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Advanced Configurations for Very Large Subsonic Transport Airplanes

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I. INTRODUCTION

Recent aerospace industry interest in developing a subsonic commercial transport airplane with 50% greater passenger capacity than the largest existing aircraft in this category (the Boeing 747-400 with approximately 400-450 seats) has generated a range of proposals based largely on the configuration paradigm established nearly fifty years ago with the Boeing B-47 bomber. While this basic configuration paradigm has come to dominate subsonic commercial airplane development since the advent of the Boeing 707/Douglas DC-8 in the mid-1950s, its extrapolation to the size required to carry more than 600-700 passengers raises several questions:

- How large can an airplane of 707/747 configuration be built and still remain economically and operationally viable?
- What configuration alternatives might allow circumvention of practical size limits inherent in the basic 707/747 configuration paradigm?
- What new or dormant technology elements might be brought together in synergistic ways to resolve or ameliorate very large subsonic airplane problems?
- What new tools, methodologies and organizational arrangements need to be developed and/or validated to allow the design of aircraft which are so highly integrated in concept and technologies that conventional design approaches using "handbook" methods are inadequate or ineffective?

To explore these and a number of related issues, a team of Boeing, university and NASA engineers was formed under the auspices of the NASA Advanced Concepts Program. The results of a Research Analysis focused on a large, unconventional transport airplane configuration[1] for which Boeing has applied for a patent are the subject of this report. It should be noted here that this study has been conducted independently of the Boeing New Large Airplane (NLA) program[2], and with the exception of some generic analysis tools which may be common to this effort and the NLA (as will be described later), no explicit Boeing NLA data other than that published in the open literature has been used in the conduct of the study reported here.

II. BACKGROUND

The basic very large subsonic transport airplane problem[3,4] revolves around accommodating over 600 passengers in an efficient airframe which is to be compatible with existing airports (gates, taxiways, runways, etc.); and meets customer requirements, expected noise regulations, safety standards and other operational constraints, etc. The obvious approach has been to take a proven configuration paradigm, increase the size to that required, and then refine 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 relative to an alternative configuration are shown in Figure 1 and has been well documented recently by Schairer[5], Cook[6] and Roskan[7] which follows from Torenbeek [8]. This approach thus represents a logical point of departure for very large airplane configuration studies. What one gets is shown in Figures 2 and 3. It also suffers from quite a list of potentially serious problems as noted in Figure 3. In the end it may be thought of as the ultimate extrapolation of 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? Before addressing this question, however, the more general question of the effect on performance and cost of increasing the size of a conventional transport airplane configuration far beyond present limits has been examined by Prof. Kroo of Stanford University and the results are reported in the following section.

III. THE EFFECTS OF AIRCRAFT SIZE ON PERFORMANCE AND COST

Introduction

A very simple study of the effect of aircraft size on performance and cost illustrates some interesting results. It has been suggested that the square-cube law may limit the feasible size of aircraft, and that proposed 600-800 passenger aircraft may be approaching this limit. The current results suggest that while a variety of practical issues may indeed limit the size of aircraft, basic structural weight and aerodynamic performance considerations permit aircraft of much larger dimensions.

There is, of course, reason to suppose that the square-cube law will at some point limit the feasible size of aircraft [cf. 9]. The wing weight, for example, would be expected to grow as Wb^3/S, just from bending strength considerations, and so would comprise a larger fraction of the total weight of the aircraft as the size and weight increased. However, the wing and fuselage structural weight remain a *relatively* modest fraction of the total aircraft weight. Evaluation of the importance of this effect requires a quantitative evaluation and this is what is presented here in a simple form.

Method

To permit a rapid trade study, many parameters were held constant that would be optimized in a more refined design. We assume, for the moment, that the following geometric parameters are held constant: wing AR, sweep, t/c, airfoil geometry, fuselage fineness ratio, tail area ratio, etc. We further assume that the initial cruise altitude and Mach number is specified.

Now, in practice, larger aircraft are designed for longer ranges and permit larger take-off and landing field lengths, but for this study, we design a wide range of aircraft for the same range and field length requirements.

For flight at Mdiv, the wing CL is limited, so we consider aircraft of constant wing loading. With fixed wing loading, we achieve similar TO performance with constant T/W, and apart from differences in lapse rate for different size engines, the initial available cruise thrust -to-weight ratio is fixed.

With these assumptions, the calculations proceed as follows.

1. Specify a fuselage cross-section from an existing or proposed aircraft.
2. Compute the number of passengers based on the assumed fuselage fineness ratio.
3. Iterate on take-off weight until the range is equal to the desired range.
4. For each TOW, compute wing area from the cruise CL constraint, sea level static thrust from the take-off field lengths constraint, component weights, then L/D and range.

The basic methodology is described in Reference 10, but the key features are summarized in the following sections.

Drag Build-Up

The aircraft drag is computed by a conventional component build-up method that includes parasite, induced and compressibility drag. The aircraft zero lift drag estimation involves computing skin friction based on flat plate boundary layers for each major component with form factor corrections for thickness. Roughness effects are estimated empirically. Lift-dependent drag includes vortex drag and lift-dependent viscous drag. Compressibility drag is estimated using a combination of theoretical and empirical results based on the section crest critical Mach number and simple sweep theory.

Weights

Component weights are computed using semi-empirical methods[10]. This involves a variety of system weights as well as major structural weight items that are computed based on fully-stressed sizing criteria and then scaled based on empirical data. The wing and tail surface weights are based on a fully-stressed bending-dominated weight calculation, while it is assumed that the fuselage structure is pressure-dominated.

Propulsion

A single rubberized engine deck is used here with no benefit of size on tsfc. The engine dimensions are scaled with the square root of thrust while the weight is assumed to scale linearly with thrust. The thrust lapse and specific fuel consumption values are typical of modern bypass ratio 6-8 engines.

Cost / Price

A variant of the ATA method is used to estimate DOC, however, individual components are individually costed using more recent data from Douglas. Aircraft price is an especially questionable result, but for the purposes of this study, we are interested in relative rather than precise values.

Results

Computations were performed for aircraft ranging from a 4-abreast commuter to a triple-deck monster with 29 seats in the cross section.

The following parameters were selected based on analysis of the baseline design:

5000	Required Range (n.mi.)
30°	Wing Sweep
130	Wing Loading W/Sw (lb/sq ft)
8	Wing Aspect Ratio
.30	Sea Level Static Thrust to Weight
467	VCruise (kts) (Mach = .80)
32000	Initial Cruise Altitude

A variety of additional parameters were selected based on typical transport aircraft. Basic results are shown in Table 1 for each cross-section that was selected. The first column indicates the number of seats in the cross-section. This is the same as the number of seats abreast in a single deck arrangement. The value of 12 for a 747-like design is an average value as the aircraft upper deck does not extend over the full length of the fuselage. The fuselage width and height are shown next based on existing or proposed aircraft layouts. Also included in the table are NSeats, the total number of seats assumed; TOW, the computed take-off weight that meets the range requirements; Sw, the wing reference area; L/D, the lift-to-drag ratio at start of cruise; the wing span; the thrust to drag ratio at start of cruise; DOC, the direct operating cost; the estimated aircraft price (in millions of dollars) and the price per seat.

Discussion

These results are, in some ways, surprising. The expected square-cube law effect, making the largest aircraft uneconomical is not observed. Rather, DOC is seen to decrease even for the largest aircraft, although very significantly, the analysis indicated that for aircraft with more than about 600 passengers the improvement in DOC is slight for these conventional configurations.

The following results should be noted:

1. The L/D increased with aircraft size, due primarily to Reynolds number effects, but also to the more efficient use of fuselage volume for the 2 and 3 deck arrangements which tend to reduce the ratio of fuselage to wing wetted areas.

2. Because of the improved L/D, the engine thrust margin at the initial cruise condition increased. The fixed T/W is maintained for take-off and climb requirements, but some opportunity exists for exploiting this effect on the larger aircraft. This would further improve their performance.

3. Although the engine T/W was fixed to maintain take-off performance, the larger aircraft employ 3 or 4 engines while the smaller aircraft are twins. The estimated TO field length for the 4-engine aircraft is thus smaller than that of the twins, so for comparable field length performance we should have reduced T/W, further improving the large aircraft performance.

4. The DOC estimate here does not include financing cost, but the total aircraft cost per passenger is remarkably constant, so including this would not be expected to reverse the trend of improved economics up to extremely large aircraft.

The fundamental conclusion is that basic aerodynamics and structure do not limit the size of aircraft that can be operated economically. Issues such as airport compatibility, scheduling, passenger loading and servicing, emergency egress, and other practical considerations are, most likely, the principal concerns.

IV. ALTERNATIVE LARGE AIRPLANE CONFIGURATIONS

Having concluded on the basis of a first order/first principles analysis that with respect to the technical elements of the problem pure size increase *alone* does not appear to limit airplane performance and economics, the question of what configuration(s) may be "best" for an unconventionally large subsonic transport airplane may be addressed. The purpose in this is to explore possible opportunities to exploit the unconventionally large physical *size* of a "Jumbo 747" (or its component parts) which, when coupled with advanced technologies available in various disciplines, might allow a designer to:

1. Obtain significant improvements in airplane performance and economics compared to those aircraft now in operation, or;

2. Find ways to circumvent practical operational and infrastructure problems to be expected in increasing the size of a conventional (e.g., Boeing B-47/707/747) configuration beyond its current limit without incurring significant performance or economic penalties.

The first objective has been a traditional target, and a typical result is shown in the recent work done by Liebeck, et al. at Douglas [11, 12] (and was the genesis for the airplane configuration studies to be reported here). As the present work progressed, the second objective above very quickly became the central focus of the investigation, however. Thus the Douglas approach to the large airplane problem and the configuration developments to be discussed here represent almost diametrical opposites to each other, with some interesting convergences in conclusions to be drawn.

Innovative Large Airplane Configurations

A "conventional approach" to innovation in dealing with a very large airplane is to examine various forms of wing-only or tail-less configuration arranged as a span-loader and optimized for maximum cruise efficiency (i.e. maximum lift-to-drag ratio or M L/D). While this approach often produces aesthetically appealing results[11, 12], the concepts generally fail to pass one or more critical (though sometimes mundane) tests of operational or manufacturing feasibility, and thus seldom find much favor when decisions regarding what to offer for sale are made. The appeal of this class of configuration remains, however, and the following line of reasoning many be pursued:

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 penalties are incurred.

2. A typical business class passenger may be assumed to be approximately six feet tall. A typical transonic cruise airfoil 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 number of items 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) and passive (slotted cruise) boundary layer control airfoils.
    3) "Extremely" 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. It may also be noted that the traditional approach to developing a new airplane has been to divide the overall problem into 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. New approaches to the design problem are needed if we are to advance beyond our present limits.

The train of thought this list generated is diagramed in Figures 4 and 5. 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 airplane development program during the early stage in design work.

Again, the large size of any greater-than-600-passenger airplane immediately suggests a span loader configuration e.g. Figure 5. 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 is not 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 number 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 [Extended Twin(-engine) Operations] as a safe and reliable procedure, for commercial transportation, suggests that a further step forward might be to reconsider the use of various forms of active boundary layer control on a commercial transport airplane. What is wanted is an unconventionally thick cruise airfoil, and an obvious candidate is the Griffith section invented in Britain fifty years ago and more recently advocated in this country by Fabio Goldschmied and others[13]. Limited (low-subsonic) test data and calculations indicate that it might work provided enough suction is provided. 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, thereby offering 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 classic (subsonic) 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 potentially ameliorating a major problem with any large airplane configuration.

Alternative Configurations

The sort of configuration which emerges from the above line of thinking is shown in Figure 5 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 Figure 6) is of considerable interest. Kroo 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. While this result is well known, a bit more intriguing from his menu of unorthodox wing shapes is the "C-wing" configuration which amounts to adding 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 Treffetz 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, just as with the horizontal tail of most conventional airplanes during cruise.

From this point it does not take much imagination to transform the simple span loader in Figure 5 into the C-wing configuration shown in Figures 7 and 8 which along the way became a quasi-3 surface (rather than a canard) airplane for the reasons outlined in References 14 and 15. This new configuration retains many of the features of the span loader with the 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 original (circa 1992) conventional baseline with 280 feet of span. The price is a pair of winglets which are *each* roughly the size of the vertical stabilizer on a 747 (which still results in an airplane with a tail height about 20 feet less than that of the baseline airplane).

V. DISCUSSION OF THE C-WING CONFIGURATION

Basic Configuration Objectives

As noted earlier, the primary purpose of developing this alternative configuration concept was to directly address the problems (c.f. Figure 3) to be anticipated in significantly increasing the dimensions of a "Boeing 747" configuration to those required to produce an economically and operationally satisfactory 600-700 passenger airplane; rather than significantly improve airplane performance. In particular, the following issues were the primary focus of attention:

1. To meet large airplane economic and performance goals, a conventional (planar) wing of very large span is required. Such wings present major difficulties in meeting ground handling and terminal area operating

requirements and were thought originally to require some form of folding wing tip arrangement with a concomitant significant weight penalty. Further, if a conventional podded, under-wing engine arrangement is to be used, the mandatory high-bypass ratio fans (when optimally located across the span) present major runway/taxi-way compatibility problems. [Note; In the configuration shown in Figure 3, the outboard engines of typical NLA are located at about the wing tip stations of an existing Boeing 747.] The use of some form of non-folding, non-planar wing in an alternative configuration would seem to resolve these issues when coupled with a suitable alternate engine placement scheme. While the C-wing configuration thus adopted "looks strange" and represents some very formidable structural dynamics and stability and control problems, it also offers the promise of significantly ameliorating the worst of the large airplane "wing span problems."

2. The problem of accommodating over 600 passengers in comfort in a conventional tubular fuselage with a length that is consistent with an airplane capable of operating in existing airport terminal areas generally forces a designer to adopt a two-deck configuration of approximately circular cross-section for volumetric and weight efficiency, and manufacturing cost reasons. Many alternatives to this basic scheme have been examined, but most have so far been shown to result in unacceptable weight, cost or performance penalties. The resulting double-deck quasi-circular cross-section configuration works well enough until airplane capacity (constrained by maximum body length) reaches the point at which meeting safety requirements for emergency evacuation becomes an over riding issue. The double-deck 600-plus passenger airplane is at that threshold. Therefore, a very central objective in developing this alternative configuration concept has been to directly address the large airplane emergency evacuation problem, preferably with a single-deck configuration. The passenger layout thus chosen and its possible synergism with a Griffith airfoil has already been mentioned and will be discussed in more detail presently.

3. While not a central objective of the development of this alternative configuration, the apparent advantages of a span loader/flying wing configuration (from which it derived) as a laminar flow control (LFC) airplane were magnified by the large percentage of airplane total wetted area represented by the fuselage in baseline (conventional) large airplane proposals. Conceptually it was imagined that if some of this fuselage wetted area could be transformed into wing (lifting surface) area without excessive penalty, then a larger percentage of total airplane wetted area would be available for effective laminar flow control, thus either improving performance or off-setting other potential penalties imposed by employing the unusual wing configuration selected.

As these three basic factors were weighed and potential airplane configuration concepts began to emerge, it became clearer that the resulting preferred concept was a highly complex system of interlocking parts with several very unconventional interrelationships between the concerns of what have in the past been more-or-less independent disciplines. The clearest example of this is in the inextricable relationship between the performance and geometry of the Griffith airfoil, details of the high-lift system, and the payloads issues of passenger compartment layout and emergency evacuation. Likewise the use of the highly non-planar C-Wing involves the judicious balancing of its characteristics as a means to potentially reduce wing span while maintaining a desired level of induced drag, while at the same time making it an intrinsic part of the longitudinal and directional (and possibly the lateral) stability and control systems. In addition, the C-Wing may, incidentally, have an important influence on the wake vortex characteristics of the resulting design--a factor of particular concern in any very large airplane development effort. In short, almost every aspect of this airplane becomes unconventional, opening opportunities for new synergisms and/or exacerbating the trades and compromises required in developing a viable system configured along more traditional lines. In several important areas, existing analysis methods (calibrated to a very large base of data for conventional airplane configurations) are not capable of providing firm answers on sizing and performance questions for highly unconventional configurations.

It was for some of these reasons that the already controversial C-Wing configuration which was evolving stopped short at incorporating the sort of high-risk, highly integrated propulsion scheme proposed by our colleagues at Douglas[11, 12] in their approach to the large airplane problem. Further, it was also decided to build our concept around the use of a central conventional single-deck cylindrical body core rather than adopt the fully blended wing-body approach taken by Liebeck, *et al.* This more conservative approach has several advantages. Most importantly, a significant portion of the "fuselage" (the payload compartment) thus remains "independent" of the complex airfoil contour constrained inner wing passenger compartment. Therefore a significant portion of the weight, etc. of the passenger compartment can be estimated reliably with well established data and methods; much of the emergency evacuation, interior layout (overhead bins, galley placement) and so on can be dealt with in a conventional manner; first class and some business passengers can be provided with conventional windows; and finally, growth can be readily provided for by the simple, traditional expedient of lengthening the fuselage (without the necessity of redesigning the wing).

Payloads

With these considerations in mind, the initial configuration of the C-Wing airplane shown in Figures 7 and 8 were developed around the fuselage of Boeing 777 modified inside to allow seating for a nominal total load of 600 passengers in the same three-class mix envisioned for a Boeing NLA. In a conventional NLA a full-length double-deck fuselage is required to accommodate 600 passengers, the layout of which is complicated not only by emergency evacuation requirements, but by the differing ratios of seat pitch and width, aisle width, galley and lavatory provision, etc. between the various passenger class compartments. The preliminary initial layout of passenger accomodations (LOPA) selected is shown in Figure 9 and (again based on Boeing NLA rules) assumes 32 (5.3%) of the passenger in First Class, 127 (21.2%) in Business Class, with the remaining 441 (73.5%) in Tourist Class. Of these, 40 Business Class and 360 Tourist Class passengers are envisioned to be accommodated in the wing.

The Griffith/Goldschmied Airfoil

At this point in the configuration development two central interconnected problems arose: (1) the complete absence of *any* data on the performance and geometry of a *transonic* Griffith airfoil, and (2) the absence of an established structural concept for the "wide, flat" pressure vessel required for the outboard passenger/freight compartments. At this early point in the project it was (rather naively) assumed that a high-speed Griffith/Goldschmied section would resemble (in shape) the corresponding classic subsonic configuration shown in Figure 10(a) with thickness reduced to 18-20% chord to meet transonic limits. Only recently has it become clear that a transonic Griffith airfoil may be substantially different in shape than its subsonic equivalent and may indeed more realistically look like the section shown in Figure 10(b). The section shown was designed to have a "good" forward upper surface transonic pressure distribution and conventional 'aft' shock location at a free-stream (2-dimensional) Mach number of 0.7, with the Griffith/Goldschmied suction slot at 90% chord allowing an unconventional aft upper surface loading and very rapid pressure recovery without separation. Since the section lift requirements for a span-loader airplane are relatively low, the remainder of the section geometry was developed to provide maximum thickness over the maximum chord extent--the limit being the point at which the *lower* surface of the airfoil reaches supercritical conditions and/or flow separation occurs because of the severe pressure gradient imposed by the need to employ a high level of aft loading to achieve desired section lift values. Such a section appears generally feasible with up to about 18% t/c at a free-stream Mach number of 0.7 but of necessity has a fairly severe pitching moment as a consequence.

With respect to the problem at hand, it should be noted that in the airplane configuration shown in Figure 8, use of an 18% t/c airfoil of the shape shown in Figure 10 (b) could result in front and rear wing spar depths of about 10-11 feet at the out board span-wise limit of the passenger compartment shown in Figure 9. This unconventionally large dimension still allows, at least in principle, the use of the emergency evacuation scheme (i.e. egress through the rear spar) originally proposed for the airplane concept. How this might work requires some further consideration of the high-lift system of airplane, particularly with reference to this new airfoil geometry.

High Lift Systems

As with the cruise condition, the large wing area of the quasi-span loader places no more than moderate demands on the high-lift performance required to meet acceptable field length and approach speed criteria. What the details of such a high-lift system compatible with the geometry and aerodynamics of a classic Griffith airfoil have remained a small puzzle although various single-slotted flap schemes can be envisioned conceptually. With the sections typically of those shown in Figure 10 (b) however, it is possible to conceive of a arrangement that could provide the necessary performance without compromising high-speed performance or emergency egress capability. Here it may be observed that:

1. Aside from its thickness, the airfoil shown in Figure 10 (b) looks remarkably conventional over the first 90% of its chord and it does not offend the eye to imagine a conventional flap of about 20-25% chord nested (retracted) within its contours.

2. At the expense of considerable mechanical complexity, the Griffith airfoil suction slot (imagined here to be part of the flap assembly) could be made to operate in any flap deflection position.

3. When the flap thus fitted in deployed (by deflection and/or moderate Fowler motion) the airfoil still resembles a conventional multi-element high-lift section. In this case, however, the suction slot may be required to keep the trailing edge of the flap, rather than the main element of the airfoil, from separating.

4. By operating this flap at a non-optimum gap and/or overlap (and in conjunction with conventionally located ground spoilers) enough space can be provided to allow deployment of escape slides to allow rear-spar emergency agress, in a balanced trade against the aerodynamic performance of a less-than-optimum high-lift flapped airfoil.

5. It has been pointed out in recent discussions that rear-spar egress may not (assuming that it is feasible) be sufficient to meet necessary safety standards and that front spar egress may also be required. This one is "easy" due to an unexpected synergism. If one imagines this airplane as an LFC platform from the outset, it will require some sort of leading edge contamination protection during ground and low altitude flight operations. A "Krueger bug shield" has been demonstrated to be effective for this purpose without serious penalty on high-lift performance. Thus, employing such a Krueger flap on the leading edge of the Griffith airfoil creates a practical looking 3-element airfoil with a large cavity opened ahead of the front spar (which is again of very large physical depth) during all take-off and landing operations -- thus providing the opportunity to meet safety standards with escape slides deployed from both the front and rear of the passenger compartments where needed. This scheme is shown conceptually in Figure 10 (c).

6. The fraction of the wing span over which these compromises must be made is quite limited and assuming that a corresponding practical structural concept for the passenger compartment can be developed, there appear to be no insurmountable problems.

Pressure Vessel Concepts

There are two rather obvious structural concepts for the required pressure compartments for a span-loader type airplane as shown schematically in Figure 11. Both of these concepts are based on use of double skins, an exterior surface to maintain aerodynamic performance working together with a more flexible inner skin capable of sustaining fluctuating pressures while providing necessary strength to support the loads. There are no data available to establish the practicality of either concept nor to assess the true weight penalty of such structures compared to a conventional cylindrical body for which design guidelines are will established. This problem is very well worth addressing in much more detail because of its very significant impact on the practicality of a wide range of possible advanced airplane configurations including the one considered in this study. If such "flat" pressure vessels could be developed with no more than an acceptable weight penalty (when compared with current practice) the *overall* configuration benefits to be had by significantly rearranging and/or reconfiguring the airplane could be substantial. Unfortunately further consideration of this topic was beyond the resources of this study, and as will be noted later, the "multi-lobe" concept shown in Figure 11 will be assumed in later analyses as being the easiest on which to make plausible weight estimates.

Additional Considerations

Major questions remain regarding several aspects of the C-wing itself which also have been beyond the scope of the resources available for this study. Prinicpal among these have been the issues of: (1) C-Wing structural dynamic characteristics (and the influence of metal versus composite material structures on performance and weight), (2) the stability and control characteristics of the "as-drawn" configuration and whether, in view of the pitching moment characteristics to be anticipated from use of transonic Griffith airfoils, there is increased justification for the use of the foreplane (quasi-3 surface airplane) configuration drawn in the initial concept.

A third topic which has been examined preliminarily at Tuskegee University is the trailing wake structure of a C-wing compared to that shed by an optimally (elliptically) loaded planar wing. The results of both an analysis and a simple wind tunnel test conducted at Tuskegee are shown in Figure 12. These results indicate significant differences in wake structure between the two wing configurations, but whether these or other differences to be established by more elaborate analyses and tests demonstrate a wake vortex alleviation advantage (or penalty) for a highly non-planar wing remains a question. Given the importance of the wake vortex issue to any large airplane program[4], demonstration of an advantage for a C-Wing or similar concept could be a very positive justification for further development work--all other factors being equal.

Final Configurations for Analysis

After weighing all the factors discussed above, several modifications to the original C-Wing design shown in Figure 8 were made. Principle of these were relocation of the two aft above-wing mounted engines to pylon mounting above the aft end of the fuselage and changes to the inboard wing planform to reflect the new understanding of transonic Griffith airfoil geometry and the relationship of this to the layout of the lateral passenger compartments. These changes are shown in Figure 13. This configuration, modified further by replacement of the twin aft engines by a single larger "GE90" class engine (with similar substitutions for the remaining wing mounted engines), and retaining the approximately 220 foot wing span of the original design, formed the basis for the sizing and optimization analyses reported in the next section.

In the meantime, further work and rethinking of large airplane problems by both Boeing[2[and Airbus[16] have resulted in somewhat smaller (in physical dimensions) airplanes than those extant (circa 1992) when the ideas discussed in this report began to germinate. The results of both company's recent studies are shown for comparison in Figure 14 with the two airplanes of very similar configuration also being similar in size and weight. It should be noted that, following extended discussion with airport operators and surveys of existing facilities it has been concluded[2] that if overall airplane dimensions can be kept within a roughly 80 meter [262 foot] square, they can operate from a significant number [but not all] of existing airports of interest without the need to employ folding wing tips.

VI. PRELIMINARY SIZING AND OPTIMIZATION

A basic objective of this study was to assess the ability of current preliminary design methodologies to deal with the class of unconventional, highly integrated airplane configuration discussed previously. The primary analysis to be reported was conducted by Boeing in part in support of this contract. An alternate, independent and earlier analysis[17] not done as part of this contract was performed at NASA-LaRC by Ms. Monica Fetty as a "familiarization exercise" as part of her initial NASA work assignment. The relevance of the results of Ms. Fetty's parallel analysis to those to be presented here, and the view it gives of the capabilities of NASA methodology, justifies its inclusion in this report. In the following, Ms. Fetty's analysis will be referred to as the "NASA study" and these results will be discussed first.

NASA C-Wing Evaluation

The NASA study depended primarily on the use of the Flight Optimization System (FLOPS) code augmented by a code, MULTOP, supplied by Kroo of Stanford for non-planar wing span efficiency factor (induced drag) calculations. The C-Wing configuration analyzed was based on sketchy overall configuration geometry taken from Reference 1. With these (limited) resources, combined with a conventional large airplane configuration from Langley to be used for comparison purposes, the problem as formulated at

NASA was as shown in Figure 15. Summary results of the analyses conducted are shown in Figures 16 and 17.

It should be noted that the baseline and study airplanes were configured to seat 800 passengers and were thus considerably different in most details to those in the Boeing comparisons to be discussed in the next section. Thus direct comparison of the detailed sizing results are impossible since they also depend on several assumptions which differ from those in the Boeing analyses. The trends in the NASA results are of interest, however, and will be shown to be broadly similar to those displayed in the Boeing results. The central conclusion of this NASA analysis was that the original small span C-Wing showed poorer performance at a weight penalty compared to a conventional baseline, but may show advantages if the span is allowed to increase to values approaching those of the planar wing used for comparison. The details of all of these results are, however, very heavily dependent on the assumptions made regarding use of composite materials, and possible Griffith/Goldschmied airfoil/wing performance--for which a range of possible estimates were made.

Boeing Analysis

The feasibility of using a C-Wing configuration for a 600 passenger/7,400 mile range/0.85 cruise Mach airplane was examined using the Boeing enhanced ACSYNT analysis tool[18]. Most of the analysis modules in Boeing-ACSYNT are different from the original NASA code. In particular, the weight module is a more detailed model than the original.

A conventional all metal airplane configuration (swept, high AR wing, aft mounted control surfaces based on a generic amalgam of the NLA and A3XX configurations shown in Figure 14 was developed to satisfy the requirements. This baseline was itself developed from a calibrated Boeing 747 base.

From this conventional base, the required changes to the geometry were made to model the C-Wing to the degree possible. The ACSYNT geometry can, in principle, model everything but the large "double winglet" directly.
This feature was modelled as follows:

1. Twin vertical tails mounted at the wingtips were used to model the primary winglet.

2. A conventional horizontal tail of the required size was used as the second segment of the double winglet (horizontal "winglet-let").

3. The induced drag characteristics of the C-Wing were modelled by applying a simple factor to the induced drag of the basic planform. Analysis by Kroo suggested the planform efficiency factor for the configuration used (cf. Figure 13) would be 1.2 to 1.3. A value of 1.2 was used. An all turbulent flow airplane was assumed for viscous drag.

A weight penalty was calculated for the additional pressure vessel volume required in the wing roots from the required surface area relative to typical fuselage structure weight per wetted area. An allowance was made for the fact that the passenger accommodations in the wing root occupy space that would normally house a considerable amount of wing structure. A maximum penalty without any allowance would have been about 35,000 pounds, and the final penalty weight used was 25,000 pounds.

The effect of the Griffith airfoil (used only on the inboard portion of the wing) was modelled by increasing the drag divergence Mach number to allow for the high wing thickness/chord ratio. For simplicity, a modest (low intermediate) thrust recover from the suction slot of the section was assumed. An analysis was also done with a conventional inboard airfoil with root t/c of 0.18 for comparison.

For the Griffith airfoil baseline, a series of cases were run for wing areas ranging from 8,000 to 14,000 sq. ft. and engine thrusts of 80,000 to 100,000 pounds per engine.

These analyses showed that limiting parameters were the takeoff field length (11,000 ft at SL/86 deg. F.) and the second segment climb gradient. These limits suggested that 12,000 sq. ft. wing area with 95,000 pound thrust engines are the best values to meet the requirements.

Some span trades were also made, ranging from 200 to 260 feet, varying thrust with a fixed wing area of 12,000 sq. ft. Again, the values that provide the best overall compromise are 240 feet span with 95,000 pounds thrust. If a reduction in span to 220 ft. is desired, all criteria can be satisfied if the thrust is increased to a little over 100,000 pounds per engine.

The conventional airfoil airplane was forced to fly slower, at Mach 0.80, but otherwise was very similar in weight, general size, thrust and performance to the Griffith airfoil airplane. The design mission block time is 16.5 hours, incresed from 15.5. This is probably not a significant issue. The simplicity of this alternative makes it an attractive option.

Selected overall results from the various analyses are summarized in Table 2. A final preliminary configuration for the airplane that results from this analysis is shown in Figures 18 and 19.

VII. CONCLUSIONS AND DISCUSSION OF FUTURE POSSIBILITIES

Based on the use of methods with limited capabilities for dealing with highly unconventional airplane configurations and with no well established data bases for key technology items (e.g. transonic Griffith/Goldschmied airfoils, structural dynamic characteristic of extremely non-planar wings), both the NASA (FLOPS) and Boeing (ACSYNT) preliminary sizing results reported in the previous section present a mixed and perhaps overly pessimistic view of the potential for further exploration and development of the C-Wing very large airplane concept which has been the subject of this study. Clearly (within the limits of the available data), all the analysis results presented seem to consistently dash a central hope that use of the proposed highly non-planar wing could significantly reduce the wing span requirements of an approximately 600 tri-class passenger transport airplane over the values projected for an optimized airplane of conventional ("Boeing 747") configuration. It must be emphasized here, however, that this conclusion seems to hold for subsonic transport airplanes carrying *up to* about 600 passengers.

It should be noted in this connection that even the simplified analysis (unconstrained by airport infrastructure and other practical operational considerations) presented in Section III of this report suggests that the performance and economic improvements to be expected from simple size (and passenger capacity) increase diminish very significantly for a conventionally configured aircraft with more than about 600 passengers. This further suggests (and seems to be verified by recent Boeing [2] and Airbus [16] experience) that even when one sharpens one's pencil and negotiates an approximately 260 foot (80 meter) span limit for a large airplane without the need for folding wing tips when operating from a significant number (but not all) of existing airports of interest world-wide, an approximately 600 (tri-class) passenger airplane of conventional configuration is approaching a practical upper bound and at this level presents a formidable developmental challenge.

Against this situation and within the limits of the available data, it has been demonstrated in this conceptual study that:

1. There is nothing in the results presented in this study which indicate that, with sufficient further effort, the C-Wing configuration proposed cannot be made to work--and perhaps reasonably well. It should be noted, for instance, that the vertical "winglets" used on the C-Wings analyzed are quite large but still remain somewhat conservative relative to what could be used (cf. Figure 6) without violating existing assembly hall and terminal gate area height limits.

2. Most of the really difficult problems encountered in attempting to converge on an acceptable 600 passenger C-Wing are related in most cases to the slightly *too small* size of the airplanes as presently configured. In short,the design problem becomes easier conceptually as the size of the C-Wing increases, with considerable apparent growth potential even within the limits of an "80-meter box."

Viewed from a second perspective, the objective of developing what may be a potentially viable *single-deck* 600+ passenger large airplane configuration concept which meets necessary constraints on emergency evacuation, etc, and which shows some promise as a laminar flow control airplane have been met - at least in principle. These same advantages could also be claimed for any of a variety of span-loader airplane concepts (e.g. as shown in Figure 5 and as described in References 11 and 12), but it can further be claimed that the C-Wing configurations examined in this study have advantages beyond those of a conventional (tail-less) span loader configuration (particularly those in which the payload/passenger compartment is very highly integrated into the basic wing/center section structure). The basic wing-fuselage concept embodied in the C-Wing configurations explored in this study have the potential virtues of providing some conventional windows for the entire First Class and a bit of the Business Class sections of the aircraft, and growth of the airplane by simple body stretch is naturally accommodated (up to whatever overall body length constraint may be imposed). In this later connection, it is also possible to imagine the same basic configuration concept being built up around a Boeing 747 center body, the passenger layout and emergency evacuations features of which are already well established. This would allow development, at least in principle, of a really very large airplane within the dimensional limits of a basic 80-meter box.

The most striking difference between the quasi-span loader C-Wing and a conventional "flying wing" is the opportunity the C-Wing (perhaps augmented with a foreplane to form a quasi-3 surface airplane) offers to deal with stability and control problems and limitations inherent in even an actively controlled tail-less airplane (e.g., the B-2 bomber). Since the basic features needed to deal with the pitching moment increments associated with very heavily aft-loaded cruise airfoils (including the transonic Griffith sections which seem to be emerging) and a proper camber-changing flap high-lift system come with the span reducing characteristics of the C-Wing and a certain unique natural synergism thus exists. If in fact a hoped for improvement in wake vortex hazard alleviation can be had from use of such unconventional wing configurations, the *sum* of its (even small) virtues may add up to a very good reason to purse further development efforts. It may also be added that until the structural dynamic aspects of the C-Wing configuration have been evaluated in some detail (a task far beyond the resource limits of the present study), particularly with respect to the advantages and penalties of "optimized" composite versus metal structures, no firm weight estimates can be made. Thus the estimates of wing weight and other important considerations which may argue either for or against further investigations of the C-Wing remain largely speculative.

In this same vein, the value of the Griffith airfoil in this concept has become more ambiguous as the more specific configuration analysis results have become available. While it is now clearer that an unconventionally thick airfoil can be developed for operation at necessary transonic Mach number conditions using principles embodied in the original Griffith/Goldschmied concept, the limits to how thick such a section might be at a given set of Mach number and lift coefficient conditions have also been slightly clarified. If the earlier discussion on "how big a transport airplane can be" is valid, the sizing analysis presented suggests that an appropriately large (i.e. greater than 600 passenger) C-Wing airplane becomes large enough to make the use of a Griffith wing (with its added risk and complexity) potentially unnecessary. Similarly, if cruise speed requirements are relaxed (e.g. to Mach 0.8 from

0.85), the analysis presented indicates a “conventional” airfoil may be sufficient to meet physical wing thickness requirements even for the “smaller” 600 passenger C-wing transport. It has further been demonstrated (conceptually) that substitution of a more conventional airfoil contour for the classic (subsonic) Griffith geometry does not have too adverse an effect on the proposed emergency evacuation scheme. The almost complete absence of any experimental data for any Griffith airfoil at transonic flow conditions and the still rather primitive understand of this class of airfoil at high speed conditions makes all discussion of its possible virtues and vices pure speculation. Good answers to the many question surrounding the practical implementation of Griffith airfoils on transonic wings would be of considerable value since they remain a potentially important “enabling technology” for concepts such as those described in this study.

Opportunities for Further Study

The work reported here has been preliminary and has been limited by the non-availability of key pieces of technical data needed to provide definitive answers to important questions regarding the advantage (or disadvantages) of the C-Wing airplane concept. To advance beyond our present understanding of the limits on large airplane size and possible unconventional airplane configurations which might allow current limits to be extended, at least the following items need to be investigated in considerable further detail:

1. The geometry, performance and power requirements for transonic Griffith/Goldschmied airfoils and wings need to be established and supported by experimental data.

2. The aerodynamic and structural dynamic characteristics of the C-Wing need to be examined in much more detail analytically *and validated experimentally*. Data required include induced drag, wake vortex, and both static and dynamic stability and control characteristics; and weight estimations for candidate structural concepts and materials.

3. Good structural concepts for minimum weight penalty “flat pressure vessels” need to be developed and validated. These concepts have potential application to a variety of unconventional airplane configurations (e.g. an oblique wing HSCT) and availability of validated practical schemes for such components would be of real value to designers of future innovative airplane concepts.

4. Tool and data base development to support evaluations of unconventional airplane configuration concepts such as those examined in this study are an on-going need. The use of emerging multidisciplinary optimization (MDO) methodology is a particularly promising approach to dealing with the sort of highly integrated configuration explored here. Such configurations pose a real test of MDO methodology.

A final important area requiring further study is the problem of how best and most cost effectively to acquire experimental data on aircraft of unothodox configuration and/or unconventionally large size. There is a limit to what can be done with highly elastic, very unconventional huge airplane configuration concepts in conventional wind tunnel testing. Traditional flight testing using full- or sub-scale manned vehicles is both a high risk and high cost adventure. As outlined in the attached appendix, it is now possible to imagine a "third possibility" in this connection, based on some simple physics, Global Positioning Satellite (GPS) capabilities, and emerging Unmanned Autonomous Vehicle (UAV) technology. It may be noted here that the scheme proposed in the appendix (originally investigated as an alternative way to acquire "wall interference free" high speed [*transonic* or supersonic] aerodynamic data at Reynolds numbers beyond the limits of existing ground based test facilities) is "made to order" for exploring both the aerodynamic, flight control, and structural dynamic characteristic of very large airplanes with "low" wing loadings (and consequent high [>40,000 ft,, cf. Table 2] cruise altitudes) typical of the C-Wing airplanes evaluated in this study.

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Appendix

An Alternative Approach to Wind Tunnel and Flight Testing

Ongoing discussions regarding high Reynolds number testing needs has led to construction of a lengthy list of possible approaches. At one point, his exercise also happened to coincide with another round in the cycle of assessment of future product development directions and opportunities. One of the opportunities considered once again was the so called "Near Sonic Cruise Transport (NSCT)" -- a possible moderate-sized, longer range transport intended to cruise as fast as possible without creating a sonic boom. Such concepts tend to find advocates, particularly during times of relatively low prevailing fuel costs, among those who retain the belief that productivity (speed) and safety are what air transportation is all about. In thinking about the developmental problems an NSCT (or any other aircraft type intended to operate near Mach 1.0) would present, the following observations were made:

- Recent Boeing experience and information regarding our competitors' research and development efforts demonstrated the increasingly severe limitations on our ability to test future transport airplanes at or near full-scale Reynolds number conditions.

- The use of large scale half models in existing atmospheric and pressure wind tunnels is a partial near-term solution to the problem but may not be adequate for future development efforts (e.g., NSCT, NLA or SST development).

- The use of large half models does not adequately address the corresponding testing needs for structures, loads, and stability and control (e.g., what happens at the boundaries of the flight envelope, particularly in yaw and roll?).

- A fundamental problem in wind tunnel testing, particularly at near sonic conditions, is how to obtain test data at sufficiently high Reynolds number on a model small enough to avoid significant contamination of test data from transonic/supersonic wall interference effects (c.f. Figure A-1).

- At some point, merely building wind tunnels with larger test sections and/or higher pressure ratios becomes prohibitively expensive or otherwise impossible. Even the huge ONERA S1 tunnel at Modane with its associated hydroelectric dam appears inadequate.

- At present the alternative to wind tunnel testing is flight testing (using anything from sub-scale technology demonstrators to existing aircraft modified to represent some portion of a new design). Using manned vehicles for such testing is generally an order of magnitude more expensive than any wind tunnel test and is usually considered prohibitive for even "final validation" purposes in civilian programs.

- If we are to maintain our present competitive position in the industry, thought must be given to innovative and/or non-traditional test techniques to supplement wind tunnel testing.
- Remotely Piloted Vehicle (RPV), Unmanned Autonomous Vehicle (UAV) and related missile and flight control technology has advanced significantly, although most engineers in the commercial airplane business have very limited knowledge of what is presently available in RPV/UAV technology.

This line of argument led to the thought that there might be a way to use RPV/UAV technology to develop a new kind of test facility which would allow performance testing for design validation purposes wherein "interference free" data could be acquired at the correct Mach number, on a vehicle flying at the correct lift coefficient, at near full-scale Reynolds numbers, and at a cost substantially less than that associated with flight testing a manned vehicle. The basis of this concept was the observation that, everything being equal, Reynolds number decreases with increasing altitude.

On the basis of a standard atmosphere, an airplane intended to cruise at say, 40,000 feet altitude will be flying at a Reynolds number of approximately one-third the corresponding value at standard sea level conditions. This factor also suggests that if we turn the problem upside down, a one-third scale model of an airplane intended to cruise at 40,000 feet, would achieve full-scale cruise Reynolds numbers if tested at the same Mach number at sea level. Alternatively, one might view the test of such a model at sea level conditions as being conducted in a "single walled (the ground) wind tunnel" operating at approximately five atmospheres of pressure. A bit of simple algebra produces the graph shown in Figure A-2 where the reference conditions are for a transonic airplane assumed to be cruising at 39,000 feet. In this example, a one-quarter scale model (Fig. A-3) of the full-scale airplane is shown to achieve 80 percent of the full-scale (reference) Reynolds number at the correct full-scale Mach number and lift coefficient if flown at 4,500 feet altitude. Under such conditions the data obtained would be essentially interference free. And in addition, a whole range of problems would arise.

The most obvious problem is how to acquire meaningful drag data from such a test. Recent test results reported by Budd, *et al.* [A-1] indicate that this issue can be resolved with further developmental effort. A second subtler problem is that if the model is flown in a straight line at 4,500 feet (at a load factor of 1g), a one-quarter scale model of a full-scale airplane intended to match the full-scale value of cruise lift coefficient would have to have a wing loading 4.7 times that of the real airplane. To avoid the need to construct such a model of some material such as spent uranium, the solution to this problem is to put the model in a constant speed banked turn (at load factor greater than unity), which would allow an arbitrary trade to be made between model wing loading (at constant lift coefficient) and bank angle/turn radius.

For the case shown in Figure A-2, a load factor of 4.7 (i.e. bank angle of 77.7 degrees) would be required to equilibrate model and full-scale wing loadings assuming constancy of lift coefficient between the two. Assuming the model was flown at a Mach number of 0.90 under these conditions, the turn radius would be 1.1 n.mi - enough to avoid serious flow field curvature effects.

On the basis of these simple calculations, an (RPV/UAV)-based testing scheme does not seem impossible, although whether it is better directed at an SST-type configuration, or exactly what the "technological niche" for such a scheme really is remains an open question. To pursue this question a bit further, the analysis was next extended to the case of an SST (Figure A-4 and A-5), in this case one presumed to cruise at an altitude of 60,000 feet. The corresponding trades of Reynolds number achievable versus model scale versus test altitude are shown in Figure A-4. Here we see that a one-fifth scale model achieves both full-scale Reynolds number and lift coefficient at the right Mach number and full-scale wing loading if flown in a 6g (80.6 degree) banked turn at 22,000 feet altitude. As shown in Figure A-5, a one-fifth scale model of the real airplane is relatively "quite small," while in absolute terms it would be the size of a small jet fighter, with roughly equivalent power requirements. These power requirements in turn should be considerably less than the 90 megawatts necessary to drive cryogenic nitrogen over a *very* much smaller model confined in a possibly too tight wind tunnel duct.

The overall scheme for an RPV-based validated facility is shown graphically in Figure A-6. The development of such a RPV system for aerodynamic configuration validation testing presents a number of formidable engineering problems. Among these are:

- Determination of the test environment (temperature, pressure, winds, etc.) in which a "free flight wind tunnel-like" model is operating.
- Instrumentation required to determine lift and drag, and to make pressure distribution and boundary layer measurements.
- Guidance and control requirements for a vehicle traveling at high Mach numbers at relatively low altitudes.
- Test range siting requirements, and range safety issues.
- Appropriate model design and fabrication techniques.

Against these problems we may observe, however, that when treated as a "facility" in the same sense that a wind tunnel (with its ducting, power supply, data system and instrumentation) is a facility, a reusable UAV-based system may offer very significant cost reductions relative to construction of a new wind tunnel system, and offers some unique new, cost-effective opportunities to acquire dynamic flight data for flight vehicle and design methods validation.

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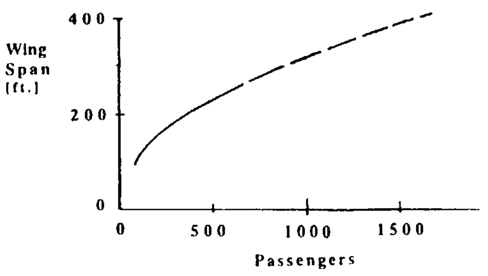
Table 1. Results of a "Square-Cube Law" Analysis of the Effects of Size Increase on a Subsonic Transport Airplane of Conventional Configuration.

Seats Abreast	Fuse. Wdth.	Fuse. Ht.	No. Seats Total	Take-off Wt. (Klb)	Wing Span (ft)	Wing Area (sq ft)	L/D	DOC cents/seat-mi	Price $M
4	8.7	8..7	68	92	75	707	16.1	4.77	11.6
5	10.6	10.8	100	137	92	1054	16.4	4.13	15.4
6	12.3	12.3	138	190	108	1461	16.8	3.73	19.9
7	16.5	18.1	217	336	144	2585	16.9	3.66	32.9
8	18.5	18.5	280	435	164	3346	17.4	3.49	41.2
9	20.3	20.3	351	555	185	4269	17.8	3.40	52.9
9	20.3	20,3	351	558	185	4292	17.7	3.50	53.1
12	21.3	25.7	492	770	218	5923	18.2	3.32	72.3
16	22.2	28	672	1025	251	7885	18.7	3.10	95.2
19	25.6	31.1	931	1460	300	11231	19.4	3.06	136.0
29	27.9	33.	1537	2500	392	19231	20.0	3.03	232,5



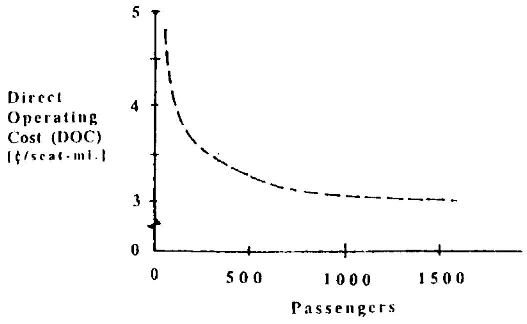


Table 2. Summary of Results of a Preliminary Sizing Analysis of C-Wing Aircraft Configurations Using the Boeing Version of ACSYNT.

GEOMETRY SUMMARY:	**Baseline** **(Conventional)** **259 ft. span** **Cruise M = 0.85**	**C-Wing I** **Griffith Wing** **220 ft. span** **Cruise M = 0.85**	**C-Wing II** **Griffith Wing** **240 ft. span** **Cruise M= 0.85**	**C-Wing III** **Conventional Wing** **240 ft. span** **Cruise M = 0.80**
ENGINE				
NUMBER	4	3	3	3
LENGTH	9.0	16.0	16.0	16.0
DIAMETER	9.5	10.7	10.2	10.2
WEIGHT	13310.3	18098.2	16374.5	16374.5
TSLS	77200.0	105000.0	95000.0	95000.0
SFC(TSLS)	.313	.313	.313	.313
FUSELAGE				
LENGTH	226.5	205.9	205.9	205.9
DIAMETER	24.4	20.3	20.3	20.3
VOLUME	81683.2	54310.7	54310.7	54310.7
WETTED AREA	14507.8	11539.6	11539.6	11539.6
FINENESS RATIO	9.27	10.12	10.12	10.12
	WING	WING	WING	WING
WIMPRESS AREA	8000.0	12000.0	12000.0	12000.0
REFERENCE AREA	8000.0	12000.0	12000.0	12000.0
TOTAL AREA	8379.3	12315.4	12385.0	12385.0
WETTED AREA	14724.2	21353.5	21574.5	21632.6
SPAN	258.7	220.0	240.0	240.0
L.E. SWEEP	41.2	37.5	37.5	37.5
C/4 SWEEP	38.9	34.0	34.7	34.7
ASPECT RATIO	8.37	4.03	4.80	4.80
TAPER RATIO	.23	.41	.41	.41
T/C ROOT	.130	.160	.160	.180
T/C TIP	.100	.100	.100	.100
ROOT CHORD	70.5	99.1	97.2	97.2
TIP CHORD	10.7	28.8	25.5	25.5
M.A.C.	31.9	56.7	51.1	51.1
LOC. OF L.E.	63.0	74.0	72.9	72.9

ENGLISH UNITS:
DISTANCES IN N.M., FT, IN
WEIGHTS IN LBS
TIME IN HOURS
TEMPERATURE IN DEGREES FAHRENHEIT
FORCES IN LBS
PRESSURES IN LBS / FT ** 2
SPEED IN KNOTS

Table 2. (continued) Summary of Results of a Preliminary Sizing Analysis of C-Wing Aircraft Configurations Using the Boeing Version of ACSYNT.

PERFORMANCE SUMMARY:	**Baseline** **(Conventional)** **259 ft. span** **Cruise M = 0.85**	**C-Wing I** **Griffith Wing** **220 ft. span** **Cruise M = 0.85**	**C-Wing II** **Griffith Wing** **240 ft. span** **Cruise M= 0.85**	**C-Wing III** **Conventional Wing** **240 ft. span** **Cruise M = 0.80**
	MISSION 1	MISSION 1	MISSION 1	MISSION 1
AIRPORT ELEV	0.	0.	0.	0.
AIRPORT TEMP	59.	86.	86.	86.
RANGE	7400.0	7399.8	7399.9	7399.9
BLOCK TIME	15.709	15.621	15.642	16.555
RAMP WEIGHT	1086132.	1214497.	1190786.	1219284.
TAKEOFF WEIGHT	1084782.	1213120.	1189540.	1218038.
LANDING WEIGHT	678535.	752482.	756056.	756594.
OEW	506209.	573303.	579565.	578499.
PAYLOAD	126000.	126000.	126000.	126000.
PASSENGERS (600)	105000.	105000.	105000.	105000.
BAGGAGE	21000.	21000.	21000.	21000.
CARGO	0.	0.	0.	0.
TOTAL FUEL	453923.	515115.	485324.	514720.
BLOCK FUEL	409347.	462780.	435422.	463383.
RESERVE FUEL	45326.	53100.	50595.	52030.
FUEL/SEAT	682.2	771.3	725.7	772.3
TAKEOFF FIELD LENGTH	8795.4	9505.6	10151.9	10688.5
LANDING FIELD LENGTH	6459.3	5424.3	5408.6	5367.8
APPROACH SPEED	141.3	123.9	123.7	123.0
ICAC (BUFFET LIMITED)	38292.6	44373.1	44810.2	41855.6
	WEIGHT (LBS)	WEIGHT (LBS)	WEIGHT (LBS)	WEIGHT (LBS)
STRUCTURE	297001.	369602.	382723.	380595.
PROPULSION	62093.	67809.	61671.	62077.
FIXED EQUIPMENT	96780.	88866.	88665.	88906.
MEW	455874.	526277.	533059.	531578.
STD & OPR ITEMS	50335.	47026.	46506.	46921.
OEW	506209.	573303.	579565.	578499.

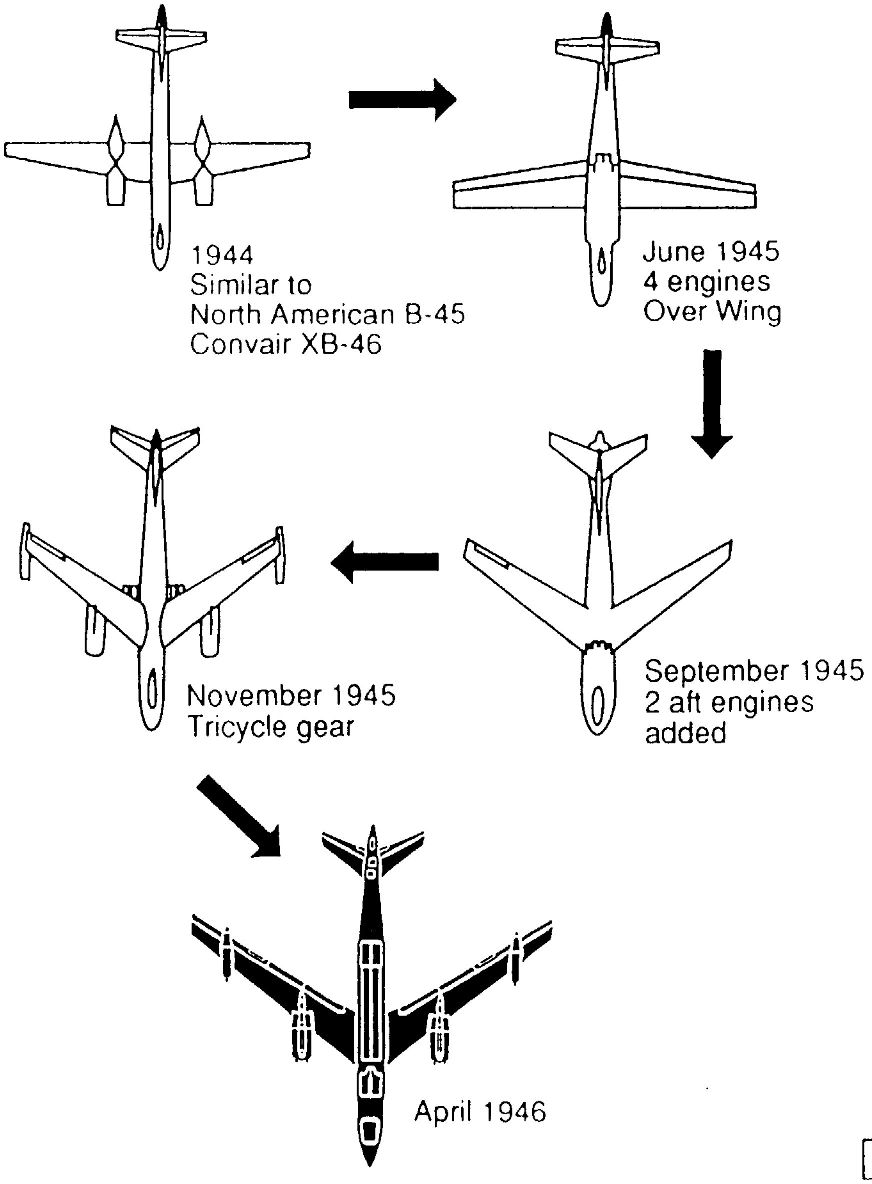
Table 2. (continued) Summary of Results of a Preliminary Sizing Analysis of C-Wing Aircraft Configurations Using the Boeing Version of ACSYNT.

			Baseline (Conventional) 259 ft. span Cruise M = 0.85		**C-Wing I** Griffith Wing 220 ft. span Cruise M = 0.85		**C-Wing II** Griffith Wing 240 ft. span Cruise M= 0.85		**C-Wing III** Conventional Wing 240 ft. span Cruise M = 0.80	
			REQUIRED	ACTUAL	REQUIRED	ACTUAL	REQUIRED	ACTUAL	REQUIRED	ACTUAL
FAR 25.111	INITIAL SEGMENT CLIMB GRADIENT (DOES NOT INCLUDE GROUND EFFECT)	(OEI)	.017	.099	.015	.031	.015	.021	.015	.032
FAR 25.121(A)	TRANSITION SEGMENT CLIMB GRADIENT	(OEI)	.005	.084	.003	.013	.003	.003	.003	.014
FAR 25.121(B)	SECOND SEGMENT CLIMB GRADIENT	(OEI)	.030	.099	.027	.031	.027	.021	.027	.032
FAR 25.121(C)	EN-ROUTE CLIMB GRADIENT	(OEI)	.017	.077	.015	.036	.015	.027	.015	.034
FAR 25.121(D)	LANDING APPROACH CLIMB GRADIENT	(OEI)	.027	.183	.024	.091	.024	.078	.024	.079
FAR 25.119	LANDING CLIMB GRADIENT	(AEO)	.032	.299	.032	.248	.032	.215	.032	.222

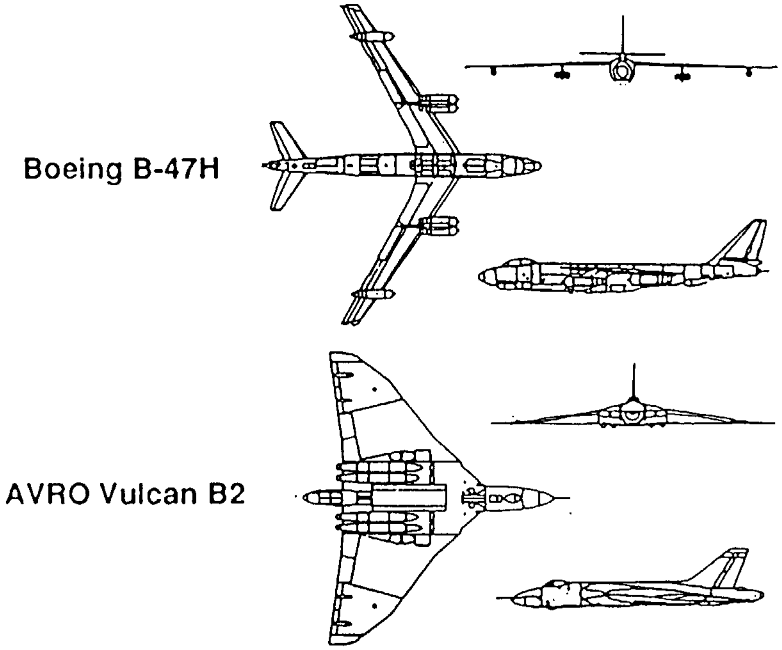
FLIGHT PROFILE SUMMARY:

	Baseline (Conventional) 259 ft. span Cruise M = 0.85				**C-Wing I** Griffith Wing 220 ft. span Cruise M = 0.85				**C-Wing II** Griffith Wing 240 ft. span Cruise M= 0.85			
PHASE	MACH	ALT	FUEL	L/D	MACH	ALT	FUEL	L/D	MACH	ALT	FUEL	L/D
MISSION												
TAXI OUT			1350.				1377.				1246.	
TAKEOFF	.00	0.	1507.		.00	0.	1544.		.00	0.	1493.	
CLIMB	.233	1500.	1270.	9.51	.388	1500.	952.	20.47	.388	1500.	938.	21.92
ACCEL	.388	1500.	1011.	18.25	.452	10000.	5052.	20.58	.452	10000.	4984.	22.10
CLIMB	.452	10000.	4516.	19.20	.713	28000.	13275.	20.05	.713	28000.	13482.	21.28
ACCEL	.506	10000.	428.	19.99	.850	31000.	2651.	18.87	.850	31000.	3046.	19.67
CLIMB	.821	35000.	17383.	19.45	.850	35000.	4887.	19.15	.850	35000.	5466.	20.38
ACCEL	.850	35000.	737.	19.21	.850	35000.	154782.	18.86	.850	35000.	142162.	19.82
CRUISE	.850	35000.	137117.	19.33	.850	39000.	5896.	18.94	.850	39000.	7217.	20.25
CLIMB	.850	39000.	3071.	18.74	.850	39000.	267271.	17.96	.850	39000.	250596.	18.75
CRUISE	.850	39000.	235960.	18.74	.435	1500.	1363.	17.68	.435	1500.	1277.	18.06
DECEL	.806	39000.	51.	19.32	.378	0.	1965.	19.29	.378	0.	1823.	19.91
DESCENT	.388	1500.	3197.	18.57			1000.				1000.	
APP&LAND			1000.				765.				692.	
TAXI IN			750.									
TOTAL:			409347.				462780.				435422.	

TOTAL RESERVE FUEL: 45326. TOTAL RESERVE FUEL: 53100. TOTAL RESERVE FUEL: 50595.



XB-47 Development Models



		Boeing B-47H	AVRO Vulcan B2
Max. take-off weight	W_{TO}	202.000	200.000
Ref. wing area	S	1,400	3,964
Wetted surface area	S_{wet}	11,300	9,600
Wing span	b	116	111
Wing loading	$(W/S)_{TO}$	144	50.5
Span loading	$(W/b)_{TO}$	1,741	1,801
Aspect ratio	AR	9.6	3.1
Skin friction coefficient	Cf (assumed)	0.0030	0.0030
Parasite drag area	$f(C_f{}^{*}S_{wet})$	34.0	29.0
	$dC_D/dC_L{}^2$ (c=0.8 assumed)	0.041	0.128
Max. lift-drag ratio	$(L/D)_{max}$	15.8	16.4
C_L at L/D Max	$CL(L/D)_{max}$	0.77	0.24

Figure 1. A Comparison of Two Very Different Aircraft Designed For Similar Missions.

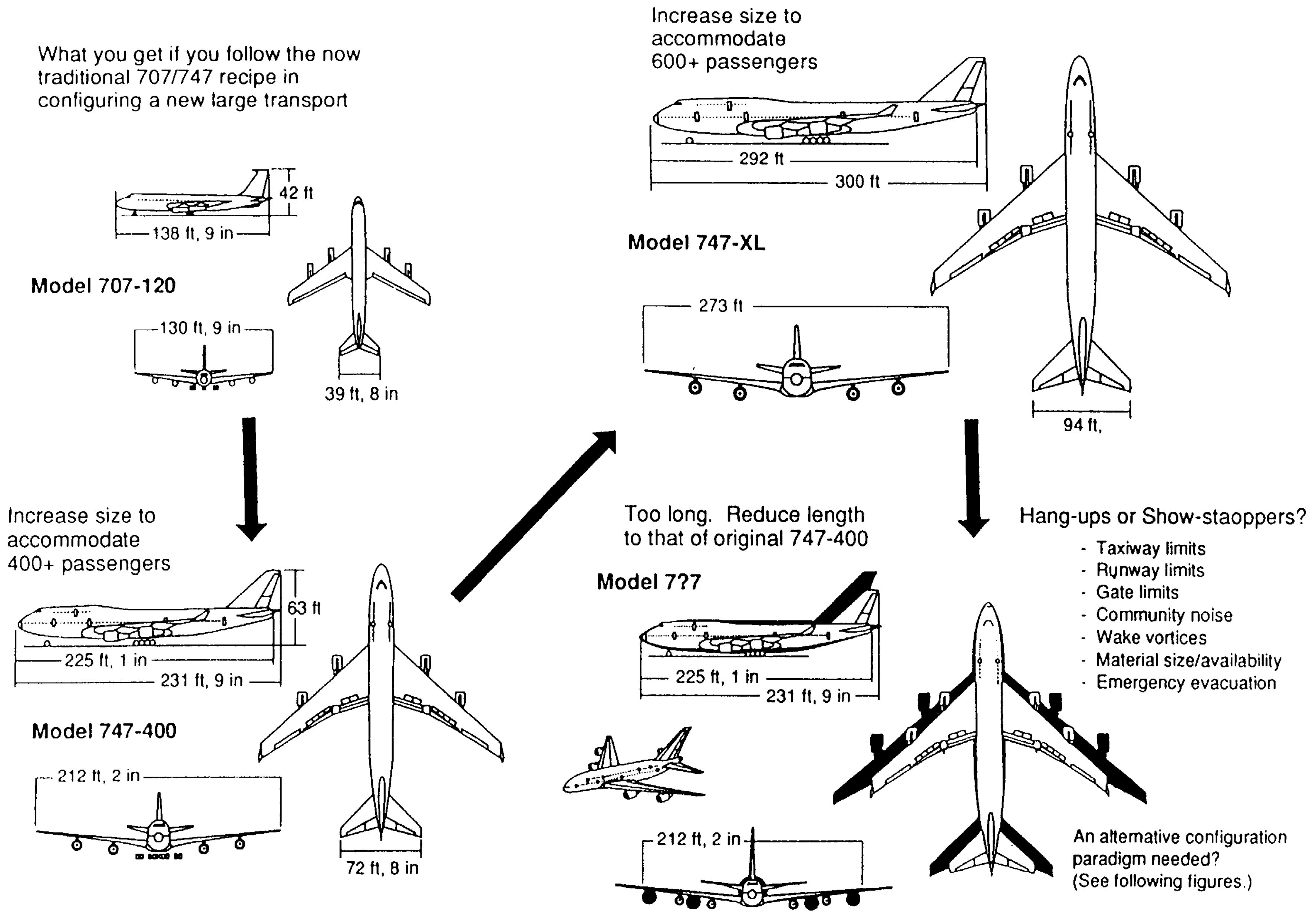
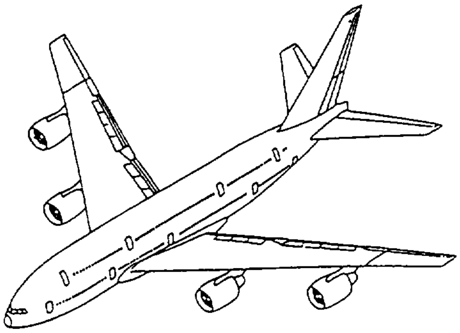
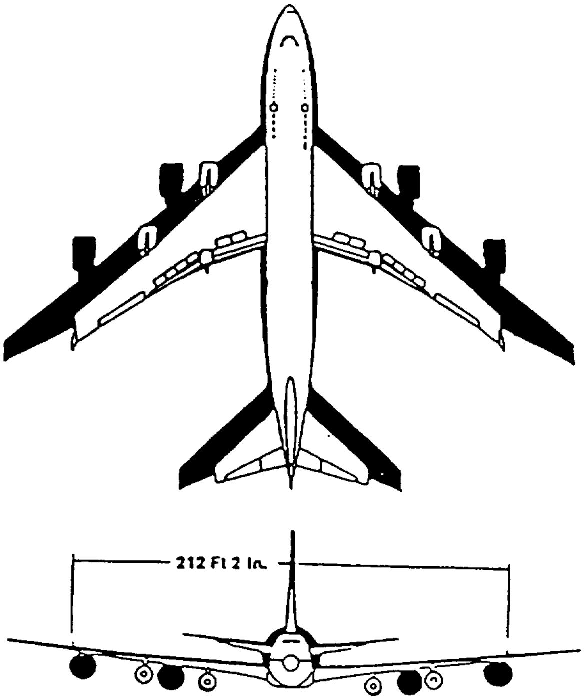


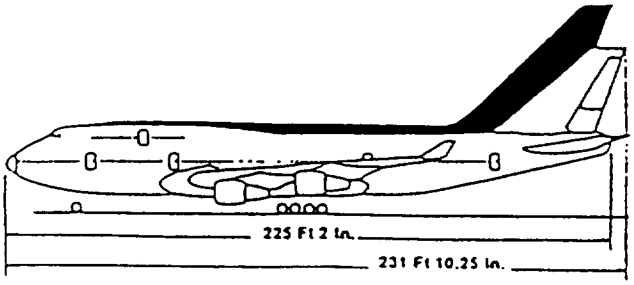
Figure 2 Demonstration of The Evolutionary Process In Aircraft Design.



PROBLEMS

- Runway Limits
- Taxiway Limits
- Terminal Gate Limits
- Emergency Evacuation
- Community Noise
- Wake Vorticies
- Wing Skin Size Limits
- Ditching/Flotation
- Passenger Comfort and
  Physiological Limits





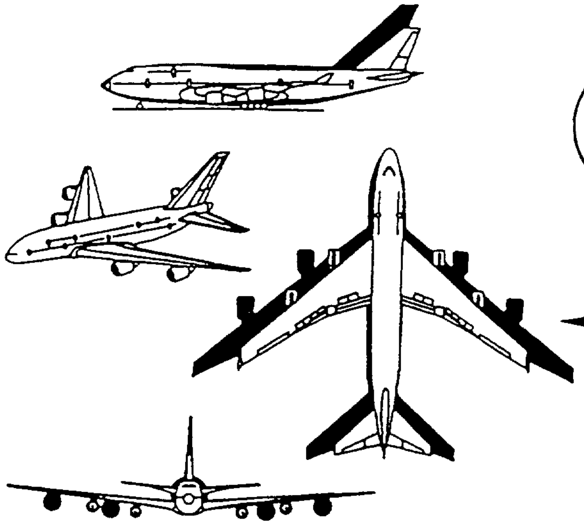
Boeing Model 747-400

Figure 3. A Conventional Configuration for a Possible Very Large Subsonic Commercial Transport Airplane (circa 1992).

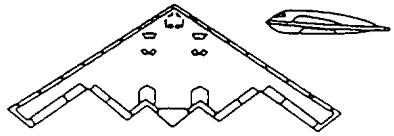
A NEW LARGE SUBSONIC COMMERCIAL TRANSPORT PLANE?
(Greater than 600 passenger capacity)

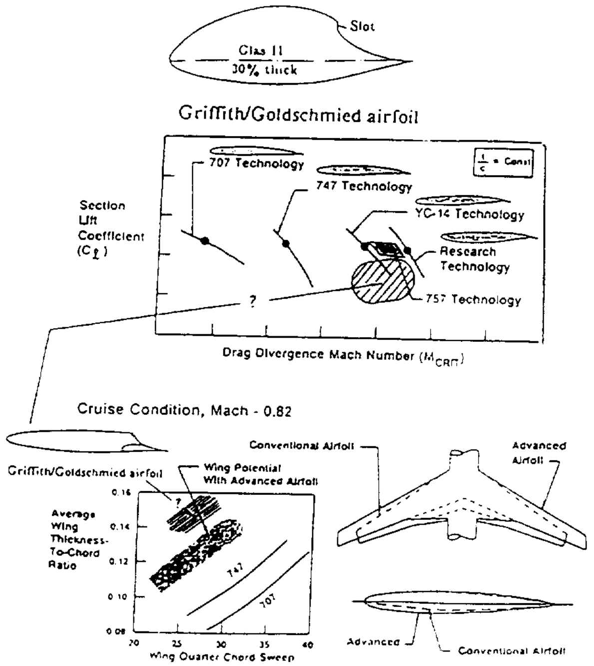
Based on 707/747 configuration paradigm?

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



- Active controls/control configurated vehicles
- Composite structures
- Advanced manufacturing techniques





LARGE SIZE PRESENTS MAJOR PROBLEMS BUT OFFERS MAJOR OPPORTUNITIES

POSSIBLE TECHNOLOGIES AVAILABLE

- Taxiway limits
- Runway limits
- Gate limits
- Community noise
- Wake vortices
- 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")

- 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 from same wingskin limits as current NLA if metal structure used.

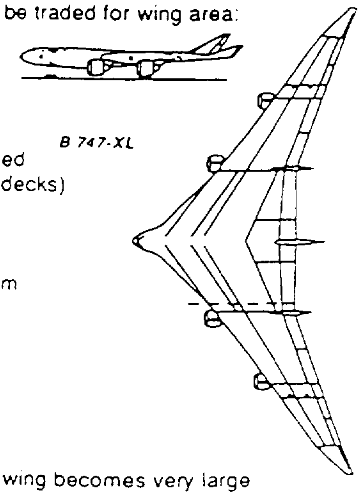
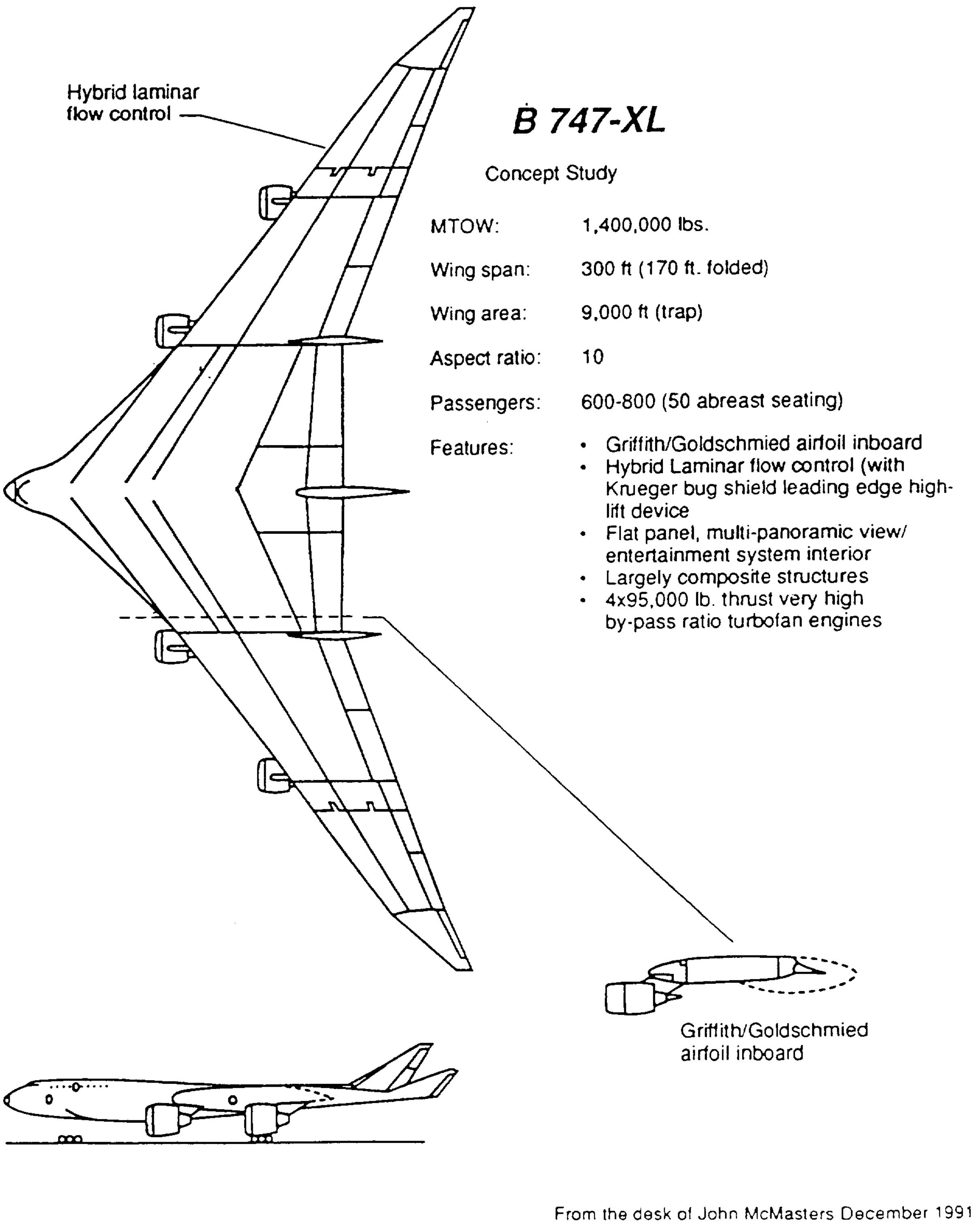


Figure 4. Evolutionary Process in Innovative Airplane Configuration Development



B 747-XL

Concept Study

MTOW: 1,400,000 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 composite structures
- 4x95,000 lb. thrust very high by-pass ratio turbofan engines

From the desk of John McMasters December 1991

Figure 5. Preliminary Concept for a Very Large Span Loader Subsonic Transport Airplane.

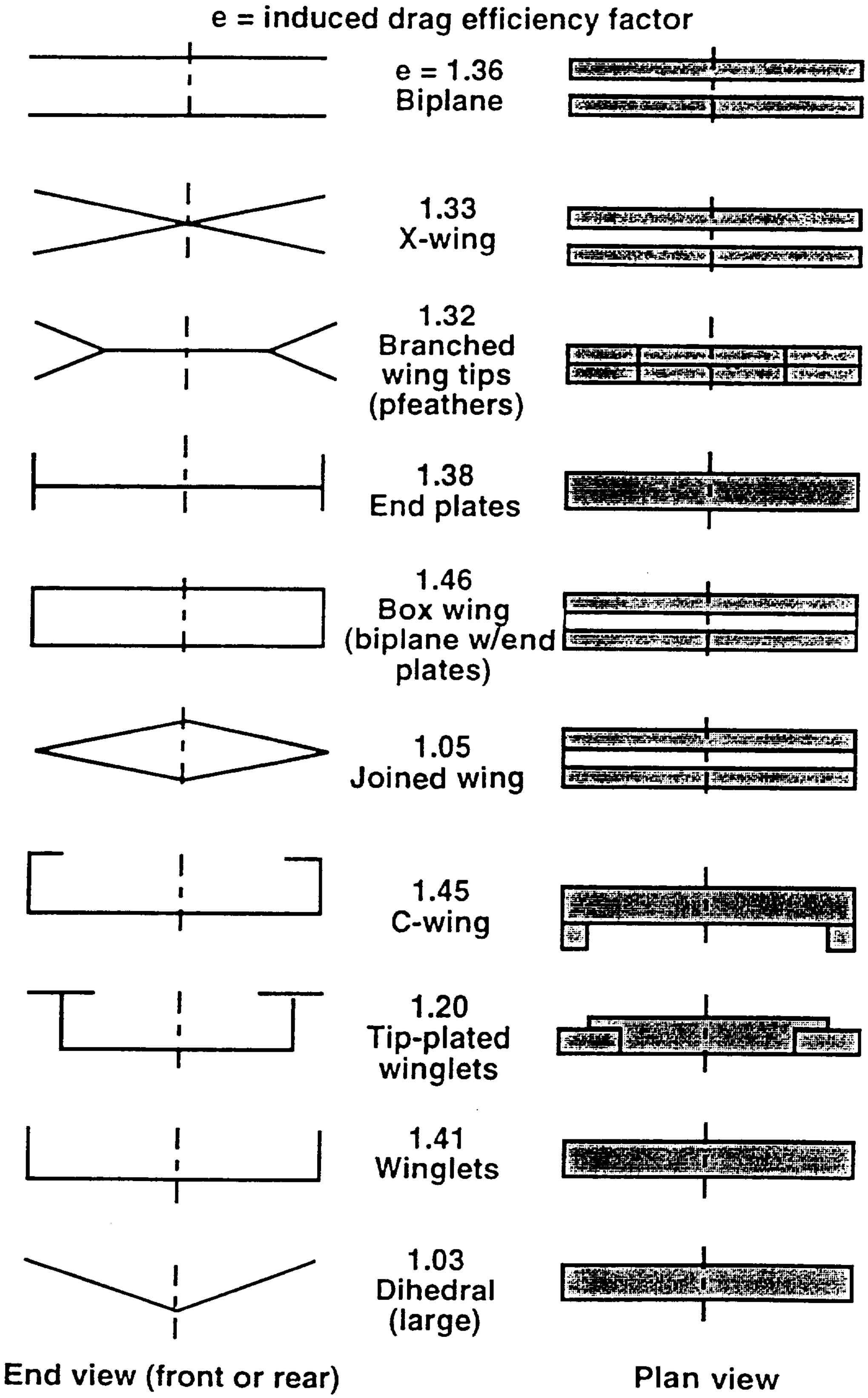


Figure 6. Theoretical Calculations of The Induced Drag Efficiency Factor (e) for Various Non-Planar Wing Configurations.

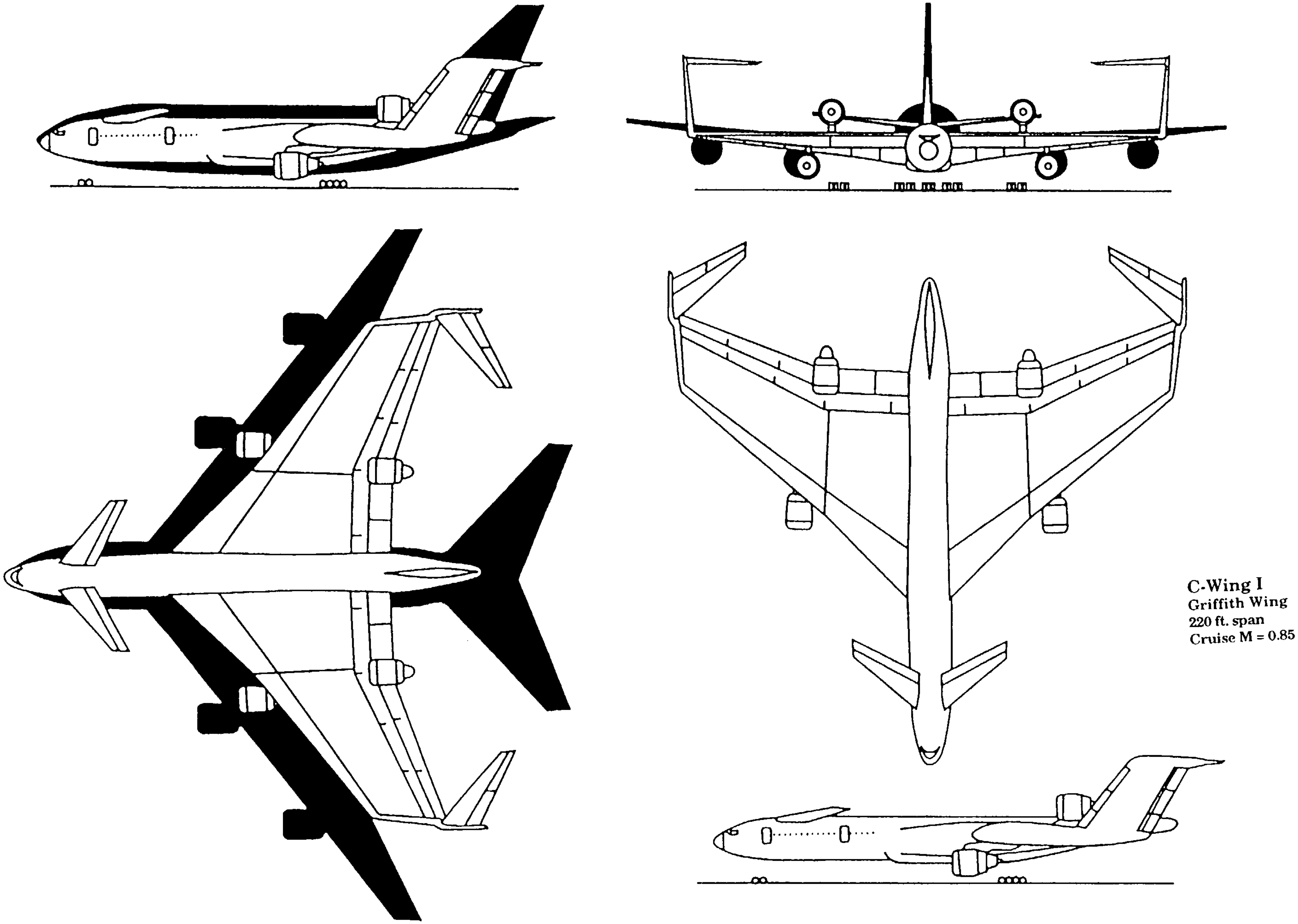
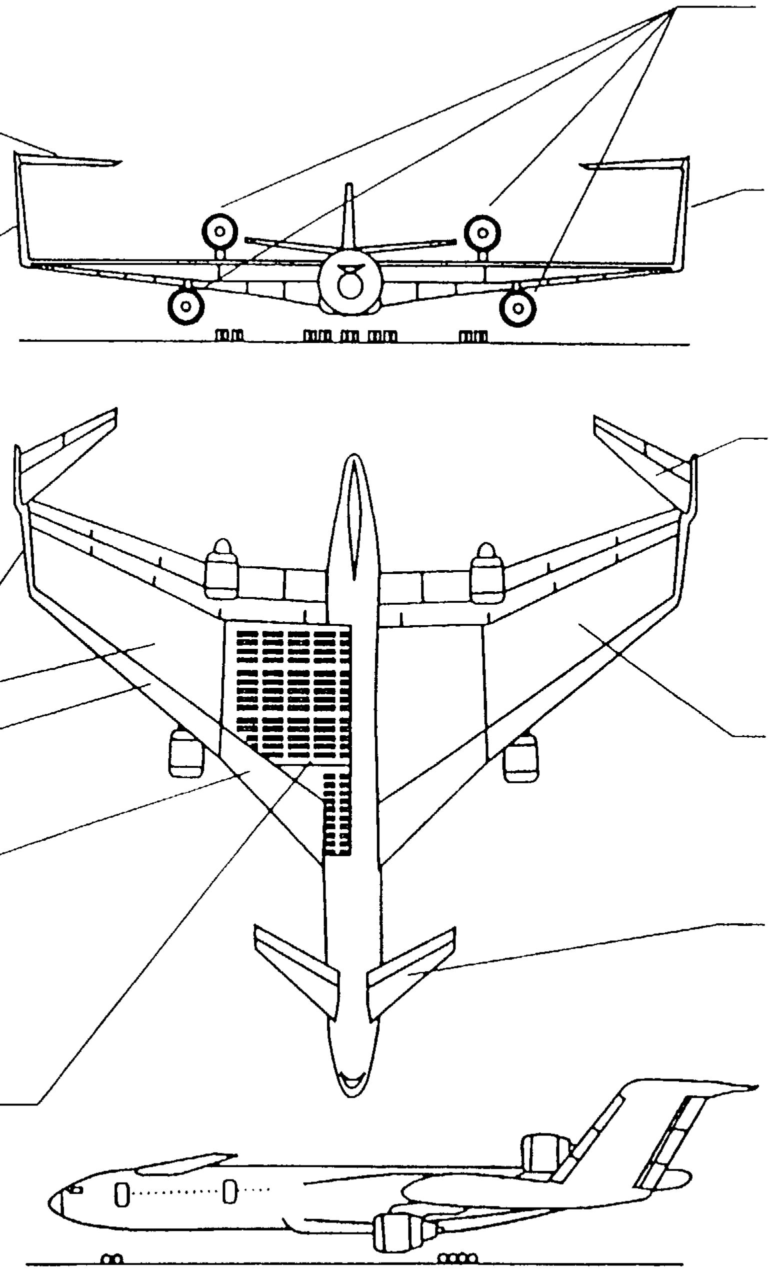


Figure 7. Configuration for an Initial Large C-Wing Transport Airplane Shown in Size Comparison to a Conventional Large Airplane Configuration [cf. Fig. 3].



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

Aft-swept "winglets" mounted aft provide directional stability.

Slotted transonic cruise airfoil outboard.

Hybrid laminar flow control on wing and vertical surfaces.

Inconventionally thick Griffith/Goldschmied airfoil inboard.

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

Two engines forward and two aft provide 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.

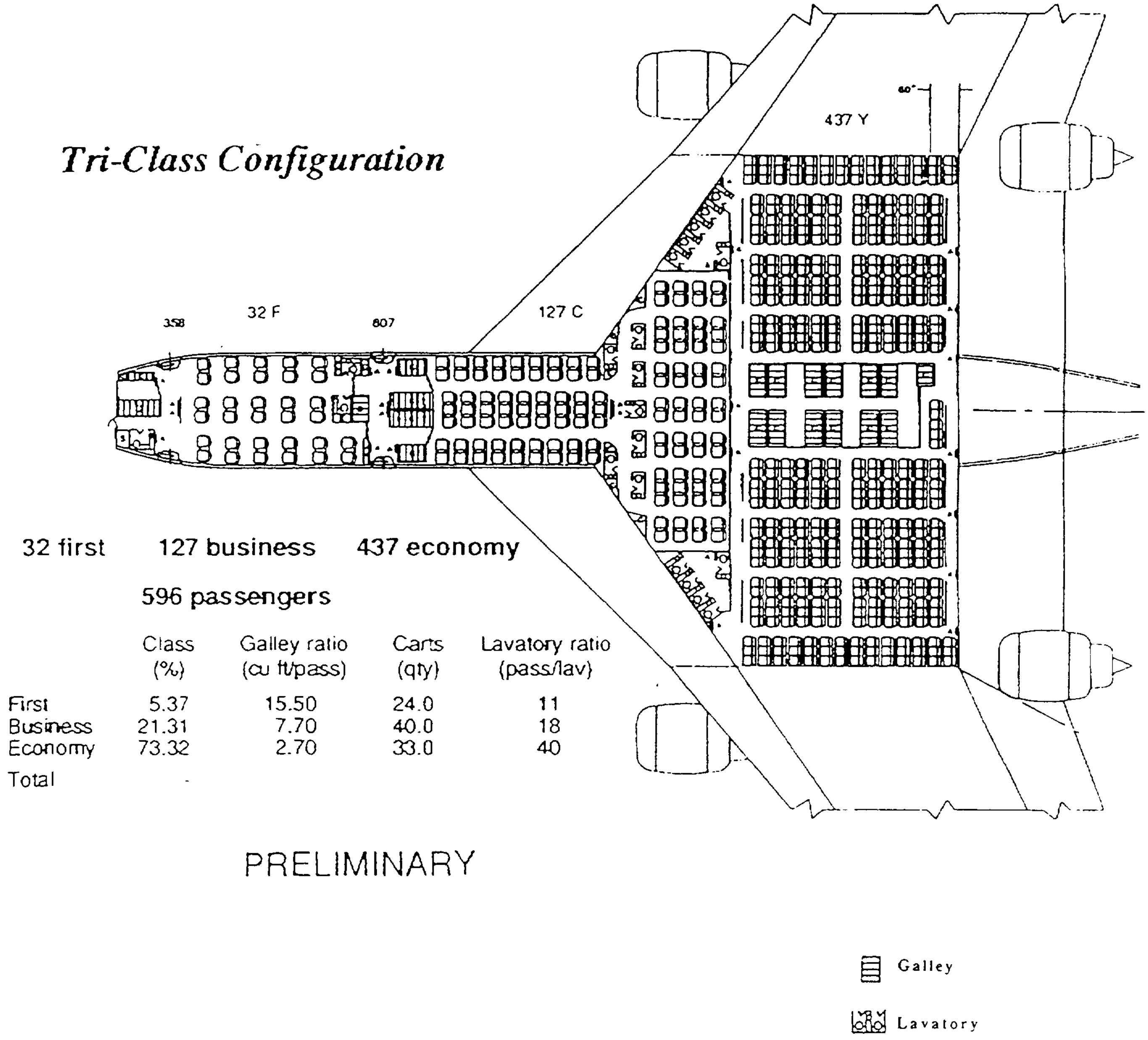
Stabilizing surface during cruise becomes control surface when flaps are extended and produce an increase in effective wing span replacing need for folding wing tips for taxiway and gate clearance.

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

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.

C-Wing I
Griffith Wing
220 ft. span
Cruise M = 0.85

Figure 8. The Principal Features of an Initial Large C-Wing Transport Airplane



Tri-Class Configuration

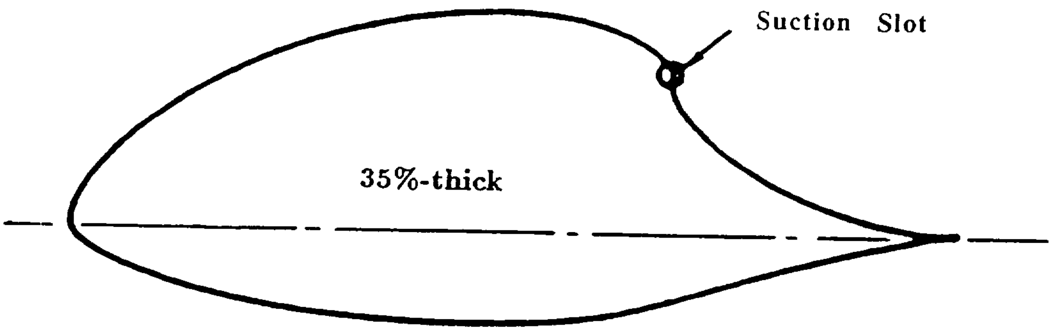
32 first 127 business 437 economy

596 passengers

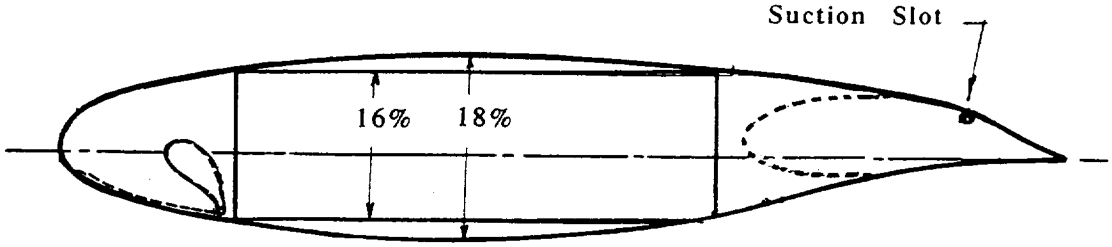
	Class (%)	Galley ratio (cu ft/pass)	Carts (qty)	Lavatory ratio (pass/lav)
First	5.37	15.50	24.0	11
Business	21.31	7.70	40.0	18
Economy	73.32	2.70	33.0	40
Total	-			

PRELIMINARY

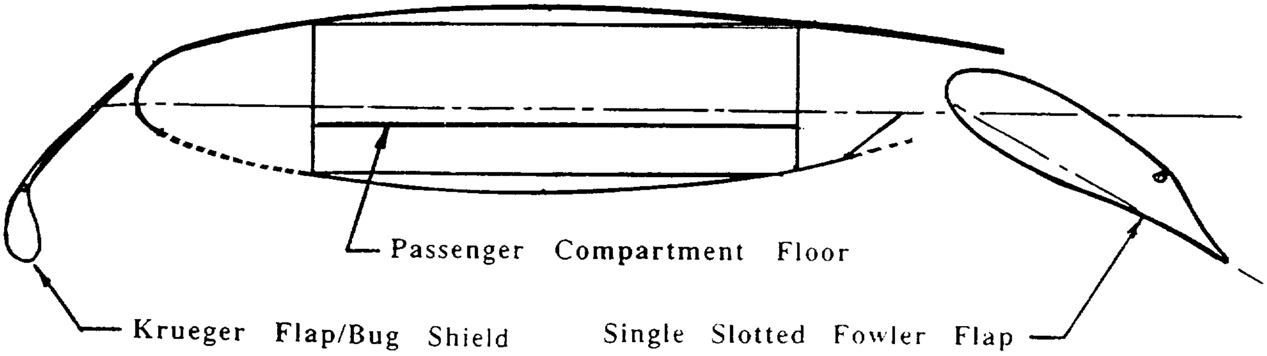
Figure 9 . Very Preliminary Layout of Passenger Accommodations for an Early Candidate C-Wing Transprort.



(a) Classic Very Thick Subsonic Griffith Airfoil



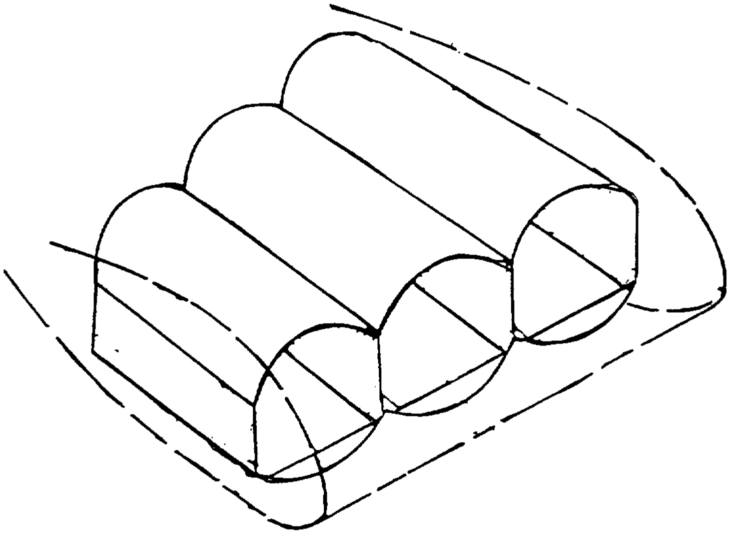
(b) Possible 18% Transonic Griffith Airfoil



(c) High-Lift System Concept for a Transonic Griffith Airfoil

Figure 10. Griffith Airfoils and High-Lift System Concepts

Concept I. Cylindrical Shells with an Outer Aerodynamic Skin



Concept II. An Integrated Two-skin Honeycomb

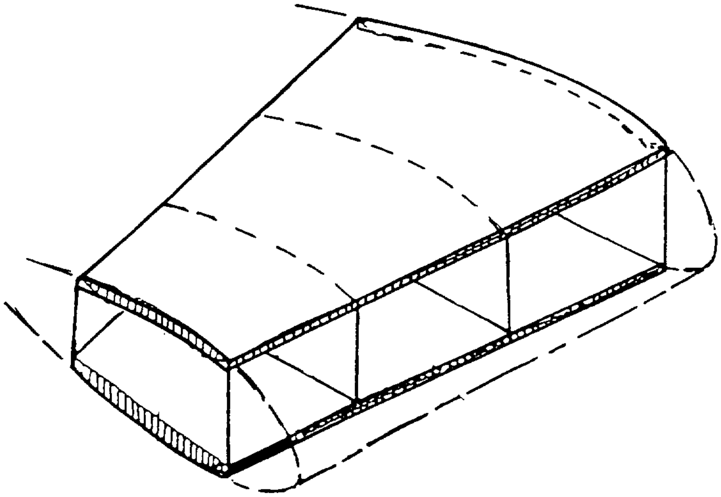
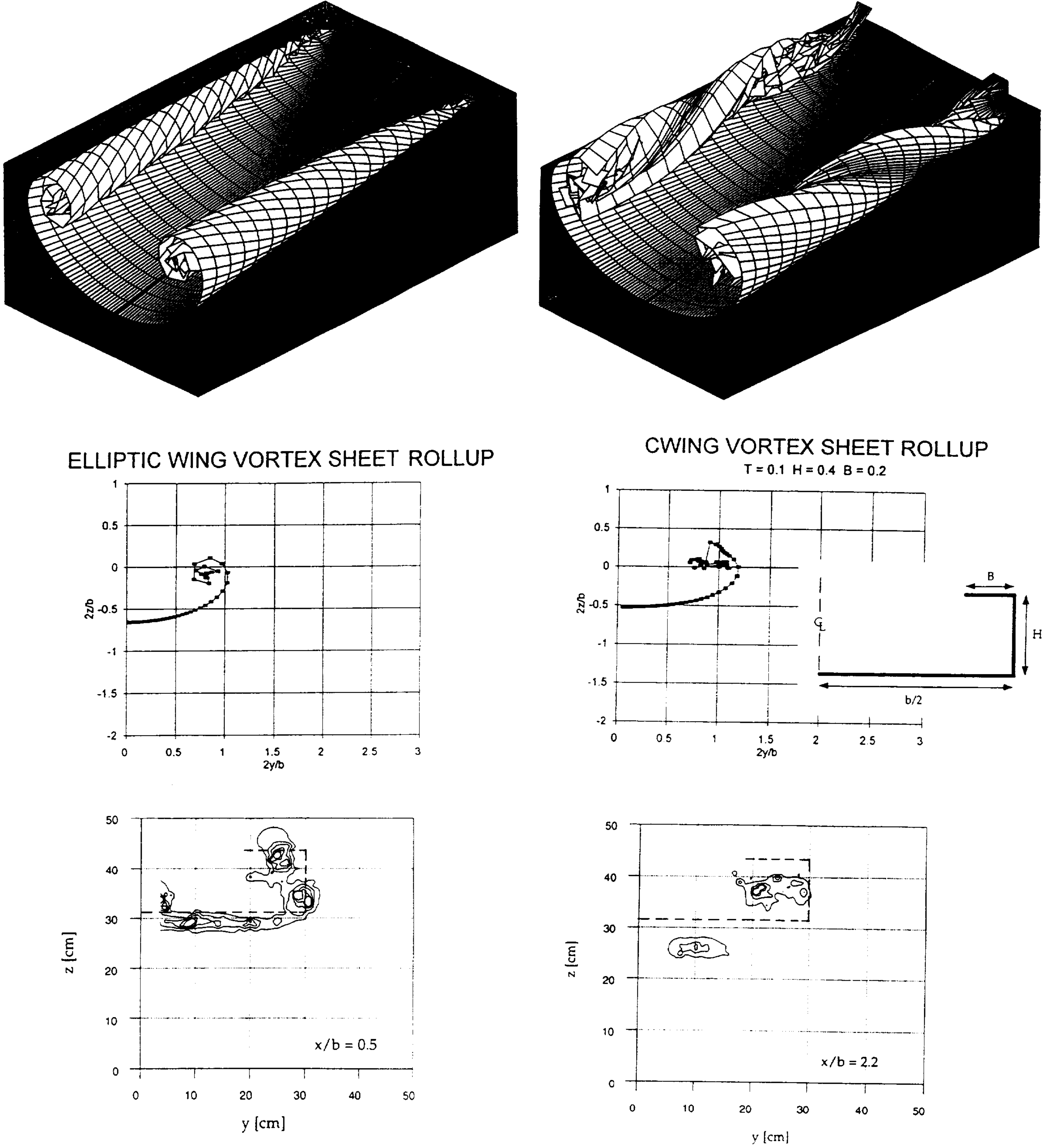


Figure 11 . Structural Concepts for a "Flat Pressure Vessel".



Total pressure contours in the wake vortex behind a C-Wing model in a Wind Tunnel at a downstream distance x/b = 0.5

Total pressure contours in the wake vortex behind a C-Wing model in a Wind Tunnel at a downstream distance x/b = 2.2

Figure 12. Calculated Wake Structure Comparison for a Planar and C-Wing Configuration (with Preliminary Wind Tunnel Data from Tuskegee University for a C-Wing)

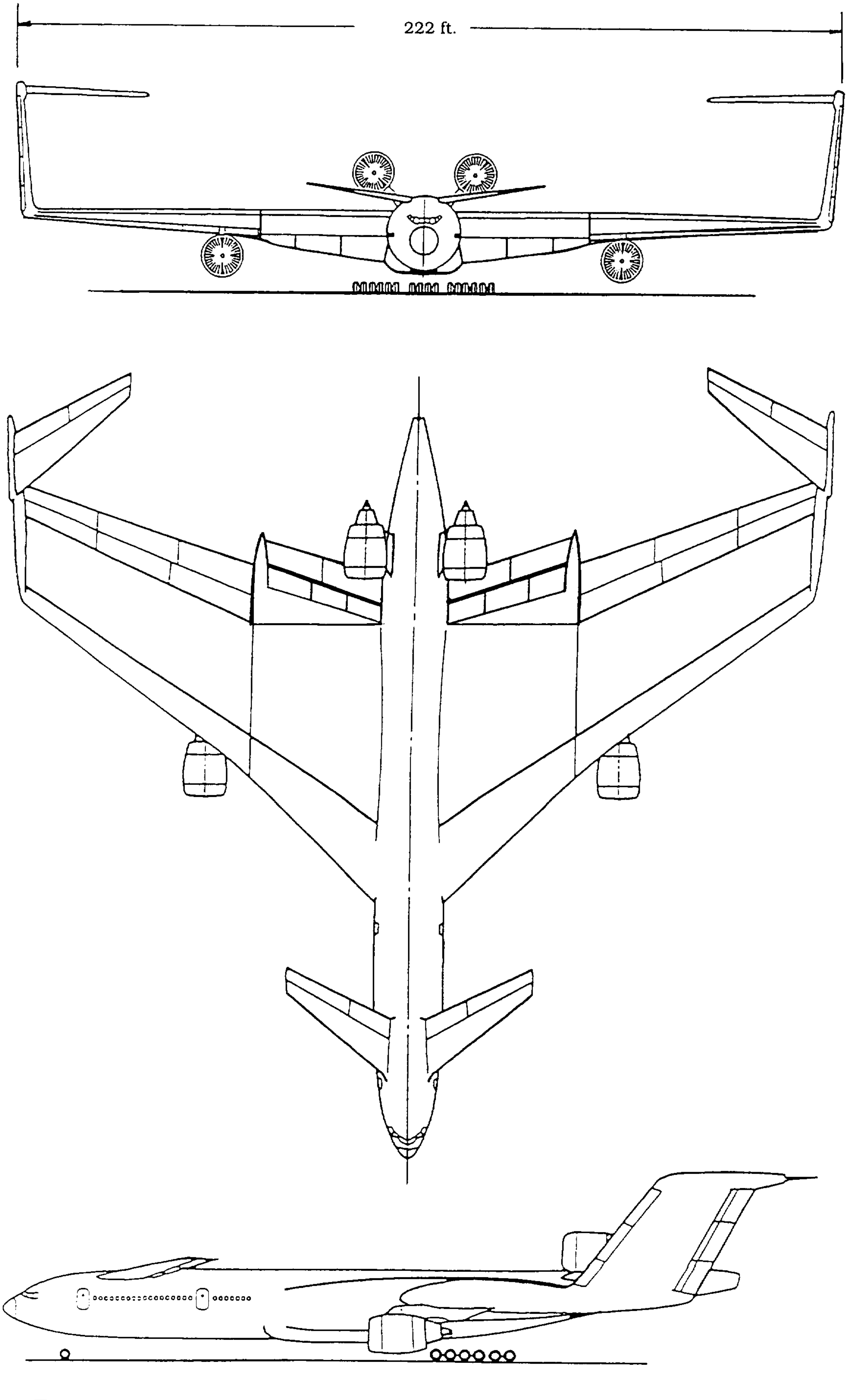
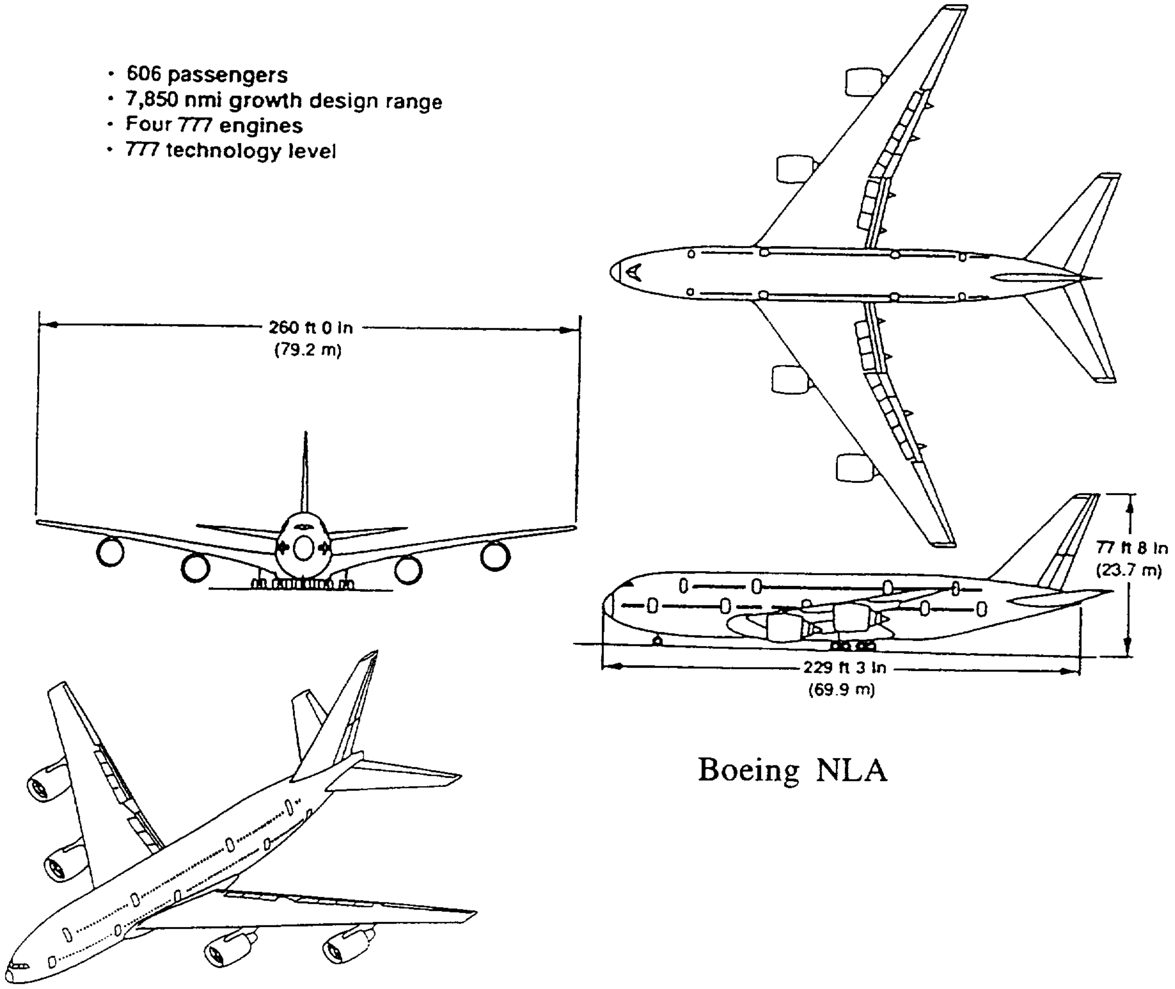
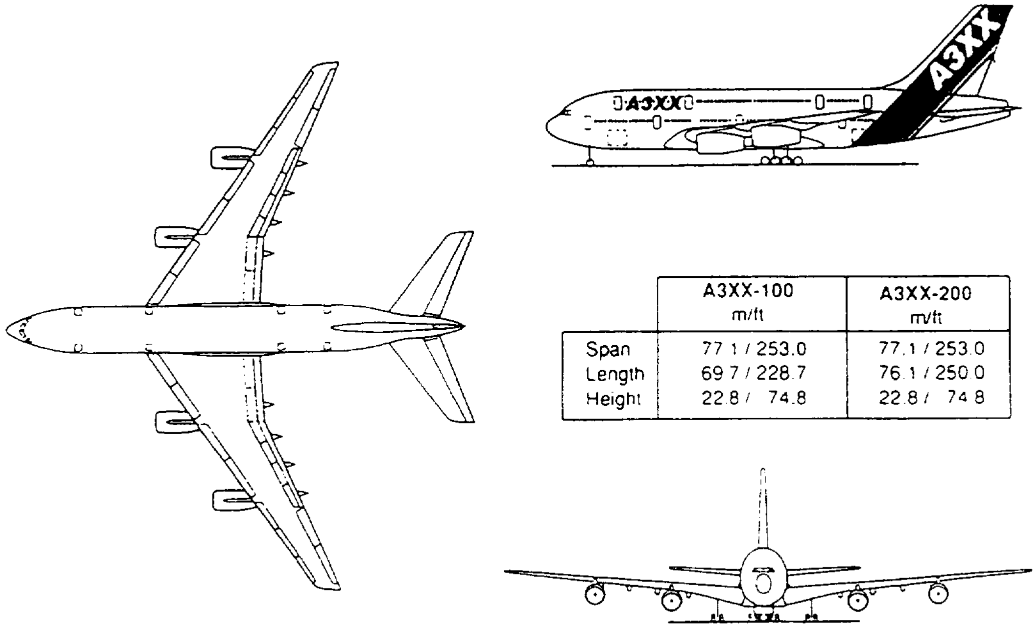


Figure 13. Evolving C-Wing Large Airplane Configuration.
[Preliminary Base for Boeing Sizing Analysis.]

- 606 passengers
- 7,850 nmi growth design range
- Four 777 engines
- 777 technology level



Boeing NLA



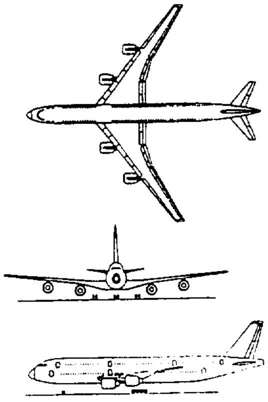
	A3XX-100 m/ft	A3XX-200 m/ft
Span	77.1 / 253.0	77.1 / 253.0
Length	69.7 / 228.7	76.1 / 250.0
Height	22.8 / 74.8	22.8 / 74.8

Figure 14. Boeing NLA [2] and Airbus A3XX [16] Very Large Transport Airplane Configurations -1995.

LARGE AIRCRAFT ISSUES

Problem:

- Runway limits
- Taxiway limits
- Gate limits
- Emergency evacuation
- Community noise
- Wake vortices
- Structural limits



DESIGN MISSION AND CONSTRAINTS

- 7000 nm range
- 0.85 cruise Mach
- Approximately 800 passengers
- Maximum takeoff and landing field length of 12000 ft
- Internal fuel volume in wing capable of holding fuel to fly mission
- Reserve mission
- Approach velocity of 150 knots
- Required to meet all FAR regulations
- Maximum cruise altitude of 50000 ft

DESIGN AND ANALYSIS METHOD

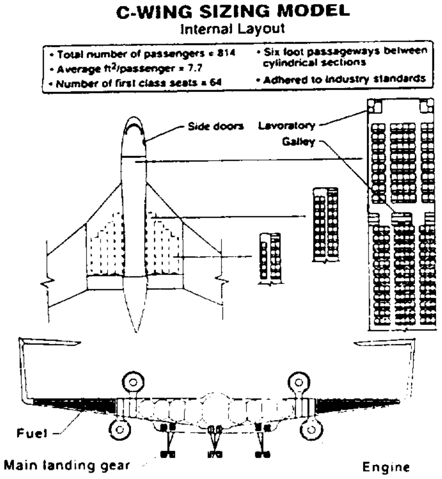
Geometry + **Structural weights** + **Aerodynamics** + **Propulsion**

- Wingtool
- PRO/Engineer

- FLight OPtimization System (FLOPS)

- EDET (FLOPS)
- MULTOP

- PW-4082 Engine Technology



Sizing and Performance (FLOPS)

Performance Results

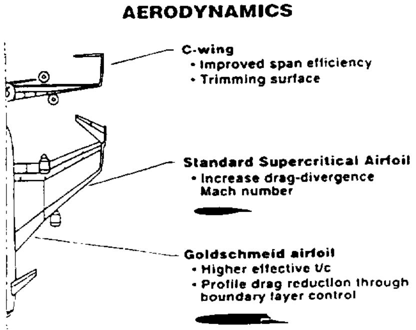
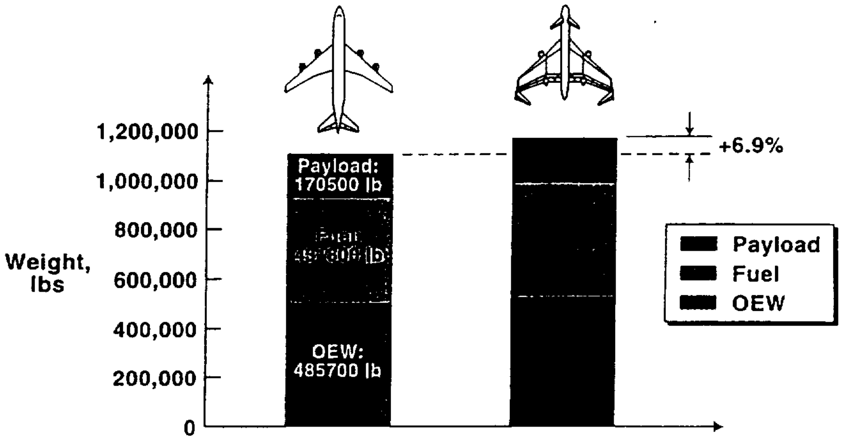
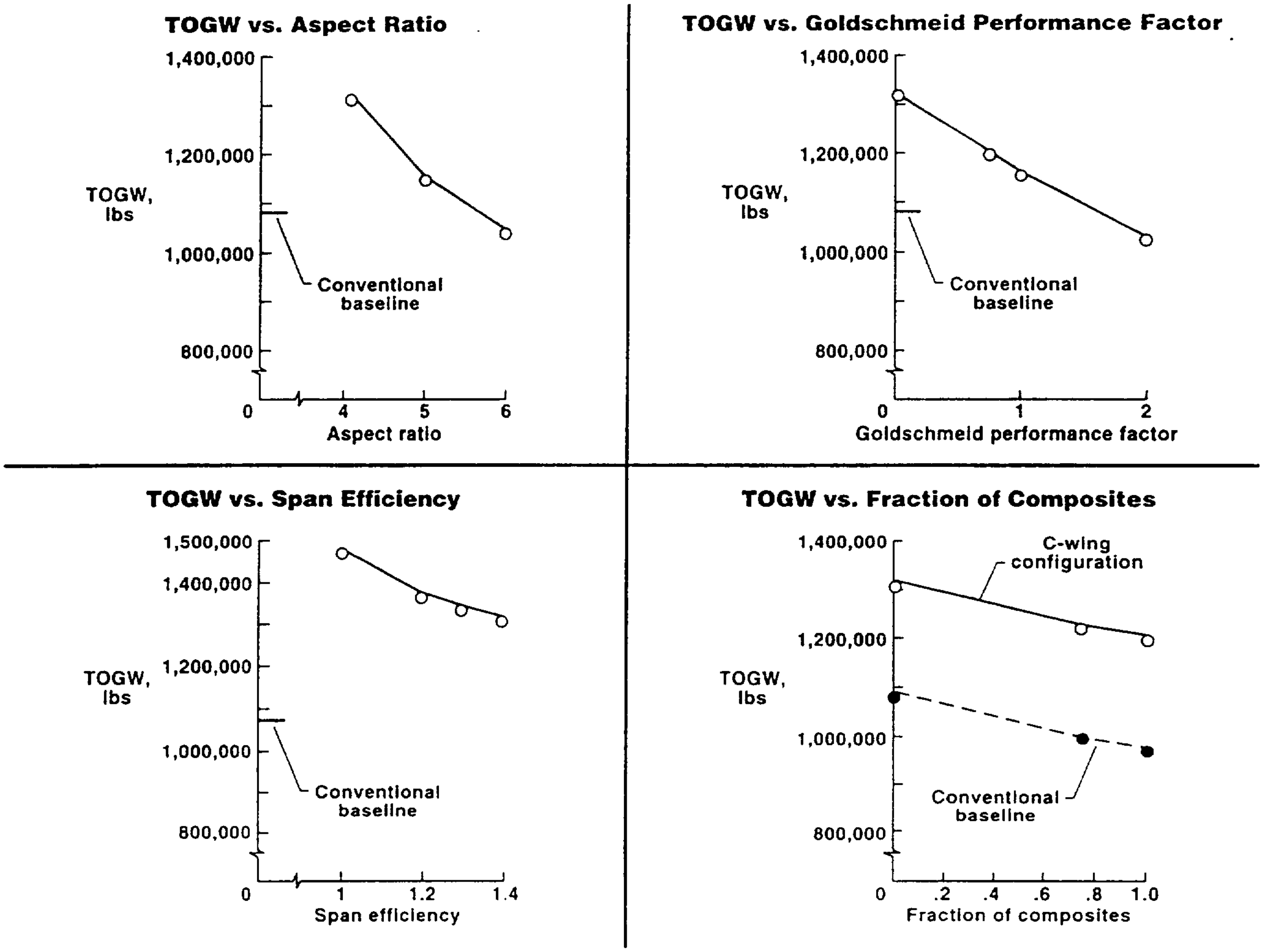


Figure 15. NASA-LaRC C-Wing Large Airplane Study [17]



Model	Conventional Baseline	C-Wing 1
Material	Conventional	Conventional
AR	8.42	4.07
Wing area, ft^2	8741	14642
Thrust/Engine, lb	55312	81533
Span, ft	237	232
TOGW	1088000	1163000

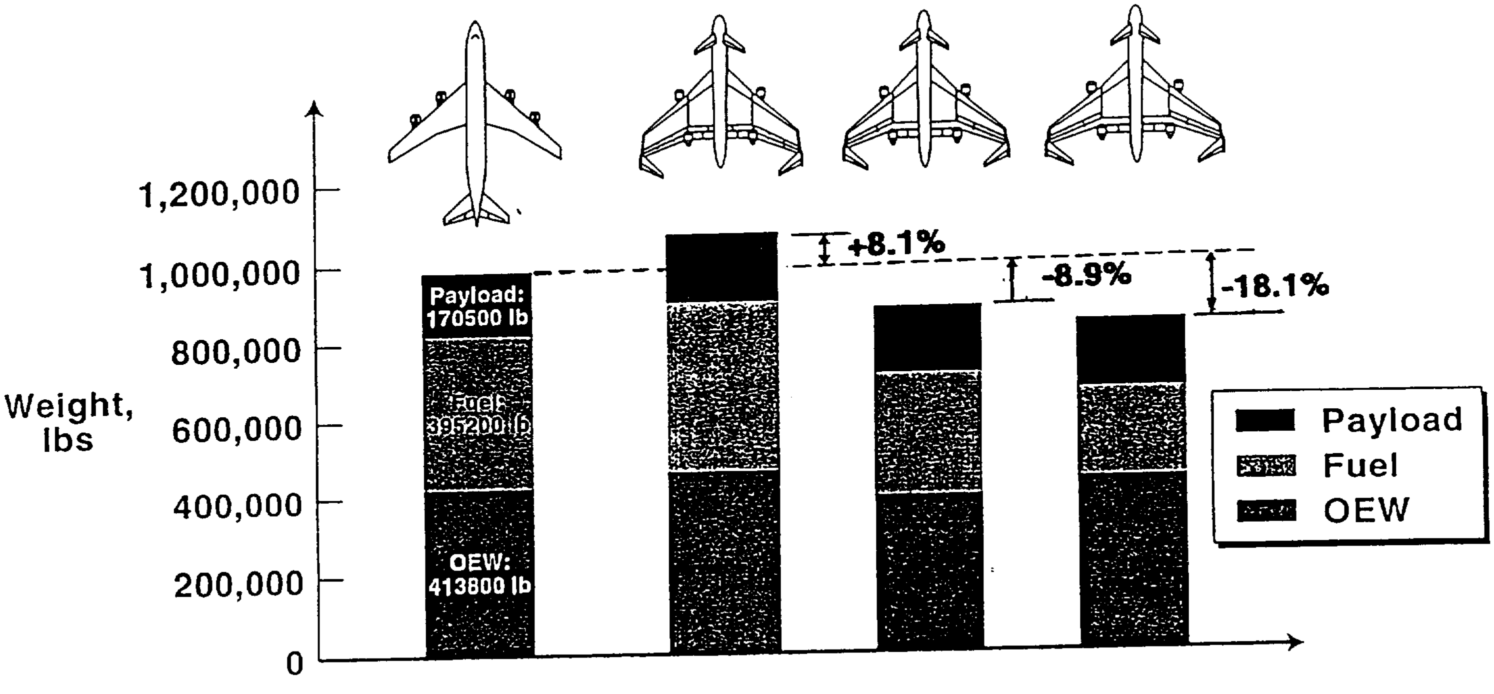

TOGW vs. Aspect Ratio

TOGW vs. Goldschmeid Performance Factor

TOGW vs. Span Efficiency

TOGW vs. Fraction of Composites

Figure 16. NASA C-Wing Initial Preformance and Sensitivity Study Results



Model	Conventional Baseline	C-Wing 1	C-Wing 2	C-Wing 3
Material	Composite	Composite	Composite	Composite
AR	8.42	4.07	6	6
Wing area, ft	8136	14465	12450	13414
Thrust/Engine, lb	52509	74240	46902	42140
Span, ft	229	236	245	260
Goldschmied factor	-	1.0	1.0	2.0
TOGW	979500	1058400	892400	802500

Figure 17. NASA C-Wing Optimization Results.

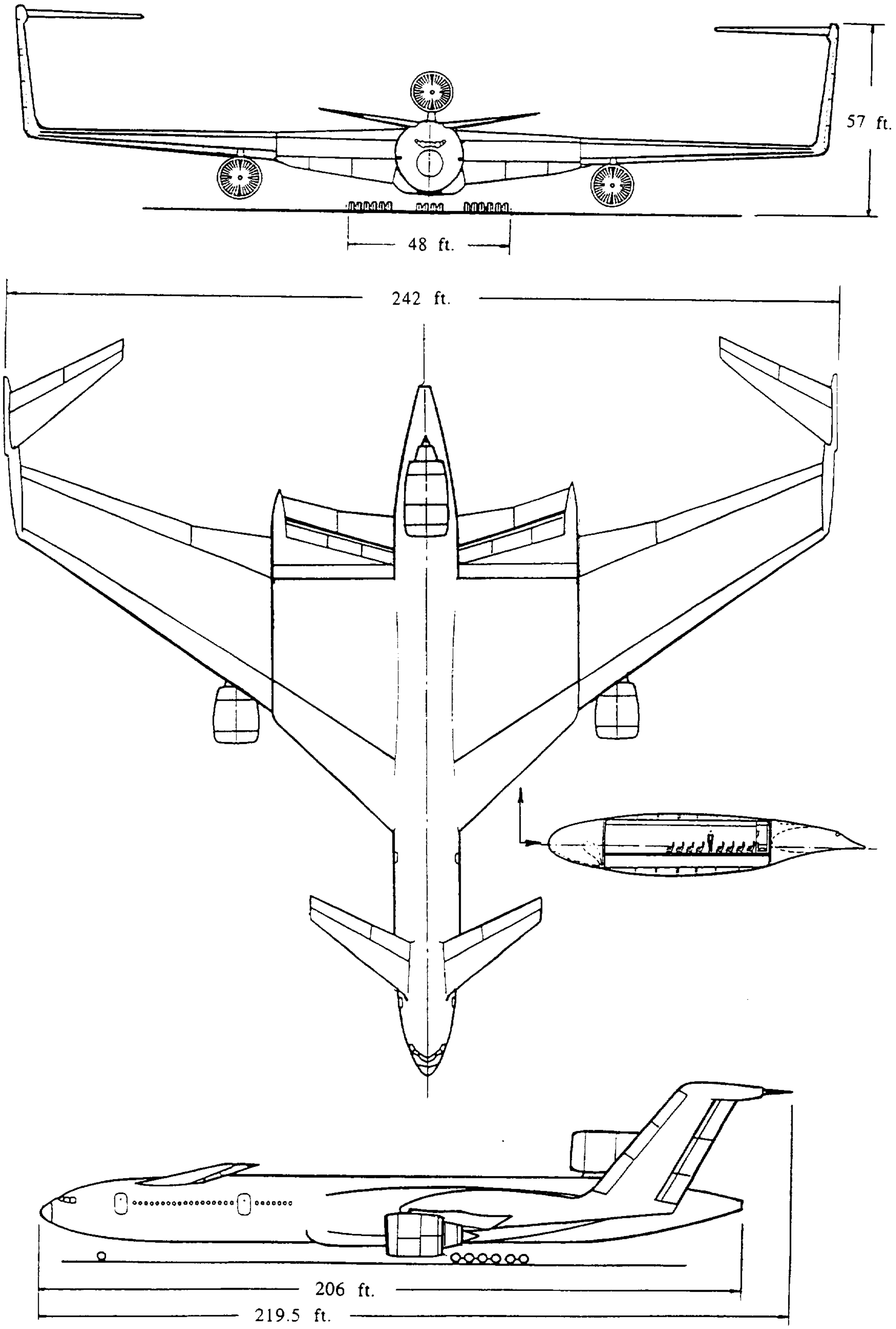
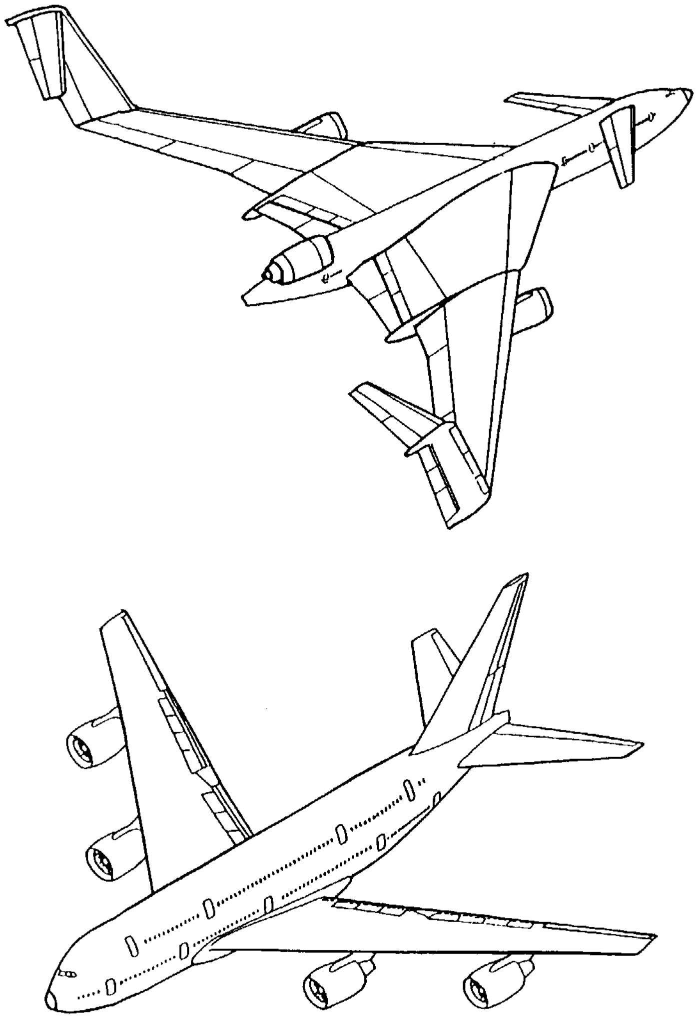
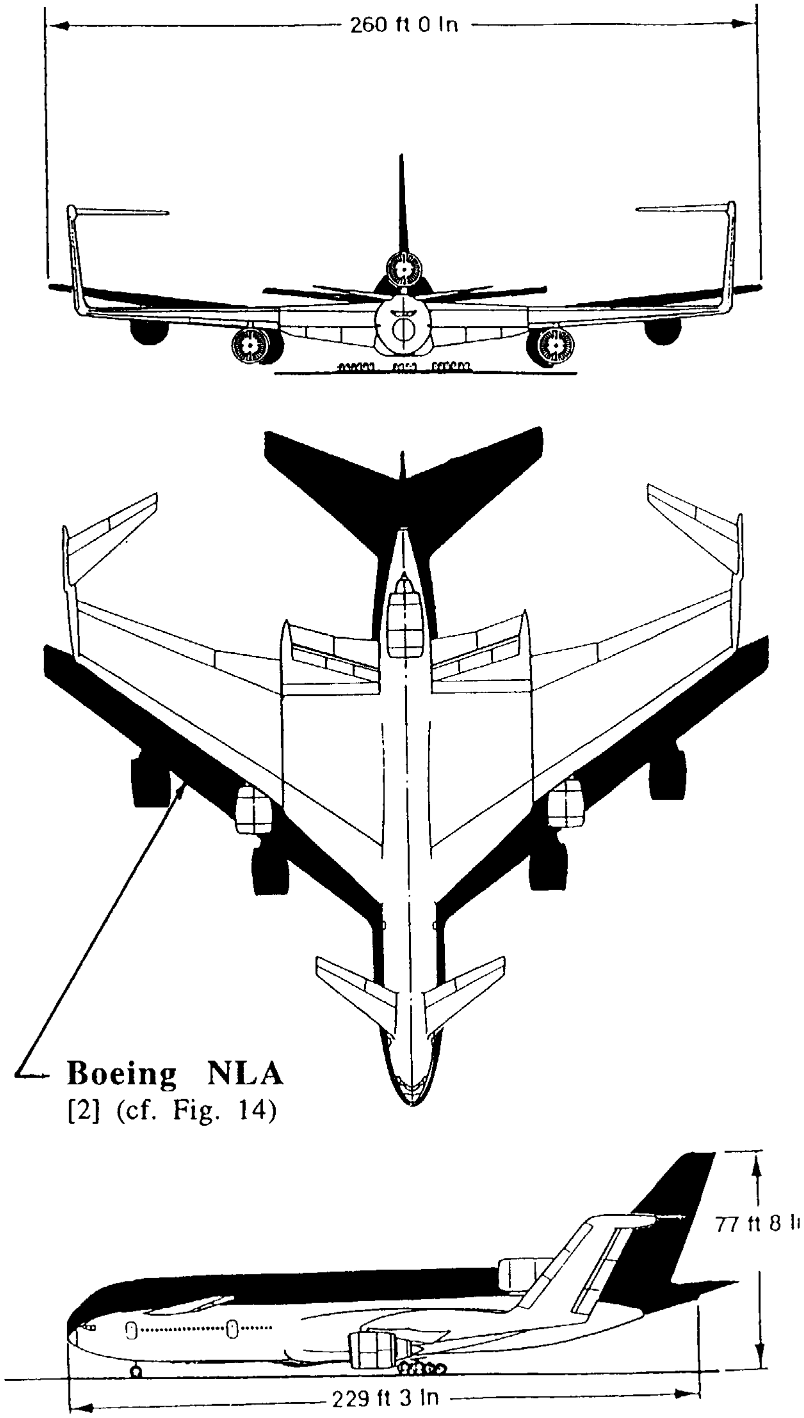
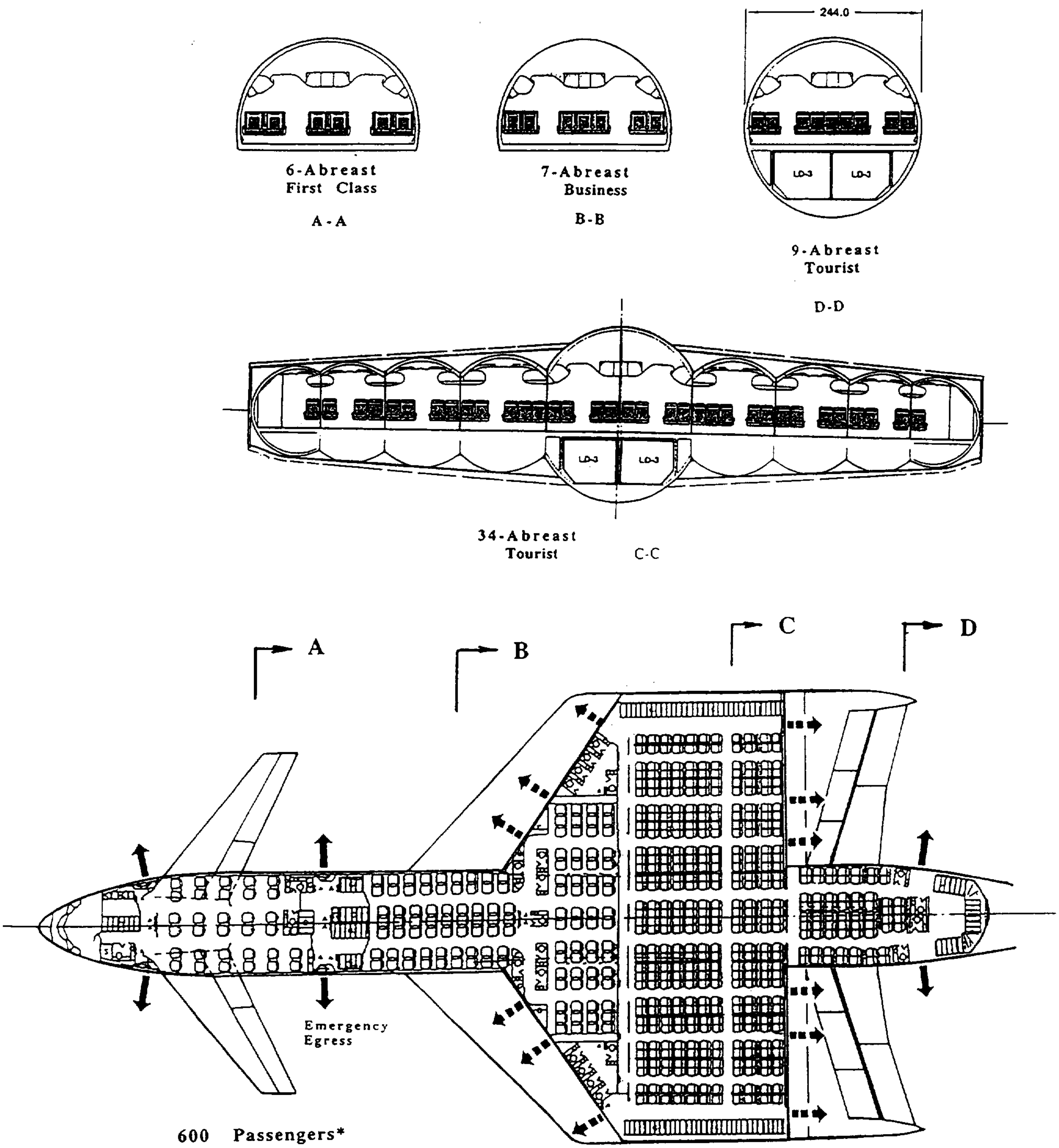


Figure 18. Final Preliminary C-Wing Transport - Model 2020A.



Size Comparison of Alternative Very Large ["600 passenger"] Subsonic Transport Airplane Configurations. (Final preliminary Boeing/NASA C-Wing and Boeing NLA)





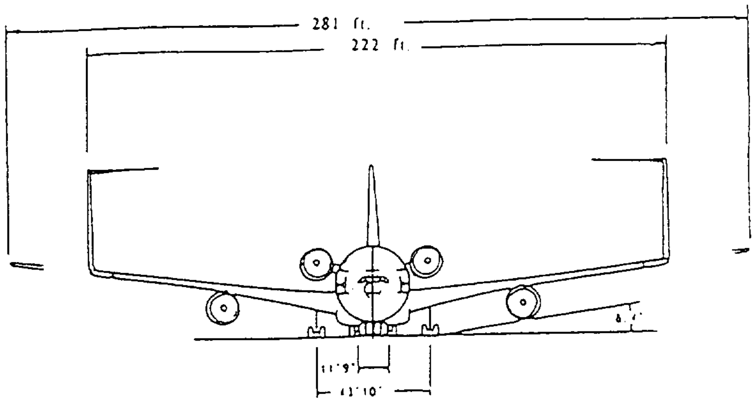
600 Passengers*

32 First **127 Business** **441 Tourist**

	Class (%)	Galley Ratio (cu ft/ pass)	Carts (qty)	Lavatory Ratio (pass/lav)
First	5.3	15.5	24	11
Business	21.2	7.7	40	18
Tourist	73.5	2.7	33	40

[*Approximately 750 passengers in an All Tourist configuration.]

Figure 19 . Layout of Passenger Accommodations (LOPA) for the C-Wing Transport Configuration - Model 2020 A.



ALTERNATIVE C-WING CONFIGURATION FOR A VERY LARGE SUBSONIC TRANSPORT AIRPLANE

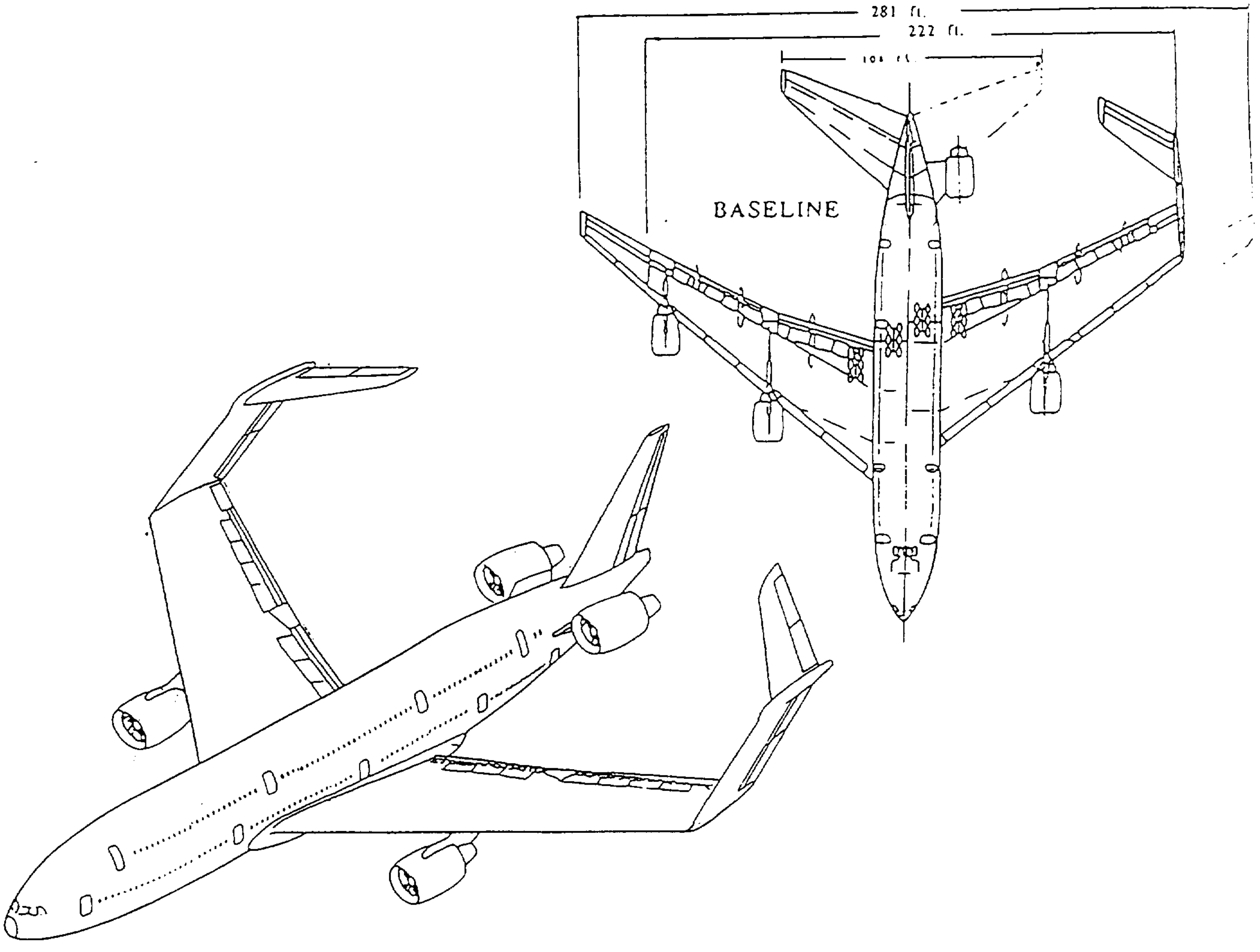


Figure 20. Schematic of the Possible Use of C-Wing Arrangement on a More Conventional Subsonic Transport Airplane.

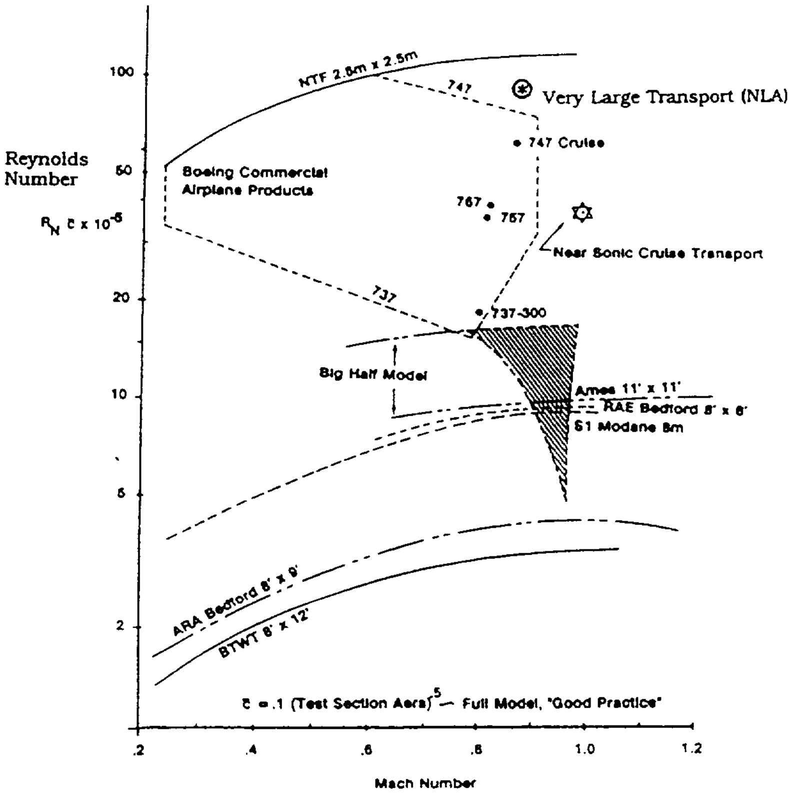


Figure A-1. Transonic Wind Tunnel Operating Envelope Comparison.

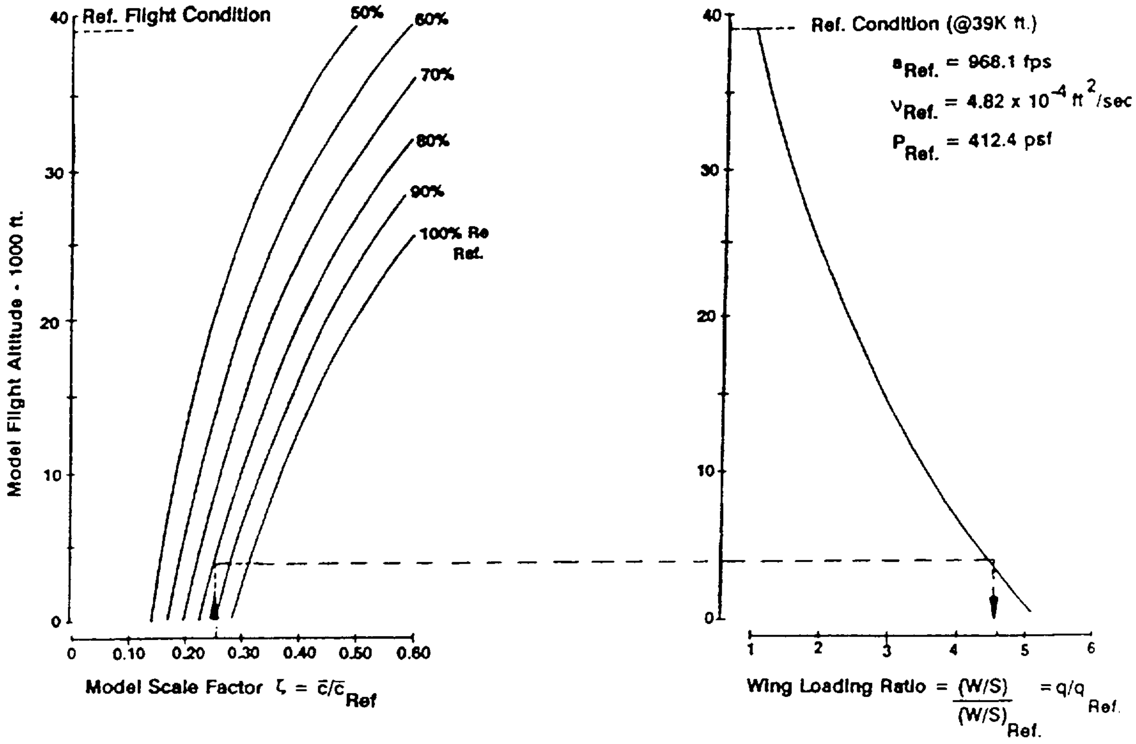


Figure A-2. The Atmosphere as a Large Transonic Pressure "Wind Tunnel".

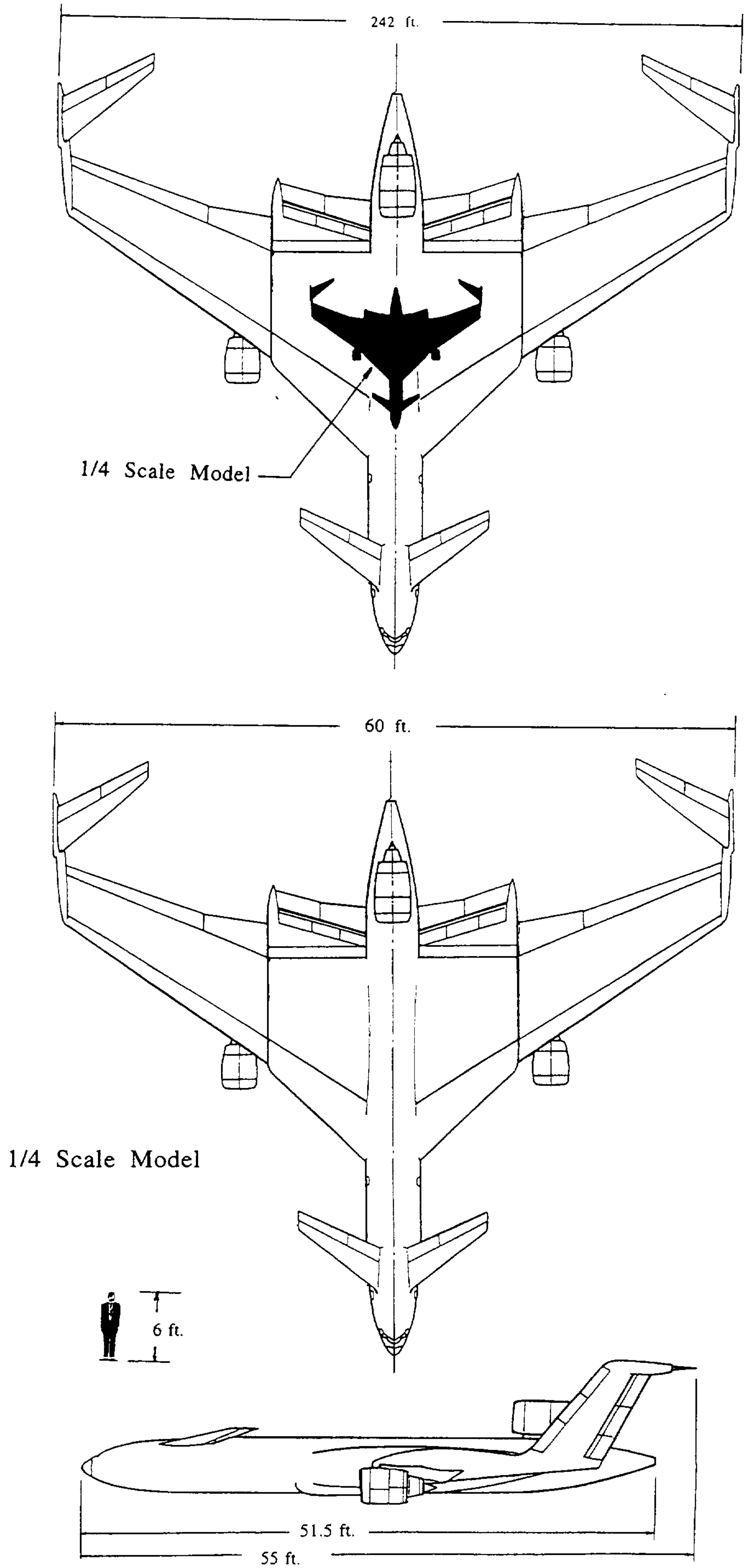


Figure A-3. A Possible Sub-Scale C-Wing Remotely Piloted Vehicle.

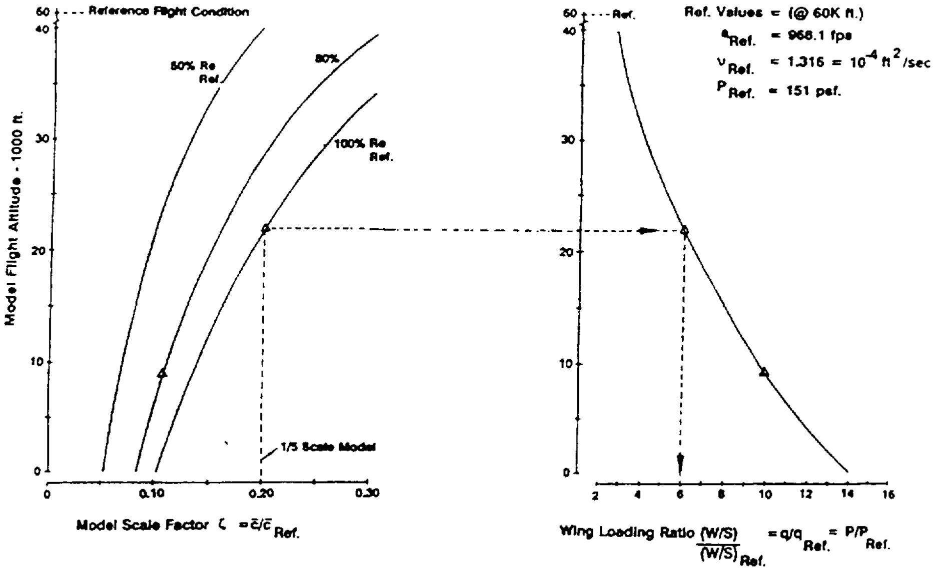


Figure A-4. The Atmosphere as a Large Supersonic Pressure "Wind Tunnel".

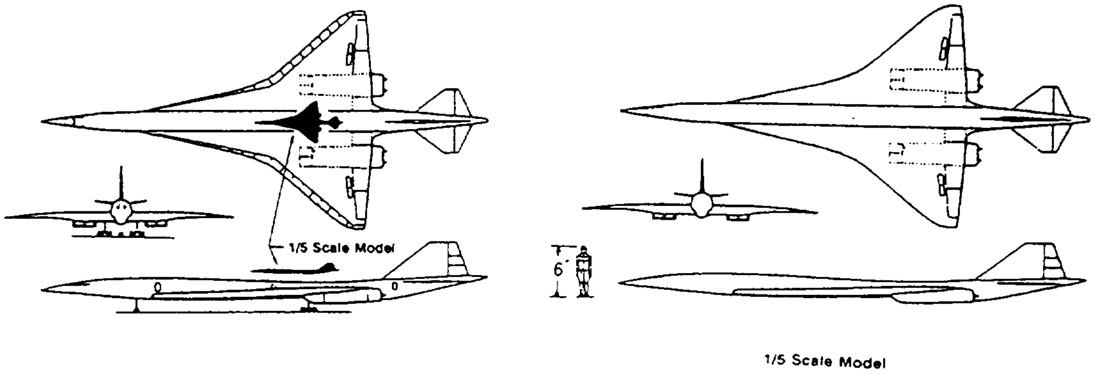


Figure A-5. A sub-Scale Remotely Piloted Vehicle for Supersonic Transport Testing.

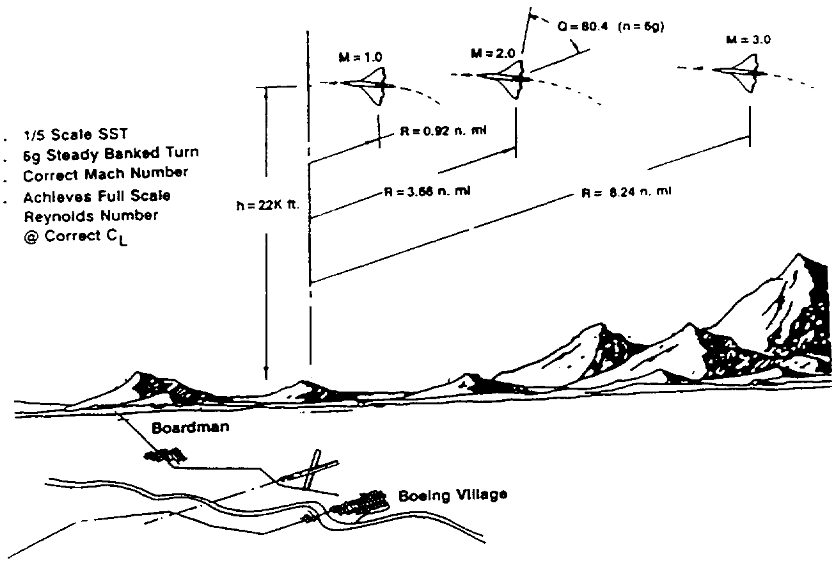


Figure A-6. A Possible Remotely Piloted Vehicle Test of a Supersonic Transport.

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13. ABSTRACT *(Maximum 200 words)*

Recent aerospace industry interest in developing a subsonic commercial transport airplane with 50 percent greater passenger capacity than the largest existing aircraft in this category (the Boeing 747-400 with approximately 400-450 seats) has generated a range of proposals based largely on the configuration paradigm established nearly 50 years ago with the Boeing B-47 bomber. While this basic configuration paradigm has come to dominate subsonic commercial airplane development since the advent of the Boeing 707/Douglas DC-8 in the mid-1950's, its extrapolation to the size required to carry more than 600-700 passengers raises several questions. To explore these and a number of related issues, a team of Boeing, university, and NASA engineers was formed under the auspices of the NASA Advanced Concepts Program. The results of a Research Analysis focused on a large, unconventional transport airplane configuration for which Boeing has applied for a patent are the subject of this report. It should be noted here that this study has been conducted independently of the Boeing New Large Airplane (NLA) program, and with the exception of some generic analysis tools which may be common to this effort and the NLA (as will be described later), no explicit Boeing NLA data other than that published in the open literature has been used in the conduct of the study reported here.

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c-wing	flying wing
Goldschmied airfoil	non-planar wing

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