N95- 28437

C-130 ADVANCED TECHNOLOGY CENTER WING BOX CONCEPTUAL DESIGN/COST STUDY*

517-24
51385
P-19

R.S. Whitehead
Northrop Corporation
Hawthorne, California

C.R. Foreman
LTV Advanced Products Group
Dallas, Texas

Capt. K. Silva
Wright Laboratories/FIBAC
Dayton, Ohio

ABSTRACT

A conceptual design was developed by Northrop/LTV for an advanced C-130 Center Wing Box (CWB) which could meet the severe mission requirements of the SOF C-130 aircraft. The goals for the advanced technology CWB relative to the current C-130H CWB were: (1) the same acquisition cost; (2) lower operating support costs; (3) equal or lower weight; (4) a 30,000 hour service life for the SOF mission; and (5) minimum impact on the current maintenance concept. Initially, the structural arrangement, weight, external and internal loads, fatigue spectrum, flutter envelope and design criteria for the SOF C-130 aircraft CWB were developed. An advanced materials assessment was then conducted to determine the suitability of advanced materials for a 1994 production availability and detailed trade studies were performed on candidate CWB conceptual designs. Finally, a life-cycle cost analysis was performed on the advanced CWB. The study results demonstrated that a hybrid composite/metallic CWB could meet the severe SOF design requirements, reduce the CWB weight by 14 percent, and was cost effective relative to an all metal beefed up C-130H CWB.

---

* This work was performed under USAF Contract No. F33657-90-D-0027 Task Order 0005, September 1990 to April 1991.

INTRODUCTION

The airframes of SOF C -130 aircraft have approximately one-third the service life of a C-130H airframe. In addition, the center wing box (CWB) structure, which is common to both the C-130H and SOF C -130, is the life limiting portion of the airframe. The reduced service life of the SOF C -130 airframe can be attributed to two primary factors, these are: a severe tactical flight mission profile and high operational weight. As a consequence, the SOF C -130 CWB structure has a fierce time compliance technical order (TCTO) maintenance burden, which generates high operating and support costs. Several life extension alternatives exist for these airframes: (1) revised mission scenarios; (2) increased inspection frequency; (3) a beefed-up metal CWB; or (4) application of advanced structures and materials technologies to a redesigned CWB. The purpose of this study (Reference 1) was to explore the latter alternative. Specific objectives were to develop an advanced technology SOF C -130 CWB conceptual design and to determine its acquisition and operation and support costs. The goals for the advanced technology CWB relative to the current C-130H CWB were: (1) the same acquisition cost; (2) lower operating and support costs; (3) equal or lower weight; (4) a 30,000 hour service life for the SOF mission; and (5) minimum impact on the current maintenance concept.

C-130H CWB STRUCTURAL ARRANGEMENT

An isometric view of the C-130H CWB structure is shown in **Figure 1.** The CWB structure spans WS 220 left to WS 220 right, minus the leading edge structure forward of the front beam and trailing edge structure aft of the rear beam. The box consists of upper and lower multi-piece hat stiffened skins, front and rear beams (spars) and ten ribs. Bladder type fuel tanks are contained between WS 61 and 178 left and right. The current design is all metal, mainly 7075-T73 aluminum alloy.

The advanced design CWB has to maintain several structural interfaces. These are (1) fuselage attachments at WS 20 ribs left and right to BL20 fuselage upper longerons, (2) fuselage attachments at WS 61 left and right - lower skin to drag angle, front beam to fuselage post, and aft beam to fuselage post, (3) the inboard engine truss mount left and right, (4) the outer wing attachment through upper and lower rainbow fittings, corner fittings, and spar web splices at WS 220 left and right, and (5) the leading edge assembly attachment to the front beam and trailing edge attachment at the rear beam. System interfaces are: (1) fuel systems that penetrate the front beam and ribs at WS 178, (2) electrical controls (engine and flight) and ECS along the front beam outside of the box, and (3) multiple penetrations in the center dry bay area.

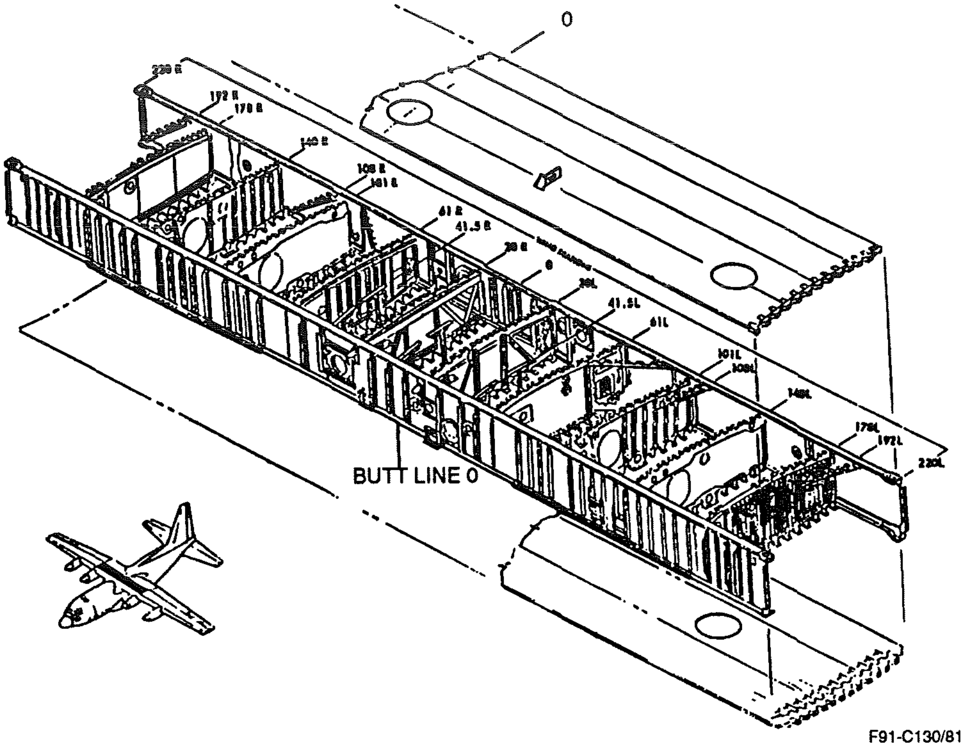


Figure 1. C-130 CWB Structural Arrangement.

A weight breakdown of the C-130H CWB is presented in **Figure 2**. Total weight is 4811 lb, where the upper and lower wing skins represent approximately two-thirds of this weight. Previous studies have shown that a metal "beef-up" of approximately 1000 lb is required to provide a durable CWB for the SOF C-130 mission profile.

The primary external loads on the C-130H CWB were derived from flight maneuver, gust loads, and ground conditions. Six critical conditions constitute the corner points of the load envelope for the middle of the CWB at WS 95. These load envelopes are shown in **Figure 3**. These six load conditions were selected for internal loads development for the baseline C-130H CWB and included maximum and minimum bending moments, shears and torsions, and combinations thereof. The loads in Figure 3 were increased by 20% to account for the more severe SOF C mission. The advanced CWB was designed to these increased loads.

The SOF C-130 CWB fatigue load spectrum was not available for this conceptual design study program. An approximate SOF C-130 CWB fatigue spectrum was developed with Air Force approval. The mission mix was specified as 20 percent proficiency training, 30 percent short range logistics, and 50 percent combat training. Exceedance data for tactical training, ferry and Red Flag

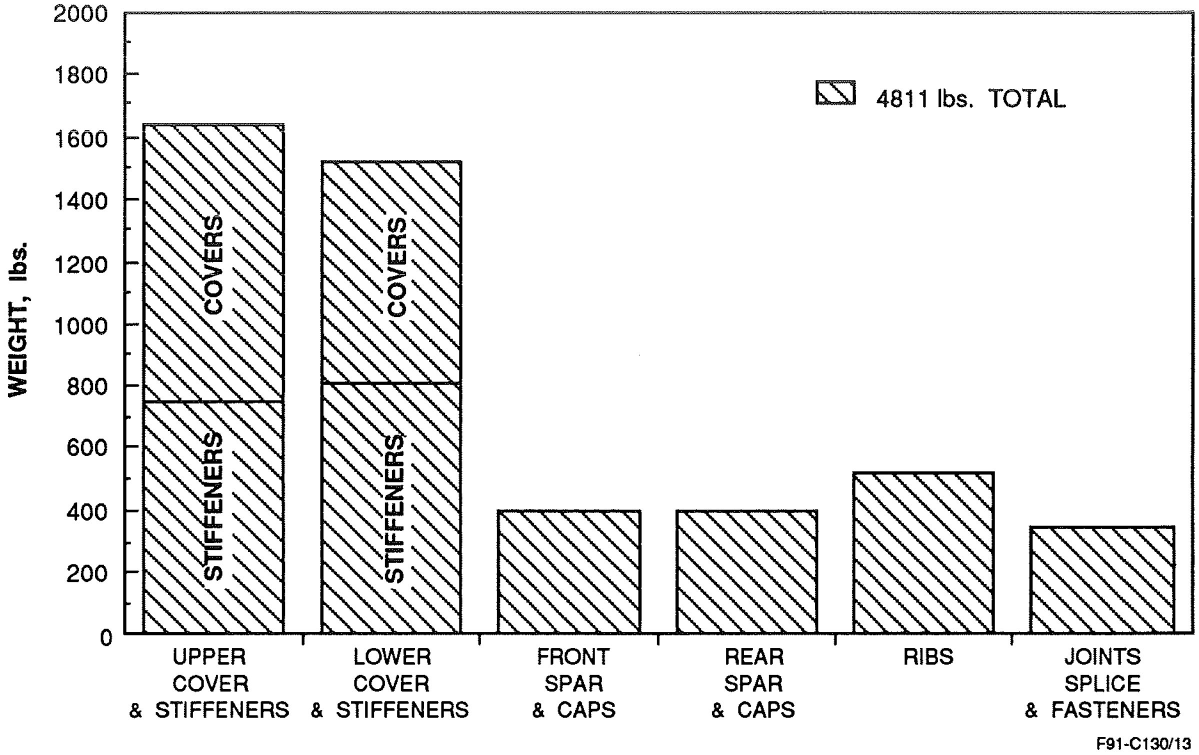


Figure 2. C-130H CWB Weight Breakdown.

were used respectively for the three specified missions. The delta load factor versus cumulative exceedances curve developed for the Red Flag mission is presented in **Figure 4**. These delta load factor exceedance data were subsequently used for fatigue analysis.

DESIGN CRITERIA

General structural design criteria were based on AFGS-87221A. For the purposes of this study, durability/damage tolerance design criteria were as follows: metallic structure was designed to a fatigue life of four times service life (120,000 hours). Fatigue life was defined as crack initiation to 0.01 inch. Composite structure was designed to damage tolerance requirements because of their insensitivity to undamaged fatigue loading. Composite upper skins were required to sustain 100 ft-lb impact or visible damage, whichever occurred first. The 100 ft-lb impact represents a 25 lb tool box drop from four feet with an impactor diameter of 1 inch. The lower skin threat was a 25 ft-lb impact or fuel leakage caused by foreign object damage such as runway debris. The residual static strength (P_{xx}) load requirement was specified as 1.2 x DLL after two design life times (60,000 hours) of fatigue loading.

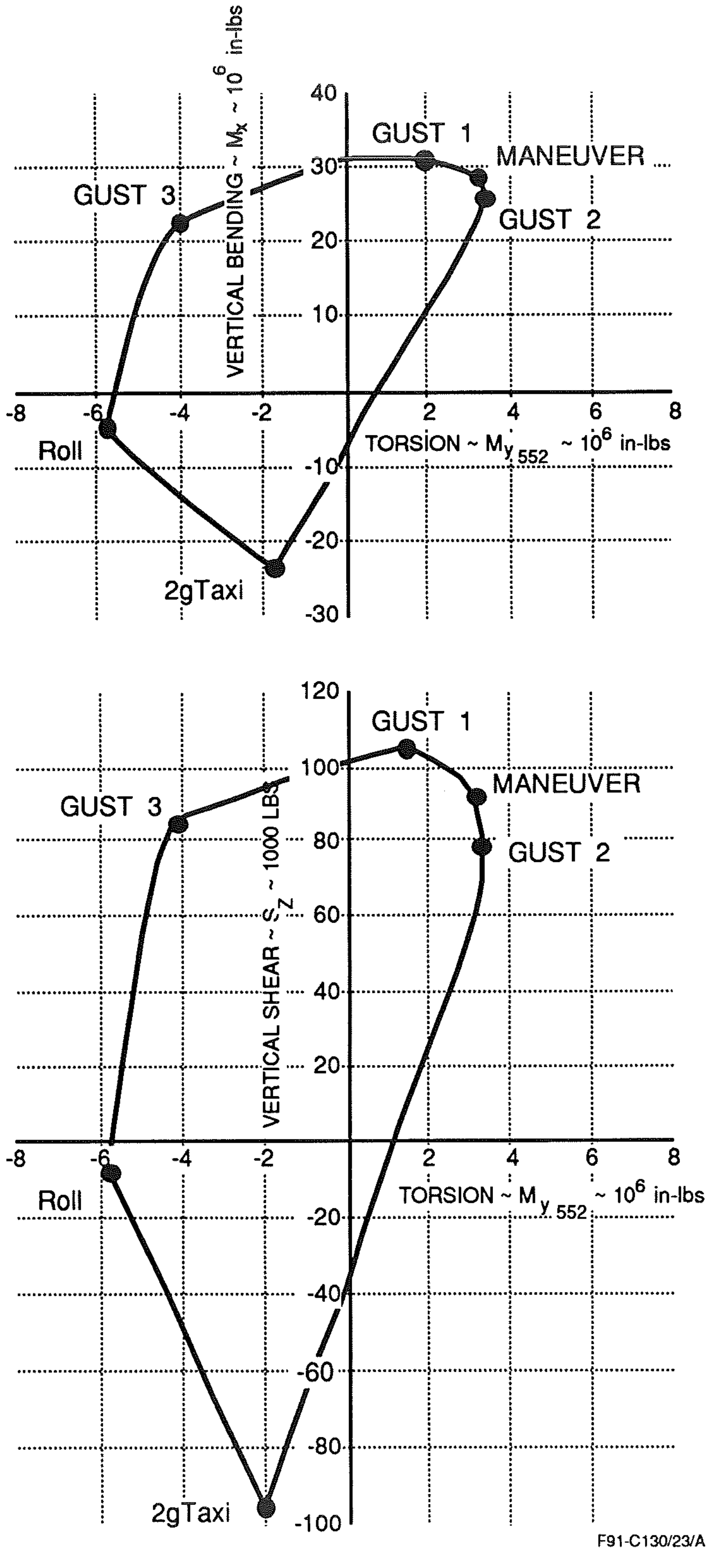


Figure 3. C-130H External Loads Envelope – Wing Station Limit Loads.

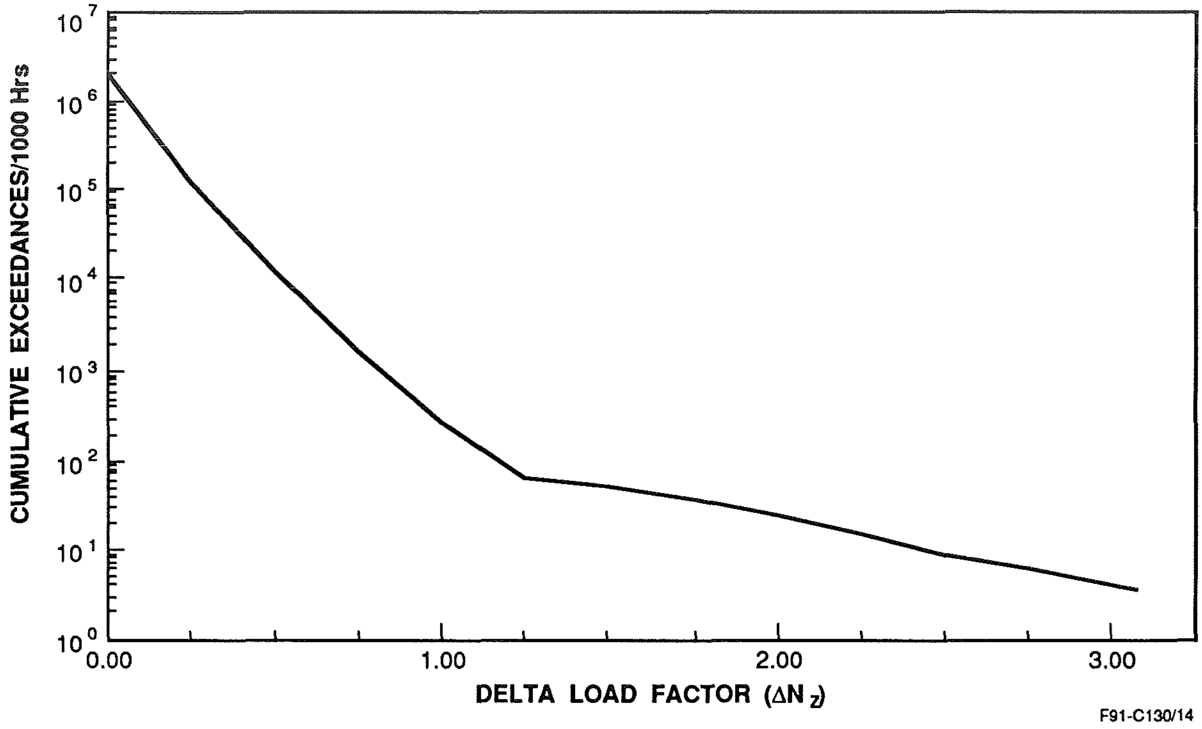


Figure 4. C-130 Red Flag Delta Load Factor Exceedances.

Design allowables for mature metallic alloys were taken from MIL-HDBK-5. Advanced metallic alloy allowables were derived from in-house data. Two classes of composite materials were utilized in the study: two first generation epoxies, AS4/3501-6 and AS4/3502, and two second generation toughened thermosets with an intermediate modulus fiber; they were IM7/8552 and IM7/5250-4. These materials were selected after a comprehensive advanced materials assessment which is documented in Reference 1. Lamina and laminate strength design allowables for unidirectional tape are given below:

Lamina Allowables

AS4/3501-6 or 3502
Tension Modulus E_1 = 18.7 Msi
Compression Modulus E_2 = 17.6 Msi

IM7/8552 or 5250-4
Tension Modulus E_1 = 22.6 Msi
Compression Modulus E_2 = 20.2 Msi

Laminate Allowables

$$\varepsilon_{\text{ALLOW}}^{\text{TENSION}} = \varepsilon_{\text{ALLOW}}^{\text{COMPRESSION}} = 5{,}000\ \mu\text{in/in}$$

Interlaminar Tension Strength

$$\sigma_{\text{ALLOW}}^{\text{TENSION}} = 2400\ \text{psi}$$

The laminate strength allowables (for all materials) of 5000 μin/in are based on a 0.25 inch fastener hole and account for an operating environment of -67°F to 180°F with end-of-lifetime moisture content. Test data indicate a potential for laminate strain allowables in excess of 5000 μin/in. However, the laminate strain allowable was limited to 5000 μin/in for three reasons: (1) bolted repair capability; (2) minimization of bolt bearing by-pass effects; and (3) ballistic damage tolerance. The interlaminar tension strength allowable is derived from test data on low-to-medium toughness thermoset systems such as AS/3501-6 and AS4/5250-3.

The durability design allowable is driven by control of hole wear in highly loaded holes. This is achieved by limiting bearing stresses such that

$$\sigma_{\text{ALLOW}}^{\text{BEARING YIELD}} = \text{DESIGN LIMIT LOAD} = 70\ \text{ksi}$$

Damage tolerance allowables at design ultimate load ranged from 3125 μin/in to 5000 μin/in because of their dependency on impact threat severity, material toughness, and laminate thickness.

TRADE STUDIES

Figure 5 summarizes the overall trade study approach, which was conducted in three phases. In Phase I, the team is selected, a kick-off meeting is convened, and the study criteria are established based on customer needs which are translated into product and process design requirements. At the end of Phase I, trade study initiation forms are completed for each task.

In Phase II, team brainstorming sessions generate design concepts from which candidate concepts are downselected for further evaluation. The brainstorming sessions develop as many viable concepts as possible in order to increase the chances of identifying and selecting the best approach. Preliminary downselection of the candidate concepts is based on the Pugh method of concept evaluation.

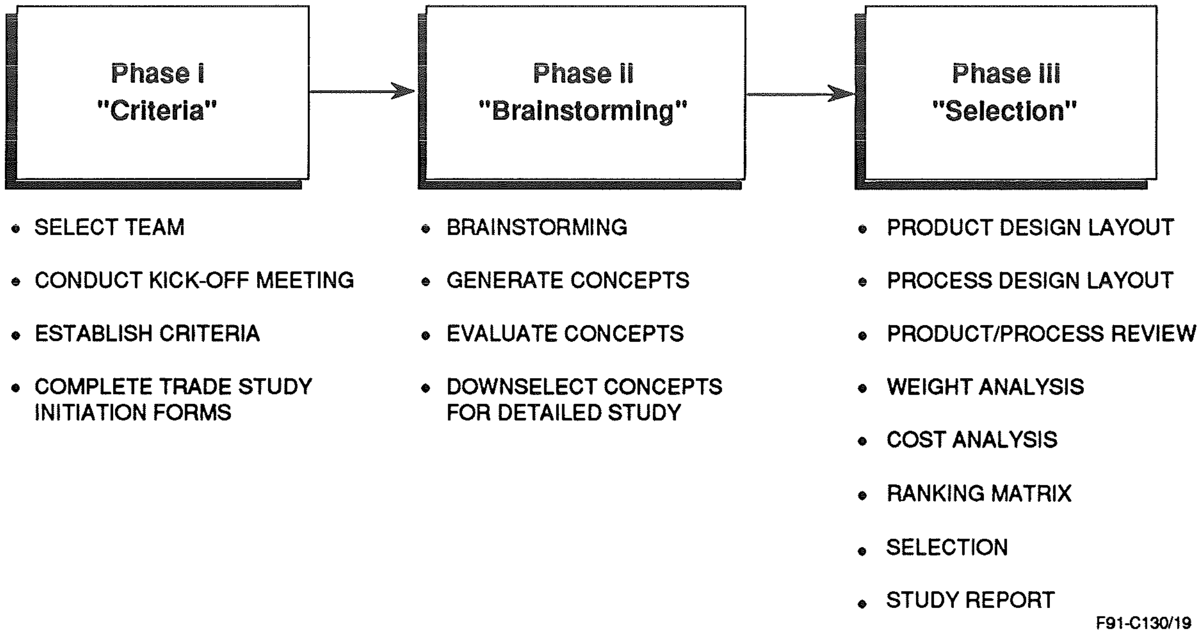


Figure 5. Overal Trade Study Approach.

The Pugh method results in a manageable number of relevant design concepts that can be evaluated in greater detail. The Phase III approach developed to accomplish this evaluation is a tailored approach which uses traditional trade study measures of merit and weighting factors. Also, elements and techniques common to the application of Quality Function Deployment and "Forced Decision Making" have been incorporated into the methodology. Included among these elements is a strong emphasis on team effort, the physical format, and the "What-How" approach to evaluating the relationships between the concepts and the selection criteria. Forced Decision Making requires each concept to be evaluated not only with respect to how well it satisfies the design requirements, but also how well it satisfies these requirements with respect to the other concepts. To adequately assess the concepts in Phase III, a thorough understanding of each of the downselected concepts is required. It is essential for the Pugh preliminary downselection process to eliminate as many concepts as possible to reduce the effort required in Phase III.

Trade studies were conducted on the CWB wing skins, spars, ribs, and rainbow fitting. The wing skin trade study is discussed because it had the most impact on the final conceptual design.

Wing Skin Trade Studies

The objective of this trade study was to compare design configurations and manufacturing methods for fabricating the stiffened upper and lower wing skins for the center wing box of the

C-130. Skin stiffener configurations and potential tooling and fabrication approaches were analyzed and evaluated to select the preferred concept for full-scale development.

Five candidate skin concepts emerged from the Phase II brainstorming for preliminary concept evaluation using the Pugh method. The first concept was an advanced metallic skin. The other four were composite wing skin design concepts which featured different stiffener configurations for integrally stiffened, monolithic one-piece composite skins. The stiffener cross-sections included blades, hats, "I-beams," and "J"s. **Figure 6** shows the results of the Pugh analysis of these five concepts. The advanced metal concept was rated unsatisfactory for weight because it could not meet the weight target and satisfy the durability requirements. It was concluded that the excellent

TRADE STUDY CONCEPT COMPARISON PAGE 1 OF 1

TITLE: **C-130 CWB - Wing Skins**
STUDY LEADER: J. LUZAR
A. HIKEN
DATE: 11/15/90

CRITERIA / CONCEPTS		1 ADVANCED METALLIC	2 COMPOSITE BLADE	3 COMPOSITE HAT	4 COMPOSITE I-BEAM	5 COMPOSITE "J"
STRUCTURES DAMAGE TOLERANCE/FATIGUE	BASELINE	+	+	+	+	+
BALLISTIC		S	S	S	S	S
LIGHTNING		S	-	-	-	-
INTERFACE		S	S	S	S	S
FUEL PRESSURE		S	-	-	-	-
WEIGHT		U	+	+	+	+
MAT'LS & PROC FUEL SEALING		S	S	S	-	-
CORROSION CONTROL		S	+	+	+	+
MANUFACTURING ACQUISITION COST		S	S	S	-	-
RISK		S	S	S	-	-
R & M INSPECTABILITY		S	S	S	S	S
MAINTAINABILITY		+	+	+	+	+
REPAIRABILITY		S	S	S	-	-
TOTAL	+	U	4	4	4	4
	-		2	2	6	6

SCALE + CLEARLY BETTER - CLEARLY WORSE S ABOUT THE SAME U UNACCEPTABLE

F91-C130/52

Figure 6. Phase II Pugh Preliminary Concept Evaluation for Wing Skin Trade Studies.

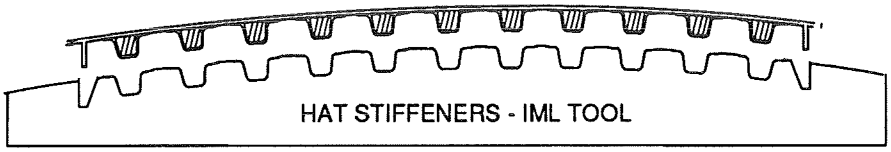
durability characteristics of composite wing skins were necessary to achieve the CWB structural weight goal. Preliminary downselection eliminated the "I-beam" and "J" configurations (Concepts 4 and 5), primarily based on the greater manufacturing risk and higher cost of these configurations compared to the blades and hats (Concepts 2 and 3). Fuel sealing requirements were also considered in this preliminary evaluation. The assessment of manufacturing risk and cost was based on the complexity of the stiffener shape, the number of details comprising the stiffener, the tooling requirements, and the manufacturing experience of Northrop and LTV. The Pugh evaluation in Figure 6 shows that blade and hat stiffeners were preferred to "I-beam" and "J" stiffeners, because they had major advantages in the areas of fuel sealing, cost, risk and repairability. Therefore, the hat and blade stiffened composite wing skin concepts were selected as the candidates for the more detailed Phase III evaluation prior to downselecting to a preferred approach. OML and IML tooling concepts were considered for both stiffening configurations; **Figure 7** shows the four candidate concepts. The detailed downselection focused on manufacturing risk issues - tooling, fabrication, and assembly - and on achieving an integral fuel tank.

A key issue in the selection of the wing skin stiffening concept was continuous versus discontinuous stiffening elements. Fuel sealing at the fuel closeout rib/wing skin-stiffener intersection was a critical requirement in the integral fuel tank design. Successful, reliable fuel sealing at this intersection is dependent on many factors, including the rib and stiffener configurations.

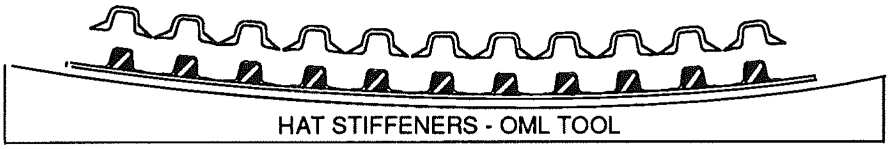
The continuous stiffening approach uses wing skin stiffeners uninterrupted at the fuel closeout rib intersections. The rib caps are joggled around the stiffeners or are relieved at the stiffener intersections and separate fittings are used to achieve the fuel seal. In the discontinuous stiffener approach, the stiffeners are interrupted at the rib intersections and a flat rib cap assembles to a flat land area on the wing skin, creating the fuel seal. It is clear from a structural load carrying perspective, that the continuous stiffener approach is preferred. The severe loading conditions and the proximity of the outboard fuel closeout ribs to the wing attach fitting do not favor the discontinuous stiffener concept. The ability to transition loads from the wing skin stiffeners around (into the skin) or through (using a separate fitting) the fuel closeout rib was a critical factor in the wing skin stiffening concept decision making process. A discontinuous wing skin stiffening approach is preferred when considering the fuel sealing requirements at the rib cap/wing skin stiffener intersections. In this approach, the fuel seal can be accomplished without the need for a complex rib cap configuration or subsequent assembly operations.

Continuous stiffening was determined to be the preferred approach for satisfying the wing skin and the integral fuel tank requirements. Using concurrent engineering in the development

HATS

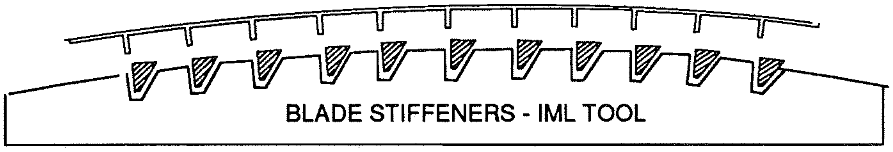


Concept A1

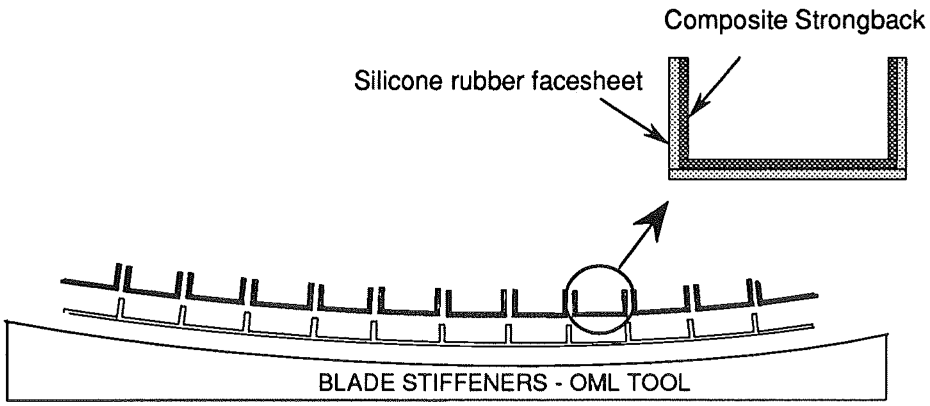


Concept A2

BLADES



Concept B1



Concept B2

F91-C130/53/A

Figure 7. Phase III Candidate Wing Skin Concepts.

process, and applying the trade study methodology, it was determined that the design and manufacturing complexity resulting from stiffener discontinuity would outweigh the potential fuel sealing benefits. As a result, the wing skin stiffener configuration candidates shown in **Figure 7** assumed continuous stiffeners in the design.

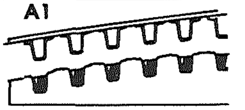
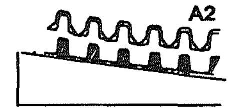
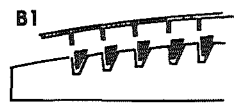
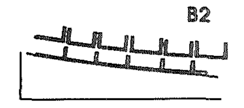
Recent successful IR&D activities for developing integral fuel tank designs using cocured hat stiffened skins and the IML tooling approach (Concept A1 in Figure 7) have identified and addressed many of the manufacturing risk issues. As a result of the IR&D development, Northrop/LTV have a high degree of confidence in this approach. IML tooling is preferred as a means of controlling the assembly surfaces to support the incorporation of an integral fuel tank into the wing box design. Concept A2 which has OML tooled hat stiffened skins (while extensively used, and highly successful on the YF-23) does not support the incorporation of an integral fuel tank into the center wing box design.

The blade stiffened skins concepts (B1 and B2) reflect the approaches currently used on bomber wing skins. Northrop uses the IML tooling concept, while LTV uses the OML tooling approach. The fabrication and tooling risks associated with an IML tooled, blade stiffened wing skin are high (relative to the other concepts) due to the size requirements for a C-130 CWB. The IML tooled blade stiffened wing skin concept (B1) is comparable to the IML tooled hat stiffened skin (Concept A1) with respect to manufacturing risk and cost, but is less preferable for the incorporation of the integral fuel tank into the CWB design. The evaluation of the candidate concepts using the downselection methodology indicated that the IML tooled, hat stiffened approach (Concept A1) was the preferred concept. The downselection matrix is shown in **Figure 8**.

Structural trade studies were conducted to determine the relative weights of hat and blade stiffened composite wing skins. The results are presented in **Figure 9.** Substantial weight savings (22%-45%) were achieved for both hat and blade stiffener configurations. For the same skin lay-up, the intermediate modulus toughened thermoset (IM7/8552 or 5250-4) provided approximately 10% additional weight savings over the first generation (AS4/3501-6 or 3502) systems. Composite wing skins are, therefore, extremely attractive from the product design viewpoint.

ADVANCED CWB CONCEPTUAL DESIGN

The selected advanced CWB design is shown in **Figures 10 and 11**. The CWB is a hybrid composite/metal structure. The upper and lower skins, front and rear spars and rib webs are composite. The rainbow fittings are titanium, and the remaining structure, except fasteners, are aluminum. The upper and lower skins are one piece with cocured hat stiffeners. All stiffeners are

PRIMARY	SECONDARY	TERTIARY			TARGET VALUE	IMPORTANCE WEIGHTING FACTOR 5 → 1 STRONG WEAK	A1 	A2 	B1 	B2 
PROCESS DESIGN REQUIREMENTS	LOW RISK	TOOLING	CONFIGURATION	FEMALE CORNERS	↓ MINIMIZE	5	9	9	3	9
				TOOLING DETAILS	EASY REMOVAL					
			MATERIAL	COST (RAW MAT'L)	↓ MINIMIZE					
				COST (FABRICATION)	↓ MINIMIZE					
				DURABILITY	↑ MAXIMIZE					
				ACCURACY	↑ MAXIMIZE					
		FABRICATION	LAYUP COMPLEXITY (STIFFENER)		↓ MINIMIZE	5	9	9	1	9
			PROCESS MATURITY		CURRENT IN-HOUSE PRODUCTION					
			STIFFENERS		↓ COST					
		ASSEMBLY	ACCESSIBILITY		MINIMIZE BLIND FASTENERS	5	3	1	9	3
			TOLERANCE BUILDUP ALLOWANCE		NO HARD SHIMS					
	LOW COST	FABRICATION OPERATIONS	(DETAILS PER PART, DEBULKING, PREFORMING, TRIM, INSPECTION, etc.)		↓ MINIMIZE	2	9	3	1	3
	PROCESS DESIGN SUBTOTAL SCORE					▨	123	101	67	111
PRODUCT DESIGN REQUIREMENTS	INTEGRAL FUEL TANK	FUEL SEALING SURFACES			TOOLED/NO MARKOFF	5	9	1	9	3
		FUEL SEALING ASSEMBLY JOINTS			↓ MINIMIZE					
		FUEL SEALING FASTENERS (QTY)			↓ MINIMIZE					
	PERFORMANCE	STRUCTURES	DAMAGE TOLERANCE/FATIGUE		↑ MAXIMIZE					
			BALLISTIC		MEETS EXISTING					
			LIGHTNING		MEETS EXISTING					
			INTERFACE		MEETS EXISTING					
			FUEL PRESSURE		13 PSI					
			WEIGHT		≤ BASELINE (LBS)					
		M & P	CORROSION		↓ MINIMIZE					
		R & M	INSPECTABILITY		CONVENTIONAL					
			MAINTAINABILITY		↓ COST					
			REPAIRABILITY		EASY ACCESS					
			PRODUCT DESIGN SUBTOTAL SCORE			▨	45	5	45	15
					TOTAL SCORE		168	106	112	126
					RANK		1	4	3	2

F91-C130/54

Figure 8. Phase III Wing Skin Concepts Downselection Methodology.

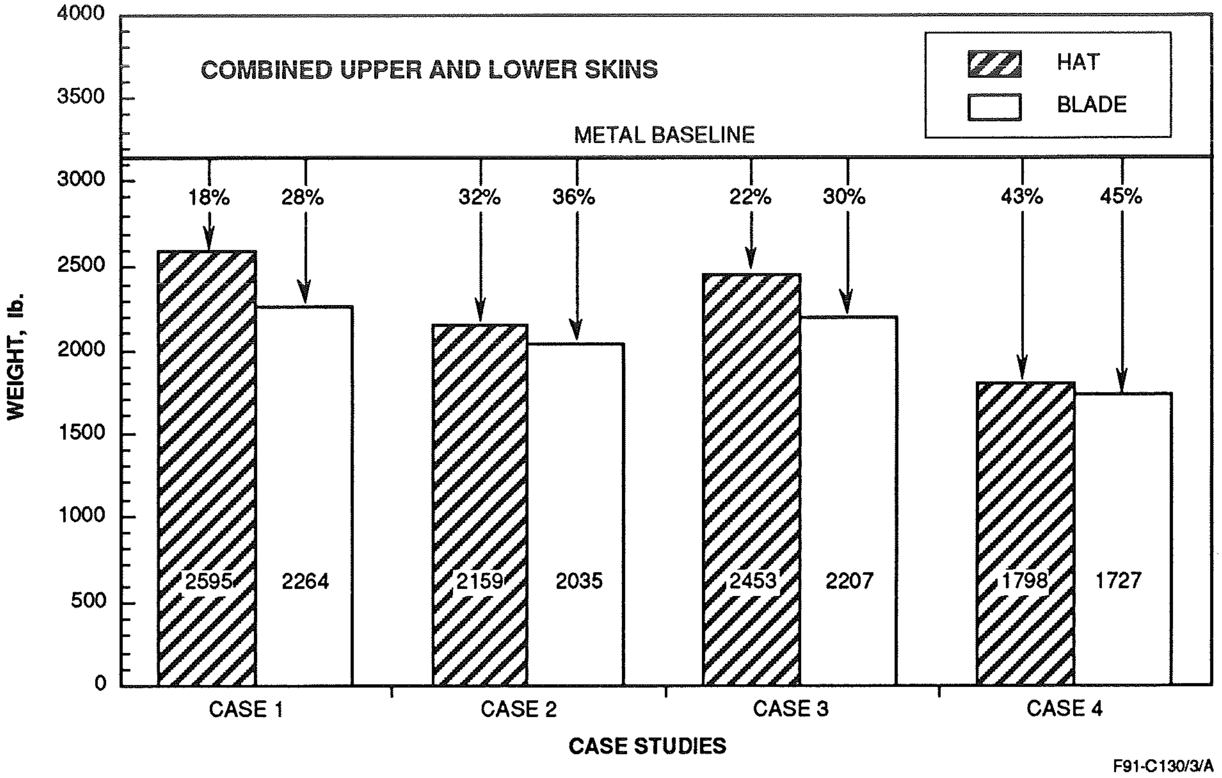


Figure 9. Combined Upper and Lower Wing Skin Weight Reults.

continuous from tip to tip except at access holes. Integral front and rear spar caps are also built into the upper and lower skins. Spar webs are flat with cocured stiffeners. The ribs are discontinuous multi-piece structure with full-depth webs and caps. Key features of the design are: assembly simplicity, 60 percent fewer fasteners than the C-130H metal CWB, two integral fuel tanks and product design robustness.

Figure 12 presents a summary of the advanced CWB weight breakdown and material distribution. The CWB weight using first generation epoxies (such as AS4/3501-6 or 3502) is 4150 lb, which represents a 14 percent weight savings over the baseline C-130H CWB. If an intermediate modulus fiber and tough resin are used for the advanced CWB composite parts (e.g., IM7/8552 or IM7/5250-4) a 24 percent weight savings can be achieved in the advanced CWB. Figure 12 also shows the advanced CWB material distribution, which is 72 percent composite, 19 percent aluminum, and 9 percent titanium.

COST ANALYSIS

A summary of the advanced CWB costs are presented in **Figure 13**. The costs assume

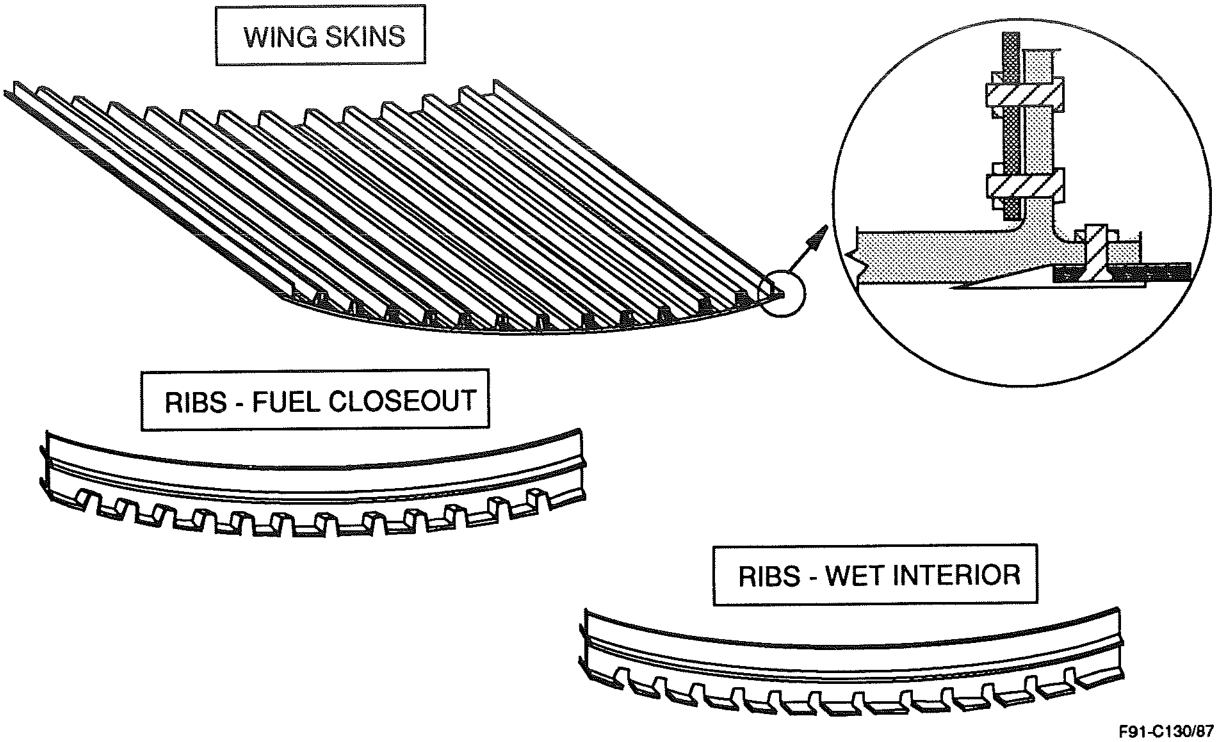


Figure 10. Selected Concepts for the Advanced CWB.

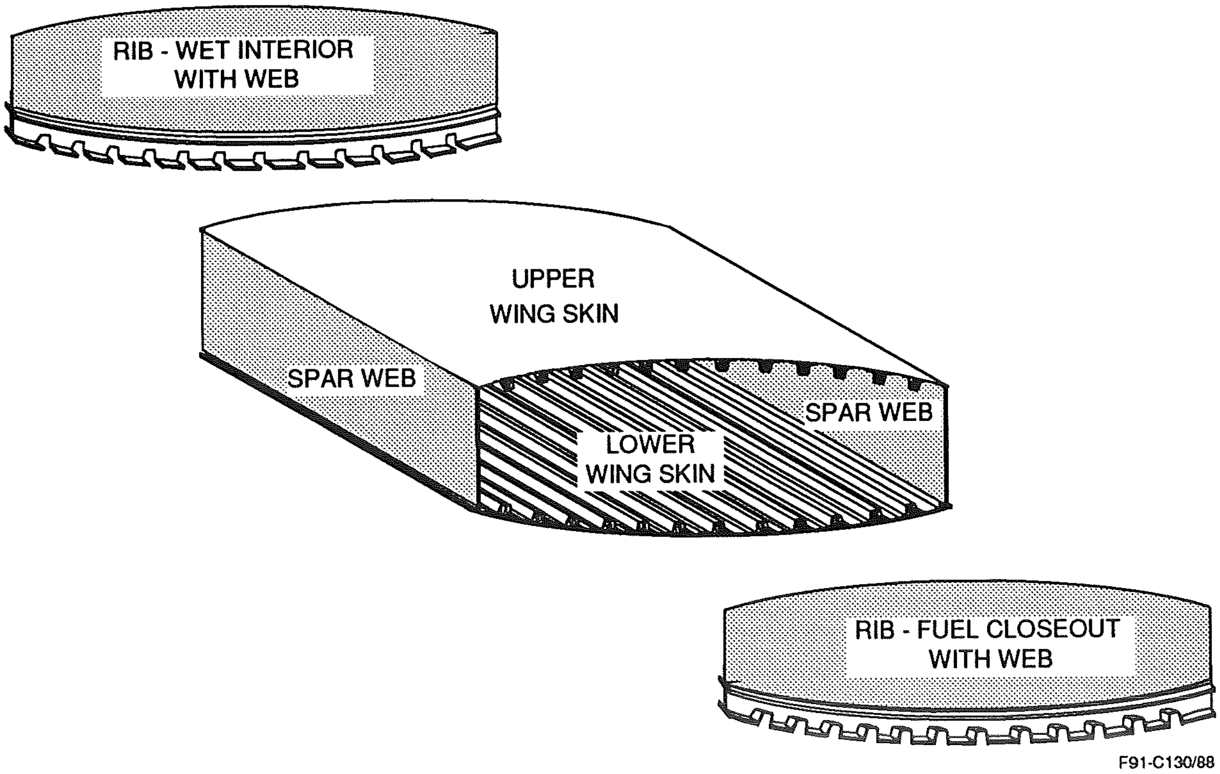
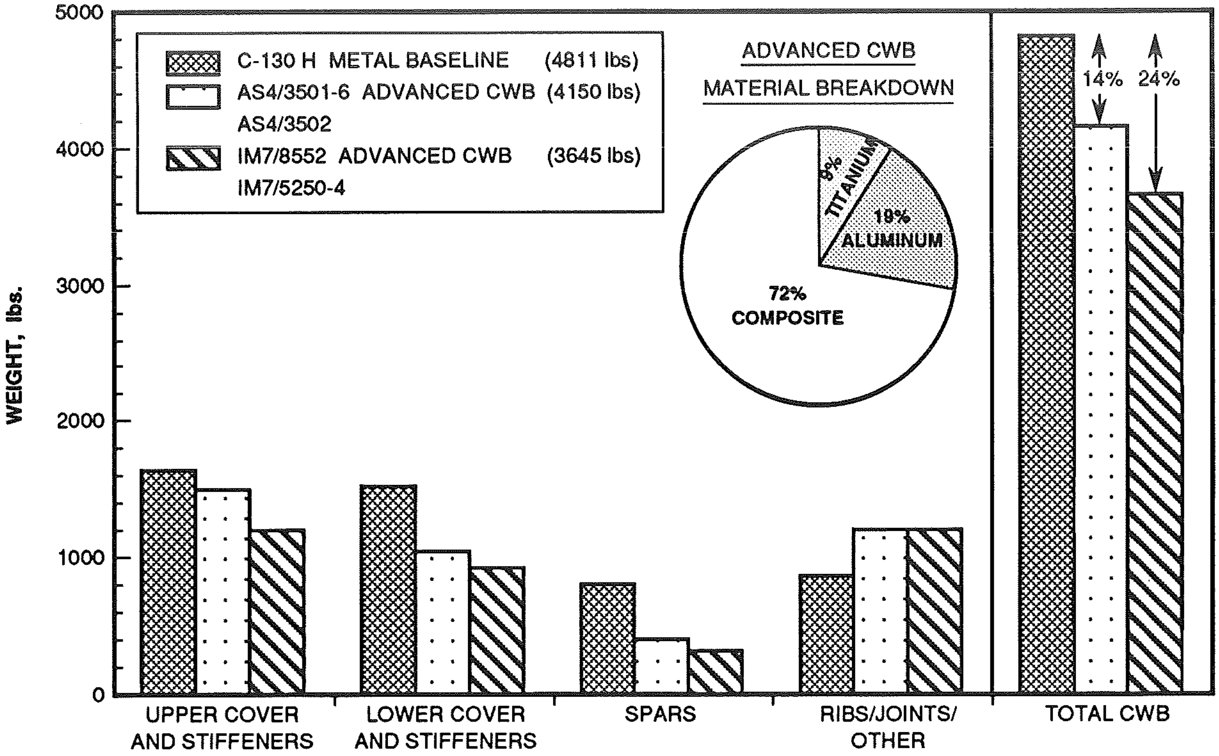
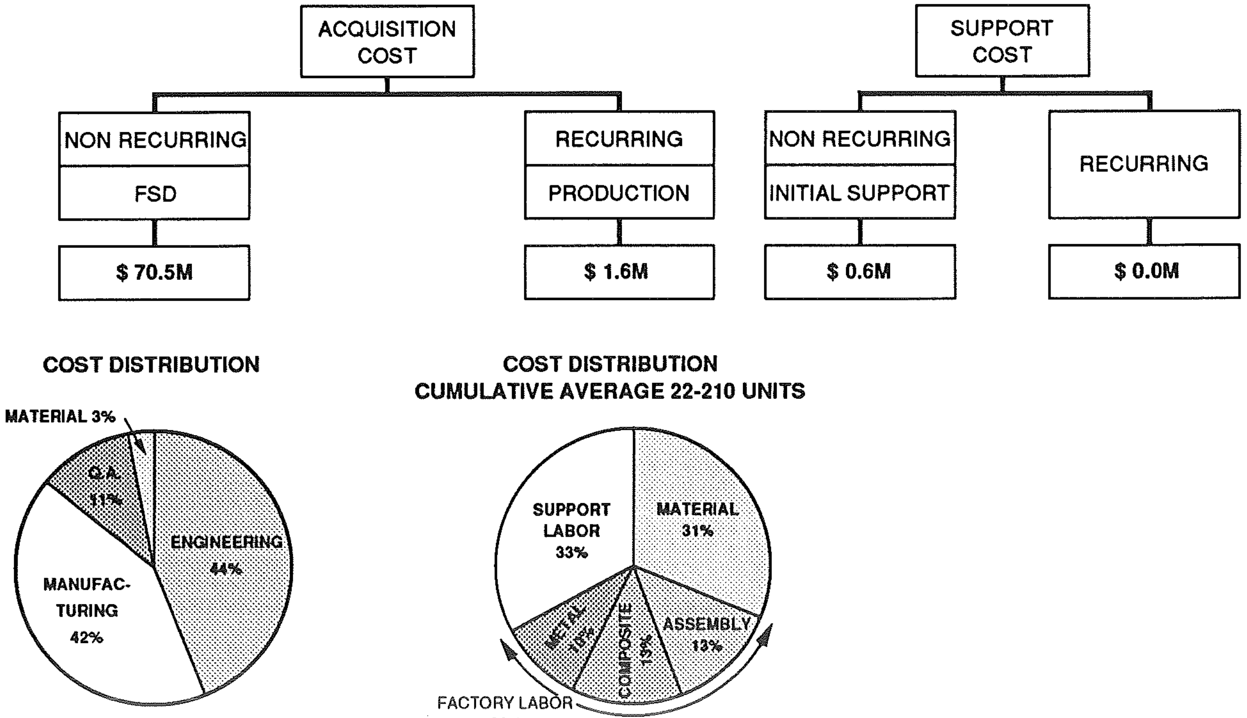


Figure 11. Selected Assembly Concepts for the Advanced CWB.



F91-C130/89

Figure 12. CWB Weight Breakdown.



* $100/hour Assumed Wrap Rate

F91-C130/90

Figure 13. Advanced CWB Cost Summary. *

a $100/hour wrap rate. Nonrecurring FSD costs are approximately $70 million. The cumulative average recurring cost for a 22-210 unit buy is $1.6 million.

Figure 14 summarizes the life-cycle cost comparison approach for the advanced CWB and the C-130H CWB flown to an SOF mission profile. Baseline operation and support (O&S) costs are common costs for all CWBs. TCTO inspection and part repair or changeout are incurred on aircraft. Thus, in the break-even life-cycle cost scenario, it is the latter two which determine the break-even point, if the advanced CWB has a higher acquisition cost than the C-130H CWB.

Figure 15 applies this methodology directly to the advanced CWB and a C-130H CWB operating under durability limits. The advanced CWB cost of $1.6 million is approximately 84 percent higher than a standard C-130H CWB at $871,000. However, since the current C-130H CWB costs $475/hour in maintenance costs, it consumes the price of its acquisition cost in 1833 flight hours. In addition, after 1540 flight hours, the current wing box has a life-cycle cost of $1.6 million, equal to the advanced CWB acquisition cost, which requires no TCTO action. Therefore, the breakeven point of the advanced CWB in total life-cycle costs is 1540 flight hours or less than two calendar years. It should be noted that if nonrecurring FSD costs are amortized over 210 units, the break-even point will be reached in the third year.

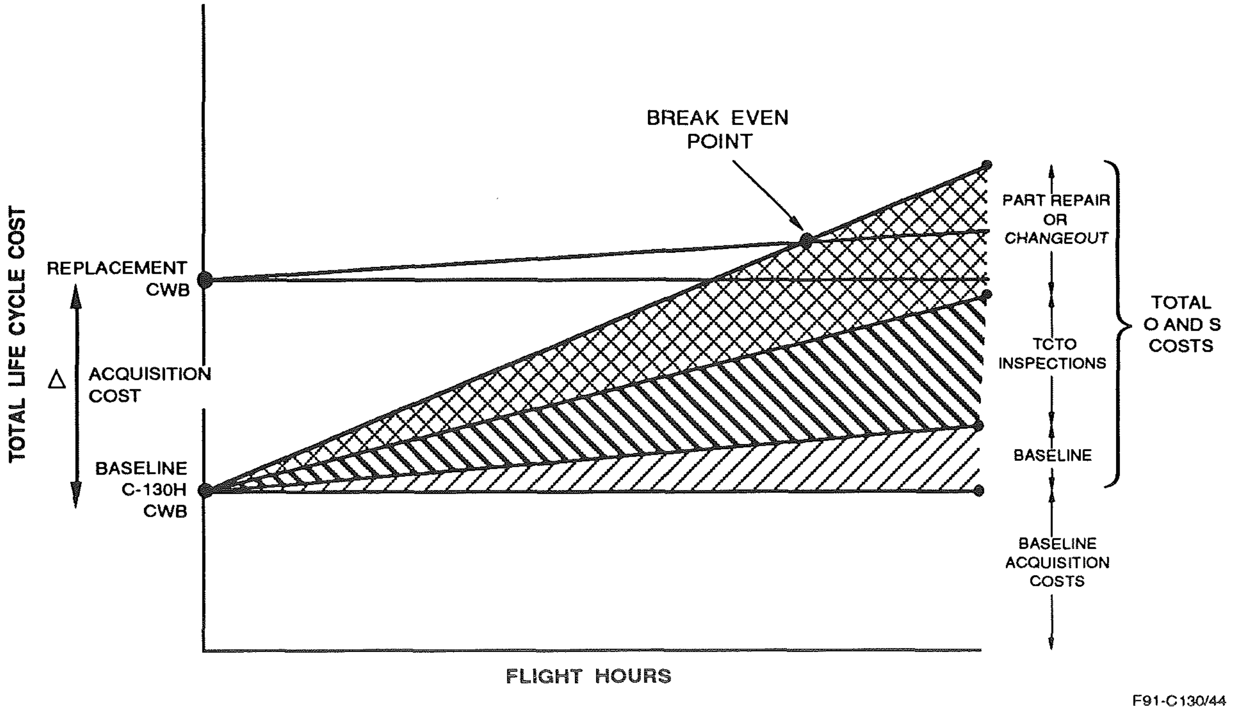


Figure 14. Life Cycle Cost Comparison Approach for the Advanced CWB versus C-130H CWB.

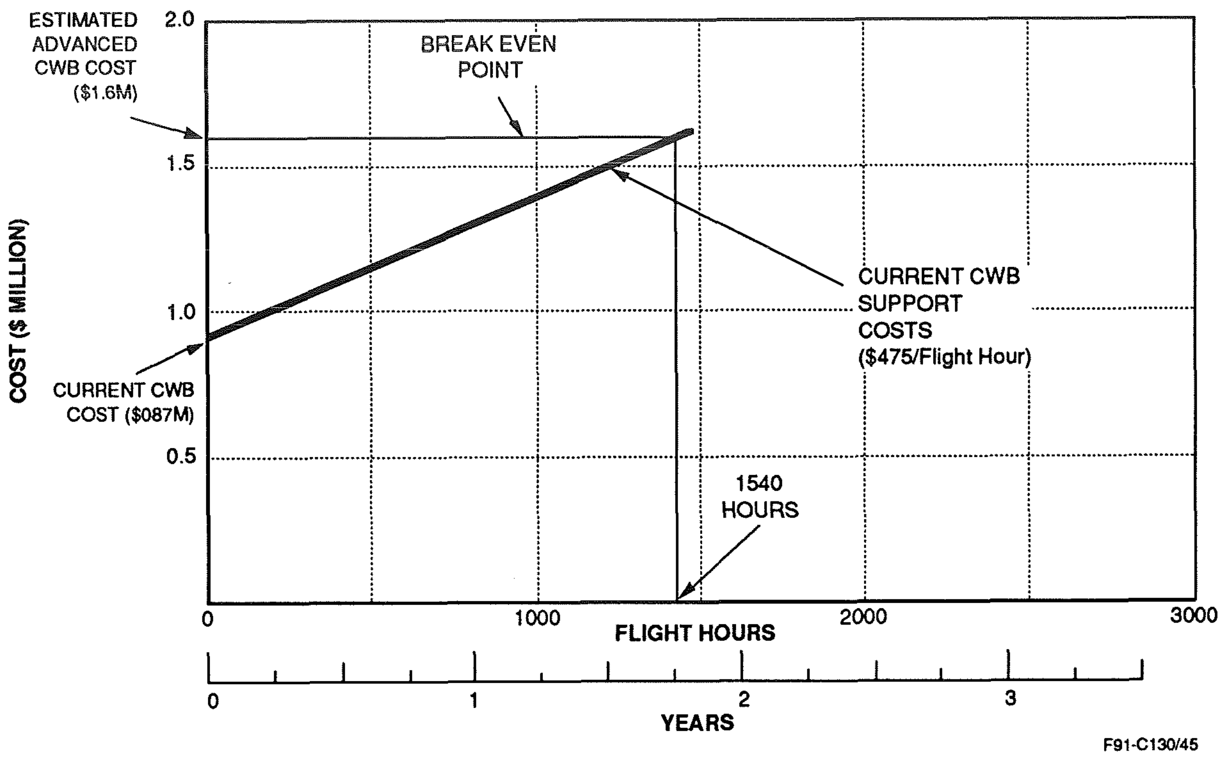


Figure 15. Break Even Life Cost for Advanced CWB versus Current C-130H CWB.

SUMMARY

The selected hybrid composite/metallic advanced C-130 CWB concept met the severe SOF design requirements, reduced CWB weight by 14%-24%, and was cost effective relative to the current metal C-130H CWB. A significant composite weight fraction was needed to meet the severe SOF mission profile and the 4811 lb target. Lessons learned from prior Northrop/LTV programs were significant drivers in design concept selection, FSD approach and cost analysis.

ACKNOWLEDGMENTS

More than fifty Northrop personnel contributed to this program; their many and varied contributions are gratefully acknowledged. Special thanks are due to Govind Chanani, J.A. Hangen, John Luzar, Mike Jankowski, Daniel Acevedo, Tod Palm, Edmund Unterreiner III, Monica Rommel, Rick Kane, Alan Hiken, Scott Harris, and Douglas Sylvers, each of whom made invaluable contributions to the program. The team members from LTV played a crucial role in the program. Their participation and experience significantly influenced and improved the end product of this effort. Special thanks are due to Charles Foreman, Digger O'Dell, John Pimm, and Steven Rice.

Special acknowledgment and thanks go to Captain Kevin Silva and Lt. David Marcontell (WR/ALC) for their tireless efforts in supplying supporting information for the program. Without their interest and dedication, the execution of this program would have been extremely difficult.

REFERENCES

1. Whitehead, R.S., et al, "C-130 Advanced Technology Center Wing Box Conceptual Design/ Cost Study", Report No. WL-TR-91-3059, August 1991.

2. Jacobson, M.J., et al., "Battle Damage Tolerant Composite Wing Structure," Northrop Subcontract P.O. 600037 to Boeing Military Airplanes, NADC Contract Number N62269-89-C-0251.

3. Horton, R.E., et al., "Damage Tolerance of Composites," Volume II - Investigation of Thermoplastics (AS4/APC-2), Configuration Effects and Battle Damage Tolerance, AFWAL-TR-87-3030, July 1988.