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Design Concepts For Low-cost Composite Engine Frames

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DESIGN CONCEPTS FOR LOW-COST COMPOSITE ENGINE FRAMES

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ABSTRACT

Design concepts for low-cost, lightweight composite engine frames were applied to the design requirements for the frame of commercial transport high-bypass turbine engines. The concepts included generic-type components and subcomponents that could be adapted for use in different locations in the engine and to different engine sizes. A variety of materials and manufacturing methods were assessed with a goal of having the lowest number of parts possible at the lowest possible cost. Evaluation of the design concepts resulted in the identification of a hybrid composite frame which would weigh about 20 percent less than the state-of-the-art metal and cost about 40 percent less.

INTRODUCTION

Composite turbofan engine frames have the potential for reducing both the weight and cost compared with state-of-the-art metal frames. Previous studies (Quiet Clean Short Haul Experimental Engine (QCSEE) program[1], e.g.) have shown that substantial improvement in weight and performance benefits are possible through the use of composites in turbofan engine frames. These benefits are derivable mainly from the high stiffness, lightweight, and property-tailoring characteristics of fiber composites. However, the cost for making composite engine frames now is almost prohibitively high. The major reason for the high cost is that design concepts to date require a large number of parts to make the frame (approx. 6000 parts for the QCSEE engine frame). It is recognized in the composites community that a significant factor in the fabrication of composite aircraft structures is the cost encountered in laminating composite materials before curing. A major manufacturing benefit of using composite materials is the reduced number of parts required to make complex aircraft composite structural components compared with the corresponding metal components. NASA Lewis Research Center sponsored a program[2] with the objective to evolve design concepts which lead to a minimum number of parts and with low-cost potential for turbofan engine composite frames. Specifically, design concepts for low-cost, lightweight composite engine frames were applied to the design requirements for the frame of a commercial transport high-bypass turbine engine. Four potential alternative composite frame design concepts were identified. Each concept consisted of generic-type components and subcomponents that could be adapted for use in different locations in the engine and to different engine sizes. A variety of materials and manufacturing methods were assessed with a goal of having the least number of parts possible at the lowest possible cost. After a preliminary evaluation of all four frame design concepts, two designs were selected for an extended design and evaluation which narrowed the final selection to one frame (hybrid) that was significantly lower in cost and lighter than the other frames.

DESIGN CONCEPTS

Four preliminary composite frame design concepts were generated and evaluated consistent with the design requirements (Table 1) and fabrication processes. In addition, each concept was required to be interchangeable with the same baseline engine. Some of the basic differences between concepts may appear to be minor; however, final weights and costs revealed significant differences among the concepts considered.

The four composite frame concepts identified for this study are herein described (see Figs. 1 and 2).

Concept	Description
1 - Consolidated	Many components combined to reduce the number of pieces and shapes for lowest cost.
2 - Modularized	Vanes in bonded assembly with structural spokes separately fabricated and inspected prior to committing them to final bonded assembly, with a cast aluminum frame core for low cost.
3 - Filament-Wound	As many components as possible are fabricated by low-cost filament winding or braiding techniques.
4 - Hybrid	Low-cost, two-piece vanes without individual spokes are separately fabricated and inspected prior to committing them to final "plug in" bonded assembly, with low-cost cast aluminum frame core and die-cast aluminum vane tip fan case blocks.

EVALUATION OF PRELIMINARY DESIGNS

Figures 2 to 7 illustrate the envelope of the baseline frame and the four frame design concepts examined. The numbers of shapes, pieces, and associated hours of labor projected for the first and 250th frame units are listed on each figure. The projected weights for the respective frame components are also included. The frame design concept associated with each of the figures is described:

Figure 2 - Baseline - This identifies the three frame structural elements of core, vanes, and fan case and shows the respective dimensions that are maintained for all frame concepts.

Figure 3 - Baseline Frame Data - These data are for an as-built composite QCSEE frame which was fabricated in 1975. All totals were obtained from actual part count and recorded man-hours expended on the QCSEE engine frame fabrication.

Figure 4 - Design Concept 1 - Consolidated Frame - This concept was generated by combining many flanges in both the fan case and the core of the baseline frame. As a result, fewer adhesive bond joints are required which translates into a modest weight reduction savings but a significant reduction in the number of shapes, pieces, and man-hours. The heavier Kevlar containment, however, overrides this weight savings and produces a slight increase in total frame weight.

Figure 5 - Design Concept 2 - Modularized - A cast aluminum frame core and machined aluminum fan case ring were selected to provide attachment points for the modularized vanes. Fabricating the vanes as individual modules facilitates their production and inspection compared with the integral fabrication of the core and fan case (as was done in the baseline frame). In addition, it may be possible to replace damaged vanes with low-cost maintenance procedures. The cast aluminum frame core and fabricated aluminum fan case ring account for the increased weight, but the fewer shapes and pieces translate into a very significant reduction in labor hours.

Figure 6 - Design Concept 3 - Filament-Wound - Many of the components consolidated in concept 1 are adaptable to filament winding or braiding techniques. Concept 3 would look very similar to concept 1, however the main advantage here is the fewer labor hours required compared with the hand layup hours associated with the concept 1. All shells, flanges, and outer diameter wheel cores are filament-wound or braided. All flanges are wound as torus rings or sections, then cut into "C" channels. Some would remain as complete 360° rings while others would be cut into sectors to facilitate assembly. Experienced fabricators advise that labor costs for filament-wound structures are about half those of the equiva-

lent structures laid up by hand using die-cut laminates. Not only is filament winding or braiding faster, but there is a more efficient utilization of material. However, fiber orientation is more restrictive filament winding than in hand layup procedures resulting in increased weight. Figure 7 - Design Concept 4 - Hybrid - The cast aluminum core, which includes double wedge-shaped pockets to receive mating double wedge-shaped vane root sections, is the chief contributor to higher weight. The vane tip waffle blocks also contribute more weight than the corresponding elements of the baseline frame concept. However, these efficient structures are the main contributors to significantly lower labor hours. Another main contribution to the low cost of this design is the simple two-piece hollow vanes that require no separate structural spokes and can be assembled, by simple plug-together features, to the core frame and fan case. Prospects for reducing the weight of this frame by including holes in the core casting are discussed later. Another prospect is encapsulating graphite in the cast aluminum to increase strength and reduce weight.

A comparison summary of statistics for the four frame concepts previously described are listed in Table 2 along with projections of relative cost and weight of an equivalent all-metal frame. Since the actual labor hours and component weights were experienced earlier for the baseline frame, these facts allowed the generation of realistic estimates of labor hours and weights for similar components of the four new frame design concepts. In addition, a study conducted by experienced personnel on the projected labor hours for all components of a current small composite frame program has been made available for this study. This data base provided a means for double-checking labor hour estimates for many similar frame components. To project the man-hours of effort for the 250th engine set a 20 percent increase in labor efficiency was assumed for the study.

The lowest cost frames, relative to the baseline design frame (Table 2), were established to be Design Concept 2 (58 percent baseline cost at 706 lb) and Design Concept 4 (37 percent baseline cost at 695 lb). These two frames were selected for the extended design analysis. Schematics of these two design concepts are shown in Figs. 8 and 9, respectively.

EXTENDED DESIGN ANALYSIS

The extended design analysis of frame concepts 2 and 4 included local stress calculations in the critical stress areas designated A to E in Fig. 2. Prior experience has shown that the two critical stress conditions for the frame are caused by a crosswind condition and by a 1-1/2 fan blade-out condition as described in Table 3. Critical frame components in areas A to E were sized to these conditions and a majority of the remaining new frame sections were sized by ratioing from the baseline frame.

The basic frame analysis was performed using a finite element computer program for 3-D spatial structures. The basic elements available in this computer program provide for modeling two-ended curved or straight beam, four-sided curved or flat trapezoidal plate, six-sided tetrahedron, rigid connector, spring, tube, and sandwich panel structures with orthotropic faces. The types of analyses performed included mechanical loading, thermal gradients, maneuver loads, forced response, and determination of critical frequencies. The output was in the form of loads, stresses, and deflections.

If the analytical results indicated that stress problems existed at certain locations within the structures (or if stress concentrations existed that were not accounted for in the modeling), a more detailed analysis of the region in question was performed using special finite-element programs. A description of the design analysis conducted for each of the critical frame areas follows.

Stress Area A - Fan Case to Vane Tips

Both concepts 2 and 4 have identical fan case structures except for the vane tip attachment areas. Concept 2 utilizes an extruded, rolled, and welded 2219 aluminum ring which has a 0.2 percent tensile yield strength of about 58 000 psi and is stressed at maximum load to about 40 000 psi. Concept 4 utilizes waffle block sectors that transition through bonded assembly between the vane tips and the fan case shells. These waffle blocks were evaluated for fabrication by assuming that they can be made from the materials listed in Table 4. The 390 aluminum die cast with 47 ksi tensile and 35 ksi yield strength was selected as the best candidate.

Stress Areas B and C - Vane End Sections

A major difference between concepts 2 and 4 is in the way the bypass vanes are constructed and attached in assembly with the frame core and fan case. The airfoil sections of each vane are illustrated in Fig. 10. In concept 2, individual molded graphite/epoxy spokes are enclosed in a bonded assembly with molded graphite/epoxy skins that are 0.050 in. thick. In concept 4, 0.075-in.-thick skins are molded integrally with thicker leading and trailing-edge sections that in total have the same material cross-sectional area as the concept 2 vanes. In addition, both concepts have vanes with a molded urethane leading-edge cap which acts to inhibit impact damage from foreign object ingestion. This urethane cap is somewhat resilient and can be replaced rather easily if required.

In the concept 2 modular vanes, the slender multilayered spokes terminate into broad spatula panels at both ends that are both bolted and bonded in assembly with the case frame core and fan case aft ring. The bolts aid in properly indexing the parts during assembly and act to maintain a compression-loaded adhesive shear joint for maximum joint integrity.

Concept 4 vane modules incorporate shear-bonded joints at both ends of the vane (Fig. 9). The skins transfer loads between the frame core and case through 7° wedge-angle bonded joints. A double wedge at the root end provides sufficient shear bond area at that region while a single wedge is adequate for the tip area. An analysis of concept 4 revealed the highest operating stress in the 0.075-in.-thick skin to be 27 000 psi resulting in a 200 percent safety margin. The vane structure of concept 4 has greater structural stiffness than concept 2 without weight penalty. This greater structural stiffness is due to the convergent angle of the integral spokes of concept 4 as compared with the bonded parallel spokes of concept 2 (Fig. 10).

Design concept 2 modularized vane attachment details involve integral extensions of both structural spokes that emerge from the vane into a broad spatula-shaped panel at both ends. This integral configuration of thin spokes and broad spatula creates an inefficient utilization of laminated graphite material in their pattern cutout fabrication process. Also, due to its shape, each ply is very delicate to handle during layup into molds. On the other hand, the concept 4 hybrid vanes rely on the thicker skins with integrally molded thick leading-and trailing-edge material that maintains a constant section of laminate material from end to end for maximum utilization of material. Due to their respective shapes, concept 2 vanes would be relatively difficult for automated processing while concept 4 vanes should be relatively easy for automated production.

Design concept 4 vane end pieces are compression-molded, wedge-shaped, graphite/epoxy pieces that bond to the sides of the vanes to provide a matching interface for the pocket in the die-cast aluminum outer blocks and core frame. The pockets in the cast aluminum core would be final-sized to close tolerance by a precision end-mill operation in final assembly. Vane loads are transmitted by shear through the adhesive bond joints with a maximum shear stress of about 800 psi at either end compared with a 2500-psi allowable for the adhesive.

To fabricate all vanes separately and fully inspect and nondestructively evaluate them before committing them to final assembly is applicable to both frame concepts 2 and 4. One important difference between the two vane concepts is the relative degree of effort required to totally replace a damaged vane. A concept 2 vane could be unbolted and removed axially with some damage requiring subsequent repairs of adhesive joints, collars, and flow path panels. A concept 4 vane would have to be cut and removed together with its bonded inserts at both ends before a new vane could be installed radially. This could involve major rework to the fan case with bonded shear panels that might impose minor steps in the outer flow-path profile. However, depending on the amount of impact damage, local repairs may be made to vanes without their total removal.

Stress Area D - Frame Core Vane Leading Edge

Maximum loads imposed by the 1-1/2-blade-out condition were used to calculate the stresses in this area. Candidate castable materials selected for comparison in the core frame are listed in Table 5 with corresponding weights and effective cost.

It should be noted that from a stress standpoint the 17-4PH and the INCO 718 could be made as thin as 0.040 to 0.050 in., but experience has shown that such castings can be no thinner than 0.08 in. and have good molten metal flow within the mold configuration. In addition, further experience has shown that a frame core of this size if cast in steel would probably have to be cast into sectors and then welded together to achieve a 360° frame core, whereas a C355 aluminum frame core could be cast in a single piece. Due to higher viscosity of molten 17-4PH metal, its sectors would have to be cast smaller than the steel sectors, hence its higher relative cost. A cast aluminum frame core was selected for the choice of material for either design concept 2 or 4.

As indicated in Figs. 5 and 7, concepts 2 and 4 could have 5 lightening holes in each cast web in the aluminum frame core at 13 locations for a total weight savings of about 6 lb. However, the cost of casting or drilling such holes would require special equipment and extra labor which may add more cost than the weight payoff would justify. If graphite material could be encapsulated in either of the two cast aluminum frame cores at a volume fraction of 40 percent, the total weight of either frame core, including the aforementioned holes, could be reduced by about 40 lb. This prospect would also add significant cost.

Stress Area E - Bearing Flange

Stresses in the frame core forward hub flange were calculated for both cast steel and cast aluminum. By casting the flange 1-1/4 in. thick in aluminum, its maximum stress would be 16 000 psi, leaving a safety margin of 150 percent. By exchanging about one-third of this thickness for axial support baffles behind the flange, as illustrated in Figs. 2 and 3, some weight reduction was achieved as a result of better distribution of loads into the surrounding casting.

Weight Analysis and Cost Analysis

To establish the labor hours required to fabricate a frame component, a novel concept was devised to project composite component costs. Empirical cost and time data obtained from past and ongoing frame programs were summarized and examined for any commonality. On first inspection, the data appeared to be quite random. It was then decided to group the components into their generic families, i.e., "L" flanges, "C" channels, shells, rings, and vane panels. By providing this arrangement, it was discovered that a common constant "K" could be established by parametrically using the component's diameter, number of plies, and length. This K factor could be established for all generic shapes and thus allow for the projection of labor hours for similar generic components. For example, on an existing program, 18.7 labor hours were projected for the 250th unit of a right-angle figure with a mean diameter of 45 in., leg lengths of 2 in., and laminate thickness of 0.125 in. By multiplying the circumference times area times thickness times K and equating it to the projected man-hours, the K factor could then be transferred to a similar formula for any size flange of similar profile to calculate similar projected labor hours.

Many imaginative and innovative approaches to the automation of composite structure fabrication have been developed and utilized throughout industry since the baseline frame was designed and fabricated during the 1975-77 time period. Some of the more promising techniques have been observed and considered during the course of this study with a projected effect on total labor hours. A summary of materials and their weights for the respective fan case, vanes, and core frame of design concepts 2 and 4 is listed in comparison with the same items of the baseline frame on Table 6.

FINAL FRAME DESIGN CONCEPT

A Cost Optimization Efficiency (COE) summary was compiled for the three major components of both frame design concepts 2 and 4. This summary first established material ultimate stresses for the respective type of composite materials projected for each component. Using a safety factor of 3 or greater on the ultimate stress, the minimum material thickness was established for each component. Alternative methods of fabricating each component were considered with associated projections of labor hours for each component in a production environment. The most efficient method of fabrication was selected and the total number of hours was summarized for each frame concept. To reinforce the validity of initial cost estimates associated with each frame, details of the eight different components that comprise the main differences of both frames were sent to various sources for estimates of labor and cost. When this information was gathered, the various component costs were relegated back to their respective frame concepts where final totals were observed to be very close to the original estimates. Since the two cast aluminum frame cores are so similar, their purchase price was estimated to be equal. Further machining of each cast frame core requires different processes, but the net effect on cost is very small. For example, 132 holes required for spatula assembly in concept 2 is nearly equivalent to the 66 end mill sizing operations for the bonded wedge assembly of vanes in concept 4. The small difference in weight of 215 lb for the frame core of concept 2 as compared with the 237 lb for concept 4 was factored in as an additional hour of labor cost for concept 4. The most significant contributor to the difference in cost between concept 2 and 4 is the separate spokes required for vane modules in concept 2. Not only do they waste considerable material due to their spatula end profiles, but they are more difficult to handle during laminating and assembly than the two-piece vane skins without separate spokes utilized in concept 4.

All the component weights, material costs, and projected labor hours were compiled for both frame design concepts 2 and 4 as well as the baseline frame. Totals were expressed in relative percentages as shown in Table 7. The total cost of the revised baseline frame was set at 100 percent. The relative costs of the concept 2 modular frame equated to 58 percent while the concept 4 hybrid frame equated to 37 percent compared with the revised baseline frame cost.

The weights and relative costs of both frames were compiled to assist in the final selection of the low-cost frame. This was accomplished by utilizing the Evaluation Analysis worksheets which provided a weighted comparison between both frames for a variety of considerations. Each frame's major components were evaluated separately then summarized in total for each full frame assembly on Table 7. The percent value assigned to the respective considerations was multiplied by a scale of comparison from 1 to 10. The totals of this numerical assessment led to the final selection of Design Concept 4 (the hybrid frame) as the most promising candidate design concept. A schematic of the final selection low-cost engine composite frame concept is shown in Fig. 11.

CONCLUDING REMARKS

Design concepts are described for low-cost, lightweight composite engine frames to meet the design requirements for the frame of a commercial aircraft high-bypass turbine engine. The concepts included generic-type components and subcomponents that could be adapted for use in different locatons in the engine and to different engine sizes. A variety of materials and manufacturing methods was assessed with a goal of having the least number of parts possible at the lowest possible cost. Preliminary evaluation of the four frame concepts led to the selection of two designs for extended design and evaluation and subsequent selecton of the hybrid frame design concept. The calculated weight of the low-cost hybrid frame is 695 lb or 200 lb less than the state-of-the-art metal frame. The projected cost for the 250th production item is about 55 percent of that for the metal frame. The relatively simple structural plug-together features of a hybrid frame demonstrate generic application to similar frames for other engines. The ability to fabricate and fully inspect the three main components (fan case, banes, and core) of the frame before committing them to final assembly provides a high potential for reducing the risk of costly problems in a production environment.

REFERENCES

1. Mitchell, S.C., "Quiet Clean Short-Haul Experimental Engine (QCSEE) Composite fan Frame Design Report," General Electric, Cincinnati, Ohio, R77 AEG439, Sept. 1978. (NASA-CR-135278).
2. Mitchell, S.C., and Stoffer, L. J., "Design Concepts for Low-Cost Composite Turbofan Engine Frames, General Electric, Evendale, Ohio, R81AEG311, Oct. 1980. (NASA CR-165217).

TABLE 1. - FRAME DESIGN REQUIREMENT

Criteria	Requirement relative to baseline	Comments
Structural	Reduce from 2-1/2 to 1-1/2 blade-out	Engine requirements
Stiffness	10- to 15-percent reduction possible	Detailed structural analysis
Aerodynamic	Same	N/A
Fan tip channels	Reduce number	Aero assessment
Acoustics	Eliminate all hub treatment	Acoustic tests
Containment	Increase thickness of kevlar	Containment tests
Weight	Increased	Experience and results of previous studies

TABLE 2. - SUMMARY OF DESIGN CONCEPT STATISTICS

Design concept	Shapes	Pieces	Cost-250th unit, percent	Weight, lb
Baseline	127	1344	100	530
1 - Consolidated	72	850	74	568
2 - Modularized	58	317	58	706
3 - Filament-wound	78	874	68	600
4 - Hybrid	42	214	37	695
Equivalent All-Metal Frame			67	895

TABLE 3. - BASELINE ENGINE LOAD CONDITIONS

(a) Limit loads[a]

Condition	Load	
I	Flight and landing	MIL-E-5007C
II	Gust	Equivalent load from 51.44-m/sec (100-kN) crosswind acting at any angle within plane 1.5708 radius (90°) to axis of engine, zero-to-maximum thrust.
III	Side	4-g side load combined with 1/3 the equivalent load as defined in Condition II, zero-to-maximum thrust.

(b) Ultimate loads[b]

IV	Flight-engine seizure	Seizure loads are due to the fan and engine basic gas generator decelerating from maximum-to-zero engine speed in 1 sec.
V	Crash	Crash load is defined as 10 g forward, 2.25 g side, and 4.5 g down at maximum thrust or down to zero thrust.
VI	1-1/2-blades-out	Engine shall be capable of withstanding unbalance loads caused by loss of 1-1/2 adjacent fan blades at maximum rpm (metal blades only).

[a]For any one of the following load conditions, all stresses shall remain within material elastic limits.
[b]Engine shall not separate from aircraft when subjected to Conditions IV, V, and VI and for static loads equivalent to 1.5 times the loads specified as limit loads in metal parts, and 3.0 times the loads specified as limits loads in composite parts.

TABLE 4. - MATERIAL CONSIDERED FOR WAFFLE BLOCKS AND RELATIVE MERITS

Material	Stress limit	Relative weight, percent	Relative cost, percent	Total weight per frame, lb
C355 Aluminum casting	16 000	100	100	86
Fiberglass molded compression	8 000	136	125	116
Graphite molding compression	8 000	112	1500	96
390 Aluminum die cast	47 000	30	50	31

TABLE 5. - CASTABLE MATERIALS

Cast metal	Density, lb/in^3	Tensile stress 0.2 percent yield limit @ 350° F, ksi	Minimum cast thickness	Maximum stress, ksi	Factor of safety	Relative weight, percent	Relative cost, percent
17-4PH	0.283	105	0.080	46	2.3	98	400
INCO 718	.296	113	.080	46	2.5	100	100
C355 Aluminum	.098	27.5	.250	21.5	1.3	100	100

TABLE 6. – EVALUATION ANALYSIS OF CORE FRAME

Component considerations	Core frame type, percent of value	Concept 2 – Modularized		Concept 4 – Hybrid	
		S[a]	S x V	S[a]	S x V
Cost, 35 percent					
Materials	10	5	50	5	50
Fabricability	15	5	75	5	75
Automation	10	5	50	5	50
Weight	30	5	150	4	120
NDE ability	20	5	100	5	100
Low maintenance	15	5	75	5	75
Total	100		500		470

[a]Scale of 1:10 (1 = Poor, 10 = Excellent).

TABLE 7. - LOW-COST COMPOSITE FRAME STUDY - WEIGHT AND COST SUMMARY

Materials	Fan case			Vanes				Core		Totals		
	1	2	3	1	2	3	1	2	3	1	2	3
Graphite/epoxy @ 0.057 lb/in^3	90	95	67	46	46	46	110	20	4	246	161	117
Kevlar/epoxy @ 0.047 lb/in^3	56	33	59	8	8	8	----	4	4	64	45	71
Glass/epoxy @ 0.069 lb/in^3	16	18	22	----	----	----	----	----	8	16	18	30
Aluminum honeycomb	53	53	53	1	1	1	3	----	----	57	54	54
Kevlar containment	47	87	87	----	----	----	----	----	----	47	87	87
Miscellaneous metal hardware	10	66	10	2	2	2	29	25	25	41	93	37
Cast aluminum	----	----	31	----	----	----	----	215	237	----	215	268
Adhesive	30	26	26	5	5	3	24	2	2	59	33	31
Totals, lb	302	378	355	62	62	60	163	266	280	530	706	695
Cost comparison of 250th unit, percent										100	58	37

[a]Baseline.
[b]Modular.
[c]Hybrid.

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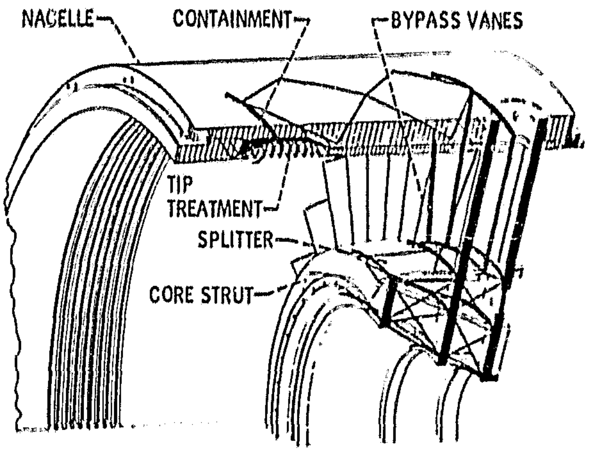


Fig. 1 Baseline frame section (trimetric).

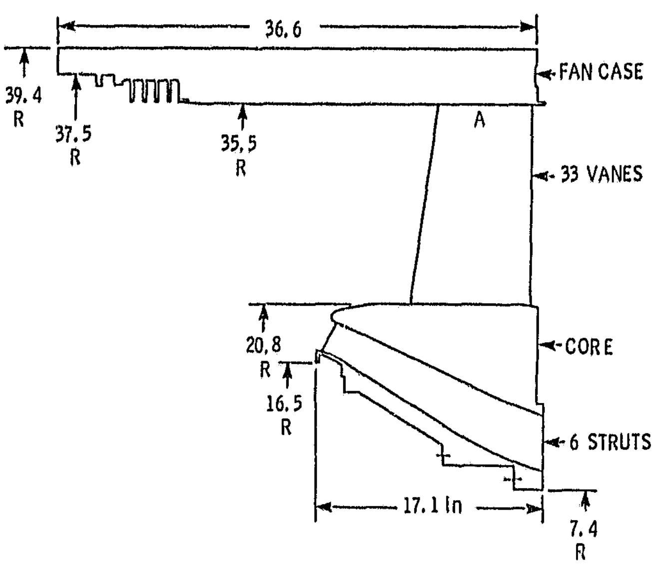
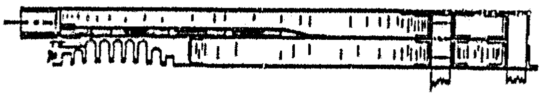
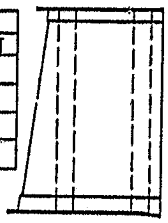


Fig. 2 Baseline envelope for four concepts - composite frames (dimensions in inches).



	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	1st UNIT	250th UNIT
FAN CASE	36	356	10000	2000
VANES	39	528	5000	1000
CORE	52	460	15000	3000
TOTAL	127	1344	30000	6000



	WEIGHT, lb
FAN CASE	298
VANES	64
CORE	168
TOTAL	530

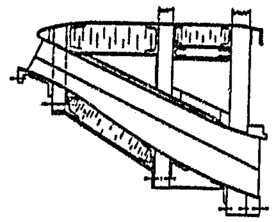
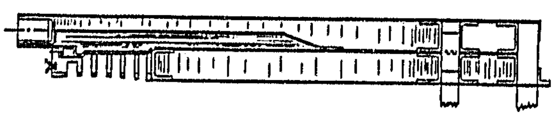
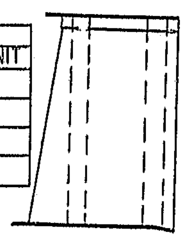


Fig. 3 Baseline frame data.



	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	1st UNIT	250th UNIT
FAN CASE	18	178	7650	1530
VANES	27	396	3500	700
CORE	27	276	11200	2240
TOTAL	72	850	22350	4470



	WEIGHT, lb
FAN CASE	346
VANES	62
CORE	160
TOTAL	568

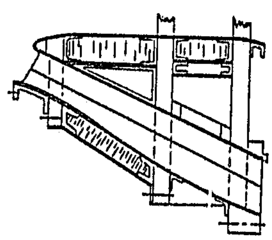
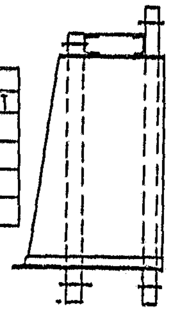


Fig. 4 Design concept 1 - consolidated frame.

	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	1st UNIT	250th UNIT
FANCASE	12	82	3400	680
VANES	36	198	2030	406
CORE	10	37	1570	314
TOTAL	58	317	7000	1400



	WEIGHT, lb
FANCASE	378
VANES	62
CORE	266
TOTAL	706

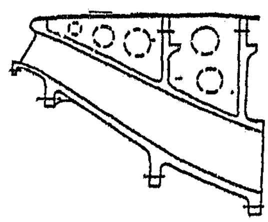
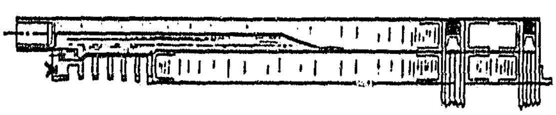
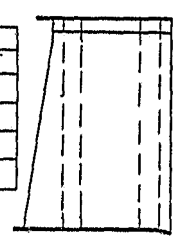


Fig. 5 Design concept 2 - modularized frame.



	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	1st UNIT	250th UNIT
FAN CASE	15	202	3600	720
VANES	36	396	2100	420
CORE	27	276	7000	1400
TOTAL	78	874	12 700	2540



	WEIGHT, lb
FAN CASE	358
VANES	62
CORE	180
TOTAL	600

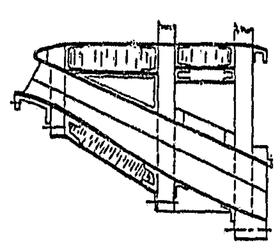


Fig. 6 Design concept 3 - filament-wound.

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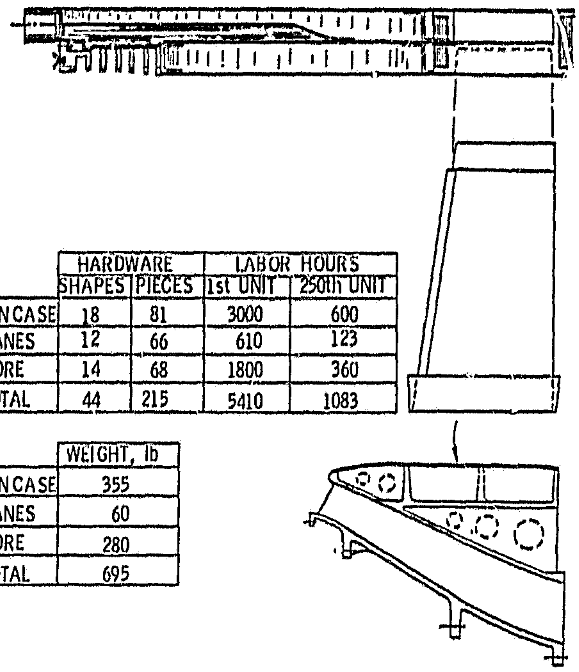

	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	1st UNIT	250th UNIT
FANCASE	18	81	3000	600
VANES	12	66	610	123
CORE	14	68	1800	360
TOTAL	44	215	5410	1083

	WEIGHT, lb
FANCASE	355
VANES	60
CORE	280
TOTAL	695

Fig. 7 Design concept 4 - hybrid frame.

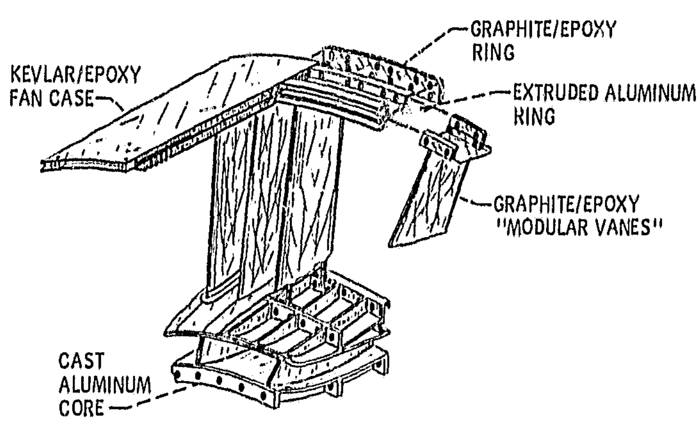

Fig. 8 Design concept 2 - modular frame.

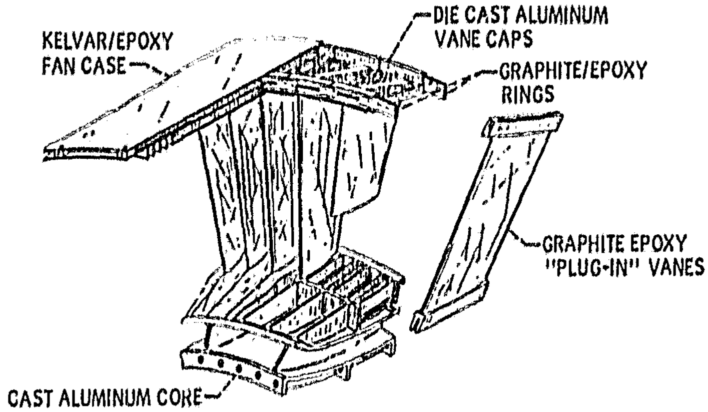

Fig. 9 Design concept 4 - hybrid frame.

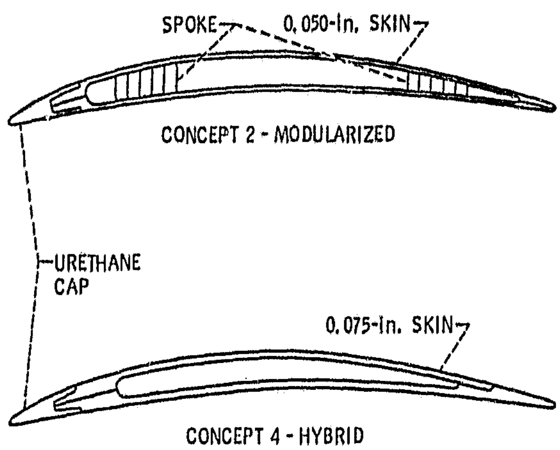

Fig. 10 Typical bypass vane section.

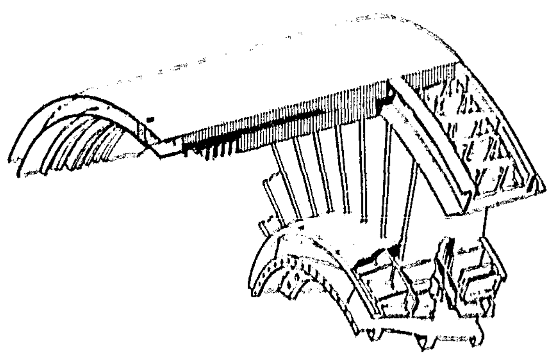

Fig. 11 Low-cost hybrid frame (final selection).