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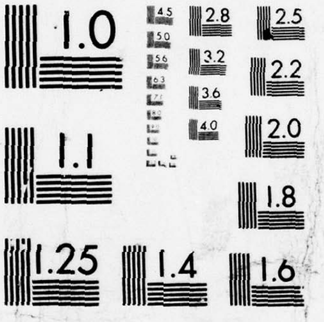
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AFML-TR-78-134

ADVANCED COMPOSITE ENGINE ROTOR DESIGN

AIRCRAFT ENGINE GROUP
GENERAL ELECTRIC COMPANY
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CINCINNATI, OHIO 45215

OCTOBER 1978

TECHNICAL REPORT AFML-TR-78-134
Final Report for Period October 1977 through March 1978

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

This technical report has been reviewed and is approved for publication.

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FOR THE COMMANDER:

Jerome M Kelble

Jerome M. Kelble, Chief
Nonmetallic Materials Division

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Comet Blisk	Graphite	Polyimide	
Compressor Rotor	Integral Wound	Tang	
Fan Blade	Pinned Blade/Hoop	Tip Shroud	

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report describes the results of an advanced composite-rotor mechanical-design-feasibility study program. Four advanced composite fan-rotor concepts and one composite reinforced compressor-rotor concept were evolved and evaluated during this study. One particular fan concept, titled "pinned-blade/hoop rotor," received extended evaluation because it allowed the replacement of blades and showed a significant weight and cost advantages over the metal counterpart. This concept was applied to both a subsonic-flight engine and a supersonic-flight engine for potential future development.

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1.0 INTRODUCTION

For the past 25 years there has been an ever-increasing effort to design lightweight components to improve engine thrust-to-weight ratio. The payoff for achieving lighter structurs is, of course, the economy attending an increase in load capacity, aircraft speed, or range.

Reducing the weight of rotating components generally results in a greater total payoff than can be achieved on stationary components. This is because rotating parts are usually heavier than stationary parts, and the stresses in the rotating mass are directly related to the square of the rotational speed. Moreover, reducing the weight of rotating components allows weight reductions in related bearings, frames, containment, and engine mount systems.

To date, efforts to lighten rotating components have focused on high strength-to-weight-ratio composite materials in fan and compressor blades with conventional dovetail configurations for attachment to metal disks. The current program has overcome every limitation of the conventional designs, permitting more efficient use of the higher strength-to-weight characteristics of composite materials.

The objectives of this program were to develop conceptual designs for advanced composite rotors. The goals were to improve engine performance in areas of rotor life, maintentance, weight, aerodynamics, and aeromechanics along with fabrication techniques to reduce manufacturing costs. The successful completion of this program would provide fan and compressor conceptual designs for potential development into full-scale demonstration hardware.

Recent Air Force efforts in the development of advanced composite components have been directed toward fan blades, turbine blades, and static structure. However, previous conceptual design studies, hardware development programs, contractor in-house design studies, and management assessments have indicated that rotors would be another attractive application for advanced composites. To optimize the use of composites, the blade, disk, and shaft attachment should be considered as a system and designed for composites from the start.

Both organic- and metal-matrix fan blades are under development. These programs are achieving varying degrees of success in meeting the design goals. It was conceived that an integrated design of the disk and blade could enhance the Foreign Object Damage (FOD) resistance (paramount among the design goals) and ameliorate other blade design constraints that accompany the use of conventional disk technology.

Future fan and compressor designs are likely to feature larger blades and significantly higher rim speeds. Current, titanium blades are nearing a metallurgical limit; at current stress levels they are limited by fatigue notch sensitivity when subjected to minor flaws and damage. Composites, with lighter weight and increased stiffness, offer an approach to implement the higher rotational speeds and larger blades. Composites must be applied selectively, however, because temperature limits are usually lower than those of the metals they replace.

2.0 SUMMARY

This report describes the results of an advanced, composite-rotor mechanical-design-feasibility study program. Four composite fan-rotor concepts were evolved during this study:

1. Comet Blisk (Composite Metal Blade/Disk
2. Integral-Wound
3. Tuning Fork
4. Pinned-Blade/Hoop

These rotor-design concepts are illustrated in Figures 1 through 4; detailed descriptions and referenced drawings follow in Section 3.1.4.

The goal of this study was to identify the relative total payoffs in advanced composite-rotor designs and equivalent metal-rotor counterparts. A three-phase program was conducted to achieve this objective:

- Phase I - Fan Rotor Design
- Phase II - Compressor Rotor Design
- Phase III - Recommendations and Development Plan

In Phases I and II, fan and compressor rotor concepts were identified, developed into preliminary mechanical-design candidates, and evaluated in terms of engine performance payoffs and technical risks. Two fan-rotor designs (one for the TF34 subsonic-flight engine and one for a supersonic-flight engine) and one compressor-rotor design were designed and then evaluated for possible future development.

The pinned-blade/hoop concept (consisting of replaceable pinned blades with high-strength, filament-wound supporting hoops) was selected as the subject for an in-depth study of stresses, projected performance, and functional life; proposed fabrication techniques and related costs were also evaluated. A program plan was established for developing the selected rotor concept into full-scale hardware for demonstration on an aircraft gas turbine engine.

When configured to the front fan of a proposed supersonic-flight engine, the pinned-blade/hoop rotor is projected to weigh about 67 pounds; a metal counterpart would weigh 179 pounds. When configured to the front fan of a TF34 engine, the pinned-blade/hoop rotor would weigh 39 pounds; the current, metal counterpart would weight 143 pounds. The cost of this composite fan in production quantities is estimated to be less than one-third the cost of a metal counterpart.

A summary of all fan weights resulting from this study is listed in Table 1.

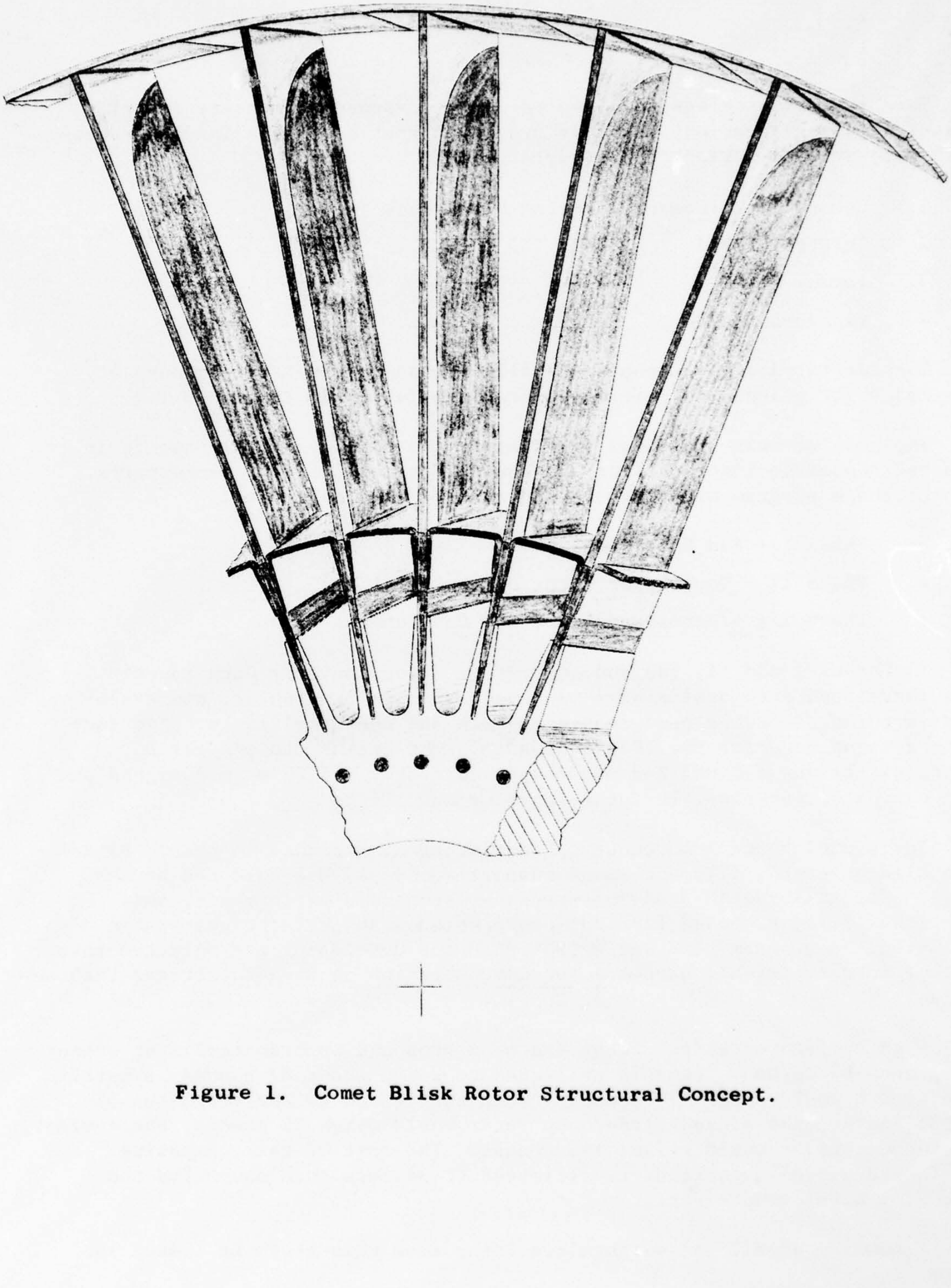

Figure 1. Comet Blisk Rotor Structural Concept.

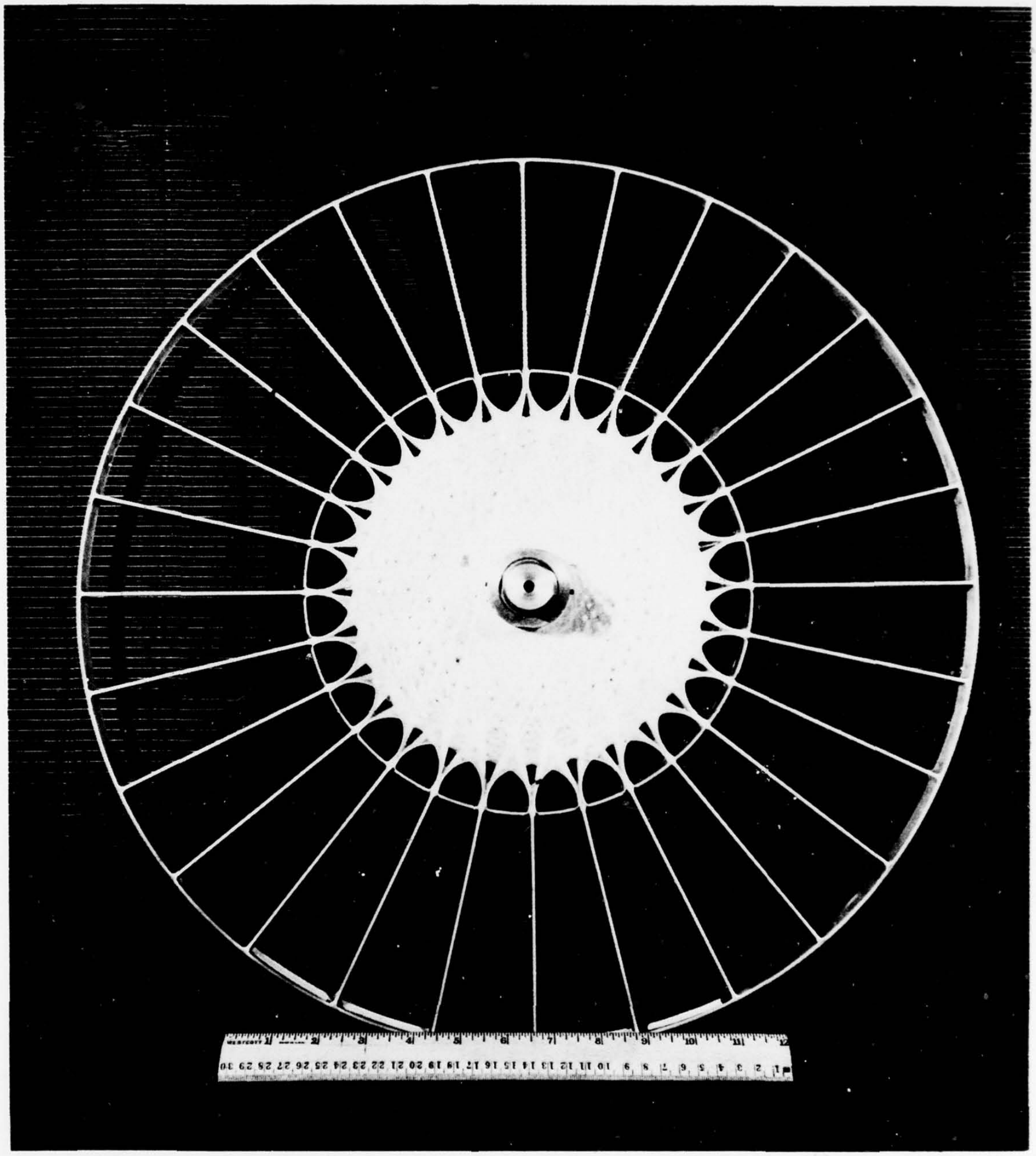

Figure 2. Integral-Wound Rotor Structural Concept.

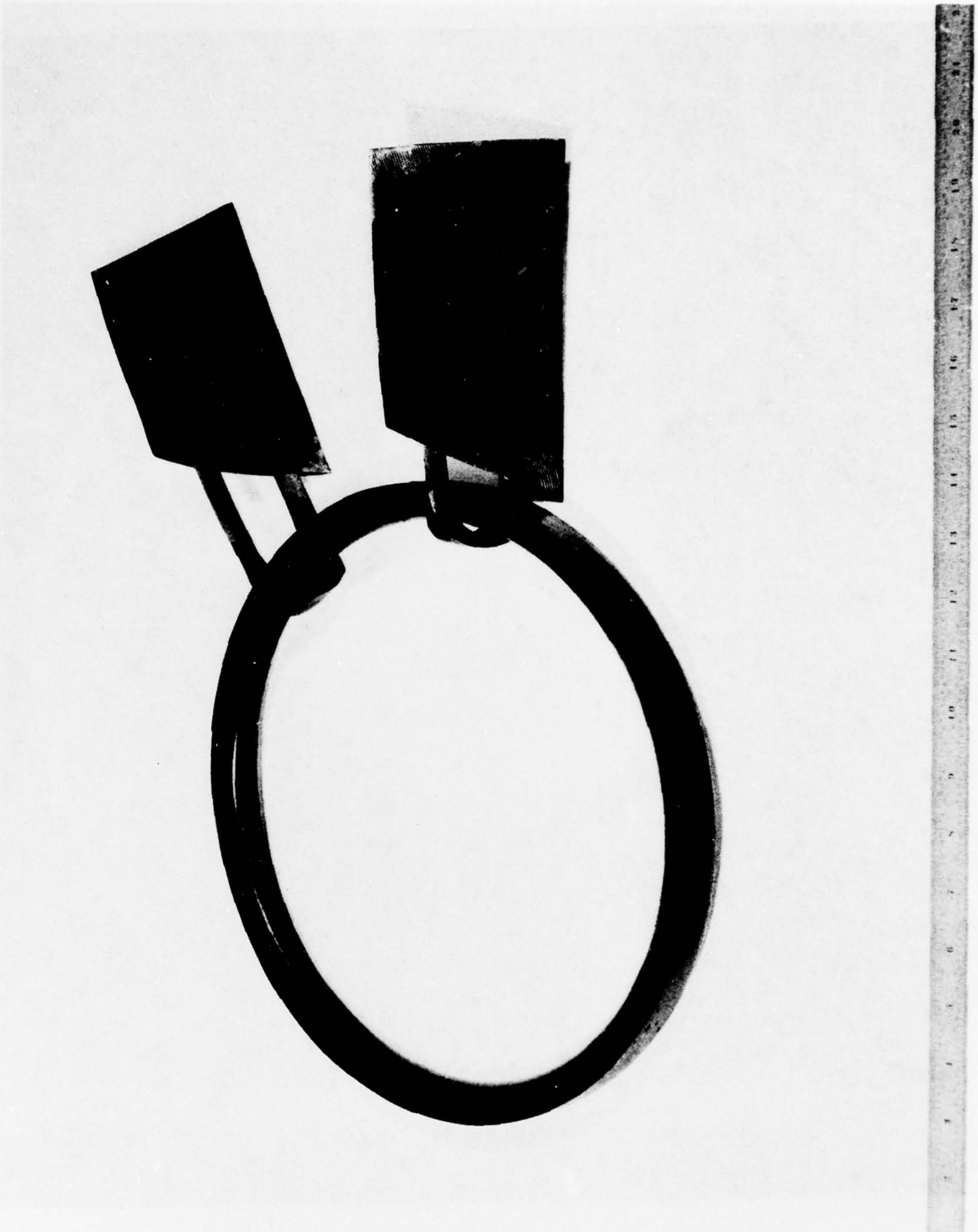

Figure 3. Tuning Fork Structural Concept.

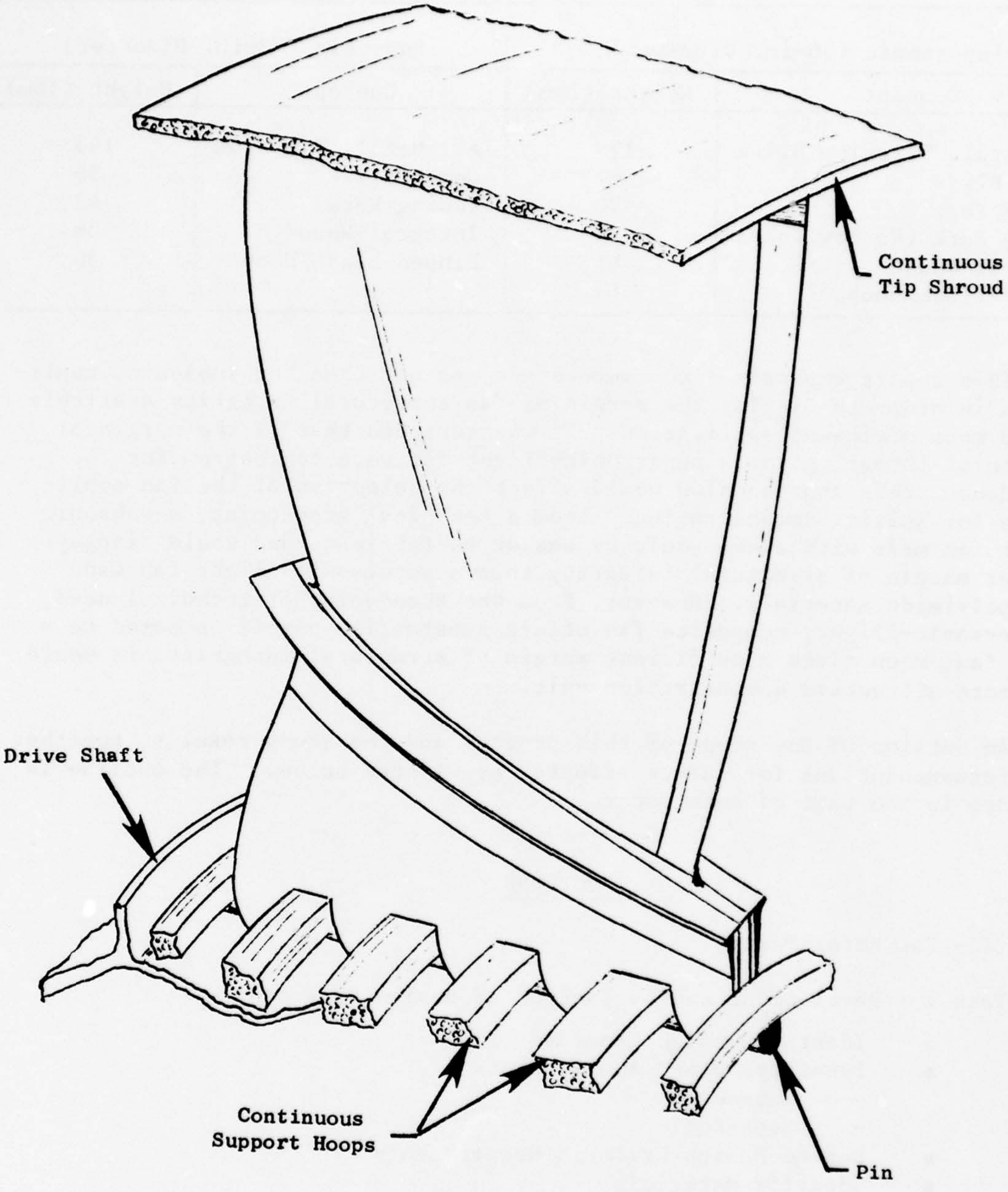

Figure 4. Pinned-Blade/Hoop Rotor Structural Concept.

Table 1. Projected Fan Weights for Advanced Composite-Rotor Concepts.

Supersonic (36-in. Diameter)		Subsonic (43-in. Diameter)	
Concept	Weight (lbm)	Concept	Weight (lbm)
All-Metal, Titanium Blisk	179	All-Metal, Titanium	143
Comet Blisk	82	Comet Blisk	56
Tuning Fork	70	Tuning Fork	43
Tuning Fork (Hollow Yokes)	64	Integral-Wound	36
Integral-Wound	61	Pinned-Blade/Hoop	36
Pinned-Blade/Hoop	67		

This report emphasizes the supersonic, rather then the subsonic, application in order to display the margin of fan structural integrity available in the more stringent application. It was reasoned that if the margin of structural integrity for a supersonic-flight fan were too narrow for confidence, this apprehension would affect the selection of the fan application for initial demonstration. From a technical standpoint, a subsonic-flight fan made with epoxy would be easier to fabricate and would display a greater margin of structural integrity than a supersonic-flight fan made with polyimide materials. However, from the standpoint of technical need, a supersonic-flight, composite fan offers substantial payoff compared to a metal fan; when given a sufficient margin of structural integrity, it would be a more attractive demonstration unit.

An outline of the scope of this program and the study results, together with recommendations for future efforts, are listed below. The outline is expanded in the text of this report.

OUTLINE

Phase I - Fan Rotor Design

Task I - Development and Evaluation of Design Concept

- Identify Design Concepts
- Identify Design Applications
  - Subsonic
  - Supersonic
- Define Design Criteria/Requirements
- Identify Materials
- Perform Preliminary Design Analysis
- Evaluate Designs
- Select One Design for Extended Study

Task II - Extended Studies of Design Concepts

- Detailed Analysis
- Material Selection

- Design Summary
  - Feasibility
  - Limitations
  - Performance Benefits
  - Manufacturing Feasibility

Phase II - Compressor Rotor Design

- Identify Concepts
- Identify Supersonic Application
- Define Design Criteria/Requirements
- Identify Materials
- Perform Preliminary Design Analysis
- Evaluate Designs
- Select One Design

Phase III - Recommendations

- Identify Needs

RESULTS

Phase I

Task I

1. Four design concepts were identified.
2. The fan designs for the supersonic and subsonic applications were selected.
3. Design criteria/requirements were defined for each application.
4. Candidate materials were identified and material properties defined for use in studies.
5. Parametric design studies were performed.
6. Fan designs were developed using design concepts and results of parametric studies. A total of 31 design layouts were made. Based on preliminary analysis, all designs appeared able to meet design requirements and criteria.
7. Designs were evaluated using several variables: weight, aerodynamic performance, cost, replacement of blades, risk, etc.
8. One design - the pinned blade/hoop rotor - was selected.

Task II

1. A refined analysis was carried out to size the various components.

2. Manufacturing methods were identified.

3. Design feasibility was identified.

4. Candidate materials were identified and material properties for use in studies.

5. Potential areas of concern were defined.

6. Overall performance was summarized.

7. Manufacturing cost estimates were made.

Phase II

1. One application was selected.

2. Four design concepts were identified.

3. Design criteria/requirements were defined.

4. Candidate materials were identified.

5. A preliminary analysis was performed.

6. The designs were evaluated.

7. No design was selected.

Phase III

Conclusions

1. An advanced composite fan is feasible both for supersonic and for subsonic applications.

2. Subsonic designs could be implemented using epoxy-matrix composite materials and some component structural development.

3. Supersonic designs result in more severe design requirements in terms of material temperature and strength requirements. Polyimide-matrix materials were required.

4. The use of composites in the compressor was not feasible for the applications selected due to the high temperature environment. Insignificant weight/aerodynamic performance benefits were found in this application.

Recommendations

1. Initiate efforts to develop a composite-fan-rotor design.

2. Development for a supersonic application would be more challenging than for a subsonic application mainly because of (a) the need to develop fabrication processes for the polyimide material and (b) the higher structural loadings.

3. The specific areas of concept development needed are:
   - Attachment of blade to root
   - Attachment of blade root to hub, and the manufacturing procedure
   - Attachment of blade tip to shroud
   - Filament-wound hub
   - Aerodynamic stall margin
   - FOD resistance
   - The efficiency of processing polyimide into components

4. The development approach recommended is:
   - Work-out the structural design details of a prototype rotor system
   - Carry on the development of joints/components
   - Fabricate a prototype rotor
   - Test the system
   - Work at the design details of the supersonic-flight, composite rotor
   - Develop low-cost fabrication techniques for the rotor
   - Run structural validation tests
   - Conduct an engine demonstration

3.0 PHASE I - FAN ROTOR DESIGN

3.1 TASK I - DESIGN CONCEPT DEVELOPMENT AND EVALUATION

The purpose of this task was to identify candidate fan-rotor structural concepts that would be feasible from the standpoints of fabrication and utility. A preliminary analysis of each concept was completed in sufficient depth to identify the positive and negative aspects of each design. One concept was selected for further detail study in Task II.

Thirty-one composite-rotor concepts were considered under this effort; they are illustrated in Figures A-1 through A-31 in Appendix A.

3.1.1 Selection of Design Applications

Rationale - The selection of candidate engines, for studying potential applications of advanced composite rotors, was based on this assumption: if the operating environment of a supersonic-flight engine proved to be too severe, or just marginal for applying the best composite materials available, a subsonic-flight engine would be more likely to accommodate the same structural rotor concept with conservative margins of safety while displaying significant advantages in weight and cost over conventional metal-counterpart rotors. Accordingly, it was decided to select both a supersonic-flight, and a subsonic-flight engine for parallel study and compare the results.

Selection - The two engines selected for this program were:

1. TF34: Figure 5 illustrates a section through the front fan. The titanium blades have pinned roots which attach to a double-structured, titanium disk.

2. Supersonic (first-stage fan): Figure 6 shows a single-piece front fan which is machined from a solid titanium forging so that there is no joint between the blades and the disk. This blisk design was required because the low-radius-ratio fan blades could not provide sufficient tangential space to accommodate a conventional dovetail- or pinned-blade attachment. Accordingly, this fan must be machined out of a solid forging - an expensive process that leaves no margin for machining error. In the event of severe blade damage in service, the entire fan would probably be replaced. Studies are being made, however, to see whether this metal fan can be fabricated with welding, or other metal-joining technlogies, which could reduce the cost significantly.

3. Supersonic (second-stage fan): Figure 7 shows a section through the titanium second-stage fan which has sufficient space to accommodate conventional blades with dovetails.

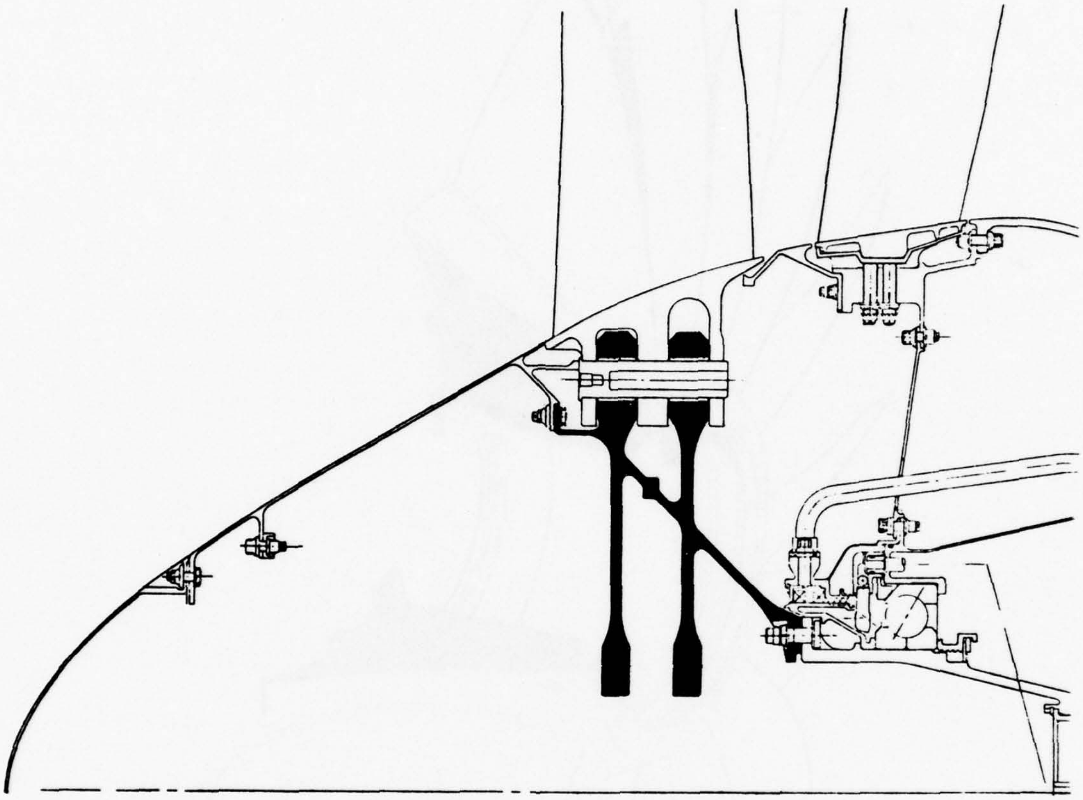

Figure 5. Present Fan Disk in TF34 Engine.

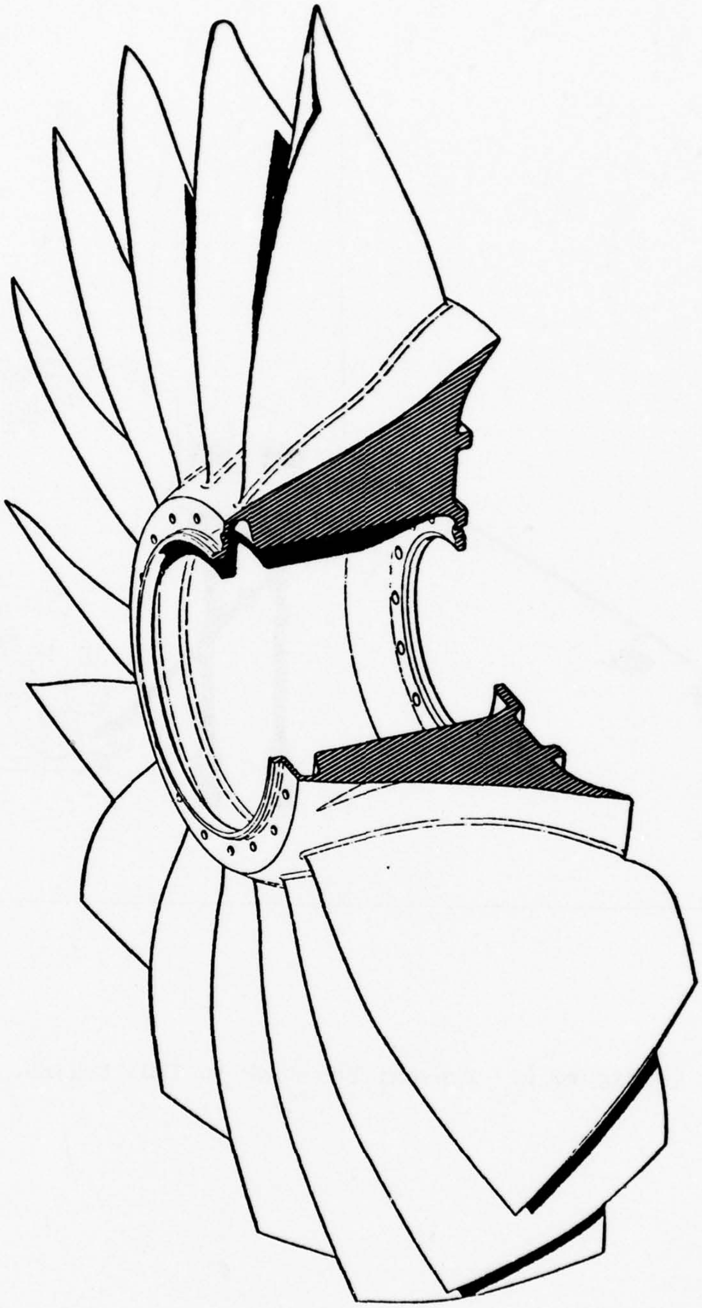

Figure 6. Supersonic-Flight
Titanium Disk.

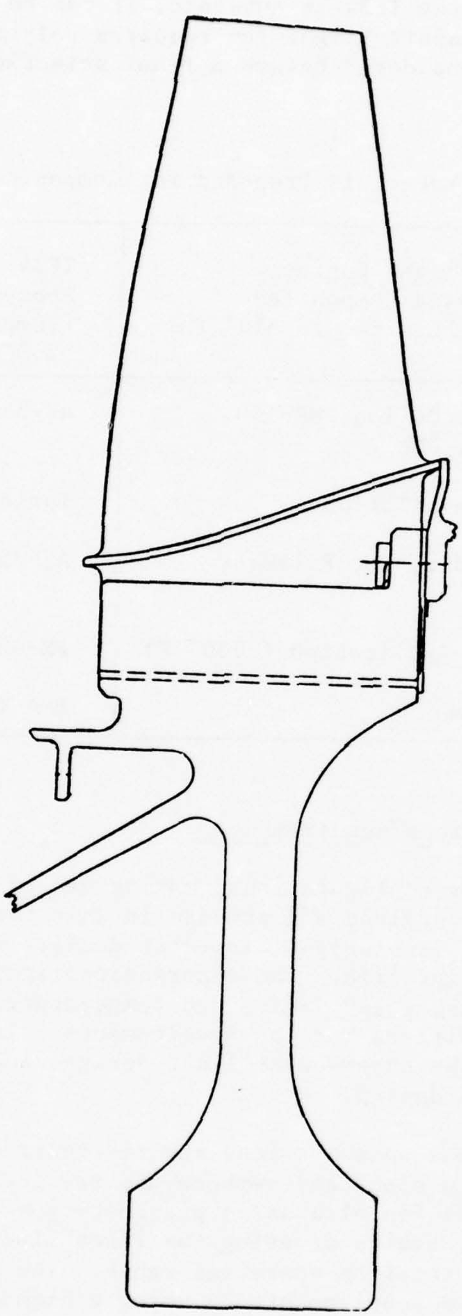

Figure 7. Supersonic-Flight Second-Stage Fan/Compressor.

Materials - Some materials proposed for the above respective fans are listed in Table 2. Since the TF34 is subsonic, it can be made with epoxy-based materials; the supersonic-flight fan requires polyimide-based materials. Other materials will be considered before a final selection is made.

Table 2. Materials Proposed for Composite Fans.

Part	Supersonic-Flight Engine, Polyimide-Based Composites (Temperature Limited to 550° F)	TF34 Epoxy-Based Composites (Temperature Limited to 350°F)
Blades	GR/PI HTS or Celion, NR-150, Thermid 600, PMR	AS-3501 or AS-PR288
Platforms	GR/Polyimide (Torlon)	Torlon
Hoops	Same as Blades, but Filament-Wound TOW	AS-3501
Adhesive	FM-400 (Hub Application < 350° F)	FM-400
Hub	6-4 Titanium	6-4 Titanium

3.1.2 Design Conditions/Requirements

A number of fan-rotor configurations, making use of composite materials in different ways, were conceived and studied in this task. These were directed toward achieving lightweight, low-cost designs with potential for higher tip speeds and longer life. The supersonic-flight and the TF34 first-stage configurations, speed, life, and temperature requirements were selected as baseline conditions for the developments. Table 3 shows the design requirements for the supersonic-flight design, and Table 4 shows the requirements for the TF34 design.

The TF34 fan rotor has somewhat less severe requirements than the supersonic-flight fan; tip speed and temperature are lower, and the radius ratio is higher. The TF34 fan also has a pin-root-type blade with a flexural vibrational response that avoids crossing the 2/rev line by operating between 1/rev and 2/rev over the complete operating range. The composite-arrangements studies incorporated these requirements by using a high-flex configuration.

Table 3. Design Requirements for a Supersonic-Flight Configured Composite Fan.

Design Mechanical Speeds

- Maximum operation (100% Design-Point Rotor Speed, Na) = 10,500 rpm
- Design (1.05 Na) = 11,025 rpm
- Design burst (1.41 Na) = 14,805 rpm
- Design tip speed = 1732 feet per second

Design Life and Cycles

- Operating life = 4000 hours
- Operating cycles = 20,000 cycles at 105% operating speed
- Vibratory cycles = 3 x 10^7 cycles

Special Conditions

- Maximum blade root temperature = 400° F
- Maximum blade tip temperature = 500° F
- Temperatures selected to meet extremely short-term dash conditions
- High-flexural-stiffness blade design that operates at 15% above 2/Rev at Na
- High-torsional-stiffness design
- Stresses within allowable-stress-range diagram and having sufficient vibratory margin
- USAF/Winnestrom-type airfoil configuration

Table 4. Design Requirements for TF34-Configured Composite Fan.

Design Mechanical Speeds

- Design (Na) = 7357 rpm
- Design burst (1.41 Na) = 10,373 rpm
- Design tip speed = 1390 feet per second

Design Life and Cycles

- Operating life = 4000 hours
- Operating cycles = 20,000 cycles
- Vibratory cycles = 3×10^7 cycles

Special Conditions

- Maximum blade root temperature = 200° F
- Maximum blade tip temperature = 300° F
- High-flexural-stiffness blade design that operates at 15% above 2/Rev at design rpm (Na)
- High-torsionsal-stiffness design
- Stresses within allowable stress range diagram, with sufficient vibratory margin

3.1.3 Design Evaluation Criteria

Each configuration was sized to meet the various speeds and special conditions outlined above. The TF34 rotor concepts were based on meeting flexural vibratory requirements using the same number of blades as the titanium design. Thus, to satisy aeroelastic stability requirements, a tip shroud was used on all designs. The supersonic-flight concepts were evaluated with different numbers of blades, different materials, and for shrouded and unshrouded configurations. The results of this evaluation, discussed in Section 5, show the desirability of using a shrouded configuration, having between 24 and 30 blades, to meet supersonic-flight requirements. On the basis of this finding, the conceptual studies were conducted using a 24-blade, shrouded configuration.

Each blade concept was evaluated and compared to the other concepts using a decision/analysis worksheet that compared various significant parameters on the basis of weighted factors of weight, cost, simplicity, replacement of blades, risk, life, aerodynamic performance, and other factors as discussed in Section 3.1.5.

The four composite-rotor structural concepts identified in Section 2.0 each have unique features that can be evaluated separately. Assuming that each candidate composite-fan design can meet the aeromechanical and structural requirements of the metal conterpart, desirability factors were selected for comparing the candidates. They are listed below, with a percentage of weighted value attached to the relative importance in a final selection. For each design concept, the desirability of each feature is graded from 1, "unfavorable," to 10, "very favorable." The final score is obtained by multiplying the relative desirability of each feature by the weighted value and summing the products.

% Weight	Desirable Features
20	Low weight
20	Low cost
15	Simplicity of structure
5	Ease of analysis
15	Replaceability of blades
10	Technical confidence (relative risk)
10	Long life
5	Low maintenance (time, cost, intervals)
100%	

The product of this evaluation of four specific composite fans in comparison with the metal counterparts is presented in Table 5; the pinned-blade/hoop concept displays the highest score.

Table 5. Decision Analysis Worksheet for Design-Concept Candidates.

SCALE
1 - Unfavorable
10 - Very Favorable

Wanted Features	% Weight	Metal Blisk		Comet Blisk		Tuning Fork		Integral-Wound		Pinned-Blade/Hoop	
		Scale	Weight Scale	Scale	Weight Scale	Scale	Weight Scale	Scale	Weight Scale	Scale	Weight Scale
Low Weight	20	1	0.20	8	1.60	9	1.80	10	2.00	9	1.80
Low Cost	20	1	0.20	10	2.00	9	1.80	8	1.60	10	2.00
Simple Design	15	10	1.50	7	1.05	5	0.75	6	0.90	10	1.50
Ease of Analysis	5	10	0.50	9	0.45	6	0.25	3	0.15	10	0.50
Replaceability of Blades	15	1	0.15	6	0.90	4	0.60	1	0.15	9	1.35
Technical Confidence	10	10	1.00	8	0.80	7	0.70	7	0.70	8	0.80
Long Life	10	10	1.00	8	0.80	8	0.80	8	0.80	8	0.80
Low-Maintenance	5	10	0,50	8	0.40	9	0.45	9	0.45	9	0.45
Total			5.05		8.00		7.15		6.75		9.20

3.1.4 Design Concepts, Analysis, and Manufacturing

The four advanced composite-fan concepts selected for study are described below. Drawings (included as Appendix A) are referenced below for reviewing the geometry of each concept for either the TF34 or the supersonic-flight engine. The tip-shroud feature is the same for all fan concepts and is discussed separately at the end of this section.

3.1.4.1 Comet Blisk (COmposite/METal BLade/DISK)

TF34: Figures A-1 and A-2

Supersonic-flight engine (first-stage fan): Figures A-3 through A-11

Supersonic-flight engine (second-stage fan): Figure A-12

Typical components of a Comet Blisk fan concept are listed below and are identified easily on Figure A-8. Similar components can be identified easily on the other drawings in this group.

1. Airfoil
2. Platform
3. "V"-Finned Hub/Drive Shaft
4. Tip Shroud
5. Blade Tip Support

Initial concepts of this fan utilized a machined, metal, disk hub with fins emerging radially from the low-profile hub to a radius well below the inner airflow path. Composite airfoils were then positioned radially on top of the fins and attached with double lap-shear pads, on either side, that profiled into integral or separate inner flow-path platforms (Figure A-9). Analysis indicated that higher integrity blade-to-hub joints could be achieved by profiling the metal fin into a low-angle "V" wedge with a mating composite-blade root profile bonded into the wedge (Figures A-3 and A-8). Several variations of these concepts are illustrated in the above drawings, and analysis indicates that most of them would withstand the rotational forces with sufficient but varying margins of safety.

Figure A-11 illustrates a composite, filament-wound hub that would replace the metal hub described above. Blades are bonded to this integral, composite hub in the same way that they would be bonded to the metal hub. It is believed that composite blades bonded to a composite hub would display higher joint efficiency and longer life than if they were bonded to a metal hub; the metal would display relative differences in coefficient of thermal expansion and modulus at the bond interface.

Figure A-7 illustrates an internal metal fin that emerges above the inner flow path to provide more bond area, for an 18-blade fan version with thicker blade root, in an attempt to eliminate the need for a supporting tip shroud.

Figure A-12 shows a second-stage, supersonic-flight, Comet Blisk fan driven by a composite drive shaft which is discussed briefly later in this report.

Either of the above versions of a Comet Blisk fan can be manufactured with state-of-the-art techniques. The finned hub would be the most costly item in each case, but it could be automatically machined with tape-controlled milling.

3.1.4.2 Integral-Wound

TF34: Figure A-13

Supersonic-flight Engine: Figures A-14 and A-15

Typical components of the integral-fan concept are listed below and are identified on Figure A-14. Similar components can be easily identified on figures A-13 and A-15.

1. Airfoil skin
2. Filament-wound wheel No. 1
3. Filament-wound wheet No. 2
4. Filament-wound wheel No. 3
5. Hub inserts
6. Hub hoops
7. Drive bolts
8. Leading-edge caps
9. Platforms
10. Tip shroud
11. Blade-tip supports
12. Drive plate
13. Spinner plate

A filament-wound, integral fan was conceived. Three separate axial planes of integrally woven, spoked wheels acting as the main structural support are clustered together in a bonded assembly. Airfoil skins, tip shroud, and hoop-supported hub inserts are located far below the inner flow path.

The three separate spoked wheels are filament-wound and separately cured. Then they are assembled in axial alignment and spacing with the premolded hub inserts and two premolded, filament-wound hub hoops that carry the drive bolts and hub inserts. Film adhesive is layered between all mating surfaces to achieve a permanent, nonfretting, bonded assembly. The hub inserts stabilize the airfoil elements as they emerge from the disk. Next, premolded-composite airfoil skins are bonded across the three spoked wheels from tip shroud down to the hoops that support the hub inserts. Premolded, hollow-ribbed, inner flow-path platforms are bonded between the blades after adding metal leading-edge caps. Then a premolded and machined, filament-wound, composite tip shroud is bonded into place.

After final bond assembly, the fore and aft extension of the hub inserts are machined to accept a rabbeted metal collector ring for drive shaft plate and spinner plate attachment. Finally, axial holes are drilled through the hub inserts for bolt assembly with the drive plate. There is no hole through the very center of this fan; the fan must be removed for access to the hardware behind it.

If the airfoil dynamics cannot withstand the two hollow radiating cavities over the hub hoops between the three structural spoked wheels, the cavities could be filled solid with fiberglass inserts carried in shear by the skins and adjacent spoke elements. If the blade cavities are left hollow, the weight of the entire stage would be about 61 pounds for a supersonic-flight version. It the blade cavities were to be filled solid, stage weight would increase to about 67 pounds.

Throughout this entire fan, the stresses encountered allow a high margin of safety. Fiber stresses at the center of the hub of a supersonic-flight version are only about 55,000 psi at 116% speed.

3.1.4.3 Tuning Fork

TF34: Figures A-16 and A-17

Supersonic-Flight Engine: Figures A-10 and A-18 through A-21

The drawings illustrate this design concept as it evolved into a multiplicity of supporting hub hoops. Each hoop carries an incremental, axial portion of the airfoils by means of filament-wound yokes that hook around the supporting hoops and line up axially to generate the airfoil profile. The airfoil is collected into a single structure with cover skins of cross-piled, composite layers. Typical components of this fan concept are listed below and are identified on Figure A-20. Similar components can be easily identified on the drawings listed above.

1. Airfoil
2. Yokes (tuning fork)
3. Supporting hoops
4. Platforms
5. Drive shaft
6. Spinner
7. Tip shroud
8. Blade-tip support
9. Tuning-fork spacer

The airfoils are hollow directly over each supporting hoop. Composite airfoil skins are bonded to the radiating yoke tangs which, in turn, are bonded to the supporting hoops and to each other where they butt together in airfoil alignment. The airfoil skins extend below the inner flow-path platforms to the top surface of the support hoops. Hollow-box platforms, with internal ribs in line with the tangs, are bonded in place to adjacent blade skins and provide tangential-moment support to the blades. The forward ends of the hollow platforms are mechanically rabbetted and bonded to a titanium ring which accepts torque and maintains concentricity from the drive shaft. The outside diameter of this drive shaft also seats the inner surface of the tuning-fork tangs for additional stabilization; however, this contact may tend to lift-off at high fan speeds.

For the supersonic-flight fan, the weight of each hollow graphite blade is about 0.62 lbm bare or 0.7 lbm with an attached, 0.010-inch-thick, steel, leading-edge cap. Each blade exerts about 30,000 lbf, which translates to about 120,000 psi supporting hoop stress at 116% speed. Total stage weight for this supersonic-flight fan is about 64 pounds.

The tuning forks are the most difficult items to fabricate in this concept; however, since they would be relatively low stressed, considerable tolerance could be allowed to promote high integrity. It is visualized that two yokes could be fabricated end-to-end, via filament winding, then nestled into profile molds for heat-cure before being cut apart to size.

Individual, composite airfoil skins could be molded with uniform thickness and bonded to the tapered yoke tangs assembled to the support hoops one at a time. Each blade thus bonded could be slipped around on the support rings until all airfoils were bonded to the tangs. This would allow the economy of only one bonding tool for development effort. Then the platform boxes could all be assembled with adhesive and the tang yokes fitted with a film adhesive, at the interface seat with the suport hoops, to inhibit fretting. With proper pressure applied and index-assembly tooling in place, the entire fan would be bonded as a solid, unitized structure. After fitting the drive spool in place, stage balance would be conducted before assembly to the drive shaft.

Blade replacement would be difficult; however, under laboratory conditions it probably could be done. This is illustrated in Figure A-21. The figure shows how the yokes could be replaced in sequence from aft to front, at an angle, then erected radially for airfoil-skin bonding.

3.1.4.4 Pinned-Blade/Hoop

TF34: Figure A-22

Supersonic-Flight Engine: Figures A-23 through A-26

Supersonic-Flight Engine (second stage): Figure A-27

Supersonic-Flight Engine (2-D demonstrator): Figure A-28

The pinned-blade/hoop, composite fan is the only concept in this study that offers relatively easy blade replacement. For this reason, it was selected for the Task II design extension.

Components of this fan are listed below and discussed in detail immediately thereafter. Figure A-23, A-24, and A-26 identify the following components of this fan concept. Similar components on other drawings of similar fans of this configuration can be easily identified.

1. Airfoils
2. Blade support tangs
3. Support hoops for blades
4. Blade pins
5. Platforms
6. Support hoops for platforms
7. Platform pins

8. Drive shaft

9. Spinner mount plate

10. Aft air-seal plate

11. Tip shroud

12. Blade-tip support

Since Items 11 and 12 are similar for all fan concepts, discussion is deferred (Section 3.1.4.6)

The following discussion is applicable to the supersonic-flight version of this fan (Figure A-25 and A-26).

(1) Airfoils - This fan, with 24 airfoils profiled with a tip Tm/c (chord thickness to length ratio) of 2% and a root Tm/c of 7%, would have airfoils fabricated with a specified cross-ply of graphite-polyimide laminates deployed uniformly for the entire length of the blade without abrupt bulk for dovetails or platform features. As the airfoil engages the inner flow path, it would continue in a streamlined configuration radially inward to the support pin at about a 3.6-inch radius from the fan axis. A slight amount of distortion may be necessary to force the projection of the blade-root termination into a true radial profile so that the curved support pin can be assembled (Figure A-25). Otherwise, with a bit more distortion, the blade root could be forced into a true axial projection so that a straight pin parallel to the fan axis could be utilized (in Figure A-26).

(2) Blade Support Tangs - Figure A-25 shows the airfoil carried in bonded shear by a loop base scalloped to engage the support hoops which are attached there by a "D" section pin. Figure A-26 shows six concepts for carrying the airfoil by the hoops, including the concept proposed in Figure A-25. The most desirable concepts are design loop No. 4 and No. 5, which show the airfoil laminates continuing around the tangs without interruption by a bonded shear joint; however, these concepts may prove too difficult to fabricate without severe fiber distortion. In fact, any of the six airfoil-root loops may be vulnerable to fiber distortion, if made all in the same cure cycle, due to debulking requirements. One solution to this problem might be to fabricate a sequence of separate, concentric, thin layers of loops bonded together with a 0.002-inch layer of adhesive. Another might be to step-cure the laminates as thin layers directly on top of each other (Figure A-26).

The airfoils would be fabricated oversize, then cut to precise length for assembly. The small pads added to the bottom of the tangs would also be ground to match the radius of the drive shaft so that the blades would be held radially outward at assembly.

The airfoil leading-edge cap would probably use the state-of-the-art, leading-edge protection utilized on other composite blades. It consists of nickel-plated, bonded-wire, woven mesh which is applied to individual blades prior to assembly.

Blades would be serialized and would have pan and moment weights recorded for proper selection of matched weights at assembly. If one blade must be replaced, thereafter, a record could be referred to for selecting the replacement, or a matched pair of blades could be installed at opposite points, if necessary.

(3) Blade Support Hoops - The support hoops would be fabricated by filament winding similar to the way rocket cases are wound but with fiber angles more circumferential for most layers. The hoops would be generated by winding onto a long, titanium shell; after curing, the individual hoops would be carefully cut from the shell, leaving the inner titanium ring (shell) as an integral part of the hoop to help in distributing the point blade loads more uniformly into the composite hoops.

The hoops may be made of graphite or fiberglass, matrixed in polyimide or epoxy, both choices depending on final analysis. Alternatively, they might be made of boron/aluminum or boron/epoxy. The choice will depend on aeromechanical decisions on whether or not to incorporate a tip shroud which, in turn, depend on the final number of blades, and that number depends on allowable limits of stall margin.

Future efforts in developing this fan concept should include a separate study to determine the best method of fabricating suport hoops with the greatest efficiency in hoop structure. It should be possible to fabricate hoop structures of this geometry, in production, that would display hoop tensile strengths in excess of 200,000 psi with unit-to-unit consistency.

It may prove more efficient to generate hoops with straight sectors, or lands, that coincide with the number of blades. This would reduce bending stresses in the hoops induced by point blade loads, but this configuration would be more expensive and would require some means for positive index relationship, between blades and hoops, that could become complex to accommodate.

(4) Blade Pins - The "D" section of the blade pin is sized to resist bending from blade loads. Bending would tend to cause stress concentrations at the edges of the blade tangs and support hoops. The pins would probably be made of hard steel or titanium and would most likely be milled out of a preturned shell profiled to their tangential projection. The front and aft ends of the pins would be thinned-down for deflection to accommodate mismatch of radial growth between the hoop-supported blades and the torque drive shaft (Figure A-25). The top surface of the pins would be rounded, and perhaps copper-plated, to inhibit fretting where the pin engages the titanium inner ring of the support hoops.

(5) Platforms - Two concepts of inner flow-path platforms have been studied. Figure A-25 shows hollow-ply, wrapped composite units that nestle between blade root profiles and are carried by hoops through a curved pin that engage tangs extending inward between the hoops. The platform hoops shown on Figure A-25 are located directly above the aft three blade-support hoops. The front portion of the platforms exerts less load than the aft portion; hence, the forward platform hoop can be eliminated to allow more structural area for blade support at the forward end of the blade.

It may prove desirable to provide a slight reverse catenary to the top surface of the platform unit to expand in a centrifugal field and induce more blade fixity or rigidity at that area. It is anticipated that a close-tolerance fit of the platforms, or even a fit with slight interference, may impose enough blade fixity that the platforms would not have to be bonded to the blades. Should bonding become necessary it could be done, but it would complicate easy blade replacement. With the reverse-catenary feature, the platform could be driven radially inward to effect slight compression at assembly, thus, reducing the responsibility of the assembler to maintain precise tolerance control over the blade-to-platform interface.

Figure A-26 shows inner flow-path platforms that bond to either side of the blades and extend to proximity with the adjacent platforms. This concept assumes that blade fixity would be no problem with the tip shroud acting to help support the blades. The mating ends of the platforms may engage each other at a a sloped interface, the tip side being made slightly stiffer than the bottom side so that centifugal force creates a good air seal.

(6) Platform Support Hoops - the Figure A-25 version of the supersonic-flight fan requires separate platform-support hoops, whereas the Figure A-22 version of the TF34 fan utilizes the same support hoops that carry the blades. This is due to the 0.4 radius ratio of the supersonic-flight fan; the 0.5 radius ratio of the TF34 fan provides for more tangential spacing to structure the hub components.

Manufacture of the platform-support hoops would be similar to that of the blade-support hoops described above.

(7) Platform Pins - the Figure A-25 version platforms would require circular pins which would probably be made with a "D" section that simply rabbets to the fore and aft torque plates as illustrated. Although they would probably be made of titanium or steel, boron/aluminum may prove adequate and would save some weight.

(8) Drive Shaft - A lightweight, titanium drive shaft for the supersonic-flight engine would deliver a total of about 245,000 in.-lb of torque to the blade pins and accept about 9,500 lbf of forward thrust against the spinner mount plate. Since the drive shaft must only carry itself centrifugally for the most part, it can be a very thin-shelled structure. Two inner-surface, thin, bulk rings spaced fore and aft would provide material for removal to effect final refinement of the rotor balance.

(9) Spinner Mount Plate - This circular plate, made of titanium, will rabbet to the front of the drive shaft and face against the forward plane of the blades and platforms (Figure A-26). If deemed necessary, a short engagement into the hollow face of the platforms, as shown in Figure A-25, would provide some blade fixity at that point. (But this added feature would increase the cost and weight.) If each blade provided one square inch of face against the spinner plate, thrust would impose about 400 psi against the total composite face of the fan hub.

(10) Aft Air-Seal Plate - The purpose of the air-seal plate is to inhibit recirculation of fan-discharge air forward through the hollow platforms. In addition, if this plate engages the hollow platforms to effect a box-like stucture to the platforms, it will enhance the blade fixity and improve blade frequency response. However, if the aft air-seal plate is not required to effect blade fixity, it can be made as a simple, self-supporting cone with less effect on stage weight than if it were structured to engage the platforms.

3.1.4.5 Assembly and Blade Replacement of Pinned-Blade/Hoop Design

With proper assembly fixtures, the hub-support and platform hoops are spaced axially, and then blades are assembled radially inward until they rest against the hoops. Once all blades are in place, the shroud is dropped directly over them and oriented so the blade tips align with the tip-support sockets prebonded to the shroud. Once the blade pins are slid into the blade-root tangs, the blades are pulled radially outward, engaging the shroud tip sockets until the pins come to rest against the hub-support hoops. Next, the drive shaft is inserted from the rear, and bolts are inserted through the drive shaft to engage the aft, hidden locknuts affixed to the blade-support pins. If separate platforms are utilized, they are inserted to engage the support hoops, and their pins are installed. Finally, the forward spinner mount plate is installed by being bolted to the drive shaft; bolts engage through it to affix the forward face of the blade-support pins which are also equipped with fixed locknuts. As the forward spinner mount plate is dropped into place, the platform pins engage a rabbet ring on the plate for radial support in the same way that the aft end is supported.

To replace a blade, the above procedure is reversed.

3.1.4.6 Tip Shroud and Blade Tip Support

The free hoop stress in a graphite tip shroud for the supersonic-flight fan would be about 64,000 psi; in the TF34 fan it would be about 40,000 psi. The blade tip-support pieces, as well as any erosion-inhibiting surface, would impose additional dead-load stress, but this addition would be minimal.

The tip shroud could possibly be made as several full-width units connected axially as a cylinder which could then be separated into individual shrouds in a manner similar to the proposed fabrication of the support hoops described earlier. This arrangement would permit easy utilization of some of the more axially oriented fibers to enhance the structural integrity of final-machined radial seal teeth, as illustrated on Figure A-25. The seal teeth would be final machined within the extra radial bulk generated during the filament-winding process.

Variations in fiber modulus, winding tension, applied heat while winding, fiber-to-resin ratio, and winding angle will each affect final part integrity. A program that could study and isolate the effects of such variables would have to be a prerequisite to a final, detailed, shroud design.

The proposed blade-tip supports illustrated on Figure A-25 could probably be made of injection-molded Torlon (polyamidimide) reinforced with short-fiber graphite. The profile would accept the blade tip with a sliding, telescoping fit that would allow full operating (rpm) range while maintaining sufficient engagement to resist loads imposed into the shroud from the blades. In the event of severe impact by a foreign-object on a blade, one side of the support may fracture away, thus, allowing the blade to deflect and return to its original position without catastropic failure. If the relative centifugal growth differences between the blade tips and the tip shroud causes either a severe compression or a tensile force at that intersection, it may be possible to provide accommodating geometry to effectively float the intersection by incorporating a tilted or bent blade geometry that could effectively allow stretch or compression in the length of the blade without inducing prohibitive stresses in the fan structure. This feature would require considerable study and proof testing.

Figure A-29 illustrates five tip-shroud-to-blade concepts that may provide a solution to the above problem, should it develop. From left to right, these are:

- "T" tip design: relative growth difference is accommodated by a "T" tip on the blade to engage the tip shroud and allow the extremities of the "T" to centrifuge out with the shroud and maintain constant attachment.

- Thin, flexible-shroud design: the thin shroud is fabricated with straight sections between blade tips. At 100% speed, the growth of the shroud allows it to become circular without lift-off at the blade tips.

- Prebow design: blades are fabricated with a predetermined bow in the stacking axis. At high speed, the blade straightens out from centrifugal force and becomes longer to match the growth of the tip shroud, or if the hub grows more than the tip shroud the blades will compress shorter.

- Pretilt design: blades are made and installed with a predetermined tilt from the root. At high speeds, centrifugal recovery forces the blades erect, causing a radial growth of the tip which matches the growth of the tip shroud. In other words, as the shroud grows it rotates tangentially relative to the hub, and the blades can match the relative growth.

- Telescoping design: if blades are stiff enough, the centifugal growth of the shroud would allow the blade tip to telescope out of the blade-tip-support socket at a unifrom rate all around the fan, thus, having no effect no rotary balance.

3.1.4.7 Tip Shroud Versus Stall Margin

Aside from the dynamics of a tip shroud, effect on aerodynamic performance would also have to be evaluated. The slotted cavities used in some casings directly over the fan blade tips provide broader stall-margin capabilities than is offered by smooth casing treatment. If a full tip shroud reduces the stall margin as expected, it might be possible to axially segment the tip shroud into bands, as illustrated in Figure A-30. Or perhaps, by perforating the shroud directly over the blade as illustrated on Figure A-26, the shroud could offer more torsional resistance to the blade tip than the segmented bands offer, Figure A-30, while achieving the desired aerodynamic response.

A study was made on what effect variation of the rotor aspect ratio (number of blades) would have on the stall margin and the efficiency of the supersonic-flight fan first stage. The results are summarized in Table 6. The stall margins listed are those calculated without the tip shroud or benefit of casing treatment. The circumferential-groove casing treatment incorporated in the supersonic-flight fan will provide about 5% additional stall margin for the base case. Stall margin efficiencies are expressed as deltas to the base case which is Case 1 in the tabulation.

Table 6. Rotor Aspect Ratio Versus Stall Margin and Efficiency for the Supersonic-Flight Fan First Stage.

Case	No. of Rotor Blades	Tm/c		Stall Margin, %	Design Point Efficiency, Δ
		Hub	Tip		
1	18	0.12	0.02	11.0	0
2	18	0.07	0.02	11.0	+0.70
3	24	0.07	0.02	8.6	+0.56
4	32	0.07	0.02	6.2	+0.23

The effect of continuous shrouds on aerodynamic performance is not well established. Much study and some actual demonstation are needed to confirm theory.

3.1.5 Evaluation of Candidates

Table 5 (Section 3.1.3) displays the Decision Analysis Worksheets - Comparison of Alternatives. Assuming that all versions of the TF34 and supersonic-flight fans meet or exceed the aeromechanical, aerodynamic, and structural requirements, the top contender fan concept turns out to be the pinned-blade/hoop concept. Until more is known about the effect of a tip shroud on aerodynamic performance, that parameter cannot be included in the comparison. Since it may be possible to eliminate the tip shroud on any of the fan concepts by trading it for higher hub stresses induced by more blade weight, the tip-shroud parameter may never be necessary in the comparison.

3.2 TASK II - DESIGN EXTENSION - PINNED-BLADE/HOOP FAN STUDY

The pinned-blade/hoop concept for the Stage 1 supersonic-flight rotor shown in Figure 4 was selected for more detailed analysis. In summary, this 24-blade design includes a tip shroud, pin root attachment, and a multiple composite-ring disk. Besides earning a high rating on the decision analysis worksheet, the concept was selected on the basis of its challenging operational requirements for use as the supersonic-flight rotor and the chance to study a large number of innovative ideas. The concept includes provisions for:

- Blade replacement
- Use of a composite disk
- A variety of blade airfoil-to-root joining methods
- The use of a blade pin root attachment
- The use of a shroud for the composite blades

The areas of analysis included:

- Blade vibration
- Blade streses, centrifugal force, and weight
- Blade airfoil attachment to support-tang lap-shear joining stresses
- Pin/loop attachment stresses
- Shroud-to-blade interaction
- Pin stresses
- Multiple composite-ring disk stresses

In addition to an overall stress analysis of a supersonic-flight version of a pinned-blade/hoop fan, a summary of projected component weight, fan development, and production costs is included in Task II.

3.2.1 Structural Design Analysis of a Supersonic-Flight-Engine, Pinned-Blade/Hoop Fan

Table 7 summarizes the results of the study and tabulates stresss, expected strengths, and margins of safety for critical locations and various requirement conditions. The primary requirement conditions are for burst speed to 141% operating speed and the 20,000-cycle-life condition at a design speed of 105% of operating speed. Figure 8 shows estimated strength-versus-life curves for the selected materials. The curves represent the high-temperature strength goals, average minus three standard deviations, that would be expected following a materials development program.

The stresses listed in the table are the most critical stresses calculated; each is either the maximum stress or the maximum effective stress. They consist of the calculated stress considering centrifugal forces, bending, and distribution effects. The blade distribution effects were based on factors estimated from stress distributions found on other composite blades where finite-element analysis and more rigorous solutions were employed. The various stress-distribution factors are also tabulated in Table 7. Specifically, the stress studies included the following:

Blade Root Stresses - Blade average centrifugal stresses were determined at 15 airfoil-span locations using a beam-solution, time-share program that was also used to compute the vibrational frequencies. A graphite/polyimide, 0±35° oriented, high-shear-strength material was assumed for the blade. Nickel-plated wire mesh was considered for the blade leading-edge protection. The maximum stress in the blade airfoil-to-root transition region was determined by correcting the average centrifugal stress in this region by a correction factor of 2.25 to account for the complex blade-camber-to-attachment transition and air loadings. The 2.25 factor assumes approximately 1.5 chordwise distribution and a 1.5 concave-to-convex distribution. Blade shear stresses are considered in the values used for allowable radial strength in Figure 8.

Blade Attachment Loop Stresses - The studied attachment design consists of predominately unidirectional fibers that extend downward from the airfoil and loop around a pin, providing high radial strength. The unidirectional plies are interspersed with layers of cross-plied material, probably of ±45° orientation, to increase the through-the-thickness compression and shear strengths. The cross-ply material would be placed mostly near the pin interaction surface to provide the compressive strength where it is most needed. A thin metal sheathing may be required at the pin-to-composite interface in a final design to provide more tolerance to fit-up mismatch and fretting.

Table 7. Stress Summary - Structural Design Analysis of Pinned Blade.

Rotor Location	Requirement Condition	Total Distribution Factor	Maximum Stress (ksi)	Allowable Strength (ksi)	Margin of Safety (%)
Blade Airfoil Root	Burst Speed*	2.25	83	110.0	33
	Operating Cyclic**	2.25	46	62.0	35
Blade Attachment Loop	Burst Speed	1.50	168	152.0	26
	Operating Cyclic	1.50	93	106.0	26
Disk Ring	Burst Speed	$\frac{1.56\ c}{1.10\ t}$	170	153.0	Negative
	Operating Cyclic	$\frac{1.56\ c}{1.10\ t}$	94	108.0	14
Disk Ring	1.27 x Operating Speed	$\frac{1.56\ c}{1.10\ t}$	152	153.0	0
Blade Root Attachment Scarf	Burst Speed	2.25	3.6	4.0	13
	Operating Cyclic	2.25	2	2.2	12
Tip Shroud/(Attached)	Burst Speed	1.0	198	145.0	Negative
	Operating Cyclic	1.0	110	100.0	Negative
Tip Shroud (Telescoped)	Burst Speed	1.1	124	145.0	17
	Operating Cyclic	1.1	69	100.0	45
Pin (Steel) Bending Shear	Burst Speed	1.0	100/54	200/110	High
	Operating Cyclic	1.0	55/30	100/60	High

*Burst speed at 141% operating speed

**Operating cyclic (design speed) at 105% of operating speed

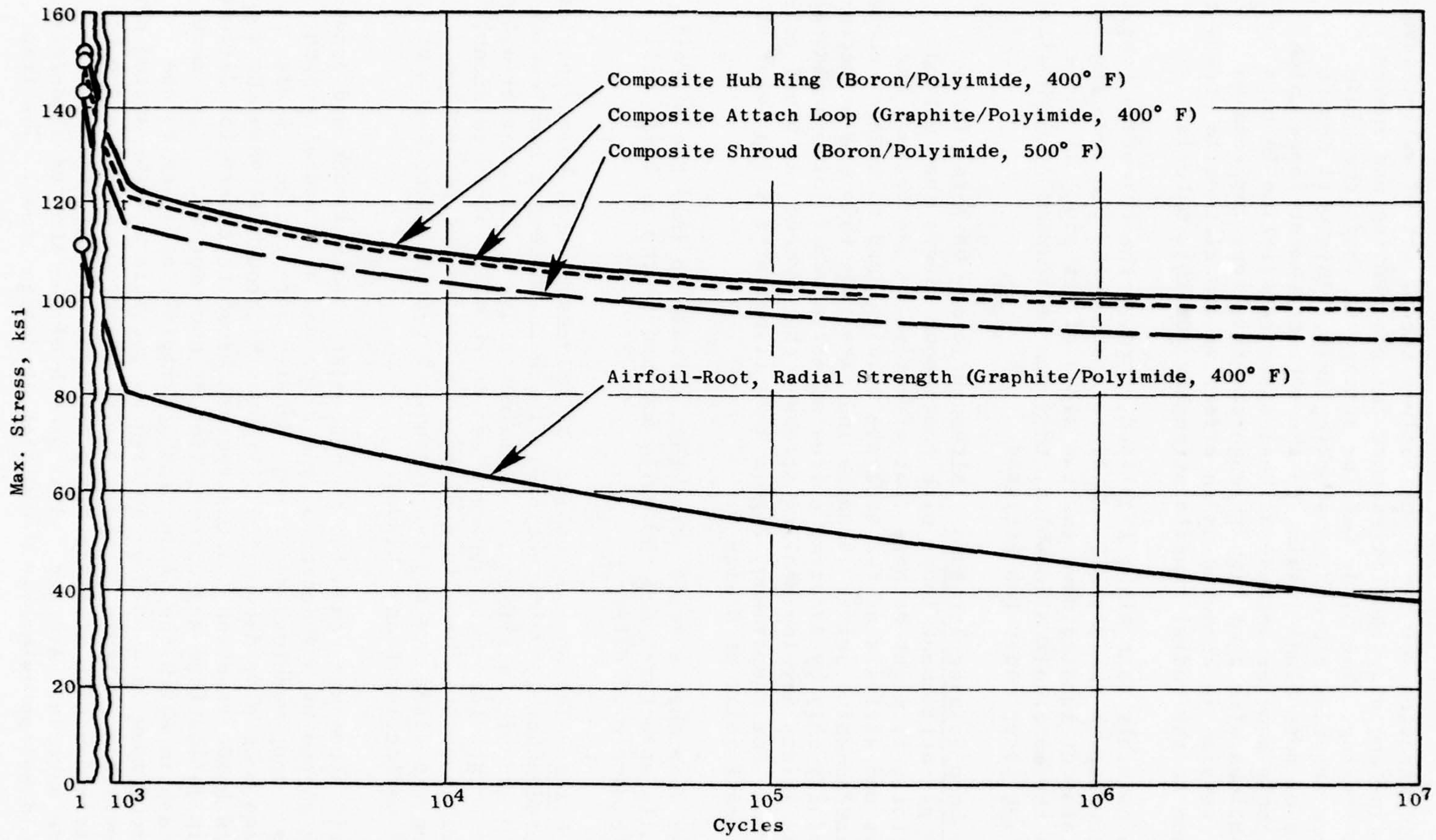

Figure 8. Estimated Allowable Strengths of Composite Rotor.

The computed stresses for the loops include the effect of wall-thickness-to-small-pin radius and distribution factors for pin bending and uneven airfoil-to-loop loading. The blade will be stacked to shift the blade centrifugal force reaction aft of the stacking axis. This will permit the transmission of more blade loading to the aft attachment loops which can be made slightly heavier because of less space restriction in this region. The combined effect of high through-the-thickness compression and high radial tension is computed as an effective radial tensile stress to permit comparison to the radial tensile strenghth for this material.

It is also possible that high, localized, through-the-thickness tensile stresses will develop in the airfoil immediately above the pin loop region due to the division of loading down the two sides of the pin. If these stresses exceed the materials allowables, they can be reduced by mechanical means as discussed later under Pin Stresses.

Airfoil-to Loop Joining Stresses - Although it may be possible to manufacture the pin-attachment loops with continuous fibers that extend up into the airfoil, it might be more cost effective to manufacture the attachment loops and airfoils as two separate moldings and to connect these using a lap shear adhesive joint. Studies indicate that this can be accomplished successfully only by adopting a true adhesive scarf joint arrangement. Conventional lap joints develop peeling stresses that exceed the usual adhesive tensile strengths. For comparison, Figure A-26 illustrates a lap joint at Design 3 and a scarf joint at Design 6.

The studies show that a scarf joint that extends up into the airfoil, and is elastically structured and thermally matched to the airfoil, will have an adequate margin of safety.

Shroud Stresses - The shroud consists of filament-wound, boron/polyimide material with predominately unidirectional fibers to achieve a combination of high strength and high stiffness. Sufficient cross-plied material will be interspersed to provide shear strength and to restrict blade torsional deflection. High hoop stiffness is desired to minimize the deflection mismatch between the blade tip and the shroud. A rotating hoop has more inherent radial deflection than a blade.

A parametric study was conducted to determine combined hoop and bending stresses in the shroud as a function of the blade and disk radial growth. Shroud thickness, hoop modulus, and shroud density were varied. Blade reaction loadings were also determined. Figures 9 through 11 show the combined stress and blade reaction loading versus shroud thickness for different blade-radial-tip deflections and three different hoop moduli. These show that, for the case in which the blade tips are rigidly attached to the shroud, the shroud modulus should be as high as possible and the shroud should be as thin as possible. Figure 12 shows a plot of shroud stresses and blade-tip reactions as a function of blade-tip growth for several thickness of boron/ polyimide shrouds. Average radial growth of the studied blade/disk arrangement would be approximately 0.050 inch at design speed. The free

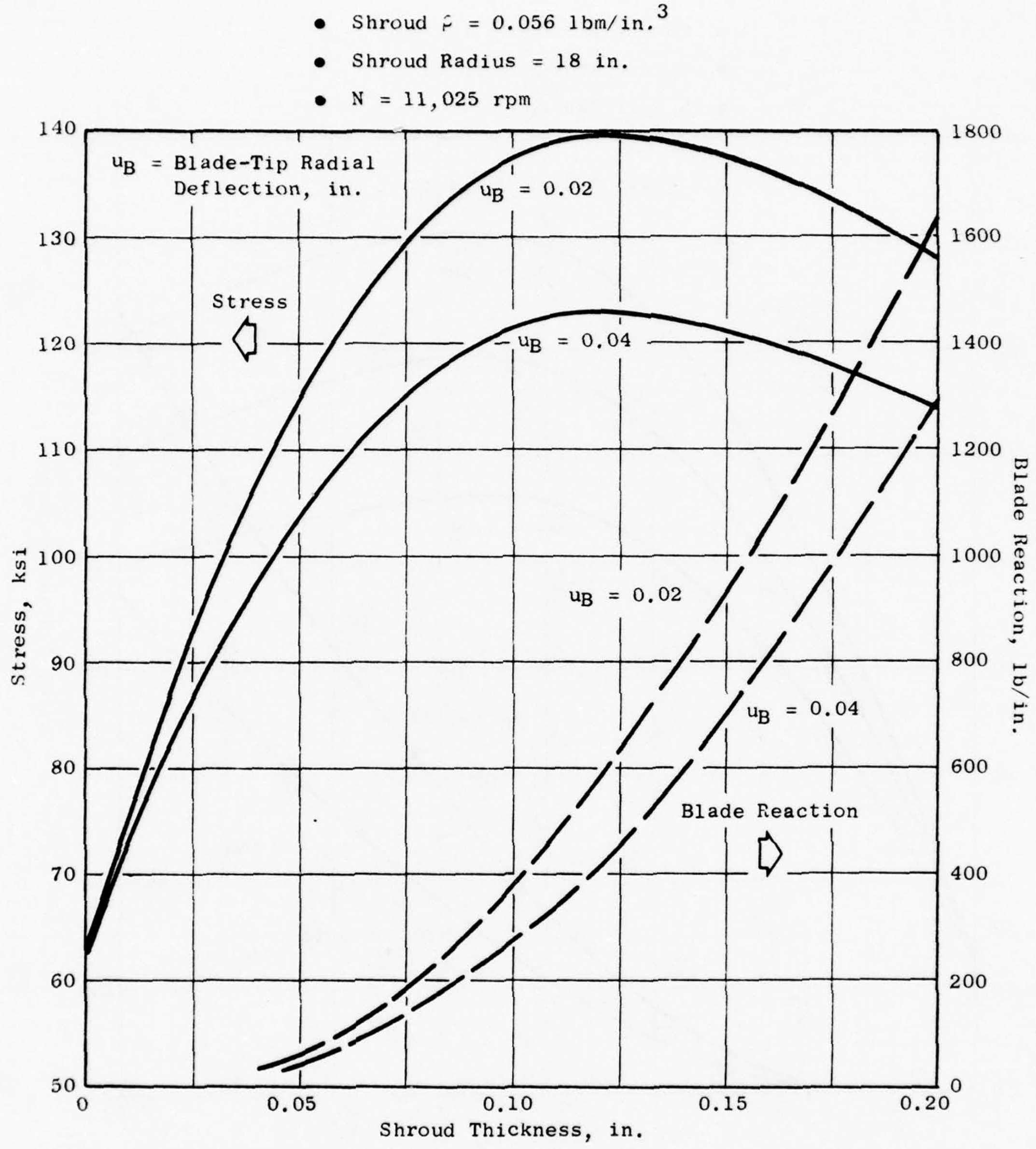

Figure 9. Shroud Max. Stress and Blade Reaction for Composite Tip Shroud; $E = 10 \times 10^6$ psi.

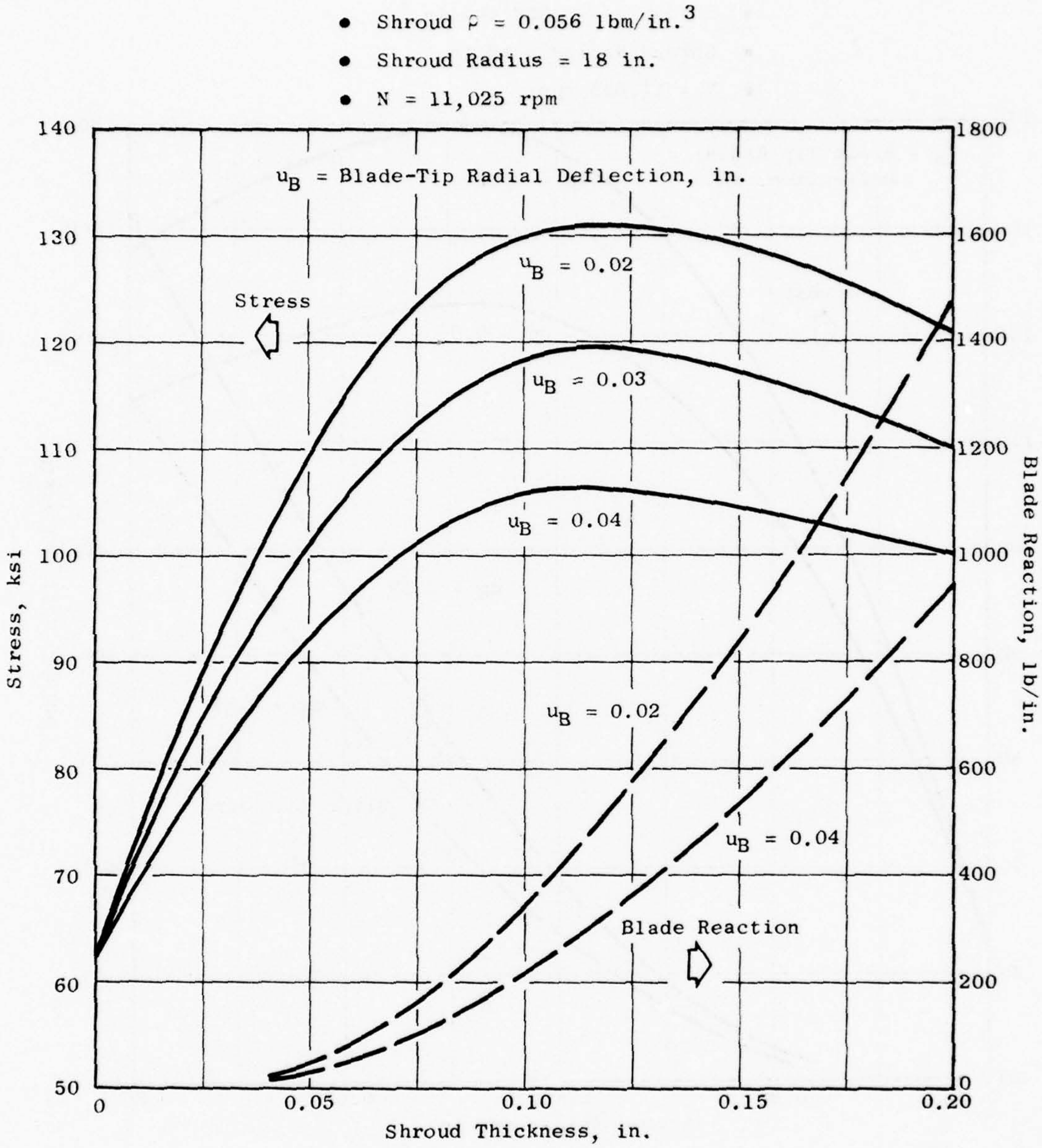

Figure 10. Shroud Max. Stress and Blade Reaction for Composite Tip Shroud; E = 15 x 10^6 psi.

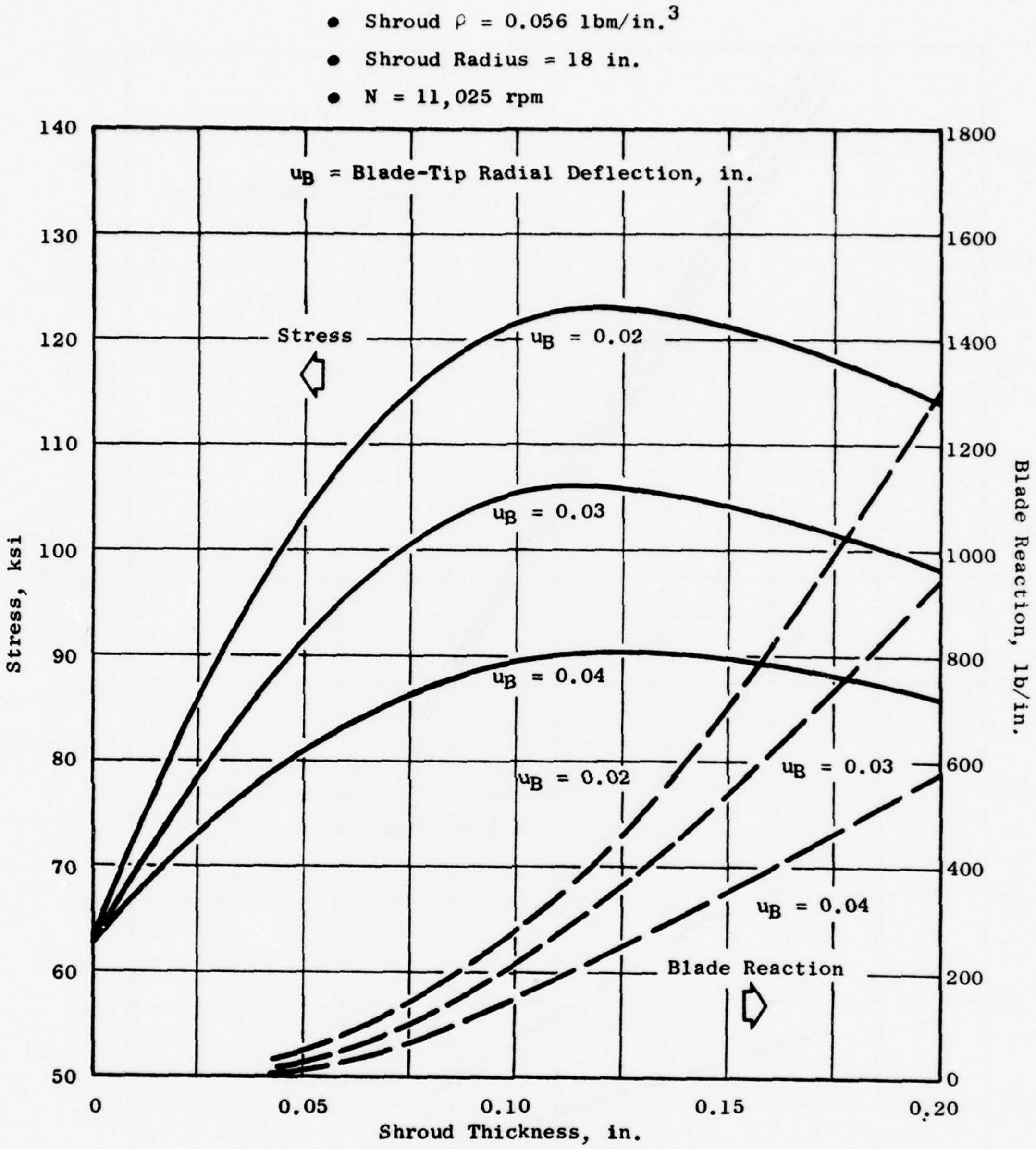

Figure 11. Shroud Max. Stress and Blade Reaction for Composite Tip Shroud; $E = 20 \times 10^6$.

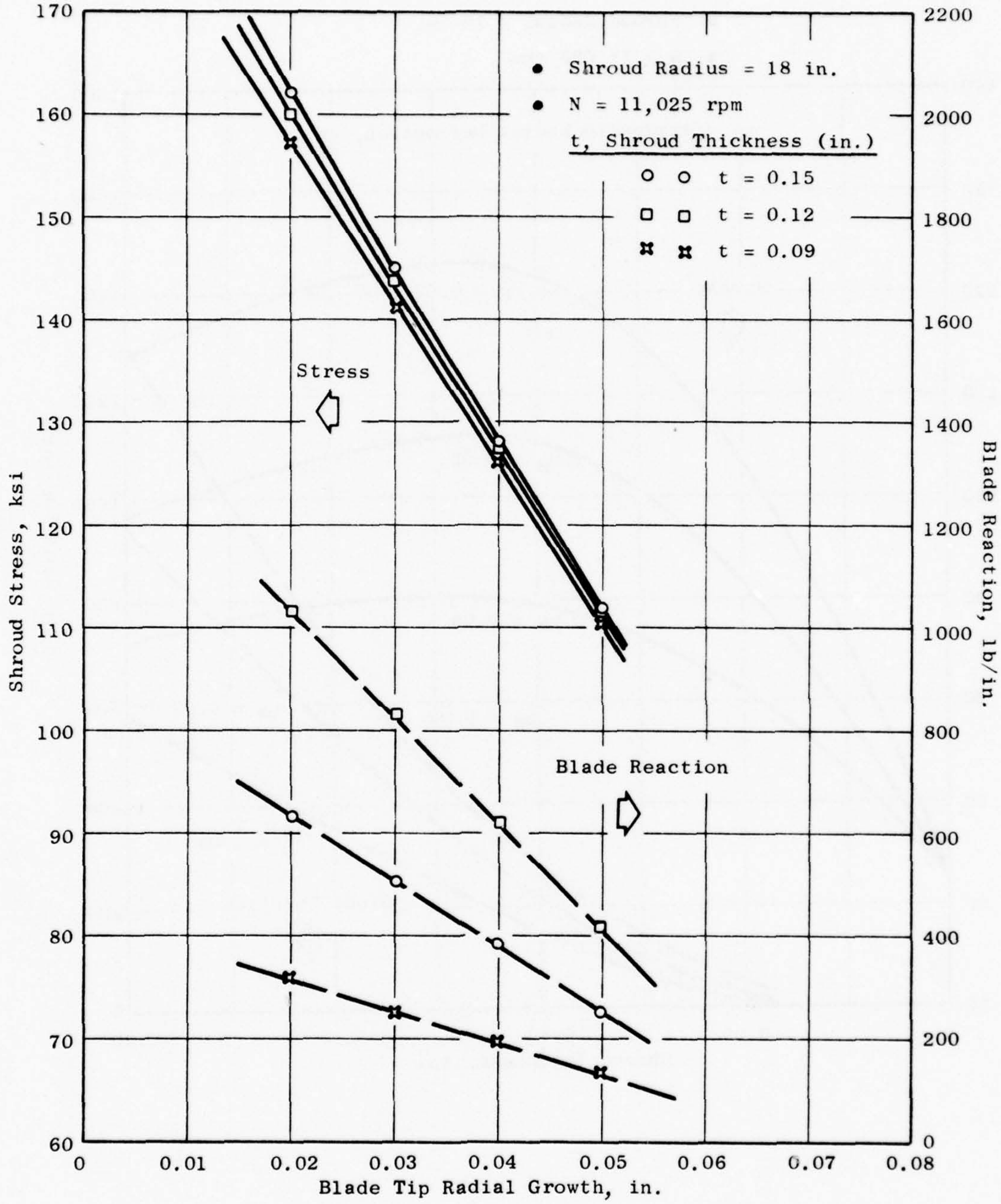

Figure 12. Boron/Polyimide Shroud Max. Stress and Blade Reaction.

shroud radial growth would be approximately 0.070 inch and the maximum shroud stress about 110 ksi. This stress is reasonably insensitive to shroud thickness, over the likely range of thicknesses to be used, but is higher than allowed to meet the selected design requirement conditions. The use of a tilted or bowed blade to increase blade-tip deflection, or some sort of tip telescoping arrangment, would be required in the final design. Figure A-29 illustrates several potentially compatible blade/shroud-growth arrangements.

Pin Stresses - For the arrangement studied, the pins are inserted from the aft face of the disk and extend through the blade-root loops and under the individual disk rings from the aft disk face to the forward disk face. The pins are subjected to bending and shear loads from the reactions of the various blade loops and disk rings. Since compressive stresses are critical both in the blade loops and in the disk rings, and require very uniform loading, it is necessary to have very low deflection rather than low stresses. Expected pin stresses are summarized in Table 7. Margins of safety are high. It is also possible that a stepped or two-piece pin may be required. This would allow making several of the aft blade-attachment loops thicker than is possible at the blade leading-edge loop.

Disk-Hoop Stresses - The primary loading on the composite disk hoops is introduced when the metal pins transmit the blade centrifugal loads. Each composite hoop is filament-wound over a thinner titanium hoop and is made up of predominatly unidirectional boron/polyimide material with interspersed, cross-plied material. The cross-plied material is required to provide high through-the-thickness compression and shear strength at the hoop inner surface. High-modulus boron is planned for the hoop, mainly to keep the titanium inner-hoop stresses from being excessive. The titanium hoop spreads the high localized compressive and shear stresses introduced by the pins. The composite-hoop maximum stress is at the inner surface and consists of thick-wall effect and pin-to-pin bending. An effective stress that considers the biaxial effect of the superimposed stress on the hoop and and bending stresses was computed for this condition. The computed effective stress is 170 ksi at the goal burst-speed condition (141% of operating speed). This exceeds the allowable stress of 153 ksi from Figure 8 and indicates an overspeed burst level of 134% of operating speed. The effective stress at the design cyclic speed (105% of operating speed) is 94 ksi, which is less than the cyclic allowable stress and provides a positive margin of safety for this condition. The results are summarized in Table 7.

3.2.2 Projected Weight Summary of a Supersonic-Flight-Engine, Pinned-Blade/Hoop Fan

Components of the latest version of a supersonic-flight pinned-blade/hoop fan, illustrated on Figure A-26, would display the following:

24 Blades	30 pounds
24 Platforms	3 pounds
24 Pins (Ti)	8 pounds

Tip Shroud	7 pounds
6 Hub Hoops	7 pounds
Titanium Drive Shaft	8 pounds
Erosion Cap and Bolts	4 pounds
Total	67 pounds

The proposed, solid-titanium Blisk counterpart would weigh 179 pounds.

3.2.3 Cost Analysis of Pinned-Blade/Hoop Fan

The following cost analysis of a pinned-blade/hoop fan, such as the one proposed for the supersonic-flight engine illustrated on Figure A-25 and Figure A-26, is based on the assumption that all preliminary designs and evaluations are complete, and the final design is frozen. Values are expressed in estimated man-hours of effort rather than in dollars. The man-hours of effort listed for tooling do not include any time for purchasing services or engineering liaison during the procurment cycle, nor do the fabrication and machining hours include any applied time for engineering or management. Hours listed are only for actual labor applied toward the job. Costs associated with the various fan components are discussed below.

(1) Six Support Hoops for Blades - A thin, titanium, seamless shell would be machined from a forging or spun from a plate to the required dimensions to encompass one fan-hoop-set unit, or some multiple in length. Thereafter, a wide hoop would be wound upon the titanium shell to a specified pattern and thickness. After cure of the resin system, individual loops would be machined out of the long hoop to the required profile. For this analysis, it is assumed that these hoops can be made circular, rather than multisided, to reduce deflection from point loading. If multisiding is required, costs would be increased significantly.

(2) Three Support Hoops for Platforms - If the design evolves to the Figure A-25 concept, three support hoops would be fabricated much like the blade-support hoops described above. However, it may not be necessary to leave the titanium shells as an integral part of the platform hoops since they are much lighter than the blades. If the platforms can evolve as shown on the Figure A-26 concept, these suport hoops can be eliminated.

(3) Tip Shroud - This cost analysis assumes that a smooth shroud, nonperforated or axially segmented, can be utilized. It would be fabricated in a connected axial series and then machined for tip-seal profile before being separated from the bulk axial wrap, much like the concept proposed for the hub-support hoops. A thin, metallic, inner surface may be included for erosion protection, but it may be segmented to fit between the blade-tip moldings so the moldings can be bonded more effectively to the parent shroud material.

By winding multiple units all at one time, the slightly more axial fibers will improve the structural integrity of the machined tip-seal teeth of the later (if, indeed, they remain a design feature).

If a perforated tip shroud evolves as a means of implementing broader stall-margin capability, the fabrication costs will increase significantly.

(4) Twenty-Four Airfoils with Root Tangs - Whether the airfoils are integrally connected with the root tangs (Designs 4 and 5, Figure A-26) or are bonded in assembly through scarf joints on lap shear (Designs 1, 2, 3, and 6; Figures A-25 and A-26), the overall costs should be about the same, especially for the initial units. The concepts of Designs 4 and 5 (Figure A-26) utilize fewer parts and require no intermediate machining for matched profile bonding, but tooling costs and labor for layup could be high enough to nullify the advantages of fewer parts.

(5) Twenty-Four Platforms - If platforms evolve in the way illustrated on Figure A-25, they may be made as thin, hollow-shell wrappings of cross-plied laminates with the top airflow surface concaved inward as as inverted catenary that would exert sideways pressure in a centrifugal field. If other internal ribbing is necessary, it could be secondarily bonded internally at a slope and likewise incorporate a catenary profile that induces sideways pressure, as illustrated on Figure A-10. These platforms would be slightly flexible and could, therefore, be driven radially inward at assembly to accommodate tolerance variations in parts while contributing significantly to blade fixity, if required.

If the platforms evolve as simple moldings bonded to the airfoils, as illustrated on Figure A-26, they could probably be formed with laminates and incorporate ribs for support, using expanding, rubber-trapped molds to achieve a dense cure; this is standard practice for similar geometry in many airframe applications.

With either approach, the cost of tooling and parts should be about the same.

(6) Twenty-Four Blade Pins - Straight - At this point, it is assumed that the blade root shank can transition from the required airfoil shape at the flow path to a straight line parallel to the fan axis at the point of attachment to the support hoops; thus, the "D" section pin can be assembled axially (Figure A-26), as opposed to curved (Figure A-25).

It is proposed that a steel shell encompassing the tangential profile of the pin be turned out of a forging. Individual pins would then be extracted from the shell by a milling operation that continues to profile the inner radius to match the blade tang loops. Pins would then have the curved, outer surface plated with copper or some other antifretting material to interface with the inner, titanium shell of the hub-support hoops.

If the pins must be made circular, as illustrated on Figure A-25, the cost could increase significantly.

(7) Twenty-Four Platform Pins - Curved - Because of the low radius ratio, it is impossible to utilize the same arrangement of support hoops for the platforms on the supersonic-flight fan as could be used on the TF34 engine, Figure A-22. Therefore, since the point of platform attachment is higher than the point of blade attachment, assembly requires that the platform pins be curved, parallel with the blade shank, and forced into a true radius. Any profile other than true radius could not be assembled.

These pins could probably be machined from a titanium shell of revolution more easily than final-curving to the required profile from an extruded shape.

(8) Twenty-Four Blade-Tip Moldings - The blade-tip moldings that position the blades to the tip shroud could possibly be injection-molded with Torlon, or they could be layed up with cross-ply laminates, for higher integrity, and cured to profile before bonding them in proper index to the shroud. Either approach would cost about the same for development, but injection-molded Torlon pieces would be more economical in production if they prove to have adequate strength.

(9) Aft Air Seal - The aft air seal would be molded from cross-plied or woven laminates to net shape. The net shape may include some taper since it is simply trapped in assembly and must carry itself centrifugally.

(10) and (11) Drive Shaft and Spinner Plates - The lightweight, titanium drive shaft and spinner plate could be machined by automatic, tape-controlled equipment from nearly net forgings.

(12) Assembly and Balance - The assembly of each fan would be accomplished with precision fixturing in the sequence described in Section 3.1.4.5. Each blade and platform would be moment-weighed and paired with an opposite mate. The tip shroud and hub-support hoops would be previously balanced along with the hub, spinner plate, and aft air seal. After assembly, balance would be refined by slight metal removal in the hub at bulk rings included for that purpose. If more pronounced balance is required, perhaps thin plies of composite material could be bonded to the inside surface of the tip shroud.

(13) Spin Test - Completed fans would be spin tested to a predetermined overspeed level prior to engine assembly.

Summary - The projected cost of producing the proposed, supersonic-flight, pinned-blade/hoop fan, such as it is conceived on Figure A-26, is summarized in Table 8 in terms of man-hours for tooling and for the first and 250th units. The estimated effort does not include any design effort or engineering/management coverage. Hours listed are reasonable estimates based on past experience, but they should only be used for budgeting estimates.

Table 8. Estimated Man-Hour Summary, Pinned-Blade/Hoop Fan.

	Fan Component	Tooling	First Unit	250th Unit
1.	6 Support Hoops/Blades	80	160	16
2.	3 Support Hoops/Platforms	80	80	8
3.	Tip Shroud (Nonperforated)	120	160	16
4.	24 Airfoils/Tangs	1600	1000	100
5.	24 Platforms	600	400	50
6.	24 Blade Pins - Straight	200	200	8
7.	24 Platform Pins - Curved	300	400	16
8.	24 Blade-Tip Moldings	400	100	8
9.	Aft Air Seal	125	40	8
10.	Drive Shaft	200	400	40
11.	Spinner Plate	100	120	20
12.	Assembly and Balance	250	80	8
13.	Spin Test (Not Instrumented)	100	20	4
14.	Contingency at 10%	345	340	40
		4500 hrs	3500 hrs	342 hrs

- Materials are not included
- Inspection is included

4.0 PHASE II - SUPERSONIC-FLIGHT SECOND-STAGE FAN, COMPRESSOR ROTOR, AND SHAFT DESIGN

This phase of the contract was limited to the following supersonic-flight engine components:

- Stage 1 fan
- Stages 1 and 2 core compressor
- Drive shaft between fan Stages 1 and 2

4.1 DESIGN CONDITIONS/REQUIREMENTS

Design conditions and requirements were defined for the supersonic-flight, second-stage-fan rotor; for the supersonic-flight, first and second stages of the compressor rotor; and for the forward, low-pressure-turbine, drive shaft between the first and second stages. Tables 9, 10, and 11 give the design requirements for these three areas. These are compatible with the design requirements listed in Section 8.1.3.

4.2 DESIGN CRITERIA

The configurations described in Sections 4.3 and 4.4 were conceptually developed and sized to meet the various speeds and special conditions outlined in the requirements. However, only minimal study was conducted for these components because the maximum operating temperatures were considered too extreme for polymeric-composite components.

The composite structural concepts identified for each area have specific unique features that would be subjected to analyses similar to those outlined for the fan rotor in Section 3.1.3.

4.3 SUPERSONIC-FLIGHT-ENGINE SECOND-STAGE FAN AND COMPRESSOR

The following conceptual designs were illustrated from preliminary analysis of the design conditions and criteria discussed above:

Figure A-12 - Second-Stage Fan - Comet Blisk

Figure A-27 - Second-Stage Fan - Pinned-Blade/Hoop Rotor

Both drawings include proposed composite drive shafts which are discussed in the following section, 4.4.

Figure A-31 - Compressor Stages 1 and 2

Table 9. Design Requirements for Composite, Supersonic-Flight Compressor, Stages 1 and 2.

Physical Speed	15,100 rpm
Design Life and Cycles	
• Operating Life	4000 hrs
• Design Duty Cycles	8000
Blade Hub Temperatures (Standard Condition)	
• Stage 1	490 ° F
• Stage 2	610° F
Vibratory and Structural Requirements	
• High-Flexural-Stiffness Design	
• High-Torsional-Stiffness Design	
• Streses within Allowable Stress Range Diagram with Sufficient Vibratory Margin	

Table 10. Design Requirements for Composite, Supersonic-Flight Fan Rotor, Stage 2.

Design Mechanical Speeds	
● Maximum Operation (Na)	10,500 rpm
● Design (1.05 Na)	11,025 rpm
● Design Burst (1.41 Na)	14,805 rpm
● Design Tip Speed	1732 ft/sec
Design Life and Cycle	
● Operating Life	4000 hrs
● Operating Cycles	20,000
● Vibratory Cycles	3×10^7
Special Conditions (Dash)	
Blade Root	520° F
Blade Tip	600° F

Table 11. Design Requirements for Composite, Supersonic-Flight Engine Shafting (Forward LPT Shaft).

Design Speed	10,500 rpm
Design Life and Cycle	
• Operating	4000 hrs
• Low Cycle Fatigue	20,000 cycles
• High Cycle Fatigue	3×10^7 cycles
Shaft Horsepower	
1st Stage	17,700
2nd Stage	15,600
Total Rotor	33,300
Shaft Torque	
1st Stage	130,000 in.-lb
2nd Stage	114,000 in.-lb
Total Rotor	244,000 in.-lb
Shaft Temperature (Standard Condition)	200 °F

Vibratory and Structural Requirments

- High Flexural Stiffness - Operates at 15% above 2/Rev at Na
- High Torsional Stiffness
- Stress Within Allowable Limits for Two-Blade-Out Vibratory Response

The Figure A-12 (Comet Blisk) version of the second-stage, supersonic-flight fan would weigh about 52 pounds; the projected all-metal Stage 2 fan would weigh 112 pounds. The Figure A-27 pinned-blade/hoop version of the second-stage fan would weigh about 43 pounds.

Since the second-stage fan would run about 150° F hotter than the first-stage fan, the extreme temperatures imposed by the dash condition may exceed the current capabilities of polyimide materials. However, it is anticipated that improvements in polyimide materials or metal-matrix composites may enhance the prospect for this fan at some future date.

The first- and second-stage supersonic-flight core compressor illustrated on Figure A-31 shows the current metal disk profile in phantom for direct comparison with the proposed filament-wound-hoop concept. The total weight saving is about six pounds (53 versus 47).

Cycle analysis indicated that the soak temperature of this hoop area of the compressor will be slightly over 600° F, which exceeds the capabilities of proposed polyimide materials. Accordingly, an in-depth analysis of the compressor concept was terminated.

4.4 SUPERSONIC-FLIGHT ENGINE COMPOSITE DRIVE SHAFT

The two sections of a proposed composite drive shaft illustrated on Figure A-27 would save weight over the current metal counterpart with two different versions as listed below:

	Weight Savings
Graphite/polyimide	4 pounds
Boron/aluminum	6 pounds

Figure A-27 illustrates shaft end attachments diffusion-bonded for boron/aluminum shafting. Figure A-12 shows just a forward shaft section which is redundantly bonded and clamped for end attachments as proposed for a graphite/polyimide version.

Both versions of composite shafting could be either filament-wound or composited with unidirectional laminates that overlap and generate more section thickness as the radius decreases.

5.0 VIBRATION ANALYSIS AND PARAMETRIC STUDY OF COMPOSITE BLADES FOR A SUPERSONIC-FLIGHT STAGE-ONE FAN ROTOR

5.1 INTRODUCTION

The number of blades in a stage, the thicknesses of the blades, and the distribution of the thicknesses are usually selected in conjunction with aerodynamic parameters to satisfy various blade vibrational requirements. The final blade configuration may vary significantly, the final form depending on the blade-material properties and whether the blades are shrouded. Blade weights, loadings, and stresses, which affect the blade attachment and disk design, are a function of the blade material and configuration. The use of composite materials permits large flexibility in the material properties employed and leads to generally lightweight designs. The use of shrouds on blades has considerable effect on raising vibratory frequencies.

Parametric studies were conducted to assess blade loading, stresses, and vibrational characteristics as a function of variations in blade properties, thicknesses, and the number of blades in the stage, with and without tip shrouds for a supersonic-flight, first-stage fan rotor. The limiting parameters were defined by comparing the results of the studies with vibration requirements.

5.2 VIBRATION ANALYSIS

Blade vibration requirements were taken as follows:

1. The first flexural frequency of the blade must be at least 10% greater than 2/rev at 115% speed.

2. The first torsional frequency must be high enough to prevent instability (flutter).

The first-flexural-frequency requirement was selected to provide a high-flex blade with a first flexural frequency that never crosses the two-per-rev line during engine operation. The two-per-rev line is the plot of two cycles or excitations per rotor revolution versus rotor rpm. Figure 13 shows a typical Campbell diagram depicting this case.

Blades can be highly stressed from vibrations induced by two-per-rev inlet distortion caused by a circumferential variation in inlet pressure or other stimuli. A high-flex blade will not be influenced by this phenomenon since the first flexural frequency never crosses the two-per-rev line throughout the entire operating range, and the blade fundamental resonance will never coincide with a two-per-rev excitation. The number of struts,

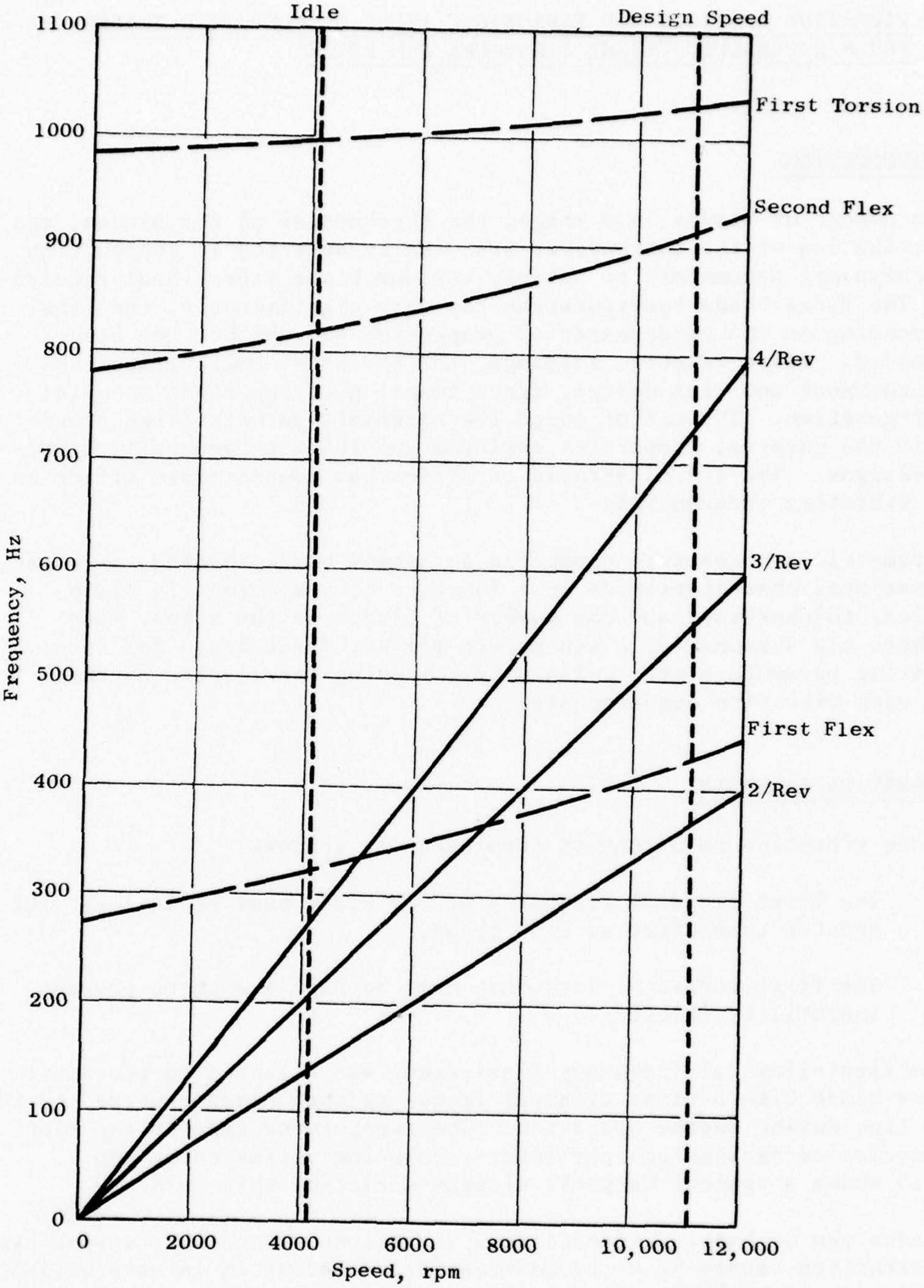

Figure 13. Supersonic-Flight; Unshrouded 18-Blade-Fan-Rotor Campbell Diagram.

vanes, bleed holes, etc., in the rotor vicinity will be selected in conjunction with the final selection of the number of blades to ensure that no excitational sources will strongly influence the blades at other resonant integer frequencies.

The second requirement, relating to the blade torsional frequency, is to prevent blade instabilty, or flutter, which is caused by self-excited vibration with aerodynamic/blade elastic feedback and airstream forces which vary as a function of blade motion. This requirement is satisfied in preliminary design by the use of limits on an empirical relation termed "the reduced-velocity parameter." The reduced-velocity parameter that is used to control this condition is defined as:

$$V_r = \frac{W}{b\,f_t}$$

where b = 1/2 chord at 5/6 span (feet)

W = average air velocity relative to the blade over the outer 1/3 of the span (feet/second)

f_t = first torsional frequency at design rpm (radians/second)

Values of V_r are normally kept below 1.4, but a value of 1.0 was used in this study to be conservative.

The vibration analysis consisted of determining the first flexural and first torsional frequencies, at operating speed for various blade designs, and then comparing them to the frequencies required to satisfy the vibratory requirement.

5.3 PARAMETRIC STUDY

Table 12 tabulates the blade chord, stagger, camber, and thickness-to-chord ratio (Tm/c) versus span for a proposed 18-blade, unshrouded design; Figure 13 shows a Campbell diagram for this fan.

For this study, the stagger and camber were kept the same at the proposed 18-blade design, but the chord was changed inversely with the number of blades. Thicknesses and material properties were varied to satisfy the the requirements of individual cases. A time-share program was used to compute blade freqeuncies, stresses, loads, and weights.

Figure 14 shows a comparison of calculated and required first-flexural and first-torsonial frequencies as functions of the number of shrouded, graphite polyimide blades in the first stage of the supersonic-flight rotor. It is seen that for the case of 9% Tm/c, 27 blades or less in the stage will satisfy the vibratory requirements. A lower number of blades in the stage gives higher vibratory margin while a higher number of blades provides lower stage weight and lower blade-root-attachment stresses.

Table 12. Proposed Supersonic-Flight, Stage 1 Fan Blade Geometry - 18 Blade Design.

Distance From Engine Centerline (Inches)	Chord (Inches)	Stagger (Degrees)	Camber (Degrees)	Tm/c
18.00	9.567	61.39	-1.84	0.0248
17.00	9.377	58.61	-0.05	0.0255
16.00	9.189	55.42	2.35	0.0263
15.00	8.994	51.79	6.31	0.0279
14.00	8.795	47.67	11.84	0.0366
13.00	8.623	43.03	20.84	0.0515
12.00	8.432	38.06	32.73	0.0692
11.00	8.223	32.39	51.92	0.0883
10.00	7.980	24.84	73.19	0.1067
9.00	7.742	17.58	85.92	0.1156
8.00	7.596	10.06	95.63	0.1170
7.00	7.580	2.45	100.68	0.1167
6.00	7.718	---	103.02	0.1139
5.47	7.851	---	103.38	0.1118

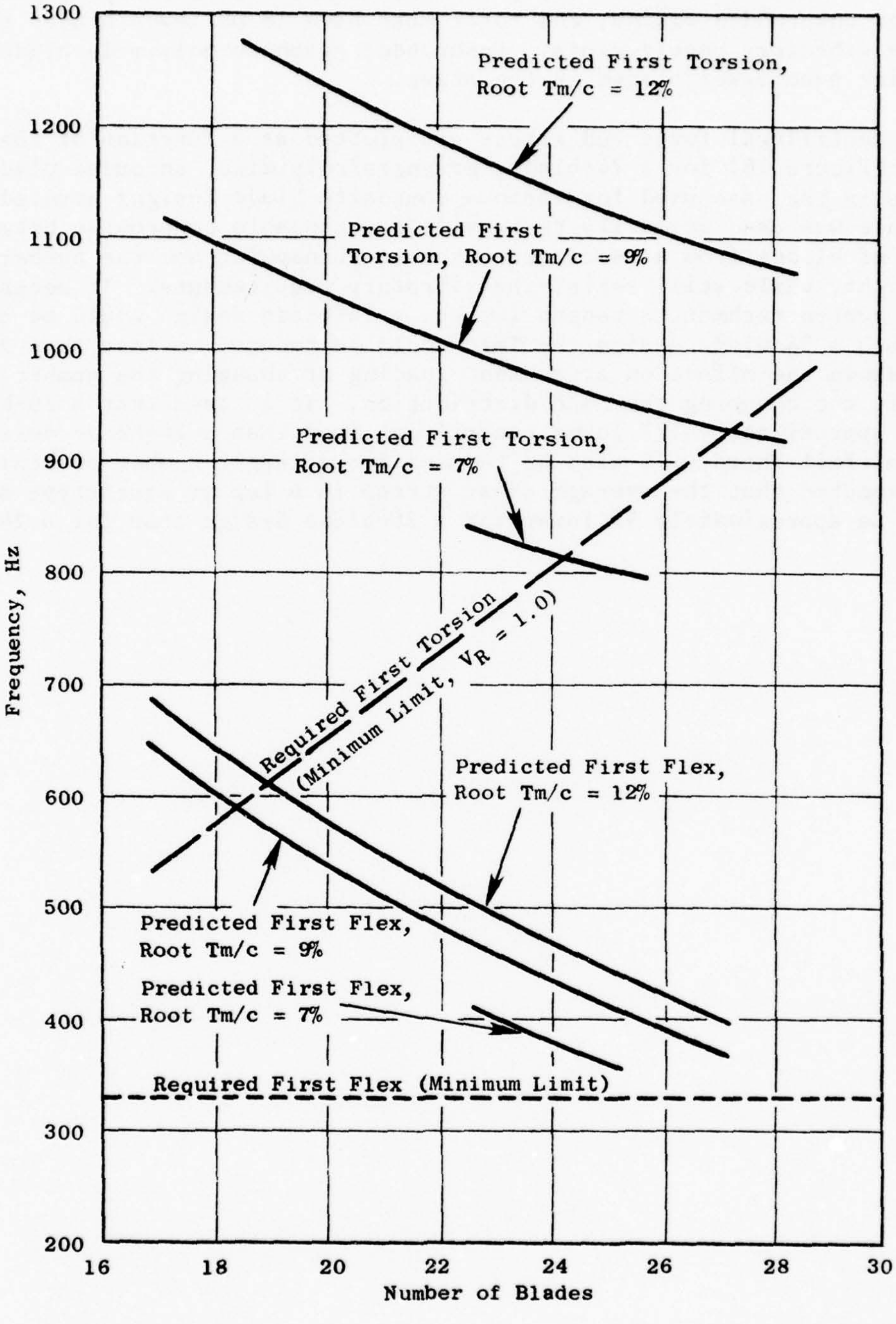

Figure 14. Predicted Vs. Required Frequencies for Supersonic-Flight Fan Rotor with Shrouded, Graphite/Polyimide Blades.

Figure 15 shows a similar comparison for unshrouded, boron-polyimide blades. For unshrouded blades, the rotor must have 18 or fewer blades to satisfy the vibratory requirements. Unshrouded graphite-polyimide blades would require even fewer blades in the stage.

Blade centrifugal force and stress are plotted as a function of the blade span (Figure 16) for a 24-blade, graphite/polyimide, shrouded-blade case. This is the case used for various composite-blade designs studied. The 24-blade case was used primarily to provide a reasonable compromise between the number of blades from a manufacturing cost standpoint and the number for minimum weight, while still satisfying vibratory requirements. If necessary, to satisfy root-attachment strength limits, a 26-blade design would be possible, and with a 24-blade design the Tm/c could be reduced to less than 9%. Figure 17 shows the effect on attachment loading of changing the number of blades while not changing the Tm/c distribution. It is seen that a 26-blade design has approximately 17% lower centrifugal load than a 24-blade design. Since the airfoil chord will also be reduced for a larger number of blades, it could be expected that the average shear stress in a lap or scarf-type attachment would be approximately 9% lower for a 26-blade design than for a 24-blade design.

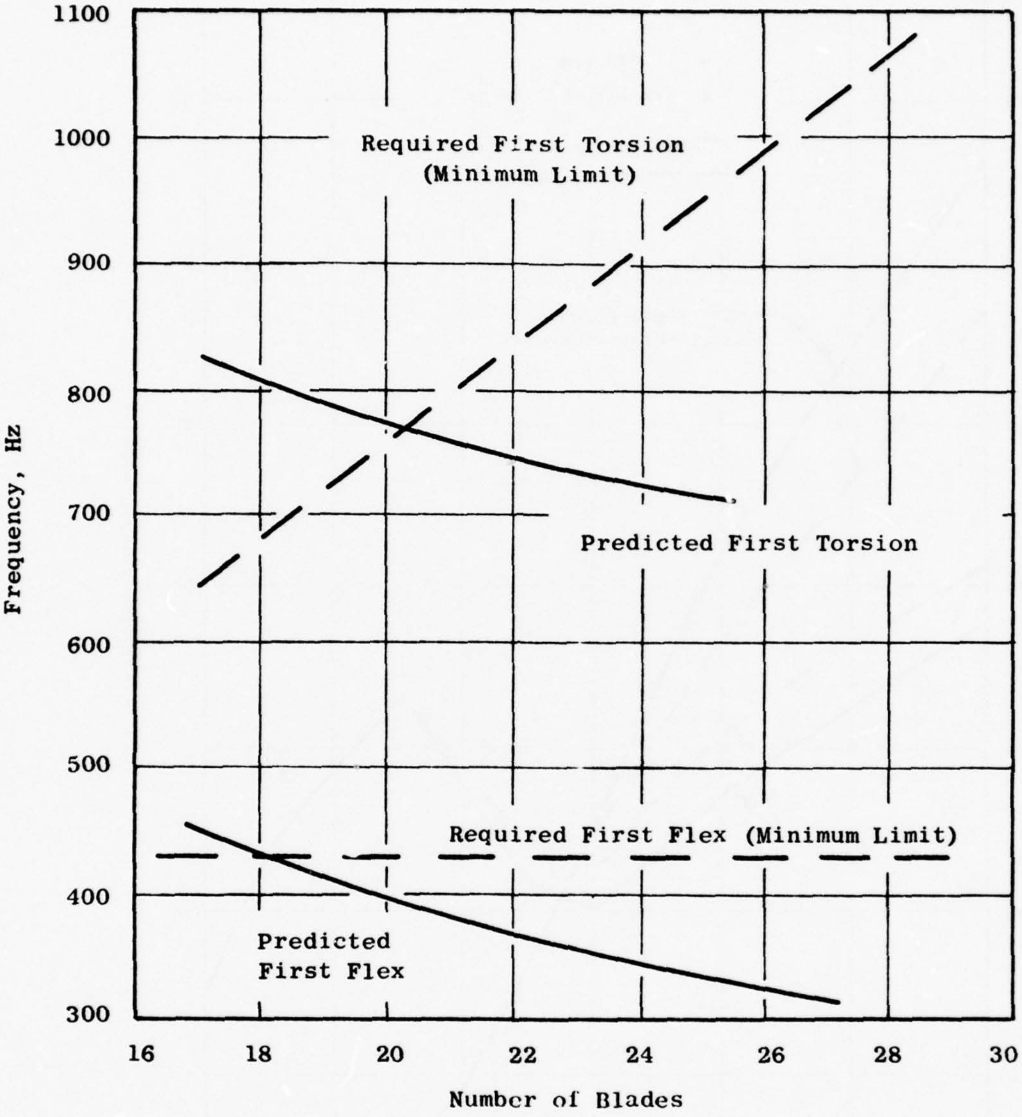

Figure 15. Predicted Vs. Required Frequencies for Supersonic-Flight Fan Rotor with Shrouded Boron/Polyimide Blades.

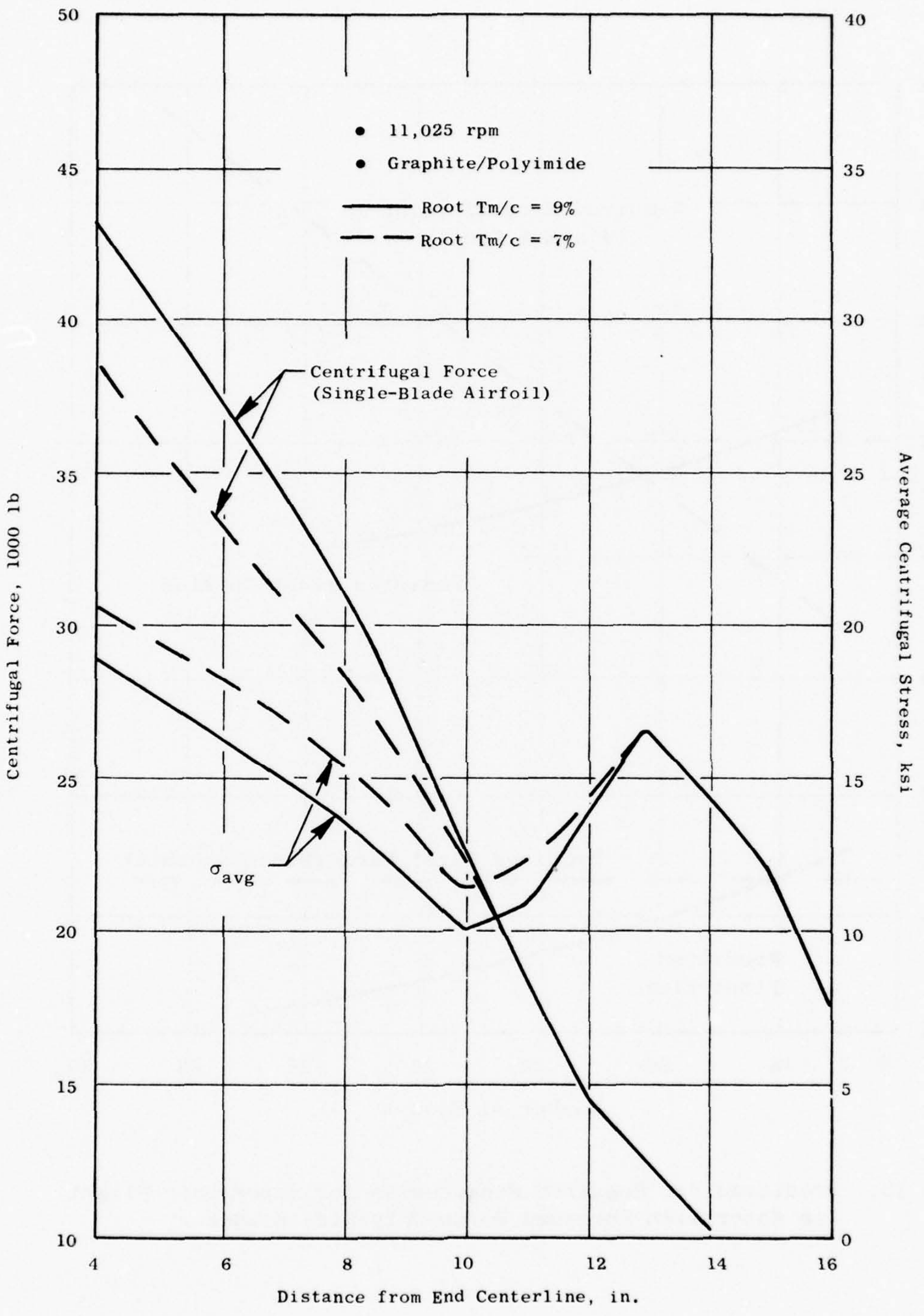

Figure 16. Airfoil Centrifugal Force and Stress Vs. Span for a Shrouded 24-Blade Stage of the Supersonic-Flight Fan Rotor.

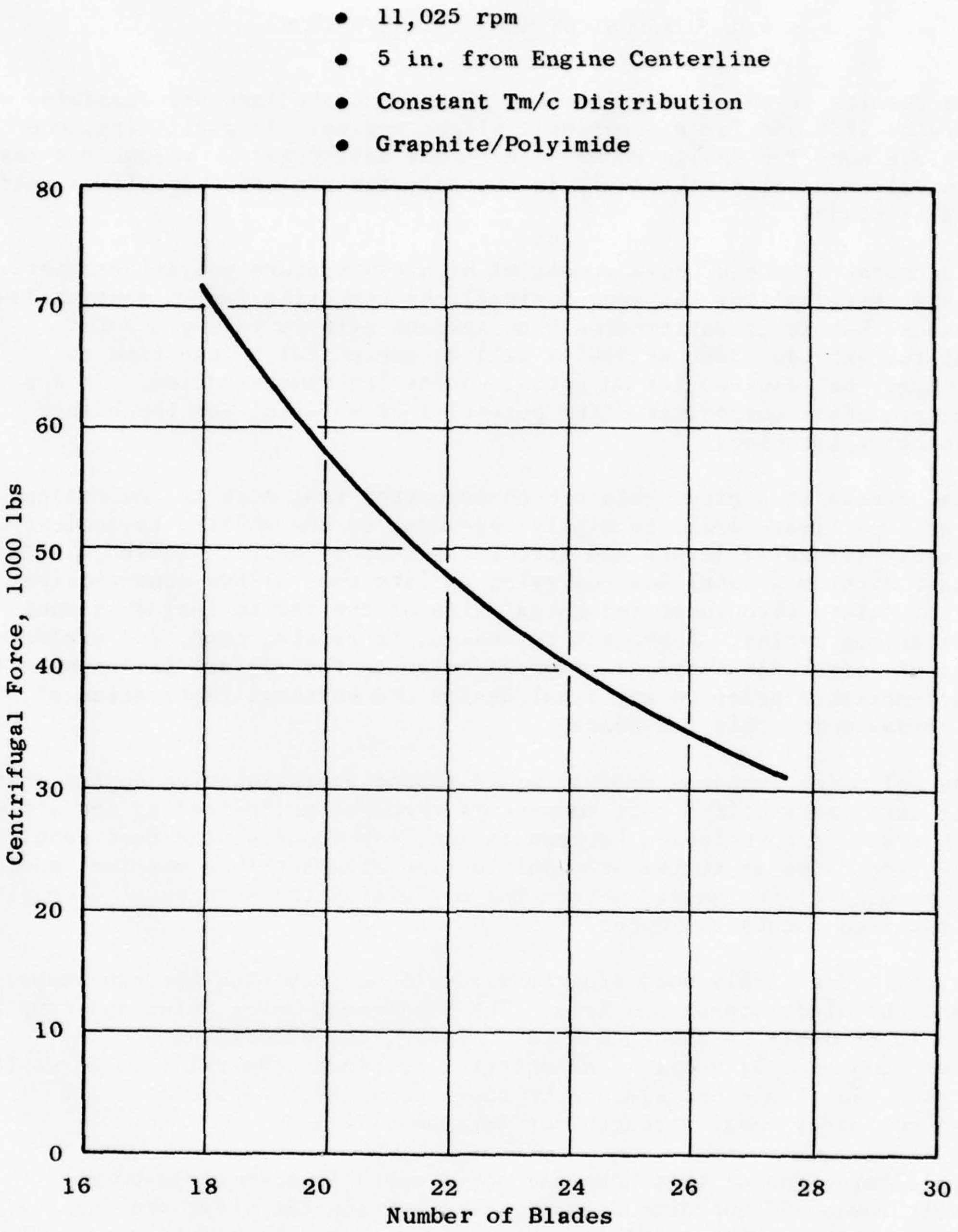

Figure 17. Airfoil Centrifugal Force Vs. Number of Blades for a Shrouded, Supersonic-Flight Fan Rotor.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The results of this study indicate that composite fans are feasible both for the TF34 and for a supersonic-flight engine. In particular, the pinned-blade/hoop fan design shows significant advantages in weight and cost over equivalent metal fans, and it is the only fan evolved that offers readily replaceable blades.

The current state of development of high-temperature polyimide materials is somewhat marginal for the supersonic-flight composite fan at maximum dash performance, but it is anticipated that current efforts to upgrade this material for extended life at 550° F will be successful by the time the polyimide may be required for an actual-engine fan demonstration. In any case, metal-matrix composites offer potential as material for the higher temperature applications.

The success of a pinned-blade/hoop-supported fan, such as the concept illustrated on Figure A-25, is highly dependent on the ability to achieve consistently effective joints and structural support hoops. These joints and hoops must display a total load-carrying ability that allows conservative margins of safety throughout the normal life of the engine including over 20,000 start-up cycles. A program to design, fabricate, test, and evaluate a series of joints and hoops is proposed below as the logical follow-on effort to be accomplished prior to any final design and eventual fabrication of actual hardware for this fan concept.

The following proposed program would impose representative engine environments onto the specific test components through cyclic-loading and ultimate-strength test. A correlation between design, fabrication, and test results would be plotted so as to isolate contributing elements in a way that would provide meaningful design parameters for optimizing the structural integrity of the required joints and hoops.

Initially, a single hoop program may well satisfy both the hub-support hoops and the blade-tip-shroud hoop. The blade-root shear joint and tang/hoop joint could probably be combined into a simple, two-dimensional, joint-test coupon. By varying the material sections, the relative strengths of the shear joint and the blade-root tangs could each be isolated and tailored to nearly equal strength for maximum efficiency.

The culmination of this hoop and joint investigation could be a relatively low-cost, two-dimensional, spin-test specimen representing the final fan structure with the full number of simulated blades (Figure A-28). This two-dimensional demonstrator would isolate the sructural dynamics of the fan, but it would require a final, three-dimensional, aerodynamic fan to verify the integrity before it could be deemed acceptable for an actual engine demonstration.

The hoop program would consider such variables as types of fibers and binders, fiber modulus, winding tension and angle, ratio of fiber to binder, cure and postcure cycles, fiber-bundle count, and the possible stratification of different fibers and fiber moduli as hoop thickness increases. Also to be explored would be the prospect of winding clustered hoops into long cylinders, similar to pressure vessels or rocket cases, and then cutting the individual hoops therefrom to reduce cost and improve hoop uniformity and fiber efficiency.

A demonstrated high degree of hoop efficiency and structural integrity may open doors to invention in other areas of engine technology with payoffs even beyond the scope of this particular program, such as FOD containment, possible compression-structured ceramic turbines, and composite frames.

The effect of a tip shroud on fan aerodynamic performance and stall margin is not known and may require a fan aerodynamic test to determine the influence.

The near-term prospects of utilizing polyimide materials in the first compressor stage of a supersonic-flight engine are not favorable because maximum temperatures in that area could exceed 600° F (which currently is beyond the limits for polyimide materials). This temperature, however, is within the limits of metal-matrix composites such as boron/aluminum.

Environmental Impact - No adverse environmental consequences are foreseen either from the development of these fans or from future scale-up to production quantities of such fans.

APPENDIX A. ILLUSTRATIONS OF TF34 AND SUPERSONIC-FLIGHT ROTOR CONCEPTS.

This appendix contains figures representing the following General Electric, Aircraft Engine Group drawings:

Figure	GE Drawing No.
A-1	4013057-814
A-2	4013057-909
A-3	4013057-812
A-4	4013057-815
A-5	4013057-816
A-6	4013057-901
A-7	4013057-903
A-8	4013057-908
A-9	4013057-913
A-10	4013057-915
A-11	4013057-916
A-12	4013057-911
A-13	4013057-912
A-14	4013057-817
A-15	4013057-904
A-16	4013057-905
A-17	4013057-910
A-18	4013057-902
A-19	4013057-906
A-20	4013057-907
A-21	4013057-917
A-22	4013057-920
A-23	4013057-918
A-24	4013057-919
A-25	4013057-925
A-26	4013057-958
A-27	4013057-922
A-28	4013057-946
A-29	4013057-921
A-30	4013057-938
A-31	4013057-914

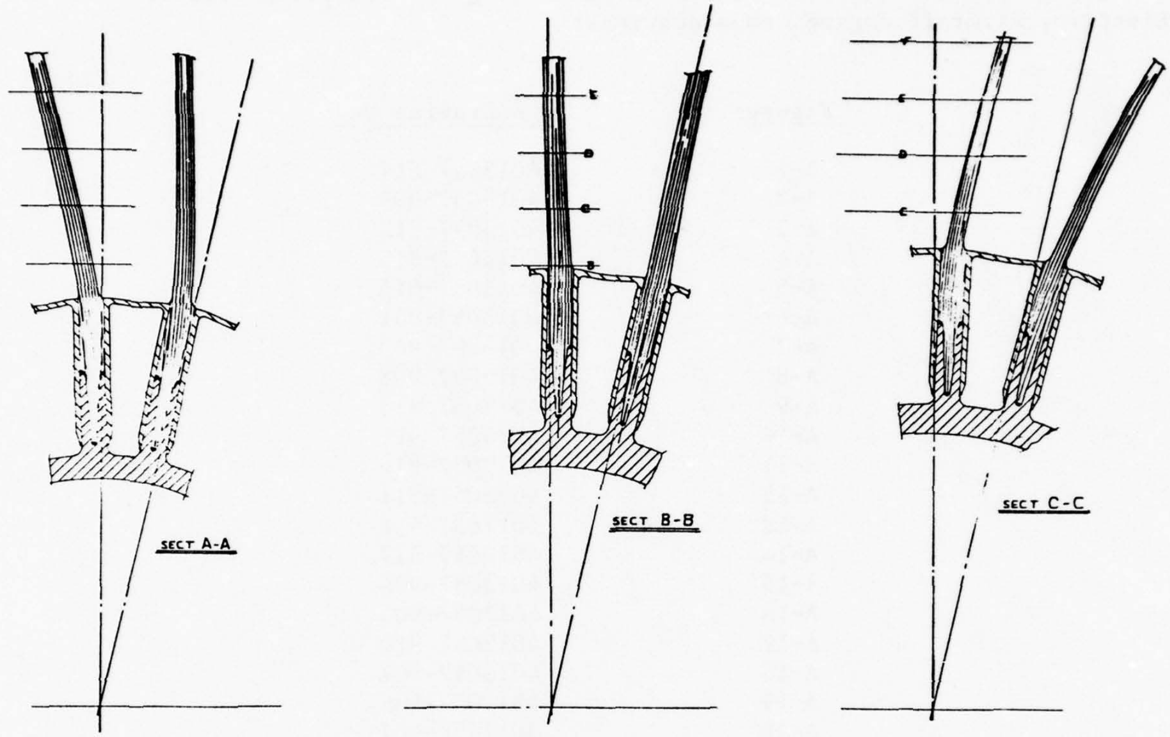

Figure A-1. TF34 Composite Blisk: Double Lap Shear Design.

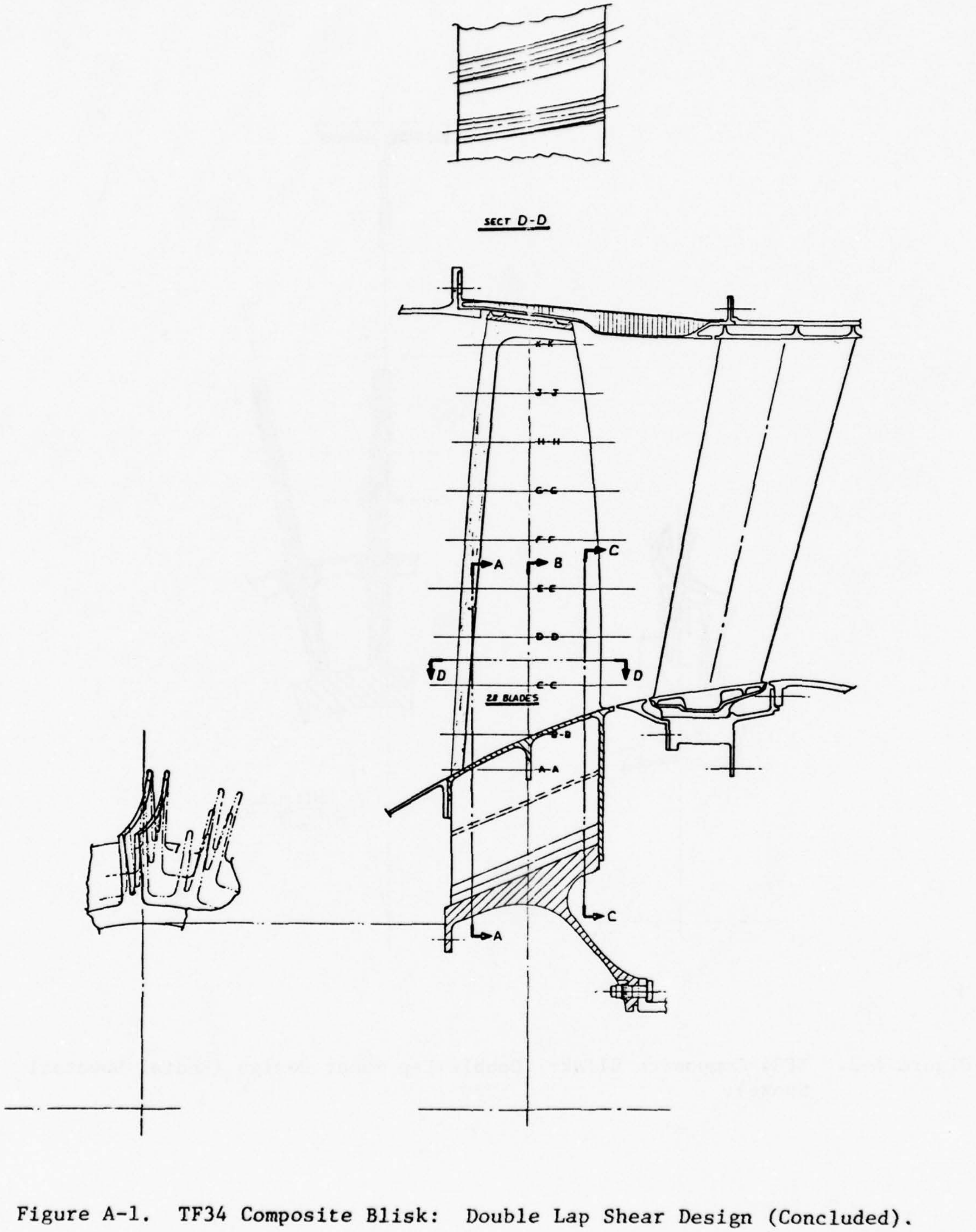

Figure A-1. TF34 Composite Blisk: Double Lap Shear Design (Concluded).

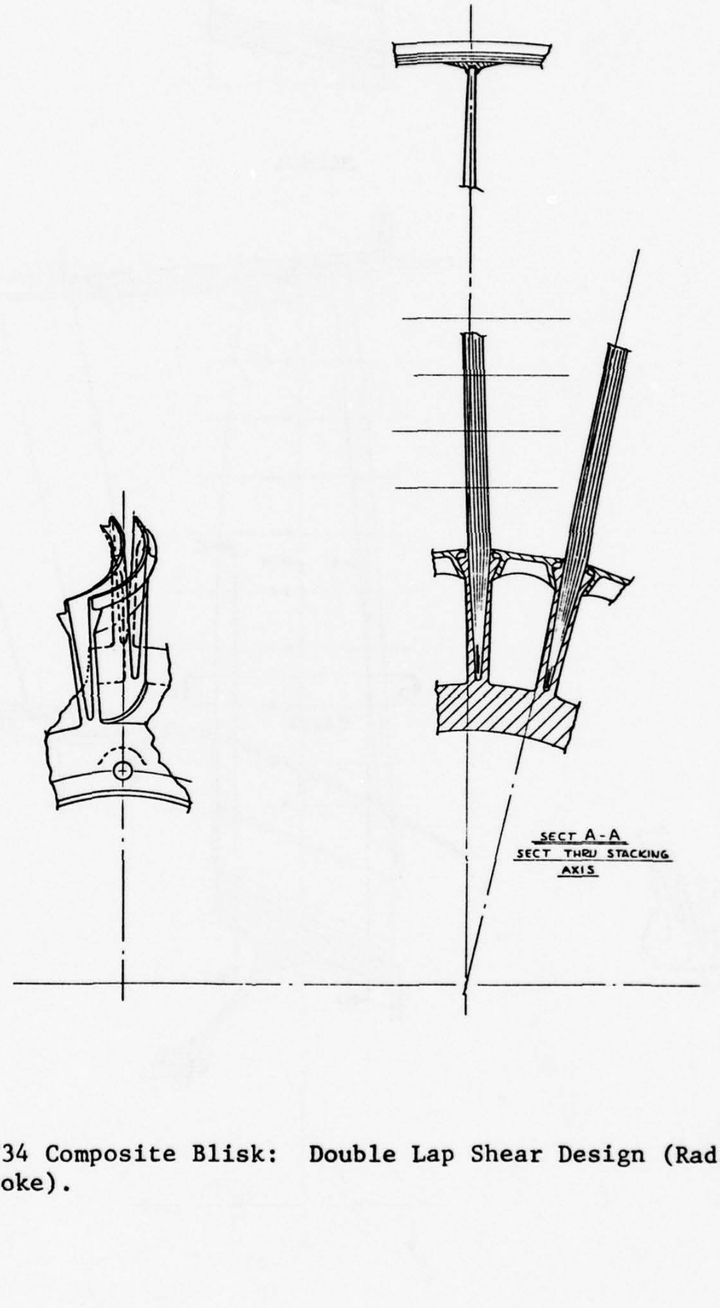

Figure A-2. TF34 Composite Blisk: Double Lap Shear Design (Radial Dovetail Spoke).

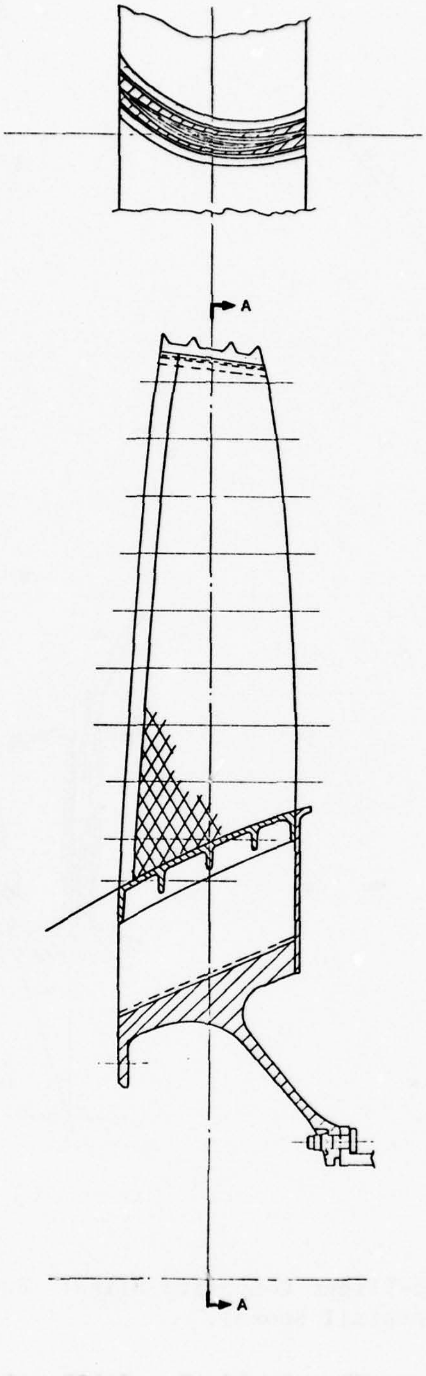

Figure A-2. TF34 Composite Blisk: Double Lap Shear Design (Radial Dovetail Spoke) (Concluded).

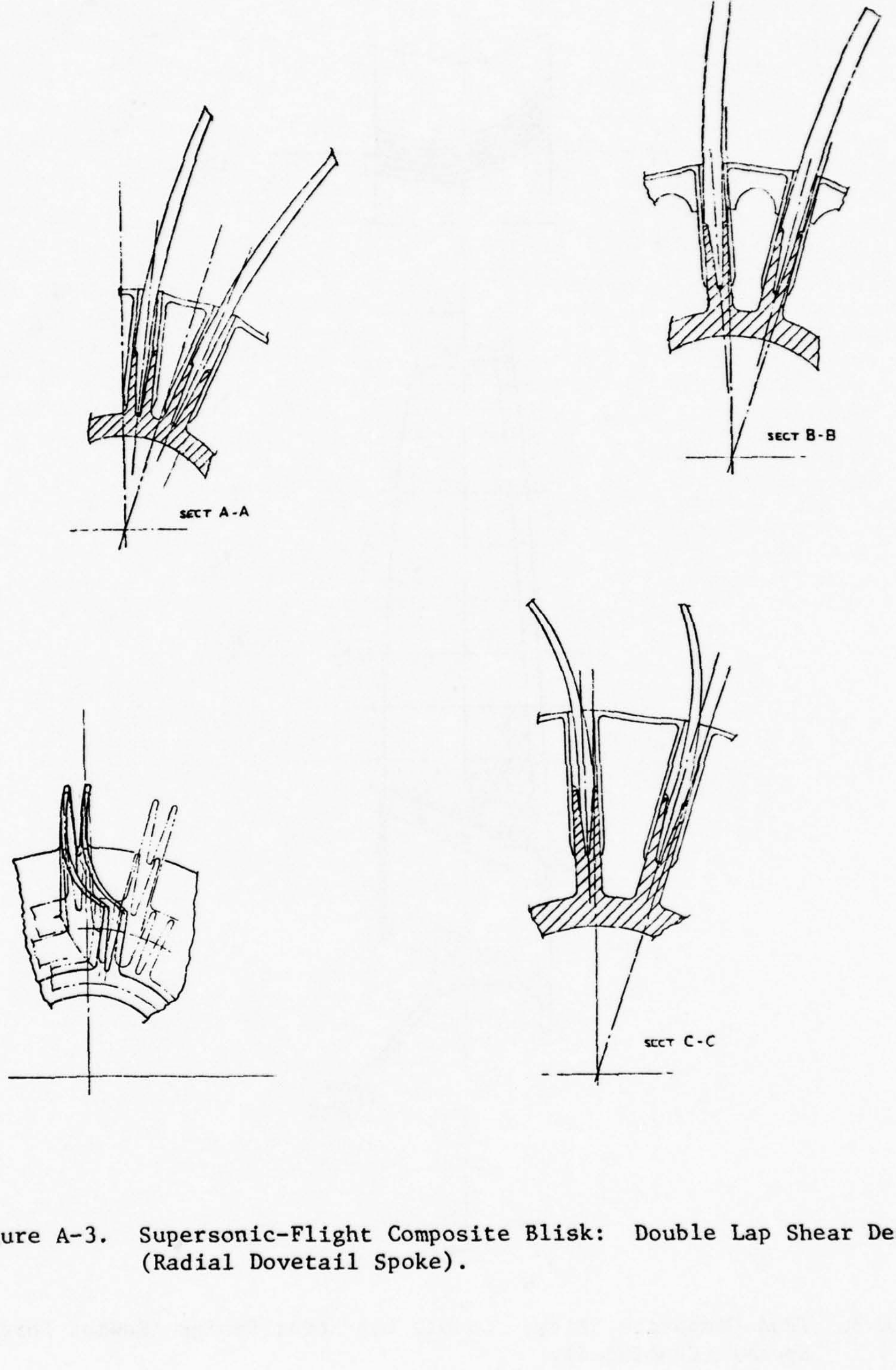

Figure A-3. Supersonic-Flight Composite Blisk: Double Lap Shear Design (Radial Dovetail Spoke).

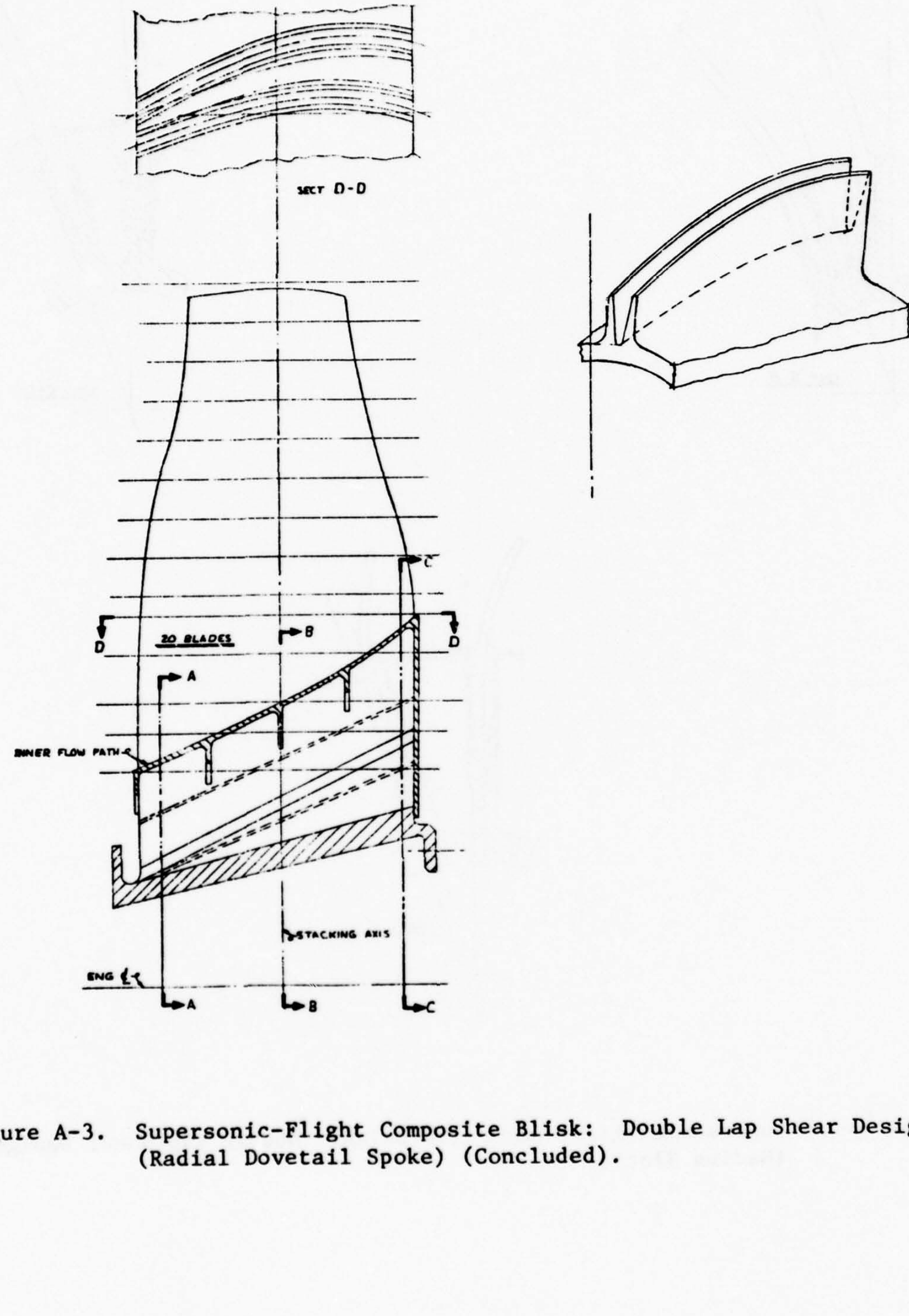

Figure A-3. Supersonic-Flight Composite Blisk: Double Lap Shear Design (Radial Dovetail Spoke) (Concluded).

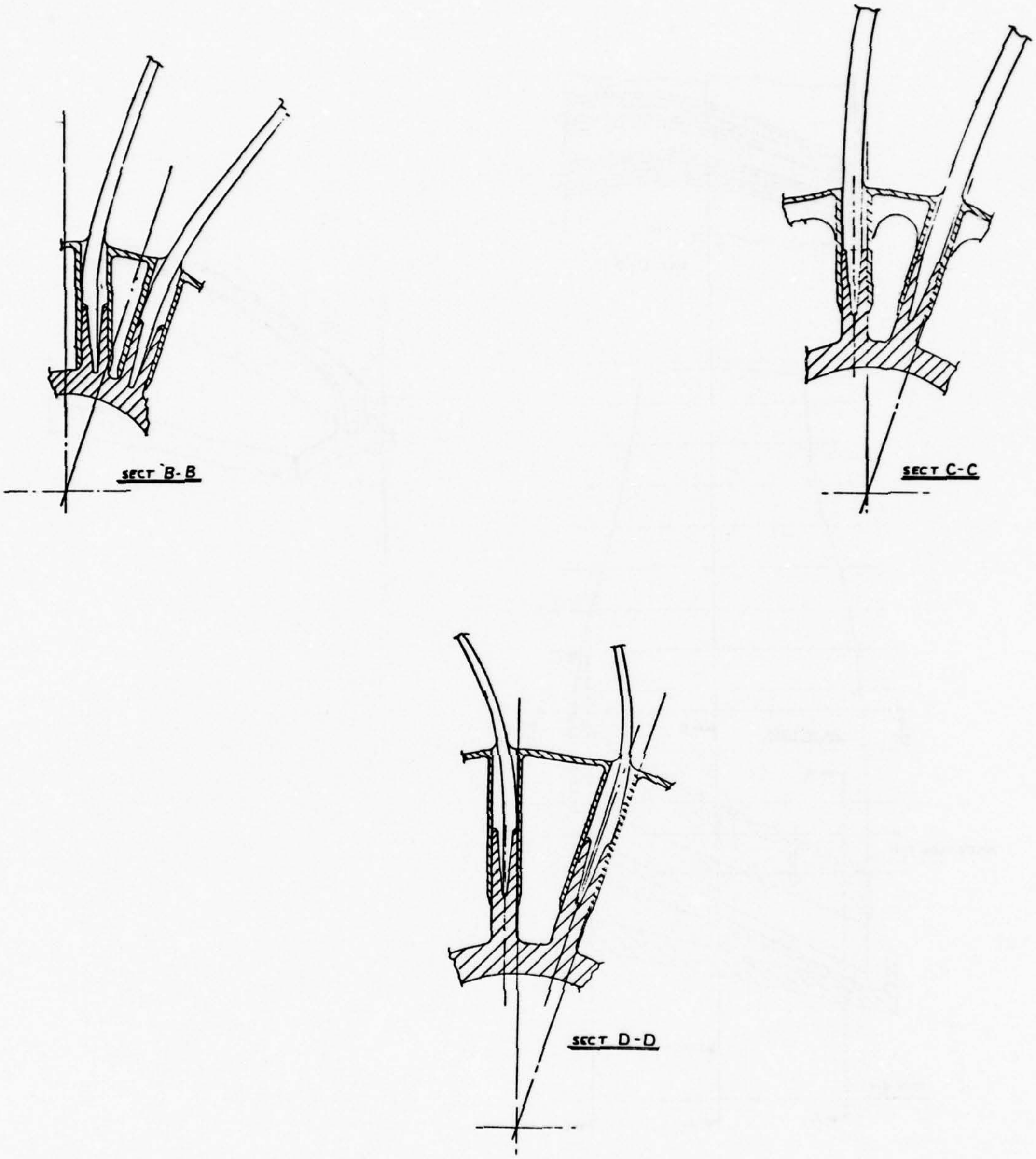

Figure A-4. Supersonic-Flight Composite Blisk: Double Lap Shear Design (Radius Slot).

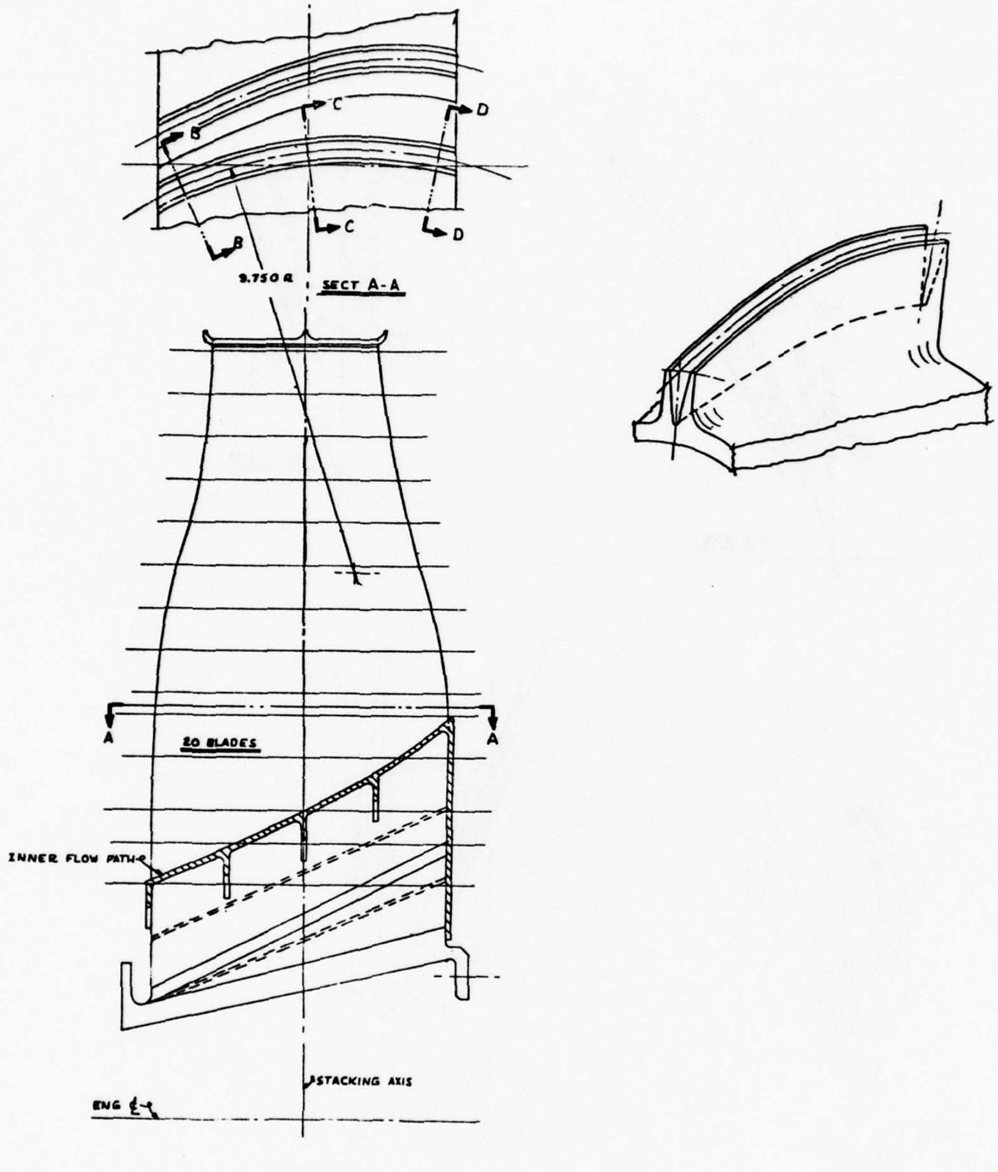

Figure A-4. Supersonic-Flight Composite Blisk: Double Lap Shear Design (Radius Slot) (Concluded).

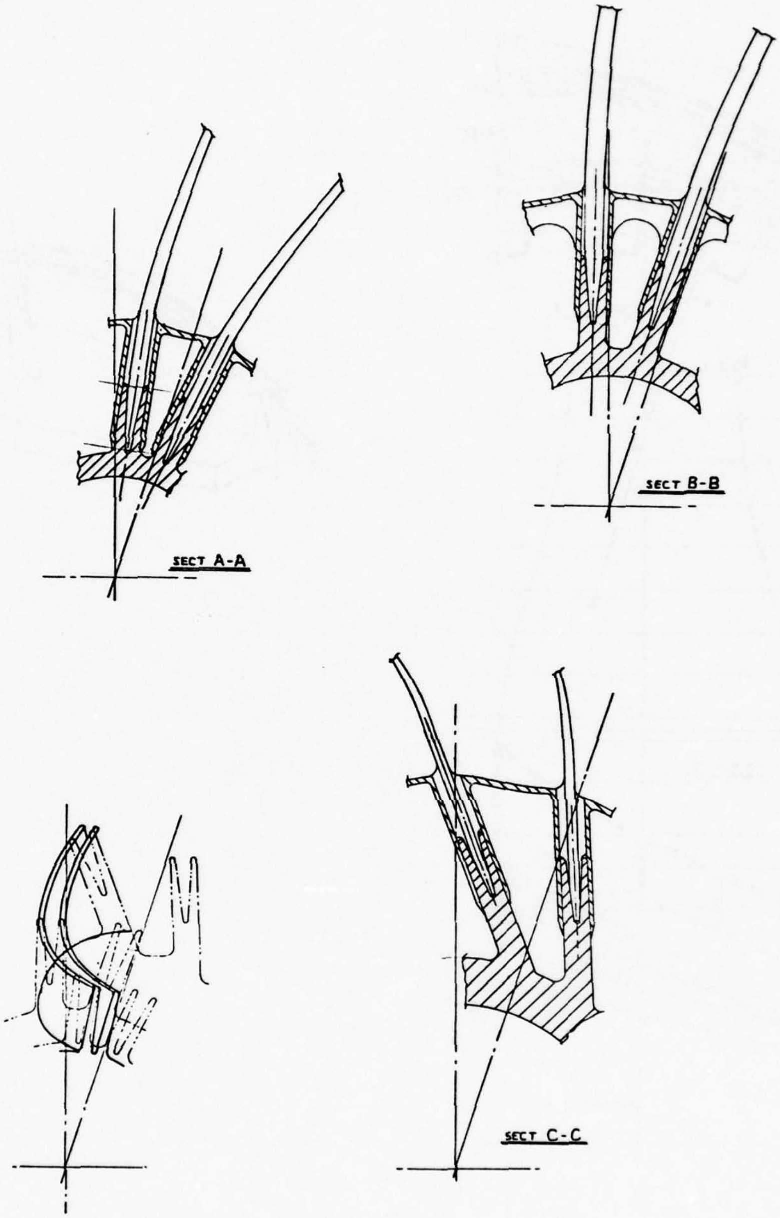

Figure A-5. Supersonic-Flight Composite Blisk: Double Lap Shear, Low-Blade-Stress Design.

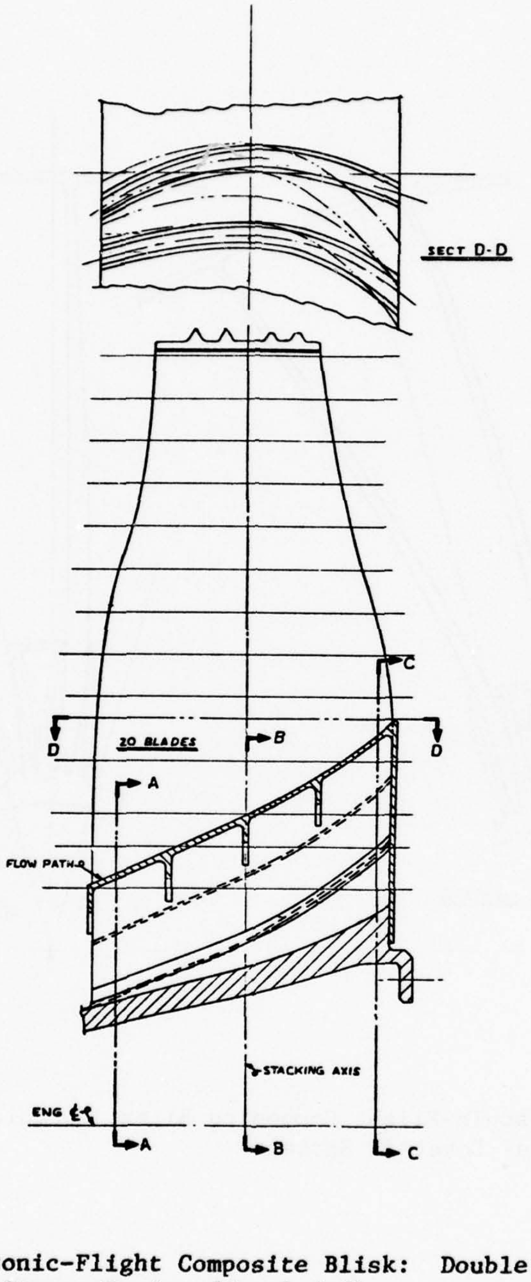

Figure A-5. Supersonic-Flight Composite Blisk: Double Lap Shear, Low-Blade-Stress Design (Concluded).

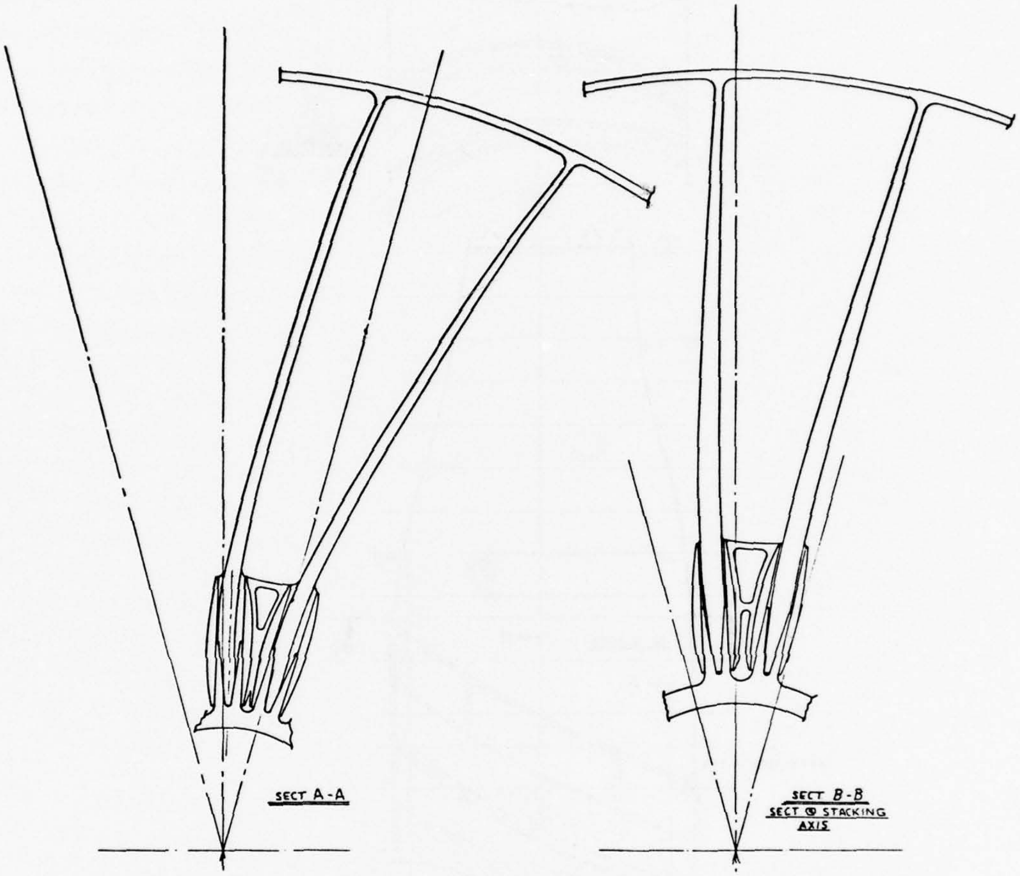

Figure A-6. Supersonic-Flight Composite Blisk: Double Lap Shear Design (Radial Dovetail Spoke).

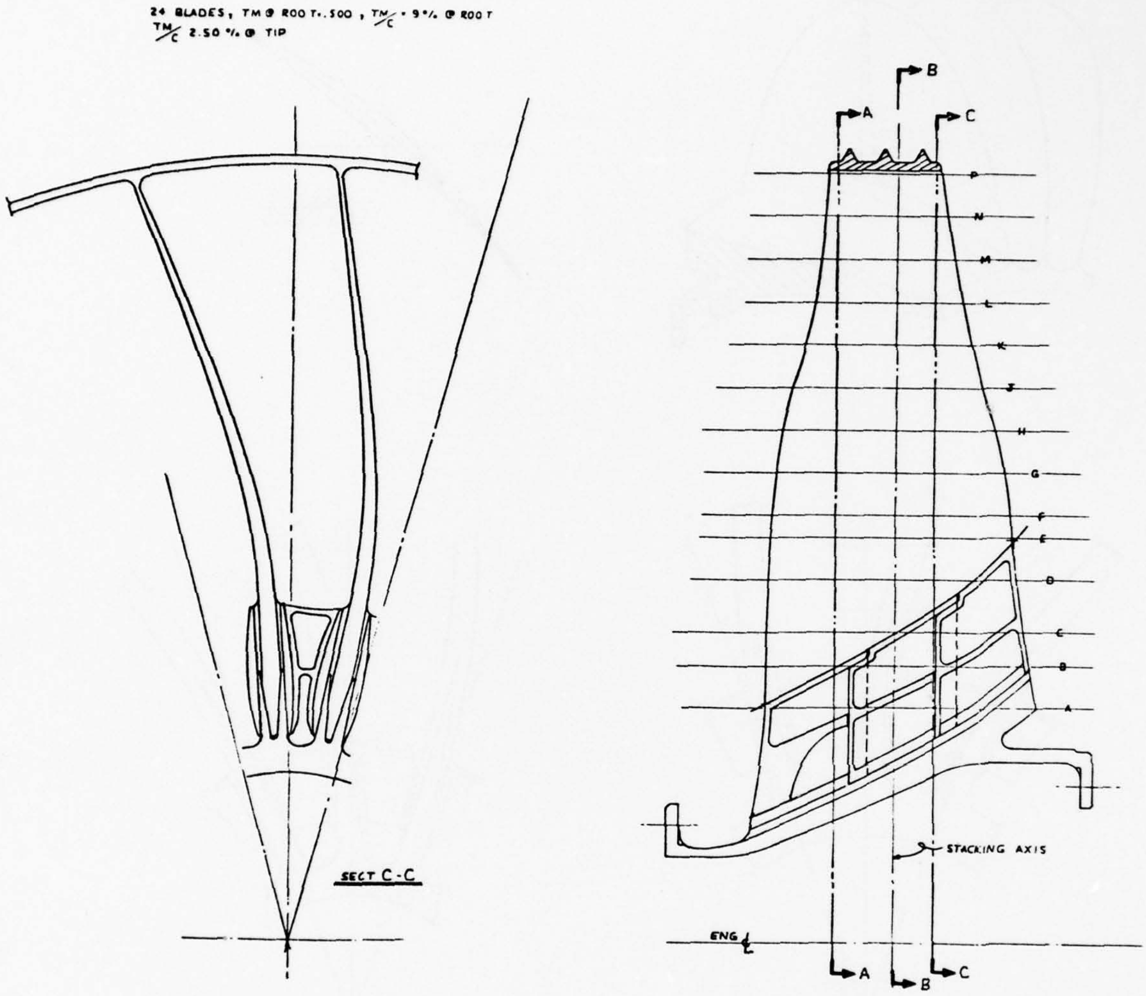

Figure A-6. Supersonic-Flight Composite Blisk: Double Lap Shear Design (Radial Dovetail Spoke) (Concluded).

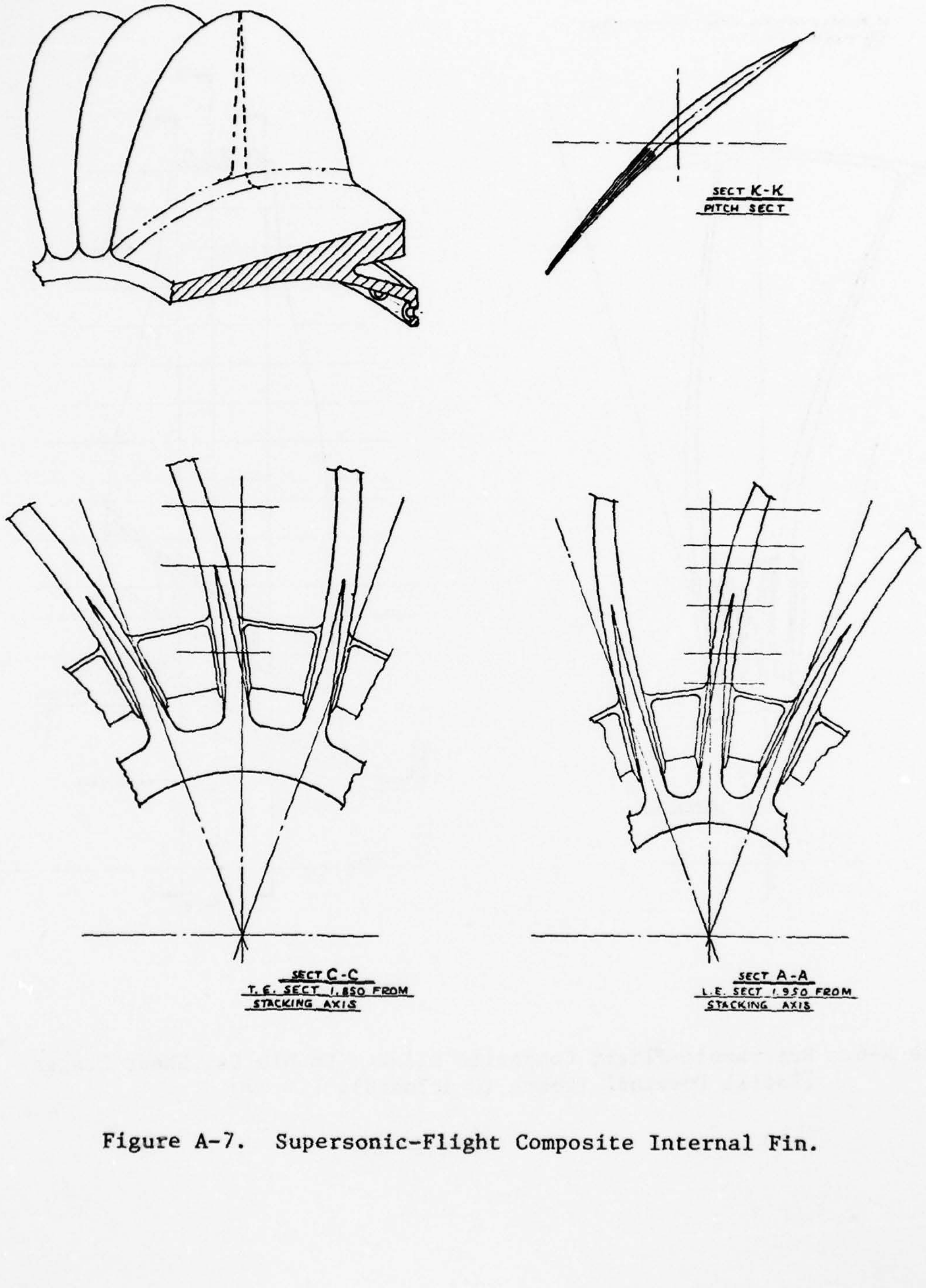

Figure A-7. Supersonic-Flight Composite Internal Fin.

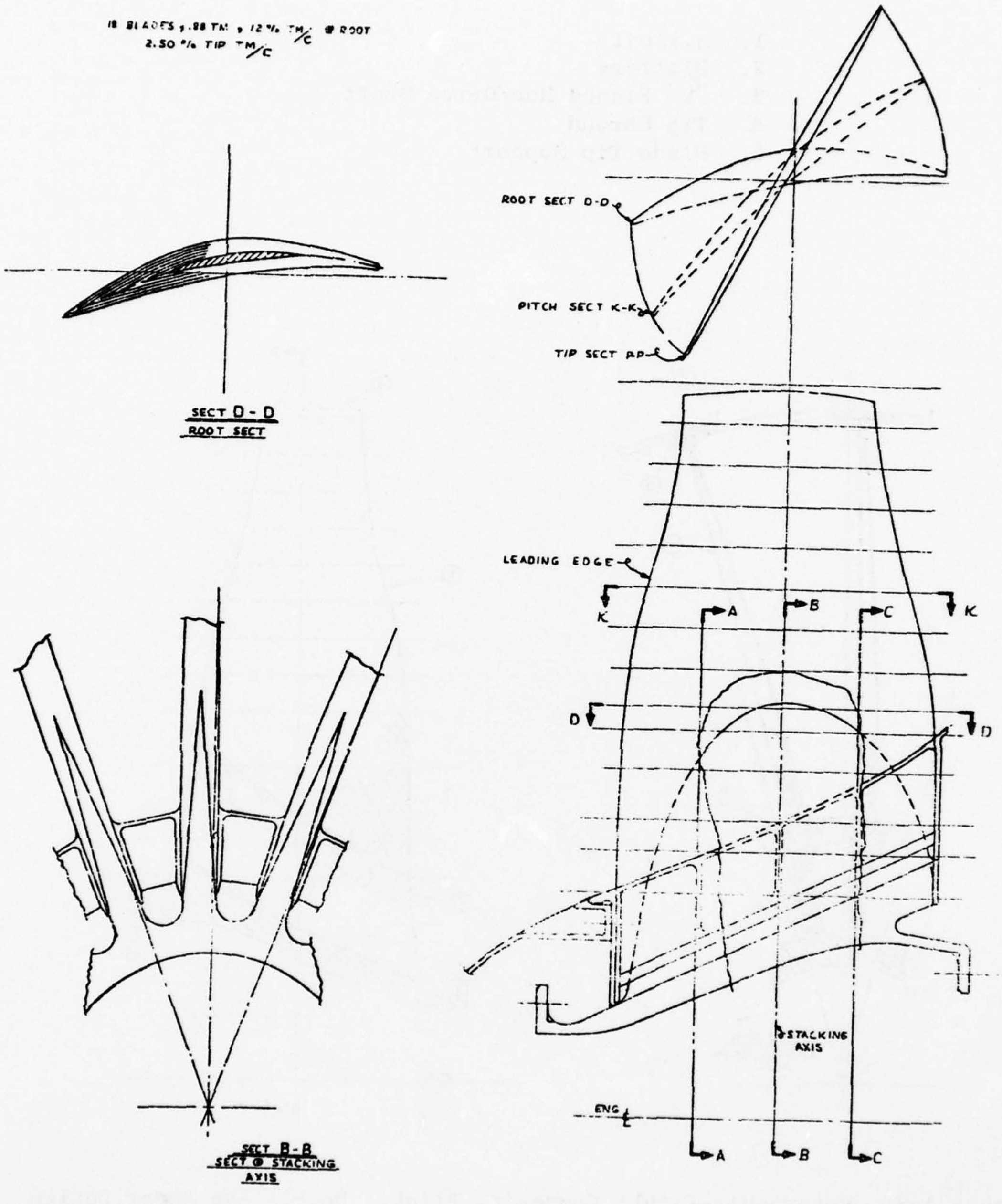

Figure A-7. Supersonic-Flight Composite Internal Fin (Concluded).

1. Airfoil
2. Platform
3. "V" Finned Hub/Drive Shaft
4. Tip Shroud
5. Blade Tip Support

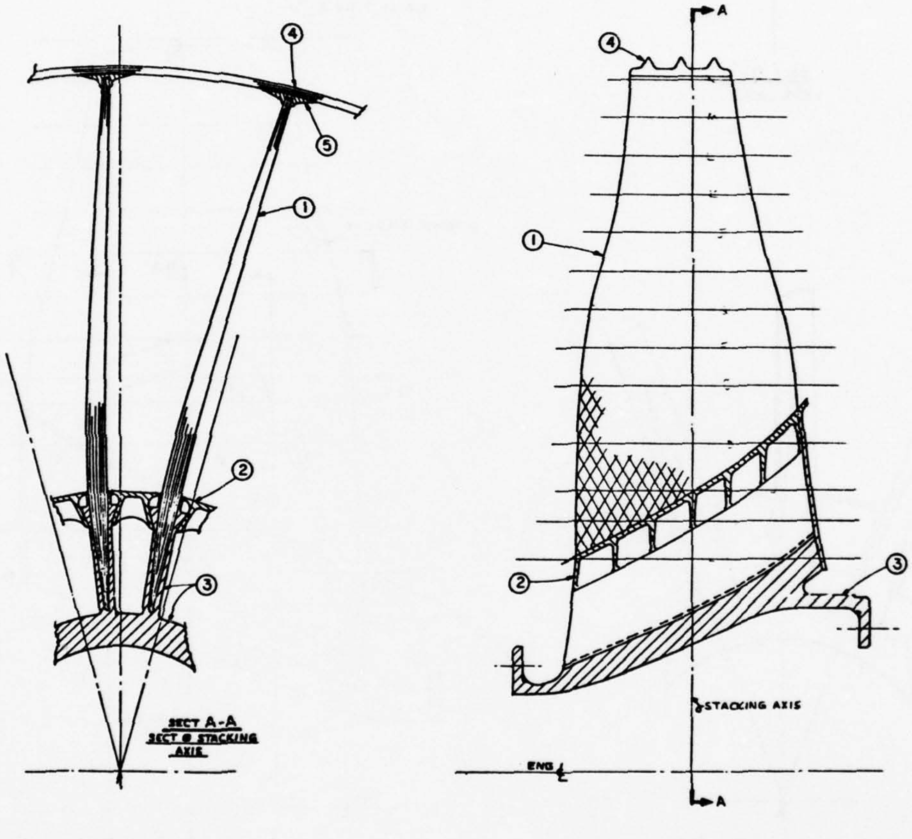

Figure A-8. Supersonic-Flight Composite Blisk: Double Lap Shear Design (Radial Dovetail Spoke).

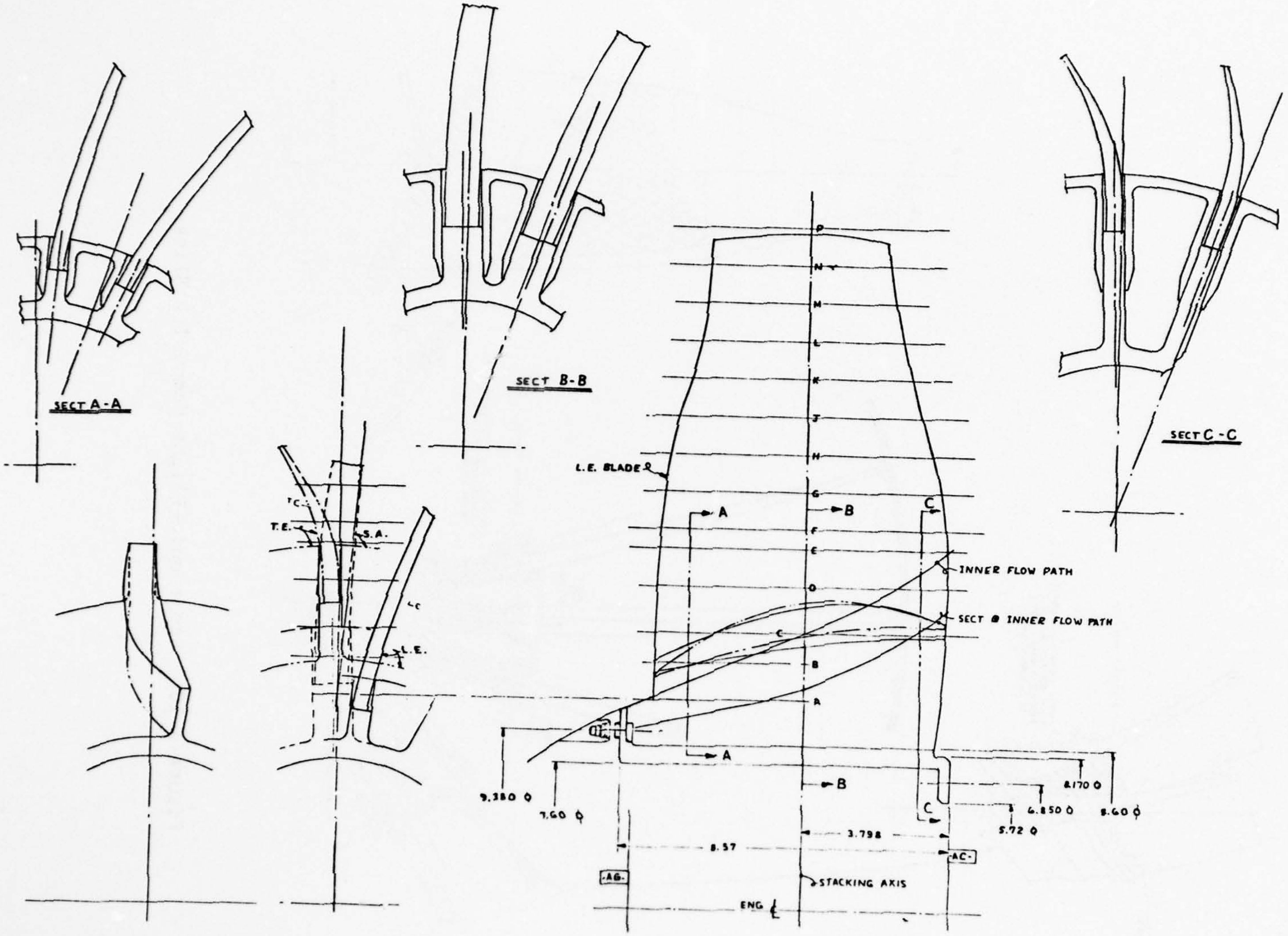

Figure A-9. Supersonic-Flight Composite Blisk: Butt Joint Design.

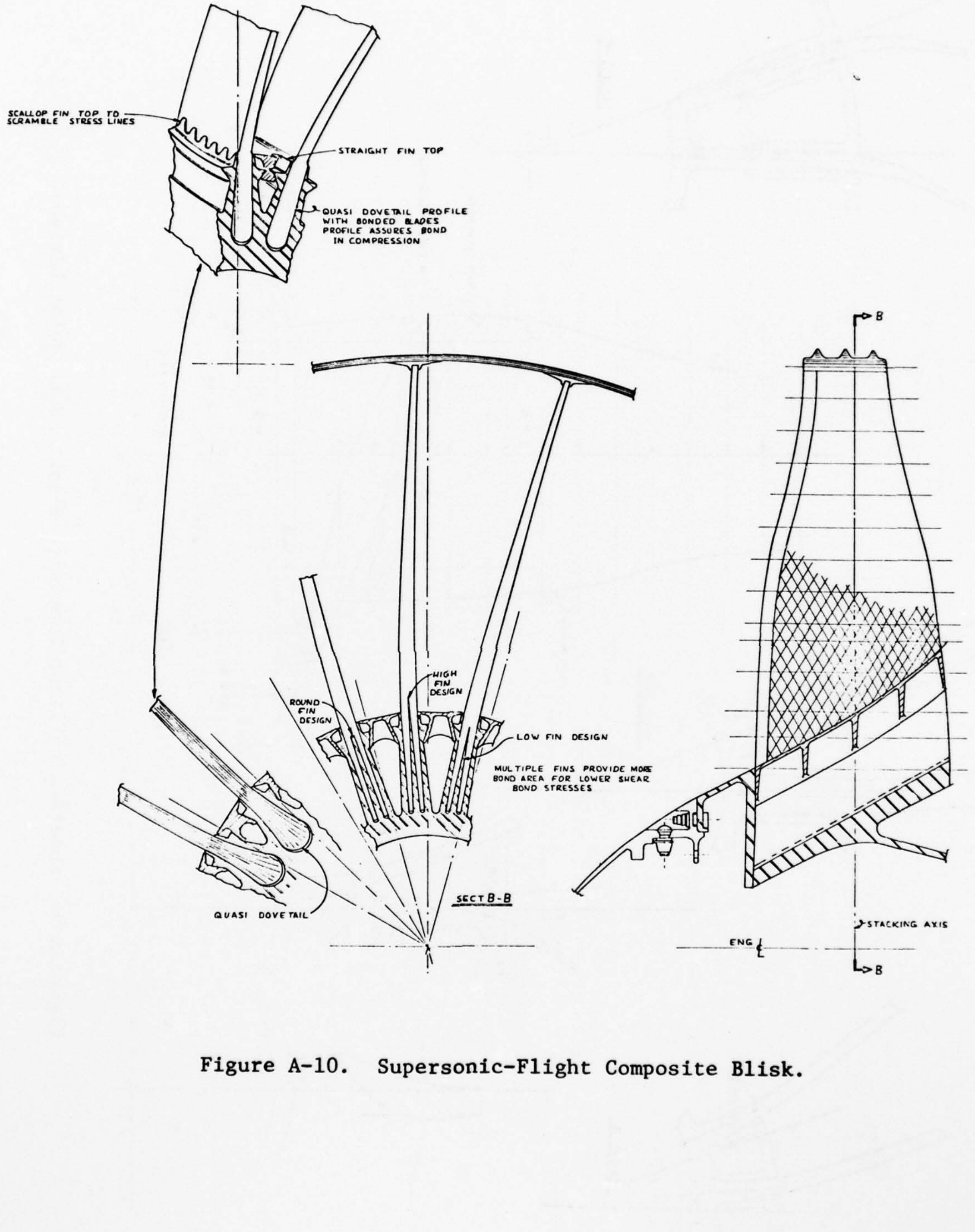

Figure A-10. Supersonic-Flight Composite Blisk.

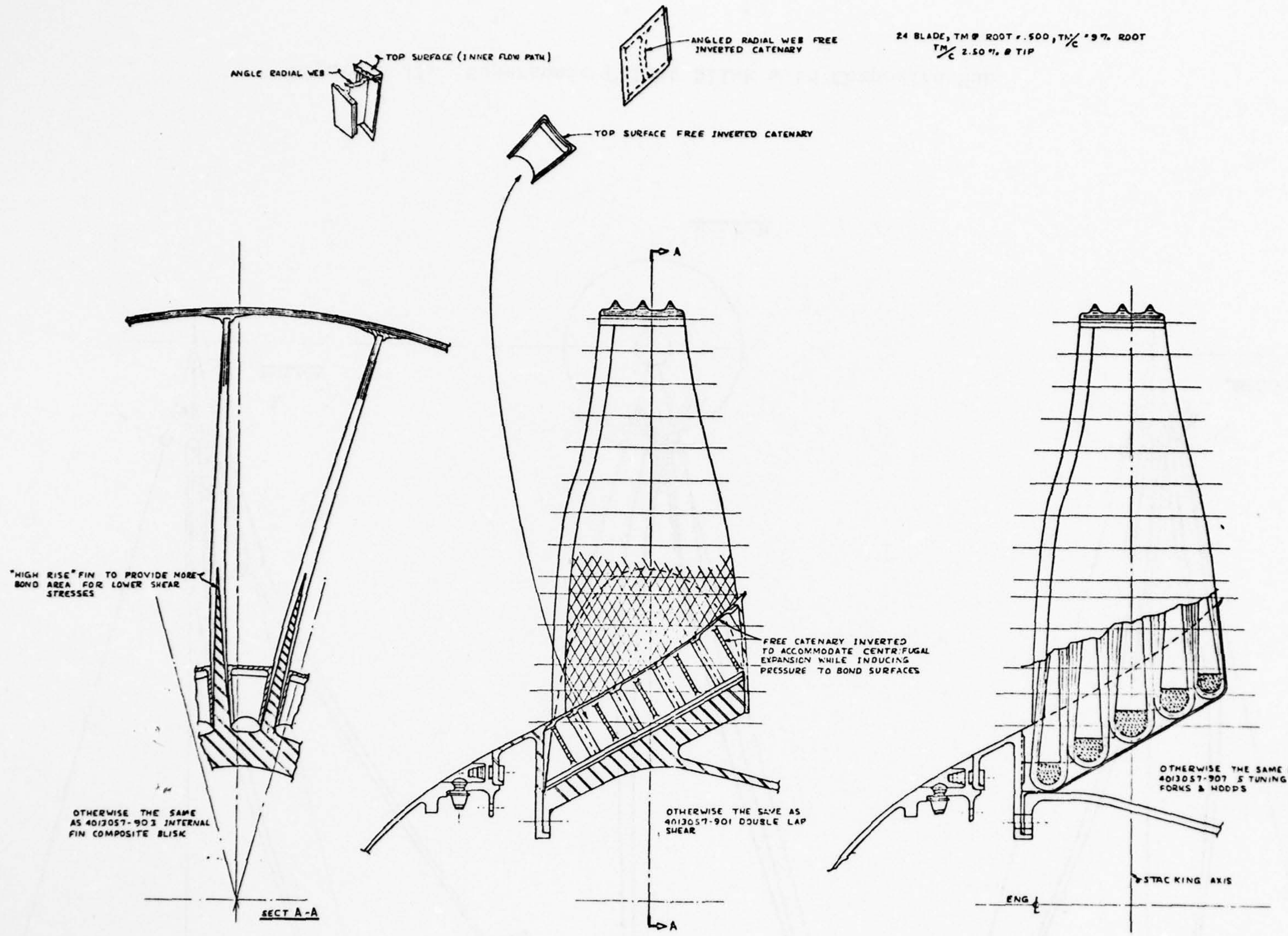

Figure A-10. Supersonic-Flight Composite Blisk (Concluded).

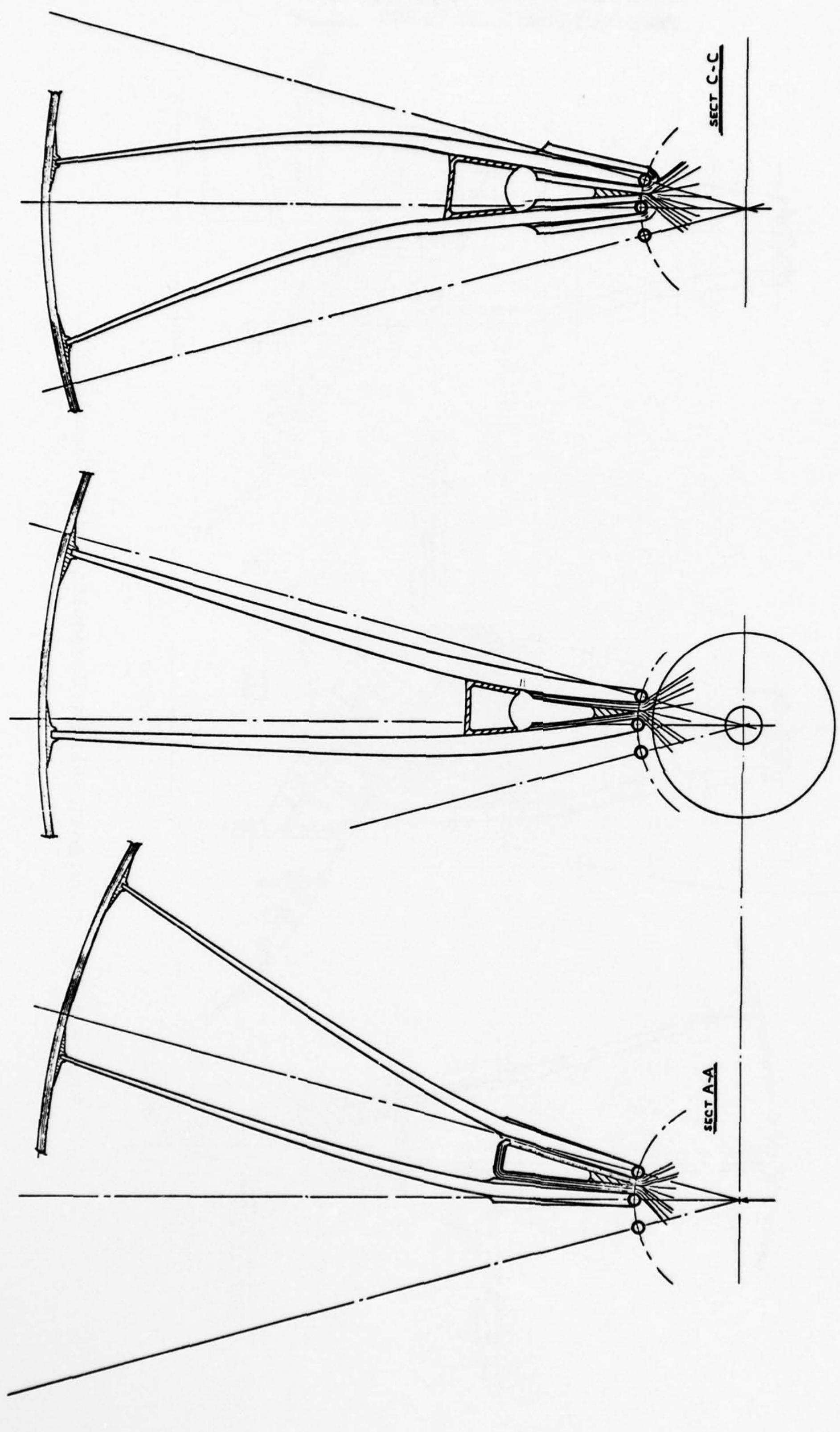

Figure A-11. Supersonic-Flight Blisk with Composite Hub.

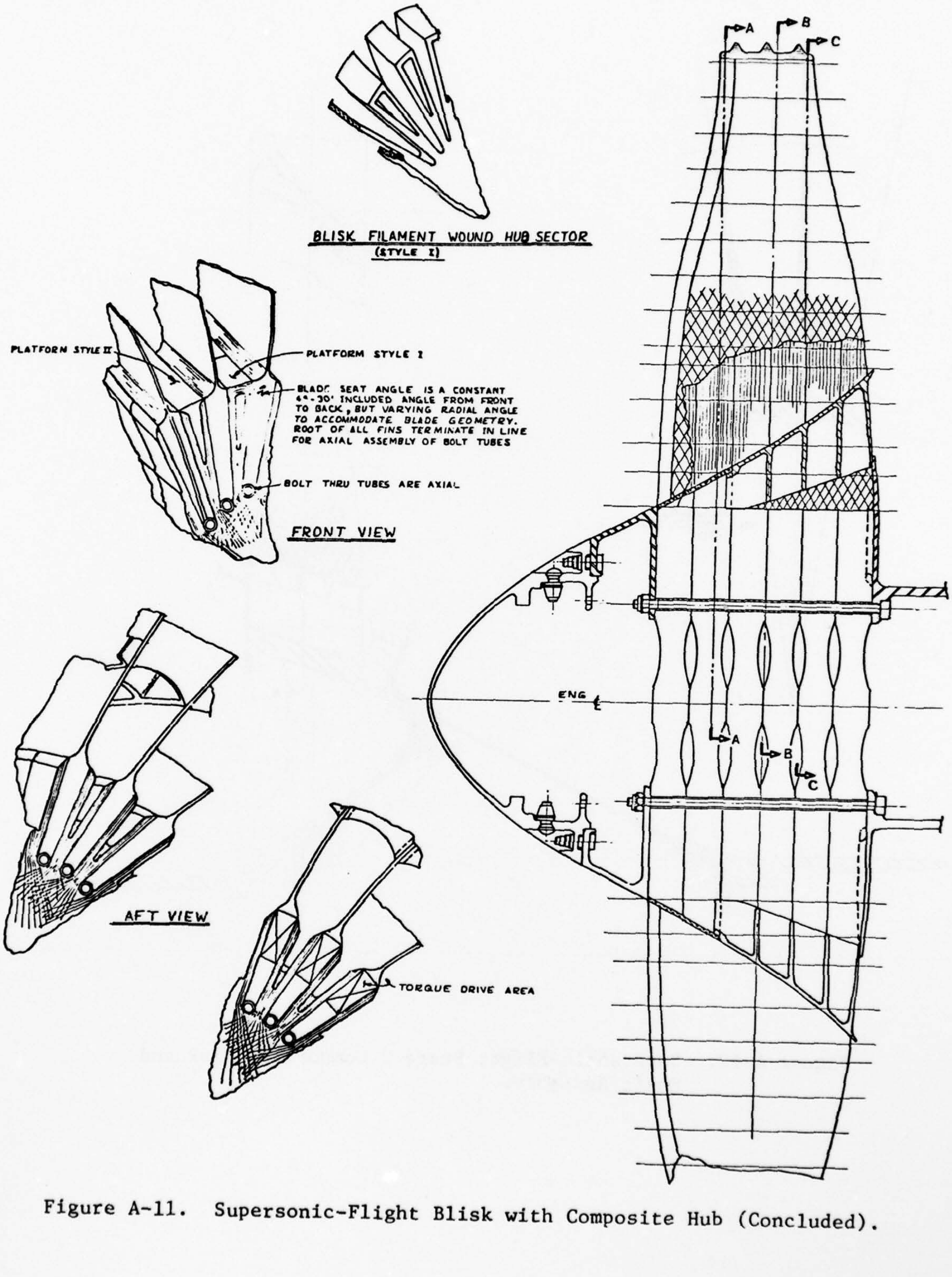

Figure A-11. Supersonic-Flight Blisk with Composite Hub (Concluded).

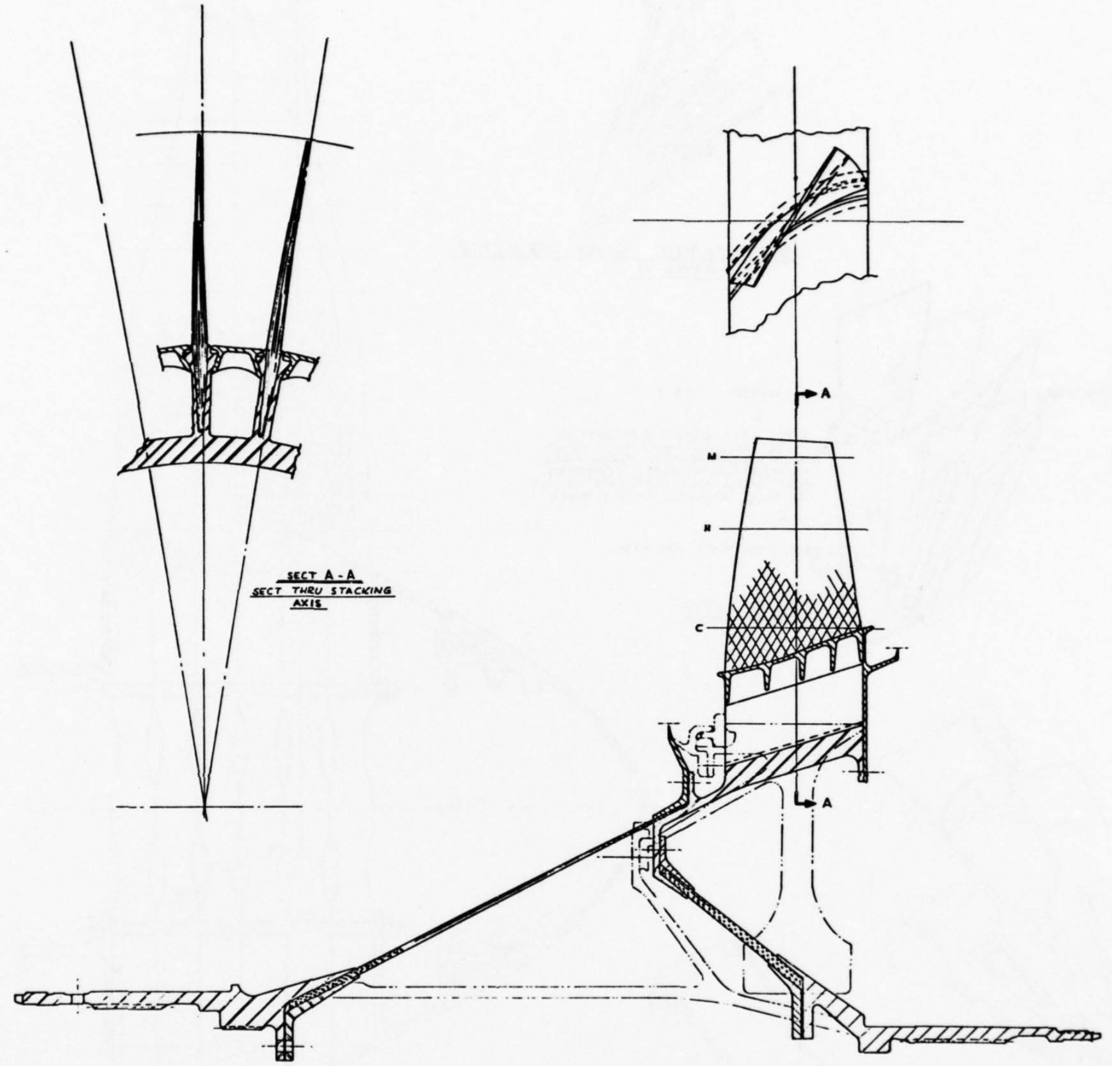

Figure A-12. Supersonic-Flight Stage 2 Composite Blisk and Shaft Assembly.

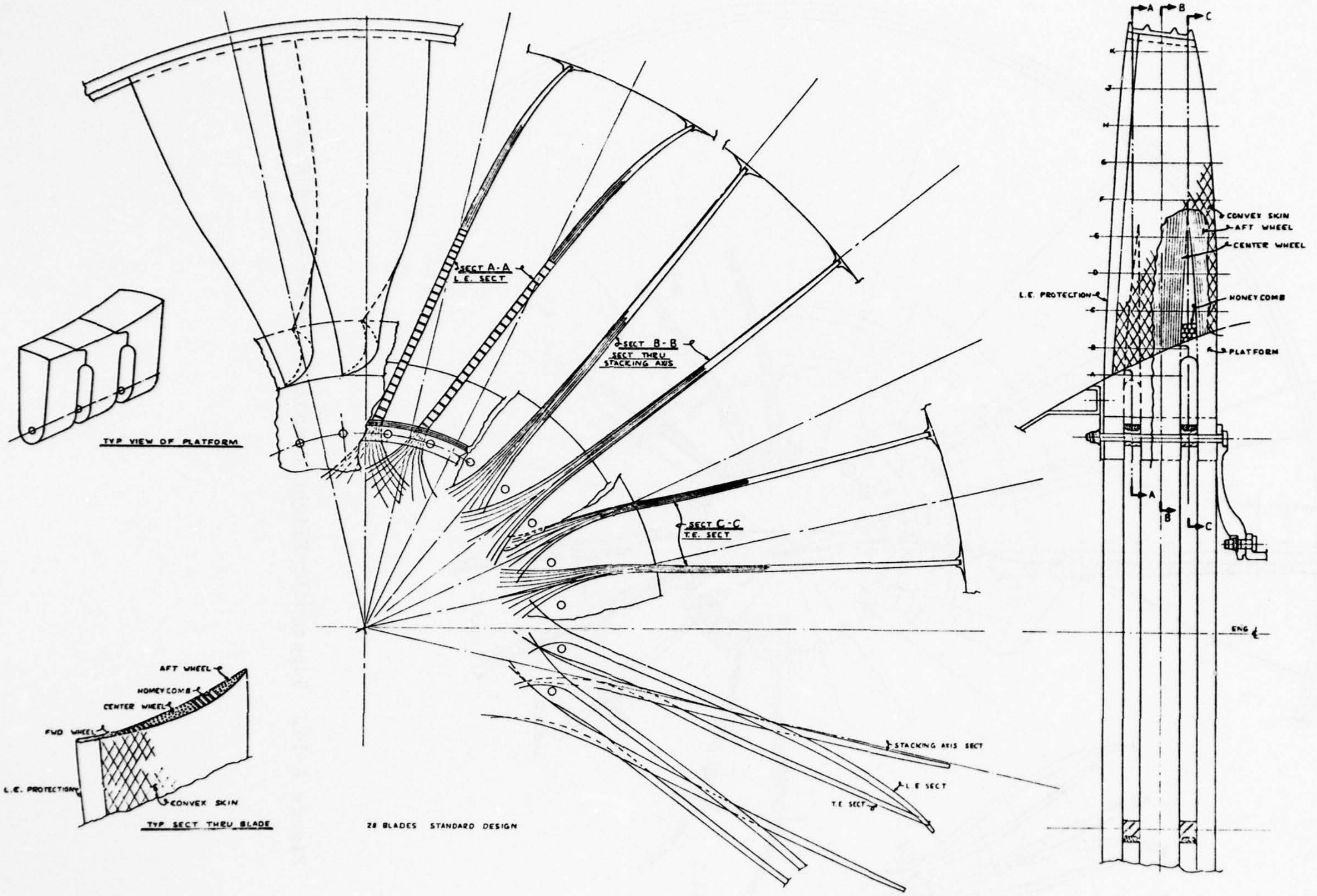

Figure A-13. TF34 Composite, Fiber-Wound Blisk.

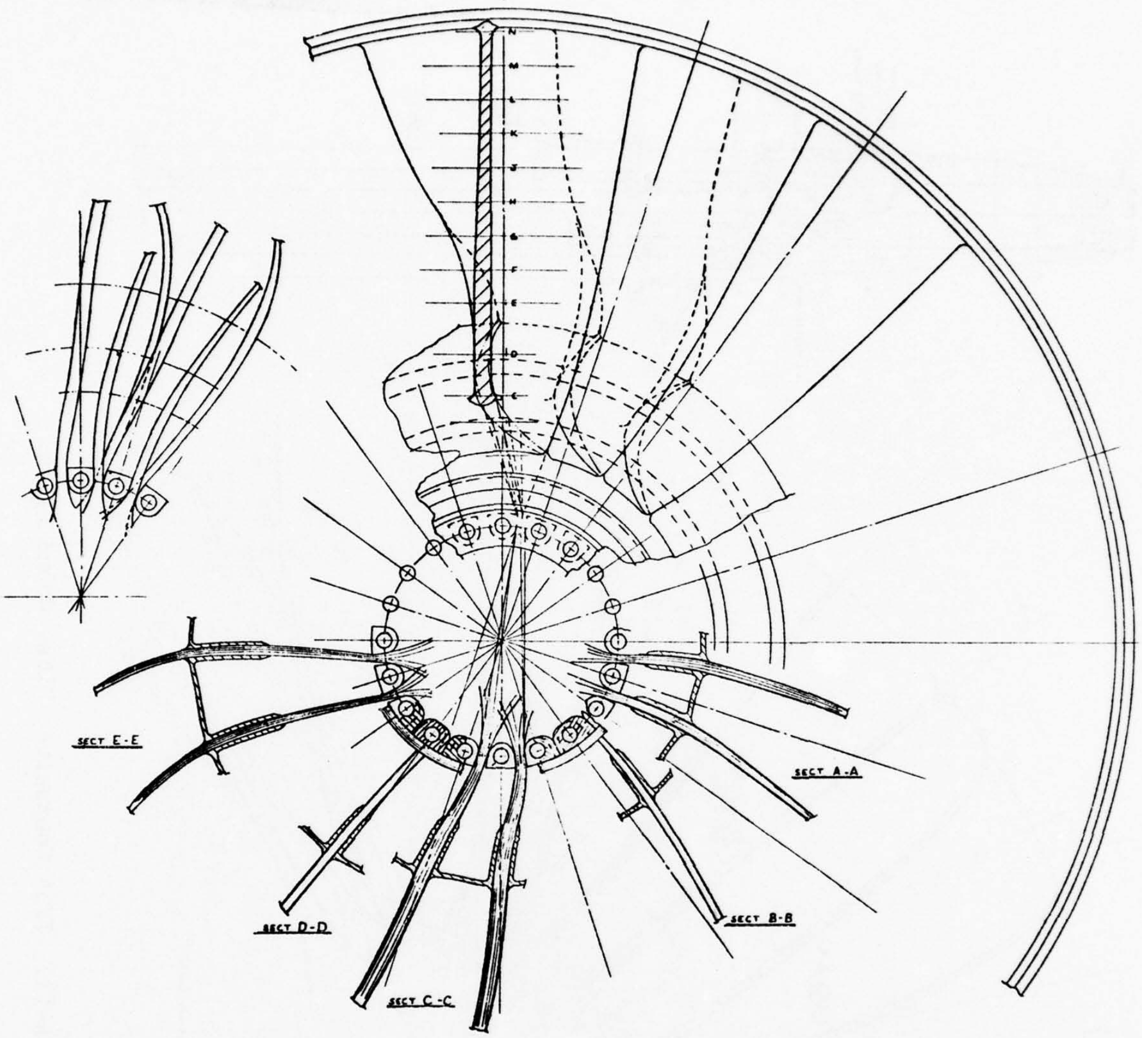

Figure A-14. Supersonic-Flight Composite, Fiber-Wound Blisk.

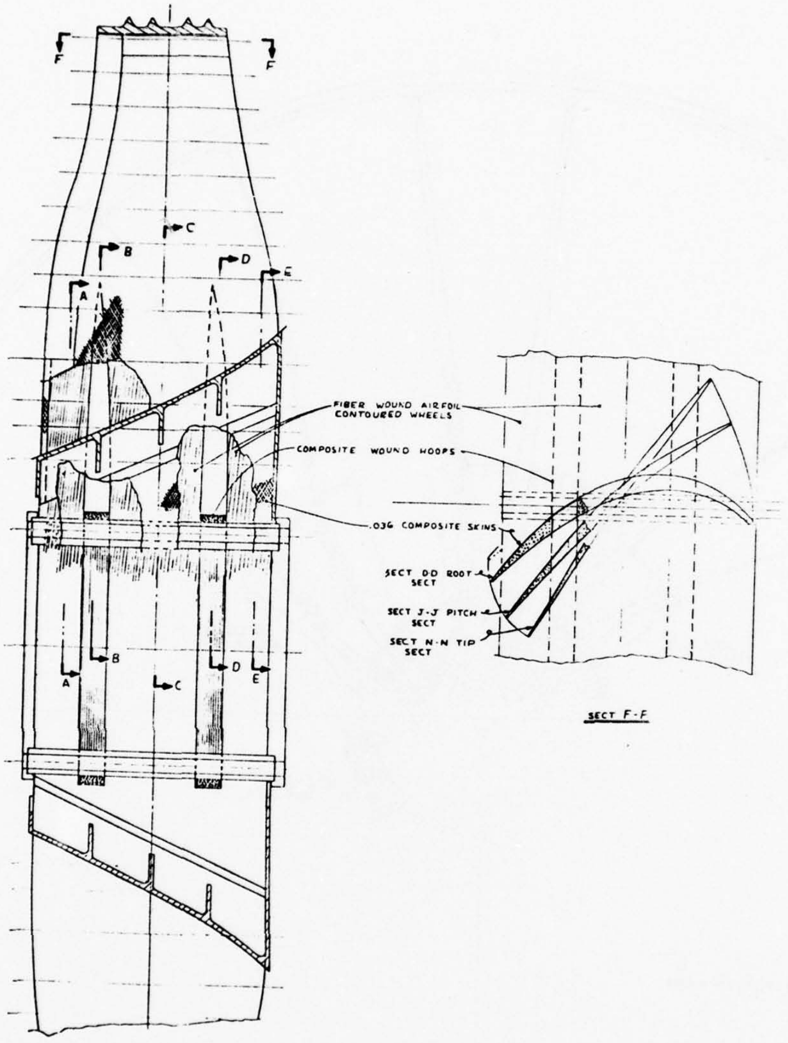

Figure A-14. Supersonic-Flight Composite, Fiber-Wound Blisk (Concluded).

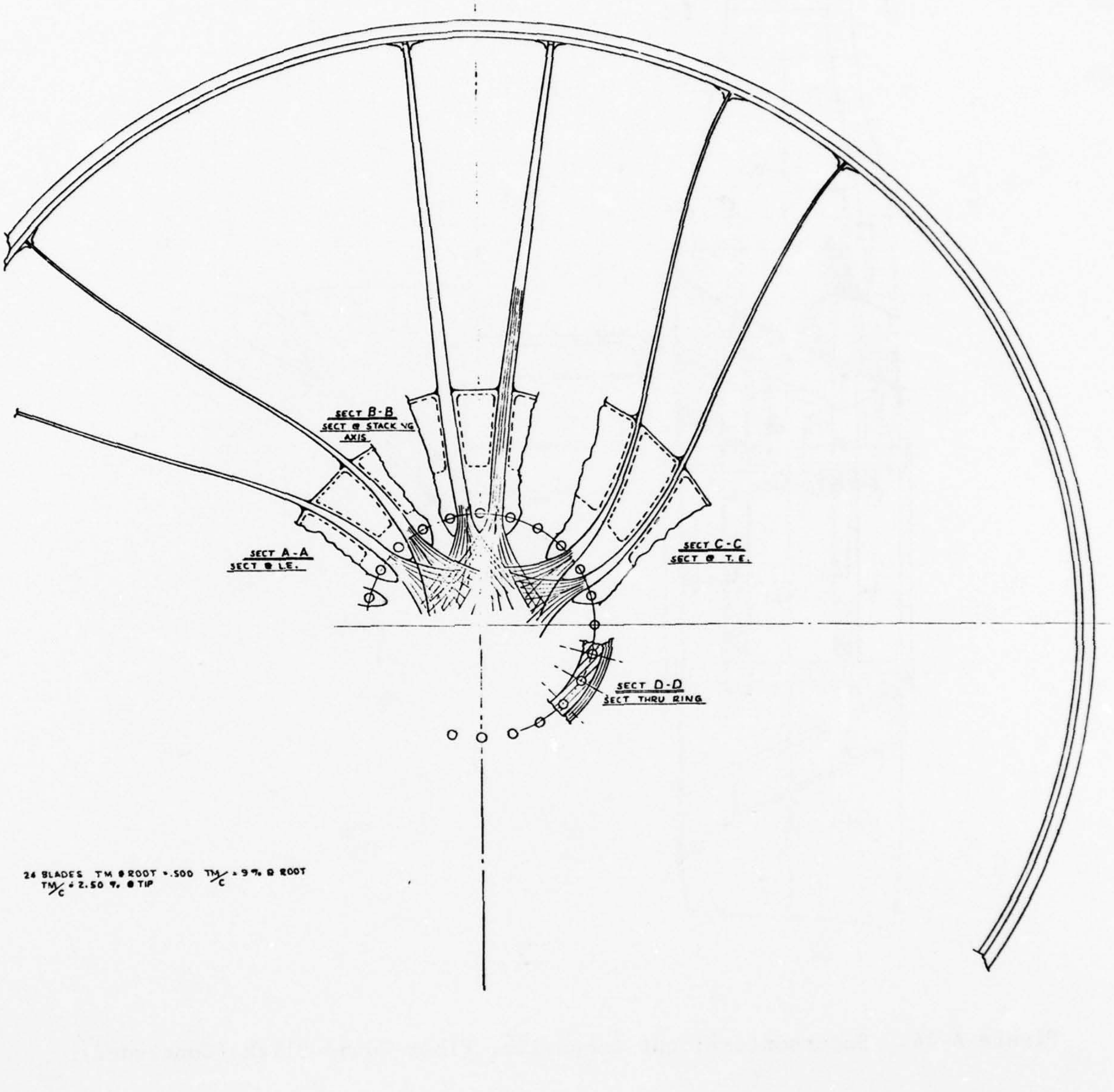

Figure A-15. Supersonic-Flight Composite, Fiber-Wound Blisk.

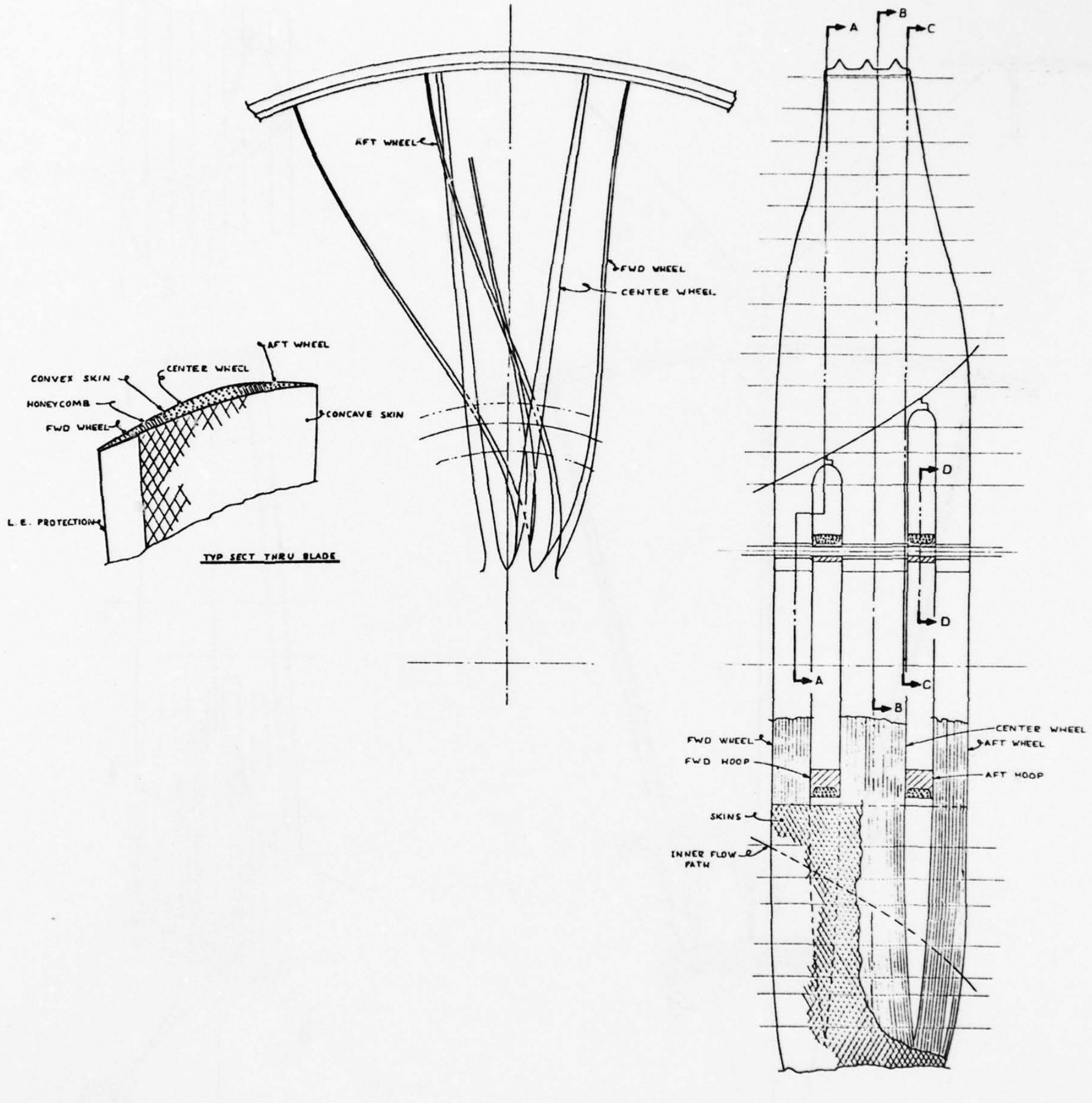

Figure A-15. Supersnic-Flight Composite, Fiber-Wound Blisk (Concluded).

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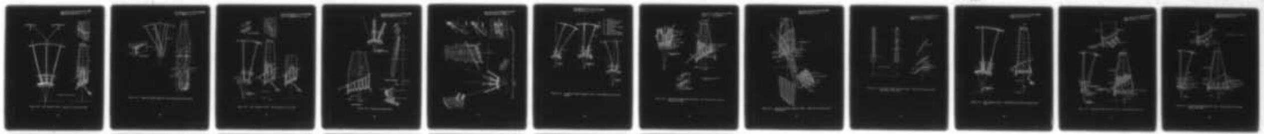

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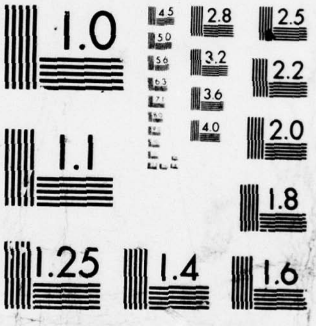

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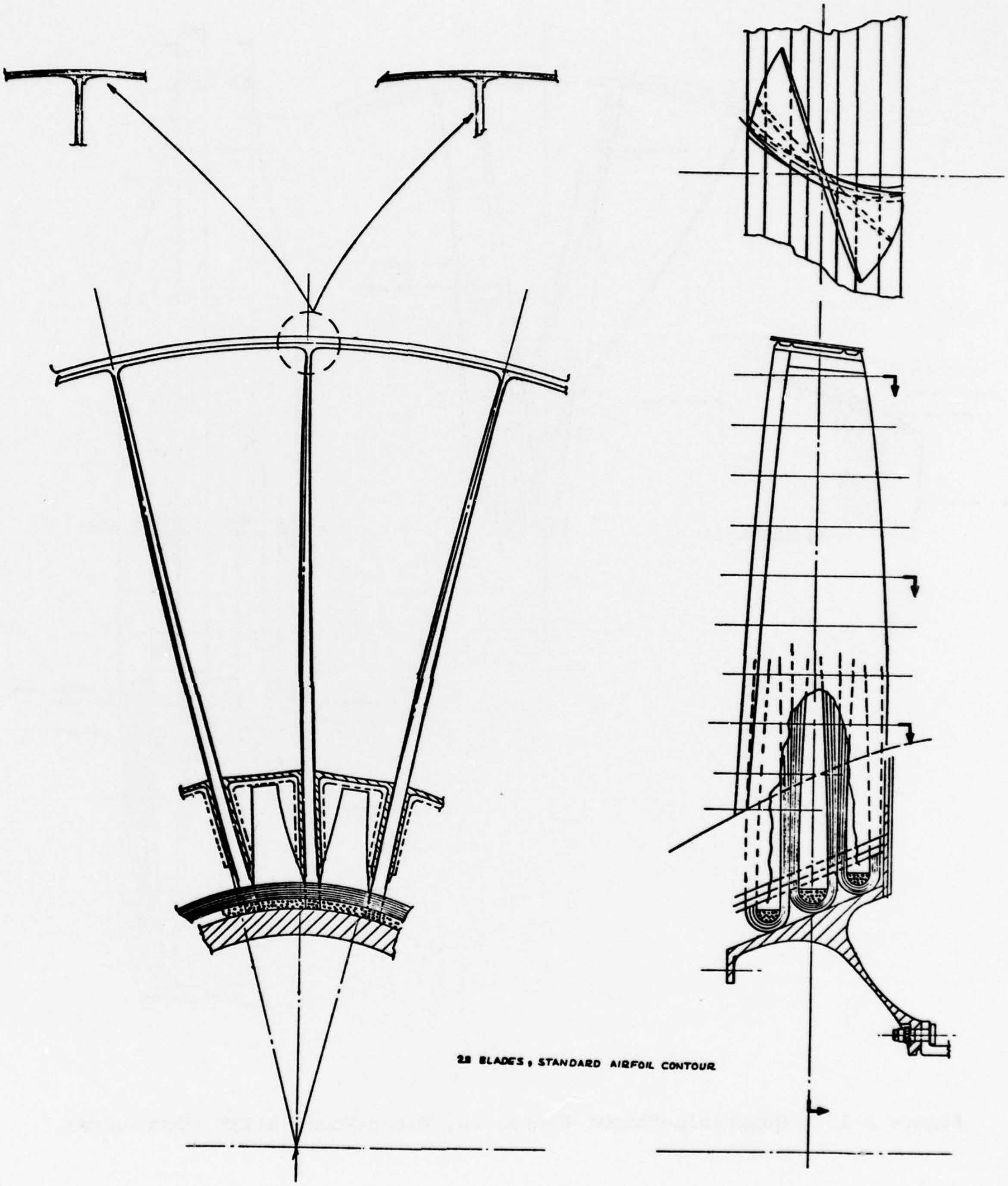


Figure A-16. TF34 Composite Blisk: Tuning Fork and Hoop Design.

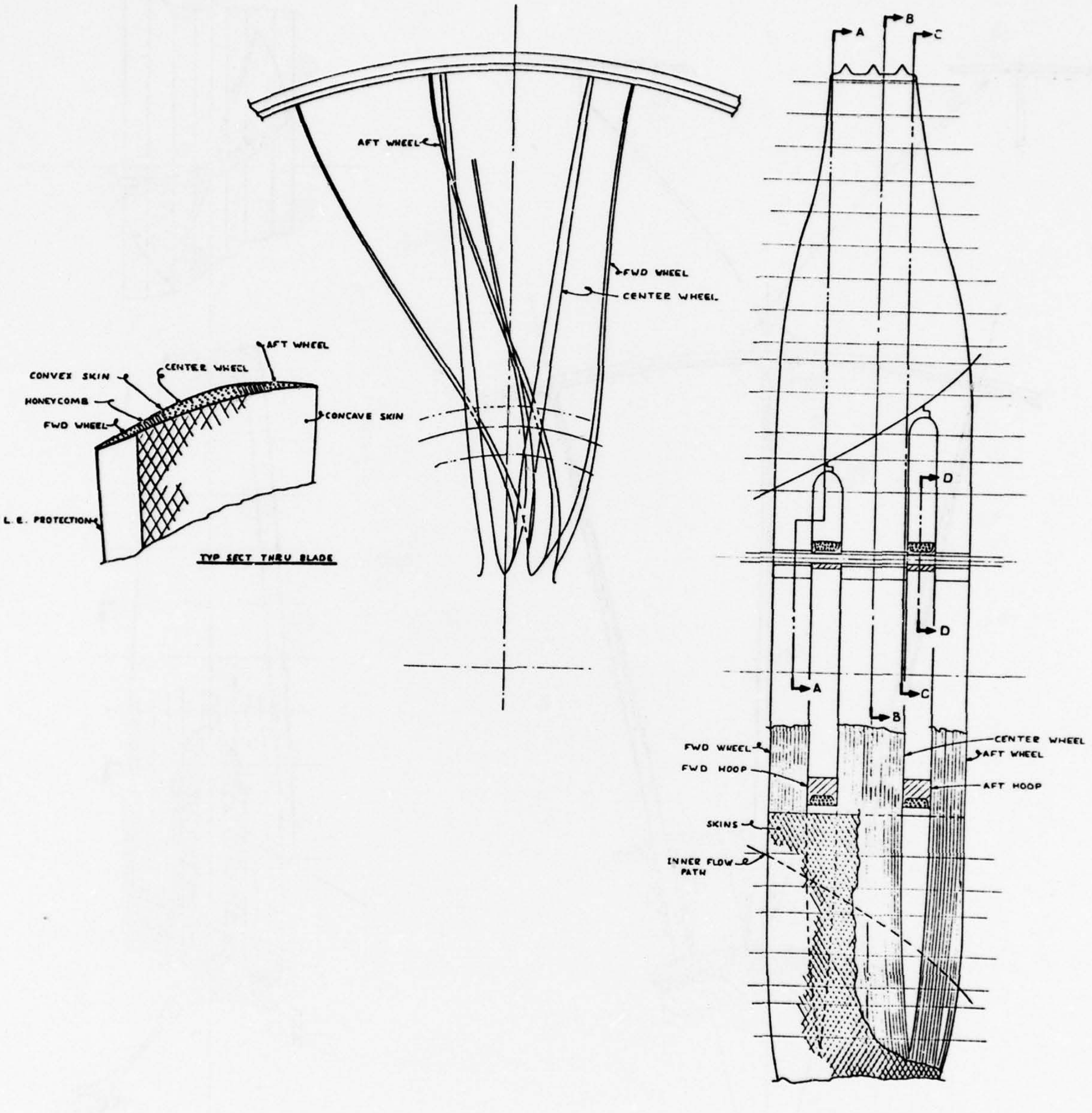


Figure A-15. Supersnic-Flight Composite, Fiber-Wound Blisk (Concluded).

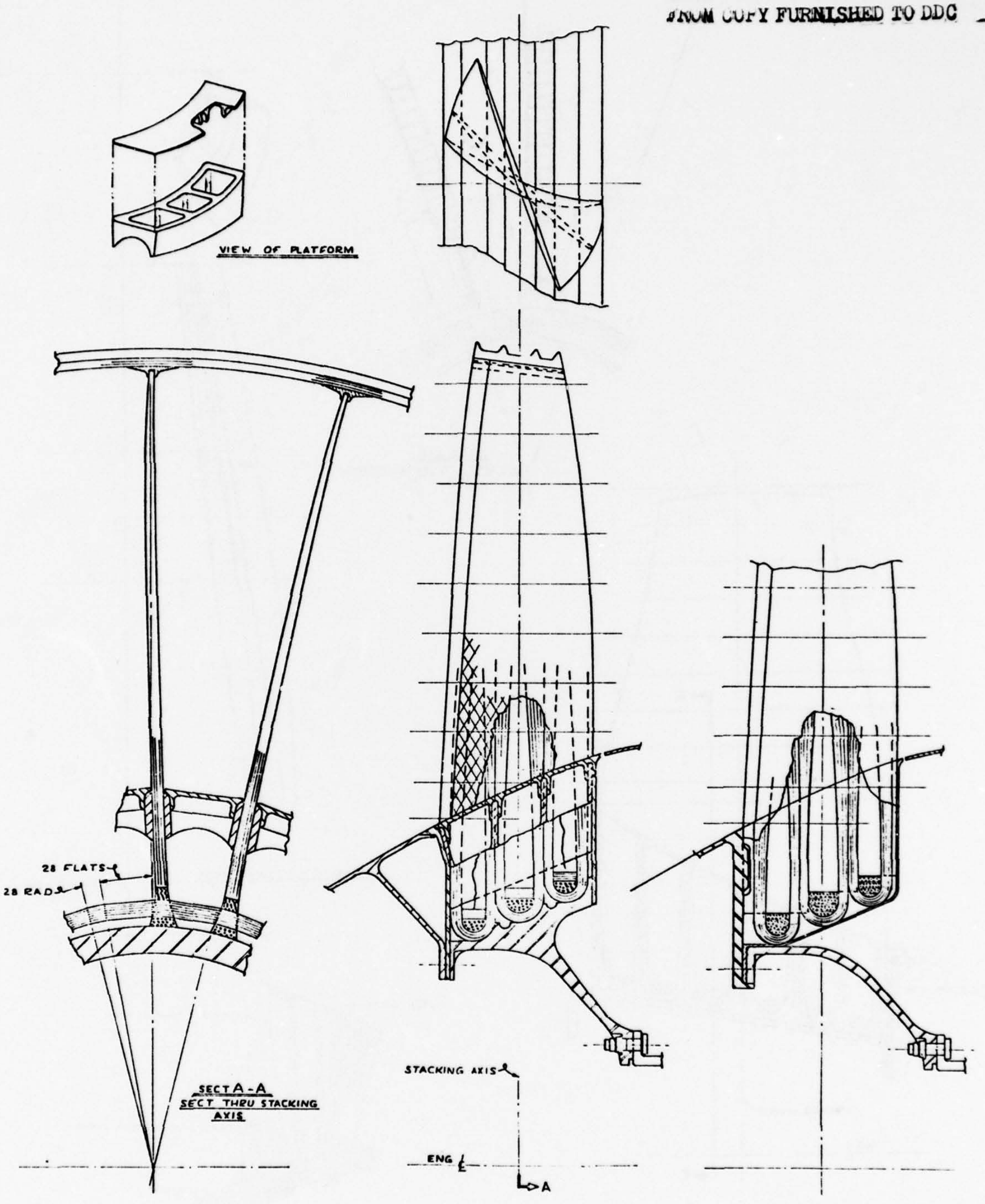


Figure A-17. TF34 Composite Blisk: Three Tuning Forks and Hoop.

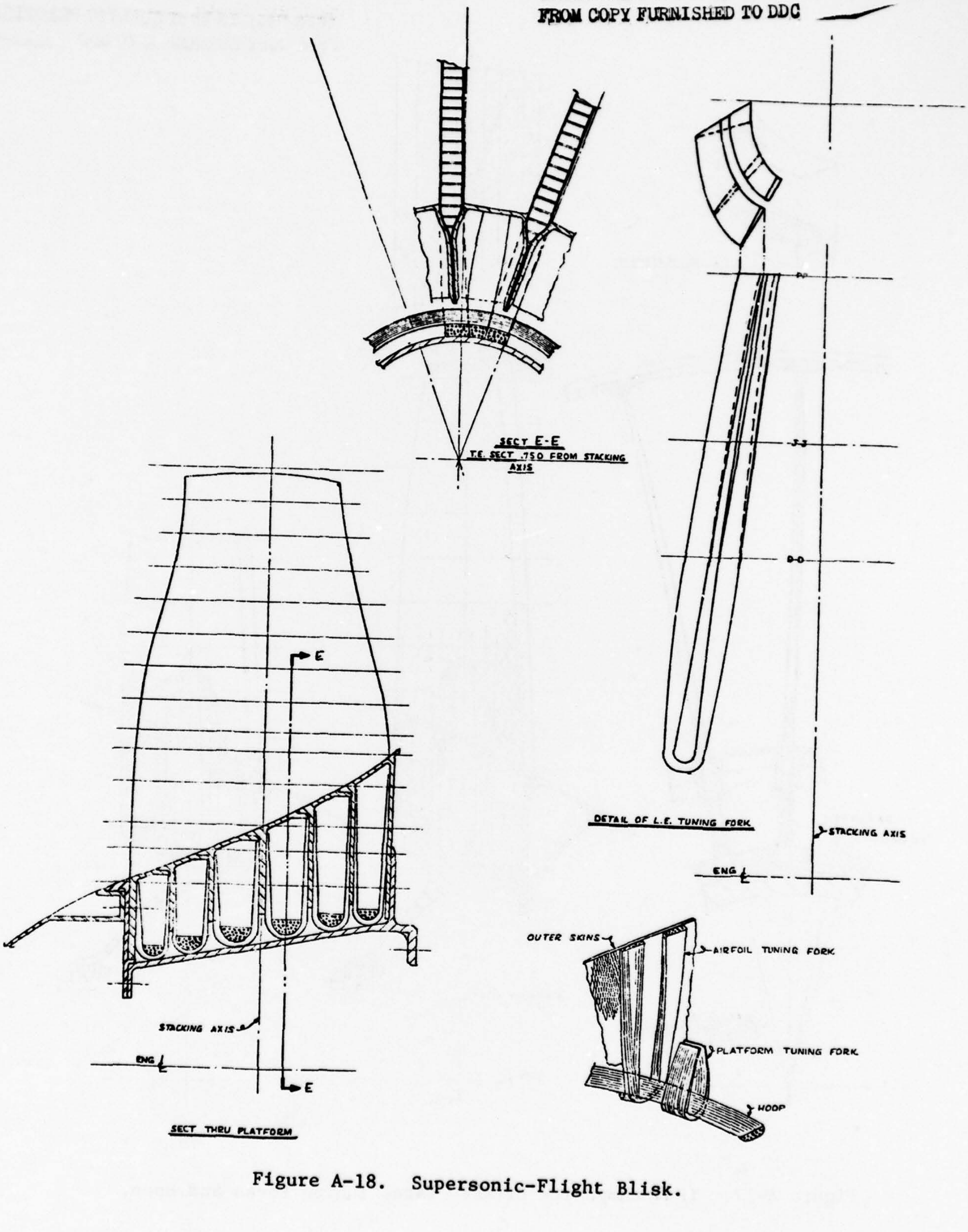


Figure A-18. Supersonic-Flight Blisk.

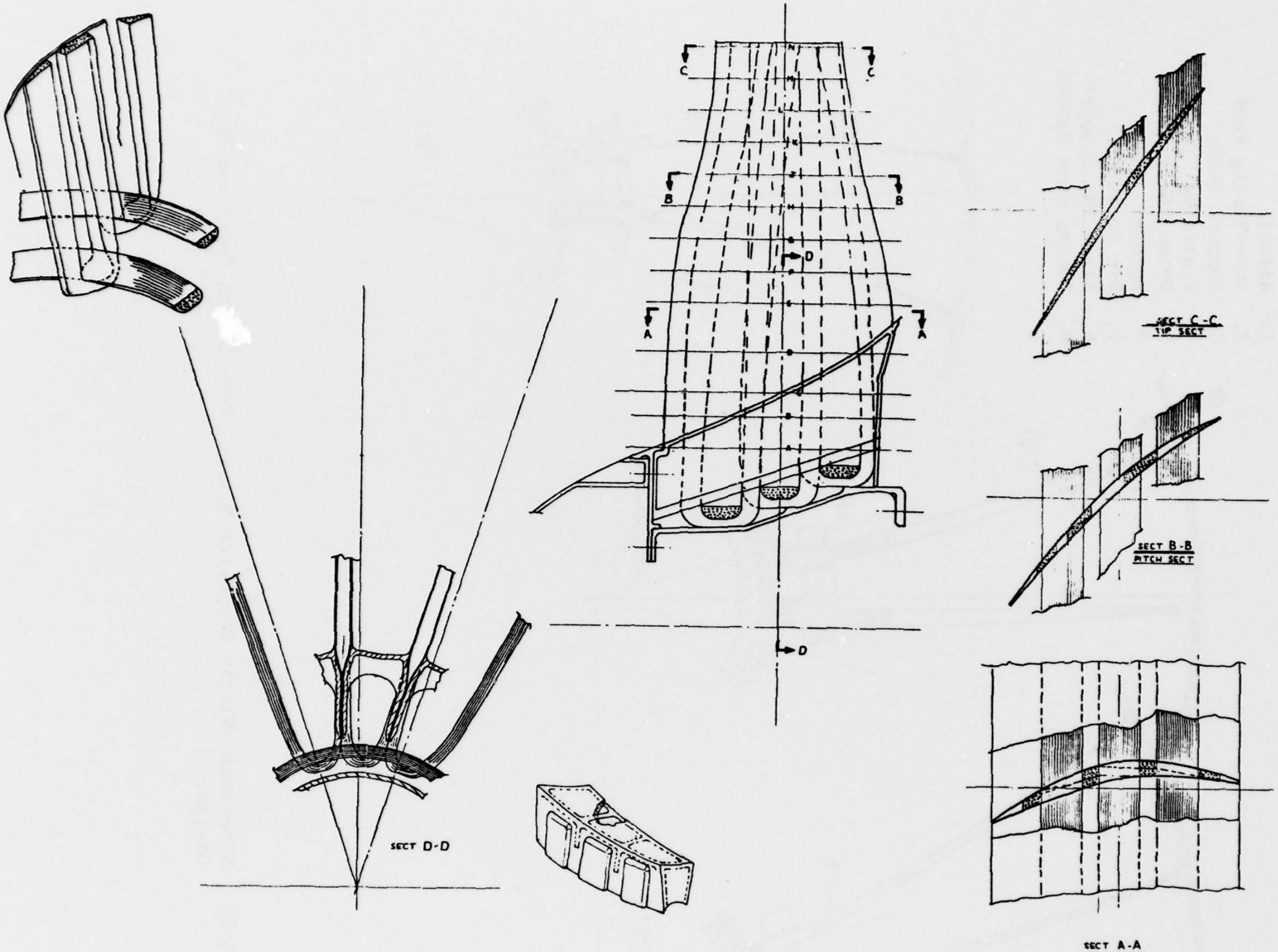
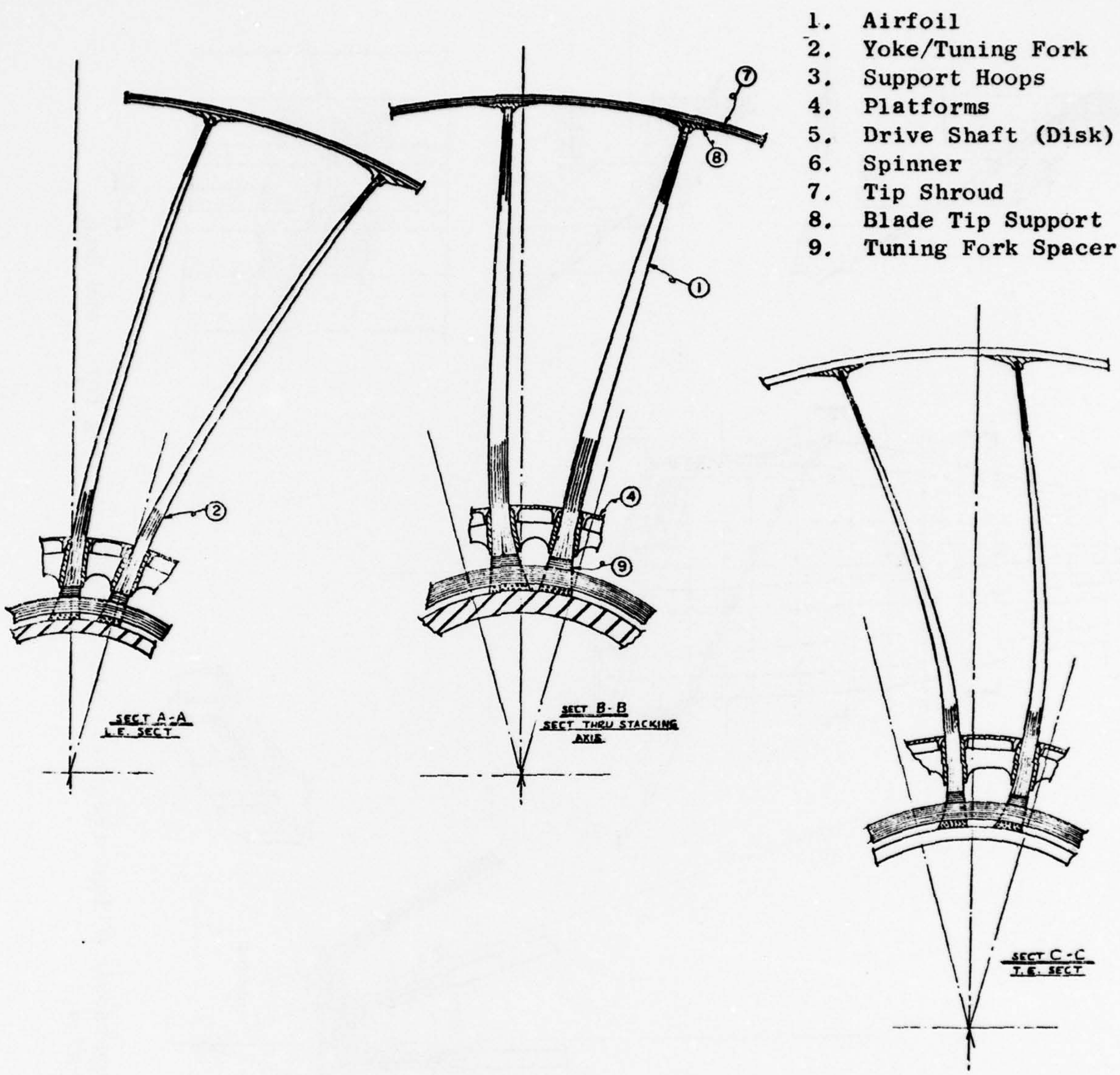


Figure A-19. Supersonic-Flight Composite Blisk: Three Tuning Forks and Hoop Design.



1. Airfoil
2. Yoke/Tuning Fork
3. Support Hoops
4. Platforms
5. Drive Shaft (Disk)
6. Spinner
7. Tip Shroud
8. Blade Tip Support
9. Tuning Fork Spacer

Figure A-20. Supersonic-Flight Composite Blisk: Five Tuning Forks and Hoop Design.

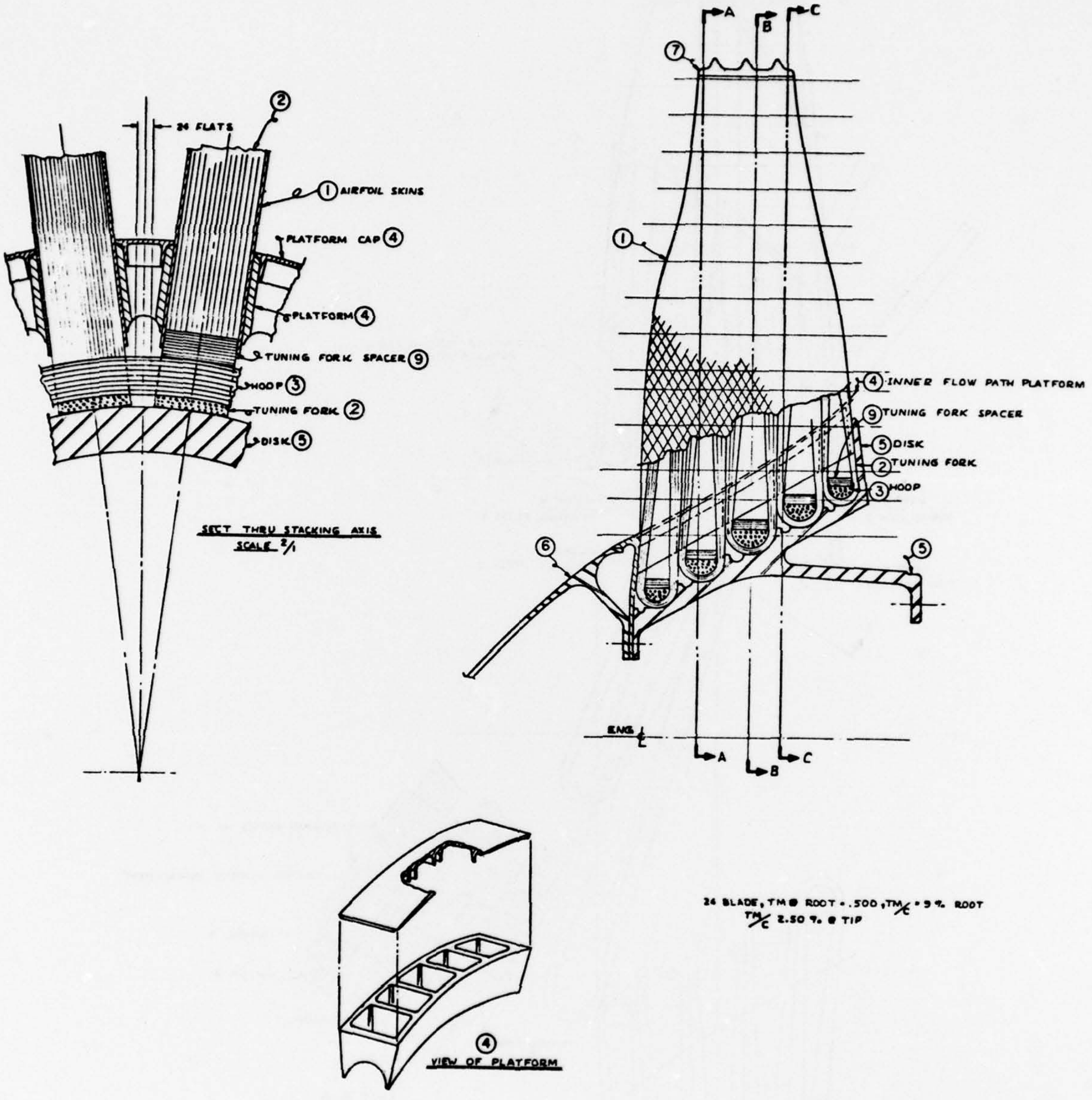


Figure A-20. Supersonic-Flight Composite Blisk: Five Tuning Forks and Hoop Design (Concluded).

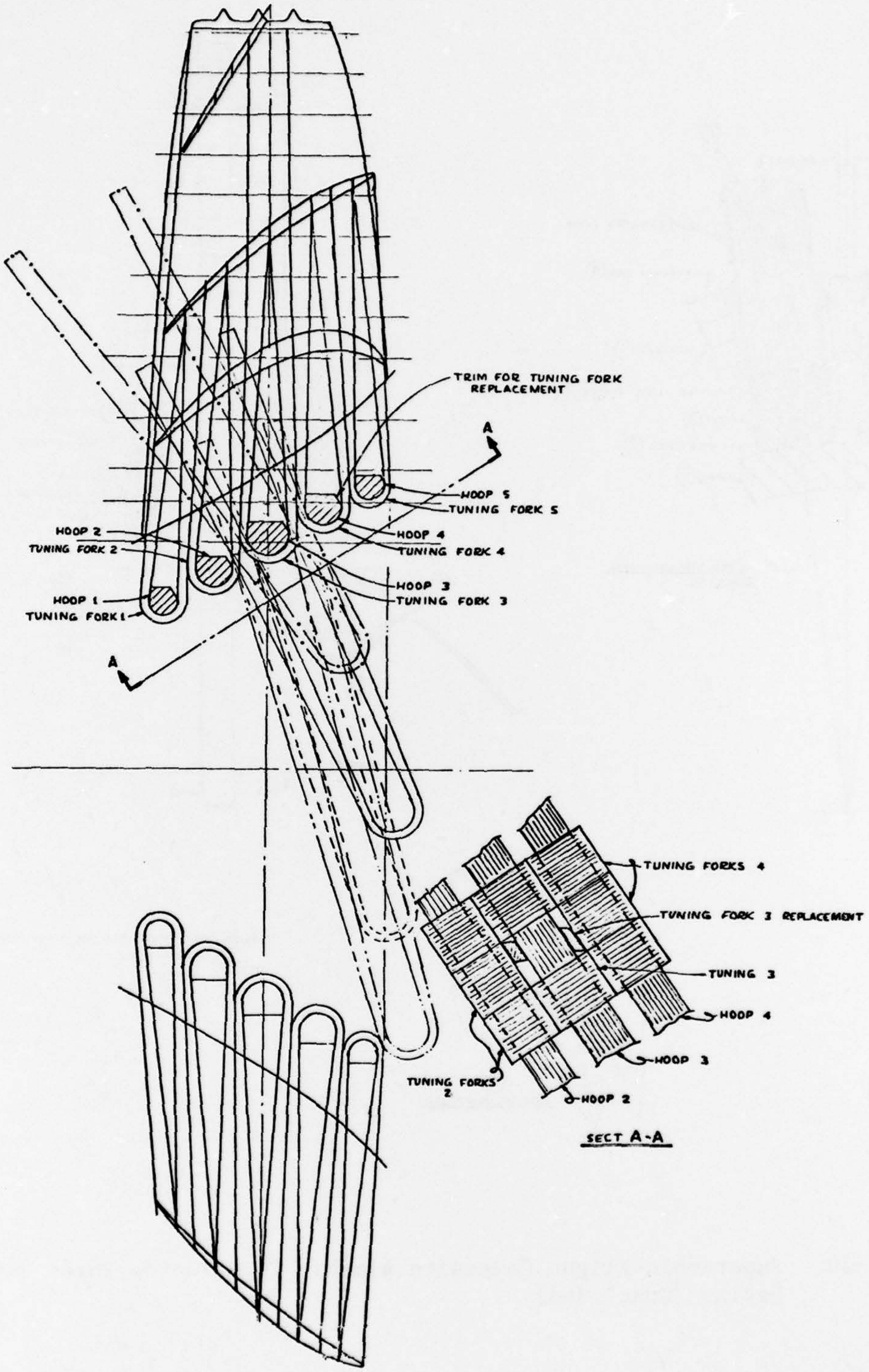


Figure A-21. Supersonic-Flight Composite Blisk: Tuning Fork and Hoop Blade Replacement.

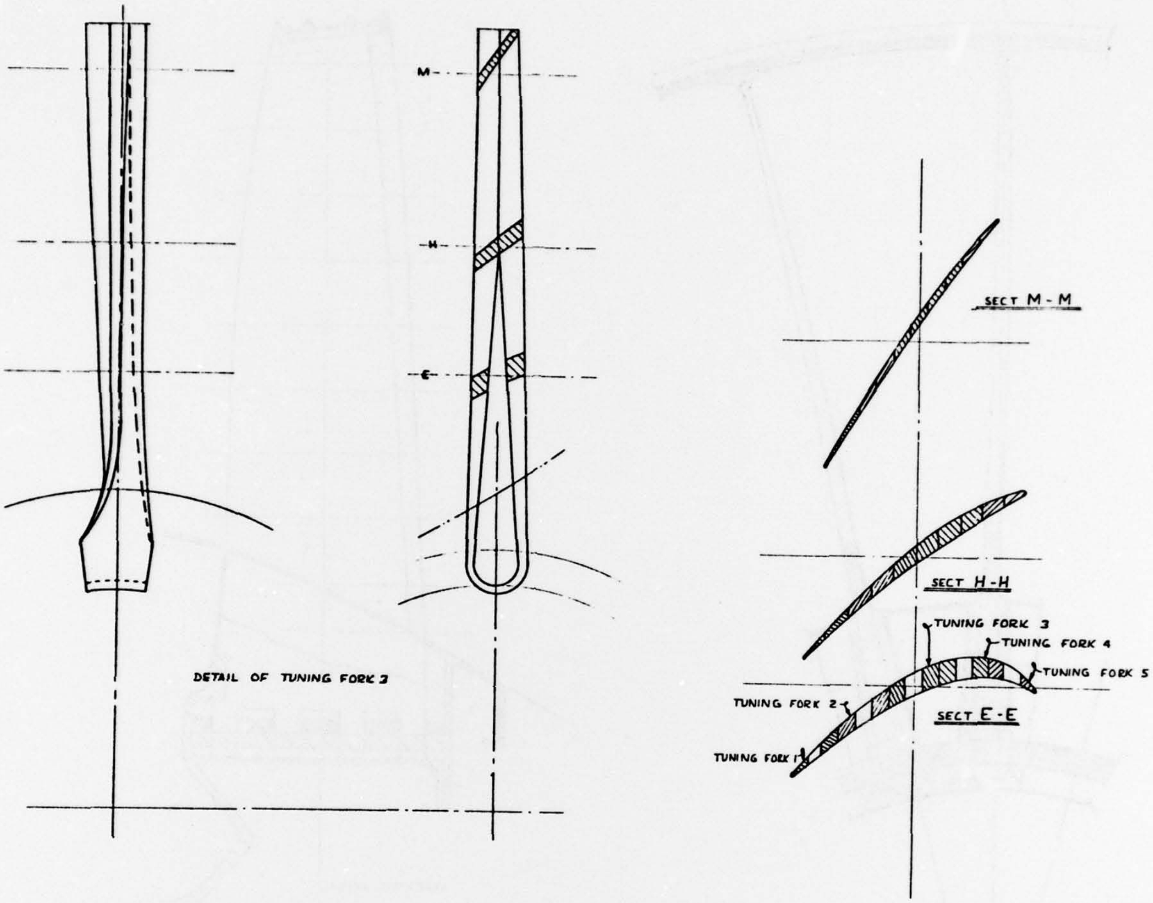


Figure A-21. Supersonic-Flight Composite Blisk: Tuning Fork and Hoop Blade Replacement (Concluded).

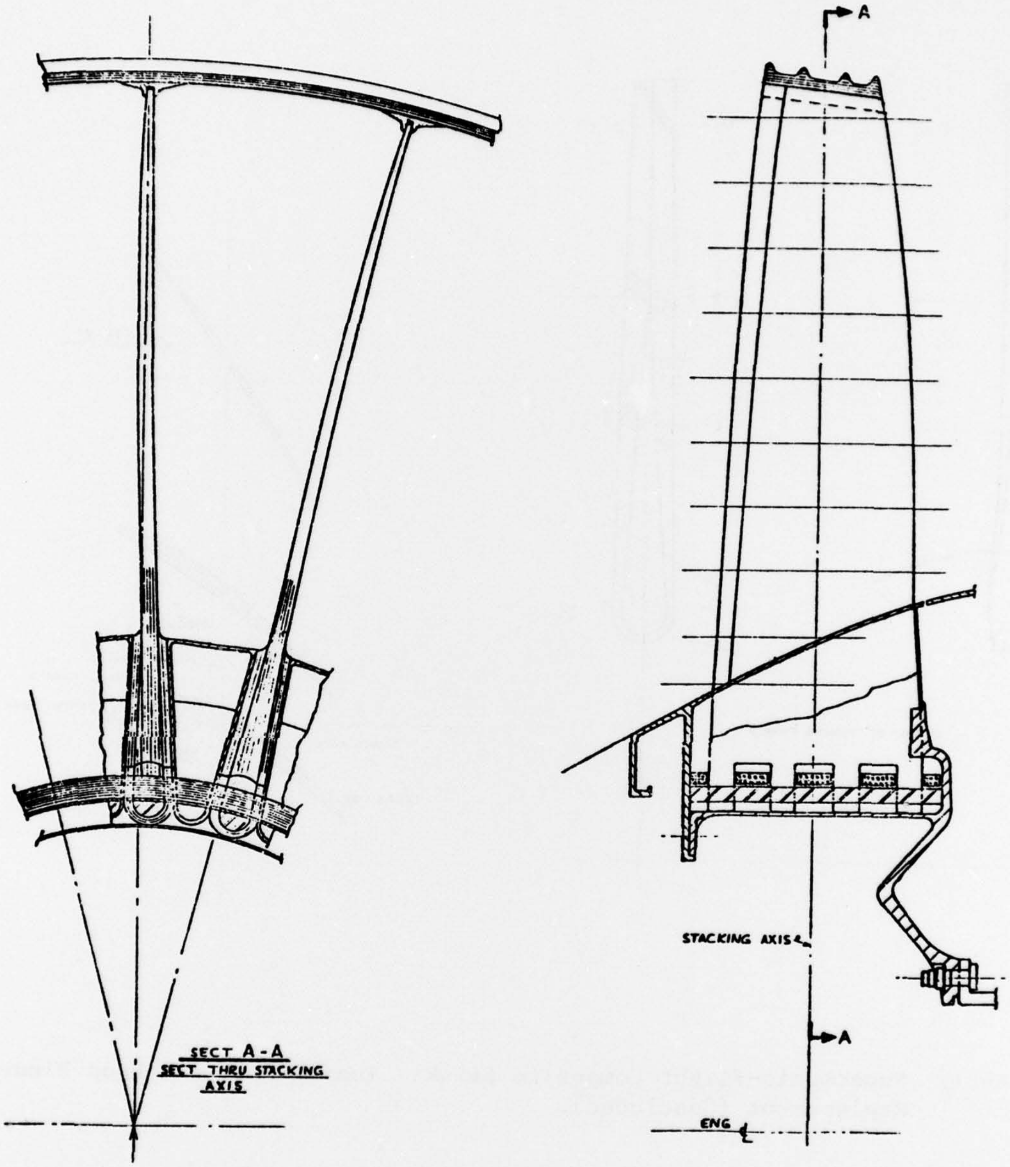


Figure A-22. TF34 Composite Blisk: Pinned-Blade and Platform-Support-Hoop Rotor.

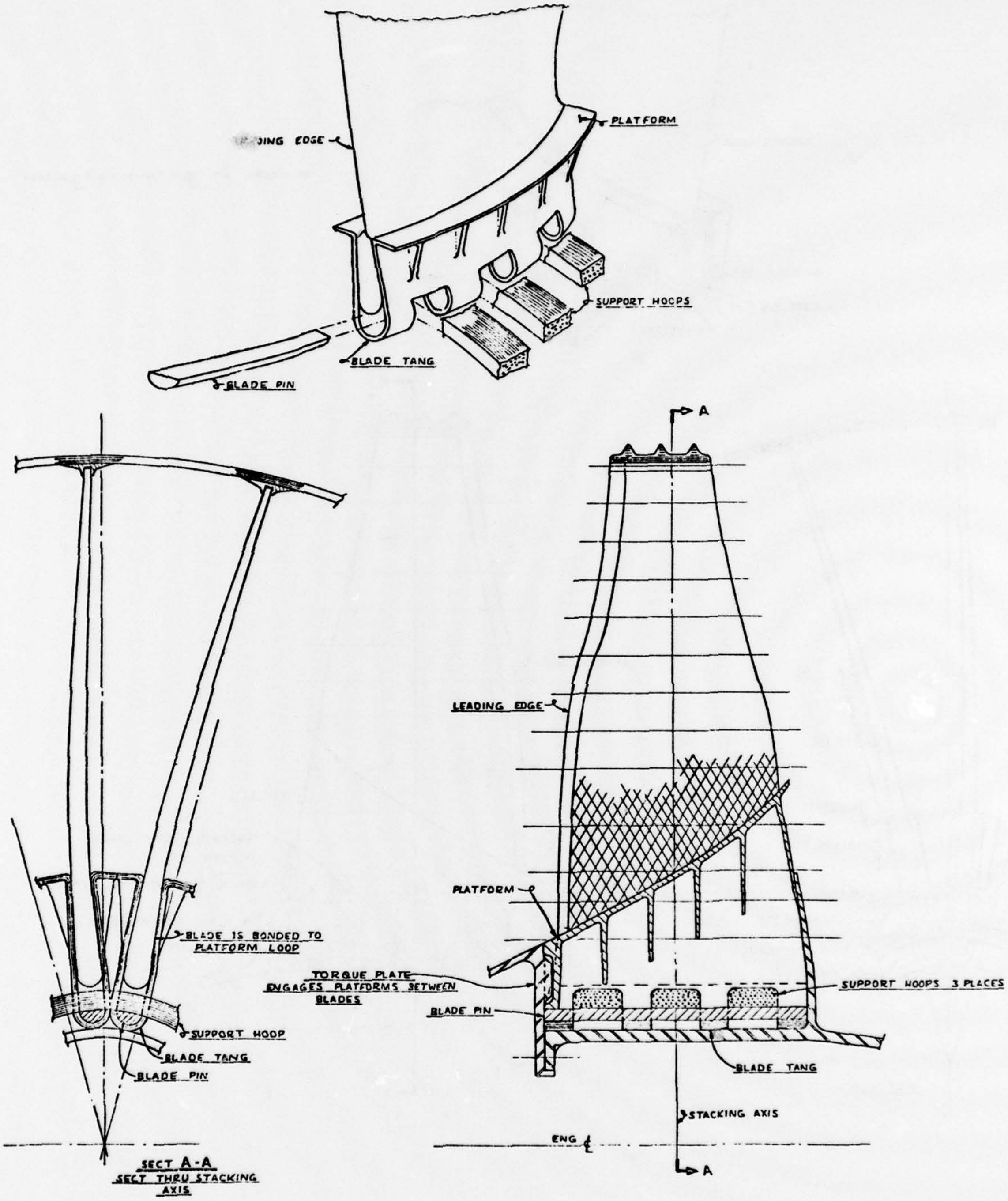


Figure A-23. Supersonic-Flight Composite Blisk: Pinned-Blade/Hoop Rotor.

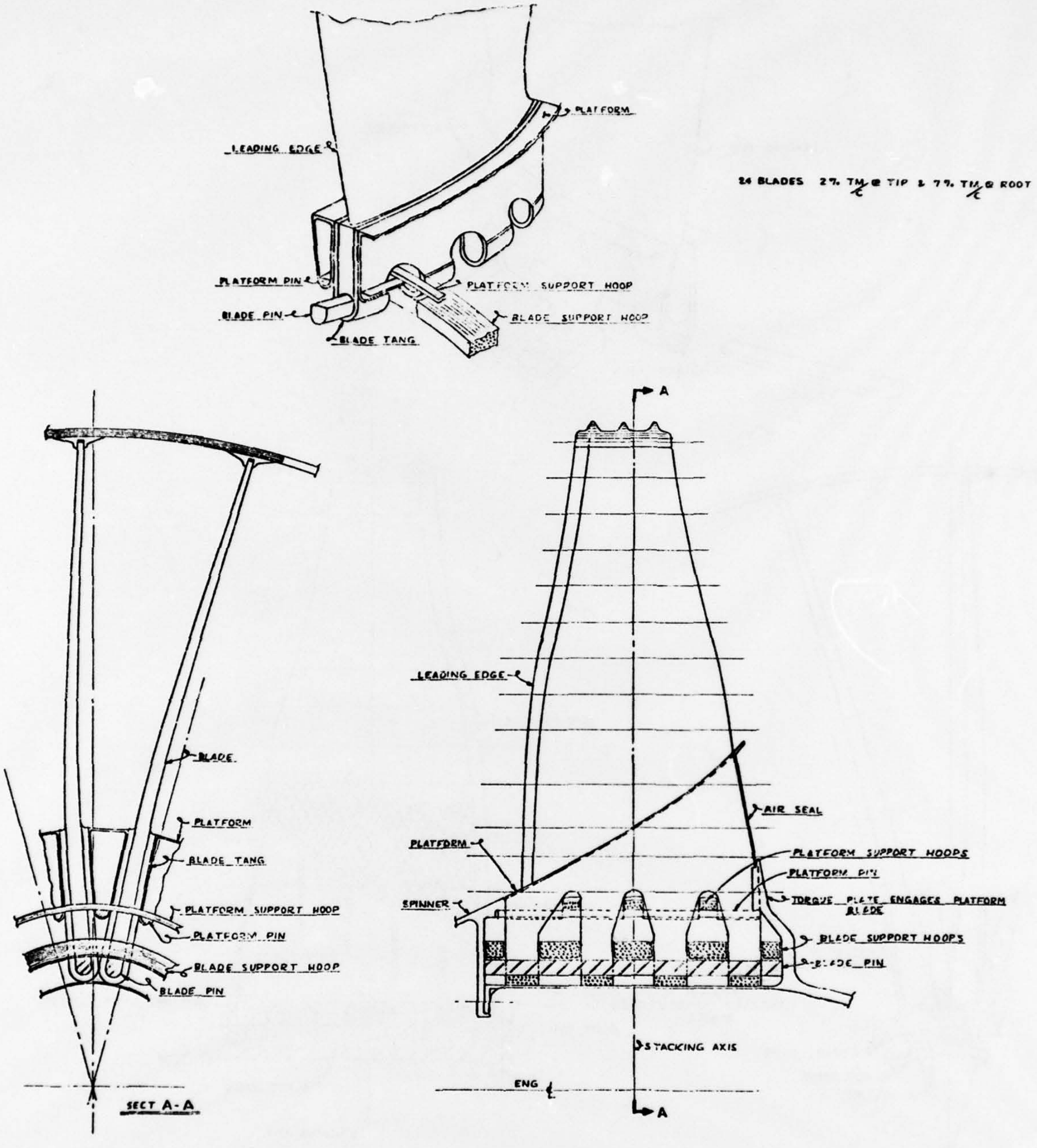


Figure A-24. Supersonic-Flight Composite Blisk: Pinned-Blade and Platform-Support-Hoop Rotor.

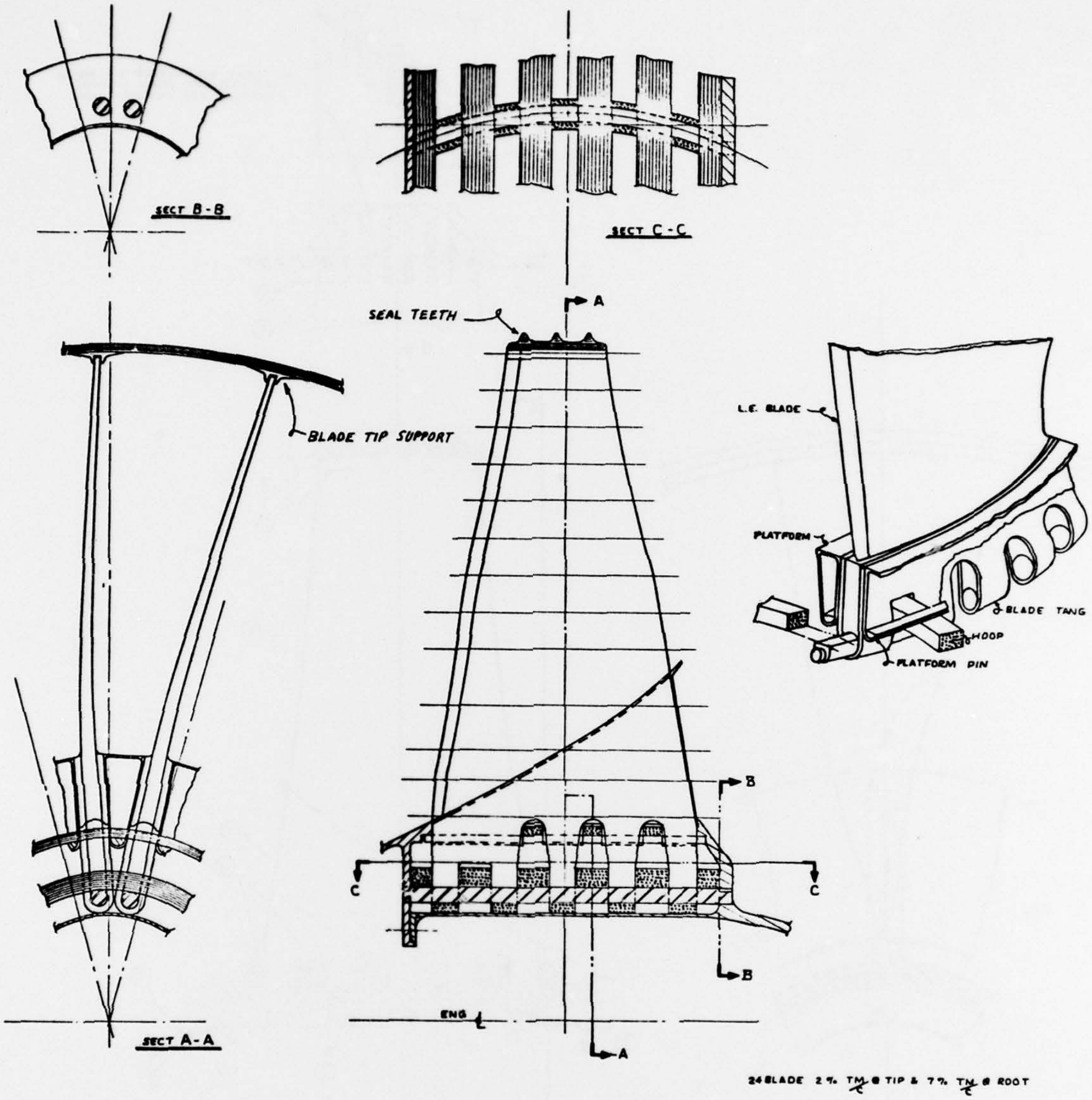


Figure A-25. Supersonic-Flight Composite Blisk: Pinned-Blade and Platform-Support-Hoop Rotor.

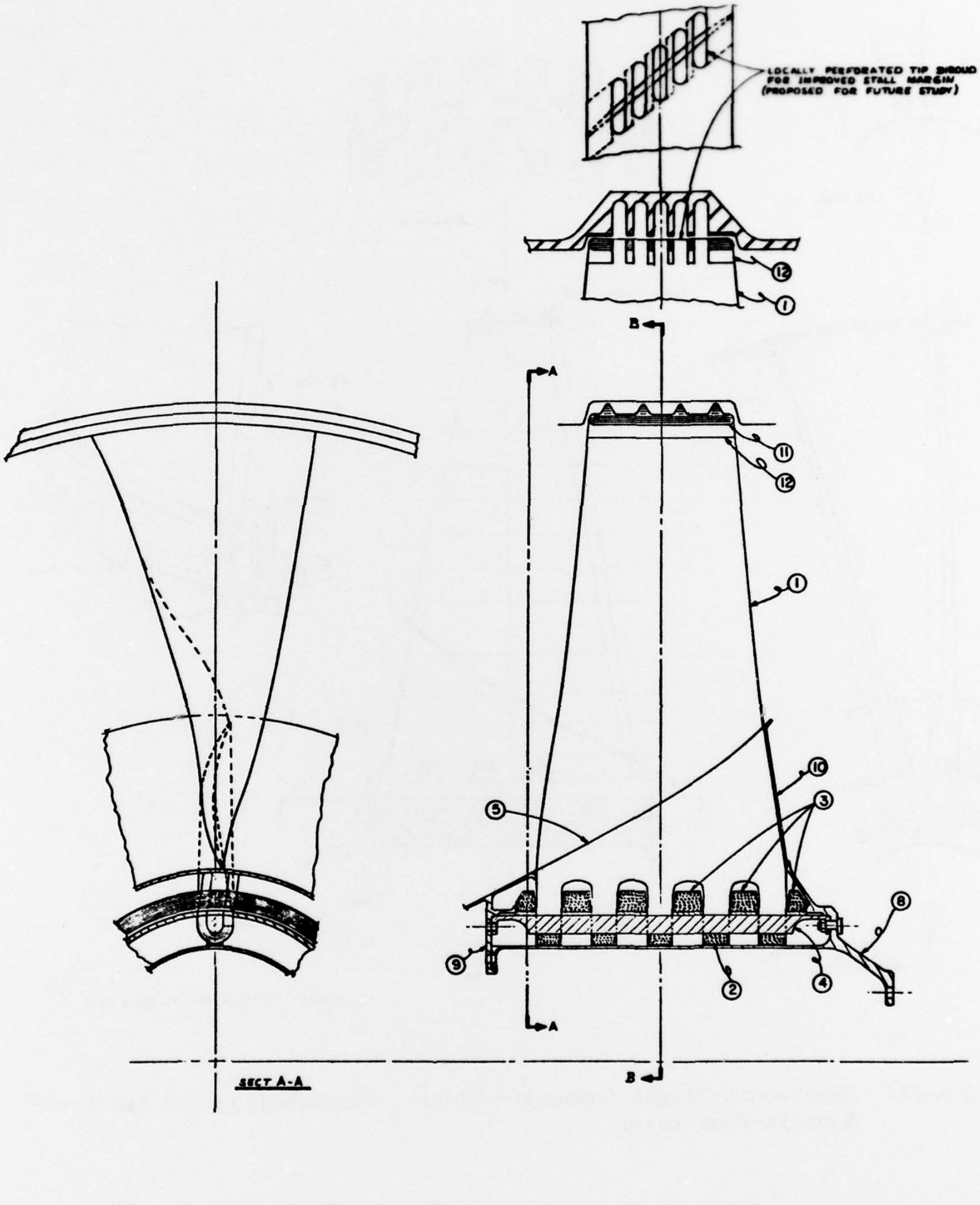
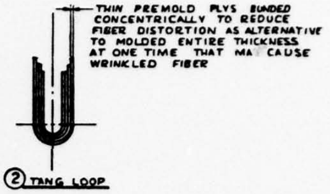


Figure A-26. Supersonic-Flight Blisk: Pinned-Blade and Support-Hoop Rotor.

1. Airfoil
2. Blade Support Tang
3. Blade Support Hoop
4. Blade Pin
5. Platform
8. Drive Shaft
9. Spinner Mount Plate
10. Aft Air Seal
11. Tip Shroud
12. Blade Tip Support



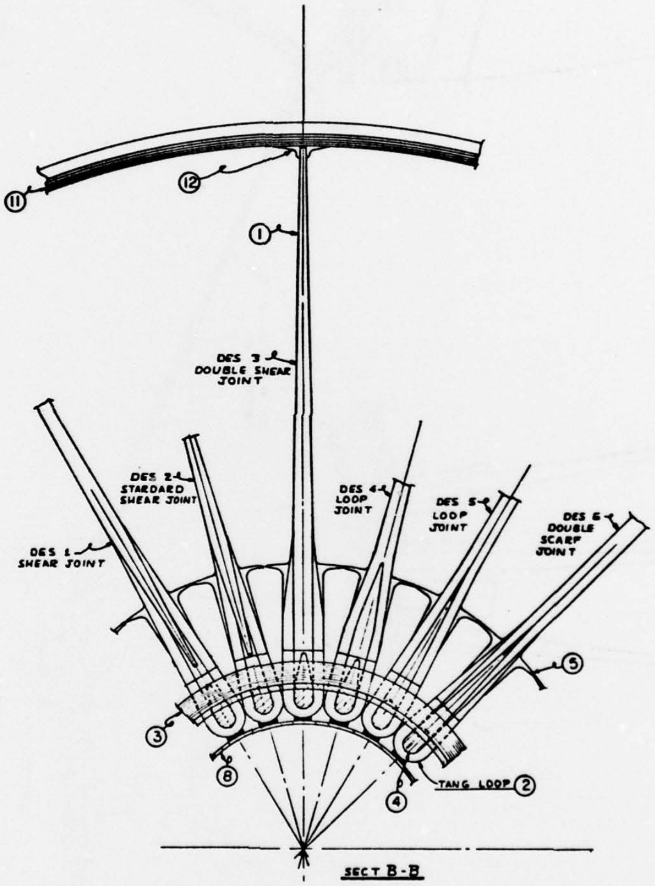


Figure A-26. Supersonic-Flight Blisk: Pinned-Blade and Support-Hoop Rotor (Concluded).

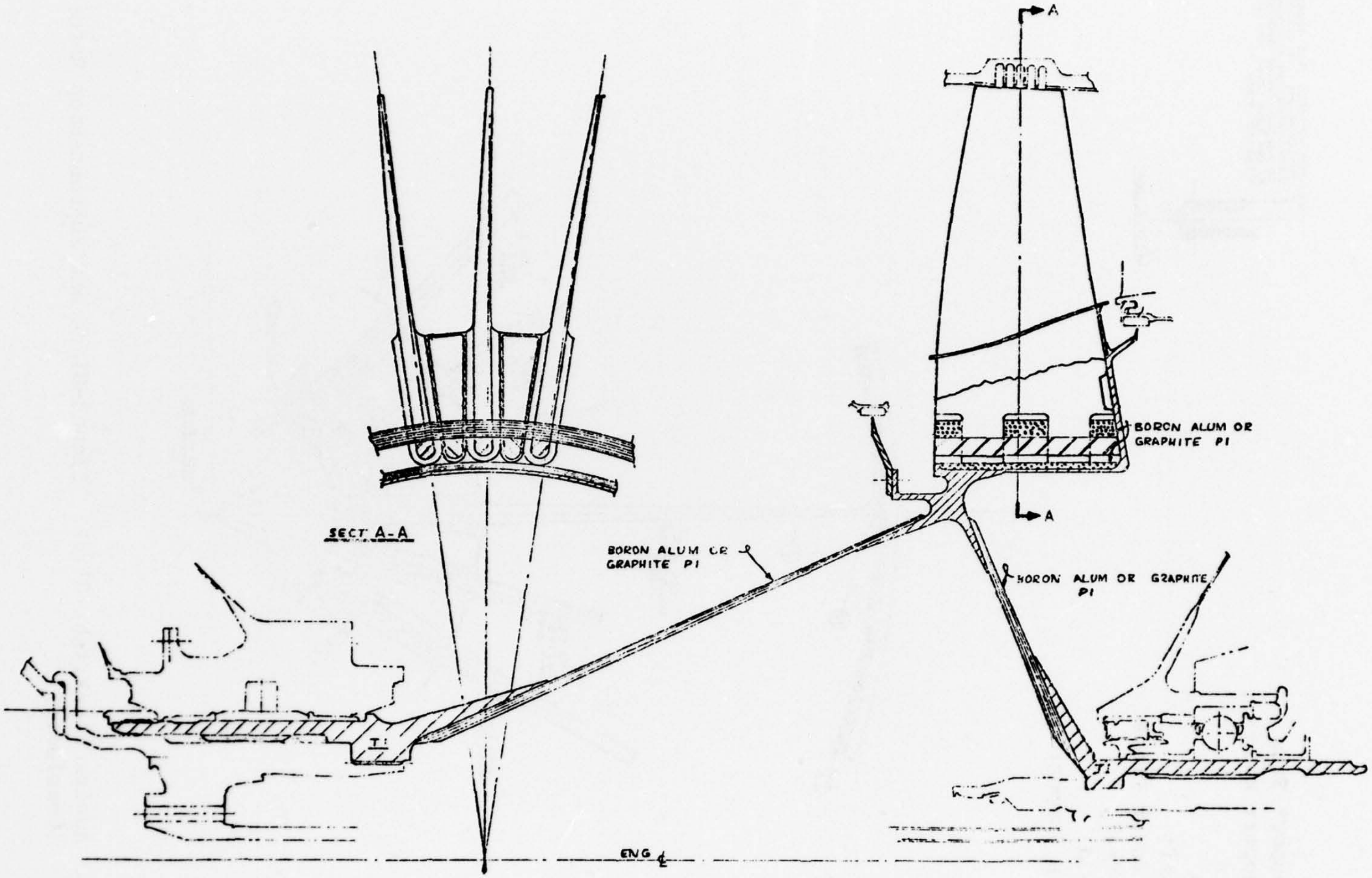


Figure A-27. Supersonic-Flight, Second-Stage Fan: Pinned-Blade and Platform-Support-Hoop Rotor.

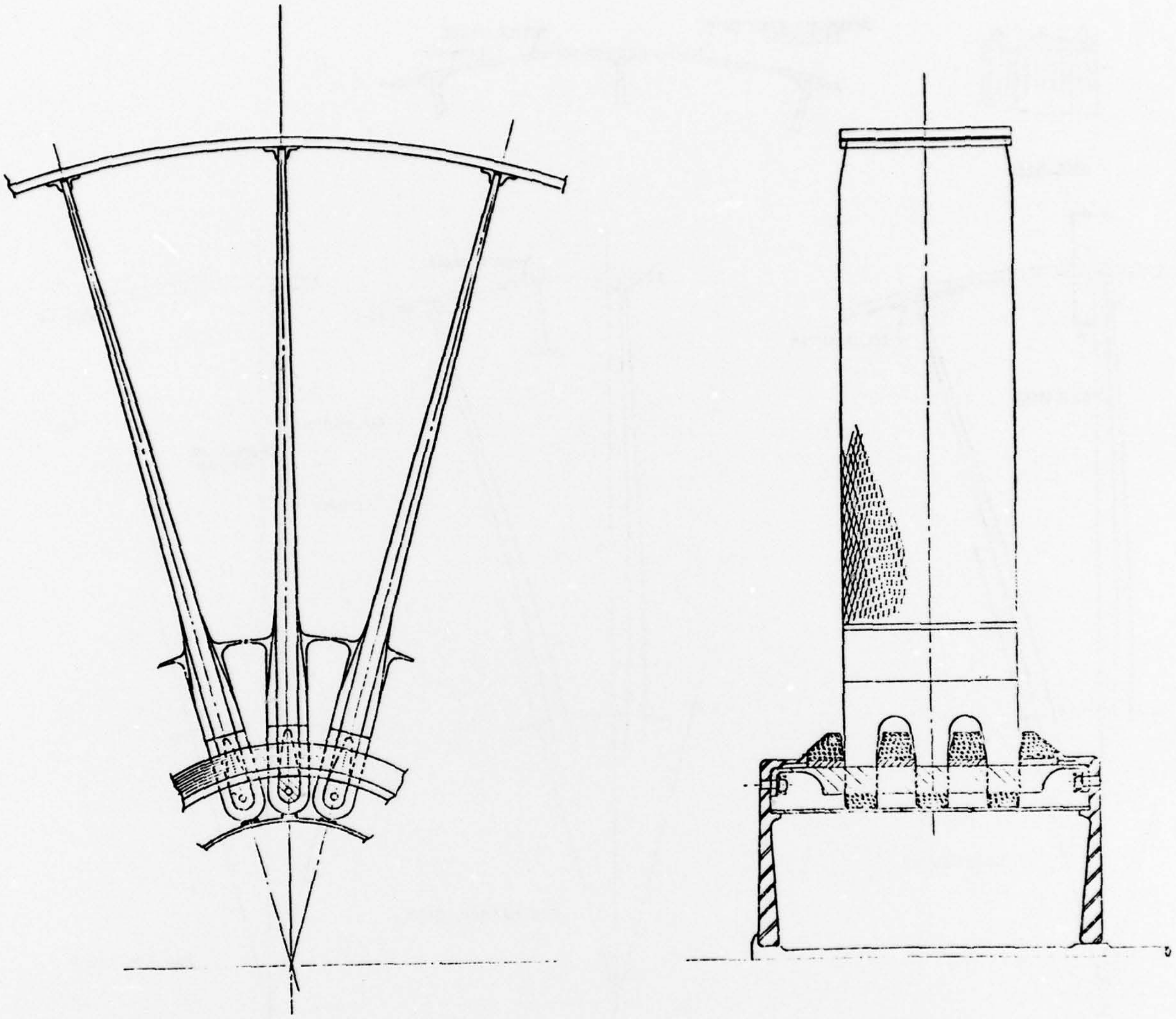


Figure A-28. Supersonic-Flight Fan: Pinned-Blade/Hoop Demonstrator.

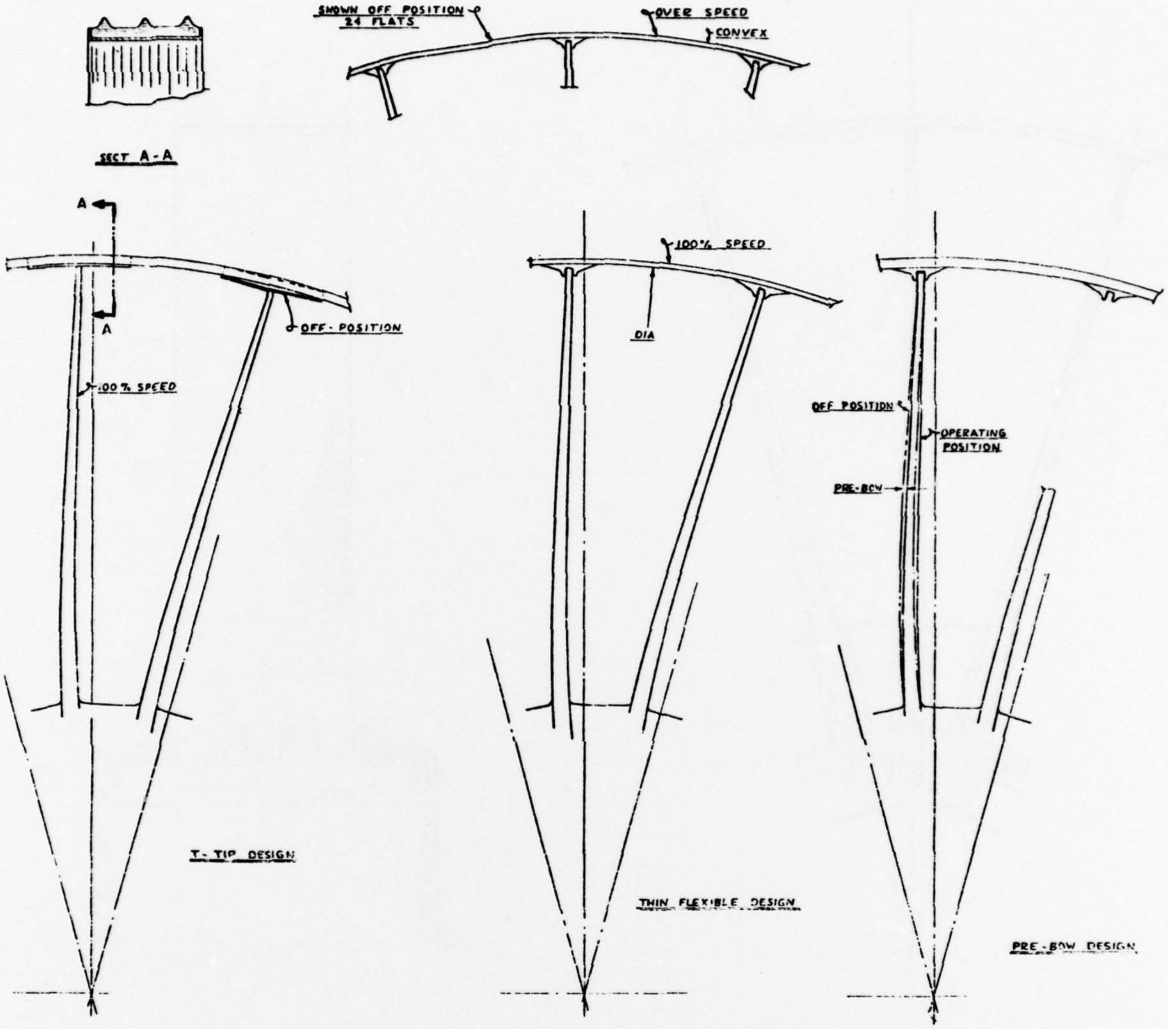


Figure A-29. Supersonic-Flight Compressor Stage 1 and 2 Composite Disk.

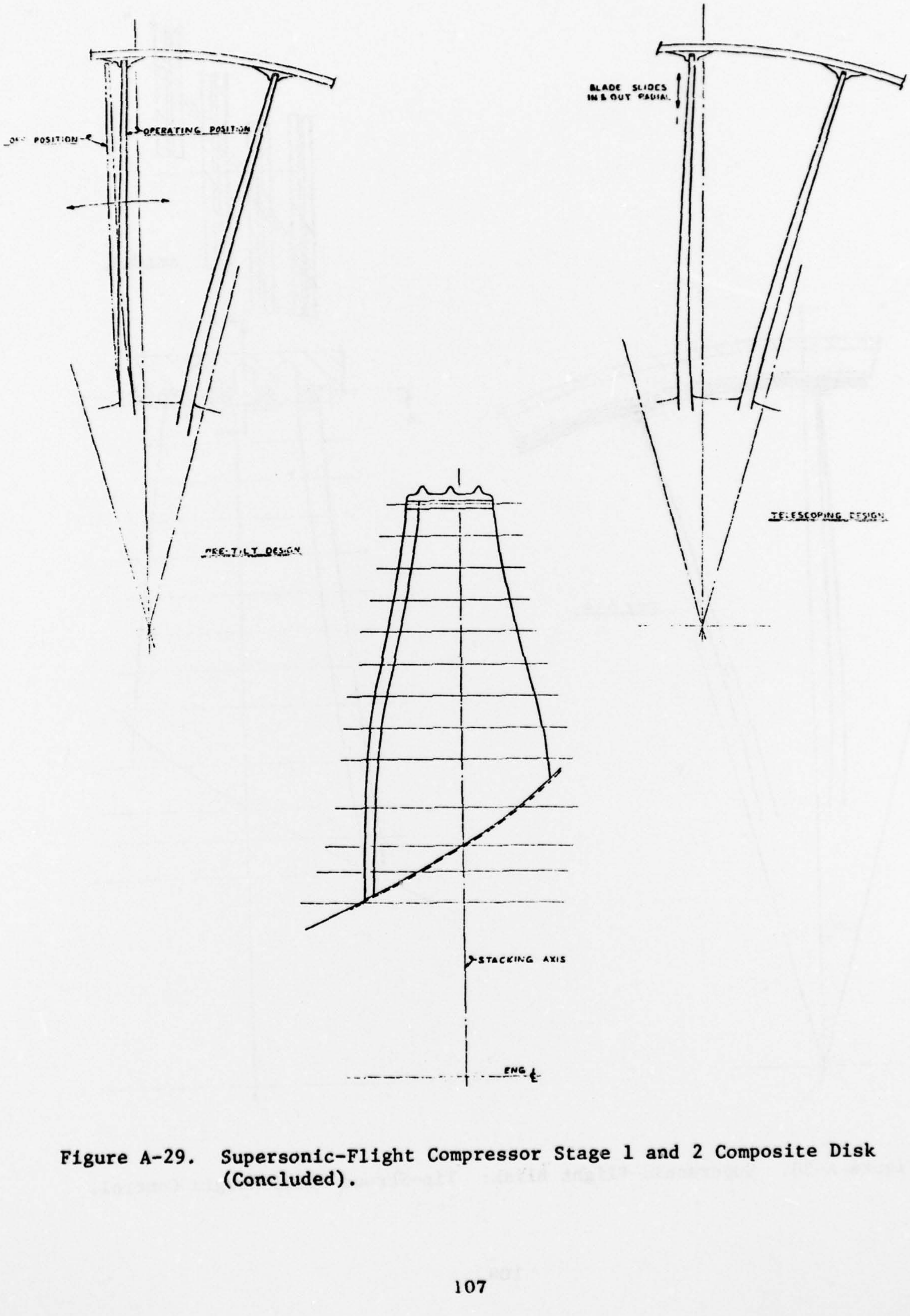


Figure A-29. Supersonic-Flight Compressor Stage 1 and 2 Composite Disk (Concluded).

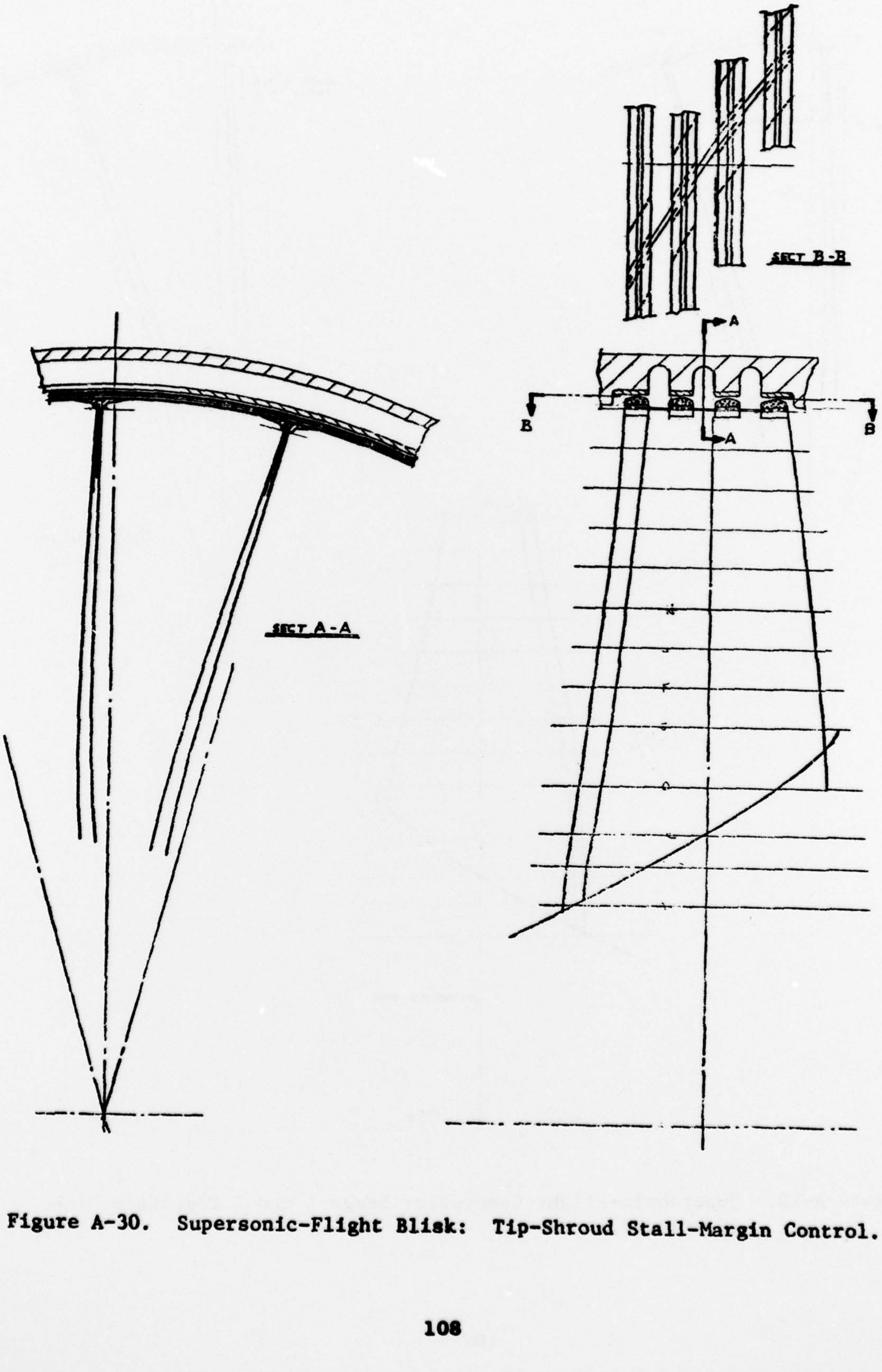


Figure A-30. Supersonic-Flight Blisk: Tip-Shroud Stall-Margin Control.

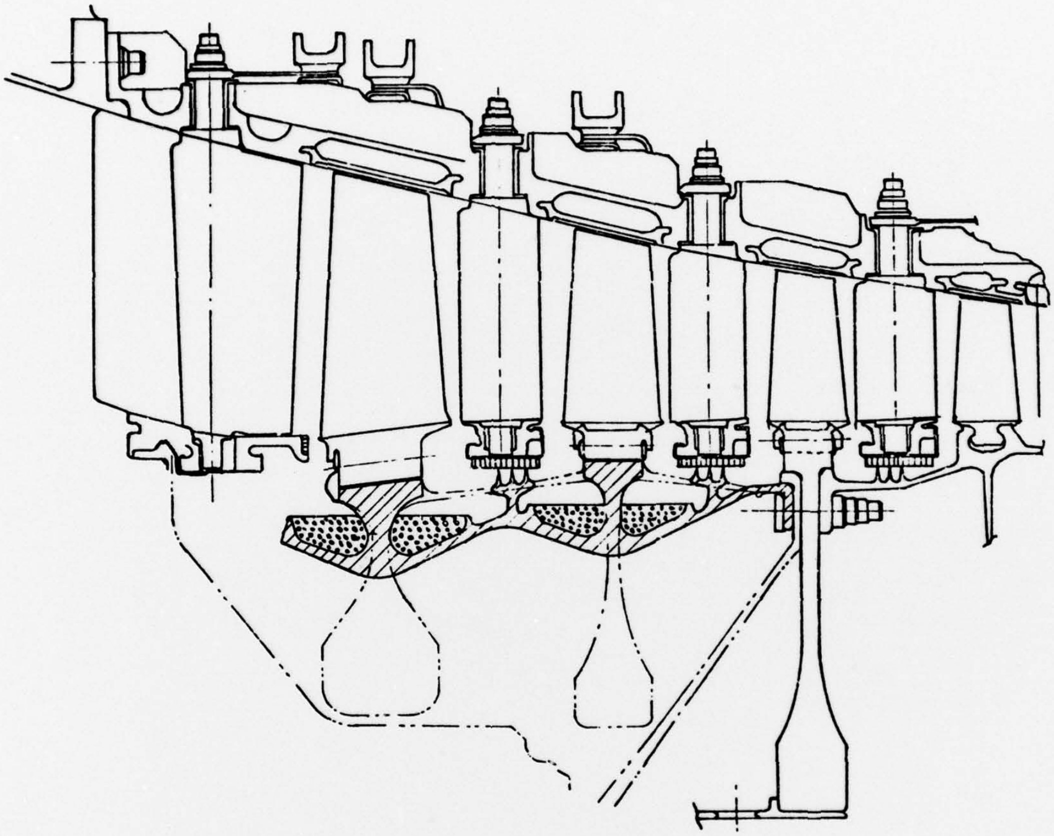


Figure A-31. Supersonic-Flight Compressor Stage 1 and 2 Composite Disk.

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