciplinary investigations of animal flight in general.

A particularly interesting study of insect wings is that of Rees (1975a, 1975b). Although the experimental results he presents are at best only qualitatively correct, what emerges is a remarkable example of wings designed to provide satisfactory aerodynamic characteristics (at the Reynolds numbers in question) coupled with desirable structural and mechanical properties, which at

A guide to Reynolds numbers



Whenever an object moves through a fluid such as air or water, forces are generated by the continual acceleration (and/or deceleration) of the fluid elements surrounding it. According to Newton's second law of motion, the sum of these forces—pressure, viscous friction, and gravity—is equal to the inertial force—mass times acceleration. This graph shows the Reynolds number range of a wide variety of natural and man-made fliers, from dust particles to jet airplanes.

Reynolds numbers, named for the British mechanical engineer Osborne Reynolds (1842–1912), quantify the relationship between viscous force and inertial force: Re = inertial force / viscous force = fluid density × speed × length / fluid viscosity. (For a wing or airfoil, the customary length is the chord.) A low Reynolds number—that is, one produced by small size and/or low speed, as in the case of insects—means that the viscous forces are relatively large; a high Reynolds number means that the viscous forces are relatively small, though far from negligible.

Reynolds numbers and Mach numbers are two of the so-called fluid-dynamic similarity parameters that are extremely important in aeronautical engineering for their use in testing scale models. If a scale model of a proposed device is tested (for example, in a wind tunnel) such that both Mach and Reynolds numbers of the full-size counterpart are matched, the behavior of the model should be identical to that of the device.

the same time are readily manufacturable from the materials at hand. As Rees notes (1975a), "Selection is likely to have resulted in the evolution of insect wings which combine aerodynamic efficiency with a rotational moment of inertia about the wing base small enough to reduce as far as possible the energy expenditure involved in their repeated accelerations. Their construction has to leave them stiff enough to remain aerodynamically efficient when under inertial or aerodynamic load, and free from buckling, however light they become. Insect wings are very light structures—11 g m^{-2} in the dragonfly *Aeschna cyanea*, 16.7 g m^{-2} in *Locusta migratoria* and 7.4 g m^{-2} in *Tipula* sp."

Based on Rees's work and that of the other researchers cited above, the story then goes like this: When the time comes for an insect to metamorphose from the larval state into its final form, it emerges as a legged body to which are attached limp, wet sacks where the wings will be. This caricature of an imago then positions itself, perhaps on a convenient branch of a tree, and begins to pump fluid through the veins in the wing sacks, expanding them to their full extent. Under the action of sun and breeze, the fluid then evaporates, leaving a series of hard hollow tubes connected by trusslike cross members, while the intervening spaces are covered by the thin membrane of the dried and collapsed sack material. The film that thus makes up the lifting surface is on the order of a mere 2 to 6 μm in thickness. As shown in Figure 2, this final structure is far from flat, but neither does it have the smooth, continuous, cambered form of a conventional airfoil. Rather, it is a ragged, rough surface in cross section, which as it turns out has major structural advantages without aerodynamic penalty.

Langmuir calculated that the impact of a 0.3-gram botfly traveling at Mach 1.1 would produce a wound equivalent to that of a large-caliber pistol bullet

While the details of the unsteady, low Reynolds number flow over a wing of such contour are not yet fully understood—and are extremely difficult to measure accurately—experiments by Rees (1975b) and work by Vogel (1967), Nachtigall (1974), Newman et al. (1977), Rossow (1978), Sompes and Luttges (1985), Buckholz (1986), Bschorr (1988), and Reavis and Luttges (1988) have shed important light on the subject. If we take Rees's results as an example, it appears that when one conducts comparison tests at the same Reynolds numbers (typically 600 to 5,000) on the insect airfoil and a smooth envelope contour resembling an airplane airfoil, even in a steady flow the insect airfoil may be superior in both maximum lift and in drag. Thus, the contour the insect can manufacture, if not optimum aerodynamically, certainly represents a good shot at the problem in a very difficult flow regime.

Altogether, the picture that Rees and others (e.g., Hertel 1966) draw for us shows a remarkable piece of systems engineering in its best sense. The neophyte designer of an airplane wing who approaches the problem only from the perspective of aerodynamic optimization might well profit from the study of examples such as this one—provided by mere entomologists.

The case of the supersonic deerfly

While engineers, and aerodynamicists in particular, remain the losers in the exchange with the popular press over the flight of bumblebees, there is an amusing story in which an entomologist's unwitting tall tale was demolished by a famous physical chemist through thought, a few simple calculations, and a trivial experiment. People frequently overestimate the speed of moving objects casually observed, but perhaps the most amazing example of this was the claim by the entomologist that a deer botfly could reach supersonic speeds. This author of an article in the *Journal of the New York Entomological Society* asserted that "on 12,000-foot summits in New Mexico I have seen pass me at an incredible velocity what were quite certainly the males of Cephenemyia. I could barely distinguish that something had passed—only a brownish blur in the air of about the right size for these flies and without sense of form. As closely as I can estimate, their speed must have approximated 400 yards per second" (Townsend 1927). The story was widely reprinted, appearing in various books of purported world records. It also annoyed the Nobel Prize–winning chemist Irving Langmuir exceedingly, and he set about deflating the claim (Langmuir 1938).

The first problem with the entomologist's estimate was that 400 yards per second at 12,000 feet happens to be about 110% of the speed of sound at that altitude (Mach 1.1), and no sonic boom was reported. Langmuir calculated that the most optimistic estimate of resistance force or drag due to the botfly's body (ignoring the wings), required it to generate nearly half a horsepower. In addition, the dynamic pressure encountered during flight at 800 miles per hour would be sufficient to crush its head.

Botflies tend not to be very graceful fliers, even running into things on occasion while zipping around—deer and people, for example. Langmuir calculated that the impact of a 0.3-gram botfly traveling at Mach 1.1 would produce a wound equivalent to that of a large-caliber pistol bullet, making hiking on the "summits in New Mexico" a somewhat risky business.

Finally, Langmuir checked the circumstances under which the observations were made by attaching a small weight the size of a botfly on the end of a thread and whirling it around to find the upper and lower bounds of speed at which such an object appears as "a brownish blur in the air." The mean value turned out to be about 25 mph (10 yards/sec), which is consistent with energy consumption requirements of the actual botfly. Thus the botfly was eliminated from the ranks of the fastest flying machines, although the entomologist's rather than Langmuir's estimates continued to appear in popular reference books for several years thereafter.

What began over twenty years ago as a naive but serious enterprise has burgeoned into a sort of merry drunkard's walk through a range of topics no self-respecting aeronautical engineer has any business getting into. My inquiries have continued despite the continual reminders from my professional colleagues that there is very little commercial value in designing better butterflies and thus no merit at all in understanding how they work in the first place. This undoubtedly accounts for the fact that the number of entomological engineers worldwide (neglecting gene fiddlers) can be counted on the fingers of two hands. On another hand, however, one can count the advantages of having a broader understanding of the underlying principles of the flight of everything that flies in making one a better designer of devices that do have commercial and/or aesthetic value. Moreover, it is valuable to stand very far back once in a while from the details of what one is deeply immersed in on a daily basis and attempt to see a whole picture—to see one's work in full perspective. The effort can be immensely refreshing—and humbling.

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POST SCRIPT

As a final note on the bumble bee/aerodynamicist controversy, I now have, thanks to the generosity of several readers of this article, all the photocopies I need of A. Magnan's book ***Le Vol Des Insects*** (Hermann and Cle, Paris, 1934). On page 8 of the introduction, one finds the statement:

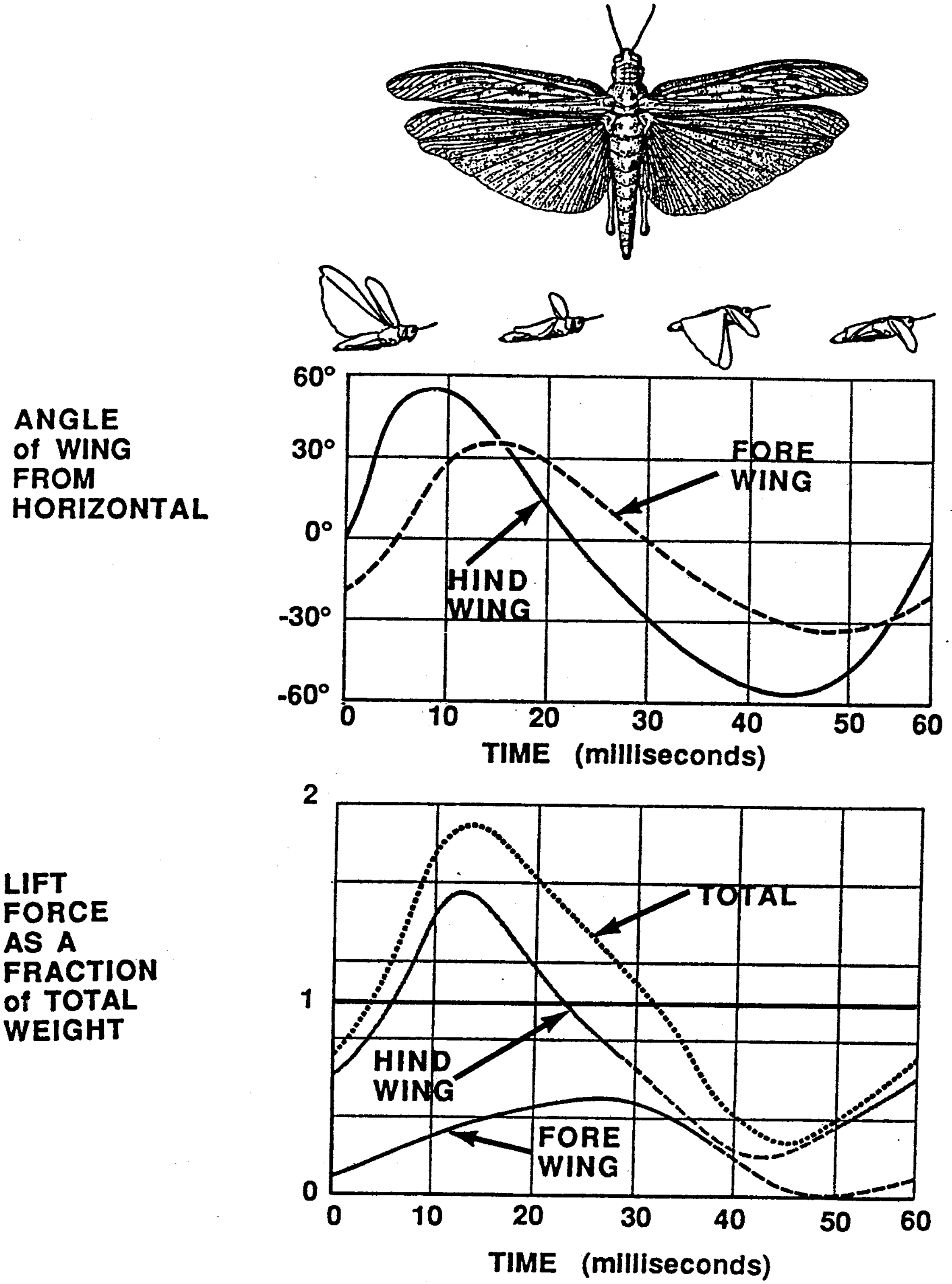
> *"Tout d'abord, pouss'e par ce qui fait en aviation, j'ai applique' aux insectes les lois de la resistance del'air, et je suis arrive' avec* M. SAINTE-LAGUE *a cette conclusion que leur vol est impossible."*

The subsequent discussion in the text suggests (although my French is nonexistent) the reason for this state of affairs is rather similar to that discussed in my version of the "bumble bee myth". So much for that! As I suspected in the beginning, the whole myth is probably polyphyletic in its origins and my version remains as serviceable as any. Beyond the myth, however, newer information on the realities of bumble bee and insect flight may be found in:

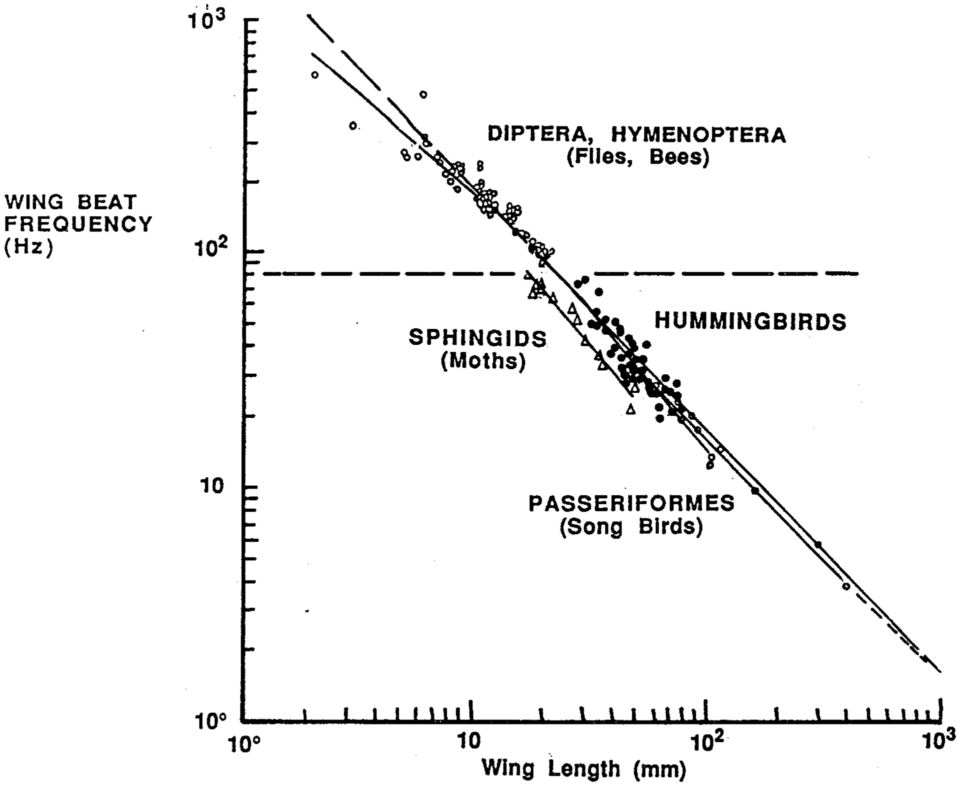
Dudley, T. R. and Ellington, C. P. (1990), "Mechanics of Forward Flight in Bumblebees, Kinematics and Morphology", *J. Exp. Biol.*, Vol 148, pp. 19-52.

__________________________(1990), "Mechanics of Forward Flight in Bumblebees. II. Quasi-Steady Lift and Power Requirements", *J. Exp. Biol.*, Vol 148, pp. 53-88.

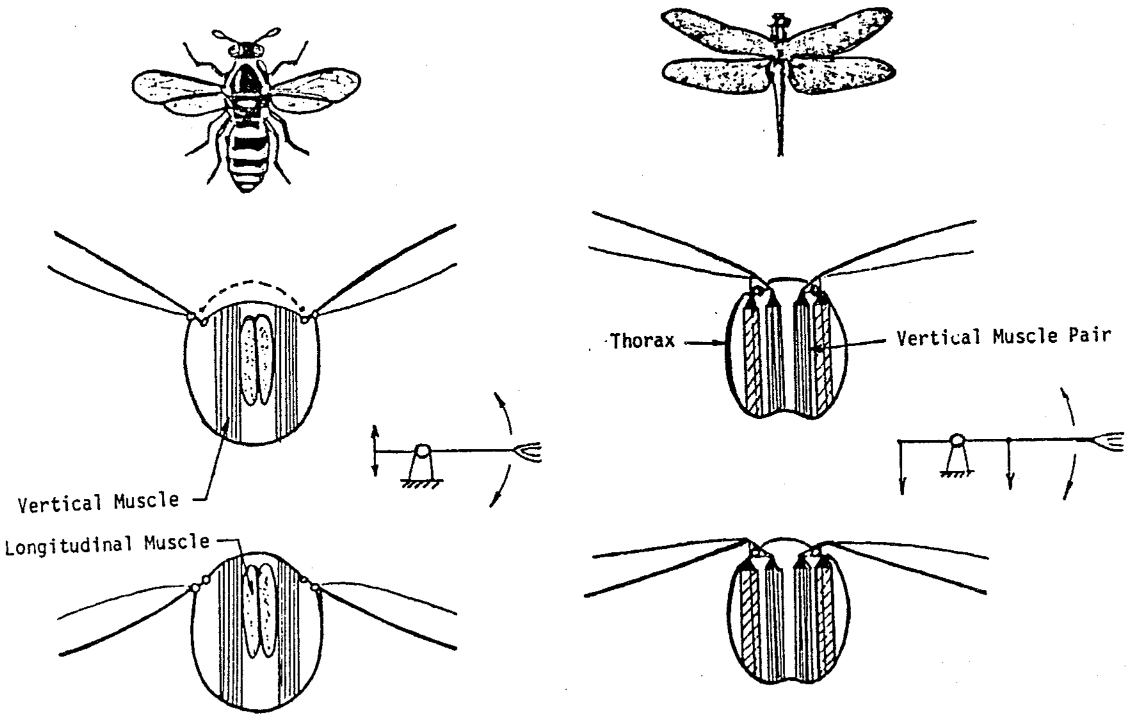
Azuma, A., Azuma, S., Watanabe, I. and Furuta, T., (1985)"Flight Mechanics of a Dragonfly", *J. Exp. Biol.*, Vol. 116, pp. 79-107.



THE DESERT LOCUST (*Schistocerca gregaria*)
IN STEADY FLAPPING FLIGHT



CORRELATION BETWEEN WING LENGTH AND FLAPPING FREQUENCY

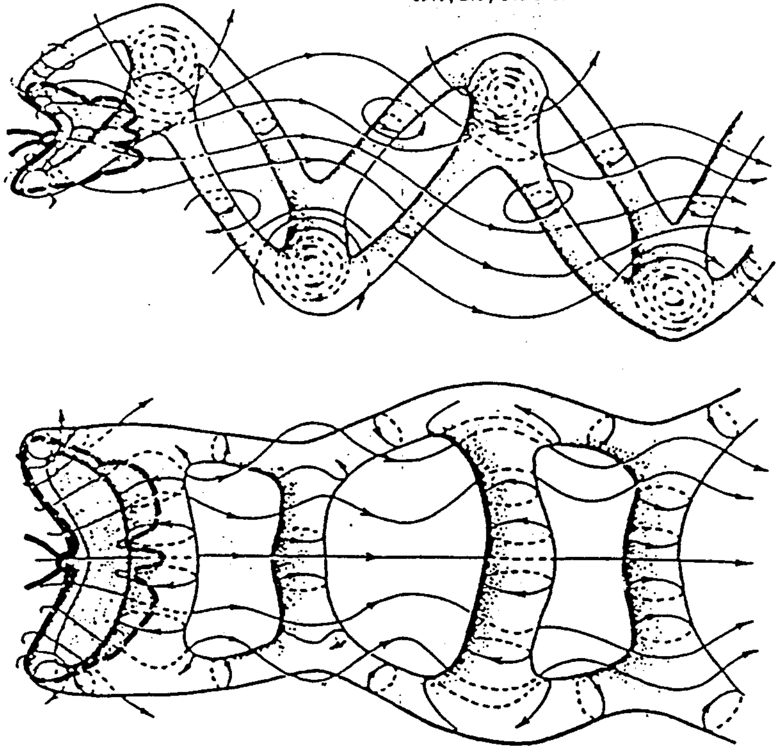


Small "Fast Flapping" Insects
(Flapping frequency > 80 Hz)

Large "Slow Flapping" Insects
(Flapping frequency < 80 Hz)

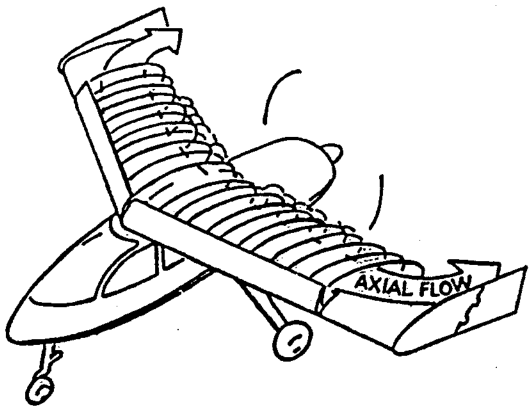
The Wing Flapping Mechanisms of Large and Small Insects

Kokshaysky, N. V. Tracing the wake of a flying bird. *Nature*, 1979, 279, 146-148.

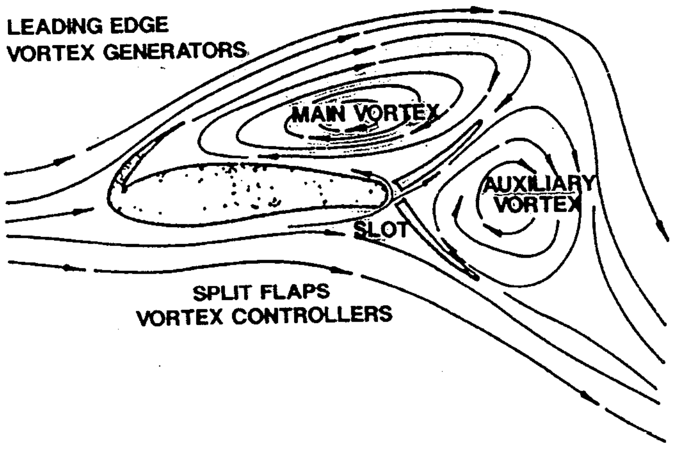


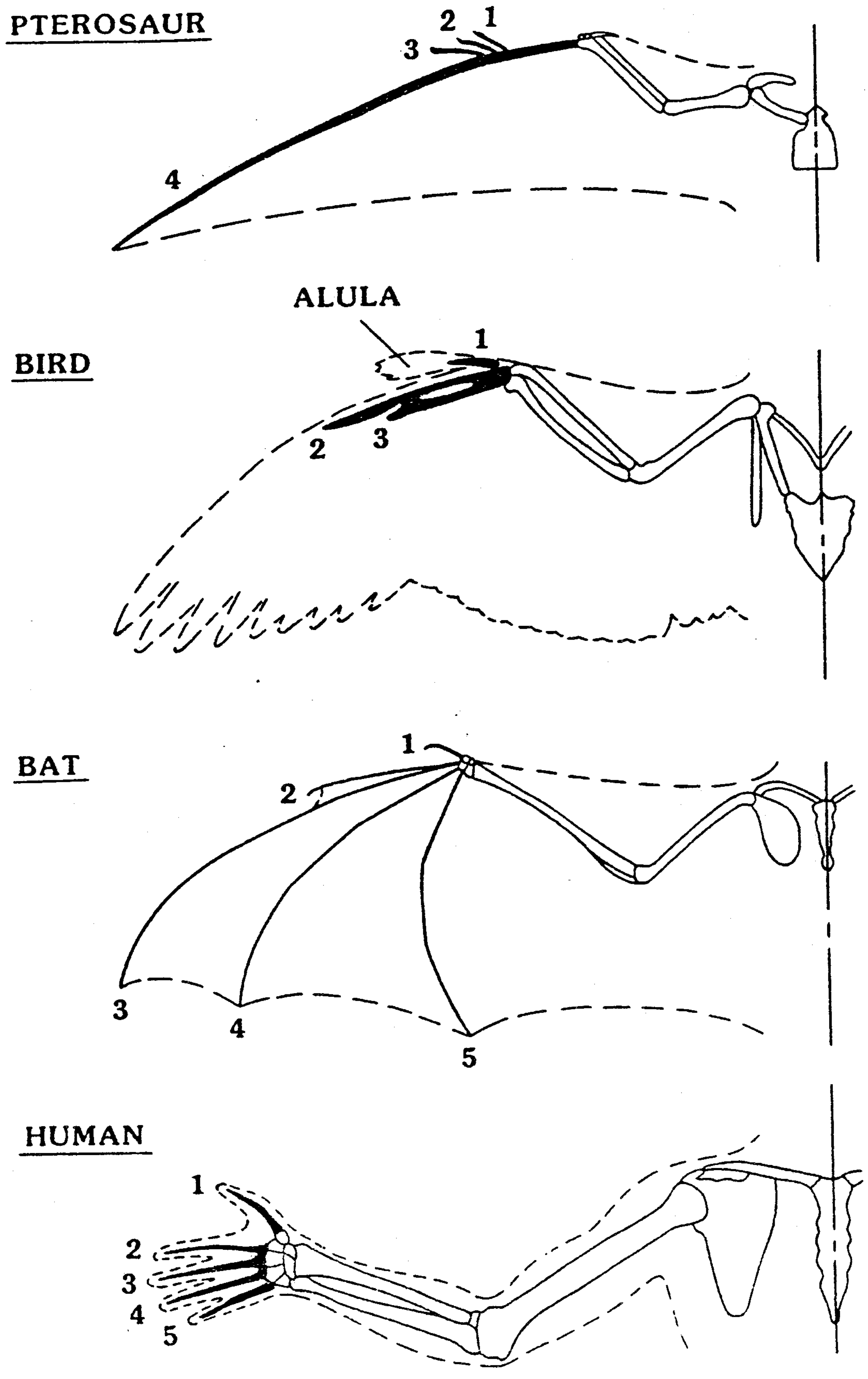
APPROXIMATE WAKE STRUCTURE
FROM A CRUISING BUTTERFLY

KASPER
POWERED
PROTOTYPE

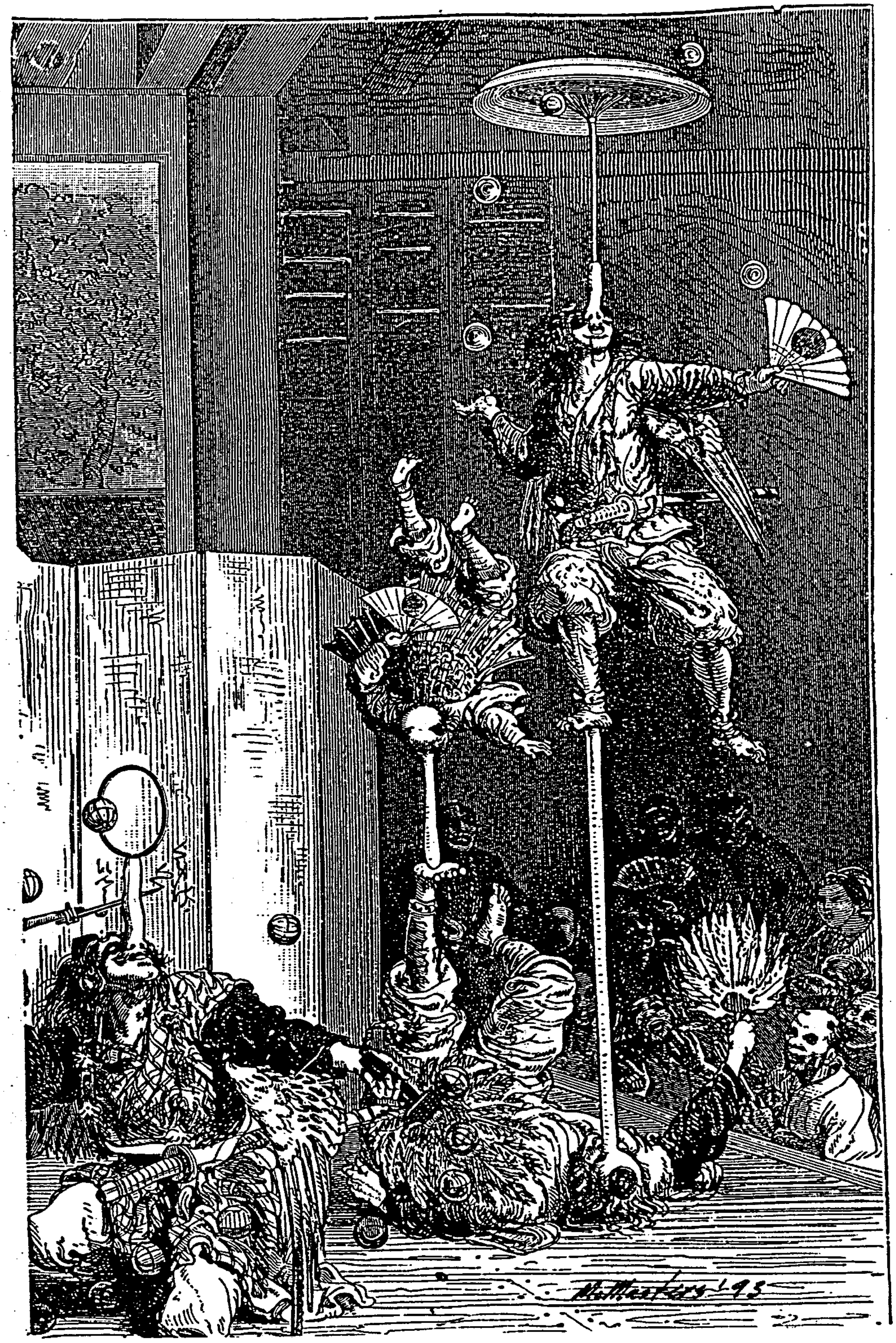


KASPER VORTEX AUGMENTED WING
and AIRFOIL SECTION





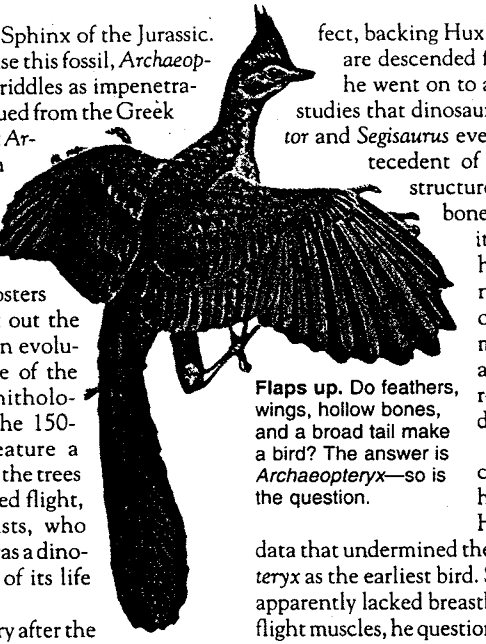
Various Vertebrate Wing Structures Compared to the Human Arm



The Foremost Paleoörnithologists Convene to Describe Their Various Theories of the Origins of Flight in Birds

Archaeopteryx: Early Bird Catches a Can of Worms

Call it the feathered Sphinx of the Jurassic. The name is apt because this fossil, *Archaeopteryx*, is the source of riddles as impenetrable as the ones that issued from the Greek original. Since the first *Archaeopteryx* specimen was discovered in Germany in 1861, scientists have been pecking at each other like bantam roosters in an attempt to sort out the creature's true place in evolution. The latest phase of the controversy pits ornithologists, who consider the 150-million-year-old creature a bird, adapted to life in the trees and capable of powered flight, against paleontologists, who claim *Archaeopteryx* was a dinosaur that spent most of its life on the ground.



Flaps up. Do feathers, wings, hollow bones, and a broad tail make a bird? The answer is *Archaeopteryx*—so is the question.

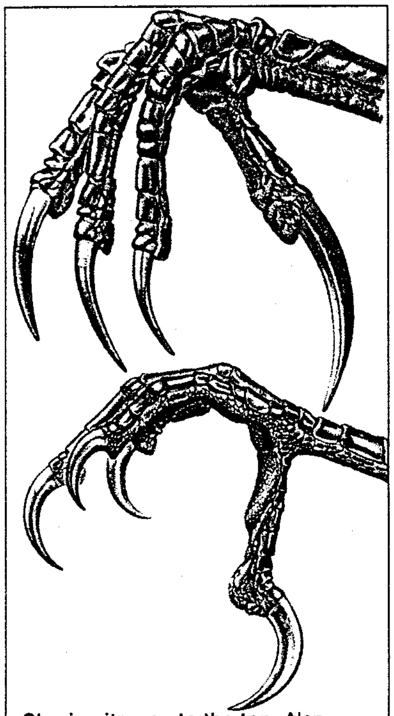
More than a century after the dispute began, the squawks keep rising in volume. In this issue of *Science*, ornithologist Alan Feduccia of the University of North Carolina at Chapel Hill argues that the claws of *Archaeopteryx* indicate that it did live in the trees and was unquestionably a bird (see page 790). "Paleontologists have tried to turn *Archaeopteryx* into an earth-bound, feathered dinosaur," Feduccia says. "But it's not. It is a bird, a perching bird. And no amount of 'paleobabble' is going to change that." Paleontologists remain far from convinced.

Partly obscured by the flying feathers are two opposing views of avian evolution. The first stems from Darwin's contemporary, Thomas Henry Huxley, who argued in the late 1860s that birds are directly descended from dinosaurs. The other view holds that both birds and dinosaurs share an earlier, crocodile-like ancestor. For much of this century, ornithologists and paleontologists were almost unanimous in accepting the second hypothesis. According to that view, rather than resulting from a single line of descent, the features shared by birds and the small running dinosaurs known as coelurosaurian theropods (including hollow bones, long hind limbs, long tails, and long necks) arose from parallel evolution.

But in 1973, John Ostrom, a paleontologist at Yale University, upset the consensus in a letter to *Nature* in which he asserted that the skeleton of *Archaeopteryx* was "that of a coelurosaurian dinosaur." Ostrom was, in effect, backing Huxley's view that birds are descended from dinosaurs, and he went on to argue in subsequent studies that dinosaurs such as *Velociraptor* and *Segisaurus* even possessed the antecedent of the most bird-like structure of all: the wishbone. By the mid-1980s, it appeared Ostrom had won; at an international conference on *Archaeopteryx*, most researchers agreed that it was directly linked to the dinosaurs.

Ostrom wasn't content to crow over his apparent victory. He kept piling up data that undermined the image of *Archaeopteryx* as the earliest bird. Since *Archaeopteryx* apparently lacked breastbones for anchoring flight muscles, he questioned whether it could fly at all and suggested that its claws resembled not those of high fliers but the feet of lowly ground dwellers such as quail and roadrunners. By the time Ostrom was finished, *Archaeopteryx* had been pushed out of the treetops and was reduced to running through the shrubs—a well-feathered but thoroughly grounded dinosaur. What is more, Ostrom claimed, if *Archaeopteryx* ran on the ground, then avian flight probably originated when creatures like *Archaeopteryx* began leaping up (after insects, say) rather than swooping down from the treetops.

Although stunned by Ostrom's apparently successful claims, the ornithologists began clawing their way back, attempting to reclaim *Archaeopteryx*, which, after all, was replete with feathers, wings, hollow bones, and a broad tail. "The paleontologists would like it to be a done deal," says Storrs Olson, curator of birds at the Smithsonian Institution. "But their terrestrial idea is almost certainly wrong, and Feduccia's paper will keep them aware that the issue has not been resolved."



Clawing its way to the top. Alan Feduccia argues that *Archaeopteryx*'s claws resemble those of the bowerbird (*bottom*), a perching specimen, not those of the lyrebird, a groundling.

Feduccia was one of the leaders in ornithologists' reclamation effort. In previous, highly regarded papers (*Science*, 9 March 1979, p. 1021), he argued that *Archaeopteryx*'s feathers and wings are identical to those of modern birds. There, at least, he's scored success, since by now even paleontologists concede *Archaeopteryx* was capable of limited flight. "Okay, in the vernacular sense, it is a bird," grouses Jacques Gauthier, a herpetologist at the California Academy of Sciences in San Francisco and a supporter of *Archaeopteryx*'s dinosaur ancestry. "If by that you mean something with feathers that sort of flies."

Those concessions don't satisfy Feduccia. In his current article, he lends additional touches to his portrait of *Archaeopteryx* as a full-fledged bird by arguing that its claws resemble those of birds that spend most of their time in the trees. To substantiate his claim, Feduccia measured the curvature of the foot claws (*Archaeopteryx* also had claws on its wings) of the three best *Archaeopteryx* specimens, then compared this arc with 500 species of modern birds. The fossils' arc fell comfortably in the range of definitive perching birds such as the South American motmots and the cuckoo-rollers of Madagascar. A further clue comes from the fossils' curved claw on the reversed first toe (the hallux), which Feduccia says is "strictly a perching adaptation; it would be a tremendous obstacle to running on the ground."

Feduccia even turns *Archaeopteryx*'s curious wing claws (or manus claws) to advantage. Other researchers, puzzled by the long claws, have suggested they were used for everything from gripping branches to aiding flight to trapping insects. To Feduccia, though, they are simply another adaptation for life in the treetops. "The claws are extremely similar" to the foot claws of modern trunk-climbing birds, he insists. "In fact, if you compared the claws of a wood creeper with the manus claws of *Archaeopteryx*, you would be hard pressed to tell them apart. They are virtually identical."

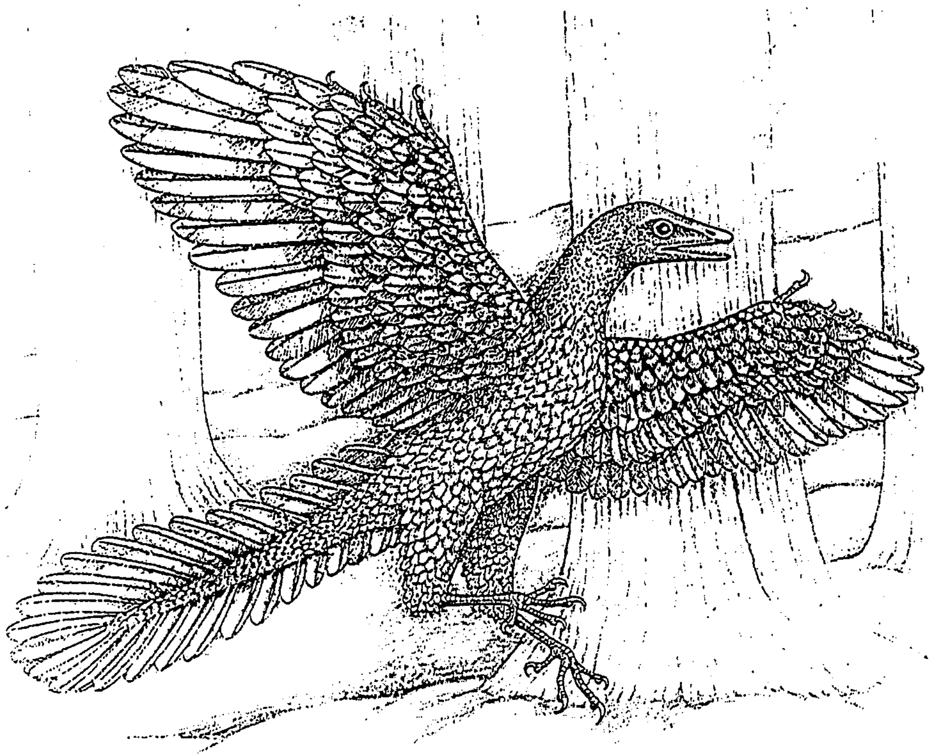
To other ornithologists, Feduccia's gripping tale clinches the case. "Feduccia's paper establishes conclusively that the claws of *Archaeopteryx* have the morphology of a perching, climbing animal," says Larry Martin, a paleo-ornithologist at the University of Kansas in Lawrence. "It was not running on the ground."

Some paleontologists, however, think Feduccia is, well, out of his tree. Paul Sereno, an evolutionary biologist at the University of Chicago, disputes whether one can use a bird's claws to draw definitive conclusions about its overall behavior. "Many so called groundbirds, for example chickens, still spend some time in the trees," he says. Sereno also questions Feduccia's claims for the wing, or hand, claws. "I think the hand claws are particularly irrelevant because he makes no comparisons to dinosaurs. In fact, *Archaeopteryx*'s hand claws are very, very similar to those of theropods." Gauthier adds, "If *Archaeopteryx* used its hand claws for climbing in trees, then all the related dinosaurs—theropods, *Velociraptor*, *T. rex*—all climbed in trees." And if that's the case says Gauthier, "You've got a problem," since *T. rex* was clearly a terrestrial creature.

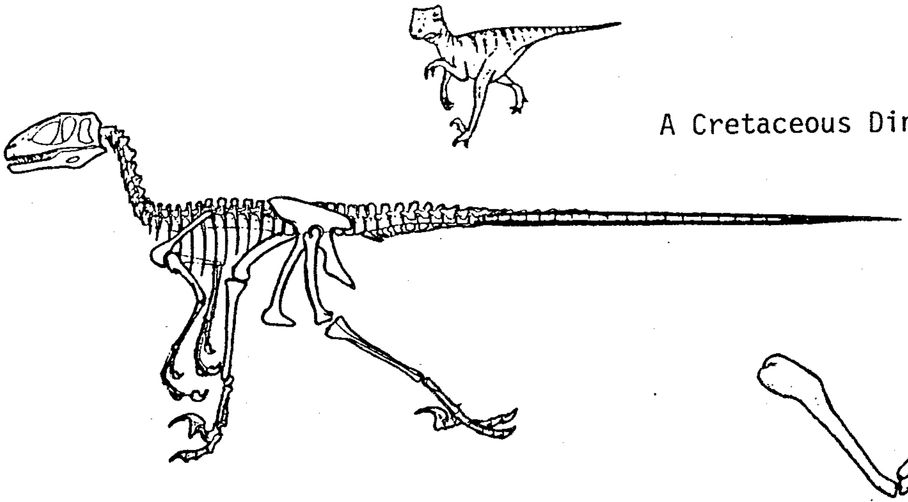
But not all the clucks from paleontologists are those of disapproval. Ostrom, whom one might expect to be outraged, is preening instead. "I'm just having a ball," he said with a chuckle. "It sounds to me as if Alan [Feduccia] has presented a very good argument; I'm not sure he's absolutely right, but I'm sure he's on solid ground." Even though Ostrom acknowledges that Feduccia may be right about the shape of the claws, Ostrom is far from giving up his own, hard-won ground. Like Sereno and Gauthier, he doesn't think the case can be closed before the claws of *Archaeopteryx* have been compared with those of the theropods.

In any case, says Ostrom, his ideas have been constructive in stimulating scholars to examine assumptions. "In the early 1970s, it was a given that birds learned to fly from the trees down," Ostrom says. "I thought people hadn't looked closely enough at the evidence, so I deliberately wrote my paper to provoke people. And I'm laughing now because it has provoked people out of their hides. It's a great big controversy—which is what it should be." And a controversy in which the world hasn't heard the final peep.

–Virginia Morell

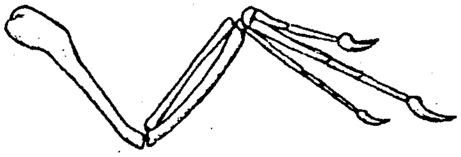


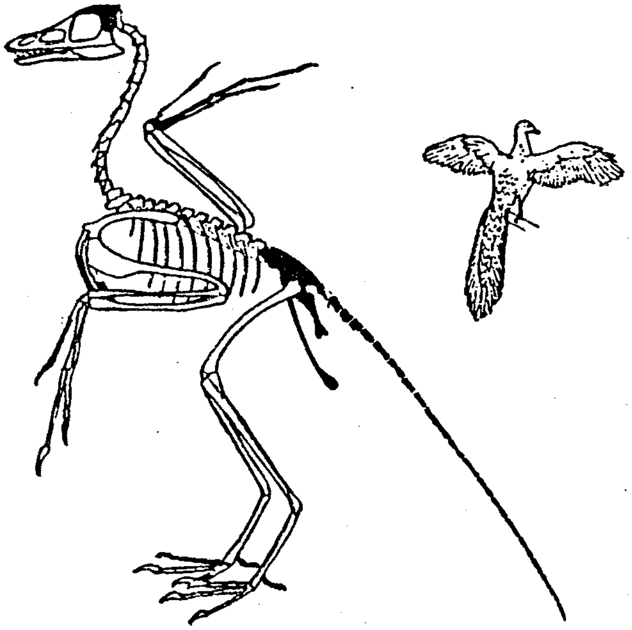
Archaeopteryx



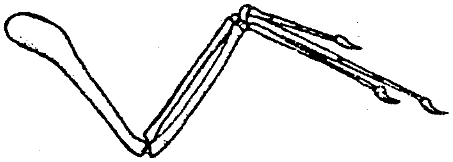
A Cretaceous Dinosaur (Deinonychus)

Forelimb





A Jurassic Bird (Archaeopteryx)



A Modern Bird (Dove)

Evolutionary Adaptations of Birds

March 15, 1993

Editors
Science
1333 H Street NW
Washington, D.C. 20005

Dear Editors,

I have just read with some surprise and amusement Virginia Morell's "Archaeopteryx: Early Bird Catches a Can of Worms" (*Science*, 5 February 1993, pp. 764-5) which sets up Alan Feduccia's latest salvo in the great Archaeopteryx debate ("Evidence from Claw Geometry Indicating Arboreal Habits of Archaeopteryx, op. cit., pp. 790-2). Ms. Morell's article is cute, with all the charm of non-partisan cheerleading at what looks suspiciously at times like a mud wrestling match between "paleontologists" and "ornithologists" over the probable origins of flight in birds. I am left wondering why this debate continues at all (since I had assumed that the real story was well known by now); and, at a more philosophical level, why scientists seem to have such a predilection to pose questions as rigid either--or propositions. As seemingly intractable dilemmas.

As a mere engineer with a long standing semi-avocational interest in "paleoaeronautics" (McMasters, 1976; 1986; 1989) I am afforded the luxury of being able to look at the overall problem of the evolution of flight from a "third point of view" and can be satisfied with a more heuristic line of reasoning. From this perspective it may be observed as an aside that we (engineers) now know a lot about flying and the design of machines which possess this capability. It may also be argued (cf. Lighthill, 1990) that much of conventional aviation history, which attributes the amazing progress made in this century to the inspiration provided by observing birds and so on, is backwards. Indeed, aside from demonstrating that animal flight was possible, nature's contributions to our technology have been modest or down right misleading (e.g. Leonardo's ornithopter). In retrospect these two lines of development diverged very rapidly after the turn of this century and most of what we should have learned from nature has been "reinvented" (at huge expense) by engineers. Much of what we now know about the mechanics of nature's flying devices comes from our experience in designing various types of airplanes; and from applications to biological problems of the tools (testing techniques and theory) developed during the past hundred years in aid of our technology. Thanks to the extensive writings of people like Alexander (1992), McMahon and Bonner (1983), Nachtigall (1985), Pennycuick (1992), and Sir James Lighthill (1975) in particular, this lesson has become increasingly well accepted in the life science community, although not always perfectly understood (e.g. Feduccia's invocation of the "classic elliptical (sic) wing of modern woodland birds" [op. cit., pp. 792] in his lengthy list of evidence for the purported flying ability of Archaeopteryx).

All of this is, however, tangential to the problem of deciding the true nature and flying ability of Archeopteryx and more importantly, how and why it evolved. Consider first some "first principles" relating to these problems:

- There seems to be operative in this world a dynamic that for want of a better term may be called a "technological imperative," i.e. If it can be done, some one (or something) will do it. Thus, whether it makes any sense or not (e.g. bungee jumping, kayaking across the Atlantic) attempts will be made to do it until success is finally achieved. The only real requirement is that the task be feasible. If there is also some further "economic incentive," so much the better.

- All motile animals travel professionally (to find food, escape a predator or to find a mate). Most machines capable of doing so travel commercially (to generate a profit) or recreationally (for fun).
- Flying can be more energy efficient than running for animals of the same weight and general form. The ability to fly also gives an animal a number of additional benefits (McMasters, 1986, 1989).
- "Flying," in the elementary sense of producing lift to balance weight in a vector space is easy. Flying in a controlled manner along an arbitrarily desired path is fantastically difficult, however. Several of the early pioneers of aviation understood this (circa 1890), but it remained for the Wright brothers to finally solve the problem. While credited with being the first to achieve powered flight, their major contribution was to solve the stability and control problems associated with this enterprise.
- Predators may profit from possession of a "high" metabolic rate. Possession of some form of insulation to control heat loss is also of benefit to such critters, especially as adult size decreases.
- Insects, while unappetizing, are highly nutritious. Flying insects aren't all that easy to catch on the wing, however.

From these basic observations it is easy enough to reconstruct the actual scenario for the evolution of a "flying dinosaur" which includes the Archaeopteryx as a moderately advanced intermediate from in its inexorable march to become a modern bird. The story begins with a small, light, agile, fast running, bipedal coelurosaurian dinosaur (or perhaps its immediate ancestor). [Unfortunately the stone tablets upon which parts of this story are recorded are fragmentary and a bit cryptic regarding some details.]

In casting about for good things to eat our little predator develops a taste for insects, some of which it catches on the wing by leaping and lunging for them. In doing this he/she uses its mouth to catch its prey while employing its (clawed) forelimbs and tail to maintain its balance while bounding about. It works, at least well enough to make it a viable species. At this point it might be noted that the motions of the forelimbs during these leaping and lunging maneuvers are remarkably similar to the sort of motions an avian wing (or the unselfconscious movements of the arms of a child broad-jumping while playing hopscotch) might make on a forward and downward power stroke.

At this point in our tale, the first bit of magic happens. For some reason, a number of individuals are hatched with scales that have gone weird. They have (at least the beginnings of) feathers. While not yet ugly ducklings among their peers, this batch has the advantage of being better insulated than their brethren, and they thus prosper and multiply. Indeed, so successful is this "new invention" that each succeeding generation has more and bigger feathers until members of the "new species" are quit different than their ancestors and are now fully pre-adapted to become fliers, even though none yet recognize this future possibility.

What is recognized, however, is that the still modest plumage on the forelimbs enhances each individual's ability to balance ("stabilize") and control its leaps and lunges, and more importantly, these enlarged surfaces produce a bit of thrust which allows them to leap a bit higher or farther, thus further enhancing their prey capturing ability. Any other value these [small] "hand/arm fans" may have, for example in aiding insect capture by acting as crude "butterfly nets," is probably incidental. How this worked has been described by Caple, Balda and Willis (1984) and is reasonably convincing as far as it goes.

Here it must be observed that our little critters still have the brains and motor control systems appropriate to a cursorial leaper rather than to a full fledged flier. It's going to take awhile before this complex system can catch up to the additional demands of operating in a fully three-dimensional set of motion coordinates. Thus in airplane parlance, the critters are very highly "stability configured," i.e., they retain their long tails (augmented now by feathers) as a stabilizing surface and in general they are stable but not very maneuverable about any of their three orthagonal body axes. At this primitive point in their development, their feathered surfaces are fragile and, ironically, almost as much emcumberances as virtues. Almost. Their foraging radius from any point on the ground has now become much larger, however, and rather than being primarily circular, it is fully hemispherical. So far, most of this capability has been developed in operations from a ground (cursorial) base from which a clumsy misstep results in a non-catastrophic tumble to earth rather than a fluttering crash from any substantial height. They are not birds in any proper sense yet except that they possess feathers and the ability to use their modest plumage to augment the strength in their powerful hind limbs.

This now goes on for awhile with selection favoring those in each successive generation with more and bigger feathers. Some of these on the outer extremities of the forelimbs begin to become recontoured asymmetrically as Feduccia (op. cit. pp. 792) suggests which enhances the efficiency with which these increasingly larger surfaces can develop thrust (and balancing/controlling forces). At the same time the feathers attached along the more proximal posterior portions of the forelimbs increase the lifting area of what is now beginning to evolve into a real wing and, slowly, our little beasts also begin to develop the ability to execute controlled and stable glides following forelimb assisted leaps.

It is at this point that our pre-bird began to fully appreciate the advantages of trees and shrubbery. While much has been made of the virtues of gliding down from a height as opposed to flapping up to justify an arboreal rather than cursorial origin for flight in all vertebrates, this advantage has been over rated. While overcoming the force of gravitational attraction is one of the very central issues in flying, it is not the only issue. The problems of producing thrust to overcome drag (fluid dynamic resistances forces) and the need for an adequate neurological/aerodynamic control system are also of very fundamental importance, and true flight (in the sense most biologists seem to insist upon) can not exist unless all of these requirements are satisfied. The central issue has always (properly) been: In which order did these capabilities develop?

Be this as it may, our critters are now capable of flapping their forelimbs to produce thrust (in limited amounts) and possess a (limited) capability to glide. They are also reasonably well coordinated, and need no longer be acrophobic. Hence they can flutter/leap to a bush or climb a tree with assurance using this height to reduce the energy required in making their next attack on a passing insect. Perhaps even more importantly they can now consider making a suitable shrub or tree their home.

Our critter is now pretty complicated and its hatchlings still have a lot to learn before they become viable self-supporting adolescents. Thus they likely require some parental attention during this vulnerable phase of their existence and leaving them unattended on the ground places them in jeopardy. Parking them at a height in a tree or bush reduces this jeopardy, and even if the adult has to climb rather than fly up to the nest, there is advantage to taking up the arboreal habit.

From here, it is but a short step to the development of an ability to perch (since the ability to pseudo-fly endows it with the concommittent balancing ability required) and as its feathers continue to develop in size and contour and its gliding and flapping ability continues to improve from generation to generation we finally see this little dinosaur for what it really is: Archaeopteryx lithographica - a bird.

True, at this stage in it evolution it can not fly as well as a crow or pigeon (though probably better than a wild chicken), since it has not yet developed the deep sternum and powerful breast muscles of its modern descendants. It is capable, however, of doing all those things we might reasonably expect of a bird--at least in principle. That is also possesses a lot of extra baggage (a long, feather embellished reptilian tail, manus claws, teeth) is of no great consequence. Although it will continue to be overshadowed by the pterosaurs, which preceded it down a very similar evolutionary path (developing fur rather than feathers and a much less versatile wing architecture) millions of years earlier, and which will continue to rule the sky far into the Cretaceous, the descendents of the Archaeopteryx will inexorably shed the excess vestiges of their cursorial origins. The manus claws will largely disappear as its flying ability continues to improve to the point where climbing is no longer necessary even in its young, and the balance of its musculature will shift from the powerful hips and hind limbs to development of even more powerful chests and forelimbs.

Most profoundly of all, the modern avian brain will evolve. Driven by the need to adapt its cursorily developed flight apparatus to a much more demanding arboreal habit, the motor control functions will continue to improve synergistically with the discovery of the advantages of being more highly maneuverable at the expense of being very stable. Thus as the brain evolves, the long stabilizing (and heavy) tail can be discarded, replaced by a surface of more modest and efficient proportions. Our bird has thus become, again in airplane parlance, "control configured" rather than "stability configured." This appears to have been the pattern in each line of vertebrate flight development and exactly parallels the development of fighter airplanes since the beginning of the First World War.

While this story of bird flight evolution seems plausible enough to me, an arborealist may object that a similarly convincing story, using many of the same way points I have identified, could be advanced for a purely arboreal origin for a flying bird. Perhaps. Most biologists of my acquaintance agree that bats evolved from a purely arboreal habit, and though quite different from birds morphologically, possess about the same overall flying ability (for animals of about equal size). There also remains disagreement on all this regarding pterosaur evolution, but that is another story entirely. What convinces me about the "rightness" of my scenario is the morphology of the hind limbs of all extant and fossil birds. While most attention is usually directed toward evolutionary changes in the chest and forelimbs as birds developed the ability to fly, it is the hind limbs which betray the cursorial ancestry of the bird. Although changed in modern forms to little more than landing/perching gear, the legs of flying birds remain in form those of a running/jumping animal in my opinion. Alan Feduccia's latest study does nothing to dispel my belief--and may even support it.

Thus having come to my own conclusions, and written over-long on the subject, I suspect my tale will do little to convince many of those with a professional interest in continuing the Archaeopteryx debated unabated. I will therefore await (with, I admit, limited enthusiasm) the publication in *Science* of the next salvo. I rather expect this to be a scholarly proof that Archaeopteryx subsisted entirely an pomegranates and thus that its plumage was pink.

Sincerely,

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$$\sum \vec{F} = \vec{0} \Rightarrow \left.\begin{array}{l} \text{SUM OF FORCES} \\ \text{PARALLEL TO FLIGHT PATH} = 0 \end{array}\right\} D = W \sin\theta = T \quad \left.\begin{array}{l} \text{SUM OF FORCES} \\ \text{NORMAL TO FLIGHT PATH} = 0 \end{array}\right\} L = W \cos\theta \quad \therefore L/D = \cot\theta = V_H/\dot{Z}$$

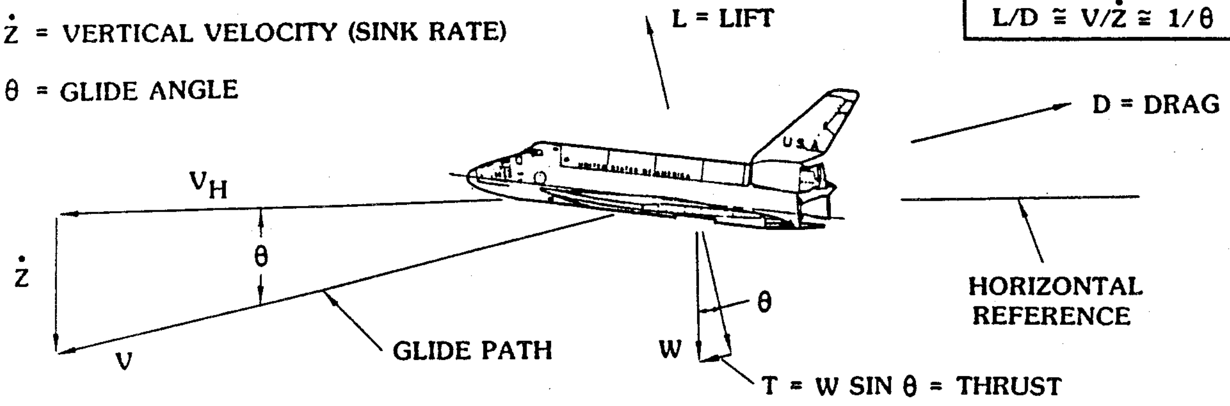
V = AIRPLANE VELOCITY

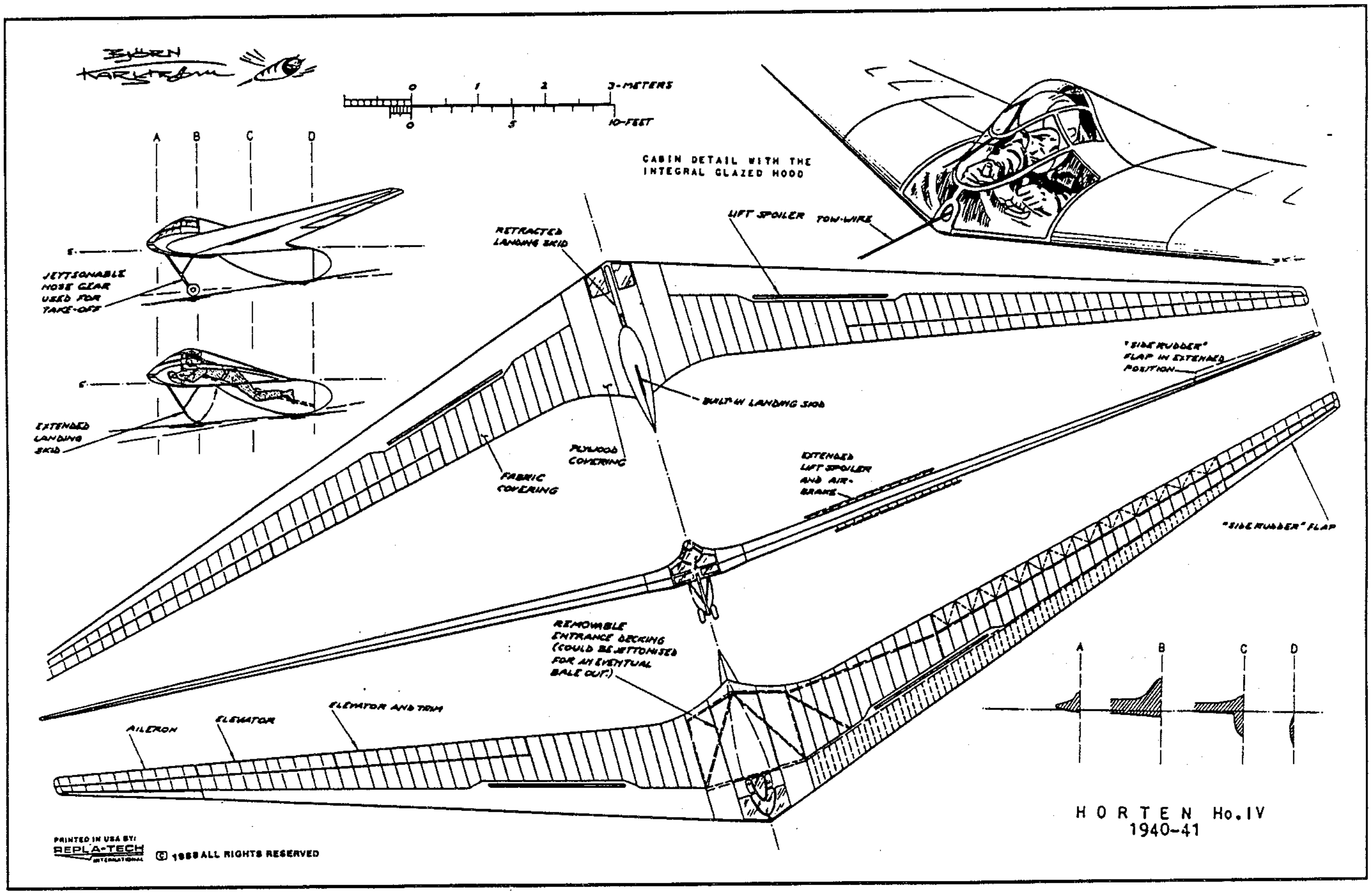
V_H = HORIZONTAL COMPONENT OF VELOCITY

$\dot{Z}$ = VERTICAL VELOCITY (SINK RATE)

θ = GLIDE ANGLE

IF L/D IS "LARGE"
$L \cong W$
$V \cong V_H$
$L/D \cong V/\dot{Z} \cong 1/\theta$





A technical history of soaring—

From Paleoaeronautics to Altostratus

by M.K. CHEN and J.H. McMASTERS

Acknowledgement

The authors wish to thank Doug Lamont, former editor of *Soaring*, and Bob Storck, archivist of the Vintage Sailplane Association, for providing data and drawings for this article. Thanks also go to Dan Knutzen who transformed the authors' sketches into art.

PART I

An unconventionally long time-line has been selected in the following history of soaring. It includes an overview of the evolutionary process in the belief that this often poorly appreciated and significant part of aeronautical development led to the technical and aesthetic triumph of the modern sailplane. Thus, the story progresses from the true dawn of flight with the emergence of biological flying devices (animophilous seeds, pterosaurs) through a discussion of future trends in sailplane development. It will outline the history of the technical developments which have allowed progress from the tentative hang glider experiments of Pilcher, Montgomery, and Lilienthal in the last two decades of the 19th Century through the present range of sport and competition sailplanes. Modern sailplanes are at the forefront of important technologies such as laminar flow aerodynamics and routine production use of advanced composite materials. Yet, in no category of modern aircraft is the influence of *natural* models of flying machines more clear and direct than in the sailplane. To put this in clear perspective, the historical time-line of this presentation extends back to the very origin of flight some 300 million years ago.

Any winged flying device can, inadvertently or by intent, become a glider. As shown in Figure 1, a steady glide is characterized by the balance of the weight by lift and drag forces with gravity acting as the propulsion device. Since the aerodynamic forces are generated in proportion to the motion of the machine relative to the air, the descent velocity (sink rate in gliding parlance) is proportional to the aerodynamic efficiency (lift-to-drag ratio) achieved at a given velocity along the flight path. But gliding flight is merely expedient or unavoidable, and, while occasionally exciting, otherwise uninteresting.

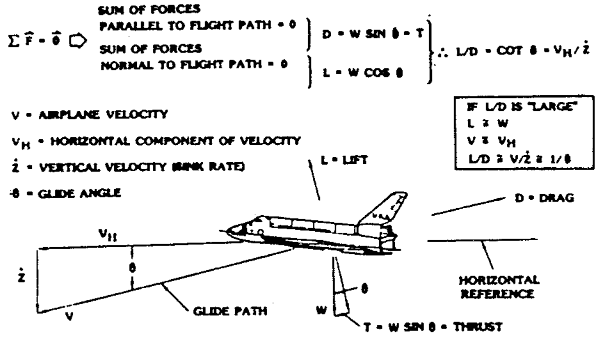


Figure 1. Forces on an Aircraft in an Equilibrium Rectilinear Glide in Still Air

The fact that the atmosphere is seldom completely quiescent leads to a splendid additional possibility, however. If the glider is capable of flying sufficiently slowly (i.e., has a low wing loading) and possesses some minimum value of aerodynamic efficiency, the resulting sink rate will be "low." As pointed out by Lord Rayleigh in 1883 (Reference 13), if the proper combination of atmospheric conditions and topographical features produces air currents which rise ("lift") as fast or faster than the glider sinks (in still air), then the machine will remain aloft or climb. This is the basic principle of *soaring* flight, the classic conditions for which are shown in Figure 2.

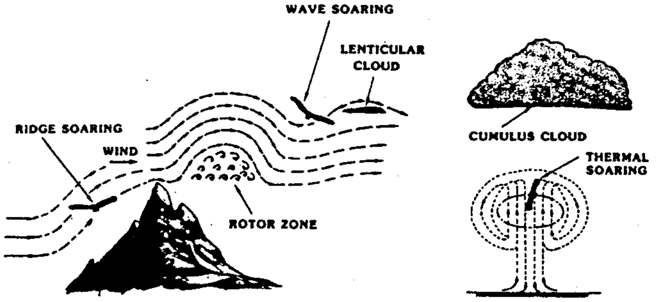


Figure 2. Classical Forms of Soaring Flight

Thus, flying in ridge lift, a crude Rogallo wing hang glider ($M/S \approx 6$ kg/m², $L/D \approx 5$ at 35 km/h), and a U-2 type airplane transformed into a glider ($M/S = 200$ kg/m², $L/D = 22$ at 150 km/hr) would have roughly the same still-air sink speed of about 1.9 m/s, making them both capable, in principle, of marginal soaring under sufficiently strong wind conditions. But the soaring performance of either aircraft pales in comparison with that of a modern fiberglass racing sailplane, as shown in Figure 3.

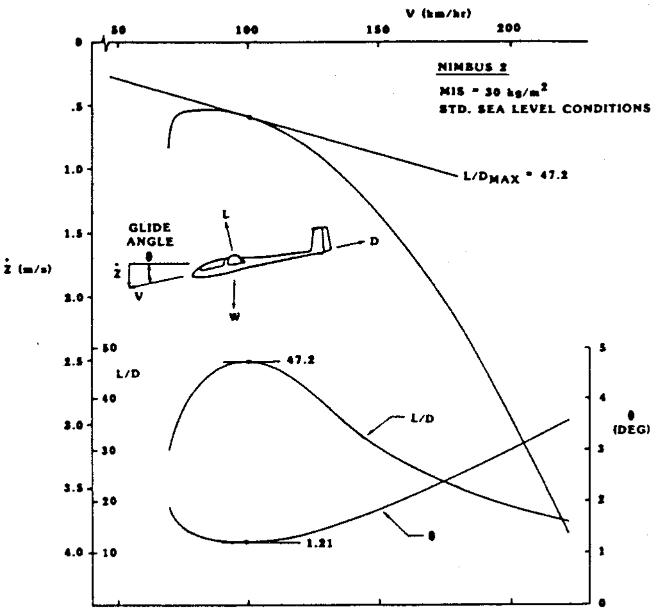


Figure 3. Typical Open Class Sailplane Performance

THE BASICS OF MODERN SOARING

Before discussing the evolution of soaring technology, it is first necessary to review a few of the finer points of how an efficient glider can sustain itself, and, in fact, fly substantial distances, borne aloft only by the motions of the atmosphere derived ultimately from energy from the sun. In the process of this review, several of the dominant principles in sailplane design will be illuminated. Further details may also be found in Reference 1.

The advances made in the evolution from gliding to soaring make an interesting story involving experimentation leading to sporting competition and then to the discovery of unsuspected aspects of dynamic meteorology. Had "motorless" flight in the historic era been limited to the range of possibilities offered by simply gliding over hills and ridges, it would have suffered the fate of the Zeppelin by the early 1920's. However, as sailplane performance capabilities (advanced by the application of wing theory and structural developments) outstripped the limits of flying techniques and competition goals, the discovery of thermal lift made possible the shift in performance objectives from endurance flights in a local area of favorable topography to more ambitious cross-country distance flying. This discovery and the rise of competition soaring resulted in even higher performance machines capable of exploiting atmospheric motions in ever more subtle and complex ways. Modern sailplanes are capable, under the right conditions, of flying literally from dawn to dusk over distances in excess of 1600 kilometers. Thus the present competitive challenge lies in racing over a specified course. Competition soaring has evolved into a sport which is a direct three-dimensional analog of competitive sailing, demanding a superb level of both physical and mental ability, a profound understanding of aerodynamics and meteorology — and good luck.

Central in the evolution from ridge soaring to cross-country racing was the discovery and appreciation of how to exploit thermal lift. While thermal flying had become common prior to WW II, it was not until the early 1950's that Dr. Paul B. MacCready, Jr., published a practical theory of optimal cross-country thermal soaring strategy. The apocryphal story goes that MacCready went on to become world soaring champion in 1956, having published the simple graphical construction shown in Figure 4 to provide his competition with a first-rate red herring, while he himself paid proper attention to the weather — and won the contest.

Be that as it may, the classical MacCready construction shown in Figure 4 demonstrates, in an idealized way, the tactics by which a properly designed sailplane should be flown in order to exploit a sequence of thermal updrafts to achieve an optimum overall cross-country speed. By flying slowly in a banked turn, the pilot seeks to achieve the greatest rate of spiraling climb in a thermal of given strength and profile. Having achieved (in the pilot's judgment) an acceptable height gain, the sailplane then is put into a high-speed rectilinear glide to the base of the next thermal upcurrent encountered, the sport in this game being, in part, the fact that the next thermal is usually invisible to the pilot. The optimum speed to fly (V^*) between thermals to maximize the average cross-country speed ($\overline{V}$), which accounts for the time spent thermaling, is determined simply from a knowledge of the total glide polar (plot of vertical versus horizontal speed) of the sailplane in still air, and the rate of climb achieved in the thermal involved, with adjustments made for any horizontal wind which may prevail.

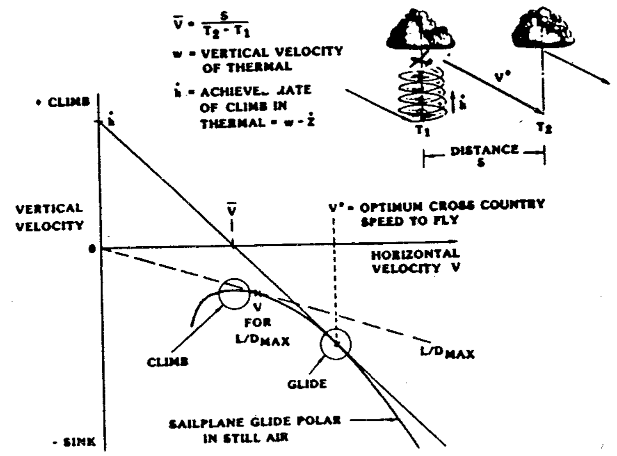


Figure 4.
Classical (MacCready) Optimal Cross-Country Soaring

According to the simple construction shown in Figure 4, the optimum sailplane needed to execute this sort of flight strategy is that which possesses both a low minimum sink rate at low forward speed (for optimum climb) and a flat glide polar (low sink rate) at high speed. The speed for maximum lift-to-drag ratio is seldom flown, although L/D maximum and the speed at which it occurs are a useful index in assessing a particular sailplane's overall performance.

Recognition of the importance of the basic features shown in Figure 4, and the fact that the L/D performance of the sailplane is independent of the weight of the machine (cf. Figure 1), leads to the construction shown in Figure 5. Under certain conditions (the presence of strong thermal lift) adding weight to the sailplane in the form of ballast can actually increase racing performance. The usual practice is to load the sailplane with water carried in bags running spanwise along the wing spar. The additional weight is then distributed across the span, providing a relieving bending load, and the wing loading can be increased by as much as 40 percent of the minimum flying weight. The effect of this is to shift the still-air gliding polar of the machine downward and to the right — the loss in climb performance hopefully to be compensated for by the increase in interthermal speed at a given sink rate for a net gain in average achieved cross-country speed.

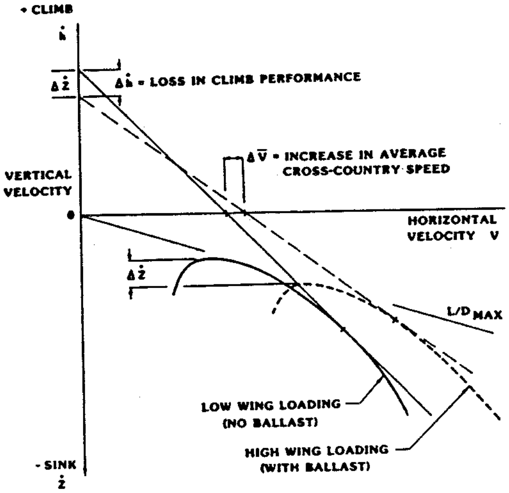


Figure 5.
The Influence of Wing Loading on Classical Cross- Country Soaring Performance

Having reached the level of performance necessary to fully exploit these effects, the sailplane now becomes (with some minor resizing) capable of thermal soaring *without* circling. This alternative *dolphin mode* in soaring is shown in Figure 6 in contrast to the more traditional approach. With the lift-to-drag ratios of modern Open Class racers exceeding 50, this approach to competition racing has become routinely viable. The next step in this progression is to provide the sailplane with the variable geometry capabilities of span and/or area change which birds possess. Despite the spectacular levels of performance (and cost) achieved by modern racing sailplanes, major advances remain possible.

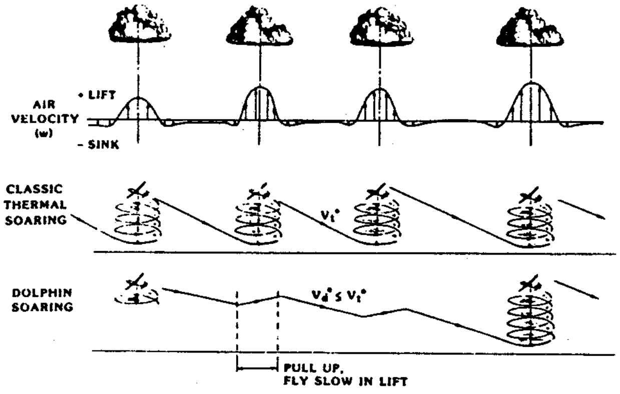


Figure 6. Variations on a Theme in Soaring

THE NATURAL HISTORY OF SOARING AND GLIDING

Lip service is paid frequently in aviation historical writing to the inspiration natural flying devices provide to the designers of airplanes. Despite the addition of high technology gadgetry such as winglets to business jets, it often remains difficult to see much direct connection between these sorts of machines and a pigeon or a bat. In the case of gliding and soaring, the parallels are far more direct and valid, although sometimes obscure or not fully appreciated. In order to put the present discussion of soaring technical development in a properly broad context, the developments which preceded human flight are briefly outlined here.

The relevant natural flying "devices" are: flying seeds, birds, bats, and pterosaurs. As shown in Figure 7, these organisms and creatures have evolved over huge time scales, and those which survive today can be assumed to have been nearly perfectly optimized (compromised) to fill their various ecological niches.

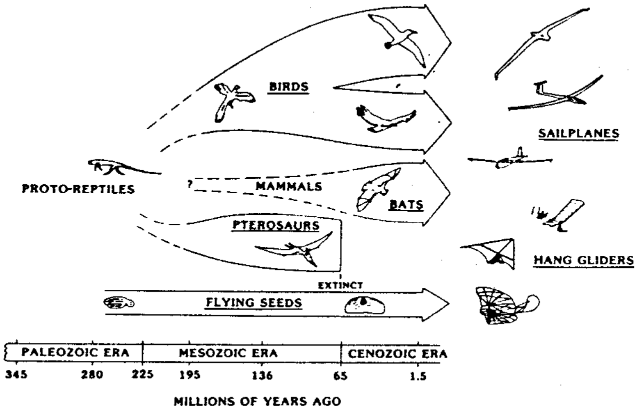


Figure 7. The Natural History of Gliding and Soaring

Earliest of the natural fliers were the animophilous seeds, evolved to provide their parent species more effective means of competing for sunlight and fertile soil even before the advent of pollenating insects and other means of dispersal. Common examples are the milkweed seed, which may be considered a direct natural antecedent of the parachute, and the maple seed, a natural prototype of the autogiro. Of considerable historical interest, because it demonstrated to aviation pioneers the feasibility of constructing a true self-stable tailless airplane, is the seed of the Javan palm tree, *Zinonia macrocarpa*.

Few insects glide or soar, and the next range of natural flying devices having a direct influence on man-made flying machines were the birds and pterosaurs which appear to share a common (although uncertain) reptilian ancestor. While often overlooked and largely unknown to the pioneers of human flight, the grand line of warm-blooded, fur-coated pterosaurs were to dominate animal flight for a period of some 120 million years until their eventual eclipse by birds and their extinction some 65 million years ago at the close of the Age of the Dinosaurs. An interesting aspect of pterosaur flight which is emerging from recent studies is the remarkable parallel in wing structure, and apparently in flight performance, of the larger species with modern high aspect ratio Rogallo wing hang gliders.

Bats are a relatively poorly studied class of flying machines, and, although several species (e.g., Central American fishing bats) do glide on a regular basis, they are generally more akin to fast-flapping smaller bird species. Of interest in this discussion is the alternative wing architecture employed by the bats (cf. Figure 8) which allows them

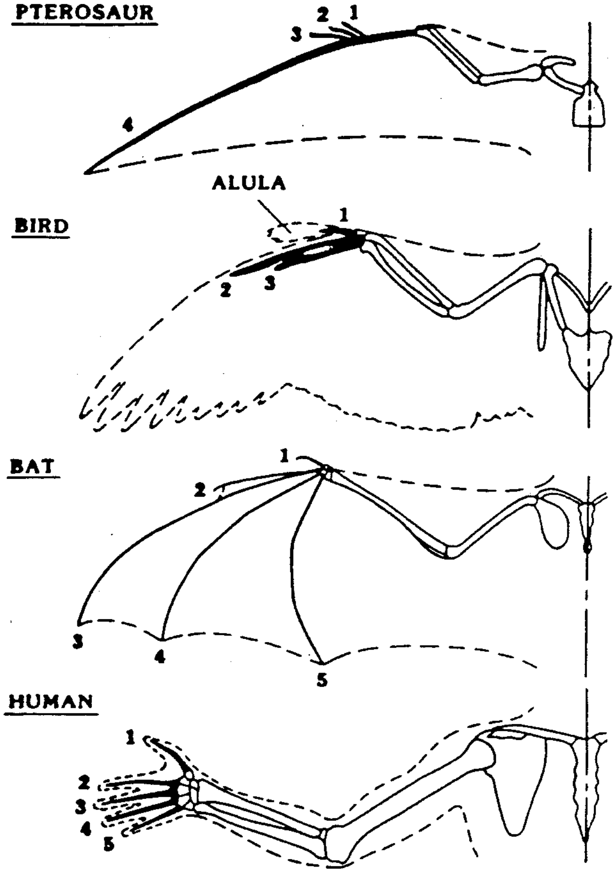
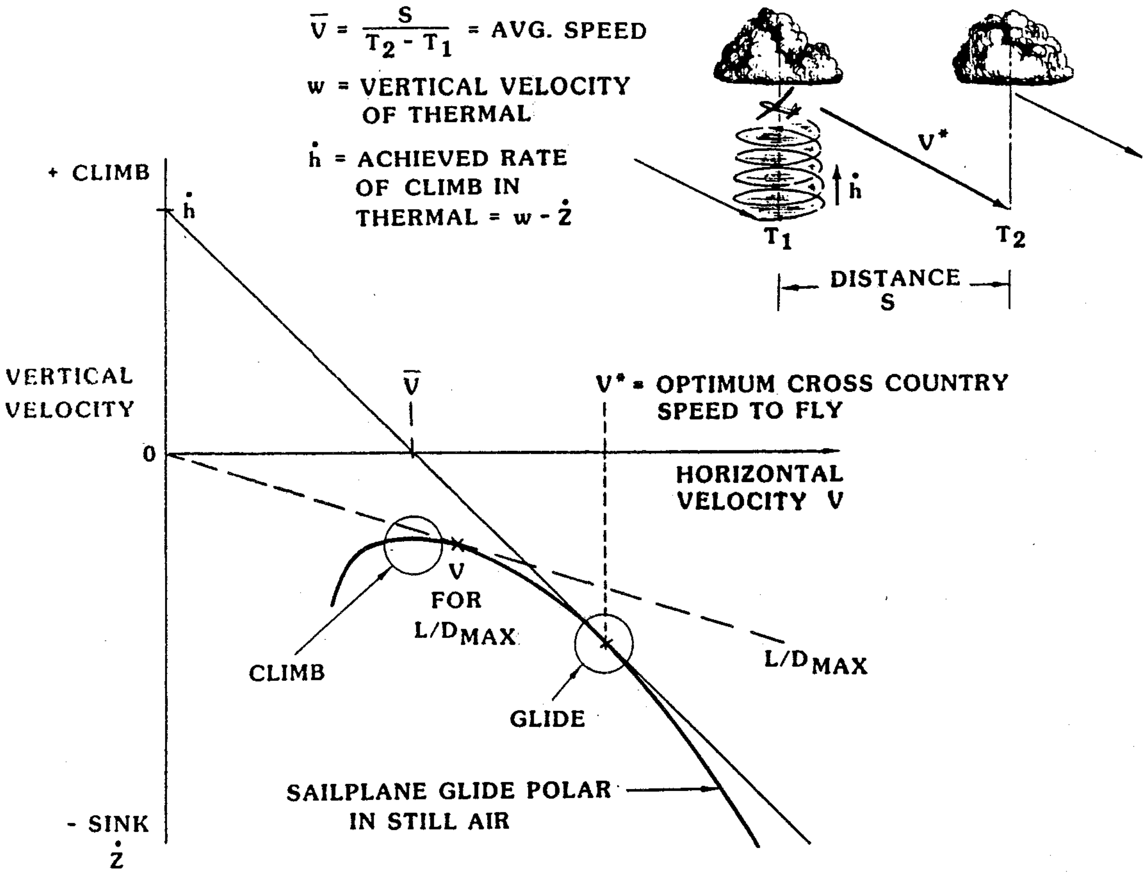
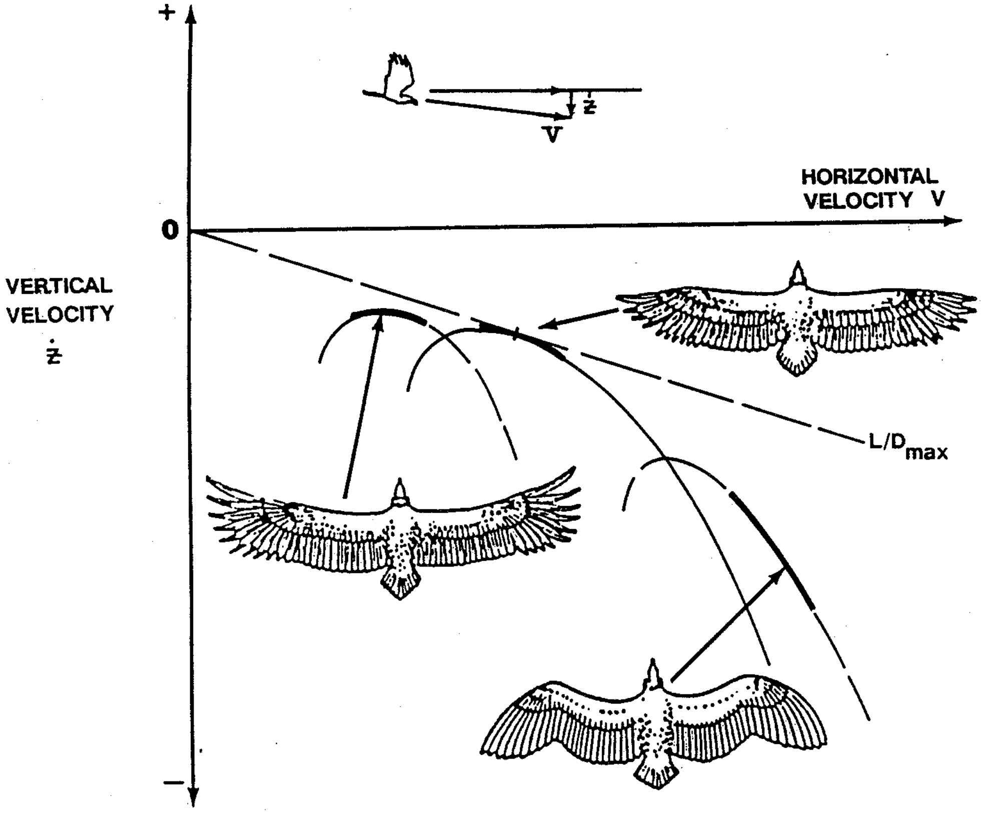


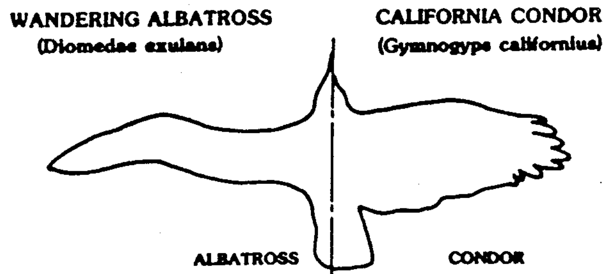
Figure 8. Natural Models of Wings and Their Homology to the Human Arm and Hand (Digits Indicated)



Cross-Country Thermal Soaring



CONQUENCES of the VARIABLE GEOMETRY CAPABILITY of SOARING BIRD WINGS



	ALBATROSS	CONDOR
WING SPAN (m)	3.5	3.0
WING AREA (m^2)	0.72	1.5
ASPECT RATIO	17	6
MASS (kg)	9.8	10
WING LOADING (kg/m^2)	13.6	6.6

Figure 9.
Planform Comparison of Large Land and Sea Soaring Birds

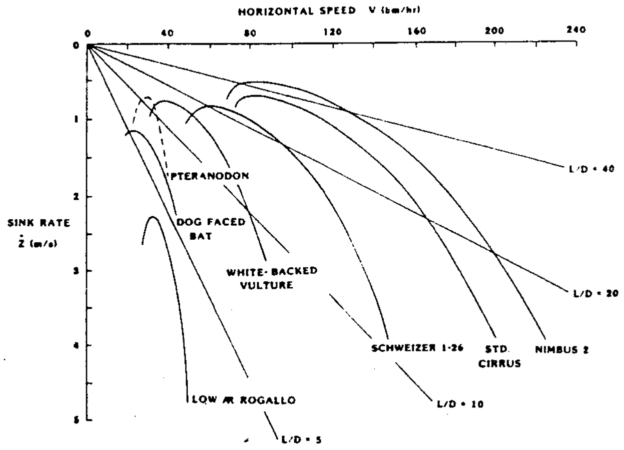


Figure 10. Relative Performance of Various Gliders

to maintain a very high degree of control over the camber and twist distribution of their wing beyond that possible for birds or pterosaurs. However, this capability is gained at the expense of the birds' ability to radically alter their wing span and area.

An interesting commentary on the general lack of appreciation of the importance of this characteristic — the ability of natural fliers to control and alter their wings' twist, camber, span, and area — was recently recounted by a paper documenting aeronautical research in the United States. In a mid-1930's attempt to determine by experiment the lift and drag characteristics of a seagull, a dead specimen was frozen in what was thought to be its optimum flight configuration (wings outstretched). The frozen bird was then placed in a wind tunnel and forces were measured. The conclusion of this experiment was that dead birds can't fly!

It is the range of soaring birds which has had the main influence on human soaring. Birds (which some modern paleontologists argue are the direct modern descendants of the dinosaurs) are a remarkably successful class and cover a very wide range of sizes and functions. Of interest here are the two divergent types of soaring flight practiced by land-soaring types (e.g., vultures, hawks) and sea-soaring types (e.g., gulls, albatross), and the differences in wing geometry and loading which the two categories exhibit (cf. Figure 9).

A book could easily be written on the topics outlined in this section, and the interested reader is referred to References 2 through 16 for further background. For comparison purposes here, the relative gliding performance of various natural and man-made gliding and soaring devices is shown in Figure 10.

This brings the discussion to the main topic of this paper — the technical development of the high-performance sailplane. As a map to the history to be discussed, Figure 11

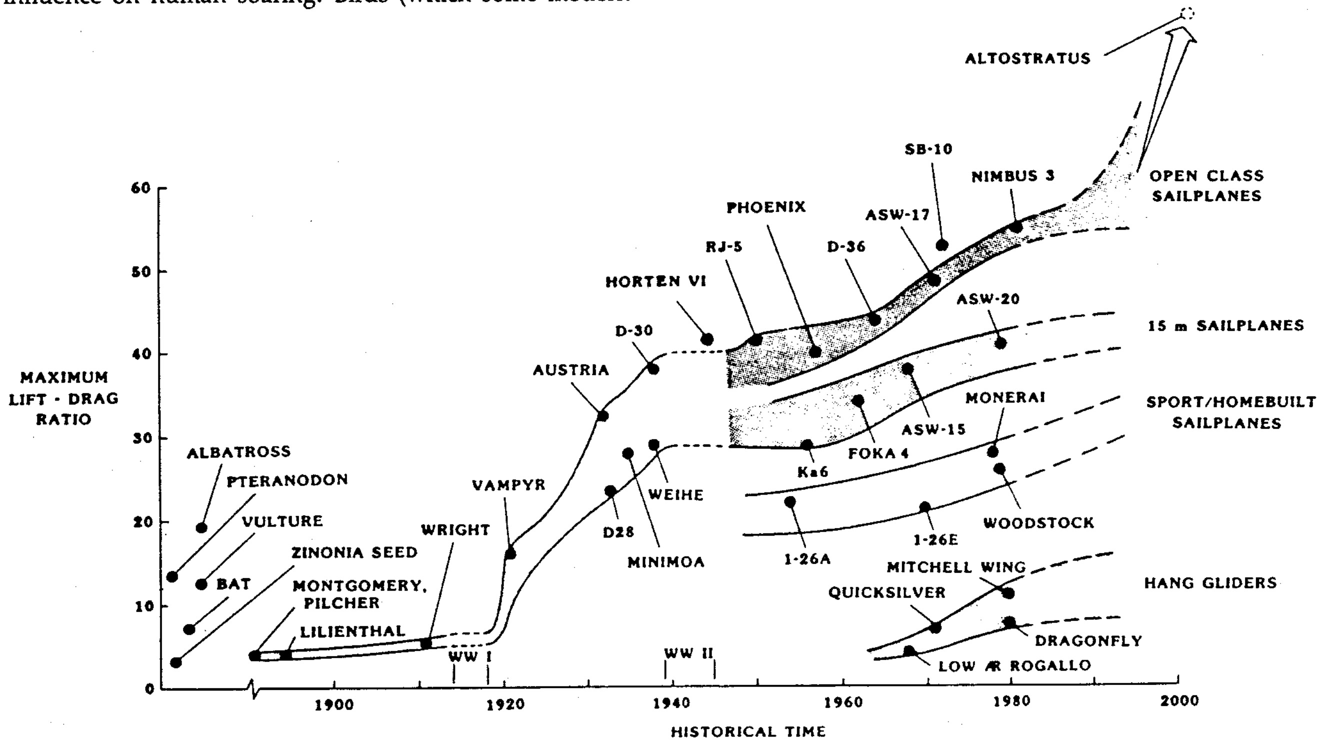


Figure 11. Historical Trends in Gliding and Soaring Performance

Table I

Type	Year	b	S	AR	M/S	M(kg)		L/D_{max}	z_{min}
		(m)	(m^2)		(kg/m^2)	empty	loaded	@ (V-km/h)	@ (V-km/h)
Wright	1911	9.8	27.9	6.8	5.7	86	160	8 (46)	.75 (42)
Blaue Maus	1921	9.5	15.5	5.8	8.3	53	128	12 (54)	.80 (52)
Vampyr	1921	12.6	16.0	9.9	12.2	120	195	17 (52)	.80 (50)
Konsul	1923	18.2	21.0	15.8	13.3	200	280	21 (52)	.75 (47)
Darmstadt II	1928	18.0	16.9	19.2	14.4	162	245	21 (58)	.70 (54)
Wien	1929	19.2	18.4	20.0	13.9	160	255	22 (54)	.60 (52)
Fafnir I	1930	19.0	18.6	19.4	16.9	220	315	24 (60)	.58 (56)
Austria	1931	30.0	35.0	25.7	13.8	392	482	26 (60)	.55 (56)
D-28 Windspiel	1933	12.0	11.4	12.6	11.9	55	136	24 (52)	.66 (47)
D-30 Cirrus	1938	20.1	12.0	33.7	24.7	198	296	36 (77)	.52 (72)
Weihe	1938	18.0	18.3	17.7	18.3	230	335	29 (70)	.58 (60)
Olympia Meise	1939	15.0	15.0	15.0	17.0	160	255	26 (69)	.67 (59)
Horten IV	1941	20.0	21.1	19.0	16.5	230	349	32 (72)	.55 (56)
RJ-5	1950	16.8	11.5	24.5	27.1	223	314	41 (80)	.55 (74)
Schweizer 1-26A	1953	12.2	14.9	10.0	17.5	161	261	23 (79)	.82 (64)
Schleicher Ka-6CR	1956	15.0	12.4	18.1	24.2	190	300	29 (78)	.68 (67)
Phönix	1957	16.0	14.4	17.8	18.5	164	265	40 (78)	.51 (69)
Foka 4	1962	15.0	12.2	18.5	31.6	245	386	34 (95)	.70 (79)
D-36	1964	17.8	12.8	24.0	32.0	282	410	44 (93)	.56 (83)
AS-W 15	1968	15.0	11.0	20.5	37.1	230	408	38 (90)	.59 (73)
SB-10	1972	29.0	23.0	36.5	39.0	577	897	53 (90)	.41 (75)
Ventus A	1980	15.0	9.5	23.7	45.0	215	430	44 (109)	.66 (93)
Nimbus 3	1981	24.5	16.8	35.7	41.8	360	703	60 (80)	.36 (76)

shows the trend in maximum lift-to-drag ratio of sailplanes from Lilienthal's to the present. The principal characteristics of these machines are listed in Table 1.

HIGH-PERFORMANCE SAILPLANE DEVELOPMENT
1911 - 1981

Early Development

The Wright brothers, celebrated as pioneers of powered heavier-than-air flight, are perhaps best credited for the practical realization of the three-axis, aerodynamic flight-control system without which the evolution of powered and unpowered aircraft could scarcely have progressed beyond the hang glider stage. The Wrights were early to grasp the significance of atmospheric lift to the soaring flight of birds. They continued to experiment with gliders even after the success of the 1903 *Flyer*, and in 1911 Orville succeeded in making a number of true soaring flights of more than five minutes duration. On October 24 of that year he was able to soar over the sand dunes near Kitty Hawk for 9 minutes and 45 seconds, establishing a duration record which was to stand for 10 years. This was slope soaring in its most elemental form, flying almost directly into the wind and essentially hovering over a small area (these early soaring flights were conducted in winds of up to 40 miles per hour).

This first "sailplane" of 1911 was typical of Wright brothers designs. It was a biplane, the two planes being of equal span with no stagger, with twin vertical stabilizers and an elevator on the fuselage frame behind the wing (a conventional configuration, except that there was also a vertical stabilizer mounted just ahead of the wing leading edge). The span was 9.8 meters, and the wing loading somewhere around 7 kg/m^2, which is about the same as a modern high-performance hang glider.

The real soaring movement began in post-World War I Germany, where aeronautical development was restricted by the Treaty of Versailles to low-powered or unpowered aircraft. The first glider meet, organized by Oscar Ursinus, was held in 1920 on a mountain in the Rhön region called the Wasserkuppe. Twenty-four young Germans showed up with their gliders. Outstanding among this early crop of soaring machines was Wolfgang Klemperer's *Schwarzer Teufel*, a streamlined, cantilever, low-wing monoplane with very low wing loading (8.3 kg/m^2). Launched into the wind by bungee cord, Klemperer easily set a world's record for gliding distance, covering 1.82 kilometers. Orville Wright's endurance record still stood, however, and neither the *Schwarzer Teufel* nor any of the other participating gliders ever actually achieved soaring flight that year.

The next year, Klemperer was back with the *Blaue Maus*, a development of the *Schwarzer Teufel* with a better cockpit enclosure (the pilot was still exposed from the chest up, however). The 1921 contest was the occasion of an interesting demonstration of the relative effect of parasite drag and induced drag on gliding efficiency at low flying speeds. The *Blaue Maus* was tied for the lowest sink rate (about 0.4 m/s) with a glider built by the Aero Club of Munich. The Munich glider was not streamlined (i.e., it had much higher parasite drag relative to the *Blaue Maus*) and was only 9 kilograms lighter (about 5 percent of the gross weight). Both gliders had the same wing area, but the Munich glider's wing had 1.5 meters more span and hence less induced drag than the *Blaue Maus*.

The most significant technical achievements of 1921, however, were embodied in the *Vampyr* (Figure 12), designed

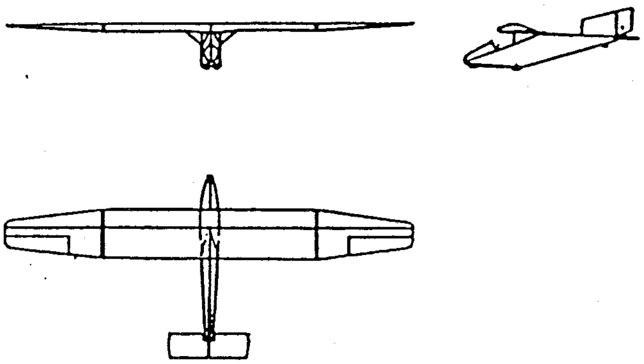


Figure 12. Vampyr (1921)

by Madelung, Blume, Hentzen, and Martens of Akaflieg Hannover. The *Vampyr's* wing was laid out in a serious attempt to minimize induced drag. With an aspect ratio of nearly 10, its wing spanned 12.6 meters, far greater than any of its contemporaries. The outer wing panels were tapered and mated to a constant chord center section. In order to keep the parasite drag level down, all but the pilot's head was enclosed in the fuselage, and the landing gear consisted only of three leather footballs on the belly of the aircraft. The airframe was constructed primarily of wood, as were nearly all aircraft of this period.

Madelung's stated design goal for *Vampyr* was a glider with minimum sink rate, the most important performance parameter for slope soaring. What Akaflieg Hannover really accomplished with *Vampyr*, however, was a dramatic increase in maximum lift-to-drag ratio. Based on wind tunnel measurements, *Vampyr's* maximum L/D was 16, compared to an L/D_{max} of about 5 for the Wrights' first "sailplane." Its measured minimum sink speed was 0.8 m/s, twice that of the *Blaue Maus* and the Munich glider.

In the *Vampyr*, Martens was able to break Orville's long-standing endurance record with a 15-minute flight, including two full circles, but in fact no altitude was gained and this was not considered true soaring flight. It was not long, however, before the first true slope soaring flight was accomplished by Friedrich Harth in a Harth-Messerschmitt glider along a ridge near Hildenstein. The following year, *Vampyr* achieved spectacular success at the hands of Hentzen and Martens slope soaring from the Wasserkuppe, including a record flight by Hentzen lasting 3 hours and 6 minutes with an altitude gain of over 300 meters.

If the *Vampyr* was a trend-setter aerodynamically, it also incorporated one very important structural innovation, the single-spar wing with stressed skin nose. The single full-depth spar carried the bending loads while the nose formed with the spar web a torsion-resisting D-tube. This construction method allows an accurate airfoil leading edge shape to be maintained from one rib to the next. The concept remains in common use today.

The German Akaflieg system has had no counterpart in the United States. Due to the many contributions of this unique institution to soaring technology throughout the history of the sport, it merits special mention before resuming this narrative. An Akaflieg (AKAdemische FLIEGergruppe or, literally, academic flying group) is essentially a combination undergraduate technical fraternity and flying club associated with a technical university (notably those in Aachen, Braunschweig, Darmstadt, Hannover, Munich, and Stuttgart). The students in an Akaflieg, at their own discretion, undertake the design, construction, and testing of experimental aircraft. University faculty serve mainly in an advisory role. Financial assistance is provided by donations from private sources and the government. The various Akafliegs have traditionally been the source of many of the major advances in sailplane technology.

Progress During the 1920's and 1930's

For the most part, sailplane development through the 1920's was characterized not by major technological breakthroughs but by refinements within the limits of existing technology. Akaflieg Darmstadt, which would figure heavily in the future technical development of soaring, took the quest for increased aerodynamic efficiency a step forward by building one of the first successful long-span cantilever wings in 1923. Their sailplane, the *Konsul* (Figure 13), had a span of 18.2 meters. It was of high aspect ratio (AR = 16) and was first to use the Göttingen 535 airfoil section which would remain popular with designers for the next 15 years. Other design innovations appeared in this sailplane which were soon widely adopted by other designers. The fuselage was well-streamlined with an elliptical cross section to minimize drag. The ailerons were rigged to move differentially in order to minimize adverse yaw.

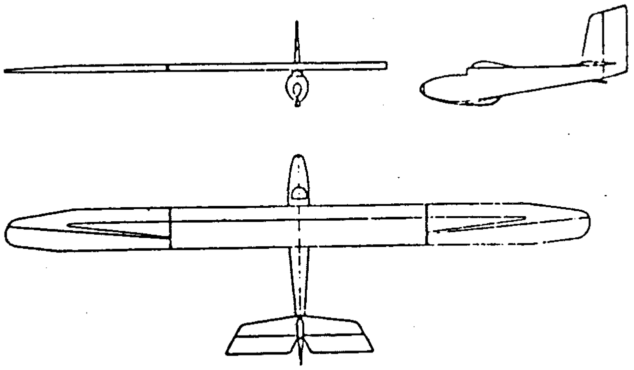


Figure 13. Konsul (1923)

Akaflieg Darmstadt introduced the elliptical planform cantilever wing in 1927. Based on the work of Trefftz, it was believed that the most efficient wing must be of elliptical planform in order to achieve an elliptical variation in span loading and hence minimum induced drag (it was also recognized that induced drag could be reduced by increasing span). A series of sailplanes was produced to exploit this idea, including the *Darmstadt I*, the *Darmstadt II*, and the *Starkenburg*. By 1928 it was clear that this line of development had reached its limit, for attempts to further improve performance by increasing span were foiled by the increased weight associated with such a change.

During the late 1920's, as slope soaring techniques were perfected, more able pilots found they could use ridge lift to soar cross-country, eventually covering distances of over 100 kilometers. Simultaneously, the possibility of using convective air movement to stay aloft began to be explored, beginning with an inadvertent ride in the updrafts of a developing thunderstorm by Kegel in 1926 (he survived).

By 1928, it was realized that a straight tapered wing could be nearly as efficient as an elliptical wing — and with considerable weight savings. Alexander Lippisch of the Rhön-Rossitten Gesellschaft (RRG), an aeronautical research institute located on the Wasserkuppe, accordingly designed the *Professor* in 1928 and, in 1929, the larger, more refined *Wien* (Figure 14) which had highly-tapered, cantilever, outer wing sections with a strut-braced, constant-chord center section. The reversion to strut bracing allowed an increase

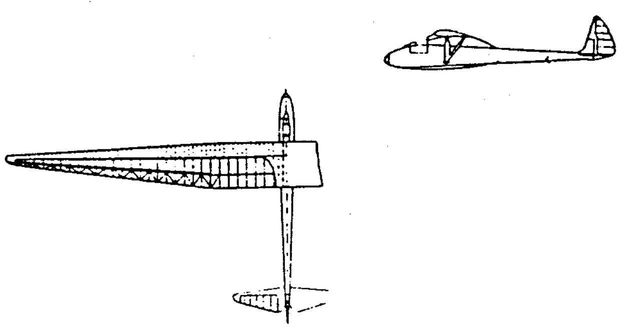


Figure 14. Wien (1929)

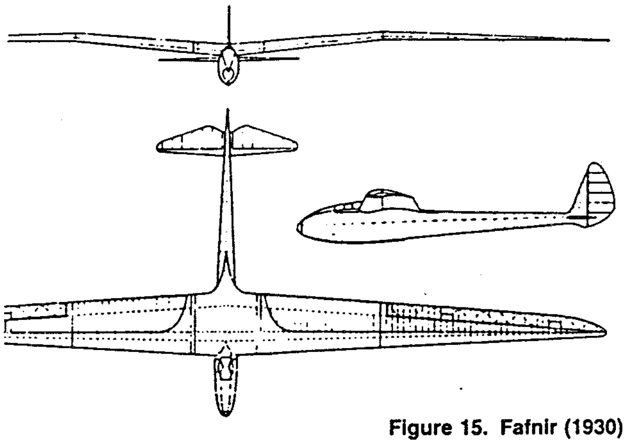


Figure 15. Fafnir (1930)

in span and aspect ratio without a corresponding weight penalty. The *Wien* proved to be outstanding in competition, and at the hands of Robert Kronfeld made one of the first cross-country flights using thermal lift as well as ridge lift.

With the increasing sophistication of soaring technique came the realization that not only low sinking speed and high glide ratios but also high maneuverability about the pitch and roll axes were required to take full advantage of ridge (and later, thermal) lift. Lippisch was the first to meet this new design challenge. Like the *Vampyr*, the *Konsul*, and the *Wien*, his *Fafnir* (Figure 15), which appeared in 1930, incorporated design features which would become standard on high-performance sailplanes for years to come. Rolling inertia was minimized by using a strongly tapered wing planform and by mounting the wing on top of the fuselage, closer to the center of gravity, rather than on a pylon. The wing was built in a cranked (gull-wing) configuration, ostensibly to provide ground clearance on takeoff and landing, and for improved stability in turns, but aesthetics may have been as much a factor in this design decision as aerodynamics. Aerodynamic twist was built into the wing by varying the airfoil section from the Göttingen 652 at the root, to the less highly cambered Göttingen 535 at midspan, to Clark Y at the tip. Several degrees of washout were also incorporated, and in this way aileron effectiveness at low speeds was improved and premature stalling of the wingtips was avoided. Aileron effectiveness was further improved by maintaining a constant aileron chord length over about 80 percent of their span from the inboard ends. With the highly tapered planform this resulted in increased aileron chord fraction and thus increased aileron effectiveness toward the tips.

Lippisch also paid attention to drag reduction. Like *Vampyr*, the *Fafnir's* wing was fully cantilevered. The potential for increased interference drag due to the proximity of wing and fuselage was recognized, and by trial and error a satisfactory wing fairing and cockpit enclosure were developed.

Fafnir was built by RRG and entered by Günther Grönhoff in the 1930 Wasserkuppe meet. The ship flew well, and the next year he set a world distance record of 220 kilometers after a bungee cord launch from the Wasserkuppe.

The patterns of sailplane development have tended to be dictated largely by the style of soaring which predominated at a given time. Through the 1920's and well into the 1930's, ridge soaring was the predominant mode of soaring flight. Designers, therefore, assumed that a glider would spend more time in lift than in sink, so their sailplanes were optimized for low sink speeds at low forward speeds, and for high maximum lift-to-drag ratio. Low wing loadings and thick highly cambered airfoils were considered necessary to achieve the desired low sink speeds. Even after the advent of thermal soaring, designers continued to emphasize low-speed performance in their sailplanes.

This pattern of sailplane development was taken to its practical limit with the *Austria* (Figure 16), designed by Dr. Kupper and constructed by Akaflieg Munich in 1931 to the order of Robert Kronfeld. Kronfeld thought that dolphin soaring might be the best way to utilize thermal lift for cross-country soaring. The design of the *Austria* represented an all-out effort to achieve high L/D and low minimum sink speed at the expense of maneuverability. According to the principle that induced drag is driven (down) by increased span, the *Austria's* wing was given a span of 30 meters, to be equaled (almost) only by the recent SB-10 of Akaflieg Braunschweig. At that time, state-of-the-art sailplanes had spans of about 20 meters. Without the benefit of modern materials, a wing of such great span was unavoidably going to be quite heavy. In order to keep the wing loading in line with contemporary practice (12-17 kg/m^2), the wing area had to be increased drastically to about 36 m^2. This resulted in an aspect ratio of about 25. All that span and all that area made for a magnificent floater, but *Austria* never set any records. Why? With such a low wing loading the airfoil section had to work at very low lift coefficients in high-speed flight. Despite the incorporation of camber-changing flaps (deflected up to reduce the camber for flight at higher

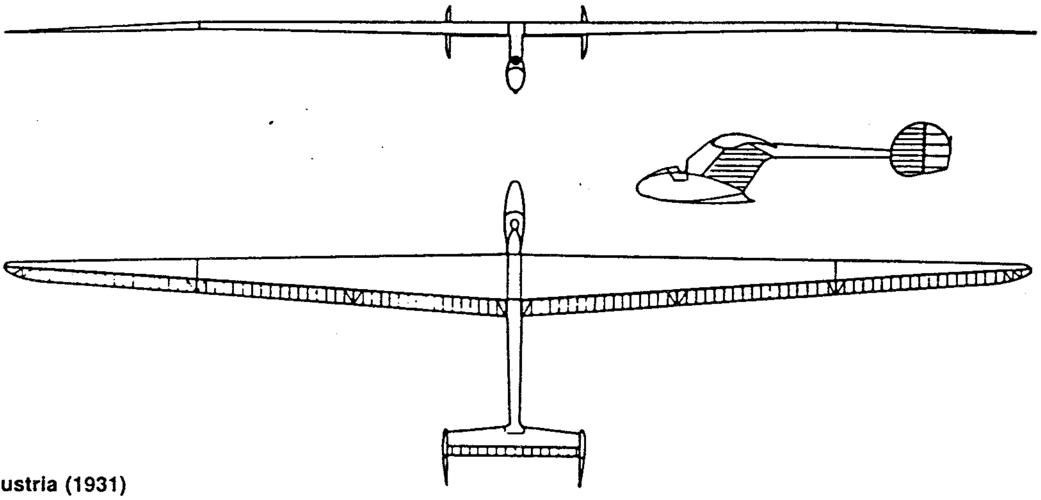


Figure 16. Austria (1931)

speeds), its thick, highly-cambered Göttingen 652 airfoil section was simply unsuitable for interthermal dashes. This airfoil had a high maximum lift coefficient and maximum L/D, but was inefficient at low lift coefficient values (more discussion on this topic later). Needless to say, the unwieldy *Austria* was not particularly well-suited for circling in thermals either, but this technique was just being developed as the *Austria* was being built.

Although not a complete success, the *Austria* was an impressive technical achievement and incorporated many innovations now taken for granted. Besides being the first sailplane to use cruise flaps, the *Austria* was also the first to have full-span segmented flaperons, a wing skinned entirely with plywood, and air brakes. The *Austria* met its untimely end in July of 1932 when the turbulence inside a large cumulus cloud proved to be more than Kronfeld and his minimal blind flying instruments could handle. The ship broke up in a steep spiral dive.

By 1932, a better understanding of how to use thermals had been reached. There was at this time a prominent school of thought which argued that most thermals were small in extent and rather weak. Akaflieg Darmstadt hypothesized that a highly maneuverable sailplane with the minimum possible sink speed would best be able to take advantage of such small thermals. From such thinking came the D-28 *Windspiel* (Figure 17), which appeared in 1933.

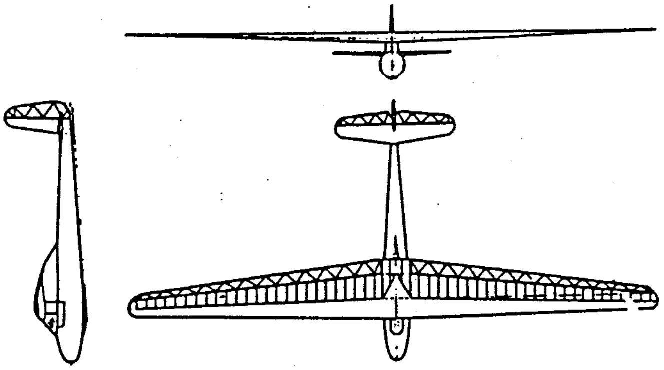


Figure 17. D-28 Windspiel (1933)

Spanning only 12 meters and weighing only 55 kilograms empty, the *Windspiel* was a true ultralight sailplane. Low structural weight was achieved by milling out most of the structural members, by keeping very close dimensional tolerances, by removing excess glue from joints, and by using light alloys for fittings and the aileron spars. As with the *Austria*, great pains were taken to minimize excrescences, and the cockpit was fully enclosed. An interesting innovation was the "flapped" rudder. The vertical fin was deflected with the rudder at a 1:2 differential, which increased rudder effectiveness and reduced required rudder area. Although the *Windspiel* was compact, it was inordinately expensive and difficult to build and required careful ground handling.

In March of 1934, Hans Fischer set a world distance record of 240 km in the *Windspiel*. The following year, however, this record was broken by Wolf Hirth, flying his 20-meter *Moazagotl*. Hirth is said to have been the first to have demonstrated that a sailplane could circle within a thermal to utilize such lift to best advantage. His 262-kilometer flight showed that a large-span sailplane could be made sufficiently maneuverable to use thermal lift effectively, thus rendering the *Windspiel* obsolete. Too great a penalty in induced drag was paid in limiting span to a mere 12 meters.

The middle to late 1930's saw a general awakening on the part of the soaring community to the importance of a flat glide polar for an effective cross-country soaring machine. Designers went to more moderately-cambered airfoils and higher wing loadings and found that good high-speed performance could be achieved while maintaining sufficient low-speed capability for climbing in thermals. The D-30 *Cirrus* (Figure 18) can perhaps be considered the crowning achievement of this period of sailplane development. Like the *Windspiel*, the *Cirrus* was a project of Akaflieg Darmstadt. Its span was only 20 meters, but with only 12m^2 of wing area (giving it an aspect ratio of 34!), its wing loading was well over 20 kg/m^2, remarkably high for its time. The *Cirrus* was a very clean sailplane as well, and its glide ratio was around 36 at a respectable 77 km/h. This kind of performance would not be equaled until the early fifties. The light weight of the *Cirrus* could be attributed to the use of aluminum and magnesium in its primary structure. The high wing loading, the incorporation of cruise flaps, and the use of an NACA airfoil section of low camber contributed to its excellent penetration (high-speed) capabilities.

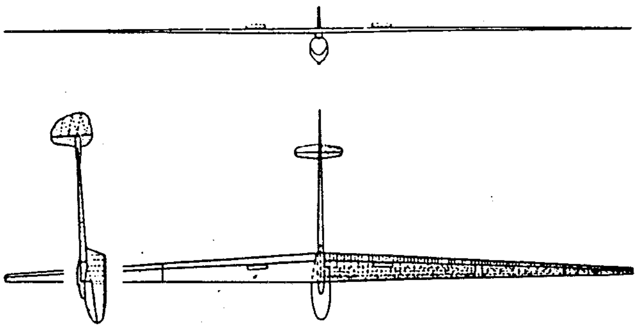


Figure 18. D-30 Cirrus (1938)

★ *Next month author John McMasters will pick up the story of soaring's technical history following WWII with sections devoted to the introduction of composite structures, the continuing evolution of sailplane airfoils, significant designs, and a rundown on recent developments.* — Ed.

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(Additional references will appear next month with Part II)

A technical history of soaring—

From Paleoaeronautics to Altostratus

by M.K. CHEN and J.H. McMASTERS

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PART II

Post-WW II Development

With the opening of World War II, the development of high-performance sailplanes came to a virtual standstill. The frantic development of transport gliders and of training gliders for military use is an interesting story in itself, but beyond the scope of this paper. One notable development in this period was the continued experimentation by the Horten brothers in Germany with flying wings. This led to the eventual development of the magnificent-appearing Horten IV (Figure 19) and Horten VI sailplanes. The latter reflected an almost absolute aesthetic, if not technical, triumph in unlimited-class sailplane development.

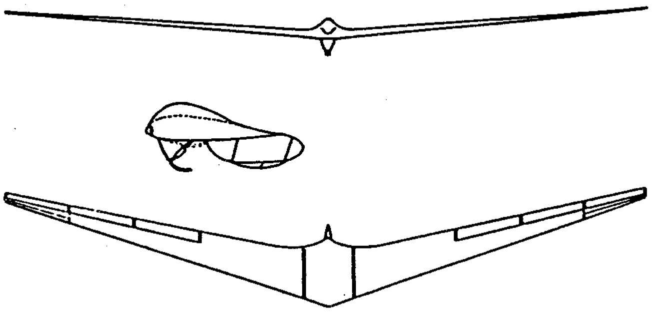


Figure 19. Horten IV (1941)

International competition soaring resumed in 1947, with most pilots flying prewar vintage machines. Perhaps the most successful sailplane in the early postwar competitions was the Focke Wulf *Weihe* (Figure 20), which had been designed by Hans Jacobs in 1938. A *Weihe* had placed fourth in the Rhön competition of 1938. Thus it is an appropriate machine on which to base our discussion of the transition from prewar to postwar sailplane development since it was representative of the better competition machines of the period.

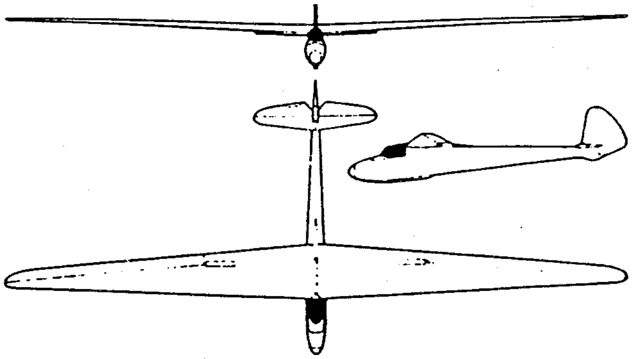


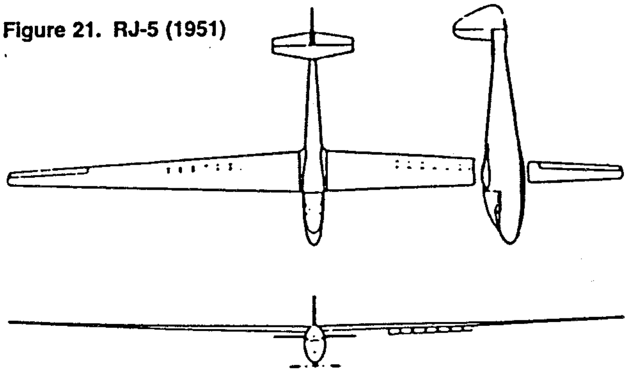
Figure 20. Focke-Wulf Weihe (1938)

The *Weihe* appears to embody many of the lessons learned from the *Austria*, the D-28, and the D-30. It was no ultralight, having an empty weight of 230 kilograms. The span was 18.0 meters, a compromise between the low-speed efficiency of the 30-meter *Austria* and the maneuverability of the 12-meter D-28. By now the importance of efficient flight at high speeds was recognized; with a wing loading of 18.3 kg/m^2 and using the moderately-cambered Göttingen 549 airfoil, the *Weihe* was better suited to this flight regime than the *Austria* or D-28. However, it can be seen that the wooden *Weihe*, intended from its inception to be a production sailplane, could not take advantage of the exotic materials and construction techniques used in the D-30, which made possible its unprecedented efficiency.

Postwar advances in sailplane performance began when August Raspet and Richard Johnson at Mississippi State College demonstrated the startling performance gains possible by systematically cleaning up a machine of basically good aerodynamic layout. The machine used was the one-of-a-kind RJ-5 (Figure 21) designed by Harland Ross. The RJ-5 was of conventional configuration and construction (wood and aluminum), employing a NACA 6-series laminar flow airfoil. Through careful sealing of leaks and gaps, reduction of wing waviness and roughness, and installing a recontoured canopy in place of the original spherical bubble, successive reductions in parasite drag were measured over a period of several years, resulting in an improvement in maximum L/D from 30 to about 41. Parasite drag was reduced by 25 percent at L/D_{max}, and about 40 percent of this reduction was accomplished by simple sealing and smoothing. With the RJ-5 the limits of sailplane performance were established for the materials and the airfoils available at the time. Raspet's work heavily influenced the design of production competition sailplanes for the next decade, but production considerations necessarily limited the performance of these ships relative to the RJ-5.

In 1958 the Standard Class was added to international competition in the World Gliding Championships, held that year in Leszno, Poland. The Standard Class concept was a revival of the class competition idea which arose before World War II with efforts to gain recognition of soaring as an Olympic sport by the International Olympic Committee.

Figure 21. RJ-5 (1951)



The Standard Class was inaugurated in order to assure the continuance of a category of competition in which sailplane costs would not climb out of sight as technical innovations were incorporated in the name of increased performance. The Standard Class sailplane was envisaged as being simple (no flaps, fixed undercarriage) and inexpensive, with performance as close as possible to that of contemporary Open Class machines, yet suitable for general club flying. Span was limited to 15 meters. In many respects the Standard Class sailplane was quite similar in concept to the prewar specification for an Olympic sailplane.

In 1957, OSTIV, the branch of the Federation Aeronautique Internationale (FAI) devoted to soaring technical and scientific advance, announced a design competition for the best Standard Class design at the 1958 World Gliding Championships. This competition was won by the Schleicher Ka-6 (Figure 22), designed by R. Kaiser, and primarily of wood.

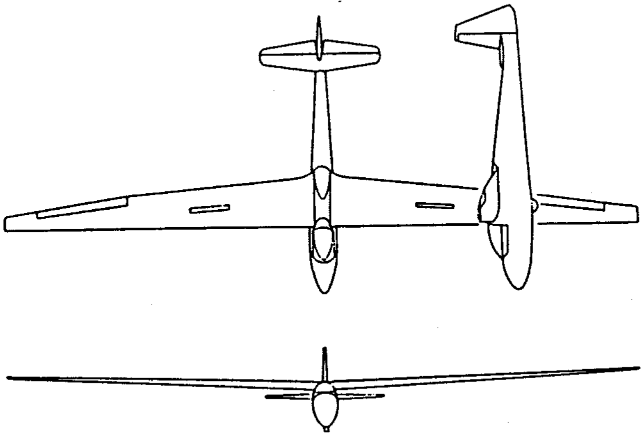


Figure 22. Schleicher Ka-6CR (1956)

The 15-meter span limitation of course limited the achievable performance for the existing level of technology. Nevertheless, the Ka-6, with its NACA 6-series airfoils and generally high degree of aerodynamic cleanness, achieved the same maximum L/D as the *Weihe* (about 29) at a higher airspeed (78 km/h vs. 70 km/h) with 3 meters of span less.

By now, the required characteristics for a high-performance sailplane were well-understood. The basic configuration had been established, and there was some understanding of how to optimize span and wing loading for a given style of flying. The significance of viscous scale effects to airfoil performance was appreciated, and designers and builders had sound recipes for parasite drag reduction. Further increases in sailplane performance could only be realized after a major breakthrough either in materials technology or in the development of more efficient airfoils. Actually, both of these breakthroughs occurred at roughly the same time.

Introduction of Composite Structures

The major development in materials technology was the introduction of fiberglass in sailplane primary structures. Fiberglass is a high-strength material of low specific gravity, but with a relatively low modulus of elasticity. In the interest of structural efficiency it is desirable to fully integrate the load-carrying members of an airframe with the aerodynamic shell that allows it to fly. Such structures are possible with fiberglass. In order to maintain desired levels of torsional and bending stiffness, wing skins must be quite thick and correspondingly stronger than required by existing sailplane airworthiness standards. Fiberglass sailplanes can thus be built with load factors approaching those of modern fighter aircraft, and, due to the low specific weight of fiberglass, this can be achieved with little weight penalty. The use of fiberglass wing skins also allows fabrication of relatively wave-free surfaces of unexcelled smoothness. With the use of molds such surfaces are also highly reproducible.

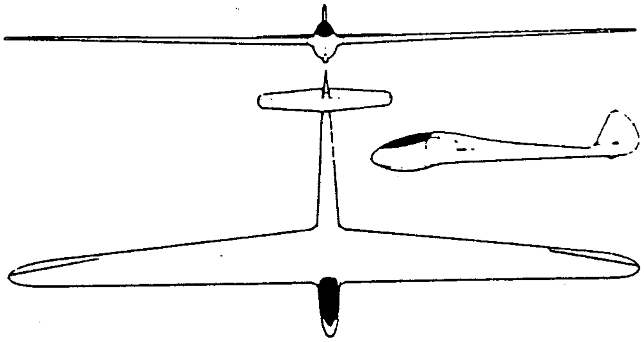


Figure 23. FS-24 Phönix (1957)

The use of fiberglass as a material for sailplane primary structures was pioneered by Nägele, Hütter, and Eppler of Akaflieg Stuttgart. They produced the first fiberglass sailplane, the Fs-24 *Phönix* (Figure 23), which first flew in November of 1957. Emphasis in the design of this 16-meter sailplane was placed on weight reduction, and in fact the empty weight of *Phönix* (164 kilograms) turned out to be little more than that of the 12-meter Schweizer 1-26 (Figure 24), a popular American metal-and-fabric sport sailplane of the period. The wing loadings of these two sailplanes were also quite similar, but the *Phönix* had a much lower minimum sink speed, thanks to its superior aerodynamic efficiency. Both achieved L/D_{max} at about the same speed (78-79 km/h). The *Phönix*, however, had an L/D_{max} of 40, compared to 23 for the 1-26. This remarkable increase in performance can be attributed largely to the *Phönix*'s more efficient wing planform and the smoothness of its surfaces, again made possible with no weight penalty by the use of fiberglass. The combination of low sink speed and good high-speed capability enabled the *Phönix* to achieve high average cruise speeds.

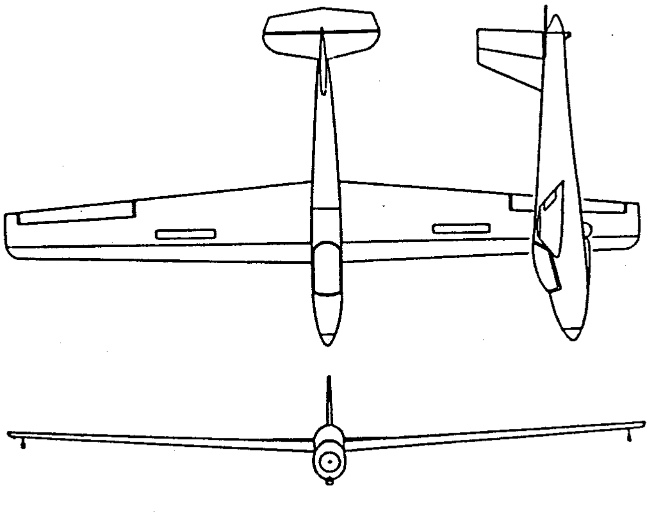


Figure 24. Schweizer 1-26 (1954)

Evolution of Sailplane Airfoils

The first efforts to develop airfoils suited for sailplanes were carried out in the 1920's at the University of Göttingen in Germany. The early Göttingen airfoils were designed using potential flow theory, ignoring viscous scale effects which are now known to have a critical effect on airfoil characteristics, especially at low Reynolds numbers. A large matrix of Göttingen airfoils underwent extensive wind tunnel testing, and of these the Gö 535 and Gö 652 were found to be particularly suited for sailplane applications. As previously mentioned, sailplanes of this earlier period were designed mainly for low sinking speeds at low flying speeds, and the thick and highly-cambered Göttingen airfoils worked well at the high lift coefficients required for this style of flying.

In the 1930's, with the development of cross-country soaring techniques, there was a general awakening to the additional importance of low drag at the lower lift coefficients required for higher cruising speeds. In this respect the Gö 535 and Gö 652 were totally unsatisfactory, for at low angles of attack these airfoils were prone to flow separation on the *lower* surface. Kupper attempted to mitigate this problem on the *Austria* by fitting camber-changing flaps to the wing trailing edge. For interthermal cruising, these were deflected up, thus reducing the camber of the wing section.

As competition led to demands for better cross-country performance, airfoils with less camber were widely adopted in the 1930's. The Göttingen 681 and 549 were popular during this period. Some use was also made of the NACA 4- and 5-digit series airfoils.

After World War II, the NACA 6-series laminar flow airfoils were widely used. These sections were derived using approximate theoretical methods with the objective of achieving very low drag by maintaining long runs of laminar flow within a design-limited lift-coefficient range. Laminar boundary layer flow is sustained over the forward portion of these airfoils by the avoidance of pressure "peaks" and a favorable pressure gradient. However, this flow condition is very sensitive to surface roughness and waviness. Before the advent of fiberglass structures, it was difficult, if not impossible, to build a wing of the requisite surface quality to sustain the full extent of laminar flow possible with these airfoils. Nonetheless, many successful sailplanes have been designed using the NACA 6-series airfoils.

In the 1950's, R. Eppler and F. X. Wortmann started conducting theoretical work on airfoils which showed that, by carefully contouring the airfoil thickness envelope, the boundary layer transition point on low-to-moderate cambered laminar airfoils could be controlled with some precision. Wortmann showed that by carefully contouring the upper surface of a fairly highly-cambered airfoil, the upper end of the laminar flow range can be extended to section lift coefficients required for low sink rate. When a highly-cambered airfoil is operated at low lift coefficient values, however, the airfoil is frequently flying at a negative geometric angle of attack, and thus the lower surface of the airfoil is the one on which transition is of primary concern in maintaining low profile drag. By carefully contouring both the upper and lower surfaces, the low-drag "laminar bucket" of the airfoil polar could be significantly extended compared to the NACA 6-series airfoils of similar thickness. The NACA 6-series were intended for a higher speed and Reynolds number range than is normally encountered in sailplanes, and the low-drag "laminar buckets" in their polars extend over a relatively limited range of lift coefficients. Wortmann, working with the benefit of a digital computer and better analytical methods, was able to exercise greater control over pressure distribution architecture and account explicitly for Reynolds number in his airfoil designs. As a result, the FX-series airfoils have a low drag (laminar bucket) operating range which extends to both higher and lower lift coefficients than the NACA 6-series, and this is achieved over a Reynolds number range more appropriate to sailplanes (Re = .7-3 × 10^6). See, for example, Figure 25 which compares the drag polars for the NACA 63_3-618 and the Wortmann FX 61-184 airfoils at a Reynolds number of 3 million. Both airfoils have been widely used in sailplanes. The extent of the bucket can be further extended by adjusting the camber line with a small-chord (10-20 percent) simple hinged flap at the trailing edge. Wortmann's FX series of airfoils began to appear on sailplanes in the 1960's, and by the end of the decade had been almost universally adopted by sailplane designers.

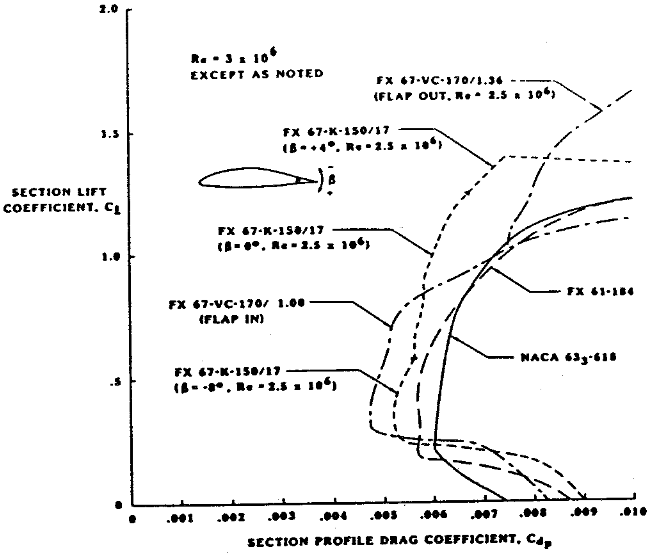


Figure 25. Sailplane Airfoil Performance Comparison

Wortmann's work on flapped airfoils has resulted in a return of cruise flaps as an almost obligatory feature of Open Class competition sailplanes. As mentioned earlier, cruise flaps first appeared as early as 1930. Then, as now, their purpose was to improve high-speed performance. The decambering of the early Göttingen sections served to partially mitigate the flow separation problem encountered on the lower surface of these airfoils at low angles of attack. The function of cruise flaps on wings which use Wortmann airfoils is to further extend the low-drag bucket at the high-speed end by controlling the boundary layer transition location. The drag polar for a popular Wortmann flapped airfoil, the FX 67-K-150/17, is shown in Figure 25. The effect of both positive and negative flap deflections may be seen.

Selected airfoil sections that have been used in some of the sailplanes discussed here are depicted in Figure 26.

Recent Developments

Akaflieg Stuttgart had begun the fiberglass revolution with the *Phönix*, but it was Akaflieg Darmstadt's D-36 *Circe* (Figure 27) that established the pattern for competition sailplanes which continues to influence designers today. The D-36 was designed by Lemke, Holighaus, and Waibel in 1963 and first flew in March of 1964. Unlike the *Phönix*, in which fiberglass construction was utilized in order to reduce weight, the designers of the D-36 took advantage of the low specific weight of fiberglass to develop an airframe which was no lighter than sailplanes of conventional structure and comparable span (e.g., *Weihe*, RJ-5), but which was much stronger and of high surface quality. The higher speed ca-

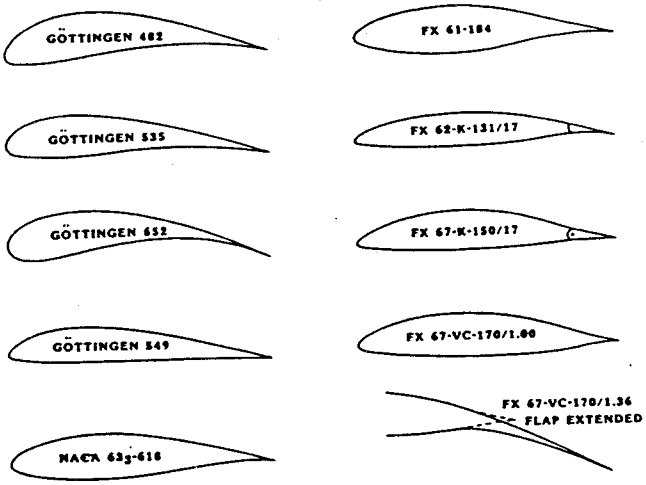


Figure 26. Some Representative Sailplane Airfoil Sections

pabilities of the Wortmann airfoils used, and the smoother surface of the fiberglass skin, enabled the D-36 to achieve an L/D_{max} of 44 at 93 km/h. Despite its high wing loading, the minimum sink speed of the D-36 was lower and was achieved at a higher flying speed than that of any of its adversaries at the 1965 World Gliding Championships, where it placed second in the Open Class. Interestingly, the winner was flying a Polish Standard Class *Foka* 4, of conventional wooden construction, demonstrating that flying skill, weather conditions, and luck remain fundamental ingredients to success in competitions.

The designers of the D-36 have all gone on to establish themselves in the German sailplane industry. The mainstream of Open Class sailplane development over the last decade has not strayed significantly from the D-36 formula. With span increases and careful attention to sealing and smoothing, measured lift-to-drag ratios of over 50 have been achieved, leading to the achievement of the long sought possibility of dolphin-style soaring on a routine basis. Most of the technical advances that have been proven in Open Class competition have also been incorporated in Standard Class sailplanes. Composite structures are now the norm in the Standard Class, and competition rules have been modified to allow the use of retractable landing gear. Some of these machines have achieved measured maximum lift-to-drag ratios of over 40.

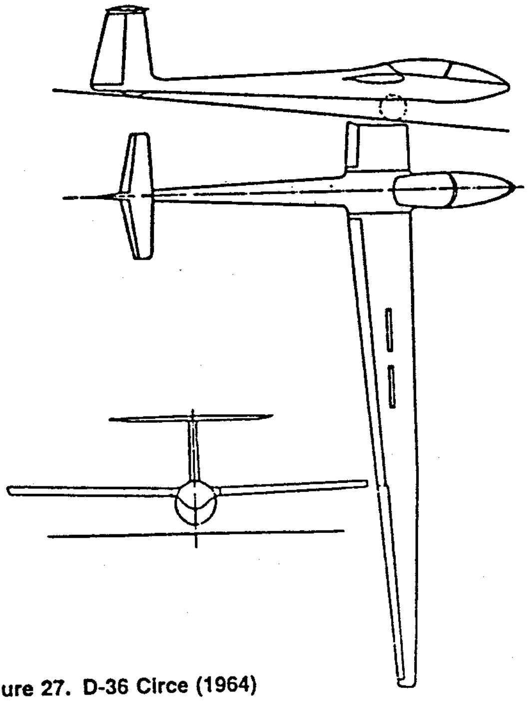


Figure 27. D-36 Circe (1964)

There are other fibers suitable for sailplane composite structures besides glass. The most important of these are Du Pont Kevlar and carbon fiber. Kevlar has high specific tensile strength and is two to three times as stiff as glass. However, it has relatively low compressive strength. Carbon fiber is twice as stiff as Kevlar and as strong or stronger than glass, depending on the type, but is expensive in comparison to the other fibers.

A sailplane wing designed for fiberglass construction can be lightened substantially (thus increasing the wing loading *range* to account for flights in both strong and weak lift conditions) and stiffened if carbon is substituted for glass (e.g., *Nimbus* 2C). The full potential of carbon fiber is realized with a sailplane designed from the start to take advantage of carbon's properties. Span can then be increased with no appreciable weight penalty relative to fiberglass, thus increasing aerodynamic efficiency, and/or thinner wings with reduced profile drag become feasible. Several Open Class and 15-Meter Class racing sailplanes have recently been developed with these objectives. Among these projects, the Schempp-Hirth *Nimbus* 3, winner of the Open Class in the 1981 World Gliding Championships held at Paderborn, West Germany, and the Schleicher AS-W 22 (Figure 28) are particularly notable. Calculated maximum lift-to-drag ratios for these machines are in the 50's, at speeds of over 120 km/h.

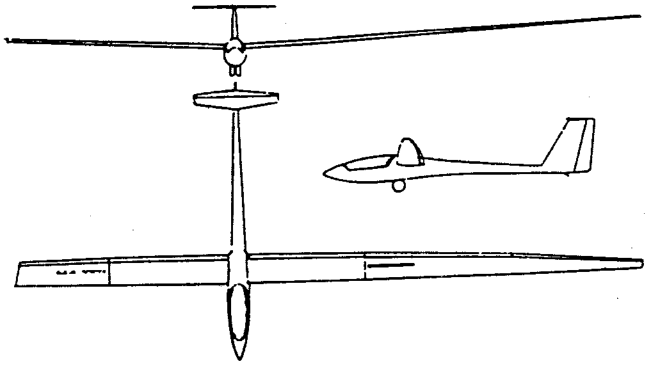


Figure 28. Schleicher AS-W 22 (1980)

.In the Standard Class and the newer 15-Meter Class (a less restrictive competition class which retains only the 15-meter span limitation of the Standard Class), the development of airfoils efficient at very low Reynolds numbers will be required in order to take full advantage of the structural properties of carbon. This has apparently been accomplished for the new *Ventus* (Figure 29), a 15-Meter Class sailplane with a carbon wing of 23.7 aspect ratio, considerably greater than most previous 15-meter wings. The wing area is only $9.5m^2$. In order to believe the claimed performance (L/D_{max} = 44 at 25 km/h), we must presume that the profile drag characteristics of the new and thinner airfoil section (designed by Althaus and Wortmann) are such that the reduced wetted area of the *Ventus'* wing is more than sufficient to compensate for the increased profile drag

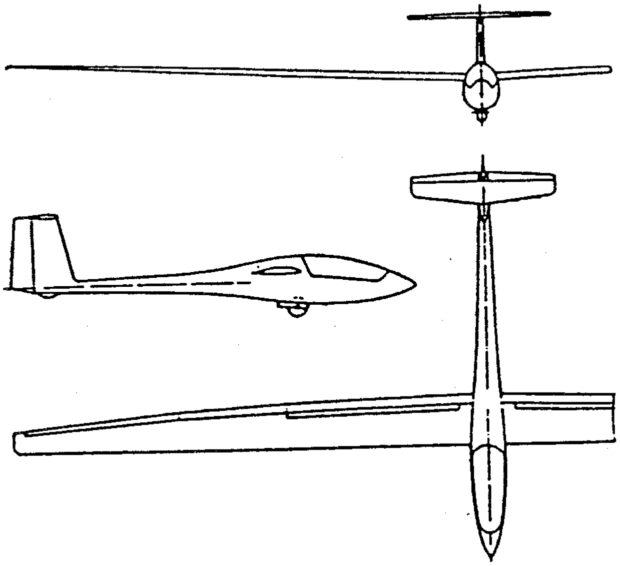
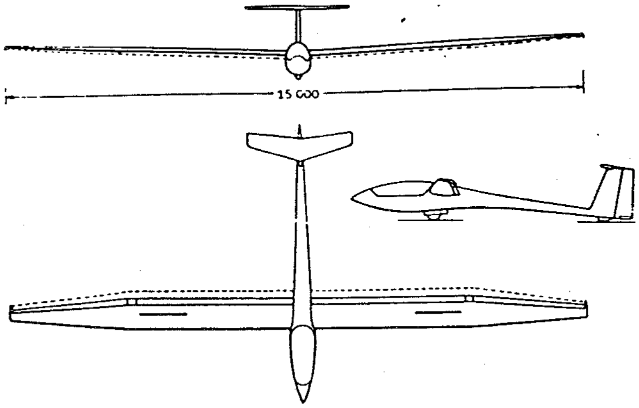


Figure 29. Schempp-Hirth Ventus A (1980)

which is normally expected of wing sections operating at lower Reynolds numbers. A further benefit from the use of carbon fiber in a sailplane wing of restricted span is an increase in the range of wing loadings at which the sailplane can be flown. The reduced empty weight of the wing allows lower wing loadings than have previously been possible (a benefit in weak lift conditions), while the increased strength of carbon (relative to fiberglass) allows more ballast to be carried in the thin wing to achieve higher wing loadings appropriate to strong lift conditions.

In order to further exploit the advantages of a wider range of allowable wing loadings needed to optimize performance in a variety of weather conditions, a number of variable geometry schemes have been developed in prototype form (Reference 32). These range from the use of chord-extending Fowler flaps (e.g., the British *Sigma* project of the late 1960's) to a true variable-span machine, the Akaflieg Stuttgart Fs-29. Of the new, highly complex and sophisticated sailplanes, only the Akaflieg Braunschweig SB-11 (Figure 30) can be considered a success so far, as measured by its winning performance in the 1978 World 15-Meter Class competition in Chateauroux, France. This line of development holds considerable promise for the future, however.

Figure 30. SB-11 (1978)



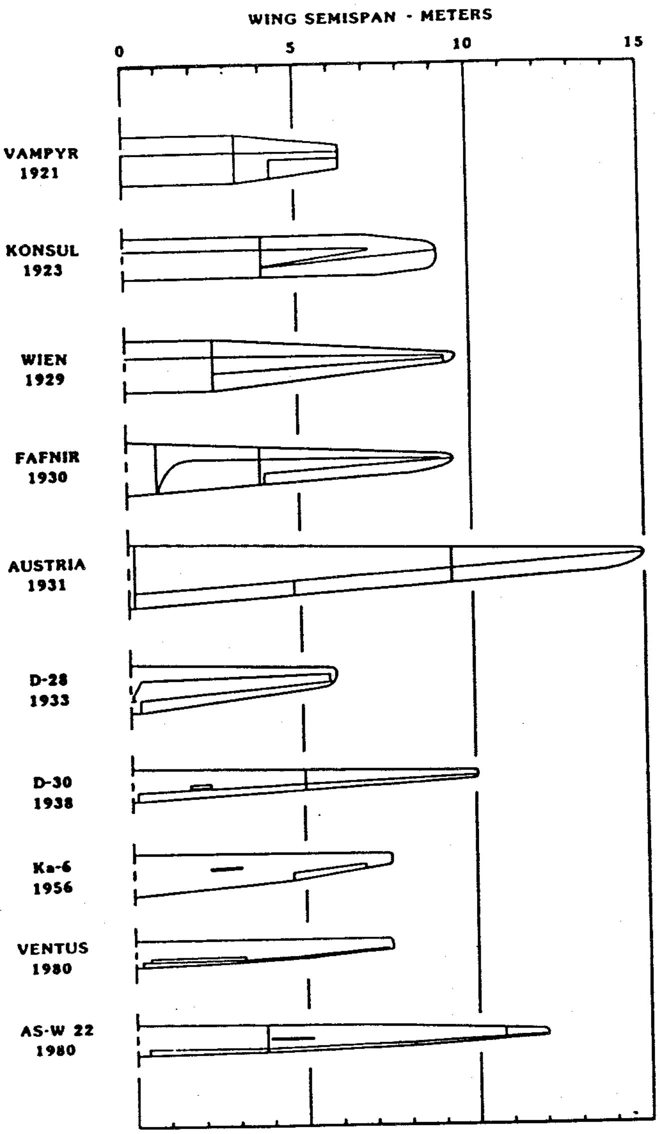


Figure 31. Evolution of Sailplane Wing Planforms

EPILOGUE

The story outlined so far has merely touched upon selected high points of the course of development which has led to the aesthetic and technical triumph of the modern high-performance racing sailplane. The reader will observe that while modern soaring began with the Wright brothers, the story has been basically one of European (and very largely German) achievement since that time. It is perhaps regrettable that with few (but noteworthy) exceptions (e.g., Raspet's work), the United States has been placed largely in the role of consumer rather than developer of this technology. The excellent work of people like Hawley Bowlus, Len Niemi, Gus Briegleb, Dick Schreder, George Applebay, and others is not to be disparaged. With the exception of Raspet and his colleagues, however, most of the machines developed domestically were largely state-of-the-art and did not embody advanced concepts of the time. While keen interest in soaring, both for recreation and for serious competition, has been displayed in this country since the 1930's by a relatively small group of enthusiasts (represented by the Soaring Society of America with 16,000 members at present), soaring has never achieved the stature or popularity it enjoyed in France, Germany, and Poland, for example. Domestic manufacture of sailplanes is presently limited to a few small-scale operations.

Only the Schweizer Aircraft Corporation in Elmira, New York, which supplies the bulk of training and sport sailplanes (e.g., the ubiquitous 1-26) to the U.S. market can be considered generally successful. Economic limitations associated in part with certification costs, as well as limited market appeal due to the cost and difficulties of normal sailplane operations are usually cited for this state of affairs. As advanced technology sailplane performance continues to increase, it becomes increasingly difficult, without a major technological and/or market breakthrough, for U.S. manufacturers to compete in this area.

It is at this point that the modern hang glider may be appropriately brought into the story. As mentioned previously, the high equipment costs associated with increased performance have led periodically to efforts to control the situation or provide alternatives. This was the motivation for the formation of the present Standard Class in soaring, and a backlash against high cost and operational difficulties with sailplanes led to modern experiments with hang gliding in the 1960's. This latter line of development was inspired foremost by the absurdly simple Rogallo wing kite which could be transformed (by the outlay of a mere $25) into a man-carrying, bamboo-and-vinyl-sheet "glider." And better, no flying license was required, and the whole thing could be collapsed into a tubular bundle transportable on a van or even a motorcycle. Thus, a new sport and industry was born. Modern evolved versions of the basic Rogallo recipe, manufactured of modern materials (aluminum, carbon fiber, and dacron sailcloth), are certainly capable of soaring, but hang gliding has gone its own route. The overlap in participation and interest between sailplane flying and hang gliding remains minimal. A modern history of these extraordinary developments has recently appeared (Reference 33).

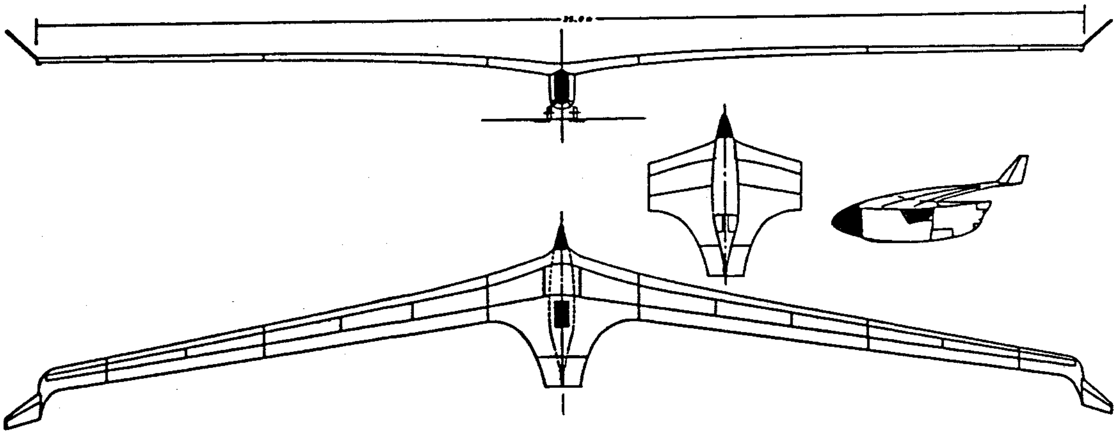


Figure 32. Altostratus I (2001)

There are other important elements of the overall history of soaring, but space limitations preclude elaboration here. Of these topics, the strong current interest in homebuilt and ultralight sport sailplanes is noteworthy. Here Dick Schreder shines as an almost unique example of just damned fine, truly American ingenuity and persistence applied to practical high-performance sailplane design suitable for home construction! These devices represent further attempts along more traditional lines to restrain the ever-rising costs of soaring. Further discussions can be found in References 34-36. Developments in motorgliding and the peripheral development of sailplane-inspired human and solar-powered aircraft also deserve mention.

The importance of soaring technology to other branches of aviation has been briefly mentioned. Direct applications to other branches of General Aviation have been discussed in Reference 37. Another potentially important use of sailplanes, which has been inadequately exploited to date, is in both atmospheric and aerodynamic research. Recent Lockheed experience in this area is noteworthy.

Returning finally to the racing sailplane, costs continue to rise as does performance, although a temporary plateau appears to have been reached in achievable performance based on known materials and passive laminar flow aerodynamic technology. There is still a great deal of advance possible, however, largely through exploitation of variable geometry and perhaps eventually in mechanical boundary layer control. Given the past dramatic advances in performance, the ultimate sailplane may yet be produced. A possible candidate for this title, the *Altostratus*, has been described in Reference 38 and is shown in artist's conception in Figure 32.

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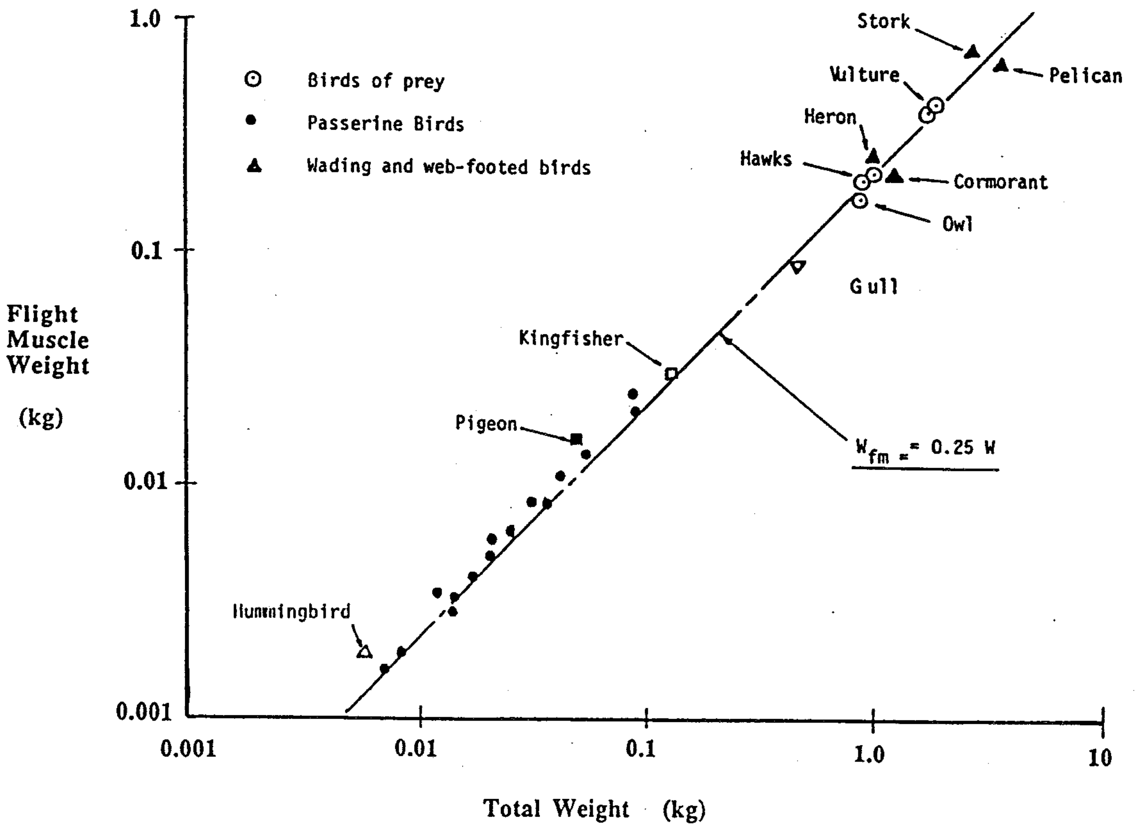
VERY BIG BIRDS

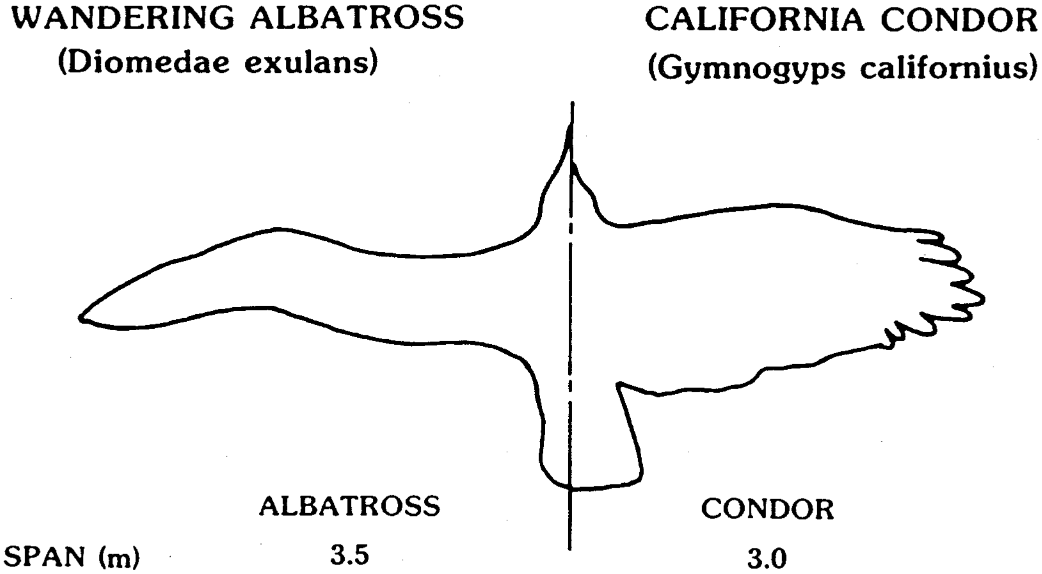
Having surveyed the detailed architecture of the bird wing, we now come to the rather hotly debated topic of how big a flying animal can get. At present this question relates to both flying birds and pterosaurs. The square-cube law says the following things on this matter: wing area varies as $W^{2/3}$; wing loading varies as $W^{1/3}$; flight speed varies as $W^{1/6}$; and power required varies as $W^{7/6}$.

Data on the subject [16] show that for various families of birds, flight-muscle weight (and hence power available) tends to be a constant fraction of total weight; that is, power *available* varies directly as *W*. The British ornithologist C. J. Pennycuick [60, 61] thus showed that square-cube law extrapolations of his own measurements of the power required to enable pigeons to fly predicted that the heaviest bird capable of flight (i.e., that bird in which power available just equals power required at one "design point") would have a mass of approximately 20 kg. This he found to be consistent with the weight of a wild South African turkey—the Kori bustard—which indeed is just barely able to fly.



Relationship Between Flight Muscle Weight and Total Weight for Various Birds

While the bustard may be the heaviest flying bird extant, it is not (dimensionally) the largest. Depending on one's point of view, the largest living flying birds are the condors (California and Andean) and/or the wandering albatross (*Diomedae exulans*), shown in comparison in figure 13. While enormous, the condor is further dwarfed by the 4-m-span Ice Age raptor *Teratornis merriami,* now extinct and known only from complete fossil remains from the La Brea tar pit in California [45]. Recent reports of a fossil teratorn found in Argentina (Campbell and Tonni [62, 63] presently credit it (based on scaling the length of a single inner wing bone to deduce total span) with a wingspan of 7 m. Taking the existing condor as a model for these larger teratorns, the square-cube law would predict weights of 23.7 kg (52 pounds) for the La Brea tar pit species and 127 kg (280 pounds) for the Argentine monster, both beyond Pennycuick's limits, the latter by a huge margin.



	ALBATROSS	CONDOR
WING SPAN (m)	3.5	3.0
WING AREA (m^2)	0.72	1.5
ASPECT RATIO	17	6
MASS (kg)	9.8	10
WING LOADING (kg/m^2)	13.6	6.6

FIG. 13.—Planform comparison of large land- and sea-soaring birds

A tentative partial explanation for these apparent anomalies lies in the fact that a major flaw in classic square-cube law predictions of the sort made so far is that they neglect the effects of fluid-dynamic scale factors—specifically Reynolds numbers. The author has been able to show [10, 64] that it is a relatively easy matter to accommodate first-order approximate Reynolds number scale effects in the context of the square-cube law. Thus it can be shown that if the vultures under discussion all had completely turbulent boundary-layer flow on their surfaces, the power required should vary not as $W^{7/6}$ but as $W^{65/57}$, an apparently small but significant difference. In fact, playing with Pennycuick's data, it can be shown that the maximum weight of a "giant pigeon" accounting for Reynolds number scale effects alone is on the order of 40 kg (compared to 20 kg when Reynolds numbers are ignored). Based on this new value, the biggest feasible pigeon would have a wingspan of about 4.75 m, a little smaller than the monster Ice Age *Teratornis incredibilis* known from a few fragmentary bones discovered in a cave in Nevada.

What all of this says is that one probably cannot manipulate a pigeon into a turkey (or a sea gull). As demonstrated by the wing-bone comparisons shown in figure 15, birds larger than those now in existence did exist during the last Ice Age—and they didn't get that big by sitting on their tails because they were too big to fly. As the American ornithologist Carl Welty [46] has observed: "Birds simply dare not deviate widely from sound aerodynamic design. Nature liquidates deviationists much more consistently and drastically than does any totalitarian dictator."

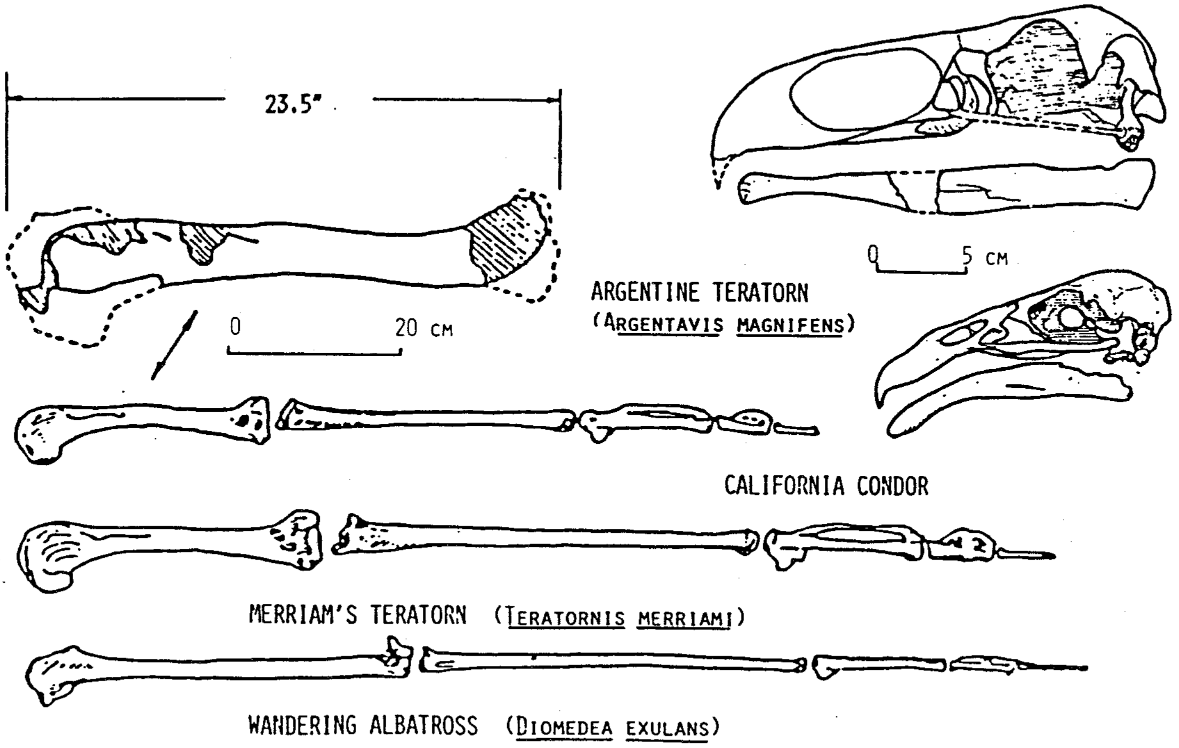


FIG. 15.—Wing bone and skull comparisons of several large soaring birds (Campbell and Tonni [64]).

One might further speculate that giantism (represented by the Argentine teratorn; fig 16) is something of a luxury in nature and generally represents an extreme in specialized development. The ability of a biological device to specialize to such a degree—to expand to the limit of some particular ecological niche and continue to survive—may depend on the stability or permanence of the environment that permitted such development. Environmental changes between the Ice Age 10,000–20,000 years ago and today may have doomed the giant teratorns to extinction. Regrettably, the modern condor seems equally close to extinction, supposedly owing to the encroachment of civilization on its habitat—a change in environment no less profound than a change in climate and food supply. As will be discussed later, the same sort of fate befell the dinosaur and its fantastic airborne counterpart, the pterosaur. Whether true or merely logically appealing, an alternative possibility is that a better model for extinction is demonstrated in the sad fate of the zeppelin.

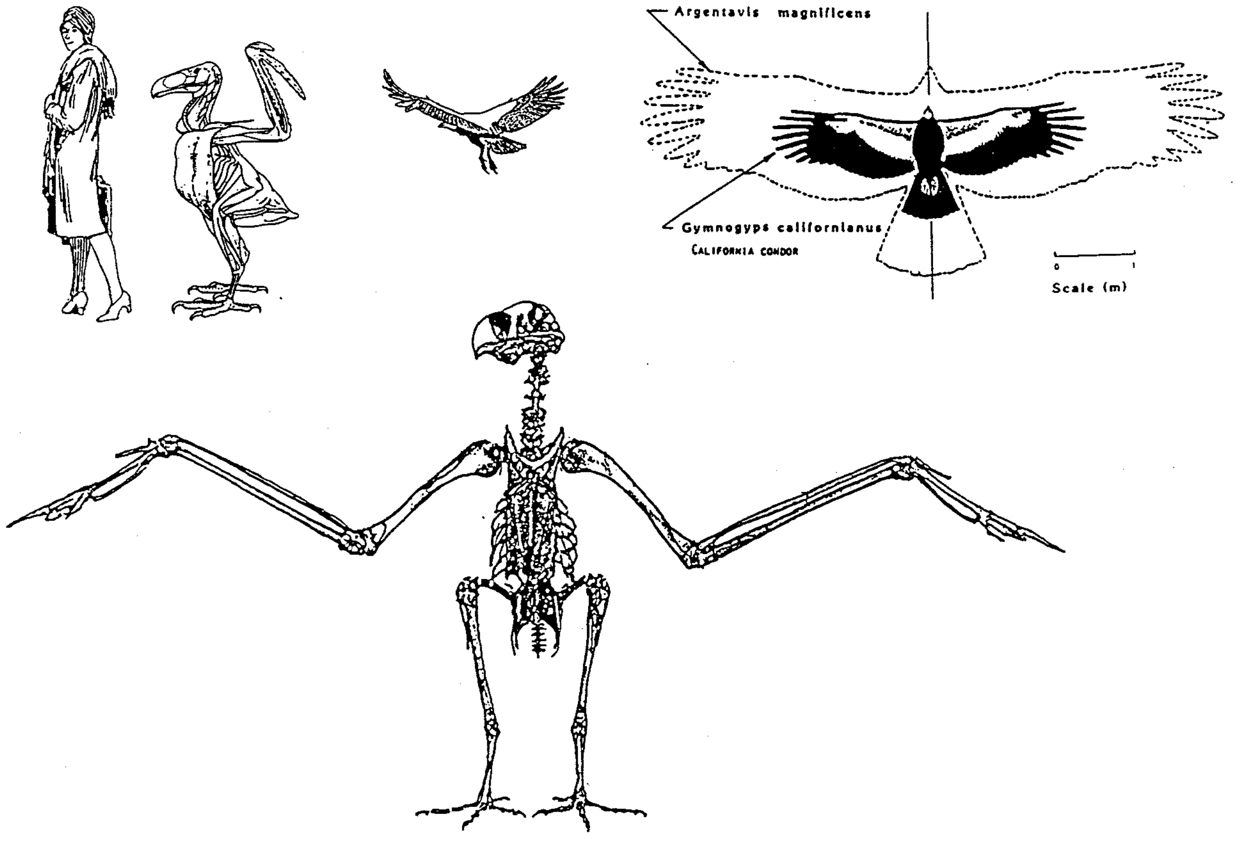


FIG. 16.—Estimated size comparison between the largest known soaring bird (*Argentavis magnificens*) and the California condor.

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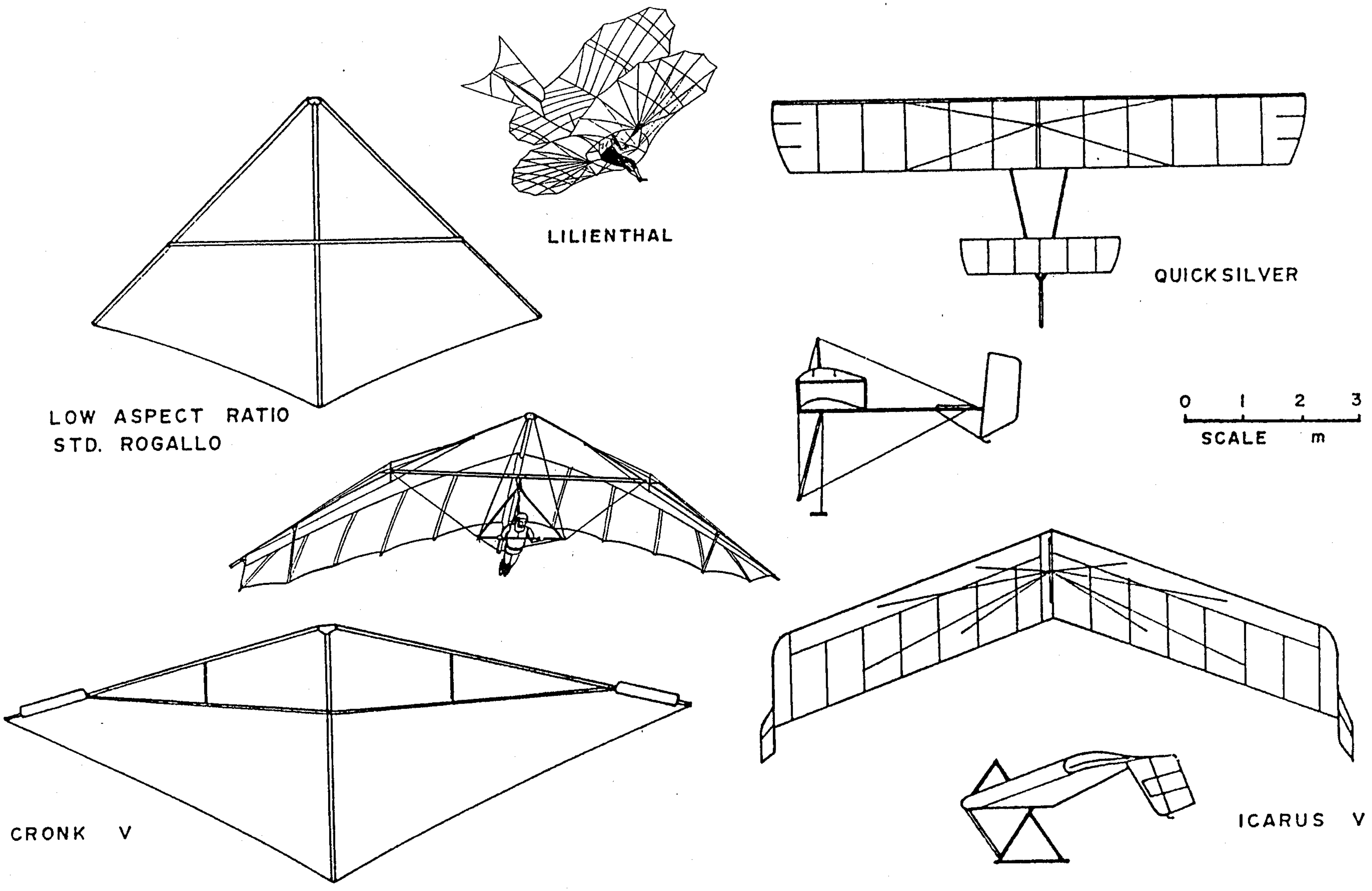
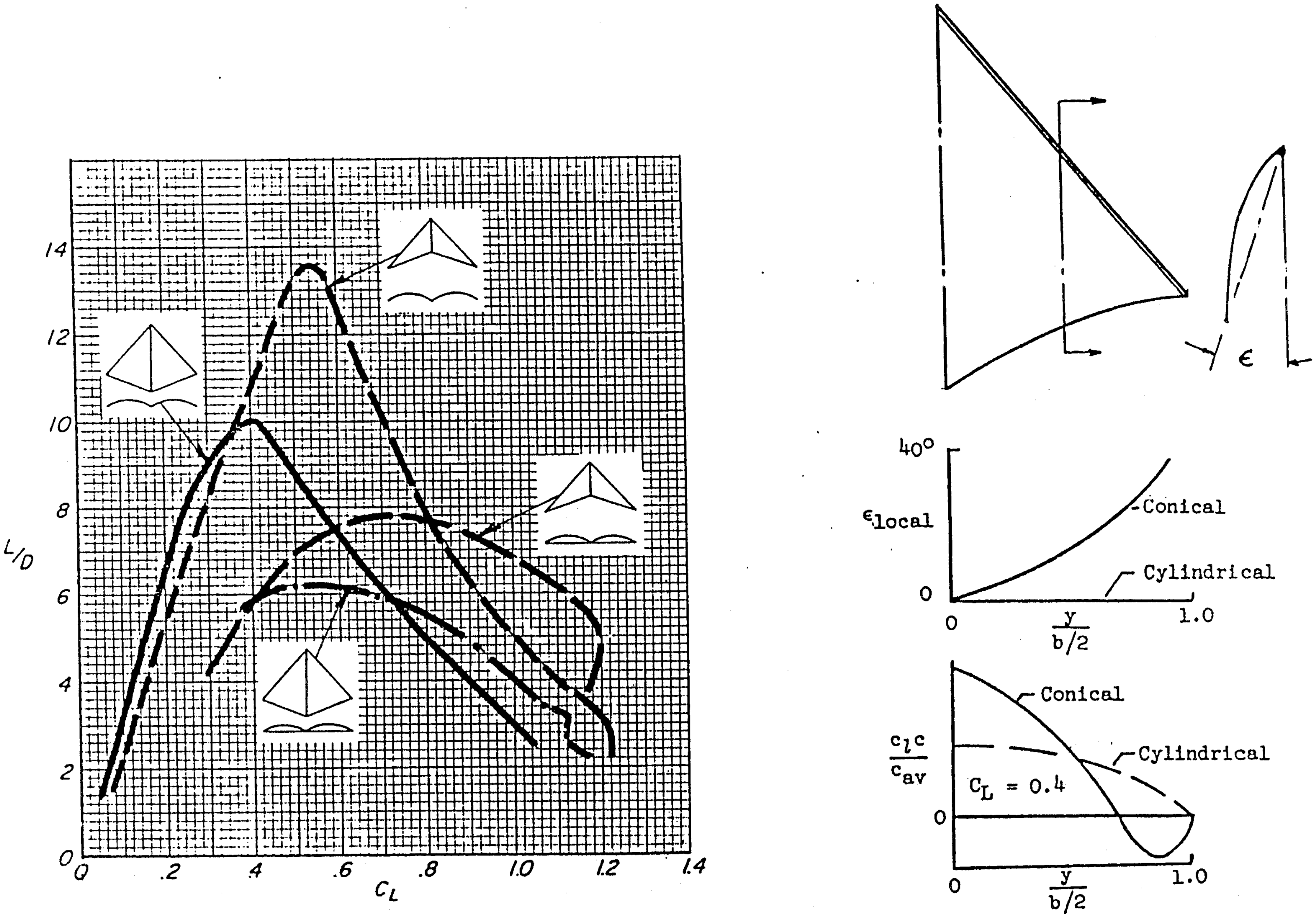
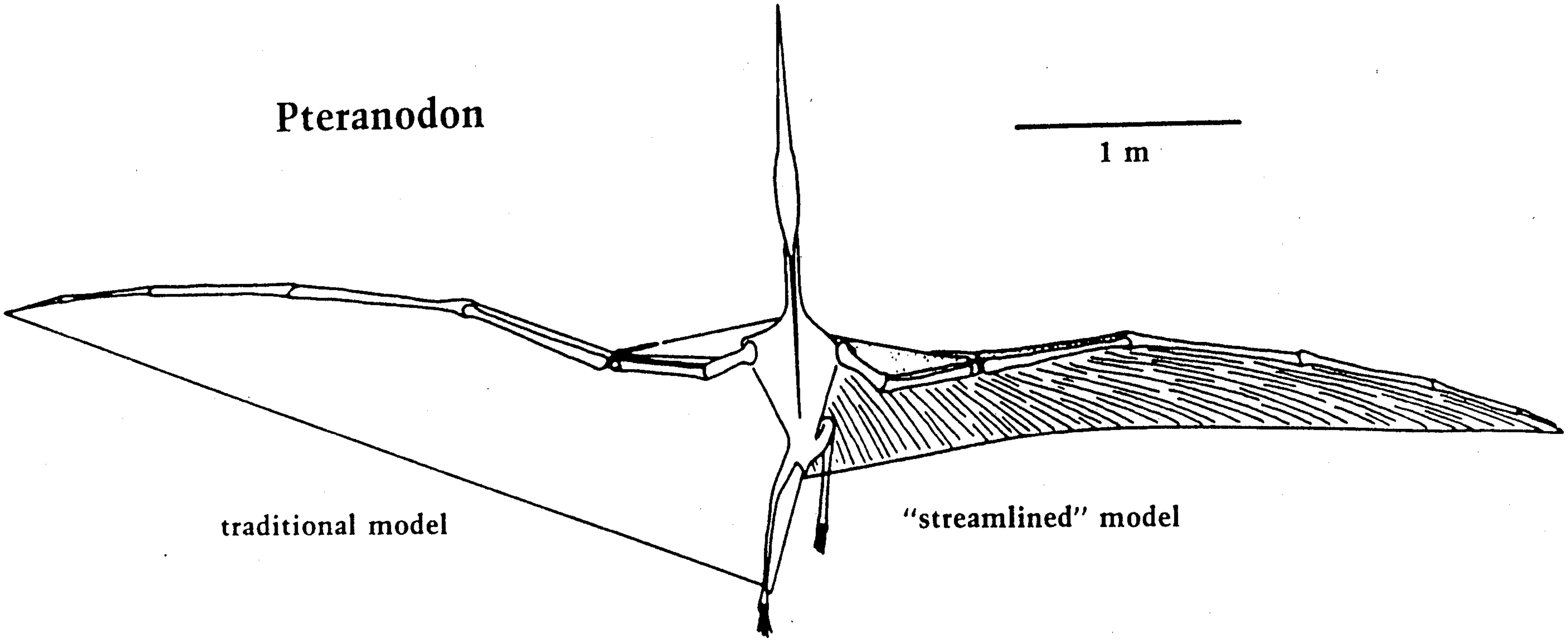


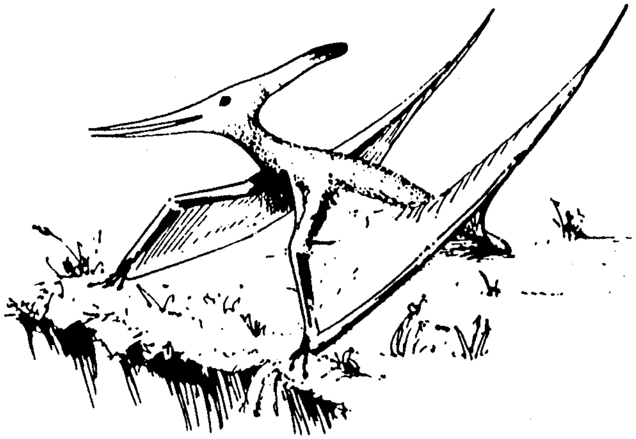
Selected Hang Glider Planforms

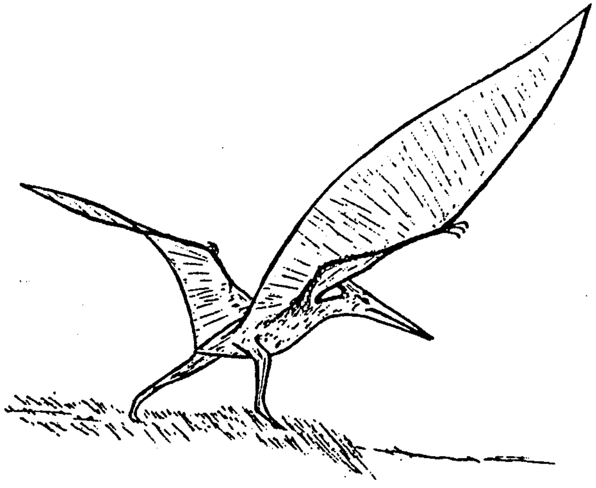


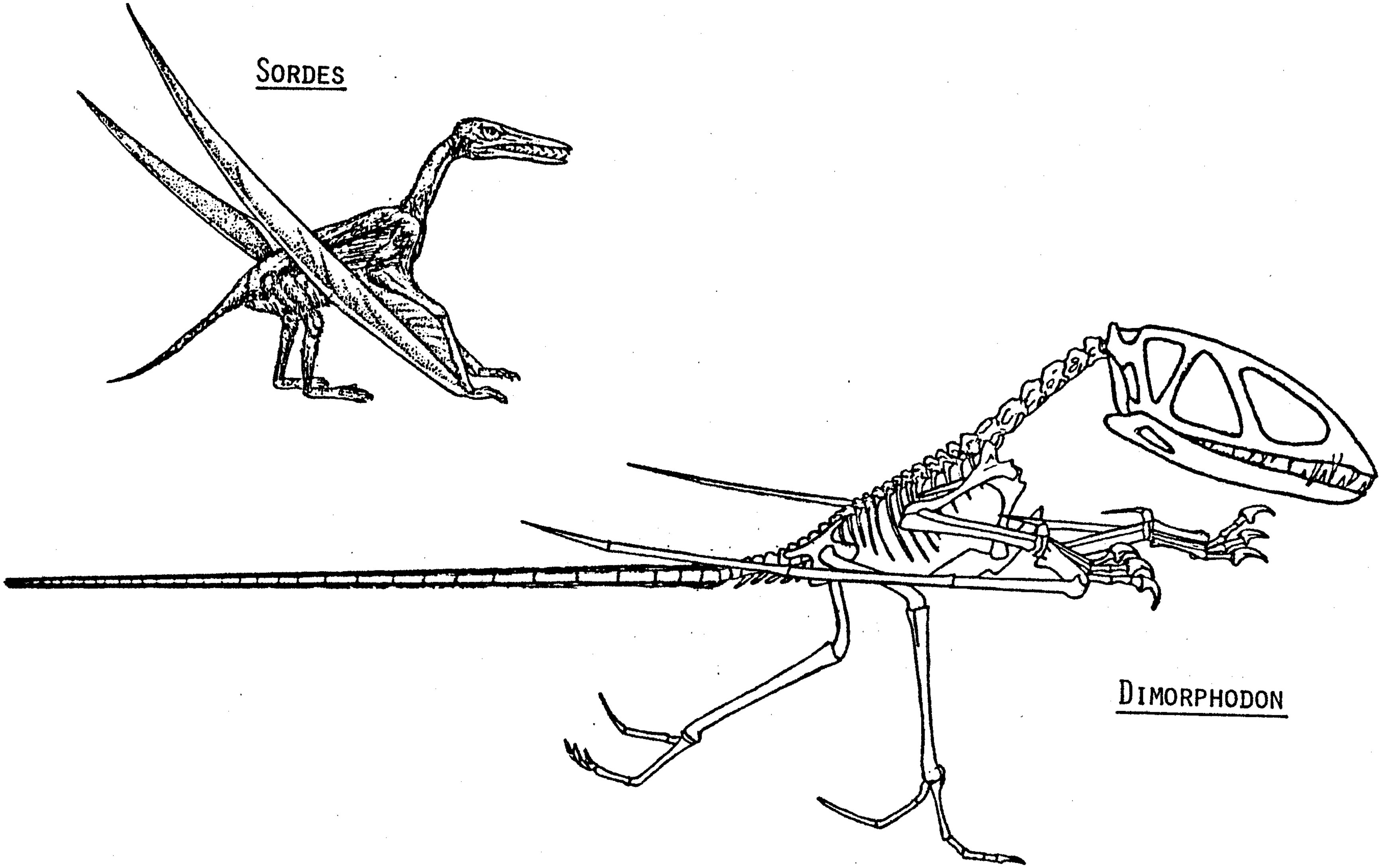
The Relative Aerodynamic Efficiency of Conically and Cylindrically Cambered Rogallo Wings

Pteranodon



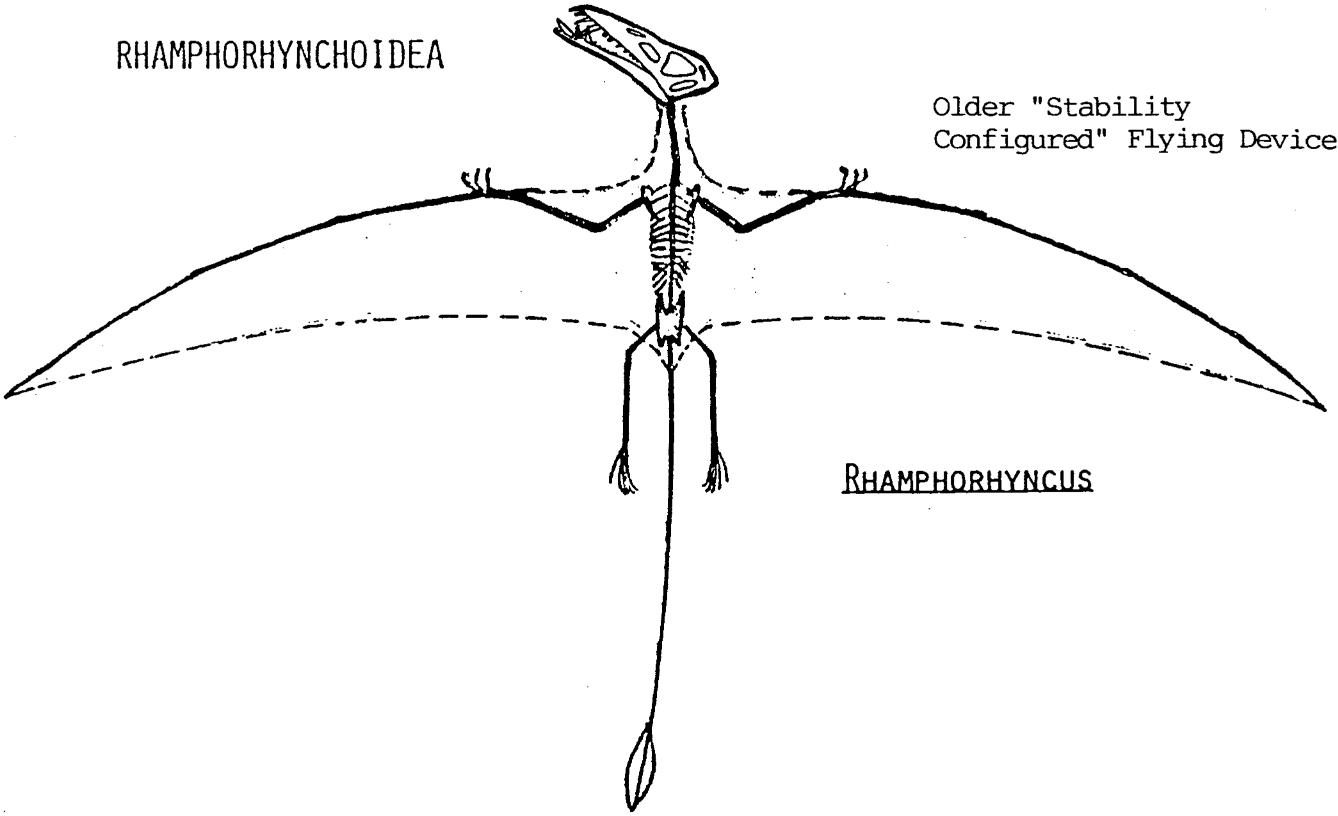






Two Rhamphorhynchoid Pterosaurs (<u>Dimorphodon</u> in Bipedal Progression) (Padian,1983)

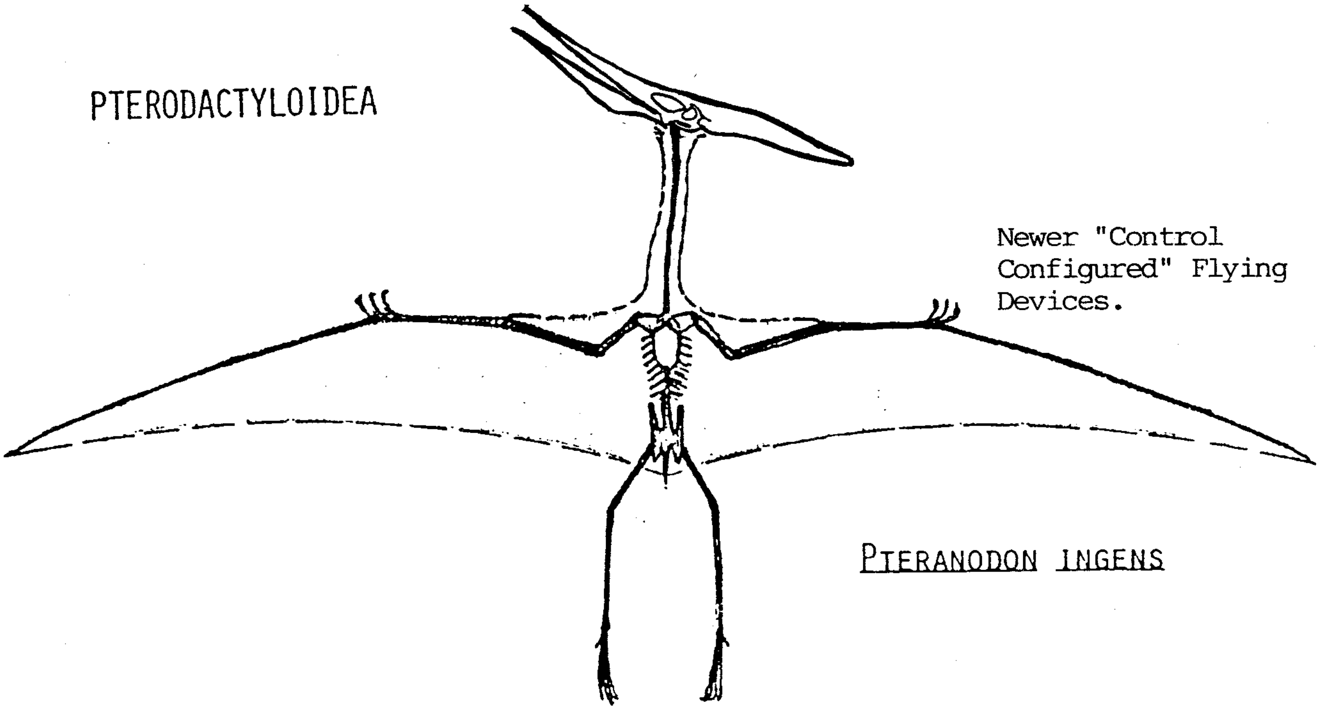
RHAMPHORHYNCHOIDEA



Older "Stability Configured" Flying Devices.

RHAMPHORHYNCUS

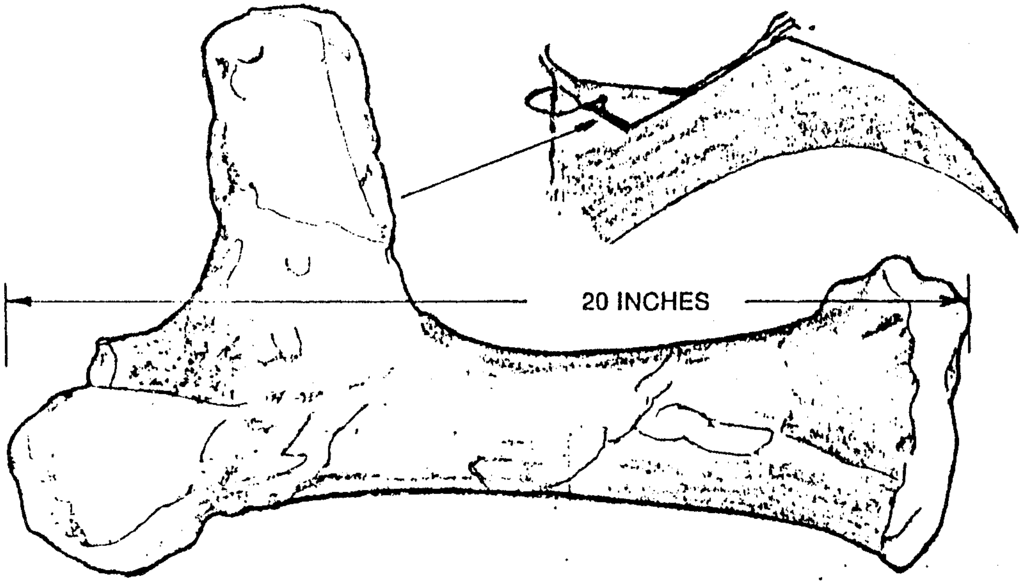
PTERODACTYLOIDEA



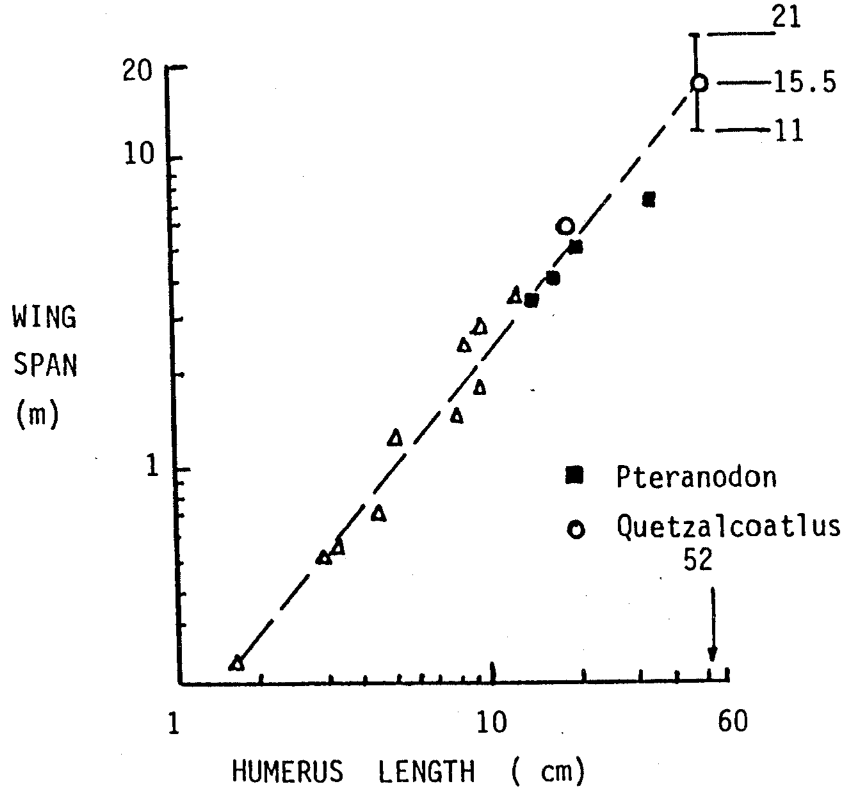
Newer "Control Configured" Flying Devices.

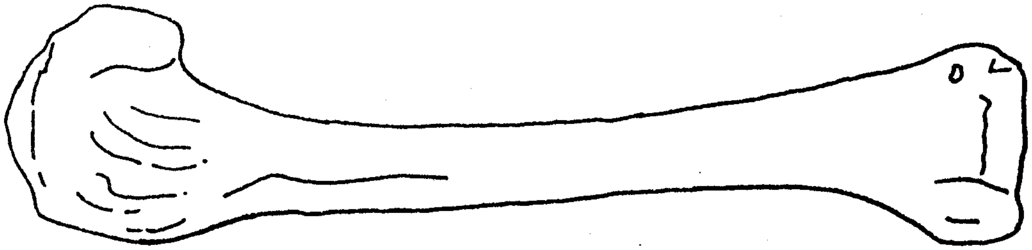
PTERANODON INGENS

The Two Sub-Orders of the Order Pterosauria



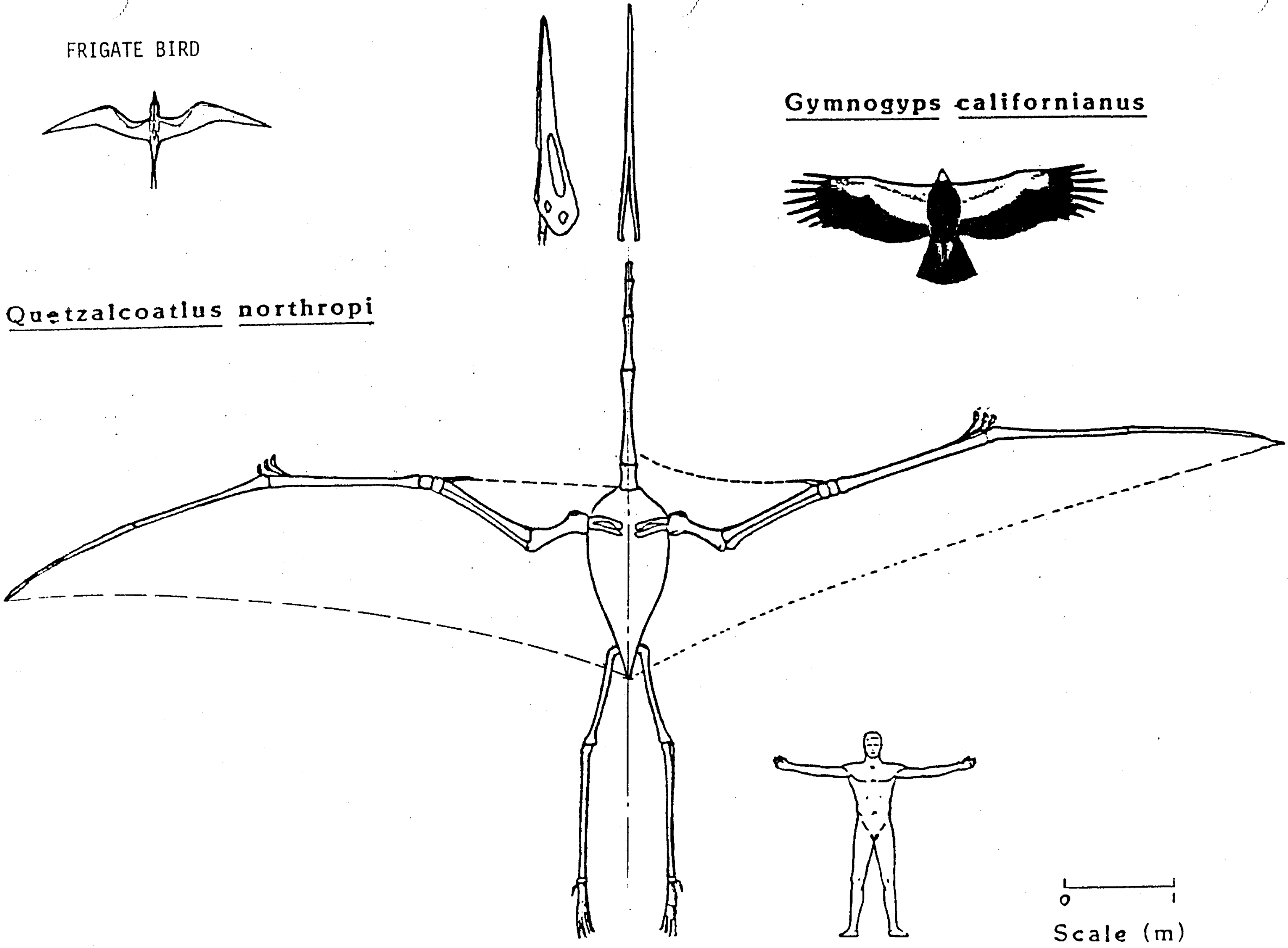
TEXAS PTEROSAUR (QUETZALCOATLUS NORTHROPI)



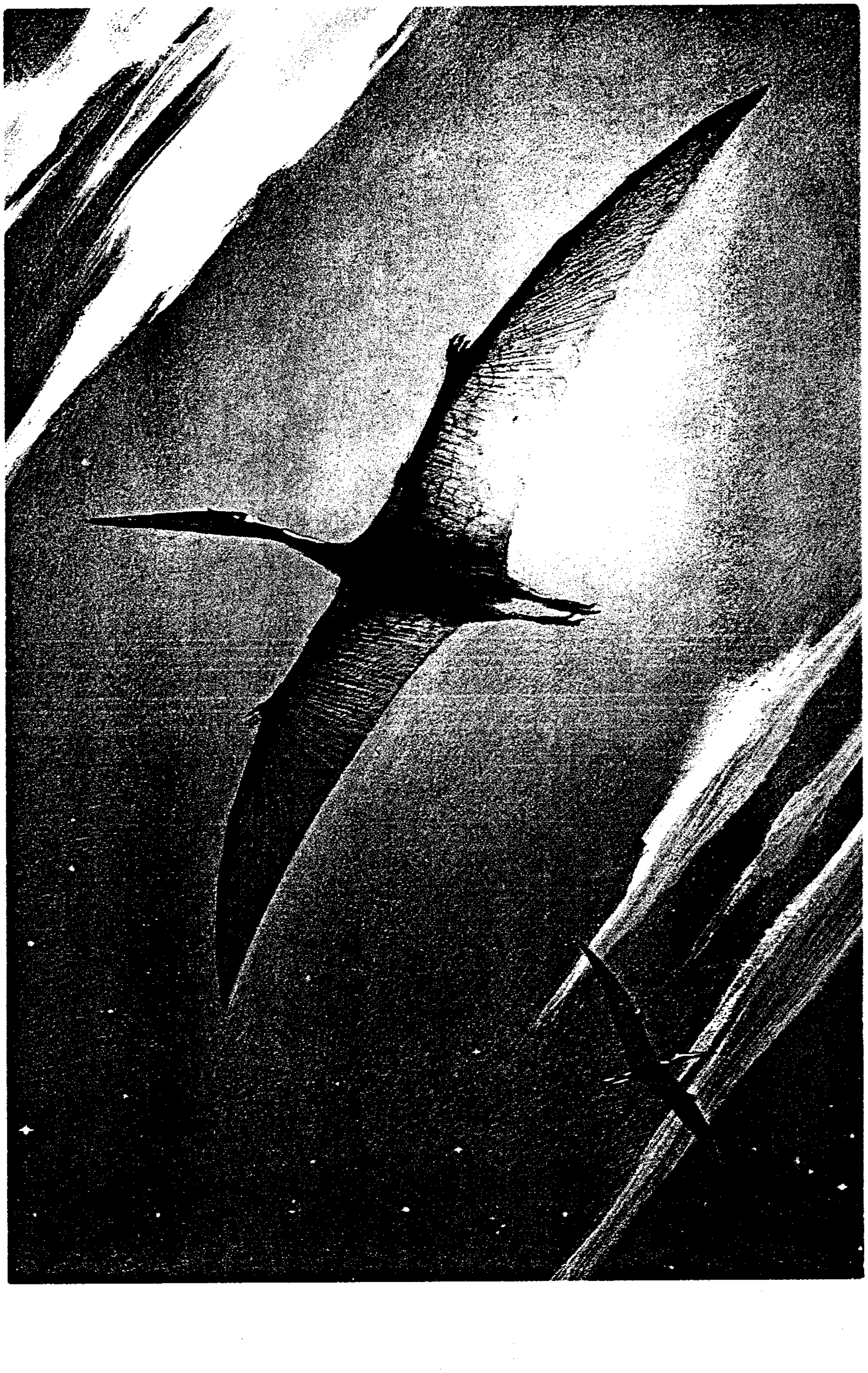


ARGENTINE TERATORN (ARGENTAVIS MAGNIFICENS)

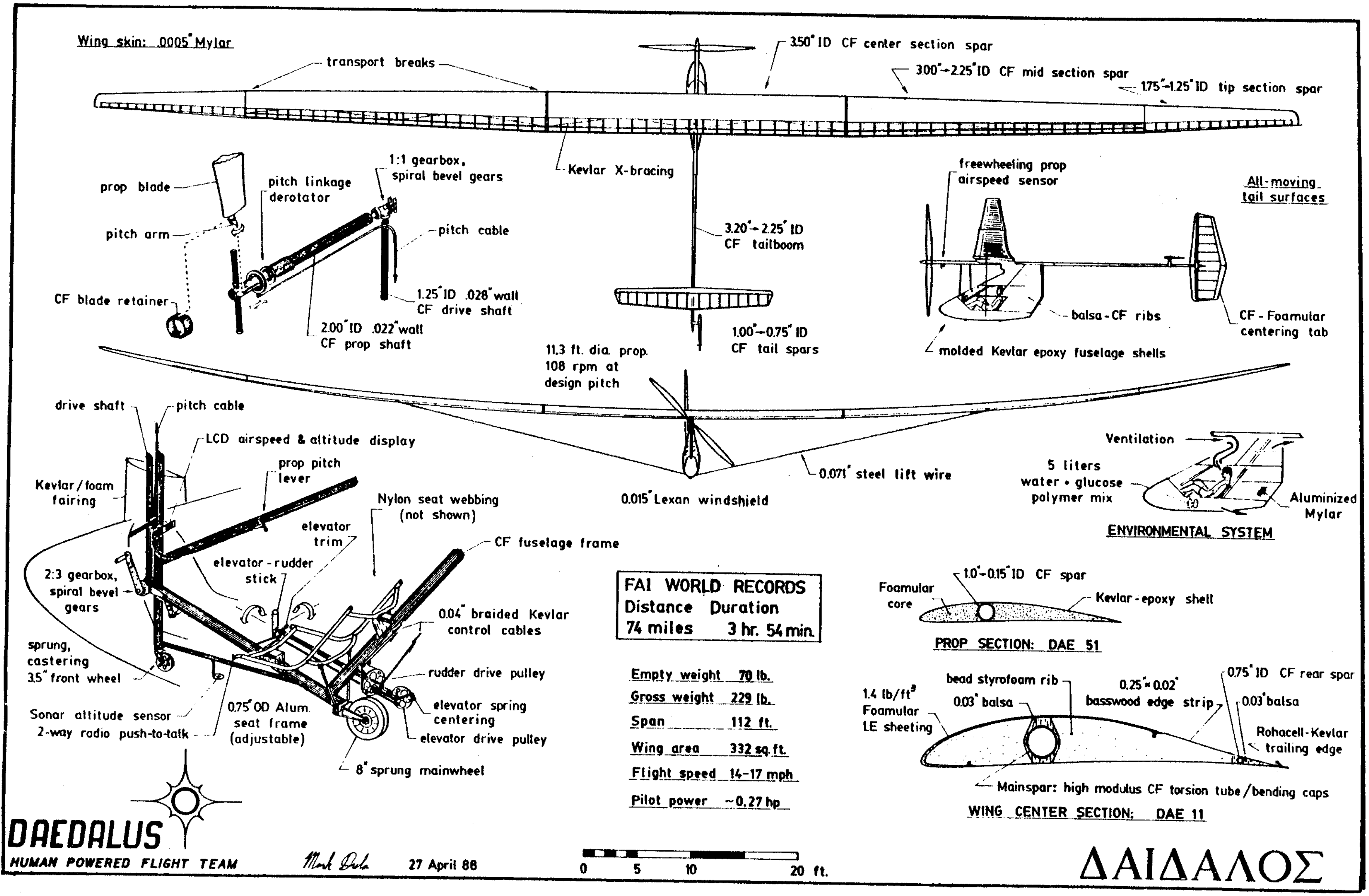
Giant Humerus Bones (To Scale) of a Bird (Argentavis) and Pterosaur (Quetzalcoatlus)



The Texas Pterosaur (Quetzalcoatlus northropi) (Langston, 1983)



QUETZALCOATLUS
Western USA • 65 million years ago



FAI WORLD RECORDS

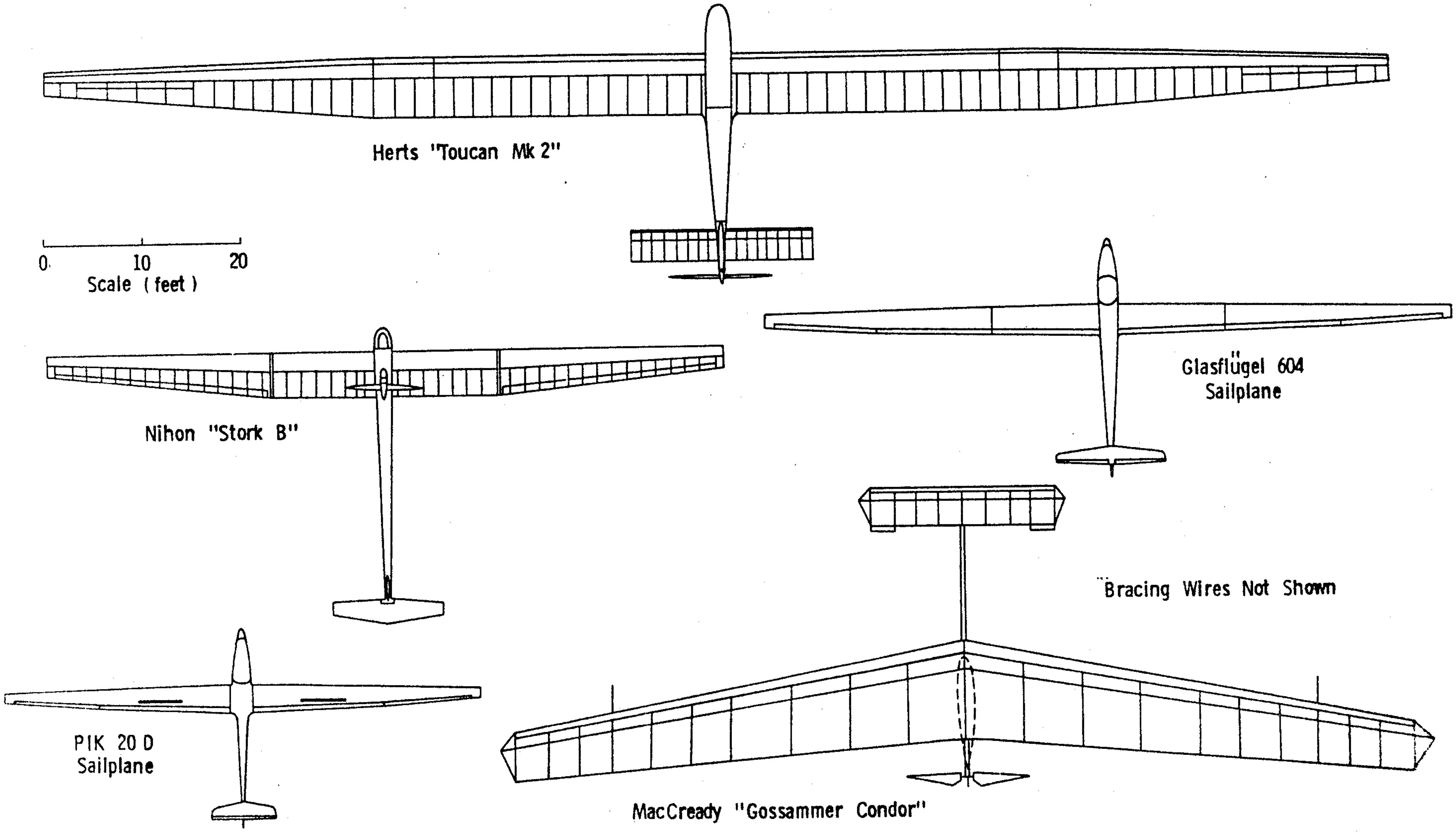
Distance	Duration
74 miles	3 hr. 54 min.

Empty weight	70 lb.
Gross weight	229 lb.
Span	112 ft.
Wing area	332 sq. ft.
Flight speed	14–17 mph
Pilot power	~0.27 hp

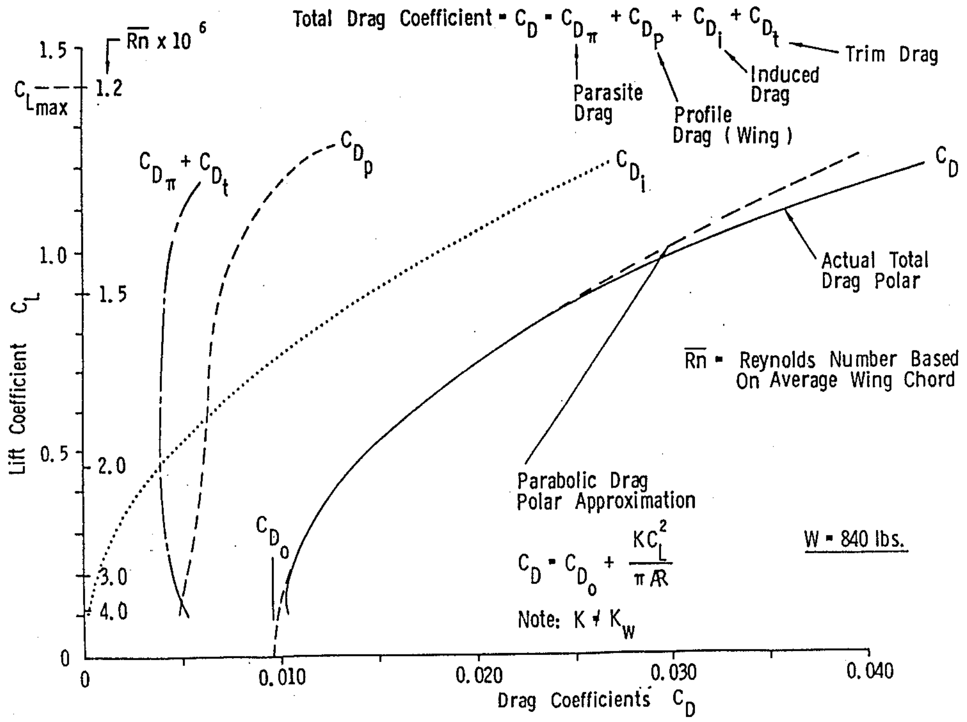
DAEDALUS
HUMAN POWERED FLIGHT TEAM

Mark Drela 27 April 88

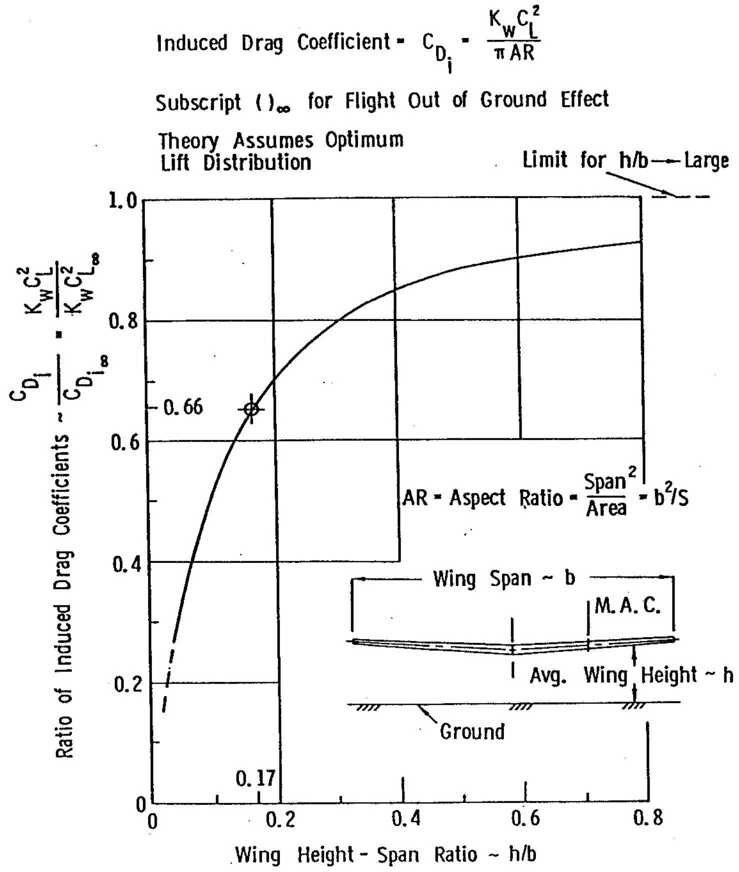
ΔΑΙΔΑΛΟΣ



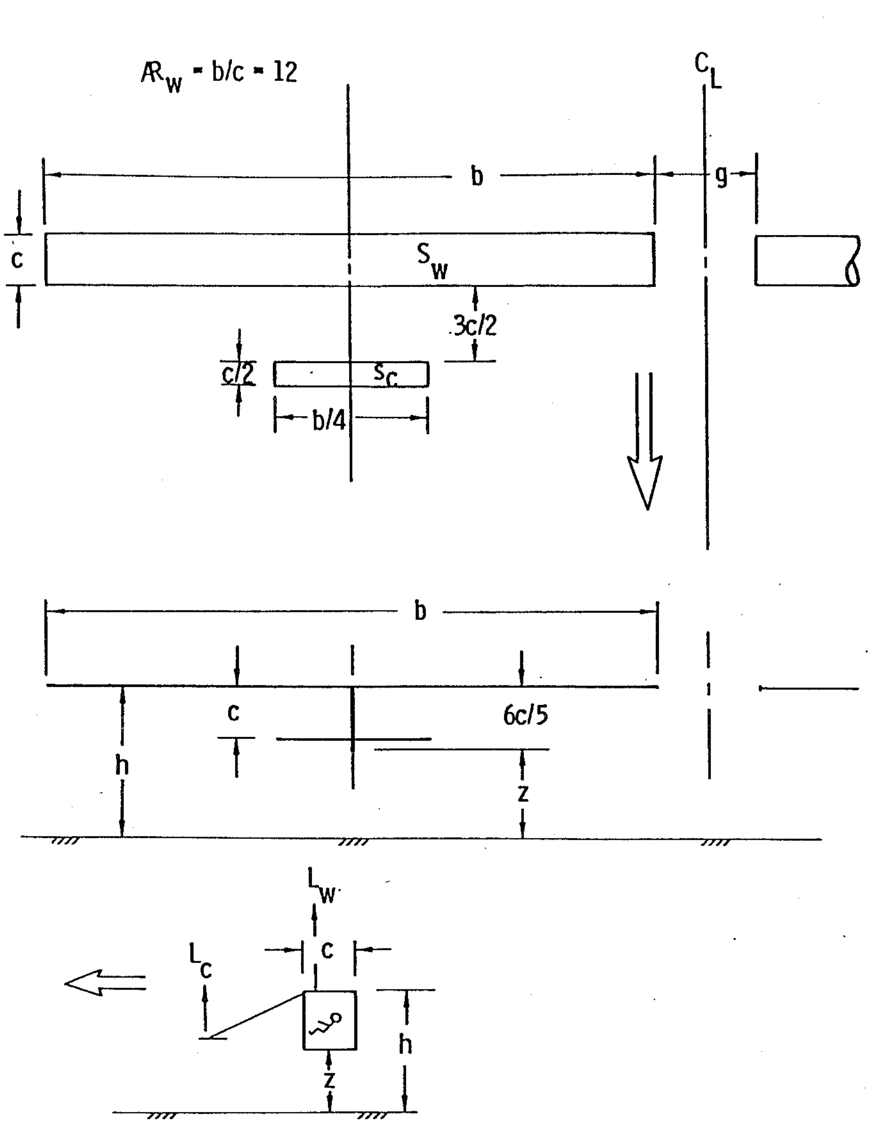
Planview Comparison of Several Human Powered Airplanes and Sailplanes



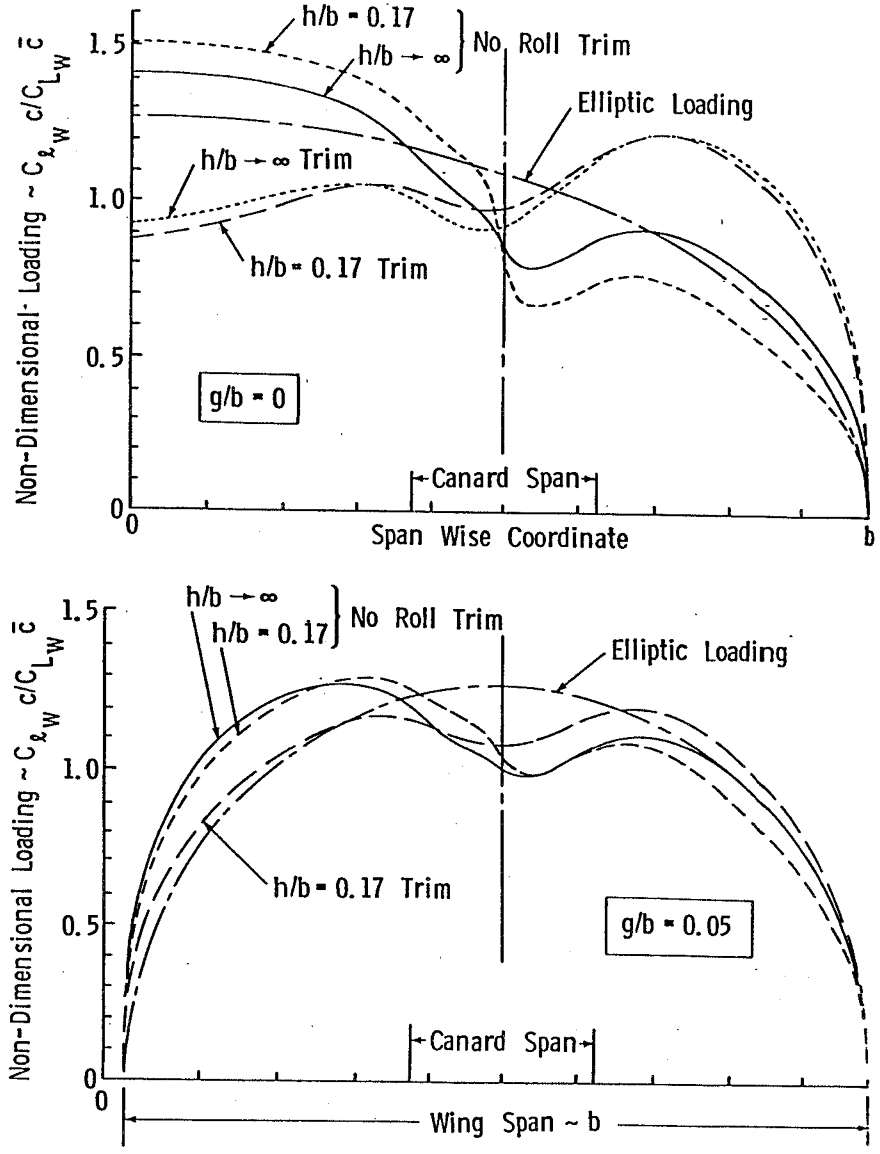
DETAIL DRAG BREAKDOWN FOR THE ASTIR CS SAILPLANE



THE INFLUENCE OF GROUND EFFECT
ON WING INDUCED DRAG COEFFICIENT



FULL CONFIGURATION HPA GEOMETRY MODEL

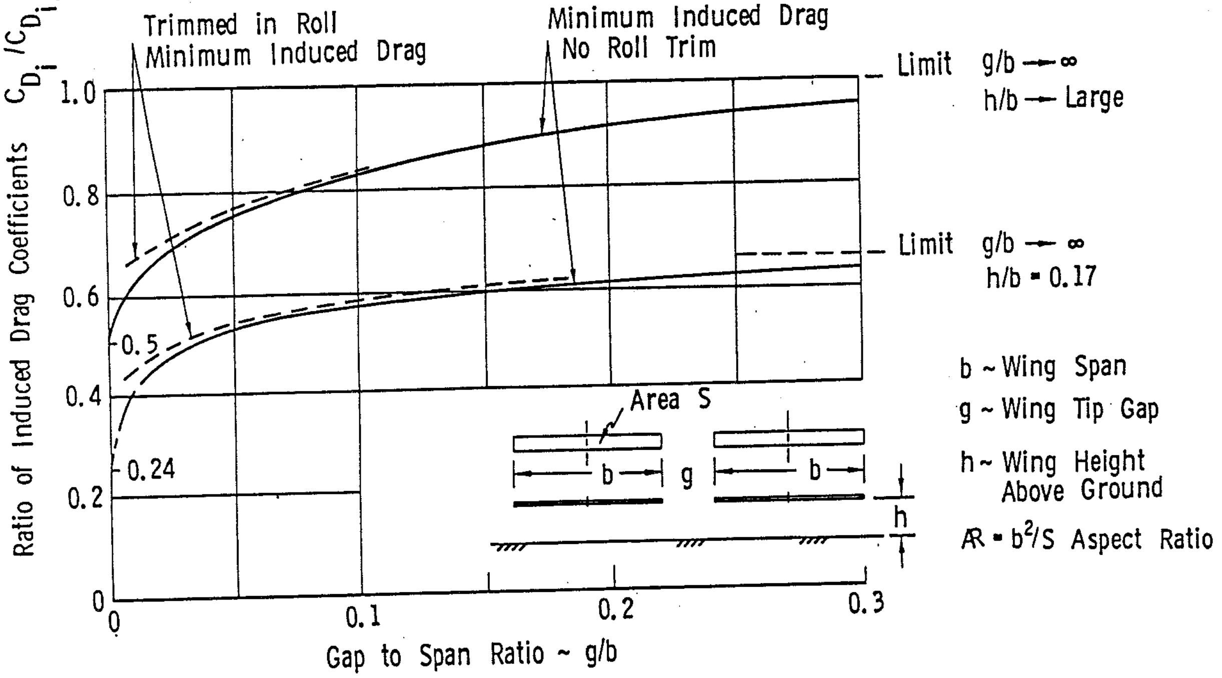


MAIN WING OPTIMAL SPAN LOADINGS
FOR COMPLETE HPA CONFIGURATIONS

Induced Drag Coefficient ~ $C_{D_i} = \frac{C_L^2 K_w}{\pi AR}$ (Per Wing)

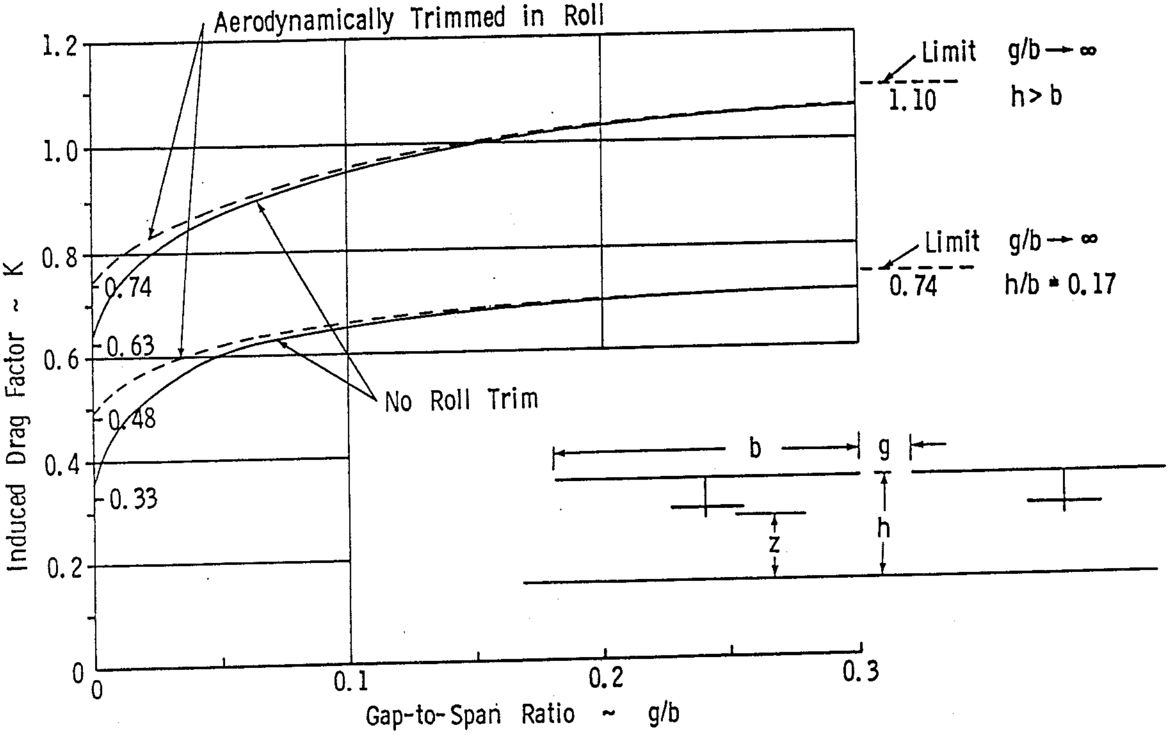
K_w = Wing Alone Span Efficiency Factor

Subscript $(\,)_\infty$ for Flight Out of Formation and Ground Effect



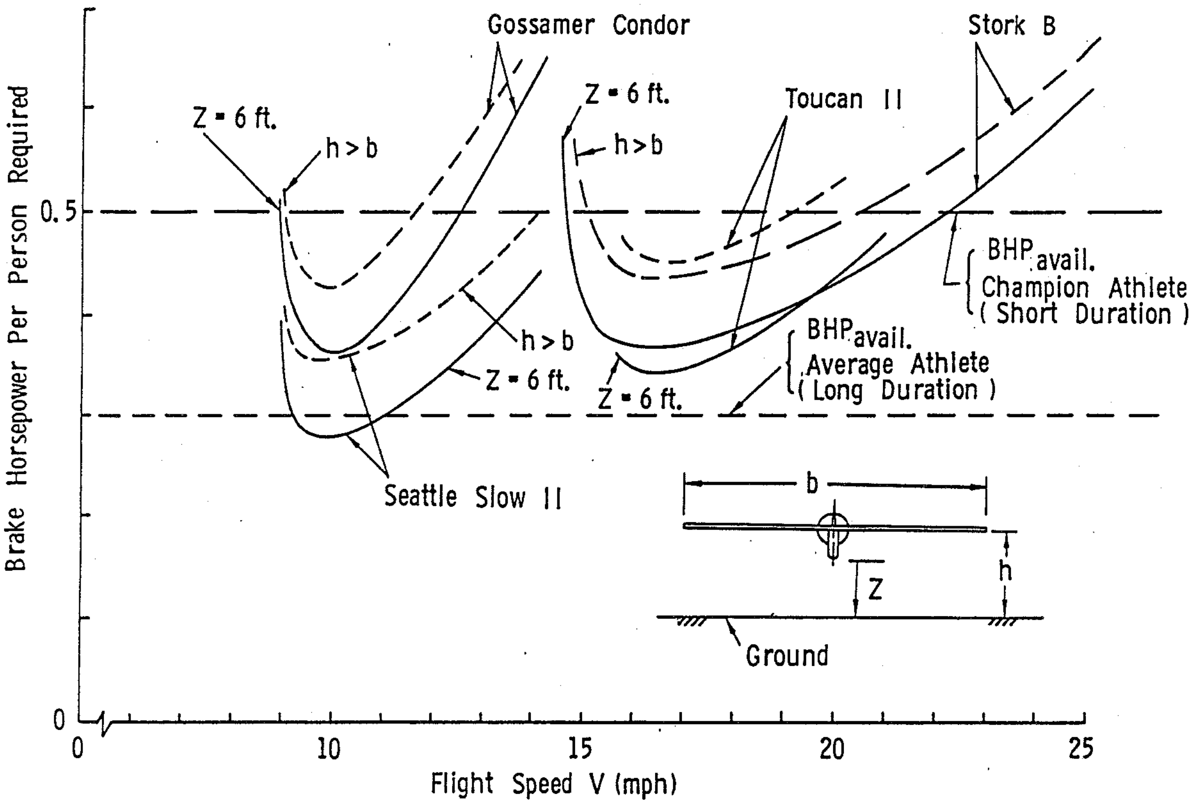
INFLUENCE OF FORMATION FLIGHT ON
WING ALONE INDUCED DRAG COEFFICIENT

$\bar{K} = C_{D_i}\,\pi AR\,/\,C_L^2$ $\quad \bar{C}_L = \frac{C_{L_w} S_w + C_{L_c} S_c}{S_w}$ $\quad AR = b^2/S_w$

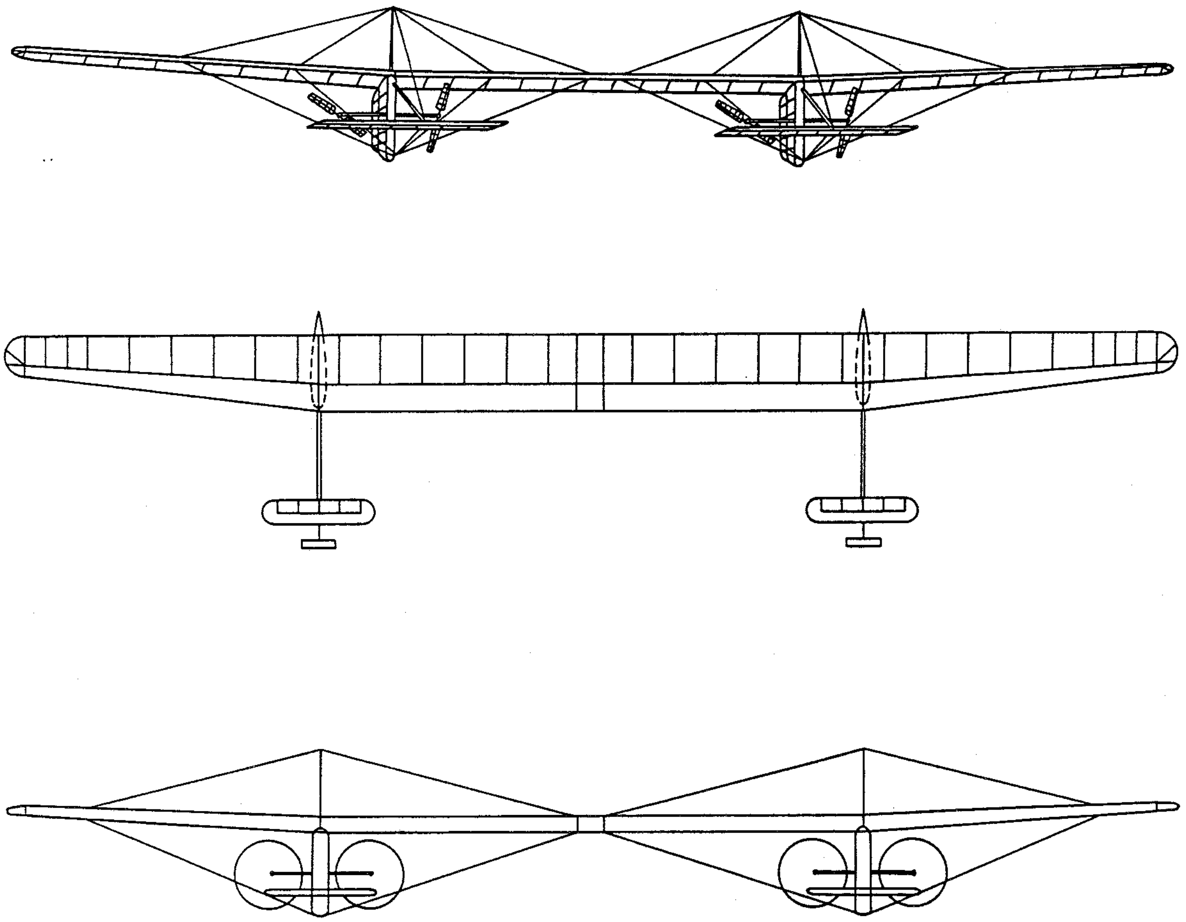


INFLUENCE OF FORMATION FLIGHT ON INDUCED DRAG OF FULL CONFIGURATION HPA

Straight & Level Flight in Std. Sea Level Conditions

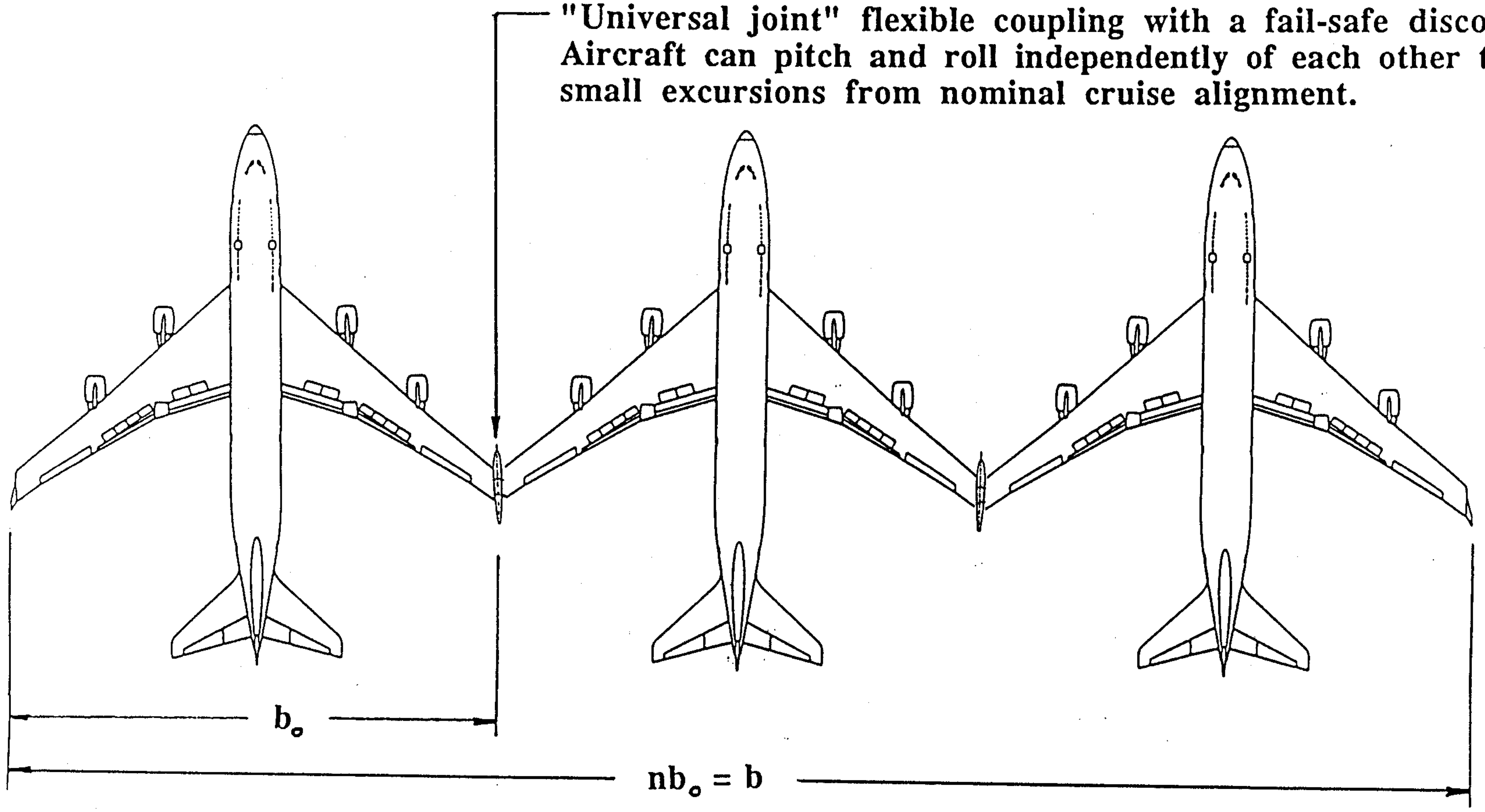


POWER CURVES FOR SEVERAL RECENT HPA's



CONFIGURATION OF THE "SEATTLE SLOW II" HPA

THE FORMATION FLIGHT OF SEVERAL *BOEING 747S* ACROSS THE PACIFIC OCEAN IN THE SPRING



"Universal joint" flexible coupling with a fail-safe disconnect. Aircraft can pitch and roll independently of each other through small excursions from nominal cruise alignment.

Aircraft take-off and land individually and join during climb by a technique similar to probe and drogue air-to-air refueling.

At criuse: $$L/D_{\text{formation}} \doteq \frac{n}{0.6n + 0.4} \times L/D_{\substack{\text{single}\\\text{aircraft}}}$$

where n = number of aircraft

Reference:

McMasters, J. H. and McLean, J. D., "The Formation Flight of Human-Powered Aircraft Across the English Channel in the Spring," XVIth Congress, Organization Scientific Technique Internationale du Vol-a-Voile (OSTIV), Chateauroux, France, July, 1978 (Swiss Aero Revue), December, 1979 and February, 1980.)

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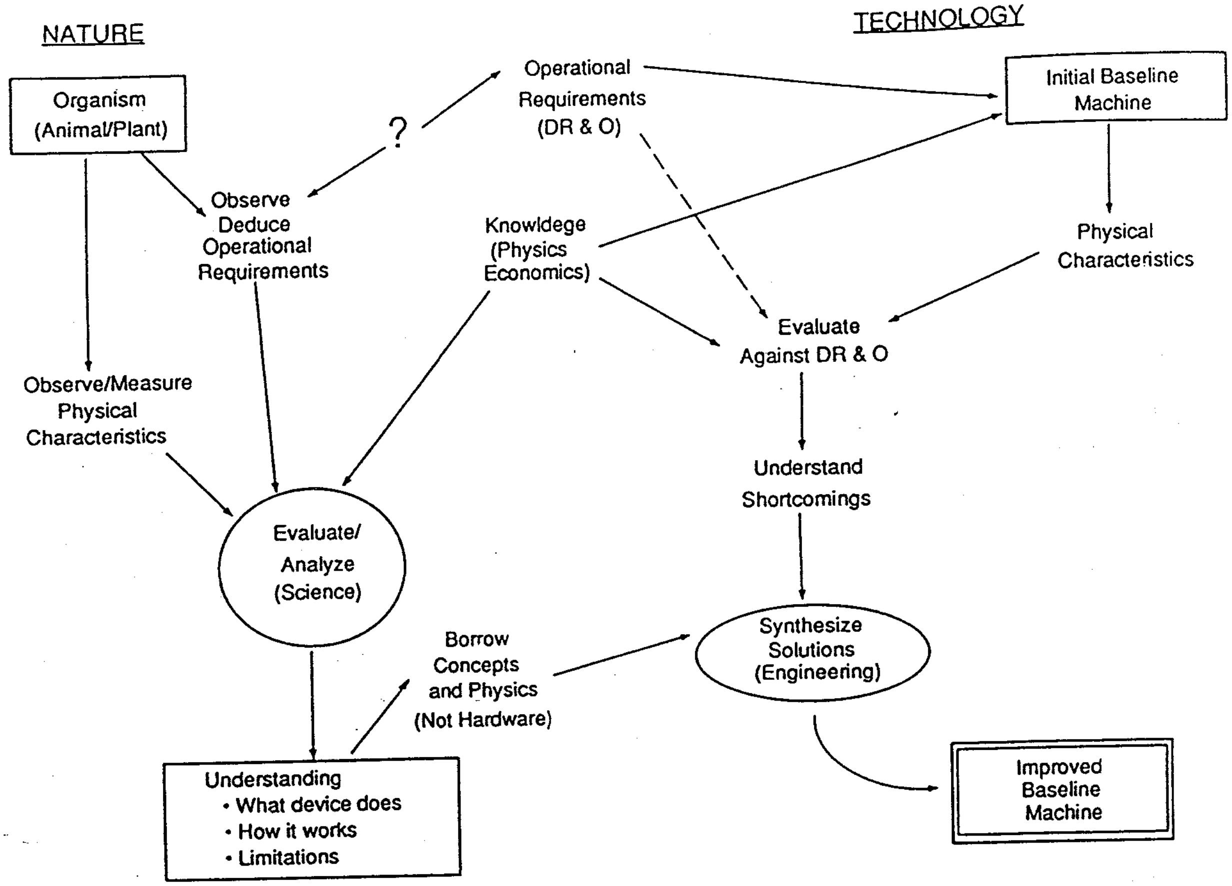
16. Liebeck, R. H., "On the Design of Subsonic Airfoils for High Lift", AIAA Paper 76-406, July 1976

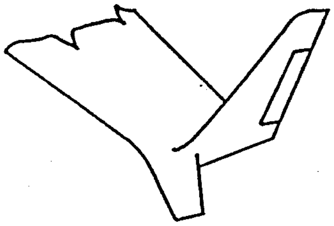
17. McMasters, J. H. and Cole, C. J., "The Prospects for Man-Powered Flight (The Future of an Illusion)", Tech. Soaring, Vol. 1, No. 2, October 1971, Also OSTIV Pub. XI, 1975

18. Wortmann, F.X., "Airfoil Design for Man-Powered Aircraft", Second Man-Powered Group Symp. Proc., R. Ae. S., London, February, 1977

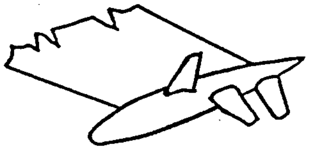
BIONICS PROCESS RELATIONSHIP DIAGRAM



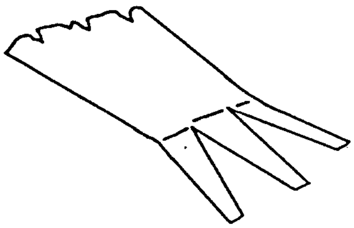
WING TIP DEVICES



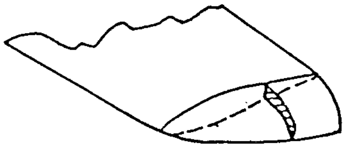
WHITCOMB "WINGLET"



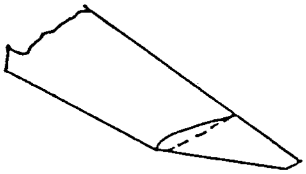
SPILLMAN "SAILS"



PFENNIGER "PFEATHERS"



HOERNER TIP



SHARPLY RAKED TIP

WINGLETS

An airplane in flight, like any moving through the earth's atmosphere, experiences a resistance due to its motion through the air. To remain in flight, this retarding force, or "drag" as it is called by aerodynamicists, must be overcome by the thrust of the engines. In a typical year of airplane service, a large jetliner can burn several million dollars' worth of fuel, most of which is directly attributable to the aerodynamic drag of the airplane. In commercial airplane design, drag reduction is therefore a subject of considerable economic importance.

A sizeable fraction--about 40 percent--of the drag of a commercial jetliner results directly from the fact that the wing must generate lift to support the weight of the airplane and all of the fuel, people and baggage it is carrying. In generating lift, the wing leaves behind it a vortex wake that starts as a thin "vortex sheet" streaming from the entire trailing edge of the wing. Behind the wing, this vortex sheet rolls up at its outer edges, forming a concentrated, tornado-like vortex behind each wingtip that can persist for several miles behind the aircraft. These vortices trailing behind the airplane represent considerable kinetic energy, energy that was supplied, indirectly of course, by the fuel burned by the airplane's engines. More directly, the effect of shedding a vortex wake is manifested as an extra drag force on the airplane's surfaces. This is the portion of the drag that aerodynamicists associate directly with the generation of lift, calling it "induced drag", because the mathematical theory they use to describe the vortex motion is similar to the theory in elementary physics describing the "induction" of a magnetic field by an electric current.

The amount of induced drag an airplane experiences depends on the amount of kinetic energy left behind in its trailing vortices, which, in turn depends on the amount of lift generated by the wing, on the wingspan, and on the manner in which the lift load is distributed along the span. Thus several possibilities are available to the aerodynamicist for reducing induced drag. One is simply to increase the wingspan, which decreases the strength of the vortices associated with a given total lift. However, increasing the wingspan is only practical to a limited extent, because it increases the weight of the wing structure and, because only limited clearance is available at airport passenger gates. An alternative to increasing the wingspan horizontally is to add small vertical (or nearly vertical) fins or "winglets" at the wingtips. A properly designed winglet changes the distribution of the lift load along the wing and spreads the shed vortex sheet above the plane of the wing, reducing the energy left behind in the trailing vortices and thus reducing the induced drag. On the negative side, winglets increase the stresses on the rest of the wing and increase the surface area exposed to the air flow, thus increasing the friction drag. In order to produce an induced-drag benefit large enough to outweigh these negative aspects, a winglet must be very carefully designed, especially when the wing was originally designed to operate efficiently without a winglet, as it was for the 747.

INDUCED DRAG - THEORY

- CLASSICAL LINEAR THEORY

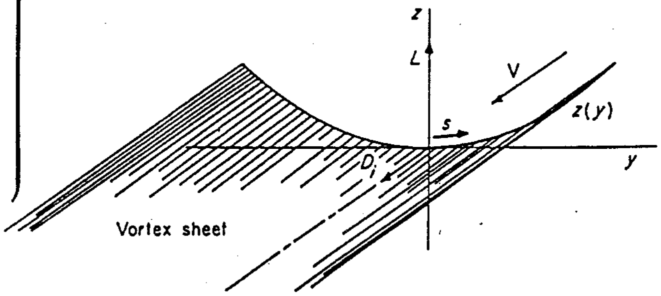
  PANEL METHODS

  LIFTING-SURFACE THEORY

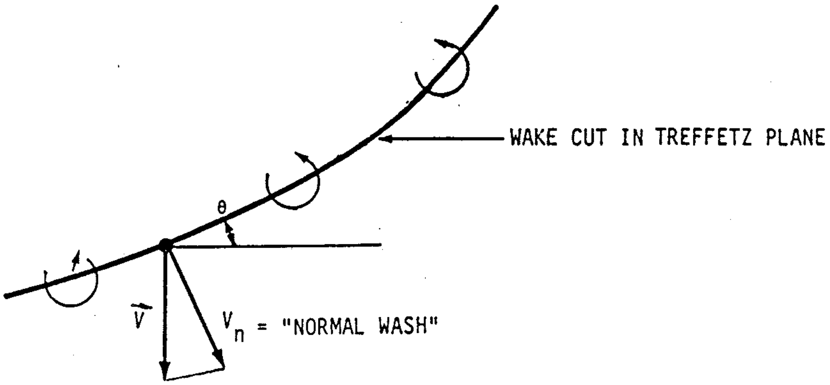
  LIFTING-LINE THEORY

  TREFFETZ-PLANE THEORY

ALL ASSUME ARBITRARY
(USUALLY STRAIGHT)
ALIGNMENT OF
VORTEX LINES
IN TRAILING SHEET



- MINIMUM DRAG IN TREFFETZ PLANE



SPANLOAD GIVING MINIMUM DRAG SATISFIES :

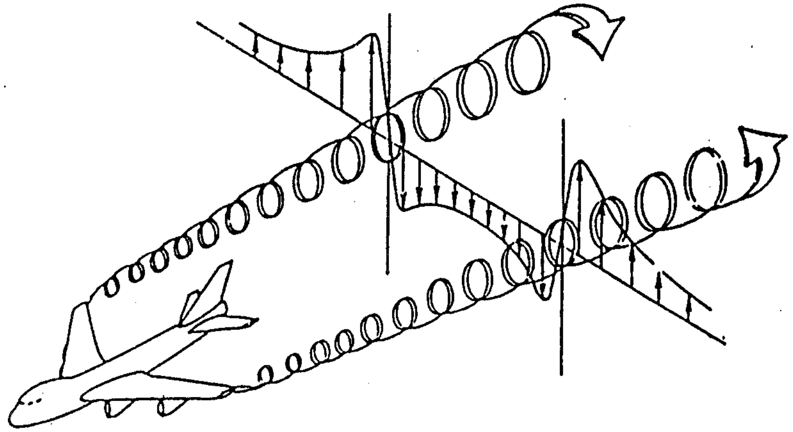
$$V_n = \text{CONSTANT} \bullet \text{COS } \theta$$

FLAT WING ⟶ COS θ = 1 ⟶ CONSTANT DOWNWASH ⟶ ELLIPTIC LOADING

VERTICAL WINGLET ⟶ COS θ = 0 ⟶ NO SIDEWASH ⟶ NO THRUST

INDUCED DRAG – BASIC PHYSICS

LIFT-INDUCED FLOW

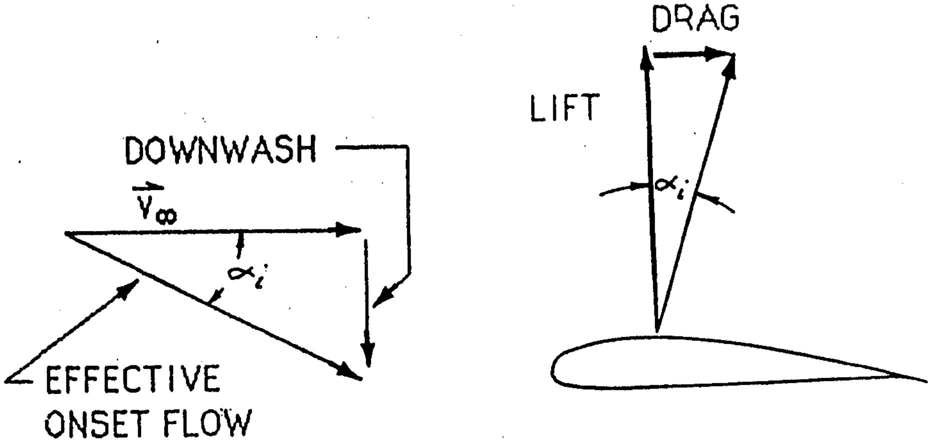


INTEGRATED FLOW QUANTITIES
IN WAKE:

MOMENTUM: DOWNWARD ⟶ LIFT
⇩
FORWARD ⟶ DRAG

KINETIC ENERGY: DRAG

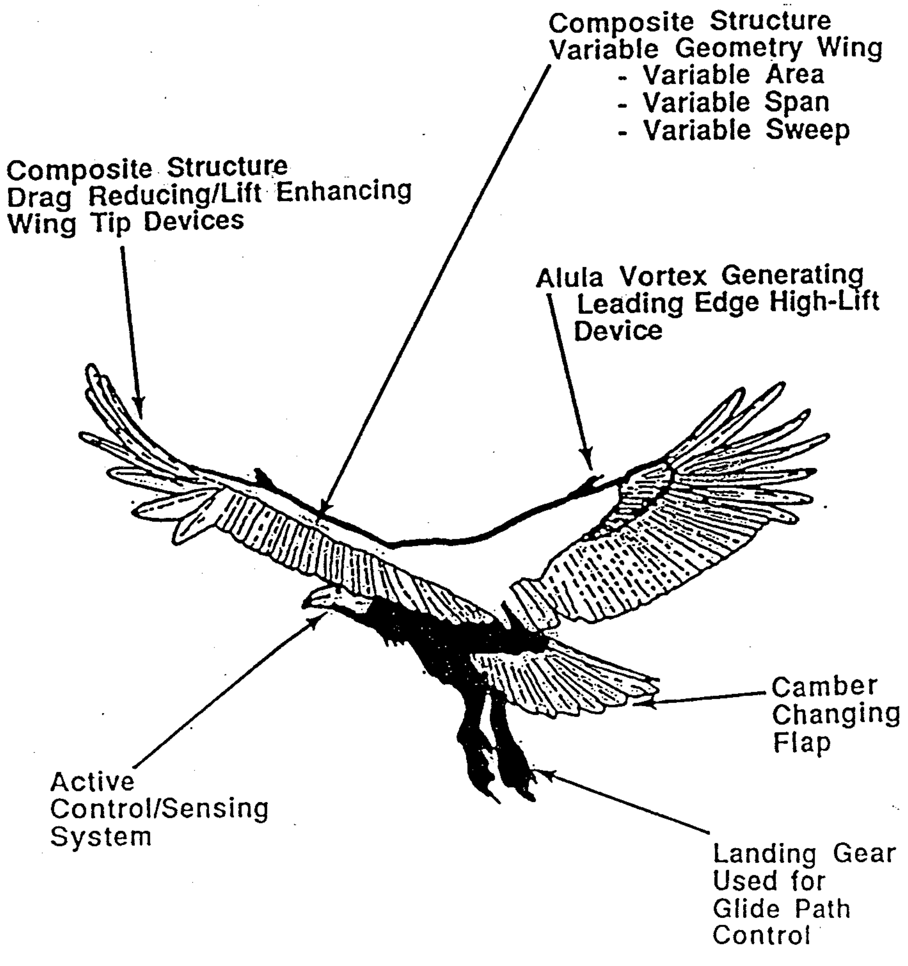
DRAG FORCE
(INDUCED DRAG)



INDUCED DRAG FELT AS EFFECTIVE BACKWARD TILT OF LIFT VECTOR.

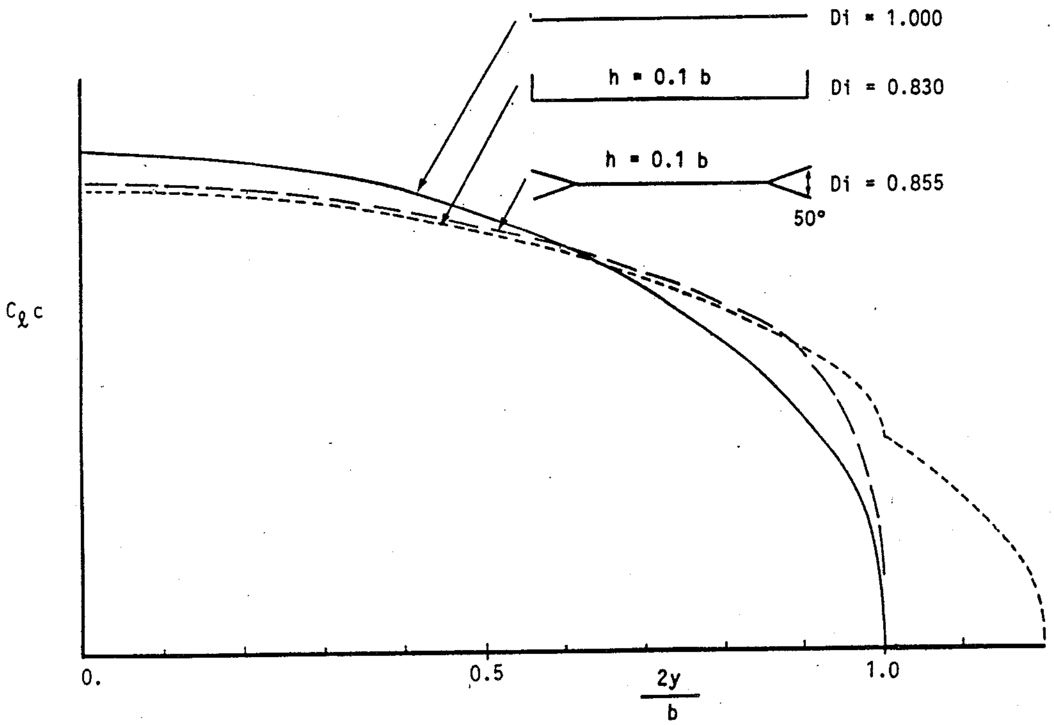
Examples of Modern Aeronautical Technology Embodied in Existing Natural Flying Devices

- Variable Geometry / Mission Adaptive Wings
- Drag Reduction Techniques
- Lift Augmentation/Powered Lift
- Active Controls / Control Configurated Vehicles
- Composite Structures
- Damage Tolerant Structures
- Fully Integrated System Design
- Advance Manufacturing Techniques

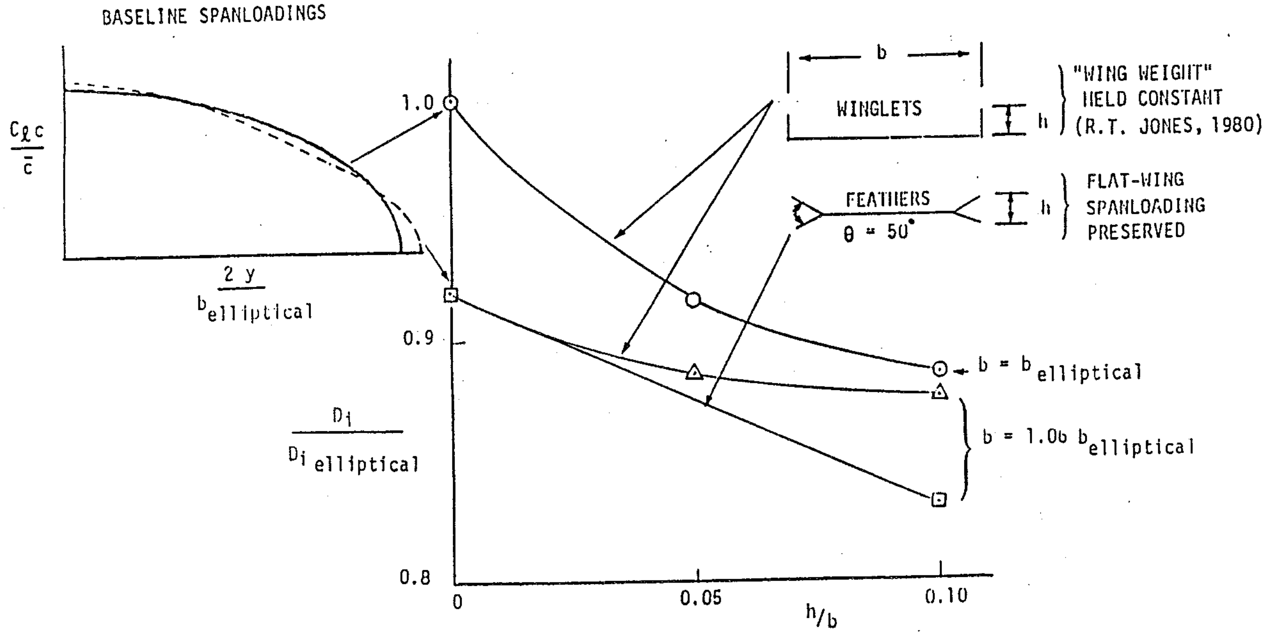


A CALIFORNIA CONDOR (Gymnogys californianus)
IN A LOW SPEED GLIDE

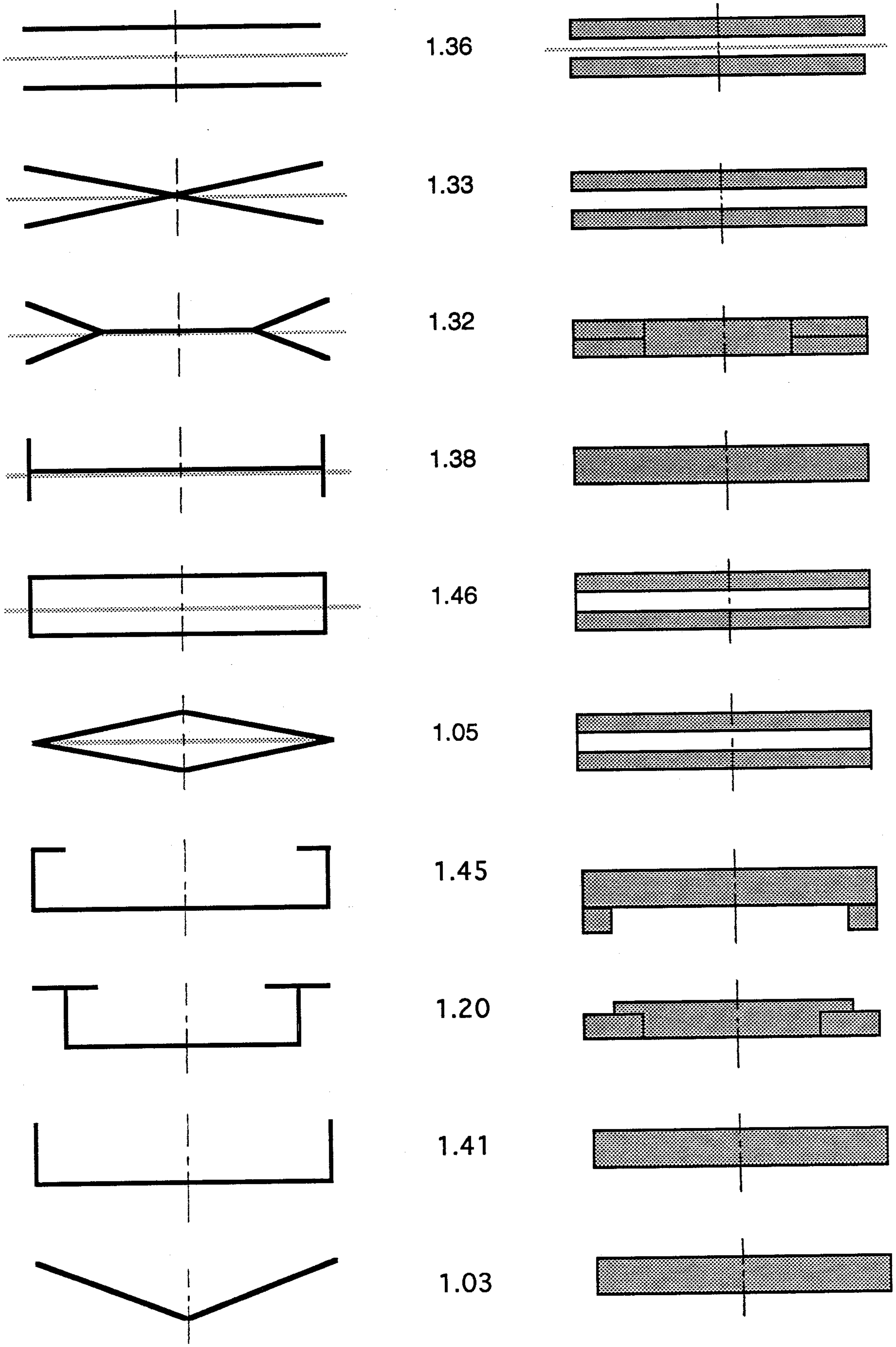
MINIMUM - DRAG LOADINGS



INDUCED DRAG AT CONSTANT STRUCTURAL WEIGHT



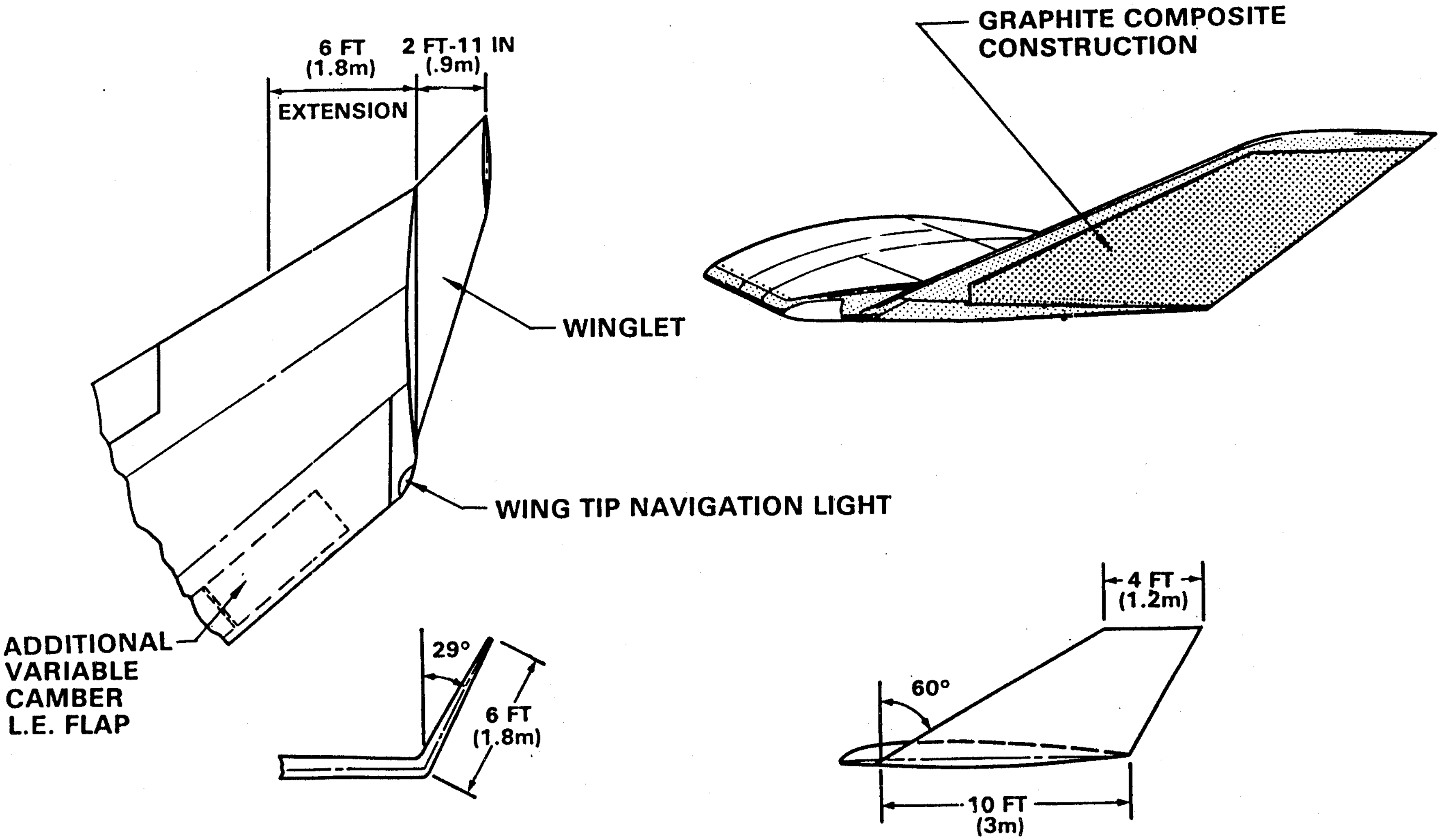
Span Efficiency of Various Nonplanar Shapes
Height / Span = 0.2



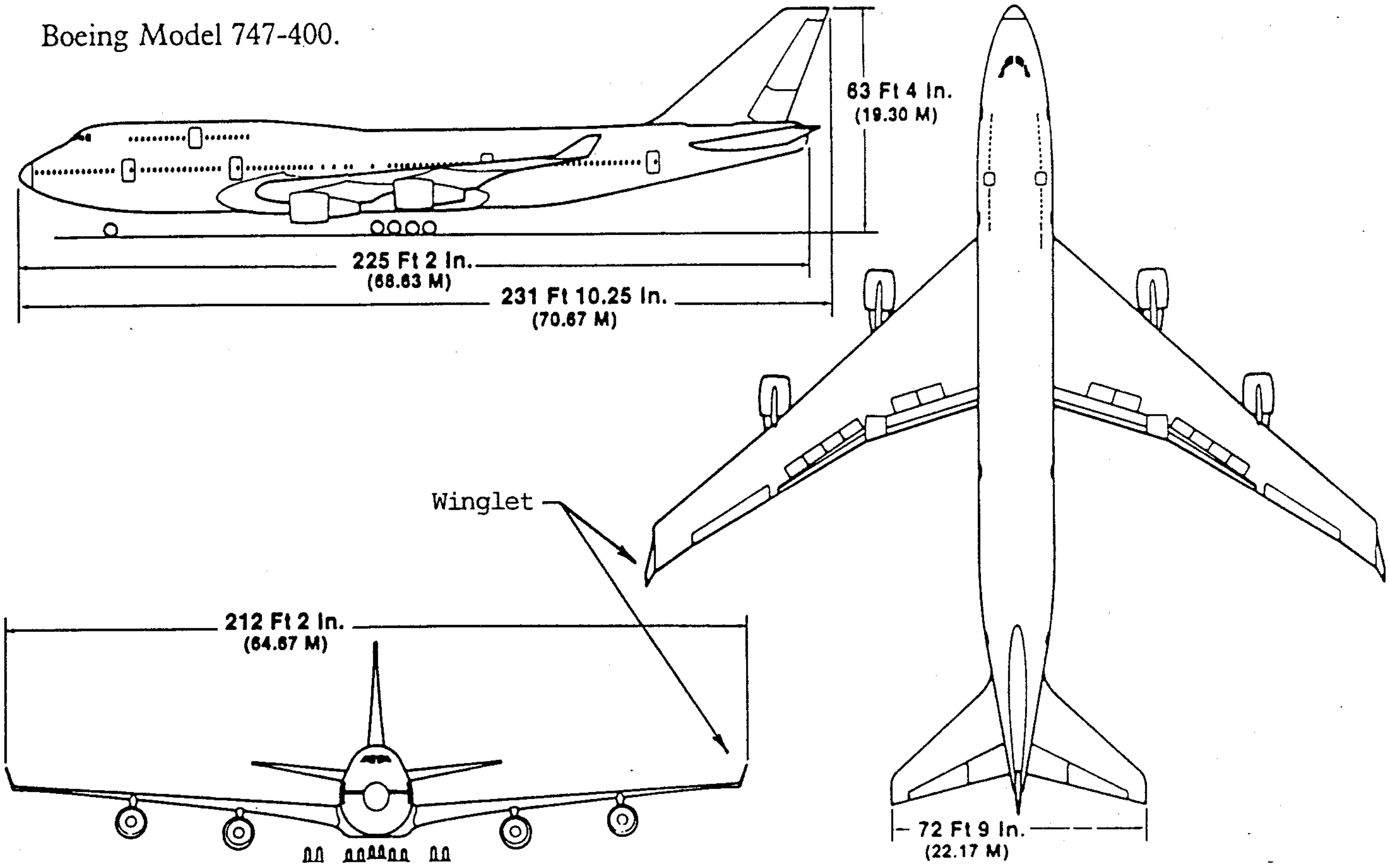
747-400 WING AERODYNAMIC CHANGES

SIX-FOOT (1.8m) TIP EXTENSION WITH WINGLET

WING SPAN: 211 FT 5 IN. (64.4m) NO FUEL
213 FT 0 IN. (64.9m) FULLY FUELED



Boeing Model 747-400.

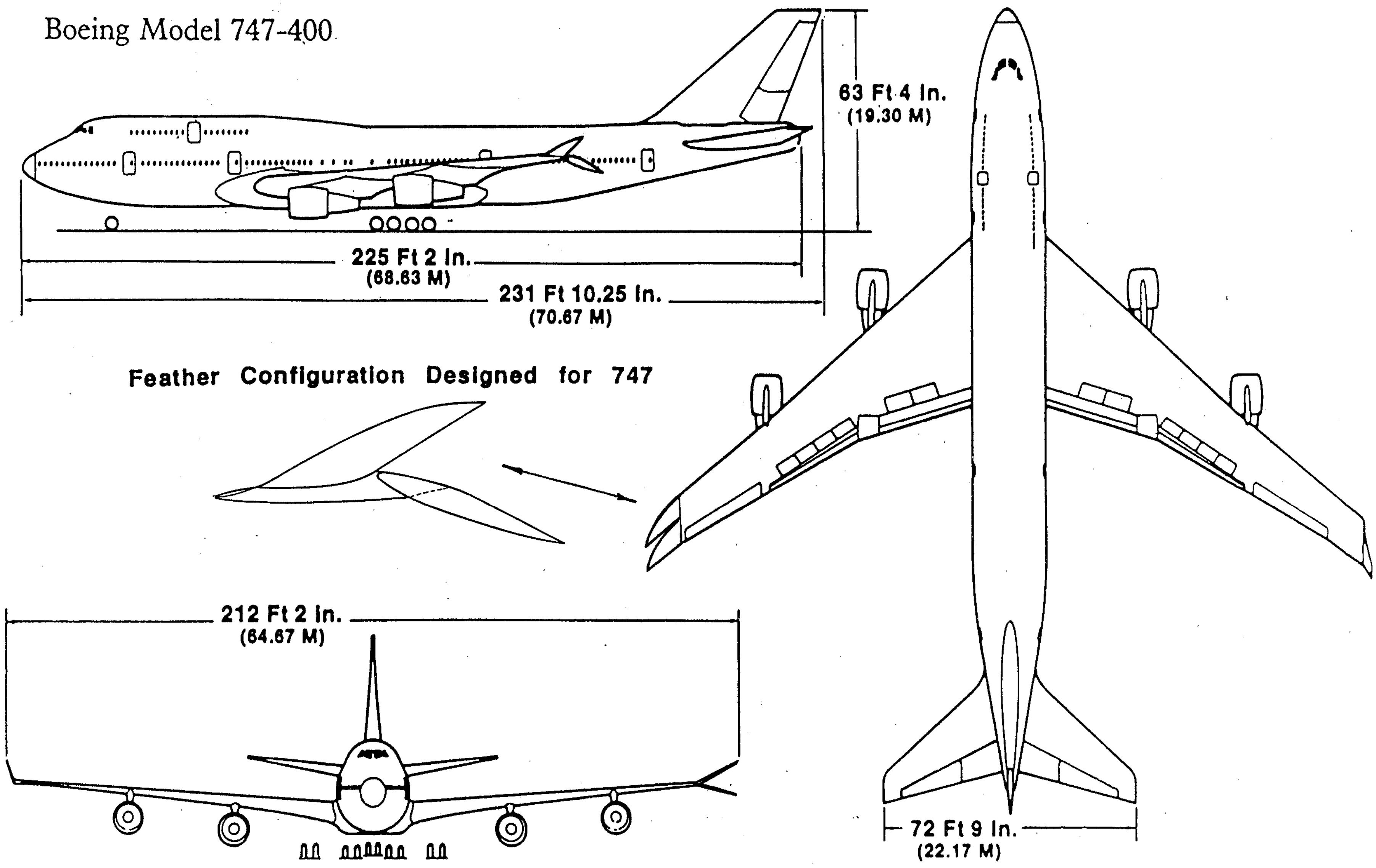


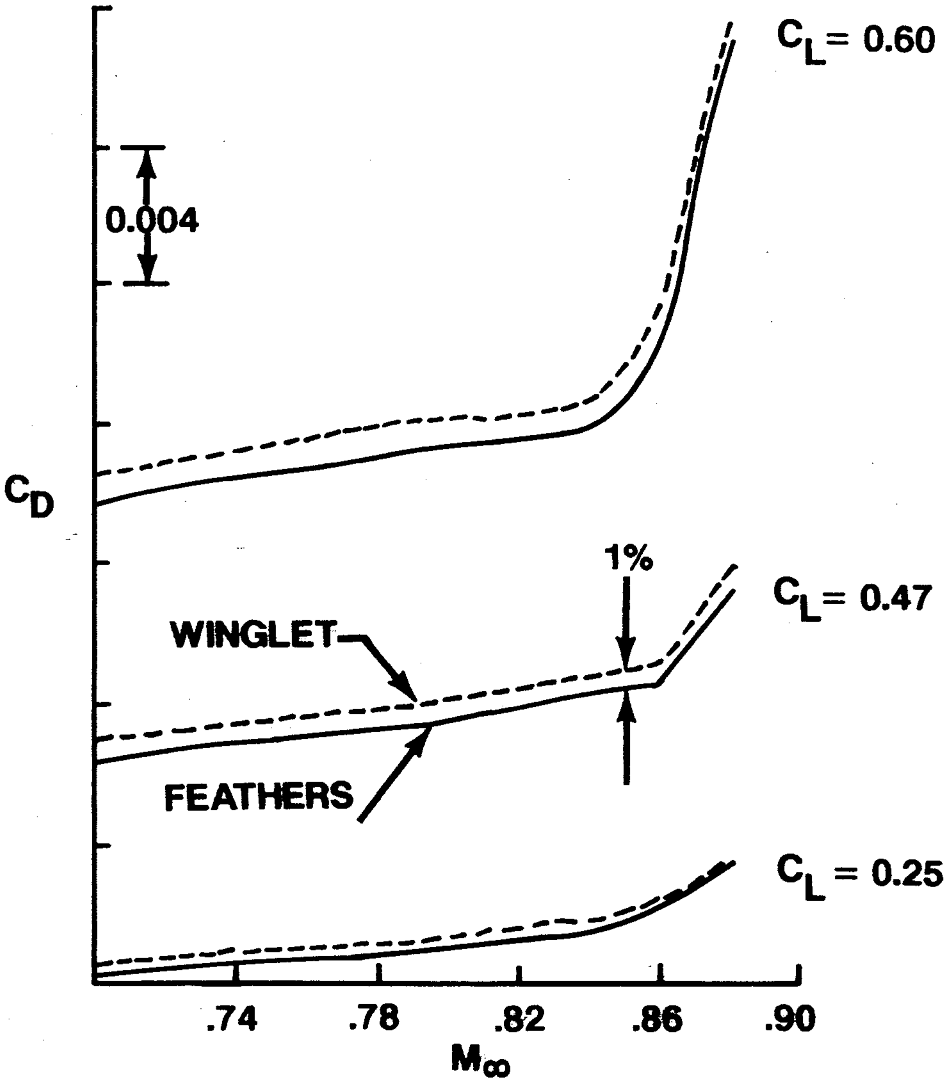
TECHNICAL DATA - MODEL 747-400

Type:	Long-range transport
Accommodation:	496 passengers (typical), 630 (maximum)
Power plants:	Pratt & Whitney 4256, 56,000 lb thrust
	General Electric CF6-80C2B1F, 57,900 lb thrust
	Rolls-Royce RB.211-524G, 50,000 lb thrust
Span:	211 ft 5 in–213 ft*
Length:	231 ft 10 in
Height:	63 ft 5 in
Wing area:	5,650 sq ft
Empty weight:	391,000–393,000 lb
Gross weight:	800,000–870,000 lb
Max speed:	612 mph
Range:	8,406 miles

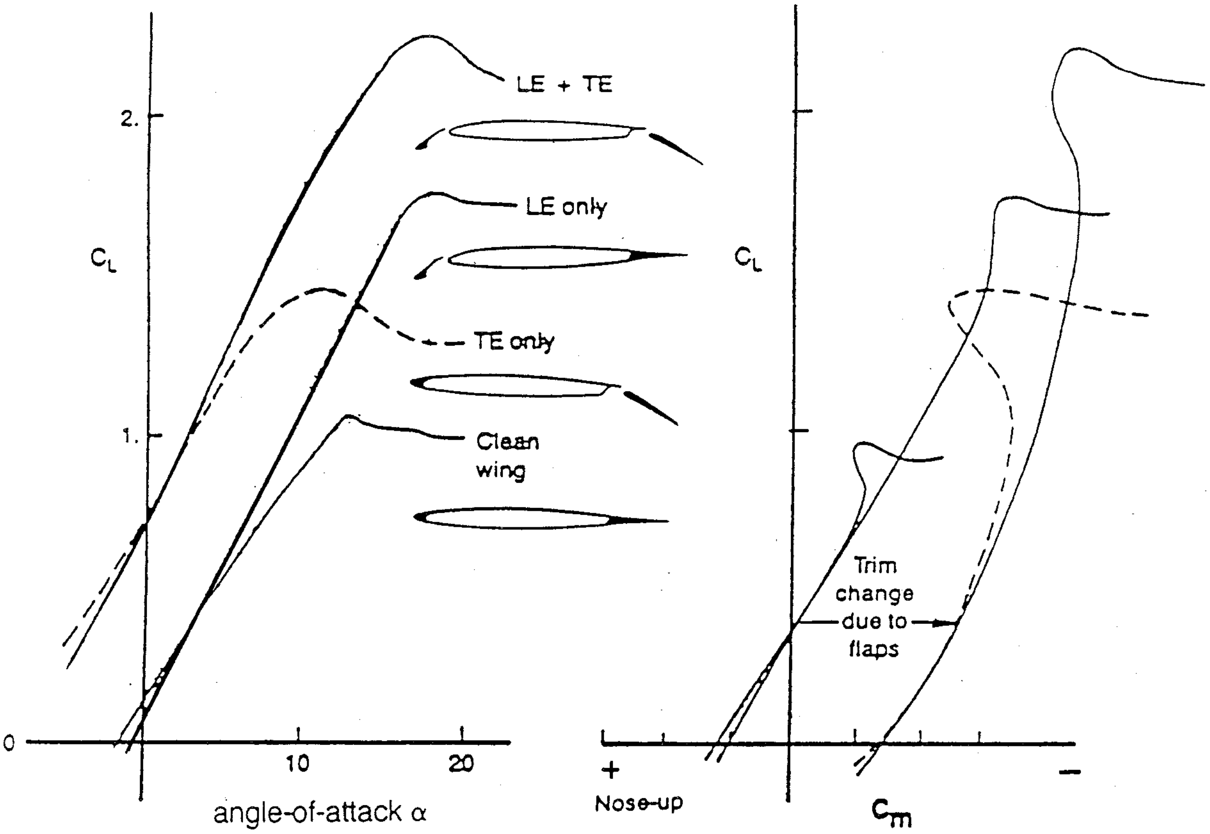
*Wing stretches when fully fuelled.

Boeing Model 747-400

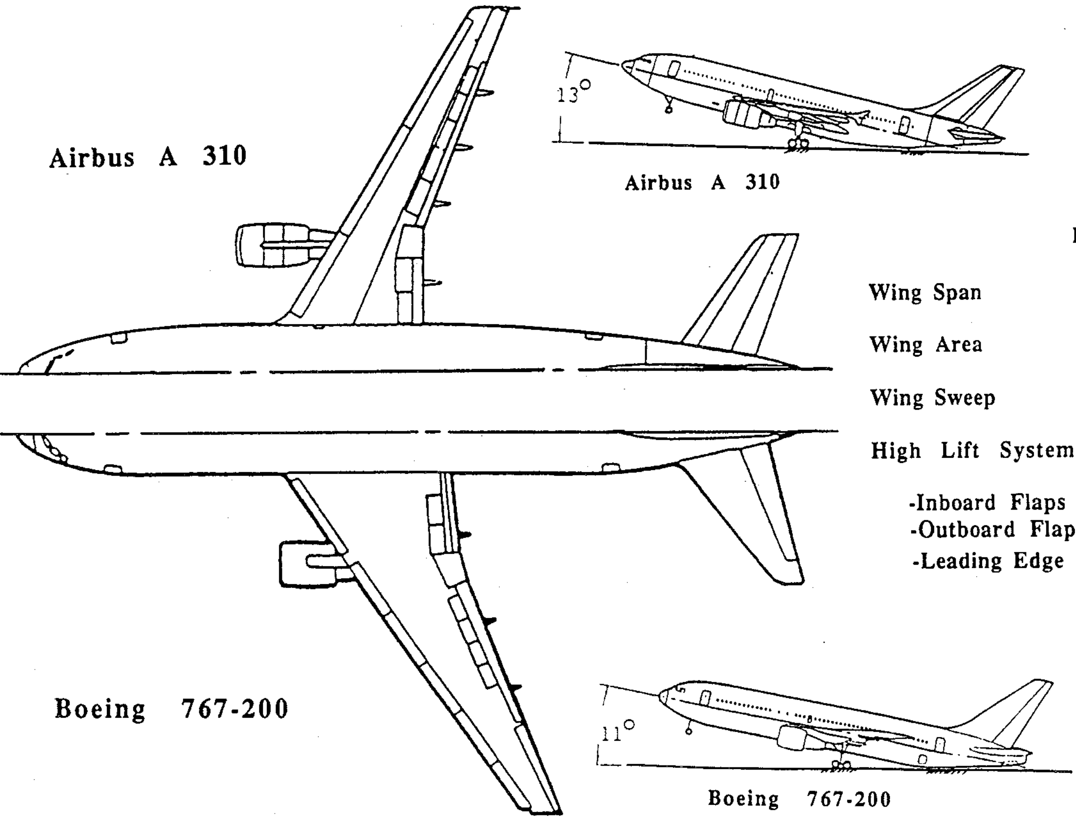




DRAG COMPARISON BETWEEN 747-400 WINGLET and FEATHERS



Typical Pitching Moment and Lift Curves for Leading and Trailing Edge Flaps



	Boeing 767	Airbus A 310
Wing Span	156 ft.	144 ft.
Wing Area	3050 ft.^{2}	2357 ft.^{2}
Wing Sweep	31.5°	28°
High Lift System		
-Inboard Flaps	Double Slotted	
-Outboard Flaps	Single Slotted	
-Leading Edge	Slat	

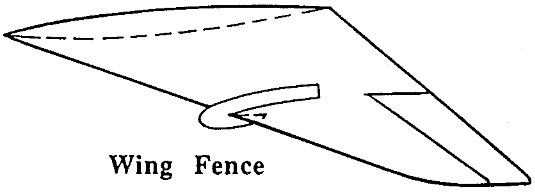
AN ALULA HIGH-LIFT DEVICE

A common feature of bird wings is the group of feathers attached at the "thumb" of the wing skeleton. These "alula" (bastard wing) feathers form a part of the bird's high-lift system and experiments (by biologists) have shown that plucking them from a live bird (e.g. a pigeon) adversely affects its low-speed performance. Note, these alula feathers are "retracted" except during low-speed/high angle-of-attack flight conditions.

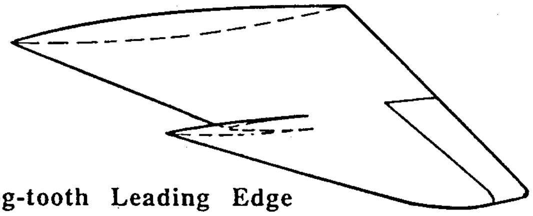
Most ornithological literature known to us describes the function of these alula feathers as the exact equivalent of a slotted leading edge slat on an airplane wing.

Since the alula feathers never cover more than about ten percent of the bird wing semi-span, however, this explanation seems unsatisfactory. Instead it would appear that the alula is a very sophisticated vortex generator/aerodynamic wing fence, functioning much as does a "snag' on the leading edge of the wing of certain fighter aircraft. If so, then a mechanical equivalent might be usefully employed on the leading edge of a swept wing aircraft during low-speed/high-lift operations.

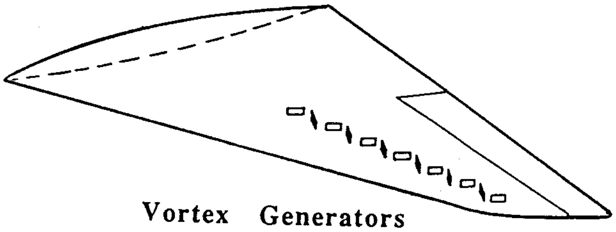
Aerodynamic Palliatives for Improving Local Airflow Over Wings



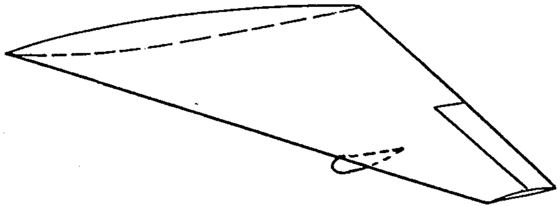
Wing Fence



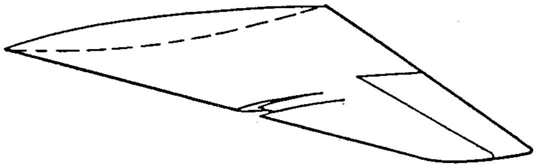
Dog-tooth Leading Edge
(Snag)



Vortex Generators

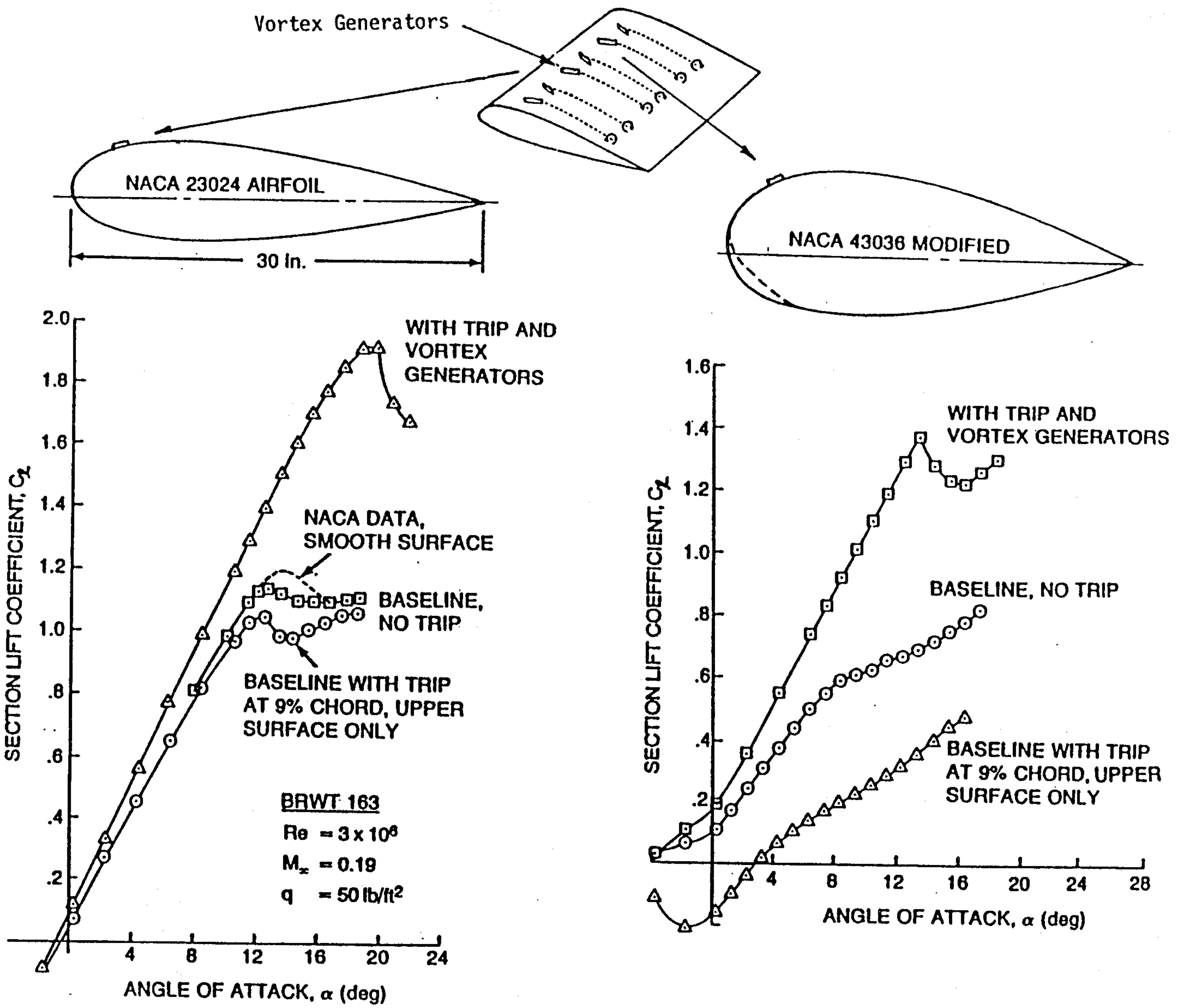


Vortilon



Notched Leading Edge

McMasters, J. H.; Crowder, J. P. and Robertson, P. E., "Recent Applications of Vortex Generators to Wind Turbine Airfoils," AIAA 85-5014, AIAA 4th Applied Aerodynamics Conference, Colorado Springs, CO, October, 1985.

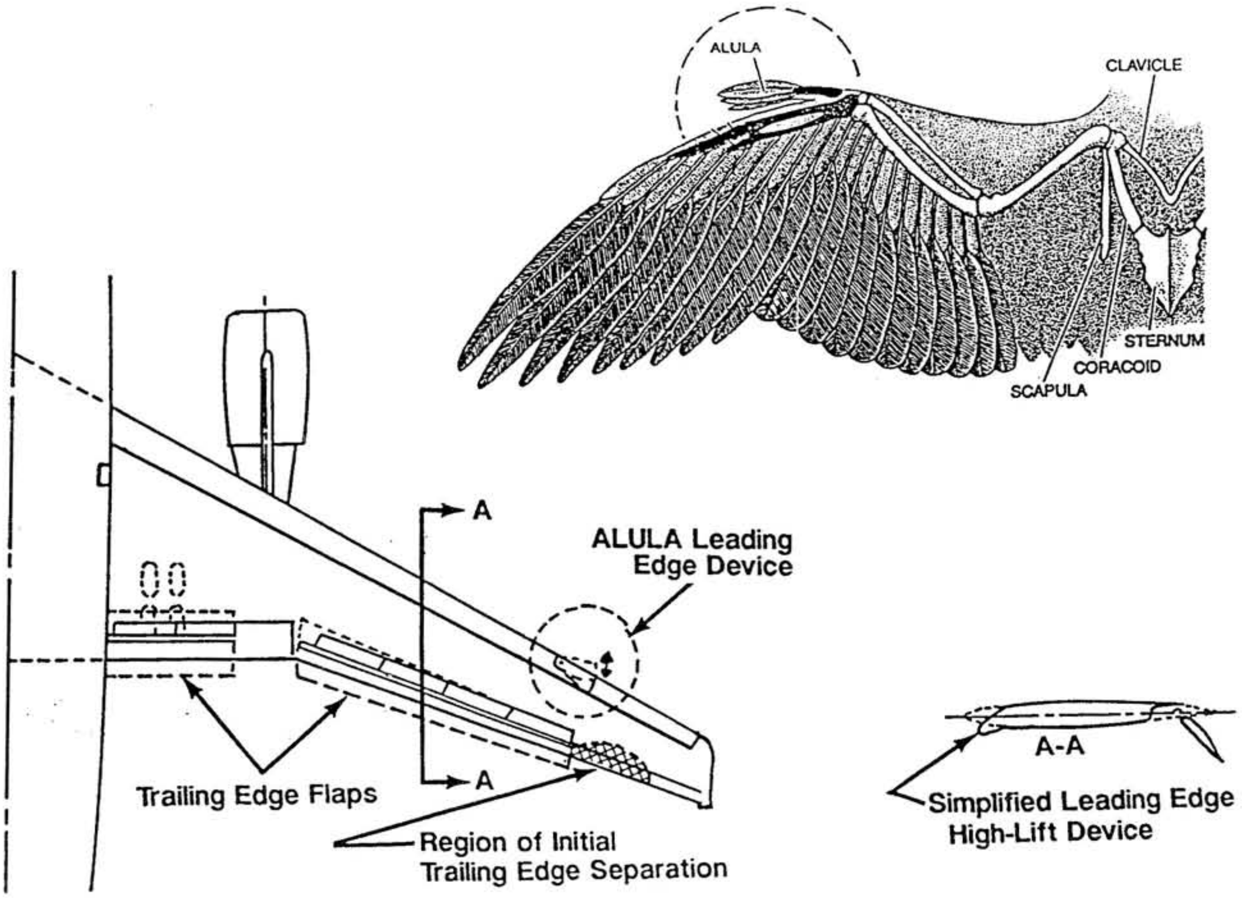


Wind Tunnel Test Results Showing the Effect on Section Lift Performance Due to the Addition of Vane-Type Vortex generators to Two Thick Airfoils.

As initially conceived, a small slotted slat type device, pivoted and sealed to the wing at one end, could be extended into the flow to produce a very powerful vortex which would flow aft over the wing into the region where the flow would begin to separate in a given high-lift configuration. The basic configuration of this alula leading edge device on a typical transport wing might be as shown.

So far the device serves the same function as a leading edge snag: i.e., it produces a vortex which acts as a barrier to spanwise boundary layer drift and, like a vortex generator, delays the onset of separation by establishing and maintaining a momentum exchange process which extracts low energy air from the boundary layer beneath it and allows higher energy air from the adjacent free stream to flow into the evacuated region. Wind turbine airfoil tests with ordinary vortex generators demonstrate that this latter effect (produced with very small devices) can be extremely powerful.

To achieve these beneficial results the vortex should be of sufficient strength to traverse a severe adverse pressure gradient and remain fully effective to the trailing edge of the wing. Here a snag or an ordinary vane-type vortex generator is limited, due to the strength of the vortex either can produce. To amplify the strength of the vortex formed by a snag type leading edge device it is possible to capitalize on the theory of multi-element airfoils. The strength of the vortex shed from the exposed tip of the alula depends on the strength of the circulation about the alula. The "slat effect" on a multi-element airfoil ensemble can produce very high values of circulation on the slat (or alula). Thus the novelty of this device is the use of the slat effect to amplify the strength of the vortex produced by a retractable snag type vortex generator to control the local separation on a swept wing.



AN ALULA LEADING EDGE DEVICE
for a TRANSPORT AIRPLANE

Having based our scheme on semi-theoretical arguments, it remained to perform an experimental verification of our hypothesis. To minimize the expense of such verification, it was decided to perform some limited proof-of-concept tests in a small (14" x 16" section) low-speed wind tunnel with existing models on an as-time-permitted basis before proposing more suitable tests in a larger facility. The quality of the results obtained in these preliminary tests are reflective of the constraints of the on-the-cheap approach taken.

The intent was to use an existing swept wing model with addition of simple sheet metal parts to simulate the partially separated flow pattern on a mildly flap deflected transport wing, i.e., with local trailing edge separation outboard of the flap. The choice of readily available candidate models was limited to the two shown. The two models were:

Model 1 A relatively low aspect ratio 767 vertical stabilizer with a symmetric airfoil section, no twist and a higher than desired sweep and taper ratio. This basic model was subsequently fitted with a simple, cambered leading edge extension and was tested with and without a part span, sheet metal flap as shown. At a tunnel dynamic pressure (q) of 20 psf, the average Reynolds number was 0.45×10^6.

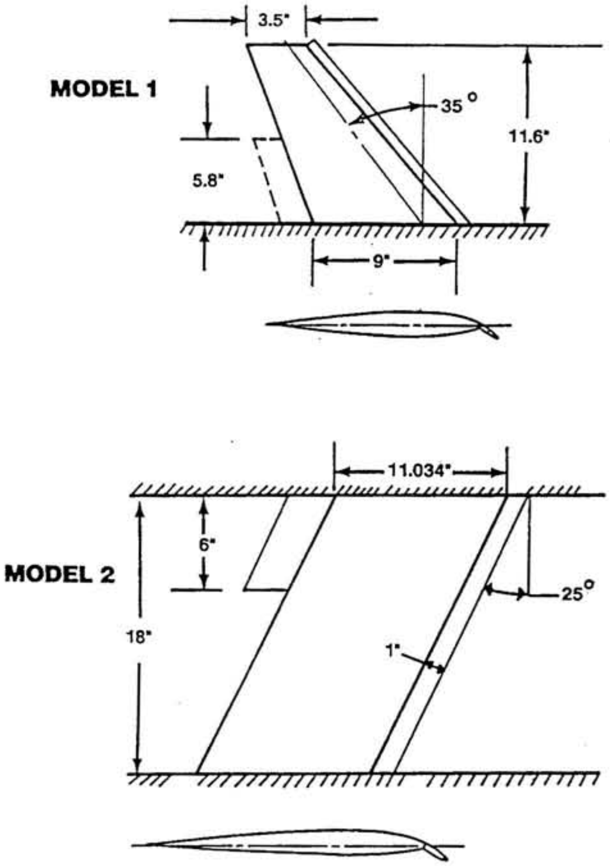
Model 2 A swept 2D wing with a thin 747 airfoil section. While the model had about the desired sweep for the proposed tests, the clumsy downstream tip mounting plate caused serious disruption of the flow over the outboard portion of the wing. Modifications were made to the plate and a leading edge extension and third-span metal plate flap were attached. At a tunnel q of 20 psf the average Reynolds number on this modified section was about 0.8×10^6.

Neither of these models, even with modification, proved to be entirely suitable. However, both produced flows which could be altered (apparently beneficially) by addition of a simple sheet metal or adhesive backed aluminum tape alula devices fabricated on a rather ad hoc basis as the tests proceeded. All data obtained in the tests was fluorescent oil surface flow visualization.

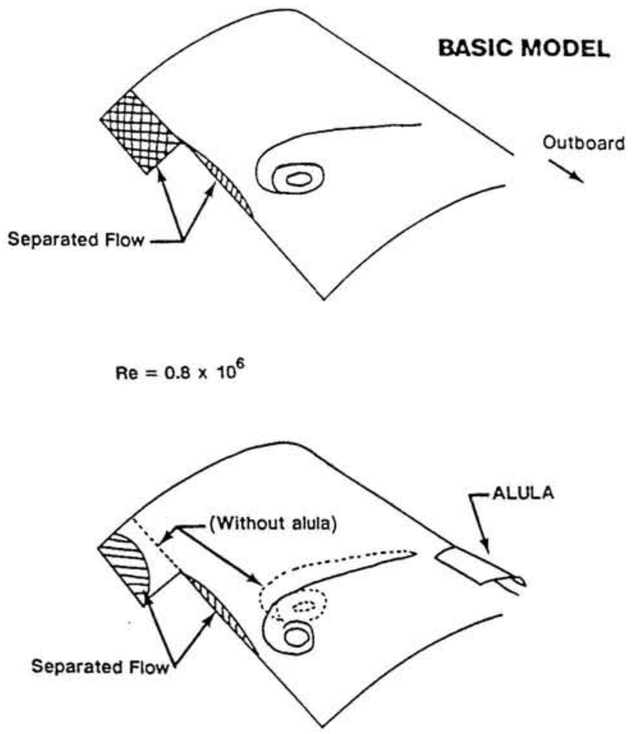
In general, the marginal suitability of the models limited the quality and quantity of data acquired. Of these data, three cases have been selected to demonstrate the effects of addition of non-optimized alula devices to the various models tested. In none of these cases did the alula clearly demonstrate that it worked as hoped, but in all three cases the separation patterns of the basic models were significantly altered in an apparently desirable direction.

Case I. Model I Without a Flap

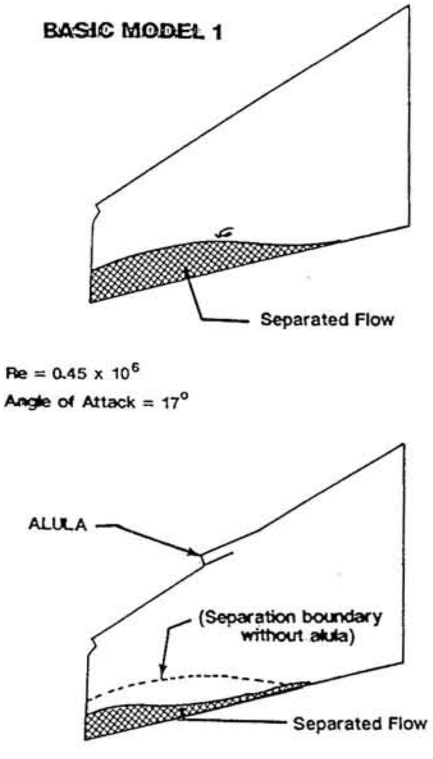
The first application of the alula device was made to the 767 vertical stabilizer model with the leading edge device but without the flap. The flow patterns with and without the alula are sketched. Without the alula there is a strong spanwise flow with a large region of separation over the trailing edge of the outboard wing at the tested angle of attack of about 17°. There is very small swirl in the flow pattern toward the inner edge of the separation zone. Early positioning of the alula too far inboard resulted in the tip vortex from the alula feeding this local swirl and resulted in a dramatic enlargement of it. In most later tests the tip of the alula was placed well outboard of such swirls and as shown the separation region is reduced in size and moved toward the tip. The strong component of spanwise flow ahead of the separated region remains similar to that of the wing without the alula, however, and the extent of improvement due to addition of the alula remains ambiguous in the absence of accompanying force data. Taping over the slot on the alula did seem to reduce its ability to alter the separation pattern and orienting the alula in the opposite sense (as a snag) showed a decrease in effectiveness.



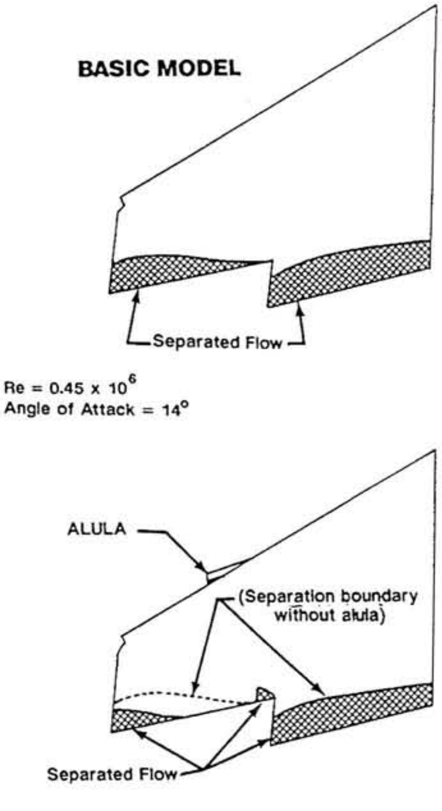
MODELS USED IN ALULA LEADING EDGE DEVICE TESTS



SKETCHES of FLOW PATTERNS on MODEL 2 WITH and WITHOUT ALULA



SKETCHES of FLOW ON MODEL 1 WITH and WITHOUT ALULA



SKETCHES of PATTERNS on MODEL 1 WITH FLAP WITH and WITHOUT ALULA

Case II. Model I With a Flap

This case shows the before and after flow patterns observed on Model I when a simple flap deflected about 20° was added to the model. For the cases shown the model was at about 14° angle of attack.

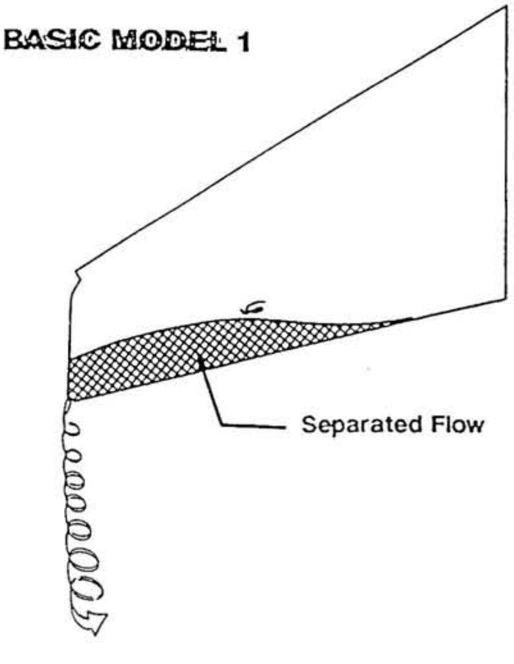
Addition of the half span flap straightened the flow over the inboard portion of the wing, but outboard trailing edge separation could not be forced to occur adjacent to the flap and tended to form a large wedge shaped region extending to the tip. Addition of a modest sized alula rather far outboard did, as before, appear to suppress the outboard trailing edge separation. Ad adverse effect is shown due to the poorly faired inner end of the alula. Here the "corner" at the wing/alula junction seems to cause a pocket of trailing edge separation just outboard of the flap end.

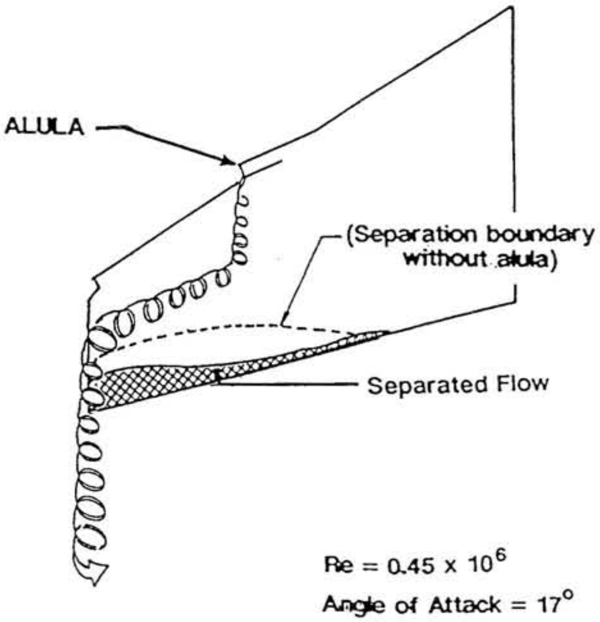
The conclusions drawn from this and the previous case are that the alula seems to work after a fashion but a conclusive demonstration is foiled by the high sweep and taper of the model, and compounded by the low Reynolds number of the tests.

Case III. Model II With Flap

Based on lessons learned with the two previous configurations, attention turned to Model II. In this case, however, even with the leading edge extension the flow on the basic model was wretched. Significant features were that the flow over the flap was completely separated and the outboard flow was dominated by a large and powerful "swirl" centered at about two-thirds semi-span. This flow showed little promise for improvement without a great deal of effort and the decision was made to try the alula anyway.

In this case a fairly large and heavily loaded vane was mounted with its tip located at nearly 90% of the semi-span. With this alula the large surface swirl was somewhat diffused and moved outboard and aft while the flow on the flap became at least partially attached.

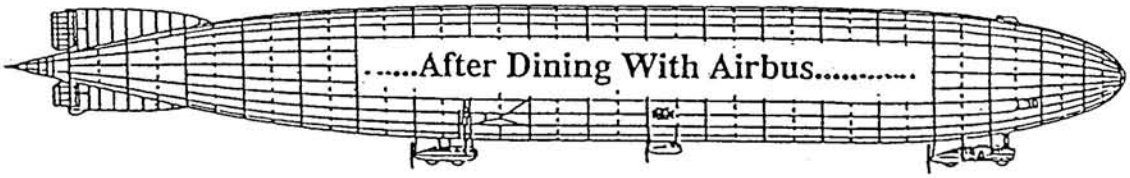




$Re = 0.45 \times 10^6$

Angle of Attack = 17°

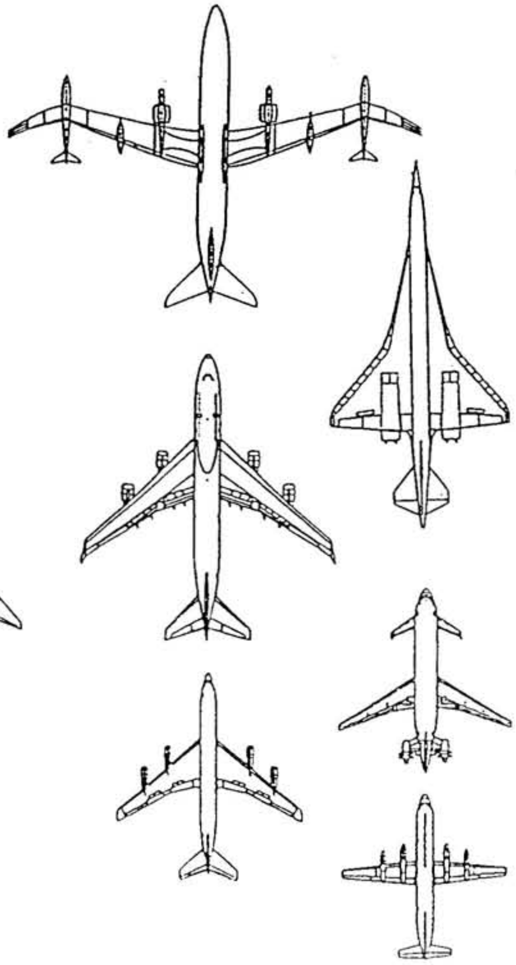
A BRIEF HISTORY OF COMMERCIAL AIRPLANE (AND RELATED TECHNOLOGY) DEVELOPMENT

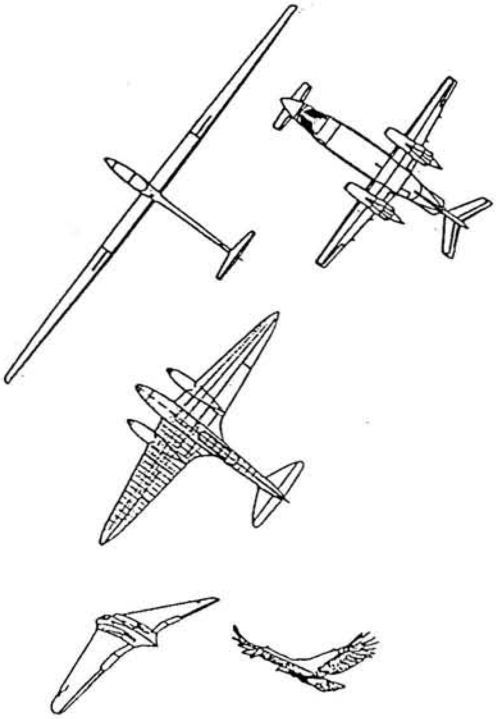


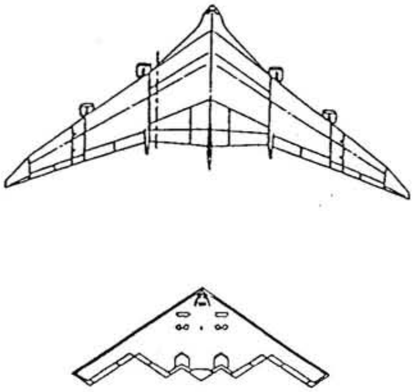
John H. McMasters
Principal Engineer
Aerodynamics Engineering
Boeing Commercial Airplane Group

Revised Version

May 1993

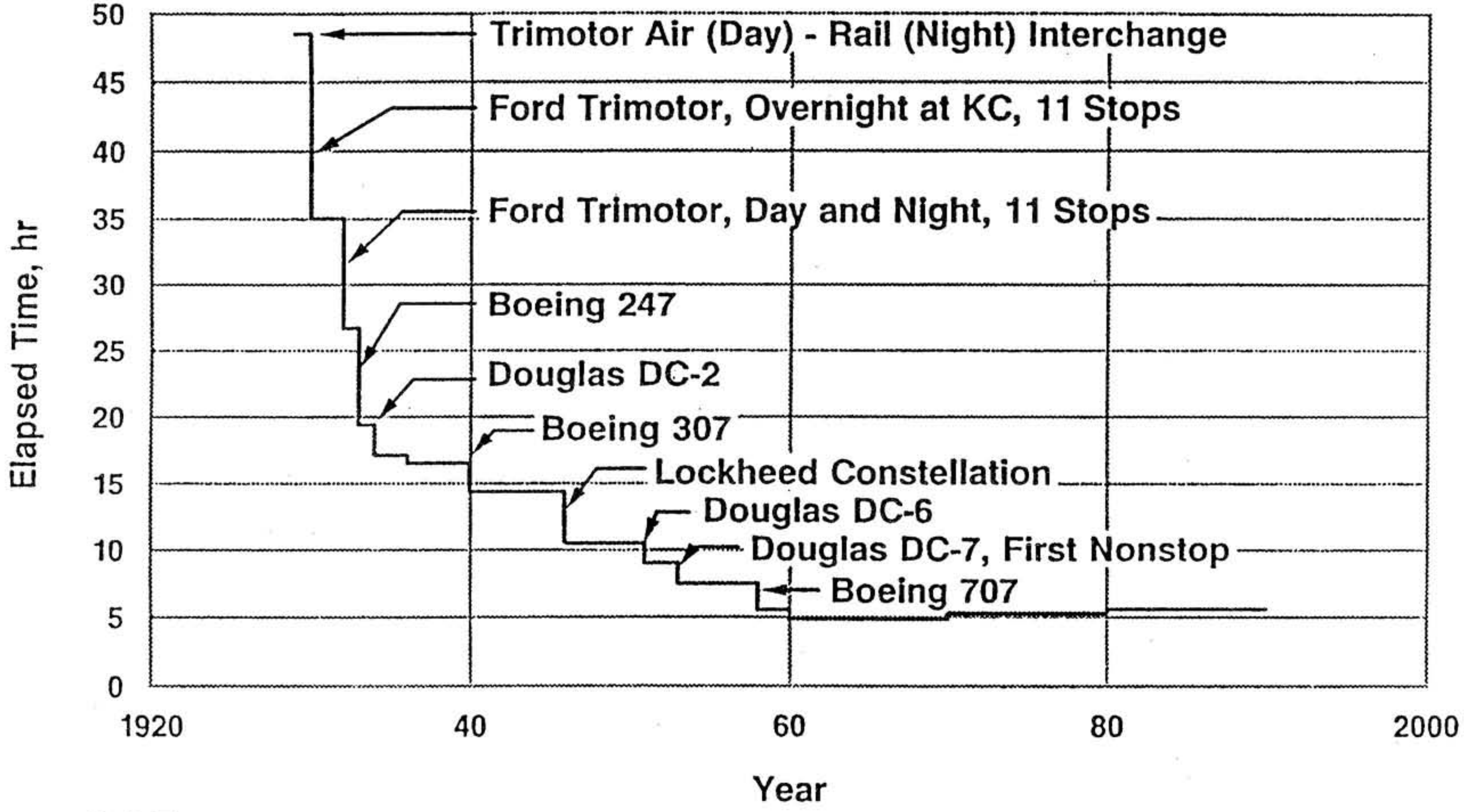






U.S.Transcontinental Trip Time

New York - Los Angeles, Scheduled Air Service



Source: C.A.B.

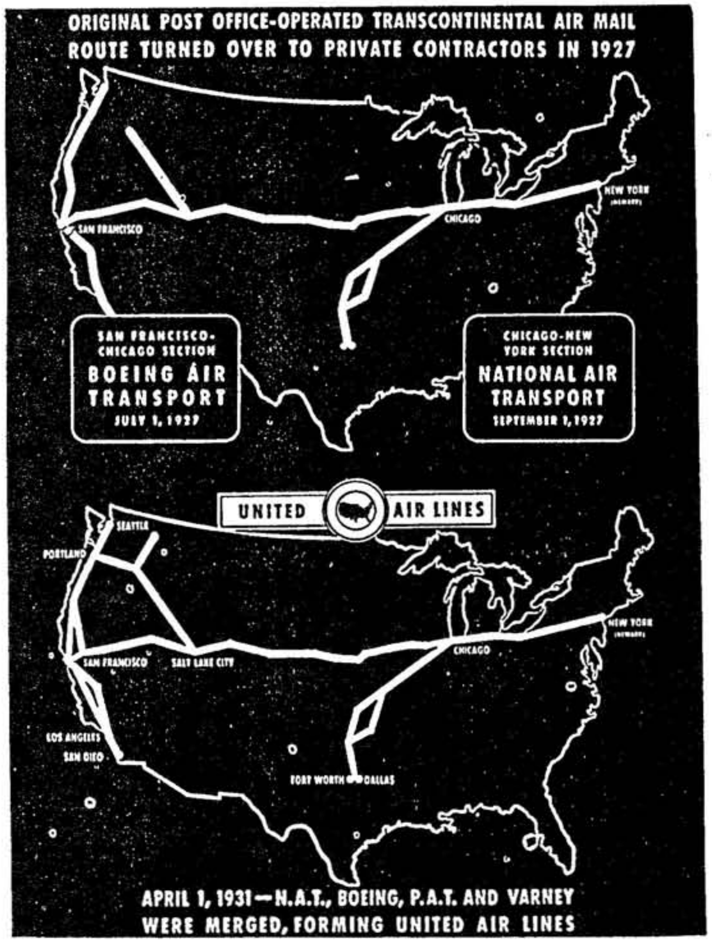
THE DAWN OF COMMERCIAL AVIATION

- Speed and range increases become the dominant performance goals.
- Lockheed and Douglas emerge as the premire developers of commercial aircraft.
- Boeing, despite a record of technical innovation and great success in long range bomber design, never quite makes it into the big time in commercial airplane sales.
- The post-war Boeing "Stratocruiser", developed from the B-29/B-50 bomber series, just about puts us out of the commercial airplane business.
- Non-stop New York-to-West Coast and New York-to-Europe becomes the target for future development. Ten to twelve hour flight times in a properller-driven airplane is not a particularly fun way to travel.

"Life is too short to spend working on propellers."

Ed Wells

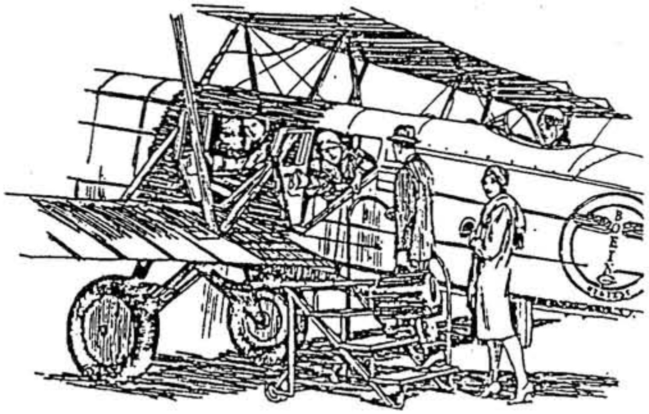
The original Boeing Bug, used as the principal Boeing trademark from 1926 to 1942, has seen but limited use since World War II.

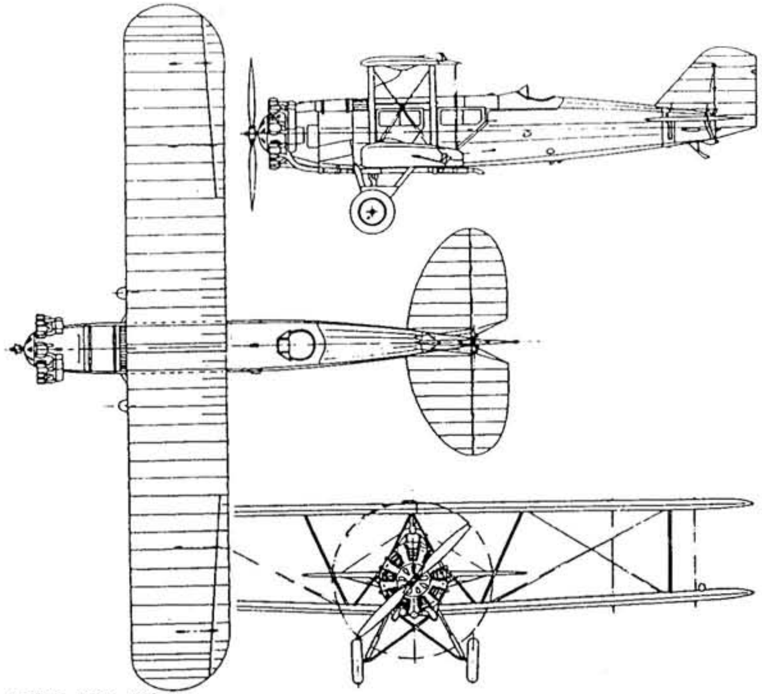


Route maps show how Boeing Air Transport, under Boeing and Rentschler, grew into coast-to-coast, United Air Lines.

June 30, 1930

- Boeing Air Transport, Inc
  - Celebrates its third birthday
- Operating on Chicago - San Francisco and Los Angeles - Seattle routes
  - Completed 10,000,000 miles
  - Carried 13,800 passengers
  - Carried 176,000,000 letters
- Flying 50 airplanes



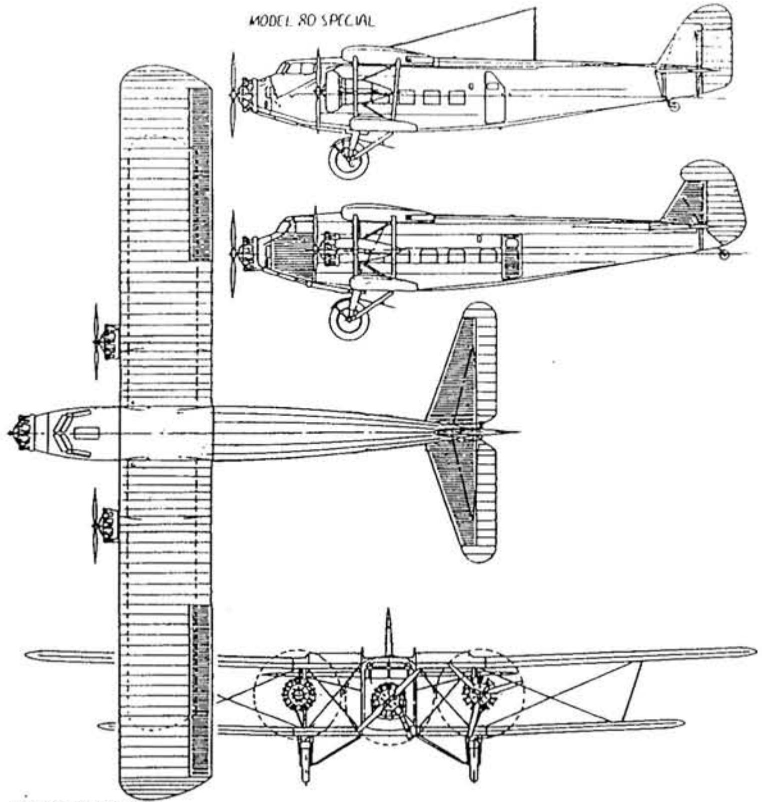


BOEING MODEL 40B-4

TECHNICAL DATA - MODEL 40B-4

Type:	Mail-passenger
Accommodation:	4 passengers, 1 pilot, 500 lb mail
Power plant:	P & W Hornet 525 hp
Empty weight:	3,722 lb
Gross weight:	6,075 lb
Max speed:	137 mph
Cruising speed:	125 mph
Climb:	800 ft/min
Service ceiling:	16,100 ft
Range:	535 miles

Boeing Model 40. First Flight: July 7, 1925 (Model 40B-4: Oct. 5, 192

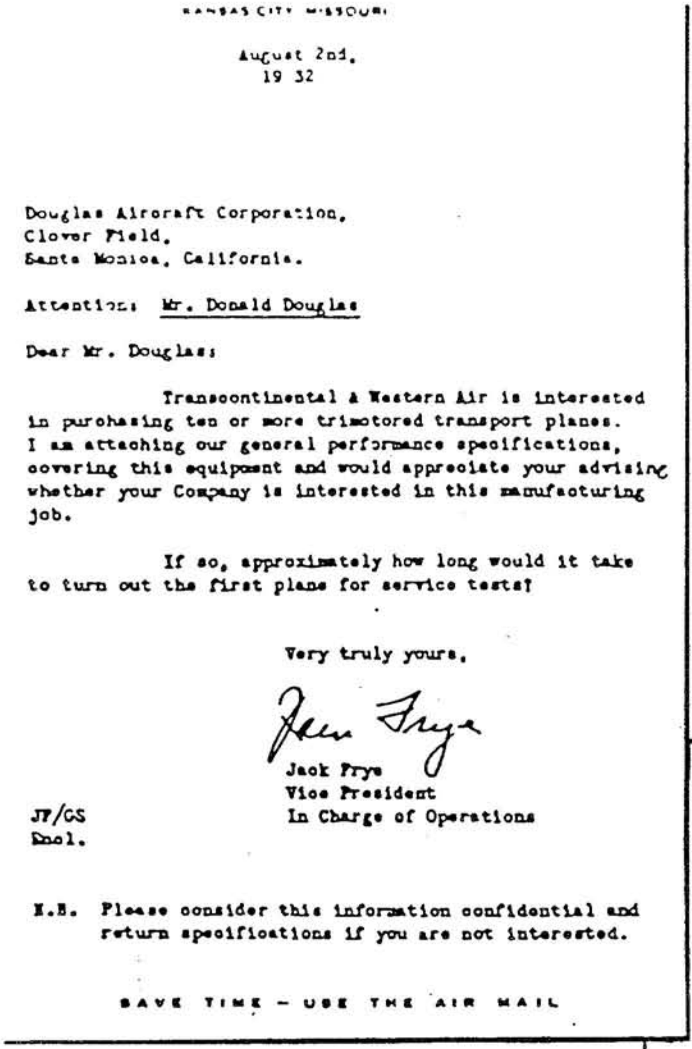


BOEING MODEL 80A

TECHNICAL DATA - MODEL 80A

Type:	Passenger transport
Accommodation:	18 passengers, 2-3 crew, 898 lb cargo
Power plant:	3 P & W Hornet 525 hp
Span:	80 ft
Length:	56 ft 6 in
Height:	15 ft 3 in
Wing area:	1,220 sq ft
Empty weight:	10,582 lb
Gross weight:	17,500 lb
Max speed:	138 mph
Cruising speed:	125 mph
Climb:	900 ft/min
Service ceiling:	14,000 ft
Range:	460 miles

Boeing Model 80. First Flight: August, 1928.



KANSAS CITY MISSOURI

August 2nd,
19 32

Douglas Aircraft Corporation,
Clover Field,
Santa Monica, California.

Attention: Mr. Donald Douglas

Dear Mr. Douglas:

Transcontinental & Western Air is interested in purchasing ten or more trimotored transport planes. I am attaching our general performance specifications, covering this equipment and would appreciate your advising whether your Company is interested in this manufacturing job.

If so, approximately how long would it take to turn out the first plane for service tests?

Very truly yours,

Jack Frye

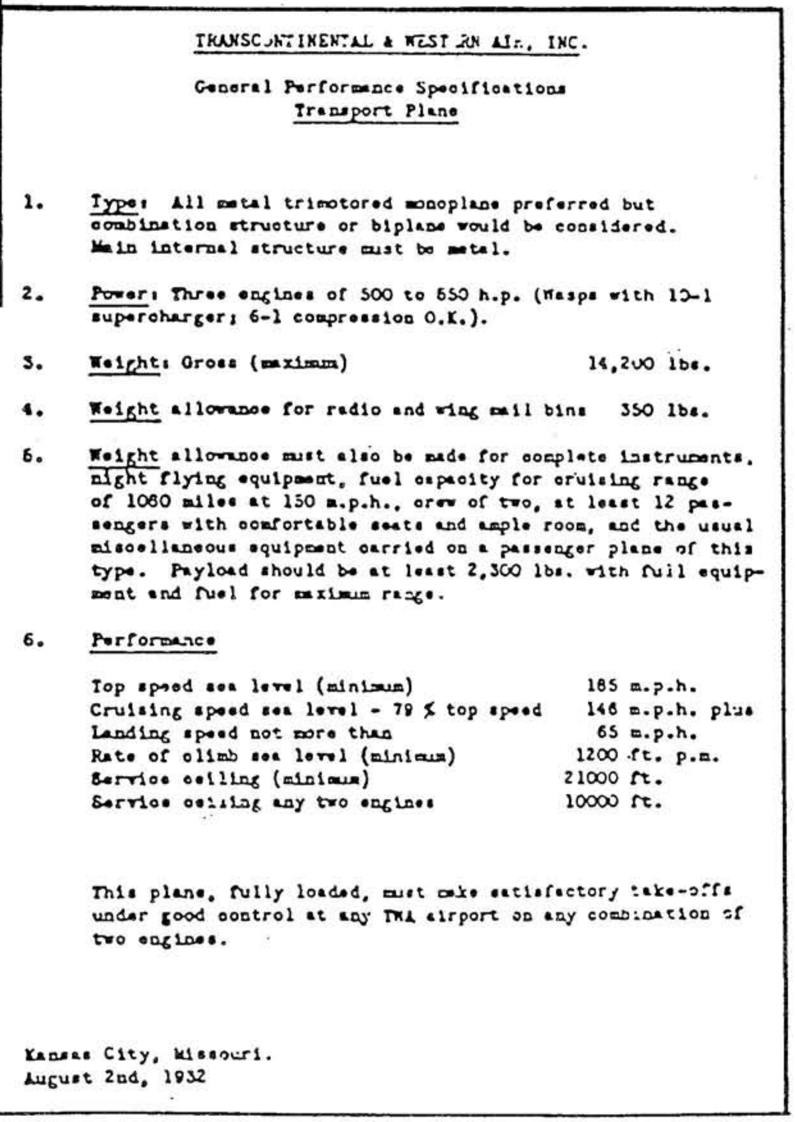
Jack Frye
Vice President
In Charge of Operations

JF/GS
Encl.

N.B. Please consider this information confidential and return specifications if you are not interested.

SAVE TIME — USE THE AIR MAIL

The letter and specifications that brought about the birth of the DC-1 which changed the concept of commercial transports for all times.



TRANSCONTINENTAL & WESTERN AIR, INC.

General Performance Specifications
Transport Plane

1. Type: All metal trimotored monoplane preferred but combination structure or biplane would be considered. Main internal structure must be metal.

2. Power: Three engines of 500 to 650 h.p. (Wasps with 10-1 supercharger; 6-1 compression O.K.).

3. Weight: Gross (maximum) 14,200 lbs.

4. Weight allowance for radio and wing mail bins 350 lbs.

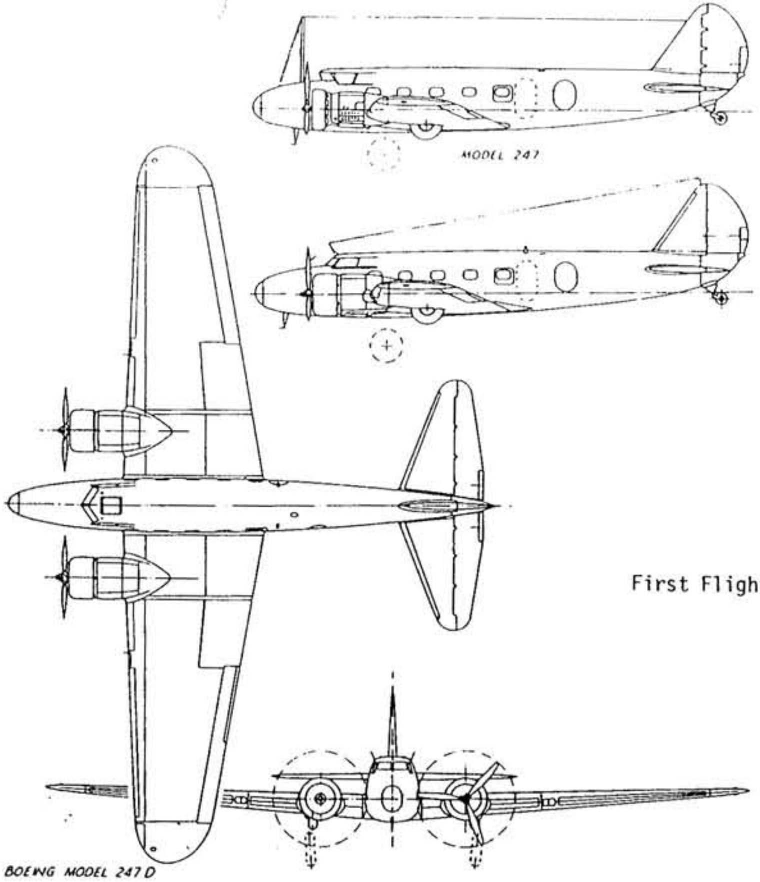
5. Weight allowance must also be made for complete instruments, night flying equipment, fuel capacity for cruising range of 1080 miles at 150 m.p.h., crew of two, at least 12 passengers with comfortable seats and ample room, and the usual miscellaneous equipment carried on a passenger plane of this type. Payload should be at least 2,300 lbs. with full equipment and fuel for maximum range.

6. Performance

Top speed sea level (minimum)	185 m.p.h.
Cruising speed sea level - 79 % top speed	146 m.p.h. plus
Landing speed not more than	65 m.p.h.
Rate of climb sea level (minimum)	1200 ft. p.m.
Service ceiling (minimum)	21000 ft.
Service ceiling any two engines	10000 ft.

This plane, fully loaded, must make satisfactory take-offs under good control at any TWA airport on any combination of two engines.

Kansas City, Missouri.
August 2nd, 1932



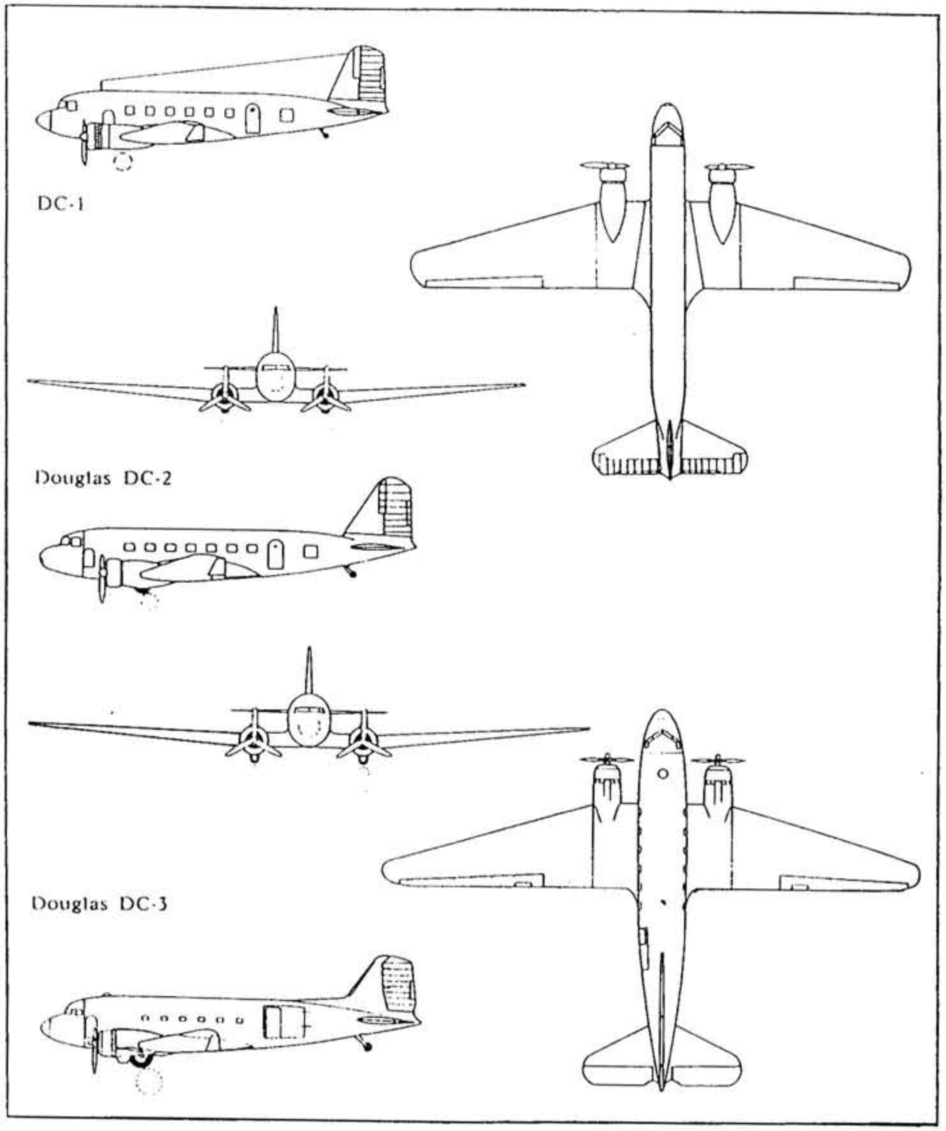
MODEL 247

BOEING MODEL 247 D

First Flight: Feb. 8, 1933.

TECHNICAL DATA - 247 SERIES

Boeing Model	*247*	*247A*	*247D*
Span:	74 ft	74 ft	74 ft
Length:	51 ft 4 in	51 ft 4 in	51 ft 7 in
Height (overall):	15 ft 5 in	16 ft 5 in	12 ft 1¾ in
Wing area:	836·13 sq ft	836·13 sq ft	836·13 sq ft
Empty weight:	8,400 lb	8,975 lb	9,144 lb
Gross weight:	12,650 lb	12,405 lb	13,650 lb
Power plant:	P & W Wasp S1D1 550 hp at 2,200 rpm at 5,000 ft	P & W Twin Wasp Jr SGR-1535, 625 hp at 2,400 rpm at sea level	P & W Wasp S1H1G 500 hp at 2,200 rpm at 8,000 ft
Max speed:	182 mph	198 mph	200 mph
Cruising speed:	155 mph	170 mph at 60% power	189 mph at 12,000 ft
Range:	485 miles (208 gal)	650 miles (290 gal)	745 miles (273 gal)
Rate of climb:	1,320 ft/min	1,170 ft/min	1,150 ft/min
Service ceiling:	18,400 ft	22,700 ft	25,400 ft
Absolute ceiling:	20,500 ft	24,100 ft	27,200 ft
Payload:	10 passengers, baggage, 400 lb mail	6 passengers or test equipment	10 passengers baggage, 400 lb mail

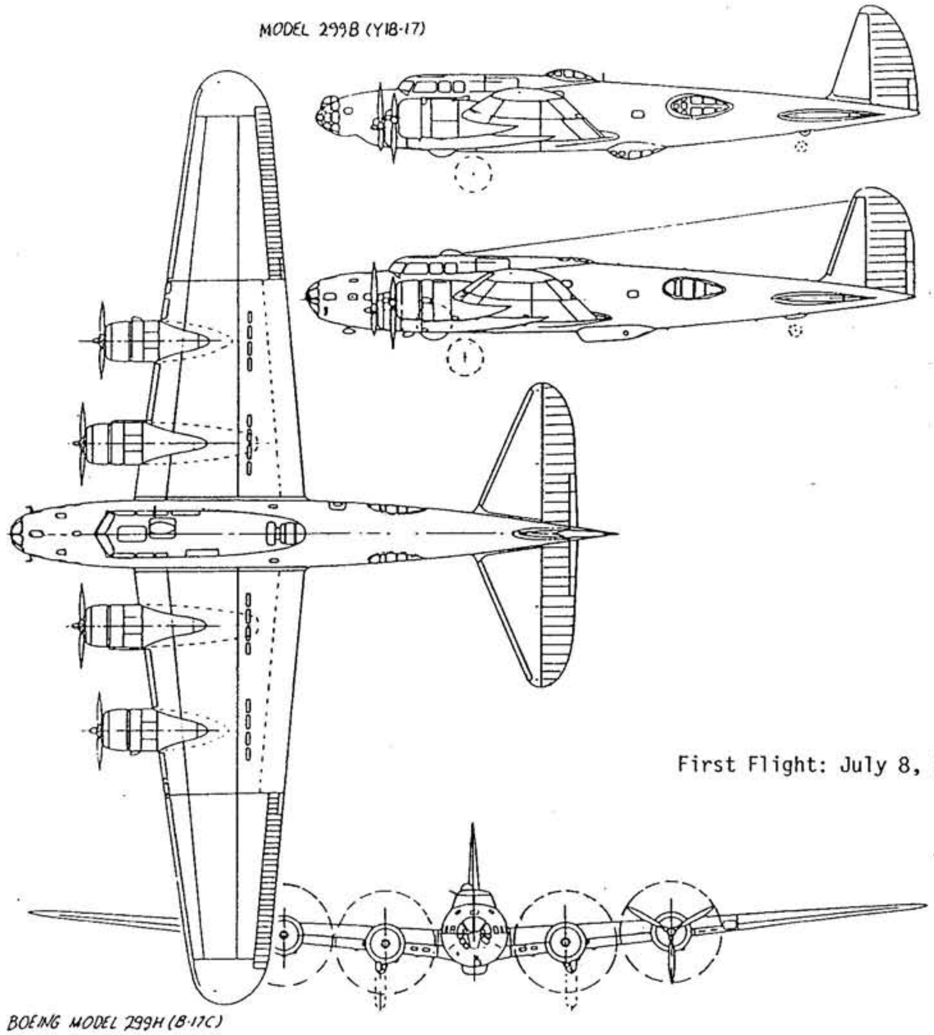


DC-1

Douglas DC-2

Douglas DC-3

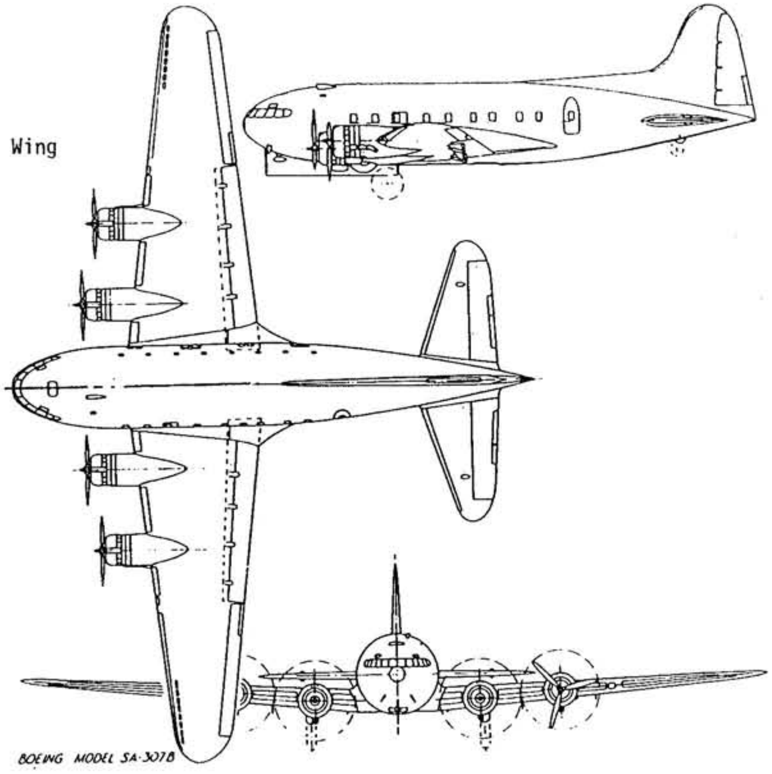
First Flights:	DC-1	December 1933
	DC-2	May 1934
	DC-3	December 1935



First Flight: July 8, 1935.

TECHNICAL DATA - Y1B-17

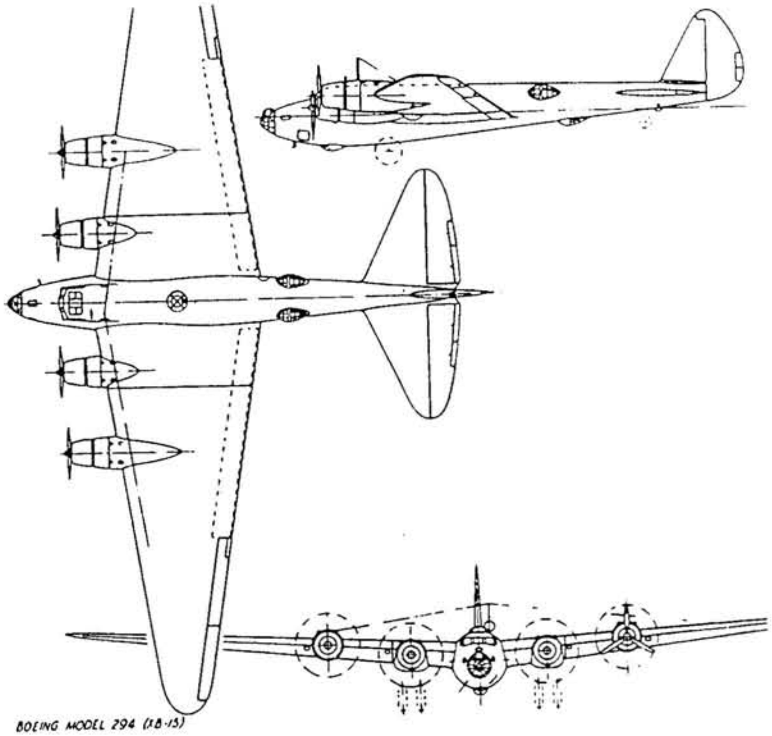
Type:	Heavy bomber
Accommodation:	6 crew
Power plant:	Wright R-1820-39 1,000 hp (take-off) 850 hp at 5,000 ft (normal)
Span:	103 ft 9⅜ in
Length:	68 ft 4 in
Height:	18 ft 4 in
Wing area:	1,420 sq ft
Empty weight:	24,465 lb
Gross weight:	34,880 lb (normal), 42,600 lb (maximum)
Max speed:	256 mph at 14,000 ft
Cruising speed:	217 mph
Service ceiling	30,600 ft
Climb:	10,000 ft in 6·5 min
Range:	1,377 miles
Armament:	Five ·30 cal MG, 8,000 lb bombs



TECHNICAL DATA - MODEL 307 (STRATOLINER, C-75)

Type:	High-altitude long-range transport
Accommodation:	33 passengers, 5 crew
Power plant:	Wright GR-1820 Cyclone, 900 hp at 2,300 rpm at 17,300 ft
Span:	107 ft 3 in
Length:	74 ft 4 in
Height:	20 ft 9 in
Wing area:	1,486 sq ft
Empty weight:	30,310 lb
Gross weight:	42,000 lb
Max speed:	246 mph at 17,300 ft
Cruising speed:	220 mph at 15,700 ft
Climb:	1,200 ft/min
Service ceiling:	26,200 ft
Range:	2,390 miles

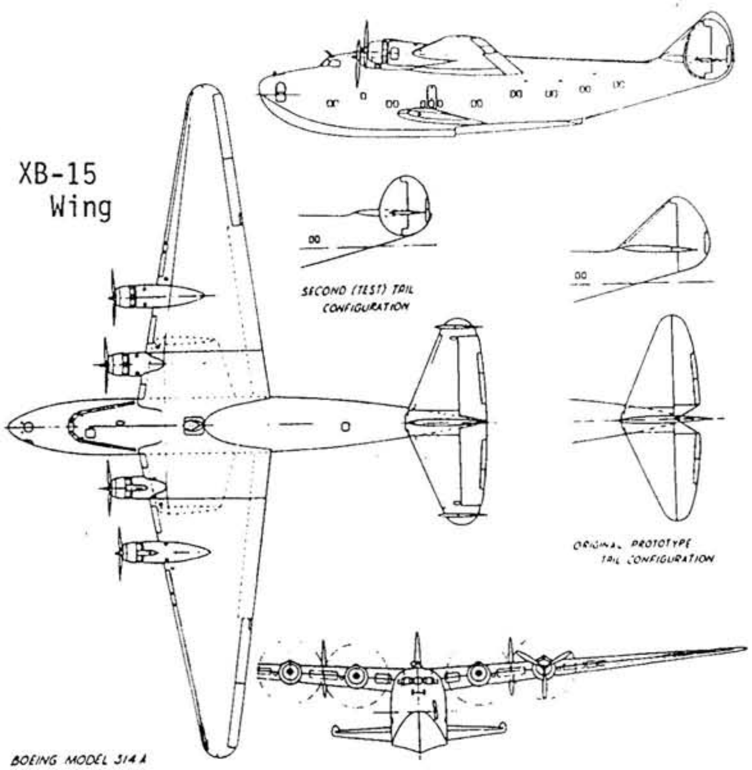
Boeing Model 307. First Flight: December 31, 1938.



TECHNICAL DATA - XB-15

Type:	Heavy bomber
Accommodation:	10 crew
Power plant:	P & W R-1830-11 Twin Wasp 850 hp a 2,450 rpm at 5,000 ft (1,000 hp for take-off)
Span:	149 ft
Length:	87 ft 7 in
Height:	18 ft 1 in
Wing area:	2,780 sq ft
Empty weight:	37,709 lb
Gross weight:	70,706 lb
Max speed:	200 mph at 5,000 ft
Cruising speed:	152 mph at 60% power at 6,000 ft
Service ceiling:	18,900 ft
Range:	5,130 miles
Armament:	Two ·50 cal MG, four ·30 cal MG, four 2,000 lb bombs

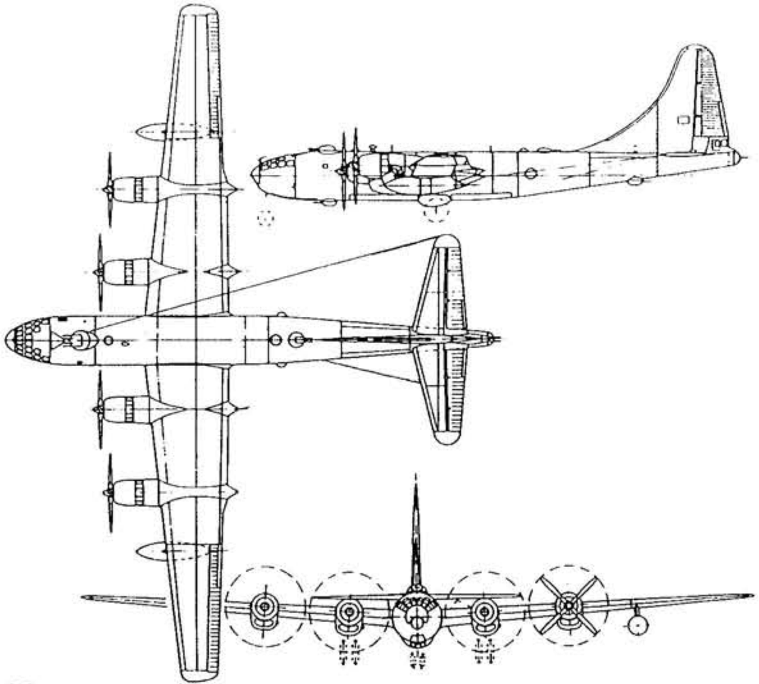
Boeing Model 294. First Flight: Oct. 5, 1937.



TECHNICAL DATA - MODEL 314

Type:	Over-water long-range transport
Accommodation:	74 passengers, 10 crew (max)
Power plant:	Wright GR-2600 Double Cyclone, 1,200 hp at 2,100 rpm at 5,400 ft (1,500 hp for take-off)
Span:	152 ft
Length:	106 ft
Height:	27 ft 7 in
Wing area:	2,867 sq ft
Empty weight:	50,268 lb
Gross weight:	82,500 lb
Max speed:	193 mph at 80,000 lb at 10,000 ft
Cruising speed:	183 mph
Climb:	565 ft/min
Service ceiling:	13,400 ft
Range:	3,500 miles

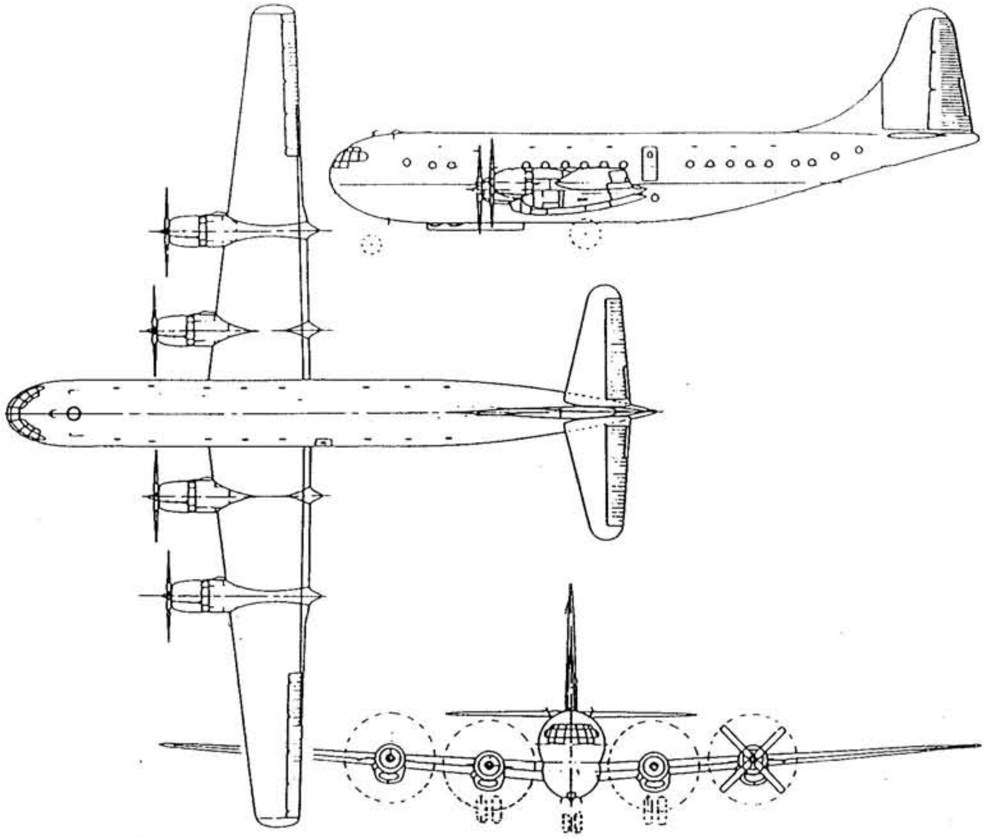
Boeing Model 314. First Flight: June 7, 1938.



BOEING MODEL 345 (B-50D)

TECHNICAL DATA - B-50A

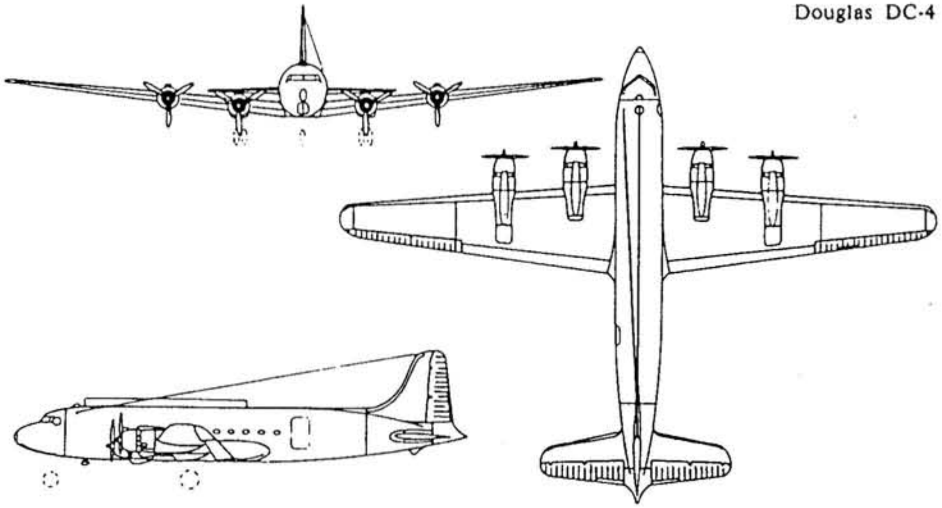
Type:	Medium strategic bomber
Accommodation:	12 crew
Power plant:	P & W R-4360-35 3,500 hp
Span:	141 ft 3 in
Length:	99 ft
Height:	32 ft 8 in
Wing area:	1,720 sq ft
Empty weight:	81,050 lb
Gross weight:	168,708 lb
Max speed:	385 mph at 25,000 ft
Cruising speed:	235 mph
Service ceiling:	37,000 ft
Climb:	2,225 ft/min
Range:	4,650 miles
Armament:	Twleve ·50 cal MG, one 20 mm cannon, 20,000 lb bombs



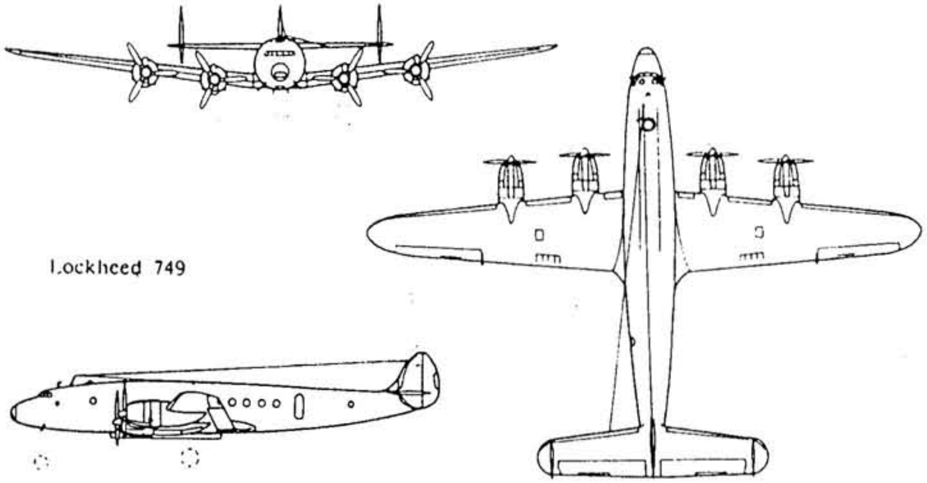
BOEING MODEL 377 STRATOCRUISER

TECHNICAL DATA - MODEL 377 STRATOCRUISER

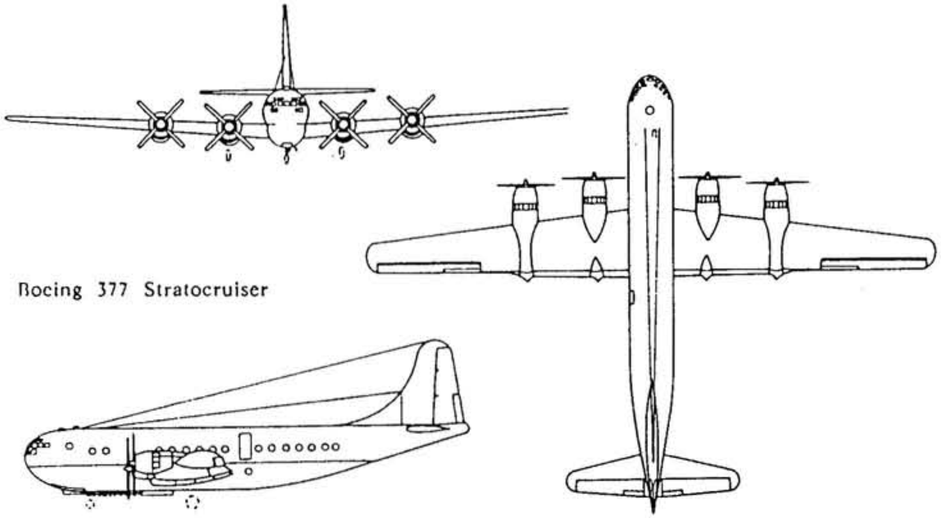
Type:	Long-range transport
Accommodation:	55–100 passengers and attendants, 5 flight crew
Power plant:	Four P & W R-4360 Double Wasp, 3,500 hp for take-off
Span:	141 ft 3 in
Length:	110 ft 4 in
Height:	38 ft 3 in (26 ft 7 in with fin folded)
Wing area:	1,720 sq ft
Empty weight:	78,920 lb
Gross weight:	135,000 lb (later 148,000 lb)
High speed:	375 mph
Cruising speed:	340 mph at 1,900 hp per engine at 25,000 ft
Initial climb:	1,040 ft/min
Service ceiling:	32,000 ft
Range:	4,200 miles with maximum fuel



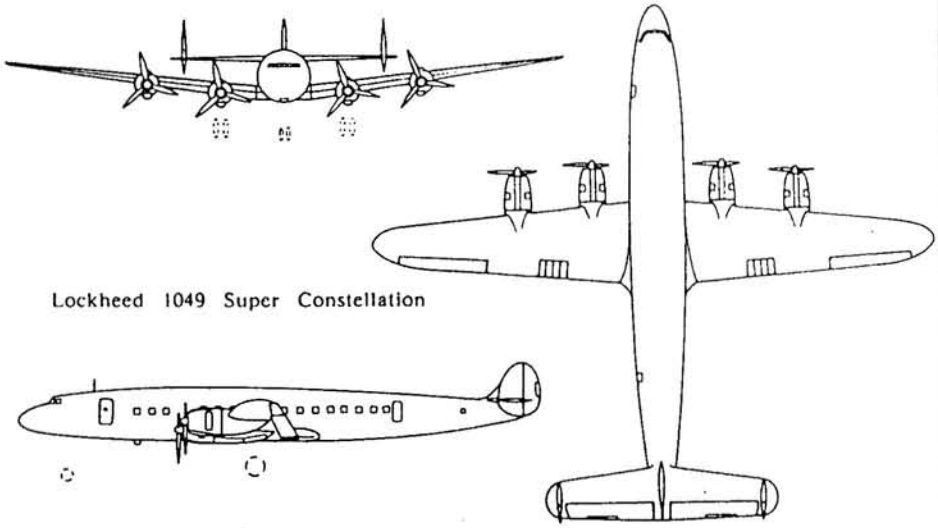
Douglas DC-4



Lockheed 749

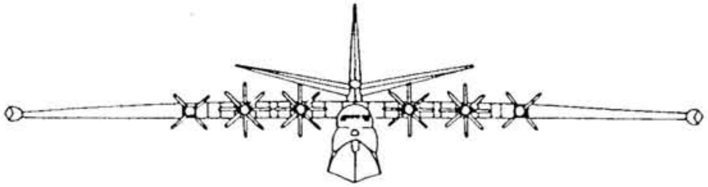


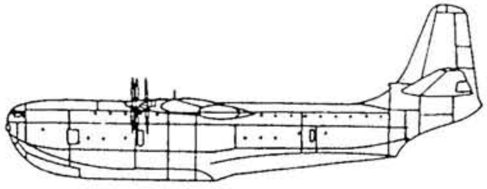
Boeing 377 Stratocruiser



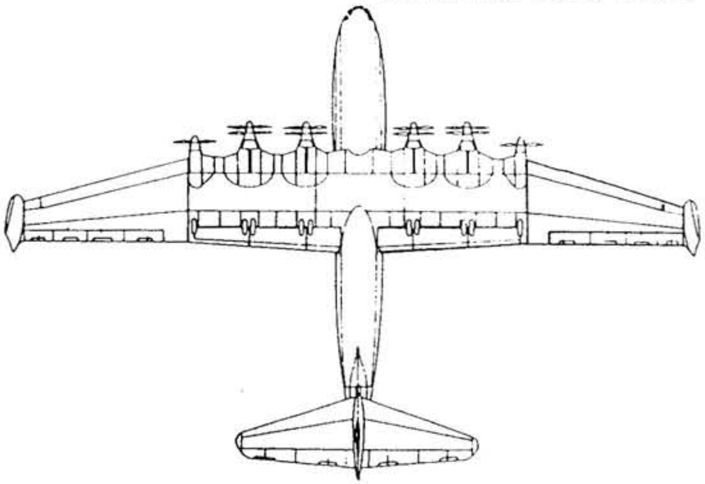
Lockheed 1049 Super Constellation

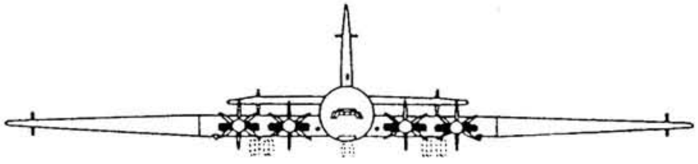
Saunders-Roe S.R.45 Princess
Country: Great Britain; *Constructor*: Saunders-Roe Ltd.; *Type*: Civil transport flying boat; *Year*: 1952; *Engines*: Ten Bristol Proteus 600 propeller-turbines (inner pairs coupled), 2,500 hp each; *Wingspan*: 219 ft 6 in (66.9 m); *Length*: 148 ft (45.11 m); *Height*: 55 ft 9 in (16.99 m); *Weight loaded*: 345,000 lb (156,492 kg); *Cruising speed*: 358 mph (576 km/h); *Range*: 6,040 miles (9,720 km); *Crew*: 6; *Passengers*: up to 220

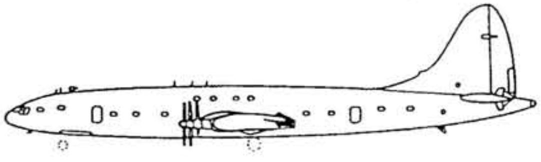




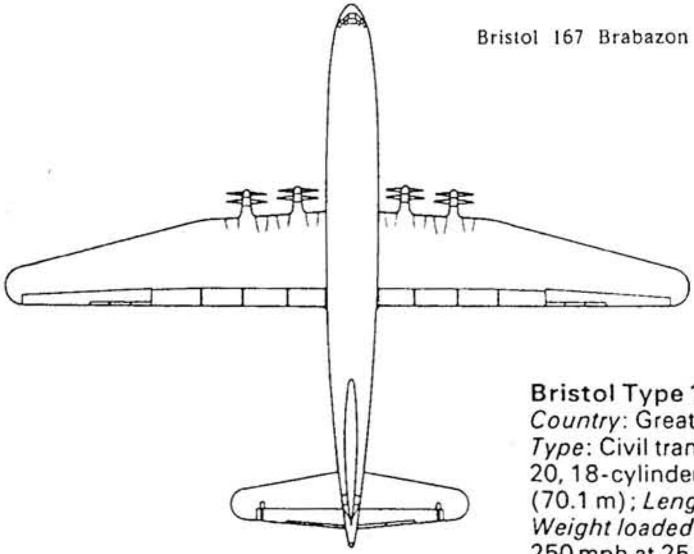
Saunders-Roe S.R.45 Princess







Bristol 167 Brabazon

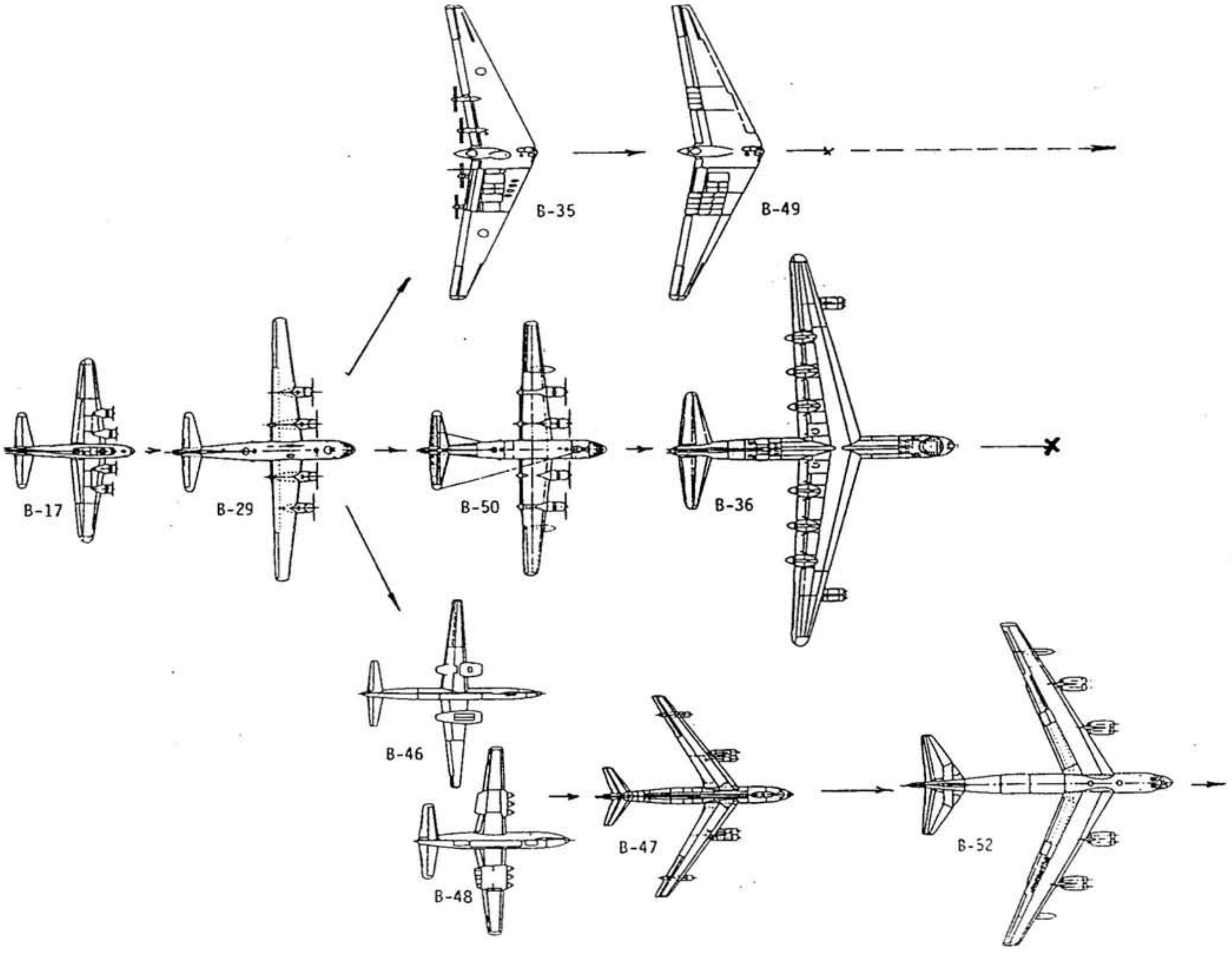


Bristol Type 167 Brabazon 1
Country: Great Britain; *Constructor*: Bristol Aeroplane Co. Ltd.; *Type*: Civil transport; *Year*: 1949; *Engines*: Eight Bristol Centaurus 20, 18-cylinder radial, air-cooled, 2,500 hp each; *Wingspan*: 230 ft (70.1 m); *Length*: 177 ft (53.95 m); *Height*: 50 ft (15.24 m); *Weight loaded*: 290,000 lb (131,540 kg); *Estimated cruising speed*: 250 mph at 25,000 ft (402 km/h at 7,620 m); *Ceiling*: 34,500 ft (10,500 m); *Estimated range*: 5,500 miles (8,850 km); *Crew*: 12; *Passengers*: 100

> *"Life is too short to spend working on propellers."*
>
> *Ed Wells*

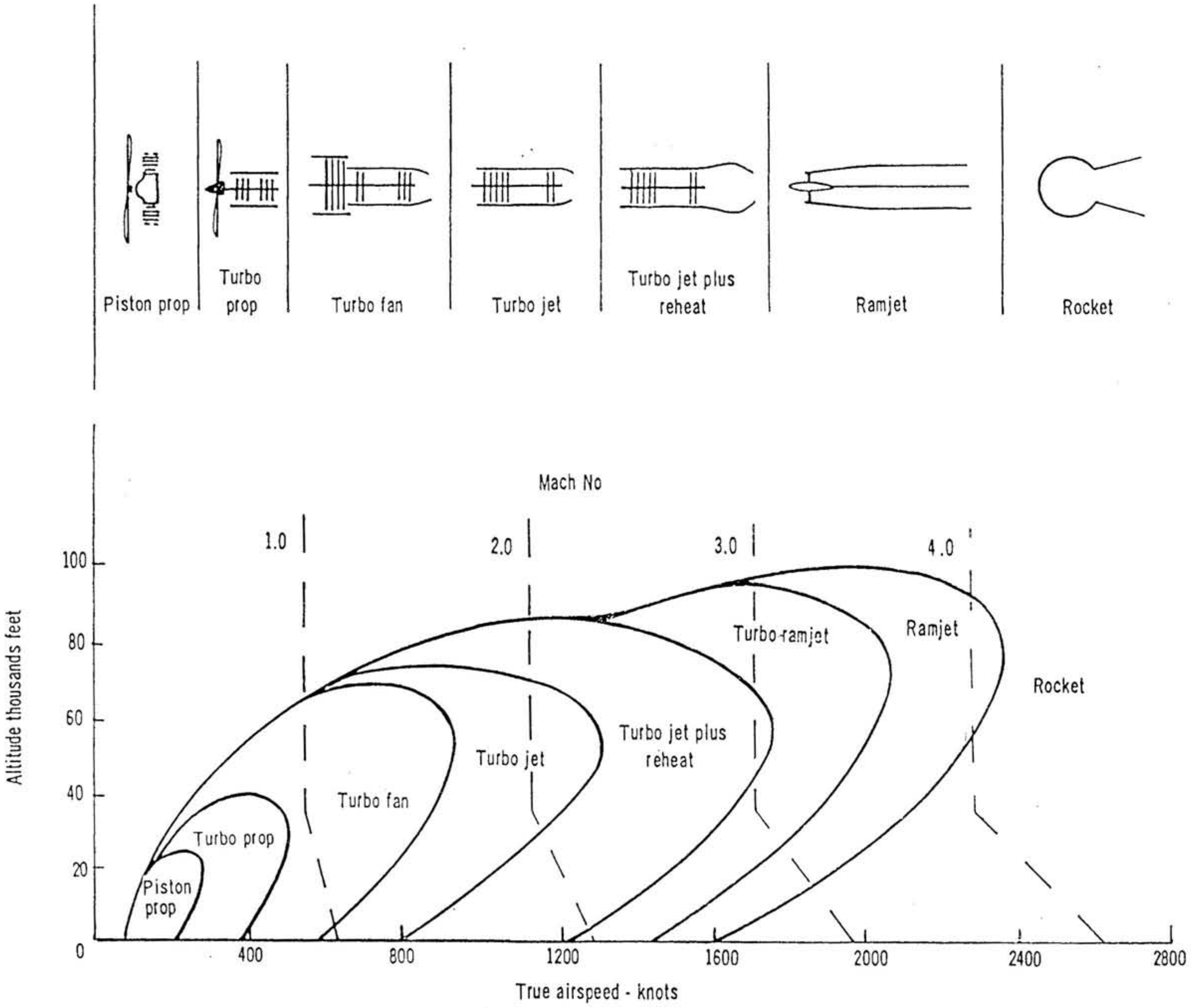
INTO THE JET AGE
(on swept wings)

- A brief digression into the initial history of jet bomber design.

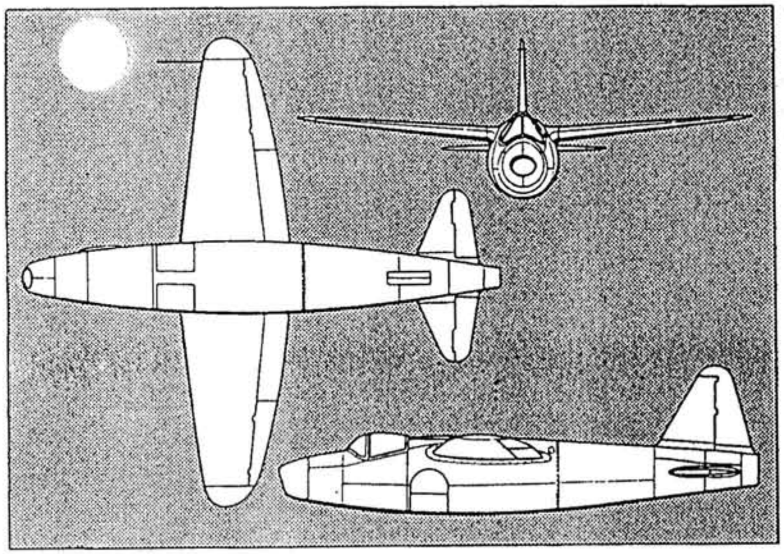


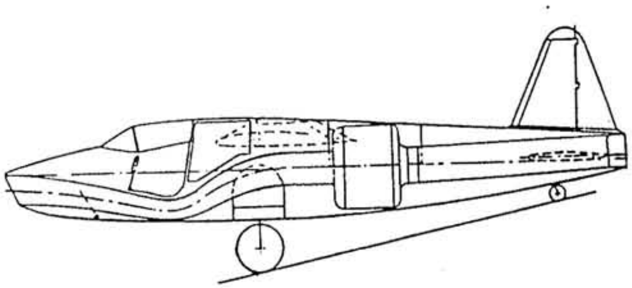
- Jet bombers required more powerful and fuel economical engines and/or tanker aircraft for air-to-air refueling.

- The precedent is thus set for the development of turbine powered transport aircraft.



The level flight propulsion picture





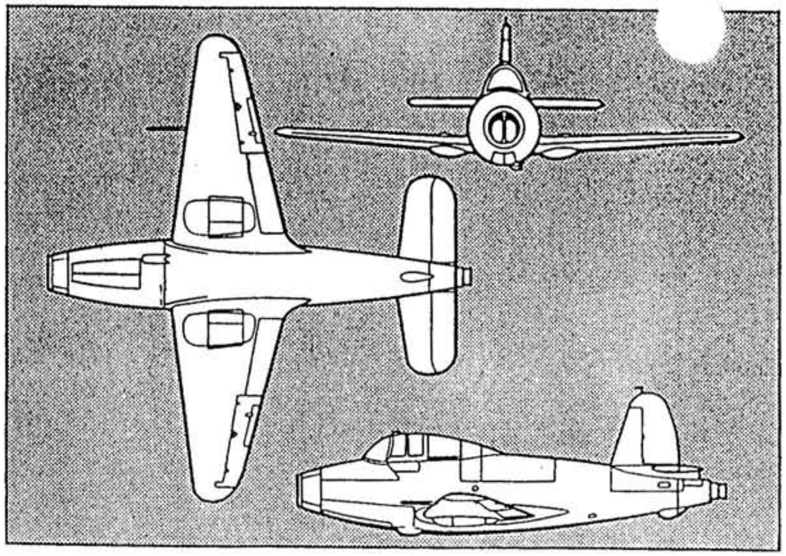
HEINKEL HE 178 (AUGUST) 1939

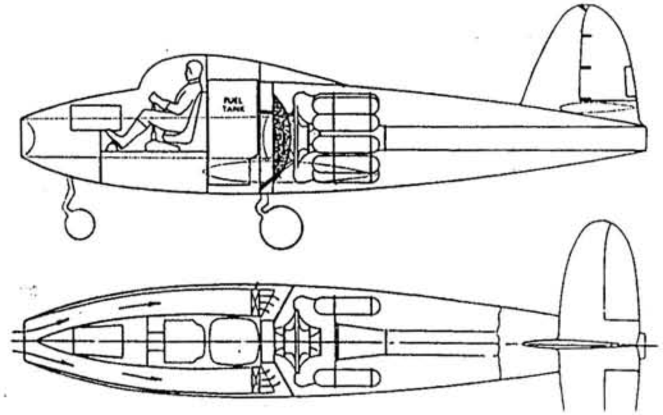
The Heinkel He 178, the world's first aircraft to be powered solely by a turbojet, was designed as a flight test-bed for the Heinkel-Hirth HeS 3B centrifugal turbojet. The layout chosen for the He 178 was surprisingly similar to that chosen for the first British jet aircraft, the Gloster E.28/39, employing a simple air intake in the nose to give full ram effect, the air then passing straight through the engine and out through a tail orifice.

The He 178, work on which was commenced in 1938, had a shoulder-positioned wing of wooden construction and a duralumin monocoque fuselage. The HeS 3B turbojet delivered 1,100 lb. thrust and burned petrol. It was installed aft of the pilot's cockpit and the air intake bifurcated and passed on either side of the pilot who was provided with a rudimentary throttle with which to control the thrust.

On August 24, 1939, the He 178 left the runway for the first time, flying in a straight line at an altitude of a few feet and landing successfully. On August 27 it flew its first circuits but the test pilot was forced to make an emergency landing. Several completely successful flights were made, and on November 1, 1939, the He 178 was demonstrated before officials of the German Air Ministry.

The He 178 weighed 3,439 lb. empty and 4,400 lb. loaded. The maximum speed attained during flight tests was 435m.p.h., and dimensions were as follows: Span, 26 ft. 8 in., length, 24 ft. 7 in., wing area, 85 sq. ft., wheel track, 5 ft. 11 in.



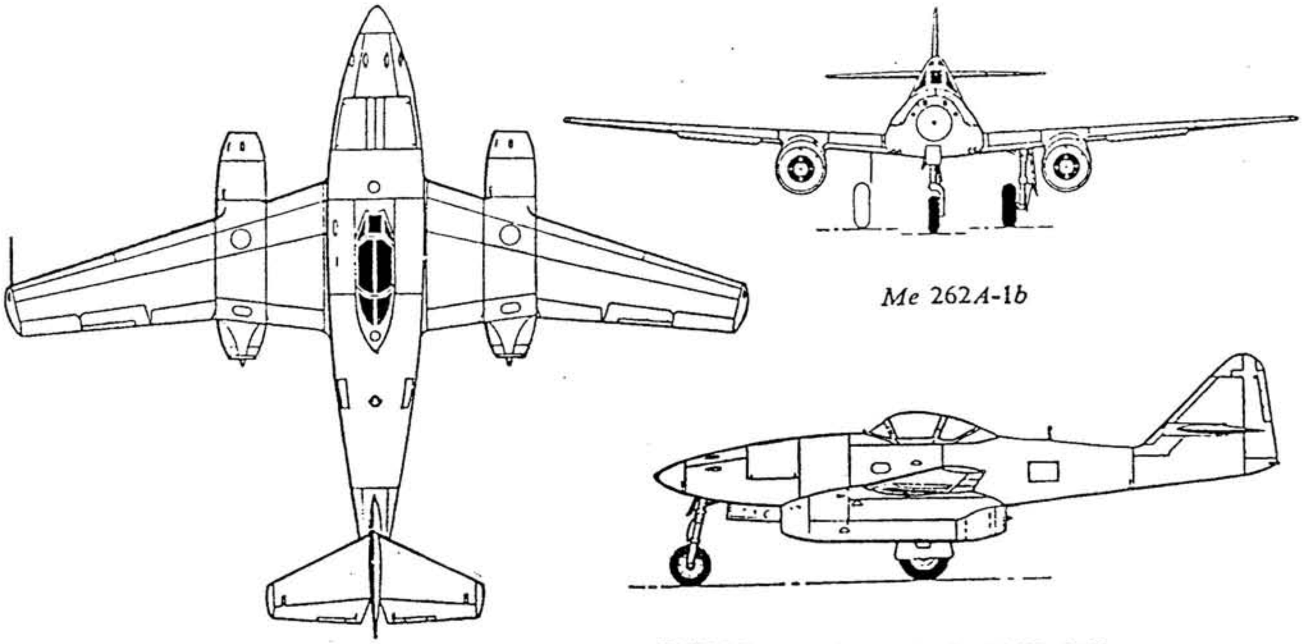


GLOSTER G.40 (E.28/39) (MAY) 1941

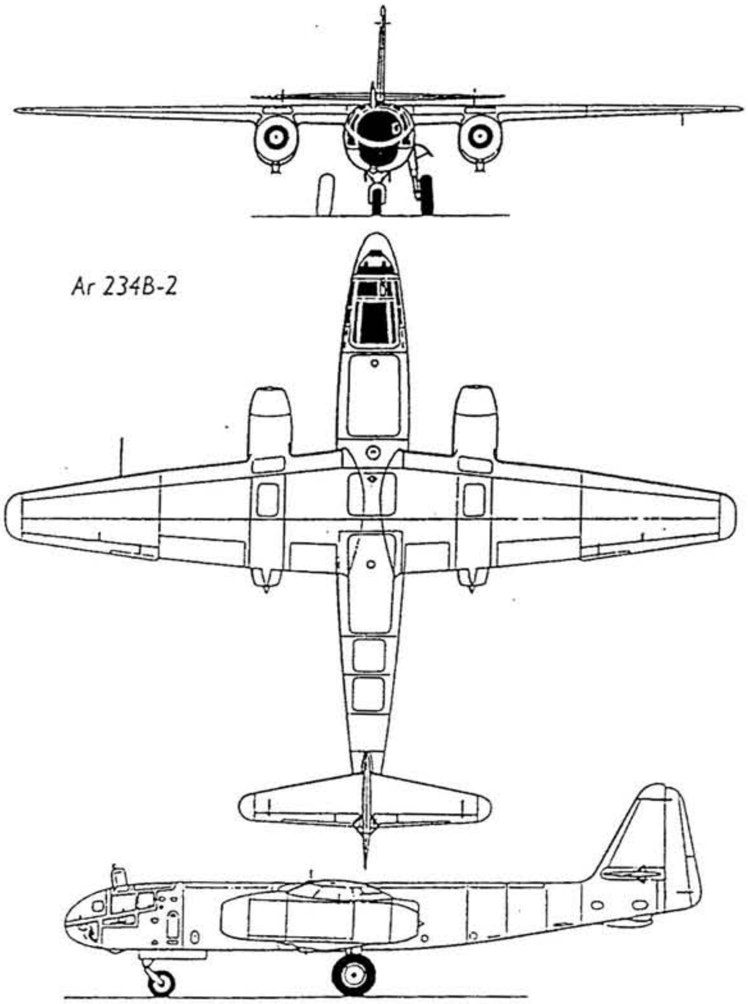
The Gloster G.40 was the first British jet-propelled aircraft to fly. Design was initiated in September 1939 to meet the requirements of Air Ministry specification E.28/39, and the aircraft was primarily intended to flight test the Power Jets W.1 turbojet. Two prototypes were built, the first initially having the unairworthy W.1X turbojet for preliminary taxi-ing trials. This was replaced by the W.1 of 850 lb. thrust for flight testing, and the G.40 first flew on May 15, 1941. After 10 hours' flying with the W.1—during which an altitude of 25,000 ft. and a speed of 300 m.p.h. were recorded—this unit was replaced by the 860 lb. thrust W.1A for further trials, and later by the Power Jets W.2/500 of 1,700 lb. thrust.

Meanwhile, a second G.40 had been completed, flying for the first time on March 1, 1943, powered by the 1,220 lb. thrust Rover W.2B, which was succeeded by the 1,400 lb. thrust Rolls-Royce W.2B/23 and, finally, a 1,526 lb. thrust W.2B. With the latter turbojet the second G.40 achieved 466 m.p.h.

The G.40 was of all-metal construction, with a nose orifice for the turbojet, the airflow being divided to pass each side of the pilot's cockpit and being ejected through an efflux duct in the tail. Weights and performance varied with the type of turbojet installed, but with the W.1A unit maximum speed attained was 338 m.p.h. and loaded weight was 3,700 lb. With the W.2B loaded weight was 3,900 lb., which, with the W.2/500, was increased to 4,180 lb. Dimensions were: span, 29 ft.; length, 25 ft. 2 in.; height, 9 ft. 3 in.

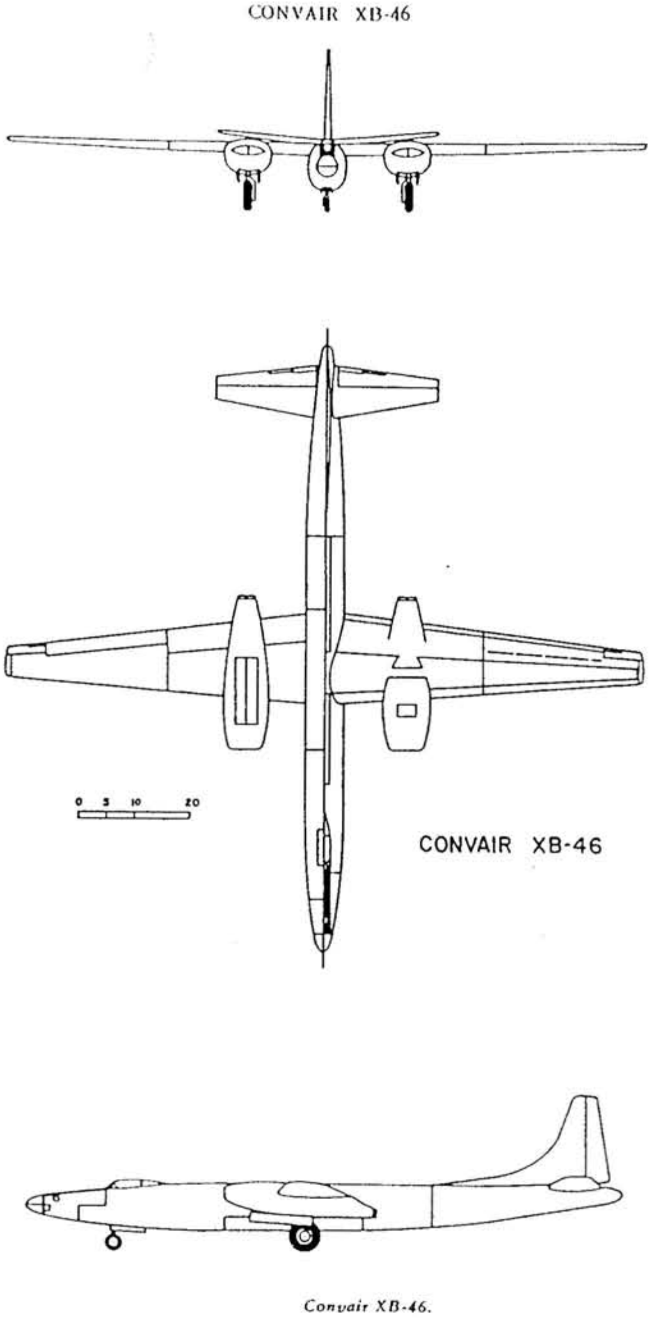


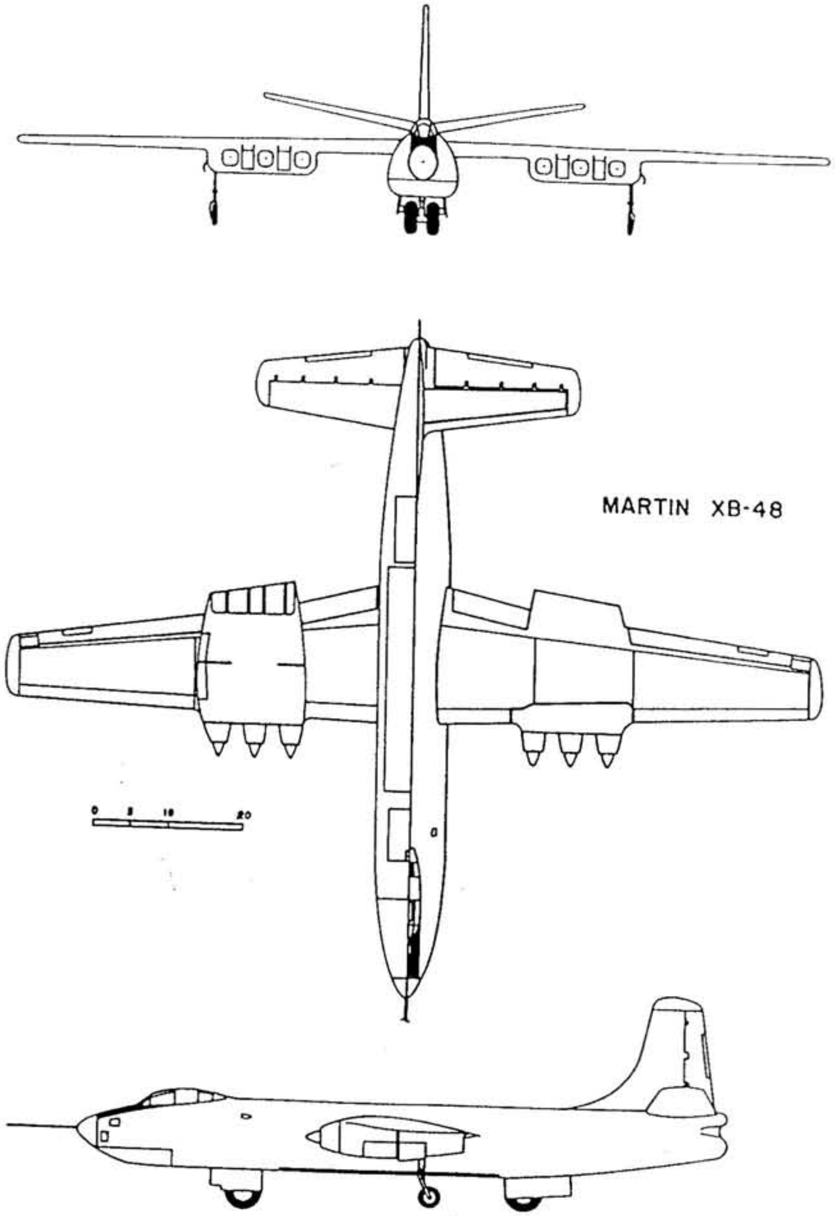
MESSERSCHMITT ME 262



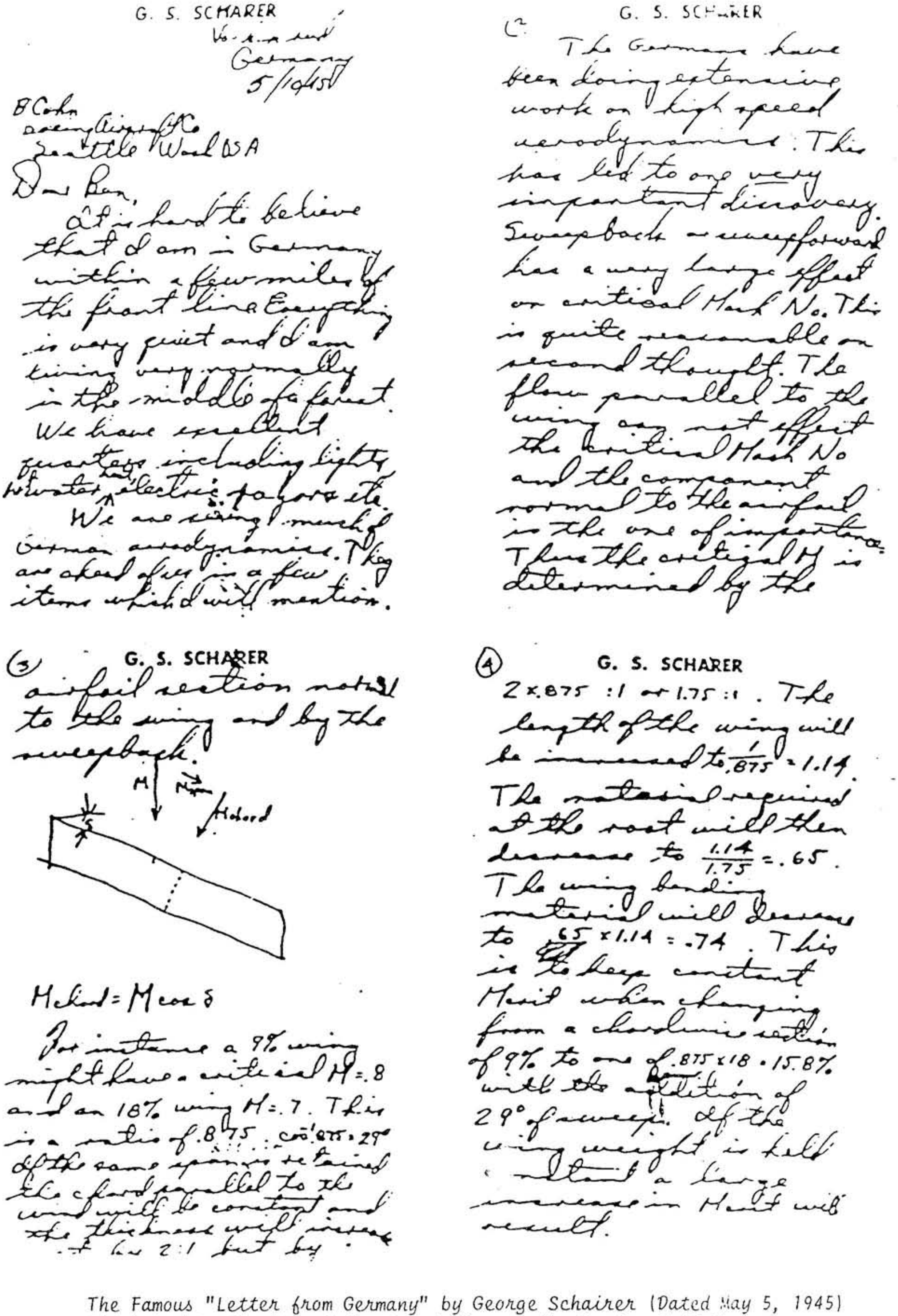
The German Arado Ar 234 B

- the world's first operational jet bomber.





The State-of-Art in U.S. Jet Bomber Design Circa Early 1945.



G. S. SCHARER

Vo-i-n-sud
Germany
5/1945

B Cohn
Boeing Aircraft Co
Seattle Wash USA

Dear Ben,

It is hard to believe that I am in Germany within a few miles of the front line. Everything is very quiet and I am living very normally in the middle of a forest. We have excellent quarters including lights, hot water, electric razors etc.

We are seeing much of German aerodynamics. They are ahead of us in a few items which I will mention.

G. S. SCHARER

(2)

The Germans have been doing extensive work on high speed aerodynamics. This has led to one very important discovery. Sweepback or sweepforward has a very large effect on critical Mach No. This is quite reasonable on second thought. The flow parallel to the wing can not effect the critical Mach No and the component normal to the airfoil is the one of importance. Thus the critical M is determined by the

(3) G. S. SCHARER

airfoil section normal to the wing and by the sweepback.

M normal = M cos δ

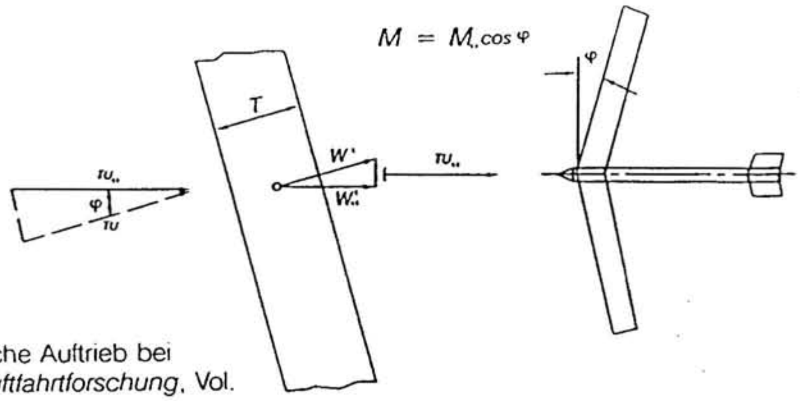
For instance a 9% wing might have a critical M = .8 and an 18% wing M = .7. This is a ratio of .875. cos⁻¹ .875 = 29° If the same span is retained the chord parallel to the wind will be constant and the thickness will increase not by 2:1 but by

(4) G. S. SCHARER

2 × .875 : 1 or 1.75 : 1. The length of the wing will be increased to $\frac{1}{.875}$ = 1.14. The material required at the root will then decrease to $\frac{1.14}{1.75}$ = .65. The wing bending material will decrease to .65 × 1.14 = .74. This is to keep constant Mcrit when changing from a chordwise section of 9% to one of .875 × 18 = 15.8% with the addition of 29° of sweep. If the wing weight is held constant a large increase in Mcrit will result.

The Famous "Letter from Germany" by George Schairer (Dated May 5, 1945) Which Led to the Use of the Swept Wing on the Boeing B-47 Bomber.

Busemann Invented Swept Wings in 1935



- A. Busemann, "Aerodynamische Auftrieb bei Uberschallgeschwindigkeit, *Luftfahrtforschung*, Vol. 12, pp. 210-220, 1935.

Jones Reinvented Swept Wings in April 1945

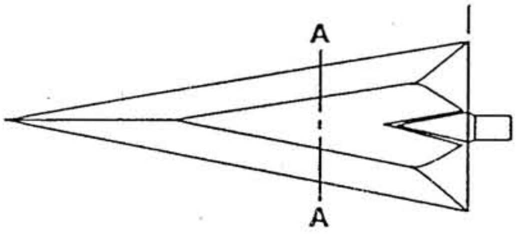
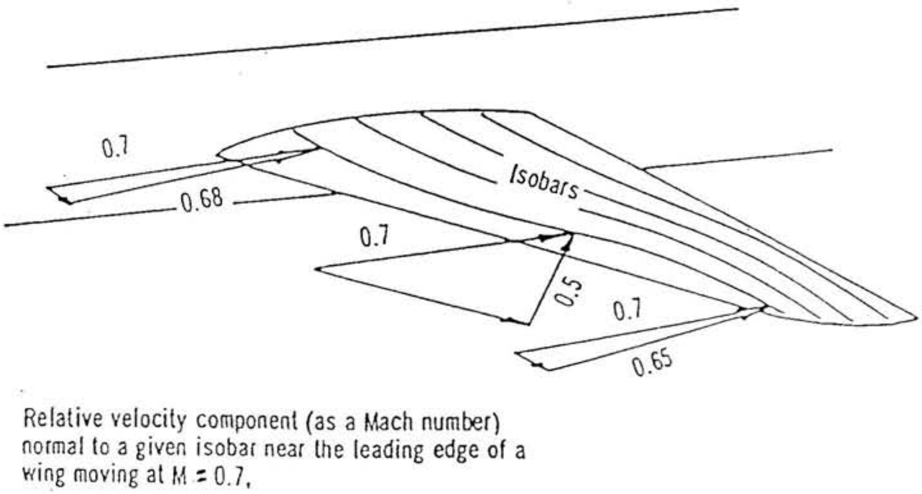


Figure 3. **WING SWEEP**

In April 1945, Boeing learned about the value of wing sweep from Robert Jones of NACA. Sweep would permit about 10% higher cruise speed and range.

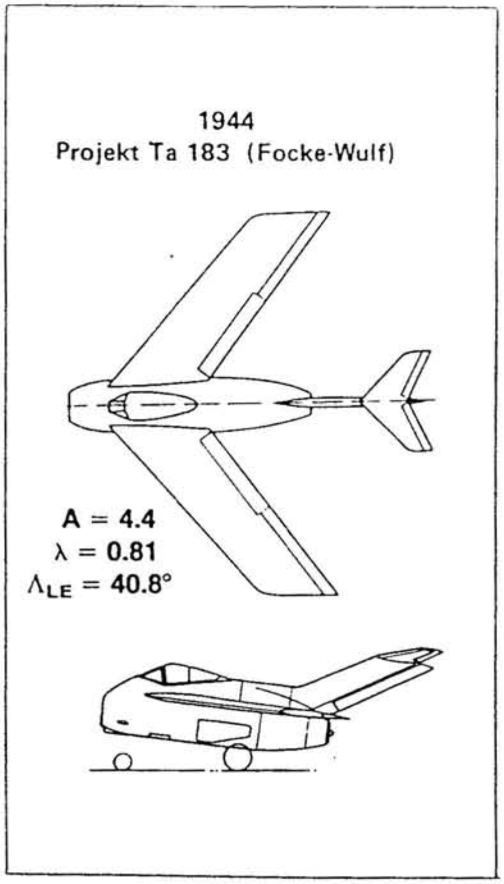
TECHNOLOGY NOTE: The use of substantial amounts of wing and tail sweep in the Boeing prototype might be the key to winning the jet bomber business.

MANAGEMENT NOTE: Be more attentive to new ideas from the research world.

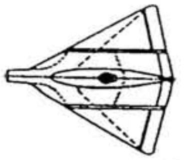


Relative velocity component (as a Mach number) normal to a given isobar near the leading edge of a wing moving at $M = 0.7$,

The theory of sweep

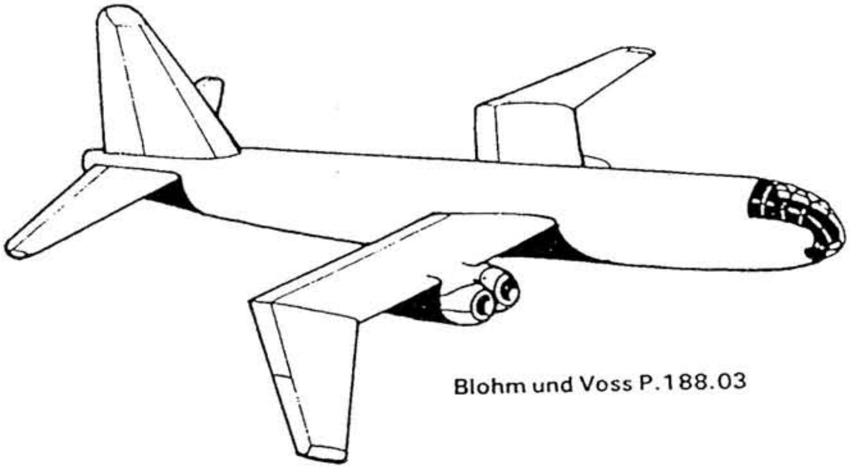


The German Ta 183 fighter project



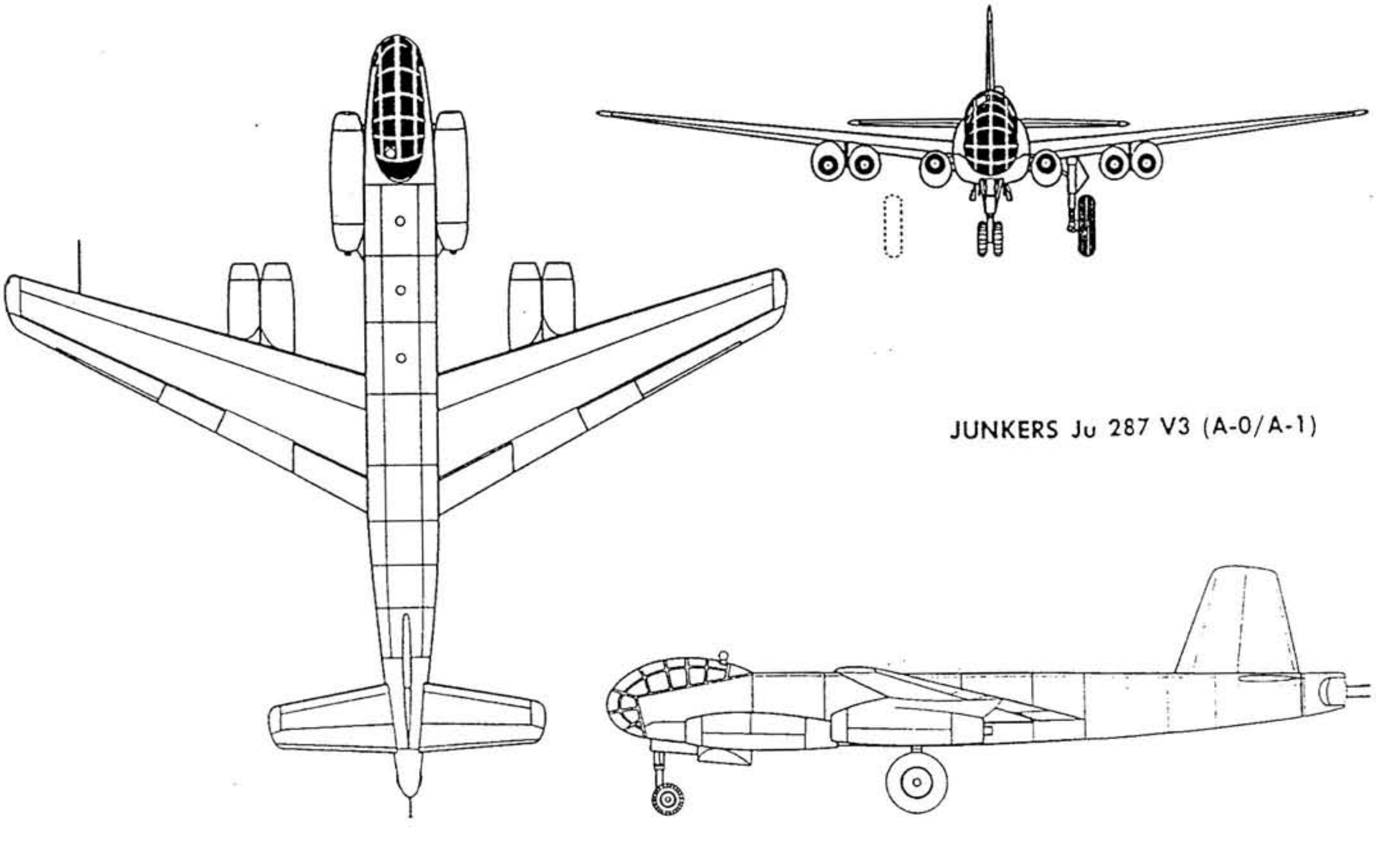
Lippisch Delta Wing Supersonic Fighter (1944)

- LIPPISCH, A. M. *The Delta Wing.* Ames: Iowa State Univ. Press, 1981.

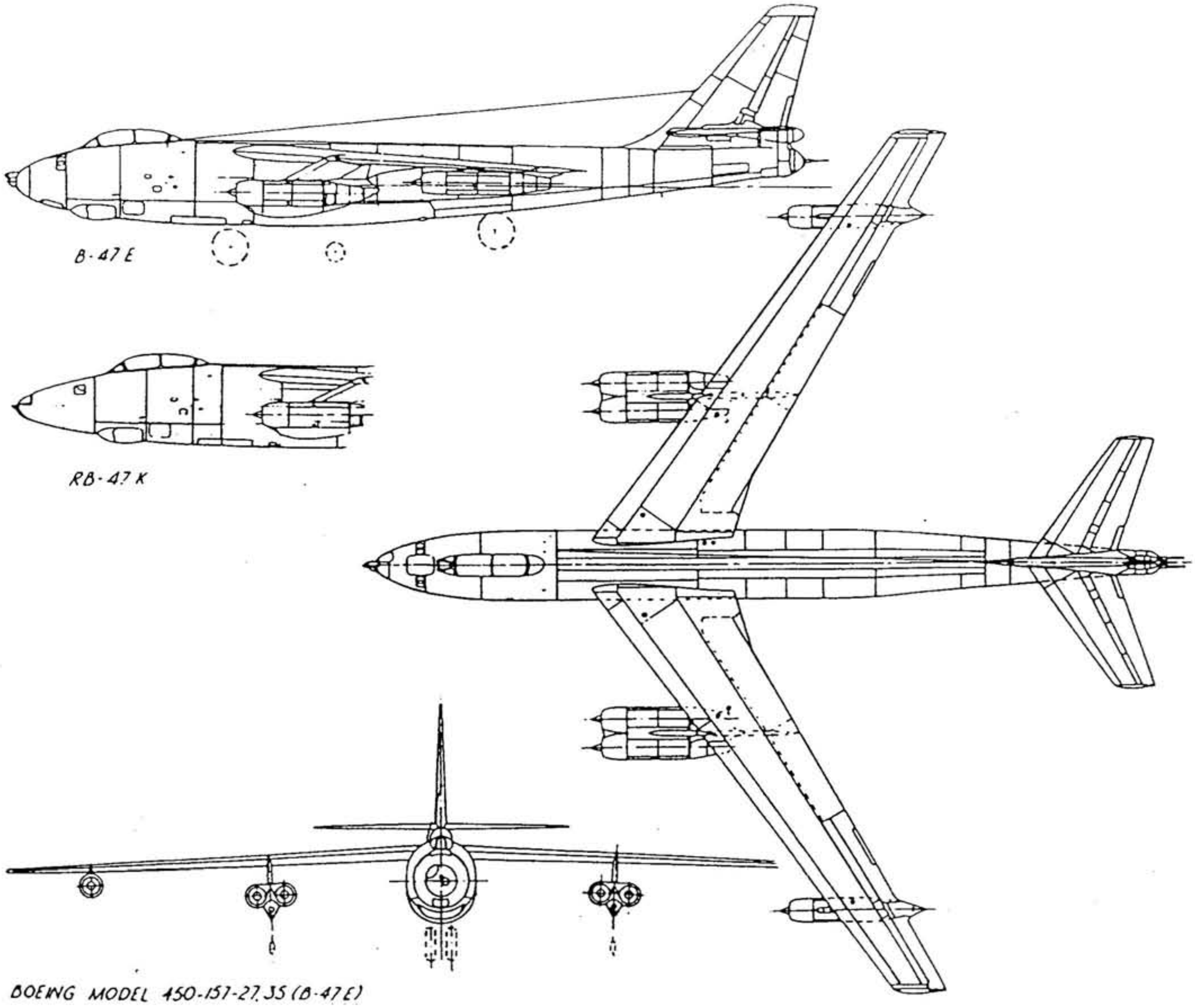


Blohm und Voss P.188.03

- D. Masters, *German Jet Genesis,* London: Jane's Publishing,-1982.
- K. Kens and H. J. Nowarra, *Die Deutschen Flugzeuge 1933-1945,* Munich: J. F. LehmannVerlag, 1961.



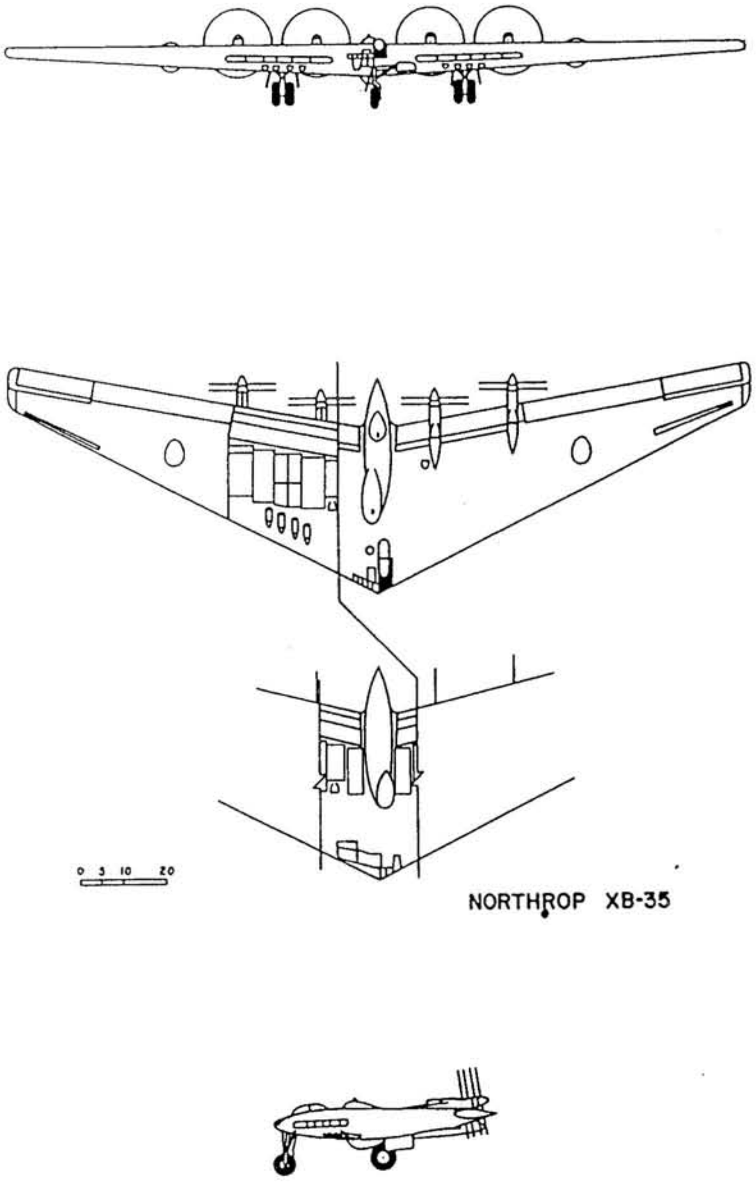
JUNKERS Ju 287 V3 (A-0/A-1)



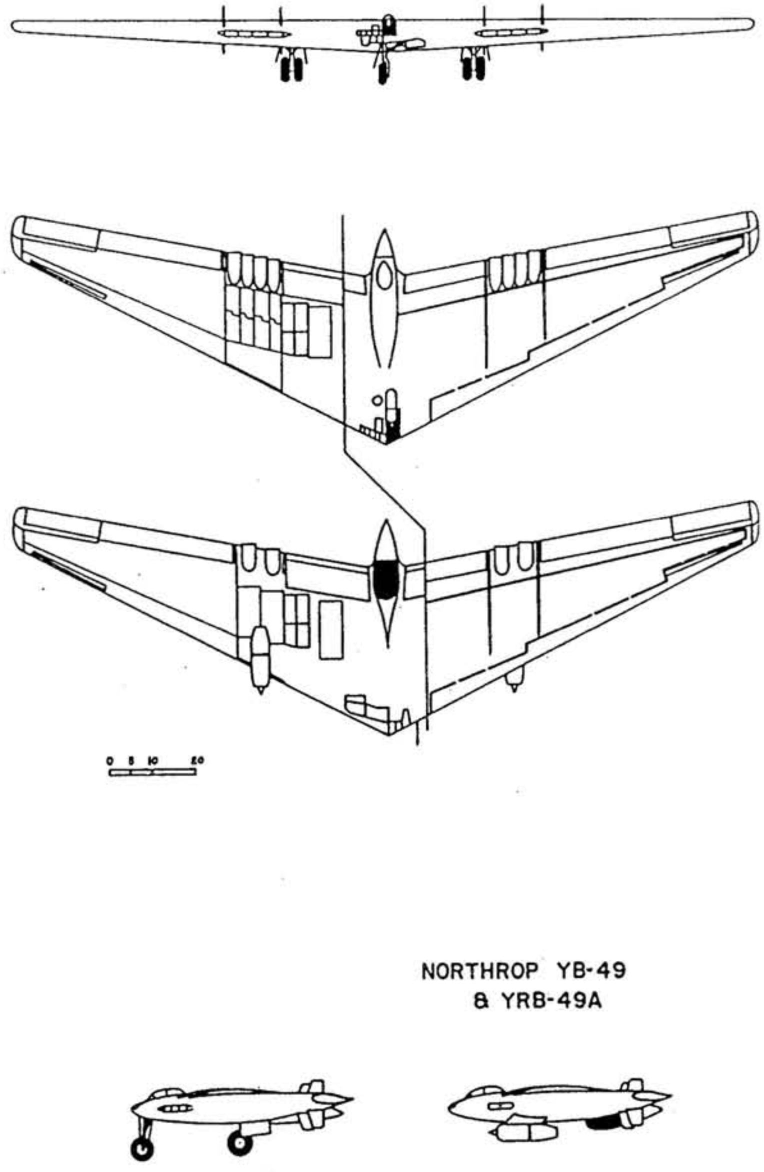
TECHNICAL DATA - XB-47

Type:	Medium bomber
Accommodation:	3 crew in tandem
Power plant:	General Electric J35, 3,750 lb thrust
Span:	116 ft
Length:	108 ft
Height:	28 ft
Wing area:	1,428 sq ft
Empty weight:	76,000 lb
Gross weight:	125,000 lb (normal), 162,500 lb (overload)
Max speed:	578 mph
Cruising speed:	Not available
Service ceiling:	38,000 ft
Climb:	3,100 ft/min
Range:	4,000 miles (ferry)
Armament:	Two ·50 cal MG, 10,000 lb bombs (normal), 22,000 lb bombs (maximum)

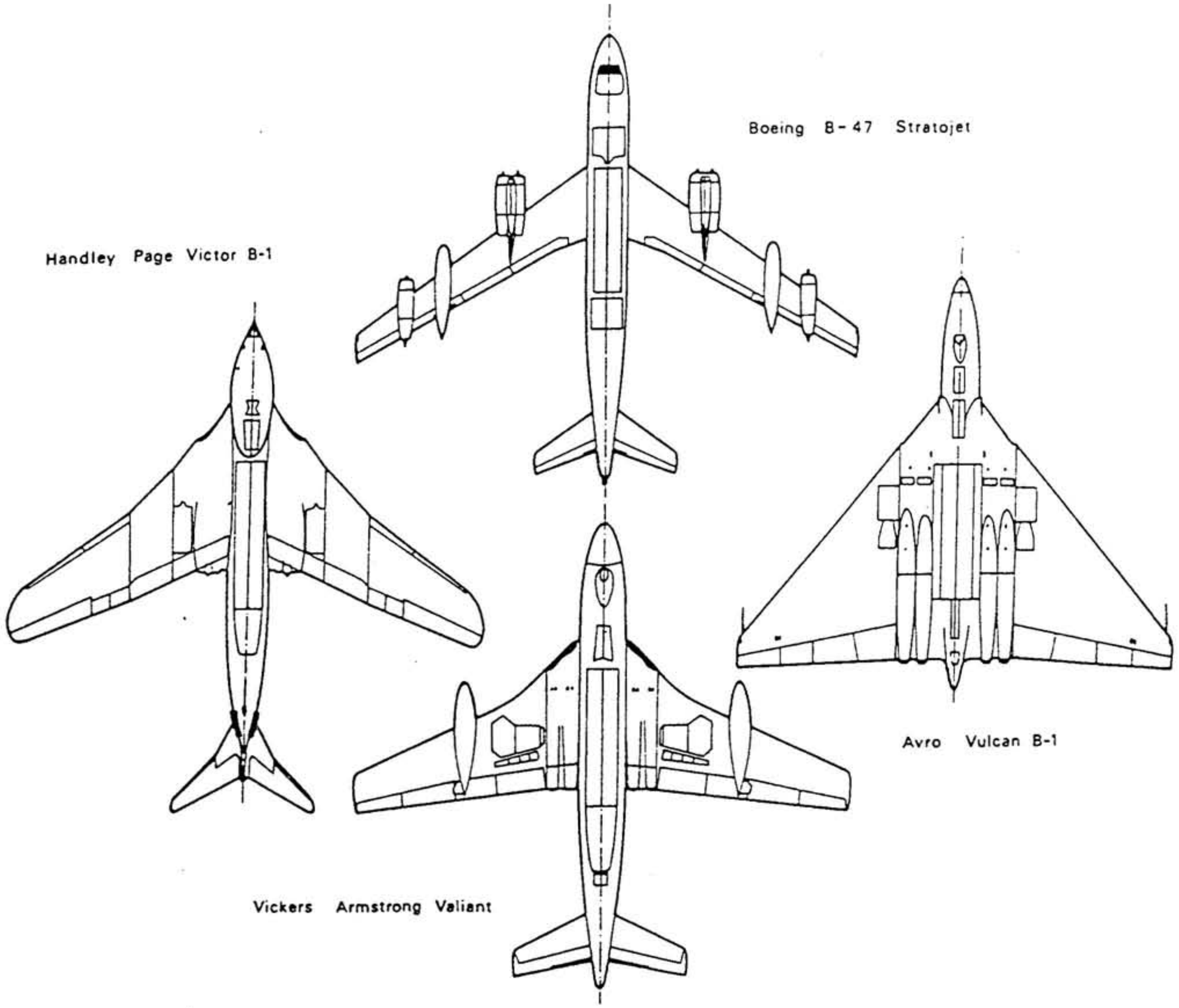
- Wooldridge, E. T. *Winged Wonders, The Story of the Flying Wings.* Washington, D.C.: Smithsonian Institution Press, 1983.



NORTHROP XB-35



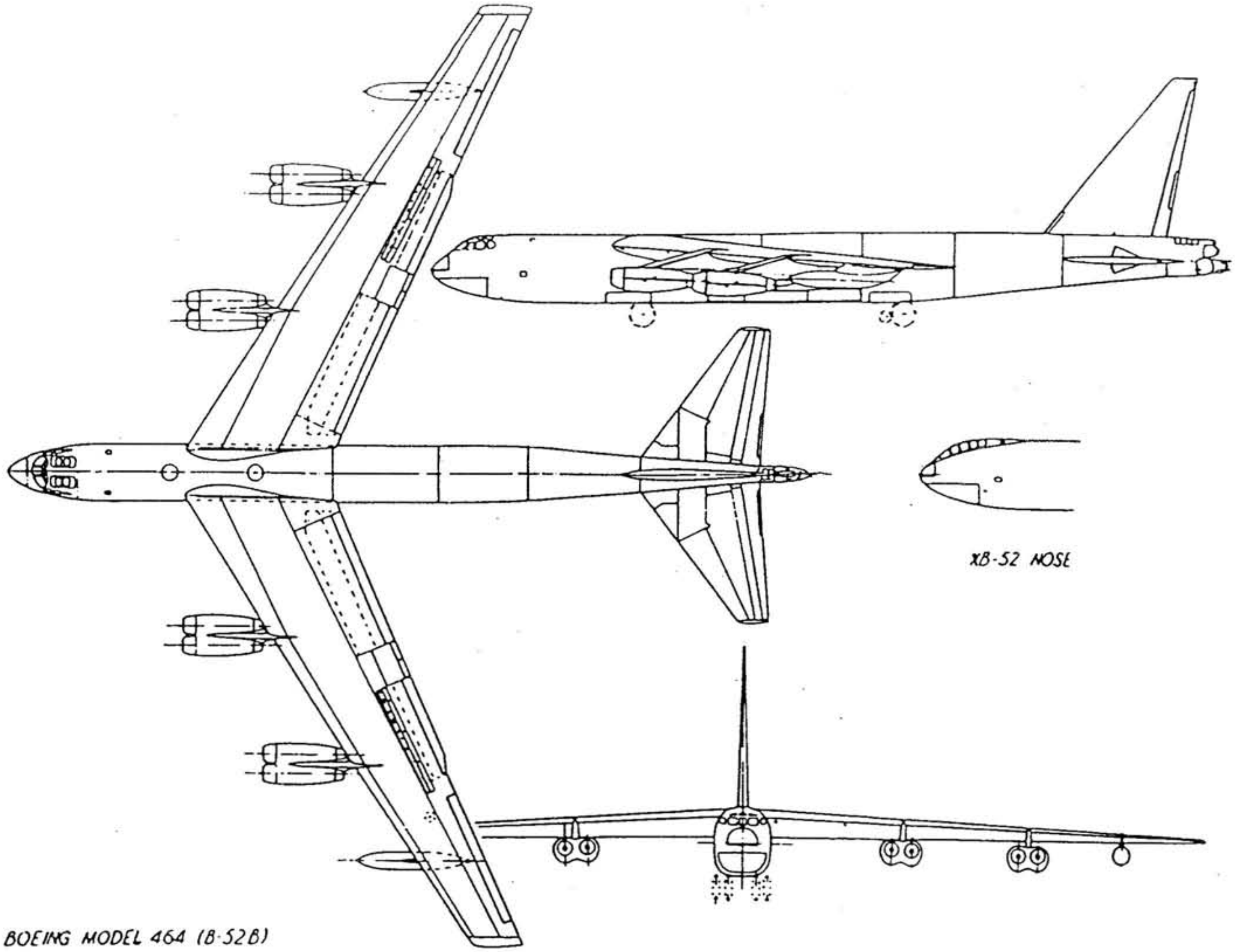
NORTHROP YB-49
& YRB-49A



Different configurations for aircraft designed to similar specifications

		BOEING B-47	AVRO VULCAN
GROSS WING AREA	~ ft^2 (m^2)	1430 (133)	3446 (320)
TOTAL WETTED AREA	~ ft^2 (m^2)	11300 (1050)	9500 (885)
SPAN	~ ft (m)	116 (35.4)	99 (30.2)
MAX. WING LOADING	~ lb/ft^2(kg/m^2)	140 (690)	43.5 (212)
MAX. SPAN LOADING	~ lb/ft (kg/m)	1750 (2590)	1520 (2250)
ASPECT RATIO		9.43	2.84
C_{D_o} (ESTIMATED)		.0198	.0069
$1/\pi Ae$ (e - OSWALD FACTOR)		.0425 (.8)	.125 (.9)
L/D_{max} ; $C_{L_{opt}}$		17.25 ; .682	17.0 ; .235

Similarity in max. lift/drag ratios for two widely different configurations



TECHNICAL DATA - XB-52, YB-52

Type:	Long-range bomber
Accommodation:	5 crew
Power plant:	8 axial-flow P & W YJ57-8-3, 8,700 lb thrust
Span:	185 ft
Length:	152·67 ft
Height:	48·25 ft (21·5 ft folded fin)
Wing area:	4,000 sq ft
Empty weight:	160,000 lb
Gross weight:	390,000 lb
Max speed:	483 knots (556 mph) at 40,000 ft
Cruising altitude:	39,000 ft
Range:	5,200 miles
Armament:	Four ·50 cal MG, 10,000 lb bombs

THE FIRST JET TRANSPORTS

- The de Havilland "Comet" -- Alas, before its time.
- Boeing 367-80
- 707 competitors
  - DC-8
  - Convair 880/990
  - Vickers VC-10
- 727 vs Lockheed "Electra"
- DC-9 vs Boeing 737
- Jet commercial aviation comes of age and because of speed and comfort (and relative safety) becomes <u>the</u> way to travel.
- Having done all this, what next?

DE HAVILLAND D.H.106 COMET

(JULY) 1949

Few aircraft have given rise to so much discussion, both from the operational and engineering viewpoints, than has the D.H.106 Comet, the world's first turbojet-driven commercial airliner. The misfortunes that befell the initial production model and resulted in its withdrawal from commercial operation were but a temporary setback in the evolution of this historic aircraft and do not detract from the boldness and foresight of its basic design and the outstanding qualities that it evinced in commercial service.

Development of the D.H.106 began in 1943, when the de Havilland Aircraft Company and the Brabazon Committee foresaw the postwar need for an advanced airliner utilising the then new gas turbine engine. The basic configuration of the D.H.106 was finalised in August 1946, an order for sixteen machines was placed in January 1947 and, in December of that year, it was decided to name the D.H.106 the Comet. The first prototype was wheeled out in April 1949, and on July 27, 1949, was flown for the first time.

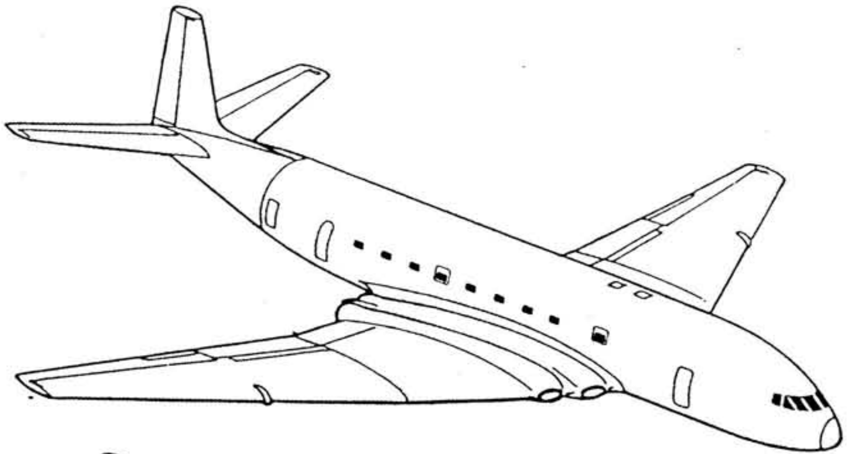
The aesthetic simplicity of the Comet belied the advanced thought in its design. The four turbojets were grouped as close to the fuselage centre line as was possible in order that flight on any two turbojets could be effected without considerable rudder trim correction, thus offering the possibility of reducing fuel consumption while holding a stand-off pattern at low altitude where the turbojet's economy is poor.

The initial production version, the Comet Series 1, was powered by four 5,050 lb. thrust de Havilland Ghost 50 Mk.1 turbojets, the first production aircraft flying on January 1, 1950. The Comet Series 1 had a moderately swept wing (20° at quarter-chord), with a gross area of 2,015 sq. ft., which resulted in a modest wing-loading at the all-up weight of 107,000 lb. Providing accommodation for thirty-six to forty passengers, the Series 1 cruised at 490 m.p.h. at 35,000–42,000 ft. and was employed on international routes in stages of up to 1,300 miles. Ultimate still-air range (with full tankage and 12,000 lb. payload) was 3,540 miles. Overall dimensions were: span, 115 ft.; length, 93 ft.; height, 28 ft. 4½ in. On May 2, 1952, B.O.A.C. began regular operations with the Comet, and in the first year of service with the Corporation the Comet carried 27,700 passengers and flew a total of 104,600,000 revenue passenger miles.

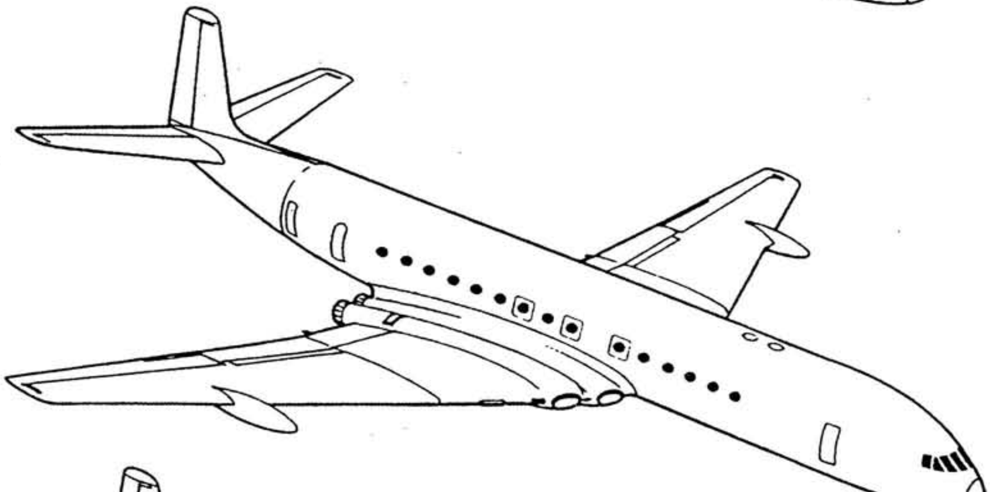
The Comet Series 1a differed in having Ghost 50 Mk.2 turbojets which, with water/methanol injection, provided 5,125 lb. thrust. Fuel capacity was increased from 6,000 to 7,000 Imp. gal., increasing stage lengths by some twenty per cent., all-up weight was increased to 115,000 lb., and seating capacity for forty-four passengers was provided. A total of twenty-three Series 1 and 1a Comets was built, including the prototype.

The Comet Series 1 was succeeded on the production lines by the Series 2, which was a logical development, taking advantage of the higher thrust and lower specific consumption of the Rolls-Royce Avon engine. By taking the sixth airframe from the Comet 1 production line and fitting four 6,500 lb. thrust Avon 502 turbojets, a prototype was produced quickly and, known as the Comet 2X, was flown on February 16, 1952. The production Comet Series 2 differs from the prototype in having 7,000 lb. thrust Avon 503 engines, a 3 ft. increase in fuselage length and a modified wing section to improve take-off characteristics, improve slow-flying performance and reduce the landing speed. The first production Comet Series 2 was flown on August 27, 1953, and this version provides accommodation for forty-four passengers, is suitable for stage lengths of 1,750–2,200 miles, and has a capacity payload of 13,000 lb. Empty and loaded weights are 53,870 lb. and 120,000 lb. respectively, and normal cruising speed is 480 m.p.h. at 40,000 ft.

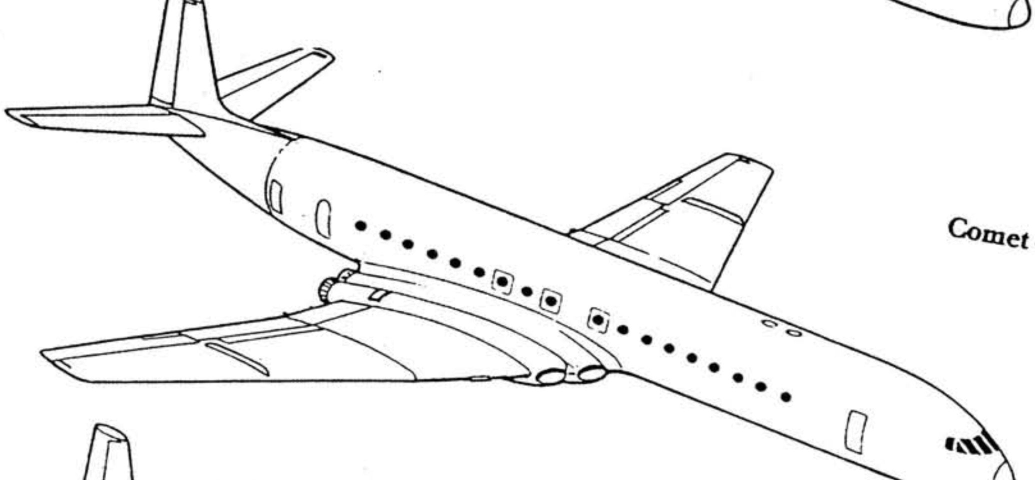
A further progressive development of the basic design, the Comet Series 3, was flown for the first time on July 19, 1954. The fuselage has been lengthened 15 ft. 6 in. as compared to the Series 2, and while the wing plan is essentially the same, there is some increase in wing and flap area, gross wing area being increased to 2,121 sq. ft. A distinctive feature of the wing is the addition of two leading-edge tanks which increase the fuel tankage from 6,900 (Series 2) to 8,050 Imp. gal. The prototype was powered by four 9,000 lb. thrust Avon R.A.16 engines, but the production Series 3 will have the 10,000 lb. thrust Avon 521. Providing accommodation for fifty-eight to seventy-six passengers, the practical stage length with a 17,450 lb. payload will be 2,700 miles. Cruising speed is 500 m.p.h. at 42,000 ft., and loaded weight is 150,000 lb.



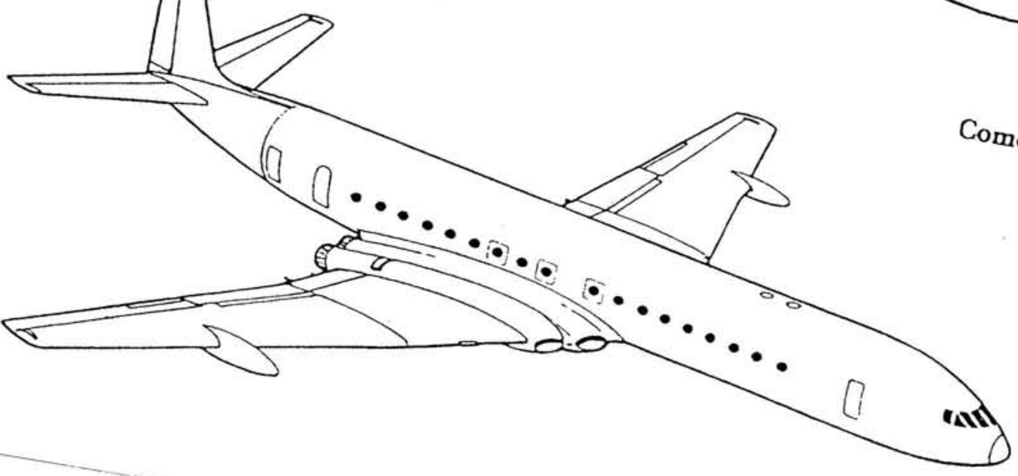
Comet 1



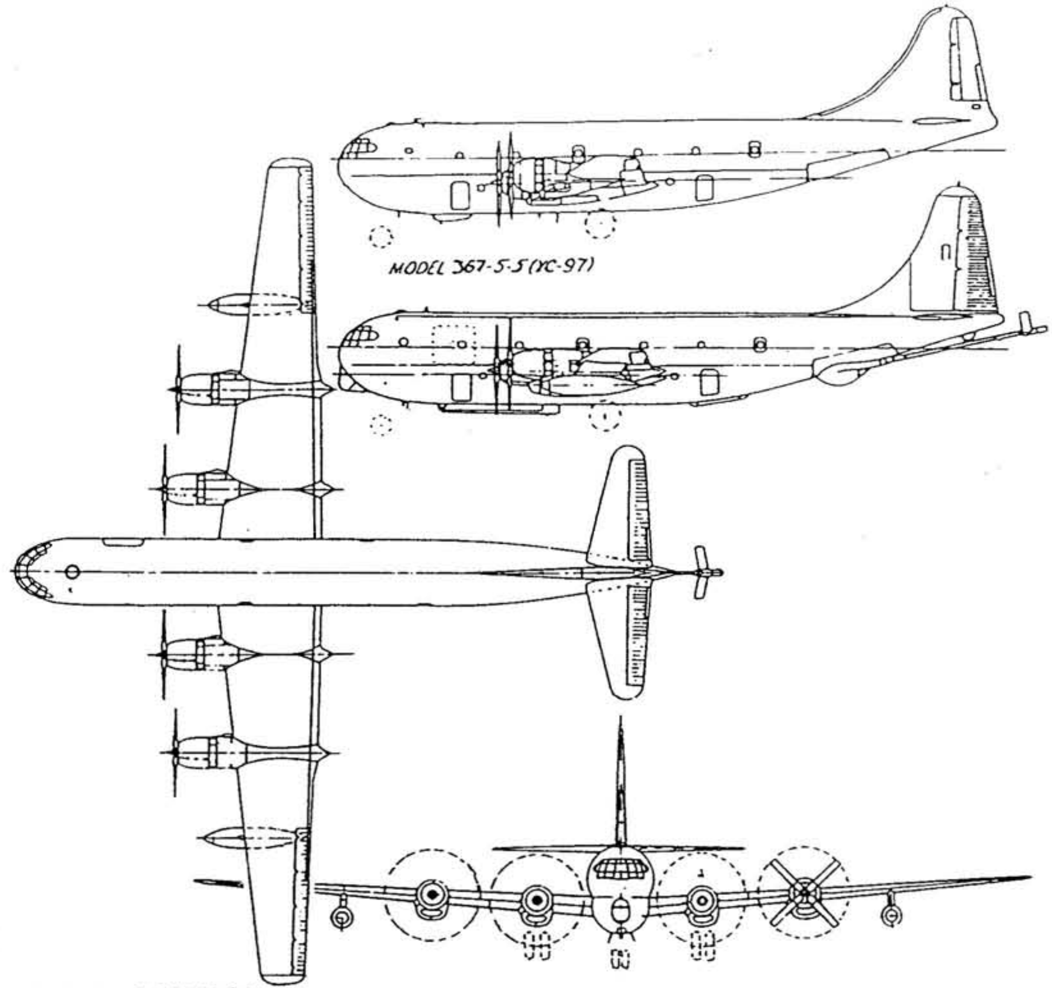
Comet 4



Comet 4B

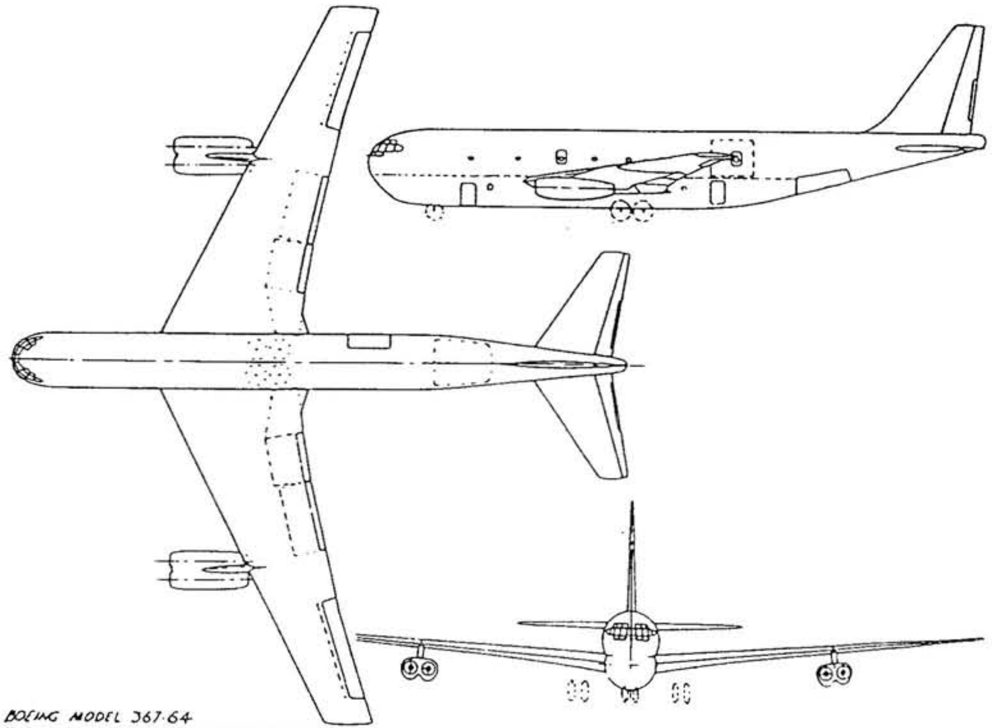


Comet 4C



MODEL 367-5-5 (YC-97)

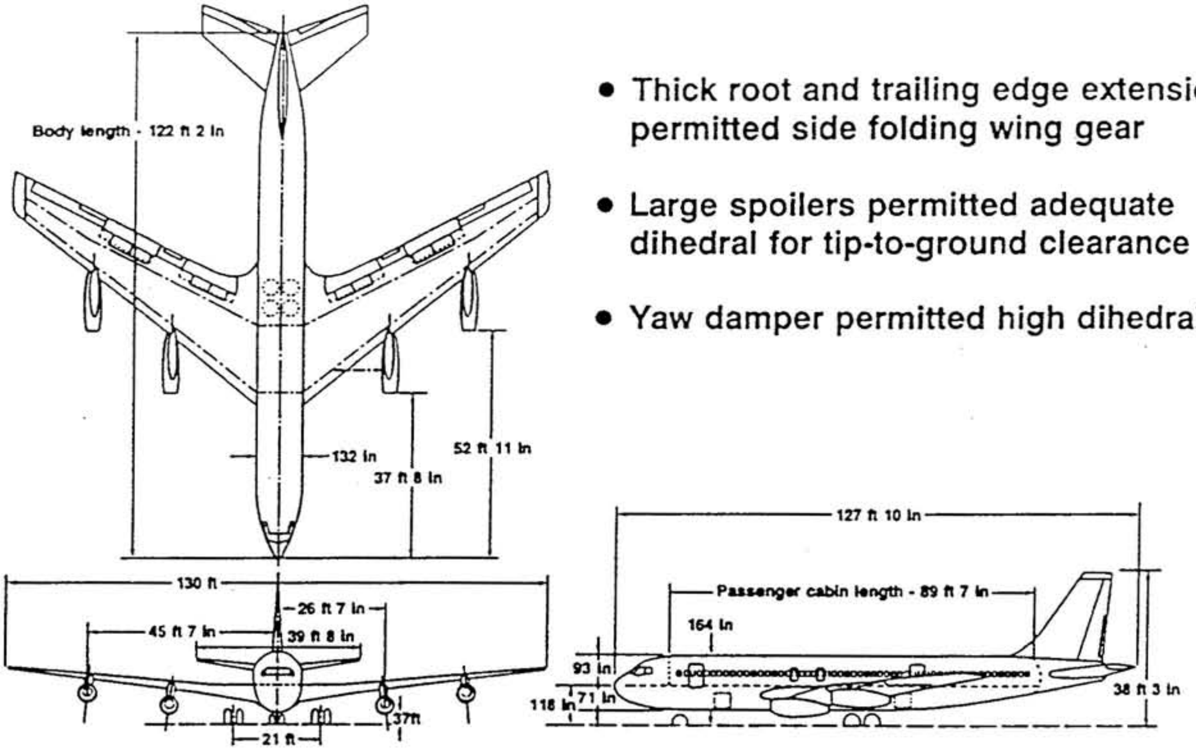
BOEING MODEL 367-76-66 (KC-97G)



BOEING MODEL 367-64

One of the many configurations studied during the transition of the Model 367 (USAF C-97) from a straight-wing piston-powered model to a swept-wing jet. Four Pratt & Whitney J-57P-1 engines in double pods in the style of the B-47/B-52. Span 140 ft, length 127 ft 6 in, gross weight 190,000 lb.

- Thick root and trailing edge extension permitted side folding wing gear
- Large spoilers permitted adequate dihedral for tip-to-ground clearance
- Yaw damper permitted high dihedral

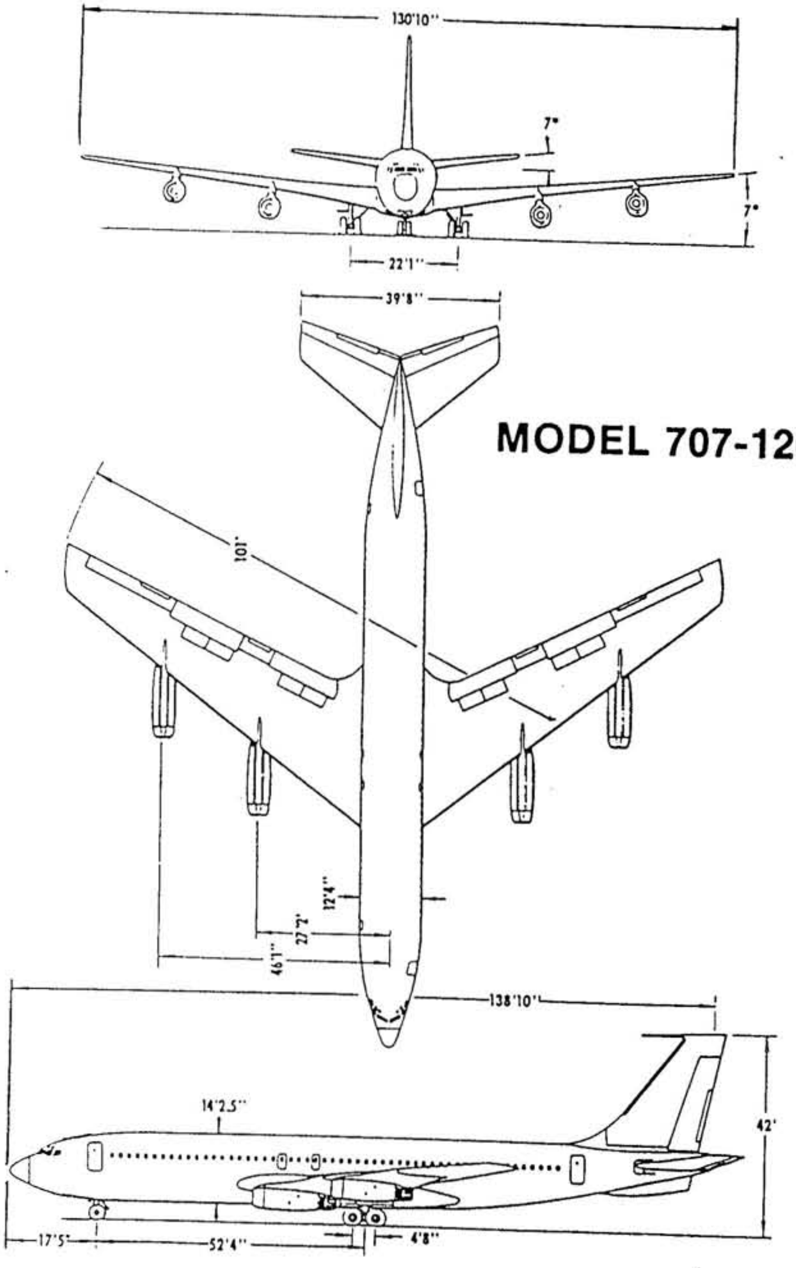


BOEING 367-80 TANKER-TRANSPORT PROTOTYPE

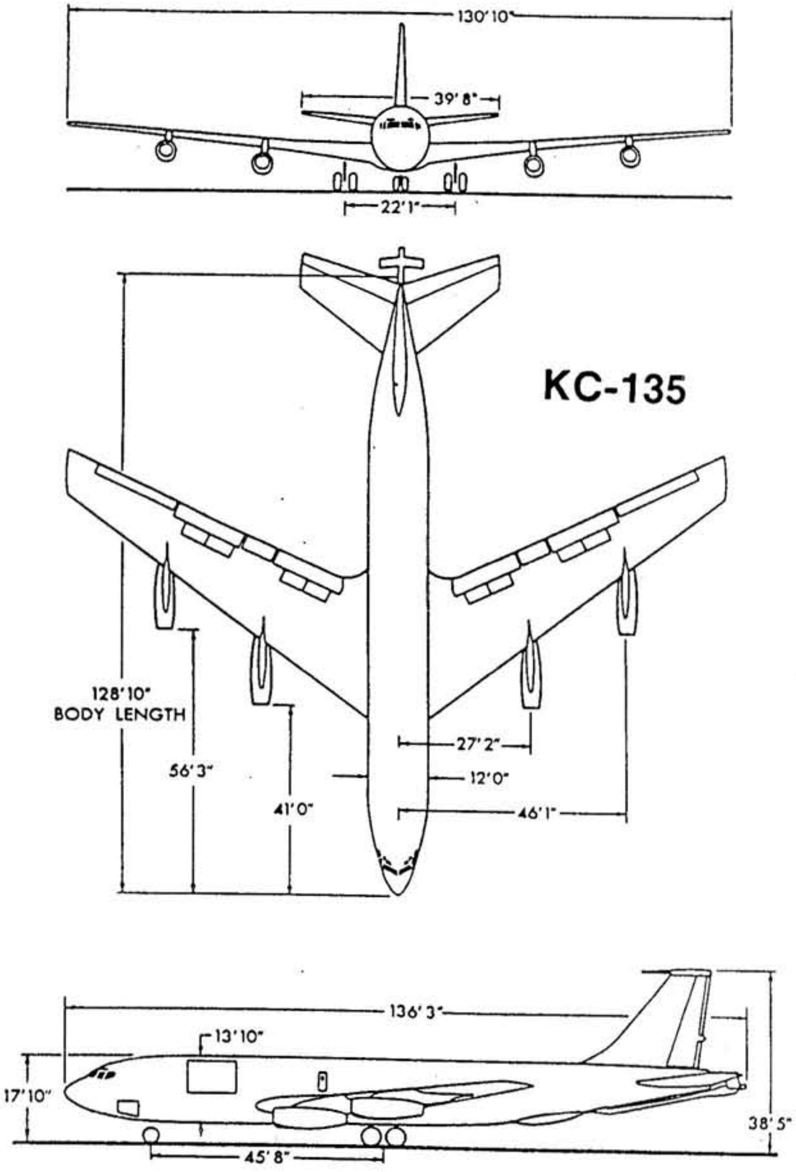
The XB-47 made its first flight in 1947; the XB-52 in 1952. Boeing built a tanker-transport prototype 367-80 that first flew in 1954. The primary Boeing objective in building this prototype was to win Air Force contracts for the B-52 support tankers. These were necessary to support the B-52 bombers as a long range bomber force. This need was committed when the B-52s were built with jets instead of propellers. The B-52 and the tankers to support them had top Defense Department priority. Lockheed won the paper competition to produce tankers to support the B-52 bombers but Boeing got the business because Boeing could deliver a proven tanker product years ahead of Lockheed. Ultimately, 744 B-52 bombers and 820 Boeing KC-135 tankers were built.

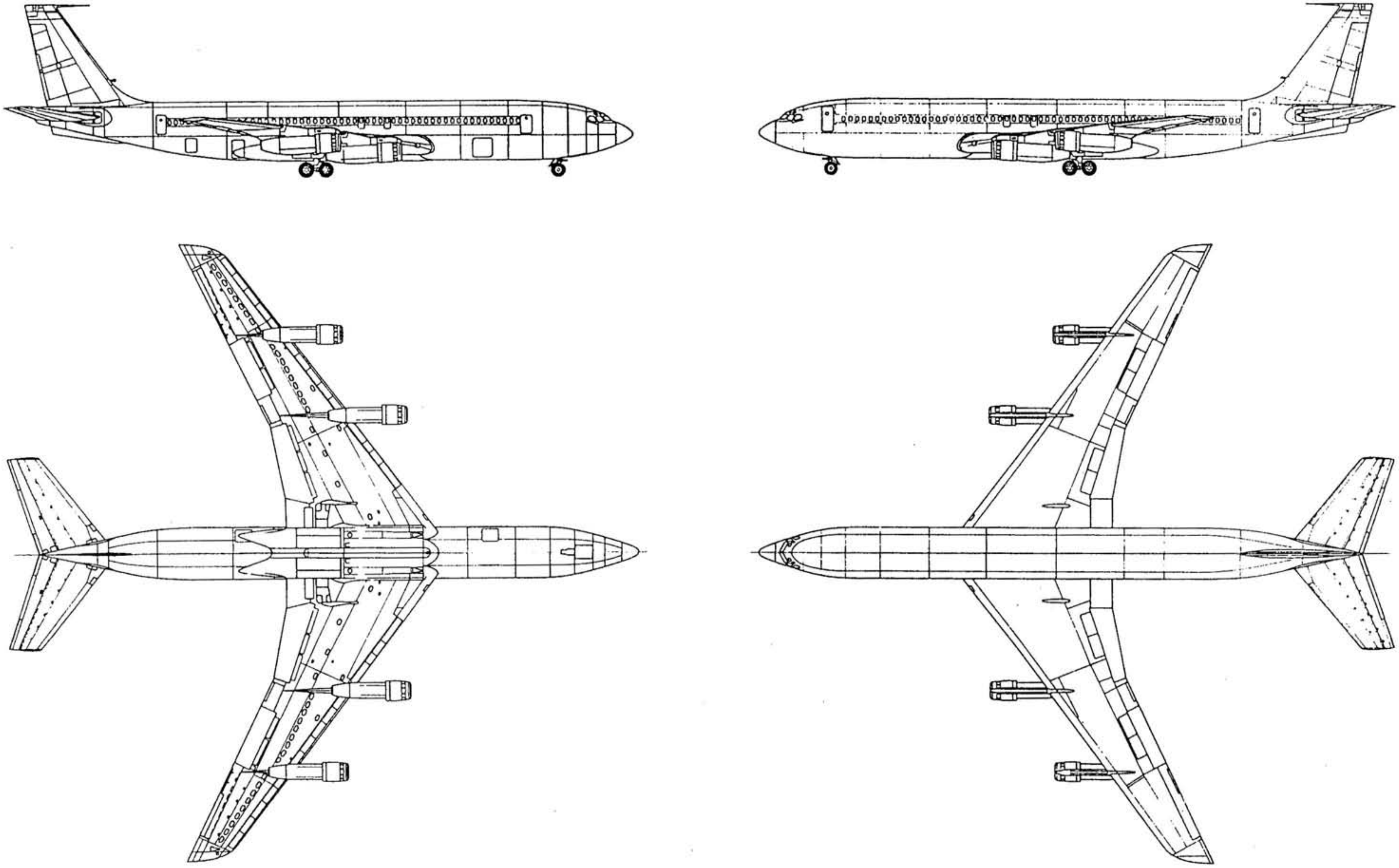
Since a tanker-transport had no need for a big bomb bay at the center of gravity and under the wing, it was possible in this prototype to consider a low-wing aircraft with a tricycle landing gear that retracted sidewise into the body behind the wing rear spar. The development of spoilers as a primary lateral control and of yaw dampers to keep Dutch roll to acceptable levels permitted enough dihedral to keep the wingtips well off the ground. Turbine burst experience led to separate pods for each engine. High-drag slotted flaps solved the approach drag problem.

MODEL 707-120



KC-135

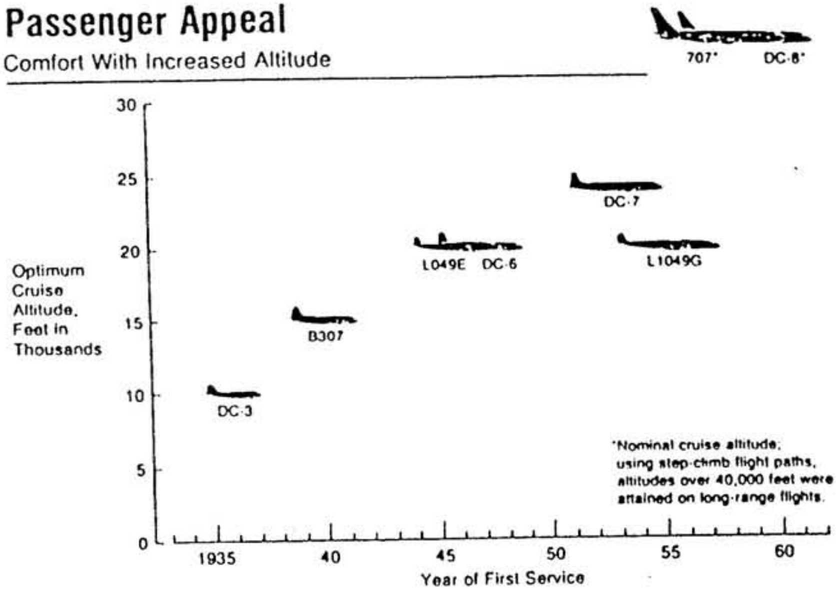




MODEL 707-320

Passenger Appeal

Comfort With Increased Altitude

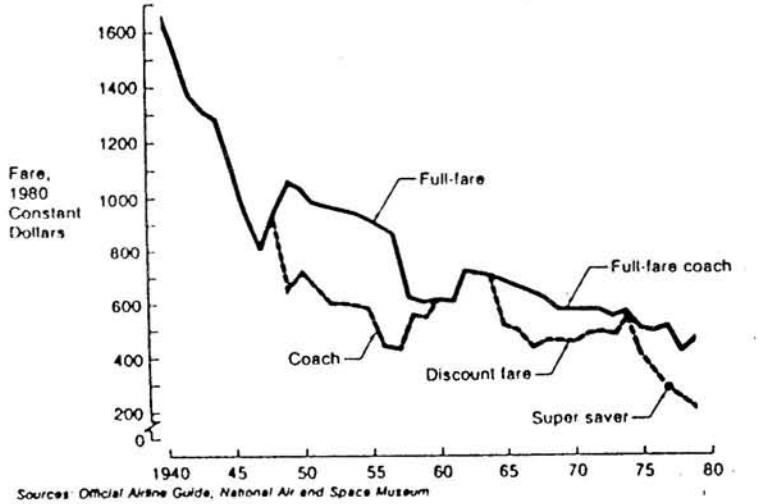


*Nominal cruise altitude; using step-climb flight paths, altitudes over 40,000 feet were attained on long-range flights.

+ Economics and safety

Round Trip Air Fare

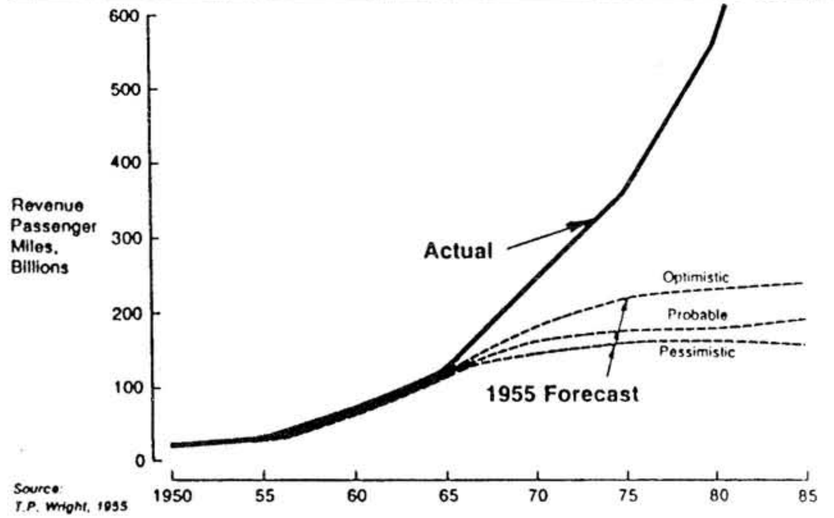
1940-1979 – New York City-Los Angeles



Sources: *Official Airline Guide, National Air and Space Museum*

World Revenue Passenger Miles

Actuals vs 1955 Forecast

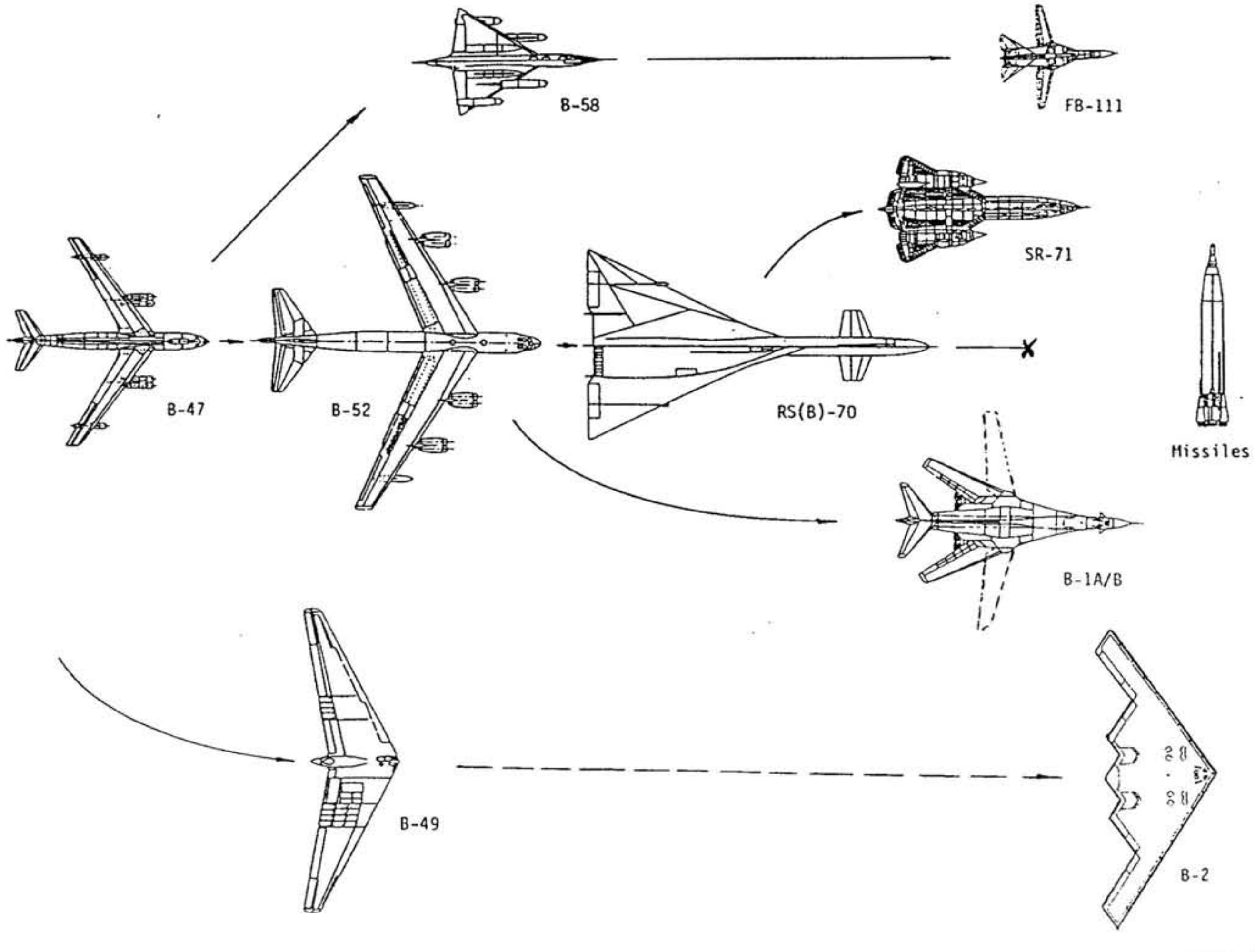


Source: *T.P. Wright, 1955*

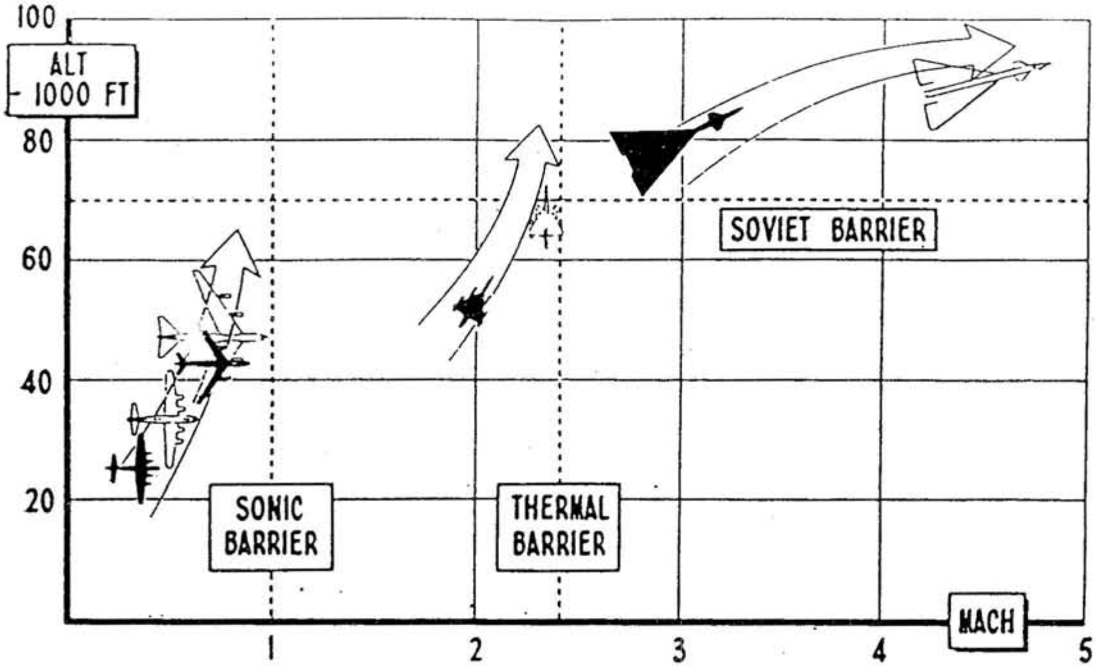
Jet commercial aviation comes of age and becomes <u>the</u> way to travel.

INTO THE SUPERSONIC ERA
"Winners" and "Losers"

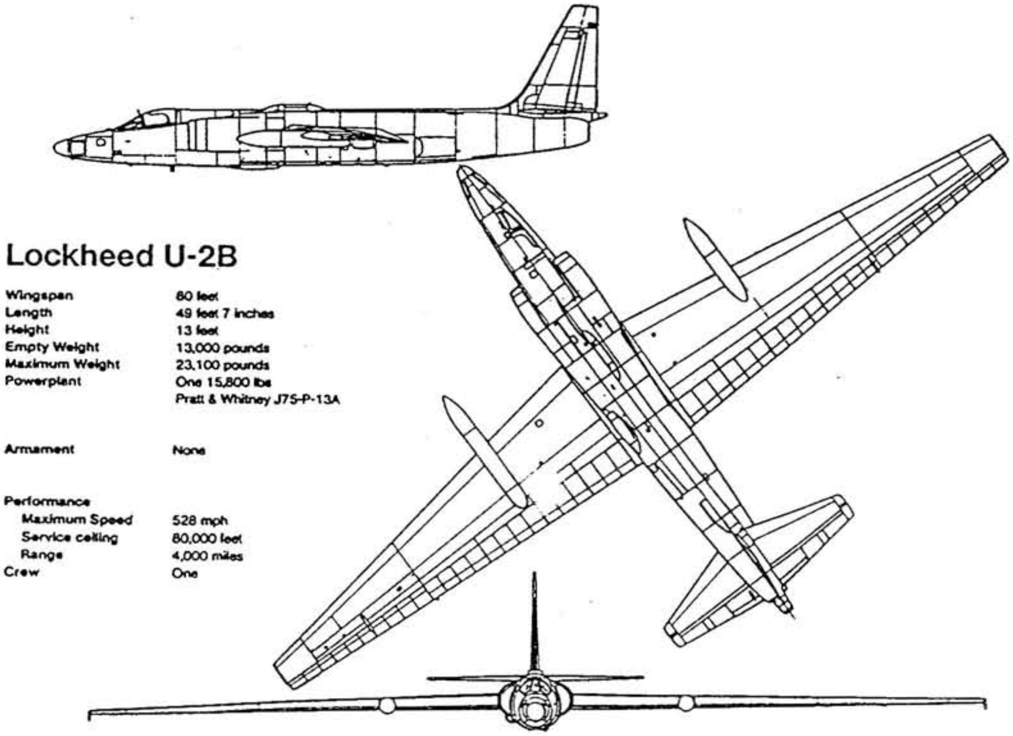
- A further brief digression into the history of jet bomber design.
- Everything gets faster and faster and faster and bigger -- and more complicated.
- The "weapon system" concept emerges as a way to think about managing big, complicated projects.
- The final pinnacle of bigger, faster manned bombers (the B-70) was obsolete before it flew. Missiles were the obvious wave of the future for military purposes.
- But the stage was now set for the next great advance in jet transportation--or so we thought in the early 1960s.



"HIGHER AND FASTER"



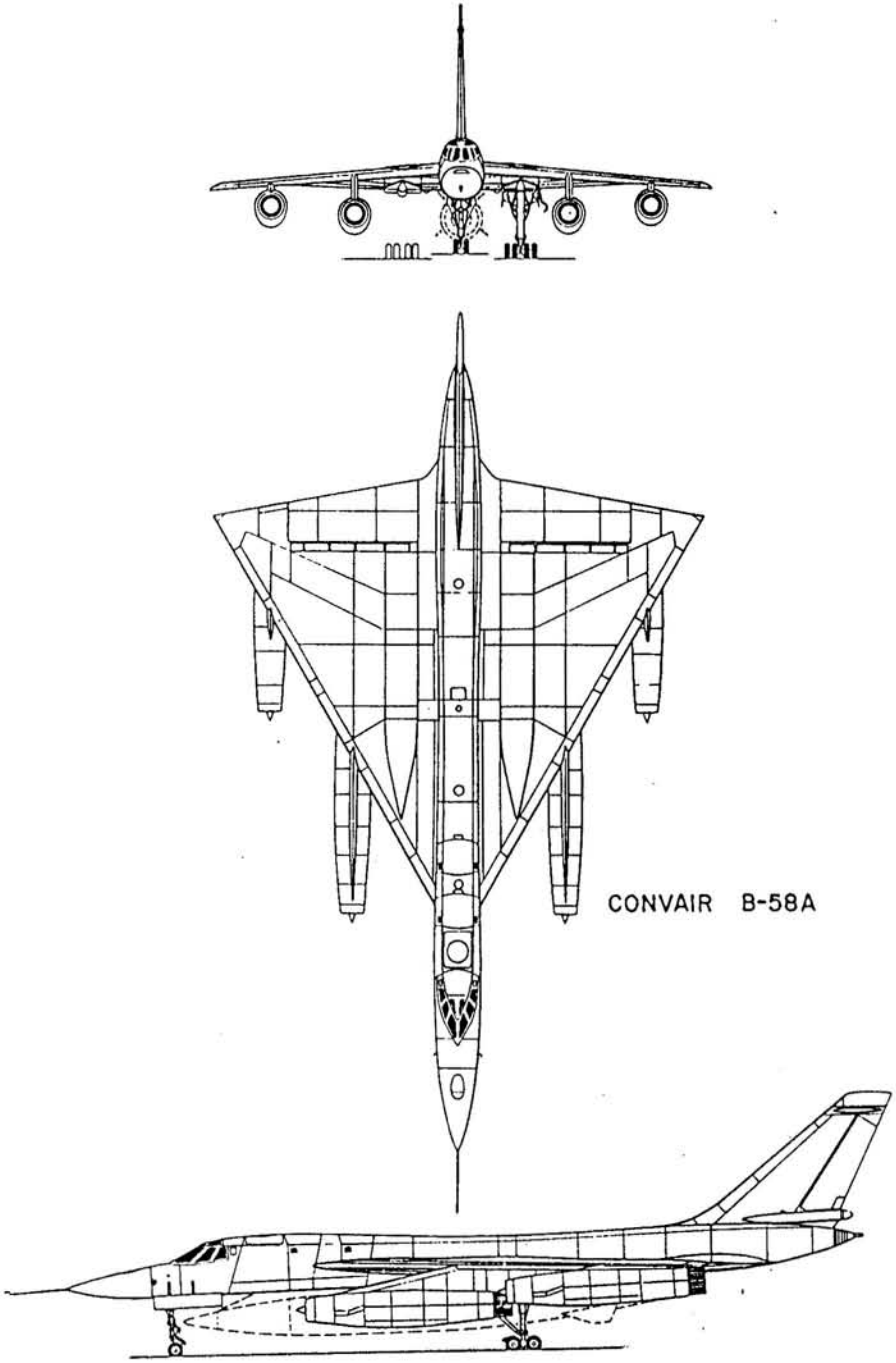
Source: Preparedness Investigating Subcommittee of the Senate Armed Services Committee, circa early 1960.



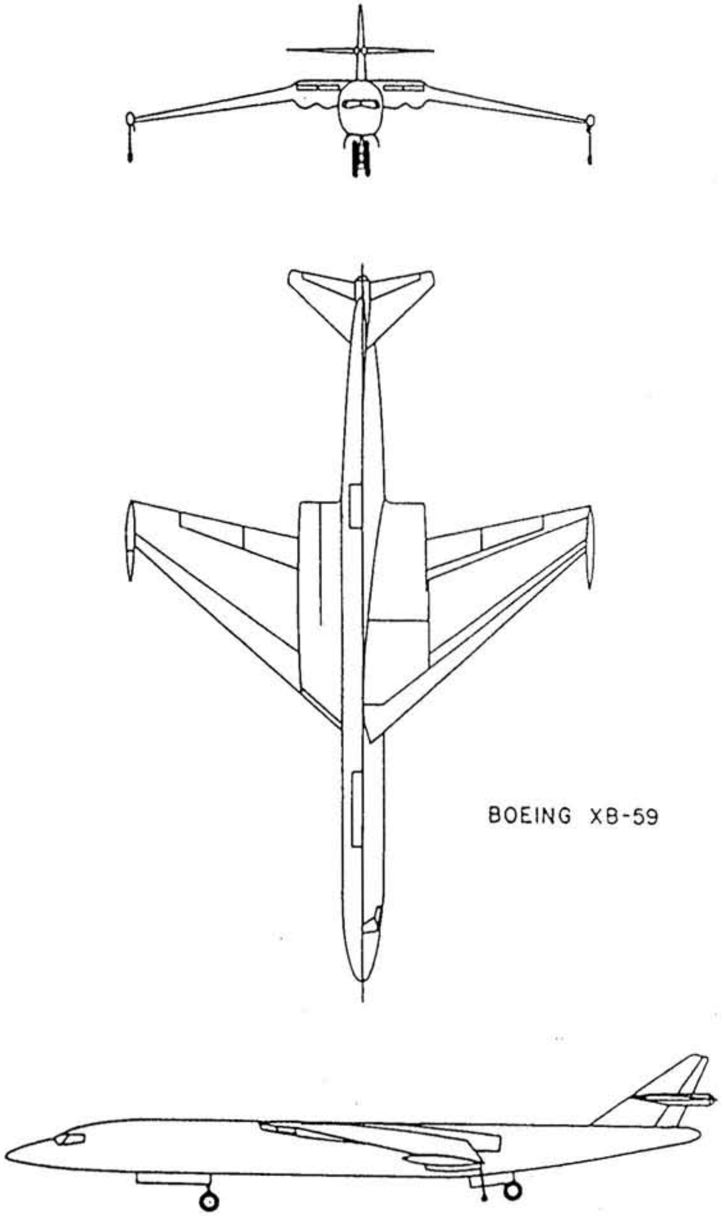
Lockheed U-2B

Wingspan	80 feet
Length	49 feet 7 inches
Height	13 feet
Empty Weight	13,000 pounds
Maximum Weight	23,100 pounds
Powerplant	One 15,800 lbs Pratt & Whitney J75-P-13A
Armament	None
Performance	
Maximum Speed	528 mph
Service ceiling	80,000 feet
Range	4,000 miles
Crew	One

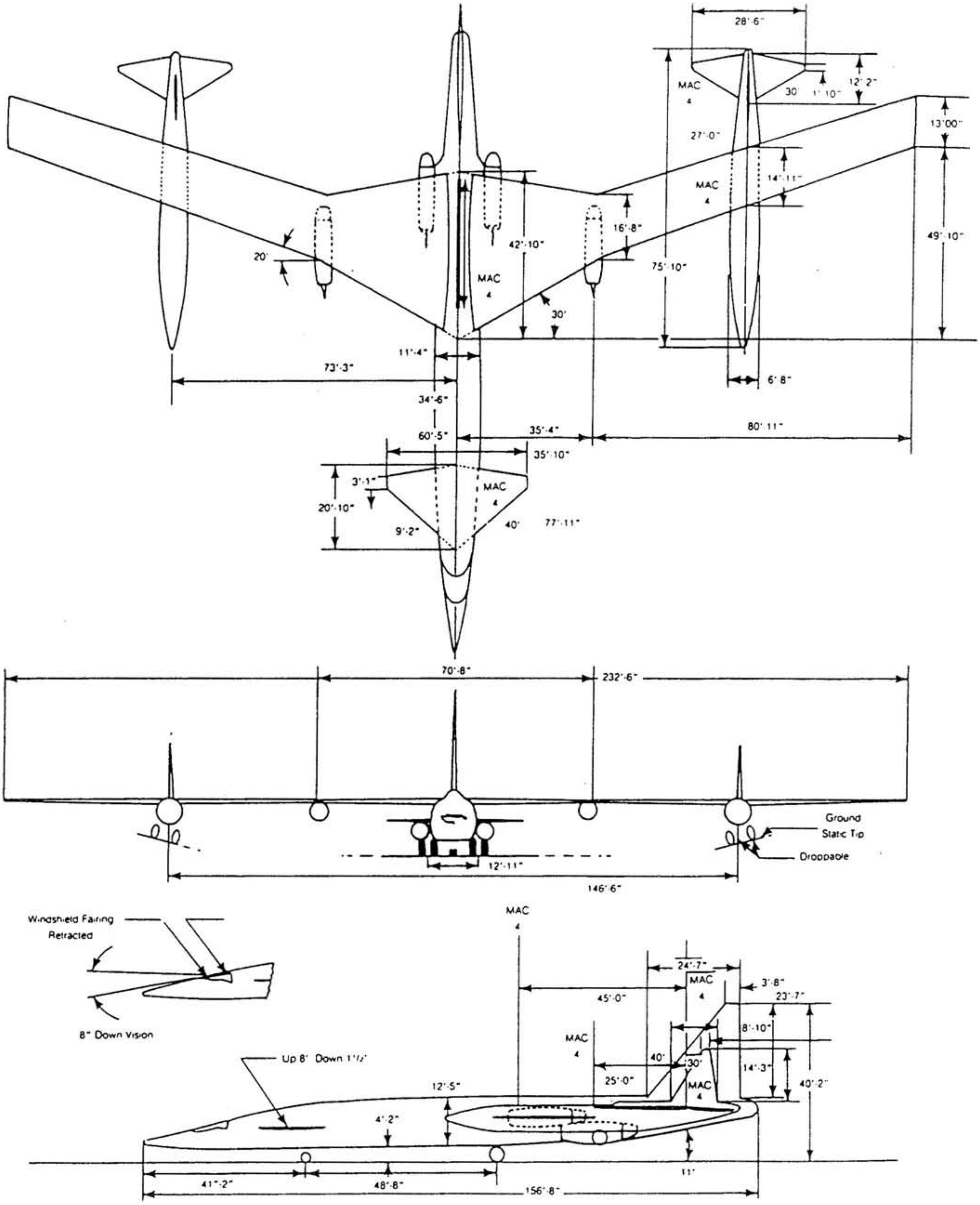
Similar to the machine in which Francis Gary Powers was shot down near Sverdlovsk in the Soviet Union on May 1, 1960,



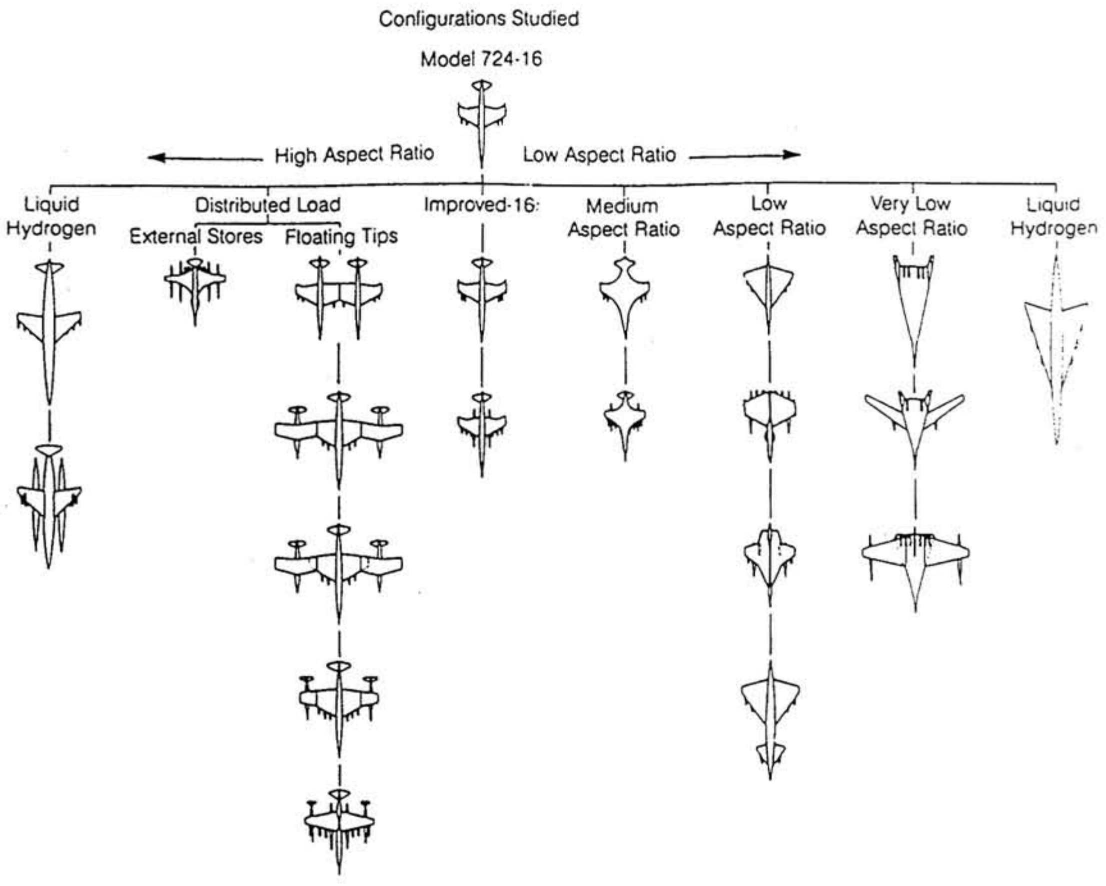
CONVAIR B-58A



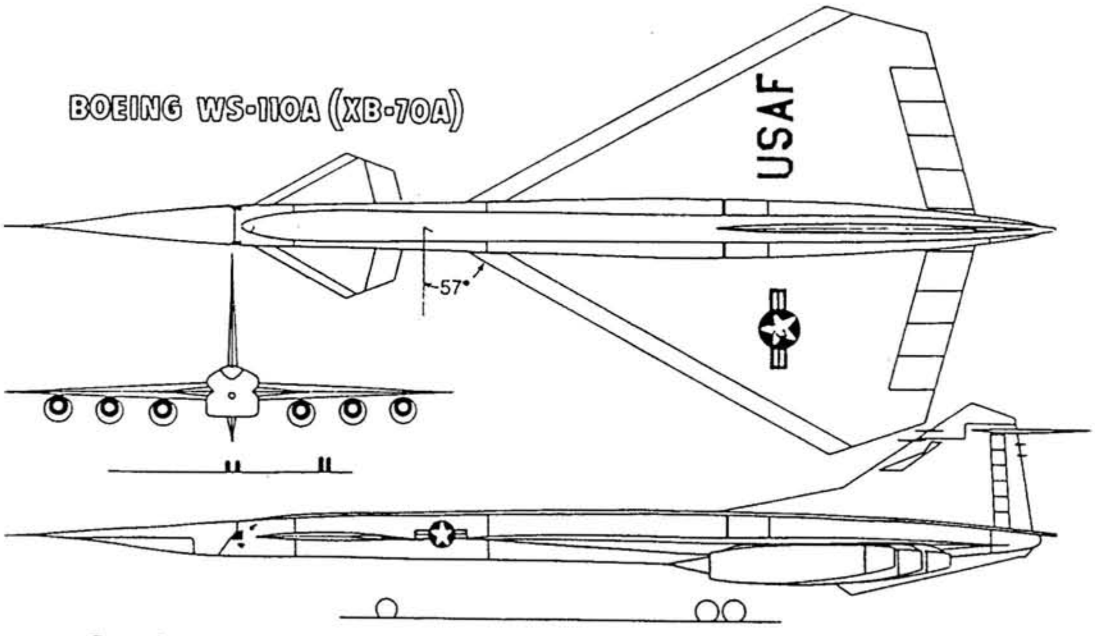
BOEING XB-59



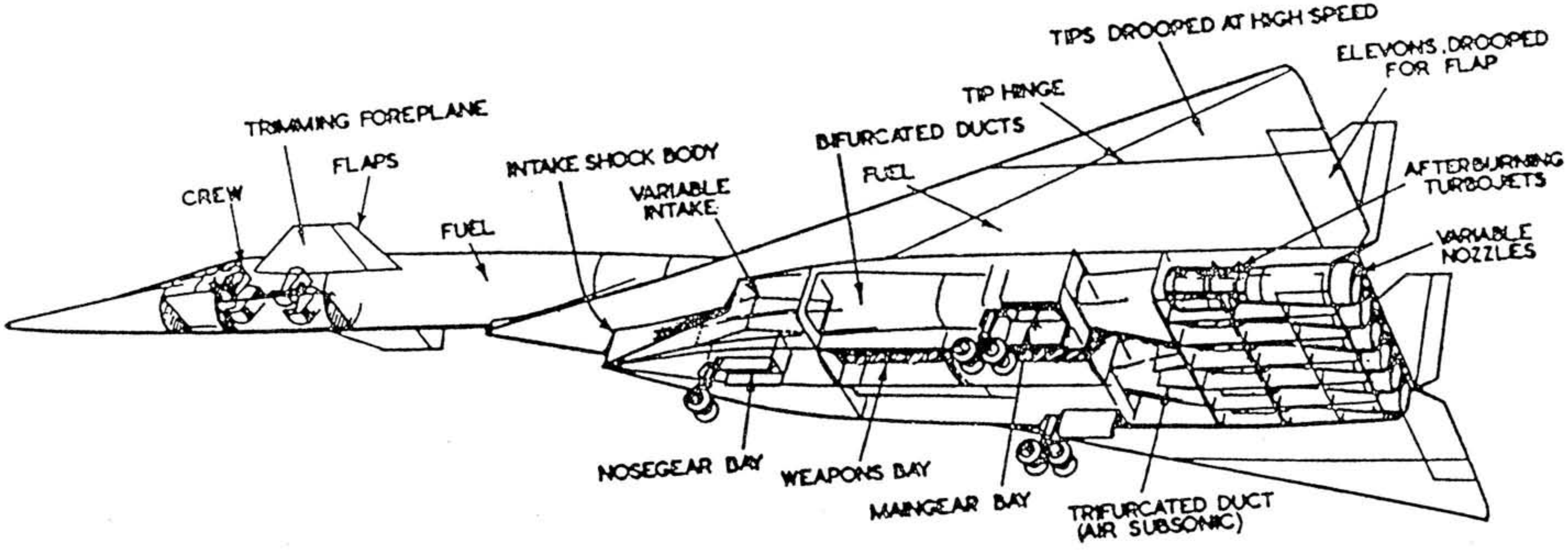
Boeing's original WS-110A proposal was, like North American's, too large and too heavy.



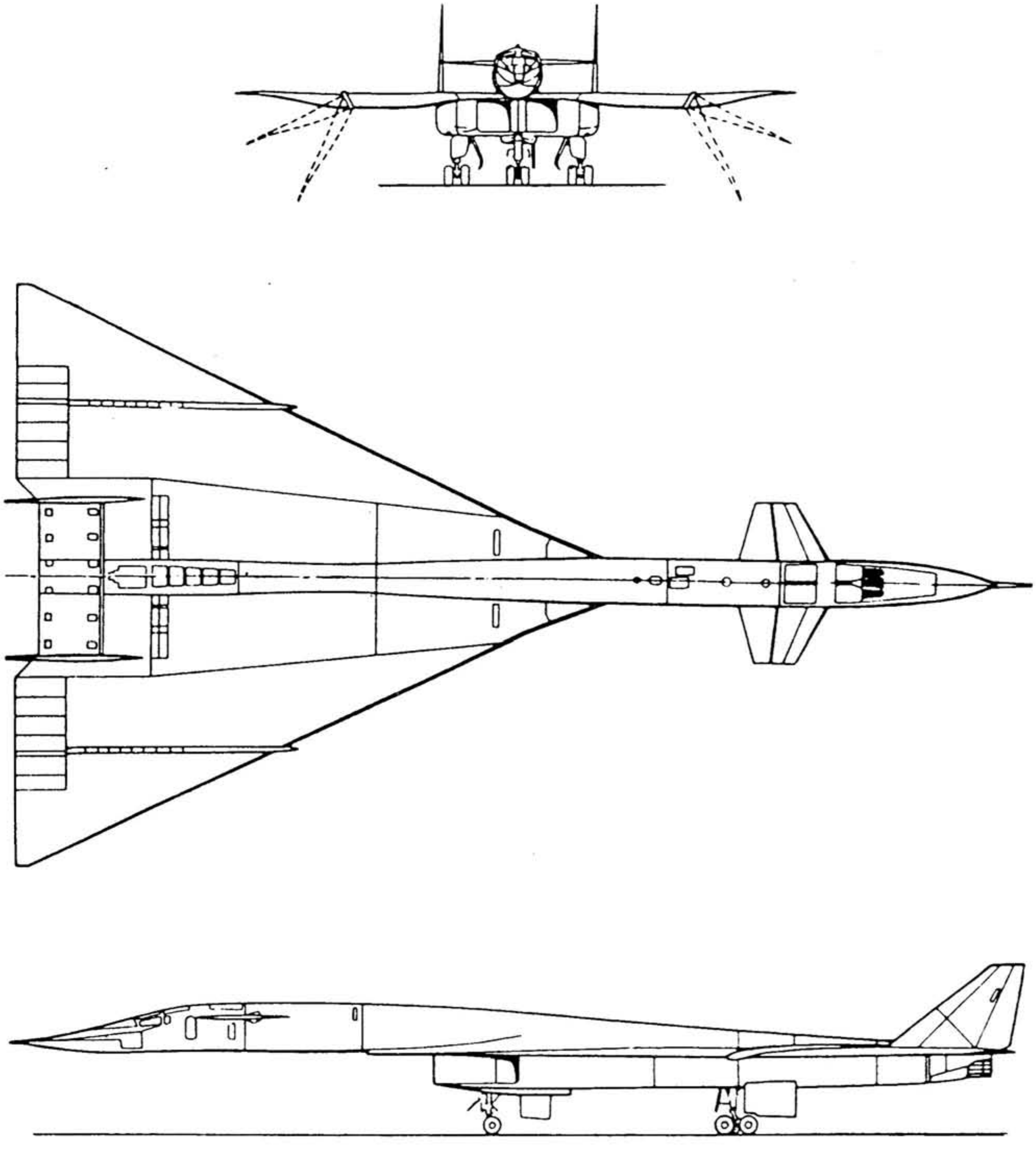
Boeing's partial WS-110A configuration studies under project Tea Bag.



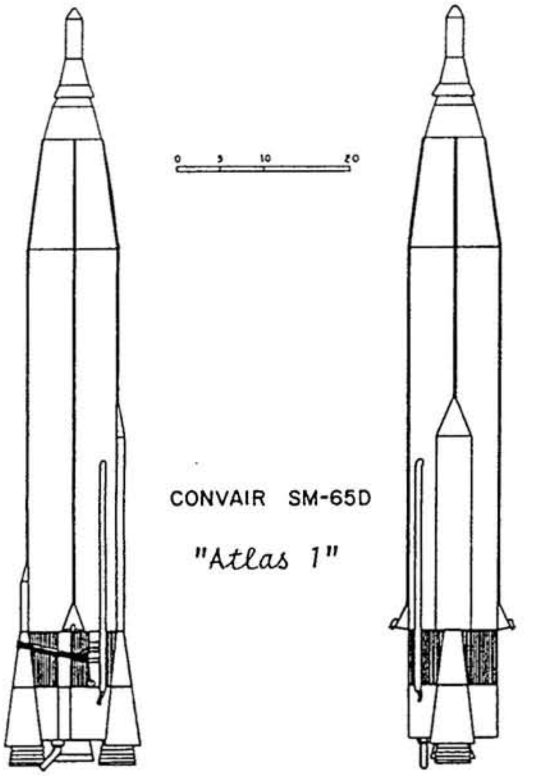
General arrangement three-view drawing of Boeing's redesigned WS-110A.



The North American B-70 showing salient features

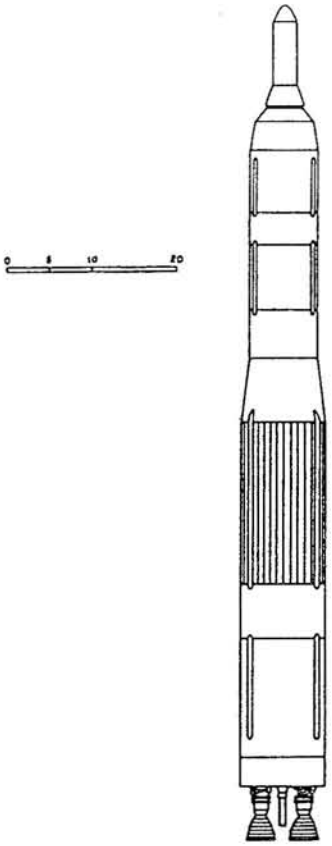


North American XB-70 Valkyrie.



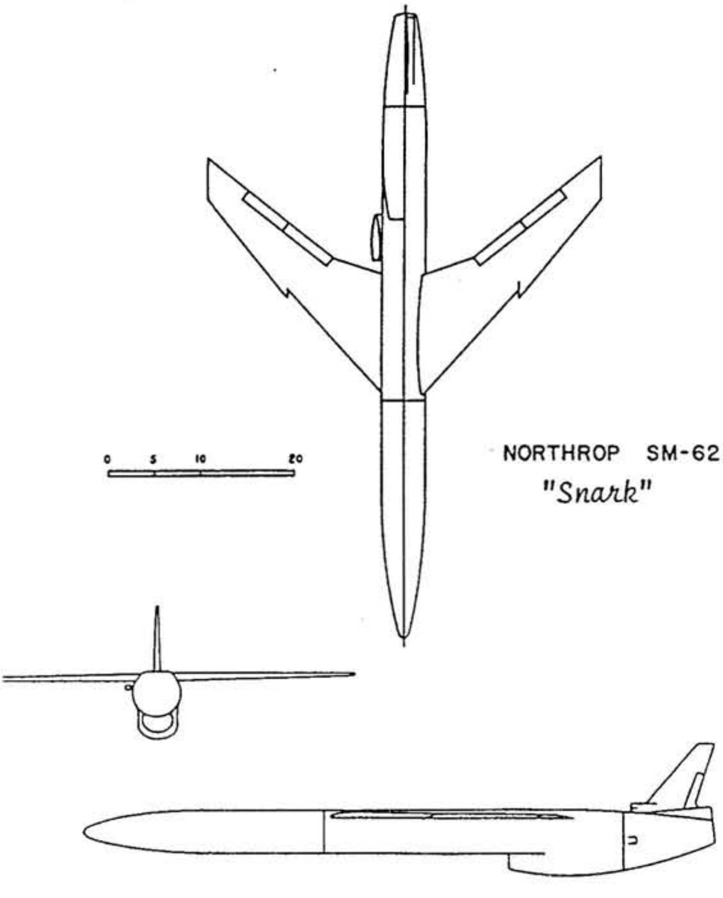
CONVAIR SM-65D

"Atlas 1"



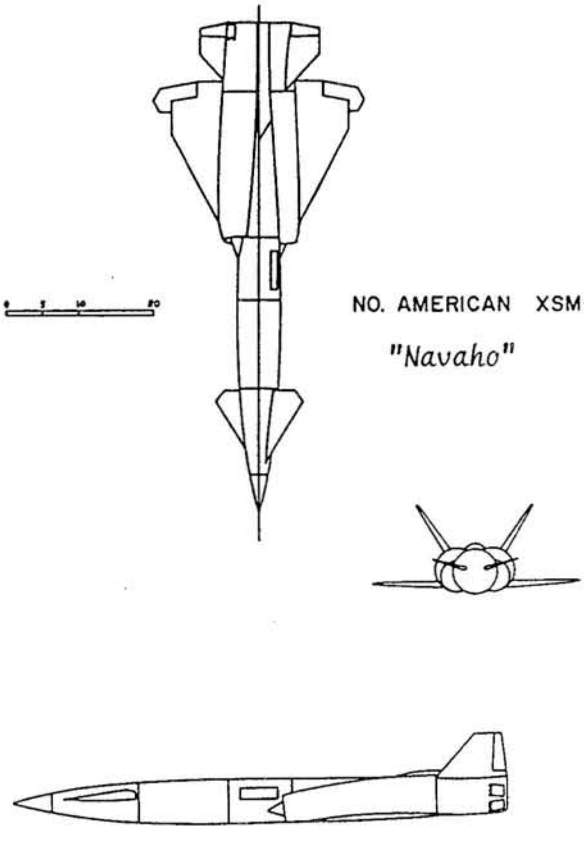
MARTIN SM-68

"Titan 1"



NORTHROP SM-62A

"Snark"



NO. AMERICAN XSM-64

"Navaho"

WHY NOT A SUPERSONIC TRANSPORT?

- Technological imperatives: If it's feasible and maybe a useful concept, then we have to do it--particularly if someone else is willing to pay for it.

- "The world supply of oil is, for all practical purposes, unlimited and jet fuel should continue to cost 10-12 cents per gallon for as long as we can foresee".

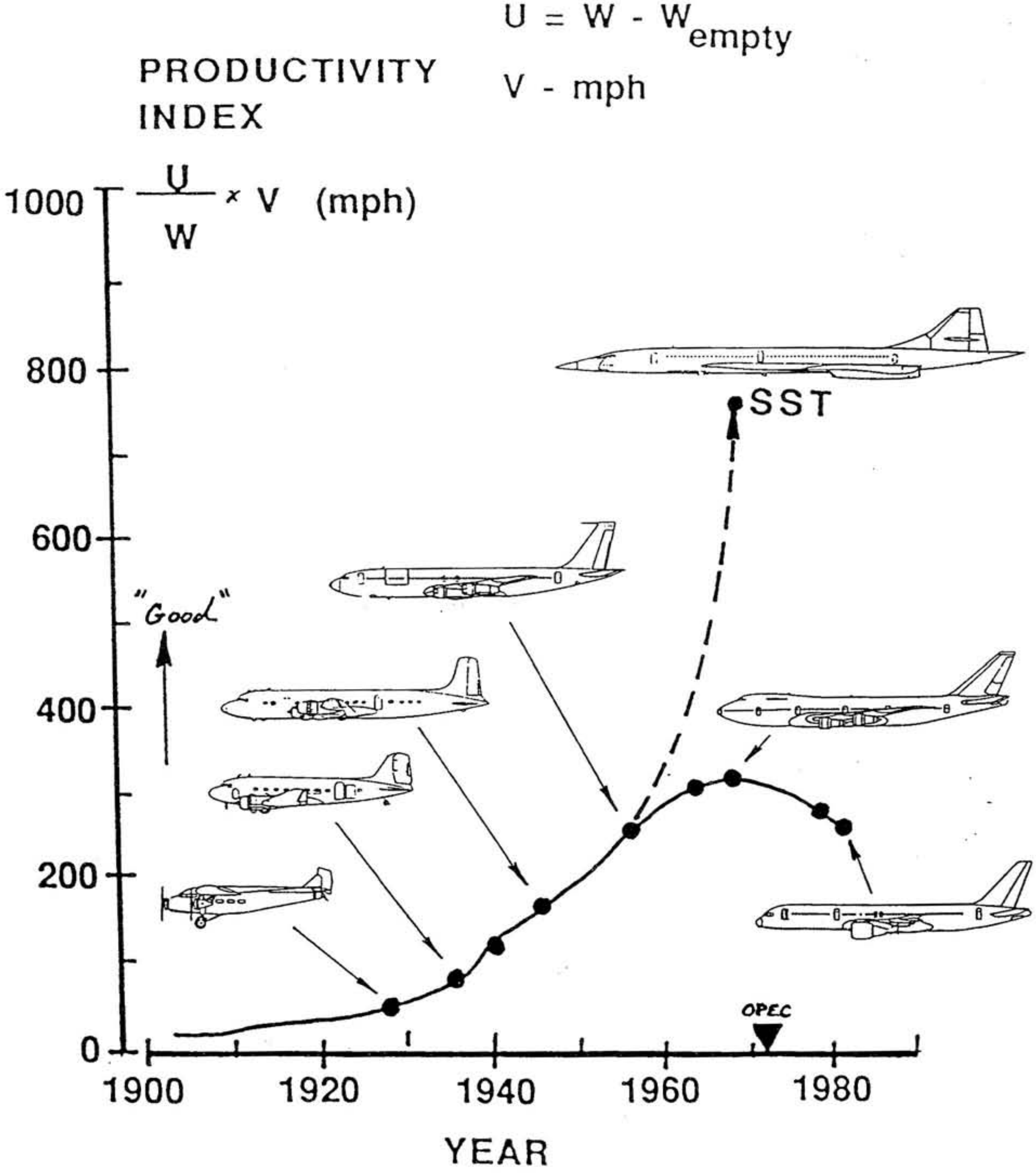
  Every major oil company consulted between 1965-70.

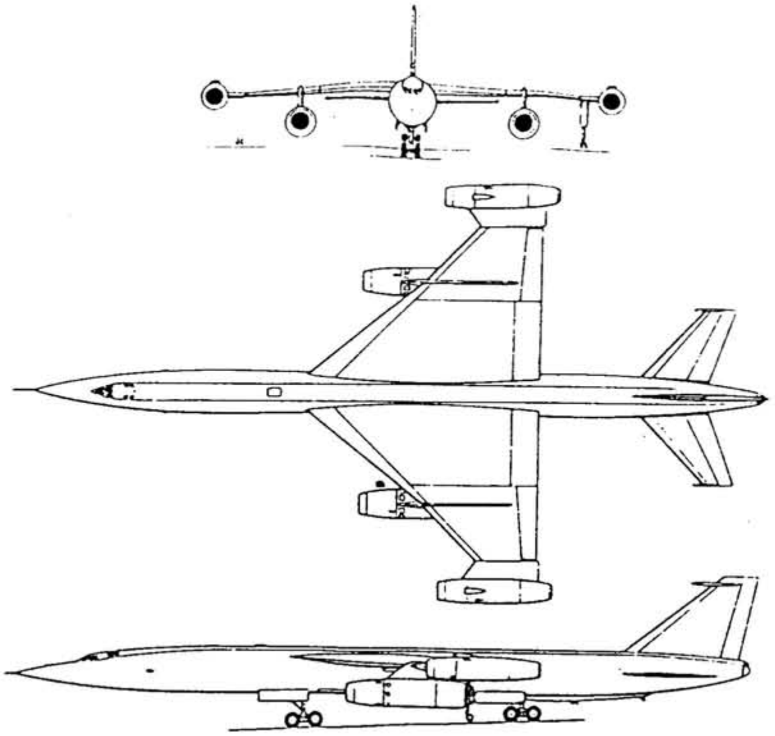
- The British and French are committed to a joint SST project and the U.S. must not be "second best".

- The development cost on an SST is beyond the risk level any U.S. company can take. It must be government subsidized.

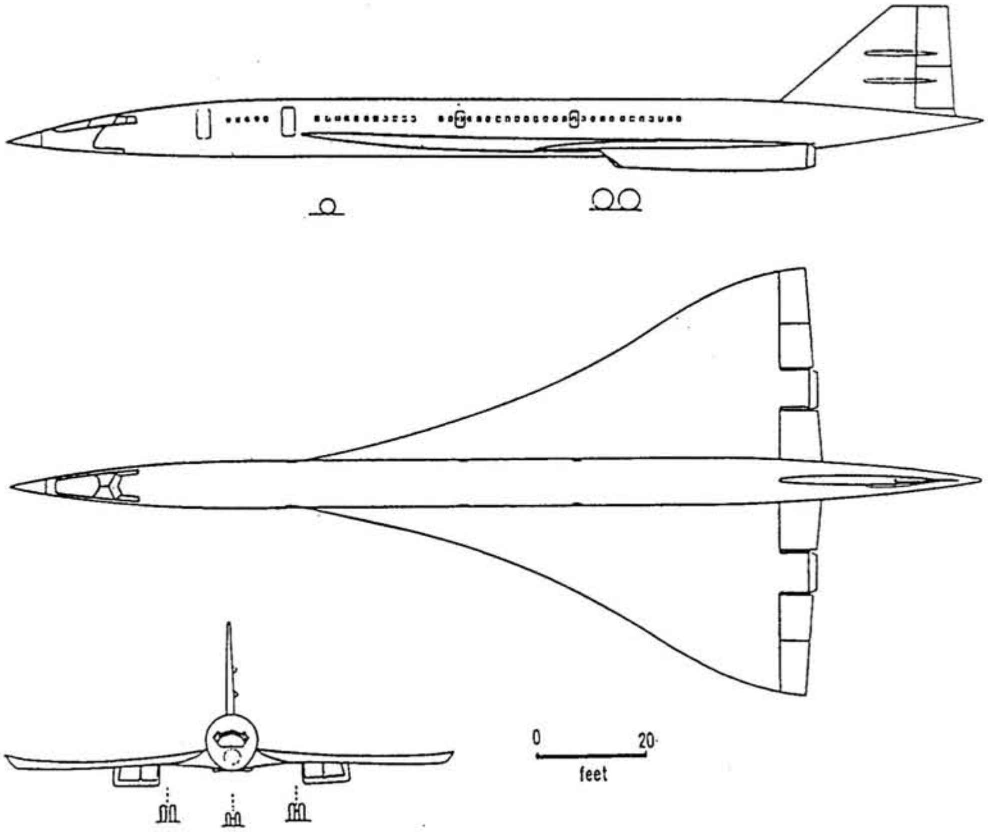
- Boeing won "the contract" with an "unbuildable" airplane.

- SST Show Stoppers:
  - Afterburning turbojets
  - Sonic booms
  - Technological hubris
  - Red herrings (ozone, etc.)
  - Cash flow and free enterprise

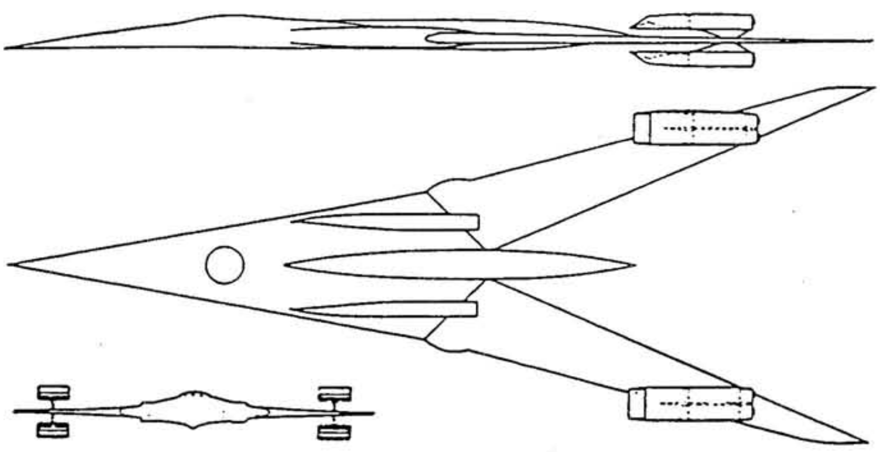

U = W - W_empty
V - mph
PRODUCTIVITY INDEX
U/W × V (mph)
1000
800
600
400
200
0
"Good"
SST
OPEC
1900
1920
1940
1960
1980
YEAR



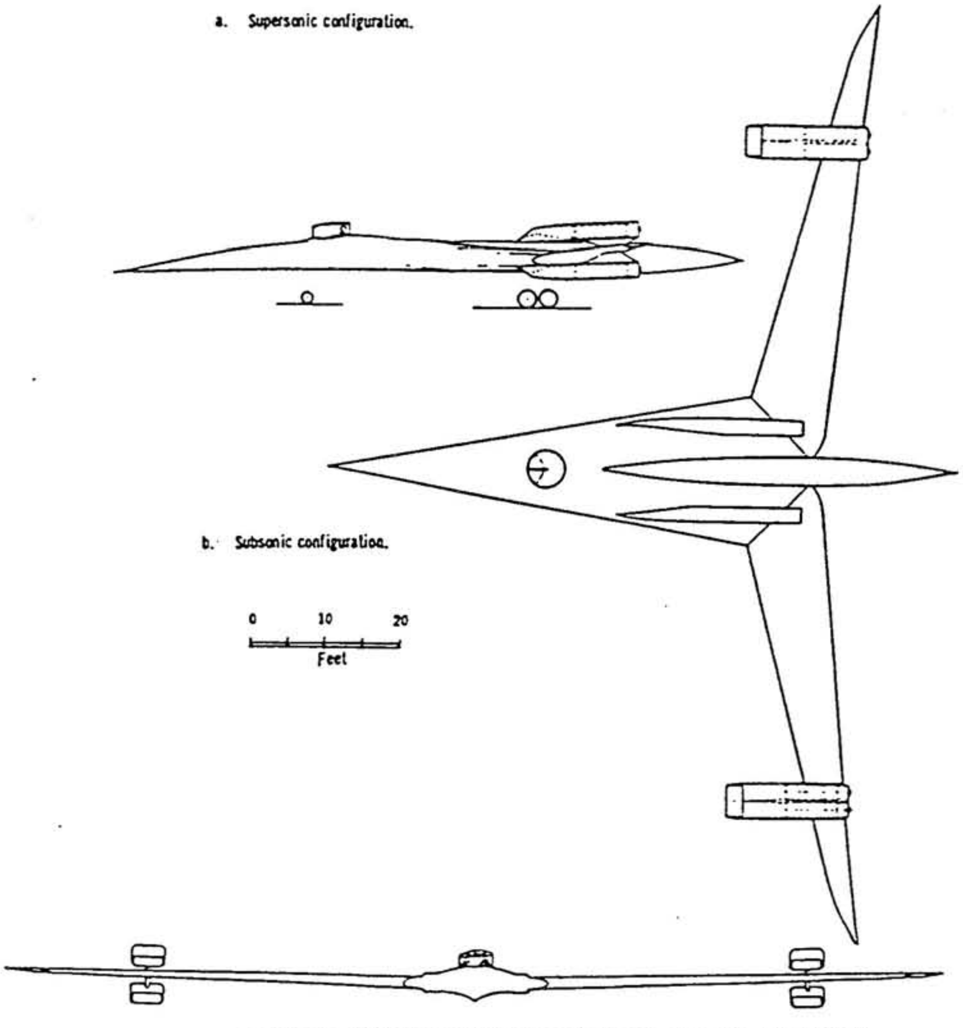
The Myasishchev M-50 (Bounder) was possibly abandoned as a result of an underestimation of the transonic drag rise



BAC-Sud Concorde as in 1965. The nose is less cambered than the original, and the fin may be given a lower drag semi-ogee profile similar to the wing. Both alterations would be to reduce cruising drag and improve the rather limited range

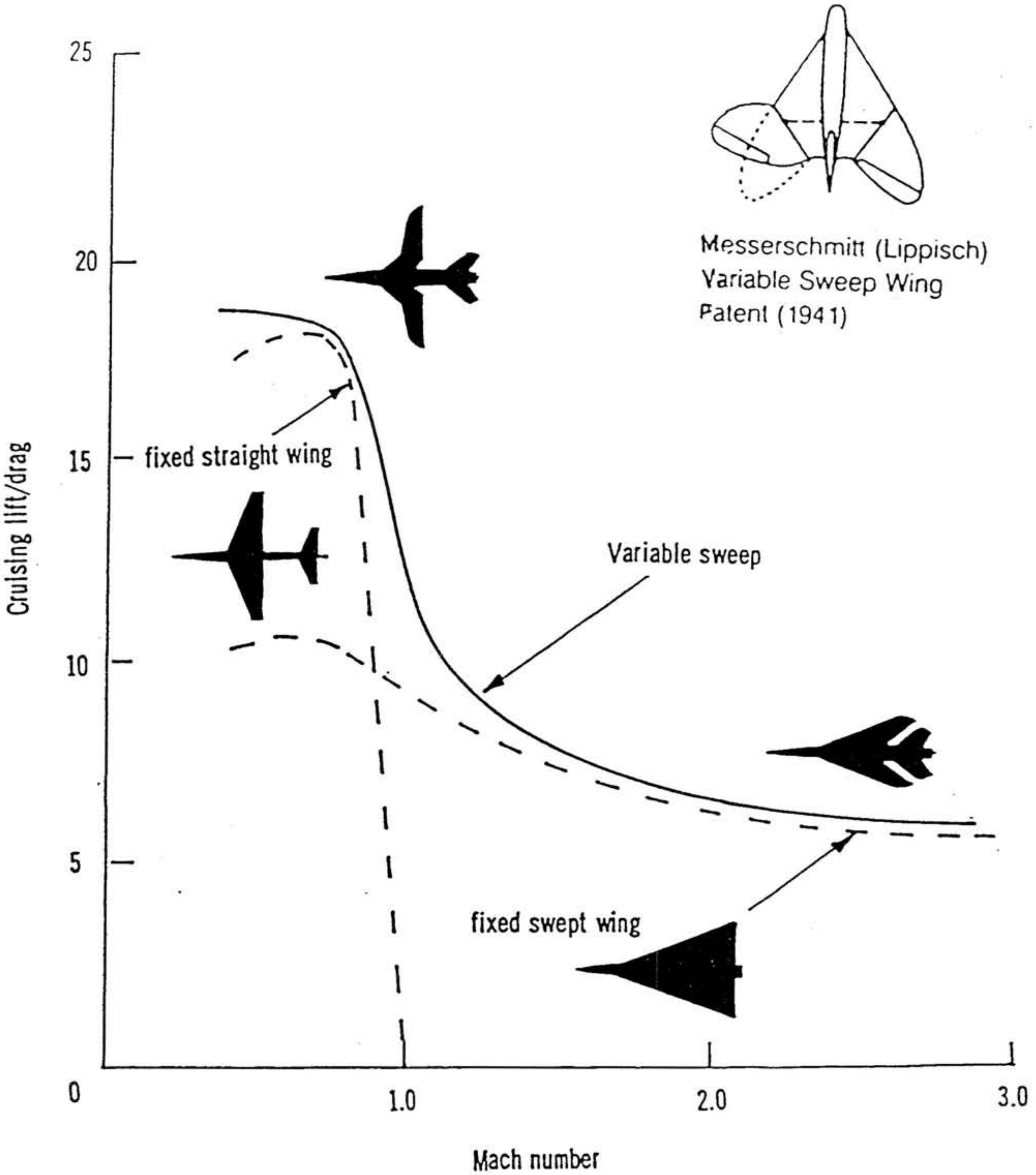


a. Supersonic configuration.

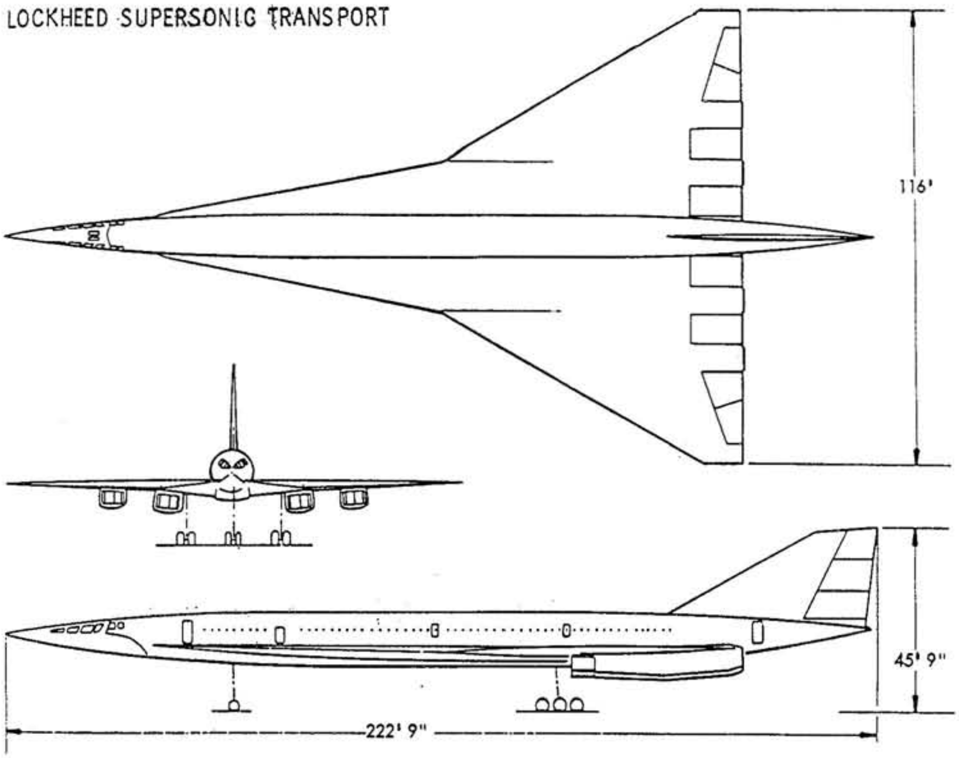


b. Subsonic configuration.

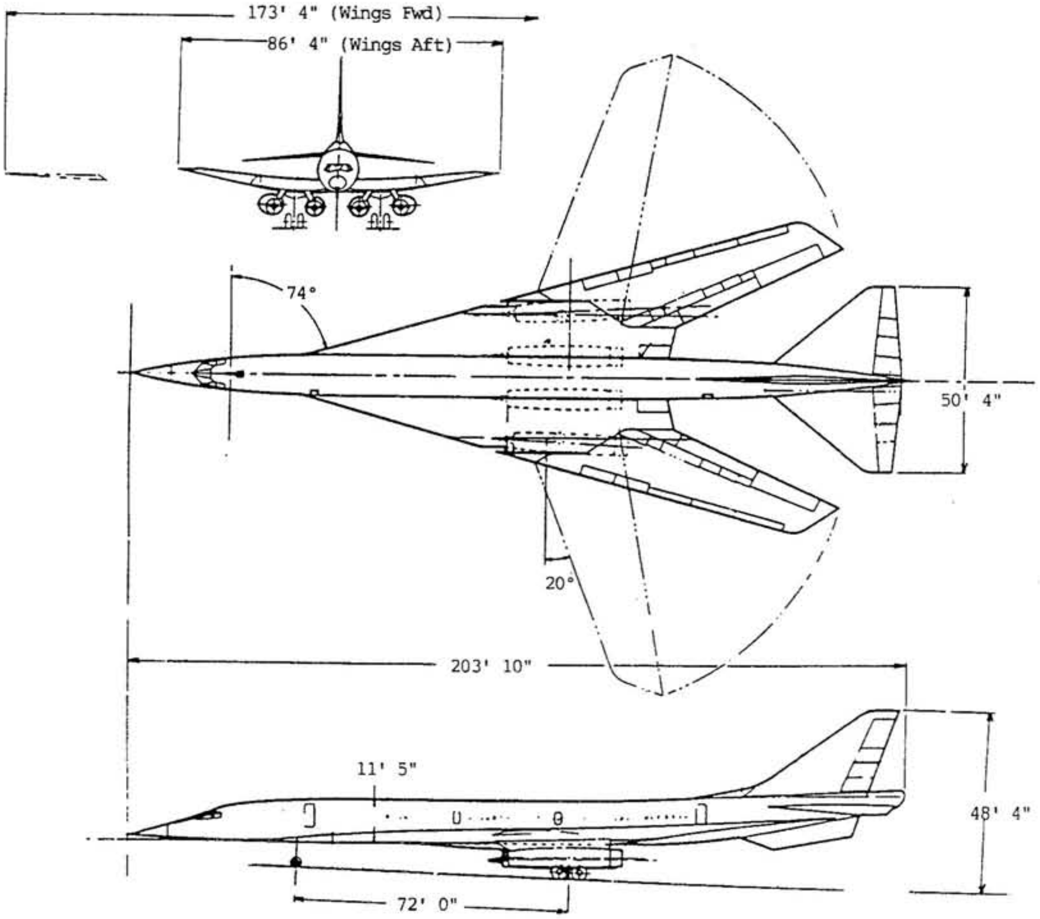
The Barnes Wallis Swallow, Development Stage II, about 1960



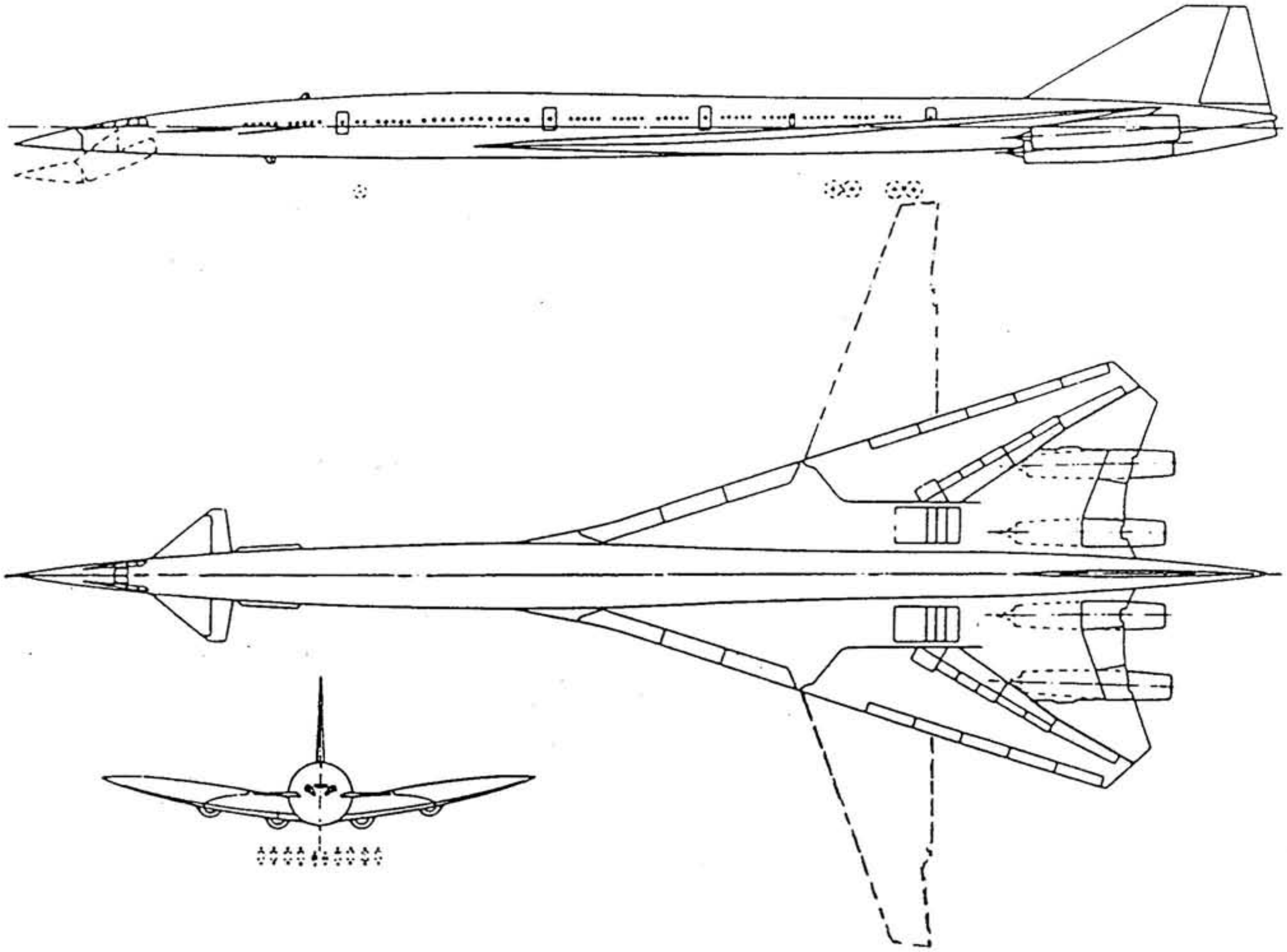
Variable sweep as a means of improving theoretical cruising lift/drag and, therefore, reducing the fuel required for range



Three views of Lockheed Aircraft's supersonic transport proposal, one of two designs selected by the FAA for the second round of SST studies.

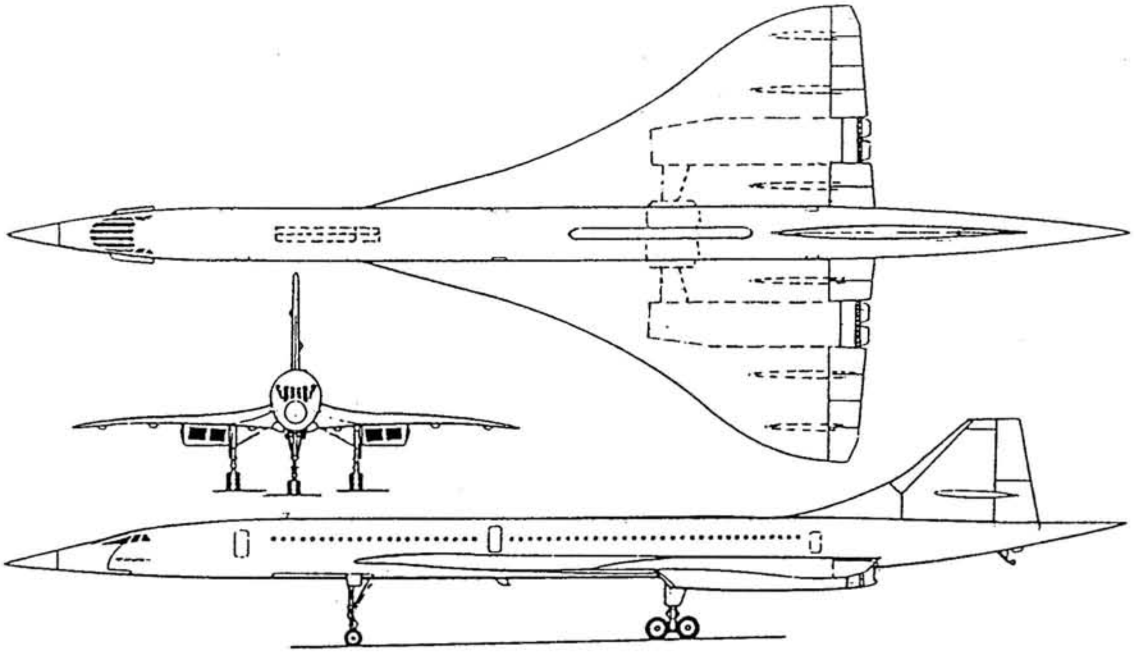


Movable wings are a feature of Boeing Company's SST design, selected for Phase 2 study along with Lockheed's proposal.



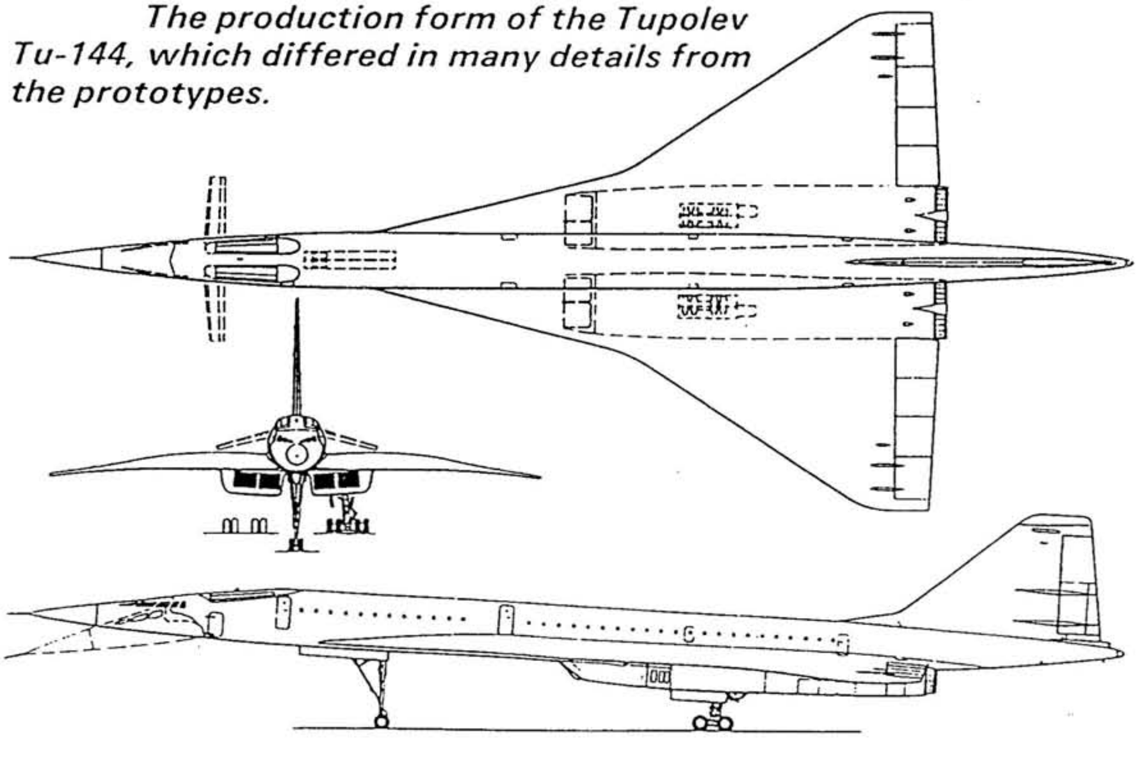
TECHNICAL DATA - BOEING SUPERSONIC TRANSPORT MODEL 2707-200

Type:	Supersonic transport
Accommodation:	250–350 passengers
Power plant:	General Electric GE4/J5
Span:	(20-degree sweep) 174 ft 2 in (72-degree sweep) 105 ft 9 in
Length:	318 ft
Height:	46 ft
Wing area:	9,000 sq ft
Gross weight:	675,000 lb
Cruising speed:	Mach 2·7 (1,800 mph)
Cruising altitude:	64,000 ft
Range:	Over 4,000 miles



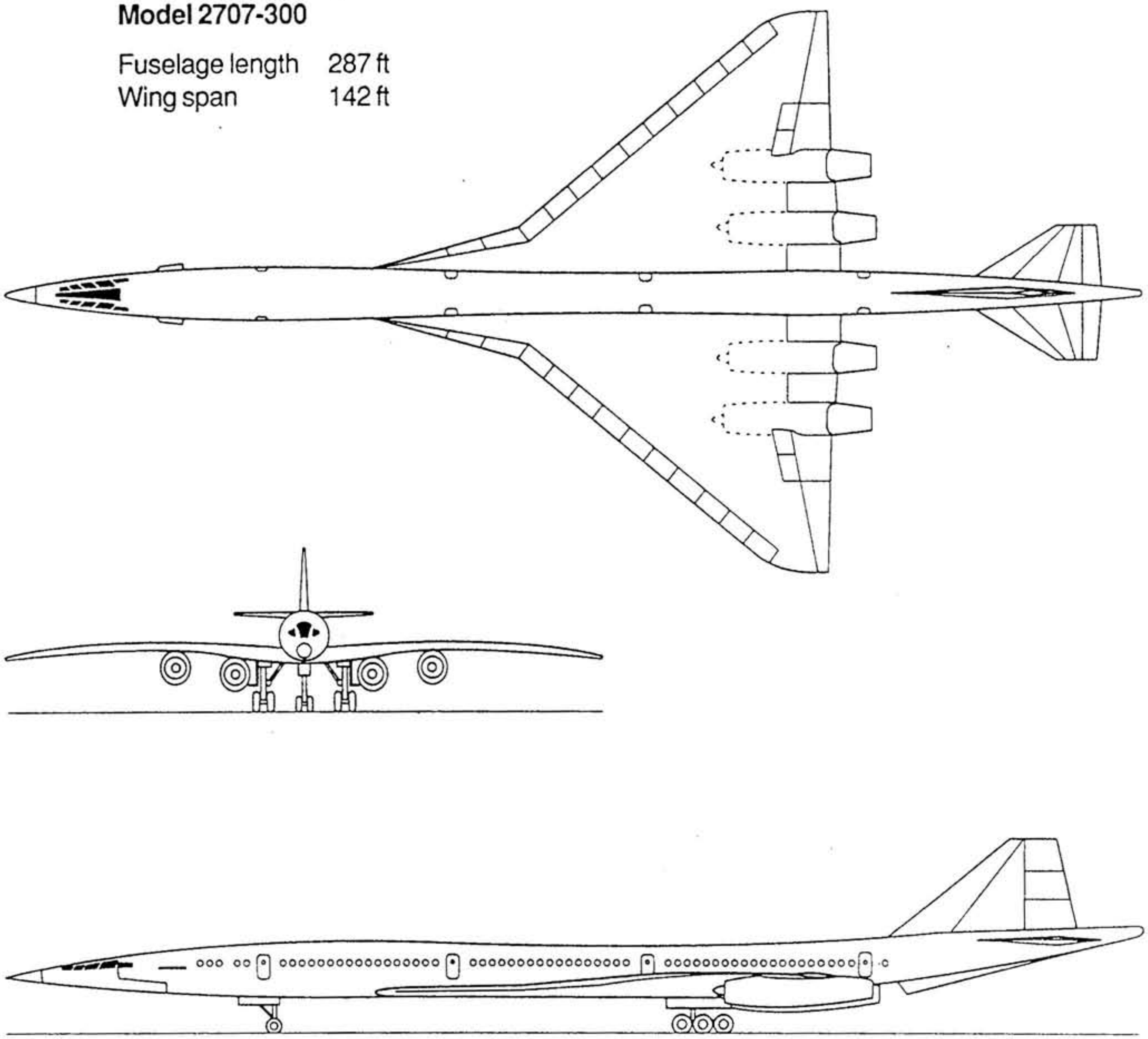
Three-view of the Aérospatiale/BAC Concorde in its final production configuration; the prototypes had a shorter fuselage.

The production form of the Tupolev Tu-144, which differed in many details from the prototypes.



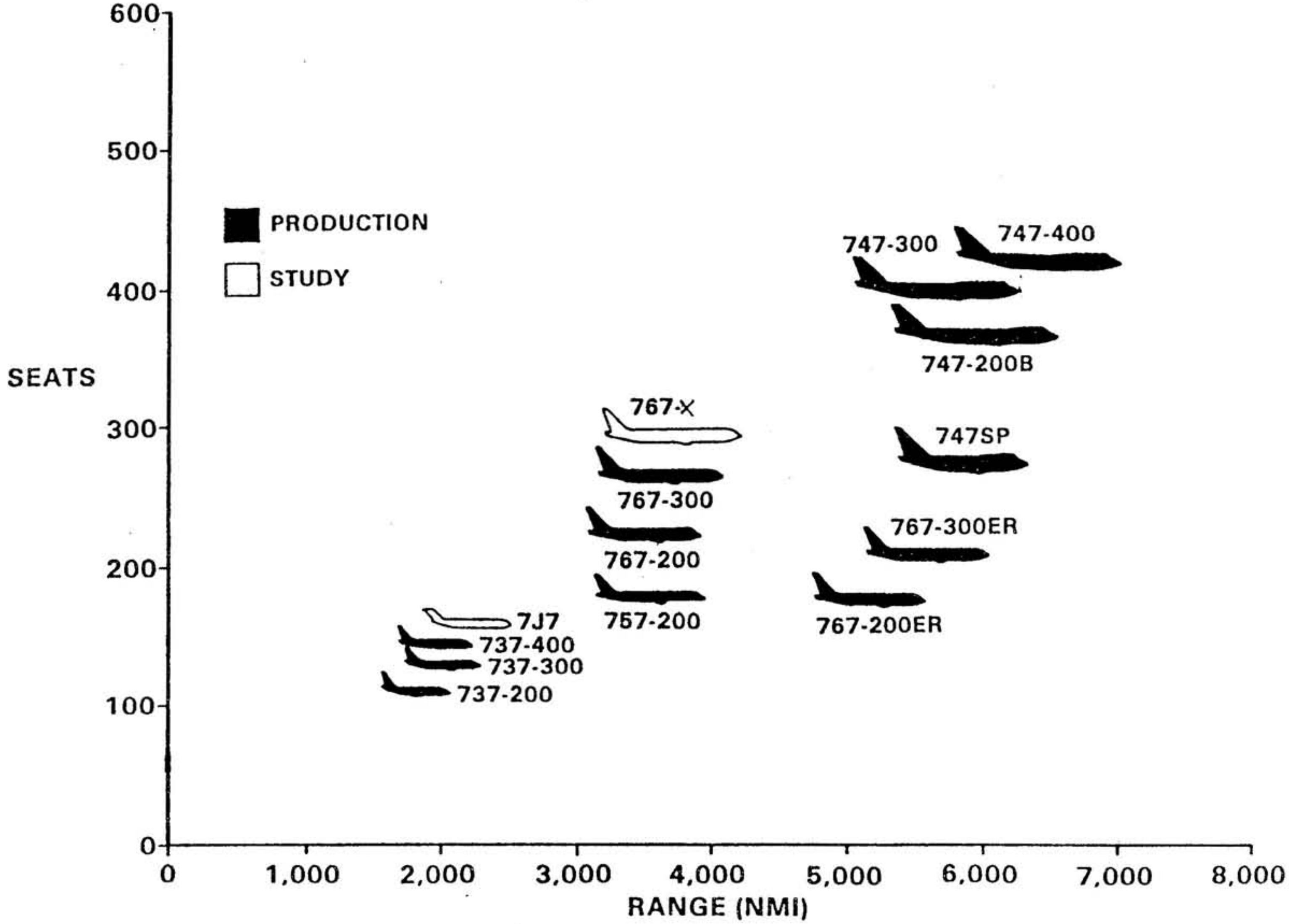
SST Prototype Airplane
Model 2707-300

Fuselage length	287 ft
Wing span	142 ft



U.S. SST Program
(1968-1971)

BOEING NEW AIRPLANE FAMILY



BACK TO BASICS -- THE MODERN SUBSONIC TRANSPORT

- The Boeing <u>family</u> of jet transports emerge as the dominant force in the world market.

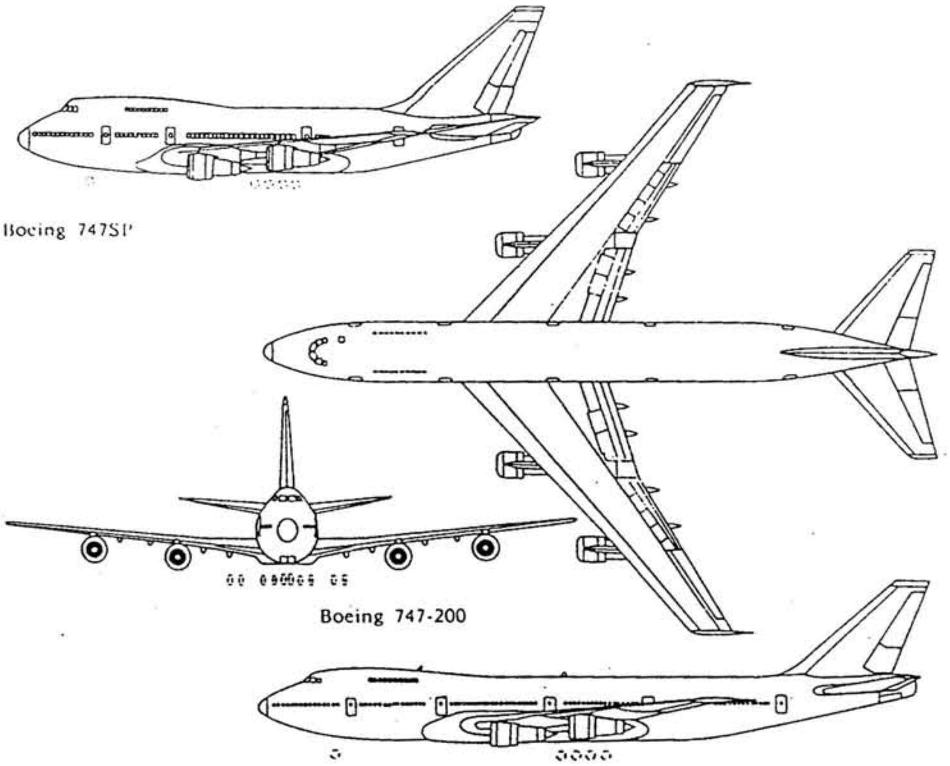
- The competition and the marketplace are changing and we now live in a post-OPEC world of uncertain fuel prices and supply. The commercial airplane business has "matured".

- Significant developments (1965-1985):

  - Boeing 747 vs Lockheed C-5
  - DC-10 vs L1011
  - Airbus
  - 767 and 757 - fuel efficient, quiet and expensive

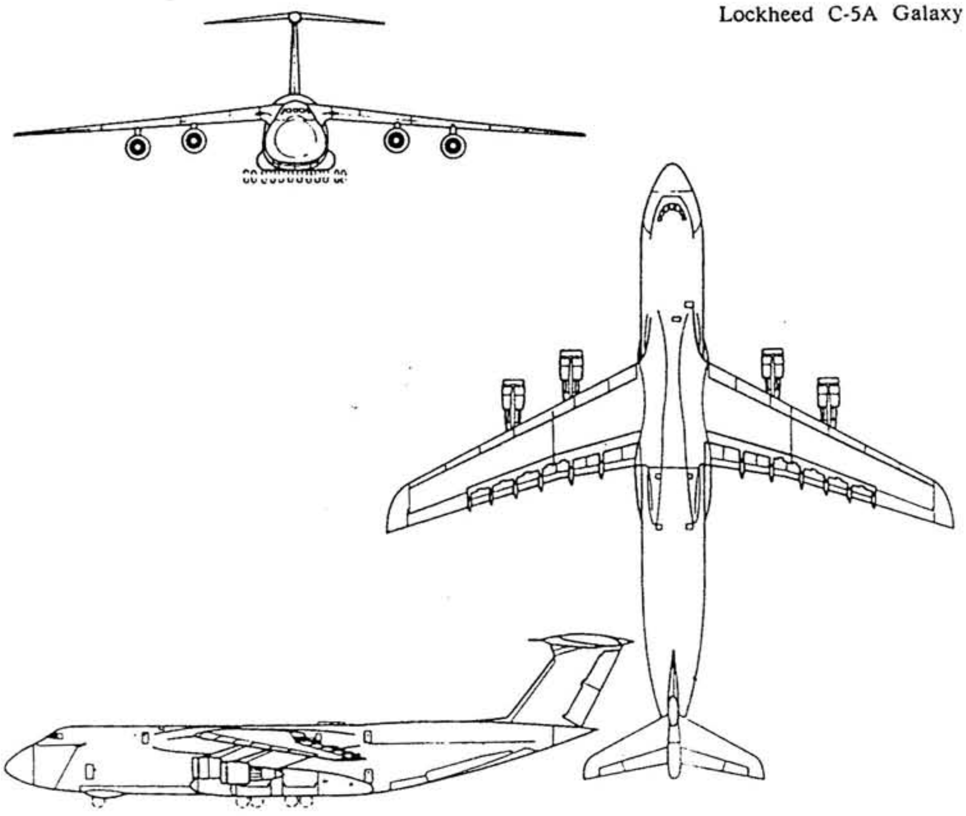
- Issues for the 1990s:

  - Where do we go from here?
    - Product line
    - Technology
  - Air traffic growth vs overcrowded airports
  - Fuel prices and fuel availability in a changing world
  - Aging airplanes
  - Deregulation
  - Etc. Etc.



Boeing 747SP

Boeing 747-200

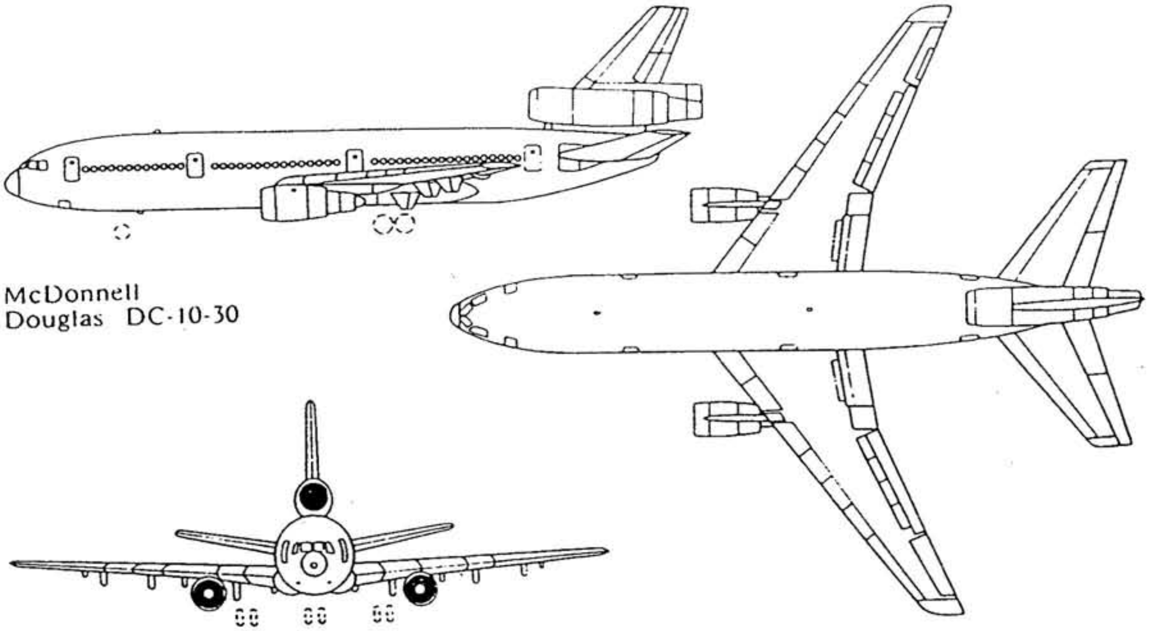


Lockheed C-5A Galaxy

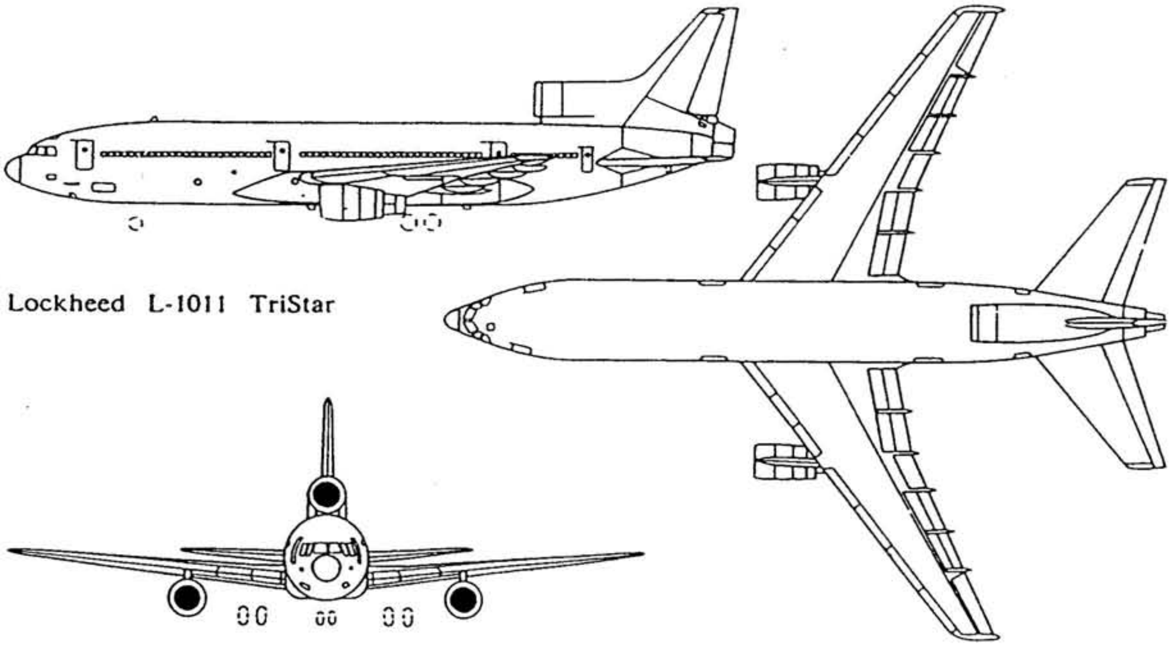
Transport Aircraft Design Objectives and Constraints

Issues	Civil	Military
Dominant design criteria	• Economics and safety	• Mission accomplishment and survivability
Performance	• Maximum economic cruise • Minimum off-design penalty in wing design	• Adequate range and response • Overall mission accomplishment
Airfield environment	• Moderate-to-long runways • Paved runway • High -level ATC and landing aides • Adequate space for ground maneuver and parking	• Short-to-moderate runways • All types of runway surfaces • Often Spartan ATC, etc. • Limited space available
System complexity and mechanical design	• Low maintenance—economic issue • Low system cost • Safety and reliability • Long service life	• Low maintenance—availability issue • Acceptable system cost • Reliability and survivability • Damage tolerance

Government regulations and community acceptance	• Must be certifiable (FAA, etc.)
	  • Safety oriented
	• Low noise mandatory
		• Military standards
		  • Performance and safety
		  • Reliability oriented
		• Low noise desirable
		  • Good neighbor in peace
		  • Dectability in war



McDonnell
Douglas DC-10-30



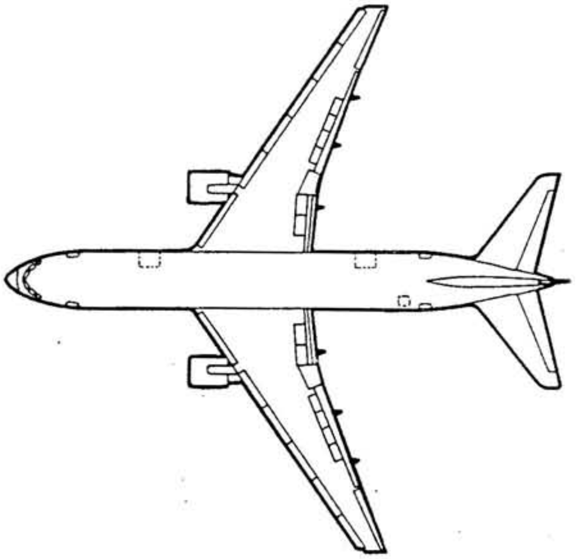
Lockheed L-1011 TriStar

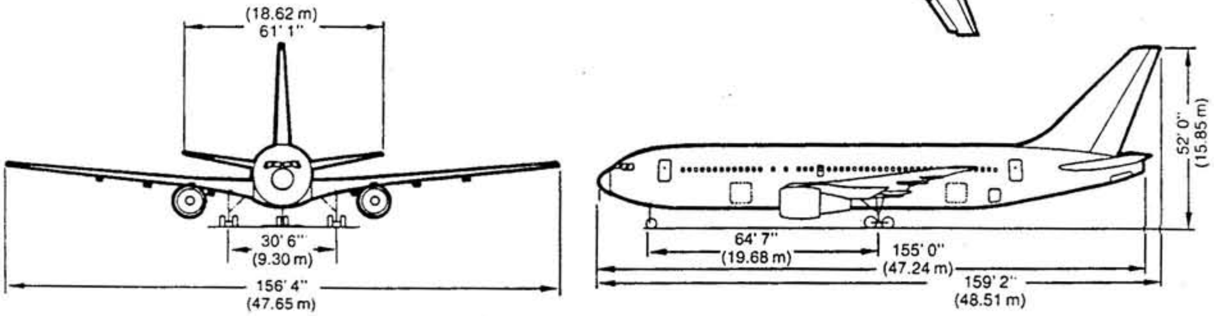
Newhouse, J., The Sporty Game, NY: Knopf, 1982.

Arrangement **767-200**

Passengers	
Basic Mixed Class	211
Basic All Tourist	230
High Density	290*
Engines	(2) JT9D-7R4 or CF6-80A
Containers	(22) LD-2

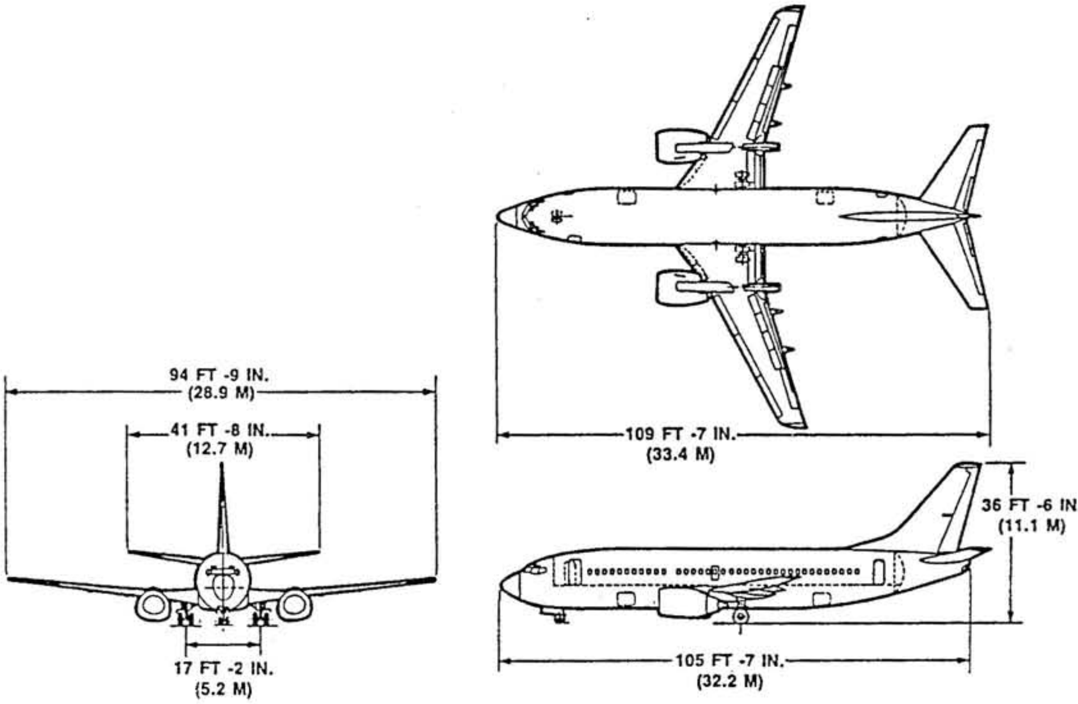
*More than 255 passengers requires optional second overwing exit

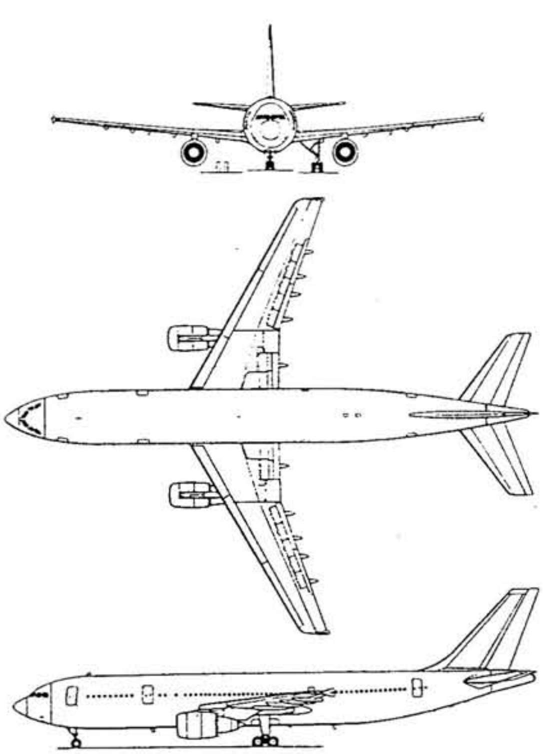




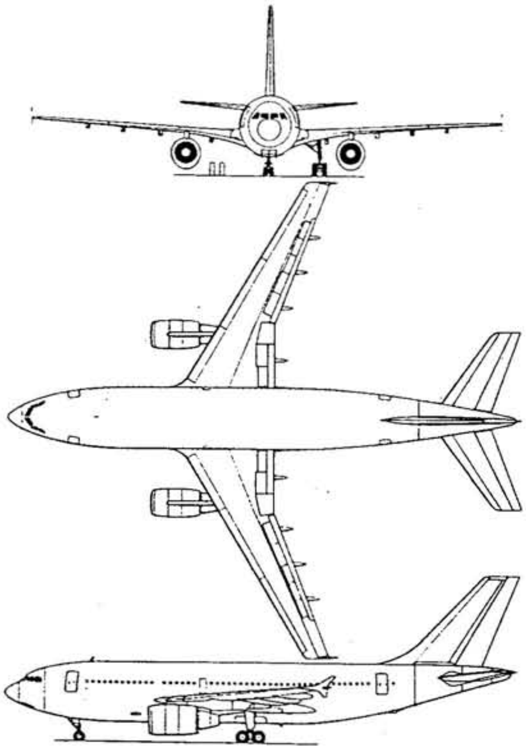
GENERAL ARRANGEMENT

737-300

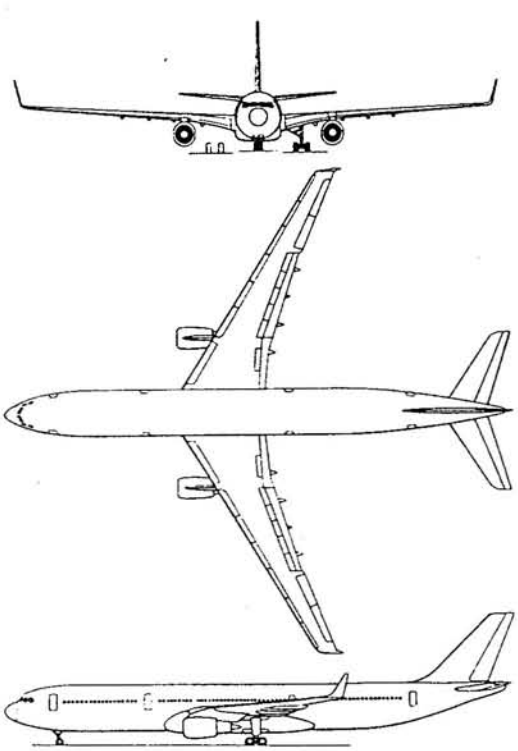




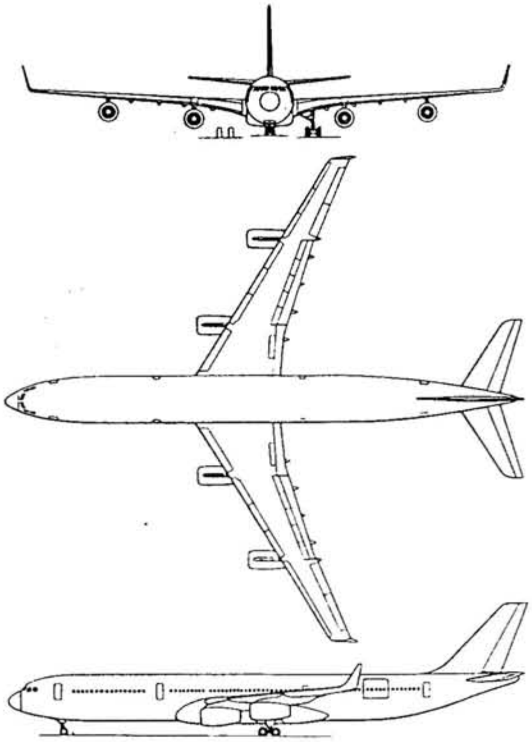
AIRBUS A300-600



AIRBUS A310-300

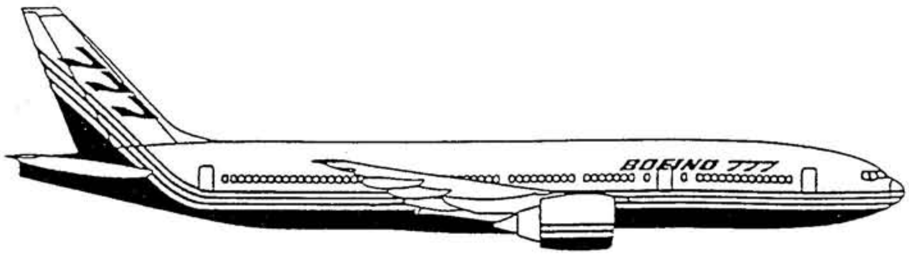


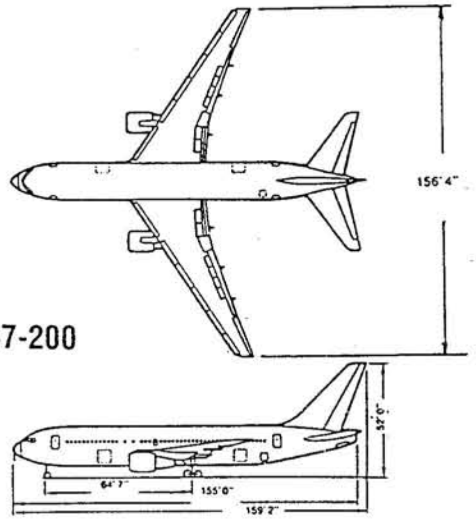
AIRBUS A330



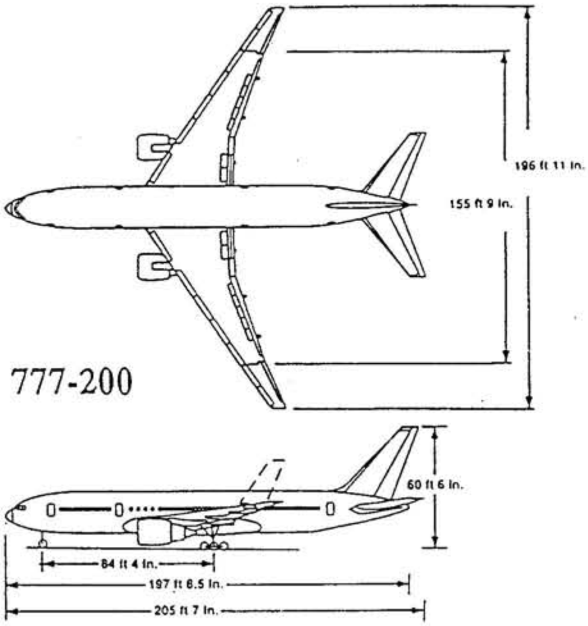
AIRBUS A340

The Competition

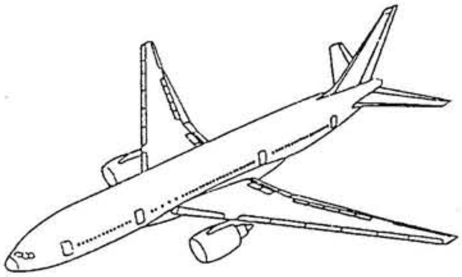




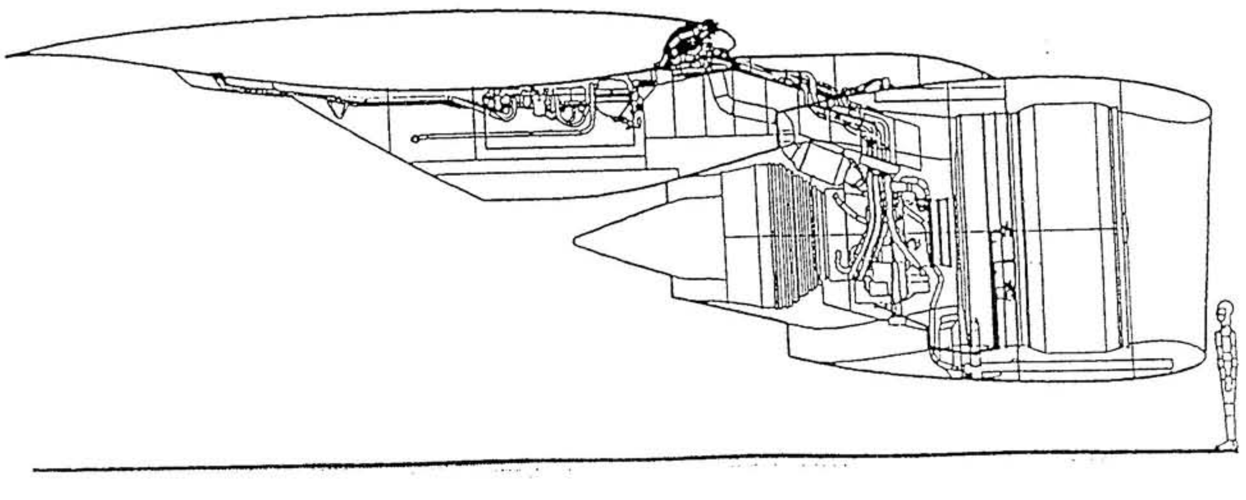
767-200



777-200

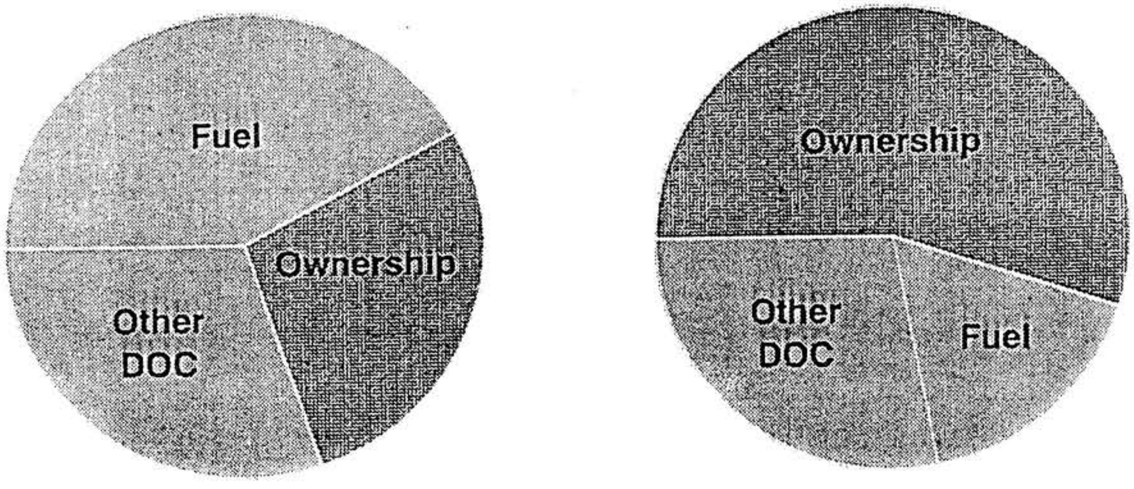


PW4073/PW4084 INSTALLATION for 777-200 Airplane



Change in Environment

Direct Operating Cost



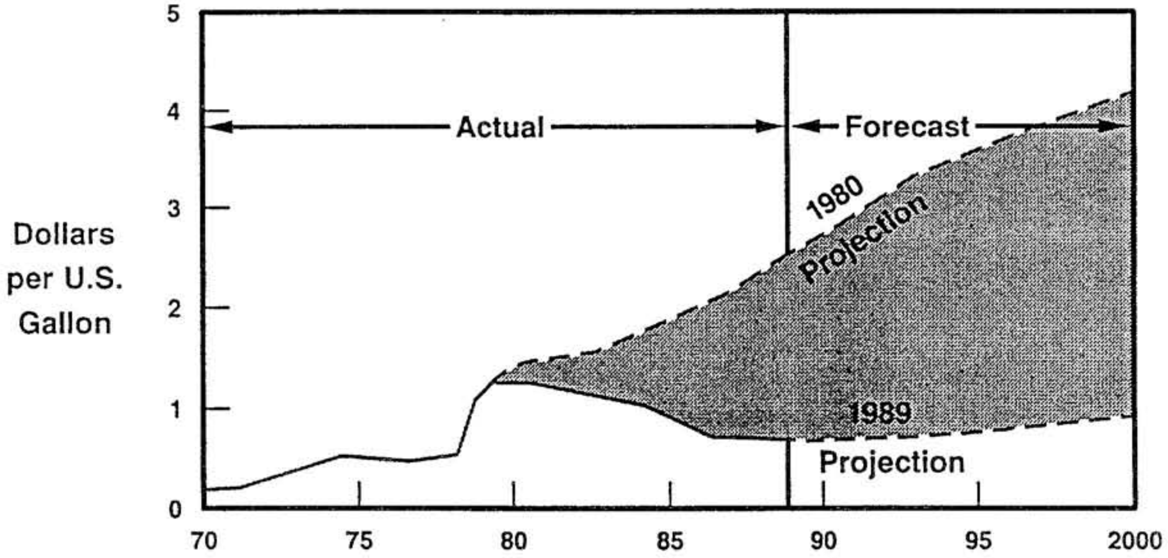
Mid-1970s

- Expensive fuel
- Low "real" interest

Current Reality

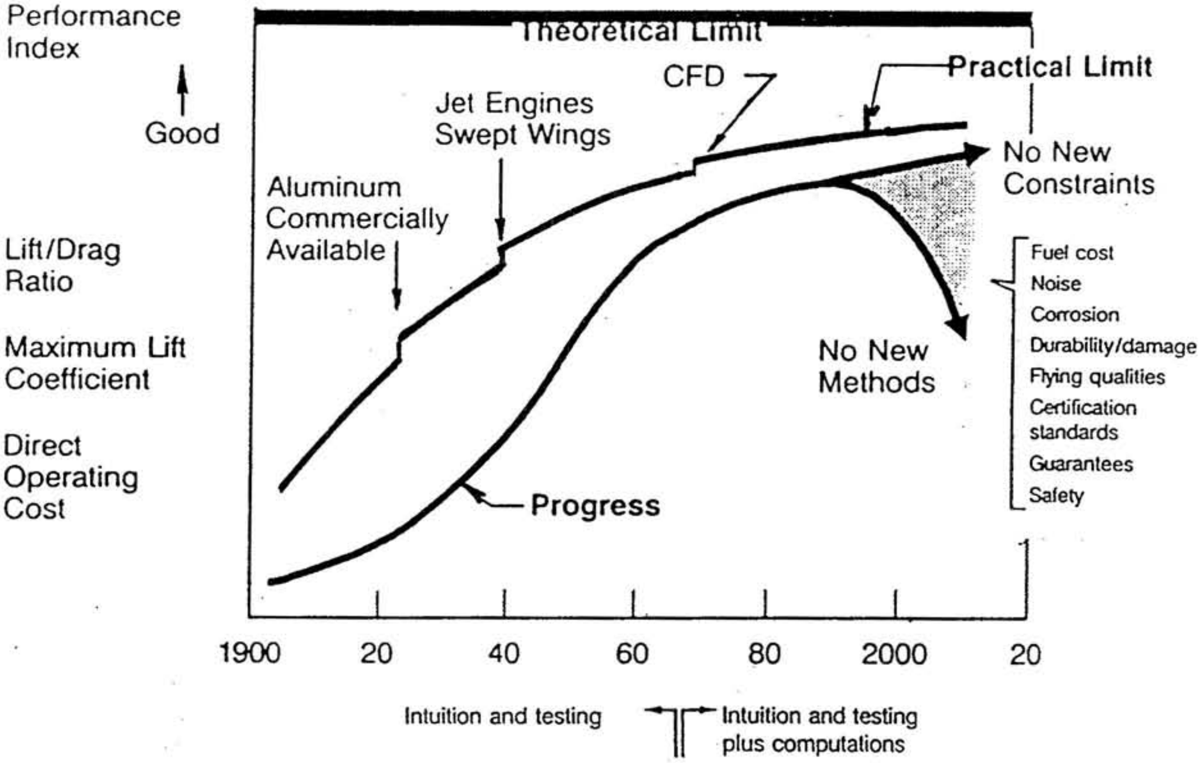
- Inexpensive fuel
- Higher "real" interest

Unpredictable World Jet Fuel Prices



Aeronautical Technology Development

Subsonic



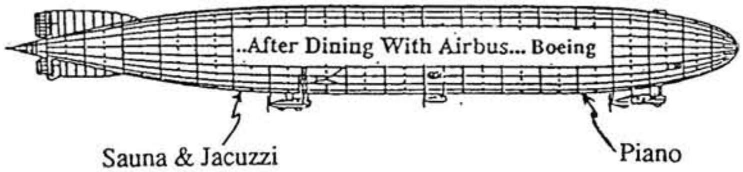
Subsonic aeronautics is a maturing technology. When progress is compared to what is practical and what is theoretically possible, we see a convergence. The gap between the practical limit and the level of performance we have currently achieved is shrinking. There are a number of ways to deal with this situation:

- Continue work in finer and finer increments until the achieved performance converges with the practical limit of the technology
- Plan technological breakthroughs that will raise the practical limit boundary, or exploit dormant technologies that would have the same effect, e.g., laminar flow control
- Start a new ball game, wherein the gap between the limit and present achievement allows more competitive leeway (e.g., supersonic and hypersonic transports)

All of these approaches are in the cards.

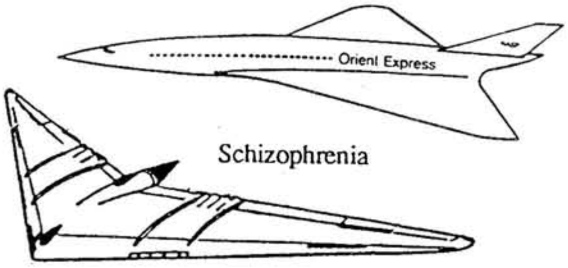
DREAM AIRPLANES

(One Person's Dream May Be Another's Nightmare)

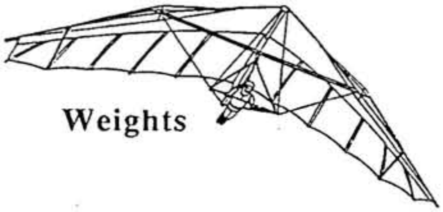


Payloads

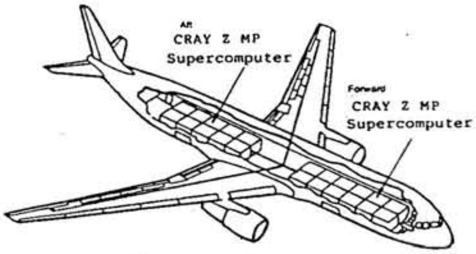
Marketing



Aerodynamics

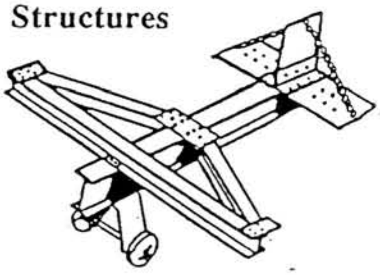


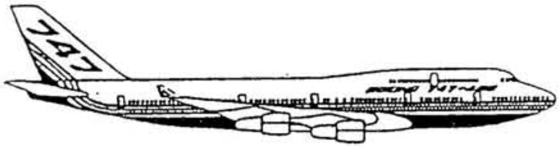
Weights



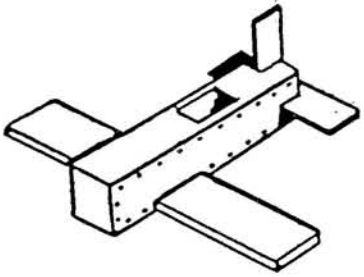
Flight Controls

Structures

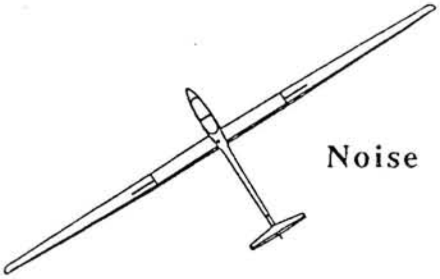




The Boeing Company

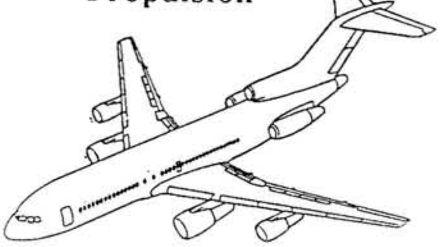


Manufacturing

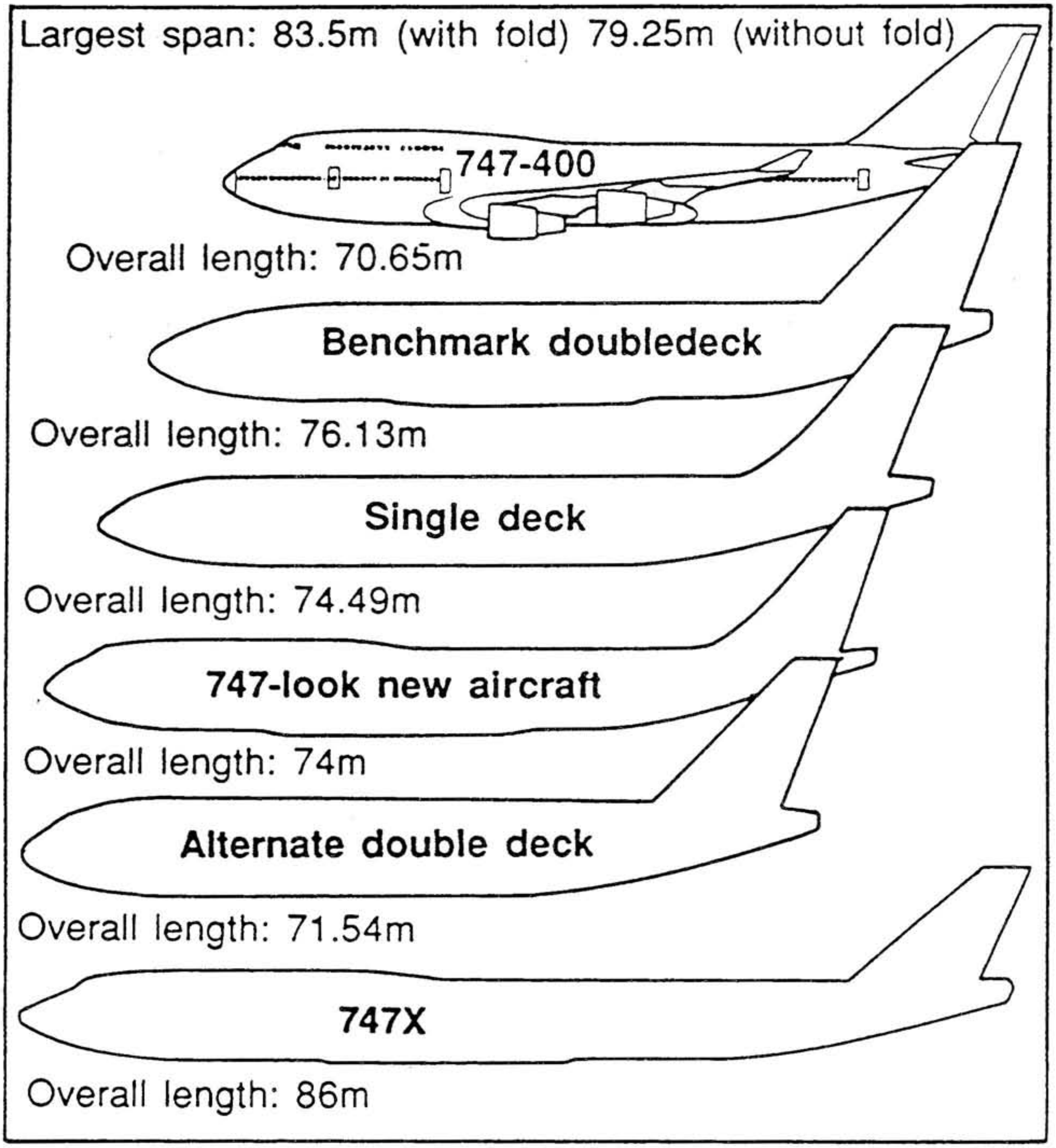


Noise

Propulsion



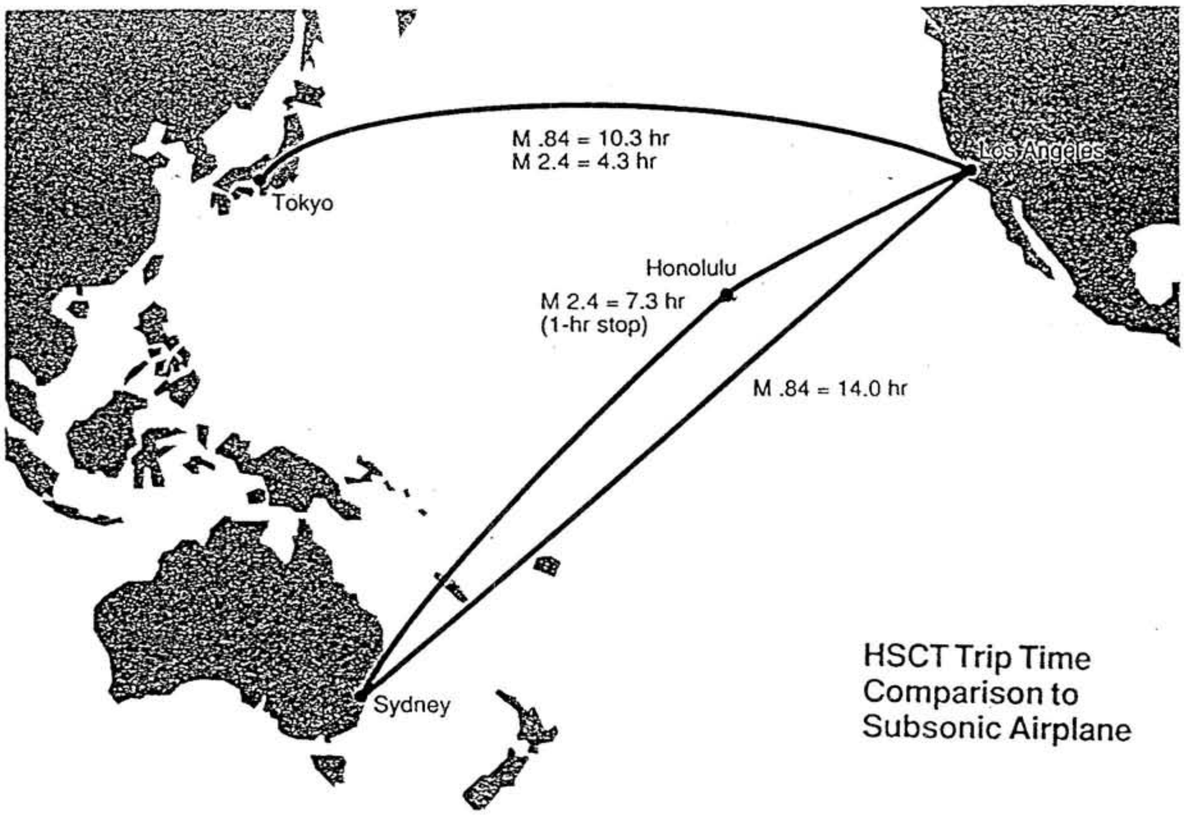
‘Possibles’ could enlarge Boeing family of airplanes



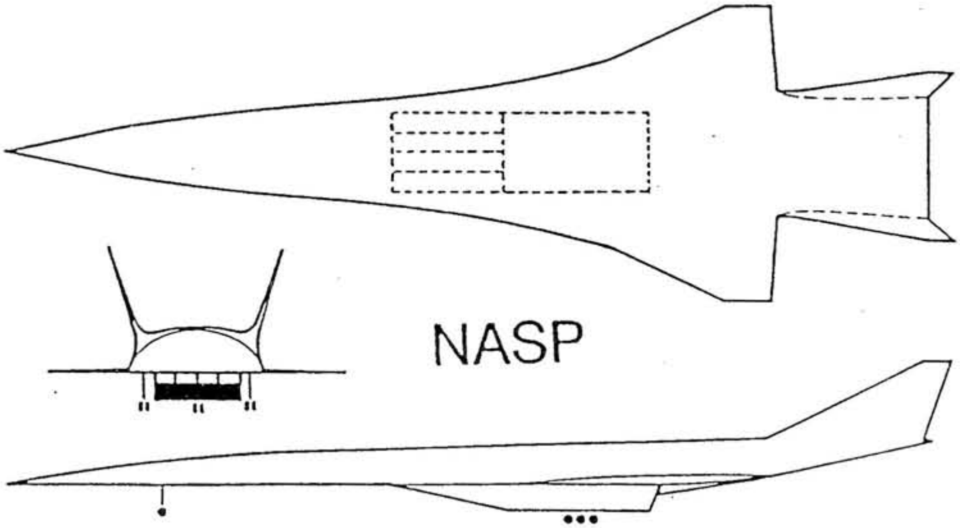
Boeing - New Large Airplane and 747X design studies

FLIGHT INTERNATIONAL 9 - 15 June, 1993

High Speed Civil Transport



HSCT Trip Time Comparison to Subsonic Airplane



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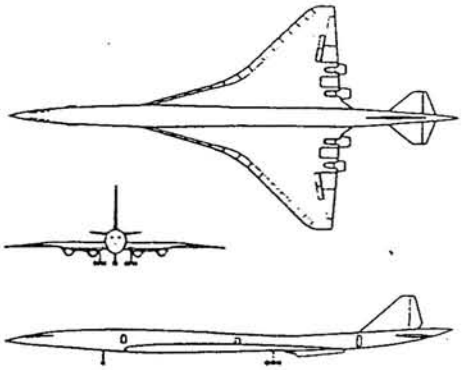
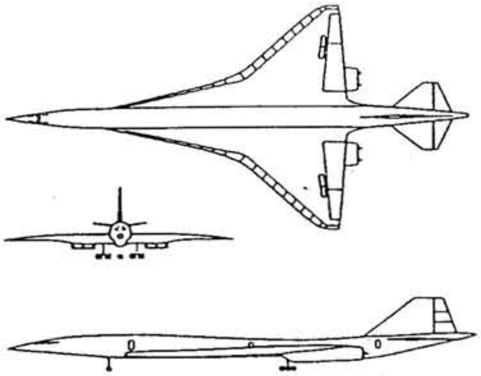
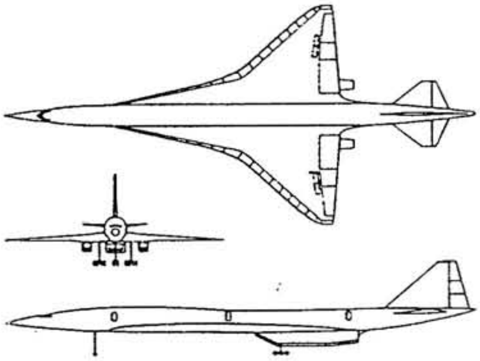
Orient Express ?



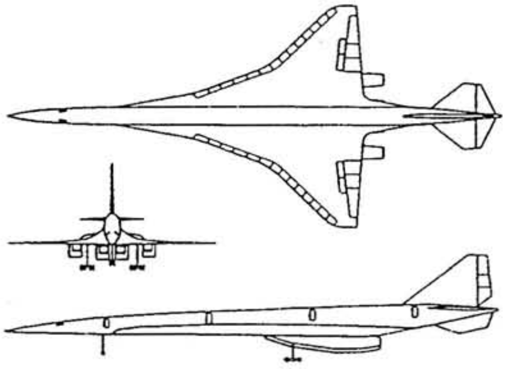
Mach 2.4 Configuration



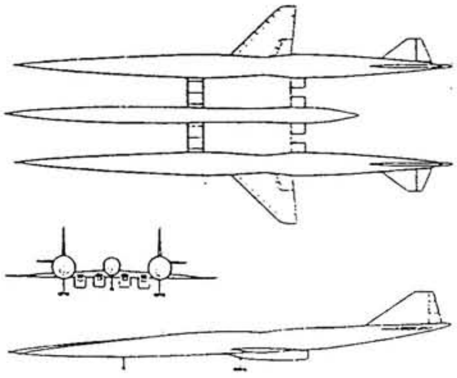
Mach 3.2 Configuration



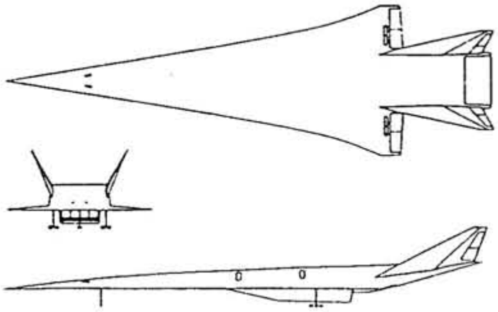
Mach 3.8 Configuration



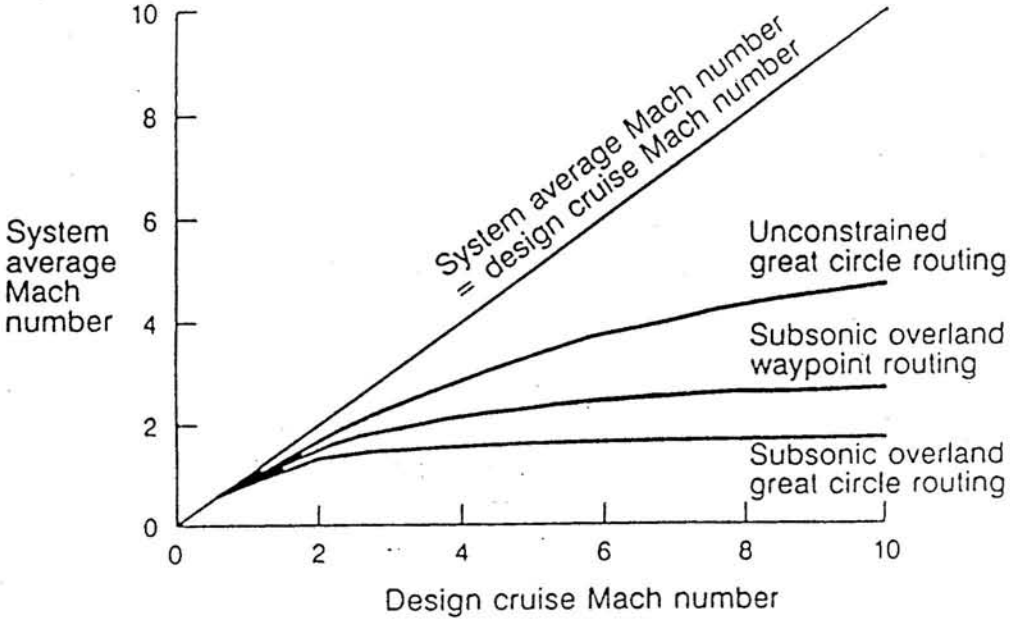
Mach 4.5 Configuration

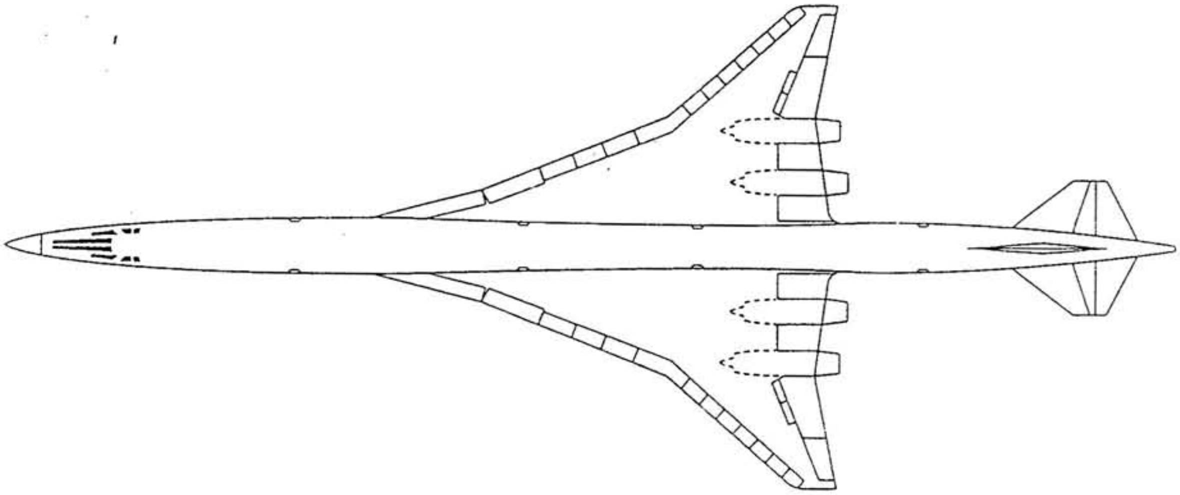


Mach 6.0 Configuration



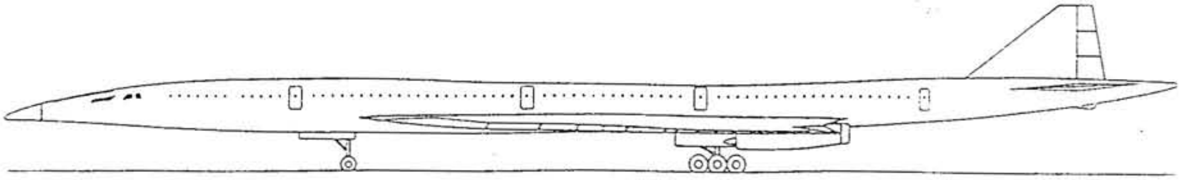
Mach 10.0 Configuration

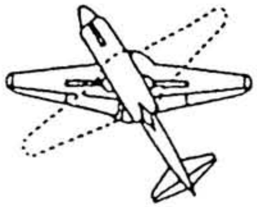




Current Baseline Airplane

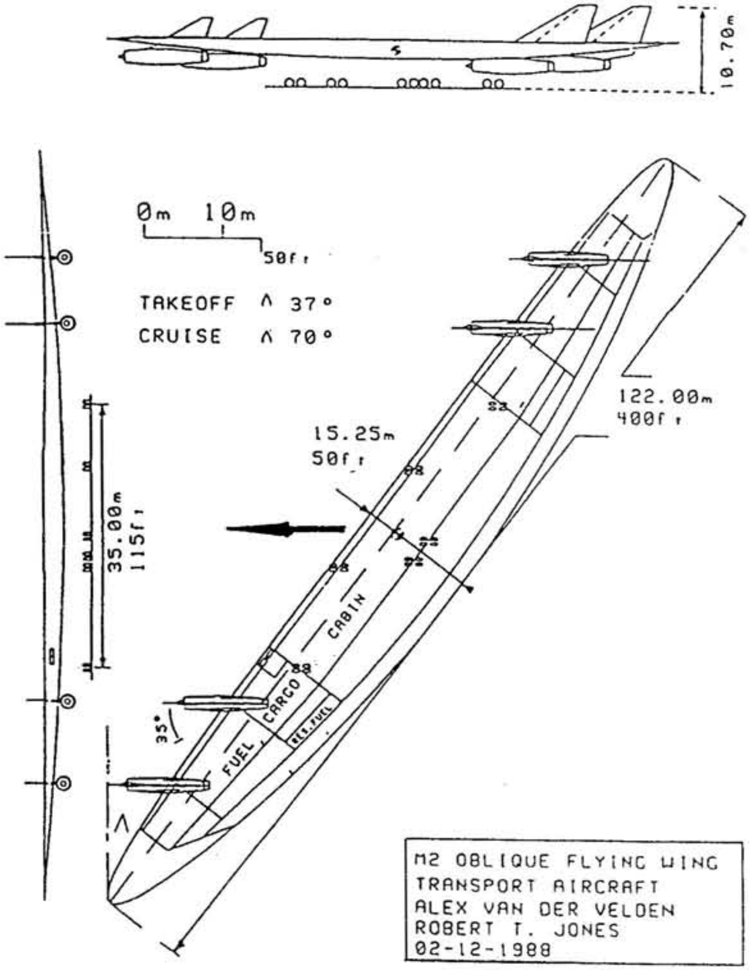
Maximum takeoff weight	700,000 lb
Fuselage length	310 ft
Wing span	130 ft
Triclass seating	292 passengers
Cruise speed	Mach 2.4
Design range	5,000 nmi
Takeoff field length	11,000 ft
Approach speed	155 kn

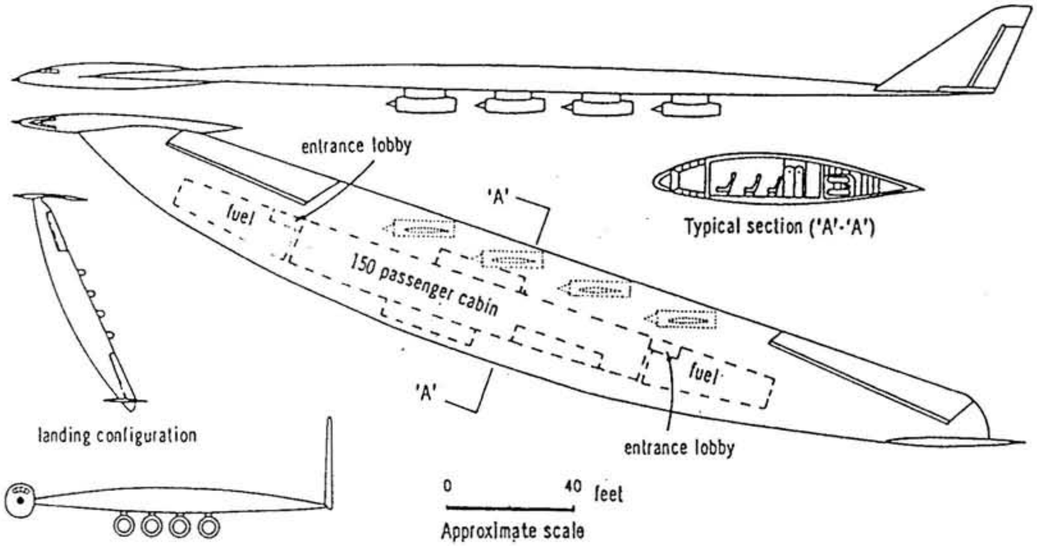




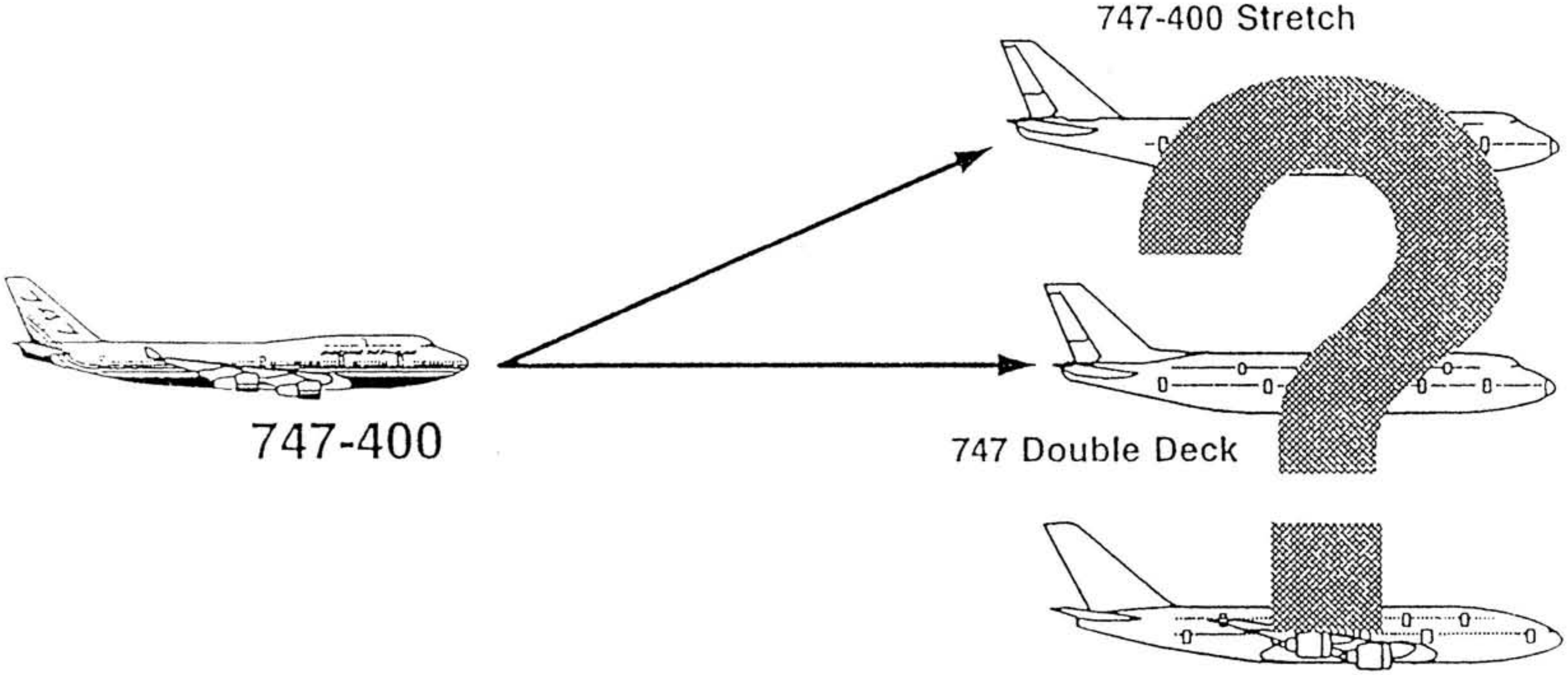
Blohm and Voss (Vogt)
Oblique Wing Fighter
Concept (1944)

NASA AD-1 Oblique Wing
Demonstrator (1978)





Handley Page Slewed-wing proposal, about 1961



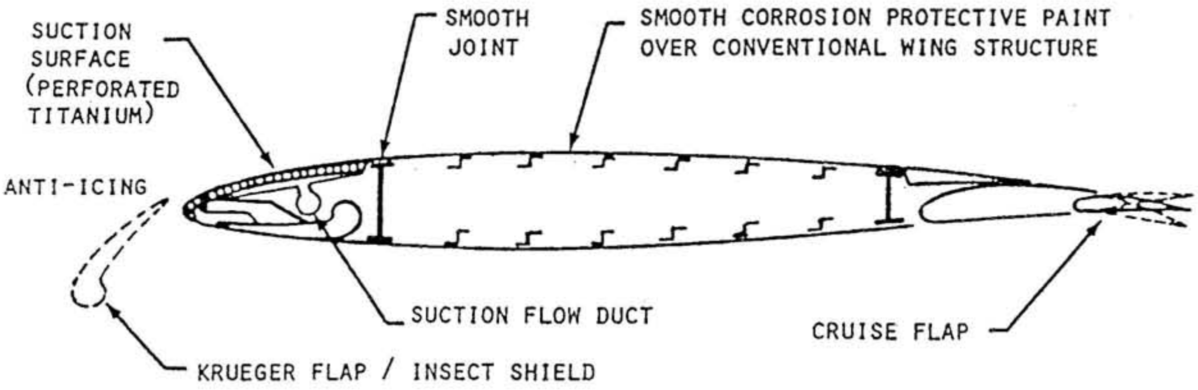
Large Airplane Development

PRACTICAL APPROACH TO HLFC APPLICATION

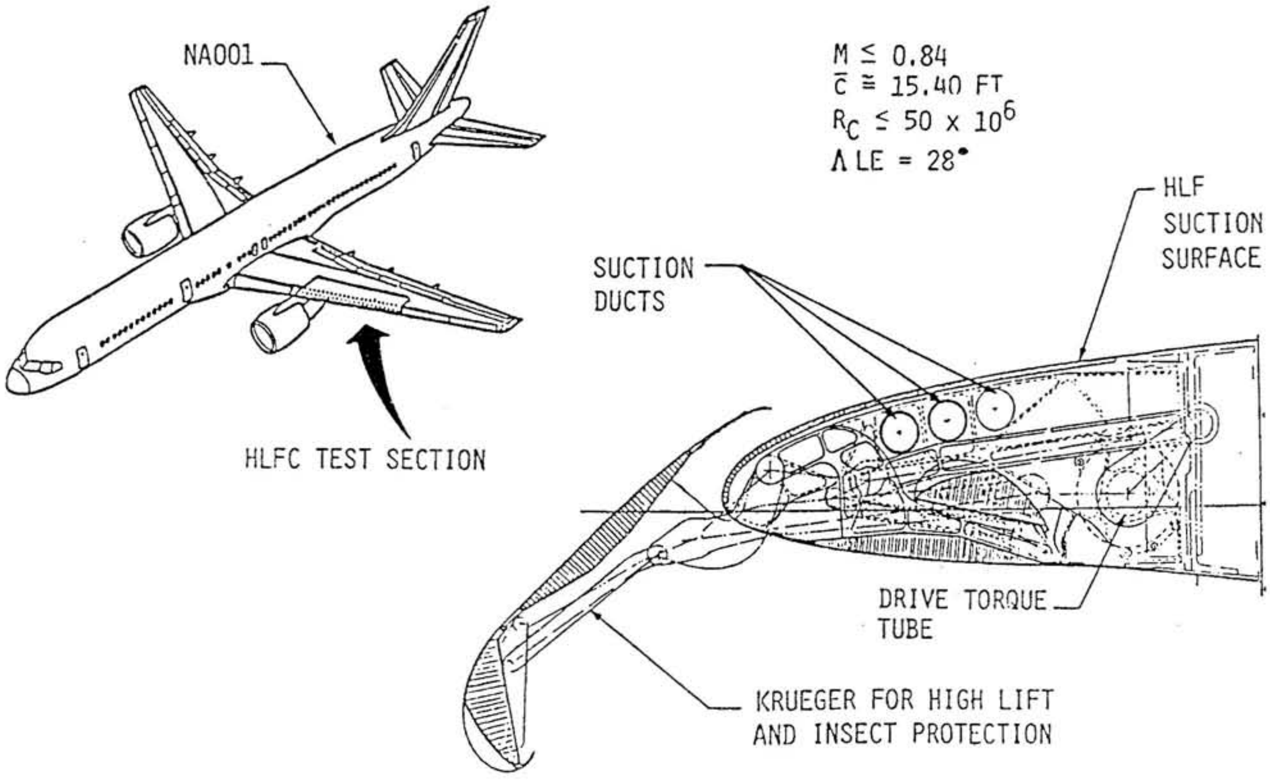
MAIN FEATURES:

- CONVENTIONAL SPARBOX CONSTRUCTION
- SUCTION IN L.E. REGION ONLY
- NATURAL LAMINAR FLOW OVER SPARBOX
- RETAINS GOOD PERFORMANCE AS TURBULENT WING

} "HLFC"



HLF DEMO CONCEPT

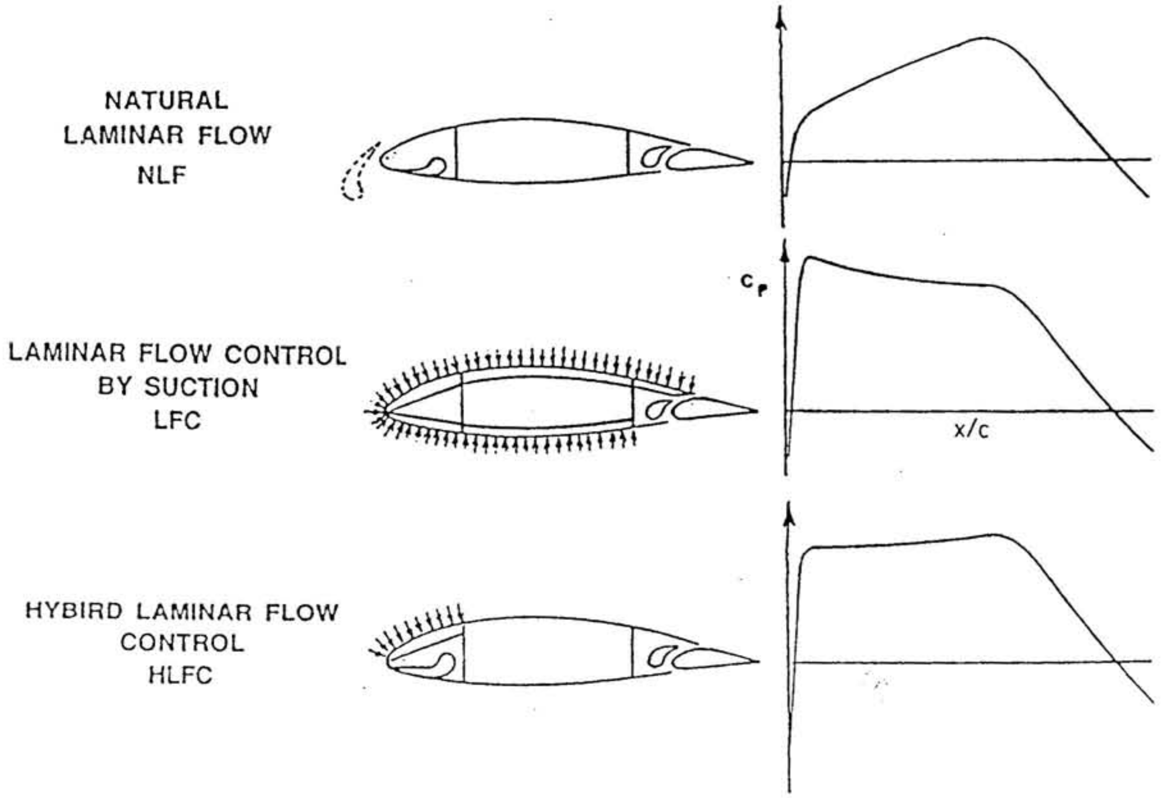


LAMINAR FLOW - THE CHALLENGE AND THE POTENTIAL

INTRODUCTION

Commercial air transportation has experienced revolutionary technology advances since WWII. These technology advances have resulted in an explosive growth in passenger traffic. Today, however, many technologies have matured, and maintaining a similar growth rate will be a challenge. We have come to the point where more complex technology must be addressed. At the Boeing Company we see the potential benefits of laminar flow as being worthy of the challenge.

TYPES OF LAMINAR FLOW CONTROL

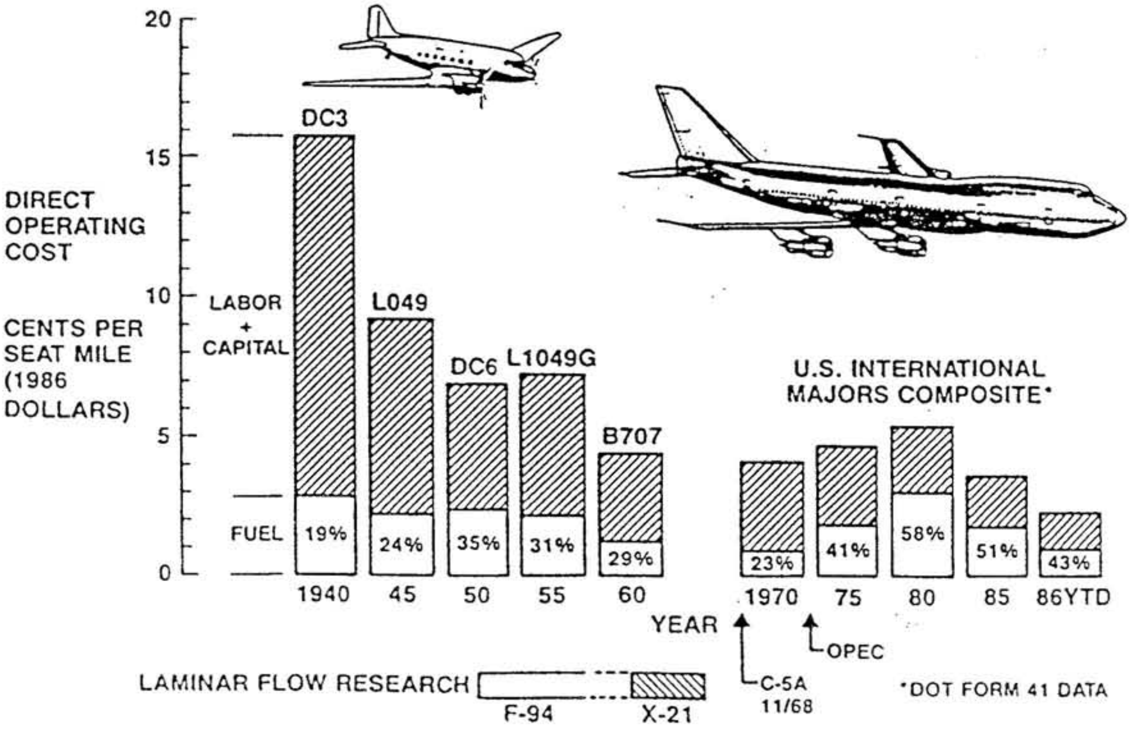


"Symposium on Natural Laminar Flow and Laminar Flow Control Research," NASA-Langley Research Center, March 16-19, 1987 (Proceedings in Press).

LFC PERSPECTIVE

The previous figures have shown some of the reasons for our interest in laminar flow. With potential gains of the magnitude shown, the obvious question is why laminar flow control isn't being applied? To put this matter in context, the data for long range transport aircraft shown in this figure has been assembled from several sources (Dept. of Transportation).

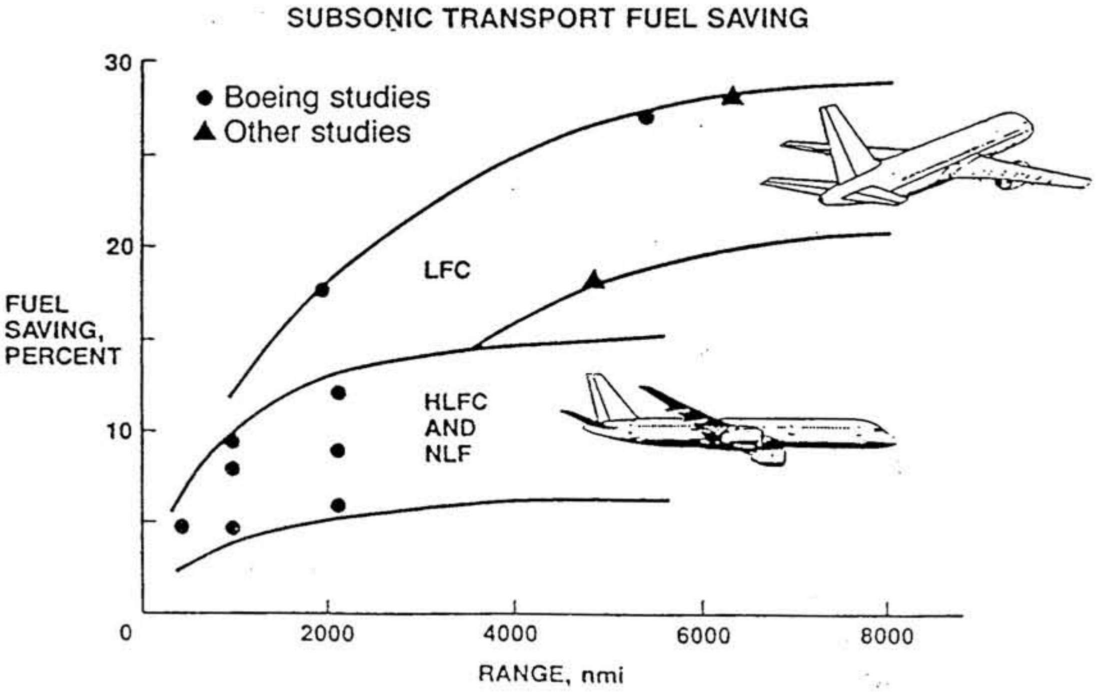
Since the era of the DC-3 we have seen dramatic improvements in commercial airplane performance and direct operating cost (DOC) reduction. For several decades fuel costs remained low and the contribution of the fuel to DOC remained relatively small. Only since the early 1970s has this equation changed, and, with the advent of OPEC and other related factors, we have entered an era where fuel prices have fluctuated dramatically. While detailed predictions of future fuel costs are controversial, the probability of a generally upward trend over time seems certain. From the viewpoint of our commercial airline customers, the cost of fuel is a major element of their overall DOC and will continue to influence their purchase decisions.



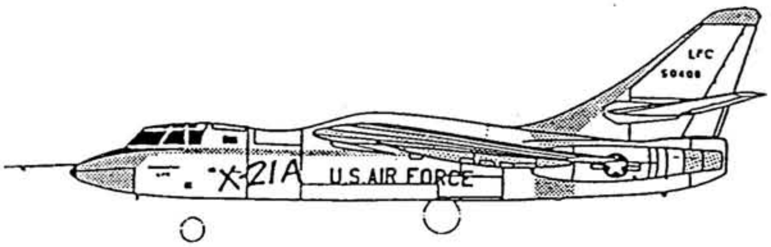
LAMINAR FLOW POTENTIAL - SUBSONIC

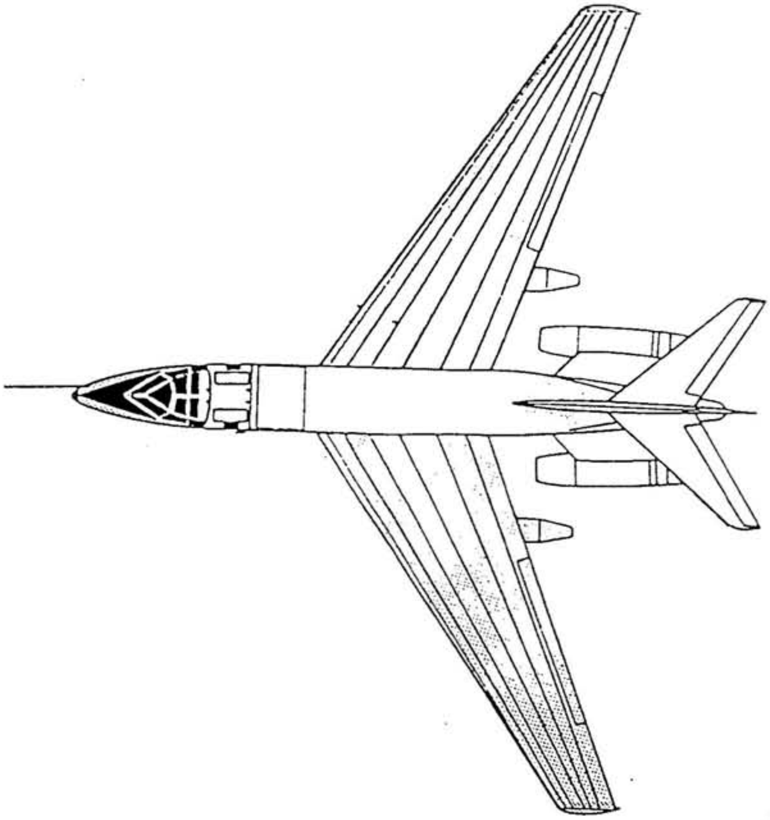
Many claims have been made over the past several decades regarding the potential advantages of "laminarizing" a transport type airplane. These claims have ranged from wildly optimistic projections to the pessimistic prognosis that it is technically feasible but economically and operationally absurd.

To place these views in perspective, consider the results of a limited number of trade-studies relating to the fuel savings anticipated from full and partial laminarization of transport aircraft. As shown in this figure, the increments in projected fuel savings are significant. The projections vary considerably depending on the nature of the laminar flow control concept employed, the extent of the airframe components to be laminarized, and the mission range of the vehicle. The conclusion one draws from these limited data is that, for long range subsonic transports, the potential fuel saving from laminar flow control is worth investigating.



Northrop X-21A





Length	75.2'
Wingspan	93.5'
Wing area	1,250 sq.'
Height	25.55'
Accommodation	5
Gross weight	83,000 lbs.
Empty weight	45,828 lbs.
Max. altitude	42,500'
Range	4,780 miles
Max. speed	560 mph

Summary: The X-21As proved conclusively that boundary layer control technique, known as Laminar Flow Control, is both effective and viable. However, they also demonstrated that LFC incurred certain maintenance penalties that were not easily overcome. Additionally, it proved that production technology for manufacturing LFC surfaces and related components, was feasible, but economically prohibitively expensive for all but experimental aircraft.

WHY LAMINAR FLOW HAS NOT BEEN USED

While the economics of long range transport operation does much to explain the lack of emphasis on laminar flow technology development, it does not fully address the question of why this technology has not been used.

One reason is that early experience with natural laminar flow airplanes was rather negative. There was not enough appreciation for the effects of skin surface condition and waviness. Smooth structure simply could not be built in those days. Recently, however, when we carefully smoothed the wing of a 30-year old T-33 trainer, we got extensive runs of laminar flow over almost the entire flight envelope.

The unfortunate history of the X-21 is another factor. Perhaps this program occurred too soon but it was driven by the potential application to the C-5. According to a summary (ref. 4) given at the 1974 NASA Langley laminar flow workshop, the X-21 "failed" in spite of many impressive accomplishments. Due to an incorrect design detail, that in retrospect appears easily avoidable, primary objectives of the test program were not met. Progress on the C-5 program could not wait for the design of a new wing and thus, laminar flow lost a major opportunity to display its real potential. The technical community recommended continuing a research program, but funds could not be made available. For laminar flow research this began a hiatus which was to last a decade.

Given its history, laminar flow technology was clearly not ready for application in a commercial environment. The risk was much too great, and necessary performance gains were more easily achieveable through other, more conventional technologies such as propulsion, structures, materials, and avionics. Generally speaking, the risk-benefit ratio for laminar flow had to be improved.

Failures of early application
+
Low cost of fuel
+
Competing technologies
+
Competition for funds

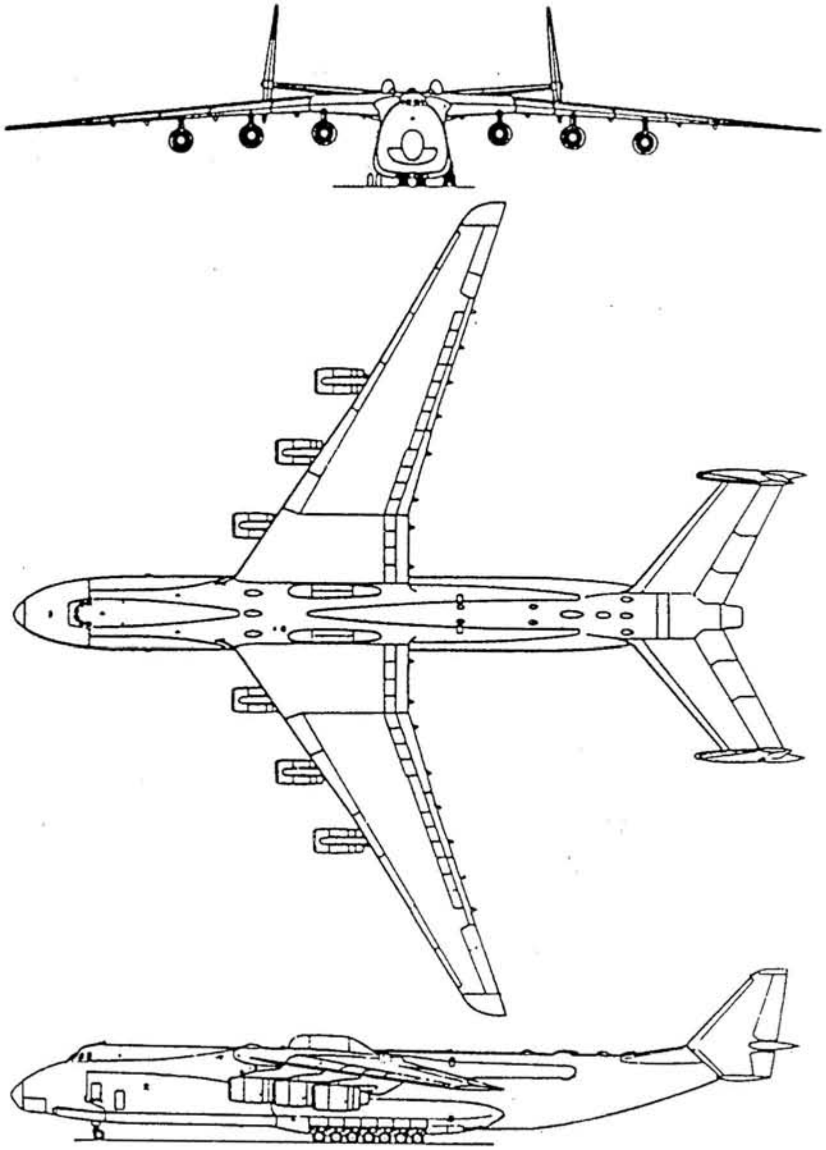
High risk/reward ratio

"Workshop on Laminar Flow Control," compiled
by C. T. D'Aiutolo, NASA-Langley Research Center,
April 6-7, 1976 (Proceedings Volume)

ANTONOV AN-225 MRIYA

Country of Origin: USSR.
Type: Ultra heavy-lift freighter.
Power Plant: Six 51,590 lb st (23 400 kgp) Lotarev D-18T turbofans.
Performance: (Manufacturer's estimates) Max cruise speed, 528 mph (850 km/h); normal cruise (with internal payload), 466 mph (750 km/h); range (with 440,917-lb/200 000 kg payload), 2,796 mls (4 500 km) at 435 mph (700 km/h).
Weights: Max take-off, 1,322,750 lb (600 000 kg).
Accommodation: Flight crew of six–eight. Freight hold of 141-ft (43-m) length can accommodate up to 551,145 lb (250 000 kg) of freight, or (externally) Buran space shuttle, a component of the Energia launch vehicle, or other outsize payload carried above fuselage.
Status: The first An-225 was flown on 21 December 1988, and a small number is expected to be built for the support of Soviet space programmes.
Notes: Evolved from the An-124 (see pages 22–23) and by far the world's largest and heaviest aircraft, the An-225 Mriya (Dream) is the result of a three-and-a-half year programme to develop a special-purpose heavy-lift transport vehicle primarily intended to carry large components of the Energia launch vehicle or the Buran space shuttle on special attachment points on top of the fuselage. For more conventional transportation tasks, the An-225 can accommodate outsize loads in its 21-ft (6,4-m) by 14·43-ft (4,4-m) cross-section freight hold. By comparison with the An-124, the An-225 has additional wing sections carrying two more turbofans, fore and aft fuselage plugs and an increased-span dihedralled tailplane with endplate fins and rudders. In addition, the number of independent twin-wheel undercarriage units has been increased to cater for the higher weights. Extensive use is made of systems thoroughly proven by the An-124, including the quadruplex fly-by-wire control system.

Dimensions: Span, 290 ft 0 in (88,40 m); length, 275 ft 7 in (84,00 m); height, 59 ft 4½ in (18,10 m).



ADVANCED CONFIGURATIONS FOR VERY LARGE SUBSONIC TRANSPORT AIRPLANES
(Some Opportunities for Interdisciplinary Synergism)

By

John H. McMasters
Bird Division
GREAT SPECKLE ENTERPRISES
An Independent Subsidiary of *THE BOEING COMPANY*

and

Ilan Kroo
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For Presentation at the
NASA Workshop on Potential Impacts of
Advanced Aerodynamic Technology
on Air Transportation System Productivity

NASA Langley Research Center
Hampton, VA

June 29 - July 1, 1993

ABSTRACT

The prospect of developing a new very large subsonic commercial transport airplane (VLSCTA) with approximately 50% greater passenger capacity than current models of the Boeing 747 presents some major challenges as well as some major opportunities. A configuration for such an airplane developed along the traditional lines of the basic B-47/707/747 paradigm suggests that major problems arise in extrapolating much beyond the size of an existing 747-400. Further, possible technological advances such as hybrid laminar flow control show only modest advantages when applied in a practical manner to conventional transport airplane configurations. For reasons described in the text of this note, a small conceptual design exercise was begun to examine possible unorthodox configurations for a "600-650 passenger airplane" which might potentially resolve some of the more obvious problems (runway/taxiway limits, emergency passenger evacuation) associated with conventional configurations. The purpose of this note is to describe one possible alternative large airplane configuration (a single deck 3-surface airplane with a highly non-planar wing) which emerged from this study and suggest the need for a different organizational approach to the design of such a vehicle should it prove to have some merit. The objective in reporting this effort is to stimulate a constructive discussion of how we might deal in the future with unorthodox airplane configurations and associated technology development, rather than to attempt to sell the specific configuration discussed.

INTRODUCTION

The conceptual design study and the subsequent recognition of its interdisciplinary design implications reported in this note had their origins in several diverse activities in which the first author currently is involved:

1. Teaching Airplane Design. Some of the initial configuration concepts discussed here were generated as part of an effort to explain to co-workers and students at the University of Washington "What a 'configurator' does." This exercise has gotten out of hand as will be described presently.

2. Aerodynamics Research and Development Process Management Team. As a member of this team, the author has an informal on-going task labeled rather ambiguously "a different perspective." The organizational implications that emerged from this conceptual design study are one example of a somewhat different perspective on our overall R & D effort.

3. BCAG Engineering Division Summer Intern Program (Ref. 1). For the past five years the author has coordinated curriculum development for the training portion of this program. For 1993 it had been tentatively decided to use the issues (rather than the specifics) from a very large subsonic commercial transport airplane (VLSCTA) effort as the basis for developing a new set of intern design exercises for the program. Homework for this effort started a bit early--with the results reported here.

4. A fifty-year fascination with everything that flies (especially big flying machines).

From these items sprang the following ideas regarding some possible opportunities to capitalize on the huge size of an airplane considerably larger than a Boeing 747 rather than fight with the problems its size poses, and an appropriate approach to organizing an R & D effort to address such opportunities.

SOME CONFIGURATION OPTIONS FOR A NEW LARGE AIRPLANE

The basic very large airplane problem revolves around accommodating (in some comfort) over 600 passengers in an efficient airframe which is to be compatible with existing airports (gates, taxiways, runways, etc.), meets customer requirements, and expected noise regulations, safety standards, etc. The obvious approach has been to take a proven configuration recipe, blow it up to the size required, and then tinker with it until it works. The Boeing 747 has worked very well for about twenty-five years based on the original Boeing B-47/B-52/707/KC-135 paradigm. The evolution of this basic configuration paradigm and its merits are shown in Figure 1 and has been well documented recently by George Schairer (Ref. 2), Bill Cook (Ref. 3) and Roskan (Ref. 3) which follows from Torenbeck (Ref. 4). This approach thus represents a logical point of departure for very large airplane configuration studies. What we get is shown in Figures 2 and 3. It also suffers from quite a shopping list of hang-ups (or potential showstoppers if design solutions cannot be found). In the end it may be thought of as the ultimate cookie-cutter airplane from a long line of successful recapitulations (by Boeing and its competitors) on a good basic scheme. The question that arises is: Is this basic, almost fifty year old paradigm really the appropriate (or best) one for an airplane substantially larger than a 747? Perhaps not, and it is useful to consider why this may be. Consider:

1. The ideal cruising airplane (at least from an aerodynamicist's viewpoint) wants to be a simple, elegant flying wing. Everything that does not contribute to the efficient generation of lift should be placed in or on the wing provided that in doing so no significant weight penalty is incurred.

2. A typical business class passenger may be assumed to be approximately six feet tall. A typical transonic cruise air foil is currently about 12% of wing chord in thickness. Thus, if the wing chord exceeds about 70 feet, it becomes feasible to imagine placing the payload in the wing rather than in a drag and weight producing fuselage. [Note: As shown in Figure 3, the MAC of the conventional very large airplane shown is about 33 feet while the root chord is almost 50 feet. Thus we are getting closer, but not close enough with existing airfoils, to being able to build a greater than 600 passenger span loader flying wing.]

3. Contrary to popular myth, aerodynamics is not a sunset technology and there are still a few tricks in our bag which have yet to be exploited in a transport airplane. Among these "new" items are:
    a) Laminar flow control.
    b) Active (e.g. Griffith/Goldschmied Refs. 6 and 7 and Fig. 4) and passive (slotted cruise) boundary layer control airfoils.
    c) Really non-planar wings (i.e. far beyond "visible technology" winglets).

4. There are similar opportunities in other disciplines. Among these we may list:
    a) Fly-by-wire/fly-by-light active control systems.
    b) Composite (anisotropic) structural materials.
    c) Computer tools to deal with "designed aeroelastics," non-planar wings, etc.

5. The traditional approach to developing a new airplane has been to dice up the overall problem into small parts that individuals and small groups can deal with, and then organized within fairly strict discipline boundaries, work each problem separately assuming that after being passed back and forth into various hands in sequential steps, the sum of these discrete parts will somehow add up to a good, competitive airplane. In very many cases this process has worked--witness Boeing's sales record over the past thirty years. At the same time it may be argued that we have become organizationally and intellectually "muscle bound" by our past success.

After stirring the above ideas around for a while and becoming increasingly discontented with the configuration shown in Figure 3, the alternative schemes shown in Figures 5 and 6 and then Figures 9 through 12 began to suggest themselves. It should be made clear here that what is displayed was never intended to be more than a sort of qualitative and unofficial concept scoping exercise wherein the objective was to see if a plausible alternative airplane configuration could be identified which directly addressed specific problems and issues confronting a very large program during the early stage in design work.

The large size of any greater-than-600-passenger airplane immediately suggests a span loader configuration e.g. Fig 6. Serendipitously, a "flying wing" is also a good candidate for laminarization. A quick (and crude) calculation suggests that using conventional airfoil technology, the needed wing still isn't physically thick enough until it carries around 800 passengers or it is swept exorbitantly, which is of course antithetical to the requirements for LFC.

A "conventional" wing of this sort also presents a lot of other problems, particularly with respect to passenger loading and emergency evacuation, gate clearance and engine placement. On the other hand, recent precedents regarding the use of folding wing tips on the Boeing 777 and establishment of ETOPS as a more-or-less okay thing to do, suggest that a further step forward might be to reconsider the use of various forms of active boundary layer control on a commercial transport airplane. Since what is wanted is an unconventionally thick cruise airfoil, an obvious candidate is the Griffith airfoil invented in Britain fifty years ago and more recently advocated in this country by Fabio Goldschmied (Refs. 6 and 7) and others (Ref. 8). Limited (low-subsonic) test data and calculations suggest it might work provided enough suction is provided. What all this implies with regard to the problem at hand is shown in Figures 4 and 5. It should also be noted that a span loader configuration is automatically going to have a lot of wing area which means in turn that at cruise conditions airfoil section lift requirements will be rather low and therefore offers an opportunity to trade section lift for thickness while retaining adequate critical Mach number on a wing of acceptable (for LFC purposes) sweep. High-lift system requirements are similarly reduced, at least in principle. As a final side benefit, the rather unorthodox geometry of a Griffith/Goldschmied airfoil suggests the possibilities that when it exceeds a given thickness, the entire aft wing spar/pressure bulkhead area becomes available as the location of emergency escape doors, thus potential ameliorating a major problem with any large airplane configuration.

The sort of configuration which emerges from this line of thinking is shown in Figure 6 and still fails because of its likely enormous wing span and an assortment of handling characteristics problems both in the air and on the ground. To address the "wing span" problem(s), a recent study by Kroo at Stanford (summarized in Figs. 7 and 8) is of considerable interest. Kroo has calculated the induced drag span efficiency factors for a wide range of non-planar (when viewed from the front or rear) wing configurations and shows the clear advantage of a wing with very large "winglets" compared to a planar wing of the same projected area and span. Well, we knew that, but a bit more intriguing from his menu of unorthodox wing shapes is the "C-wing" configuration which amounts to a pair of small horizontal winglets on top of the ordinary (very large) vertical winglets. While this configuration shows only a small increase in span efficiency (in a Treffefz plane sense) compared to the simpler wingleted configuration, quite a different picture emerges when one contemplates sweeping such an arrangement by a conventional amount (say, about 35° on all surfaces). This arrangement puts the horizontal "winglet-lets" in roughly the position of a T-tail horizontal stabilizer relative to the rest of the wing and operating with a down load.

From this point it doesn't take much imagination to transform the simple span loader in Figure 6 into the C-wing configuration shown in Figures 9 and 10 which along the way became a 3-surface (Not a canard!) airplane for the reasons outlined in Refs. 9 and 10. This new configuration retains many of the features of the span loader with a projected wing span reduced to that of the conventional (baseline) very large airplane with its wing tips folded and about the same (on paper) induced drag characteristics as the conventional baseline with 281 feet of span. The price is a pair of winglets which are each roughly the size of the vertical stabilizer on a 747 (which is still a lot shorter than the tail height of the baseline). This all goes on and on from here as outlined in Figure 10.

BUT WHAT DO WE "DO WITH IT?"

The airplane configuration thus described is unconventional in more ways than its mere size and configuration suggest. Traditional design/evaluation approaches which deal with each technology element from a discipline specific viewpoint are not capable of adequately dealing with the opportunities for interdisciplinary synergism a fully integrated system approach could provide. As an example, it is hard to recall a commercial airplane program in which airfoil technology had any very direct relation to the problems confronted by a payloads group. [Note: At Boeing the Payloads organization deals with everything a passenger sees upon entering the airplane (e.g. seats, interior panels, lighting, galleys, lavs, etc.)]. In the configuration proposed here, aerodynamic and payload issues are tightly bound together and seem to demand a bit more than simple "design/build teams" and "concurrent engineering" to satisfactorily resolve.

As a first step towards organizing a proper research and development effort, the organizations involved should experiment with not only the advanced technologies which might be incorporated in future products, but also the new organizational structures which will conduct such design and development efforts. Two key elements of an advance organizational structure which can be envisioned are:

1. Traditional discipline (aerodynamics, structures, etc.) boundaries should be erased--except in so far as necessary skills are retained and as specific discipline identifications serve some useful administrative function.

2. Our new products should be thought of as complete systems made up of major interlocking subsystems, the design of which are to be conducted by appropriate (and perhaps non-traditional) teams of people with the right expertise and outlook.

The conceptual design proposed earlier serves as a convenient vehicle to describe in more specific terms how this might work.

Consider two major aspects of the overall airplane system proposed here: air flow and noise. Neither of these is a traditional "sub-system" but to satisfactorily resolve the many varied issues involved, they may be thought of as "processes" to be managed (designed) with ensembles of mechanical devices which do add up to a "system." Thus consider a design organization which includes:

1. An Air Flow Management Team
   A major job of this team would be the traditional one of developing the overall aerodynamic configuration of the vehicle (as a joint effort between aero configurations, stability and control, propulsion, structures, weights, and so on). In this case, however, much of the aerodynamic advantages (and disadvantages) of the configuration depend on efficiently sucking (or possibly blowing) various quantities of air inside the airframe. Thus the central job of this team is to synergistically deal with all the air that flows through and around the configuration. Thus it should deal not only with the lift and drag optimization of the vehicle but the combined flow of the environmental control system, the various boundary layer control systems, the de-icing flow and the associated auxiliary power unit (APU) and engine systems, etc. Such a team would be made up of individuals (supported by a myriad of satellite groups looking at specific elements of each sub-subsystem) who adopt a new attitude: What can I (as, say, an aerodynamicist) proactively, rather than reactively, do to solve a problem traditionally assigned the responsibility of some other member of the team with expertise in another discipline? How might I creatively "compromise" my design to solve someone else's problem, perhaps even before they realize they have one?

2. A Noise Management Team
   A major problem identified in connection with the new large airplane program is that of the community noise generated by such a huge, heavy airplane. It is apparently not now clear how a 747-type configuration with reasonable operating economics and safety margins can meet even current Stage 3 noise regulations. This issue holds for any large airplane configuration of course, and on a more fanciful level might be dealt with by trying to manage the noise that, after all reasonable steps have been taken to get rid of it, remains unavoidably present. Recognizing that there is a sometimes fine line between "noise" and "music," suppose we manage the noise we have with a team that includes a perceptual psychologist and a musician. Thus, if I as an aerodynamicist on the team have a stray vortex which I can control, I might add its dulcet woodwind tone to the Symphony for a New Large Airplane on Approach is G-Whiz Major which my team is trying to compose. And so on.

If one continues to think along such lines, it becomes clear that our enabling research efforts ought to be conducted along similar lines. The principle "new" things we need to do are:

1. Use our imaginations.
2. Adopt a new attitude (i.e. think with a truly "one team" outlook).
3. Forget old organization boundaries (without forgetting the bases of our individual expertise).

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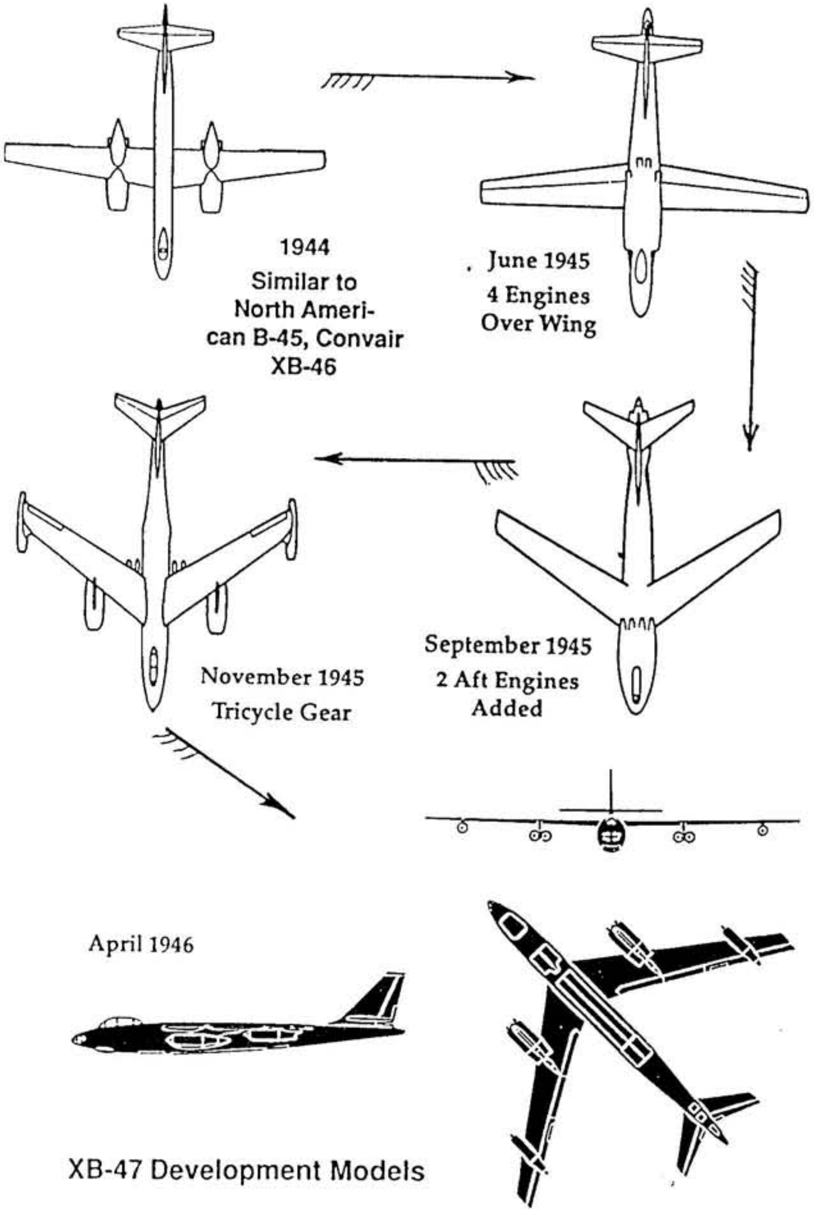
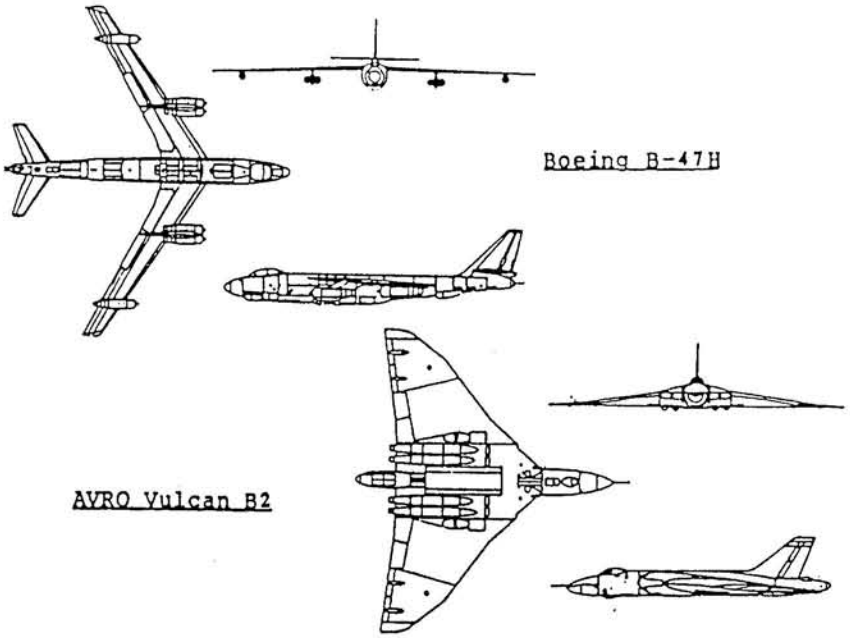




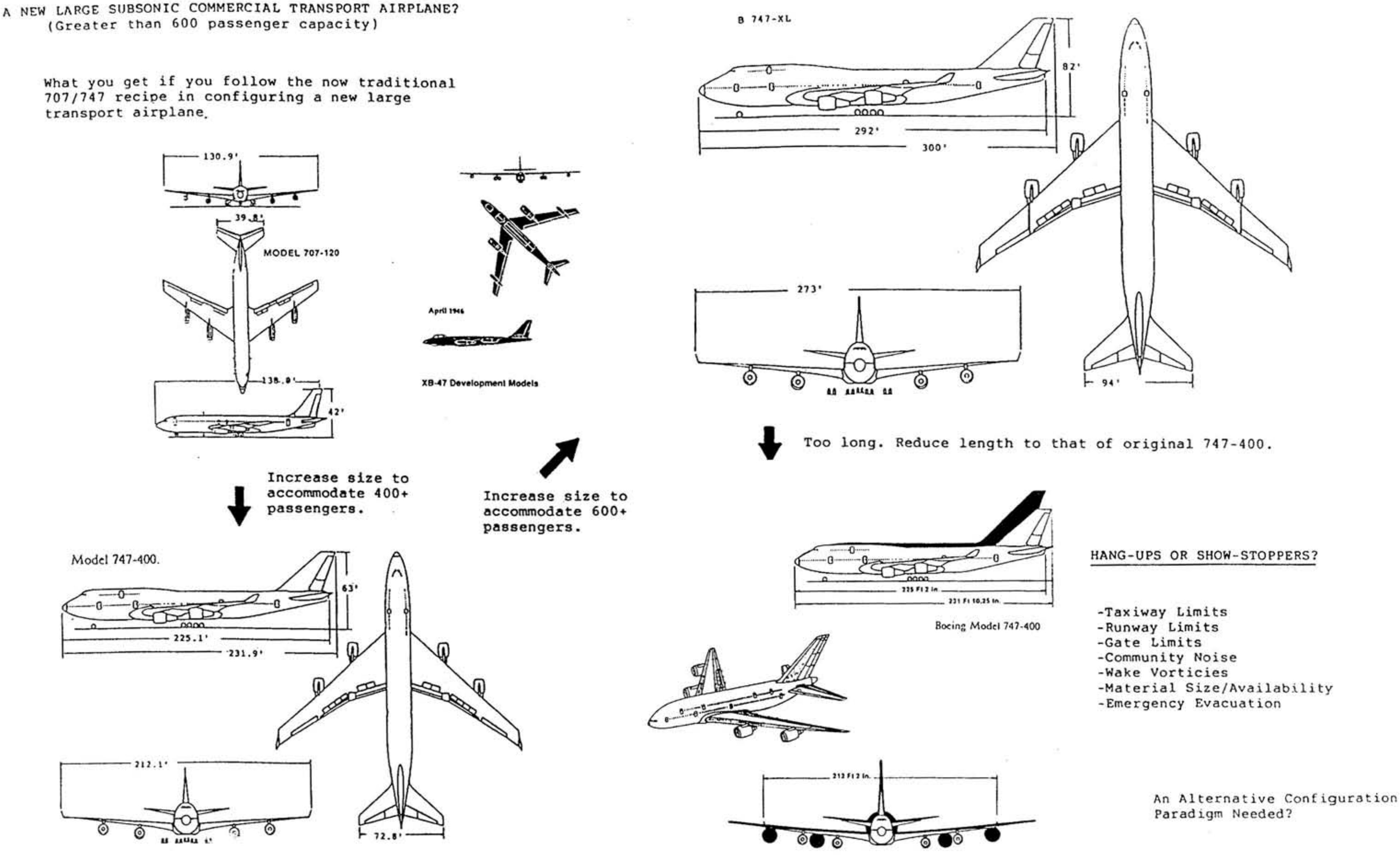
			Boeing B-47H	Avro "Vulcan B2"
Max. Take-Off Weight	W_{TO}	(lbs)	202,000	200,000
Ref. Wing Area	S	(ft^2)	1,400	3,964
Wetted Surface Area	S_{wet}	(ft^2)	11,300	9,600
Wing Span	b	(ft)	116	111
Wing Loading	$(W/S)_{TO}$	(psf)	144	50.5
Span Loading	$(W/b)_{TO}$	(lbs/ft)	1,741	1,801
Aspect Ratio	AR		9.6	3.1
Skin Friciting Coefficient	C_f (assumed)		0.0030	0.0030
Parasite Drag Area	$f\ (C_f \cdot S_{wet})$	(ft^2)	34.0	29.0
	$dC_D/dC_L{}^2$ (e = 0.8 assumed)		0.041	0.128
Max. Lift-Drag Ratio	$(L/D)_{max}$		15.8	16.4
Max. Lift-Drag at L/D Max.	$C_{L(L/D)max}$		0.77	0.24

Two Very Different Solutions to the Same Airplane Design Problem (after Roskam after Torenbeek).

Figure 1. The Evolution of the Configuration of the Boeing B-47 Bomber.

A NEW LARGE SUBSONIC COMMERCIAL TRANSPORT AIRPLANE?
(Greater than 600 passenger capacity)

What you get if you follow the now traditional 707/747 recipe in configuring a new large transport airplane.



Increase size to accommodate 400+ passengers.

Increase size to accommodate 600+ passengers.

Too long. Reduce length to that of original 747-400.

HANG-UPS OR SHOW-STOPPERS?

- -Taxiway Limits
- -Runway Limits
- -Gate Limits
- -Community Noise
- -Wake Vorticies
- -Material Size/Availability
- -Emergency Evacuation

An Alternative Configuration Paradigm Needed?

Figure 2. The Traditional (Evolutionary) Approach to the Development of a Baseline Configuration for a Possible Very Large Subsonic Commercial Transport Airplane.

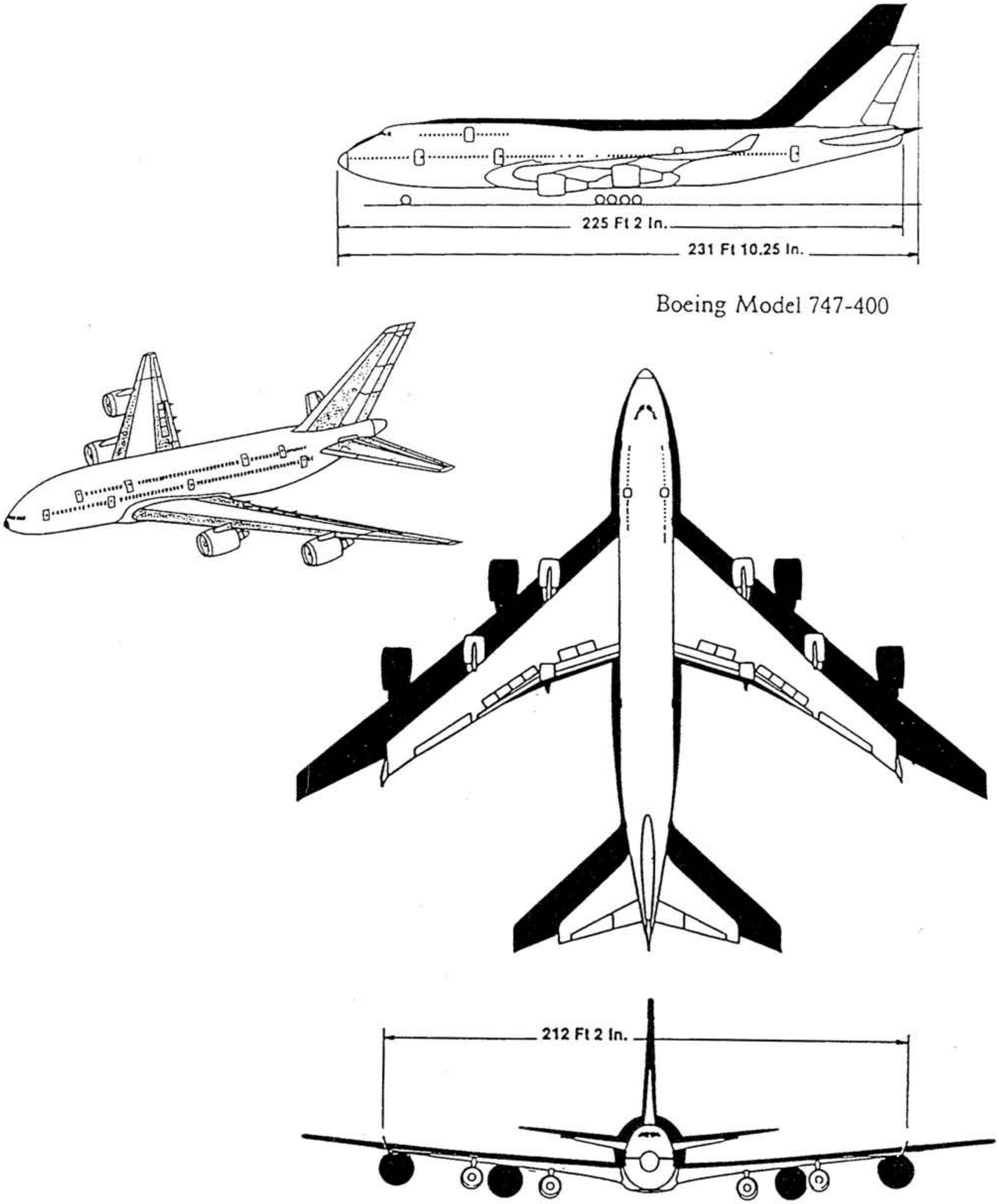
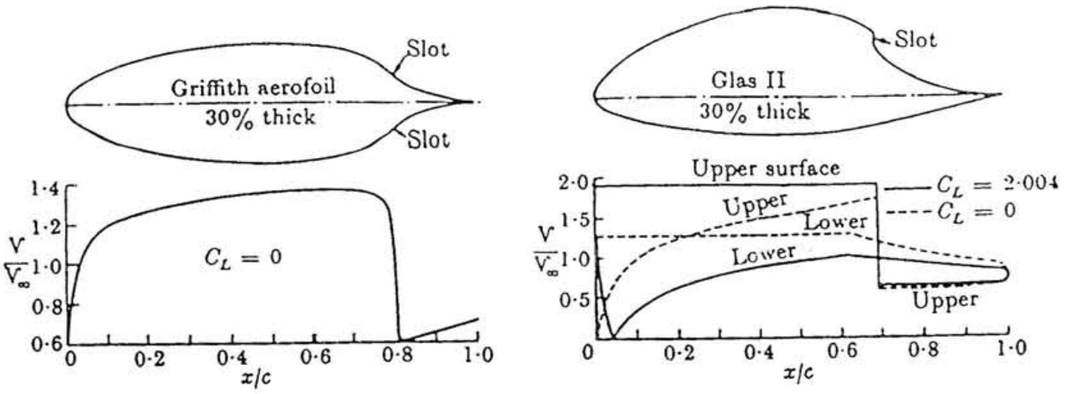


Figure 3. A Conventional Configuration for a Possible Very Large Subsonic Commercial Transport Airplane.



Thick low-drag aerofoils with suction slots. (Ref.74)

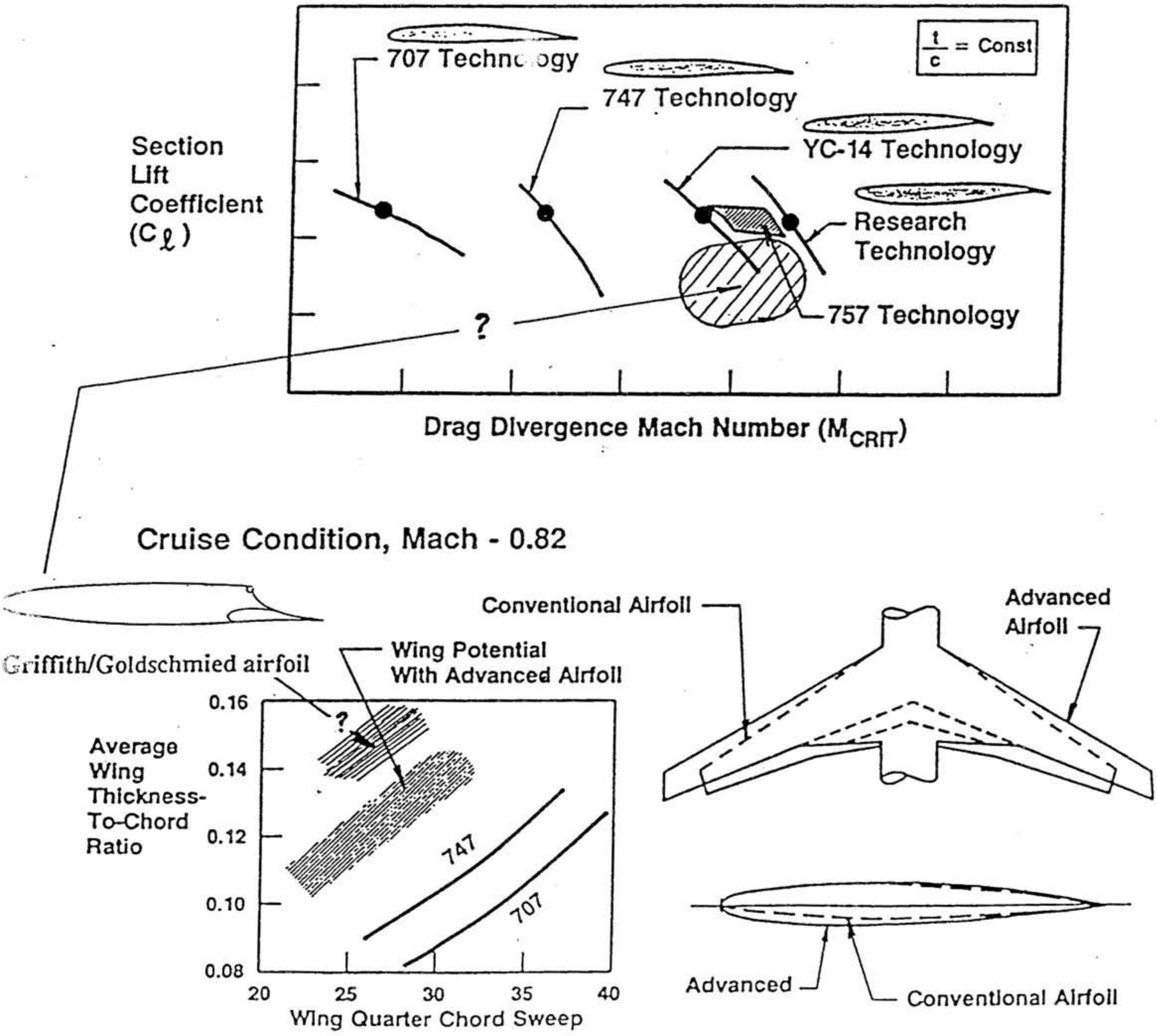
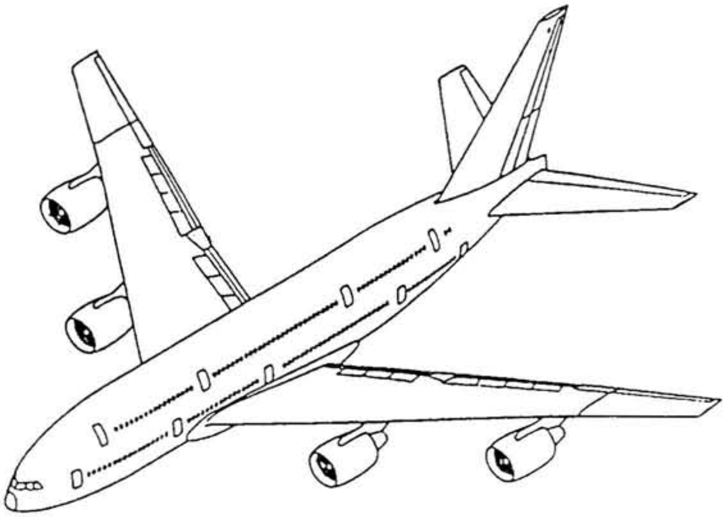


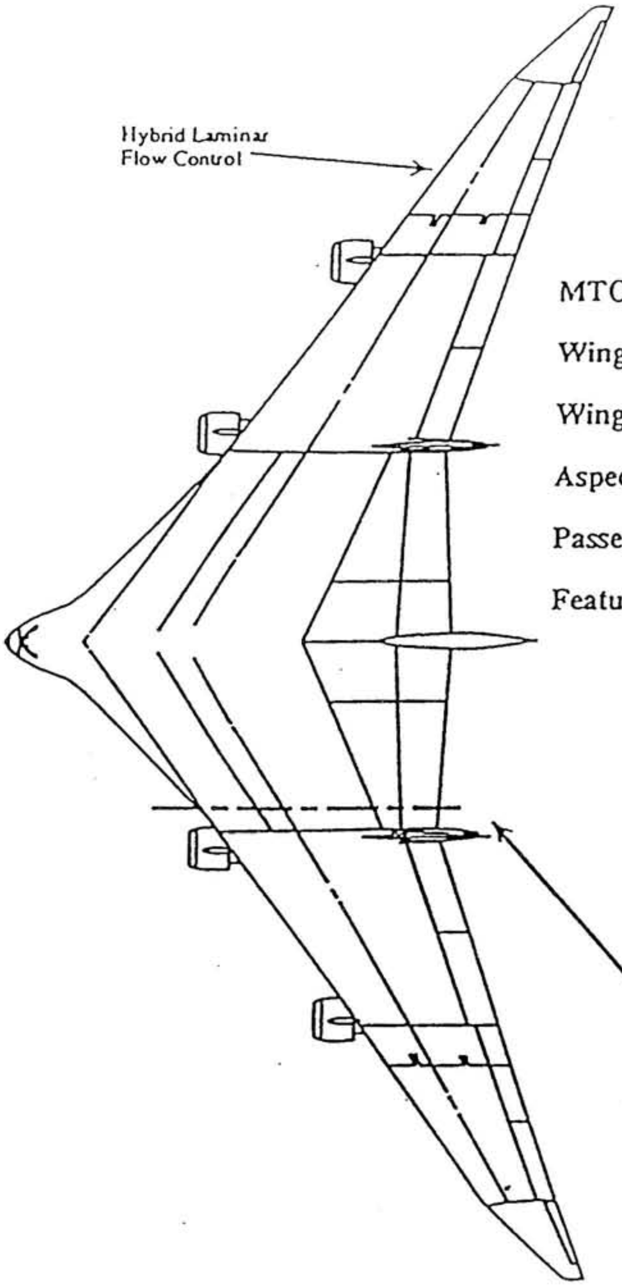
Figure 4. Prospects for Advances in Airfoil Technology.

HANG-UPS OR SHOWSTOPPER?

In the Design of Very Large Transport Aircraft

- Runway Limits
- Taxiway Limits
- Terminal Gate Limits
- Community Noise
- Wake Vorticies
- Material Size/Availability
- Emergency Evacuation
- Ditching/Floatation
- Passenger Comfort and Physiological Limits





B 747 - XL

Concept Study

MTOW: 1,400,00 lbs.

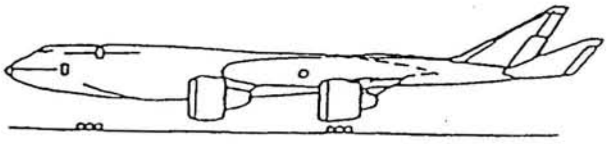
Wing Span: 300 ft. (170 ft. folded)

Wing Area: 9,000 ft (trap)

Aspect Ratio: 10

Passengers: 600-800 (50 abreast seating)

Features:
- Griffith/Goldschmied airfoil inboard
- Hybrid laminar flow control (with Krueger bug shield leading edge high-lift device
- Flat panel, multi-panoramic view/ entertainment system interior
- Largely composit structures
- 4x 95,000 lb. thrust very high by-pass ratio turbofan engines



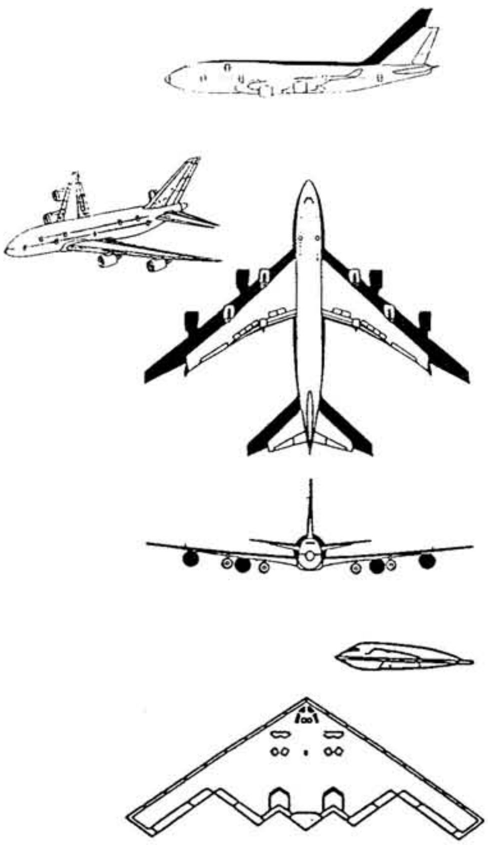
From the Desk of John McMasters December 1991

Figure 6. A First Attempt to Develop an Alternative Configuration for a Very Large Subsonic Commercial Transport Airplane.

A NEW LARGE SUBSONIC COMMERCIAL TRANSPORT AIRPLANE?
(Greater than 600 passenger capacity)

Based on 707/747 configuration paradigm?

Possible new configuration paradigm?
(Unique to this class of airplane)



LARGE SIZE PRESENTS MAJOR PROBLEMS BUT OFFERS MAJOR OPPORTUNITIES

POSSIBLE TECHNOLOGIES AVAILABLE

- -Taxiway Limits
- -Runway Limits
- -Gate Limits
- -Community Noise
- -Wake Vorticies
- -Material Size/Availability
- -Emergency Evacuation

But:

-Laminar Flow Control becomes more attractive for large, long-range airplanes

-Large wing size for given thickness/chord ratio yields wing approaching passenger height in absolute thickness

-Griffith/Goldschmied airfoil
-Slotted cruise airfoils
--Hybrid Laminar Flow Control
-Composite structures
((anisotropic materials)
--Active Controls
(Fly-by-wire, fly-by-light)
-Very high bypass ratio, very high thrust turbofan engines (GE 90,etc)
-B-2 bomber experience demonstrates feasibility of an all-wing configuration
-CFD tools available to deal with complex configurations, non-planar wings, complex aeroelastics,etc.

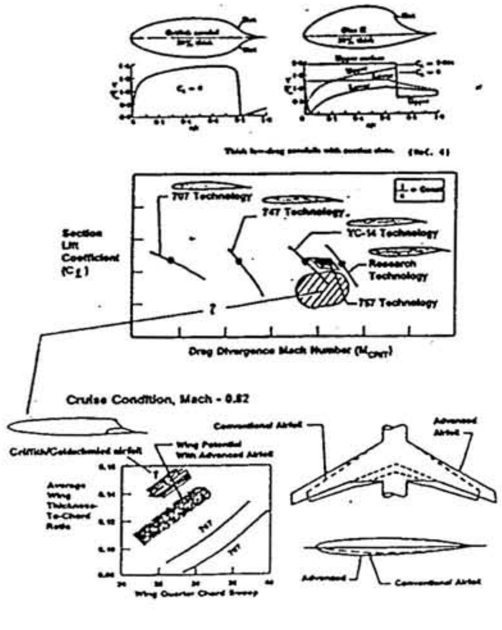
WITHOUT AIRPORT CONSTRAINTS, A VERY LARGE AIRPLANE WANTS TO BE A SPAN-LOADER (a "FLYING WING")

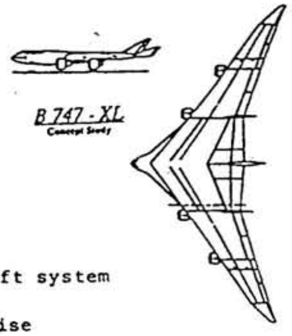
- **Active Controls / Control Configurated Vehicles**
- **Composite Structures**
- **Advance Manufacturing Techniques**

-A "wing" is easier to laminarize than a fuselage

-Conventional fuselage wetted area can be traded for wing area:

- increases chord
- increases thickness
- provides space for passengers seated laterally rather than vertically (multi-decks)
- may ease emergency evacuation
- requires less powerful high-lift system
  - -reduces airframe noise
  - -reduces cost to manufacture and maintain





BUT:

Using "conventional technology, the wing becomes very large in both span and chord

-Violates all airport constraints,even with large foldable wing-tips

-Suffers form same wing skin limits as current NLA if metal structure used.

Figure 5. Alternative Very Large Airplane Configuration Development.

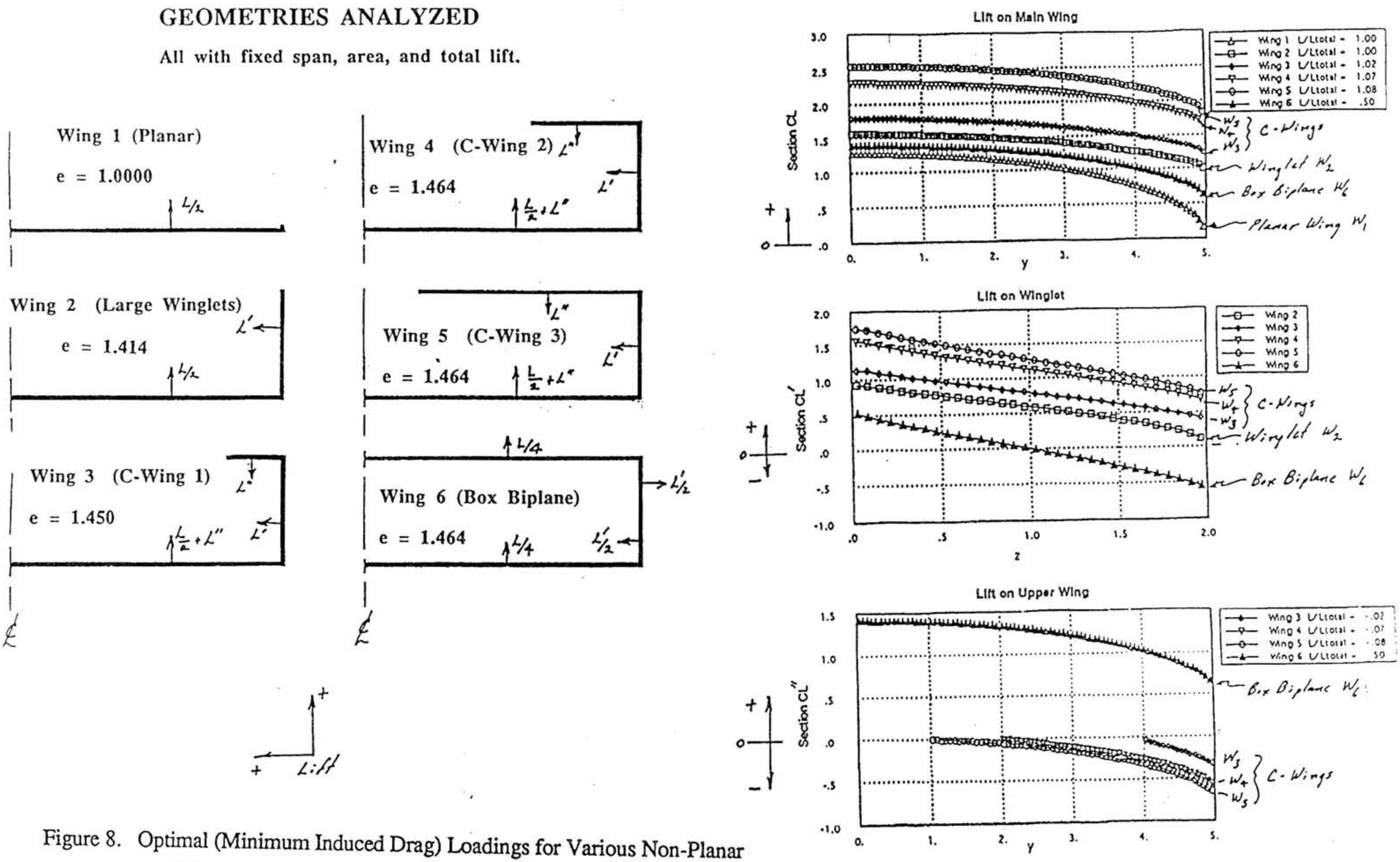


Figure 8. Optimal (Minimum Induced Drag) Loadings for Various Non-Planar Wing Configurations.

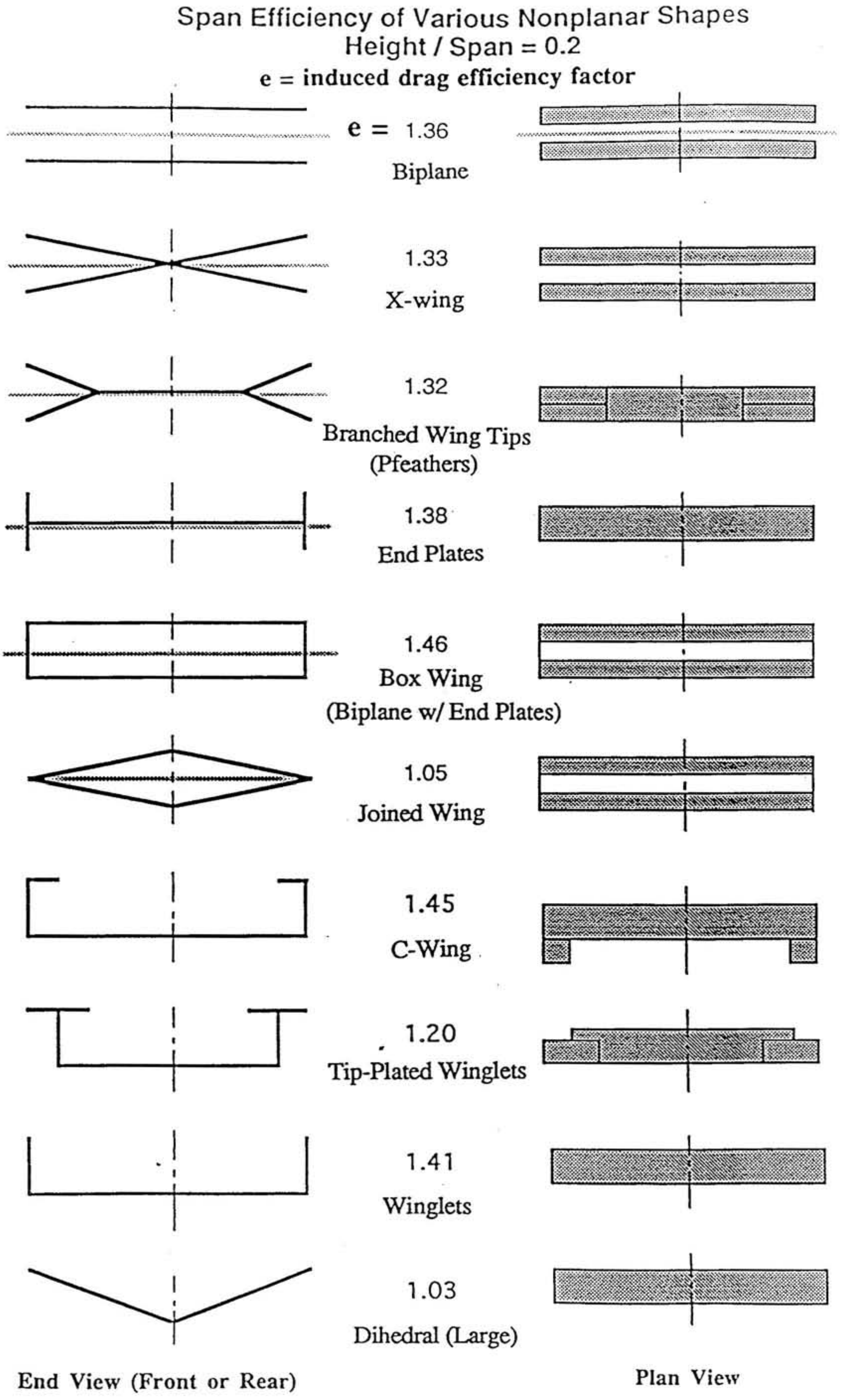
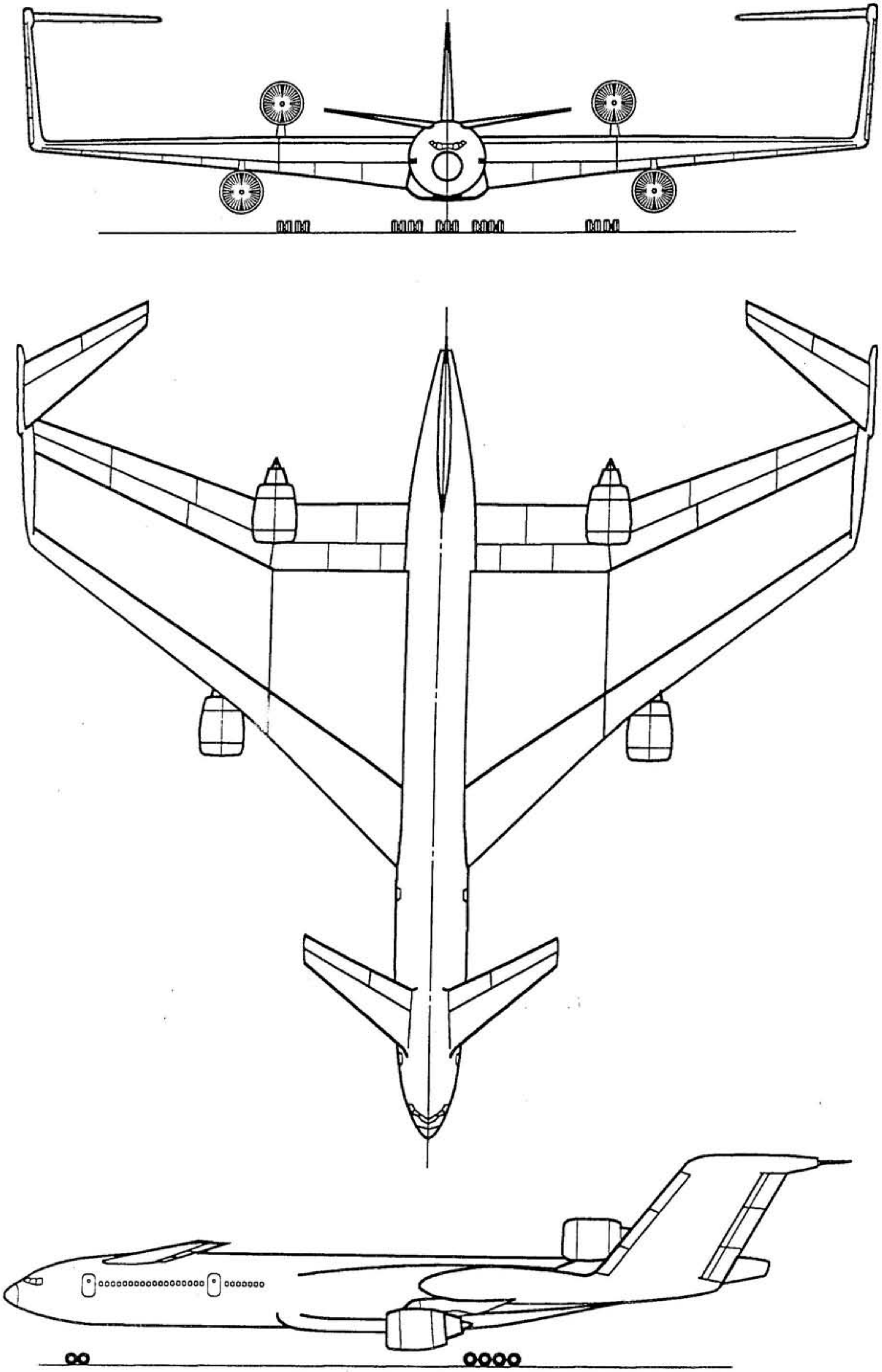


Figure 7. Theoretical Calculations of The Induced Drag Efficiency Factor (e) for Various Non-Planar Wing Configurations. [Note: All configurations shown have a constant value of height-to-span ratio and all have equal lifting surface areas.]



A NEW LARGE SUBSONIC COMMERCIAL TRANSPORT AIRPLANE?
(Greater than 600 passenger capacity)

Based on 707/747 configuration paradigm?

Possible new configuration paradigm?
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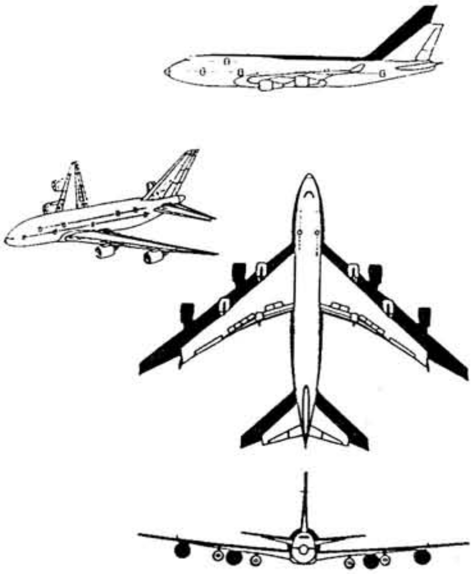

LARGE SIZE PRESENTS MAJOR PROBLEMS BUT OFFERS MAJOR OPPORTUNITIES

POSSIBLE TECHNOLOGIES AVAILABLE

- -Taxiway Limits
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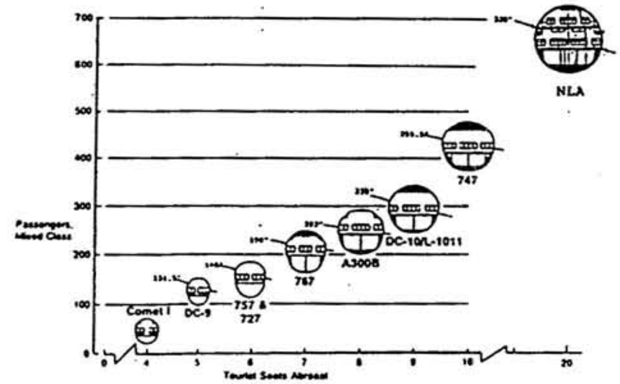
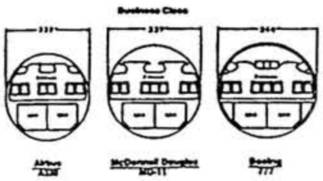
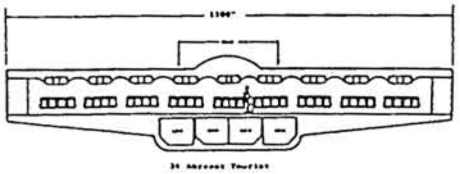
WITH REALISTIC CONSTRAINTS
+
SYNERGISMS OF NEW TECHNOLOGIES

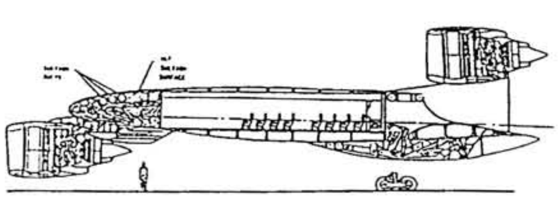
Cross-Section Configuration Comparison

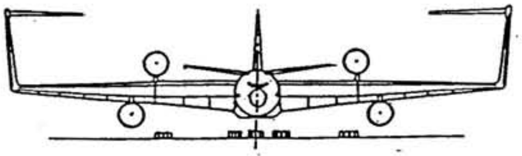


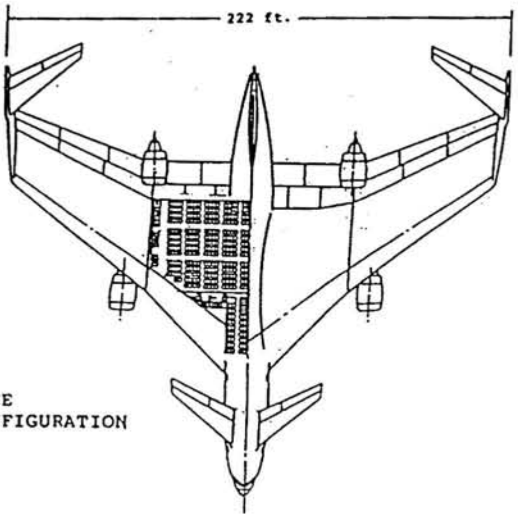




A VERY LARGE SUBSONIC TRANSPORT







LARGE 3-SURFACE SPANLOADER CONFIGURATION

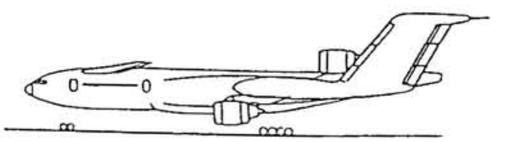


Figure 9. A Second Alternative Configuration Candidate for a Very Large Subsonic Transport Airplane

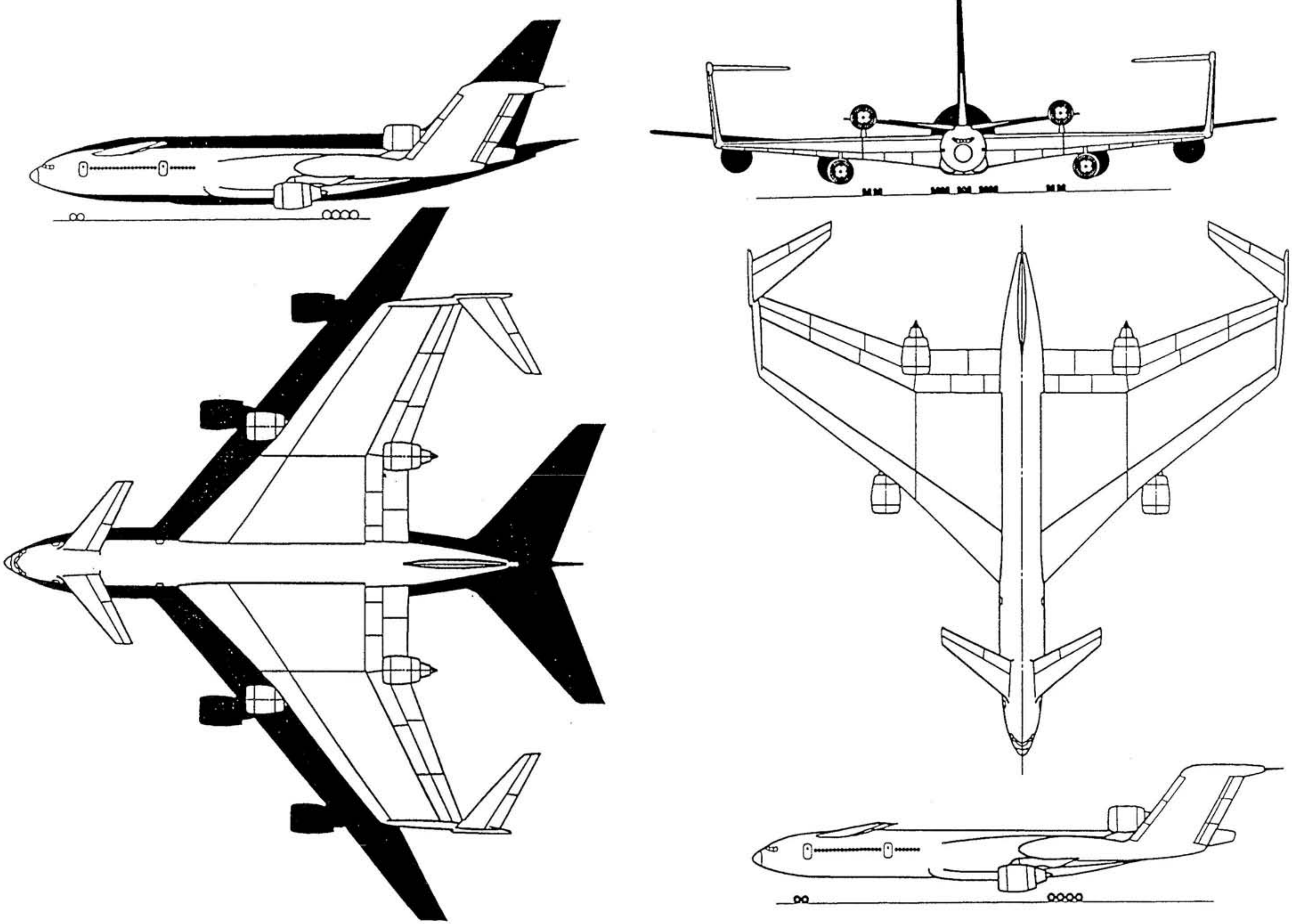
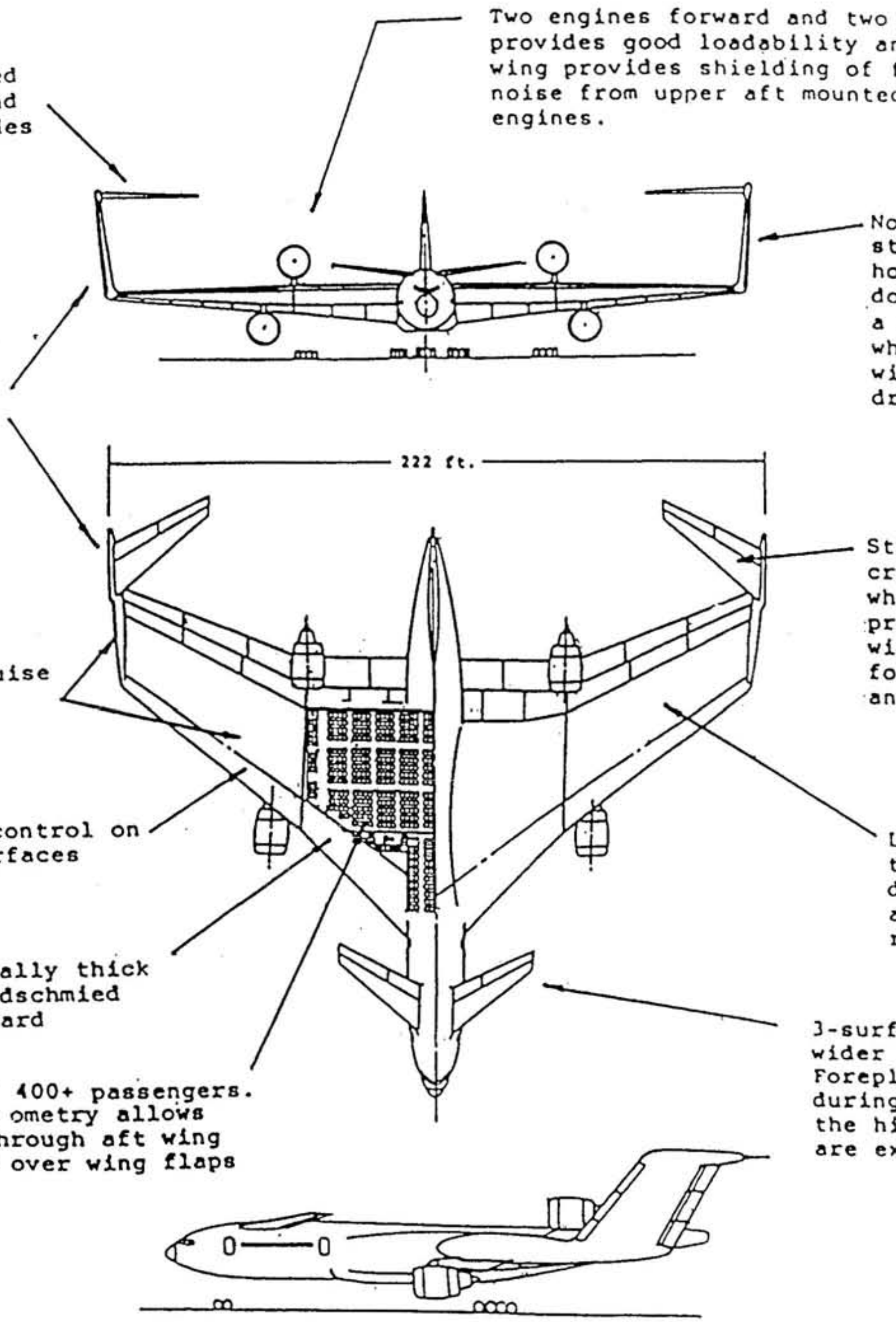


Figure 10. Configurations and Size Comparisons for Very Large Subsonic Commercial Transport Airplanes.



Combination of tailored composite structure and active controls provides control of structural dynamics(flutter,etc)

Two engines forward and two aft provides good loadability and wing provides shielding of fan noise from upper aft mounted engines.

Non-planar "C-wing" when swept, staggers lifting surfaces so that horizontal "winglets" produce a downward lift component replacing a conventional horizontal stabilizer while limiting physical wing span without serious loss of induced drag efficiency.

Aft-swept "winglets" mounted aft provide directional stability

Stabilizing surface during cruise becomes control surface when flaps are extended and produce an increase in effective wing span replacing need for folding wing tips for taxiway and gate clearance

Slotted transonic cruise airfoil outboard

Hybrid laminar flow control on wing and vertical surfaces

Large wing area provides thickness for spanwise distribution of payload and reduces high-lift requirements

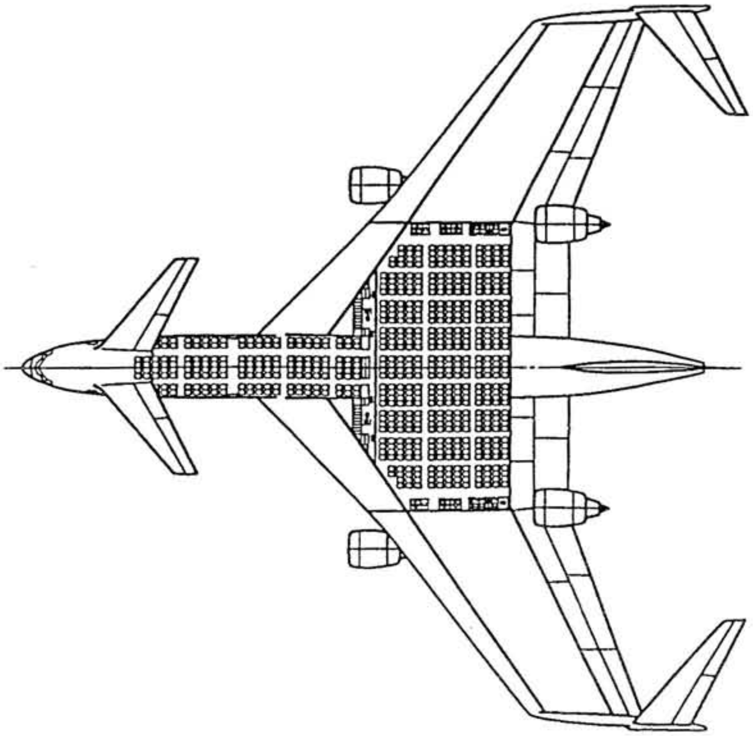
Unconventionally thick Griffith/Goldschmied airfoil inboard

3-surface configuration provides wider allowable c.g. range. Foreplane acts as a control surface during cruise and becomes part of the high-lift system when flaps are extended

36-abreast seating for 400+ passengers. Goldschmied airfoil geometry allows emergency evacuation through aft wing spar with escape slide over wing flaps

Figure 11. General Features of a Three-Surface Spanloader Very Large Subsonic Commercial Transport Airplane.

RETURN TO A NEW ERA OF COMPLETE PASSENGER SATISFACTION



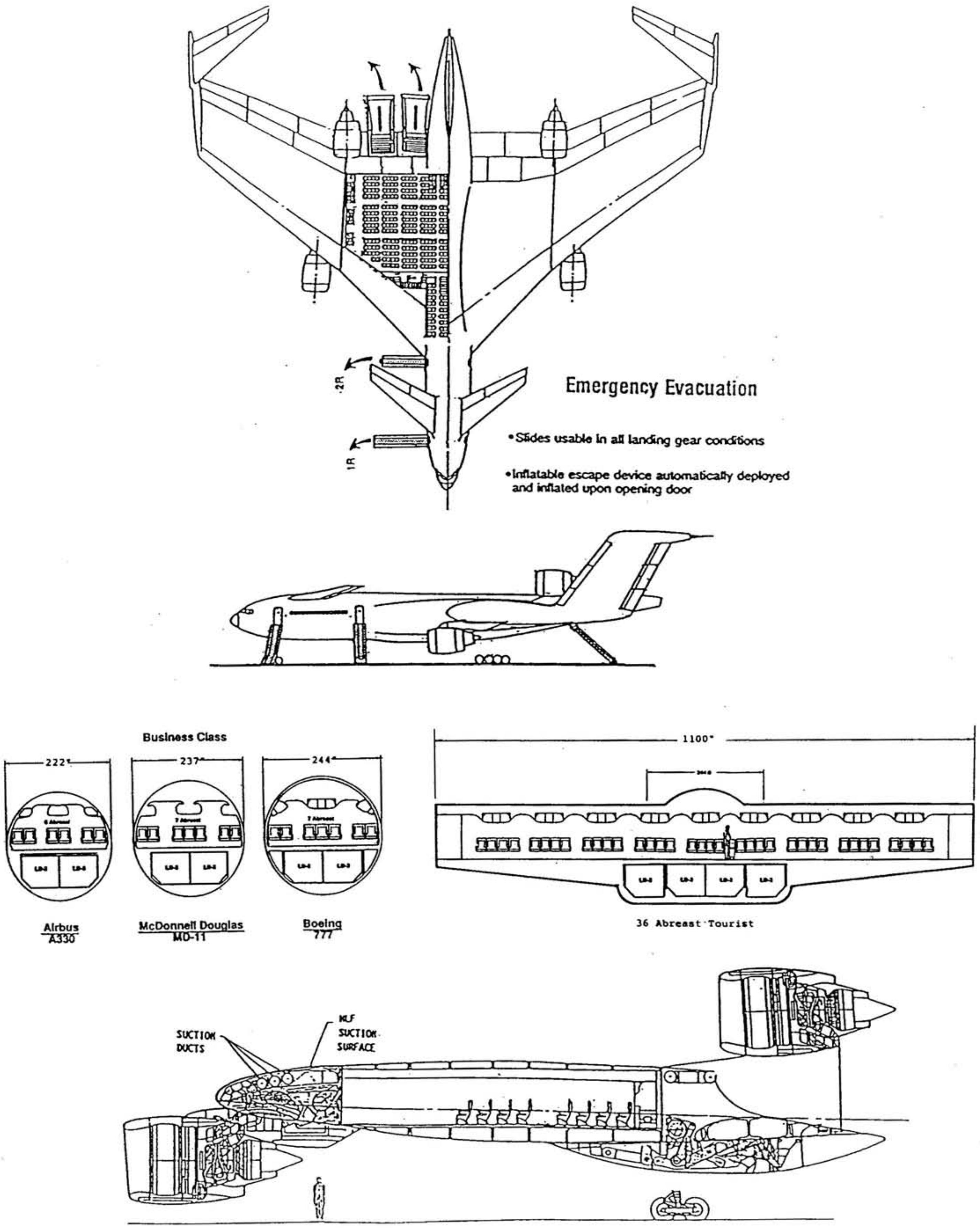


Figure 12. Payload and Emergency Evacuation Features of a Candidate Very Large Subsonic Commercial Transport Airplane.

Fig. 1

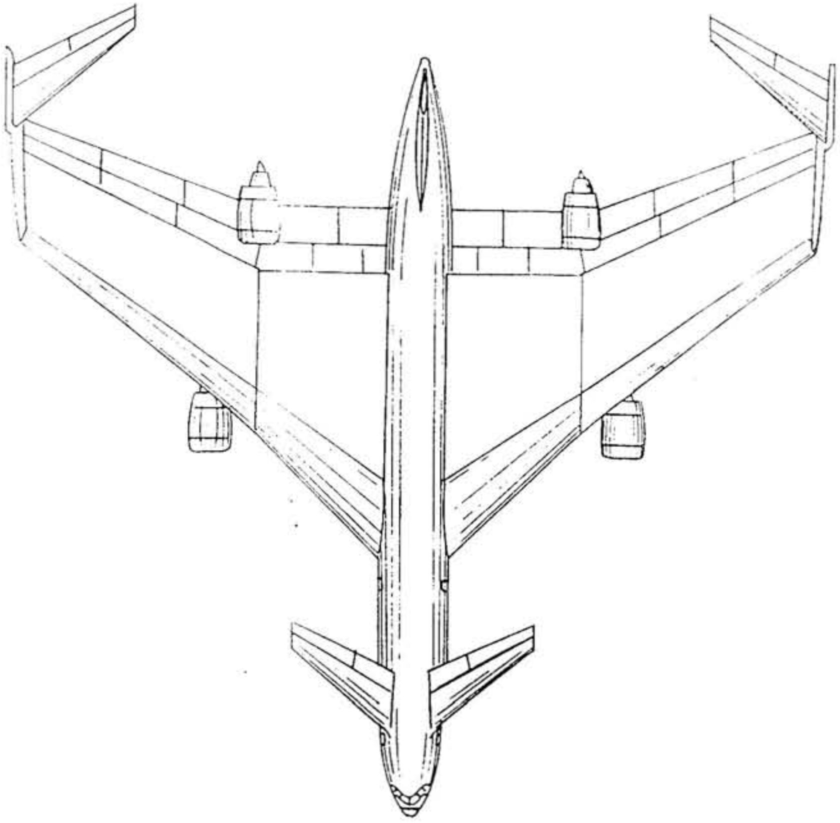


Fig. 2

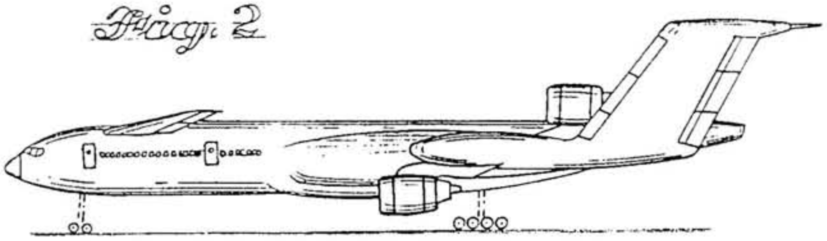


Fig. 3

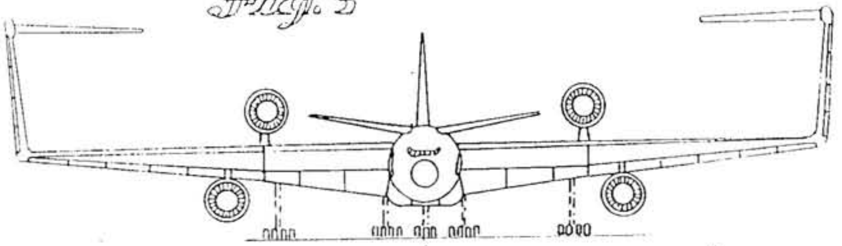


Fig. 5

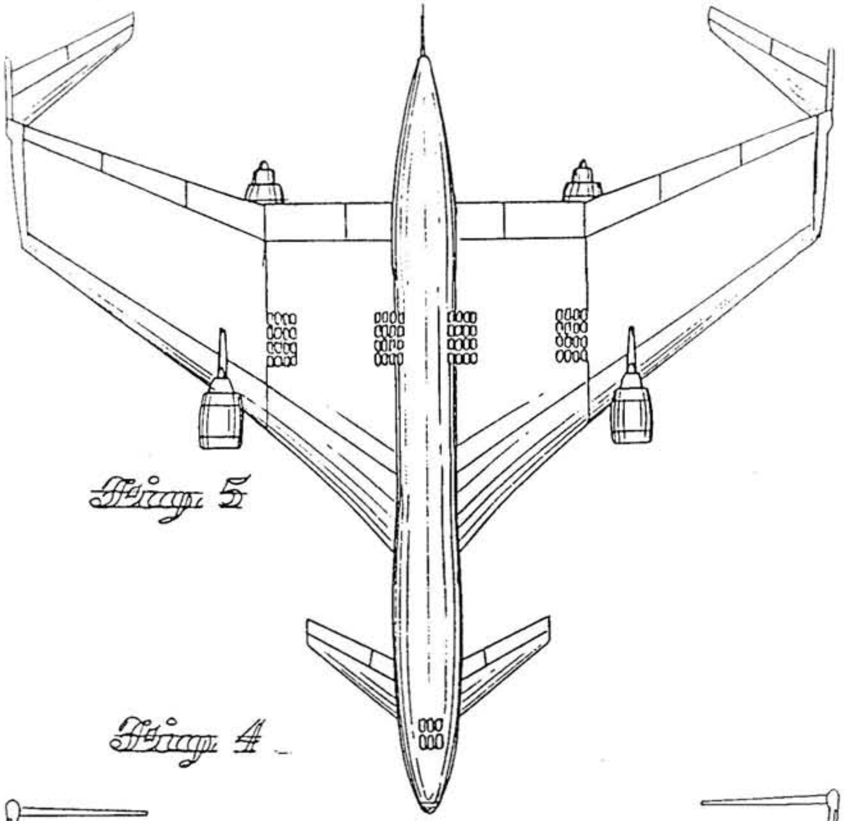
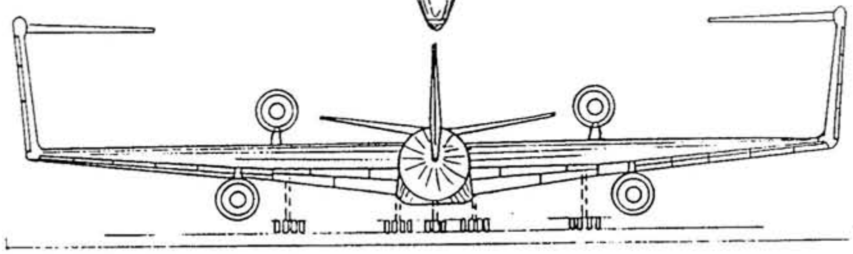


Fig. 4



Boeing Patent Application filed June 28, 1993 (McMasters, Kroo and Pavek)

From the desk of *John McMasters* May 1993

crew of 40 (pilots, flight attendants, musicians, etc.)

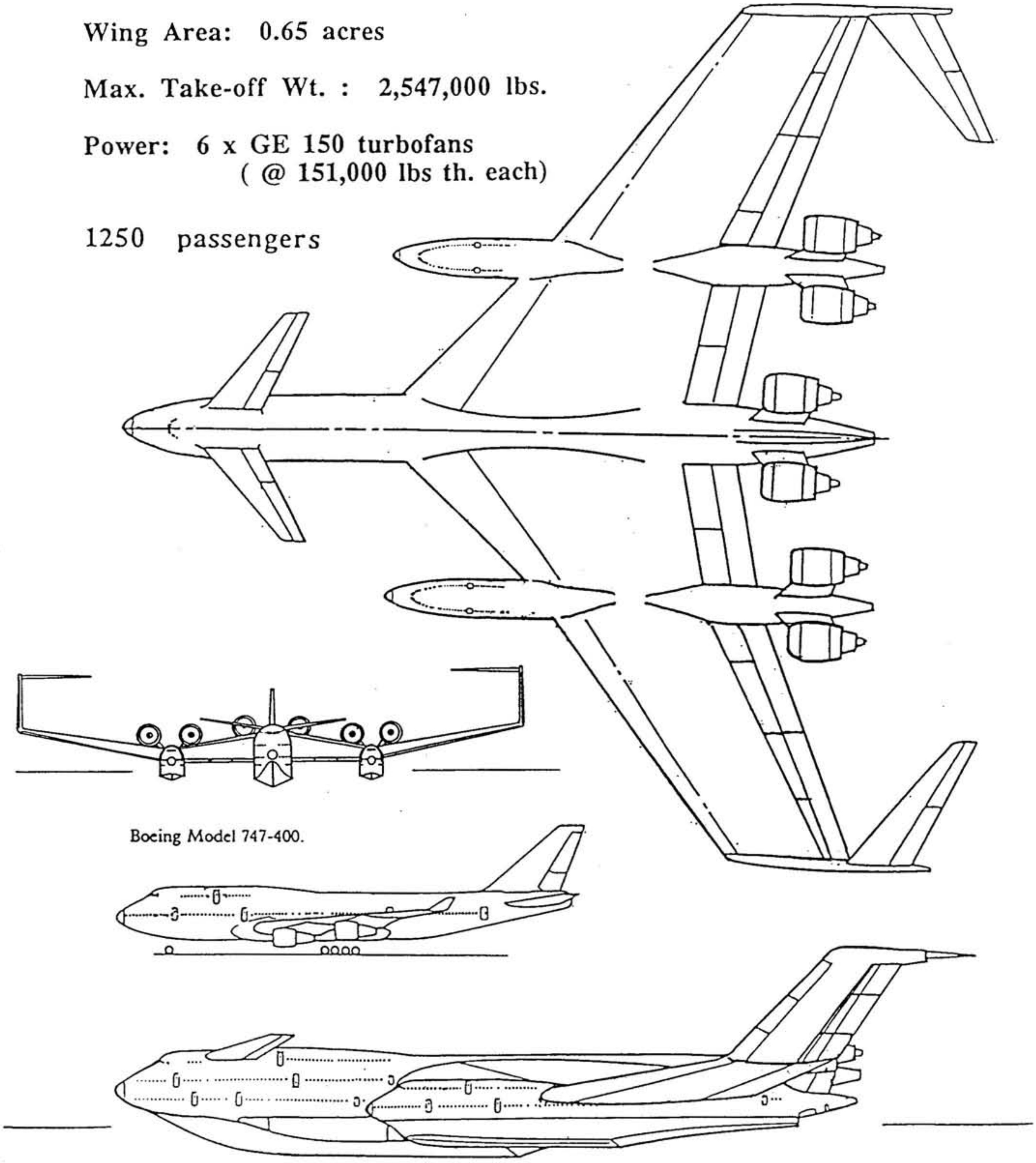
Wing Span: 400 ft.

Wing Area: 0.65 acres

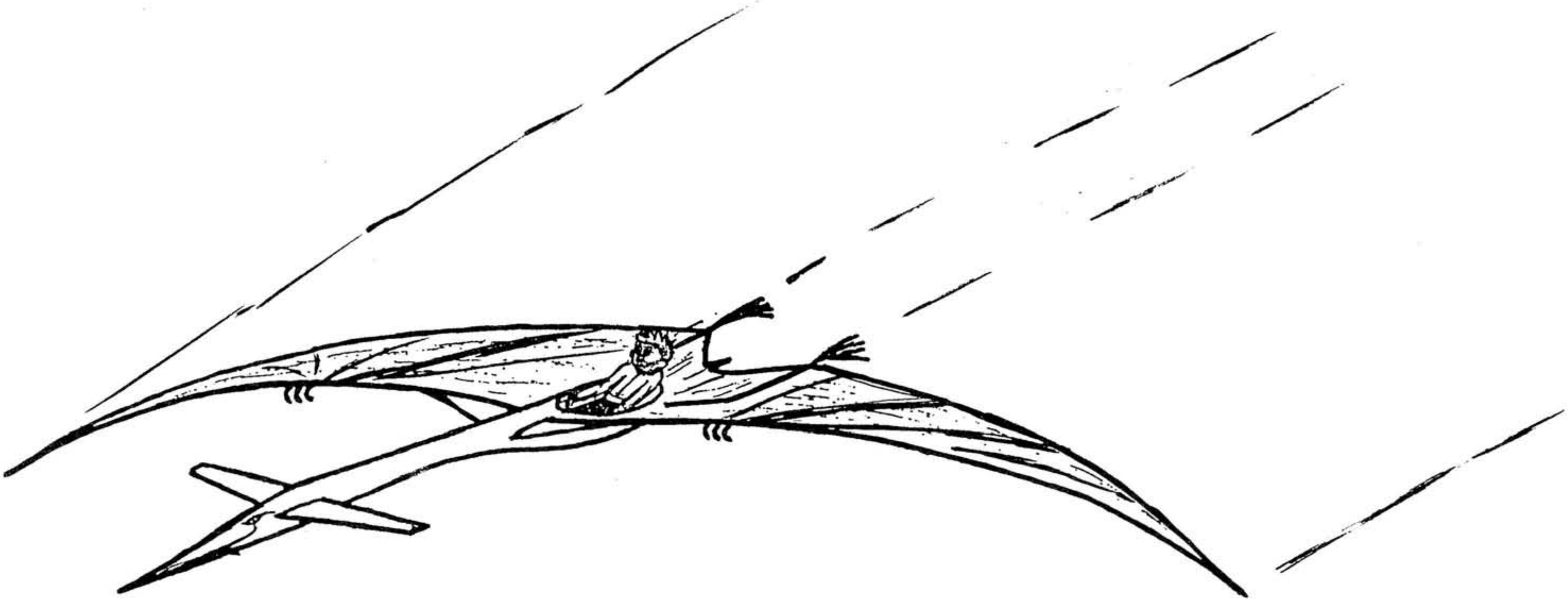
Max. Take-off Wt. : 2,547,000 lbs.

Power: 6 x GE 150 turbofans
(@ 151,000 lbs th. each)

1250 passengers



BOEING *SUPER CLIPPER*

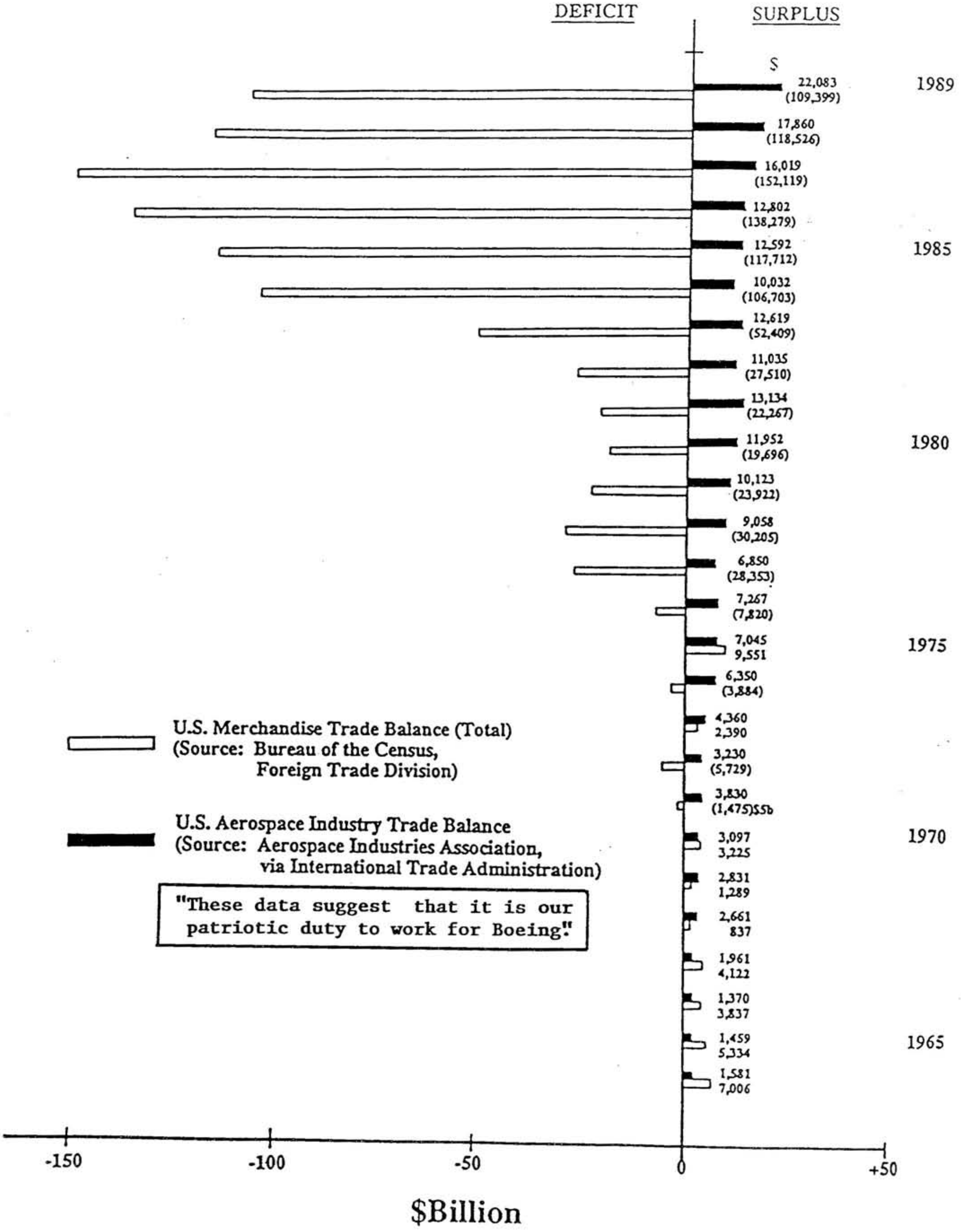


...And Perhaps Eventually by a Process of Convergent Evolution...

Concluding Comments

- The past 100 years of aeronautical development has done much to clarify flight in nature.
- Further investigations of natural flight technology may lead to ideas of practical use in aeronautical technology.
- Whether of practical value or not, the examples shown are the sort of tent poles that keep our imaginations from collapsing around us.
- A study of paleoecology (of which biotechnology is a subset) makes a grand hobby encompassing, life, the universe and everything.

U. S. Merchandise and Aerospace Balances of Trade 1964-1989



"These data suggest that it is our patriotic duty to work for Boeing."

Professor McMasters , may I be excused?
My brain is full.”

AFTERWORD

WHAT THE H . . . IS A "REYNOLDS NUMBER?"

> *"Reynolds number is one of those terms engineers made up to make them good company at dinner. . . . We use it to get dates."*
>
> A Boeing (Engineering) V.P.
> who shall remain unnamed

Reynolds number is one those terms often heard around the wind tunnel that, even among some of the engineers who use it, is poorly understood. Like a lot of technical jargon, it turns out to be a lot easier to tell you where its at than what it is. A basic reason Reynolds number is hard to understand is that the usual (technically correct) explanations of it are based in some industrial strength mathematics which is about as clear to most of us as a coded message from Mars. Unfortunately, most engineers, having "gotten mathematics," have a hard time explaining stuff like this in any other way. As it turns out, you don't have to be a rocket scientist to get a useable grip on the term if you're willing to think a little bit and read a couple of paragraphs of modestly technical explanation. Let's try to get at Reynolds number in the following way . . .

This story is about aerodynamics which is actually a rather specialized branch of classical physics (as explained to us by Isaac Newton over 300 years ago) called fluid mechanics. Fluid mechanics deals with, among other things, the motion of both liquids and gases including air, water, molasses, freon, alcohol, etc. All of these substances share a number of common characteristics and properties. They all have a density, all are "compressible" (which in practical terms means that sound-pressure disturbances-travel through them at some finite speed), and all have viscosity and so on. "Aerodynamics" as we're used to thinking about it can happen in any fluid if we account for the differences in the magnitudes of the density, viscosity, etc. of the various fluids. For example, water is about 980 times denser than air and sound travels through water roughly five times faster than through air. To really understand all this, one has to study fluids at the molecular level--that is, how do each of the zillions of individual molecules in a cubic inch of air or molasses behave. That is the subject for another lecture, however. All we need here is some notion of fluids having viscosity and a speed at which sound is transmitted (or simply a "speed of sound"). Here in the basement of the Aero Lab, the speed of sound of air on an ordinary day is about 750 mph. Viscosity is a little harder to deal with and we'll return to that in a minute. Water, by the way, is about 200 times more viscous than air.

To get at Reynolds number (and several other things related to it) we have to understand why we test models of anything (airplanes for example) in the first place. Basically, if we're going to spend a lot of money developing some complicated thing that we hope to sell for a lot of money we'd better get it right. In the beginning of this whole process we don't have the final prototype yet and we can't justify the risk of just building it to find out if it works, so we build some models of what we might eventually build and test them instead. For these tests to be of any use, the model had better behave pretty much like the full size version. How we do this in aerodynamics (fluid mechanics) is not easy, but science gives us some help. Specifically, we apply the theory of dynamic similarity. What this theory says when we're doing aerodynamics is:

> If we build an exact replica (exact shape but different in size) of our intended final product, the flow of a fluid (and the forces thus generated) on the model will be identically related to those on the full scale object if the correct "similarity parameters" are matched. In wind tunnel testing there are three main similarity parameters, all of which depend on each other. They are:

1. Force coefficient (Newton number) = $C_F = \dfrac{\text{Force}}{\text{dynamic pressure x reference area}}$

   where: Force = lift, drag, skin friction, etc.
   Dynamic Pressure = $\frac{1}{2}$ x fluid density x (fluid speed)^2 = $\frac{1}{2}\rho V^2$

   Reference Area = whatever area one chooses (but usually the wing area).

2. Mach Number = M = $\dfrac{\text{fluid speed}}{\text{speed of sound in the fluid}} = \dfrac{V}{a}$

3. Reynolds Number = $R_n = \dfrac{\text{fluid density x fluid speed x reference length}}{\text{fluid visocity}} = \dfrac{\rho VL}{\mu}$

Note: In our wind tunnel tests we usually hold the model stationary and blow the air past it. We then measure the forces (lift or drag) which this air flow produces. About four hundred years ago, Galileo proved (as a primitive form of the theory of relativity) that this is exactly equivalent to moving an airplane at the same speed through a stationary atmosphere. If the airplane is flying through the air while the wind is blowing, the story still doesn't change--everything just gets more complicated.

What the above hocus-pocus says is: We want, as an example, to develop the new Boeing 787. Like all Boeing airplanes it's going to be big and we want to get it right. Among other things, we want to know what the lift and drag forces on the real airplane are going to be before we commit to building one. So, we build a 1/10 scale model of it (actually 1/10 scale version of its exact shape) and put it in the wind tunnel. In these tests we measure the forces (lift and drag) that the model produces and we know (by measurement) what the density and temperature of the air is in the tunnel and we also know the speed of the air blowing over the model. Knowing these things we can calculate the force coefficients (Newton numbers) for a model of an airplane of this shape. If we do this right, these Newton numbers do not have any dimensions--they are just a set of numbers which describe the important forces on an airplane of this shape flying at a given (known) speed. The question is: Do these numbers relate in some way to the forces which will be produced on the real airplane? The answer is yes! If, in our test, we somehow produced the right Mach and Reynolds numbers.

The Mach number is easier to grasp in this little exercise. By its definition, Mach number is just the ratio of the speed of the air (or the airplane) to the speed of sound in the air under the test or flight conditions. Thus, an airplane (no matter how big or small it is) flying at 80% of the speed of sound is flying at eight tenths (0.8) Mach number. We call any airplane speed less than the speed of sound "subsonic." The forces on an airplane change significantly (everything else being equal) as the Mach number changes, and these changes are big enough that we have to take special care to test our model at the right Mach number conditions. Thus, we build wind tunnels which consume a lot of power to be sure we can measure model forces at the right (speed-to-speed of sound) conditions.

By the same token, the forces on our model (again everything else being equal) change with changes in Reynolds number. Here we run into a problem though. Going back to the simple formula for a Reynolds number we see that its value depends on a "characteristic length"--or simply the size of the model. With a little manipulation we can show that:

Reynolds number = (gas properties) x (model size) x Mach number

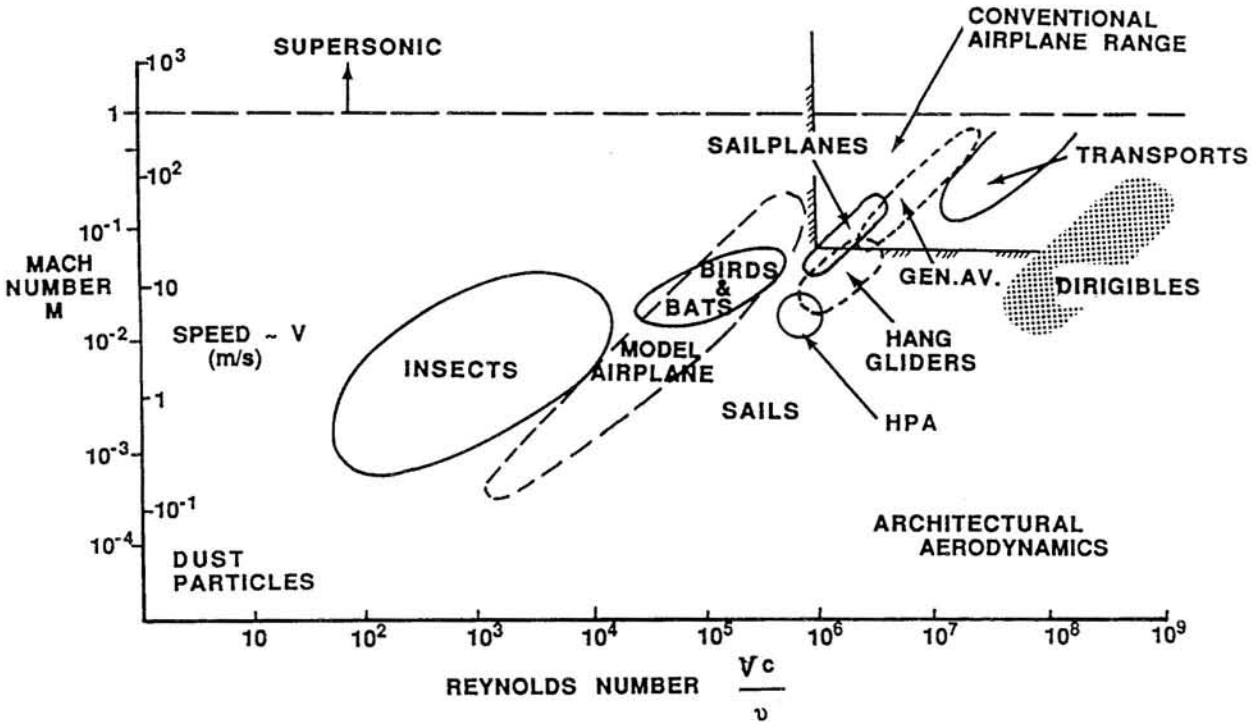
This means that if we test our 1/10 scale model in air at the same conditions (temperature, altitude, etc.) that the full size airplane will fly, and do the test at the right Mach number, we will be testing at a Reynolds number which will be only 1/10 that at which the full size airplane will fly. If instead we try to match Reynolds number, we'd have to fly the model 10 times faster and thus be at supersonic Mach numbers. You can't seem to win. That in turn means that the aerodynamics on the model will (usually) not be the same as those on the full sized airplane despite the fact that the model and the full sized item are exactly the same shape. This is exactly what happens in wind tunnels like the BTWT, and this is one of the reasons Boeing has to employ so many aerodynamicists--we have all these people running around trying to figure out the right "Reynolds number corrections" to make to wind tunnel data so we can predict the right answers on our future products. This limitation on our existing wind tunnels was also a primary factor behind our plan to build new high Reynolds number wind tunnels--a plan which has, alas, been abandoned. From now on we'll just have to make do with what we've got.

So what is a Reynolds number. After all of the above, we still haven't really said what a Reynolds number is. Let's now try it one more time this way. Reynolds number is related to the fact that all fluids have viscosity. This means that when a fluid (air, etc.) flows over a solid surface it produces a friction force on the surface. This friction eats energy and causes a major part of the aerodynamic force we call drag. If a fluid had no viscosity, our airplanes would produce no drag (and incidentally, the Reynolds number of the flow would be infinity). This sounds good at first, but it also turns out that if the fluid had no viscosity a wing would not produce any lift either and we could not build an airplane the way we do now. From this good news-bad news situation we go back to the fact that all fluids do have viscosity. It also turns out that when we move a solid object (like an airplane or a brick) through any real fluid, the fluid produces forces on the object and the object reciprocates by disturbing the fluid. It fights back. While air may seem to be nearly weightless and invisible, the mass of air surrounding an object the size of a Boeing 747 is quite large and you have to horse on it quite a bit to make it move--or stop moving. Thus, according to our old friend Newton, the air surrounding our airplane has inertia. Having said something along the lines that F = ma, Newton thus set the stage for a definition of Reynolds number. If we calculate the inertia force (ma) of the mass of air being influenced by an object like an airplane wing and compare that to the friction force produced by the air scrubbing the wing as it flies through it we have:

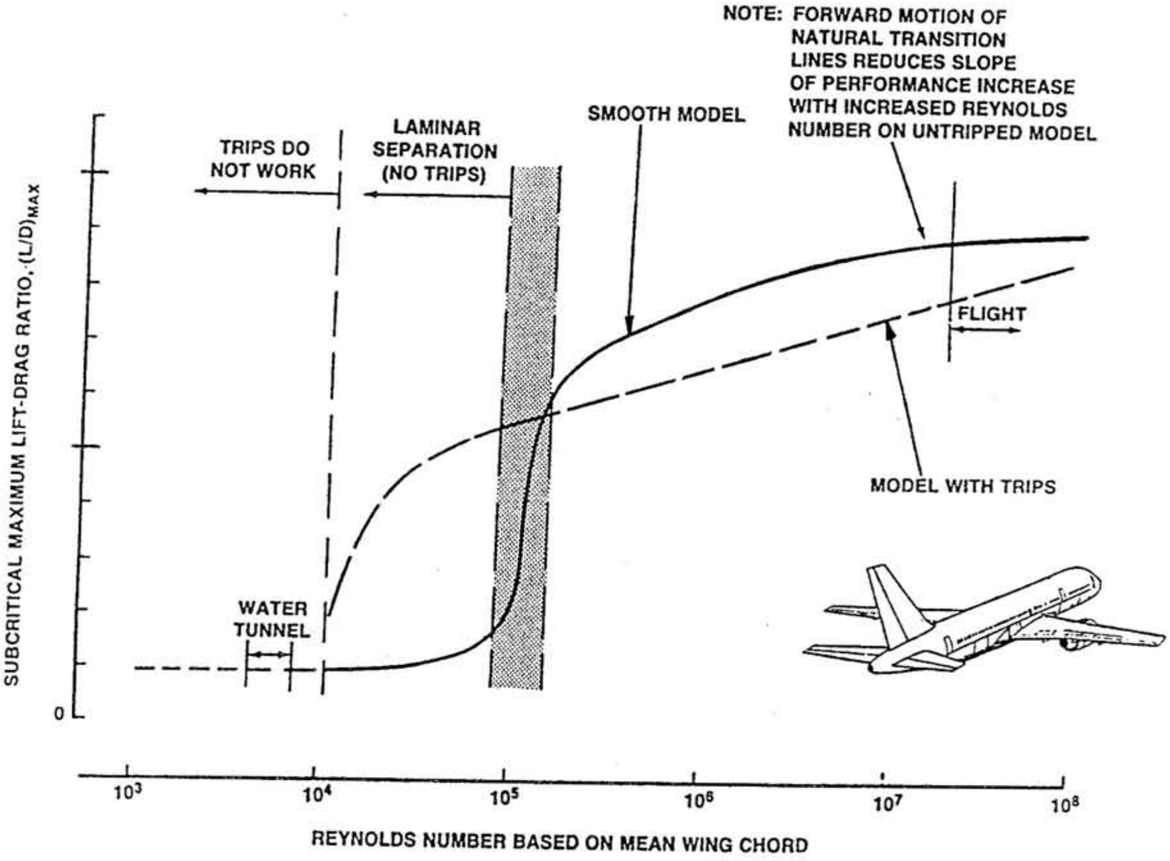
$$\text{Reynolds Number} = \frac{\text{inertia force}}{\text{fricition force}} = \frac{\rho V L}{\mu}$$

Thus, Reynolds number is an index, the magnitude (size) of which tells one skilled in the art (of aerodynamics or fluid mechanics) the relative importance of the viscous frictional forces acting on an object in a moving fluid to the size of the total force acting on that object. The higher the Reynolds number (and usually it turns out to be in the millions) the smaller the relative influence of viscous friction forces. These friction forces are never negligible, however, and a whole raft of complicated cause and effect relations are tied up with the fact that fluids are viscous substances. It also keeps a whole bunch of us employed trying to sort them out.

Still doesn't help? How about asking for a one-hour, on-hours short course on all this as part of your necessary training for the jobs you do. It really is not too hard to understand all this if you want to. Writing it all down seems to require a book, however.



REYNOLDS NUMBER VERSUS FLIGHT SPEED for a VARIETY of FLYING DEVICES



Reynolds Number Ranges of Various Experimental Facilities and Their Implications n Aerodynamic Performance

SOME DEFINITIONS

FLUID - A substance which cannot resist a shear force without moving. Both liquids and gases are fluids.

LIQUID - A fluid whose molecules are so closely spaced that intermolecular forces hold it together in a definite volume, but without definite shape. A liquid poured into an empty container will fill the container up to the level of the volume of liquid poured, and will form a free surface.

GAS - A fluid in which the spacing between molecules is large compared to the dimensions of the molecules. A gas has neither fixed volume or shape. It will expand to fill any empty (closed) container into which it is placed.

PERFECT FLUID - A fluid which is homogeneous (not composed of descrete molecules), inelastic (incompressible) and has no viscosity. This is the stuff of classical (19th Century) hydrodynamics.

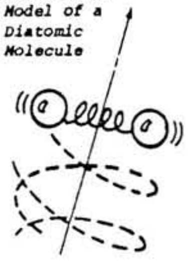
IDEAL GAS - A gas which is homogeneous, <u>compressible</u>, and has no viscosity.

	In Continuum Mechanics	In Kinetic Theory
Static Pressure	The compressive force per unit area acting perpendicular to a surface placed in a fluid or on adjacent fluid elements.	The time averaged sum of the forces acting perpendicular to a unit area of surface immersed in a fluid caused by the impact (and consequent change in momentum) of fluid molecules in motion.
Temperature	A measure of the heat content of a fluid.	A measure of the average kinetic energy of the molecules.
Viscosity	A measure of a fluids resistance to shear when the fluid is in motion.	A measure of the transport of momentum across the interfaces of adjacent streams of flowing molecules.
Density	The mass per unit volume of a fluid.	The mass of the total number of molecules within a given volume.

The Composition of Dry Air at Standard Sea Level Conditions.

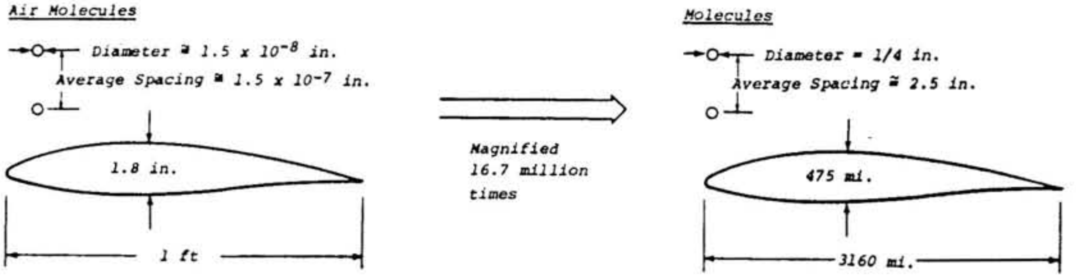
			(By Volume)
Nitrogen	N_2	diatomic molecule	78.09 %
Oxygen	O_2		20.95 %
Argon	A		0.93 %
Carbon Dioxide	CO_2		0.03 %

Engineering Model of a Diatomic Molecule

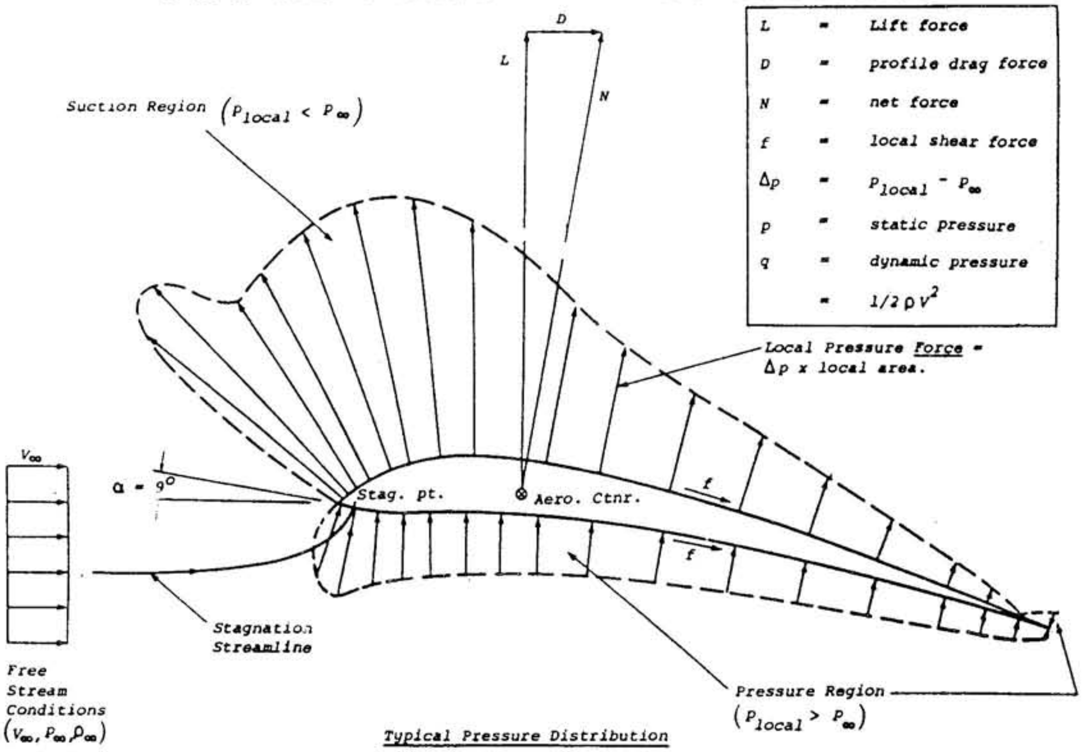


Standard Sea Level Atmospheric Conditions

	English	Metric
Pressure	2116.2 lb/ft^2 (14.7 psi)	101325.0 N/m^2
Temperature	59° F	15°c
Density	0.00238 slugs/ft^3	1.225 kg/m^3
Speed of Sound	1116.4 ft/sec (661.5 kt)	340.3 m/s
Kinematic Viscosity	1.572×10^{-4} ft^2/sec	1.461×10^{-5} m^2/sec



AIRFOIL PRESSURE DISTRIBUTIONS



L = Lift force

D = profile drag force

N = net force

f = local shear force

Δp = $p_{local} - p_\infty$

p = static pressure

q = dynamic pressure

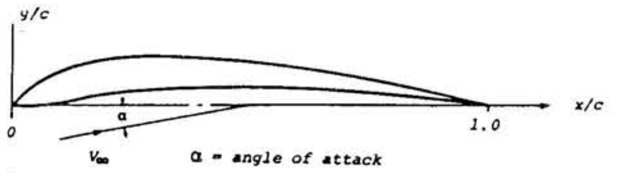
= $1/2\,\rho V^2$

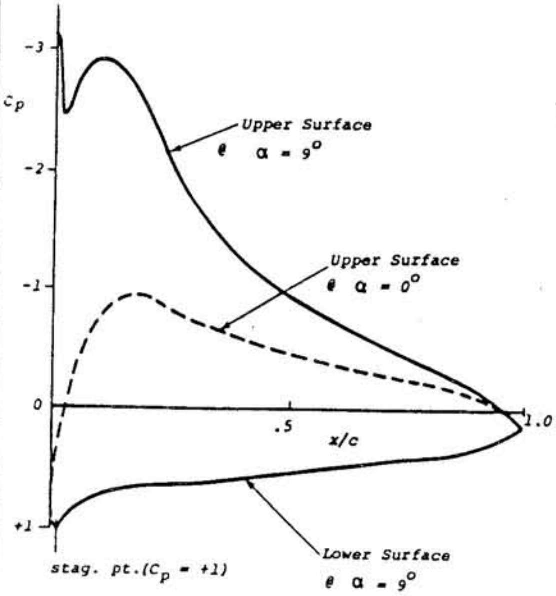
Typical Pressure Distribution on a Low - Speed Airfoil

Section Lift Calculation

$$C_n = \oint C_p \, d(x/c)$$

$$C_\ell = \frac{C_n}{\cos\alpha} - C_d \tan\alpha$$



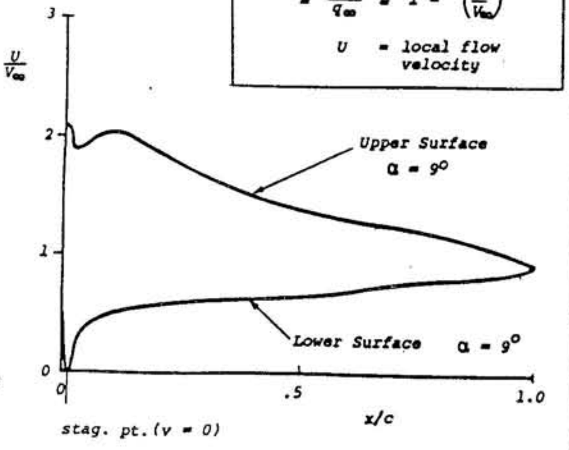


Engineering Presentation of Airfoil Pressure Distribution Data

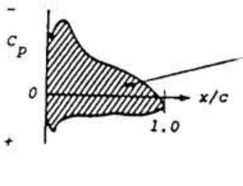
C_p = pressure coefficient

$$= \frac{\Delta p}{q_\infty} = 1 - \left(\frac{U}{V_\infty}\right)^2$$

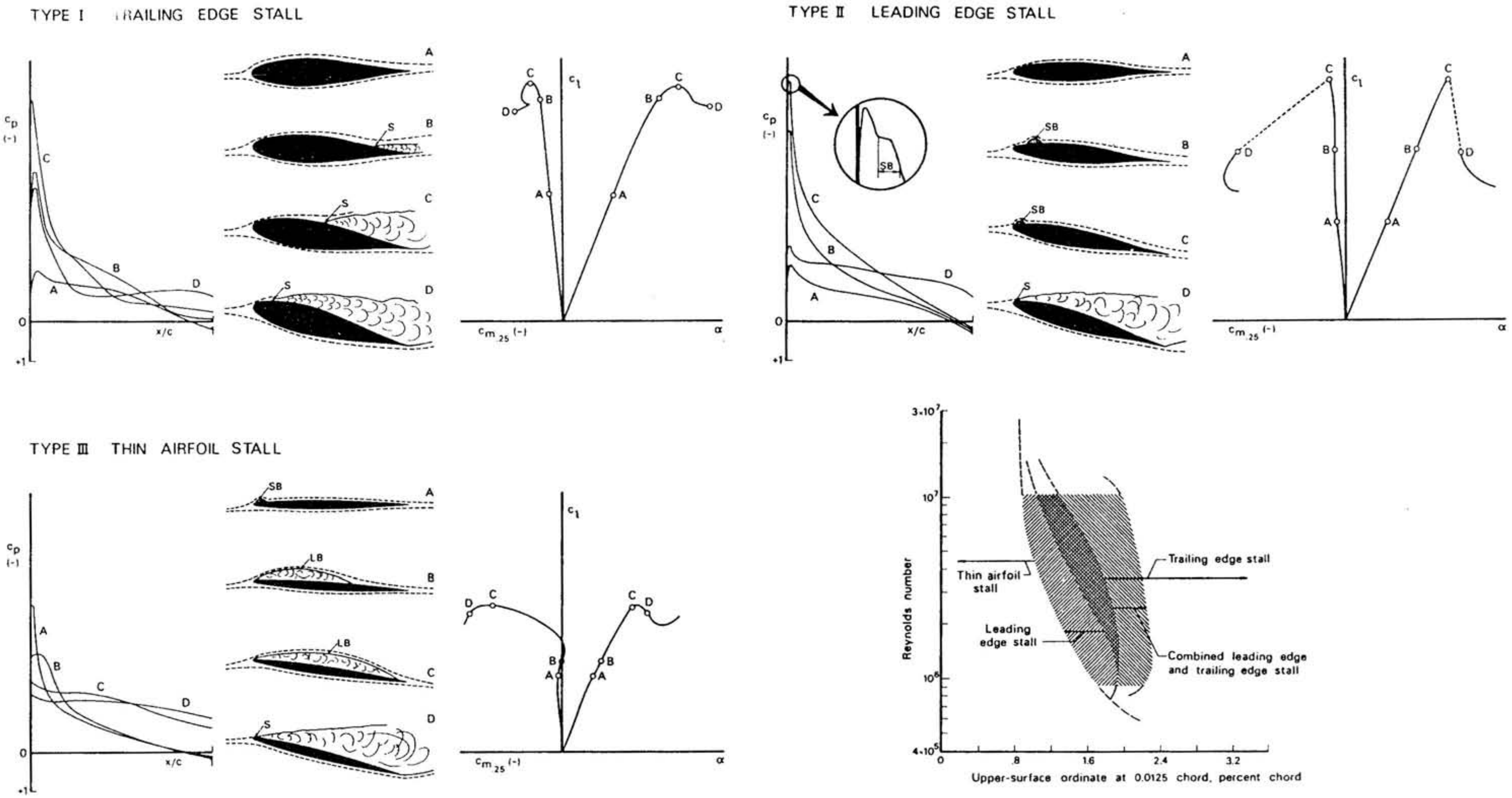
U = local flow velocity



Airfoil Velocity Distribution



[illegible] first approximation, [illegible] shaded area in this diagram divided by the cosine of the angle of attack equals the section lift coefficient.



a. Upper surface pressure distributions, growth of the boundary layer and separation regions and lift and pitching moment curves.

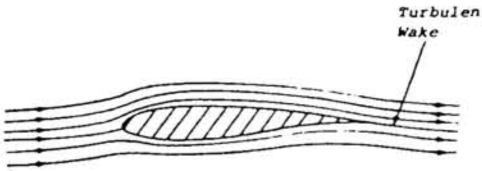
b. Stalling characteristics correlated with Reynolds number and airfoil geometry

NOTES: 1. Drawings are not exactly to scale
2. S = separation, SB = short bubble, LB = long bubble

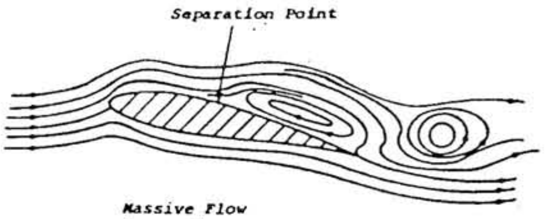
Representative types of low-speed airfoil stall

D.E. Gault: "A correlation of low-speed, airfoil-section stalling characteristics with Reynolds number and airfoil geometry". NACA TN 3963, 1957.

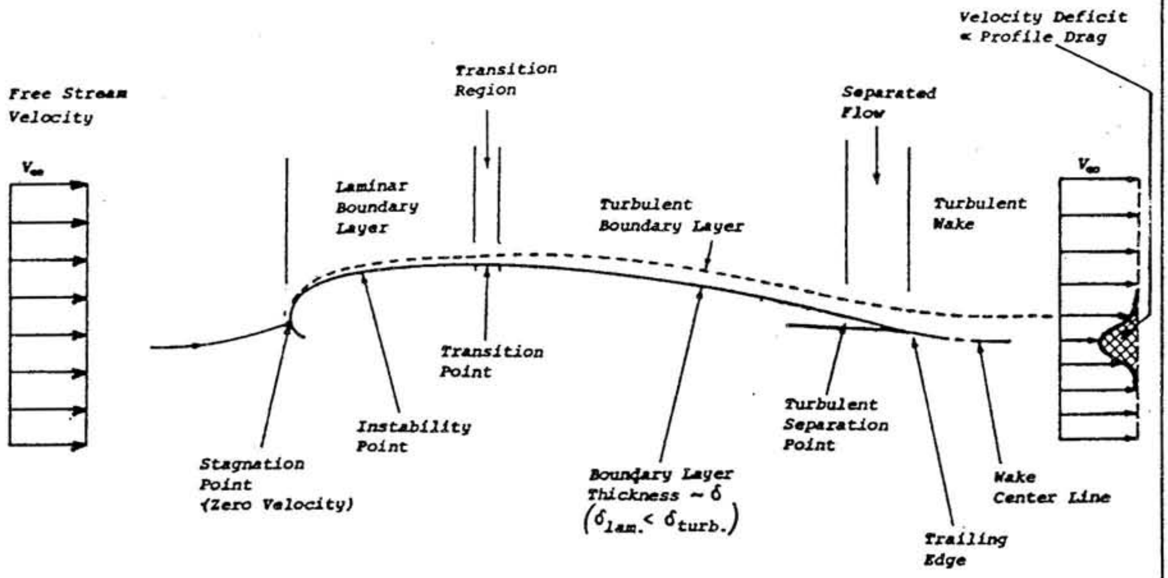
BOUNDARY LAYERS ON AIRFOILS

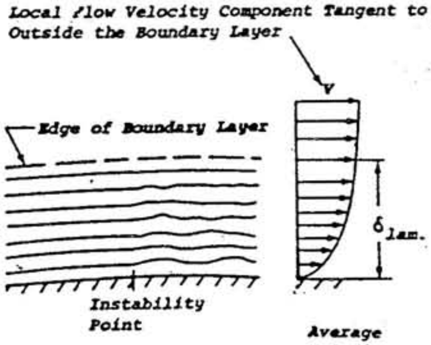


Attached Flow
(Low Angle of Attack)



Massive Flow
Separation
(High Angle of Attack)





Instantaneous Picture
of Laminar Boundary
Layer Flow

Average
Velocity
Profile

⟹ Transition
to Turbulent
Boundary Layer
Flow

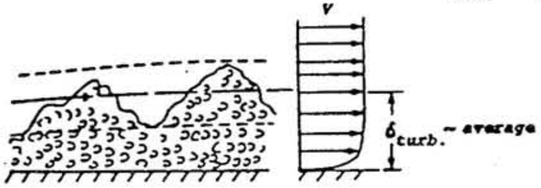
OR:

Laminar
Separation
Occurs ⟹ The Flow Reattaches
to the Surface
as a turbulent
Boundary Layer
After Formation
of a Laminar
Separation Bubble

OR:

The Flow remains
separated to
the trailing edge.

$\delta_{lam} < \delta_{turb.}$



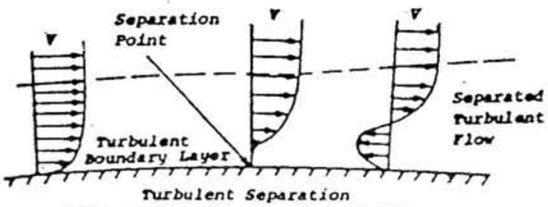
Instantaneous Picture
of Turbulent Boundary
Layer Flow

Time Average
Velocity
Profile

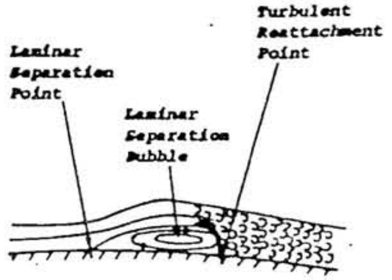
⟹ Turbulent Flow Remains attached
to surface and Flows on into a
Turbulent Wake.

OR:

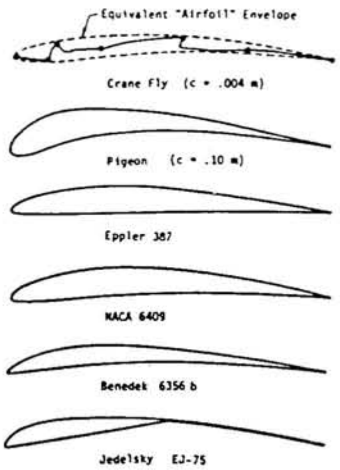
Flow Separates before Trailing
Edge is Reached.

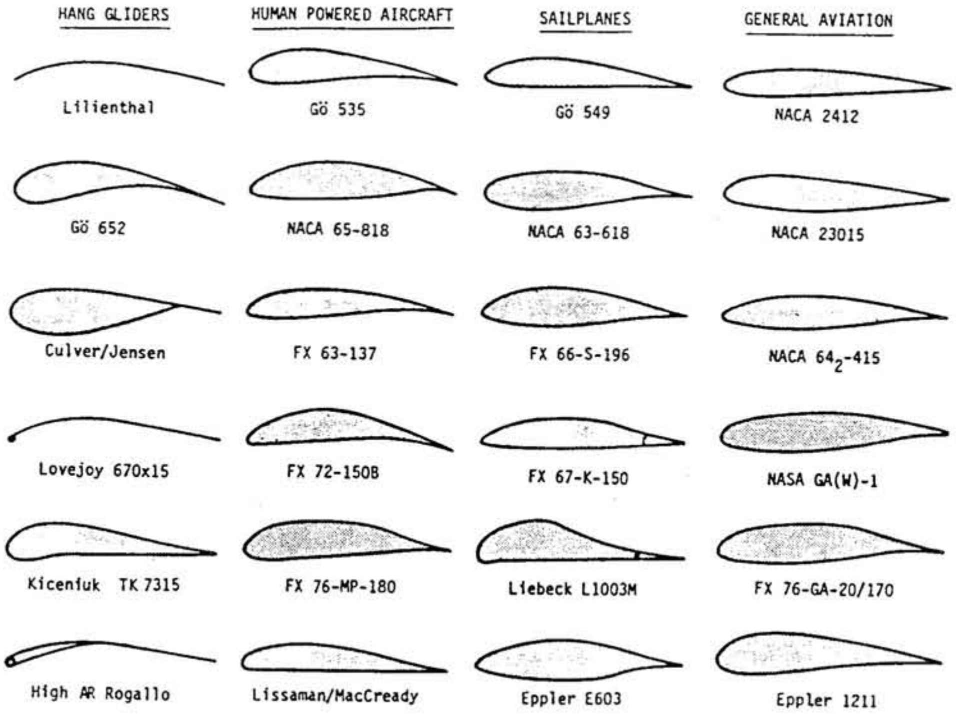


Turbulent Separation
Time Average Velocity Distributions



Laminar Separation with Turbulent Reattachment.





REPRESENTATIVE LOW-SPEED AIRFOIL SECTIONS

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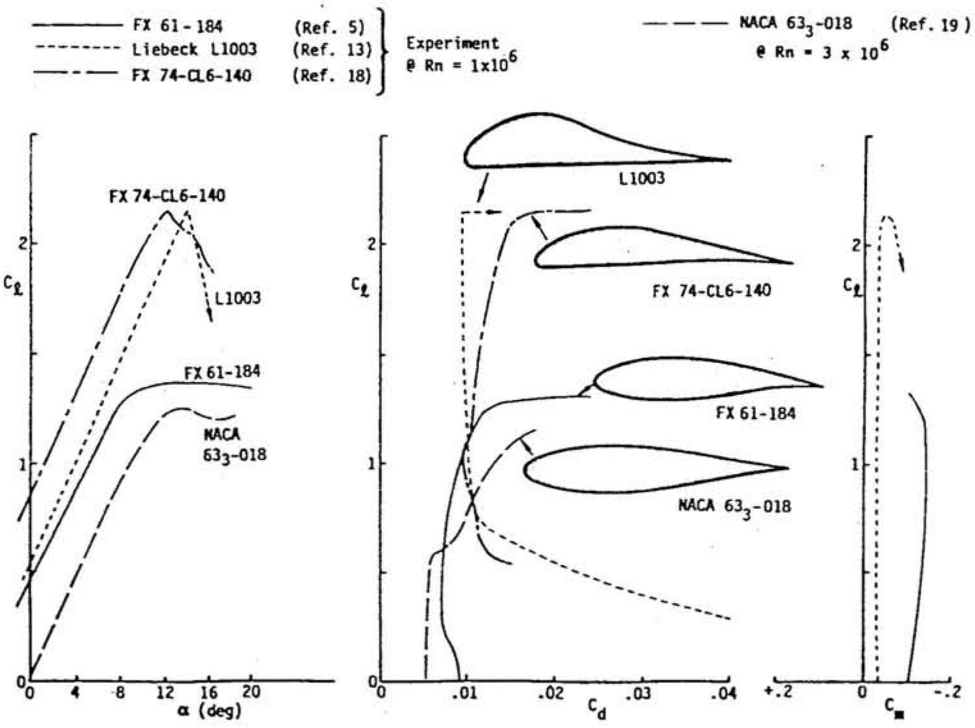

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