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ADVANCED COMPOSITE STRUCTURAL CONCEPTS AND MATERIAL

TECHNOLOGIES FOR PRIMARY AIRCRAFT STRUCTURES

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SUMMARY

Structural weight savings using advanced composites have been demonstrated for many years. Most military aircraft today use these materials extensively and Europe has taken the lead in their use in commercial aircraft primary structures. A major inhibitor to the use of advanced composites in the United States is cost. Material costs are high and will remain high relative to aluminum. The key therefore lies in the significant reduction in fabrication and assembly costs. The largest cost in most structures today is assembly.

As part of the NASA Advanced Composite Technology Program, Lockheed Aeronautical Systems Company has a contract to explore and develop advanced structural and manufacturing concepts using advanced composites for transport aircraft.

Wing and fuselage concepts and related trade studies are discussed. These concepts are intended to lower cost and weight through the use of innovative material forms, processes, structural configurations and minimization of parts. The approach to the trade studies and the downselect to the primary wing and fuselage concepts is detailed. The expectations for the development of these concepts is reviewed.

INTRODUCTION

The Lockheed program consists of two phases. Phase 1 is currently underway and Phase 2 is an option scheduled to start in 1992. Phase 1 consists of five tasks: Task 1, Design/Manufacturing Concept Assessment, is the subject of this paper; Task 2, Structural Response and Failure Analysis, involves structural analysis methods development; Task 3, Advanced Materials Concepts, covers the development of new polymeric matrix systems for HSCT; Task 4, Assessment Review, is the phase final review leading to a decision on whether to exercise the option for Phase 2; and Task 5, Box Beam, the subject of another paper at this conference, involves the fabrication and assembly of the C-130 wing center box developed under a previous NASA contract.

The goals of this program are to identify emerging technologies which will lead to a 25 percent cost saving, a 40 to 50 percent weight saving, and a 50 percent reduction in parts count to validate the low cost manufacturing and to verify both the structural response and the weight savings.

APPROACH

Four wing and three fuselage concepts were selected for this program. These concepts are shown in Figure 1. The concepts were selected based on their potential for meeting the criteria, with a moderate risk. The Lockheed L-1011 was selected as

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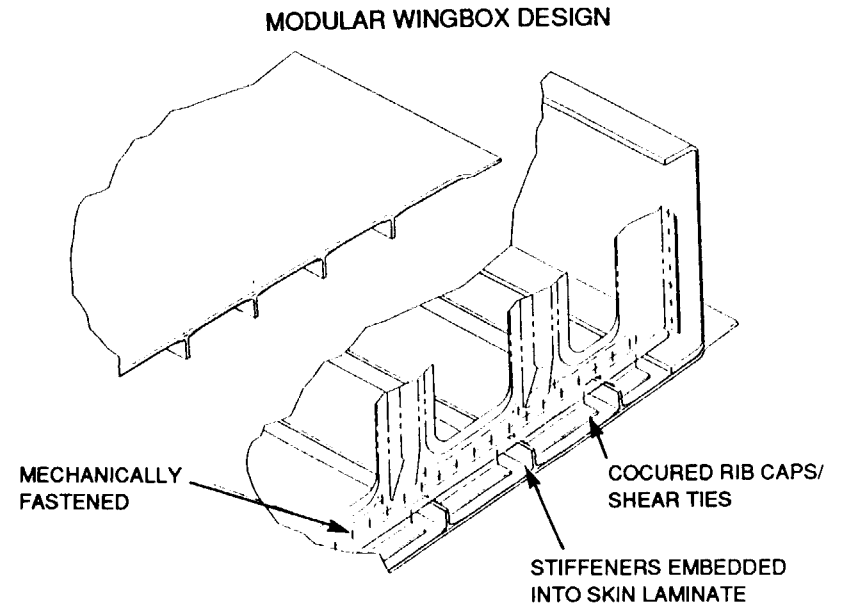
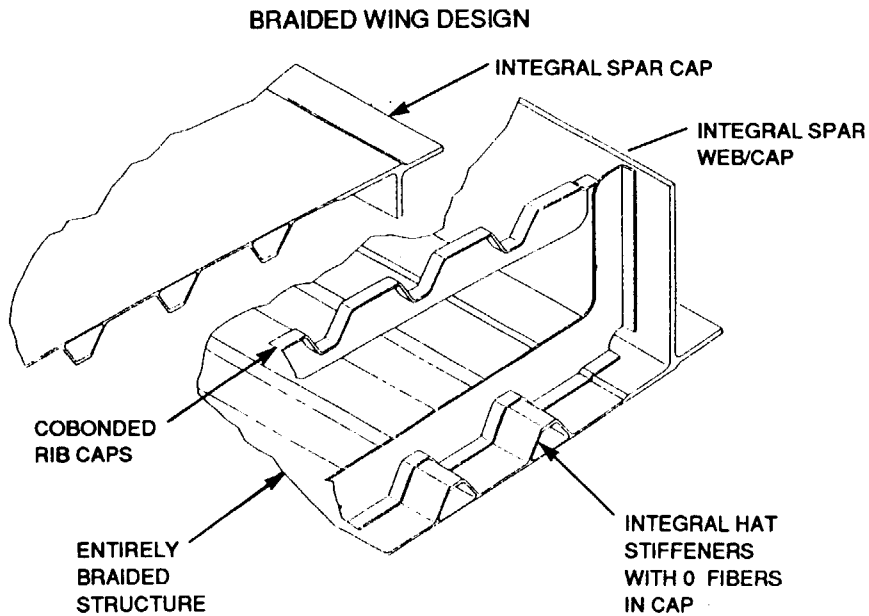
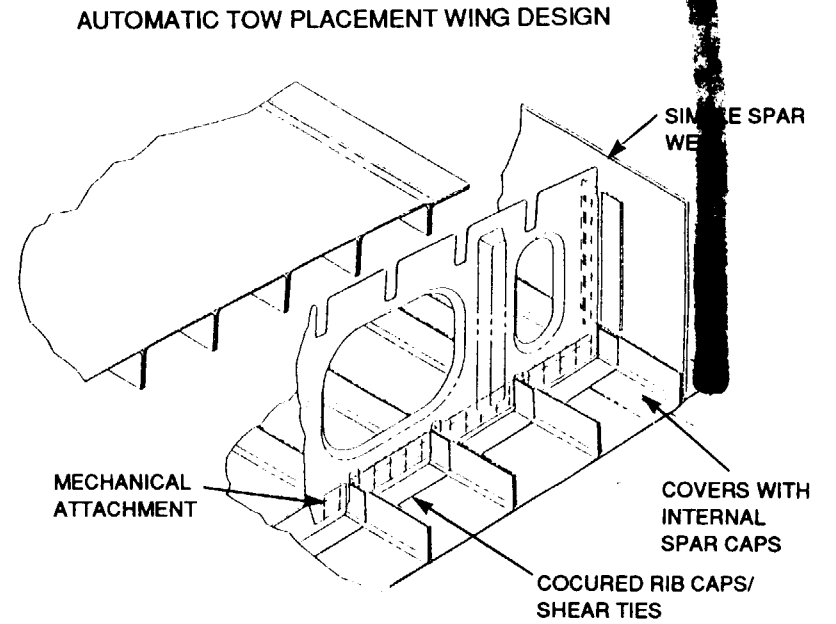
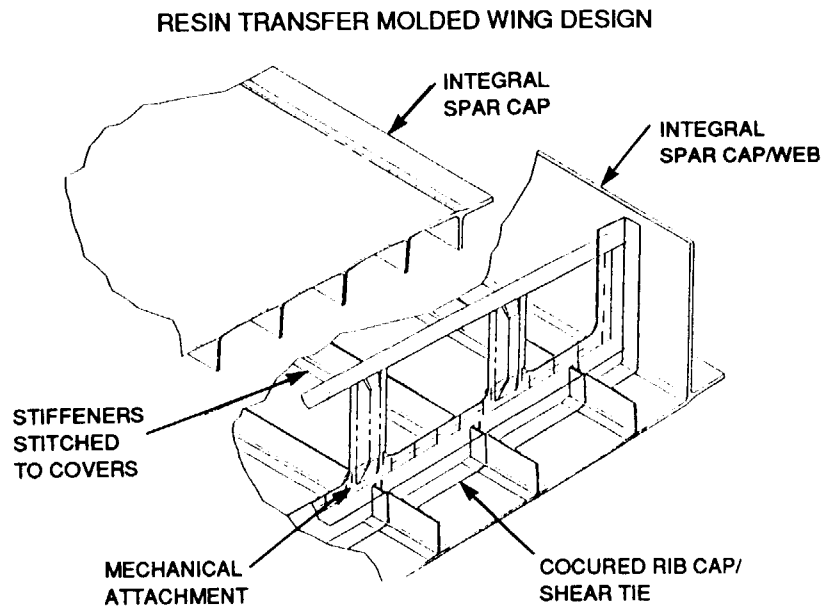


Figure 1a. Wing Concepts

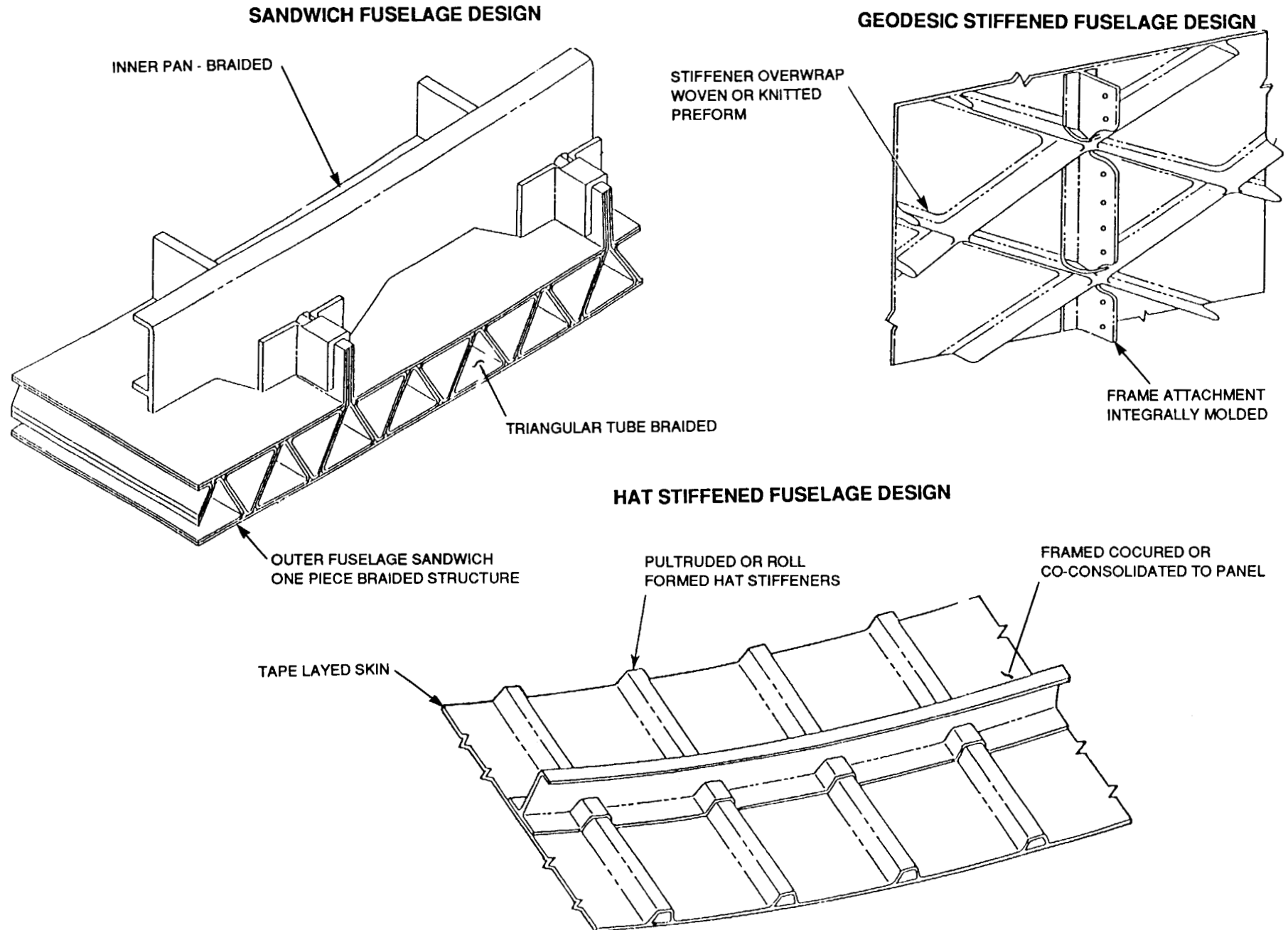


Figure 1b. Fuselage Concepts

the baseline airplane for this study. A wing location was selected which is relatively highly loaded and will yield test panels which can be tested in existing test machines and fixtures. The upper surface has to be buckling critical. The fuselage location was selected in a similar manner. Figure 2 shows the location of the wing section, and Figure 3 shows the location of the fuselage section. The design criteria for the wing are shown in Figure 4 and for the fuselage in Figure 5.

### WING CONCEPTS

Four wing concepts were selected for the trade studies. Concept #1 is the Modular Wing. This concept is built up of various components each of which is fabricated using a different process. The stiffeners are pultruded, the skins are automatic tape placed, the ribs are press formed and the spars are filament wound. Concept #2 is the Resin Transfer Molded Wing. This concept is made from woven stitched preforms and is molded in two pieces. Concept #3 is the Advanced Tow Placement Wing. This concept also involves other fabrication processes, but the covers are made by automatic tow placement (ATP). Concept #4 is the Braided Wing. This concept is fabricated mainly by 2D and 3D braiding.

### CONCEPT #1 - MODULAR WING

This design is shown in Figure 6. The covers, spars and ribs are fabricated separately and are assembled by conventional methods. The covers are blade stiffened. The stiffeners are fabricated from dry preforms which are resin infused and either B-staged or fully cured Tee sections. The skins are fabricated in two parts. The inner skin is discontinuous at the stiffeners. It can be laid up by automatic tape dispenser and can be cut into strips by a waterjet cutter or by a Gerber cutter. The outer skin is laid up over a tool containing the stiffeners and inner skin strips by automatic tape dispenser. The fabrication sequence is shown in Figure 7.

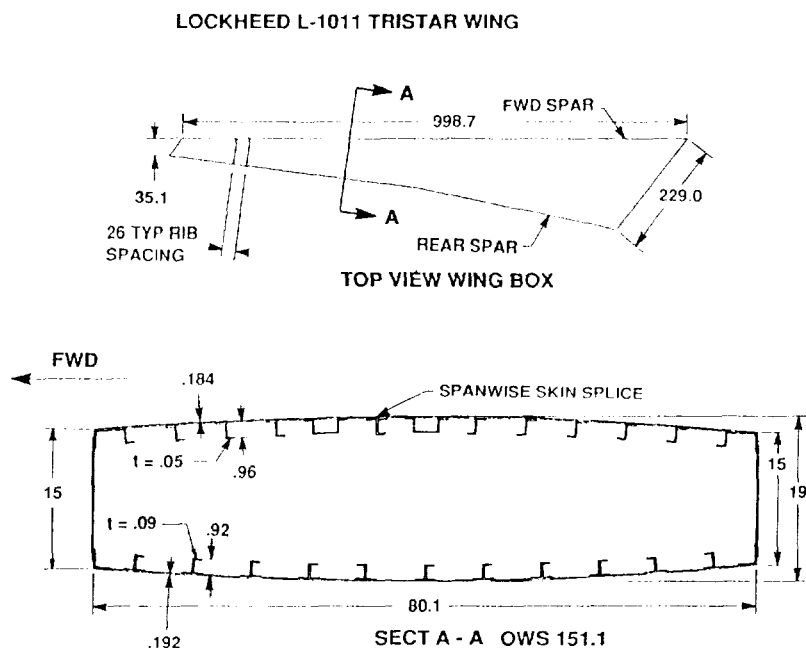


Figure 2. Baseline Wing and Study Location

LOCKHEED L-1011 TRISTAR FUSELAGE

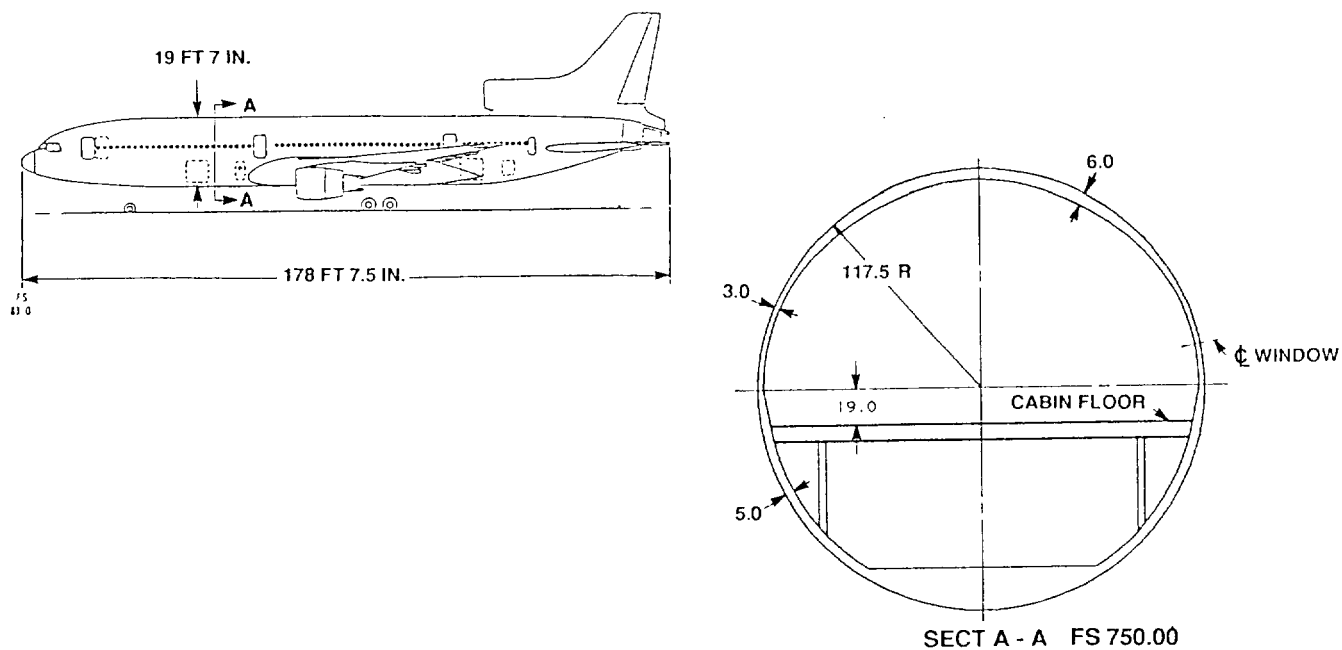


Figure 3. Baseline Fuselage and Study Location

NX	14,000 LB/IN
NXY	2,000 LB/IN
P	10.38 PSI BURST
	7.82 PSI CRUSHING
ECCENTRICITY	.1%
Gt MIN.	.70 E6 PSI

UPPER COVER LOADS O.W.S. 151.00

- COVERS BUCKLING RESISTANT
- MAX. ALLOWABLE STRAIN .006 IN/IN TENSION  
.0044 IN/IN COMPRESSION

Figure 4. Wing Design Criteria

CONDITION		CROWN	SIDEWALL	KEEL
MAXIMUM TENSION	(LB/IN)	1307	432	318
MAXIMUM COMPRESSION	(LB/IN)	489	705	943
SHEAR	(LB/IN)	150	600	300

LOADS AT F.S. 750.00

- SKINS SHEAR BUCKLING RESISTANT BELOW 1G
- MAX. ALLOWABLE STRAIN .006 IN/IN TENSION  
.0044 IN/IN COMPRESSION

Figure 5. Fuselage Design Criteria

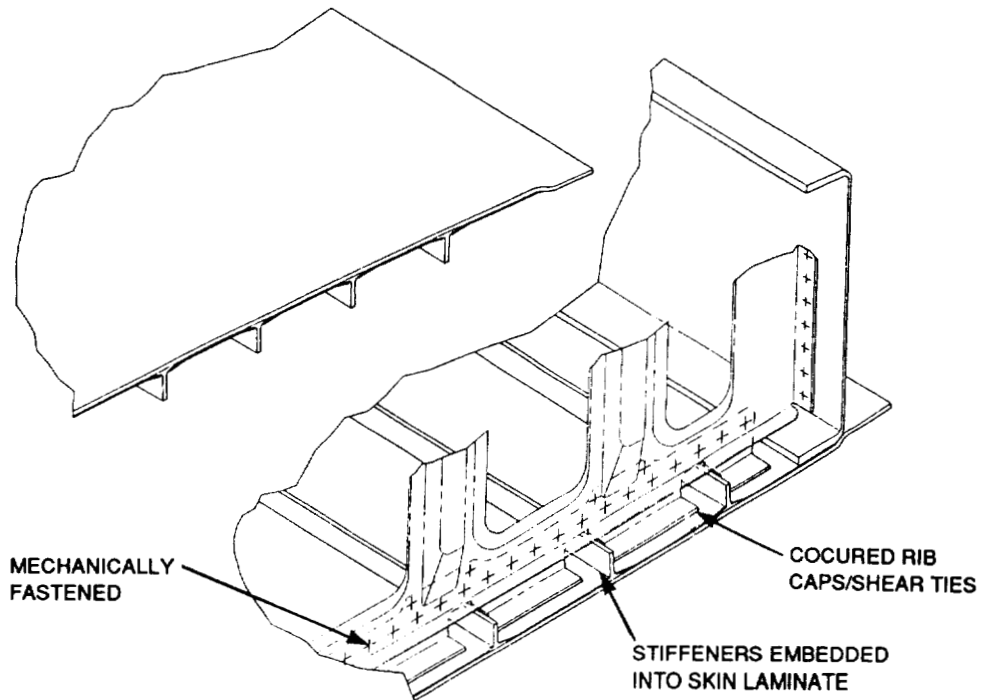


Figure 6. Modular Wing Concept

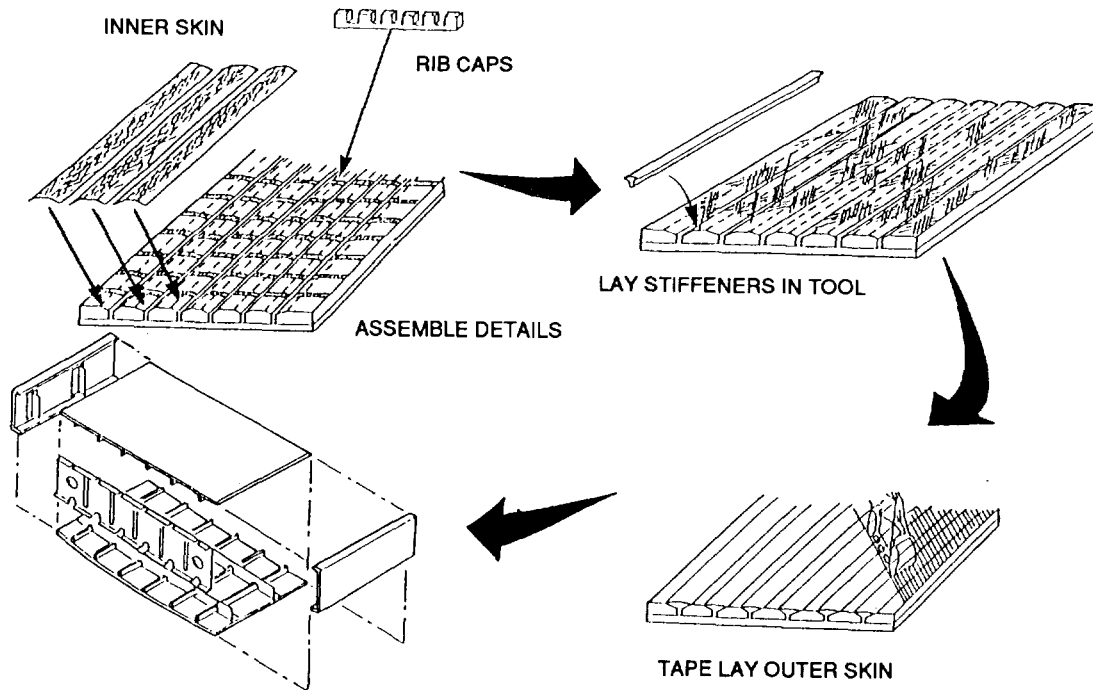


Figure 7. Modular Wing Fabrication

The front and rear spars are fabricated by automatic tow placement. Alternatives are filament winding or tape winding. The spars are designed as C-sections and can be wound as pairs in the form of a rectangular box and cut into C-sections after cure.

The ribs are fabricated as separate caps and webs. Prepreg plies are cut by Gerber cutter, stacked, formed to shape and B-staged. The rib caps are then placed in the cover fabrication tool along with the inner skin strips and the stiffeners before the outer skin is laid directly on the curing tool. A caul plate is placed over the assembly which is then bagged and cured.

The rib webs are compression molded using either thermosets or thermoplastics.

Final assembly is achieved by using mechanical fasteners.

#### CONCEPT #2 - RESIN TRANSFER MOLDED WING

The design concept for the resin transfer molded (RTM) wing is shown in Figure 8. The design calls for the wing box to be fabricated in two halves. Each half consists of one complete cover and part of the integral front and rear spars and with integral rib caps. Consequently, this design has no mechanical fasteners penetrating the outer surfaces.

The wing box would require large woven/stitched preforms. Close stitching would be required to debulk the preforms sufficiently to allow them to be assembled in the RTM tool. Assembly of the final molded halves would be accomplished by mechanical fasteners in the spar webs and by mechanical attachment of the separately molded rib webs. Figure 9 shows the fabrication approach.

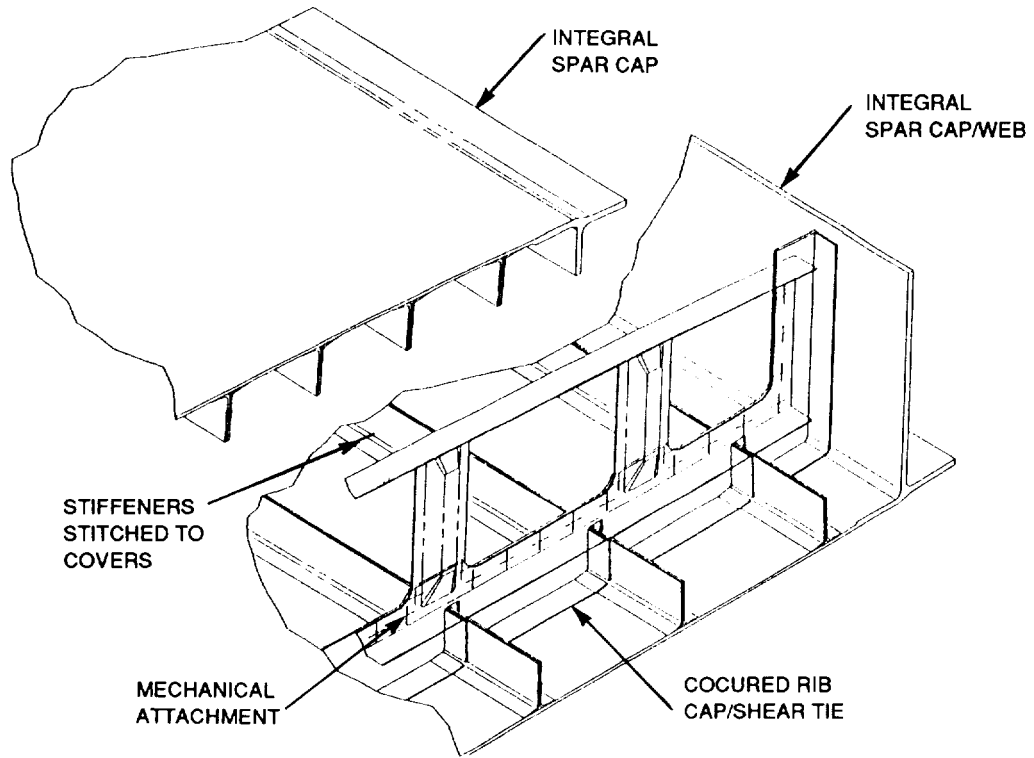


Figure 8. RTM Wing Concept

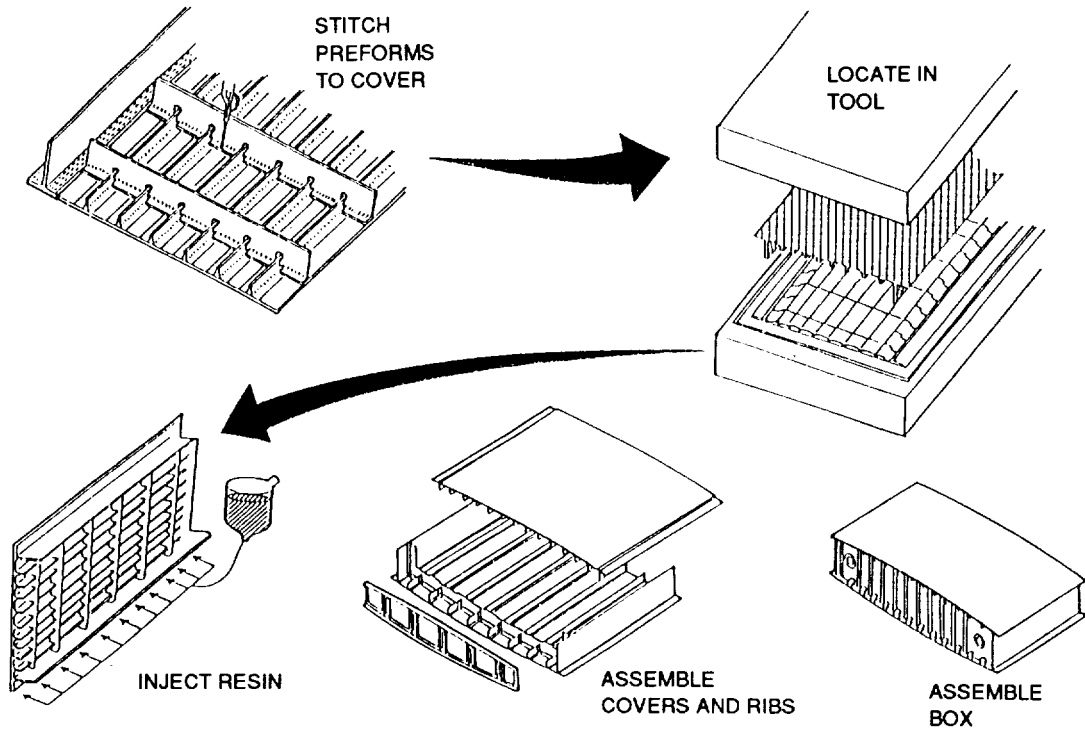


Figure 9. RTM Wing Fabrication



The wing cover assemblies will weigh approximately 2500 pounds. The largest RTM assemblies fabricated today weigh about 250 pounds. This design would thus require considerable scale-up of current technology.

A major concern with this design is the large number of tool parts which would be required. Stiffeners are usually normal to the skin, thus giving closed angles which would require segmented tools between each adjacent pair of stiffeners. At various locations along the wing span and probably chordwise, sets of vents would be required for resin to escape and to release trapped air. These vents would be closed progressively as the resin migrates outward from the injection ports. After all vents are closed some pressure would be maintained via the injection port to reduce the chance of entrapped air settling and causing voids.

#### CONCEPT #3 - ADVANCED TOW PLACEMENT WING

The design concept for the advanced tow placement (ATP) wing is shown in Figure 10. This design calls for the wing box to be tow placed and cured on a single mandrel. The large size of the wing box, however, made the handling of a single mandrel a major logistical problem. Consequently, the design was modified to fabricate the covers and spars separately. Rectangular tubes would be tape wound on mandrels and cut into two channel sections to form the blade stiffeners. This process allows plies to be picked up and dropped off to add localized reinforcements and 0 degree plies in the stiffener webs.

Spars can be tow placed in pairs around mandrels. An alternative approach would be to incorporate the spar caps in the covers and to tow place the webs in groups. The fabrication approach is shown in Figure 11.

The ribs would be press or diaphragm formed.

#### CONCEPT #4 - BRAIDED WING

The design concept for the braided wing is shown in Figure 12. This design calls for a one-piece wing box. Both 2D and 3D braiding were considered. The physical size of the wing box being considered does not fit within the confines of any current or planned braider. Today's largest 2D braider would have difficulty braiding 45-degree angles with 12k tow over a one-foot diameter mandrel. The size of carrier for this type of braider is five feet in diameter. A machine capable of braiding an L-1011 size wing box would require an enormous amount of floor and air space. More importantly, the individual carriers could not dispense a high enough quantity of fiber to make the process automatable. The carriers would require such frequent replacement that the process is not feasible in the foreseeable future.

This is also partly true for 3D braiding. The limitations of closed section tubular structures is less severe. Atlantic Research has developed an automated 3D braider which utilizes 9216 fiber carriers. A fabrication approach is shown in Figure 13.

Because of the problems in fabricating a complete wing box, this concept was dropped from further consideration. The braiding process was retained as an option for smaller assemblies as part of the modular wing box concept.

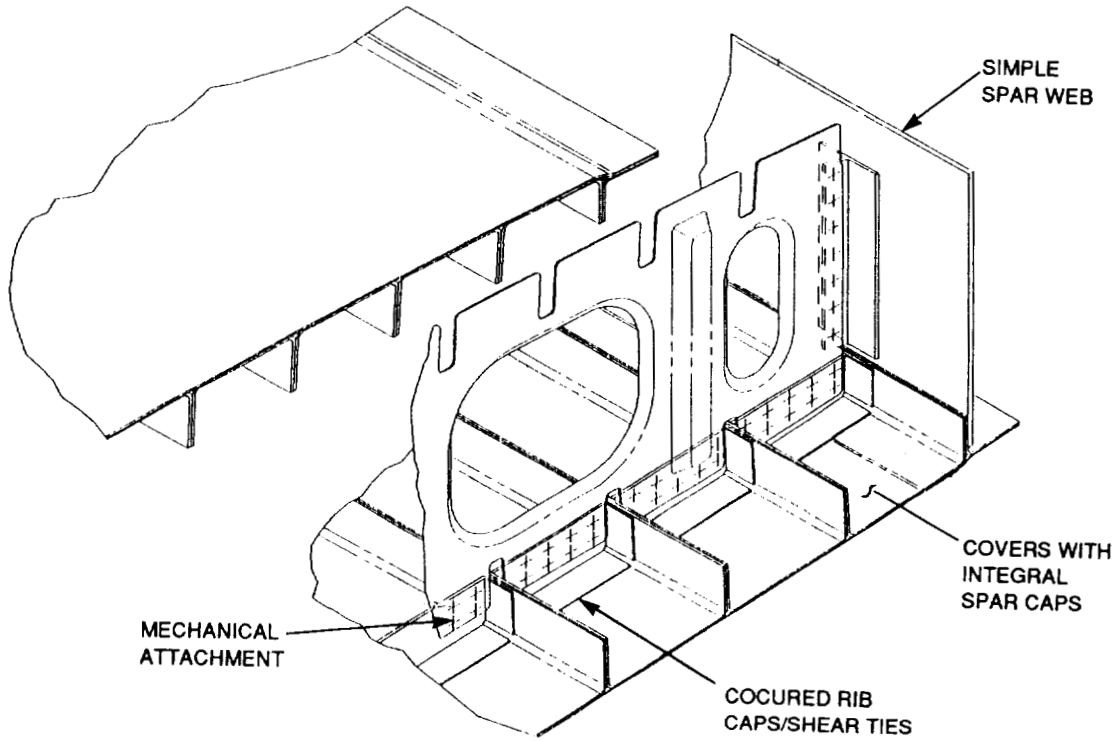


Figure 10. ATP Wing Concept

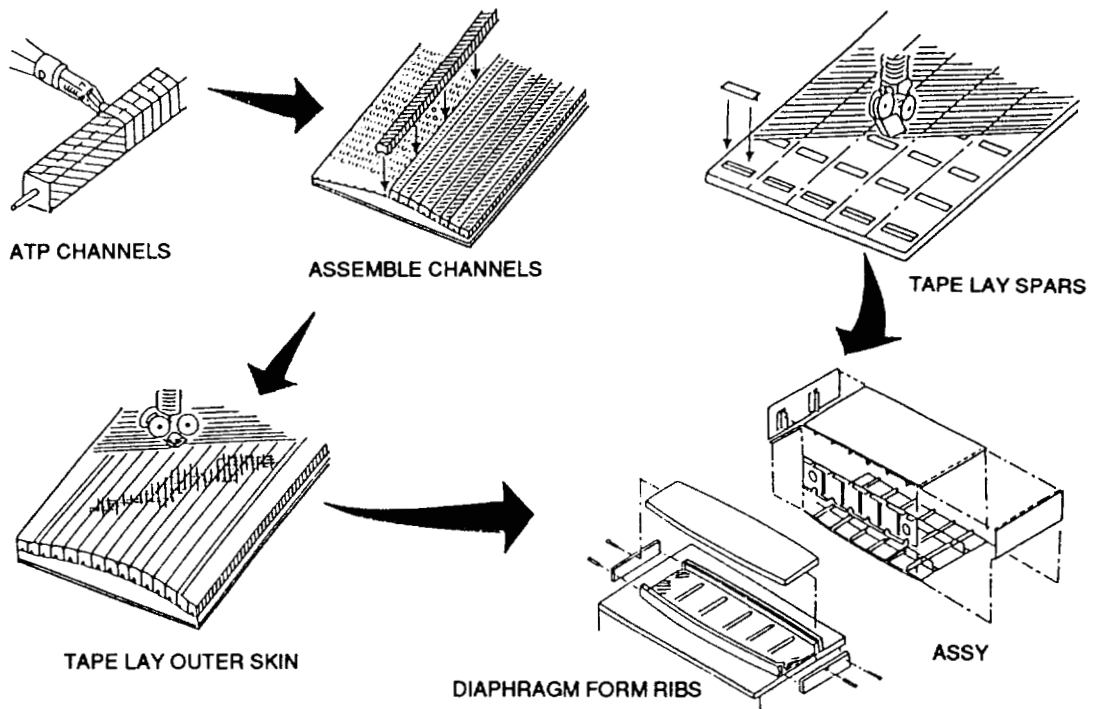


Figure 11. ATP Wing Fabrication

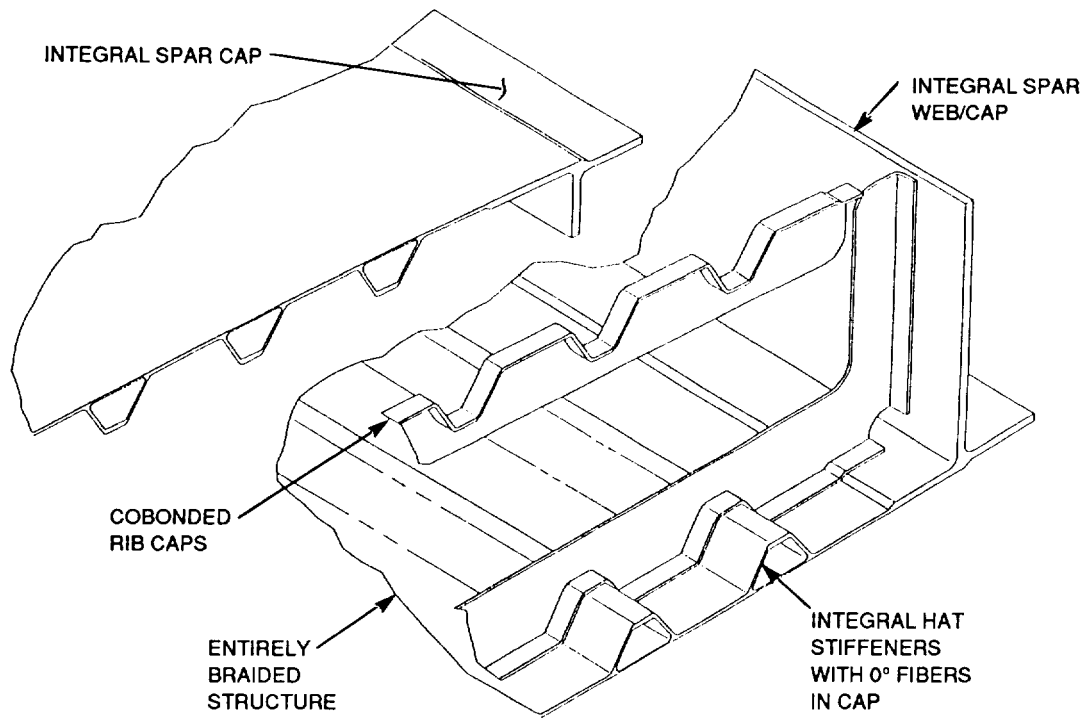


Figure 12. Braided Wing Concept

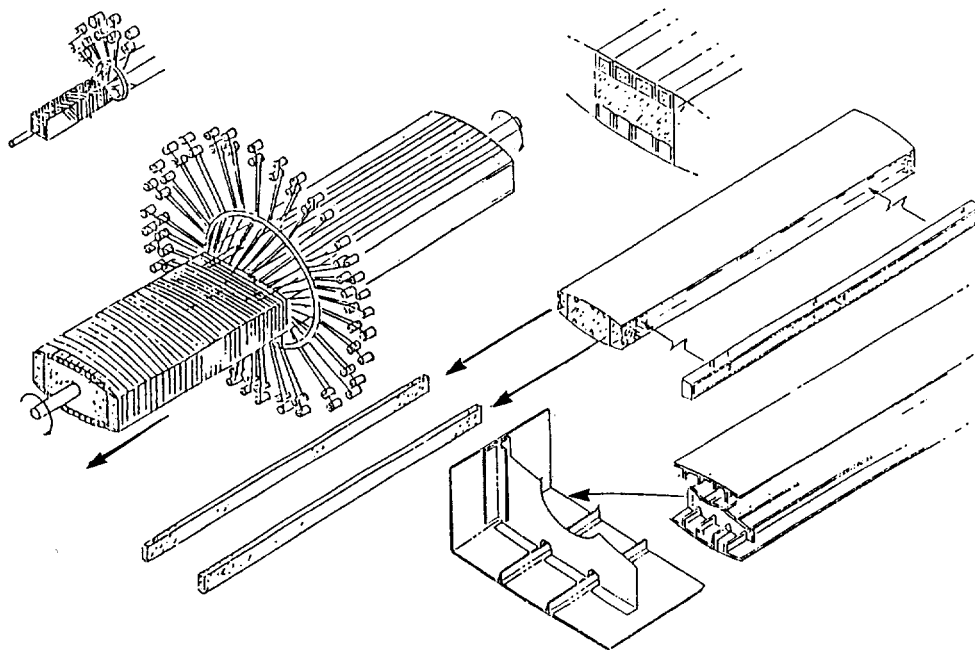


Figure 13. Braided Wing Fabrication

## FUSELAGE CONCEPTS

Three fuselage concepts were selected for the trade studies. Concept #1 is a sandwich design incorporating braided triangular tubes in the sandwich. Concept #2 is a geodesic design based on an isogrid concept. Concept #3 is a hat stiffened shell design.

### CONCEPT #1 - SANDWICH STIFFENED SHELL

The design concept for the sandwich shell is shown in Figure 14. This design consists of a sandwich using braided triangular tubes as the core. The tubes are oriented longitudinally. Periodically, there are flanged tubes as shown in Figure 15 which act as longerons.

The fabrication approach is to braid the tubes using dry fiber, then to pultrude through a resin bath and B stage. A fly-away foam mandrel would be required with this approach. The tubes can be fully cured and then assembled using an adhesive. This would eliminate the need for foam mandrels but would create many bond lines which would be difficult to inspect.

The inner skin is built up from C-sections which could also be pultruded. The outer skin is formed by overwrapping with tow or tape. The fabrication plan for a complete barrel section is shown in Figure 16.

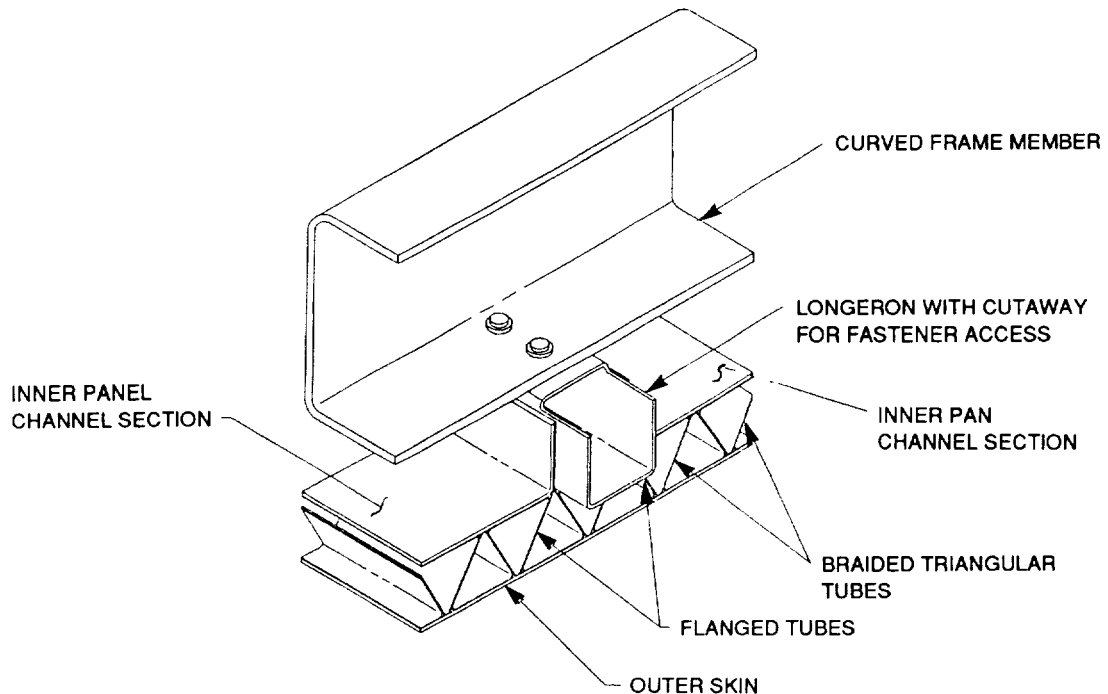


Figure 14. Sandwich Stiffened Shell Concept

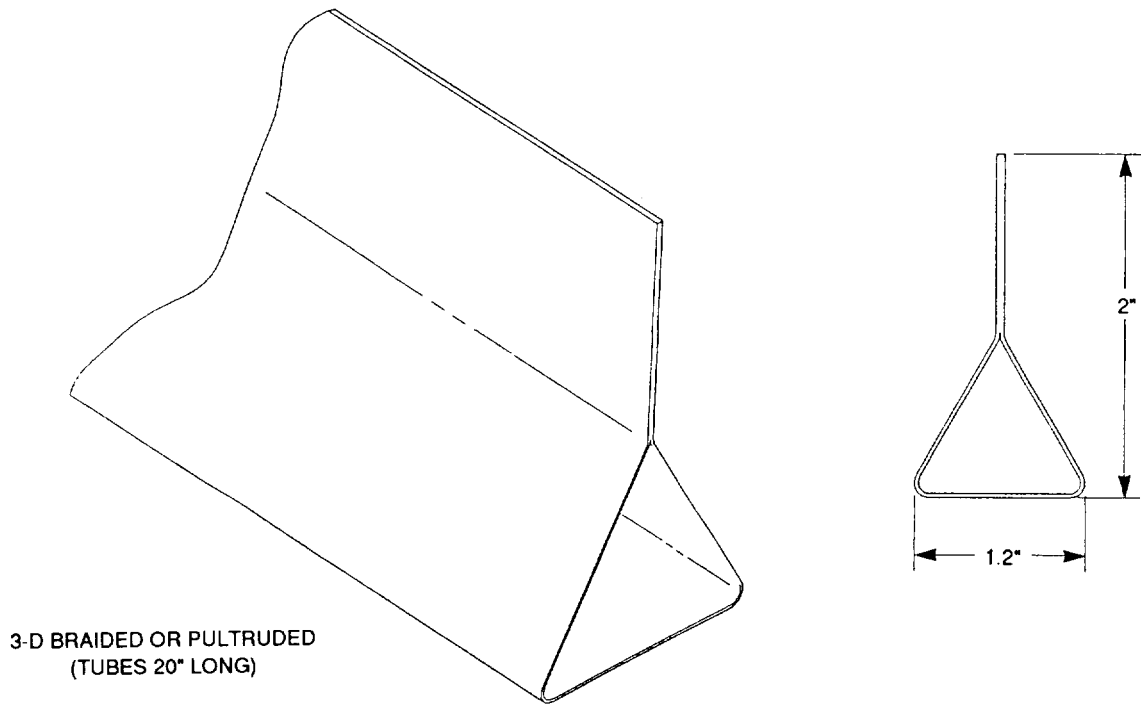


Figure 15. Flanged Triangular Tube Section

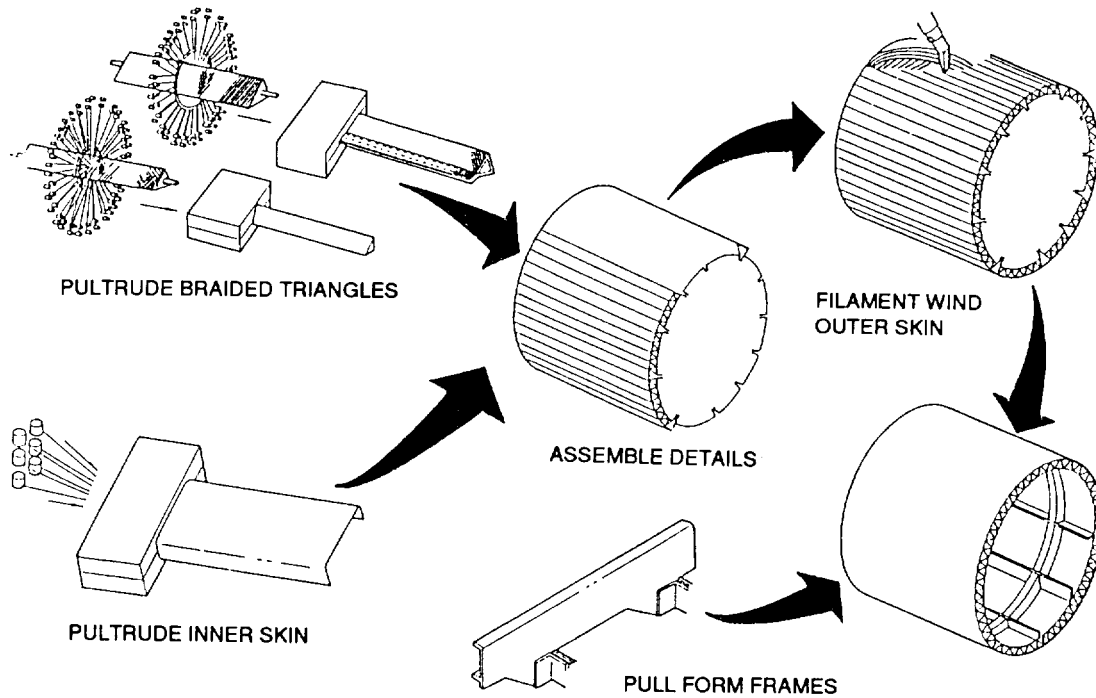


Figure 16. Sandwich Fuselage Fabrication

## CONCEPT #2 - GEODESIC FUSELAGE

The design concept for the geodesic fuselage is shown in Figure 17. This design calls for an isogrid stiffened shell. The helical stiffeners are formed by winding Filcoat material alternately in each direction. Filcoat is a patented Lockheed designed material consisting of Gr/Ep tape coated with an equal thickness of epoxy filled with glass micro-balloons called syntactic. At intersections the syntactic is squeezed out. Figure 18 shows a schematic of an intersection. The fibers in each direction are continuous and the intersections are the same height as the stiffeners.

The hoop stiffeners are not continuous. They are pull-formed and cut to their individual lengths. Intersection clips and overwraps are stitched dry fiber forms containing mainly  $\pm 45$  degree and 90 degree plies to provide shear and flange bending strength. These clips and overwraps can be combined to minimize parts and are resin transfer molded and B-staged.

The skin is finally tape or tow wrapped over a mandrel. The fabrication process is shown in Figure 19.

## CONCEPT #3 - HAT STIFFENED SHELL FUSELAGE

The design concept for the hat stiffened shell fuselage is shown in Figure 20. This design consists of pultruded hat stiffeners cocured to an advance tow placed skin. The frames are designed to be resin infusion molded and the complete assembly is cocured. An alternative fabrication method for the stiffeners is to braid prior to pultrusion. The fabrication process is illustrated in Figure 21.

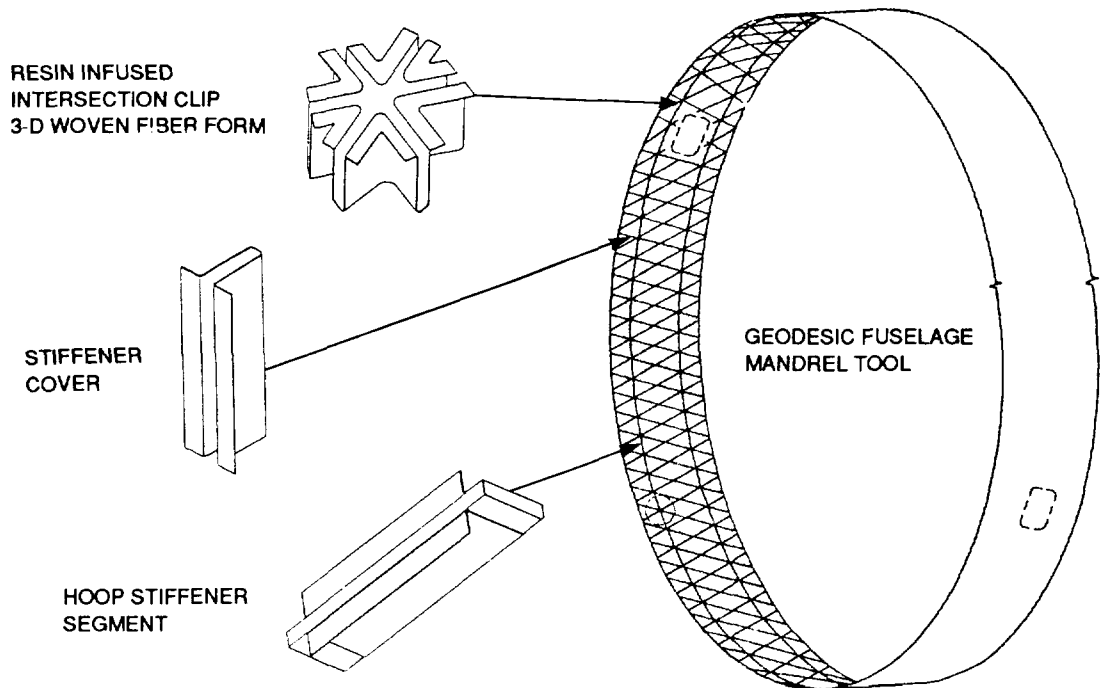


Figure 17. Geodesic Fuselage Concept

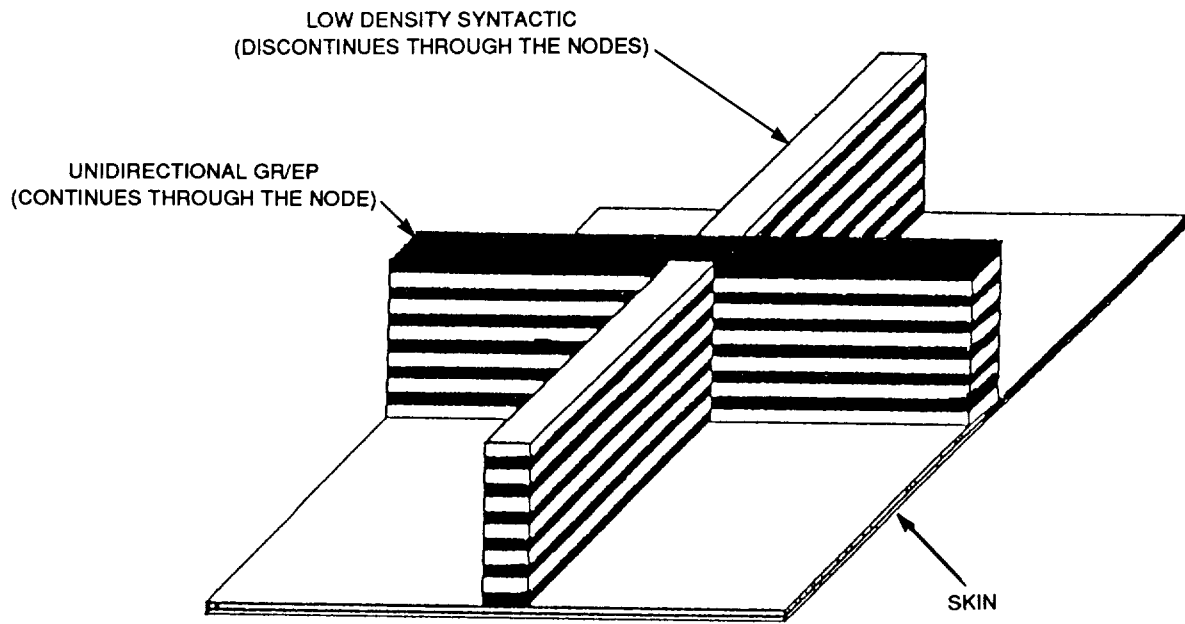


Figure 18. Geodesic Intersection

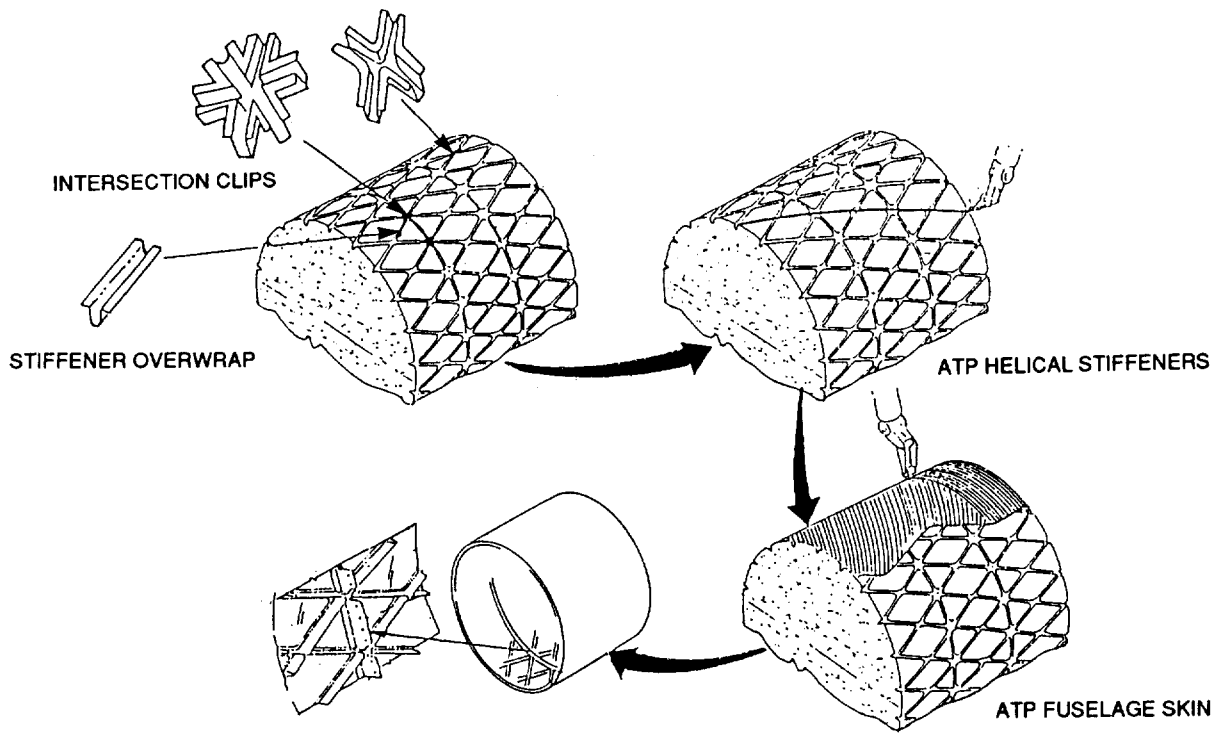
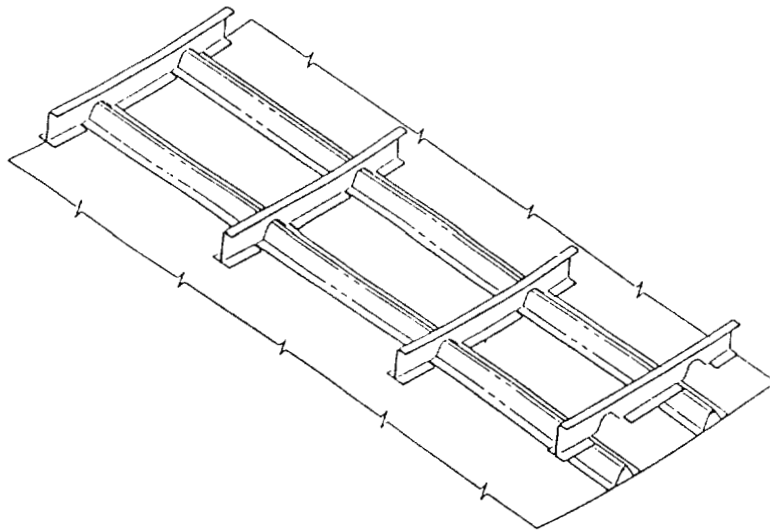


Figure 19. Geodesic Fuselage Fabrication



DESIGN FEATURES

- HAT STIFFENED TO INCREASE SPACING BETWEEN STIFFENERS
- CO-CURED ASSY
- GOOD DAMAGE TOLERANCE
- RFI FRAMES
- PULTRUDED HAT STIFFENERS

Figure 20. Stiffened Fuselage Shell Concept

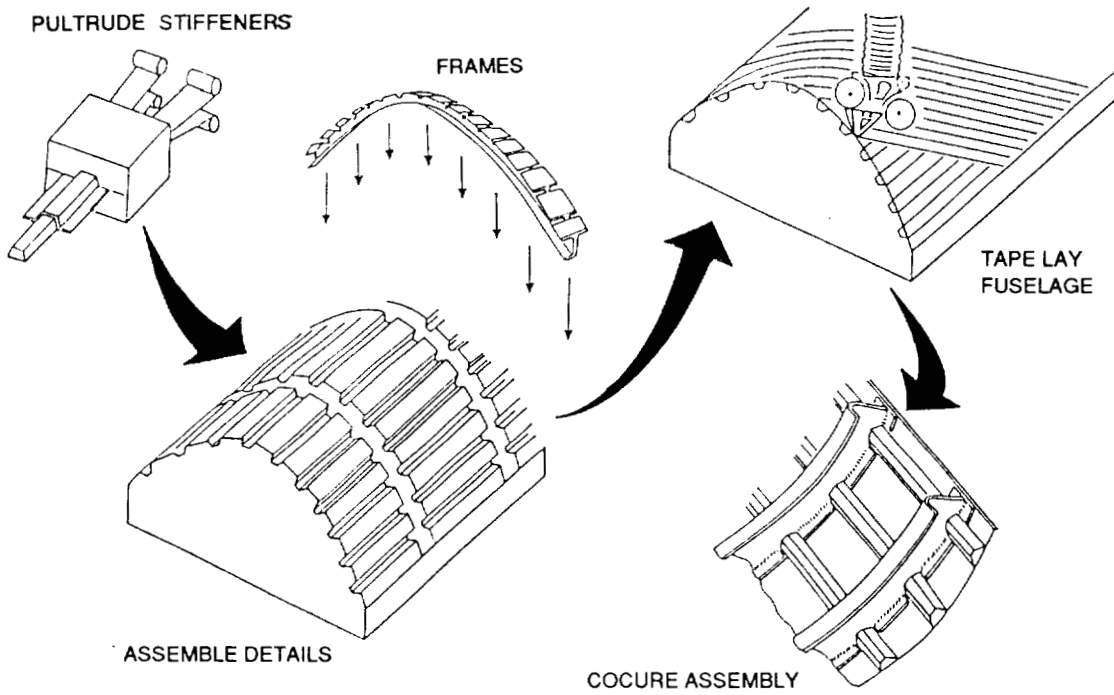


Figure 21. Stiffened Shell Fuselage Fabrication



The most effective way to fabricate these panels is as quarter panels. Essentially, upper, lower and side panels would be required. The use of closed hat stiffeners in the lower, or keel section, needs to be studied further because of problems associated with entrapment of bilge fluids. This is not considered to be a major problem as composites do not corrode. Drainage must, however, be provided to prevent accumulation of fluids and bacteria growth as well as the additional weight.

#### TRADE STUDIES

Figure 22 shows a summary of the options which were considered during the trade studies.

Blade, Jay and hat stiffeners were considered as options for wing skin stiffening. The Jay stiffener was eliminated because it is more difficult to fabricate than the blade and it did not show a significant enough weight saving to justify a higher cost. Hat stiffeners posed several problems in fuel tanks. They can trap fuel, they can provide leak paths and, being wide, they are difficult to terminate outboard effectively. This led to the use of blade stiffeners in all of the wing concepts. The blade configurations are, however, different. The blade configurations for the three concepts which were carried to completion are shown in Figure 23. The ATP stiffeners are built up from side by side channel sections. For the modular wing the stiffeners are pultruded with tapered flanges so that they can be buried in the skin. For the RTM wing the stiffeners are built up from woven stitched fabric.

The fuselage concepts are unique in themselves, so the stiffener configuration was not tradeable.





CONCEPT	CONFIGURATION				FABRICATION METHODS				MATERIALS	
					BRAID	ATP	RTM/RFI	PULT	T/S	T/P
MODULAR WING	•	•	•		•	•	•	•	•	•
RTM WING	•		•		•		•		•	•
ATP WING	•					•		•	•	•
BRAIDED WING	•		•		•				•	•
SANDWICH FUSELAGE				•	•	•	•	•	•	
GEODESIC FUSELAGE	•					•	•		•	
STIFFENED SHELL FUSELAGE			•		•	•	•	•	•	•

Figure 22. Trade Study Options

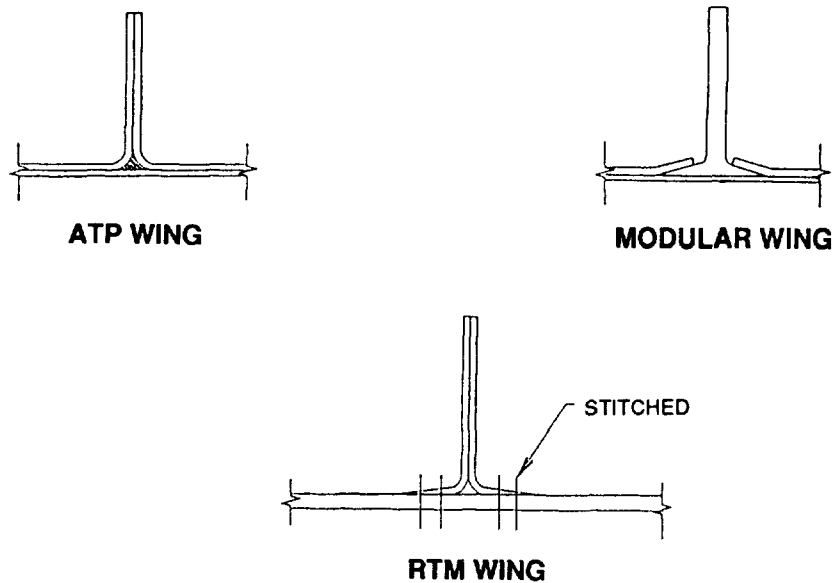


Figure 23. Stiffener Comparison

The fabrication methods looked at for each concept are summarized in Figure 22. The method selected for each component has already been discussed.

The trade study also looked at the possible use of thermoplastic materials instead of thermosets. The high cost of thermoplastic materials today makes their use in subsonic aircraft unlikely. The inherent toughness of the thermoplastic materials has some advantages, but the toughened thermosets are much more cost effective. Thermoplastics do look good for press formed ribs and even for frames. The main disadvantage of mixing materials is that mechanical fasteners would be required for assembly as thermosets and thermoplastics are very difficult to bond together. Figure 24 shows typical thermoplastic material costs today. Figure 25 shows a comparison of current and projected material costs. If projected prices do in fact become reality, then thermoplastics may be viable candidates for future commercial subsonic transports.

#### CONCEPT EVALUATION

Each concept was evaluated for cost, weight, design technology advancement, manufacturing technology advancement, producibility, damage tolerance, inspectability, maintainability and repair. The ability of the concept to meet the program goals was a major consideration. The scoring system used in the evaluation gave 40 points to cost, 30 points to weight and 30 points to all other factors. The cost score is the cost goal divided by the concept cost multiplied by 40. The weight score is the weight goal divided by the concept weight multiplied by 30. The other factors' score is the total of all points other than cost and weight divided by the maximum possible score multiplied by 30. This is summarized in Figure 26. The individual scores for the other factors are shown in the appendix along with the rationale.

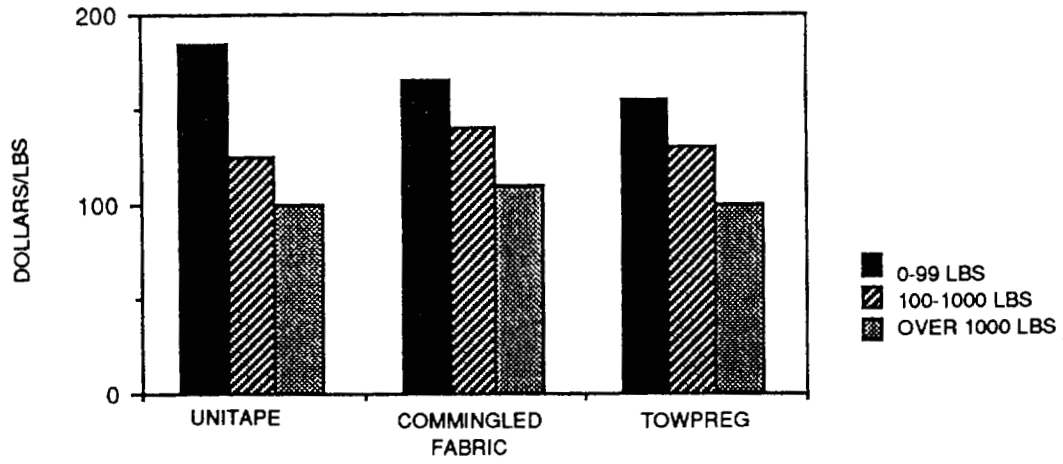


Figure 24. Thermoplastic Material Forms Cost Comparison

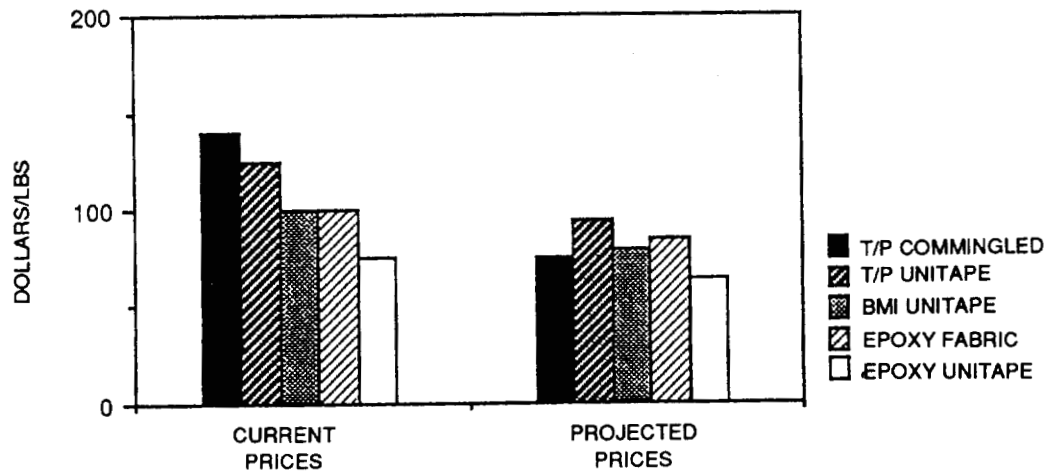


Figure 25. Cost of Various Composites

**EACH CONCEPT WAS ALLOCATED A MINIMUM SCORE OF 100 POINTS BROKEN DOWN AS**

• COST (40 POINTS)

$$\text{COST SCORE} = (\text{COST GOAL} / \text{COST OF DESIGN}) \times 40$$

• WEIGHTS (30 POINTS)

$$\text{WEIGHTS SCORE} = (\text{WEIGHT GOAL} / \text{WEIGHT OF DESIGN}) \times 30$$

• OTHER FACTORS (30 POINTS)

$$\text{OTHER FACTORS SCORE} = (\text{SUM OF POINTS OF DESIGN} / \text{MAXIMUM POSSIBLE POINTS}) \times 30$$

Figure 26. Scoring System

WEIGHT TRADES

The weights for the wing concepts were based on the total weight of the wing box structure per aircraft. Optimum sizing of the structure at outer wing station 151.1 was obtained. A spanwise variation was then used based on previous wing studies. Additional weight was added to account for landing gear attach fittings, engine mount fittings and access doors.

Weights for the fuselage concepts were based on sizing of the upper shell at station 750. The sizing assumed maximum tension and shear or maximum compression and shear. The sizing was then conservatively assumed to be constant at all circumferential locations. Total weight between Fuselage Stations 235 and 983 was taken.

A comparison of wing box weights is shown in Figure 27 and the fuselage segment weights in Figure 28. A summary of the weight trade study is shown in Figure 29.

COST TRADES

The cost trades were based on recurring costs only, although nonrecurring costs were considered in the producibility trades. Recurring costs were based on a production run of 300 ship sets at a rate of five per month. Labor rates are 1995 projected as agreed among the ACT program contractors at the Cost Workshops. Material costs were assumed to be \$40/lb. A sensitivity study on material cost will be performed. It was assumed that there would be no purchase of facilities or equipment. The fly to buy was dependent on fabrication method. The cost analysis program used was ACCEM. It includes material burden, support labor, quality control, learning curves and industrial engineering standards. A comparison of the wing concept costs is shown in Figure 30 and a comparison of the fuselage costs is shown in Figure 31. The cost trade study results are summarized in Figure 32.

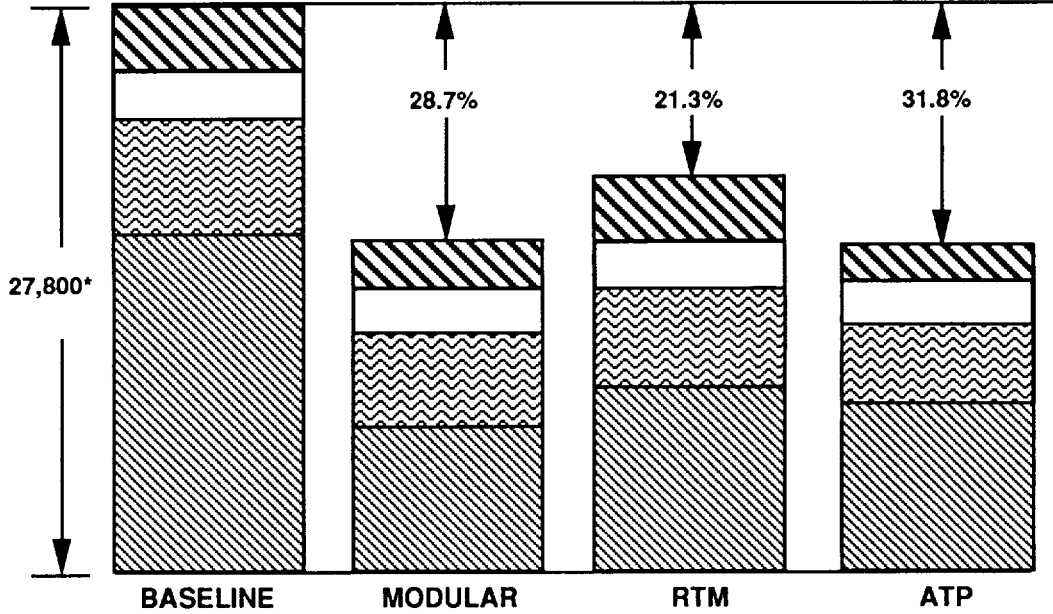
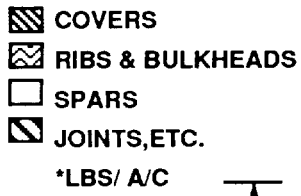


Figure 27. Wing Box Weights



\*FS235-FS983

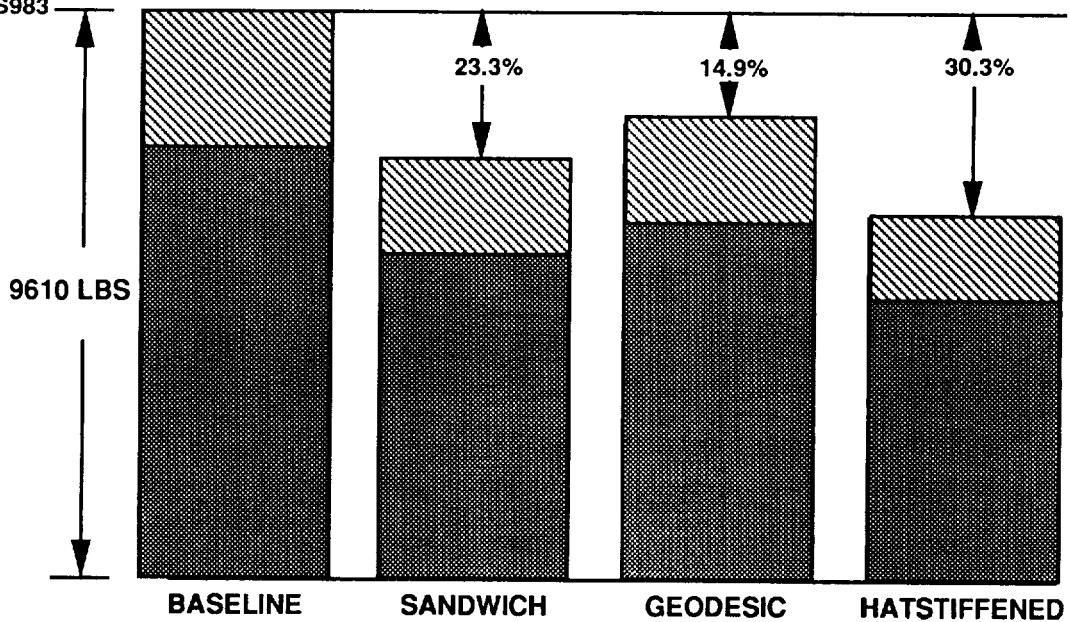


Figure 28. Fuselage Shell Weights

	CONCEPT	WEIGHT	SCORE
WING	BASELINE (GOAL)-34%	27,800 (17,792)	
	MODULAR	19,831	26.91
	RTM	21,976	24.29
	ATP	18,953	28.16
FUSELAGE	BASELINE (GOAL)-34%	9,610 (6,150)	
	SANDWICH	7,367	25.04
	GEODESIC	8,175	22.57
	HAT STIFFENED	6,700	27.54

Figure 29. Weight Trade Study Results

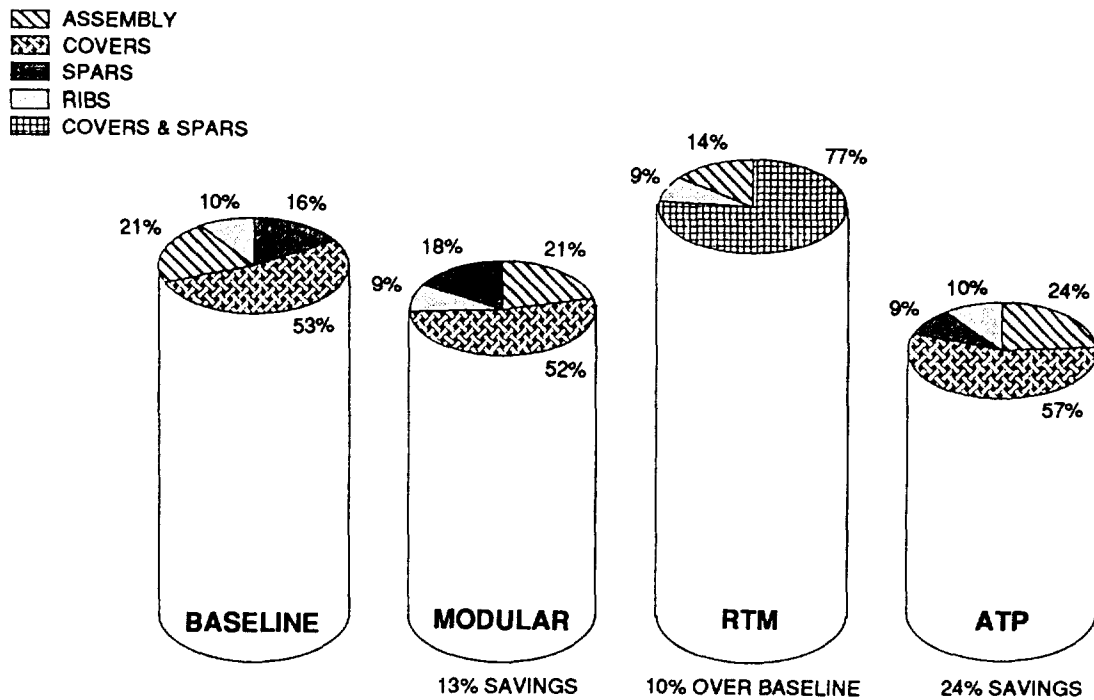


Figure 30. Wing Concept Cost Comparisons

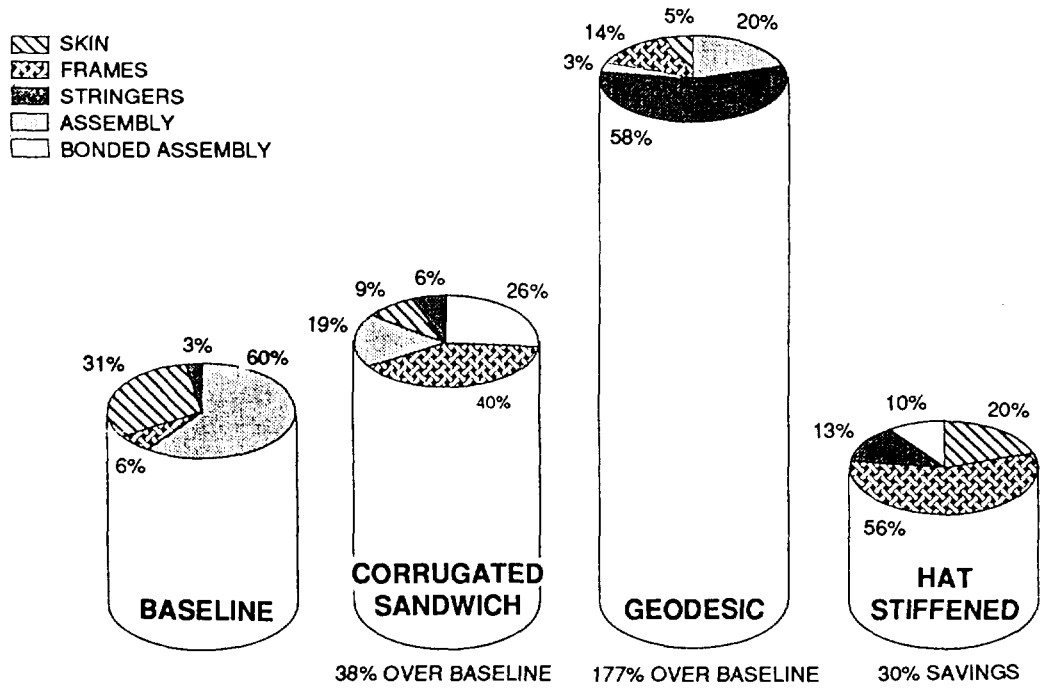


Figure 31. Fuselage Concept Cost Comparison

	CONCEPT	COST \$	SCORE
WING	BASELINE (GOAL)-25%	2,636,425 (1,977,318)	
	MODULAR	2,301,918	34.36
	RTM	2,912,135	27.16
	ATP	2,002,760	39.49
FUSELAGE	BASELINE (GOAL)-25%	161,704 (121,278)	
	SANDWICH	221,985	21.85
	GEODESIC	448,918	10.81
	HAT STIFFENED	112,962	42.95

Figure 32. Cost Trade Study Results

Cost benefits and drivers for each concept are summarized in Figure 33.

DOWNSELECT

Based on the trade studies, one wing and one fuselage concept was selected from the concepts shown in Figures 34 and 35. Figure 36 shows a summary of the rankings of the concepts. The Advanced Tow Placement Wing and the Hat Stiffened Shell Fuselage designs finished the clear winners. Both came close to the 25 percent cost saving target and the 40 percent weight saving target and exceeded the 50 percent reduction in parts count. The weight saving goal shown has been reduced to 34 percent to account for resizing. The 34 percent was an overall goal bearing in mind the fact that the wing would be expected to have a larger savings from resizing than would the fuselage which has volume constraints. The selected concepts are shown in Figures 37 and 38.

The original program plan had called for continuing with a backup design for both the wing and the fuselage through the end of Phase 1. The primary concepts, however, emerged as such clear winners that it was decided to put all the remaining effort into developing and validating the primary concepts.

EXPECTATIONS FOR DEVELOPMENT

Both the selected concepts depend on minimization of mechanical fasteners and the fabrication of large components. The development of these concepts depends on the minimization of discontinuities, the development of analytical methods, the demonstration of repeatable process and the use of in-process controls which will in

CONCEPT	COST BENEFITS	COST DRIVERS
MODULAR WING	<ul style="list-style-type: none"> <li>• MORE EFFICIENT USE OF MATERIALS</li> </ul>	<ul style="list-style-type: none"> <li>• TOOL LOADING</li> <li>• MATERIAL COST</li> <li>• ADDITIONAL FASTENERS</li> <li>• INCREASED ASSEMBLY</li> </ul>
RTM WING	<ul style="list-style-type: none"> <li>• STIFFENER SIMPLICITY</li> <li>• REDUCED PART COUNT</li> <li>• MINIMAL MECHANICAL ASSEMBLY</li> </ul>	<ul style="list-style-type: none"> <li>• TOOL LOADING</li> <li>• COMPLEX TOOLING</li> <li>• MATERIAL COST</li> </ul>
ATP WING	<ul style="list-style-type: none"> <li>• USE OF ATP EQUIPMENT</li> <li>• INTEGRAL SPAR CAPS</li> <li>• REDUCED ASSEMBLY</li> </ul>	<ul style="list-style-type: none"> <li>• HANDLING</li> <li>• TOOL LOADING</li> </ul>
SANDWICH FUSELAGE	<ul style="list-style-type: none"> <li>• USE OF AUTOMATED FABRICATION PROCESSES</li> </ul>	<ul style="list-style-type: none"> <li>• HIGH PART COUNT</li> <li>• ASSEMBLY</li> <li>• MATERIAL COST</li> </ul>
GEODESIC FUSELAGE	<ul style="list-style-type: none"> <li>• COMMONALITY OF DETAILS</li> </ul>	<ul style="list-style-type: none"> <li>• HIGH PART COUNT</li> <li>• HAND PLACEMENT OF DETAILS</li> <li>• MATERIAL COST</li> </ul>
STIFFENED SHELL FUSELAGE	<ul style="list-style-type: none"> <li>• REDUCED NUMBER OF PARTS</li> <li>• COCURED FRAMES</li> </ul>	<ul style="list-style-type: none"> <li>• COMPLEX TOOLING</li> </ul>

Figure 33. Cost Benefits and Cost Drivers



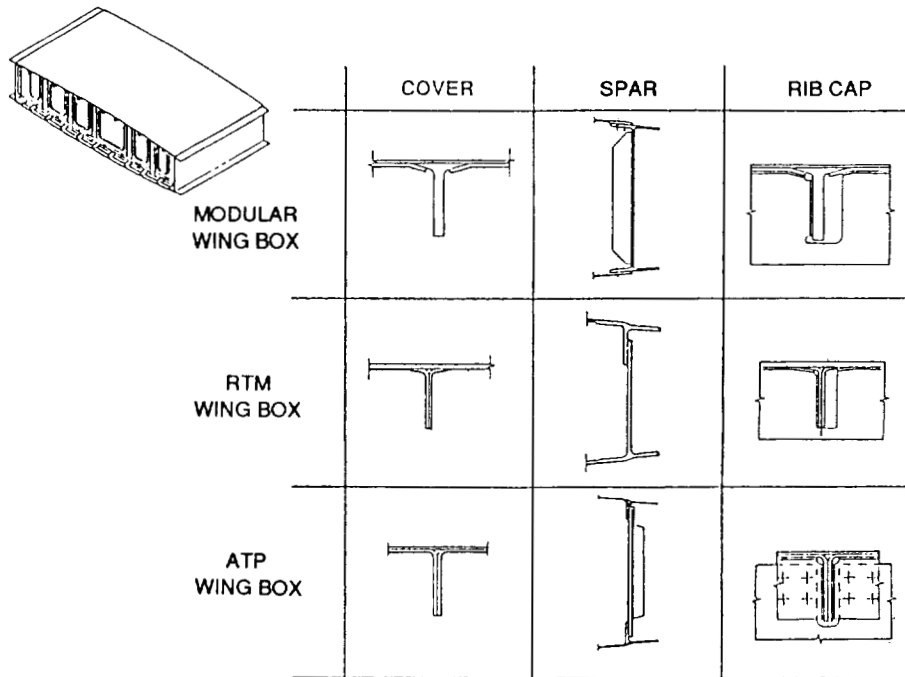


Figure 34. Wing Box Concepts

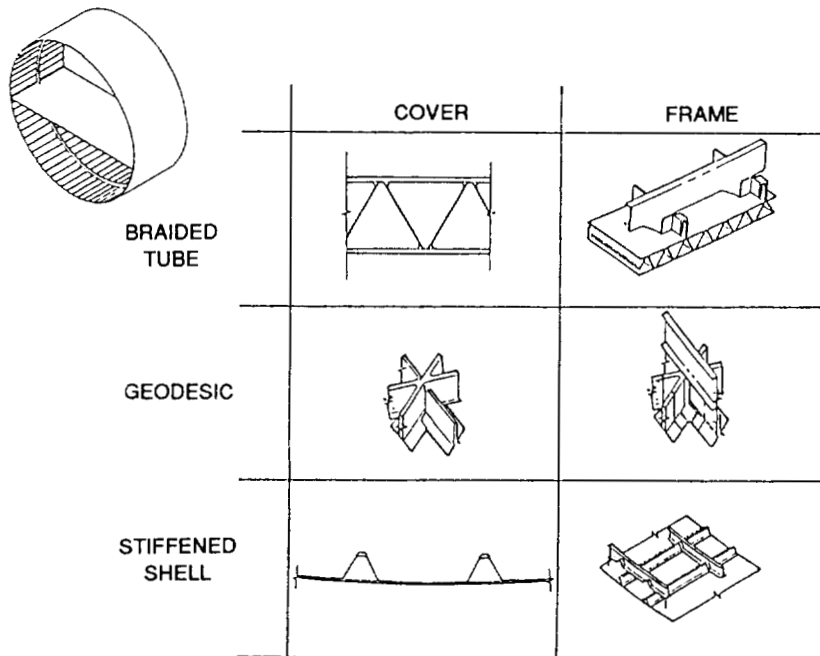
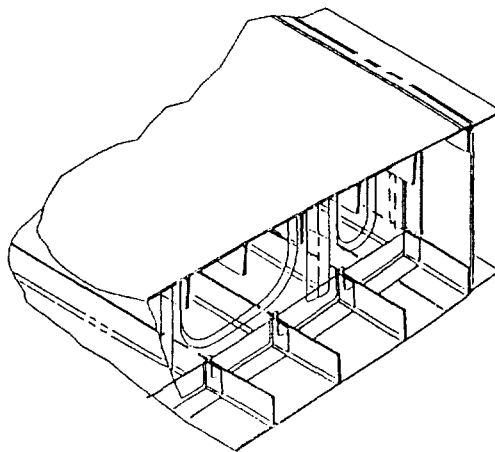
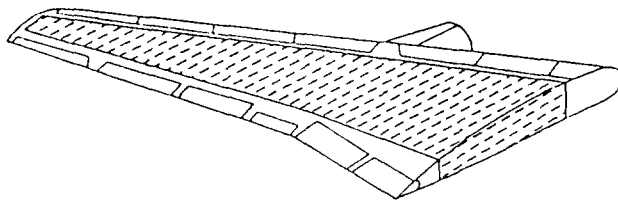


Figure 35. Fuselage Concepts

CONCEPT		WEIGHT	COST	ILITIES	TOTAL	RANK
WING	MODULAR	26.91	34.36	12.5	73.77	2
	RTM	24.29	27.16	20.5	71.95	3
	ATP	28.16	39.49	18.0	85.65	1
FUSELAGE	SANDWICH	25.05	21.85	17.0	63.90	2
	GEODESIC	22.57	10.81	15.5	48.88	3
	STIFFENED SHELL	27.54	42.95	17.5	87.99	1

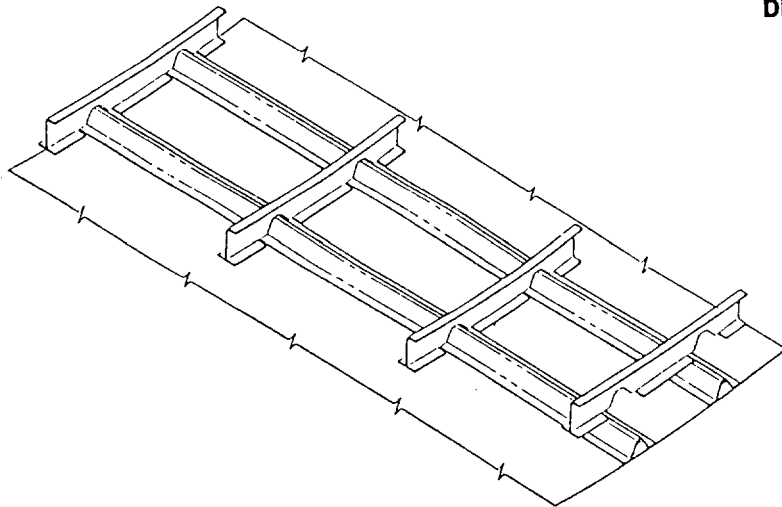
Figure 36. Downselect Summary



**DESIGN FEATURES:**

- ONE PIECE DESIGN - NO SPANWISE/ CHORDWISE JOINTS
- INTEGRAL CONTINUOUS BLADE STIFFENERS
- UPPER/LOWER COVERS WITH INTEGRAL SPAR CAPS
- NO FASTENERS/LEAK PATHS THROUGH THE COVERS
- INTEGRAL RIB CAPS WITH SHEAR CLIPS

Figure 37. Selected Wing Concept



#### DESIGN FEATURES:

- HAT STIFFENED TO INCREASE SPACING BETWEEN STIFFENERS
- CO-CURED ASSY
- GOOD DAMAGE TOLERANCE
- RFI FRAMES
- PULTRUDED HAT STIFFENERS

Figure 38. Selected Fuselage Concept

effect build in the quality and minimize scrap and buy-off. The concepts involve a moderate risk but can be approached in an incremental manner which will improve the chances of success. Neither concept involves an all or nothing approach and alternative paths are available if needed.

#### SUMMARY AND CONCLUSIONS

Advanced structural and material trade studies were carried out on four wing and three fuselage concepts. The trade studies showed that the Advanced Tow Placement Wing concept and the Hat Stiffened Shell Fuselage concept both showed excellent potential for meeting the program goals. The weight savings are close enough to the goal that there is a reasonable chance of meeting or exceeding this goal with further development and refinement. The wing cost is within one percent of the goal and the cost of the fuselage concept exceeds the goal. Efforts are now underway to validate these designs by more detailed analyses and by fabrication and test.

APPENDIX

CONCEPT	DESIGN TECHNOLOGY ADVANCEMENT	RATIONALE
MODULAR WING	4	CONVENTIONAL ASSEMBLY METHODS. LARGE COCURED COVER ASSEMBLIES REPRESENT A SLIGHT TECHNOLOGY ADVANCEMENT.
RTM WING	5	CONVENTIONAL DESIGN CONFIGURATION WITH EXCEPTION OF COVER/SPAR INTEGRATION AND STITCHED PREFORM.
ATP WING	5	CONVENTIONAL DESIGN CONFIGURATION. EMPHASIS ON LARGE COCURED ASSEMBLIES. MECHANICAL FASTENERS SIGNIFICANTLY REDUCED.
SANDWICH FUSELAGE	8	UNIQUE DESIGN CONCEPT AMENABLE TO AUTOMATED FABRICATION TECHNIQUES. SIMPLIFIED FRAME TO COVER ATTACHMENT.
GEODESIC FUSELAGE	6	HIGHLY EFFICIENT, DAMAGE TOLERANT DESIGN. DESIGN SUITABLE FOR AUTOMATED MANUFACTURING METHODS.
STIFFENED SHELL FUSELAGE	4	DESIGN CONCEPT IS CURRENT STATE OF THE ART. CONFIGURATION ALLOWS FOR COCURING OF ALL STRUCTURAL ELEMENTS.

CONCEPT	TECHNOLOGY ADVANCEMENT MANUFACTURING	RATIONALE
MODULAR WING	3	DIFFICULT TO LAY UP RIB CAPS AND COCURING TO THE COVER AND STIFFENERS. LITTLE TECHNOLOGY ADVANCEMENT.
RTM WING	9	ONE-SHOT COMPLETE RTM WING HALF WOULD BE A TREMENDOUS ADVANCEMENT OF THE TECHNOLOGY. DESIGN ELIMINATES MANY COMPONENTS AND FASTENERS.
ATP WING	7	ATP OF C-CHANNEL BLOCKS AND ASSEMBLY TO FORM COVERS REPRESENTS AN ADVANCEMENT OVER CURRENT METHODS. CO-CURING OF INTEGRAL RIB CAPS IS A SIGNIFICANT ADVANCEMENT.
SANDWICH FUSELAGE	7	SIGNIFICANT ADVANCEMENT IN MANDREL TECHNOLOGY. SOME ADVANCEMENT IN COMPONENT LOCATION ARENA WITH THE MANY TUBES. A SIGNIFICANT ADVANCEMENT IF PULTRUDED.
GEODESIC FUSELAGE	7	ATP OF HELICAL STIFFENERS AND RFI OF INTERSECTION CLIPS IS A SIGNIFICANT ADVANCEMENT. PULL FORMING OF FRAMES IS AN EXTENSION OF TECHNOLOGY.
STIFFENED SHELL FUSELAGE	3	LITTLE ADVANCEMENT ASIDE FROM THE FACT THAT THE FRAMES ARE COCURED.

APPENDIX

CONCEPT	INSPECT-ABILITY	RATIONALE
MODULAR WING	6	SEPARATE COMPONENTS CAN BE INSPECTED, BUT ALSO WILL REQUIRE EXTENSIVE POST PROCESS INSPECTION DUE TO COCONSOLIDATION AND/OR BONDING
RTM WING	8	PREFORM MAY BE INSPECTED BEFORE MOLD FILLING. WIDE RANGE OF IN-PROCESS METHODS COULD BE USED FOR MONITORING THE MOLD FILL AND CURE, INCLUDING PROCESS MODELS.
ATP WING	6	TOW QUALITY, SIZE AND PLACEMENT MUST BE MONITORED AT ALL TIMES, WILL DEPEND ON MACHINE. PLACEMENT MONITORING NEEDS TO BE DEVELOPED.
SANDWICH FUSELAGE	5	TUBES COULD BE INSPECTED IN-LINE, BUT POST PROCESS WILL BE VERY DIFFICULT BETWEEN TUBES.
GEODESIC FUSELAGE	2	VERY COMPLEX GEOMETRY. THE TRUSS INTERSECTIONS ARE UNINSPECTABLE.
STIFFENED SHELL FUSELAGE	8	HIGH SCORE BECAUSE COMPONENTS MAY BE INSPECTED BEFORE FINAL CURE. IN-PROCESS INSPECTION OF PULTRUDED HATS AND RTM FRAMES HAVE EASY GOEMETRY.

CONCEPT	MAINTAIN-ABILITY	RATIONALE
MODULAR WING	6	MODULAR CONSTRUCTION FACILITATES LESS COSTLY REPAIR TECHNOLOGY. HEAVY STRUCTURAL DAMAGE IS UNREPAIRABLE AT FIELD LEVEL.
RTM WING	6	LEAK PATHS ARE ELIMINATED. CONSTRUCTION FACILITATES LESS COSTLY REPAIR TECHNOLOGY. HEAVY STRUCTURAL DAMAGE IS UNREPAIRABLE AT FIELD LEVEL.
ATP WING	7	LEAK PATHS ARE ELIMINATED. REPAIR AT FIELD LEVEL IS LESS COSTLY. HEAVY DAMAGE WILL INDUCE REMOVE AND REPLACEMENT OF ENTIRE STRUCTURE.
SANDWICH FUSELAGE	8	COMPOSITE MATERIALS ELIMINATE MOST MAINTAINABILITY ISSUES. REPAIR CAN BE EASILY DONE AT THE FIELD LEVEL.
GEODESIC FUSELAGE	4	CREATES REPAIR PROBLEMS THAT CANNOT BE SATISFIED WITHOUT MAJOR RECONSTRUCTION OF LARGE AREAS. REQUIRES EXCESSIVE SPARE /REPAIR PARTS INVENTORY.
STIFFENED SHELL FUSELAGE	6	REPAIR PROBLEMS IN TRANSFERING LOAD ACROSS DAMAGED AREA.

APPENDIX

CONCEPT	PRODUCIBILITY	RATIONALE
MODULAR WING	3	RIB CAP CONFIGURATION DIFFICULT TO FABRICATE AND EXPENSIVE. NO PROVISION FOR TOLERANCE FLOAT. LIMITED ACCESS FOR INTERNAL FAST.
RTM WING	6	THIS CONCEPT IS HIGH RISK, BUT HAS HIGH PAY-OFF. ALSO, HAS SAME ACCESS PROBLEMS AS THE MODULAR DESIGN.
ATP WING	6	CONCEPT HAS LESS RISK THAN RTM DESIGN, AND ALSO LESS PAY-OFF. SAME ACCESS PROBLEMS AS OTHER WING CONCEPTS.
SANDWICH FUSELAGE	3	TOO MANY PIECES. THE LENGTH AND SMALL CROSS SECTION OF THE TRIANGLES MAKE MANDREL REMOVAL DIFFICULT. INSPECTION OF BONDED ASSEMBLY PRESENTS PROBLEMS.
GEODESIC FUSELAGE	3	TOO MANY PARTS. JUNCTION CLIPS VERY DIFFICULT TO FAB WITH CONTINUOUS FIBER COMPOSITES. VERY COMPLEX TOOLING, MANY PARTS.
STIFFENED SHELL FUSELAGE	8	ALL PROCESSES ARE AUTOMATED INCLUDING RTM, PULTRUSION AND FILAMENT WINDING.

CONCEPT	DURABILITY / DAMAGE TOLERANCE	RATIONALE
MODULAR WING	3	CONCERN IS THAT IMPACT DAMAGE WILL CAUSE STIFFENER TO PULL AWAY FROM SKIN DRASTICALLY REDUCING MECHANICAL PROPERTIES.
RTM WING	7	THROUGH THE THICKNESS REINFORCEMENT SHOULD PREVENT STIFFENER UNBOND AND MINIMIZE IMPACT DAMAGE. LOWER FIBER VOLUME IS STILL A CONCERN, AS IT WOULD REDUCE STRUCTURAL INTEGRITY.
ATP WING	5	THIS IS TYPICAL OF CURRENT STRUCTURES.
SANDWICH FUSELAGE	3	THINNESS OF FACINGS IS A DURABILITY CONCERN. IMPACT COULD CAUSE SEPERATION OF TRIANGULAR TUBES OVER A LARGE REGION. THIS COULD REDUCE RESIDUAL PROPERTIES.
GEODESIC FUSELAGE	9	THIS CONFIGURATION IS HIGHLY REDUNDANT AND SHOULD HAVE OUTSTANDING DURABILITY AND DAMAGE TOLERANCE. HOWEVER, THERE IS A HIGH RISK OF CRITICAL MANUFACTURING FLAWS IN THE DIAGONAL CROSS-OVERS.
STIFFENED SHELL FUSELAGE	6	CONSIDERED SLIGHTLY BETTER THAN CURRENT STRUCTURES BECAUSE OF THE ELIMINATION OF FASTENERS AND HOLES.

APPENDIX

CONCEPT	TECHNOLOGY ADVANCEMENT		PRODUCIBILITY	DAMAGE TOL/ DURABILITY	INSPECTABILITY	MAINTAINABILITY/ REPAIR	TOTAL	SCORE
	DESIGN	MFG						
MODULAR WING	4	3	3	3	6	6	25	12.5
RTM WING	5	9	6	7	8	6	41	20.5
ATP WING	5	7	6	5	6	7	36	18.0
SANDWICH FUSELAGE	8	7	3	3	5	8	34	17.0
GEODESIC FUSELAGE	6	7	3	9	2	4	31	15.5
STIFFENED SHELL FUSELAGE	4	3	8	6	8	6	35	17.5