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DESIGN CONCEPTS FOR LOW-COST COMPOSITE TURBOFAN ENGINE FRAMES

FINAL REPORT
October 1980

by

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GENERAL ELECTRIC COMPANY

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16 Abstract

Design concepts for low-cost, lightweight composite engine frames were applied to the design requirements for the frame of a commercial, high-bypass engine. Four alternative composite frame design concepts were identified which consisted of generic-type components and subcomponents that could be adapted to use in different locations in the engine and to different engine sizes. A variety of materials and manufacturing methods were projected with a goal for the lowest number of parts possible at the lowest possible cost. After a preliminary evaluation of all four frame concepts, two designs were selected for an extended design and evaluation which narrowed the final selection down to one frame that was significantly lower in cost and slightly lighter than the other frame. An Implementation Plan for this lowest-cost frame is projected for future development and includes prospects for reducing its weight with proposed unproven, innovative fabrication techniques.

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FOREWORD

This study of Design Concepts for Low Cost Composite Turbofan Engine Frames was conducted by the General Electric Company, Aircraft Engine Business Group, under NASA Contract NAS3-22160. Dr. C. Chamis was the NASA Project Manager.

This report presents the results of a study conducted by the Advanced Frame Design Group under the direction of Mr. S. Mitchell, Technical Manager - General Electric Company, with Mr. L. Stoffer responsible for portions of design, analysis and frame concepts compatible with proven fabrication techniques.

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LIST OF DEFINITIONS

Vacuum Injection Molding - Pure plastics or very short fiber reinforced plastics molded by high pressure injection into an evacuated mold where it is cured to a solid state.

Resin Transfer Molding - Molds are filled with resin dry fiber or fabric arranged in a specific pattern and densely packed. After the molds are closed to net profile, resin is forced to follow throughout the voids between fibers until the mold is filled then the resin is cured to a solid state.

Compression Molding - Resin impregnated fibers or fabric (pre-preg) are compressed to desired shape between hot mold faces where it cures to a solid state.

QCSEE - Quiet, Clean, Shorthaul, Experimental Engine.

Urethane Cap - A plastic cover that protects the leading edge of a vane. From erosion caused by dust ingestion.

ROBOT - An automatic machine that does repetitive operations.

BRAIDING - A filament winding process that interweaves filaments into seamless tubing that can be profiled into airfoil configurations or shells.

SPOKES - Radial spars located in the interior of a strut or vane.

WHEELS - Structural element of a frame comprised of rings and spokes.

1.0 SUMMARY

The objective of the program was to evolve a frame design that would yield the lowest fabrication cost for a composite turbofan engine frame. The objective was met by first selecting the QCSEE (Quiet, Clean, Short-Haul, Experimental Engine) frame as shown in Figure 1 as the baseline configuration representing a composite turbofan frame. Next, four alternate design concepts were devised, and after evaluating the results listed in Table I the two most promising designs were selected and are shown in Figures 2 and 3. The goal of the program was to generate sufficient engineering and cost data concerning these two designs so that a rational selection of the lowest-cost design could be made for a final Implementation Plan.

A final fan frame selection was made based on the ability of the design to satisfy commercial engine structural and aerodynamic requirements while remaining light in weight and low in projected cost. It is anticipated that the features of the final selected fan frame design will have generic value applicable to many commercial, high-bypass turbofan engines.

The program to accomplish the objectives was divided into three Tasks:

- Task I - Design Concepts Identification
- Task II - Preliminary Designs
- Task III - Extended Designs, Cost and Weight Analyses, Final Selection, and Implementation Plan.

Under Task I, four frame design concepts were identified and projected to exchange directly with the revised Baseline QCSEE composite frame. The revision to the new criteria was based on actual QCSEE test experience and other more recent test experience regarding failed fan blade containment.

Under Task II, a screening of projected weights and costs of the four preliminary frame concepts identified two candidate frames for an extended evaluation effort. Task III narrowed the choice down to the lowest-cost frame for a projected final Implementation Plan. This final composite frame concept is identified as the No. 4 - hybrid frame, which is shown in Figure 4 and consists of a cast aluminum core frame, modularized "plug-in" composite vanes and a fan case quite similar to the previously tested Baseline QCSEE frame fan case. Although this No. 4 hybrid frame is somewhat heavier than some of the other frame concepts considered, its cost was significantly lower than the costs of the other candidate frames. Costs and weights listed in Table I were projected using conventional materials and manufacturing techniques.

Prospects for reducing the weight of the Hybrid Frame by using unique composites of graphite/aluminum and/or other unique fabrication techniques are discussed in Section 5.0, Recommendations, of this report.

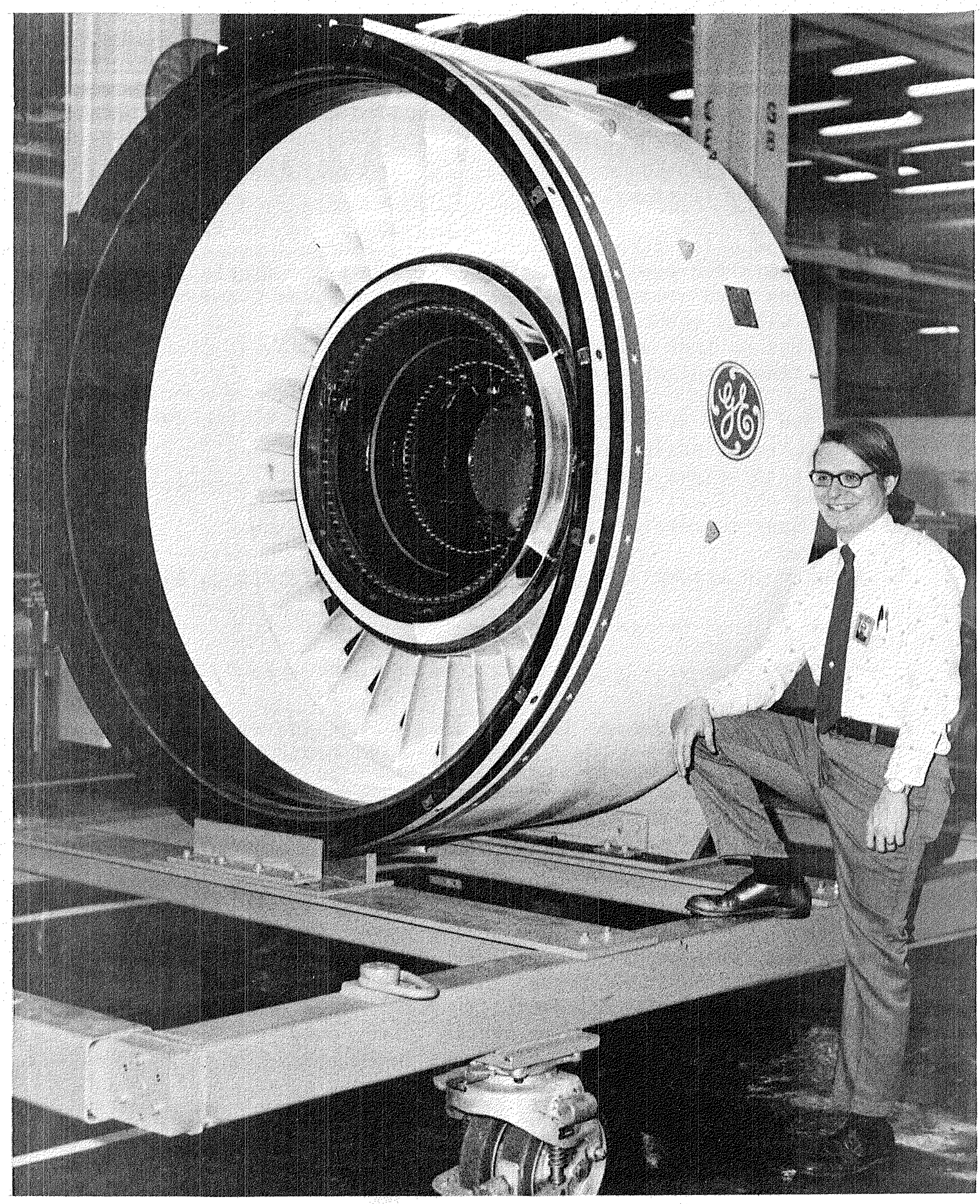


Figure 1. QCSEE Frame.

Table I. Summary of Design Concept Statistics.

Configuration	Shapes	Pieces	Cost-250th Unit	Weight, lb
QCSEE Baseline	127	1344	111%	530
Revised Baseline	122	1197	100%	563
#1 - Consolidated	72	850	82%	568
#2 - Modularized	58	317	64%	706
#3 - Filament Wound	78	874	75%	600
#4 - Hybrid	42	214	41%	695
Equivalent All-Metal Frame			74%	895

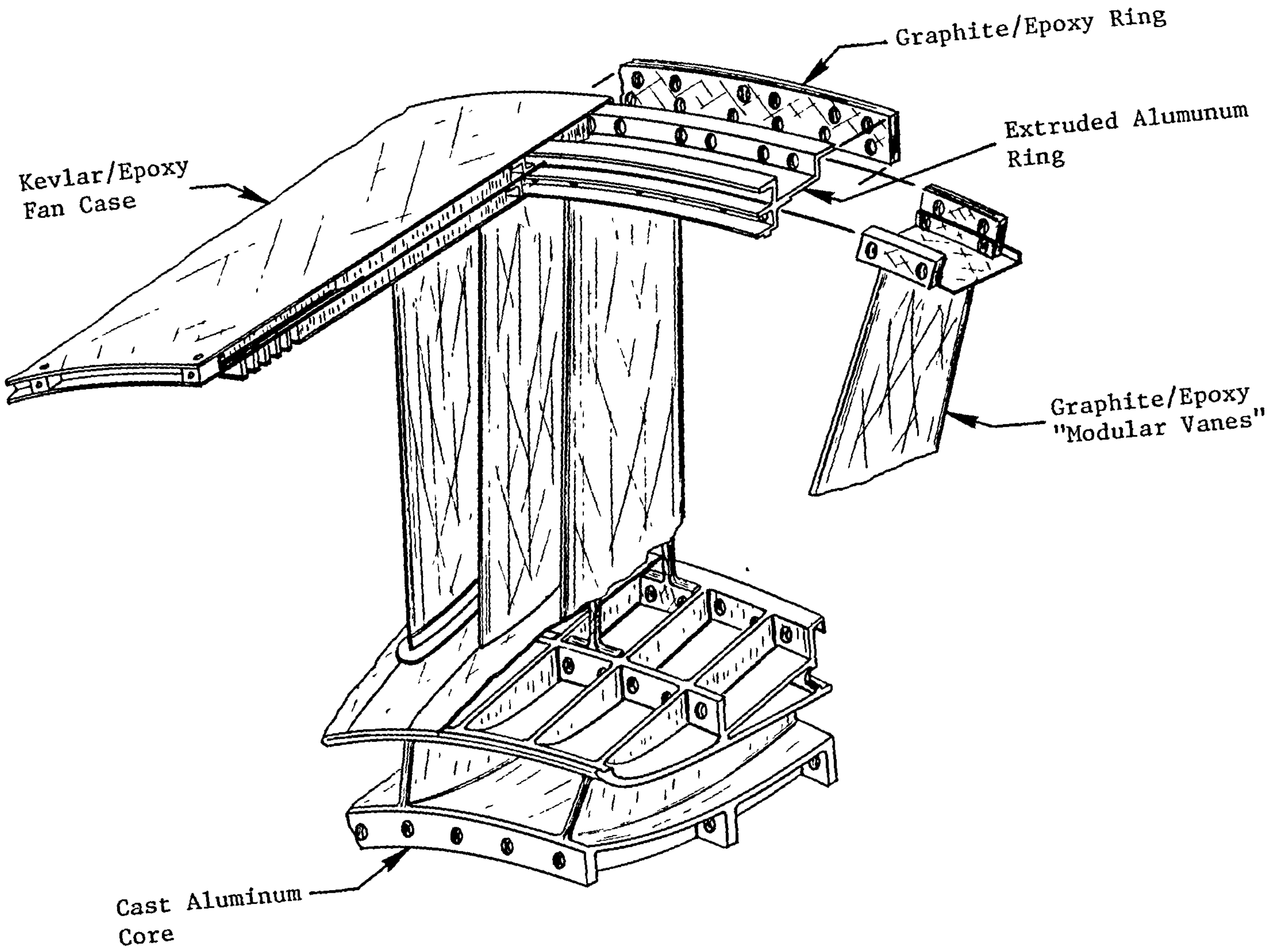


Figure 2. Modular Frame - Concept No. 2.

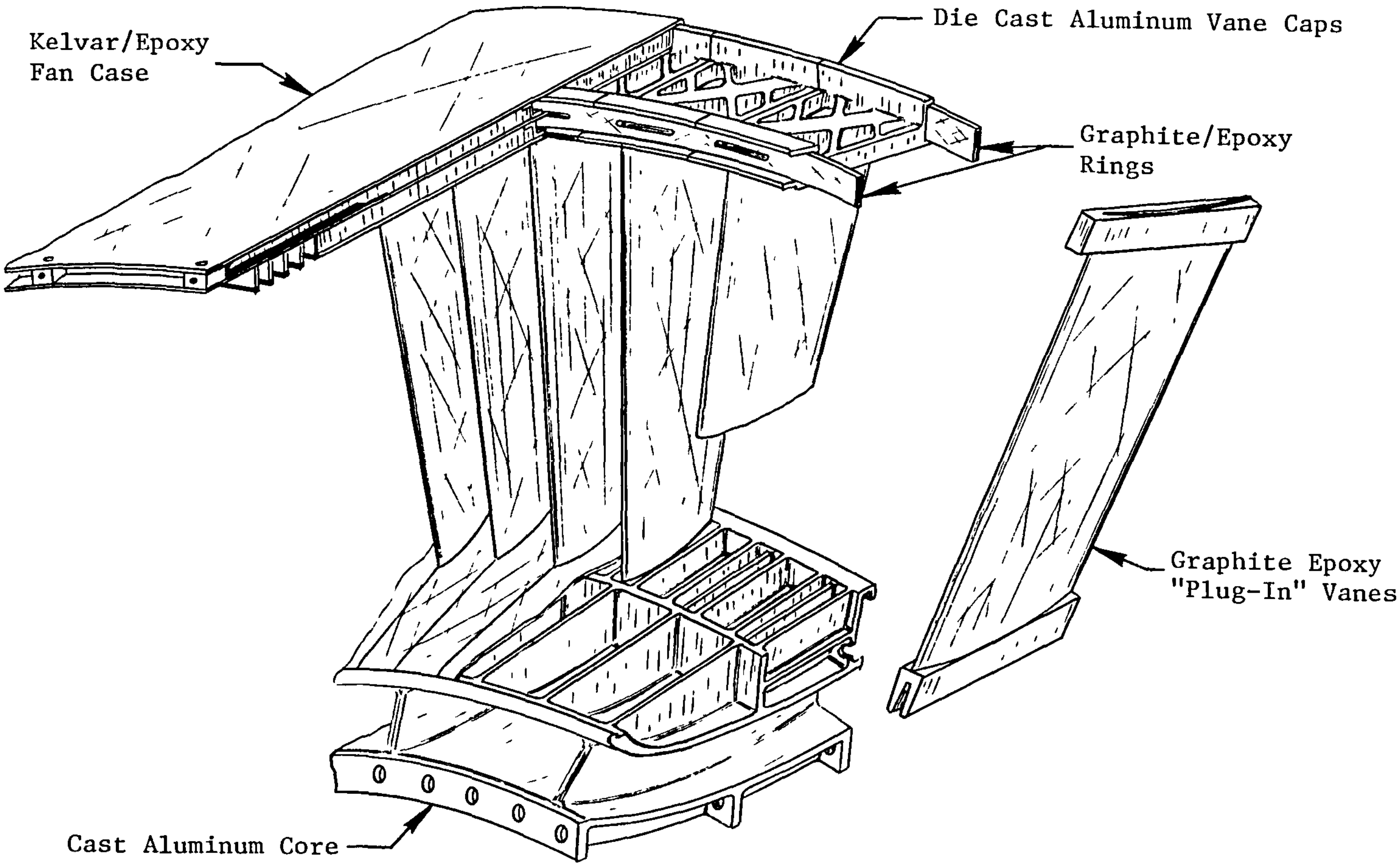


Figure 3. Hybrid Frame - Concept No. 4.

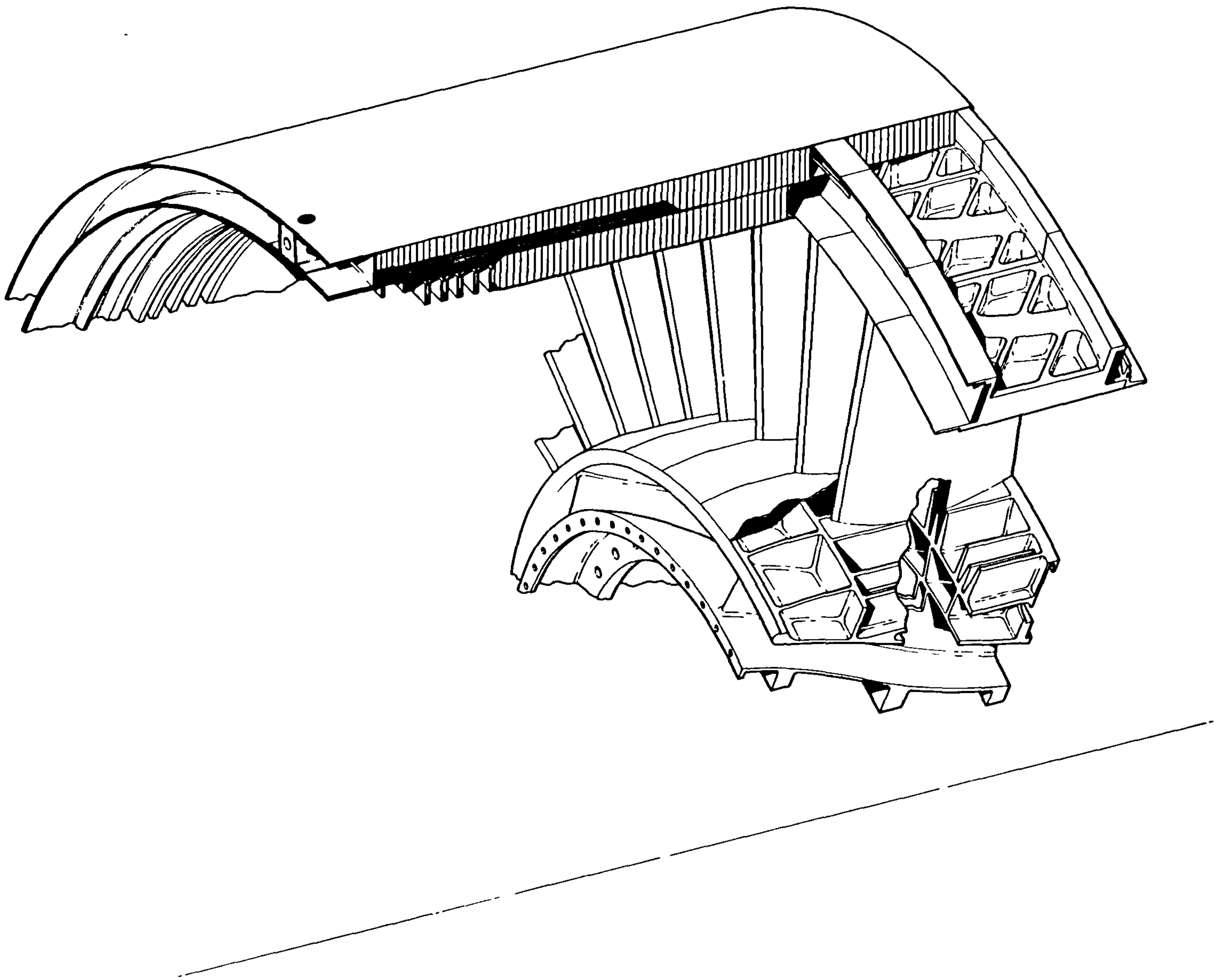


Figure 4. Low Cost Hybrid Frame (Final Selection).

2.0 INTRODUCTION

The baseline QCSEE fan frame selected for this study is a flight-weight integrated design constructed of advanced composite materials. Design integration is achieved by combining the functions of the fan stator vanes, fan outer casing, and fan frame into one unitized structure as shown in Figure 5. This approach saves considerable duplication of structure, resulting in a significantly lighter weight design. The unitized approach is particularly suited to the use of composite materials since these materials are more efficient when employed in large bonded structures rather than smaller structures that must be bolted together.

During this study, four preliminary frame design concepts were identified and projected to exchange directly with the baseline QCSEE composite frame. Each frame incorporated the revised QCSEE frame criteria listed on Table II which was assembled from a review of design requirements based on actual QCSEE engine test experience. Each frame concept utilized low-cost forms of composite materials and standard proven fabrication techniques. It should be noted however that during the course of this program, several new approaches to composite materials and fabrication techniques that could possibly further reduce cost and weight were studied, but were deleted in the final analysis because their fabrication techniques were undeveloped. However, prospects for future utilization of these items are considered in Section 5.0, Recommendations, of this report.

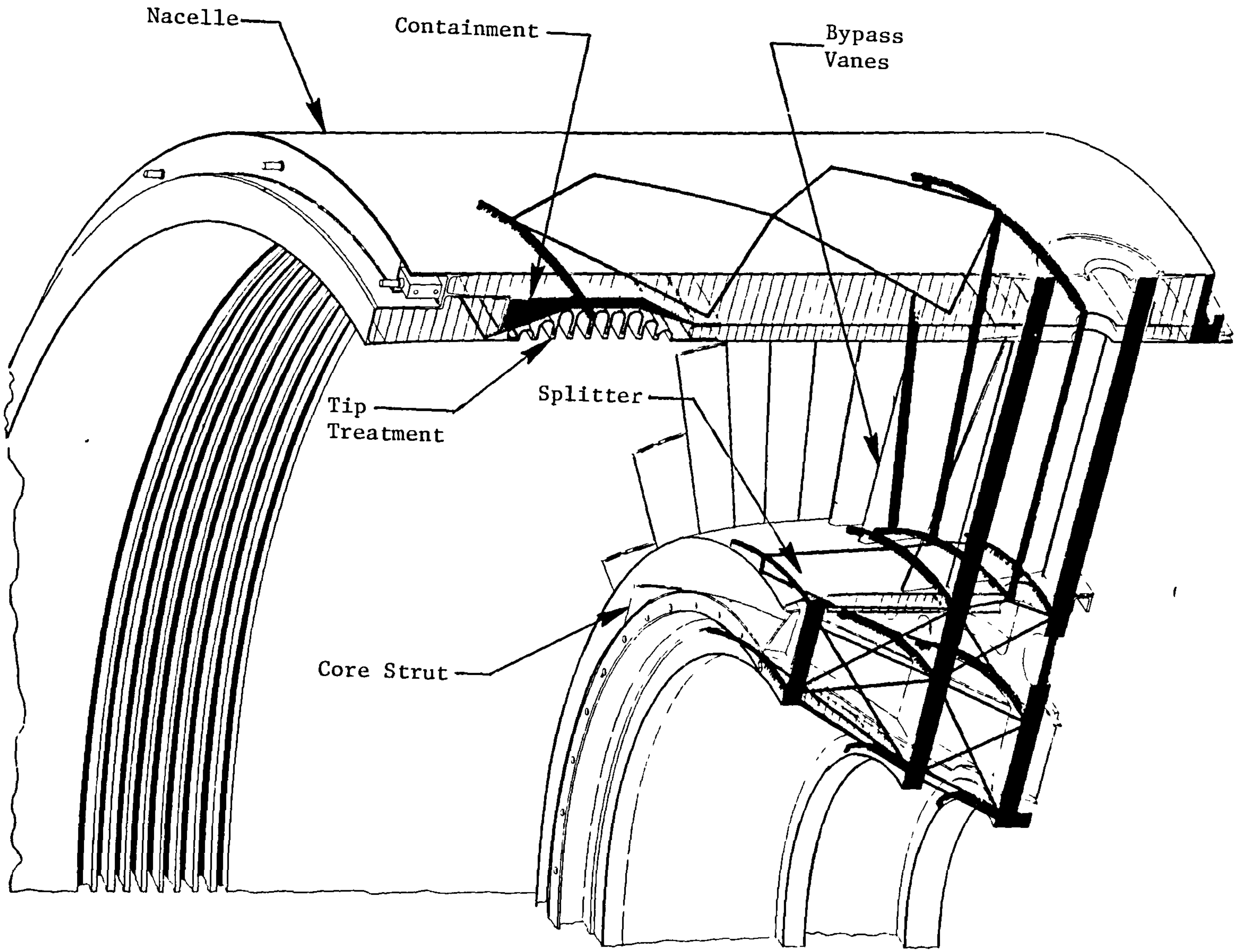


Figure 5. QCSEE Baseline Frame Section (Trimetric).

Table II. Frame Design Requirement Revisions.

Criteria	Requirement Relative to QCSEE Baseline	Basis for Revisions
• - Structural	Reduce From 2-1/2 to 1-1/2 Blades Out	CF6 Requirements
• - Stiffness	10% - 15% Reduction Possible	QCSEE Vast 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 Study

3.0 PROGRAM

3.1 TASK I - DESIGN CONCEPTS IDENTIFICATION

The four preliminary composite frame design concepts generated for this program were established from input from many different design and fabrication sources in the General Electric Company. Since each concept was to be interchangeable with the same baseline engine, final concepts were, of necessity, somewhat restrictive in their variety; therefore, some of the basic differences between certain concepts may appear to be minor. However, a review of final weights and costs will reveal significant differences between all the concepts considered.

The four composite frame concepts identified for this study are described below.

Concept	Concept Identification
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 core frame for low cost.
3	Filament Wound - As many components as possible are fabricated by low-cost filament-wound 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 core frame and die-cast aluminum vane tip fan case blocks.

3.2 TASK II - PRELIMINARY DESIGNS

Figures 6 through 12 illustrate the basic envelope of the baseline QCSEE frame, a section of the baseline frame, the baseline frame as revised to Table II criteria, and the four frame concepts evolved for this study. 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. Each of the above figures are described below:

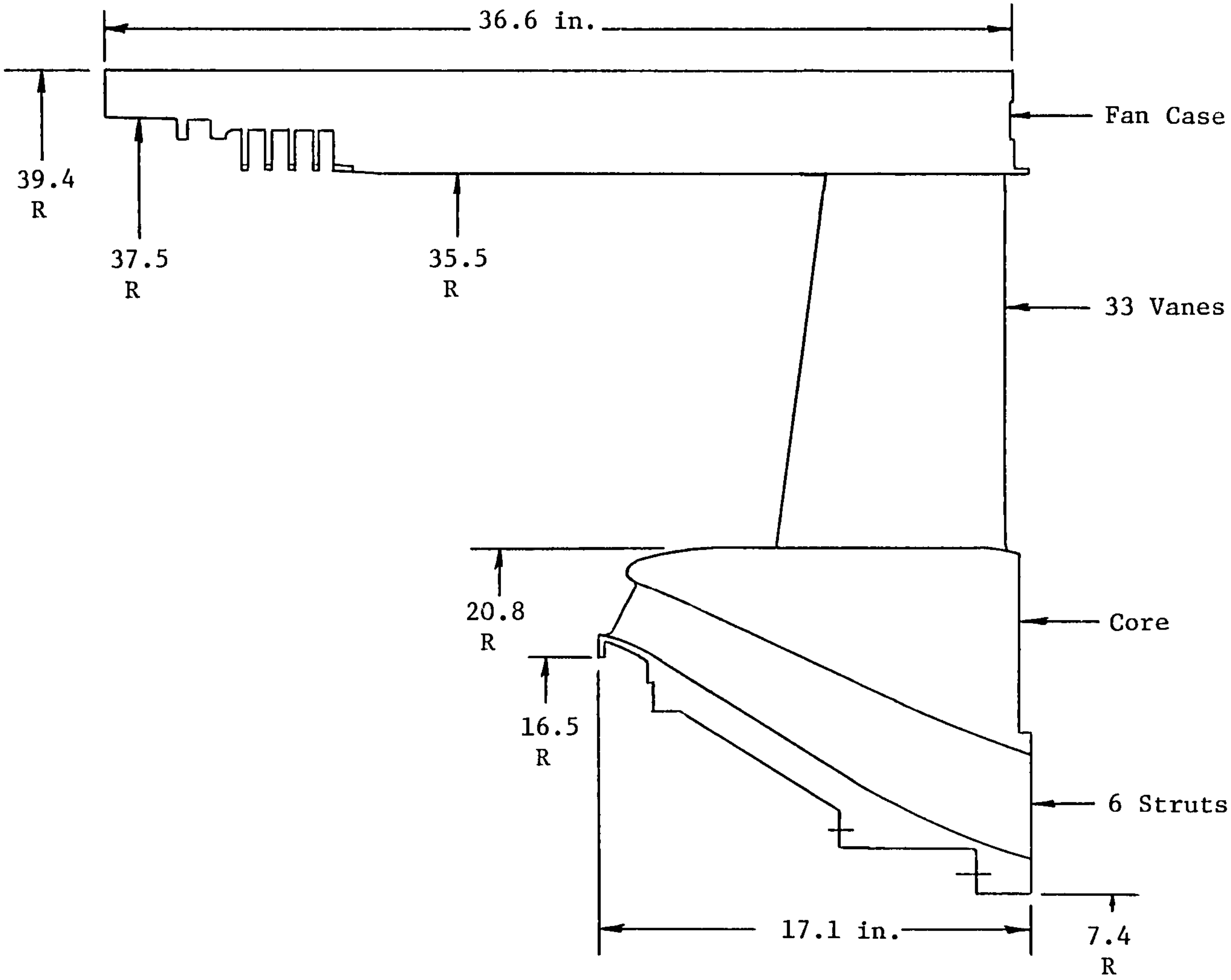
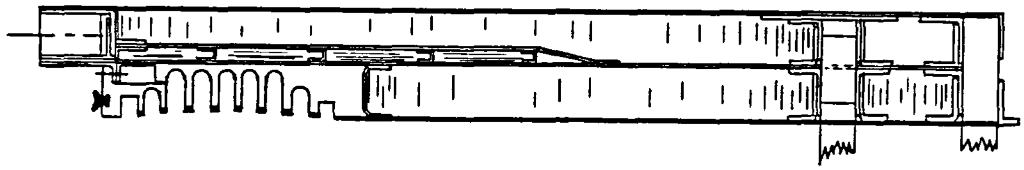
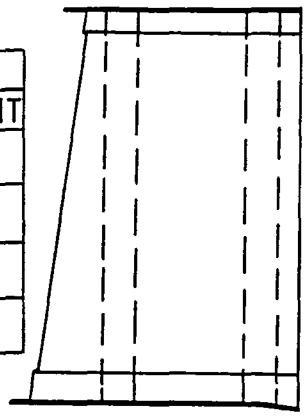


Figure 6. Baseline Envelope for Four Concepts - Composite Frames.



	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	Ist UNIT	250th UNIT
FAN CASE	36	356	10,000	2000
VANES	39	528	5,000	1000
CORE	52	460	15,000	3000
TOTAL	127	1344	30,000	6000



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

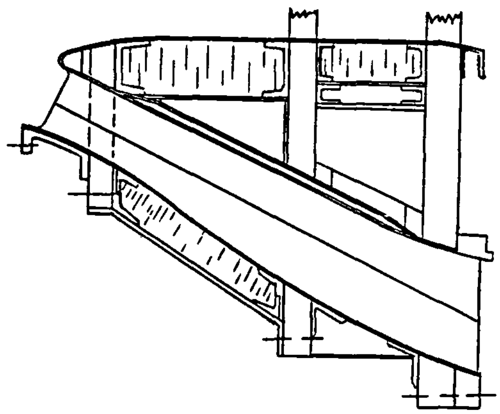
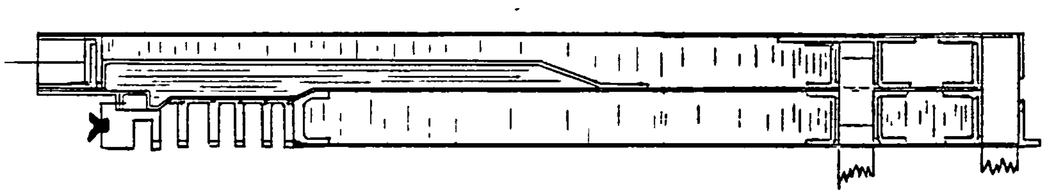
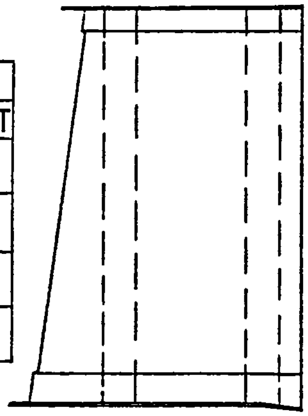


Figure 7. Baseline Frame.



	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	1st UNIT	250th UNIT
FAN CASE	33	299	9500	1900
VANES	39	462	4000	800
CORE	50	436	13500	2700
TOTAL	122	1197	27000	5400



	WEIGHT, LB
FAN CASE	338
VANES	62
CORE	163
TOTAL	563

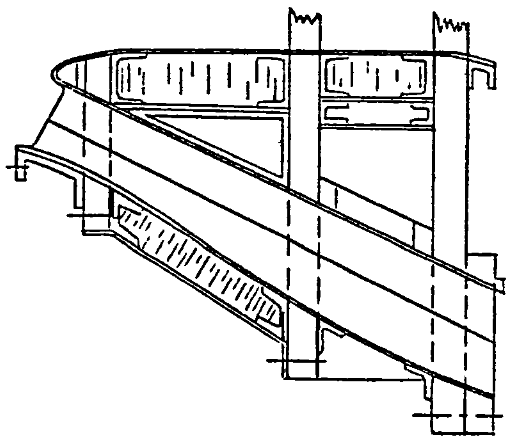
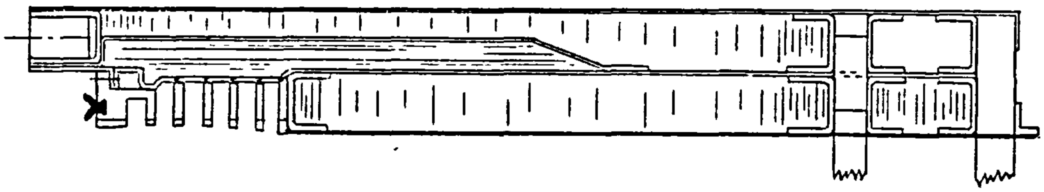
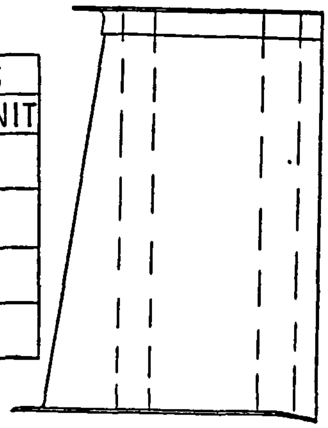


Figure 8. Revised Baseline Frame.



	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	Ist 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

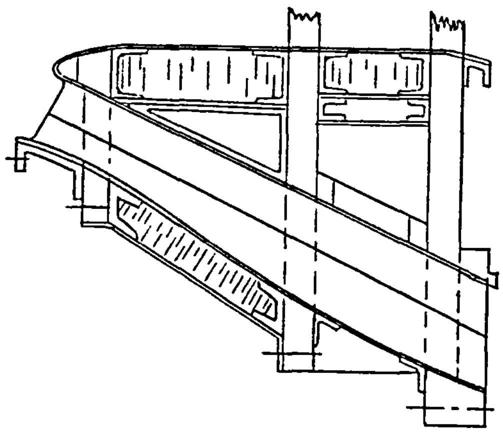
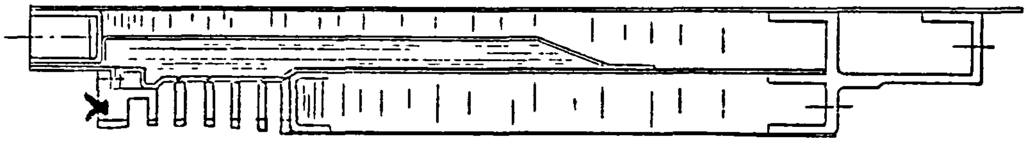
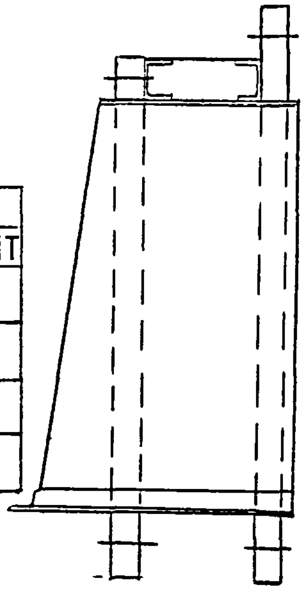


Figure 9. No. 1 - Consolidated Frame.





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

	WEIGHT, LB
FAN CASE	378
VANES	62
CORE	266
TOTAL	706

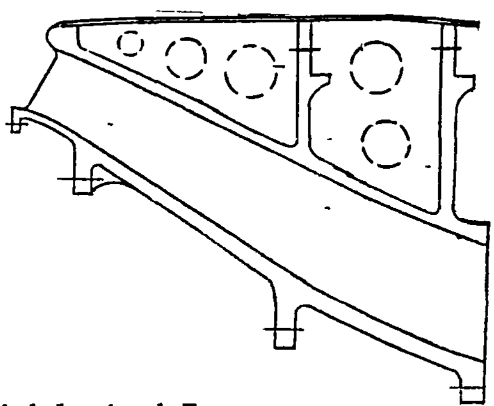
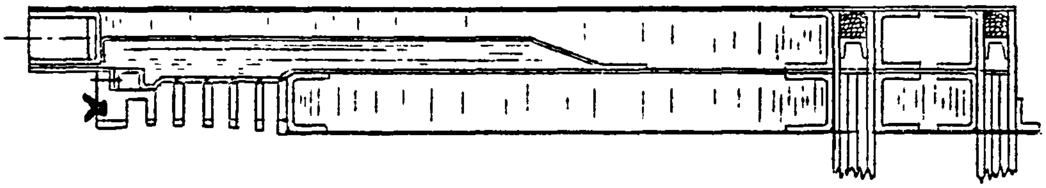
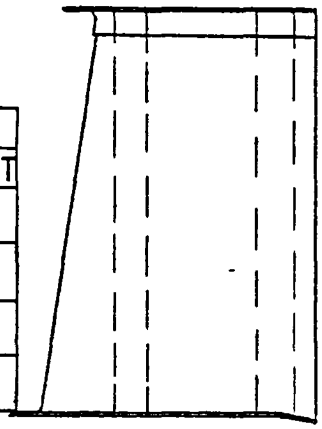


Figure 10. No. 2 - Modularized Frame.



	HARDWARE		LABOR HOURS	
	SHAPES	PIECES	Ist UNIT	250th UNIT
FAN CASE	15	202	3600	720
VANES	36	396	2100	420
CORE	27	276	7000	1400
TOTAL	78	874	12700	2540



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

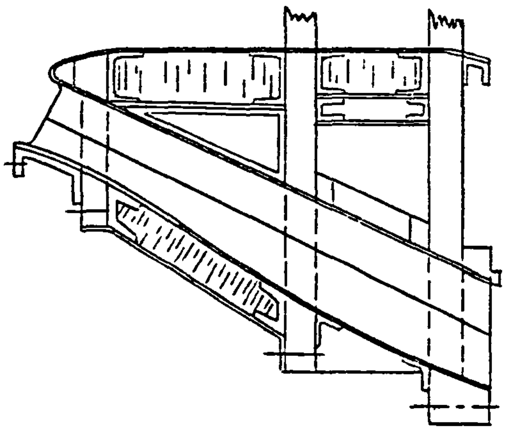
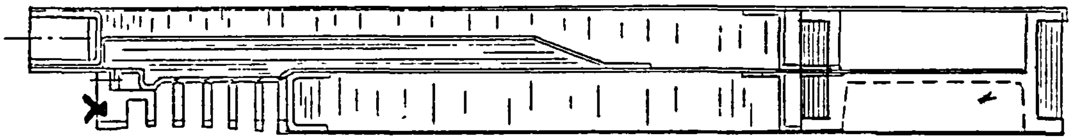
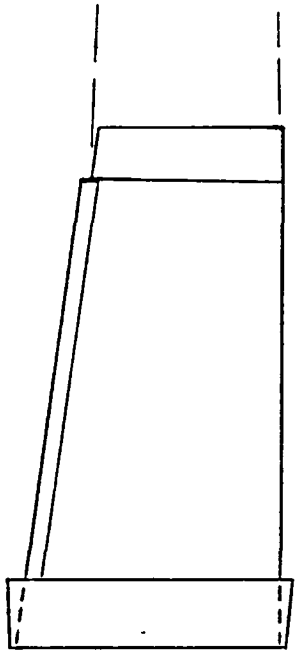


Figure 11. No. 3 - Filament-Wound Frame.





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

	WEIGHT, LB
FAN CASE	355
VANES	60
CORE	280
TOTAL	695

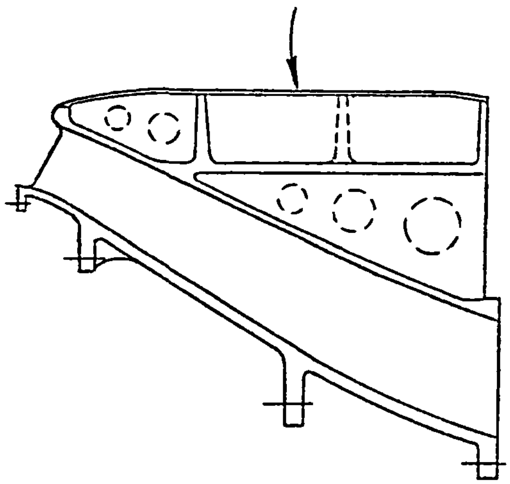


Figure 12. No. 4 - Hybrid Frame.

Figure 6 - Envelope - This identifies the three structural elements of core, vanes, and fan case and shows the respective dimensions that are maintained for all frame concepts.

Figure 7 - Baseline - This represents the original composite QCSEE frame that was fabricated in 1975. All totals were obtained from actual part count and recorded manhours expended on the previous QCSEE engine frame program.

Figure 8 - Revised Baseline - By imposing the revised design criteria listed in Table II, fewer layers of structural wheel and spoke elements were required to achieve adequate stiffness. Fewer pieces were also required to structure the heavier Kevlar containment which would weigh 43 pounds more than the original baseline Kevlar containment. As a result of deleting the acoustic treatment in the core flowpath, fewer pieces were required and some minor weight was saved in that area. The net effect of these revisions would be fewer shapes, pieces and manhours, but a slight increase in weight.

Figure 9 - Concept No. 1 - Consolidated - By combining many flanges in both the fan case and the core, fewer adhesive bond joints are required which translates into a modest weight savings but a significant reduction in the number of shapes, pieces, and manhours. The heavier Kevlar containment, however, eradicates the above-mentioned weight savings and produces a slight increase in total frame weight.

Figure 10 - Concept No. 2 - Modularized - A cast aluminum core and machined aluminum fan case ring provide attachment points for the modularized vanes. By fabricating the vanes as individual modules on separate production facilities their production and inspection can be more efficient than in an integral fabrication with the core and fan case as was done on the baseline frame. In addition, it may be possible to replace damaged vanes with low-cost maintenance procedures as compared to other concepts with integral vanes.

The cast aluminum core and fabricated aluminum fan case ring account for the increased weight. But the fewer shapes and pieces translates into a very significant reduction in hours of labor.

Figure 11 - Concept No. 3 - Filament Wound - By orienting fibers in many of the components consolidated in Concept No. 1 so as to be adaptable to filament winding or braiding techniques, this concept would look very similar to Concept No. 1. The main advantage of this concept was revealed in the fewer hours of labor as compared to the hand lay-up hours associated with the Consolidated Frame Concept No. 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 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 that of the equivalent structures layed 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, the flexibility of fiber orientation relative to design requirements is more restrictive with filament winding than lay-up procedures allow. This limiting parameter proved to have an adverse effect on weight.

Figure 12 - Concept No. 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 equivalent structures on 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 in this report. Another prospect of encapsulating graphite in the cast aluminum to increase strength and reduce weight is also discussed in Section 5.0, Recommendations, of this report.

A comparison summary of statistics of the four frame concepts described above are listed in Table I along with projections of relative cost and weight of an equivalent all-metal frame.

Since the actual labor hours and component weights were recorded earlier for the baseline QCSEE frames, these facts allowed the generation of realistic estimates of labor hours and weights for many similar components of the four new frame concepts. In addition, a study conducted by experienced personnel at Rohr on the projected labor hours for all components of the current TF34 composite frame program has been made available for this study. This data base provided a valuable means for double-checking labor hour estimates for many similar frame components. To project the manhours of effort for the 250th engine set, a learning curve of 80% was arabitrarily set for the study.

Since the lowest cost frames were established to be the relative 64% No. 2 - Modularized at 706 pounds and the 41% No. 4 hybrid at 695 pounds, these two frames were selected for the extended evaluation analysis conducted under Task III.

3.3 TASK III - EXTENDED DESIGN ANALYSIS

The extended evaluation of frame Concepts No. 2 and 4 that were selected for an in-depth design and cost evaluation under Task III of this program was assisted by trimetric sketches illustrated in Figures 2 and 3. The two concepts were sized in the critical stress areas designated A through E in Figure 13. Prior experience has shown that the two critical stress conditions for the frame are caused by a cross-wind condition and by a 1-1/2 fan blade-out condition as described in Table III. Critical frame components in Areas A through E were sized to these conditions and a majority of the new remaining frame sections were sized by ratioing from the baseline QCSEE frame.

The basic frame analysis was performed using General Electric's computer program system (entitled "MASS") for the analysis of 3-D redundant structures. The MASS system provides the means of analyzing almost any structure. The variety of available elements gives the program a great deal of versatility; with care, most structures can be modeled accurately or closely approximated.

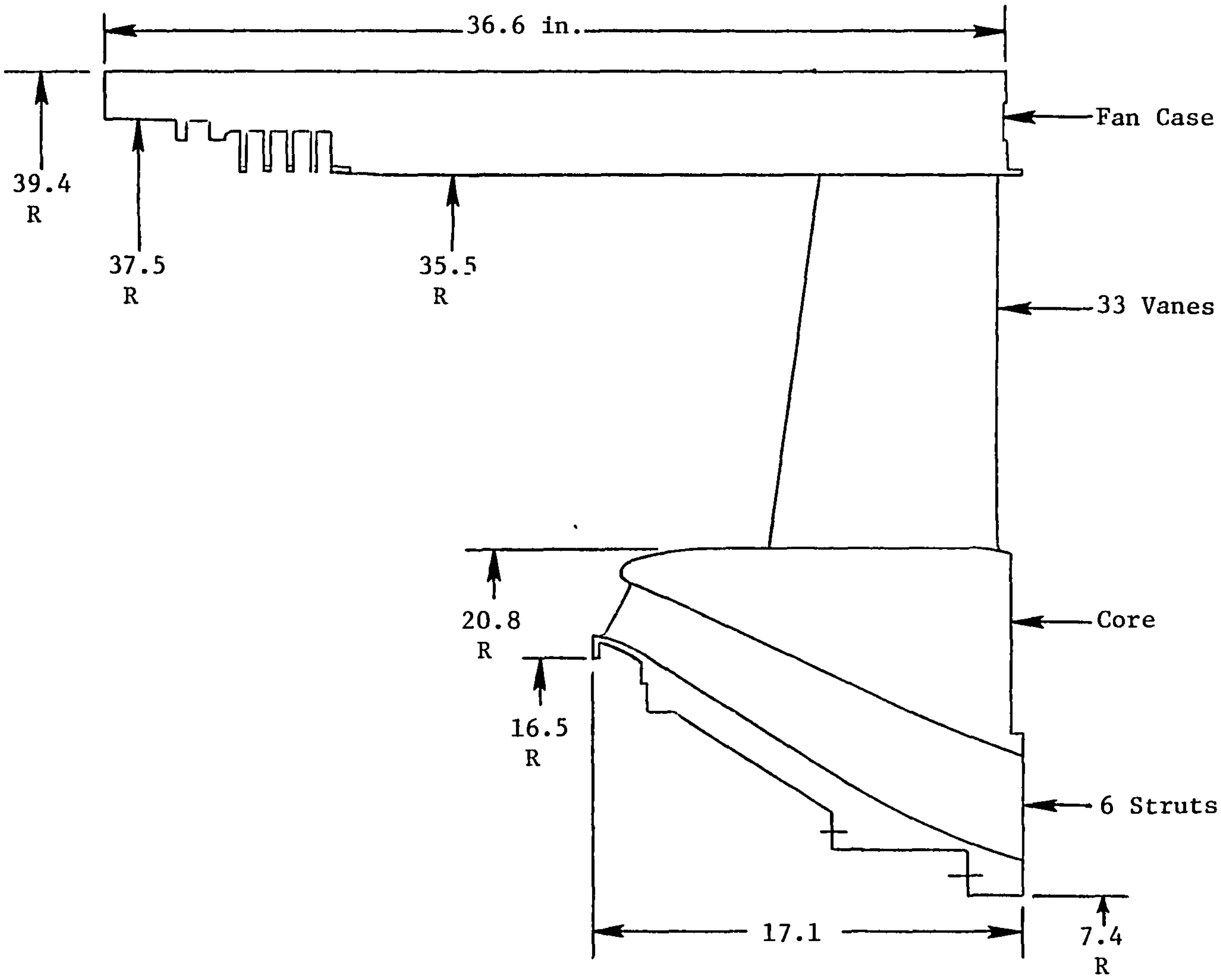


Figure 13. Stress Study Areas A Through E - Composite Frames.

Table III. QCSEE Engine Load Conditions.

Limit Loads

For any one of the following load conditions, all stresses shall remain within the material elastic limits.

Condition I: Flight and Landing - MIL-E-5007C

Condition II: Gust Load - An equivalent load from a 51.44-m/sec (100-kn) crosswind acting at any angle within a plane 1.5708 radians (90 degrees) to the axis of the engine, zero-to-maximum thrust.

Condition III: Side Load - A 4-g side load combined with 1/3 the equivalent load as defined in Condition II, zero-to-maximum thrust.

Ultimate Loads

The engine shall not separate from the 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 limit loads in composite parts.

Condition IV: Flight-Engine Seizure - The seizure loads are due to the fan and engine basic gas generator decelerating from maximum-to-zero engine speed in one second.

Condition V: Crash Load - The crash load is defined as 10-g forward, 2.25-g side, and 4.5-g down at maximum thrust or up to zero thrust.

Condition VI: 1-1/2-blades-out - The engine shall be capable of withstanding unbalance loads caused by the loss of 1-1/2 adjacent fan blades at maximum rpm (Metal blades only).

The basic elements available for modeling are the two-ended curved or straight beam; the four-sided curved or flat trapezoidal plate; the six-sided tetrahedron; rigid connectors, springs, tubes, and sandwich panel structures with orthotropic faces.

The types of analyses available in MASS are: mechanical loading, thermal gradients, maneuver loads, forced response, and determination of critical frequencies. An instability check is optional. Resulting output is in the form of loads, stresses, and deflections.

If the MASS analysis indicated that stress problems exist at certain locations within the structure (or if stress concentrations exist that were not accounted for in modeling), a more detailed analysis of the region in question was performed with the finite-element programs, SAP, TAMP, and FINITE.

SAP, TAMP and FINITE can account for thermal, mechanical, vibrational, and body force loading or orthotropic materials. Plane stress, plane strain, or axisymmetric structues can be solved more economically using FINITE since this program utilizes a two-dimensional triangular element. Also, a computerized routine is available for automatically generating the finite-element grid work.

The three-dimensional orthotropic finite-element program, TAMP, is available for nonplanar problems. Since spring and friction-force boundary conditions are permissible, TAMP is ideal for modeling joint regions.

The basic laminate elastic properties for the various orientations that were considered during the program were obtained using MPEP (Material Property Evaluation Program). If the properties of a single ply are known, MPEP allows the designer to calculate the elastic properties of any chosen layup using basic laminate theory.

A more detailed discussion of the analysis is found in Section 3.3.5.1 entitled Design, Analysis, and Performance Requirements. Since the analysis performed under the QCSEE program was utilized in many areas of this program, the QCSEE fan frame final design report contains an exhaustive analysis section. This report was issued in September 1978 under the title Quiet Clean Short-Haul Experimental Engine (QCSEE) Composite Fan Frame Design Report with report number NASA CR-135278, R77AEG439.

A description of the design analysis conducted for each of the critical frame areas follows:

<u>Stress Area A - Fan Case to Vane Tips</u>

Both Concepts No. 2 and 4 have identical fan case structures except for the vane tip attachment areas. Concept No. 2 utilizes an extruded, rolled, and welded 2219 aluminum ring which has a 0.2% tensile yield strength of about 58,000 psi and is stressed at maximum load to about 40,000 psi. In similar fashion, Concept No. 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 out of the various materials listed below. The 390 die cast aluminum with 47 ksi tensile and 35 ksi yield strength was selected as the best candidate.

Material	Stress Limit	Relative Weight, %	Relative Cost, %	Total Wt. Per Frame, lb
C355 Aluminum Casting	16,000	100	100	86
Fiberglass Molding Comp.	8,000	136	125	116
Graphite Molding Comp.	8,000	112	1500	96
390 Aluminum Die Casting	47,000	30	50	31

Stress Areas B and C - Vane End Sections

A major difference between frame Concepts No. 2 and 4 is in the way the bypass vanes are constructed and attached in assembly with the core frame and fan case. The airfoil sections of each vane are illustrated in Figure 14. In Concept 2, individual graphite molded spokes are enclosed in bonded assembly with graphite molded skins that are 0.050 inch thick. This structure is identical to the revised baseline QCSEE frame bypass vane section. In Concept 4, 0.075-inch-thick skins are molded integral with thicker leading and trailing edge sections that in total have the same area material section 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. Such a cap is currently being utilized on a composite frame for the General Electric TF34 engine.

In the Concept 2 modular vanes, the slender multilayered spokes terminate into broad spatula panels (see Figure 2) at both ends that are both bolted and bonded in assembly with the cast core frame and fan case aft ring. The bolts aid in the proper index at 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. The skins transfer loads between the core frame and 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-inch-thick skin to be 27,000 psi. With a 300% safety factor, this stress is still below a stress ultimate of 83,500 psi for graphite/epoxy skins with a 40% at 0°, 40% at ±45°, and 20% at 90° ratio of fiber distribution.

As illustrated in Figure 15, the vane structure of Concept 4 offers greater structural stiffness than Concept 2 without penalty of additional weight due to the convergent angle of the integral spokes of Concept 4 as compared to the bonded parallel spokes of Concept 2.

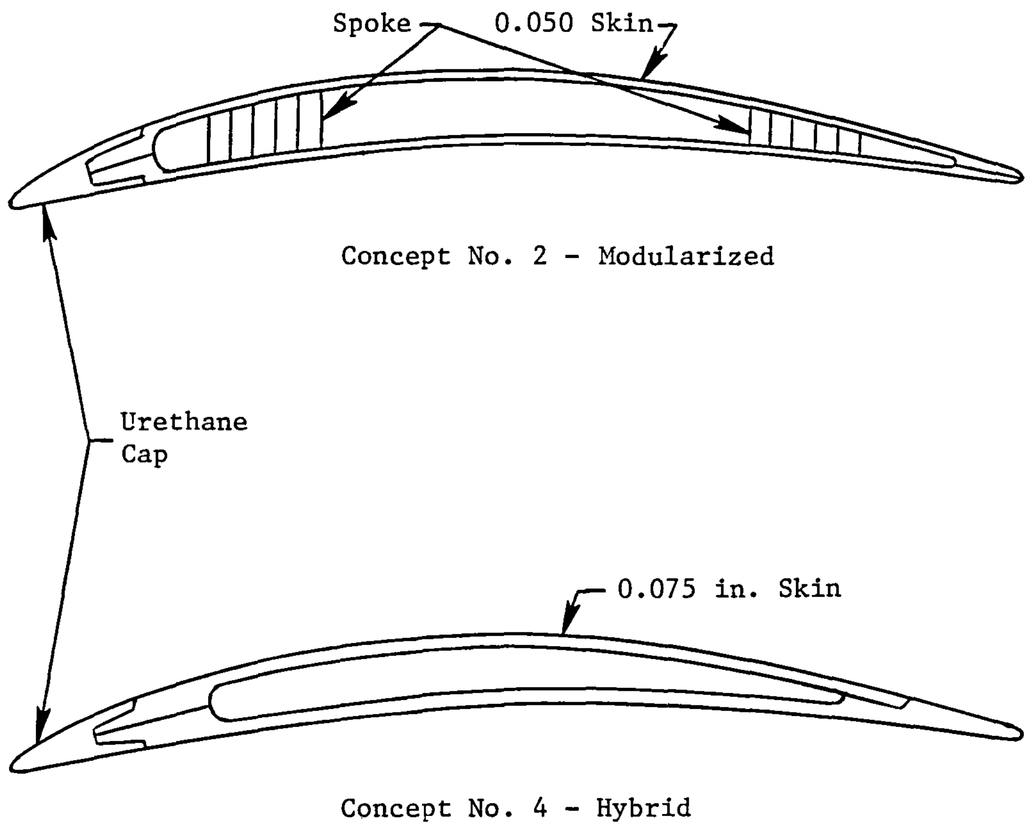


Figure 14. Typical Bypass Vane Section.

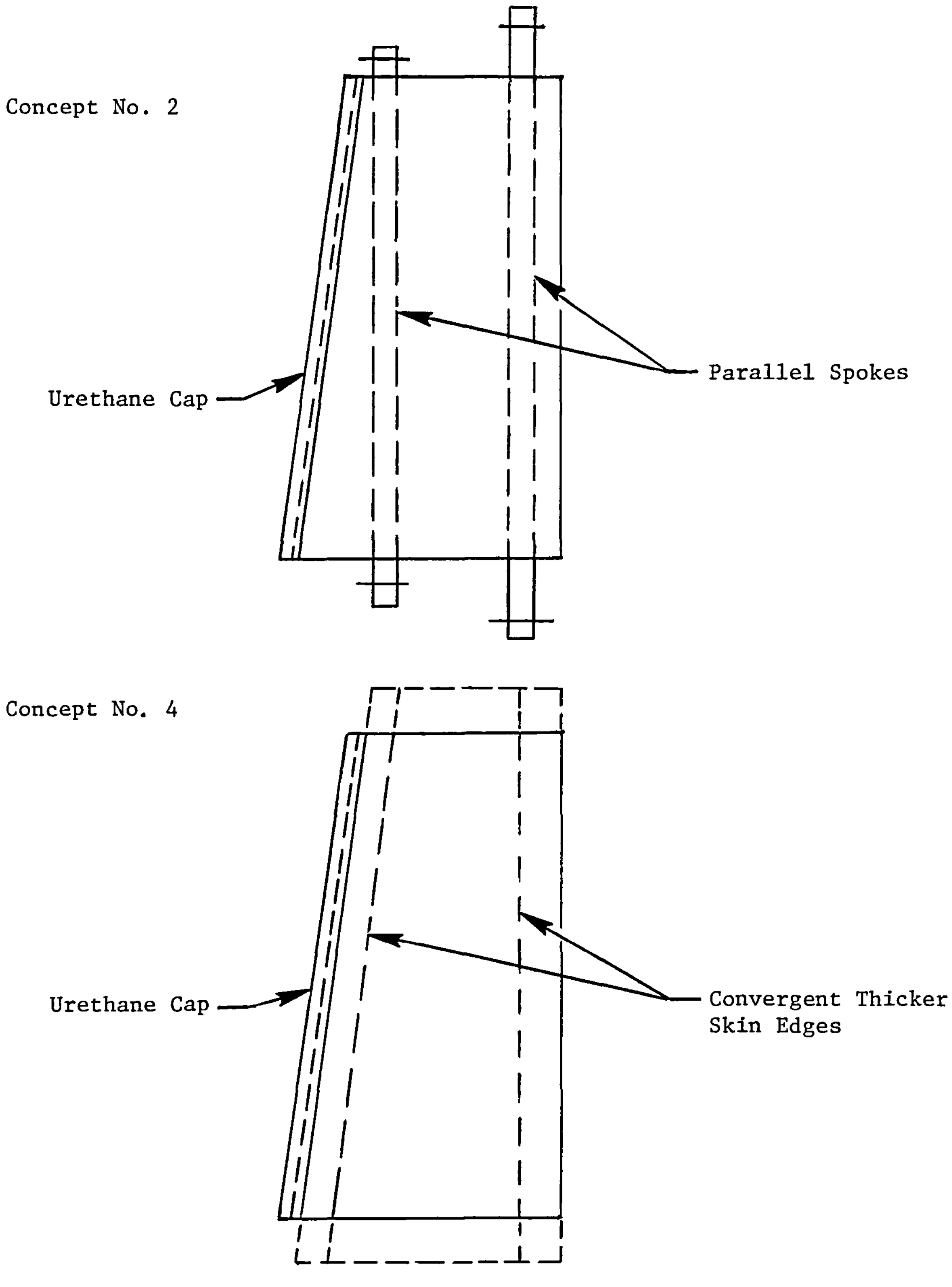


Figure 15. Vane/Spoke Structures.

The ability to fabricate all vanes separately and to fully inspect and nondestructively evaluate them prior to committing them to final assembly is applicable to both frame Concepts No. 2 and 4. One important difference between the two vane concepts is the relative degree of effort it would require to totally replace a damaged vane. A Concept 2 vane could be unbolted and removed axially with some tedious benching of spatula adhesive joints, collars, and flow path panels. A Concept 4 vane would have to be cut and benched away with total removal of its bonded insert features at both ends before a new vane could be installed radially. This may involve major rework to the fan case with bonded shear panels that might impose minor steps in the outer flowpath profile. However, depending on the amount of impact damage, local repairs may be made to vanes without their total removal.

The No. 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 cut-out fabrication process. Also, due to it 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 integral 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 shape, Concept 2 vanes would be more difficult for robot processing while Concept 4 vanes should be relatively easy for robot production.

The Concept 4 vane end pieces are compression-molded, graphite/epoxy, wedge-shaped 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. This would allow for a safety factor of 300% in the adhesive joints.

Stress Area D - Core Frame Vane Leading Edge

Coordinates of the core strut leading edge configuration, as illustrated in Figure 16, were fed into a section-properties computer program with iterations performed in wall thickness effects on inertia. Then by applying the maximum loads imposed by the 1-1/2-blade-out condition, the highest stresses were calculated for points of concern.

Candidate castable materials selected for comparison in the core frame are listed below with corresponding weights and effective cost.

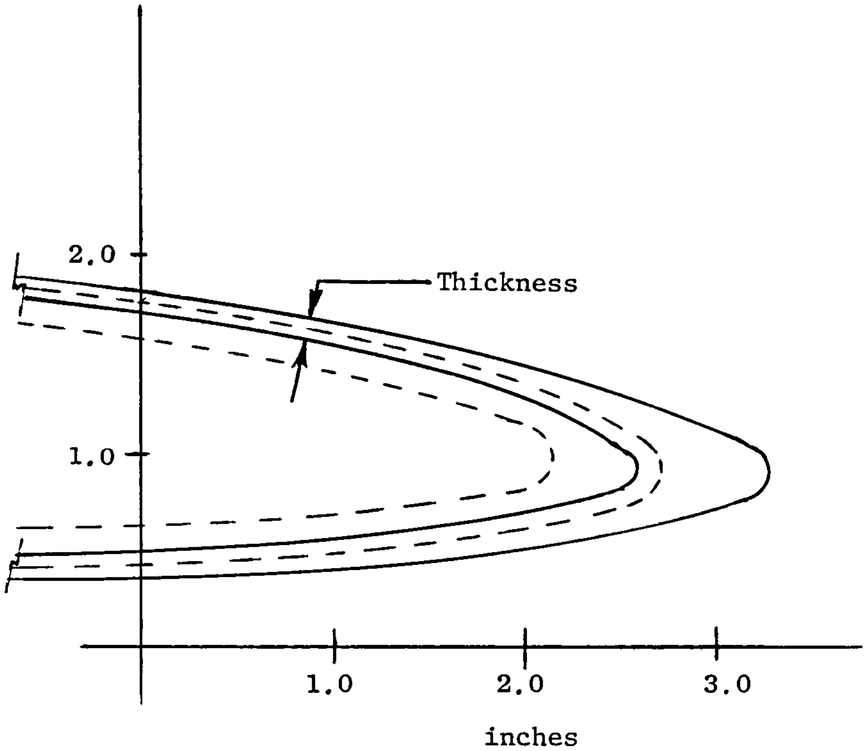


Figure 16. Core Frame Vane Leading Edge.

Cast Metal	Density lb/in^3	Tensile Stress 0.2% Yield Limit @ 350° F, ksi	Min. Cast Thickness	Max. Stress, ksi	Factor of Safety	Relative Wt., %	Relative Cost, %
17-4PH	0.283	105	0.080	46	2.3	98	400
INCO 718	0.296	113	0.080	46	2.5	100	300
C355 Alum.	0.098	27.5	0.250	21.5	1.3	100	100

It should be noted that from a stress standpoint the 17-4PH and the INCO 718 could be made as thin as 0.040 inch to 0.050 inch, but experience has shown that such castings can be no thinner than 0.080 inch in order to achieve good molten metal flow within the mold configuration. In addition, further experience has shown that a core frame of this size if cast in steel would probably have to be cast into sectors and then welded together to achieve a 360° frame, whereas a C355 aluminum frame could be cast in a single piece. Due to higher viscosity of 17-4PH, its sectors would have to be smaller than the INCO 718 sectors; hence its higher relative cost. A cast aluminum frame for either Concept No. 2 or 4 was selected for the choice of material.

As indicated in Figures 10 and 12, Concepts No. 2 and 4 could have five lightening holes through cast webs in the aluminum core frame at 13 locations for a total weight savings of about 6 pounds. However, the cost of casting or drilling such holes would require special equipment and extra labor that may add more cost than the weight payoff would justify. If graphite material could be encapsulated in either of the two cast aluminum core frames at a volume fraction of 40%, the total weight of either core frame, including the above-mentioned holes, could be reduced by about 40 pounds. However, this prospect would also add significant cost.

Stress Area E - Bearing Flange

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

3.3.1 Weight Analysis

A summary of materials and their weights for the respective fan case, vanes, and core frame of Concepts 2 and 4 are listed in comparison with the same items of the Revised Baseline Frame on Table IV.

3.3.2 Cost Analysis

In order to establish the hours to fabricate a frame component, a novel concept was devised to project composite component costs. Empirical cost and time data obtained from past and on-going 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 a TF34 program, Rohr projects a total of 18.7 manhours for the 250th unit of a right-angle figure with a mean diameter of 45 inches, leg lengths of 2 inches, and laminate thickness of 0.125 inch. By multiplying the circumferences x area x thickness x "K" and equating it to the projected manhours, the "K" factor could then be transferred to a similar formula for any size flange of similar profiles to calculate similar projected manhours.

Many imaginative and innovative approaches to the automation of composite structure fabrication have been developed and utilized throughout industry since the baseline QCSEE 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 manhours. The following types of fabrication processes describe some of the processes studied that could impact costs significantly over techniques utilized during the fabrication of the baseline QCSEE frame.

Robot Material Handling

A visit was made to the West Complex of Northrop Corporation, Aircraft Group, Hawthorne, California, on 21 May 1980, to attend Air Force/Industry Briefing on:

> "Automated Composite Material Transfer Program" per Contract F33615-77-C-5121 and
>
> "Composites Manufacturing Operation Production Integration - Phase II" review of Contract F33615-78-C-5215.

Some highlights of this briefing are listed below:

- The development and validation of two graphite sector controlled (vacuum and pressure) transfer heads for automated fabrication of composite assemblies.

- Verification of the ability of a computer-controlled off-the-shelf industrial robot to automatically pick up, transfer, index, and lay down various composite materials (graphite, fiberglass, Kevlar, etc.) and material forms (unidirectional, woven, preplied) with the transfer heads providing accuracies well within production specifications.

- Demonstration of the ability to lay composite materials with the robotic transfer mechanism into and over mildly contoured female and male tools.

- Verification of the manufacturing and structural integrity of the automated lamination approach through the fabrication and testing of large laminates, access doors, bulkheads, and full-size horizontal stabilizer skin assemblies.

- A cost savings of approximately 34% when the robot is used individually in the fabrication of full-size horizontal stabilizer skins and a cost savings of approximately 73% when used in an integrated fashion with the additional equipment of the Integrated Flexible Automation Center.

Figure 17 shows the layout of automation and robot systems that were displayed by Northrop during this briefing.

Some actual comparison of robot fabrication versus hand layup was cited during this meeting with the following results:

	Robot Hr	Hand Labor Hr
Material Dispensing From Stock Roll	0.137	0.550
Material Cutting (Gerber @ 50"/sec.)	0.094	0.135
Material Transfer to Mold Area	0.398	0.566
Material Transfer into Mold	0.190	0.270
Scrap Removal	0.768	1.090
Total	1.58	2.61

If two robots were utilized, the 1.58 hours were projected to reduce to 1.08 hours.

During the above 0.137 hours of robot dispensing of material, the stock is automatically scanned for discrepancies at the rate of 350 ft/minute. Any serious flaws are then electronically remembered and avoided during the computer-controlled Gerber cutting. It is projected that such robot equipment could reduce costs significantly in the fabrication of frame vane struts, skins, and certain fan case components.

Other fabrication processes considered in the projection of labor hours compiled for each frame concept included the following:

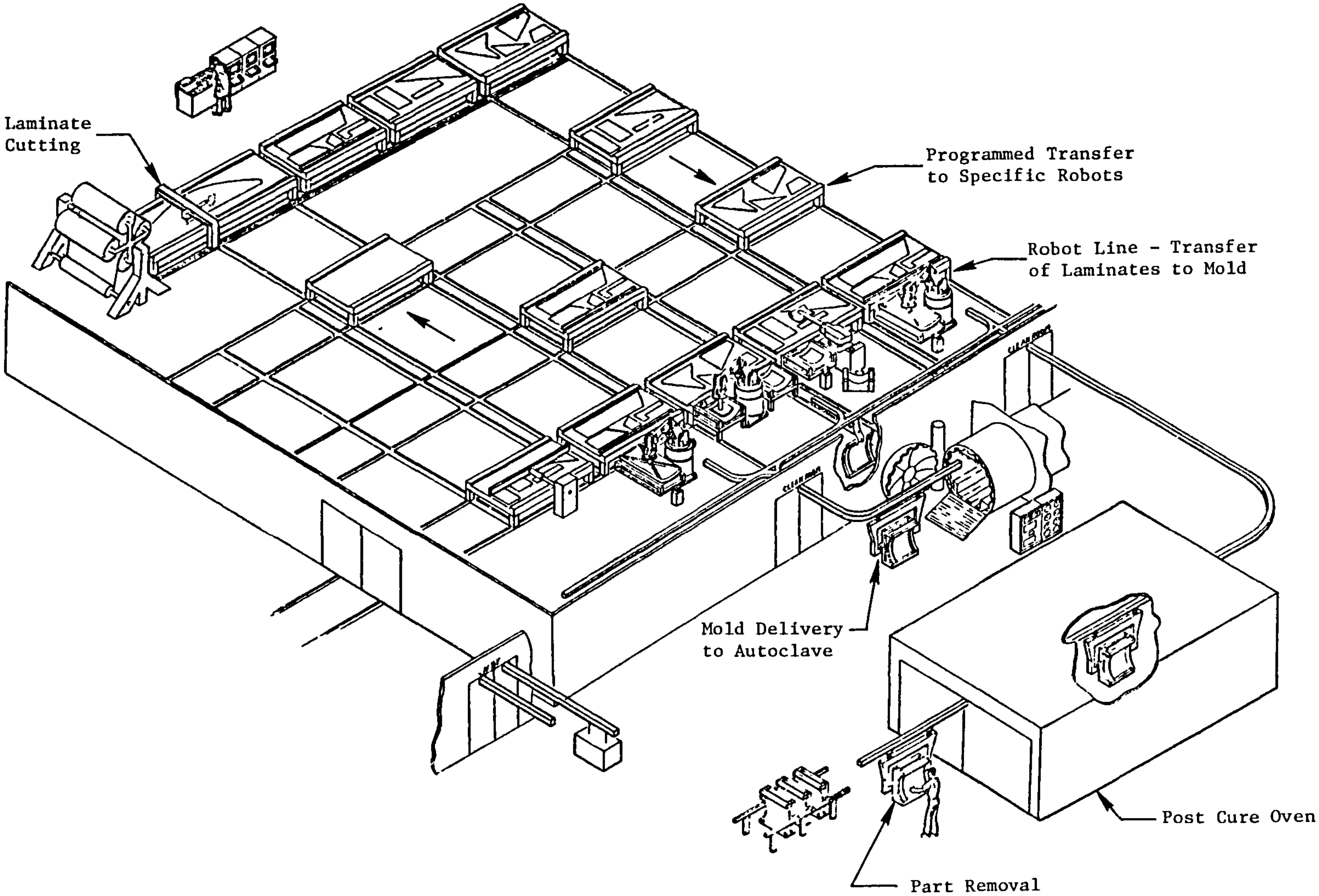


Figure 17. Integrated Flexible Automated Composite Fabrication Center.

Vacuum Injection Molding - for vane leading edge, vane collars and fan tip channel components.

Resin Transfer Molding - for vane skins, struts, fan case shells and core shells.

Filament Winding and Braiding - for certain fan case shells, structural wheel rims and flanges.

Compression Molding - for vane root and tip inserts, certain flanges and braces.

Cast Aluminum - for Concepts No. 2 and 4 core frame.

Die Cast Aluminum - for Concept 4 vane tip blocks in the fan case.

Material Considerations

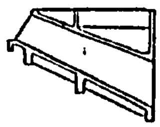
A visit was made to Rohr Industries, Riverside, California, to review progress on Contract F33615-78-C-5086, "Manufacturing Technology for Low Temperature Composite Engine Frames," It was observed that by substituting woven graphite fabric for certain unidirectional tape laminates in the fabrication of specific right-angle circular flanges, the total hand labor time dropped from 10 to 2-1/2 hours. This is due to the fact that fabric material drapes and profiles better than tape, it is thicker per ply than tape, and it can be cut to cover greater arc length in one piece than tape. The substitution of fabric for tape required careful study to validate its true payoff because woven graphite fabric is approximately 1-1/4 times more expensive than an equal weight of unidirectional graphite tape. Also, structures made with woven fabric will display different properties of stiffness and weight than equivalent structures made entirely with unidirectional material. Each generic component shape required separate analysis to determine if woven fabric could replace unidirectional material and to what extent it would be cost effective from the standpoint of fewer number of pieces and associated reduced labor hours or robot time.

To establish the cost for materials for each frame concept, the total weights of the respective materials listed on Table IV for each frame was multiplied by a factor of 1.5 to account for projected material scrap losses which is based on past experience.

Pie charts showing projections of the total material and fabrication costs for frame Concepts 2 and 4 in 1979 dollars are illustrated in Figure 18. A similar pie chart was prepared from a study conducted by Rohr on the TF34 composite frame per Figure 19. The similarities of relationship between material costs and labor hours are apparent between the three pie charts. A study was also made on the likely variation in the cost of composite materials for 1985. This variatin is plotted versus percent confidence as shown in Figure 20. For this study, a 60% confidence level was used on each design to project a 250th unit cost as listed earlier on Table II.

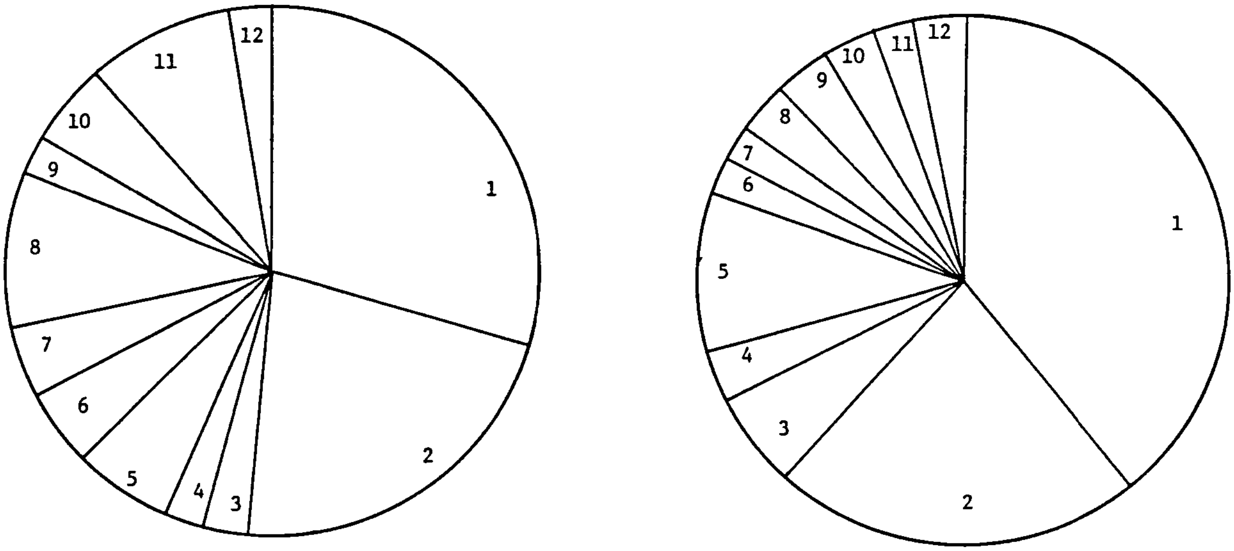
Table IV. Low-Cost Composite Frame Study - Weight and Cost Summary.

1 - QCSEE Revised Base | 2 - Modular | 3 - Hybrid

												
	Fan Case			Vanes			Core			Totals		
Materials	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	87	87	87	---	---	---	---	---	---	87	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	26	26	26	5	5	3	21	2	2	52	33	31
Totals/Lbs.	338	378	355	62	62	60	163	266	280	563	706	695
Cost Comparison - 250th Unit										100%	64%	41%

1. Cast Aluminum and Other Metals
2. Composite Materials
3. Filament Winding
4. Hand Lay-up
5. Robot Lay-up
6. Press Molding
7. Autoclave Molding
8. Resin Transfer Molding
9. Vacuum Injection Molding
10. Adhesive Bonding
11. Intermediate Machining
12. Final Machining

Concept #2 - Modularized | Concept #4 - Hybrid

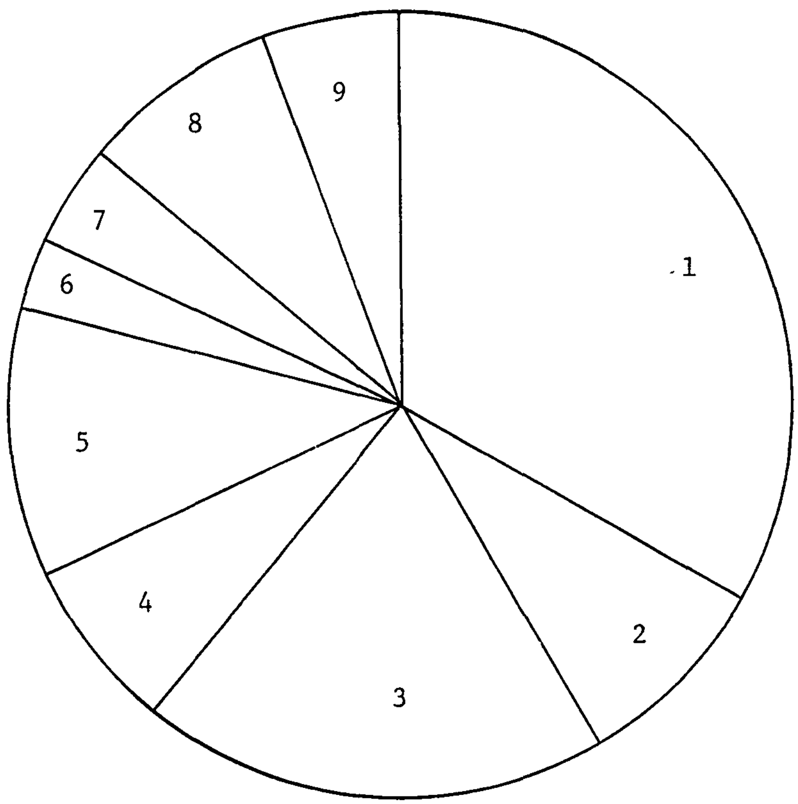


1 and 2 = $33,755 (1979)
3 thru 12 = 1400 Labor hrs.

1 and 2 = $40, 750 (1979)
3 thru 12 = 1082 Labor hrs.

Figure 18. 250th-Unit Production Pie-Chart Cost Items.

1. Cast Aluminum and Other Metal Materials
2. Composite Materials
3. Hand Layup
4. Press Molding
5. Autoclave Molding
6. Injection Molding
7. Adhesive Bonding
8. Intermediate Machining
9. Final Machining



1 and 2 = $12,665 3 thur 9 = 777 hrs.

Figure 19. TF34 Composite Frame - 250th-Unit Production Pie-Chart Cost Items.

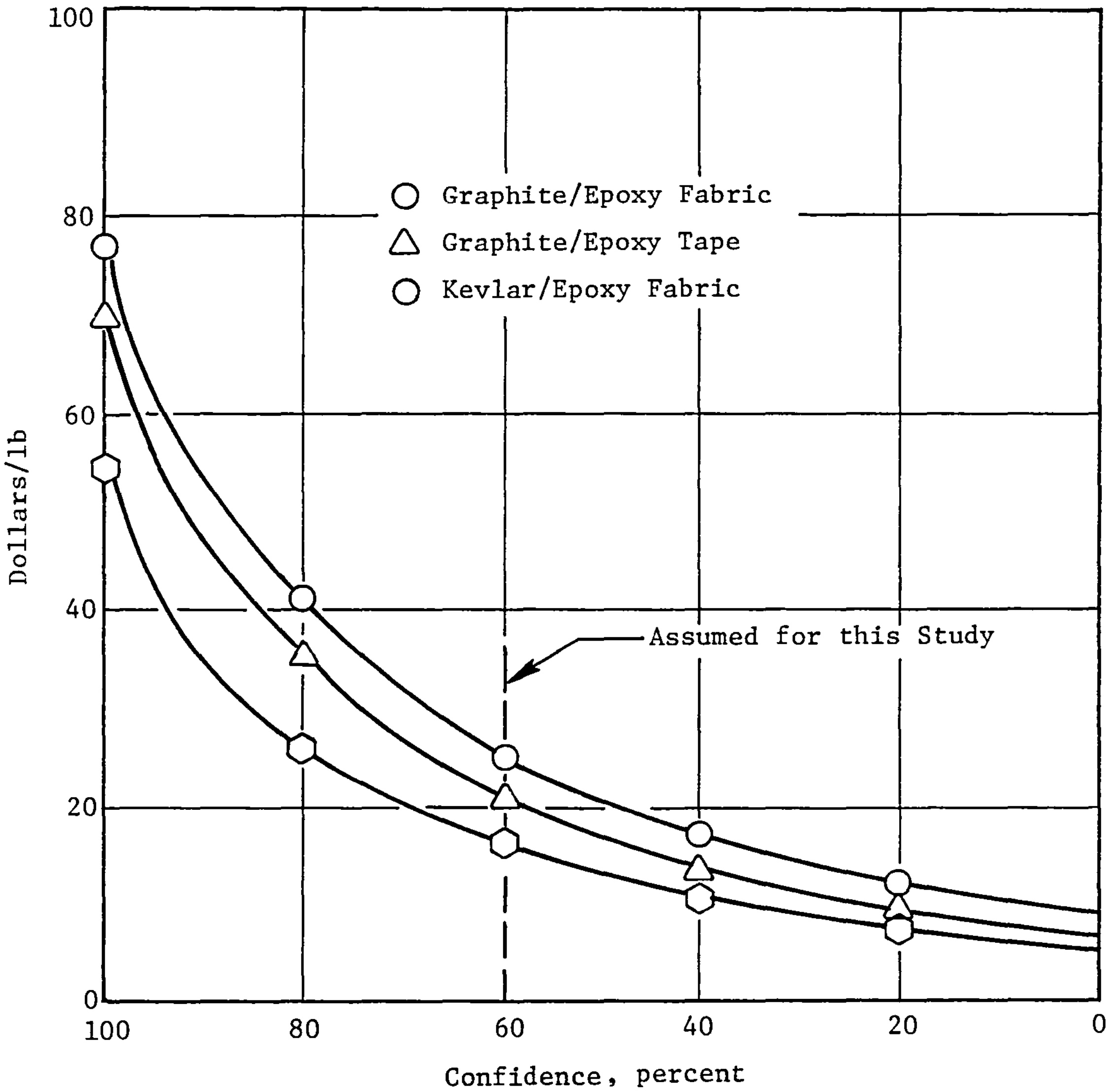


Figure 20. 1985 Cost of Prepeg.

3.3.3 Final Frame Selection

A Cost/Optimization/Efficiency (COE) Summary was compiled for the three major components of both frame Concepts 2 and 4. This summary first established material ultimate stresses for the respective type of composite materials projected for each component. Then, by limiting stresses to a 300% or greater safety factor, the minimum material thickness was established for each component. Figures 21 and 22 illustrate all the composite components and their specific material details of both frame Concepts 2 and 4. Alternative methods of fabricating each component were then considered with associated projections of hours of labor for each component in a production environment. The most efficient method of fabrication was then selected and the total number of hours were summarized for each frame concept. To reinforce the validity of initial cost estimates associated with each frame, details of the eight different components (Figure 23) 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 core frames are so similar, their purchase price was estimated to be equal. Further machining of each cast core frame requires different processes, but the net effect in 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 slight difference in weight of 215 pounds for the core of Concept 2 versus the 237 pounds for the core of Concept 4 was factored in at an equivalent of one hour of additional labor cost for Concept 4. The most significant contributor to the difference in cost between Concept 2 and 4 are 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 compositing and assembly than the two-piece vane skins without separate spokes utilized in Concept 4.

After all the component weights, material costs, and projected hours of labor were assembled, for both frame Concepts 2 and 4 as well as the Revised Baseline QCSEE frame, totals were expressed in relative percentages as shown previously in Table IV. With the total cost of the Revised Baseline Frame set at 100%, the relative cost of the No. 2 modular frame equated to 64% while the No. 4 hybrid frame equated to 41%, as listed on Table I.

After compiling the weights and relative costs of both frame Concepts 2 and 4, a final selection of the low-cost frame was made by utilizing the Evaluation Analysis worksheets illustrated in Tables V through VII, which provide a weighted comparison between both frames for a variety of listed considerations. Each frame's major components were evaluated separately, then summarized in total for each full frame assembly on Table VII. By multiplying a scale of comparison from 1 to 10 for each item by the percent value assigned to the respective considerations, a numerical assessment was totalled to reveal that the No. 4 hybrid frame is the final selected frame for a projected Implementation Plan.

CONFIGURATION	ITEM NO	TITLE	MATERIAL	LAY-UP PATTERNS	THICKNESS NOM	0° DATUM	COMMENTS
	2	C CHANNEL FWD	SEE NOTE 3	$(45,0,0,45,90,45)_S$	.060	AXIAL	—
	3	L FLANGE FWD	SEE NOTE 3	$(45,90,-45,0)_S$	.035	CIRCUM	—
	4	CHANNEL	SEE NOTE 5	N/A	—	—	INJECTION MOLDED
	5	C CHANNEL MID	SEE NOTE 3	$(45,0,0,-45,90,45)_S$	.060	AXIAL	—
SCALE NONE	6	SKIN MID - BYPASS	SEE NOTE 3	$(-45,90,45,0)_S$	.035	CIRCUM	—
SCALE NONE	7	SKIN MID - OUTER	SEE NOTE 3	$(45,90,-45,0)_S$	.066	CIRCUM	—
SCALE NONE	8	SKIN OUTER BYPASS	SEE NOTE 3	$(45,0,-45,90)_S$	.035	AXIAL	—
FLANGE, AXIAL LEG, SCALE NONE	9	SKIN FLOW[illegible] INNER BYPASS	SEE NOTE 3	$(45\ 90,-45,0)_S$	.035	CIRCUM	AXIAL LEG
			SEE NOTE 3	$(45,90,-45,0)_{S2}$	.070	CIRCUM	FLANGE
SCALE NONE	10	DOUBLER FRAME FWD	SEE NOTE 4	$((0,0\ 45\ 90,-45)_2)_S$	100	CIRCUM	—
SCALE NONE	11	DOUBLER FRAME AFT	SEE NOTE 4	$((0,0,45\ 90-45)_2)_S$	100	CIRCUM	—
	12	SUPPORT COVER	SEE NOTE 4	$((0,0,45,90-45)_2)_S$	100	CIRCUM	—
	13	SUPPORT COVER	SEE NOTE 4	$(0,45\ 90,-45,0)_S$	.050	CIRCUM	—
	14	BOSS	SEE NOTE 7	N/A	—	—	PULTRUDED ROD
SCALE 1/2	15	PLATE COVER	SEE NOTE 3	$((0,0,45\ 90,-45)_2)_S$	100	CIRCUM	—
	16	SUPPORT LATCH	SEE NOTE 3	$((0,45\ 90,-45)_3)_S$	120	CIRCUM	—
SCALE NONE	17	SUPPORT	SEE NOTE 6	N/A	—	—	COMPRESSION MOLDED
SCALE NONE	18	HOUSING	SEE NOTE 5	N/A	030		INJECTION MOLDED
	19	C CHANNEL INNER BYPASS	SEE NOTE 3	$(45,0-45\ 90)_S$	035	AXIAL	—
SCALE NONE	20	VANE PANEL (CONVEX)	SEE NOTE 1	$(0\ 45,90-45)_S$	.050	—	—
SCALE NONE	21	VANE PANEL (CONCAVE)	SEE NOTE 1	$(0,45,90,-45)_S$	.050	—	—
	22	LEADING EDGE	SEE NOTE 5	N/A	—	—	INJECTION MOLDED
SCALE NONE	23	SPLITTER UPPER	SEE NOTE 3	$(0,45\ 90,-45,0)_S$	.090	CIRCUM	—
SCALE NONE	24	Z CHANNEL OUTER OC	SEE NOTE 3	$(45,0,0,-45\ 90\ 45)_S$	.060	CIRCUM	—
SCALE NONE	25	RING FWD	SEE NOTE 1 & 2	$(45,0_6,-45,90,45,0_3,45,90-45,0_6,45)_S$	.50	CIRCUM	—
SCALE NONE	26	RING AFT	SEE NOTE 1 & 2	$(45,0_6,-45\ 90,45,0_3,45,90,-45,0_6,45)$	.50	CIRCUM	—
UPPER LEG, BOTTOM LEGS	27	C CHANNEL INNER OC	SEE NONE 3	$(45,0,0-45,90\ 45)_S$	060	CIRCUM	UPPER LEG
			SEE NONE 3	$((0,45\ 90,-45)_2)_S$	120	CIRCUM	BOTTOM LEGS
	28	SKIN MID PANELS	SEE NOTE 3	$(45,90,-45,0)_S$	.035	CIRCUM	—

7 GLASS/EPOXY ROD PER NEMA GRADE G-11 OR EQUIVALENT
6 COMPRESSION MOLDING TO BE IN FORM [illegible] SUPPLIED BY U.S. POLYMERIC OR EQUIVALENT
5 INJECTION MOLDING TO BE IN FORM [illegible] SUPPLIED BY [illegible], OR EQUIVALENT
4 GLASS/EPOXY FABRIC TO BE IN FORM [illegible] SUPPLIED BY [illegible], OR EQUIVALENT
3 KEVLAR/EPOXY FABRIC TO BE IN FORM [illegible] SUPPLIED BY [illegible], OR EQUIVALENT
2 GRAPHITE/EPOXY FABRIC TO BE IN FORM [illegible] SUPPLIED BY HERCULES OR EQUIVALENT
1 GRAPHITE/EPOXY TAPE TO BE IN FORM [illegible] SUPPLIED BY HERCULES OR EQUIVALENT

Figure 21. Frame, Front Composite - Modular - 4013266-506.

CONFIGURATION	ITEM NO	TITLE	MATERIAL	LAY-UP PATTERN	THICKNESS NOM	0° DATUM	COMMENTS
	2	C CHANNEL FWD	SEE NOTE 3	$(45,0,0,45,90,45)_s$	.060	AXIAL	—
	3	L FLANGE FWD	SEE NOTE 3	$(45,90,-45,0)_s$	.035	CIRCUM	—
	4	CHANNEL	SEE NOTE 5	N/A	—	—	INJECTION MOLDED
	5	C CHANNEL MID	SEE NOTE 3	$(45,0,0,-45,90,45)_s$	.060	AXIAL	—
SCALE NONE	6	SKIN MID-BYPASS	SEE NOTE 3	$(-45,90,45,0)_s$	.035	CIRCUM	—
SCALE NONE	7	SKIN O'D-OUTER	SEE NOTE 3	$(45\ 90,-45,0)_s$	.035	CIRCUM	—
SCALE NONE	8	SKIN OUTER BYPASS	SEE NOTE 3	$(45,0,-45,90)_s$	.035	AXIAL	—
FLANGE / AXIAL LEG / SCALE NONE	9	SKIN FLANGED INNER BYPASS	SEE NOTE 3	$(45,90,-45,0)_s$	.035	CIRCUM	AXIAL LEG
			SEE NOTE 3	$(45,90,-45,0)_{2s}$	.070	CIRCUM	FLANGE
SCALE NONE	10	DOUBLER FRAME-FWD	SEE NOTE 3	$((0,0\ 45,90,-45)_2)_s$	.100	CIRCUM	—
SCALE NONE	11	DOUBLER FRAME AFT	SEE NOTE 3	$((0,0\ 45,90,-45)_2)_s$	.100	CIRCUM	—
	12	SUPPORT COVER	SEE NOTE 4	$((0,0\ 45,90,-45)_2)_s$	.100	CIRCUM	—
	13	SUPPORT COVER	SEE NOTE 4	$(0,45\ 90,-45,0)_s$	.250	CIRCUM	—
	14	BOSS	SEE NOTE 7	N/A	—	—	PULTRUDED ROD
SCALE NONE	15	PLATE COVER	SEE NOTE 3	$((0,0,45,90,-45)_2)_s$	.100	CIRCUM	—
	16	SUPPORT LATCH	SEE NOTE 3	$((0,45,90,-45)_2)_s$	.120	CIRCUM	—
SCALE NONE	17	SUPPORT	SEE NOTE 6	N/A	—	—	COMPRESSION MOLDED
SCALE NONE	18	HOUSING	SEE NOTE 5	N/A	.030		INJECTION MOLDED
	19	C CHANNEL INNER BYPASS	SEE NOTE 3	$(45,0,-45,90)_s$	.035	AXIAL	—
SCALE NONE	20	VANE PANEL (CONVEX)	SEE NOTE 1	$(0\ 45,90,-45)_s$	.050	—	—
SCALE NONE	21	VANE PANEL (CONCAVE)	SEE NOTE 1	$(0,45,90,-45)_s$	.050	—	—
	22	LEADING EDGE	SEE NOTE 5	N/A	—	—	INJECTION MOLDED
SCALE NONE	23	SPLITTER UPPER	SEE NOTE 3	$(0,45\ 90,-45,0)_s$	.050	CIRCUM	—
SCALE NONE	24	Z CHANNEL AFT	SEE NOTE 3	$(45,0,0,-45,90,45)_s$	.060	CIRCUM	—
UPPER LEGS / LOWER LEG	25	Z CHANNEL OUTER O.C.	SEE NOTE 3	$(45,0,0,-45,90,45)_s$	.060	CIRCUM	UPPER LEGS
			SEE NOTE 3	$((0,45\ 90,-45)_2)_s$	.120	CIRCUM	LOWER LEGS
SCALE NONE	26	RING AFT	SEE NOTE 1 & 2	$(45,0_6,-45\ 90,45,0_3,45,90,-45,0_6,45)$	.50	CIRCUM	—
SCALE NONE	27	U CHANNEL INNER O.C.	SEE NOTE 2	$(45,0,0,-45,90\ 45)_s$	.060	CIRCUM	—
WEB / RIB	28	AFT SPOKE	SEE NOTE 1	[illegible]	.80	RADIAL	RIB
			SEE NOTE 1	[illegible]	.80	RADIAL	WEB
WEB / RIB	29	FWD SPOKE	SEE NOTE 1	[illegible]	.80	RADIAL	RIB
			SEE NOTE 1	[illegible]	.80	RADIAL	WEB

7 [illegible]
6 [illegible]
5 [illegible]
4 [illegible]
3 [illegible]
2 [illegible]
1 [illegible]

Figure 22. Frame, Front Composite - Hybrid - 4013266-505.

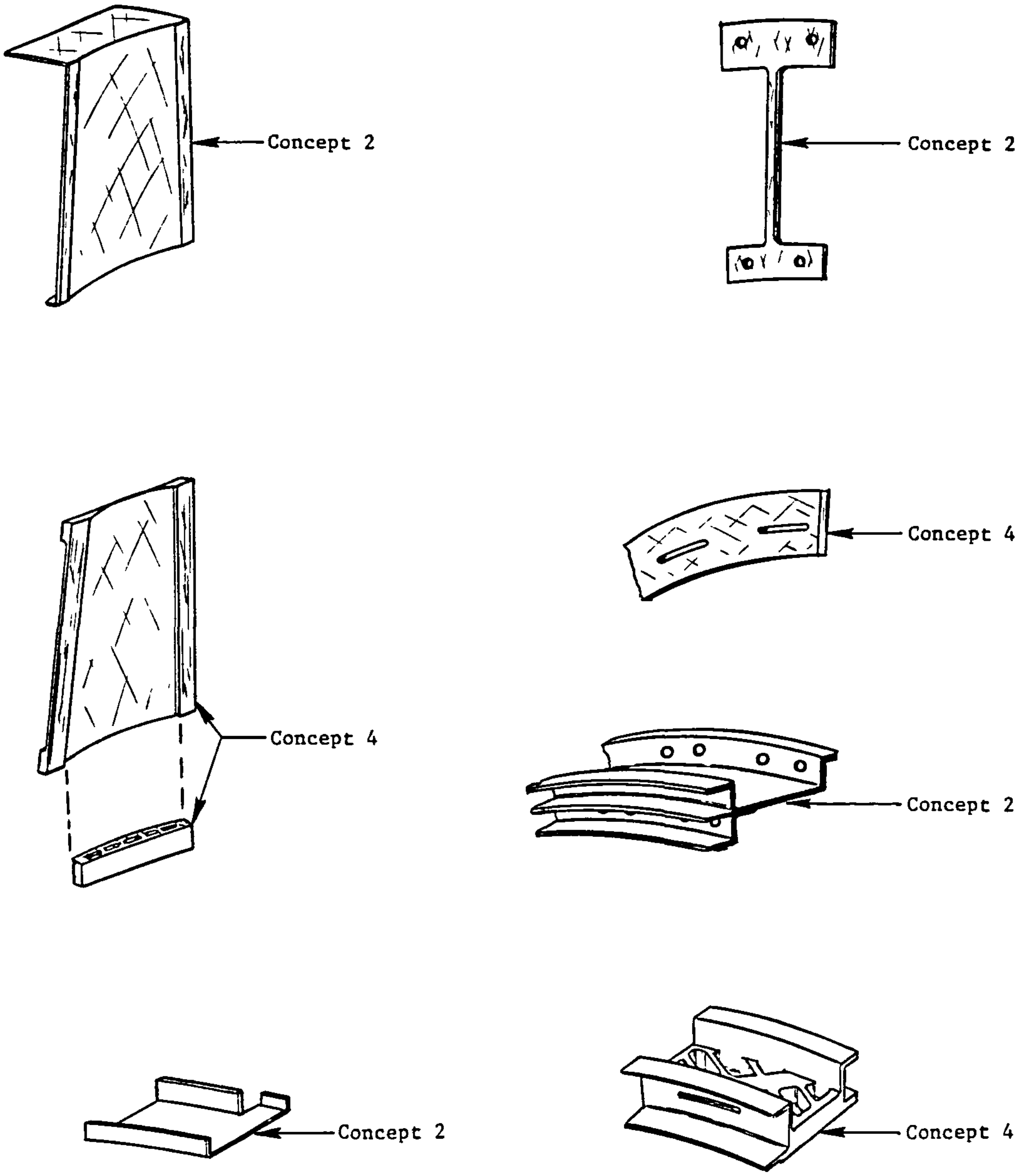


Figure 23. Components of Main Differences Between Concepts No. 2 and No. 4.

Table V. Evaluation Analysis - Fan Case.

For Component Considerations	Fan Case Type (V) % Value	No. 2 - Modularized S*	No. 2 - Modularized S x V	No. 4 - Hybrid S*	No. 4 - Hybrid S x V
• - Cost (35%)					
- Materials	10%	5	50	6	60
- Fabricability	15%	5	75	5	75
- Automation	10%	5	50	6	60
• - Weight	30%	5	150	4	120
• - NDE Ability	20%	5	100	5	100
• - Low Maintenance	15%	5	75	5	75
	100%	Total	500	Total	490

*(S) Scale of 1:10   1 = Poor,   10 = Excellent

Table VI. Evaluation Analysis - Vanes.

For Component Considerations	- Vanes Type (V) % Value	No. 2 Modularized S*	No. 2 Modularized S x V	No. 4 Hybrid S*	No. 4 Hybrid S x V
• - Cost (35%)					
- Materials	10%	5	50	6	60
- Fabricability	15%	4	60	9	135
- Automation	10%	3	30	8	80
• - Weight	30%	5	150	5	150
• - NDE Ability	20%	5	100	5	100
• - Low Maintenance	15%	5	75	5	75
	100%	Total	465	Total	600

*(S) Scale of 1:10 1 = Poor, 10 = Excellent

Table VII. Evaluation Analysis - Core Frame.

For Component Considerations	Core Frame Type (V) % Value	No. 2 - Modularized S*	No. 2 - Modularized S x V	No. 4 - Hybrid S*	No. 4 - Hybrid S x V
• - Cost (35%)					
- 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
	100%	Total	500	Total	470

*(S) Scale of 1:10 1 = Poor, 10 = Excellent

Grand Total - No. 2 = 1465 versus No. 4 = 1560 - Type

3.3.4 Implementation Plan

The four frame concepts studied under this contract were designed to exchange directly with the baseline QCSEE frame developed under NASA Contract NAS3-18021. Accordingly, the Implementation Plan for the final selected frame concept will closely follow the original QCSEE baseline frame development effort. This plan will allow for the evaluation of all the design and performance requirements and criteria to produce a flight-ready frame as modified to the revised baseline criteria explained earlier and listed in Table II.

The Implementation Plan generated for the hybrid frame concept is described with respect to the following details:

1. All design and performance requirements and criteria to produce a flight-ready frame plus detailed analysis procedures to verify all aspects of design and to ascertain service performance.

2. Concepts of selected joints and complex subcomponents with associated testing to verify fabrication procedures and structural design and integrity of critical items.

3. An inspection plan.

4. A repair plan.

5. The projected cost of all the above effort in 1979 dollars.

3.3.4.1 Design, Analysis, and Performance Requirements

In addition to the normal range and combination of steady-state pressure, thermal, thrust, and torque loads, the engine (including all nacelle and aircraft-furnished components attached to or mounted on the engine and supported through the engine mounts) would be designed to withstand, within the limits specified, the loads defined in Conditions I through VI, which are listed in Table III. Table VIII summarizes the bearing loads on the frame for the following set of conditions: 1 g down, 1 radian/sec., and 1 metal fan blade-out.

Air loading for some of the bypass vanes is shown in Figure 24. The bypass of the frame is spanned by 33 vanes which are shaped into 6 different contours arranged in groups of 1, 6, 6, 8, 6, and 6. At top vertical is the pylon; next to it (clockwise, aft looking forward) is the vane group with highest camber, Closed 2. Then come (still clockwise) Closed 1, Nominal, Open 1, and finally - the vane grouping with the lowest camber - Open 2. The main purpose of the various vane shapes is to equally distribute the bypass airflow around the large pylon at top vertical. Also shown on Figure 24 are the OTW and UTW bypass vane air loads. The OTW and UTW refer to "over the wing" and "under the wing" versions of QCSEE baseline engine concepts.

Table VIII. Frame Radial Bearing Loads.

1 g Down Bearing No.	UTW Radial Load		OTW Radial Load	
	N	lb	N	lb
1	3,425	(770)	4,822	(1,084)
2	1,099	(247)	1,882	(423)
3	364	(82)	364	(82)
4	823	(185)	823	(185)
1 radian/sec Bearing No.				
1	27,397	(6,159)	69,232	(15,564)
2	27,397	(6,149)	69,232	(15,564)
3	1,699	(382)	1,739	(391)
4	9,559	(2,149)	9,906	(2,227)
1 Metal Fan Blade-Out Bearing No.				
1	471,254	(105,942)	452,916	(101,820)
2	165,704	(37,252)	116,908	(26,282)
3	14,982	(3,368)	14,902	(3,350)
4	57,978	(13,034)	38,718	(8,704)

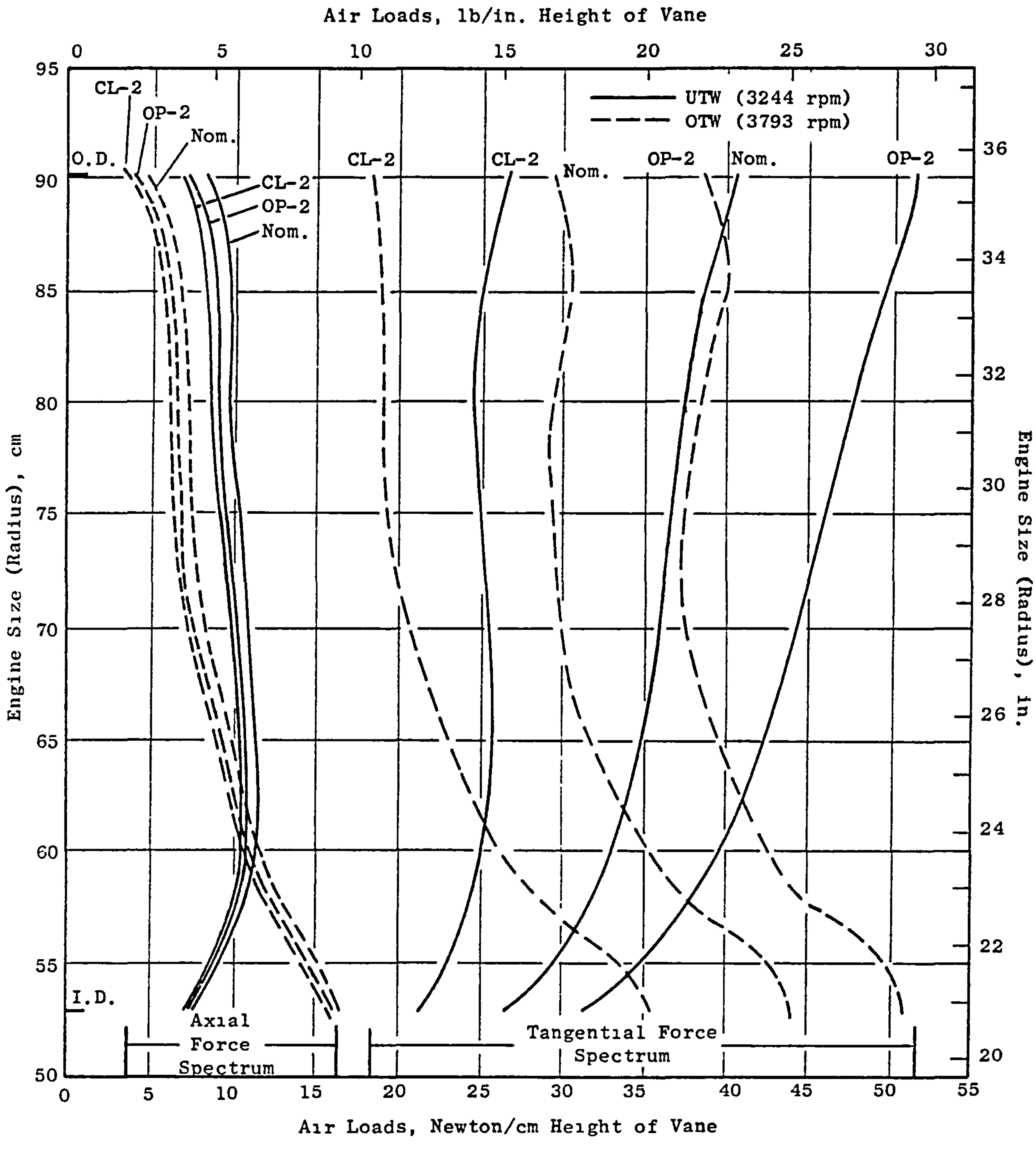


Figure 24. Bypass Vane Air Loading.

The first step of the analysis procedure would be to activate an iterative design analysis cycle for the hybrid frame. Figure 25 illustrates a typical design analysis cycle. As seen in the figure, this cycle reflects the design optimization parameters embodied in a typical composite static structure. Refinement of each structural component is accomplished by cycling each component through the above-mentioned process until its ply orientation, geometry, and cost have been optimized for the particular loading environment.

The optimization procedure would be initiated by assuming practical orientations and thicknesses for all of the component parts of the basic design. Next, a finite element model of the hybrid frame would be constructed similar to that shown in Figure 26. Due to the simple design philosophy of the frame, the computer model would quite accurately represent the actual frame structure. This similarity is shown in Figure 27.

In order to accurately model the load-extraction structures that are attached to the frame, both the engine mounting system and the core engine would also be modeled. Figure 28 depicts the similarity of the computer model and the actual frame/core engine structure.

The iterative optimization procedure shown in Figure 25 is based on the philosophy that if (at some region) the margin of safety at ultimate load is high, weight savings can be realized by diminishing the amount of load-carrying material in that region. Conversely, if the margin of safety is low, material can be added locally to maintain structural integrity. The designer utilizing reinforced composite material has the additional option of tailoring the fiber orientations to suit his strength and stiffness requirements.

This particular iterative procedure was specifically established for designs using composite materials. For isotropic materials, the method simplifies into a finite-element analysis since elastic and strength properties of the materials are available from handbooks. These properties can be directly coordinated with the finite-element program.

The basic frame analysis would be performed using General Electric's computer program system (entitled "MASS") for the analysis of 3-D redundant structures. The MASS system provides the means of analyzing almost any structure. The variety of available elements gives the program a great deal of versatility; with care, most structures can be modeled accurately or closely approximated. The basic elements available for modeling are the two-ended curved or straight beam, the four-sided curved or flat trapezoidal plate, the six-sided tetrahedron, rigid connectors, springs, and tubes. A modification of the plate subprogram permits the analysis of sandwich panel structures with orthotropic faces.

The types of analyses available in MASS are: mechanical loading, thermal gradients, maneuver loads, forced response, and determination of critical frequencies. An instability check is optional. Resulting output is in the form of loads, stresses, and deflections.

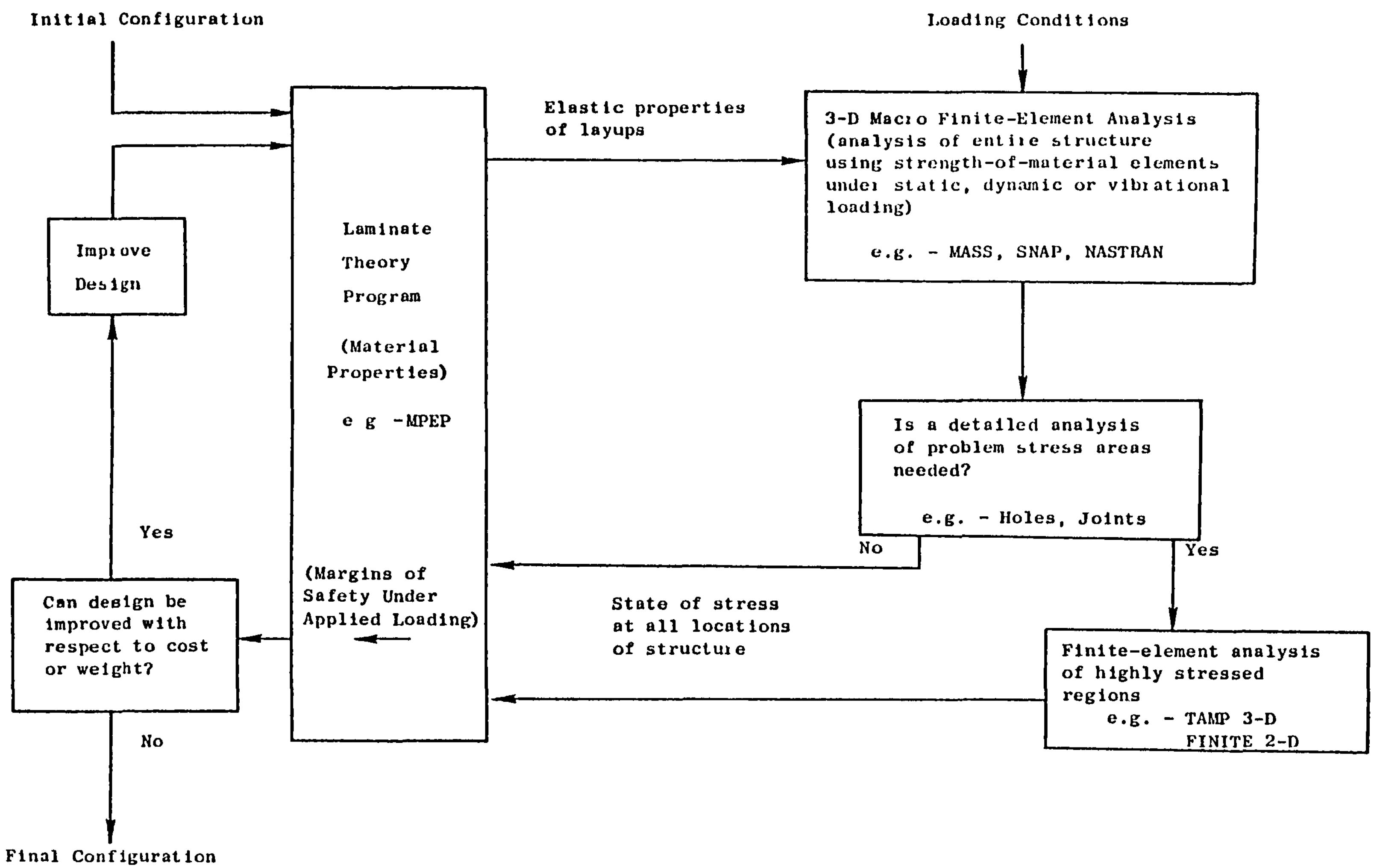


Figure 25. Design Optimization Cycle.

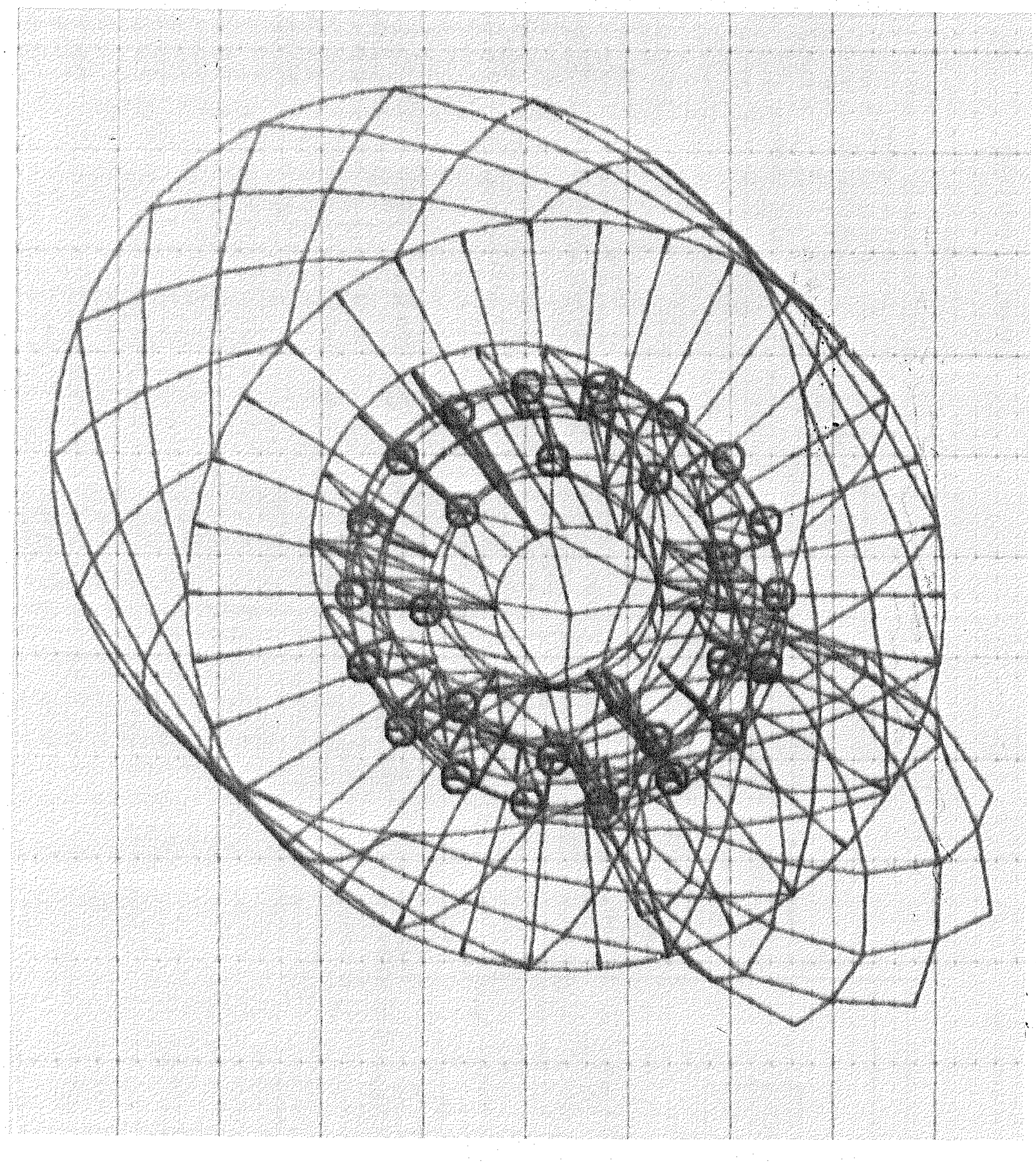


Figure 26. Analytical Model Trimetric.

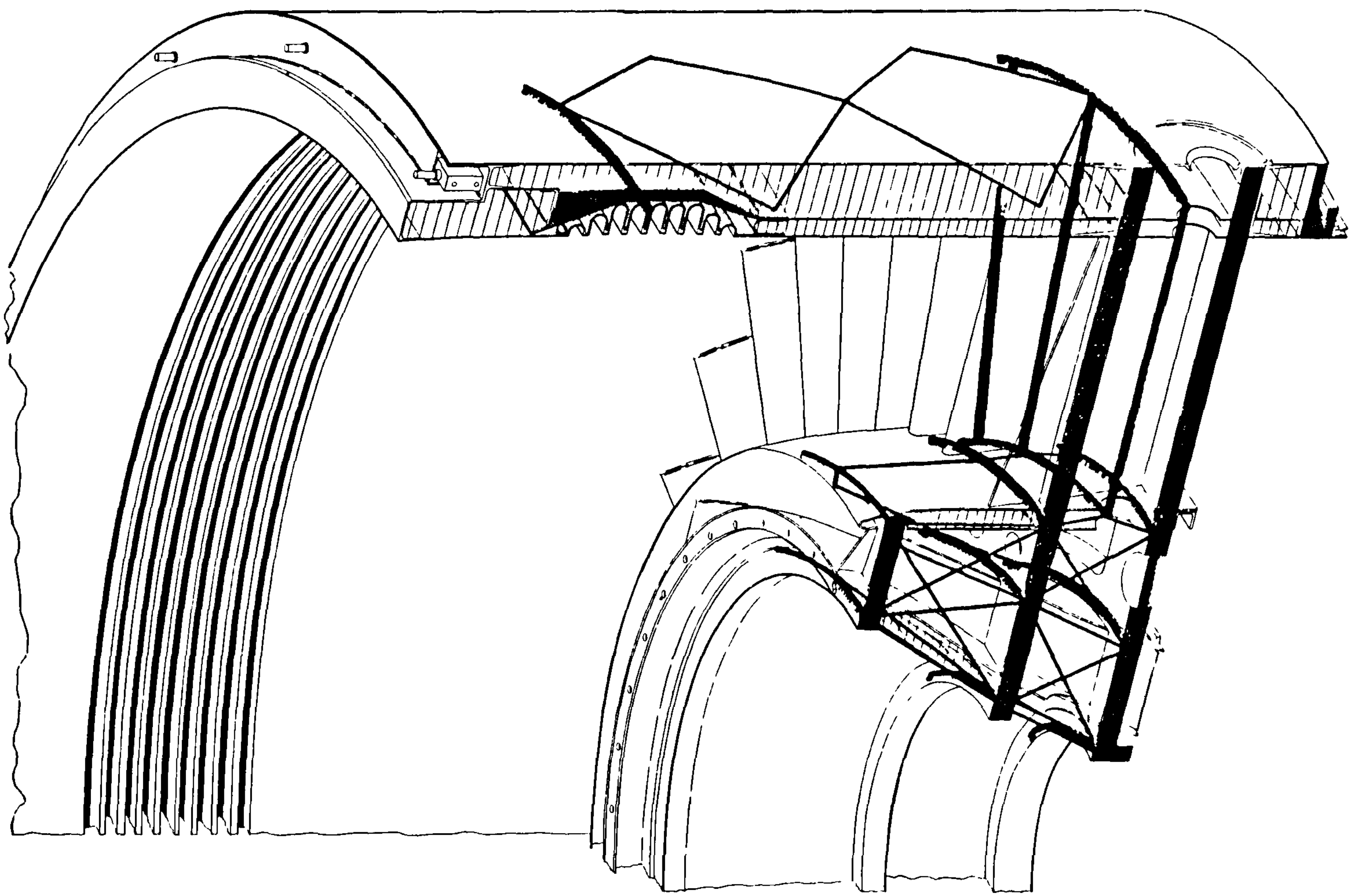


Figure 27. Analytical Model Representation.

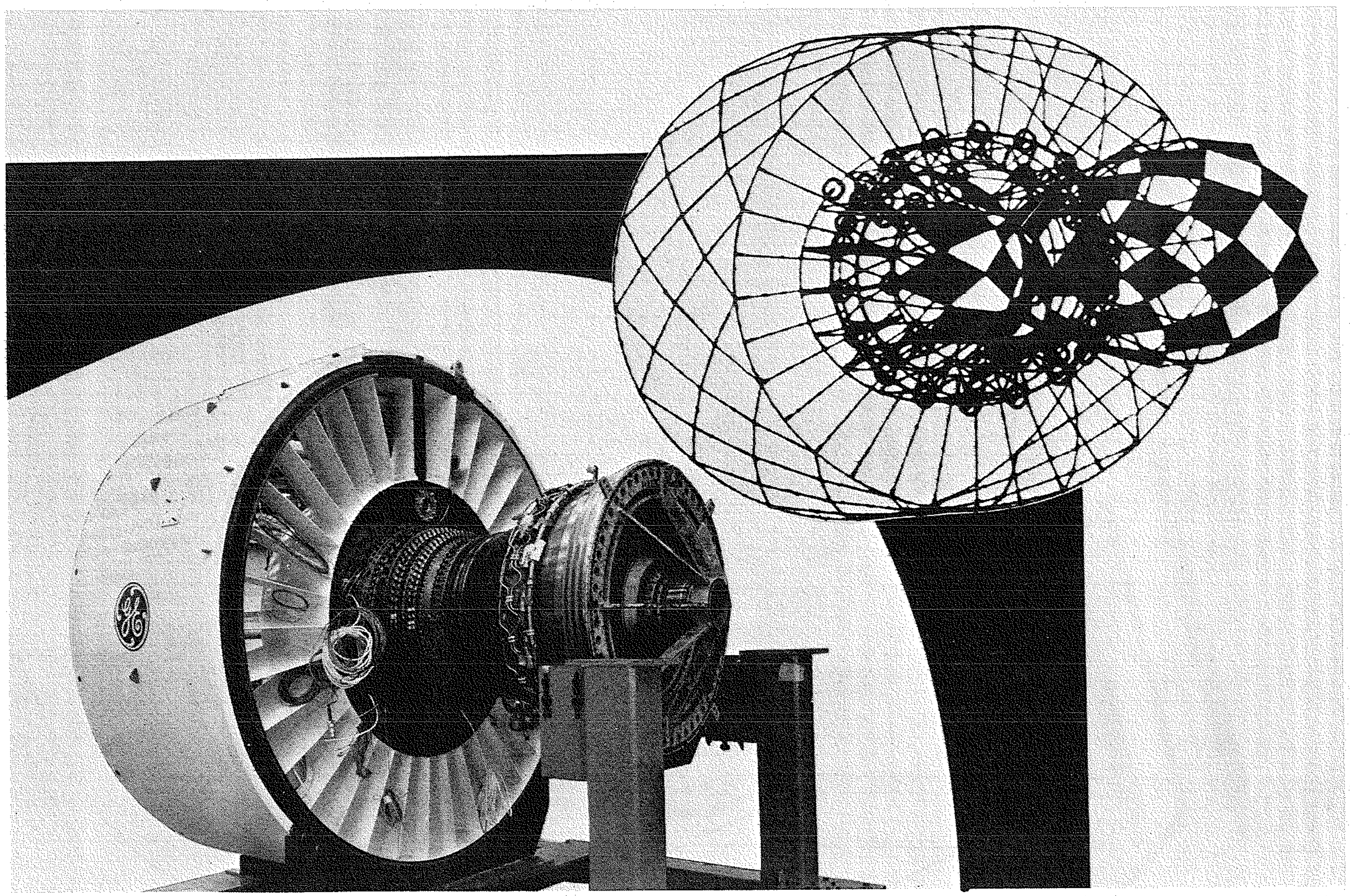


Figure 28. Analytical Model Comparison.

The mechanical loadings include all types of distributed forces and application of point loads and moments. Thermal cases will consider temperature variations throughout the structure as well as gradients through the thickness of the member and along the member. Deflections forced on the structure due to external temperature conditions (or for other reasons) can also be considered.

If the MASS analysis indicates that stress problems exist at certain locations within the structure (or if stress concentrations exist that were not accounted for in modeling), a more detailed analysis of the region in question can be performed with the finite-element programs, SAP, TAMP, or FINITE.

SAP, TAMP, and FINITE can account for thermal, mechanical, vibrational, and body force loading of orthotropic materials. Plane stress, plane strain, or axisymmetric structures can be solved more economically using FINITE since this program utilizes a two-dimensional triangular element. Also, a computerized routine is available for automatically generating the finite-element grid work.

The three-dimensional orthotropic finite element program, TAMP, is available for nonplanar problems. Since spring and friction-force boundary conditions are permissible, TAMP is ideal for modeling joint regions.

The basic laminate elastic properties for the various orientations that would be considered during a program would be obtained using MPEP (Material Property Evaluation Program). If the properties of a single ply are known, MPEP allows the designer to calculate the elastic properties of any chosen layup using basic laminate theory.

With respect to the use of composite materials, the following design criteria would be employed for the proposed program.

1. For composite laminate structures subjected to significant biaxial loading, the material allowable criteria shall be as follows:

    (a) Design ultimate loads shall result in a stress that does not exceed the ultimate allowable stress for the laminate used, where the ultimate allowable stress is the maximum laminate stress attainable without rupture of any lamina.

    (b) Design limit loads, as defined by the vehicle specifications, shall result in a stress that does not exceed the limit allowable stress for the laminate used, where limit allowable stress is that stress below which no lamina suffers intolerable degradation of stiffness, permanent deformation, or matrix failure in any lamina.

2. For laminate structures which are only subjected to primarily uniaxial loads, the criteria shall be as follows:

(a) Design ultimate loads shall result in a stress that does not exceed the ultimate allowable stress for the laminate used, where ultimate allowable stress is the maximum laminate stress attainable. Matrix failure in off-axis lamina is permitted.

(b) Same as (b) in Item 1 above.

3. All adhesive-bonded joints shall be designed using long-term temperature data.

4. No purely adhesive-bonded joint shall be subjected to large peel stresses.

5. Mechanically fastened joints shall, insofar as practical, be designed to fail in bearing rather than shear-out or net tension, so that catastrophic failure is prevented.

6. All composite material properties used for design shall be "A" basis properties as defined in MIL-HDBK-5B.

7. All composite areas that might be subjected to an adverse environment (e.g., hot oil, sand, etc.) shall be either isolated from that environment or protected by external coatings.

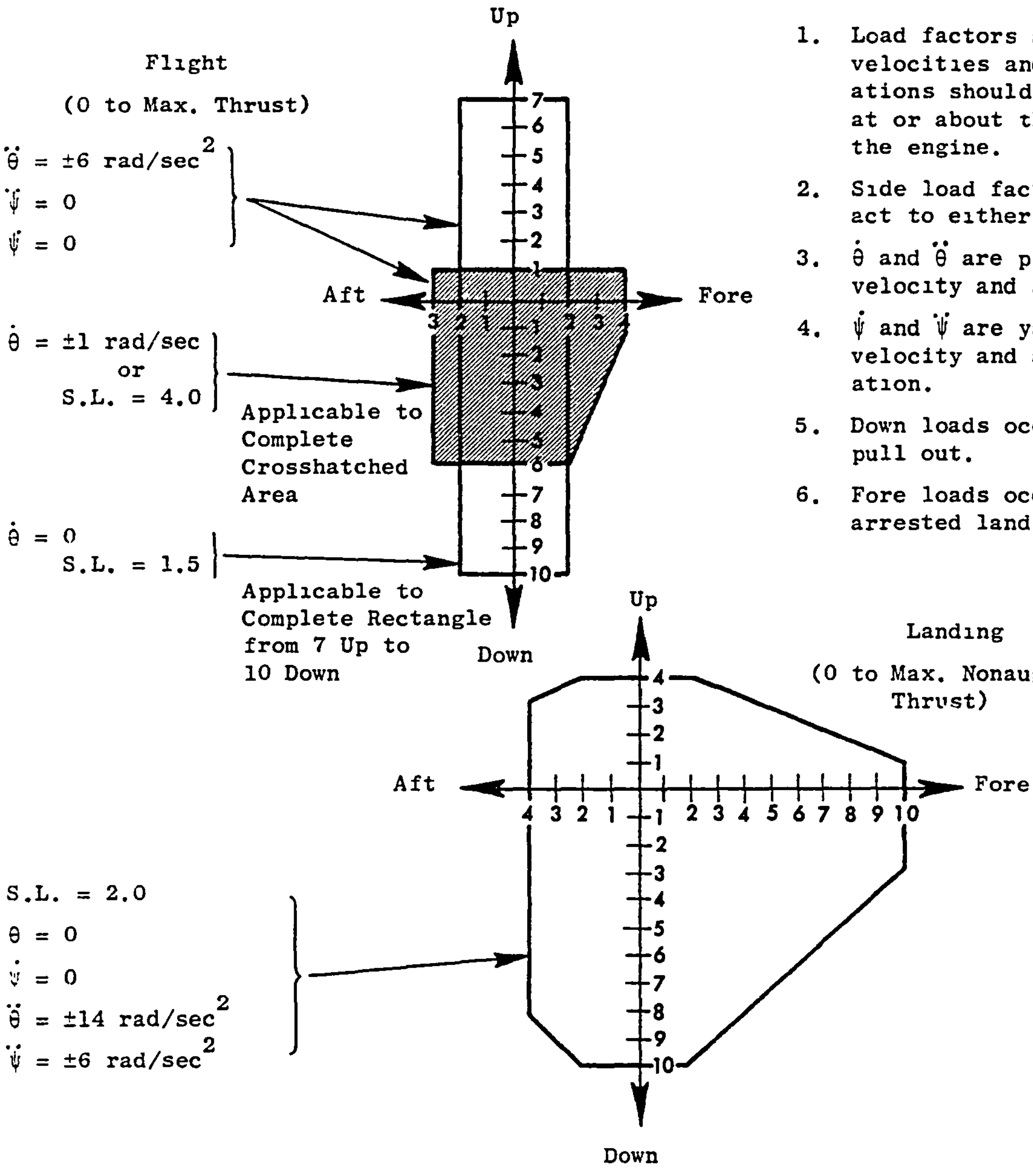
The next step of the analysis procedure would be to establish the worst loading environments for the frame. The frame structure, in conjunction with the engine mounts, must withstand the maneuver loads as imposed by the conditions depicted in Table III. The frame must withstand these loads and maintain structural integrity without permanent deformation. In addition to the normal range of maneuver loads and combinations of steady-state pressure, thrust, and torque loads, the engine must withstand the loads defined in Conditions 1 through 6 listed in Table IX. Table VIII summarizes the bearing loads on the frame for 1 g down, 1 radian/sec., and one metal fan blade-out conditions collectively for UTW/OTW engines. Air loading on the UTW/OTW frame bypass vanes is shown in Figure 24.

The hybrid frame structures must also be capable of transmitting mount loads equivalent to three times the worst possible combination of maneuver loads without failure, even though the members may acquire permanent deformation. In the QCSEE frame design phase, an investigation of the total mission requirements yielded the following two critical loading cases.

The first case is Condition 2 (gust loading). Design conditions require the frame to withstand three times the loads of a 51.44-m/sec (100-kn) crosswind acting at any angle within a plane perpendicular to the axis of the engine at zero-to-maximum thrust. This conditon sizes the outer fan case shell and bypass vanes.

The second case is Condition 6 (blade-out). The blade-out condition requires the frame to withstand the unbalanced load resulting from a one-and-one-half metal blade-out condition on the fan rotor, a condition that would

Table IX. Maneuver Load Map.



1. Load factors and angular velocities and accelerations should be taken at or about the C.G. of the engine.
2. Side load factors (S.L.) act to either side.
3. $\dot{\theta}$ and $\ddot{\theta}$ are pitching velocity and acceleration.
4. $\dot{\psi}$ and $\ddot{\psi}$ are yawing velocity and acceleration.
5. Down loads occur during pull out.
6. Fore loads occur during arrested landing.

cause a dynamic 1/rev radial load on the No. 1 bearing support. This condition sizes the cast aluminum core struts, hub, and splitter.

Internal loads, stresses, and deflections in the frame incurred by the above-mentioned load conditions would be analyzed using the MASS computer program and the finite element model of the frame illustrated in Figure 26.

3.3.4.2 Concepts of Joints and Subcomponents to be Tested

The structural integrity of the joints between the bypass vanes and the cast-aluminum-core frame and aluminum fan case vane tip waffle blocks could be demonstrated by testing in the subcomponent test rig illustrated in Figure 29. This rig could accept a full-scale hybrid frame bypass vane fabricated with final materials to accurately represent the hybrid frame design. The arrangement of threaded holes in both end pieces would allow for all modes of test loads to be imposed on the vane and its bonded joints.

Since the hybrid fan case structure is very similar to the previously tested baseline QCSEE frame fan case, the only significant testing that would be required is a containment test of the fan for a 1-1/2 blade-out condition. Figure 30 illustrates a test rig arrangement that could accommodate this requirement. A fan blade containment test could be performed by releasing a full airfoil at 100% rotational speed to determine the integrity of the Kevlar containment shell.

3.3.4.3 Inspection Plan

Inspection of all materials to be used in both the fan case and vane/joint test rigs would incorporate the same quality checks as would be projected for full-scale production frame materials. This would include testing specimens for tensile, compression, modules, interlaminar shear, rail shear, and fatigue using the same selected adhesives projected for actual frame assemblies. Materials must pass specified GE requirements before they would be utilized.

Inspection of components of both test rigs would incorporate the same techniques that would be be projected for the full-scale production frames. This would include the usual techniques of die-penetrant and zyglo for metal components and selected ultrasonic gray-scale, C-scan, and Eddy Current inspection of all composite components and final bonded joints.

3.3.4.4 Repair Plan

Repair techniques would vary in relation to the type and extent of damage or unbond that may occur during engine testing. Due to the permanent nature of the assembly of the hybrid frame, it would probably be important to try to replace an entire damaged vane. However, with careful splicing techniques, a new vane may be reconstructed with sufficient strength without significant

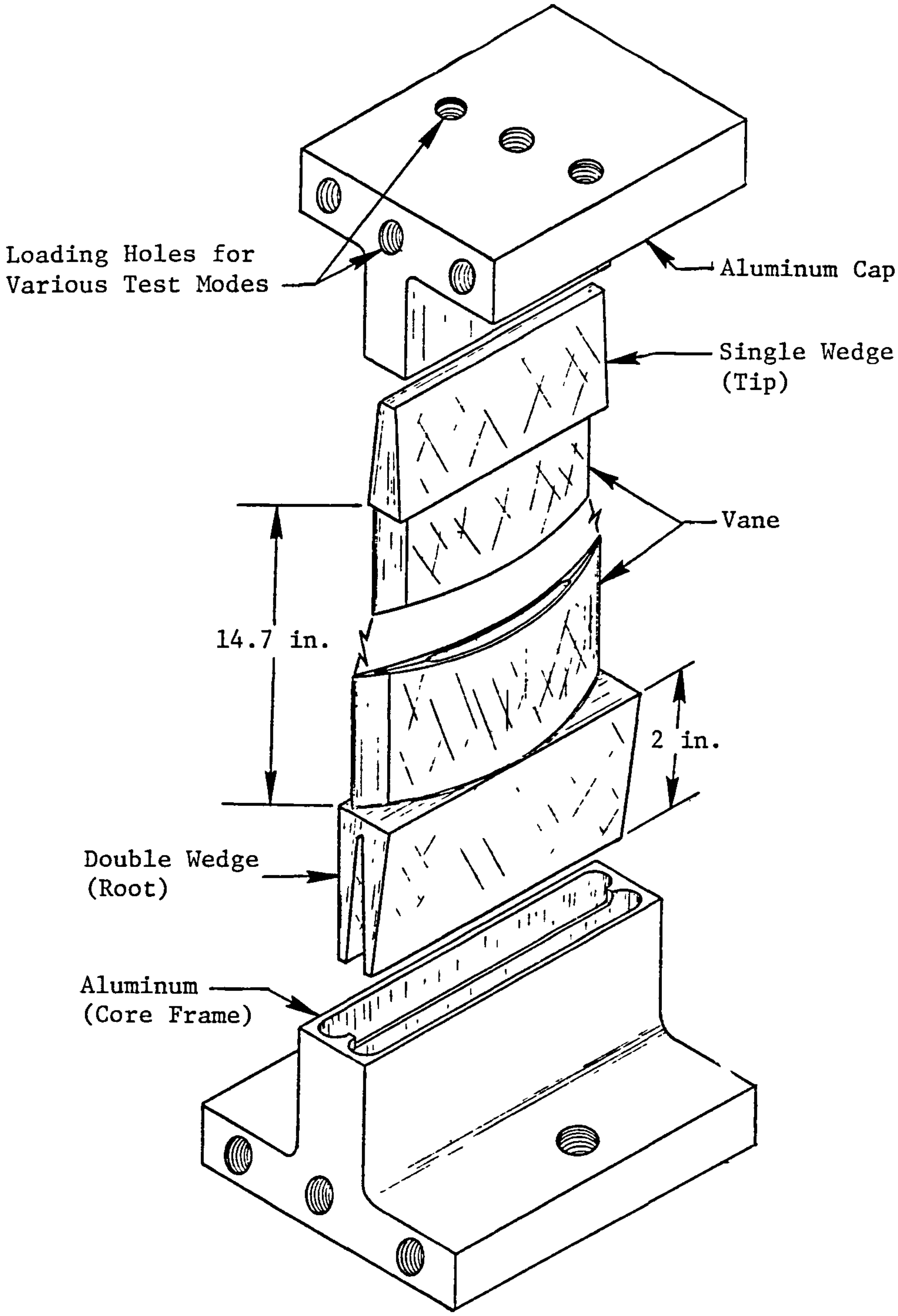


Figure 29. "Hybrid" Frame Vane/Joint Test Rig.

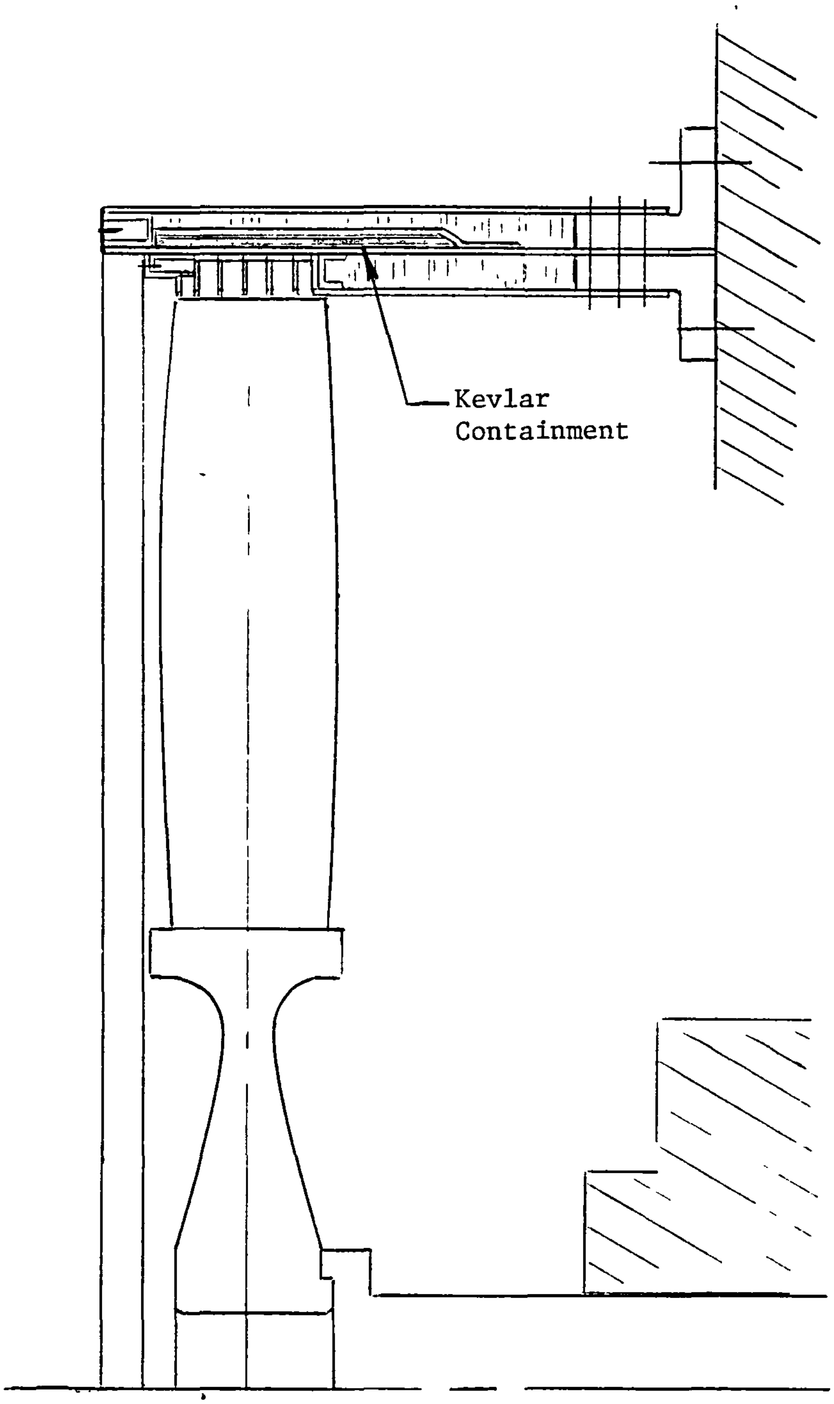


Figure 30. Hybrid Frame Fan Case Test Rig.

buildup on the surface to adversely affect the aerodynamic profile of a spliced vane. Impact damage to the fan case could be repaired with simple techniques previously demonstrated on the baseline QCSEE frame. Any unbonded joints would be benched away to expose the entire new surface, then new adhesive and splice joint would be applied locally and cured with infrared or heat gun.

3.3.4.5 Projected Cost of Implementation Plan

In order to prove the validity and integrity of the Hybrid Frame Concept, it would be necessary to design, fabricate, and test an entire frame using test data generated from the two full-scale test rigs shown in Figures 29 and 30. The respective costs projected to implement these tests are discussed below.

Vane/Joint Test Rig per Figure 29

An attempt should be made to demonstrate the feasibility of casting the double-wedge vane root pocket to net shape so that a final end-mill operation may not be necessary in production. A satisfactory net wedge profile would also be stronger than a machined pocket since the removal of the outer layer of cast aluminum tends to diminish the material strength.

In similar fashion, the aluminum cap illustrated in Figure 29 should be a die-cast aluminum block with a wedge pocket wall thickness equal to the actual thickness of the waffle blocks illustrated in Figure 3. It would be more desirable to utilize an entire actual die-cast waffle block so that the waffle pattern could also be evaluated in this same test rig. This would add cost, but if successful, the die-cast mold could be used to fabricate components for the final hybrid frame.

The vane required in the test rig (Figure 29) would be an actual bypass vane including a urethane leading edge cap. Tooling to fabricate this vane would be utilized in the final hybrid frame.

A summary of projected preliminary manufacturing costs for the design, tooling, fabrication, and testing of the hybrid frame vane/joint per Figure 29 is listed below in 1979 dollars.

Analysis and Design	130K
Fabrication and Test	60K
Total	190K

Hybrid Frame Fan Case Test Rig per Figure 30

The full-scale Hybrid Frame Fan Case test rig is illustrated in Figure 30. The test would determine the ability of the Kevlar containment ring to capture a severed blade. Tooling to produce this full-scale test rig could be directly applicable to a full-scale hybrid frame. However, rather than invest in the different profiles of fan tip treatment rings as required in a final frame structure, a single fan tip treatment ring configuration could be used for this test rig. The single tip treatment ring configuration would also apply directly to a full-size hybrid frame.

The testing of a rotating fan with a single blade failure is required to evaluate the containment and frame integrity during rotor dynamic unbalance. Previous tests conducted at GE on commercial engine containment systems have proved the value of this form of testing. Similar hardware could be assembled for the test rig hardware shown in Figure 30.

A summary of the estimated preliminary manufacturing costs for designing, tooling, fabricating, and testing a Hybrid Frame Fan Case Test Rig as proposed in Figure 30 is listed below in 1979 dollars:

Analysis and Design	90K
Fabrication and Test	405K
Total	495K

It should be noted that in the containment test, the cost was established by assuming that applicable tooling and hardware will be utilized from the previous QCSEE Engine Program.

Full-Scale Hybrid Frame Test

By factoring test results from the test rigs illustrated in Figures 29 and 30 into a full-scale hybrid frame, it should be possible to design a frame that could withstand the required design loads. Tooling from test rigs per Figures 29 and 30 could be utilized to fabricate the entire fan case. Five more sets of tooling would be required to fabricate the full compliment of vane profiles. A full-size cast aluminum core frame would be purchased and finished machined. A summary of estimated preliminary costs for covering the design, tooling, fabrication, and static testing of a full-size hybrid frame is projected below in 1979 dollars:

Analysis and Design	200K
Fabrication and Test	1845K
Total	2045K

In summary, the three tests to prove the Hybrid Frame Concept are listed below:

Test 1, Vane Joints	$ 190,000
Test 2, Fan Case and Containment	495,000
Test 3, Hybrid Frame Static	2,045,000
	$2,730,000

4.0 CONCLUSIONS

Relative to the QCSEE baseline frame, the hybrid frame concept has avoided costly fabrication features and lends itself to techniques that require no new materials or process verification. All critical bonded joints during final assembly can be C-scanned for a full check on their integrity before they are bonded onto other components.

The final calculated weight of the hybrid frame was 695 pounds which is 132 pounds heavier than the all-graphite revised baseline frame but 200 pounds ligher than an equivalent all-metal frame.

The cost of a 250th production hybrid frame calculated to 41% of the cost of a 250th revised baseline frame. Based on 1979 dollars, this amounted to a projected cost of $64,554 by setting labor hours at $22 per hour and the cast aluminum core frame and all materials at $40,750 as listed in Figure 18.

The relatively simple structural plug-together features of a hybrid frame could demonstrate generic application to similar frames for other engines. The ability to fabricate and fully inspect the three main components of fan case, vanes, and core frame before committing them to final assembly should reduce the risk of costly problems in a production environment.

5.0 RECOMMENDATIONS

The prospects of reducing the weight of the hybrid frame by incorporating up to 40% of graphite in the volume of the cast aluminum core should be evaluated. The graphite would enhance its strength and could reduce its weight by as much as 42 pounds for a final frame weight of 653 pounds. The feasibility of encapsulating graphite with aluminum has been demonstrated by industry, but its application to the configuration of a core frame would need actual demonstration.

This prospect could follow or parallel an initial hybrid frame development effort using a standard cast aluminum core frame.

The possibility of filament winding or braiding a single-piece hollow graphite/epoxy vane should also be explored for the prospect of increased integrity, reduced weight, and cost.

Another concept involving the use of super plastic forming and diffusion bonding of titanium tubes in clusters with sheet stock to form lightweight hollow metal vanes should also be explored. This concept has been demonstrated on a small laboratory scale, but much remains to establish a basis for further evaluation.

It is recommended that the hybrid frame concept be fully demonstrated to show the significant cost reduction payoff for future commercial engine designs.

6.0 REFERENCES

Input to this report was gathered from many sources within the General Electric Company and from selected vendors and customers of the General Electric Company. Some specific references are listed below:

1. Mitchell, S.C., "QCSEE Composite Fan Frame Design Report," NASA CR-135278/R77AEG439.

2. Northrop Corporation briefing on "Automated Composite Material Transfer Program," Contract F33615-77-C-5121.

3. Rohr Industries, "Manufacturing Technology for Low Temperature Composite Engine Frames," Contract F33615-78-C-5086.

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