Feasibility Study of the Low Aspect Ratio All - Lifting Configuration as a Low-Cost Personal Aircraft



Prepared For

Mr. Mark D. Moore NASA Langley Research Center Mail Stop 348 Hampton, VA 23681-2199

by

Mr. Barnaby Wainfan Mr. Hans Nieubert

And the

California State Polytechnic University Pomona California Space Grant Foundation Student-Mentor Program 8340 Clairemont Mesa Blvd. Suite 203 San Diego, CA 92111

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EXECUTIVE SUMMARY

Introduction:

For the majority of the history of general aviation designers and manufacturers of light airplanes have emphasized improvements in performance in the development of new aircraft. While this has resulted in airplanes that perform very well, the vision of the light personal aircraft as a primary mode of personal travel has not been realized. Today, light aircraft are not widely used for routine personal travel. For personal aircraft to become a common, useful mode of transportation, the overall system must offer a combination of characteristics that are not fully available in current-generation light airplanes.

Performance is not unimportant, but it does not have the overriding significance it is usually given. The cruise performance of current generation airplanes is quite adequate for most personal travel needs. Further increase in cruise speed is of secondary importance. Increasing performance will not create a breakthrough in the use of small airplanes for personal transport.

Cost:

A major impediment to the wider use of personal aircraft for routine transportation is the cost of acquiring an airplane. The price of a new basic airplane is about five times that of a mid-size automobile, and two to three times the price of a top-of-the line production luxury car. At this price level, the market for new production light airplanes is limited to a small number of wealthy individuals, and to commercial operators purchasing aircraft for business use such as rental and training. In order to achieve widespread acceptance the price of a basic personal aircraft must be low enough to be affordable by the traveling public. In practical terms, this means that a new certified airplane must cost no more than a new luxury automobile.

Ease of Operation:

Pilot skill is also a significant concern. The aircraft and its systems must be easy enough to operate to allow the airplane to be used primarily for transportation. For the airplane to be useful as a transportation system, the pilot must be able to safely operate the air vehicle with a modest level of skill. Maintaining the required level of pilot proficiency should require minimal proficiency-maintenance flying beyond normal everyday transportation use. To this end, the airplane itself must have safe, docile flying qualities, and be forgiving of minor mishandling by the pilot. It should be resistant to stalling, spinning or similar departures from controlled flight.

A New Approach:

Efforts to date to reduce airframe cost for personal aircraft have centered on using new manufacturing techniques, detail design concepts, and materials to reduce the cost of aircraft with relatively conventional wing-body-tail configurations. These efforts were successful in reducing cost somewhat, but not to the level required to reach the personal air vehicle cost needed to make the aircraft affordable to a significant number of users.

In order to gain a significant cost reduction beyond that achievable by applying modern techniques to a relatively classical configuration a new vehicle architecture is needed. The new design approach should be intrinsically simpler, and more cost-efficient that the conventional approach and take advantage of the modern design and manufacturing technologies and materials that were not available when the light airplanes currently in production were designed.

This report describes a study of an integrated low-aspect ratio all-lifting configuration. The concept features an integrated all-lifting body that performs the functions of the wing, tail and fuselage of a conventional light airplane with a single, simple structure. The integrated lifting body has an aspect ratio between approximately 1.0 and 2.5, and is deep enough to contain the crew and payload without a conventional fuselage. The configuration is further simplified by the use of a faceted shape composed of flat panels. The faceting greatly simplifies the manufacture of the major parts of the airframe, although it does exact a small penalty in parasite drag.

This study builds on the results achieved with the Wainfan FMX-4 Facetmobile research aircraft.

The FMX-4 first flew in 1993, and flew a total of approximately 130 hours. This included a cross-country trip from Chino, California to Oshkosh, Wisconsin and return.

The FMX-4 test program demonstrated that the configuration offers many advantages as a personal air vehicle. The primary advantages demonstrated are:



FMX-4 Research Airplane

- Simple primary structure, with low parts count
- Airframe structure composed of low-cost materials
- High useful load fraction
- Benign flying qualities
- Stall and Spin resistance
- Large tolerance of center of gravity travel
- Superior occupant protection
- Roomy cabin
- Performance comparable with conventional airplanes.

The current study investigated the potential of a low aspect ratio all-lifting airplane (shown below) derived from the FMX-4 for the 2-seat sport/trainer mission currently performed by the Cessna 152, the Diamond DA-20, and the Alarus CH-2000 among others.



Unlike the FMX-4, which had an aluminum tube structure covered with aircraft fabric, the study airplane structure is composed of flat composite sandwich panels that are cut using CNC routers and bonded together to form the airframe. This structural technology is extensively used in spacecraft, but has not seen wide application to airplanes because of the complex curved shapes of most airframes. The faceted shape of the low aspect ratio configuration makes the use of this technology possible.

The low aspect ratio vehicle is structurally efficient. It has a relatively short, deep structure. This keeps the stress levels in the major structural members low. The low stress levels have major advantages for reducing cost. First, the structure will be lightweight, and require less total material to fabricate. Second, the gross weight of the airplane will be significantly lower than that of a conventional airplane carrying the same useful load. This lower gross weight improves performance significantly.

The configuration shown above has an empty weight that is only 55% of that of a comparable conventional airplane, and a gross weight that is only 70% of that of the conventional airplane.

During the study, the overall performance of the configuration shown above was determined and compared to that of several conventional airplanes performing the same mission. The majority of the performance analysis was based on experimental data taken from the FMX-4 and other low aspect ratio airplanes, and on wind tunnel data from tests performed by the author (Wainfan).

The analysis showed that the study low aspect ratio configuration could deliver performance comparable to that of a Cessna 152 using 80 horsepower to carry the same useful load as the Cessna carries with 100 horsepower. The analysis also showed that, with 120 horsepower, the performance was comparable to the modern composite Diamond DA-20 airplane with the same power.

The simple structure of the study airplane has many fewer parts than that of a conventional airplane. The structure of the low aspect ratio light airplane will be simple to assemble, and will require fewer touch labor hours to assemble than a conventional structure.

The parts can be fabricated on common automated CNC machinery without the need for specialized tooling or equipment. Accordingly, third-party vendors can make the parts and the airframe manufacturer need not invest in expensive specialized tooling or machinery to begin production. The technology to produce such structures exists, and has been used to build spacecraft for many years. The materials and manufacturing and assembly techniques have been tested and fielded successfully on in-service vehicles.

Due to its combination of light weight, compatibility with automated manufacture, and reduction in assembly labor hours, a low aspect ratio all-lifting sport/trainer airplane similar to the study configuration can cost up to 50% less than a conventional airplane designed for the same mission. The performance of such an airplane will be as good, or better than a conventional airplane. The low aspect ratio machine will offer the pilot the added benefits of a roomy cabin and very safe, departure-resistant flying qualities.

1.0: INTRODUCTION:

For personal aircraft to become a common, useful mode of transportation, the overall system must offer a combination of characteristics that are not fully available in current-generation light airplanes.

1.1:Affordability:

A major impediment to the wider use of personal aircraft for routine transportation is the cost of acquiring an airplane. The price of a new basic airplane is about five times that of a mid-size automobile, and two to three times the price of a top-of-the line production luxury car.

1.1.1 At this price level, the market for new production light airplanes is limited to a small number of wealthy individuals, and to commercial operators purchasing aircraft for business use such as rental and training. Private owners are, in large limited to used airplanes and experimental kit-built machines.

1.1.2 In order to achieve widespread acceptance the price of a basic personal aircraft must be low enough to be affordable by the traveling public. In practical terms, this means that a new certified airplane must cost no more than a new luxury automobile.

1.2: Pilot Skill:

The pilot must be able to safely operate the air vehicle system with a modest level of skill, and minimal proficiency-maintenance flying beyond normal everyday transportation use. The aircraft and its systems must be easy enough to operate to allow the airplane to be used primarily for transportation. Ideally, maintenance of acceptably safe piloting skills should not require a significant amount flying strictly for training and maintenance of pilot proficiency once the pilot has completed the initial learning phase of training.

To this end, the airplane itself must have safe, docile flying qualities, and be forgiving of minor mishandling by the pilot. It should be resistant to stalling, spinning or similar departures from controlled flight. The airplane should also be relatively insensitive to center of gravity travel, so that it can be loaded for trips quickly, with a minimal concern for loading condition beyond staying within the maximum allowable gross weight.

1.3: Performance:

The aircraft should have sufficient performance to offer a significant advantage over travel by personal automobile or surface public transportation such as busses and trains. For mid-range trips (100 to 500 miles), a cruise speed comparable with current fixed-gear single-engine light airplanes e.g Cessna 172, Cessna 182, Piper Dakota, is adequate. Although higher cruise speeds are desirable, once the threshold of "fast enough" is crossed the marginal value of extra speed drops quickly. Extra cost to get extra speed

above the threshold acceptable value will decrease the overall acceptability of the system to the customer.

1.3.1 Comparing the sales of the Cessna 172, with that of the Beechcraft Bonanza gives some indication of this cost/performance tradeoff. The C-172 is a good example of an airplane with "good enough" performance. The Bonanza is contemporary with the C-172, but has significantly greater cruise performance. It also costs significantly more both to acquire and maintain, and because it is a complex airplane requires significantly greater pilot proficiency to fly safely.

1.3.2. Over a 25-year production run, Cessna sold approximately 37 thousand 172's. Over the 50 year production run of the Bonanza, about 3000 were sold. The cost/performance combination offered by the 172 was an order of magnitude more successful in the marketplace than that of the Bonanza.

2.0: REDUCING COST

Aircraft manufacturers have become quite efficient at producing conventional airplanes. The majority of the benefits that could be derived from learning curves and improved methods of producing conventional parts and assemblies are already incorporated into the price of current-day airplanes. In order to significantly reduce cost below today's levels, we must take a closer look at the overall machine, and determine how changes in the concept of the airplane might offer cost reduction opportunities.

The overall cost of producing an airplane incorporates many elements. Some of these are within the control of the OEM airframe manufacturer, or are directly affected by the design of the airframe itself. These are the components of the cost that can be affected by a change in the overall configuration concept of the airplane.

The cost to the manufacturer of producing the complete, ready-to-sell aircraft divides into two major categories, the cost of purchased items, and the cost of manufacturing and assembling the airframe and integrating all of the systems.

2.1: Purchased Items:

Typically, aircraft manufacturers purchase rather than build major systems including engine, propeller, landing gear components, instruments, and avionics. To achieve a meaningful reduction in overall vehicle cost, it is highly desirable to reduce the cost of purchased components as well as those produced by the airframe manufacturer

2.1.1: Instruments and Avionics: The instruments and avionics required are primarily a function of how and where the airplane is operated. The capabilities needed to enable the pilot communicate, navigate, and fly the airplane are set by the type of airspace and the meteorological conditions the airplane will operate in. Accordingly, the manufacturer of the airplane has little choice about what capability must be aboard the airplane, and hence little ability to affect cost of these items. While there is little doubt that there is much room for cost reduction through innovations in avionics systems, these are essentially independent of the configuration of the airframe, and not within the scope of this study.

2.1.2: Engine and propeller: Although the engine and propeller are purchased items, the airplane manufacturer has considerable discretion in the choice of engine and propeller used by the airplane. The two most important variables from a cost viewpoint are the rated power of the engine, and the choice of a fixed-pitch or constant-speed propeller.

Figure 2.1.2.1 shows the original equipment manufacturer (OEM) price of typical aircooled aircraft piston engines manufactured using modern numerically controlled machinery. As the figure shows, the cost of engines varies approximately linearly with rated horsepower.



Accordingly, an airframe design that requires less installed power to perform the design mission will reduce the overall cost of the airplane by reducing the cost of the purchased engine, even if the airframe concept is not, in and of itself, less costly to manufacture.

The cost of the propeller is also a significant component of the cost of the propulsion system. A constant-speed propeller typically costs about 25% of the price of the engine turning it, while a fixed-pitch metal propeller costs about 10% of the price of the engine. Accordingly, using a variable pitch propeller increases the overall cost of the propulsion system by about 15%.

2.1.3: *Airframe design:* The cost of the airframe can be reduced by several methods. The most important of these are:

- 1) Minimize Overall Parts Count.
- 2) Minimize the complexity of parts and systems.
- 3) Minimize the amount of special tooling and machinery required to fabricate parts.
- 4) Minimize labor required to fabricate parts
- 5) Minimize touch labor required to assemble the airframe and install systems.
- 6) Minimize materials cost.

Efforts to date to reduce airframe cost for personal aircraft have centered on using new manufacturing techniques, detail design concepts, and materials to reduce the cost of aircraft with relatively conventional wing-body-tail configurations.

These efforts were successful in reducing cost somewhat, but not to the level required to reach the personal air vehicle cost needed to make the aircraft affordable to a significant number of users. In general, although the methods investigated achieved some reduction in the labor hours required to assemble the airplane, they did not significantly affect enough of the other elements of the cost of the airplane, including materials cost, tooling cost, and cost of fabricated parts to effect a revolutionary change in overall cost. As a consequence of this, the airplanes using these concepts that did reach production (e.g. Republic SeaBee, Emigh Trojan, Rockwell Commander 112) had to compete in the marketplace on the basis of performance and flying qualities, since they did not offer an overwhelming cost advantage over their more conventional rivals.

3.0: A NEW HIGHLY AFFORDABLE PERSONAL AIRCRAFT CONFIGURATION CONCEPT

3.1: Concept Goals:

In order to gain a significant cost reduction beyond that achievable by applying modern techniques to a relatively classical configuration a new vehicle architecture is needed. This new architecture should be intrinsically lower cost to manufacture than the conventional wing-body-tail airplane configuration. To achieve this, the concept should attack several areas that control cost. If at all possible, the new vehicle concept should exploit technology that has already been developed for other applications and not require any costly development of enabling technologies to be completed before the concept can be implemented.

The new design approach should take advantage of the modern design and manufacturing technologies and materials that were not available when the light airplanes currently in production were designed, specifically 3-D CAD, numerically controlled manufacturing machinery (CNC mill, laser cutting, water-jet cutting, and CNC routers) and composite materials.

It should be structurally simple so that the total parts count is dramatically reduced, and should be simple to assemble to minimize the cost of assembly labor and fixtures. The parts themselves should be a simple to manufacture as possible, and require a minimum of specialized tools such as large molds, or custom dies or forms.

3.2: Low-Cost Airframe Configuration Concept:

A configuration concept that has the potential to significantly reduce cost for the reasons just discussed is an integrated low-aspect ratio all-lifting configuration. The concept features an integrated all-lifting body that performs the functions of the wing, tail and fuselage of a conventional light airplane with a single, simple structure. The integrated lifting body has an aspect ratio between approximately 1.0 and 2.5, and is deep enough to contain the crew and payload without a conventional fuselage.

The configuration can be further simplified by the use of a faceted shape composed of flat panels. The faceting greatly simplifies the manufacture of the major parts of the airframe, although it does exact a small penalty in parasite drag.

3.3: Advantages of the low aspect ratio tailless configuration for personal aircraft:

3.3.1: Airframe cost: The low aspect ratio all-lifting tailless configuration has several characteristics that make it intrinsically lower cost than conventional aircraft. When combined with modern manufacturing technology, and detail design aimed specifically at compatibility with low-cost manufacturing techniques, the result will be a dramatic reduction in the total cost of the airframe.

3.3.2: Structural Efficiency: The low aspect ratio vehicle is structurally efficient. It has a relatively short, deep structure. This keeps the stress levels in the major structural members low. The low stress levels have major advantages for reducing cost.

First, the structure will be lightweight, and require less total material to fabricate. Second, the low stress levels allow the structure to be fabricated of materials that are relatively low-strength compared to the materials required in the high-stress areas of a conventional airframe. Many of the structural elements will be sized by buckling or similar stability criteria rather than material yield strength. Accordingly, the stiffness of the material in the structure will be as important at its ultimate tensile or compressive strength. In the case of a metal airframe, common low-cost commercial alloys of aluminum such as 6061-T6 can be used for the structure rather than the stronger, but much costlier 2024 or 7075 alloys. Simply changing to 6061-t6 from either 2024 or 7075 reduces material cost per pound by about 35%. Similar cost savings can be realized in composite structures since the price difference between high-strength materials and moderates strength materials (i.e. glass vs. carbon or aramid fiber) When the combination of lower structure weight and lower cost materials are combined the material cost savings can exceed 40%

The low stress levels in the structure can also lead to major simplifications of the structural design. The primary structure can be either a truss structure composed of straight tubes made from standard extrusions, or a monocoque stressed skin structure with minimal internal stiffeners and spars.

3.3.3: Parts count: A properly configured low-aspect-ratio airplane combines the functions of the wing, fuselage, and horizontal tail into a single relatively simple "hull" or wing structure. The parts count of this hull is comparable to the parts count of a conventional fuselage. Accordingly, the configuration eliminates all of the parts normally associated with the wings and horizontal tail. In addition, the interfaces and joints associated with attaching the flying surfaces to the fuselage of the conventional machine are eliminated. Exploiting the fact that major sections of the hull can be built as single large parts rather than an assemblage of smaller ones can further reduce the parts count.

3.3.4: Simplified Structural Shapes: The outer mold line of a low aspect ratio airplane can be composed exclusively of single-curved panels or flat panels. The Wainfan FMX-4 Facetmobile, which is described more fully below demonstrated that a low aspect ratio faceted shape composed entirely of flat panels could have performance comparable to a conventional airplane with the same power and useful load.

3.3.5: Simplified Systems Installation: The high internal volume of a low-aspectratio shape leaves large volumes for systems. The systems are easily accessible, and the number of wires, fuel lines, control cables, etc/ that must be strung through narrow, hard-to-reach spaces is minimized. With proper design of the flight controls, all of the primary flight control actuation mechanisms can be in the vehicle center section, and no control runs into the outer panels will be needed.

3.3.6: Simplified Assembly: The primary structure of the vehicle will be composed of a small number of large parts. These can be designed to key together, and be automatically self-aligning. The small number of assemblies minimizes the work required to join them together. The self-aligning feature of the major components reduces the need for precision assembly tooling.

3.3.7: Safety: A properly configures low-aspect ratio configuration does not exhibit a classical aerodynamic stall. At high angles of attack, the leading edges, or outer edges of the planform shed strong, stable vortices that generate lift and maintain stable roll damping to very high angles of attack (over 30 degrees). This effect can be exploited to produce a configuration that is highly resistant to departures from controlled flight, and to spinning. This departure resistance is a significant enhancement to safety, since approximately 25 to 35 percent of all fatal general aviation accidents involve loss of control due to stall/spin.

A low aspect ratio all-lifting configuration will typically have a lower wing loading than a conventional airplane. Although it will also have a lower maximum lift coefficient, the lower wing loading will more than offset this, giving the low aspect ratio vehicle the ability to land slowly, particularly if flared to high angle of attack to take advantage of vortex lift in an emergency. Low landing speed is also a significant safety enhancement, since speed at impact is one of the most significant factors affecting the survivability of a mishap. This Page

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4.0: THE FMX-4 FACETMOBILE

This study builds on the results achieved with the Wainfan FMX-4 Facetmobile research aircraft.

The FMX-4 is an experimental low-aspect-ratio all-lifting light airplane. It was built by Barnaby Wainfan, Rick Dean, and Lynne Wainfan to explore the characteristics and potential of this type of airplane. First flight was April 22, 1993. During the period between 1993 and 1995 the airplane was flown a total of 130 hours.



In 1994, the airplane was flown to Oshkosh, WI from Chino, California and back. On the outbound flight it covered 2,253 miles in a total flight time of 25 hours and 46 minutes.

Length:	19 ft. 6 in.
Span:	15 ft.
Empty Weight:	370 lb. (includes BRS parachute)
Gross Wt. (max):	740 lb.
Engine	Rotax 503DC (46 Hp.)

The outer mold line of the FMX-4 lifting body is composed of 11 planar surfaces, 8 on top, and 3 on bottom. The leading edges are sharp. The only curved portion of the airframe OML is the fiberglass engine cowling. The entire primary structure of the FMX-4 airframe was built of 1-inch diameter, .035-inch wall 6061-t6 aluminum tubing. All of the structural tubes are straight. The main structural truss members form the outer mold line of the airplane without using false ribs or formers to smooth the shape.

The tricycle landing gear is fixed, and does not have fairings over the wheels.

Table 4.0.2: FMX-4 Performance:

Maximum Speed:	96 knots true airspeed @ 4,000 feet.
Cruise Speed:	80 knots
Stall:	No stall: stable mush.
Minimum Speed:	Less than 33 knots.
Rate of Climb:	750 ft/min.

4.1: FMX-4 Flight Test Results:

The FMX-4 flight test program conclusively demonstrated that the low-aspect-ratio, faceted, tailless configuration is viable for a light general aviation airplane. The overall performance of the airplane compared well with the performance of conventionally configured airplanes using the same power plant. The airplane demonstrated the ability to carry a useful load equal to its empty weight.

The flying qualities of the FMX-4 are benign and conventional. Control forces are linear, and well harmonized. The airplanes motions are well damped about all axes. Very little rudder is required to coordinate turns in up-and-away flight.

In the approach configuration, the airplane has a strongly stable dihedral effect. Dutch roll is well damped, so the primary effect of the strong lateral stability is the need for significant lateral stick force to maintain a steady-state sideslip during a crosswind approach.

The airplane is highly departure resistant at high angles of attack. The airplane did not have angle of attack instrumentation, but wind tunnel results indicate that full aft stick should trim the airplane to approximately 30 degrees angle of attack. In flight test, in the full-aft-stick condition, the airplane exhibited a moderate high-frequency aerodynamic buffet, and a power-off sink rate of about 1000 feet per minute. Roll damping remained stable, and the airplane exhibited no tendency to roll off or depart, even during gentle lateral maneuvering. The controls remained effective about all axes.

The aircraft was not equipped with a flying pitot head. Accordingly, the true minimum airspeed could not be measured because the fixed pitot tube stalled at high AOA, leading to an airspeed reading of zero on the airspeed indicator before buffet onset. Wind tunnel

data predicts that the steady-state airspeed at the angle of attack for maximum lift is approximately 33 knots.

These flight test results, as well as results of more aggressive high angle of attack investigations conducted with the ¼ scale radio-controlled model indicate that the FMX-4 is highly spin resistant and will not be prone to the typical stall/spin accident seen with conventional airplanes.

The FMX-4 test program demonstrated that the configuration offers many advantages as a personal air vehicle. The primary advantages demonstrated are:

- Simple primary structure, with low parts count
- Airframe structure composed of low-cost materials
- High useful load fraction
- Benign flying qualities
- Stall and Spin resistance
- Large tolerance of center of gravity travel
- Superior occupant protection
- Roomy cabin
- Performance comparable with conventional airplanes.

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5.0: TRANSPORT EFFICIENCY

In the course of this study we will be comparing the usefulness of highly dissimilar airplane configurations, Accordingly, it is desirable to evolve a figure of merit that is configuration-independent and will give a meaningful indications of the relative "goodness" of airplanes with fundamentally different configurations.

The mission of an airplane, in its simplest form, is to transport payload from one point to another. A reasonable metric of its transport efficiency is the amount of fuel consumed per mile per pound of payload transported. Note that the efficiency of the airplane as a useful transportation vehicle (transport efficiency) is tied to its ability to transport the weight of its payload, not to its ability to transport its total gross weight. The non-payload portion of the weight of the airplane exists to transport the payload. The user of the airplane derives no utility from transport of the airplane itself, only from the transport of the payload. The crew and fuel are critical to this task, and comprise part of the useful load of the airplane. Accordingly, the portion of the gross weight that is useful to the user of the machine includes crew, fuel, and payload. It is therefore desirable to formulate an approach to evaluating the overall efficiency of an airplane as a useful bad-transportation system.

The fuel burn of an airplane flying at a given speed is directly proportional to the drag of the airplane. Thus, it initially appears reasonable to look to the cruise lift-to-drag ratio (L/D) of the airplane as a measure of its efficiency.

From a payload-transport-efficiency point of view, the L/D of the airplane is not the whole story. L/D would be a valid metric of transport efficiency if all other factors were equal for competing configurations. This is not the case however. The structural weight and useful load fraction of the machine also play a major role.

The drag of the airplane is the gross weight of the airplane divided by the L/D.

In order to determine the transport efficiency of the airplane carrying useful load, we one must consider not *lift-to-drag ratio*, but "*useful load*"-to-drag ratio:

First, note that the gross weight of the airplane can be expressed as:

$$W_G = W_u (W_G/W_u)$$

Where:

 W_G = Airplane Gross Weight W_U = Useful Load Weight

The drag of the airplane can thus be expressed as:

$$D = W_{U} (W_{G}/W_{U})/(L/D)$$

Further manipulation shows that:

$$D = W_{U} \{ 1/[(W_{U}/W_{G}) (L/D)] \}$$

OR:

W_u /D = (W_P/W_G) (L/D) (eq. 5.0.1)



From the foregoing analysis, it can be seen that the drag of an airplane carrying a specified useful load is affected equally by the aerodynamic efficiency of the airplane as determined by L/D, and the useful of load fraction the airplane (Wu/WG). The most efficient airplane is found when the product of these two quantities, (W_U/W_G) (L/D) which is the ratio of pavload weight drag, is maximized, thus to minimizing the drag per unit useful load.

The quantity (Wp/Wg) (L/D) is particularly useful as a comparative figure of merit to evaluate dissimilar configurations intended for the same mission. It is applicable when the majority of the mission is performed in steady-state 1G flight. This is illustrated by the comparisons between the Cessna 150, a conventional wing-body-tail airplane with an aspect ratio of 6.8 and the FMX-4, an all-lifting configuration with an aspect ratio of 1.07 shown in figs 5.0.1 and 5.0.2. For the purposes of this comparison, the characteristics of the Cessna were based on the manufacturers published performance figures and the pilots operating handbook for the airplane. FMX-4 characteristics were derived from flight test of N117WD.

The L/D comparison in fig. 5.0.1 shows that the Cessna 150 has a higher L/D than the low aspect ratio FMX-4 at all airspeeds. From and aerodynamic viewpoint the C150 appears to be a significantly more efficient airframe. The picture changes dramatically when we take into account the relative structural efficiencies of the two airframes. The Cessna 150 has a useful load faction 0f 0.338, while the FMX-4 has a useful load fraction of 0.471. While the Cessna is more efficient aerodynamically, the FMX-4 is more efficient structurally. The effect of these two factors is shown in Fig. 5.0.2, which illustrates the useful load to drag ratio (Wu/D) of the two airplanes.

As figure 5.0.2 shows, the C-150 has slightly higher maximum transport efficiency, but this occurs at an impractically low airspeed. At airspeeds above about 75 knots, the FMX-4 has slightly higher transport efficiency then the Cessna. In the 90 to 100 knot speed range that is typical of normal cruise for both airplanes, the FMX-4 is slightly superior.

From a practical viewpoint, the two configurations are essentially equally efficient at transporting their useful load. In essence, the higher structural efficiency of the low aspect ratio configuration is just sufficient to overcome its aerodynamic disadvantage relative to the conventional airplane.



This comparison was presented to illustrate the relative effect of structural and aerodynamic efficiency on the overall transport efficiency of an airplane. Neither of the aircraft used in this example should be construed to represent an optimum configuration. What is important to note from this comparison is that using L/D as a primary figure of merit would be highly misleading with regard to the overall effectiveness of the two configurations.

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6.0: STUDY CONFIGURATION DEFINITION:

The FMX-4 is a single-seat research airplane. The information gained from the FMX-4 flight test program is directly applicable to the design of a slightly larger two-seat airplane. Such an airplane would be useful for training, sport flying, and short-range (up to 500 NMI) cross-country flying.

This study concentrates on the application of the low aspect ratio all-lifting concept to such an entry-level two-seat sport/trainer airplane.

6.1: Existing Aircraft in this Category:

Table 6.1.1 shows the published specifications for four certified aircraft currently in service in the 2-seat sport/trainer class. These aircraft were used as a basis of comparison for the current study, and were also surveyed to set target performance and useful load for the low aspect ratio study configuration.

Туре	Gross Weight	Empty Weight	Useful Load (lb.)	Span (ft.)	Wing Area	Aspect Ratio
	(lb.)	(lb.)			(sq.ft.)	
Cessna 152	1670	1155	515	32.7	157	6.8
Piper PA-38	1670	1128	542	34	124.7	9.3
Alarus CH 2000	1692	1085	607	28.8	137	6.1
Diamond DA20-	1653	1166	487	35.7	125	10.2
C1						

Table 6.1.1: Characteristics of Current Sport/Trainer Airplanes:

The Cessna, the Piper, and the Alarus are all-metal airplanes using traditional riveted sheet metal structures. The Cessna 152 is a high-wing strut-braced configuration, while the Alarus and the PA-38 both have cantilevered low wings.

The Diamond DA20-C1 "Eclipse" is a modern molded composite airplane with a cantilevered low wing and a "T" tail. It is interesting to note that although the Eclipse has higher performance then its all-metal competitors, it has the lowest useful load fraction of the four airplanes surveyed.

6. 2: Study Configuration:

A drawing of the study configuration is shown in Fig. 6.2.1. It is a low aspect ratio, faceted configuration derived from the FMX-4. The outer mold line is composed entirely of planar facets in order to make the configuration compatible with low-cost automated manufacturing techniques. It has a fixed, tricycle landing gear.

This study configuration airplane was designed to provide cruise performance comparable to the current-generation all-metal airplanes listed in Table 6.6.1. The match to the metal airplanes rather than the Diamond Eclipse was chosen to emphasize cost

rather than all-out performance. The marketplace has clearly determined that the performance of the C-152 is acceptable for the sport/trainer mission. The additional performance of the Diamond Eclipse, while desirable if it is achieved at small cost, is not of sufficient value to justify a significant increase in airplane price.

The study configuration is powered by an 80 horsepower piston engine driving a fixedpitch propeller. This gives cruise performance similar to that of the Cessna 152 carrying the same useful load.

Empty Weight (lb.)	635
Useful Load (lb.)	530
Gross Weight (lb.)	1165
Span (ft.)	22
Wing Area (sq. ft.)	260
Aspect Ratio	1.86

Table 6.2.1: Study Configuration Specifications



Figure 6.2.1: Low Aspect Ratio All-Lifting Sport/Trainer Configuration

6.3: Study Configuration Aerodynamic Drag:

Estimates of the aerodynamic performance of the study airplane are based on two sources: Flight test of the Wainfan FMX-4 airplane (N117WD) and wind test data for the FMX-5 model as tested in the Cal Poly Pomona subsonic wind tunnel.

6.3.1: Parasite Drag. Flight test data for the FMX-4 was used to derive parasite drag for performance estimates of other faceted low aspect ratio configurations. Results are shown in Table 6.3.1.1 The data used for this estimate were taken from full-throttle runs at an altitude of 4000 feet.

Item	Drag Area (D/q) (Square Feet)
Landing Gear	0.27
Fins	0.20
Cooling	0.129
Interference	0.028
Hull	1.895
Total Airplane	2.746

Table 6.3.1.1: FMX-4 Parasite Drag Breakdown:

In the configuration tested, the landing gear wheels were exposed and not enclosed in any form of wheel pant or fairing. The landing gear legs were faired to an airfoil shape. The surface finish of the airplane was of average quality, and not extraordinarily smooth. Accordingly these items are likely representative or slightly worse than that which would be expected on a production airframe.

The cooling drag of the FMX-4 was relatively high due to the configuration of the engine and the extremely conservative approach used to minimize the chances of overheating of the 2-stroke engine. The engine itself is fan cooled, with the fan placed at the rear of the engine. The convoluted cooling air path this dictated ensured that there would be little or no pressure or momentum recovery at the cooling air exit. The inlet was also oversized to ensure adequate cooling flow. A production aircraft with a conventional 4-stroke aircraft engine and properly designed cooling system would have lower cooling drag than FMX-4.

The drag of the hull of the airplane corresponds to a drag coefficient (normalized using planform area as though it was a wing) of 0.00885. This corresponds to an effective skin friction coefficient (C_{fe}) of 0.00436. The skin friction coefficient of a fully turbulent flat plate at the flight Reynolds Number (13 million based on mean geometric chord) is approximately 0.00318. Comparing this to the C_{fe} of the airplane hull yields a form factor of about 1.37.

From the foregoing analysis we can see that the measured drag of the FMX-4 is reasonable. The C_{fe} is well within the range that has been measured for typical light

airplanes, and the form factor is within the range measured by other experimenters in wind tunnel tests of bevel-edged and faceted delta wings.

The parasite drag characteristics of the vehicle hull derived above were used for the performance analysis of the study configuration in this report.

6.3.2: Drag Due to Lift: In December 1994, the author (Wainfan) tested a configuration for a 2-seat airplane designated FMX-5. The 15% scale radio control model shown in Fig.6.3.2.1 illustrates the general shape of the airplane. The wind tunnel model shown in Fig.6.3.2.1 was tested in the subsonic wind tunnel at the California Polytechnic Institute at Pomona. The wind tunnel model was tested in several configurations. For the purpose to this study the data for the hull alone, without the tip fins were used.



Figure 6.3.2.1: FMX-5 Models

As stated above, the wind tunnel data were used to derive a polar shape for the computation of drag due to lift. Because of the camber of the vehicle, an offset polar of the form:

$$(C_D - C_{Dmin}) = (C_L - C_{L0})^2 / (\Pi e AR)$$
 was used.

For the FMX-5 model hull-alone configuration without tip fins $C_{L0} = 0.02$ and e=0.77. A comparison between this curve-fit polar shape and test data from the wind tunnel test are shown in Fig 6.3.2.2:



The lift coefficient range covered in the polar shape shown in Fig. 6.3.2.2 covers the normal flight envelope of the FMX-5 airplane and the example airplane configuration used in this study.

6.4: Study Configuration Weight:

A primary advantage of low aspect ratio all-lifting configurations is structural efficiency. The efficient structure provided by the relatively short, thick load paths and the lower bending moments that arise from the combination of shorter span and distributed loads yield a vehicle that has a significantly lighter structure, and hence empty weight for a given useful load. This structural efficiency translates into a reduced takeoff gross weight.

Accordingly, a low aspect ratio all-lifting airplane will be lighter at takeoff than a conventional wing body tail airplane carrying the same useful load. As we have seen in the discussion of transport efficiency above, this directly affects the drag of the airplane and hence the power required to fly.

6.4.1: Existing Airplanes: Although low aspect ratio all-lifting airplanes are not common, a few have been built and tested over the years. Table 6.4.1.1, below shows mass properties data for several of these. All of the aircraft referenced are powered by single piston engines. The FMX-4, Hatfield airplanes, and the Arup have fixed landing gear and fabric-covered structures. The Dyke airplanes have retractable landing gear, and fiberglass skins over welded steel tube truss structure.

						<u> </u>	
TYPE	Empty	Gross	Span	Wing Area	Aspect	Useful	Wu/W _G
	Weight	Weight			Ratio	Load	
	(lb)	(lb)	(Ft.)	(Sq. Ft.)		(lb)	
FMX-4	370	740	15	214	1.05	370	0.5
Hatfield LB3	253	483	18	182	1.78	230	0.47619
Hatfield LB1	248	458	17	144	2.01	210	0.458515
DYKE JD1	725	1400	18.5	158	2.17	675	0.482143
ARUP #2	400	740	19	151	2.39	340	0.459459
DYKE JD2	1060	1950	22.25	173	2.86	890	0.45641

The data from Table 6.4.1.1 are plotted in Fig. 6.4.1.1: below:



A quadratic curve fit to the data in Table 6.4.1.1 is shown in Fig. 6.4.1.1. This curve fit gives:

 $W_u/W_g = 0.5484 + .0081 AR^2 - 0.0551 AR$ (eq. 6.4.1.1)

As the plotted weight data for low aspect ratio airplanes shows considerable scatter, but equation (6.4.1.1) gives a reasonable weight estimate for preliminary design.

6.5: Empty Weight Estimates For the Study Configuration:

Several methods were used to get an initial estimate of the empty and gross weight of the study configuration.

6.5.1: Statistical Parametric Weight: The study configuration has a useful load of 530 pounds and an aspect ratio of 1.86. Equation (6.4.1.1) gives a useful load fraction for this aspect ratio of 0.474. For the 530-pound useful load this gives a gross weight of 1,118 pounds and an empty weight of 588 pounds.

6.5.2: Bottom-Up Estimate: A second weight estimate was generated by estimating the weights of the individual components. Table 6.5.2.1 shows the results of this estimate.

ltem	Weight (Lb)
Engine	132
Prop And Spinner	10
Landing Gear	55
Avionics And Panel	20
Seats	15
Battery	25
Transparencies	35
Skin	208
Bulkheads And Spars	50
Cowling	5
Mount	10
Paint	15
Fuel Tanks	15
Controls And Cables	10
Ballistic Parachute	30
Total	635

Table 6.5.2.1: Study Configuration Component Weight Estimate

The empty weight generated by the bottom-up summation of estimated component weights is 635 pounds, which is 46 pounds heavier than the parametric empty weight estimate generated using Equation 6.4.1.1. The primary reasons for this discrepancy are the addition of the ballistic parachutes system and the weight of the skin panels. The skin weight in the bottom-up estimate is based on a panel weight of 0.4 pounds per square foot. This is an easily achievable weight but it does not represent the lightest possible sandwich panel. Panel weights as low as 0.25 pounds per square foot are possible. Using such lightweight panels for the skin of the vehicle would reduce the empty weight by 78 pounds, to 557 pounds. While such lightweight panels might be structurally adequate, it is unlikely that they will be sufficiently resistant to damage due to minor bumping and other "hangar rash" types of incidents to be acceptable.

The preceding analysis illustrates one of the more important sensitivities of low aspect ratio configurations. Although they are structurally efficient carriers of bending loads, they tend to have a large amount of lightly loaded skin area. Accordingly the weight of such an airplane is quite sensitive to the weight per square foot of the skin. Due to the light loading of the skin, the majority of the material forming the vehicle outer mold line will be sized by minimum gauge considerations and damage tolerance rather than by the ability to safely withstand flight loads. This should be taken into consideration during the preliminary design phase so that the skin material used does not exact an unnecessary weight penalty due to local buckling, damage tolerance, or similar minimum-gauge consideration.

6.5.3: Estimate based on FMX-4: Another useful method of estimating weight is to base the estimate on measured weights of existing airplanes. Table 6.5.3.1 shows the results of such an estimate for the example configuration based on the FMX-4. The estimate starts with the empty weight of the FMX-4, and then applies a systematic set if increments to correct that weight to the weight of the example configuration. This estimate assumes that the airplane will have a fully load-bearing truss structure like that of FMX-4 but adds weight for a non-load bearing metal skin.

Item	Weight (lb)
FMX-4	370
Remove Rotax 503	-100
Install Jabiru 2200	135
Add Battery	15
Add Extra Seat	10
Additional Avionics	20
Stronger Main Gear	10
Structural Reinforcement for	30
Higher Gross Weight	
Addition Electrical Systems	10
Remove Fabric Skin	-30
Add .02 AI Skin	133
Total	603

Table 6.5.3.1: Weight Estimate Based on FMX-4 Airplane

This weight estimate (603 lb) is quite close to the value given by the paramedic estimate using equation 6.4.1.1 (588 lb). The bottom-up weight estimate is somewhat heavier (635 lb), but takes into account the structural inefficiency imposed by the use of sandwich skin panels designed to tolerate minor impacts and be damage tolerant.

For the purposes of the performance analysis that follows the bottom-up estimate of 635 pounds was used for the vehicle empty weight. This is the heaviest, and hence most technically conservative empty weight estimate.

7.0: STUDY AIRPLANE PERFORMANCE:

The performance of the study airplane was determined using the drag and weight characteristics described in the preceding sections. The airplane has a gross weight of 1165 pounds (635 lb empty plus 530 lb. useful load). It is powered by an 80 horsepower piston engine driving a fixed-pitch propeller. The propeller design point was chosen to give cruise performance similar to that of the Cessna 152.

The resulting performance of the airplane is shown in Fig. 7.0.1: below



The figure shows full-throttle rate of climb as a function of true airspeed and altitude. Top speed at any altitude is the highest speed at which the rate of climb is zero at full throttle. Accordingly, the study airplane will have a maximum speed of approximately 112 knots at sea level, and will cruise at 9000 feet at full throttle (approximately 75% rated power) at approximately 104 knots. Sea level rate of climb will be just over 1000 feet per minute. This performance is comparable to the well-known Cessna 152, which has a top speed of 110 knots and cruises at 107 knots at 8,000 feet. The climb performance of the study airplane (1000 ft/min) is significantly better than that of the C-152 (715 ft/min).

It is important to note that the study airplane achieves performance comparable to the Cessna with the same useful load using 31% less horsepower. This significantly reduces the cost of the engine, and also reduces direct operating cost by reducing fuel consumption proportionately to the reduction in engine power.

7.1: Takeoff performance:

Roskam and Lan (ref. 8) give the following statistically based equation for calculating takeoff distance of a piston engined airplane:

Ground roll (Sg) in feet : Sg = $4.9(TOP_{23}) + 0.009(TOP_{23})^2$ (eq. 7.1.1)

Where (TOP₂₃) is the FAR-23 take-off parameter, which is given by;

 $(TOP_{23}) = {(W/S)(W/P)}/(\sigma C_{Lmax})$

W = Gross weight in pounds S = Wing area in square feet P = Engine rated power in horsepower

All of the parameters used in the equation above are for the airplane in its takeoff configuration.

Total takeoff distance over a 50-foot obstacle (Sto) is given by:

Sto = 1.66 Sg

Takeoff performance for the study airplane, the Cessna 152 and the Diamond Eclipse, as calculated using the above equations are shown in Table 7.1.1.

Aircraft	Sea Level Takeoff Ground Roll (Feet)	Sea Level Takeoff Over 50-Foot Obstacle (Feet)			
Cessna 152	715	1187			
Diamond Eclipse	868	1441			
Low Aspect Ratio	460	763			
Study Airplane					

 Table 7.1.1: Takeoff Performance

These values are approximate, but they serve to give a useful comparison of takeoff performance. The low aspect ratio study airplane has considerably better takeoff performance than either of the two conventional airplanes in the same class. This is primarily because of the much lower wing loading of the low aspect ratio all-lifting configuration.

The conventional airplanes take off with the flaps retracted or at very small deflections, so their maximum lift coefficient is relatively low (about 1.35). Although the low aspect ratio airplane has a lower maximum lift coefficient (about 1.0) than either of the conventional airplanes, it is not enough lower to offset the effect of the low wing loading.

7.2: Maximum Rate of Climb:

Full-throttle maximum rate of climb as a function of altitude for the four airplanes studied is shown in Fig. 7.2.1



At altitudes up to about 4,000 feet the 80-hporsepower low aspect ratio study airplane has the highest rate of climb. At higher altitudes, the Diamond Eclipse out climbs the study airplane. The study airplane has a higher rate of climb than either of the two all-metal airplanes at all altitudes up to 15,000 feet.

The high initial rate of climb of the study airplane is a function of its light weight. Climb rate is a function of specific excess power, and the lower gross weight of the low aspect ratio airplane causes it to gain 30% more rate of climb per excess horsepower than the other, heavier airplanes. At higher altitudes, the higher L/D of the Diamond Eclipse airframe aids rate of climb more than the lower weight of the low aspect ratio configuration. The rate of climb picture is somewhat muddled by the fact that all of the airplanes have fixed-pitch propellers, so climb performance is strongly affected by propeller pitch and diameter.

7.3: Lift-to-Drag Ratio (L/D):

The aerodynamic performance of the study airframe as measured by lift to drag ratio (L/D) is shown in Fig. 7.3.1, below



Data for the Cessna 152, the Alarus Ch-2000 and the Diamond DA20-C1 "Eclipse" are shown for comparison. The study airframe has a maximum L/D of 10.5 at an equivalent airspeed of 75 knots. This is very close to the maximum L/D of the Cessna 152 (10.3).

The curves of L/D vs equivalent airspeed show that the low aspect ratio study airplane achieves its peak L/D at a higher speed than the conventional Cessna. Accordingly, at all equivalent airspeeds above approximately 68 knots, the study airplane is more aerodynamically efficient than the Cessna. The difference is pronounced at typical cruise speeds. At 100 knots equivalent airspeed, the Cessna has an L/D of 7 while the study airplane has an L/D of 8.9, which is 27% higher.

While the faceted low aspect ratio study airplane is comparable to the classic high-wing strut-braced all-metal Cessna 152 in terms of aerodynamic efficiency, it is not as good as the modern all-composite Diamond Eclipse. The Eclipse has significantly higher aerodynamic efficiency over the entire airspeed range.

7.4: Drag and Power.

The actual drag of an airplane is a linear function of both the aerodynamic efficiency as reflected by L/D, and the gross weight.

$$D = W/(L/D)$$

Fig. 7.4.1 shows the drag in pounds of the four airplanes as a function of equivalent airspeed.



Note first, that the drag of the study airplane is lower than that of the Cessna 152 at all airspeeds, even though the Cessna has a higher L/D at airspeeds below 68 knots. This is because of the lighter gross weight of the low aspect ratio study airplane. Due to its higher payload fraction and structural efficiency, the study airplane with a useful load of 530 pounds has a gross weight of 1165 pounds, while the Cessna 153 weighs 1670 pounds when flying with a useful load of 515 pounds. This 30% difference in gross weight is great enough to overcome the difference in L/D at low airspeeds, and further increases the study airplane's advantage over the Cessna at cruise speeds. At 100 knots equivalent airspeed, the drag of the study airplane is approximately half that of the Cessna 152.

The structural efficiency and attendant lower gross weight of the study airplane is almost sufficient to overcome the aerodynamic efficiency (L/D) advantage of the composite Diamond Eclipse. As Fig.7.4.1 shows, the drag of the study airplane is slightly higher than that of the Eclipse, but the difference is small. At typical cruise airspeeds, the study airplane's drag is approximately 5% higher than that of the Eclipse.

The trends shown by the drag curves in Fig. 7.4.1 are reflected in the power required to fly. Curves comparing power required for the four airplanes are presented in Fig. 7.4.2 for two cruise altitudes.


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7.5: Airplane Transport Efficiency:

As we saw in Section 5.0 the transport efficiency of an airplane is the useful load to drag ratio and is defined by:

$$W_{\rm U}/D = (W_{\rm P}/W_{\rm G}) (L/D)$$
 (eq. 5.0.1)

Curves of transport efficiency for the four airplanes studied are shown in Fig 7.5.1,



The two conventional all-metal airplanes (Cessna 152 and Alarus CH-200) are comparable in terms of transport efficiency. The Alarus has a somewhat lower L/D than the Cessna, but carries a greater useful load. The two aircraft have essentially the same transport efficiency.

The low aspect ratio study airplane and the Diamond Eclipse are essentially identical in terms of transport efficiency. As we have already seen, the Diamond Eclipse airframe is much more efficient aerodynamically, but the airplane has a relatively low payload fraction. It carries a useful load of only 485 pounds and has a gross weight of 1653 pounds. The low aspect ratio study airplane is structurally much more efficient, carrying a useful load of 530 pounds flying at a gross weight of 1165 pounds. The greater structural efficiency of the low aspect ratio configuration almost exactly compensates for the greater aerodynamic efficiency of the Diamond Eclipse, and the two airplanes have essentially

the same system-level transport efficiency, although they achieve it by very different means.

7.6: Performance Summary:

Since the focus of this study was low cost rather than maximum performance, the engine chosen for the study airplane was sized (80 hp.) to match the up-and-away performance of the Cessna 152.

The low aspect ratio study airplane, with 80 horsepower has up-and-away performance comparable to the current-generation all-metal trainers powered by the 110 horsepower Lycoming O-235. It is significantly superior to the conventional all-metal airplanes in terms of takeoff distance and rate of climb.

The low aspect ratio study airplane has better takeoff and initial climb performance than the all-composite Diamond Eclipse. Its cruise performance matches that of the Cessna 152, so it is significantly slower than the Eclipse. This is unsurprising since the study airplane has 80 horsepower vice the 125 horsepower of the Eclipse.

The overall system-level transport efficiency of the low aspect ratio study airplane is significantly superior to the classical riveted all-metal airplanes, and comparable to a modern, molded all-composite machine.

8.0: AIRFRAME STRUCTURE

8.1: Introduction:

Since the Wright brothers, airframe designers have improved on the performance, structural weight ratio and efficiency of aircraft through innovative design approaches, improved aerodynamics and advancements in material technology.

All of the following design and fabrication methods have been used to build airplanes, and to a greater or lesser extent, all are still in use today:

- Bonded Wood Construction with fabric covering
- Welded Tubular Steel Construction with fabric covering
- Riveted/Bonded Aluminum Semi-Monocoque Construction
- Hand Layup Pre-Preg Composite Construction
- Filament Wound Composite Construction
- Composite Tape Laying Machines

With the exception of the last 2 highly automated methods, all current means of constructing an airframe are "touch labor intensive". The minimum cost of airplanes produced by such methods is relatively high because to the total number of manual operations that must be performed to build the airplane. Large-scale production and learning curves help somewhat, but only to a point. Even when Cessna produced 2000 C-150's in one year, it was reported that 750 man-hours of labor were required to just produce the basic airframe.

Light aircraft construction methods have changed relatively very little over the last 50 years. Composite construction became popular in the homebuilt aircraft movement during the latter part of the 1970's. Composites were touted as a means of reducing assembly cost. The real cost savings potential of using composites is based on combining parts or details into larger subassemblies to reduce parts count and assembly time. Reducing part count will nearly always reduce overall fabrication plus assembly cost as long as the cost per part is not allowed to increase unduly.

In practice, composite light airplanes have not realized any significant cost savings over metal airplanes because of the large amount of touch labor involved in laying up the major composite components. The parts are composed of a large number of hand-placed individual plies. From a manufacturing cost point of view each ply, rather than the complete cured assembly, is a part.

Many observers believe that composites are a relatively recent development, but in fact, composites have been in use for many years. Pre-preg composites have been used in the aviation industry since the 1960's. During the 1950's, a US Army Air Corps study investigated the use of filament winding as a means of producing a lower cost AT-6 wing.

Actual test hardware was produced, and cost savings were realized for a production run estimate, but the concept never caught on.

What is new are the high strength, high stiffness carbon and graphite fibers which, when constructed in a quasi-isotropic manner, meet or exceed the properties of conventional aircraft aluminum at a potential 40% weight savings. The fiber cost is now competitive with traditional aircraft grade materials because of the large production of these fibers for sporting goods and commercial and aerospace industries

This study brings together two diverse, but proven technologies as a means of reducing the manufacturing labor content, hence cost, of a small general aviation aircraft.

The concept of a low aspect ratio lifting surface combined with sandwich construction using the mortise-tenon and bonded clip assembly method can produce a low cost airframe with performance that is competitive with conventional airplanes.

Wainfan's FMX-4 Facetmobile, the Dyke Delta, and the USAF F-117A are all examples of successful low aspect ratio all-lifting aircraft configurations. The mortise-tenon assembly approach has been use in the spacecraft industry for over 25 years.

To our knowledge, these two technologies have not been merged as a viable construction and assembly method for a complete airframe because the shapes required for conventional airplane configurations are curved and not compatible with mortise-tenon assembly.

8.2: A Brief Review of Current Materials and Construction Methods

8.2.1: Bonded Wood Construction with Fabric Covering. During the early days of aviation, this has been the method of choice. Most of WW1 fighters were constructed of wood. Fine grain selected woods, typically spruce or birch, are assembled and bonded together to produce the wings and fuselage. At corner joints, plywood gussets add additional strength. Animal based adhesives were the common method of combining the numerous pieces into a viable structure.

A key point to consider is that these aircraft are assembled using bonded construction methodology.

Modern glues, anti-rot treatments, and coatings have kept bonded wood construction viable. The Bellanca Viking is an example of an airplane with an all-wood wing that was produced in quantity long after most airplanes in its class were made of metal. Recently introduced, the Pioneer 200/300 aircraft is a fully assembled wood structure, and uses bonded construction throughout. Produced in Italy, it resembles a scale version of the elegantly designed Sia-Marchetti 260.

8.2.2: Welded Tubular Steel Construction with Fabric Covering After WW1, as aircraft become larger, the use of 4130 tubular steel construction for the fuselage became the norm. Typically, the wings were still wood. Wood formers are added to the fuselage exterior to give a more pleasing and aerodynamic shape. Tubular steel construction is still widely used in current general aviation aircraft, most notably the unlimited aerobatic airplanes and a number of custom-built designs.

Each piece of tubing comprising the structure is cut and shaped to minimize any gaps between adjacent members prior to welding. This is a time consuming and labor intensive process. Aircraft-quality welding is done by hand, and requires skilled labor to perform.

8.2.3: *Riveted/Bonded Aluminum Semi-Monocoque Construction*: In the 1930's, the materials employed began to change from bonded wood and tubular steel construction and transition towards the aluminum semi-monocoque design using rivets and mechanical fasteners for structural assembly. The majority of the current personal and light airplane fleet uses this type of structure.

Installation of the fasteners is a major component of the cost of such an airframe, and can account for up to 25% of the total airframe fabrication and assembly cost. Installing each rivet requires a drilling and bucking operation. Using manual methods, this is very time consuming, both because of the number of rivets needed to hold the structure together and because two persons are required to perform the operation, one to buck the rivet and one to drive it. In the production of commercial transports, automated drilling and riveting machines are used for some components but the non-recurring capital outlay for the equipment and tooling is quite high, making it uneconomical for the production of small aircraft.

In the design of classical light aircraft with conventional configurations, the main spar is the primary member supporting wing aerodynamic loads. Although the spar carries most of the load, the wing skin can account for as much as 80% of the wing weight. In order to minimize weight for structural efficiency, very thin skins are specified. These thin skins require additional stiffeners in order to maintain the aerodynamic shape of the wing under *air loads*. The stiffeners are additional structural elements that add significant additional part fabrication and installation cost.

The revival of the Cessna series of single engine aircraft is still based on thin aluminum wing skin construction employing riveted stiffeners for aerodynamic shape management. This type of construction is labor intensive, consequently costly.

Riveted aluminum construction is still the most common method for type certified and many homebuilt aircraft.

8.2.4: Filament Wound Composite Construction: This method reduces airframe cost by combining dry fiber and resin at the winding machine, which has been programmed to repeat the process for each part. Today, many commercial parts are created by filament winding. The process is best suited for designs that are axisymmetric, such as pipe, tubing, pressure vessels and anything round. When the shape to be wound tapers or has an unusual shape, the fibers tend to slip and change their orientation relative to the winding axis.

For pressurized aircraft fuselages, which are typically round, filament winding is a viable means production at a relatively low cost. Raytheon Beechcraft produces two models of executive jets using filament winding for the fuselage, although pre-preg unidirectional type rather than wet winding is employed.

Filament winding requires an internal mandrel, which is extracted after resin cure, to create the desired shape. For typical wing structures having many internal details such as spars and ribs, the tooling can become complicated and costly. Even for round, axisymmetric shapes, filament winding is capital-intensive because of the high non-recurring cost of the tooling and filament winding machinery. While it can reduce the cost of fabricating relatively large, high-production aircraft, it is not cost-effective for smaller personal aircraft, particularly at relatively low production rates.

8.2.5: Hand Layup Pre-Preg Composite Construction: Composite construction of airframe structures is not a new technology. Fiberglass was developed in the 1940's, while carbon fiber was developed in the early 1960's. The matrix material is typically Bisphenol A resin and one of numerous curing agents. The epoxy resin systems were developed in the early 1950's.

Moldless fiberglass/epoxy construction became popular in the late 1970's, and is still popular today as a means of creating a one-off composite aircraft. The primary advantage of moldless composite construction is very low non-recurring cost for molds and tooling. The method is attractive for homebuilts and one-off prototypes because it requires very little tooling to produce the desired shapes. It is also labor-intensive because the touch labor needed to create a smooth outer mold line surface is high.

In the aerospace industry, the end user of composite materials purchases the fiber/resin in the form of a pre-preg. The resin is added to the fibers and is partially cured by third party suppliers, called prepreggers. The material is purchased to a specification, and is ready for use by the end user upon receipt. The material is stored at 0°F, and has a very long shelf life. A polyethylene film separates the material from sticking to itself as it is rolled up for storage in a freezer. The pre-impregnation process eliminates the time consuming difficulty of maintaining the proper fiber/resin ratio for optimum properties.

During manufacture of the airframe the material is warmed to room temperature. The individual plies that will comprise the part are cut to shape. The material layers are

placed in a mold sequentially in accordance with the design/analysis and drawing requirements. The part vacuum bagged and cured in an oven or autoclave. It is removed from the mold after curing. The cured parts are then bonded together to assemble to complete airframe.

Several current popular general aviation aircraft manufacturers including Diamond, Lancair and Cirrus produce their airframes in this manner.

Methods for reducing touch labor costs of this construction method include CNC controlled pre-preg cutting machines, re-usable vacuum bags, and net resin cures. There still is a lot of touch labor involved since the shop workers place each ply of the total layup in the mold one at a time. Tooling cost is also relatively high, since precise molds are needed to fabricate each major part of the airframe.

8.2.6: Pre-Preg Composite Tape Laying Machines: Numerically controlled automated tape laying machinery can be used to eliminate the majority of the touch labor required to lay up a molded composite part. Composites can be specified as unidirectional tape or as a woven cloth product. For maximum strength, the unidirectional tape material is used.

Large molds are placed within the confines of the tape laying machines, and CNC controlled tape head places the material in the mold, and cuts and slits the unidirectional tape to conform to changes in the mold contour. Tape width is typically 3 inches with a cured per ply thickness of .005 inches. Transport aircraft composite parts can have over 200 layers of tape material at highly loaded regions.

This method of composite construction removes the limitation size and shape associated with filament winding, and the shifting fiber orientation with complex aerodynamic shapes.

Boeing, for example, has a number of tape laying machines that are about 12 feet wide and 60 feet bng. The acquisition cost for these units are many millions each. As a result, large, complicated composite parts are produced cost effectively since touch labor is at a minimum. The machine cuts the material and places it in the mold simultaneously. An operator is required to monitor the process, and reload the head with additional pre-preg tape material when depleted. This method of producing airframe parts is only cost effective on large production runs, usually 250 parts or more. Boeing plans to fabricate major portions of their new 7E7 from carbon composites using their tape laying equipment.

While numerically controlled tape-laying machinery dramatically reduces the labor required to produce a large molded composite part, it is only effective in reducing overall cost if it is used for relatively large runs of large parts. Due to the high non-recurring infrastructure cost of the tape-laying machinery, only the major airframe manufactures can justify the use of this method of construction. The machinery and molds are specialized, and must be owned by the manufacture of the parts. The non-

recurring and maintenance cost of tape-laying machinery and the molds used with them is too high to be useful in reducing the cost of small personal airplanes.

8.2.7: Current Airframe Construction Methods Summary As aircraft designs have evolved into sleeker and more efficient configurations, construction methods and materials have evolved to meet the need for improved strength and stiffness at minimum weight. The emphasis has been on speed and structural efficiency.

Progress in reducing airframe cost has been relatively slow because the emphasis has been on performance. As a result, the purchase price of personal airplanes remains high. A typical modern 4-place airplane costs well over \$200K, which is too costly for the large majority of the population to afford.

The first three construction methods described above i.e: Bonded wood and Fabric, Welded Steel Tube, and Aluminum Semi-Monocoque are the traditional approaches used in the majority of light general aviation aircraft. While they are all obviously viable, they all evolved under conditions that are very different from the present day.

All of these methods are relatively labor intensive. When they were developed, the cost of labor was relatively low and the cost of tooling to make specialized parts was relatively high. Numerically controlled machinery did not exist. Accordingly, the optimum mix of touch labor and prefabrication tended to bias heavily in favor of touch labor.

In today's environment, labor is relatively expensive, and the combination of Computer Aided Design (CAD) and numerically controlled fabrication machinery can be used to reduce the cost of component fabrication. Accordingly, to minimize cost, a new concept should be highly compatible with numerically controlled automated fabrication techniques, and minimize touch labor required for fabrication and assembly.

8.3: Structural Airframe Concepts to Reduce Cost:

Low cost methods for producing a viable general aviation aircraft do exist, but to achieve the maximum reduction in cost requires a fundamental change in the configuration of the airplane, the materials it is made of and the methods used to fabricate and assemble it.

All aspects of the cost of producing the airframe should be addressed. As we have seen in our review of current methodology, it is not enough to reduce the cost due to a single variable (e.g. labor). The overall combination of materials cost, non-recurring cost, and recurring costs such as assembly labor must be significantly reduced to make a meaningful difference in the purchase price of the airplane **8.3.1:** Sandwich Construction: Sandwich construction is a means of creating a structure using facesheets bonded to a central core. The facesheets may be aluminum, fiberglass cloth or tape, or carbon cloth or tape. The core may be aluminum honeycomb, aramid (Nomex) paper, or foam. Other combinations exist, but for this study, those are the most likely choices.

Sandwich construction separates the strength and stiffness parameters into two independent design variables. This fact gives the airframe designer greater flexibility to create a weight efficient structure.

When the design requires increased strength due to loads, the facesheet material thickness is increased with constant core thickness. When the design requires increased stiffness due to buckling or large displacements, the core thickness increases with constant facesheet thickness.

Increasing the core thickness to increase flexural stiffness adds a relatively small amount of weight due to the core's low density compared to the facesheet density. Many airframe components on small aircraft are sized by the flexural stiffness needed to maintain the aerodynamic shape under air loads, and to remain stable and resist buckling caused by compressive flight loads.

8.3.2: Flat Honeycomb Panels: Sandwich construction is widely used in airframe construction. In transport aircraft, flat sandwich panels are used primarily in flooring, galleys, and the dividers between seating classes.

In spacecraft design, virtually all commercial satcoms and many classified configurations are based on structures assembled using flat honeycomb panels.

Commercial and aerospace grade sandwich panels are typically fabricated by third party vendors using large multi-platen steam heated presses. The end user specifies the facesheet material, facesheet thickness (number of layers), core type and core thickness. The cost of these prefabricated panels is competitive with high strength aluminum alloy sheet. However, since most light aircraft rarely become strength critical except at highly loaded locations, the full advantage of high strength materials becomes moot. More often, typical design configurations become stiffness critical, an area where sandwich construction excels. Aluminum facesheet and aluminum core panels cost about \$8 per square foot, while fiberglass facesheet and Nomex core panels cost about \$10 per square foot. In quantity, these costs can be reduced.

Commercially available honeycomb panels are fabricated in large presses, and are available in sizes up to 64 inches by 148 inches.

8.3.3: Applying Flat Panels to Aircraft Structure: Flat pre-cured sandwich panels have been used extensively on aircraft interiors, for floors and partitions, but they do not lend themselves to curved aerodynamically shaped fuselages and wings. Pre-made flat panel sandwich construction has been used in a few applications for some

airplane major airframe frame components, notably the aft fuselage side panels for the AA Yankee/Lynx/Tiger and the fuselage of the Edgley EA-9 Optimist sailplane. In both these cases, the advantages offered by using pre-made flat panels were significant but not revolutionary. In the case of the Yankee, the flat-panel components were a relatively small portion of the aircraft structure. On the Edgley sailplane, flat panels were used extensively, but were bent into curved shapes during assembly. This was yielded a fuselage structure that was lower cost that conventional hand laid up composite structures, but still needed significant tooling and hand labor to assemble

The unique architecture of the faceted low aspect ratio configuration offers the opportunity to extensively exploit the advantages of flat honeycomb panel construction to create a low cost airframe.

As we have seen earlier, the low aspect ratio study configuration can have performance competitive with conventional airplanes. Because the entire outer shape of the study configuration is formed from planar facets, it is uniquely suited to exploiting the advantages of flat-panel construction for cost savings.

8.3.4 Study Airframe Structural Layout. The lowest cost method of creating a structural sandwich panel is through the use of hydraulic actuated multi-platen presses in a high volume production environment. This method is used to produce large flat panels.

Unfortunately flat honeycomb panels do not lend themselves to the construction of the curved contours typical of the majority of the outer mold line of a conventional airplane. As we have seen earlier, the low aspect ratio study configuration can have performance competitive with conventional airplanes. Because the entire outer shape of the study configuration is formed from planar facets, it is uniquely suited to exploiting the advantages of flat-panel construction for cost savings.

A conceptual structural layout for the study configuration is shown in the sketches in Fig.8.3.4.1. The primary structure is composed entirely of flat panels.

Unless there are very large shear gradients within a sandwich panel, Nomex core is preferred for the concept aircraft design due to its corrosion resistant properties. Using Nomex core also helps reduce manufacturing cost. Nomex core sandwich panels can be cut full depth, trimming both facesheets and the core simultaneously. When the sandwich panel is constructed using aluminum core, then a cut can only be made through one facesheet plus about .020 inches into the core. The panel then must be turned over to cut the other facesheet. If a deeper cut is attempted, the router bit will rip the aluminum honeycomb.

The following sections highlight the general design concepts that might be used in the construction of the concept airplane. Much of what is shown derives from similar methods currently used on spacecraft.

To minimize material cost, nesting of detail parts for the airplane unto the standard size panel optimizes material utilization. CAD data files are transferred into machine cutter paths, and the detail parts can be cut by high-speed CNC routers.

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8.3.5: Flat Panel Assembly Method: The following sections highlight the general design concepts as might be used in the construction of the concept airplane. Reference is made where necessary giving heritage to similar methods used on spacecraft.

<u>8.3.5.1:Substructure</u>: A typical cross-section concept of the proposed design configuration might look like the sketch shown in figure 8.3.5.1.1 below.

In this conceptual drawing, a large honeycomb panel forms the equivalent of a full depth spar. Fore/Aft members bond to the spar at locations where the exterior facets form the shape of the airplane. These members are indexed to the spar by slots in the spar and machined tabs in the ribs. The exterior panels, which are thinner than the internal details are bonded to the spar/rib substructure. Bonded angle clips (not shown in the sketch) are used at each intersection to transfer shear load between panels.

Landing loads are introduced to the airframe at high strength locations via metallic fittings. These loads are then sheared into the remaining and adjoining structure via the bonded construction. In areas where concentrated loads are very high, such as the landing gear attachment, potting of the core with high density, high strength materials may be required. The potting material is a mixture of epoxy resin, mill-end glass fibers, micro-balloons and Cab-O-Sil titanium dioxide. The core is selectively removed, and the potting material is injected into the removed core zone with an air driven caulking gun.



<u>8.3.5.2: Skin Attachment:</u> A concept for the attachment of the exterior panels to the substructure is shown in Fig 8.3.5.2.1: below:



The cross-section for this example assumes the spar member has a greater thickness and core thickness than the skin panels. Using CNC tooling, the skin panel is routed, removing one facesheet and the entire core segment. The skin is located over the substructure, and bonded to the internal member along the entire internal mating surfaces. After that initial cure, the angle clips are then bonded in place.

<u>8.3.5.3: Corner Joints</u>: Other areas of the structure will require corner joints. The preferred method of creating a corner joint is shown in the following sketch (Fig 8.3.5.3.1).



In this detail, one facesheet and the core is machined away, leaving the remaining facesheet exposed. The mating sandwich panel is bonded to the machined panel over all surfaces. Reinforcing internal and external angle clips completes the joint. This method of creating a corner joint has proven to be quite robust.

<u>8.3.5.4: Mortise-Tenon Construction</u>: The mortise-tenon method of assembly is to create a series of precisely located slots in the receiving member, and matching series of tabs in the bonding member. The slot width is controlled by the cutter diameter, and is typically specified as the bonding member facesheet thickness plus .010 for bond line thickness all around. Router cutters can be obtained for virtually any diameter.

The sketch of this method of assembly (Fig. 8.3.5.4.1) shows the bonding member in the side view and the receiving member in the normal view. When these two elements are bonded together, full adhesive filleting is created along the full length of the joint. Additional adhesive is injected into the slot to capture and create facesheet to facesheet bonding. The joint strength of just this amount of bonding is rather remarkable, and can be in the order of 40 pounds shear per inch of length, and 60 pounds of tension per inch of length. With the addition of angle clips on each side of the bonded member, these load capacities can easily be 8 to 10 times greater.



<u>8.3.5.5: Attach Points</u>: Post potted inserts are common place in sandwich panels for attachment of payload boxes, operational hardware and details. A typical NAS 1832 insert is shown in the following figure. These inserts have both a knurled surface for increased bonding surface area and anti-rotation flats. In cross section, these inserts have the following configuration (Fig. 8.3.5.5.1).



For attachment of hardware to the panels, additional inserts are added to the panel at the required locations. For example, if a pulley mount were required for the control system, then inserts are added to the panel to match the pulley-mounting bracket, as shown in Fig. 8.3.5.5.2, below.



Another method of joining panels is through the use of "Cup" inserts bonded to one panel. The joint between mating panels by mechanically attaching to another panel having a "C Clip" bonded to its facesheets as shown in Fig. 8.3.5.5.3. The C Clip is pre-fabricated to contain a non-venting nut plate. The C Clip is typically an aluminum extrusion, cut to length, and bonded to the panel using tooling for location. In this manner, the joint between panels becomes primarily mechanically fastened. This permits an assembly without the need for a blind bonded joint, which is difficult to control and inspect.

In normal flight, the bottom skin is primarily in tension, and this type of joint could be used to join the skin to the substructure. Using this concept, the aircraft is built upside down, and the substructure is bonded and clipped to the upper skin in the methods described above. After all internal systems, structure and design features are installed, the aircraft will be finished by installing the bottom skin using mechanical fasteners. The aircraft is built upside down and turned right side up after final assembly. A cross section of this approach is shown below. This methodology of completing the structure is common on spacecraft since the propellant tanks and other systems are installed after the buss structure vender delivers the assembly.

The cup insert bonds to both facesheets of the upper panel, offering excellent inplane shear transfer to the sandwich. In a similar manner, the C Clip bonds to both facesheets of the vertical member. The concentrated loads of the mechanical fastener is smeared into the facesheets through the adhesive bond, and redistributed by core shear.



8.3.6: Examples of Flat Panel Structure: In spacecraft construction, bonded and clipped methods are used to join the structure into an assembly. For space structures, the mortise and tenon assembly method is common practice. Mortise and tenon is to literally "place tab A into slot B". With this assembly method, the structure is self jigging, requiring minimal assembly tooling. Machining of these panels is typically done on large CNC routers.

Spacecraft launch loads are far in excess of normal category aircraft 'g' loads, and temperature extremes are substantially greater. Accordingly, assembly techniques that have been used successfully for years on spacecraft will likely prove suitable for personal airplane structures.

To demonstrate how spacecraft are assembled using today's technology, a series of examples showing joints, post potted inserts, and mechanically fastened connections from actual structures follow.

<u>8.3.6.1: Mortise and Tenon Joints</u>: Normally, the panels are machined on CNC routers in order to maintain tolerances. For the present study, it is assumed that a CNC tooling template is required, with the actual panel cutting done by hand using portable equipment.

Figure 8.3.6.1.1 shows a honeycomb assembly that is used on an existing spacecraft as a large equipment platform.



Figure 8.3.6.1.1: Spacecraft Equipment Platform Made of Flat Sandwich Panels

This example shows an assembly made from flat panels and joined by tabbing the inner panel to the outer panels at the slots. All assembly is done by bonding. On the inner panel, core is locally removed, and a full thickness panel installed at the bolt locations.

Another example of mortise-tenon assembly is the WMAP center truss, constructed from large flat panel stock. Shown in Fig 8.3.6.1.2, the upper section uses I beam configuration, while the lower section uses box beams, all constructed of flat stock. The entire assembly is bonded together.

The laminate stock is .080 inches thick, so the slots are difficult to see in the picture. The edges of the box beams are tab and slot flush nested. This truss assembly supports the primary mirrors, and is subjected to 20 g's at launch. The WMAP spacecraft has been in orbit at L2 for three years.



Another example of slots, tabs and bonded assembly is the center section of the

Another example of slots, tabs and bonded assembly is the center section of the LAMP mirror. (Fig.8.3.6.1.3) Again, this is done using laminate stock, and bonded on assembly. This composite structure then becomes the support for mirror elements attached via actively controlled actuators.



Figure 8.3.6.1.3 LAMP Mirror Assembly

In the LAMP mirror assembly, mortise-tenon and slotting is used, "ala Lincoln Log". Slots are machined into the vertical members, with all joints bonded together. This results in a mock honeycomb internal structure, with the top and bottom facesheets slotted to accept the tabs from the vertical members.

<u>8.3.6.2: T Joint Construction Methods:</u> Flat honeycomb panel joints, intersecting at right angles, are typically bonded on edge, and joined with right angle clips. Shown in the next figure are sample test coupons demonstrating this method. For panels constructed with honeycomb core, typical tension strength values are about 300 pounds per inch of length. Nomex core panels typically test out in the 250 pound per inch of length range, depending on core density.



Figure 8.3.6.2.1: T Joint Test Articles

<u>8.3.6.3: Flat Panel to Cylinder Joint Details</u>: In some spacecraft configurations, a central cylinder is employed which provides support for the fuel tank and attaches to the upper stage separation ring. Shown in the photo is a close-up detail of one such configuration where the vertical shear panel is bonded to the central cylinder using angle clips that matches the cylinder radius. The box structure is the solar array mount. Notice also the round bonded aluminum bosses. These aluminum fittings are two pieces nested within each other, bonded to the cylinder, one from the inside and the visible outer. Bolts pass through and attach the fuel tank skirt. This example shows how high concentrated loads are sheared into the sandwich structure.

A more distant view shows how the flat panels are assembled to the cylinder, and how additional bonded details are used as attachment zones for more flat panels.



Figure 8.3.6.3.1: Flat Panels Joined to Cylinder

8.3.6.4:: Honeycomb Panel with Potted Edges and Post-Potted Inserts: Attachment of boxes, electronic payload, wire harness and propulsion hardware to the honeycomb panels is typically accomplished with post potted inserts, usually of the NAS 1834 type. The panel facesheet and the core is machined, creating a hole. A bonding cap is attached to the insert, and a lightweight adhesive is injected into one side of the insert vent hole until the entire cavity is filled and excess adhesive emerges from the opposite vent hole. After cure, the insert is fully contained and trapped. These inserts are available in a variety of thread sizes and overall shape, and contain locking features on their outer surface. Typical shear strength values are in the order of 200 to 300 pounds shear, 400 to 600 pounds of pull out tension, and have torque values greater than the torque strength of the fastener. Higher strength inserts bond to both facesheets.



This example shows how aircraft details, such as pulley brackets, equipment, and structural details would be attached to the sandwich construction.

<u>8.3.6.5:: Honeycomb Panel with Rib Structure</u> The next example of large sandwich construction begins to approach the configuration as might be used in aircraft. A large flat panel on the work table could be considered the outer surface of the



plane, and the interior egg-crate assembly representing the ribs and spars. The assembly shown has mortise-tenon features, and after assembly, additional angle clips are bonded at each corner for additional strength.

It is envisioned that a low cost airframe would use similar assembly methods. All necessary inserts and attachment details are incorporated into the panels prior to the assembly and bonding. At areas where high loads exist, core densification and additional doublers are bonded at the panel level. The structure becomes complete when the close-out outer panels enclose the internal egg-crate assembly.

<u>8.3.6.6: Honeycomb panel with Truss Rib Cutouts:</u> For internal structure, the egg crate construction does not need to be continuous and uniform. To reduce unnessary weight, the panels can be machined/routed into a truss configuration. In the photo, a sandwich rib used on a large parabolic reflector is shown. The rib bonds to the reflector shell, and provides overall stiffness due to launch loads, and shape maintenance when on-orbit.



In the photo, an additional edge doubler is being bonded to the truss rib using a simple clamping arrangement to establish bonding pressure.

8.3.6.7: Summary As demonstrated by the examples shown above, a low cost airframe can be constructed by using methods not typically employed in the general aviation industry.

Prefabricated honeycomb panels, made in a production environment, are relatively low cost. Touch labor to assemble pre-cut and indexed panels is reduced compared to more conventional aircraft assembly methods. The primary assembly method is bonding, a relatively low tech skill once the labor force is trained in the proper bonding procedures.

One aspect of composite construction, in general, is the need for attention to detail. Composites, unlike metals, have low strain to failure values. They are not elastic-plastic in their deformation prior to failure. Consequently, concentrated loads require fittings and methods that distribute the loads into the panel facesheets via shear. Examples of how this is done have been shown.

Since the panel construction consists of facesheets and core, each can be specified in the design process and dictated to the panel vendor. Areas requiring strength or stiffness (or both) will be thicker and heavier than those used in begnin areas of the structure. In addition, weight optimization can be realized by trussing internal structure.

For high value sandwich panels, as currently used in the spacecraft industry, each panel is CNC routed. This includes the exterior edges, cutouts, and all insert pockets. For construction of a low cost airframe, it is envisioned that a router tool be created by CNC methods, and the actual aircraft panel be hand routed using the precision tool as the cutting guide.

Repair methods on sandwich construction are well documented in Mil-Hdbk-23.

The faceted configuration of the proposed study aircraft lends itself to the sandwich panel fabrication method.

8.3.7: Flat Panel Cost Considerations: Manufacture of an airplane requires cost trade-offs between Recurring and Non-Recurring costs. In the case of the concept aircraft using commercially available sandwich panels, the panels themselves are considered purchased items.

The cost of the purchased panels depends on the facesheet material and thickness, and the core type and density. For relatively thin facesheet panels, the labor cost remains more-or-less constant, independent of the materials used. A much larger cost variable is quantity, based on \$/sq. ft. A larger order allows the panel fabricator the benefit of efficient production methods and a steep learning curve. Vendor data is shown in the chart.

Another cost driver is the cost of the Nomex honeycomb core when facesheet thickness is held constant. In this example, the facesheet is fiberglass/epoxy having a constant thickness of .020 inches. Again, using vendor data, the Nomex core cost significantly affects panel cost per square foot.





As we have seen in previous sections, the major drawback of current highlyautomated techniques used to manufacture airframe structure (e.g. filament winding, automated tape laying) is that a large capital investment is specialized machinery and tooling is must be made before a single part can be produced. Flat panel construction does not suffer from this problem because the CNC highspeed router used to fabricate the parts are relatively common machines that are used for multiple purposes. Parts can be made on demand by third-party vendors, so the airframe manufacturer need not purchase or maintain the high cost machinery to begin production.

There are two ways to employ CNC high-speed routers in the production of flat-panel airframe parts. The first is to cut the airframe panels directly on the CNC machine. The second is to use the CNC machine to make a set of precise router tooling that can then be used to cut out panels with a hand-held or hand-guided router using moderately skilled labor. The choice of which method to use will depend largely on production rate and the cost of labor.

CNC router time typically costs approximately \$300/hour.

A preliminary estimate shows that for a single airframe 24 hours of machine time would be needed to cut all of the sandwich panels. This 24 hours estimate includes set-up time. Accordingly, producing all panels for a single aircraft would cost \$7200 in machine time rental. A significant portion of this cost is to pay for set-up time.

At low production rates, the set up time cost becomes important, because only a small number of each type of part is made each time the machine is set up. Accordingly, the set-up time is a relatively large portion of the total cost. At larger production rates, the set-up time is amortized over many parts and becomes much less significant.

An alternative approach is to use CNC machinery to make a set of flat-plate tooling patterns that are used to guide a hand-held router to make the panels. A preliminary estimate shows that the tooling necessary to cut the panels by hand can be produced by CNC equipment for approximately \$200K including materials cost. Skilled labor can route single panels in about the same amount of time as done on the CNC equipment since the cutter speed and feed rate determines total time.

The choice of method will depend on the trade-off between the initial cost of the tooling, the labor cost rate for personnel skilled enough to make good parts using the combination of tooling and hand-held routers, and the cost incurred dues to set-up of the CNC machines for direct cutting of parts.

At his stage in the study it is not possible to quantitatively determine which method will be preferred. A preliminary, subjective examination of the cost factors suggests that the preferred method will change with production rate. For prototypes and very low production rates, direct cutting appears preferable because of the cost of the tooling needed to hand cut panels. For moderate production rates, it is likely that the "tooling plus hand cutting" method will be preferred because of the large percentage of time spent on set-up for direct cutting. For large production rates, where many ship sets of parts are cut at a time, the setup cost becomes a much smaller percentage of total cost, and direct cutting may be preferred. In either case, the total cost to fabricate the component parts of the airframe is dramatically lower than that required to make the parts of a conventional airframe.

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9.0: AIRCRAFT COST COMPARISON:

Raymer (Ref.9) details the DAPCA IV cost model developed by RAND Corporation. This model gives an estimate of the recurring and non-recurring cost of aircraft.

The recurring costs of production are dominated by three factors: Materials cost, Manufacturing labor hours, and the cost of the engine.

The DAPCA IV model was used to estimate the relative cost of materials and manufacturing labor hours for the study low aspect ratio configuration and a conventional airplane with the empty weight and performance of the Cessna 152. The results are shown in Fig 9.0.1: The figure shows the cost of materials and manufacturing labor normalized by the value the model estimates for the Cessna 152.



According to this cost model, the combined cost of materials and manufacturing labor for the study airplane (empty weight 635 pounds) is approximately 60% of that of a conventional airplane (empty weight 1155 pounds) having essentially the same performance and useful load. The estimates presented in Fig 9.0.1 are based on a production run of 500 airplanes, and a labor cost of \$50/hour. During the study, costs were evaluated for a large variation of production run (100 to 10,000) and labor cost (\$20/hr to \$100/hr). Although these parameters produce significant changes in the absolute value of predicted cost, they have very little effect on relative cost.

9.1: Engine Cost

Although the engine and propeller are purchased items, the choice of engine and propeller used by the airplane is strongly driven by the performance of the airframe. The two most important variables from a cost viewpoint are the rated power of the engine, and the choice of a fixed-pitch or constant-speed propeller.

The cost of the propeller is a significant component of the cost of the propulsion system. A constant-speed propeller typically costs about 25% of the price of the engine turning it, while a fixed-pitch metal propeller costs about 10% of the price of the engine. Accordingly, using a variable pitch propeller increases the overall cost of the propulsion system by about 15%. The study configuration low aspect ratio airplane and all of the airplanes it is compared with in this study use fixed-pitch propellers. It is interesting to note, however, that the Diamond Eclipse was developed from the earlier Diamond Katana by replacing the propulsion system of the Katana (geared Rotax engine driving variable-pitch Hoffman propeller) with a larger direct-drive Continental engine turning a fixed-pitch propeller.

The cost of the engine itself is a strong function of rated horsepower. Figure 9.1.1 shows the normalized original equipment manufacturer (OEM) price of typical air-cooled aircraft piston engines manufactured using modern numerically controlled machinery. This figure is based on pricing data for the Jabiru line of engines. Jabiru manufactures aircraft engines rated at 80, 120, and 180 horsepower. These engines are all manufactured using the same modern processes, and have a high degree of parts commonality between them. Accordingly, pricing of his line of engines gives a useful indication of the intrinsic variation of engine cost with size. The data are normalized to a rated



horsepower of 115, which corresponds to the powerplant installed in most certified trainers in service today including the Cessna 152, The Piper PA-38 Tomahawk, and the Alarus CH-2000

As the figure shows, the cost of engines varies approximately linearly with rated horsepower. Accordingly, utilizing an airframe design that requires less installed power to perform the design mission will reduce the overall cost of the airplane by reducing the cost of the purchased engine, even if the airframe concept is not itself less costly to manufacture.

As was shown in Section 7 the low aspect ratio study airplane with an 80 horsepower engine achieves performance equal to or better than that delivered by the Cessna 152 or the Alarus CH200, which are powered by the 116 horsepower Lycoming O-235 engine. Referring to Fig. 8.1.1 shows that the 80-hp engine of the study airplane will cost 74% of the 115 horsepower "baseline conventional" airplane power plant.

9.2: Instruments and Avionics Cost

The instruments and avionics required are primarily a function of how and where the airplane is operated. The capabilities needed to enable the pilot communicate, navigate, and fly the airplane are set by the type of airspace and the meteorological conditions in which the airplane will operate. Accordingly, the manufacturer of the airplane has little choice about what capability must be aboard the airplane, and hence little ability to affect cost of these items. While there is little doubt that there is much room for cost reduction through innovations in avionics systems, these are essentially independent of the configuration of the airframe, and not within the scope of this study. For the purposes of this study it is necessary to assume that the cost of the instrument and avionics package in the study airplane will be the same as that in a conventional airplane.

9.3: Total Cost

Cost Analysis: Ref. 13 (Moore and Hahn) shows that the approximate breakdown of the cost of general aviation airplane is as shown in Table 9.3.1: Below

Item	Cost
Materials and Manufacturing Labor	26%
Engine and Propeller	22%
Avionics	10%
Indirect Costs	42%

Table 9.3.1: Complete Airplane Cost Breakdov
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The indirect costs include overhead, G&A, taxes, and mark-ups. These are proportional to the direct costs and will accordingly drop proportionately if direct costs are reduced. For the purposes of this study, the avionics costs are assumed to be fixed for the reasons articulated in Section 8.2. Accordingly the effect of cost changes in manufacturing or engine on total airplane cost are given by:

 $C/C_0 = K\{(.26 \text{ M/M}_0)+(.22 \text{ E/E}_0)\}+0.1 \text{ (Eq. 9.3.1)}$

Where: C/C_0 = relative total cost of the airplane M/M_0 = relative cost of materials and manufacturing labor E/E_0 = relative cost of engine and propeller K = Indirect cost factor

For the cost breakdown in Table 9.3.1, with the avionics cost held constant, K has a value of 1.876.

Equation 9.3.1 can be used to determine the effect of changes in either airframe or engine cost on the overall cost of the airplane.

9.4; Low Aspect Ratio Study Airplane Relative Cost:

As shown in Section 9.0 the DACPA IV cost model predicts that the materials and manufacturing cost of the study airplane will be 60% of that of the conventional airplane having the performance of the Cessna 152. As shown in Section 9.1 the engine of the study airplane will cost 74% of that of the equivalent performance conventional airplane. Per equation 9.3.1 the relative cost of the low aspect ratio study airplane will be:

 $C/C_0 = 1.876\{.26(0.6)+.22(0.74)\}+0.1 = 0.698$

Accordingly, a low aspect ratio all-lifting trainer-class airplane will cost approximately 30% less than a conventional airplane having the same performance if both airplanes are manufactured using similar methods and processes. The 30% cost reduction arises from the greater structural efficiency and lighter weight of the low aspect ratio configuration, which reduces empty weight and allows the airplane to use a smaller engine to deliver comparable performance.

The DAPCA IV model used to estimate manufacturing cost has an implicit assumption that the manufacturing and assembly processes used for any two airplanes of similar empty weight will incur he same manufacturing and assembly labor cost per pound. It does not capture cost savings that might be achieved through improvements in manufacturing processes, reduced parts count, and other fundamental changes in vehicle architecture that reduce assembly labor per pound of airframe.

The study configuration has several features that will dramatically reduce labor hours per pound relative to either a conventional metal airplane, or a current-technology molded composite airplane. The airframe has relatively few parts, and the parts themselves can be made on automated, numerically controlled machines. The number of joints and fasteners is significantly lower than for a conventional configuration. Accordingly, the manufacturing cost savings predicted by the DAPCA IV model are less than can actually be achieved with a properly designed low aspect ratio all-lifting configuration composed



primarily of flat panels. In order to evaluate these effects, equation 9.3.1 was used with a range of labor-reduction factors applied to the manufacturing cost. Results of this analysis are shown in Fig. 9.4.1. For the purposes of this analysis, empty weight, overhead rate, avionics cost and engine cost were held constant.

The figure presents three cases:

1) Labor reduction for a conventional configuration: The first case represents the effects of advanced manufacturing and labor saving on the cost of an otherwise conventional airplane. A 25% labor savings on such an airplane will result in a 12% reduction in airplane total cost, while a 50% labor savings reduces cost by about 24%.

2) Low aspect ratio airframe, with the same engine as the baseline conventional airplane: The second case is a low aspect ratio all-lifting airplane like the study configuration where the engine and avionics costs are constrained to stay the same as the baseline conventional airplane. This is an unrealistic case since, as we have seen, the low aspect ratio all-lifting airplane requires less power, but it serves to illustrate the cost savings that arise from the structural efficiency of the low aspect ratio airframe. At the baseline labor rate per pound, the low aspect ratio airplane costs approximately 80% as much as the conventional airplane. To reduce the cost of a conventional airplane to this level would require a 40% reduction in labor per pound.

Reducing labor per pound to build the low aspect ratio airplane by 25% reduces cost to 73% of the baseline conventional airplane, while reducing labor 50% drops cost to 66% of the baseline conventional airplane, a 34% reduction.

3) Low aspect ratio airplane with engine sized to match conventional airplane cruise performance: This case represents the low aspect ratio all-lifting that would be the direct replacement for the conventional airplane. The engine is sized to match cruise performance carrying the same useful load and as we have already seen, this low aspect ratio airplane has superior takeoff and climb performance.

At the baseline labor rate, the low aspect ratio study configuration costs 69% of the price of the conventional baseline airplane. Reducing labor by 25% drops cost to approximately 62% of the baseline conventional airplane. A 50% labor reduction reduces cost to 55% of that of today's conventional airplane.

The low aspect ratio all-lifting configuration composed of flat panels is well suited to automated manufacture of components, and will require many fewer hours to assemble than a conventional configuration. While the labor reduction this will produce is difficult to estimate precisely, it is clear that the cost of such an airplane will be dramatically lower than that of a conventional airplane, and cost reductions approaching 45% are possible using current engines and avionics. Reductions in cost of the engine and avionics can reduce the cost of a low aspect ratio all-lifting personal airplane to less than 50% of the cost of a current-generation airplane with similar useful load and cruise performance.

The analyses performed in this study did not quantitatively address the effect of tooling and other non-recurring production cost on the relative cost of the study airplanes, but it is clear that these costs will be significantly lower than those for a conventional airplane

10.0: CONCLUSIONS

Flight tests of the Wainfan FMX-4 have shown that a faceted low aspect ratio all-lifting airplane can have good flying qualities, compatible with a modest level of pilot skill and be highly departure resistant

A faceted low aspect ratio all-lifting airplane can have performance comparable or superior to a conventional airplane having the same power carrying the same useful load.

Due to its intrinsic structural efficiency, a low aspect ratio all-lifting airplane will have an empty weight that is approximately 55% of that of a conventional airplane having the same useful load and cruise performance.

The low aspect ratio study airplane, with 80 horsepower has up-and-away performance comparable to the current-generation all-metal trainers powered by the 115 horsepower Lycoming O-235. It is significantly superior to the conventional all-metal airplanes in terms of takeoff distance and rate of climb.

The overall system-level transport efficiency of the low aspect ratio study airplane is significantly superior to the classical riveted all-metal airplanes, and comparable to a modern, molded all-composite machine.

The low aspect ratio all-lifting configuration composed of flat panels is well suited to automated manufacture of components, and will require many fewer hours to assemble than a conventional configuration.

The flat-panel construction of the study configuration allows it to take advantage of cost savings available from use of CNC high-speed machinery without the need for the airframe manufacturer to purchase or maintain expensive machinery or tooling. Large cost savings can be realized even at low production rates.

The non-recurring cost of tooling and specialized machinery required to fabricate the parts for a faceted low aspect ratio all-lifting airplane and assemble the airframe will be much lower than comparable costs for a conventional wing-body-tail configuration.

Due to its combination of light weight, compatibility with automated manufacture, and reduction in assembly labor hours, a low aspect ratio all-lifting sport/trainer airplane similar to the study configuration can cost up to 50% less than a conventional airplane designed for the same mission.

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