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HIGH BYPASS TURBOFAN COMPONENT DEVELOPMENT
PHASE II DETAILED DESIGN

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SELECTED
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Aircraft Engine Group
General Electric Co.
Lynn, Massachusetts 01910

August 1979

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

A detailed aerodynamic, aeromechanical and mechanical design of the high bypass turbofan fan stage selected during Phase I of this program was satisfactorily completed. This fan design is the result of aero and aeromechanical iterations and trade-offs which achieved the objectives of meeting aerodynamic performance as well as the life and mechanical considerations of MIL-E-5007D. The resulting fan design compares very closely to the fan originally proposed.

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SECTION I

SUMMARY

This report describes those efforts expended by the Contractor in Phase II - Detailed Design of the High Bypass Turbofan under USAF Contract F-33615-78-C-2060.

With the completion of Phase II, eleven months of the twenty-seven months of effort associated with this program have been completed. The time to date spent on Phase I and Phase II has been devoted to preliminary design and detailed design respectively. The fabrication and test phase remains to be accomplished.

In Phase II, the subject of this report, the Contractor has been able to meld the aerodynamic and the mechanical requirements into a cohesive design which satisfies all of the aero, aeromechanical and mechanical requirements imposed and which, incidentally, comes quite close to the design originally proposed for this program.

The report which follows - the second Interim Technical Report associated with this Contract - documents fully the specific investigations carried out as part of the detailed design effort. The organization of the report is as follows:

o   Fan aerodynamic parametric studies

o   Fan aeromechanical parametric studies

o   Fan aerodynamic design

o   Fan aeromechanical analysis

o   Fan mechanical detail design

Other topics covered in this report include discussions of test equipment and reliability, maintainability and systems safety.

SECTION II

INTRODUCTION

The current primary trainer (T-37) fleet is approaching the end of its useful life and will necessitate the development of replacement aircraft in the near future. In light of the current awareness of life cycle cost and decreasing fuel reserves, the replacement aircraft must have a fuel efficient engine as the propulsion system, i.e., modern turbofan engine. Technology in the large turbofan engines has been well demonstrated, but little has been done in the size applicable to a twin-engine primary trainer aircraft. Today, there is sufficient effort to provide the necessary technology for the development of the engine with the exception of the fan component. It is the objective of this program to develop such a fan using the latest compressor technology.

Phase I - Preliminary Design was successfully completed, as reported in the first interim technical report, including the identification of fan design objectives required for a small turbofan engine intended to power the future Air Force Primary trainer.

This document presents the second interim technical report on the High Bypass Turbofan Program describing the technical work which was done under Phase II - Detailed Design in accordance with the Contract Statement of Work. Specifically, a detailed design of the fan component was generated based upon the Phase I preliminary design. Trade-off studies between aerodynamic design and mechanical design were performed. The detailed design addressed to the design requirements of MIL-E-5007D with special emphasis on foreign object tolerance, distortion and low cycle fatigue.

In recognition of the successful completion of Phase II Detailed Fan Design AFAPL has authorized the execution of Phase III - Fabrication and Test of the Detailed Fan Design.

SECTION III

DESCRIPTION AND RESULTS OF PHASE II TECHNICAL WORK

The following subsections provide details of the technical work performed in accordance with Phase II of the Statement of Work and the significant results obtained.

3.1 FAN AERODYNAMIC PARAMETRIC STUDIES

This subsection describes the aerodynamic parametric studies and trade-offs which were carried out to achieve the performance objectives in a practical and cost effective manner.

3.1.1 Description of Parametric Studies

The first phase of the detailed design of the High Bypass Fan was to perform parametric studies of the important aerodynamic design parameters. The objective of these fan aerodynamic parametric studies are the following:

o   Determine effect of fan design parameters on fan performance.

o   Utilize aerodynamic parametric study trends for trade-off studies with aeromechanical and mechanical parametric studies.

o   Select values of fan design parameters for best balanced fan design.

The standards used to evaluate each of the fan design parameters are listed in Table 1 and reflects a desire to select the best balanced fan design for the trainer engine configuration as defined in Phase I.

The parametric studies utilized a pitchline compressor model to estimate the effect of the design variables on fan efficiency and stall margin. The details of the aerodynamic model used in the parametric study are described in Table 2.

Eleven parameters were selected for the parametric study. These are listed in Table 3. The range studied reflects judgement based on GE experience with other fans and the results of the preliminary parametric studies used for the proposal.

The base point values for the aerodynamic parametric studies are compared to those in the proposal in Table 4. The values were selected to be in the center of the range studied.

Certain parameters were held constant during the parametric studies. These are listed in Table 5. The correct airflow and average pressure ratio were selected in Phase I of the High Bypass Fan contract. The fan does not have an inlet guide vane to reduce cost and complexity. Fan discharge swirl was set equal to 0° for good duct performance. Rotor tip clearance reflects GE experience with similar fan designs.

TABLE 1. STANDARDS FOR EVALUATION OF PARAMETRICS

<u>PARAMETRIC STUDY: STANDARDS OF "GOODNESS"</u>

o   HIGH EFFICIENCY

-   EQUAL TO OR BETTER THAN PROPOSAL EFFICIENCY (.855)

o   STALL MARGIN

-   20% OR BETTER @ 100% $N/\sqrt{\theta}$

o   MEET MECHANICAL AND AEROMECHANICAL DESIGN OBJECTIVES

o   DESIGN COMPATIBLE WITH TRAINER ENGINE CONFIGURATION

-   INNER DUCT

    -   DISCHARGE MACH NO.

    -   DISCHARGE HUB RADIUS

-   TURBINE

    -   RPM

-   CORE COMPRESSOR

TABLE 2. AERODYNAMIC MODEL

GE COMPRESSOR MODEL FOR PARAMETRIC STUDIES

- Pitchline Compressor Model

  - Approximate Hub and Tip Calculations

- Estimates Efficiency Potential Considering:

  - Blade Profile Losses

    Utilizes Compressible Boundary Layer Theory to Extend
    Lieblein's Equivalent Diffusion Factor Model to Higher
    Mach No. Region.

  - Shock Losses Due to Passage Shocks and Bow Shocks.

  - End Wall Losses Due to Boundary Layer and Clearance.

- Estimates Stall Margin Potential

  - Utilizes term "Effectivity" Defined as Ratio of Static Pressure
    Rise Coefficient to Maximum Static Pressure Rise Coefficient
    Possible at Stall.

    o Based on Empirical Correlations Comparing Compressor
      Performance to 2-D Diffuser Performance.

    o Similar Technology Compressors Utilized to Establish Appropriate
      Level of "Effectivity".

TABLE 3. LIST OF PARAMETERS SELECTED FOR STUDY

PARAMETRIC STUDY: RANGE OF VARIABLES

o Rotor Tip Speed – Varied from 1400 to 1500 ft/sec

o Flow/Annulus Area – Varied from 41 to 44 lbm/sec/ft^2

o Inlet Radius Ratio – Varied from .31 to .43

o Stator Discharge Mach No. – Varied from .5 to .6

o Ratio of Rotor Annulus Area Convergence to Stage Annulus Area Convergence – Varied from .6 to .9

o Rotor Pitch Solidity – Varied from 1.7 to 2.05

o Stator Pitch Solidity – Varied from 1.4 to 1.7

o Rotor Aspect Ratio – Varied from 1.0 to 1.5

o Stator Aspect Ratio – Varied from 1.6 to 2.3

o Rotor Tip Flaring (RTOUT/RTIN) – Varied from 1.0 to 1.05

o Stator Tip Flaring (RTOUT/RTIN) – Varied from 1.0 to 1.05

TABLE 4. BASE POINT VALUES FOR AERO DYNMIC STUDY

HIGH BYPASS FAN

PARAMETRIC STUDIES: BASE POINT

Variable	Base Point	Proposal
Rotor Tip Speed (ft/sec)	1450	1455
Flow/Annulus Area (lbm/sec/ft^2)	42.5	43.0
Inlet Radius Ratio	.37	.36
Stator Discharge Mach No.	.55	.55
Ratio of Rotor Annulus Area Convergence to Stage Annulus Area Convergence	.75	.8
Rotor Pitch Solidity	1.9	2.04
Stator Pitch Solidity	1.56	1.71
Rotor Aspect Ratio	1.26	1.27
Stator Aspect Ratio	1.9	2.3
Rotor Tip Flaring (RTOUT/RTIN)	1.0	1.0
Stator Tip Flaring (RTOUT/RTIN)	1.0	1.0

TABLE 5. PARAMETRIC STUDY CONSTANTS

PARAMETRIC STUDY: PARAMETERS HELD CONSTANT

Corrected Airflow	41.6	lbm/sec
Pressure Ratio	1.758	
No Inlet Guide Vane		
Discharge Swirl	0°	
No Shroud		
Clearance	rotor (inches)	.018
	stator	0 (supported on both ends)
Surface Finish		24 RMS
Blade Thickness	Rotor (Tip/Hub)	.03/.096
	Stator (OD/ID)	.09/.05

Stator clearance was set equal to zero since the stator was supported at both ends. The blade/vane surface finish was selected to be 24 RMS to assure good performance at a reasonable cost. The blade thickness reflects a preliminary aeromechanical analysis made for the proposal.

3.1.2 Parametric Study Results

The effect of each fan design parameter on fan stall margin and efficiency was determined by individually varying each parameter about the baseline values to the limit of the range. The results of these perturbations are presented in the following figures:

PARAMETER	FIGURE
Rotor tip wheelspeed	1
Flow per annulus area	2
Rotor inlet radius ratio	3
Rotor discharge axial velocity (rotor area convergence)	4
Fan discharge Mach No.	5
Rotor aspect ratio	6
Stator aspect ratio	7
Rotor solidity	8
Stator solidity	9

The effects of various fan parameters on fan stall margin and efficiency are summarized in Table 6. Lowering the flow per annulus area improved stall margin and efficiency. Efficiency is improved by lowering rotor tip wheelspeed, rotor discharge axial velocity or rotor solidity, but at the expense of stall margin.

A review of the internal details of the fan flow field indicated that flow conditions were most severe in the hub region. Therefore, special attention was directed towards reducing the severity of conditions in the hub which could increase the risk of not meeting the performance predicted by the model. These conditions examined are:

o   Rotor hub discharge relative angle

o   Stator hub inlet Mach No.

o   Stator hub diffusion factor

It is desirable that the rotor hub discharge relative air angle be positive. The combination of a high stator hub inlet Mach No. and high stator hub diffusion factor was considered risky and so either one or both should be reduced to improve efficiency. Reducing the stator hub diffusion factor would also help stall margin potential.

The fan performance should be balanced against inner duct performance to assure good engine performance. The prime considerations would be:

HIGH BYPASS FAN

AERODYNAMIC DESIGN PARAMETRIC STUDIES

Figure 1. Rotor Tip Wheel Speed

HIGH BYPASS FAN
AERODYNAMIC DESIGN PARAMETRIC STUDIES
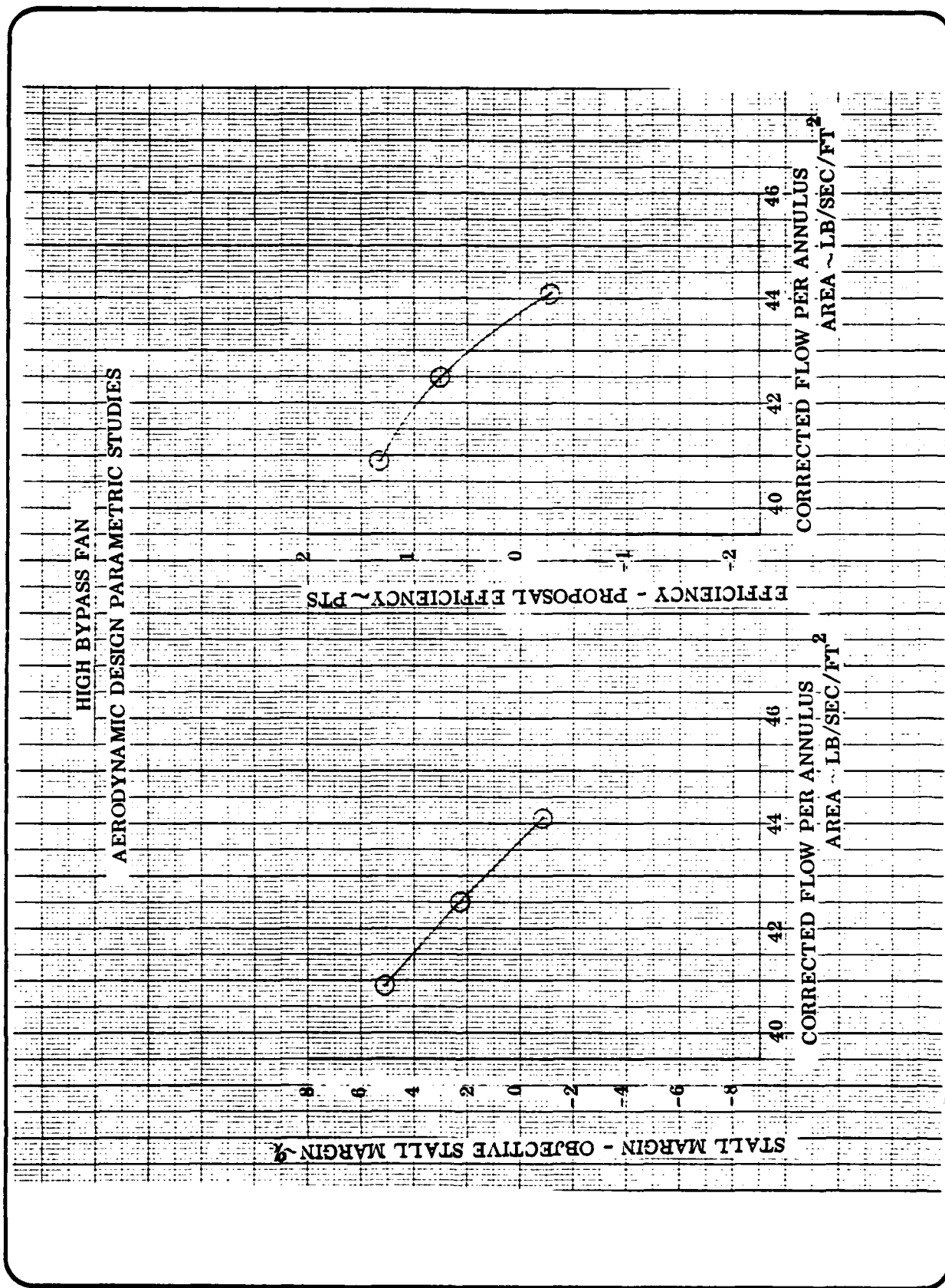
Figure 2. Flow Per Annulus Area
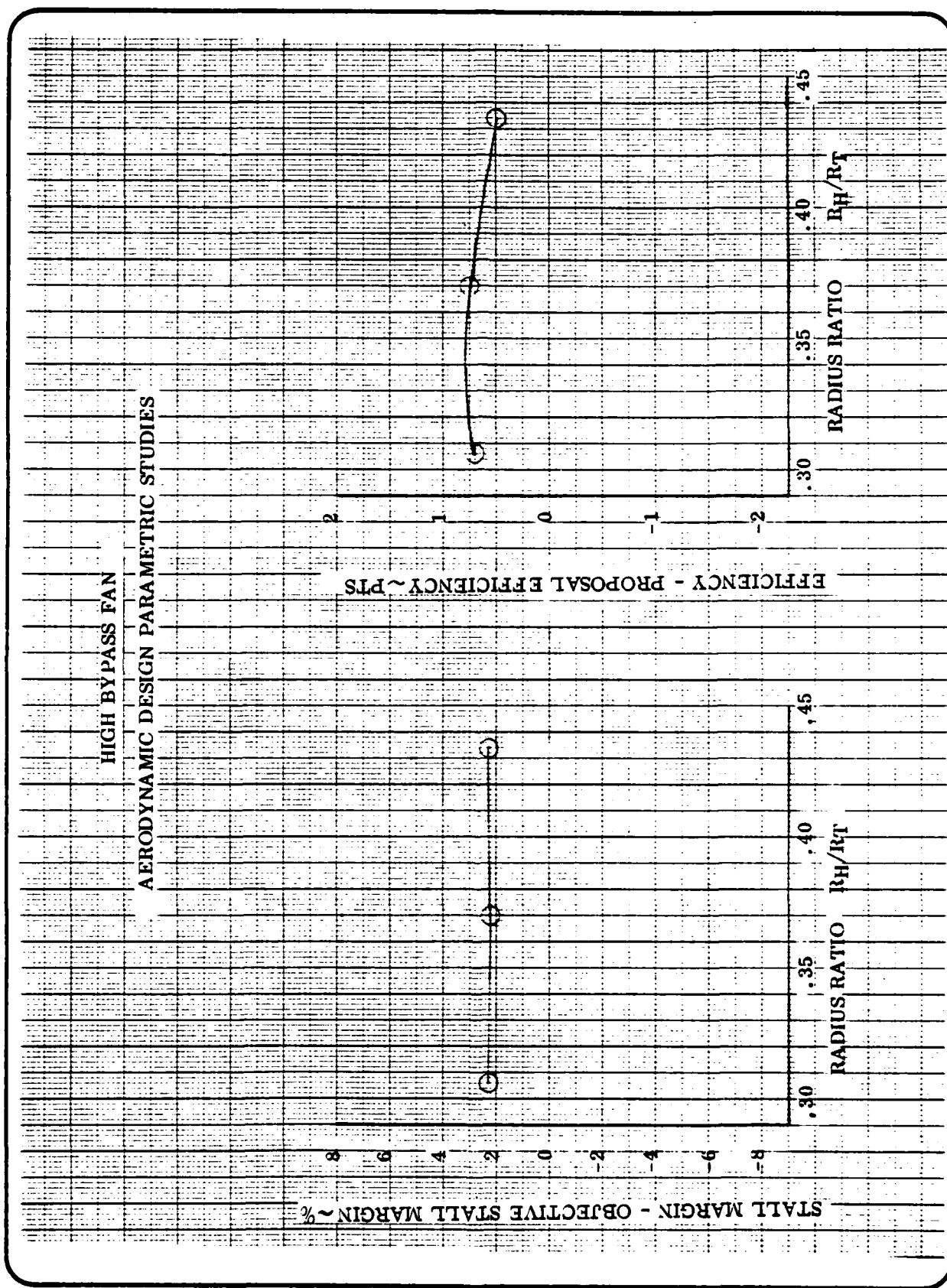
Figure 3. Rotor Inlet Radius Ratio

Figure 4. Rotor Discharge Axial Velocity (Rotor Area Convergence)
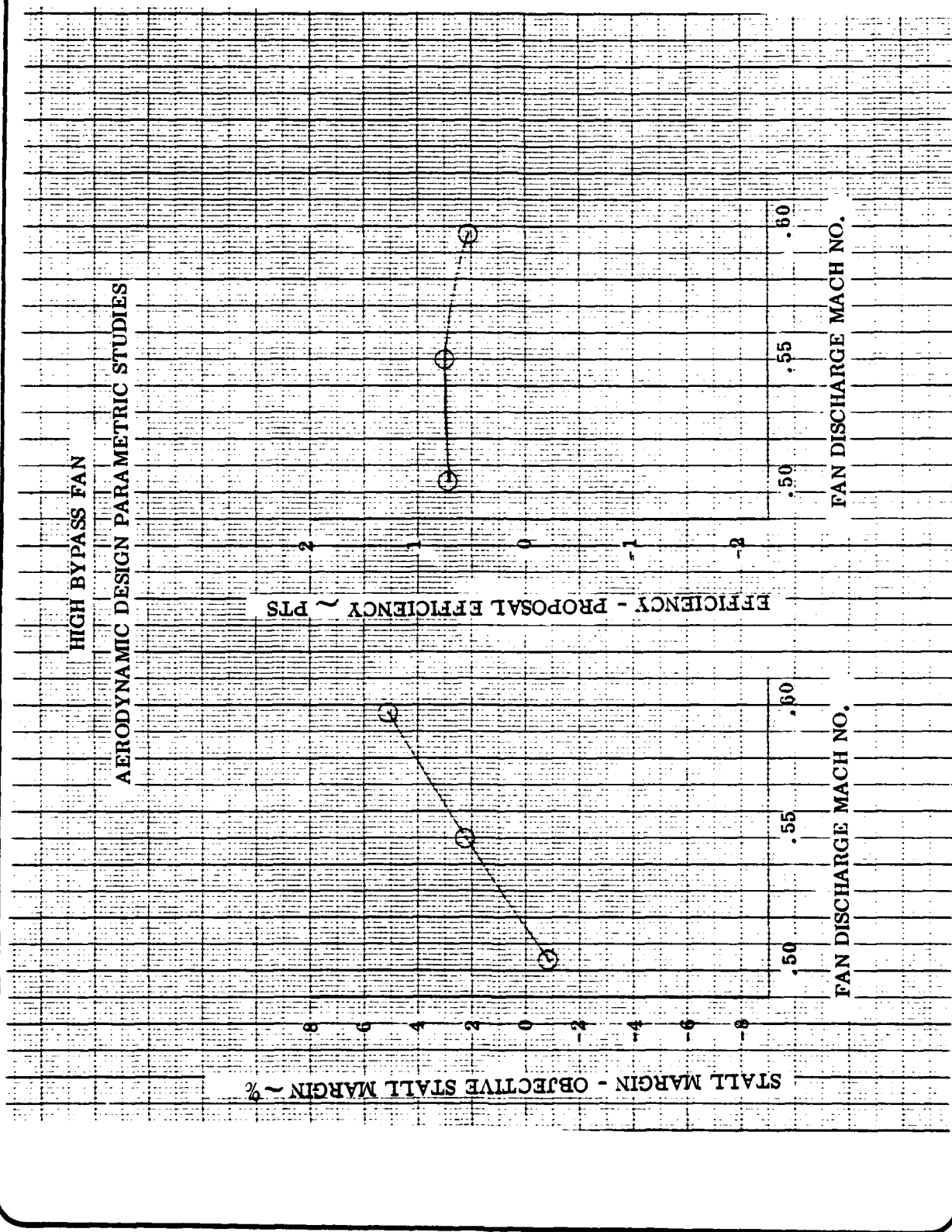
Figure 5. Fan Discharge Mach No
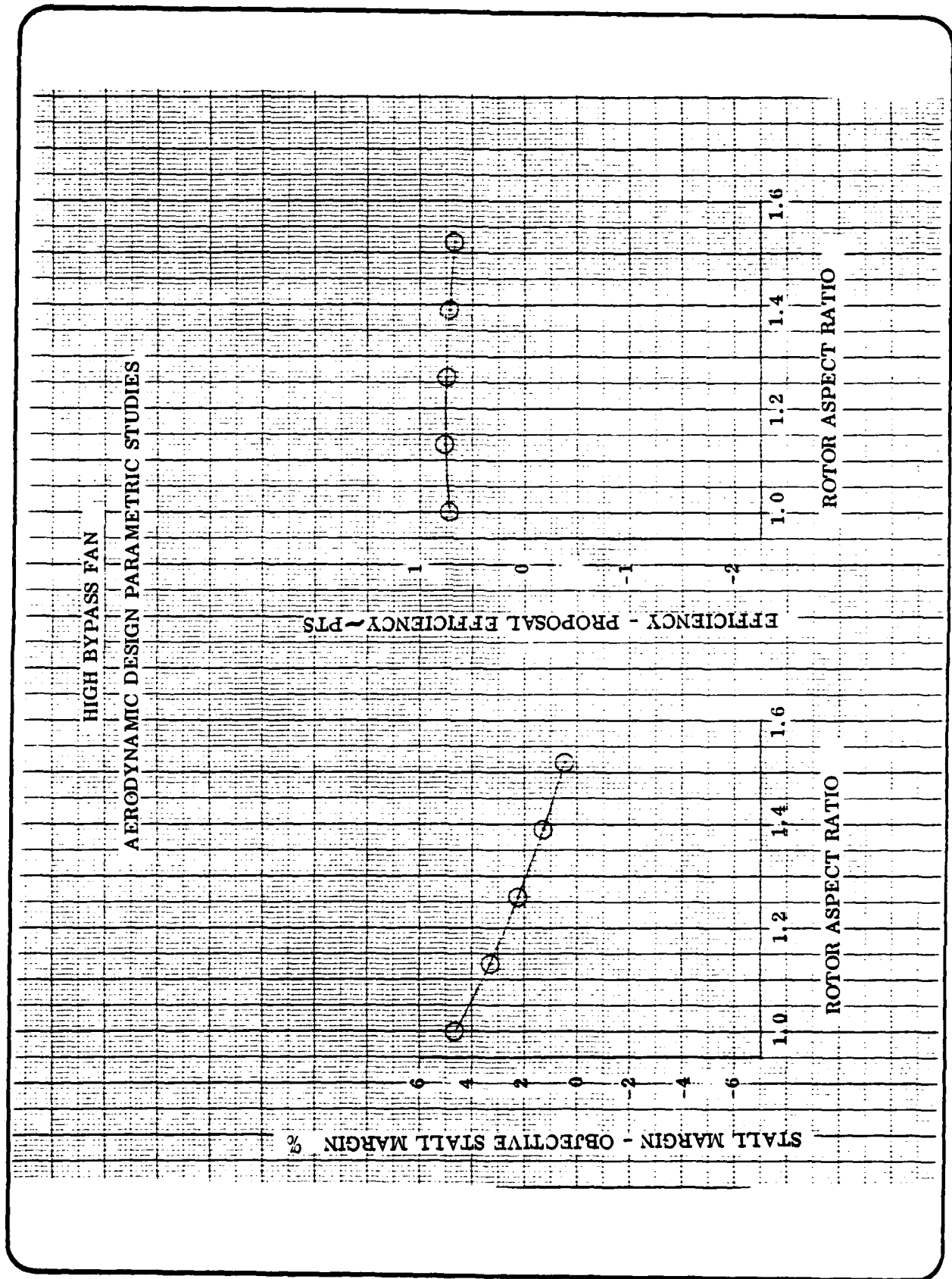
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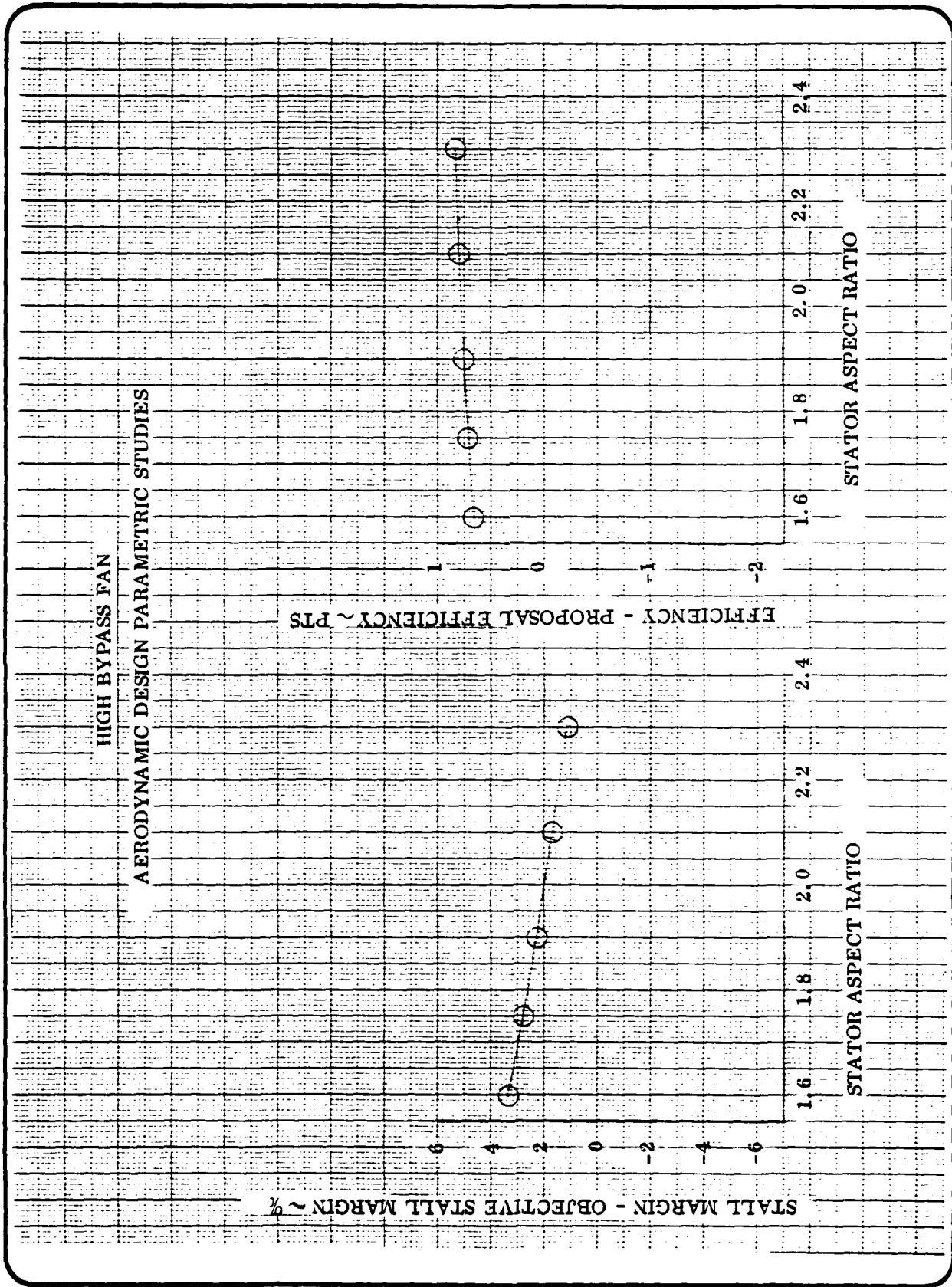
Figure 7. Stator Aspect Ratio
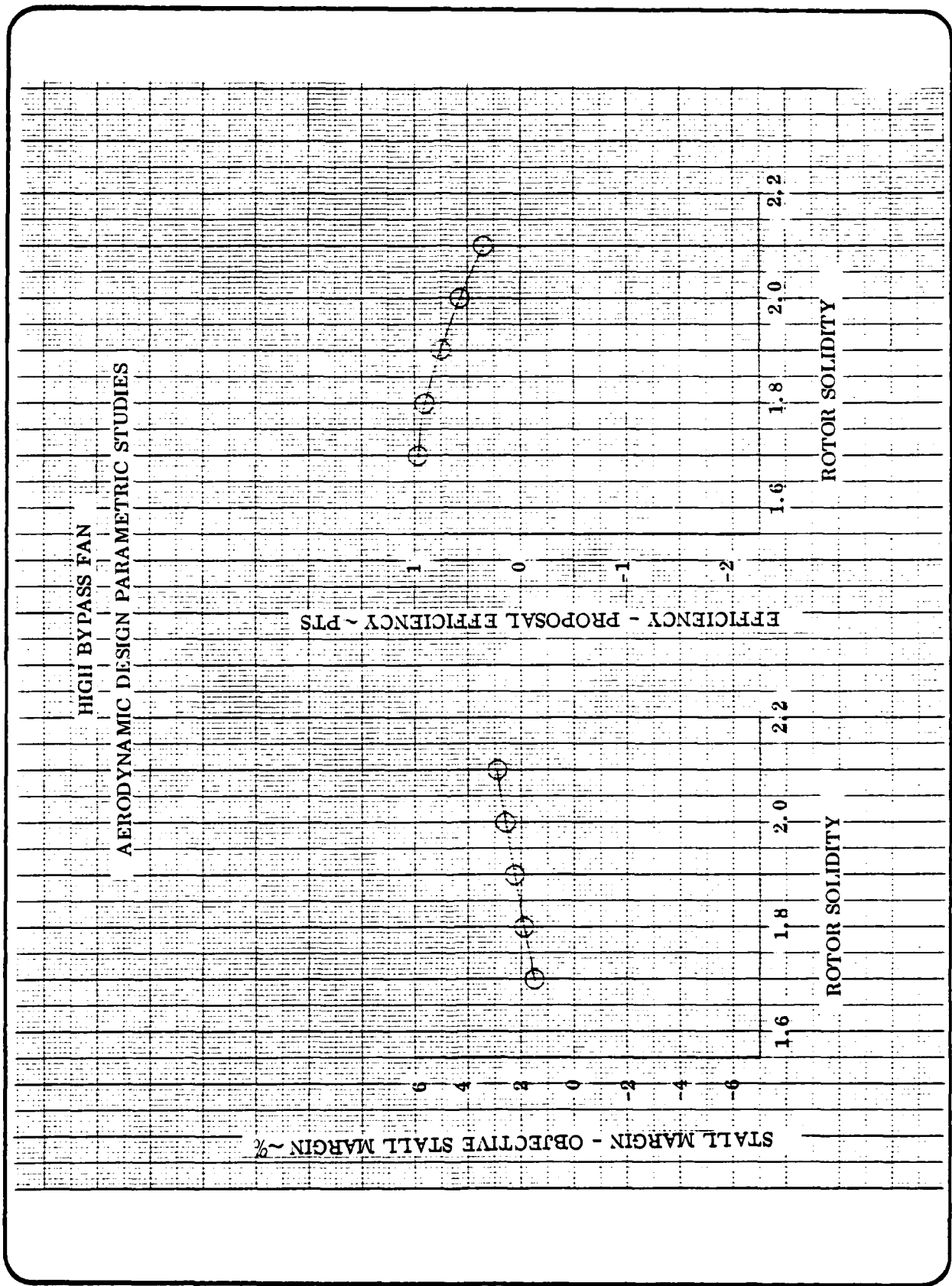
Figure 8. Rotor Solidity
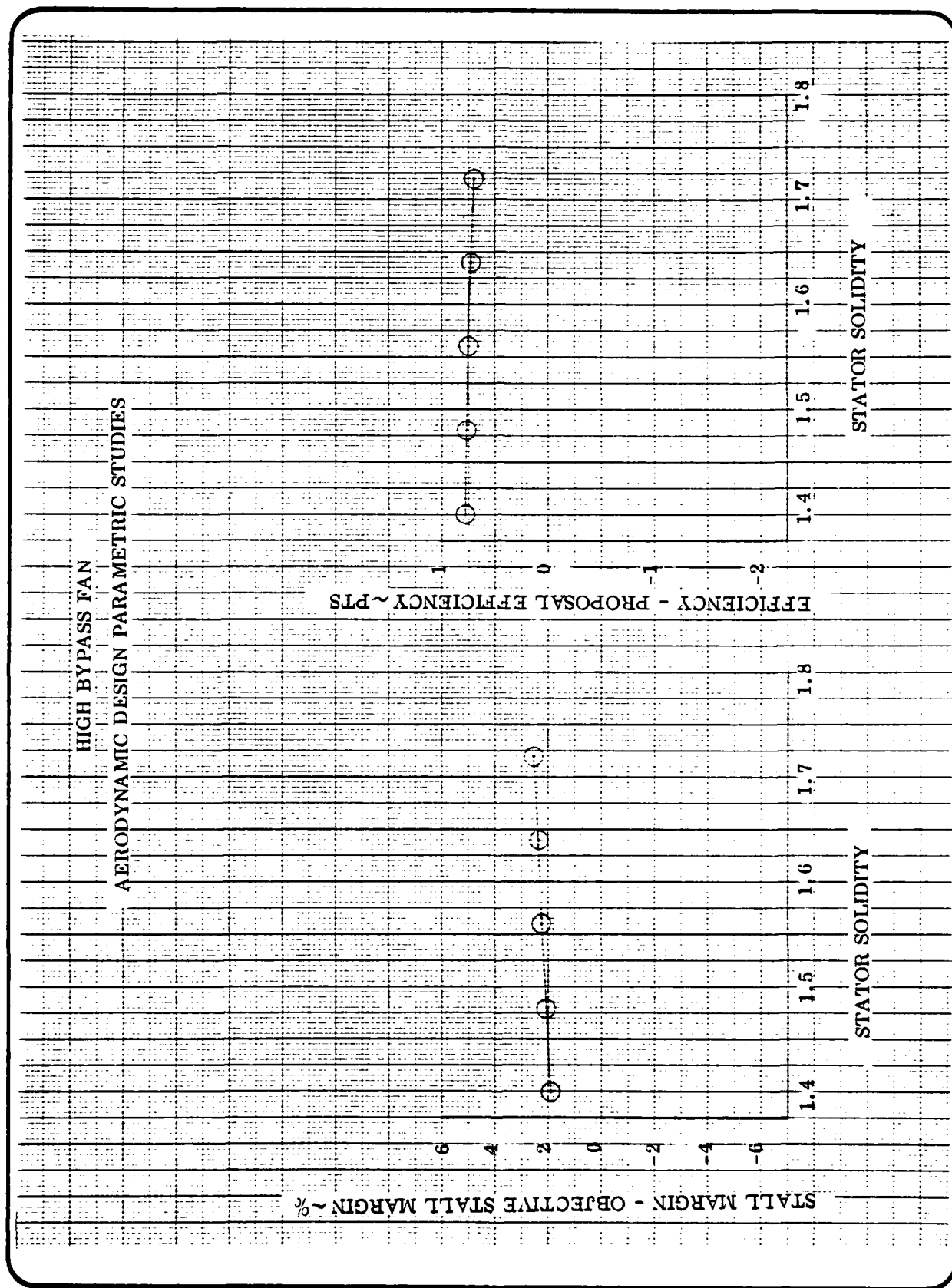
Figure 9. Stator Solidity

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TABLE 6. EFFECTS OF PARAMETRIC ON STALL MARGIN AND EFFICIENCY

HIGH BYPASS FAN

AERODYNAMIC PARAMETRIC STUDY RESULTS

CHANGE IN PARAMETER FROM BASE VALUE TO OPTIMIZE PERFORMANCE

Parameter	Stall Margin	Efficiency
Rotor Tip Wheelspeed	increase	decrease
Flow/Annulus Area	decrease	decrease
Rotor Inlet Radius Ratio	no effect	optimum
Rotor Discharge Axial Velocity	increase	decrease
Stator Discharge Mach No.	increase	optimum
Rotor Aspect Ratio	decrease	no significant effect
Stator Aspect Ratio	decrease	no significant effect
Rotor Solidity	increase	decrease
Stator Solidity	increase	no significant effect

o   Stator discharge Mach No.

o   Stator discharge Hub Radius

For the trainer fan configuration defined in Phase I, a stator hub discharge radius greater than 4.5 inches would require a longer duct or more gooseneck than previous GE fan-compressor ducts.

The effect of the fan design parameters on fan hub conditions and intercompressor duct are presented in the following figures:

PARAMETER	FIGURE
Rotor tip wheelspeed	10
Flow per annulus area	11
Rotor inlet radius ratio	12
Rotor discharge axial velocity	13
Fan discharge Mach No.	14

A summary of the effects of various fan design parameters on the fan hub flowfield and stator discharge hub radius is given in Table 7. It shows that increasing rotor tip wheelspeed and rotor inlet radius ratio or decreasing flow per annulus area help the fan hub flow conditions. Increasing flow per annulus area or decreasing rotor inlet radius ratio and stator discharge Mach No. reduce fan discharge hub radius.

The concept of flaring the casing over the rotor and/or stator was also explored during the parametric studies. Figure 15 illustrates the concept of flaring. The flared rotor has a higher discharge radius for a given set of through-flow velocities and so the rpm can be reduced to maintain discharge wheelspeed. Consequently, the inlet Mach No. and the associated losses are reduced.

The effect of rotor casing flaring on fan efficiency and stall margin is shown in Figure 16. Rotor casing flaring improves stall margin but fan efficiency is lower. Lowering the rotor tip wheelspeed improves the efficiency, but gives up some of the stall margin gained by flaring. The fan discharge hub radius is much higher with the flared casing.

Stator casing flaring did not alter flow field parameters and so it is not shown. The fan discharge radius is higher with stator casing flaring.

The parametric study indicated that rotor casing flaring improves stator hub inlet Mach Number and stator hub diffuser factor (Figure 17). But lowering the rotor tip wheelspeed gives up some of the gains due to flaring. Considerations of curvature effects not accounted for in parametric model would raise stator hub
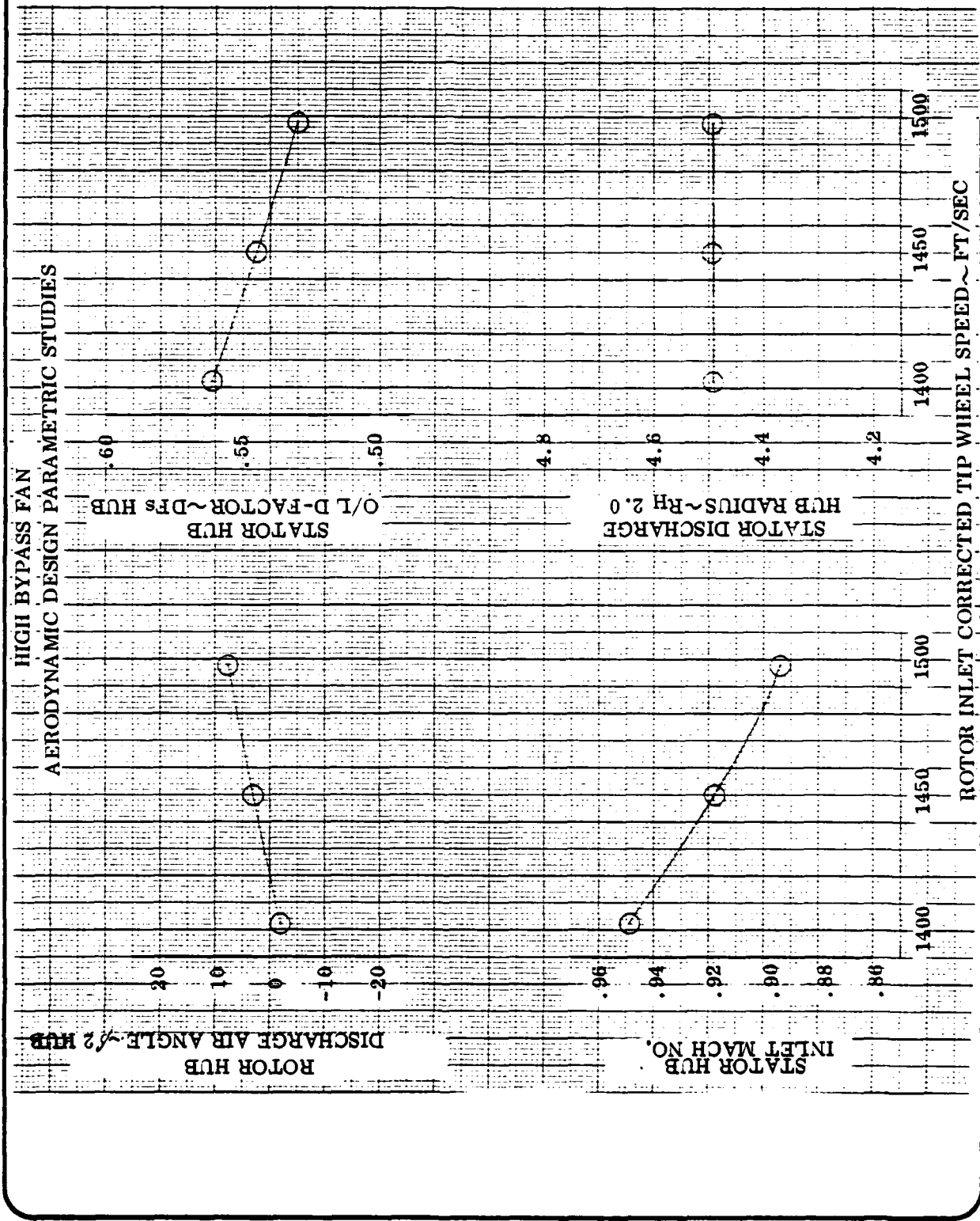
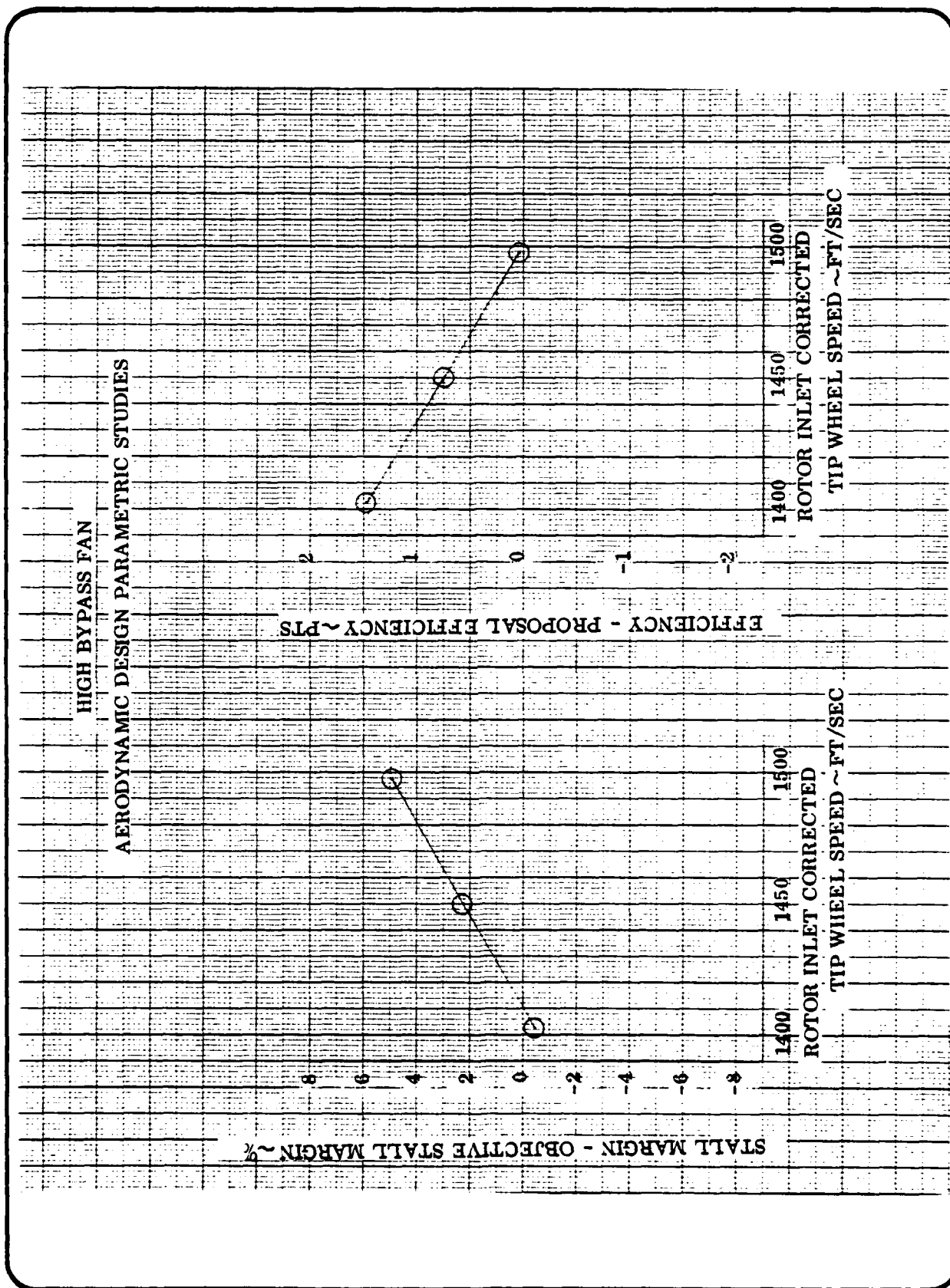Figure 10. Rotor Tip Wheelspeed
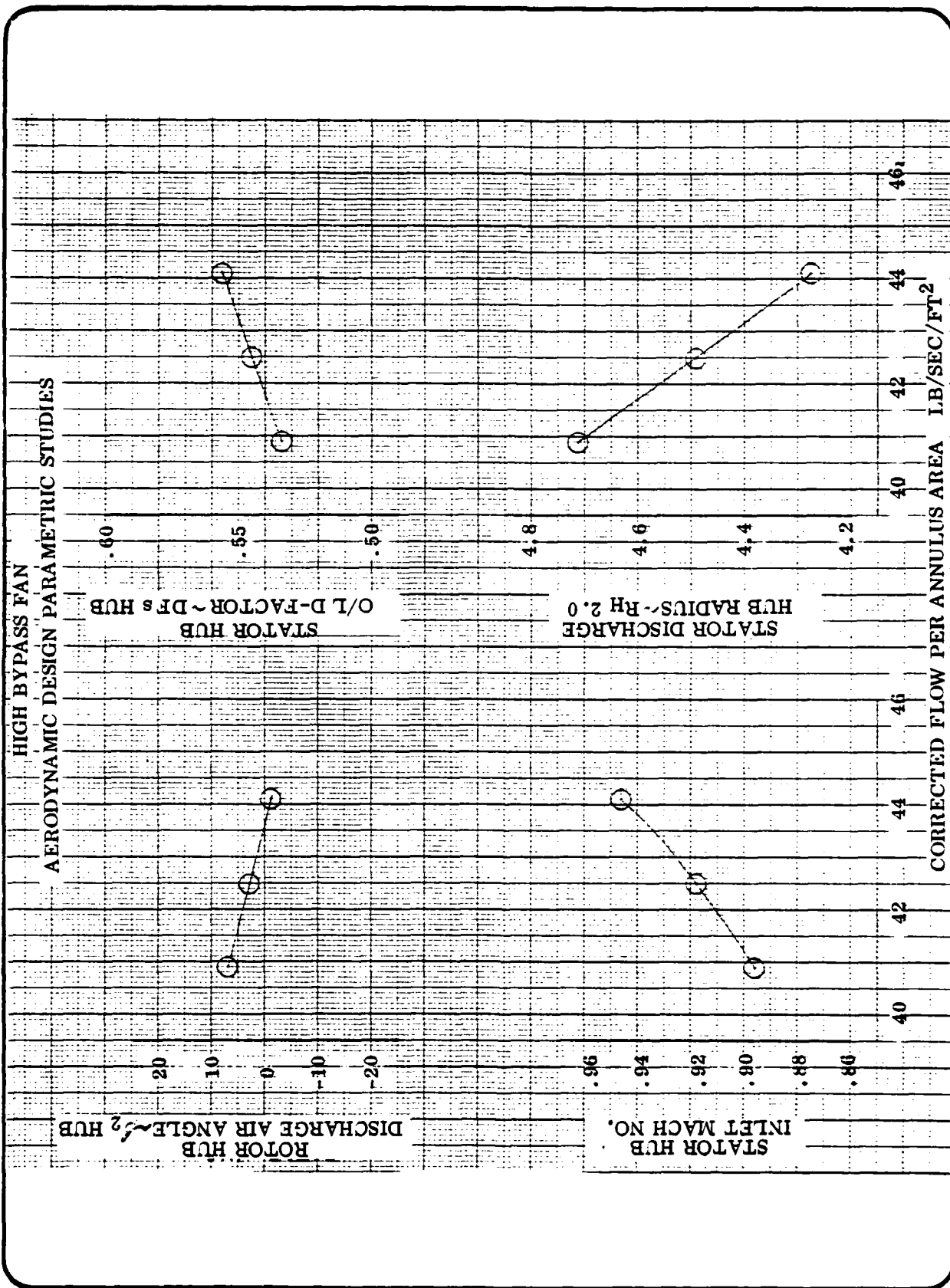
Figure 11. Flow Per Annulus Area
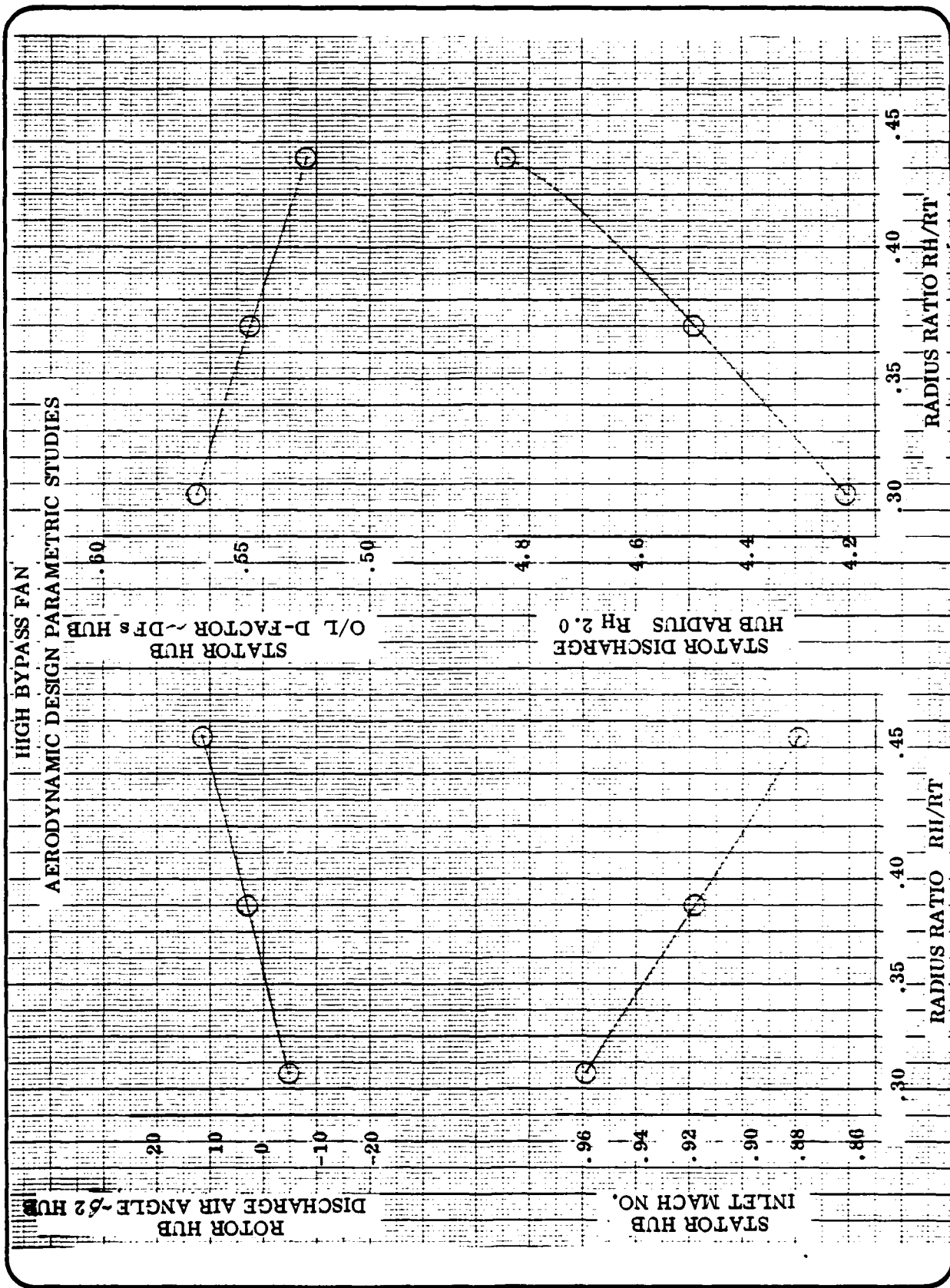
Figure 12. Rotor Inlet Radius Ratio

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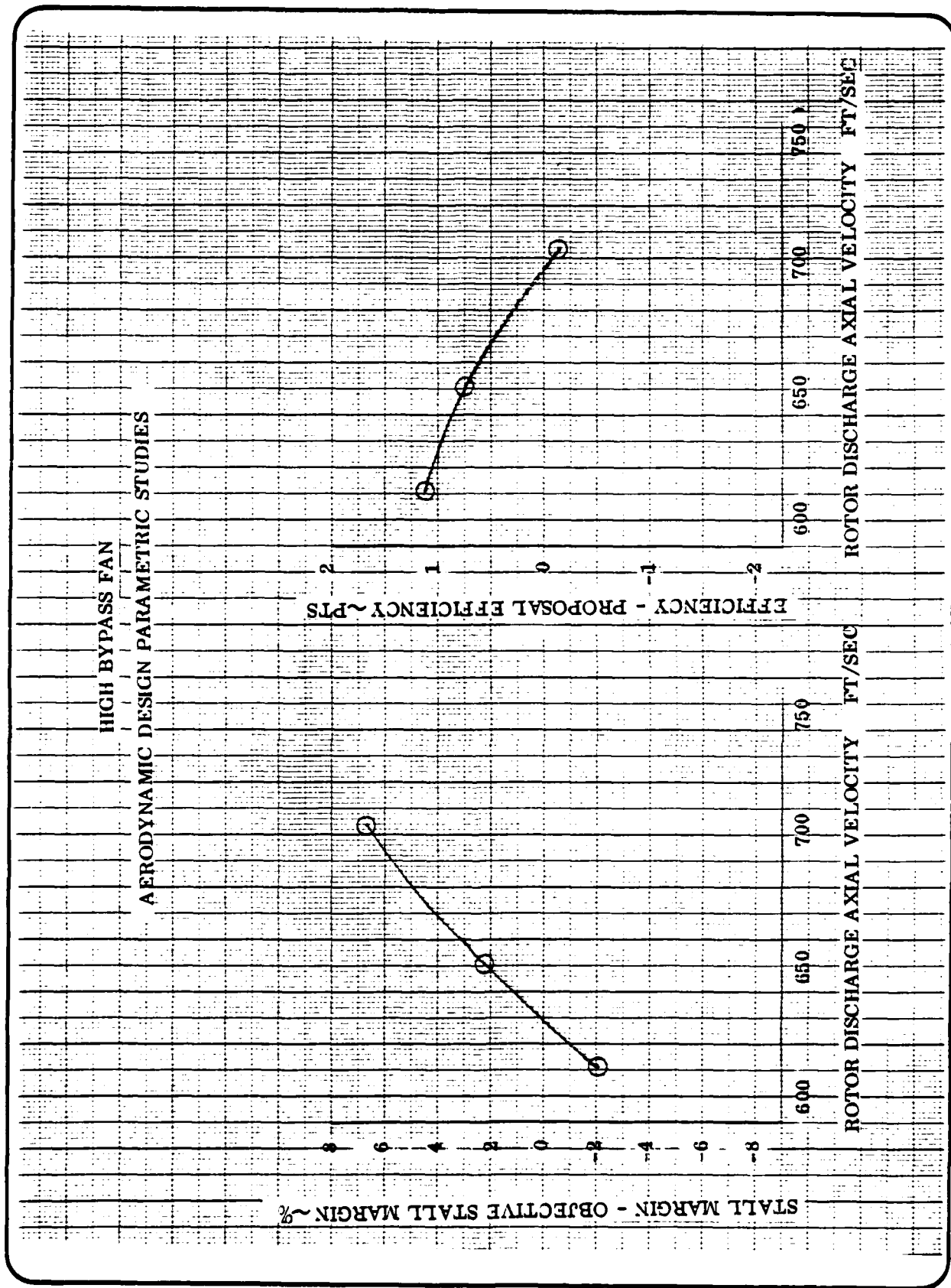
Figure 13. Fan Rotor Discharge Axial Velocity
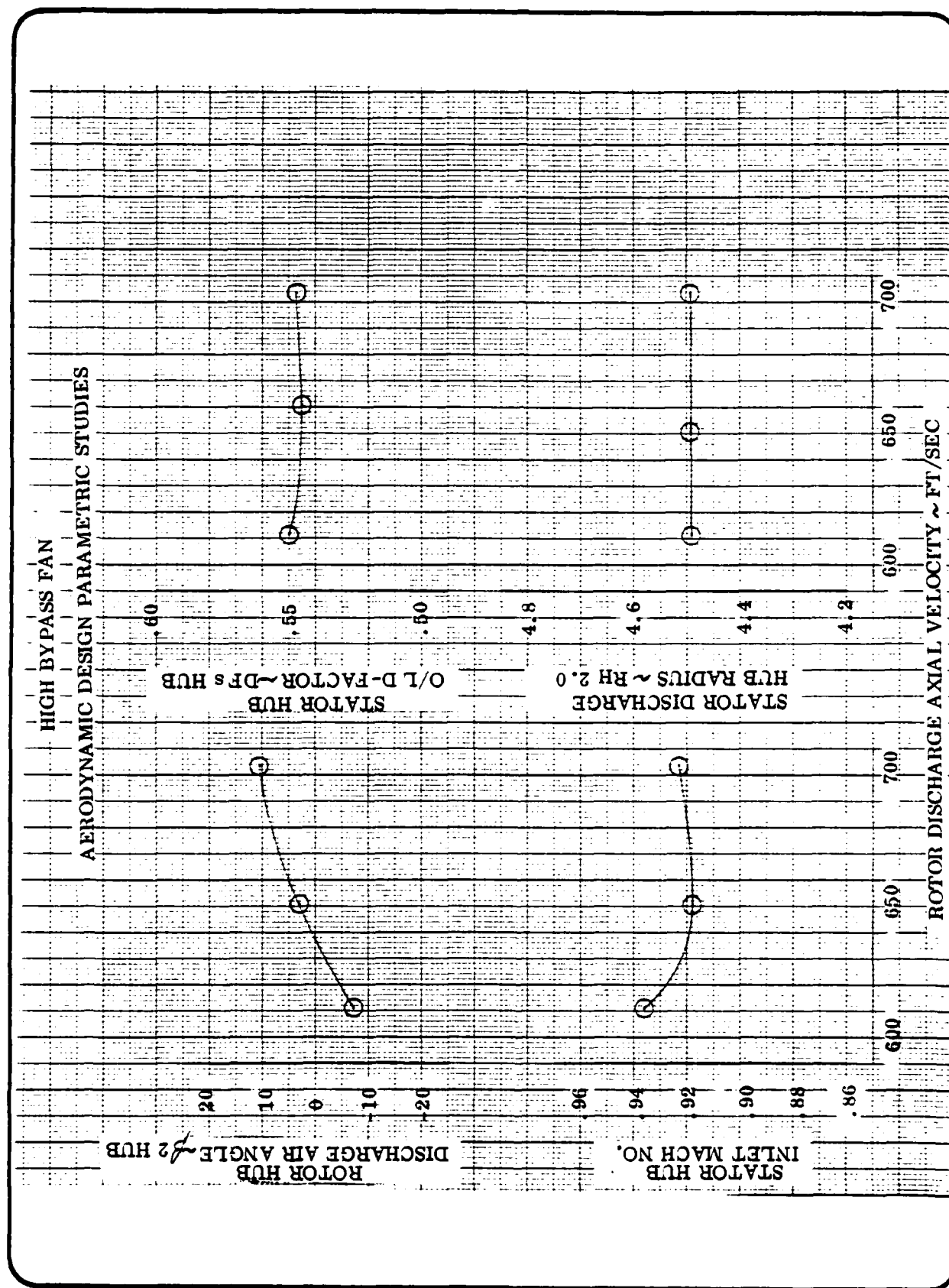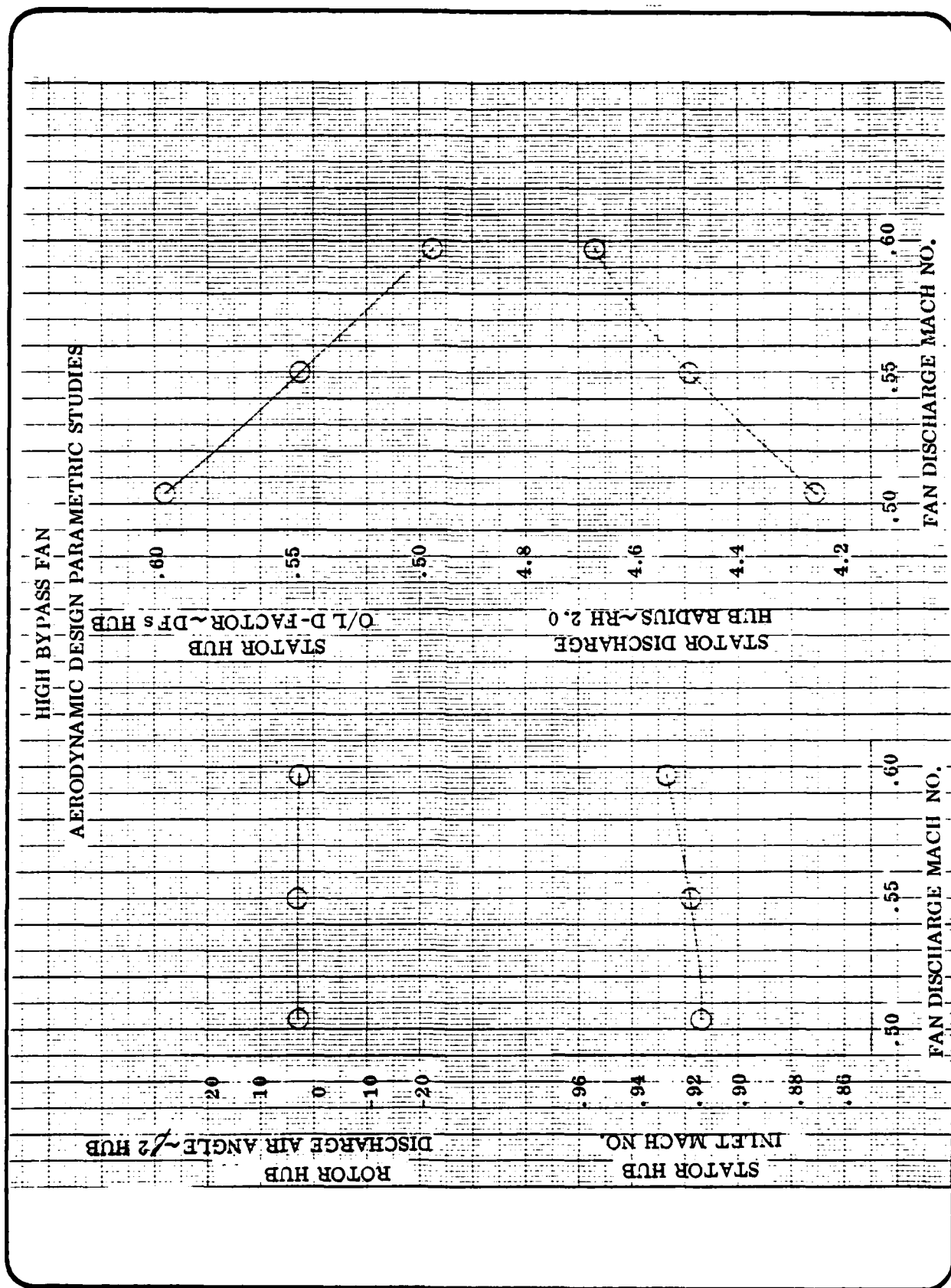
Figure 14. Fan Discharge Mach No.

TABLE 7. SUMMARY OF FAN PARAMETRIC EFFECTS

HIGH BYPASS FAN

AERODYNAMIC PARAMETRIC STUDY RESULTS

CHANGE REQUIRED TO IMPROVE CRITICAL HUB CONDITIONS AND TO IMPROVE INNER DUCT PERFORMANCE

Parameter	Rotor Hub Discharge Air Angle	Stator Hub Inlet Mach No.	Stator Hub D-Factor	Stator Discharge Hub Radius
Rotor Tip Wheelspeed	Increase	Increase	Increase	No Effect
Flow/Annulus Area	Decrease	Decrease	Decrease	Increase
Rotor Inlet Radius Ratio	Increase	Increase	Increase	Decrease
Rotor Discharge Axial Velocity	Increase	Optimum	Optimum	No Effect
Stator Discharge Mach No.	No Effect	Decrease	Increase	Decrease

HIGH BYPASS FAN

SCHEMATIC OF FLARED CASING CONFIGURATION

CYLINDRICAL CASING

FLARED ROTOR CASING

FLARED ROTOR & STATOR CASING
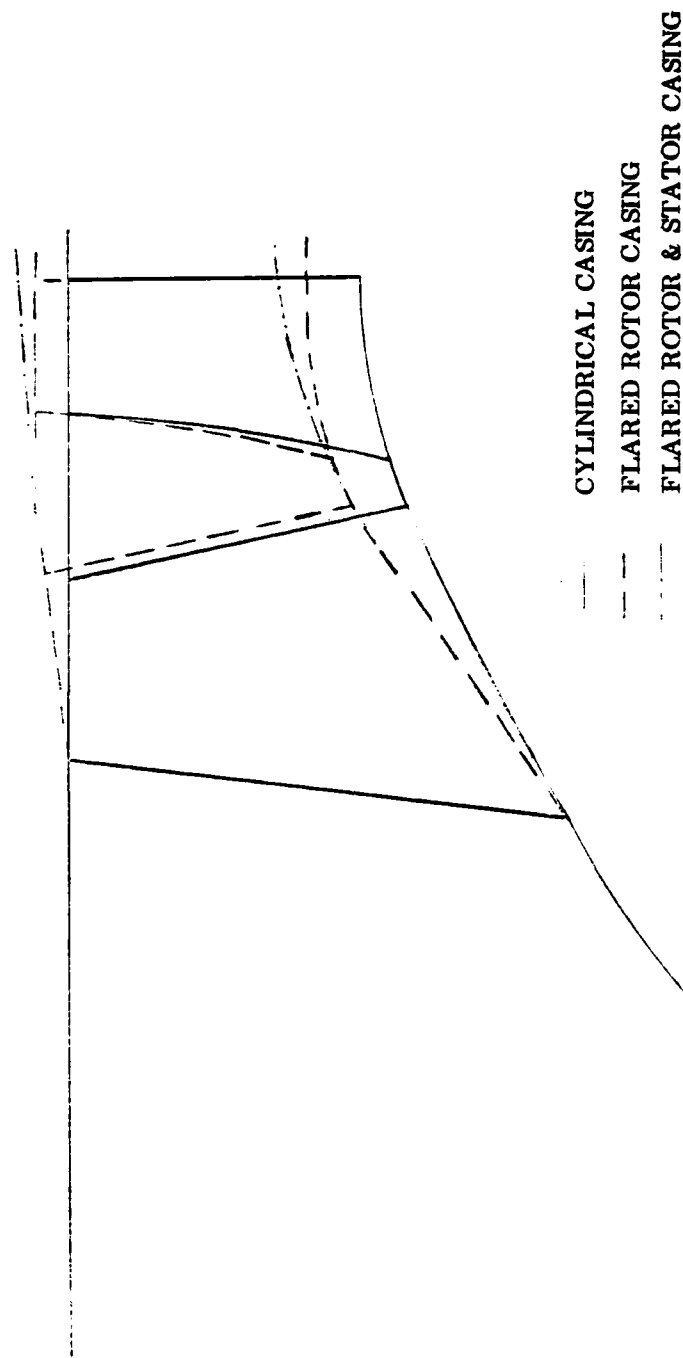
Figure 15. Flowpath Flaring Concept
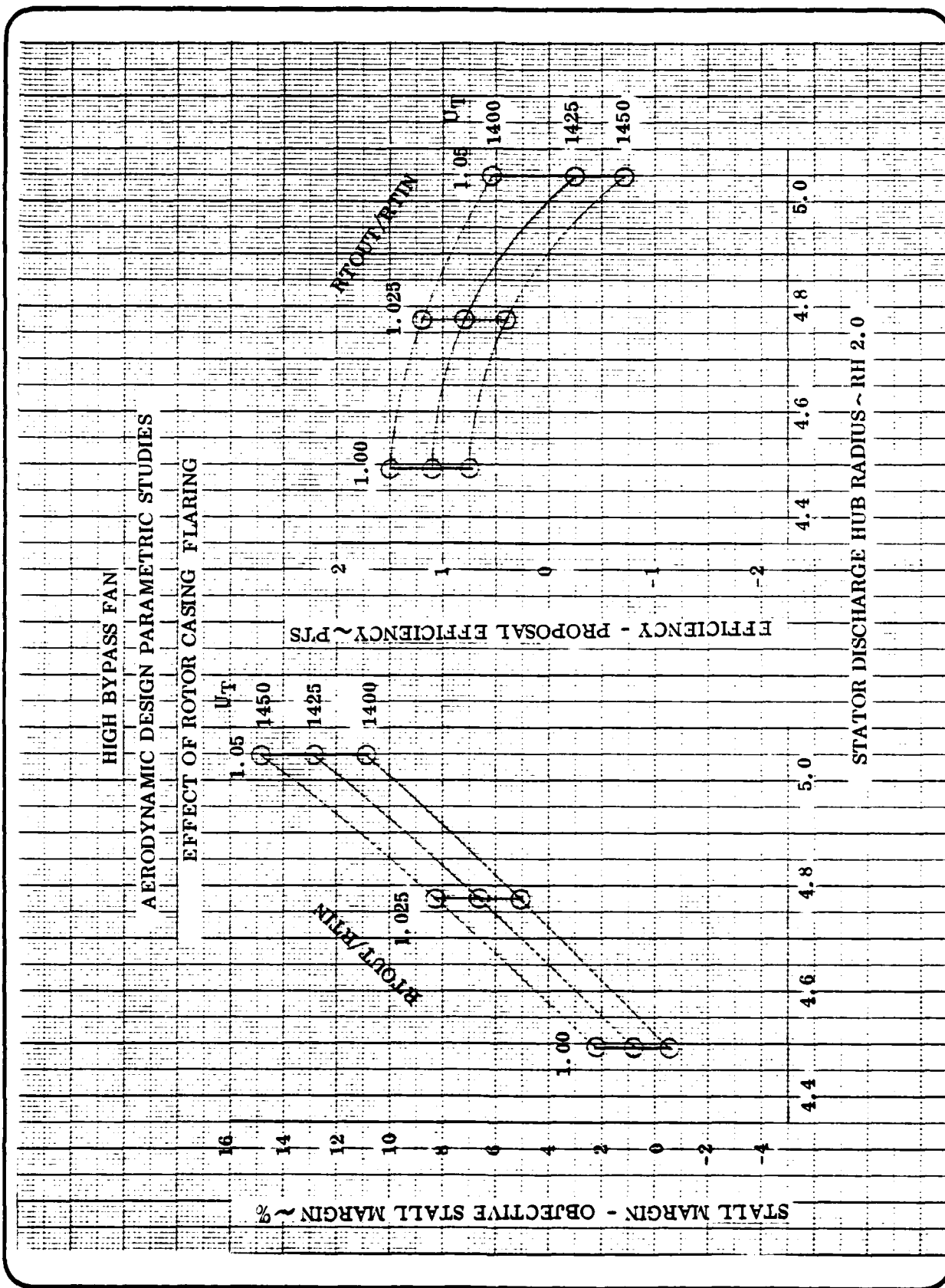
Figure 16. Effects of Flaring on Efficiency and Stall Margin

HIGH BYPASS FAN

AERODYNAMIC DESIGN PARAMETRIC STUDIES
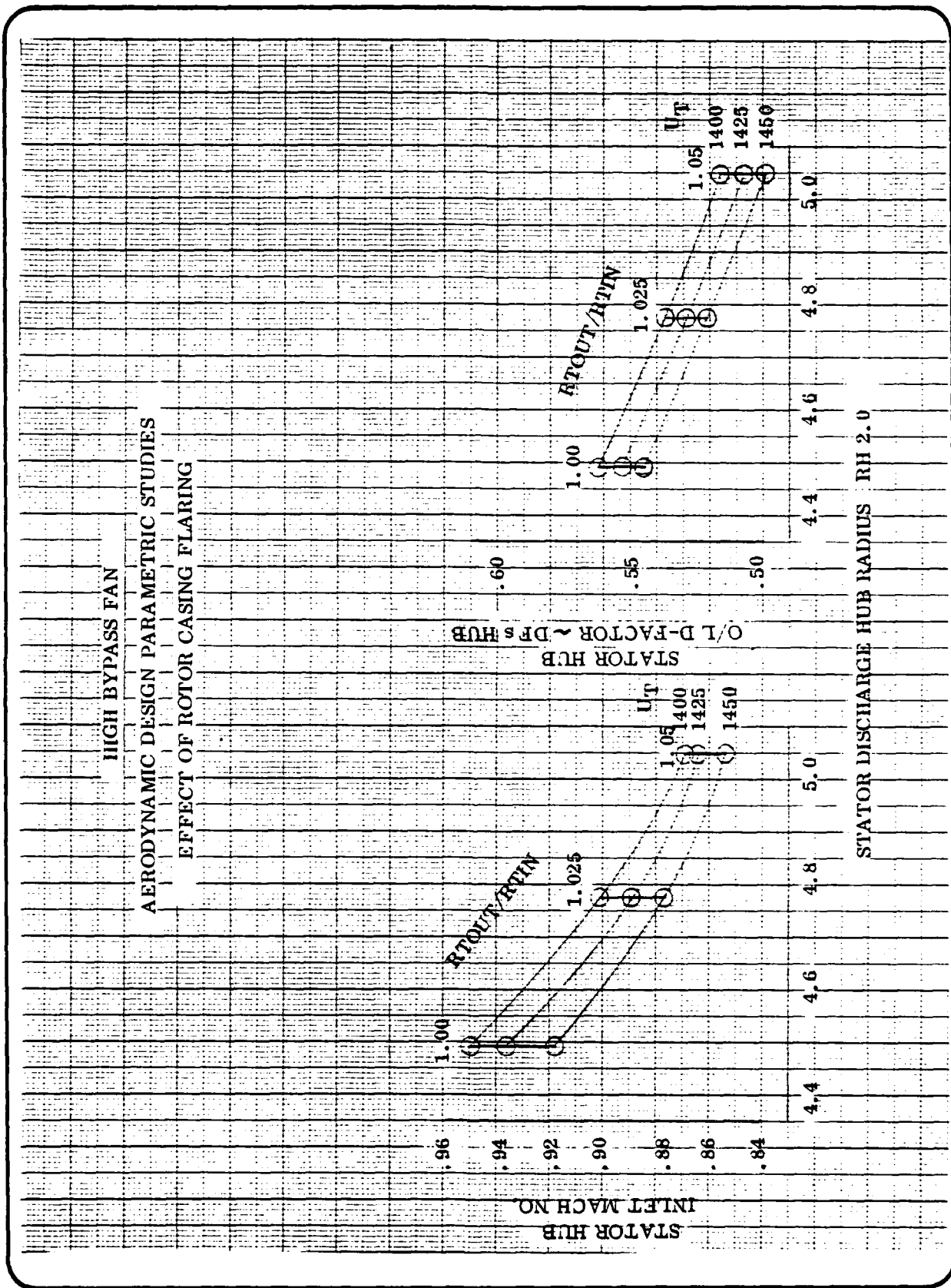
EFFECT OF ROTOR CASING FLARING

Figure 17. Rotor Casing Flaring Effects

inlet Mach Number for the case of rotor casing flaring, reducing the improvement predicted by the model.

The effect of rotor casing flaring is summarized in Table 8. Flaring did improve fan performance, but the resultant penalties in other components offset the gains for this engine cycle.

TABLE 8. ROTOR CASING FLARING EFFECTS SUMMARY

ROTOR CASING FLARING

o FLARING COMBINED WITH LOWER TIP SPEED, IMPROVES FAN EFFICIENCY

o FLARING RAISES DISCHARGE HUB RADIUS

   - MORE SEVERE DUCT

o LOWER TIP SPEED (RPM) HURTS LP TURBINE PERFORMANCE AND COULD REQUIRE OGV

o PENALTIES OFFSET GAINS FOR THIS ENGINE CYCLE

3.2 FAN AERO-MECHANICAL PARAMETRIC STUDIES

This subsection describes the aeromechanical parametric studies necessary to serve as a basis for selecting a fan design mutually compatible with aerodynamic/aeromechanical/mechanical program design objectives. Parametric study results for the selected fan configuration are presented and evaluated.

3.2.1 Fan Aeromechanical Design Objectives

Advanced turbofan technology tends toward higher performance, lighter weight and lower cost. The resulting aerodynamic design trends impose greater challenges for both the aerodynamic and aeromechanical design analysis areas. Furthermore, optimization to improve, or provide for, certain mechanical design features - e.g., airfoil resistance to ingestion/FOD damage - can be in direct opposition to optimization for aerodynamic considerations. Therefore, it is necessary that the fan design be carefully derived and all design parameters fully exercised in order to achieve a balance between both aerodynamic and aeromechanical objectives. The requirements relative to mechanical performance and the criteria established to insure achieving these performance goals are identified in Tables 9 and 10 respectively.

3.2.2 Parametric Studies

The design of the fan blade and vane airfoils is derived from an iterative process. The basic performance requirements and program goals establish a preferred selection (or preferred range) of radius ratio, tip speed, aspect ratio and solidity. The aeromechanical rationale for choosing amongst these parameters is embodied in the influence that each has in contributing to the attainment of the goals/criteria established for the design. Values for the design parameters mentioned previously are chosen to give the most favorable mechanical results of frequency, stress, stability. The blade geometry, to include area, camber and stagger distribution is then utilized to obtain the desired mechanical design objectives. For example, Figure 18 shows in parametric fashion the method used to size airfoils for 2/rev avoidance and what the attendant stability (reduced velocity parameter) implications are. Note that the parameters of tip speed (U_T), root aspect ratio, average radius ratio and blade geometry all can be manipulated to identify mutually acceptable values for attaining both the aerodynamic and mechanical design goals. In like fashion, Figure 19 employs the same parametric philosophy to select airfoil design parameters consistent with achieving objectives with respect to high cycle fatigue capability. Advantage can be taken of relative geometric size relationships between rotor and stator designs, as shown in Figure 20, to obtain optimum panel mode resonant placement characteristics. This might have constituted the bulk of the design problem were it not for the requirement to satisfy the MIL spec bird ingestion criteria. In addressing to the MIL spec, Table 11 outlines the requirements and identifies the related general considerations/concerns. Because the GE26/F4 frontal area is 165 in.^{2}, only 4 oz. and 2 lb. bird sizes are relevant.

TABLE 9. MECHANICAL PERFORMANCE REQUIREMENTS

AERODYNAMIC/AEROMECHANIC DESIGN TRENDS

HIGH PERFORMANCE FAN DESIGN REQUIRED AERODYNAMIC GOALS:

- HIGH SPECIFIC FLOW (I.E., FLOW/ANNULUS AREA), GENERALLY REQUIRING HIGH TIP SPEED AND RELATIVE MACH NO., WITHOUT SACRIFICING EFFICIENCY.

- HIGH AVERAGE PRESSURE RATIO

- ADEQUATE STALL MARGIN

- MORE, ACTIVE CLEARANCE CONTROL

  RESULT: THIN, HIGHLY TWISTED, LOW RADIUS RATIO, LOW ASPECT RATIO, HIGHLY LOADED, FAN STAGE

- RECOGNIZING AERODYNAMIC INTENT/CONSTRAINTS, MECHANICAL PERFORMANCE MUST:

  - Avoid Forced Vibration Problems Through Frequency and/or Stimulus Control.

  - Provide Suitable Aeroelastic Stability Margin for Unrestricted Fan Mapping.

  - Satisfy MIL-E-5007D FOD/Ingestion Requirements.

  - Assure Adequate Airfoil HCF Capability By Controlling Induced Steady-State Stresses.

- TRADEOFF STUDIES/ITERATIONS REQUIRED TO ACHIEVE A BALANCED AERODYNAMIC/ AEROMECHANICAL DESIGN

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TABLE 10. AEROMECHANICAL CRITERIA

AEROMECHANICAL OBJECTIVES/CRITERIA

THE AEROMECHANICAL OBJECTIVES INCORPORATED INTO THE DESIGN ARE:

- **FORCED VIBRATION . . . FREQUENCY/STIMULUS CONTROL**

  - First Fundamental Mode of Vibration Avoidance of 2/Rev Excitation

  - Fundamental Mode Vibration (Flex, Torsion) Avoidance of Integral Order Excitation (3/Rev, 4/Rev, etc.) at the Design Speed

  - Fundamental Panel Mode Passing Stimulus Resonance Below Idle Speed (Rotor) and Above Design Speed (Stator)

  - Attenuate Wake Strength Potential by Setting Adequate Axial Spacing Between Rotor and Stator

- **FORCED VIBRATION . . . HCF CAPABILITY**

  - Airfoil Steady Stress Levels Consistent with Previous Experience on Production Parts

- **AEROELASTIC STABILITY (SUBSONIC AND SUPERSONIC)**

  - Stable Operation Over the Range of Anticipated Operating Conditions to Include Operational Extremes and Inlet Pressure Distortion Characteristics

- **MIL SPEC FOD/INGESTION**

  - Bird Ingestion Capability Will Be an Integral Part of Design Selection Procedure

  - Minimize Leading Edge Steady State Stresses

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Figure 18. Method for Airfoil 2/Rev Avoidance

PARAMETRIC FOR SELECTING AIRFOIL PARAMETERS CONSISTENT WITH ACHIEVING STRESS OBJECTIVES

ASSUMES: Tip Speed = 1440 fps

$\overline{RR}$ = Average radius ratio
AR_0 = Root aspect ratio
b = Ratio of tip to root area
$\sigma P/A$ = Root nominal centrifugal stress
σMAX = Max root stress
σa = Goodman diagram alternating stress

AR_0

CURRENT EXPERIENCE

$\sigma MAX \sim K_{psi}$

$\sigma P/A$

$\sigma a \sim K_{psi}$

AM355

$\overline{RR}$

b
.70
.50
.30
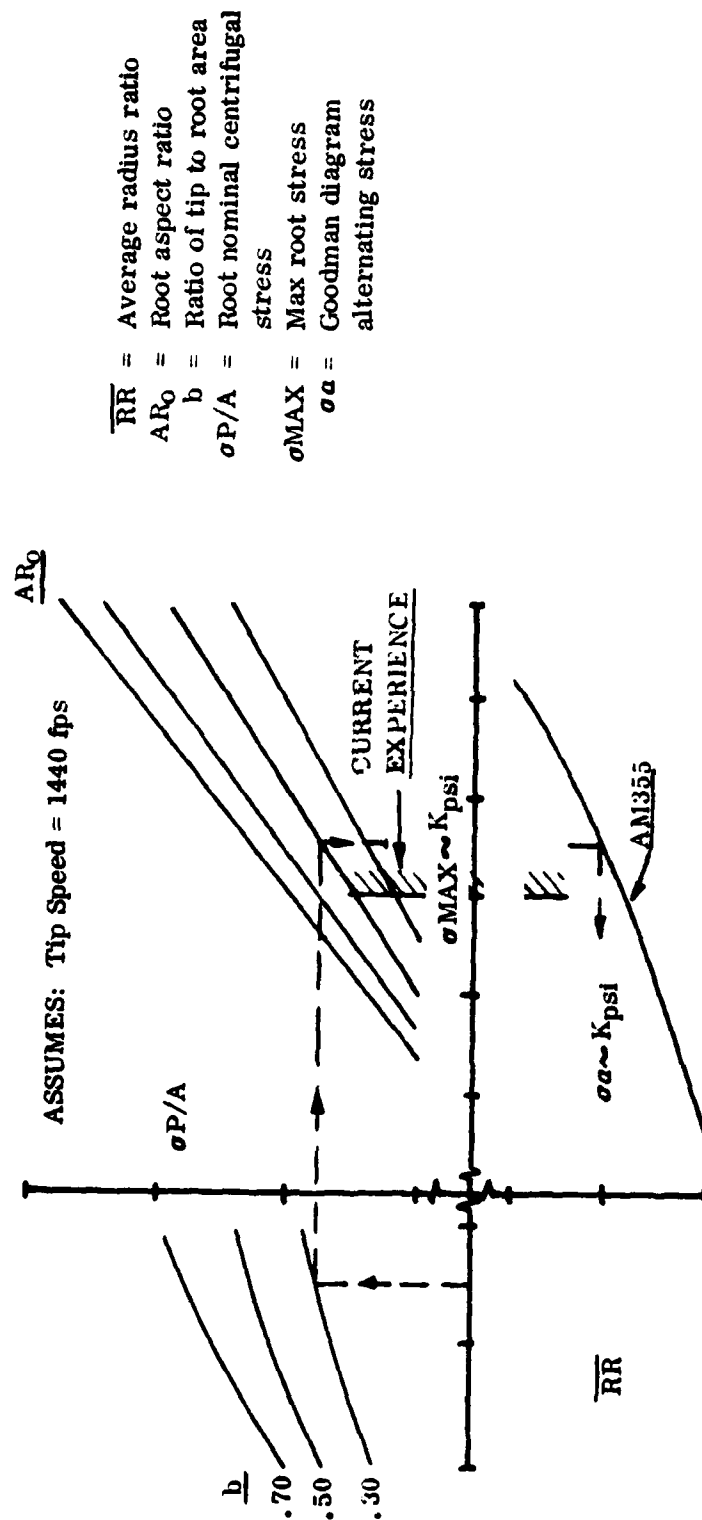
SIGNIFICANCE:

- HIGHLY TWISTED AIRFOILS INDUCE SIGNIFICANT ROOT STRESS --- CAN BE MEASURED AS A MULTIPLIER ON NOMINAL CENTRIFUGAL STRESS
  -- PROBLEM BECOMES AGGRAVATED BY LOW ASPECT RATIO BLADING
- CAREFUL SELECTION OF AR, RR, TAPER AND DISTRIBUTION OF TWIST ANGLE (STAGGER) IS REQUIRED TO KEEP AIRFOIL ROOT STRESSES AT ACCEPTABLE LEVELS.

Figure 19. Method for Airfoil HCF Optimization

METHOD FOR FREQUENCY TUNING PANEL MODES

- RELATIVE ROTOR/STATOR ASPECT RATIO SELECTION
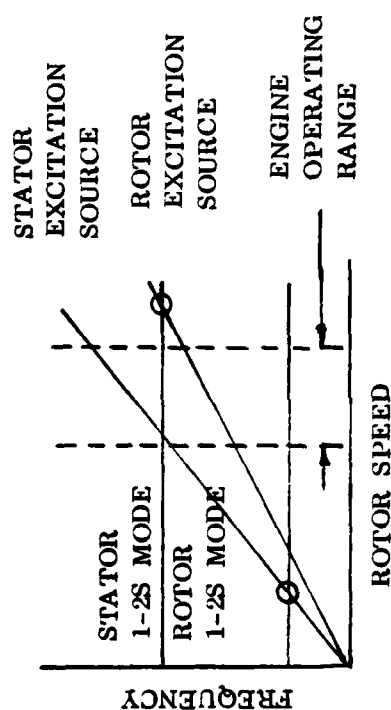
SIGNIFICANCE:

- LOW ASPECT RATIO ROTOR (FEW BLADES, LOW 1-2S MODE FREQUENCY) AND

  HIGH ASPECT RATIO STATOR (MANY VANES, HIGH 1-2S MODE FREQUENCY)

  COMBINE FOR OPTIMUM 1-2S MODE PLACEMENT FOR BOTH

Figure 20. Method for Airfoil Frequency Control

TABLE 11. BIRD INGESTION TOLERANCE DESIGN CRITERIA

BIRD INGESTION CRITERIA

MIL-E-5007D

- NUMBER AND SIZE OF BIRD BASED ON FRONTAL AREA:

  - One 2 or 4 oz Bird for Each 50 in^2 or Fraction > 50% thereof
  - One 2 lb Bird for Each 275 in^2 or Fraction > 50% Thereof
  - One 4 lb Bird for Each 400 in^2 or Fraction > 50% Thereof

- NO FAILURES RESULTING IN ENGINE SHUTDOWN AT CONDITIONS OF TAKEOFF, CRUISE, DESCENT

  - Engine Shall Promptly Recover to Pre-Ingestion Operating Point

CONSIDERATIONS IN ADDRESSING TO MIL-E-5007D

- AIRFOIL DAMAGE . . . FRAGMENTATION, FRACTURE, TEARING, BULGING, FOLDING

- STRUCTURAL DAMAGE . . . SPINNER, CASING, ROTOR UNBALANCE, VANE DISENGAGEMENT

- CONTAINMENT

- SECONDARY DAMAGE

CONCERNS

- MAJOR DISADVANTAGES INHERENT IN SMALL ENGINES

  - Bird Size (Weight) Which Can Be Safely Ingested is Proportional to (Scale Factor)^3
  - Number of Blades Impacted Is Proportional to (Scale Factor)$^{-1}$
  - Bird Footprint is Proportional to (Scale Factor)$^{-1}$

- POTENTIAL FOR GREATER DAMAGE REQUIRES HIGHER FACTORS OF SAFETY . . . MORE SEVERE AERO/WEIGHT PENALTIES

Related to Table 11 is a graphical presentation of the criteria requirements, Figure 21 showing quite distinctly the penalty that the requirement imposes on the smaller engine. For instance, a 6" diameter fan blade would be expected to have a 4 oz. bird reside over 90% of the blade span, whereas, the same size bird resides over only 10% of the blade span for a 28" diameter fan blade. Similar examples can be constructed for the larger bird sizes. This implies that smaller engines have higher risks of suffering severe gross blade deformation. The consideration discussed in this section, and which the design analysis procedure addresses to is airfoil separation under impact loading, specifically, fracture and fragmentation. The rationale is to avoid the spectre of creating potential severe secondary damage/non-containment due to airfoils exiting the fan, thus, decreasing the potential damage attributed to bird ingestion and improving the ability of the fan to recover power.

The elements in the analytical formulation of the bird impact problem are developed by considering, in order, Figures 22-24 and Table 12. The most important elements contained in this approach are the bird approach angle and footprint shown in Figure 22. The "slicing" action which occurs during bird impact is shown schematically in Figure 23. As the bird velocity is increased relative to the blade velocity, the bird is sliced into fewer pieces, i.e., fewer blades impacted. One final observation based on Figures 22 and 23 is that if the bird velocity were equal to the air velocity, no footprint would result since the bird approach angle is essentially equal to the leading edge metal angle. Obviously, the smaller the bird footprint, the smaller the pressure load exerted on the airfoil; translating to an increased airfoil tolerance to bird impact. Throughout the discussion on bird impact, the structural parameter used to identify/compare impact tolerance is material shear strength. As identified in Figure 24 and Table 12, the bird impact load is theorized to be resisted in shear. Comparison of this developed shear stress under impact to the material shear capability is the governing factor in identifying the acceptability of a given design.

A very basic ingredient of the bird impact problem is a determination of the impact conditions which are to be imposed upon the airfoil. Considerations such as bird size, bird velocity, impact location all must be evaluated, and appropriate decisions arrived at using the MIL spec input. In general, impact at the blade tip location during aircraft takeoff or descent represents the most severe impact condition as depicted in Figure 25.

The culmination of this analytical procedure is embodidied in the parametric shown in Figure 26 depicting the iterative method utilized to insure that the fan blade design incorporated sufficient thickness (at the extremities of the bird footprint) to prevent fragmentation. This figure is derived using the assumptions rationalized by Figure 25, i.e., bird velocity of 150 fps and impact at blade tip region. Based on a given bird velocity, choosing a blade speed at the reference (or impact) location produces a bird approach angle. Combining a leading edge metal angle with the bird approach angle, recognizing the bird size (bird diameter),

GRAPHICAL REPRESENTATION OF MIL-SPEC WITH PERSPECTIVE
ON EXTENT OF AIRFOIL PRESSURIZATION ZONE
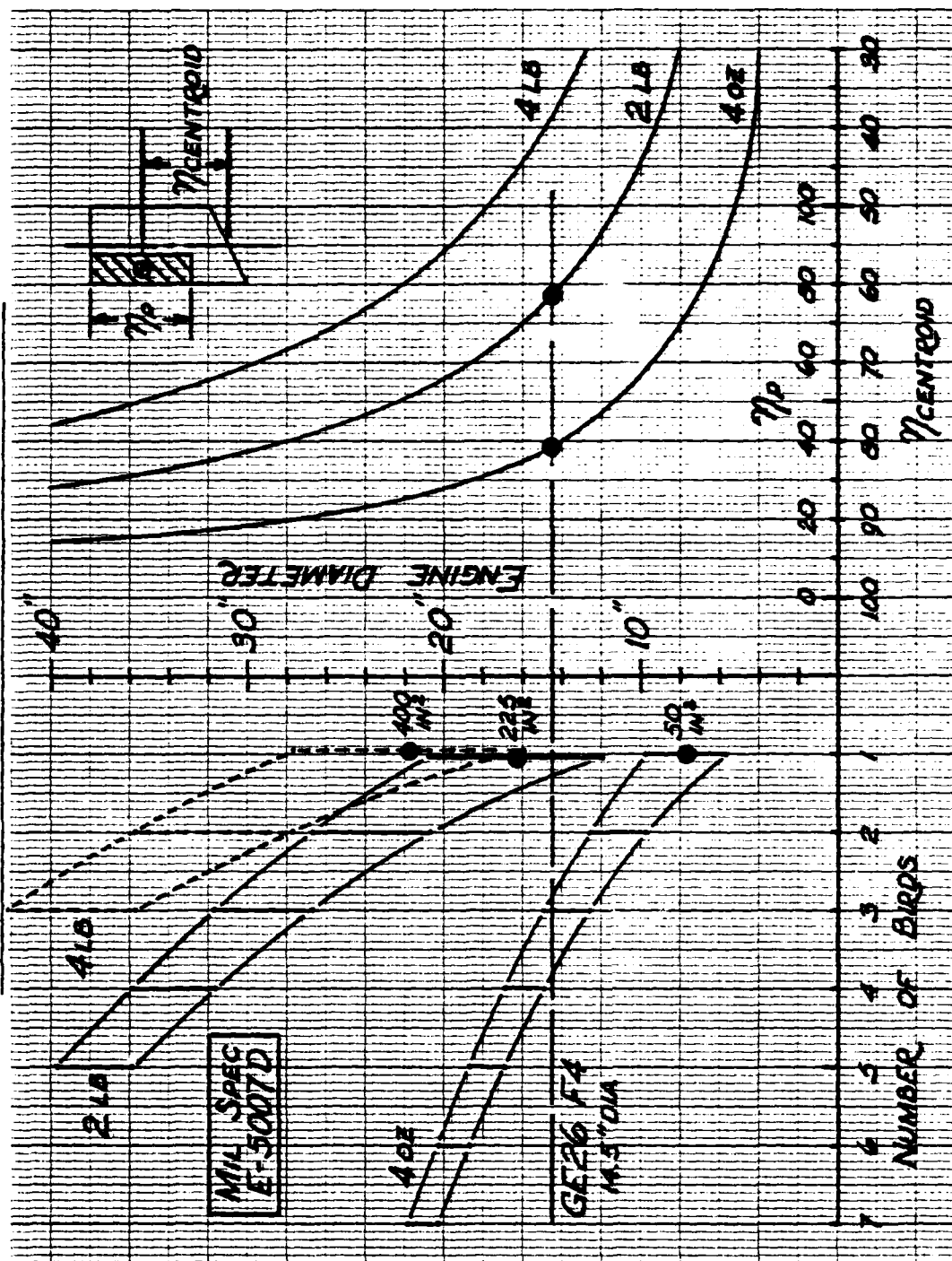
Figure 21. Airfoil Pressurization Due To Bird Strike

ELEMENTS OF BIRD STRIKE ANALYSIS

B— Leading edge metal angle

θ— Bird approach angle = $\text{Tan}^{-1}\left(\frac{V_B}{U_\theta}\right)$

i_B— Bird incidence angle = B - θ

C_p— Chordal extent of impact
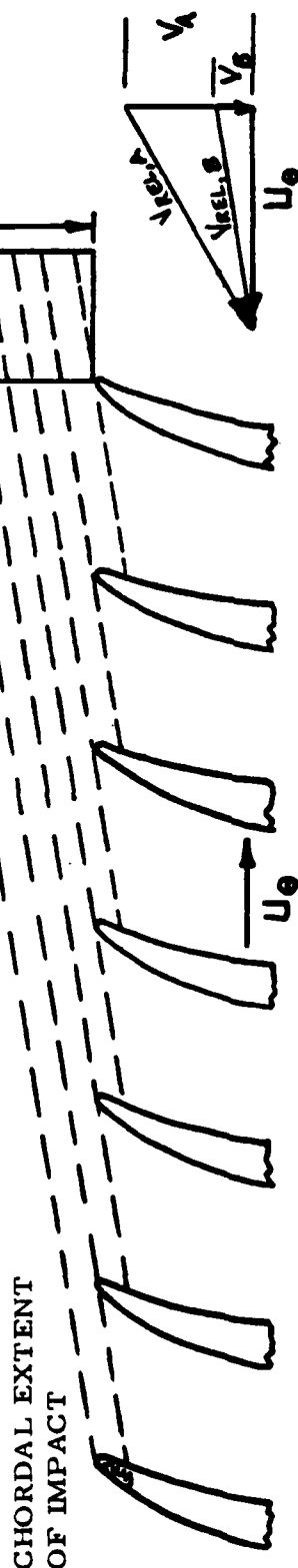
D_B— Bird diameter (related to bird weight)

V_B— Bird velocity

U_θ— Tangential wheel speed

V_{REL}— Bird relative velocity

Pressurized Zone— Bird footprint = $C_p \times D_B$

Figure 22. Bird Approach Angle and "Footprint"

Figure 23. Slicing Action During Bird Impact

BIRD STRIKE ANALYSIS . . . PROBLEM FORMAT FOR FRAGMENTATION

OBJECTIVE: Prevent Separation and Loss of Airfoil Fragments During Inadvertent Bird Ingestion Encounters
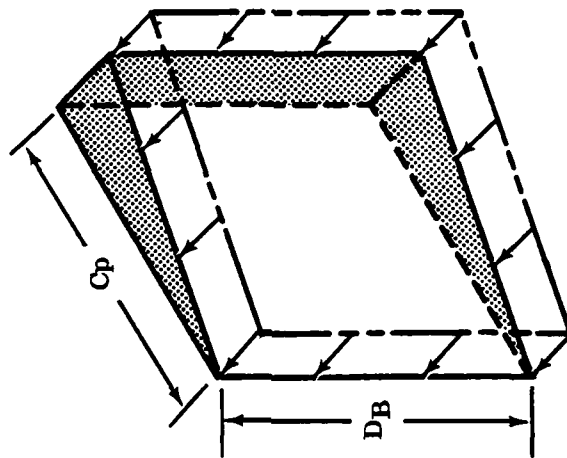
Distributed load which exists in the pressurized zone must be resisted in shear, and not cause bird footprint to be "punched out" of the airfoil

Cross hatched region represents shear area available to resist distributed load.

• Define Threshhold Shear Stress (τ_{CRIT}) which Causes Separation of the Footprint Fragment from the Airfoil

• Define a Shear Area which will Cause Max Developed Shear Stress (τ_{MAX}) below (τ_{CRIT})

Figure 24. Bird Impact Load/Stress Mode

TABLE 12. BIRD STRIKE PROBLEM/SOLUTION FORMAT

BIRD STRIKE ANALYSIS --- PROBLEM FORMAT FOR FRACTURE

OBJECTIVE

- PREVENT GROSS DAMAGE FROM OCCURRING TO FAN BLADES, WITH RESULTING
  SEVERE SECONDARY DAMAGE / CONTAINMENT

PROBLEM

- AVOID SEPARATION (VIA ROOT FRACTURE) AND LOSS OF ROTOR AIRFOIL DURING
  INADVERTENT BIRD INGESTION ENCOUNTERS

- WANT TO UTILIZE FULL CAPABILITY OF MATERIAL AND AVOID PREMATURE
  CONTACT BETWEEN ROTOR AND STATOR

SOLUTION

- SUDDENLY APPLIED TRANSIENT DISTRIBUTED LOAD EXISTING ON THE AIRFOIL
  MUST BE RESISTED IN THE ROOT REGION BY SECTION SHEAR
  - ASSUME LOAD EXISTS OVER A MAJORITY OF THE AIRFOIL SPAN

- DEFINE THRESHOLD SHEAR STRESS (τ_{ult}) WHICH CAUSES FRACTURE

- DEFINE SHEAR AREA WHICH WILL YIELD MAXIMUM DEVELOPED SHEAR STRESS
  (τ_{max}) BELOW τ_{ult}

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BIRD INGESTION CAPABILITY/EVALUATION

FRAGMENTATION

EFFECT OF A/C VELOCITY

SHEAR STRESS FACTOR

4 OZ BIRD

IMPACT RADIUS
80% SPAN

60% SPAN

1.0
.8
.6
.4
.2

T/O — CLIMB CRUISE

BIRD VELOCITY ~ FPS

100   200   300   400

EFFECT OF BIRD SIZE

SHEAR STRESS FACTOR

2 LB

4 OZ

IMPACT RADIUS
60% SPAN

60% SPAN

.6
.4
.2

T/O — CLIMB CRUISE

BIRD VELOCITY ~ FPS

100   200   300   400
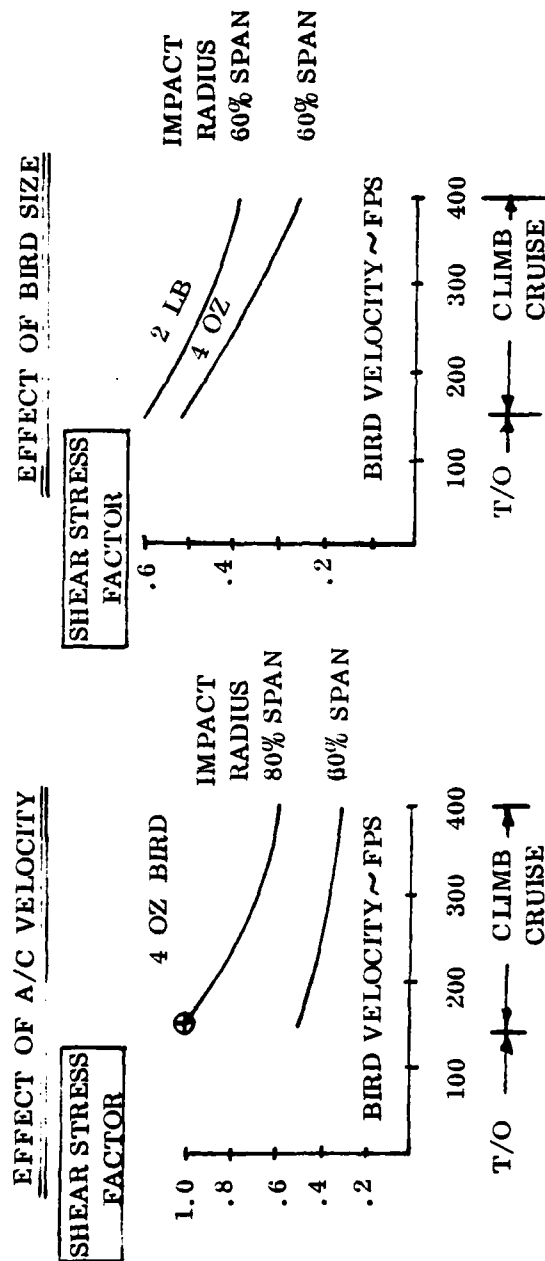
SIGNIFICANCE:

- BIRD IMPACT PROBLEM IS MOST SEVERE AT TH E TAKEOFF(T/O) CONDITION

- SMALL BIRD (4 OZ) IMPACT AT BLADE TIP DURING TAKEOFF IS MOST SEVERE CONDITION

GE26/F4 FAN DESIGNED FOR BIRD INGESTION AT T/O SPEED ASSUMING IMPACT AT BLADE TIP.

Figure 25.   Severity of Bird Strike as a Function of Impact Location

BIRD INGESTION PARAMETRIC STUDY FOR FRAGMENTATION PREVENTION

- Define Bird Size, Velocity
- Define Reference Section
- Calculate Pressure Load
- Define Required Airfoil
  Thickness
  - Max Shear Stress Less
    Than Fragmentation
    Threshold Stress Level

THICKNESS/CHORD
AT EDGE OF BIRD
FOOTPRINT

Tip Speed
U_T*

LEADING EDGE METAL
ANGLE

*AT REFERENCE SECTION
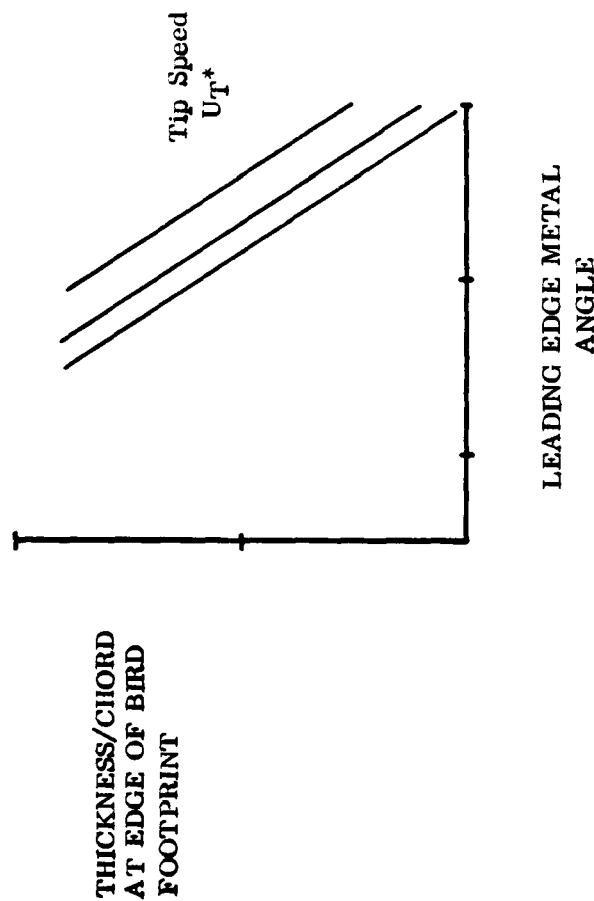
SIGNIFICANCE:
- Utilize Parametric Concept for Integration with Aero Objectives and
  Quick Convergence to a Realistic Preliminary Design
- Select Appropriate Parameter Values, Conduct Detailed Analysis

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Figure 26.   Method for Selecting Blade Thickness for Bird Strike

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produces a footprint. This derived footprint then implies an impact pressure load which then sets a shear area such that the developed shear stress does not exceed the material shear strength capability.

Another aspect of the parametric study is the airfoil material selection process. The information contained in Table 13 depicts the rationale for choosing among the available material options based on identified aeromechanical considerations. Both the shear strength capability and the modulus of toughness (ability to absorb energy in the plastic range) pertain to the bird impact problem, and as such, are weighted very heavily given equivalent high cycle fatigue (HCF) capability. The overstress capability is of importance as it addresses to airfoil stall capability and was not considered on the same level of significance as the other parameters especially for a product design.

The final aspect of the design evolution procedure involved the rotor blade airfoil attachment. Having arrived at a reasonable airfoil design, an airfoil load and radial position are now available. The problem then addresses to whether sufficient area exists in which to design a dovetail form capable of supporting the airfoil load. As suggested by the data depicted in Figure 27, the GE26/F4 airfoil and flowpath constraints result in a nominal blade dovetail neck stress of 50 Kpsi due to centrifugal effects. This is considered an undesirably high level since dovetail axial position, airfoil bending loads and stress concentration effects could easily double that value. The blisk (integral blade disc) design was utilized in order to alleviate this attachment stress problem. A side benefit of the blisk construction is that it allows a lighter airfoil weight. Satisfying the forced vibration objectives, namely first flex 2/rev margin, tends to set the airfoil area distribution. With a low airfoil inlet radius ratio, conventional dovetails have long shanks thus providing significant bending flexibility. This flexibility acts to reduce the blade design frequency and must be compensated for by increasing the airfoil frequency, i.e., more area thus more weight.

TABLE 13. RATIONALE FOR BLADE MATERIAL SELECTION

AIRFOIL MATERIAL SELECTION

● AEROMECHANICAL CONSIDERATIONS

-   TOUGHNESS -- BIRD INGESTION / FOD

-   HIGH CYCLE FATIGUE -- FORCED VIBRATION

-   OVERSTRESS -- STALL, RUB

-   SHEAR STRENGTH -- BIRD INGESTION

● FOR BIRD INGESTION REQUIREMENTS, TOUGHNESS AND SHEAR STRENGTH CAPACITY
BECOME MAJOR CONSIDERATIONS

| | | RANKING | | |
| | | MODULUS OF | | |
MATERIAL	SHEAR STRENGTH	TOUGHNESS	HCF	OVERSTRESS
AM355	2	2	1	4
TI-6-4	4	4	2	5
IN 718	1	1	3	1
17-4PH (CAST)	5	4	5	3
A286	3	3	3	2

● BEST CHOICES, CONSIDERING AEROMECHANICAL CONSIDERATIONS ONLY, ARE
AM355 AND IN718

● CONSIDERATIONS OF COST, WEIGHT, MANUFACTURABILITY GIVE AM355 THE ADVANTAGE

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BLADE AIRFOIL ATTACHMENT

DOVETAIL
NECK STRESS (KPSI)

INLET RADIUS RATIO

.8
.6
.4
.2
0

0   1   2   3   4

ROOT SOLIDITY

10   30   60

I   II   III

GE 26/F 4

REGION I   BLISK
       II   AXIAL D/T
       III   CIRCUMFERENTIAL D/T

Designing An Airfoil Attachment

- Dovetail neck width is sized by airfoil load.
  - Length determined by airfoil chord.
- Tang contact area is sized by crush stress criteria.
- Once the airfoil attachment is sized, the available disc post neck thickness falls out.
  - Disc neck width must be capable of supporting ~ 1.5 x airfoil load.
- Blade and disc dovetail stresses should be equivalent for optimum design.

SIGNIFICANCE:
- Low radius ratio, high root solidity do not allow sufficient material to satisfy both airfoil and disc dovetail stress objectives.
- Blisk design utilized
  - Avoids shank flexibility . . . lower weight airfoil.

Figure 27.   Method for Selecting Blade Airfoil Attachment

3.3 FAN AERODYNAMIC DESIGN

This subsection describes the approaches and execution of the detailed fan aerodynamic design based upon the combination of the preceding Fan Aerodynamic and Fan Aeromechanical Parametric Studies.

3.3.1 Effect of Birdstrike Requirement on Fan Performance

The requirement that the fan be able to withstand bird ingestion per MIL Spec 5007D leads to thicker rotor airfoils than one would normally design. It is then desirable to select fan design parameters such that the thickness increase is minimized.

The velocity vector diagram in Figure 28 shows the velocity and direction of a bird striking the rotor and compares that to the air velocity/direction and to the blade metal angle. CZ air is primarily a function of flow per annulus area. The diagram is used to determine the velocity component normal to the airfoil, and hence the force on the airfoil, and to study ways to reduce that force. Design parameters available to reduce the force are the wheelspeed U, flow/annulus area (determines CZ air) and blade incidence.

The velocity triangles in Figure 28 were used to determine the blade thickness required to meet bird strike requirements as a function of rotor wheelspeed and rotor inlet metal angle. Then aerodynamic parametric study results were used to determine lines of constant flow per annulus area for a specified incidence (Figure 29). The curve shows that flow per annulus area is the most important parameter to reduce blade thickness for bird strike. The final selection of design parameters requires less thickness than the proposal configuration would have required.

The resultant axial thickness distribution of the high bypass fan blade is shown in Figure 30.

In order to understand the impact of the thickened blade on fan design/performance, it is necessary to review the blade-to-blade design parameters.

The blade passage design parameters are defined in Figure 31. The region forward of the first covered wave (FCW) determines the maximum airflow. It is desirable to keep AM as small as possible to minimize total blade passage diffusion. The internal area contraction from the mouth to the throat must be minimized to assure that the shock structure is "started." The discharge area must be large enough to achieve the desired work input.

The suction surface incidence, defined in Figure 32 is used to set the blade forward of the first covered wave to assure adequate flow capability.

HIGH BYPASS FAN

VELOCITY VECTOR DIAGRAM FOR FAN ROTOR INLET
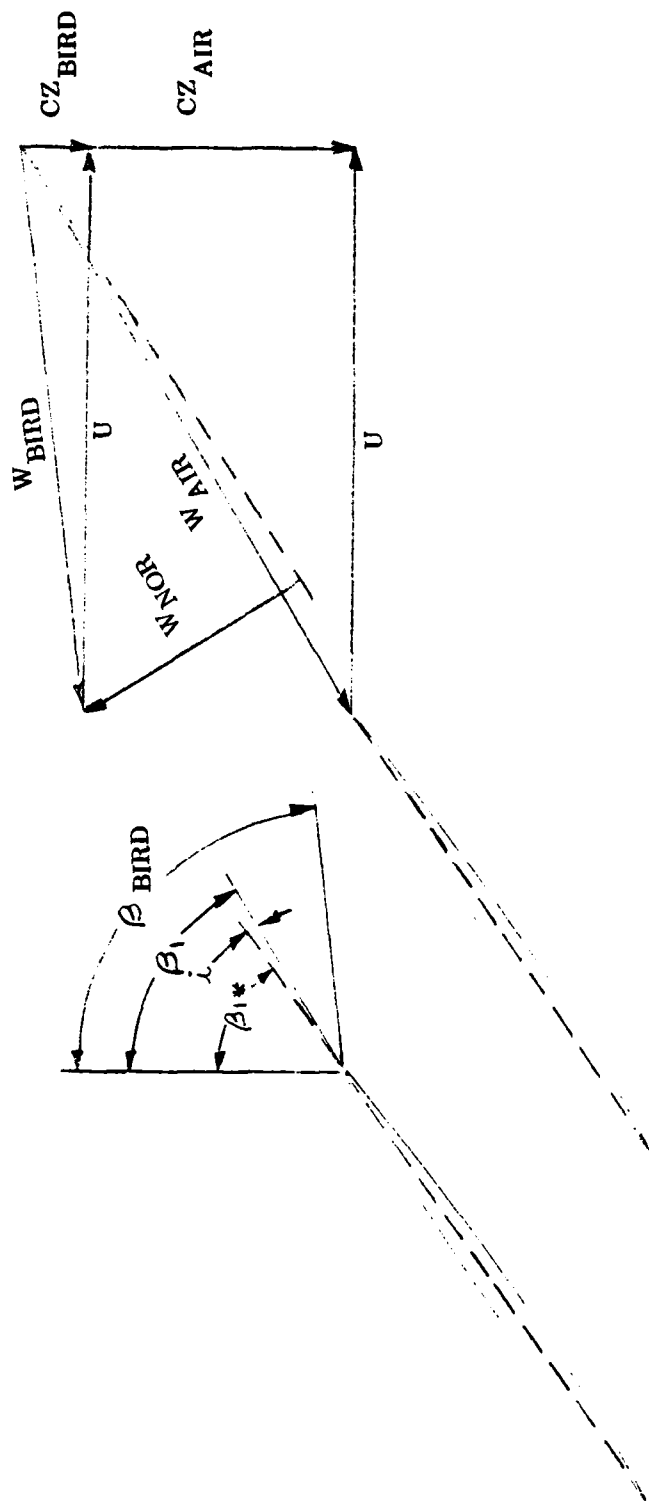
Diagram Utilized to Reduce Impact Force Due to Birdstrike

Velocity Components to Scale

Figure 28. Velocity Vector Diagram Including Bird Path

Figure 29. Airfoil Thickness Requirements to Satisfy Bird Strike Conditions
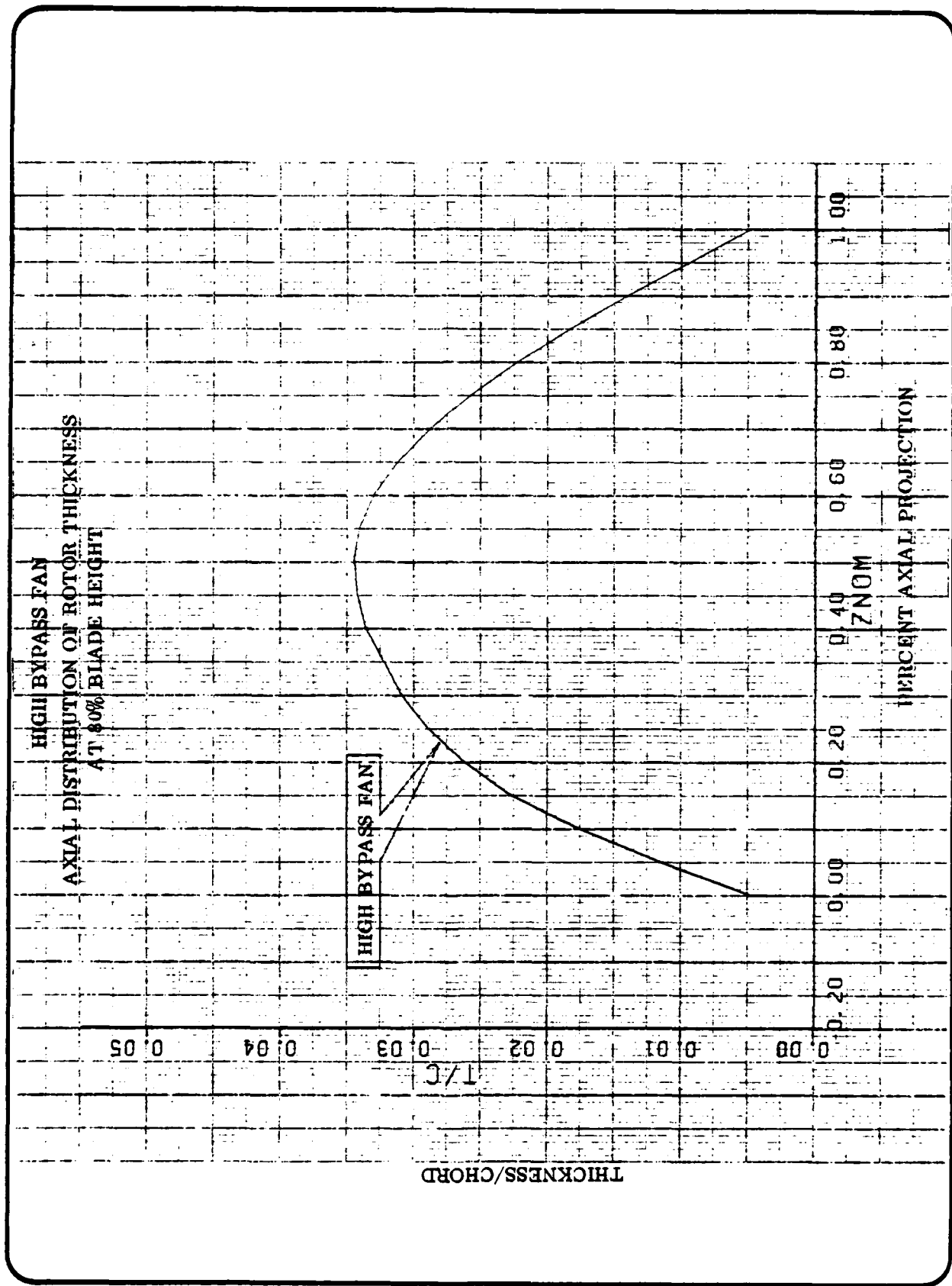
Figure 30. Rotor Airfoil Thickness Axial Distribution

HIGH BYPASS FAN

BLADE PASSAGE DESIGN PARAMETERS

Region where suction surface
shape determines max. airflow

FCW

AM

SS

AT

PS

AD

U
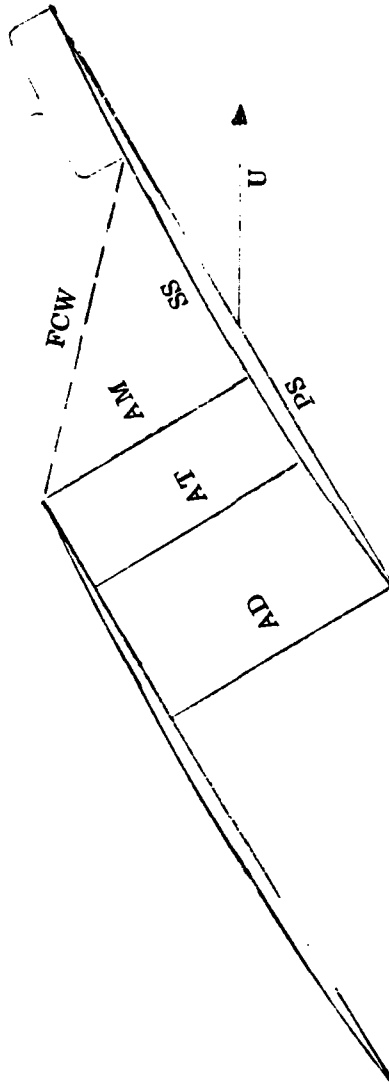
FCW   First Covered Wave
AM   Mouth Area
AT   Throat Area
AD   Discharge Area
SS   Suction Surface
PS   Pressure Surface
U   Wheelspeed

Figure 31. Blade Passage Design Parameters

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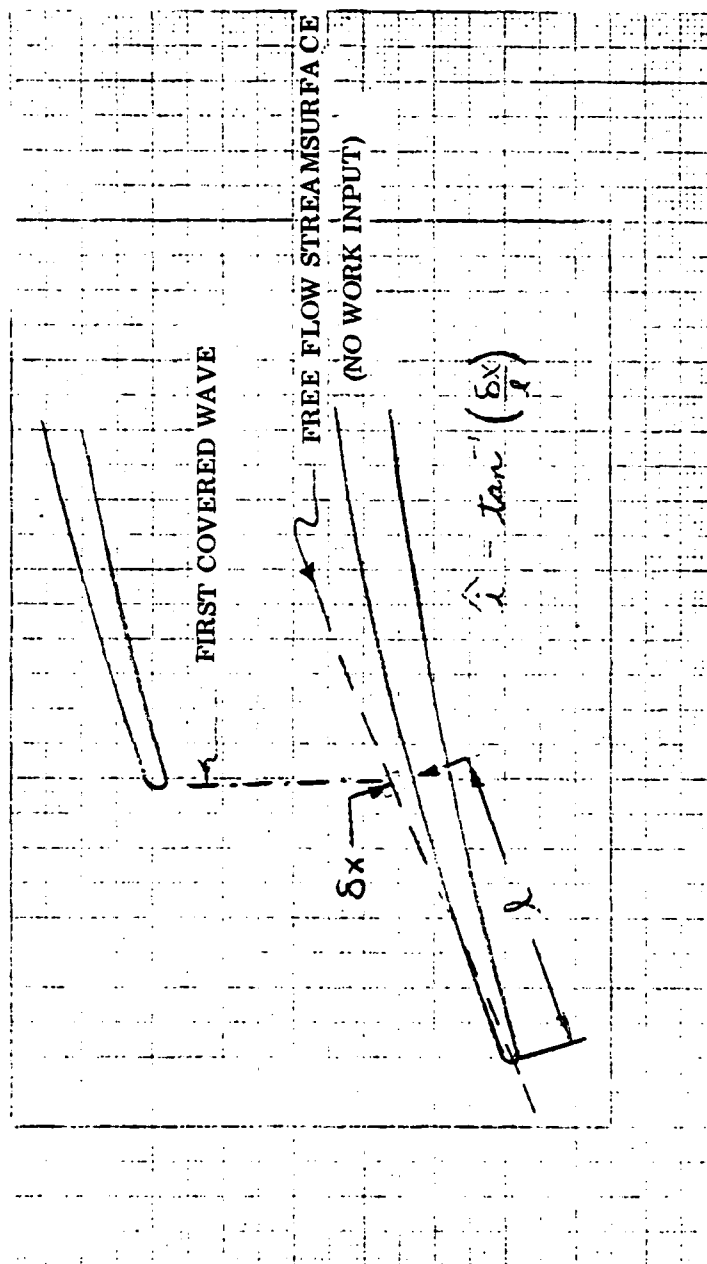
Figure 32. Suction Surface Incidence Considerations

The effect of the birdstrike requirement on blade passage design is illustrated in Figure 33 by superimposing a blade designed to meet bird strike over a blade with conventional thickness distribution. The meanline angle must be lowered forward of the first covered wave to maintain the suction surface and flow capacity. The rapid increase in thickness aft of the leading edge closes the pressure surface and hence it is more difficult to maintain low internal area contraction and to keep the throat forward. The blade angle must be opened more rapidly aft of the mouth to control blade passage area.

The leading edge wedge angle is larger for the high bypass fan thickness distribution than for a typical fan thickness distribution. The leading edge bow shock is pushed forward when the wedge angle exceeds the maximum wedge angle for attached shock, creating higher losses (Figure 34).

The effects of meeting the bird strike requirement are summarized in Table 14.

3.3.2 Selected Configuration

The final selection of fan aerodynamic design parameters is tabulated in Table 15.

The principle reasons for the selection of each of the design parameters are given in Tables 16, 17, and 18.

The important design conditions of the final GE26/F4 fan are compared to the values of the proposal in Table 19. In general, the final configuration is very similar to that of the proposal. The most significant change is the reduction in flow/annulus area to reduce the thickness necessary to meet the MIL Spec 5007D bird ingestion requirement.

3.3.3 Fan Axisymmetric Flowfield Specification

The final selection of fan aerodynamic parameters were used to generate an axisymmetric flow model of the fan. The axisymmetric model was then used to study the radial and axial distribution of the various design parameters to obtain a well balanced fan design.

The final flowpath of the high bypass fan is given in Figure 35. The forward portion of the rotor hub is scalloped to provide more throat margin. The hub flowpath near the rotor discharge through the stator was contoured to control the hub Mach No. The conical spinner prevents ice buildup on the spinner. The leading edge of the stator is swept at the ID to help control losses due to the high stator hub inlet Mach No.

HIGH BYPASS FAN

EFFECT OF BIRDSTRIKE REQUIREMENT ON BLADE PASSAGE DESIGN

Region where suction surface shape determines max. airflow

Region where Bird Strikes Airfoil
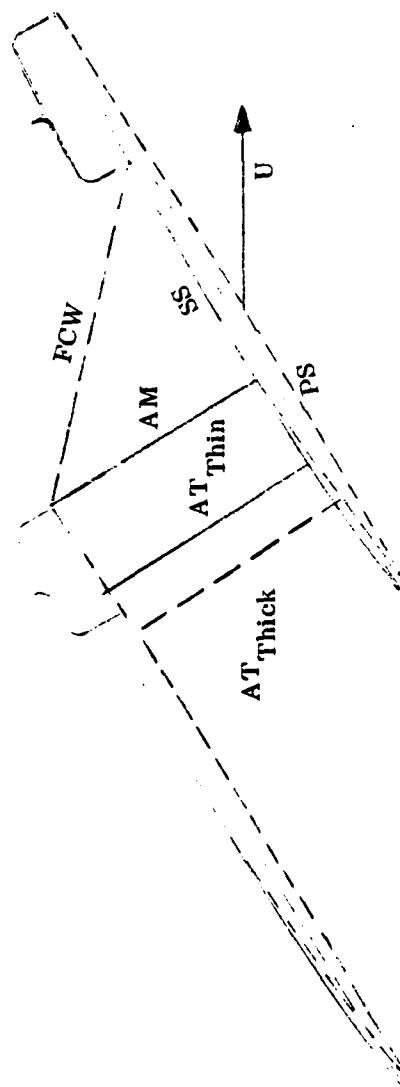
FCW	First Covered Wave
AM	Mouth Area
AT_{Thin}	Throat Area Typical Blade Tip Section
AT_{Thick}	Throat Area Blade Thickened for Birdstrike
SS	Suction Surface
PS	Pressure Surface
U	Wheelspeed

Figure 33.   Effect of Birdstrike Requirement on Blade Passage Design
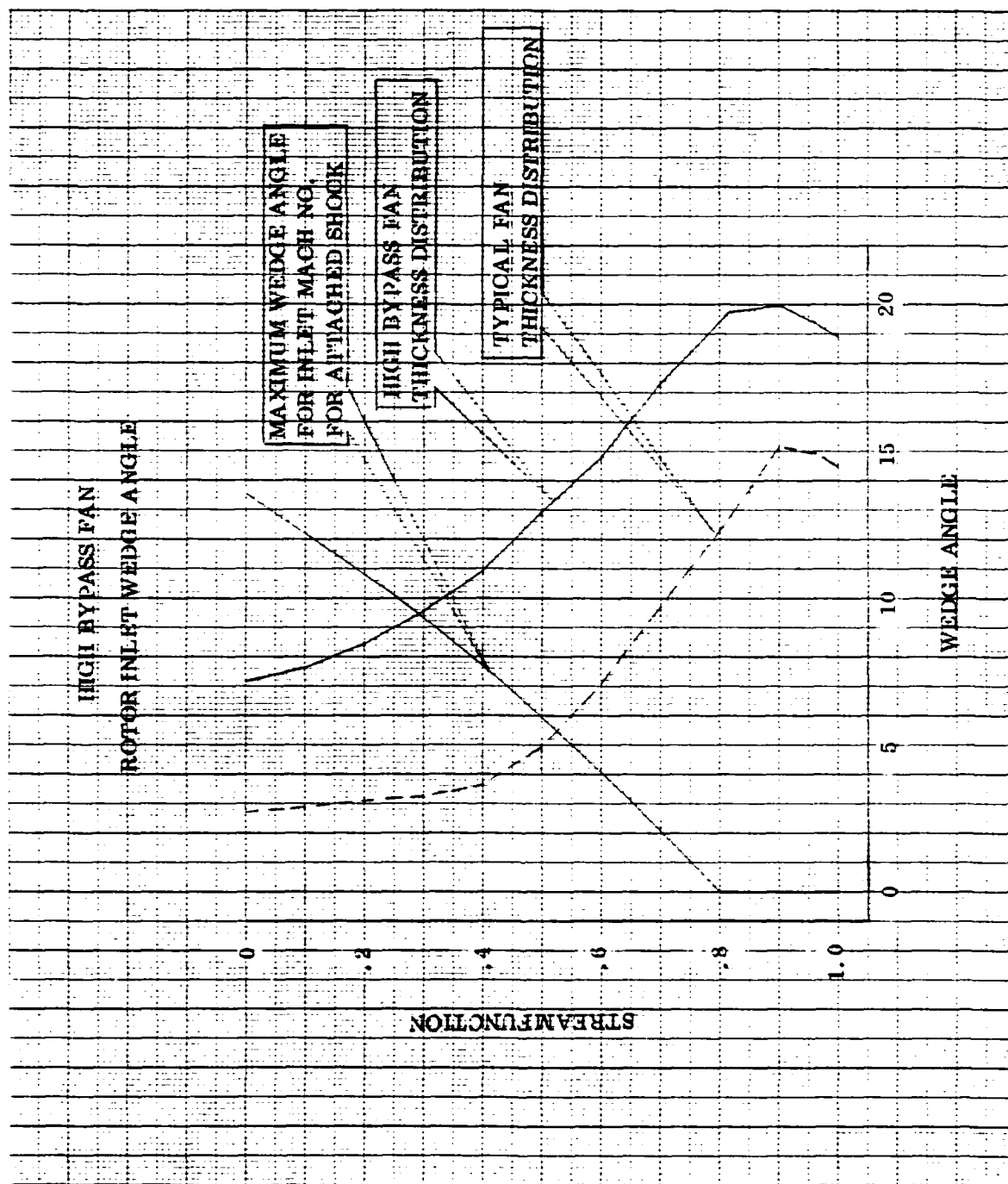
Figure 34. Wedge Angle for Various Fan Blade Shapes vs. Maximum Wedge Angle

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TABLE 14. IMPACT OF MEETING BIRD STRIKE REQUIREMENT

HIGH BYPASS FAN

BIRDSTRIKE REQUIREMENT: IMPACT ON PERFORMANCE

o Thicken Blade Rapidly After Leading Edge

- Larger wedge angle pushes shock forward in pitch region, increasing bow shock losses

o Rapid Increase in Thickness Makes

- Blade passage design more difficult

- LE suction surface set by flow requirements

- Pressure surface angle tends to

  . Force throat aft

  . More difficult to minimize internal contraction

  . Blade must be opened more abruptly aft of mouth

TABLE 15. FINAL SELECTION OF AERODYNAMIC DESIGN PARAMETERS

HIGH BYPASS FAN

AERODYNAMIC DESIGN PARAMETERS

FINAL SELECTION

ROTOR TIP SPEED	1440 ft/sec
FLOW/ANNULUS AREA	41.5 lbm/sec/ft^2
INLET RADIUS RATIO	.36
STATOR DISCHARGE MACH NO.	.54
RATIO OF ROTOR ANNULUS AREA CONVERGENCE TO STAGE ANNULUS AREA CONVERGENCE	.70
ROTOR PITCH SOLIDITY	1.87
STATOR PITCH SOLIDITY	1.60
ROTOR ASPECT RATIO	1.26
STATOR ASPECT RATIO	1.94
ROTOR TIP FLARING	1.0
STATOR TIP FLARING	1.0

60

TABLE 16. REASONS FOR FINAL DESIGN SELECTION

HIGH BYPASS FAN

AERODYNAMIC DESIGN PARAMETERS

REASONS FOR FINAL SELECTION

FLOW/ANNULUS AREA   41.5 lbm/sec/ft^2

- W/A SELECTED TO MINIMIZE BLADE
  THICKNESS REQUIRED TO MEET BIRD STRIKE

- OPTIMUM FLOW ANNULUS AREA IS 41.5

ROTOR TIP SPEED   1440 ft/sec

- IMPROVED EFFICIENCY BY LOWERING
  ROTOR INLET MACH NO.

- FURTHER REDUCTION WOULD RAISE INTERNAL
  LOADING, REDUCE STALL MARGIN AND
  RAISE LP TURBINE LOADING

INLET RADIUS RATIO   .36

- PARAMETRIC CONFIRMED ORIGINAL CHOICE

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TABLE 17. REASONS FOR FINAL DESIGN SELECTION

HIGH BYPASS FAN

AERODYNAMIC DESIGN PARAMETERS

REASONS FOR FINAL SELECTION

STATOR DISCHARGE MACH NO.   .54

- BALANCE BETWEEN INCREASED FAN STALL MARGIN
  AND INNER DUCT PERFORMANCE

RATIO OF ROTOR ANNULUS AREA
CONVERGENCE TO STAGE ANNULUS
AREA CONVERGENCE   .70

- OPTIMIZED EFFICIENCY

TABLE 18. REASONS FOR FINAL DESIGN SELECTION

HIGH BYPASS FAN

<u>AERODYNAMIC DESIGN PARAMETERS</u>

REASONS FOR FINAL SELECTION

o ROTOR ASPECT RATIO   1.26

   - MEETS AEROMECHANICAL REQUIREMENTS

   - LOW ASPECT RATIO HELPS STALL MARGIN

o STATOR ASPECT RATIO   1.94

   - SATISFIES AERODYNAMIC AND
     AEROMECHANICAL REQUIREMENTS

o ROTOR PITCH STUDY   1.87

   - GOOD BALANCE BETWEEN STALL MARGIN
     AND EFFICIENCY

o STATOR PITCH SOLIDITY   1.60

   - GOOD STALL MARGIN

SELECTED GE26/F4 FAN DESIGN CONDITIONS COMPARED WITH ORIGINAL PROPOSAL

PARAMETER	PROPOSAL	GE26/F4
Flow – lbms/sec	41.57	41.6
Flow/Annulus Area – lbm/sec/ft^2	43.0	41.5
Tip Speed, Rotor – ft/sec	1455	1440
Pressure Ratio, stage	1.758	1.758
Stator Exit Mach No. ($\gamma = .95$)	.547	.54
Inlet Hub Radius Ratio	.36	.36
Rotor Hub Speed Ratio $\dfrac{\text{Outlet}}{\text{Inlet}}$	$\dfrac{819}{524} = 1.56$	$\dfrac{821}{519} = 1.58$
Rotor Hub Work Coefficient $\sim 2 g\, J\, \Delta H/U^2$	2.013	1.99
Solidity, Rotor Avg.	2.04	1.87
Aspect Ratio, Rotor	1.27	1.26
Rotor Construction	Shroudless/Blisk	Shroudless/Blisk
Number of Rotor Blades	21	20
Number of Stator Vanes	52	42
Max Thick/Chord – rotor tip/hub	.030/.096	.03/.093
Tip Radius	7.134	7.263
RPM	23368	22720
Adiabatic Efficiency	85.5	85.5
Stall Margin @ Constant Flow, Percent	20	20

HIGH BYPASS FAN
FINAL FLOWPATH

RADIUS

AXIAL LOCATION
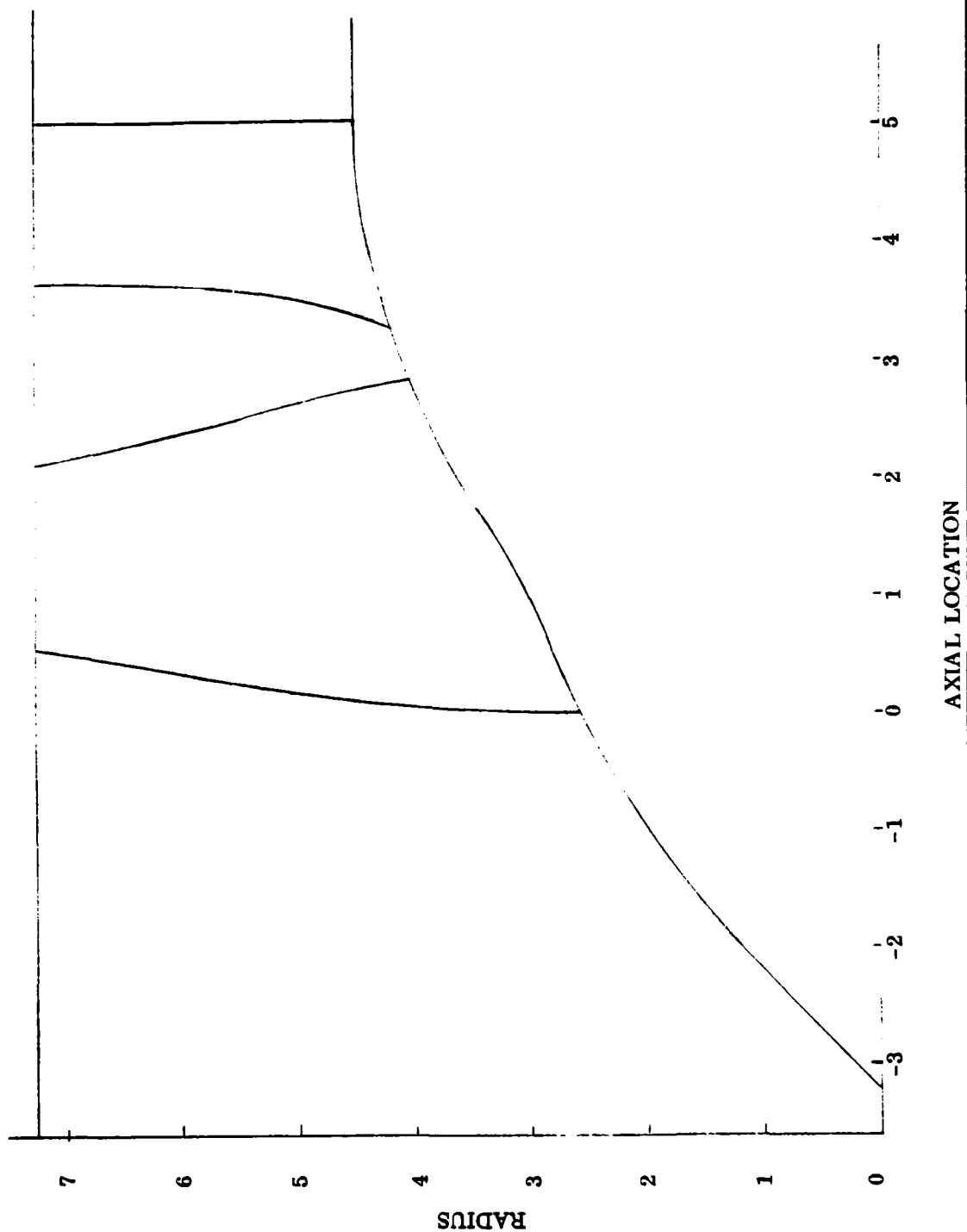
Figure 35. Final Aerodynamic Flow Path

The rotor and stator discharge profiles of pressure ratio and adiabatic efficiency are shown in Figure 36. The average bypass stream pressure is 1.75 and the average core stream pressure is 1.80 at the stator discharge.

The rotor total pressure loss coefficient (PT2 - PT1)/(PT1 - PS1) used in the design is shwn in Figure 37. The profile and level of loss coefficient reflects experience on similar GE fans, when operating at the same tip Mach No. with adjustment for differences in radial distributions of Mach No. and loading level profiles. The stator total pressure loss coefficient used in the design is shown in Figure 38.

The percent cumulative change in total temperature used to define the axisymmetric flow field within the rotor is shown in Figure 39. The temperature is imparted to the flow on the aft portion of the blade at the tip, since the blade must be kept closed forward of the mouth to control passage area and suction surface Mach No. The nearly linear rate of work input at the hub reflects the high hub slope of the rotor.

The percent cumulative change in stator air angle used to define the axisymmetric flow field within the stator is shown in Figure 40. The stator angle change follows a quarter sine wave distribution at the OD, but the turning is removed further aft at the ID to control the suction surface Mach No. at the stator inlet where the inlet Mach No. is very high.

Figure 41 shows that the rotor diffusion factor is reasonable everywhere. Rotor hub diffusion factor is very low. The stator diffusion factor is reasonable everywhere (Figure 42). Careful attention was paid to stator hub diffusion factor during parametric studies selection. Hub flowpath and axial/radial distribution of stator turning were tuned during the axisymmetric flow studies to reduce diffusion factor.

The rotor inlet and discharge relative air angles are shown in Figure 43. The rotor discharge angle at the hub is .5°. The stator inlet and discharge angle are shown in Figure 44. The air is turned back to axial at the stator discharge.

The rotor relative inlet Mach No. is shown in Figure 45. The stator absolute inlet Mach No. is shown in Figure 46. The stator inlet Mach No. reaches .99 locally at the ID. The absolute Mach No. at the discharge of the stator is shown in Figure 47. The average discharge Mach No. is .54, but the Mach No. of the core stream is about .6.

The ratio of discharge axial velocity to inlet axial velocity across the rotor is shown in Figure 48. There is considerable streamtube contraction across the hub, due to the high value of rotor annulus area convergence required for the high hub boost pressure profile. The axial velocity is nearly constant across the stator, as shown in Figure 49.
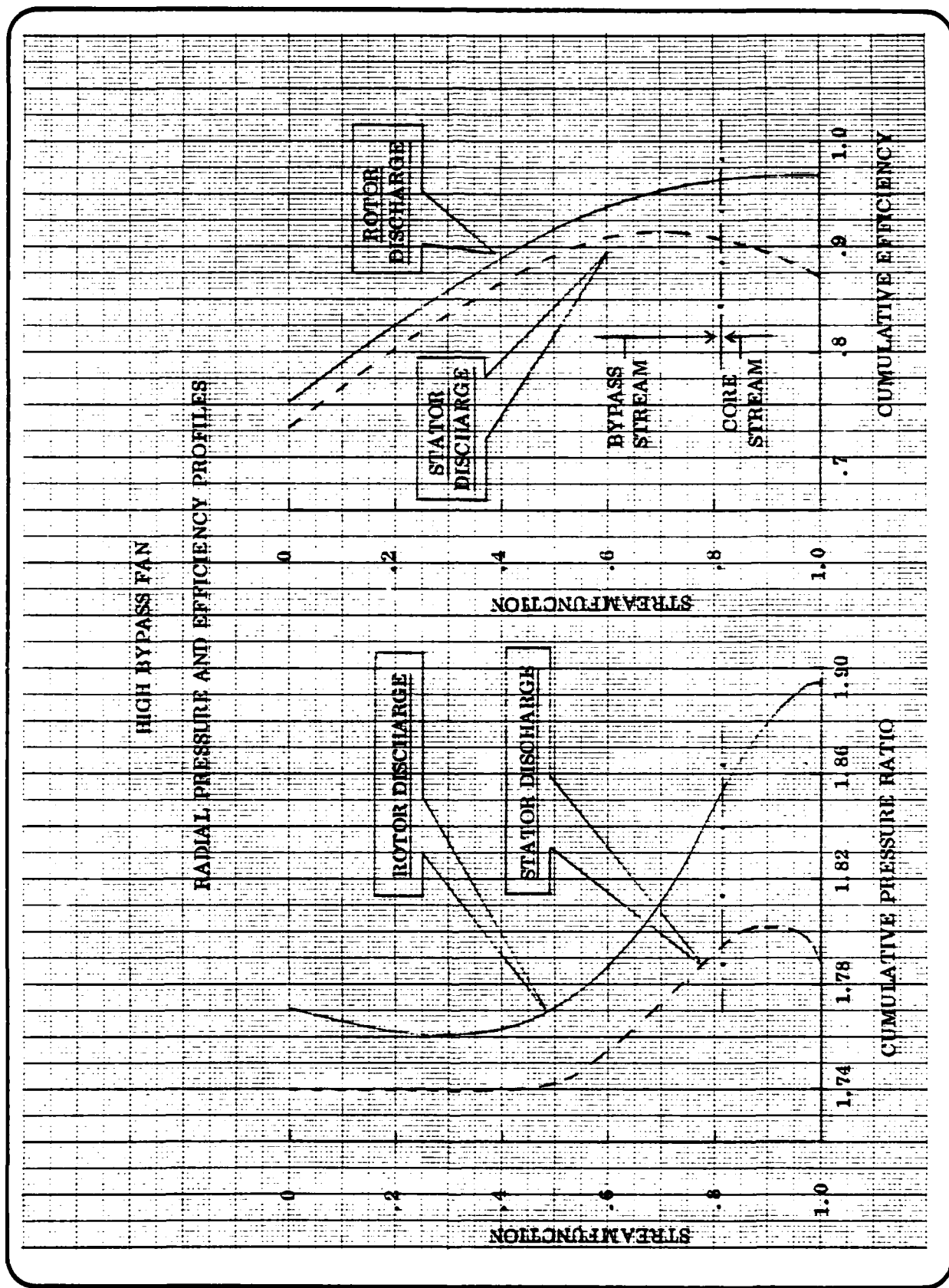
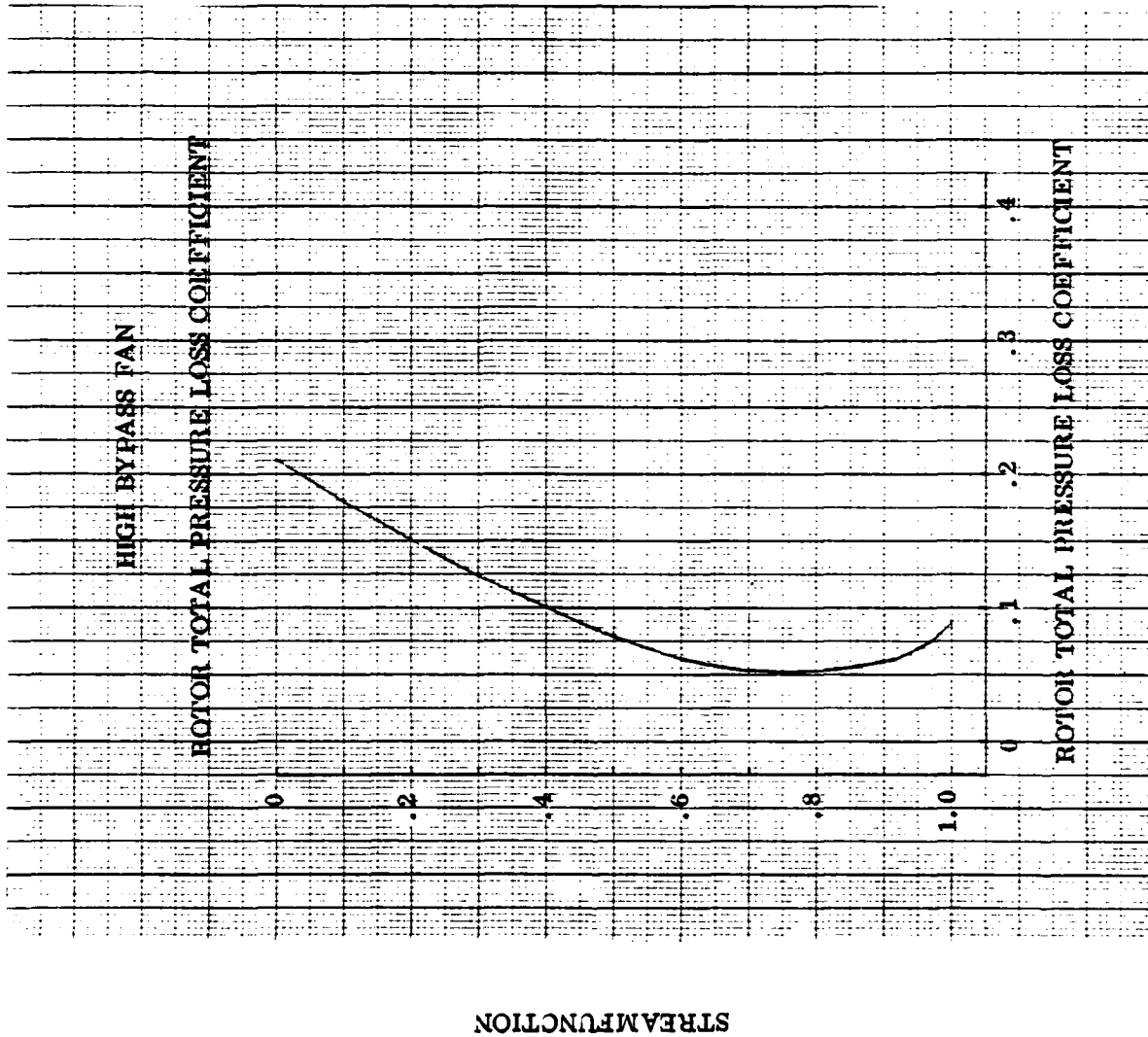Figure 36. Rotor and Stator Discharge Profiles

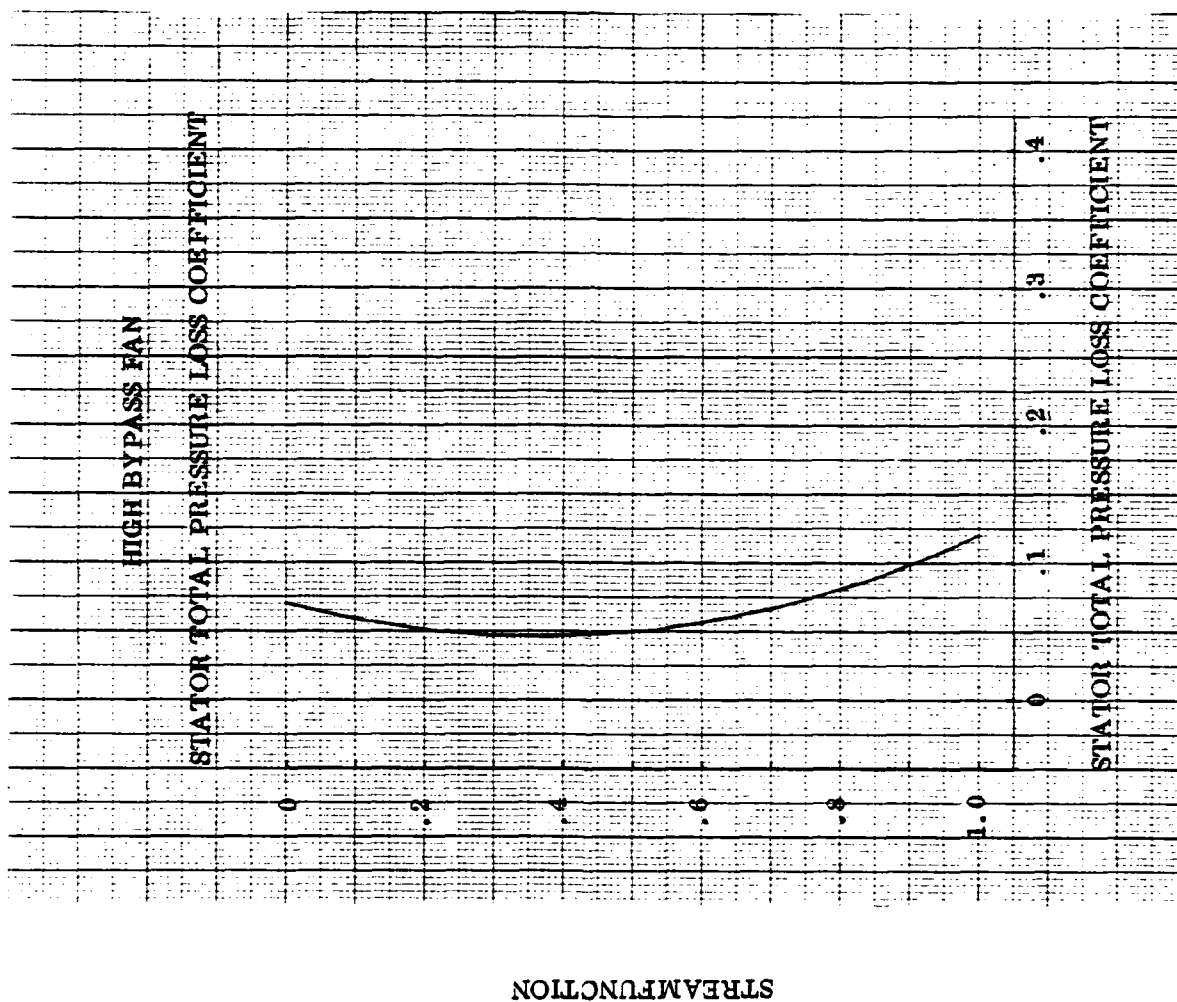Figure 37. Rotor Total Pressure Loss Coefficients

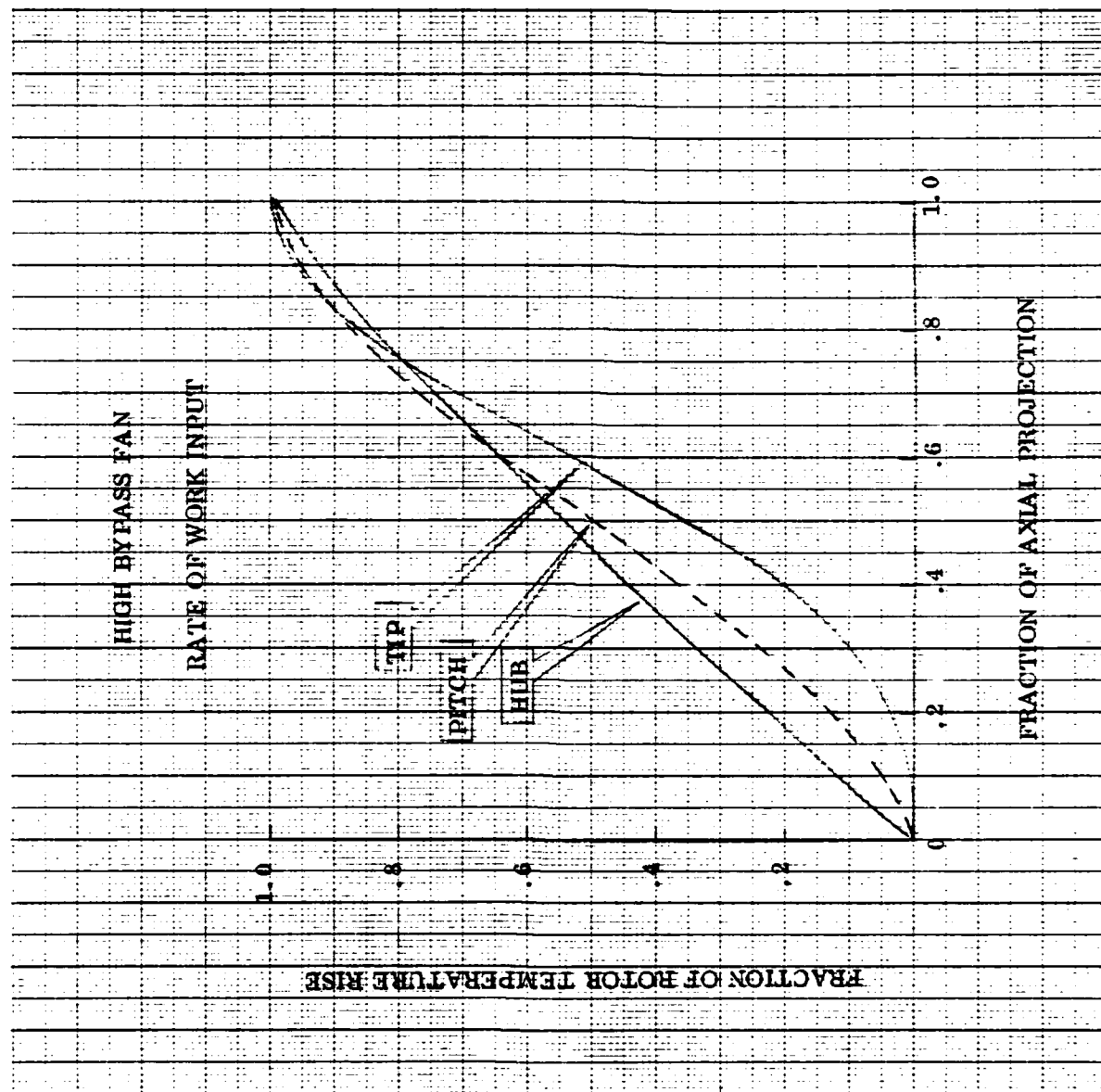Figure 38. Stator Total Pressure Loss Coefficients

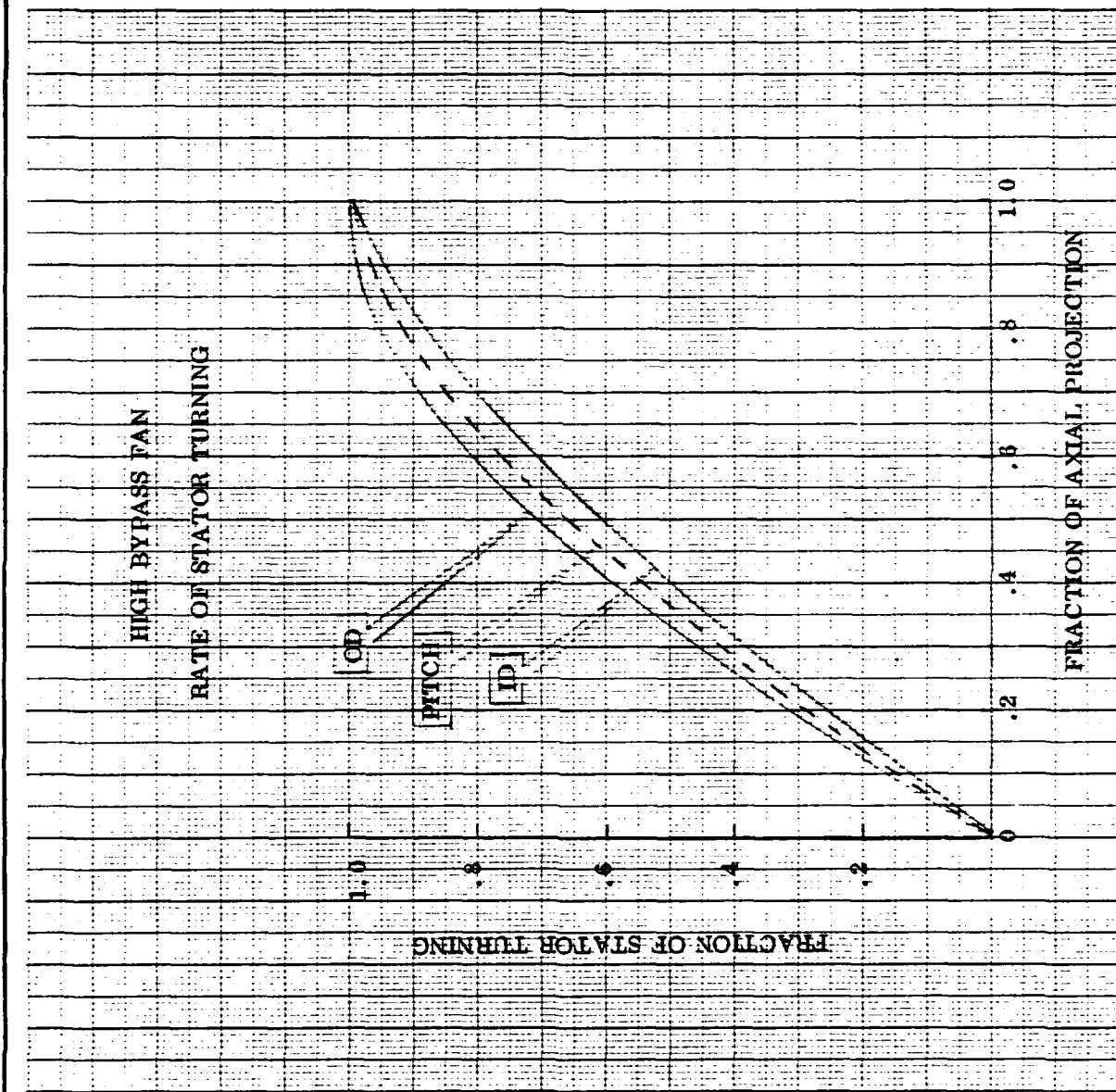Figure 39.   Percent Cumulative Change in Total Temperature

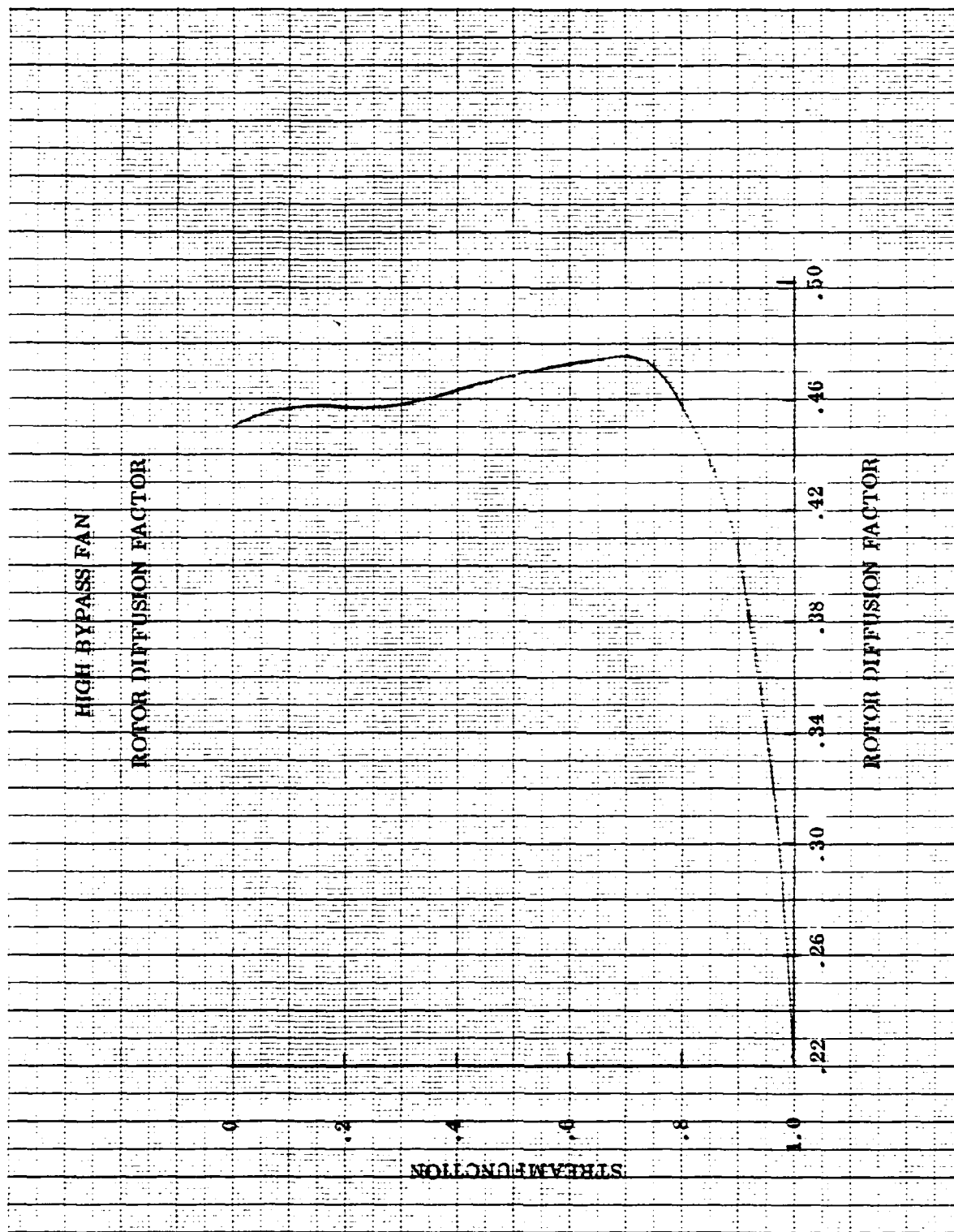Figure 40. Percent Cumulative Change in Stator Air Angle
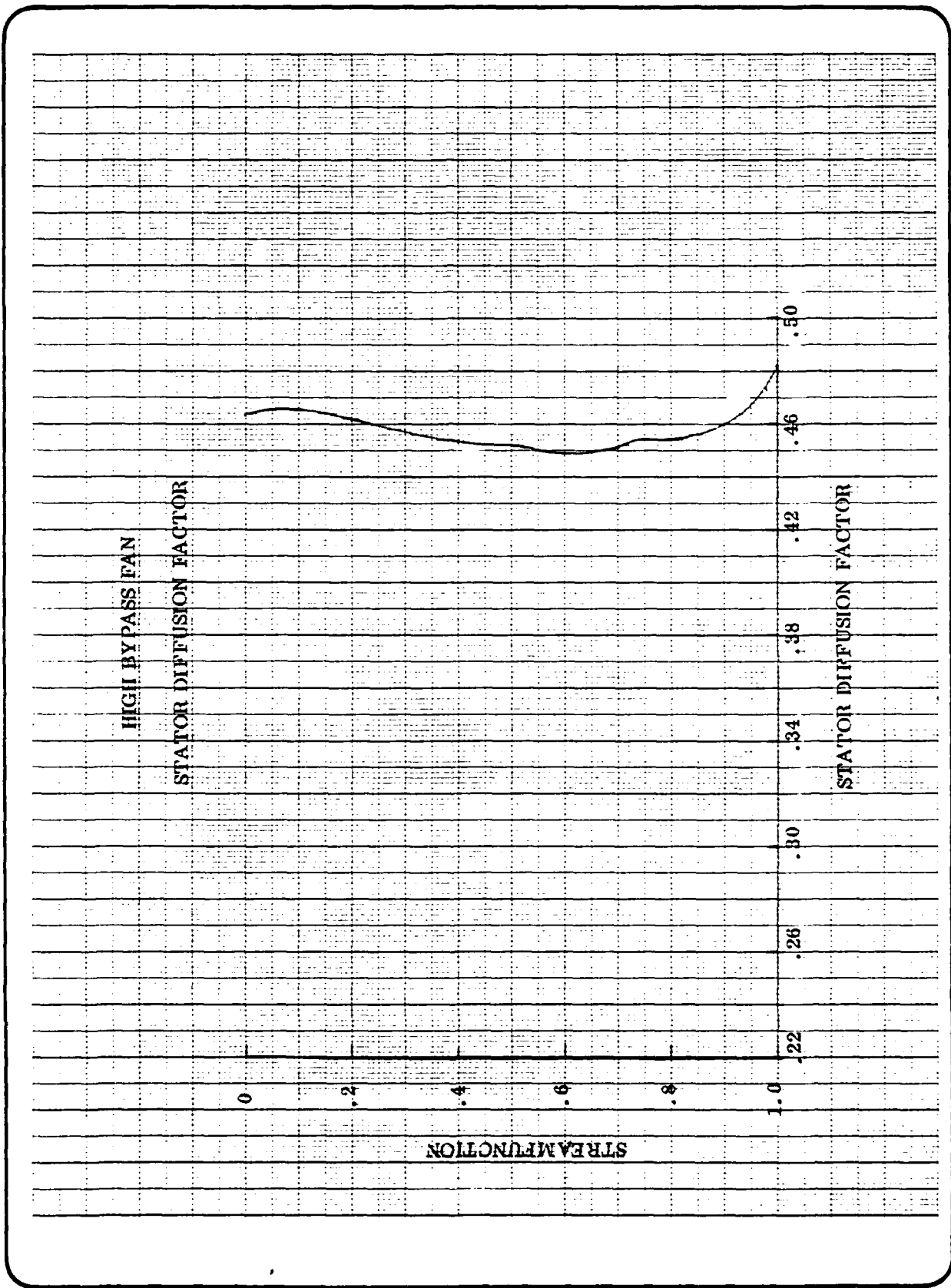
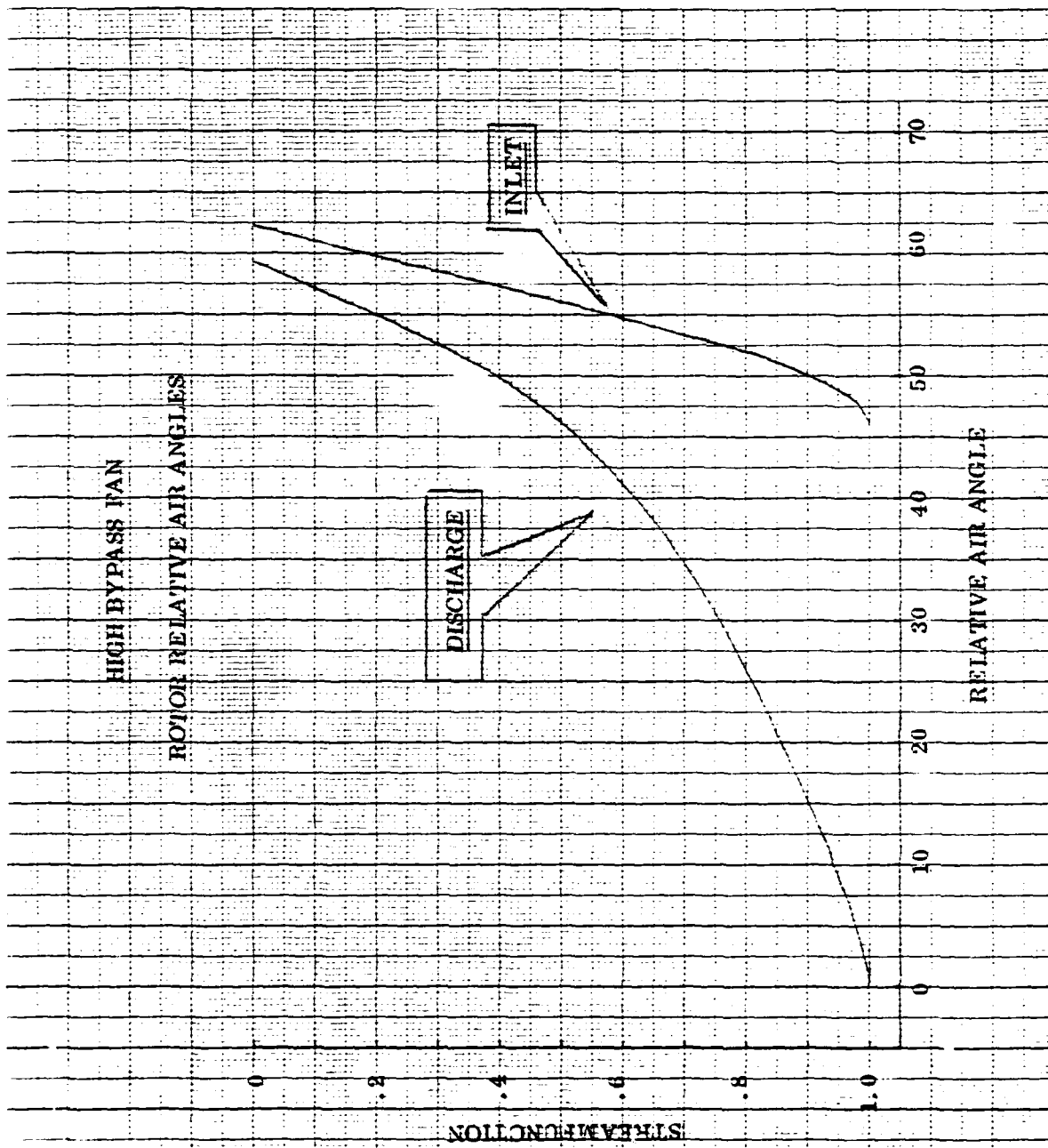Figure 41. Rotor Diffusion Factor

Figure 42. Stator Diffusion Factor

73

Figure 43. Rotor Inlet and Discharge Relative Air Angles
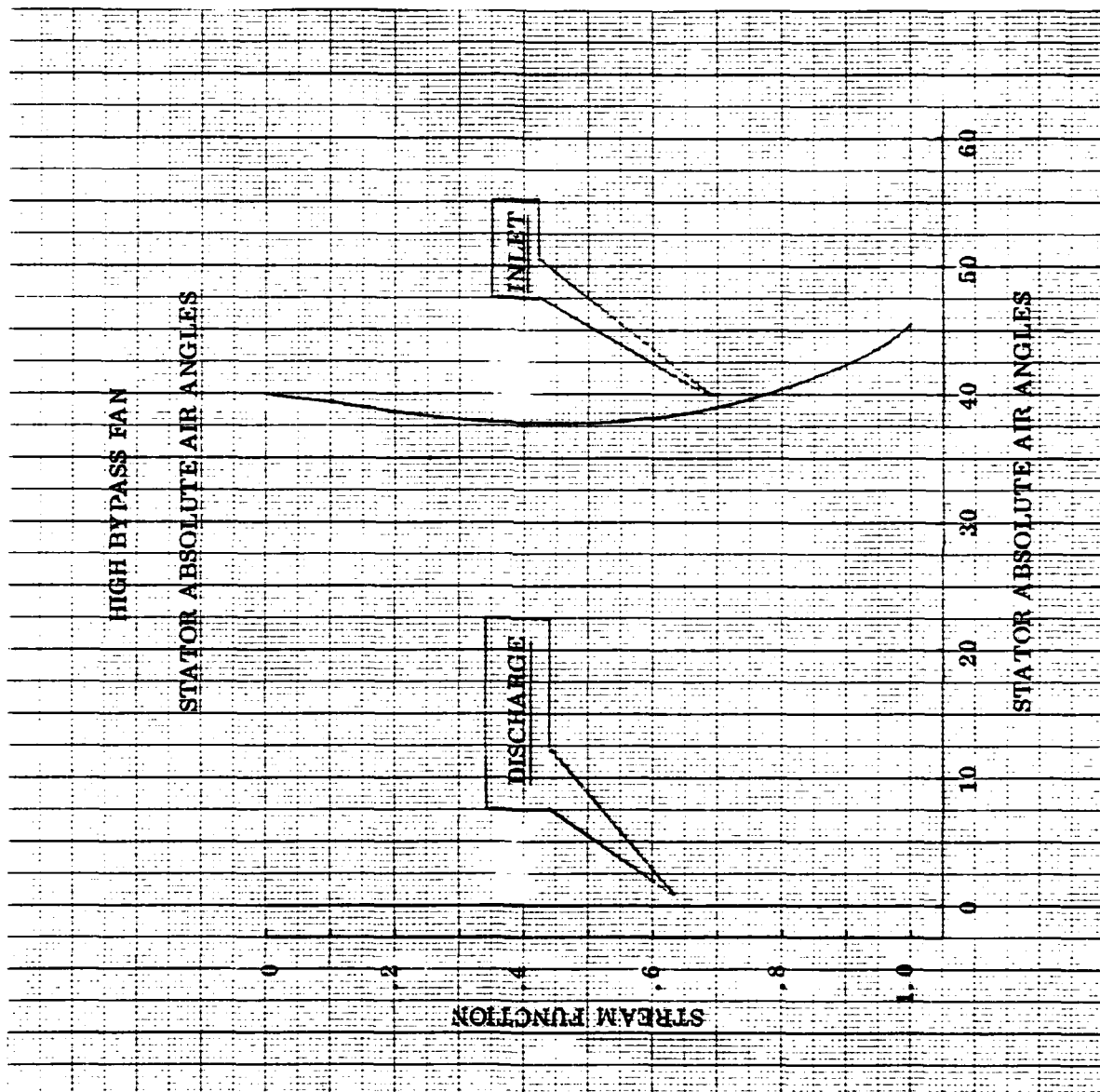
Figure 44. Stator Inlet and Discharge Angles

75
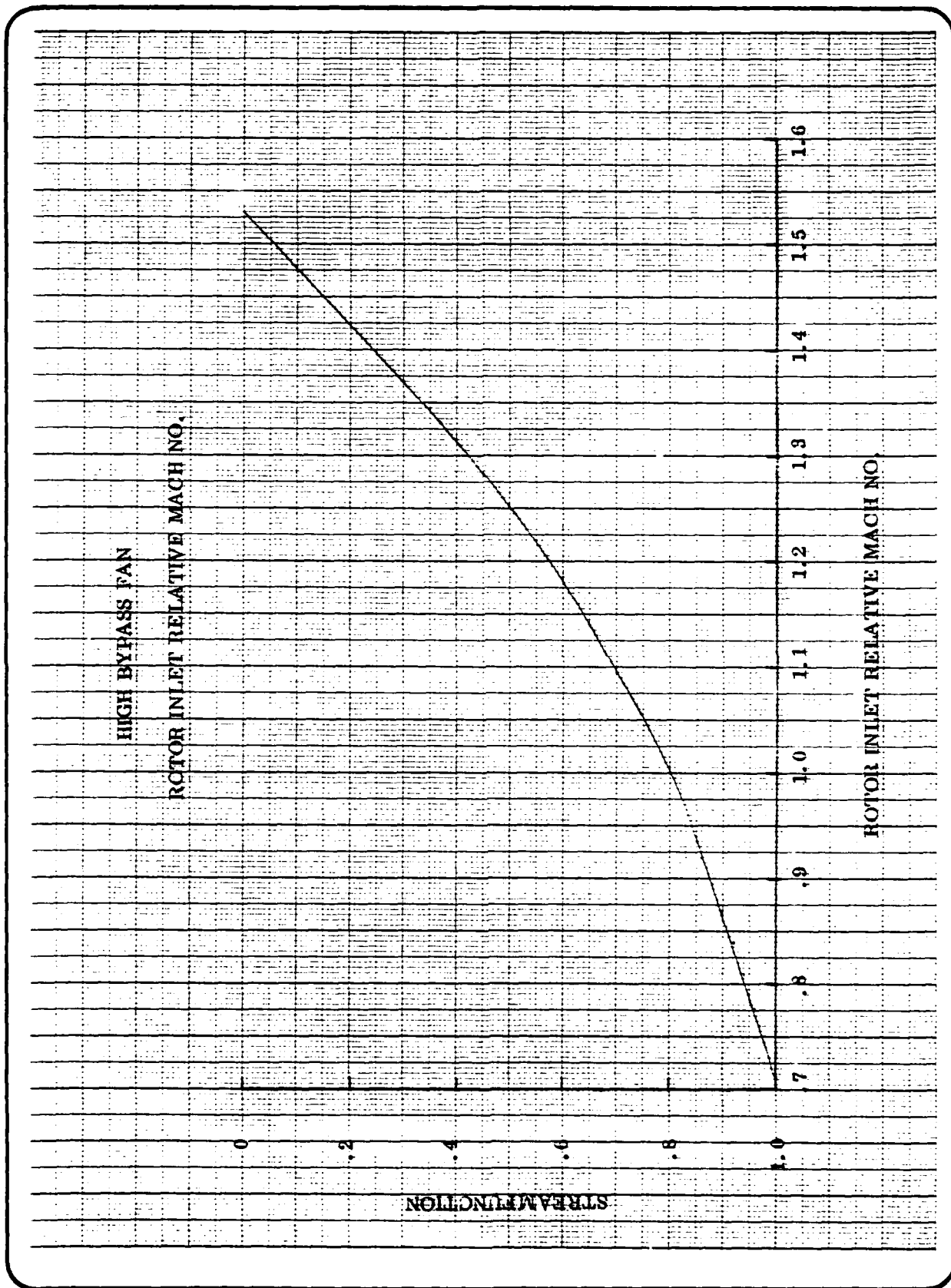
Figure 45. Rotor Relative Inlet Mach No.

HIGH BYPASS FAN

STATOR INLET ABSOLUTE MACH NO.

STREAMFUNCTION

STATOR INLET ABSOLUTE MACH NO.
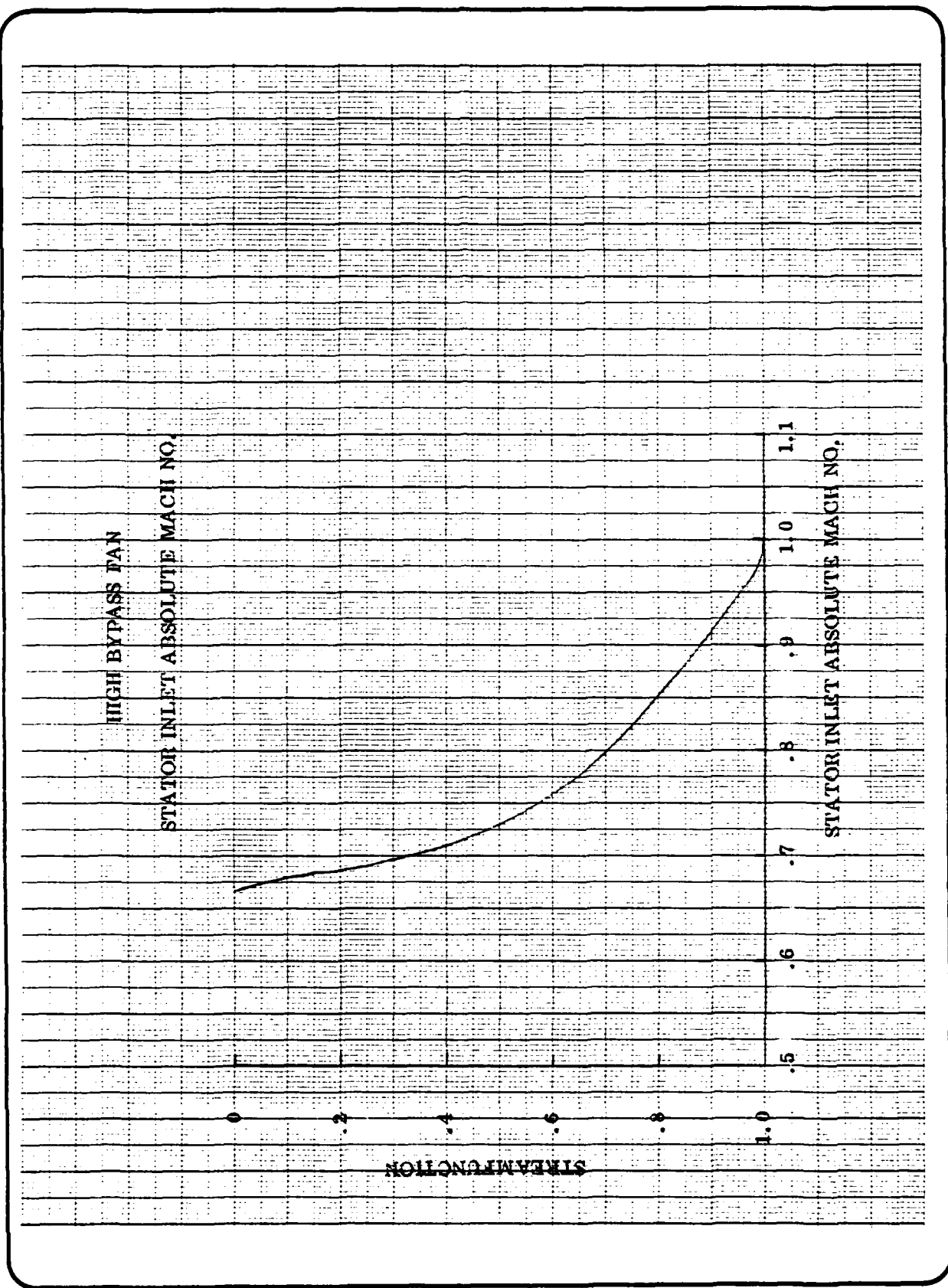
Figure 46. Stator Absolute Inlet Mach No.
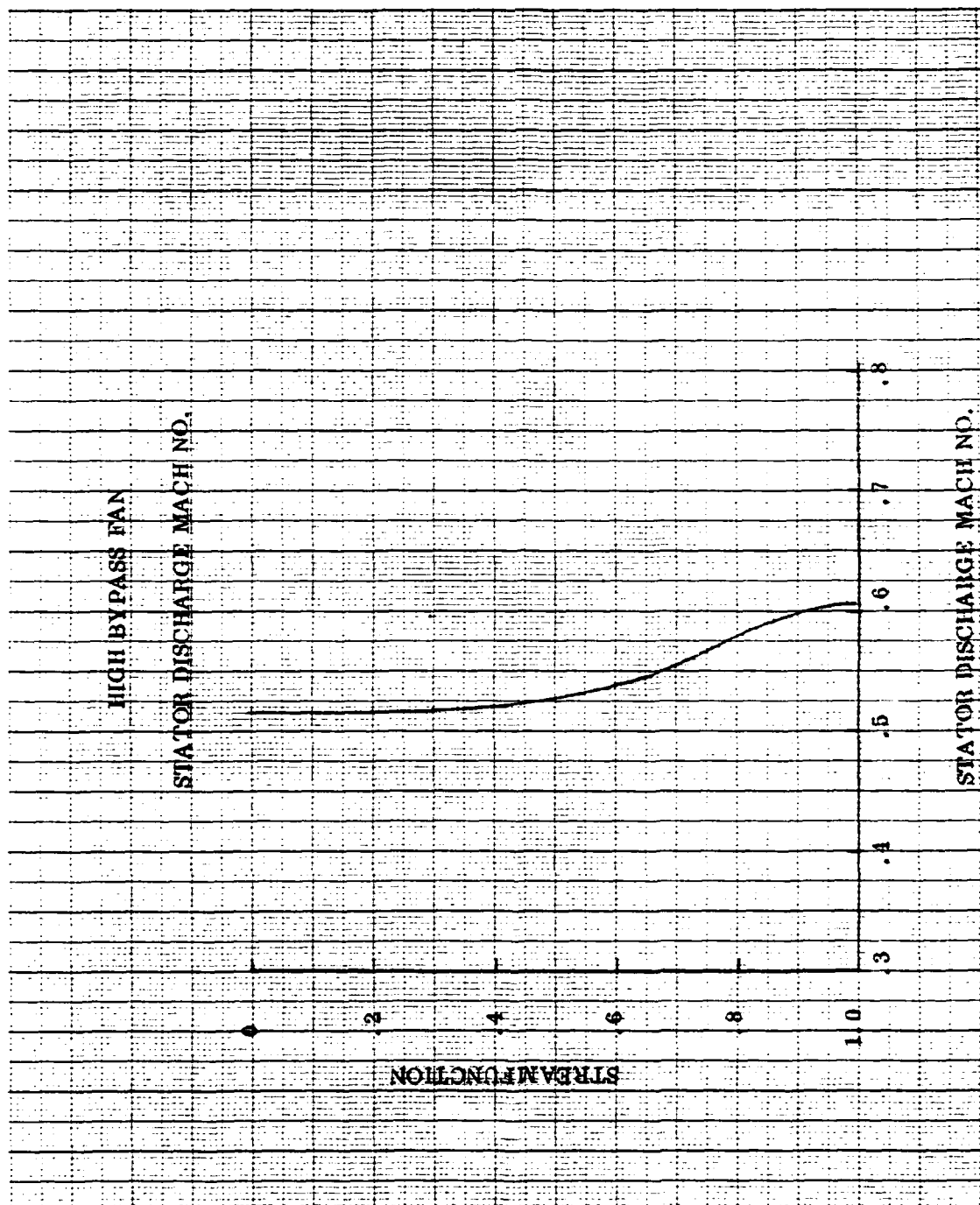
Figure 47. Stator Discharge Absolute Mach No.

HIGH BY PASS FAN

ROTOR AXIAL VELOCITY RATIO

STREAMFUNCTION

0

.2

.4

.6

.8

1.0

AXIAL VELOCITY RATIO

.6

.8

1.0

1.2

1.4

1.6
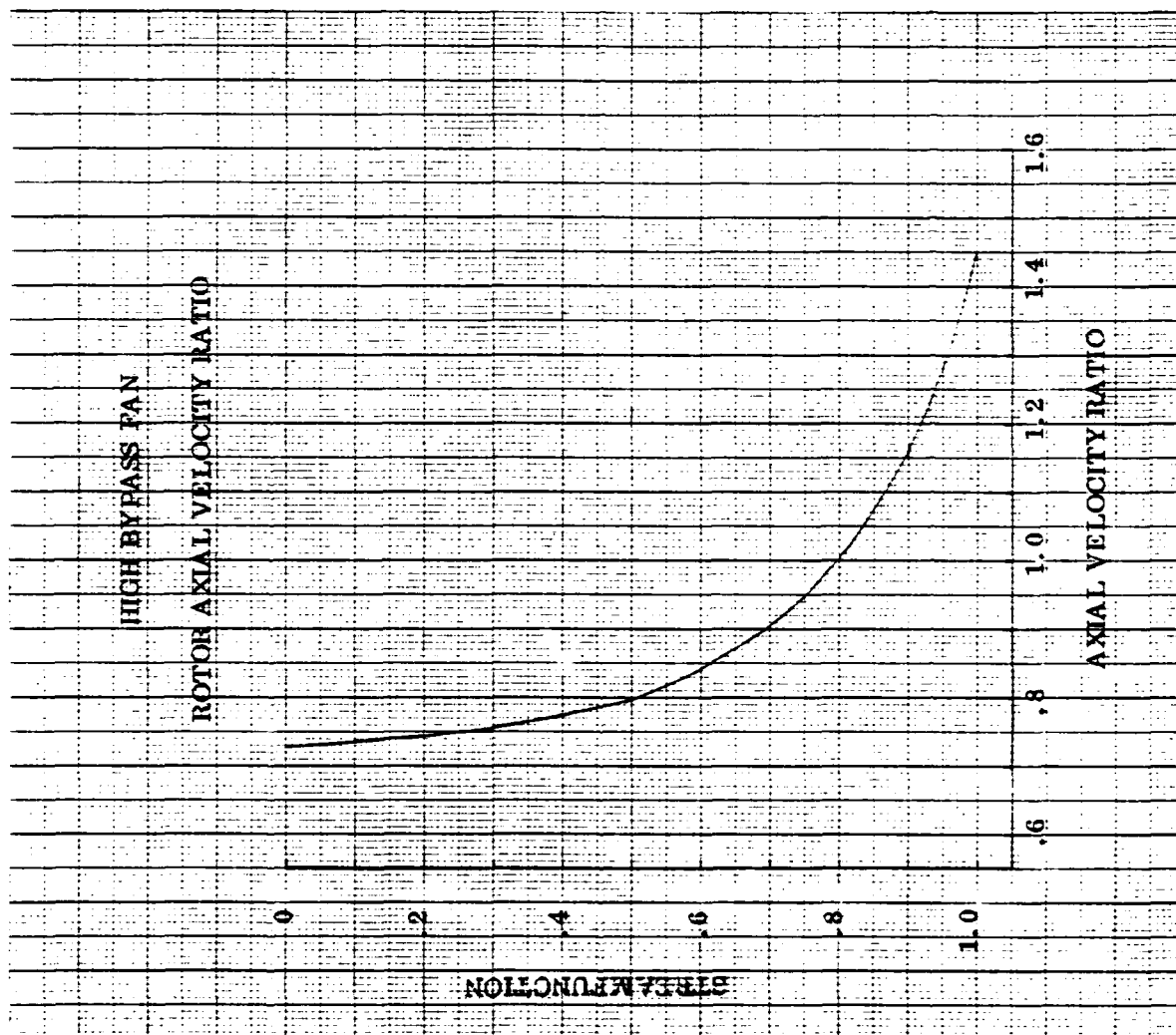
Figure 48. Ratio of Discharge to Inlet Axial Velocity Across Rotor
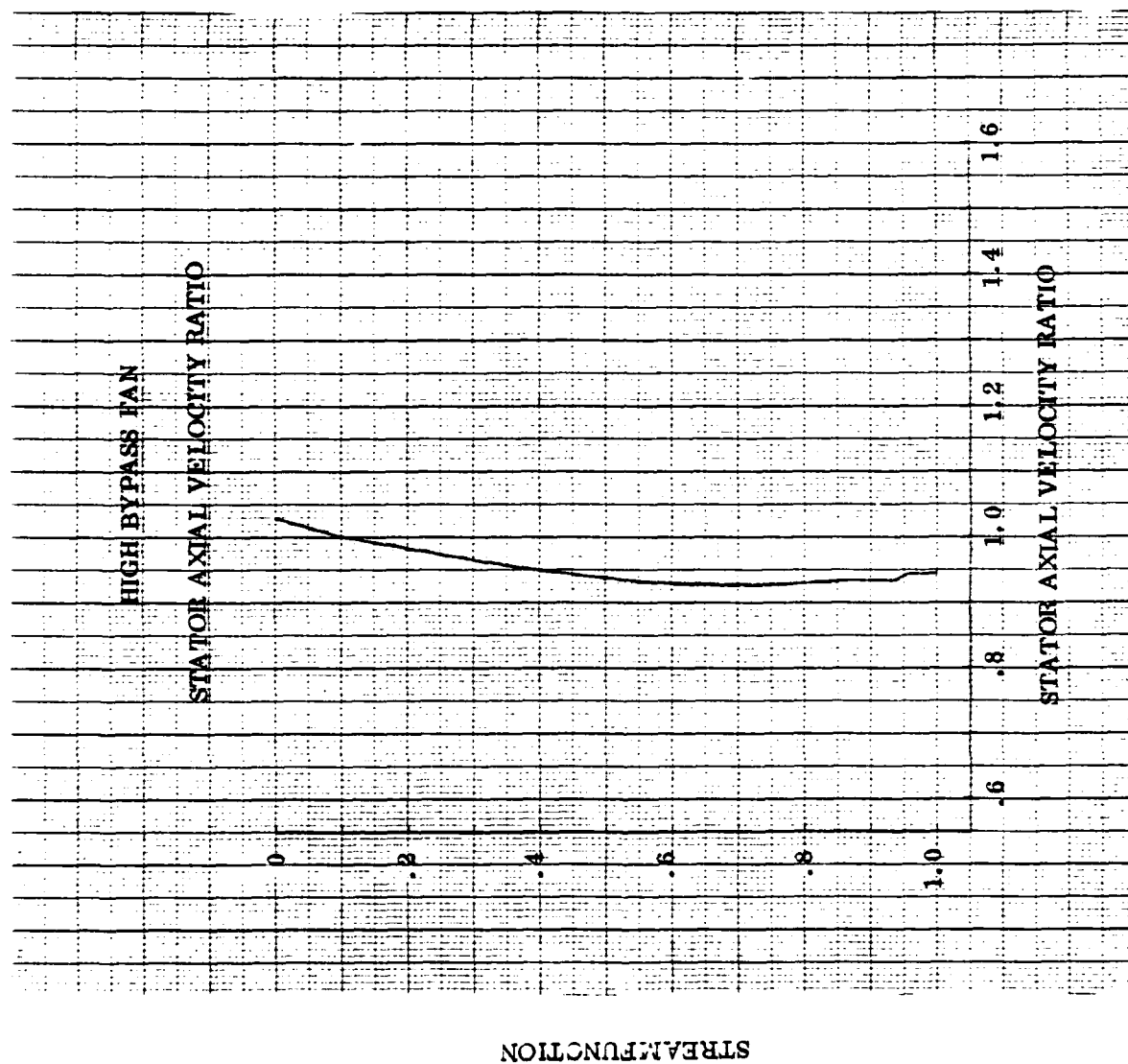
Figure 49. Stator Axial Velocity Ratio Profile

3.3.4 Detailed Blade Design

The detailed blade design was performed by analysis of blade passages along streamlines to determine the best blade shape to meet the fan performance objectives. Radial variations of parameters such as chord and thickness were iterated with the aeromechanical design to achieve a good balance between aerodynamic and aeromechanical design objectives.

The radial distribution of rotor chord is shown in Figure 50. The average chord was selected during the parametric studies. The radial distribution of chord was set to provide higher solidity in the tip and pitch region and to provide an adequate covered passage at the tip, but reduce the chord at the hub where the diffusion is very low. The increase in chord from tip to pitch also provides sweep which may reduce shock losses in the high Mach No. tip region. The resulting radial distribution of rotor solidity is shown in Figure 51.

The radial distribution of stator chord is shown in Figure 52. The average chord was set by the parametric studies. The hub chord is larger than the tip chord to reduce the diffusion factor and to assure adequate stall margin. The resultant radial distribution of stator solidity is shown in Figure 53.

The radial distribution of rotor maximum thickness to chord ratio is shown in Figure 54. The radial distribution of stator maximum thickness to chord ratio is shown in Figure 55. Both rotor and stator tm/c distributions were selected to achieve satisfactory stress and vibration characteristics with the least impact on aerodynamic performance.

The radial distribution of rotor incidence is shown in Figure 56. The selection of tip incidence reflects a good balance to meet design flow capacity (desire high incidence) and birdstrike and stall margin (desire lower incidence) requirements. The pitchline incidence was selected to provide zero incidence on the suction at the leading edge. The hub incidence provides adequate throat margin.

The radial distribution of stator incidence is shown in Figure 57. The level was chosen primarily for optimum efficiency. The low tip (OD) incidence should help stall margin while the high hub (ID) incidence helps throat margin.

The radial variation of rotor deviation is shown in Figure 58. The deviation general follows Carter's rule, but is adjusted to account for secondary flow and to assure adequate discharge area for supersonic flow sections. The radial variation of stator deviation is shown in Figure 59. The deviation is based on Carter's rule.

The rotor meanline angles are shown as a function of percent axial projection for each streamline in Figure 60. Rotor streamline camber and

---
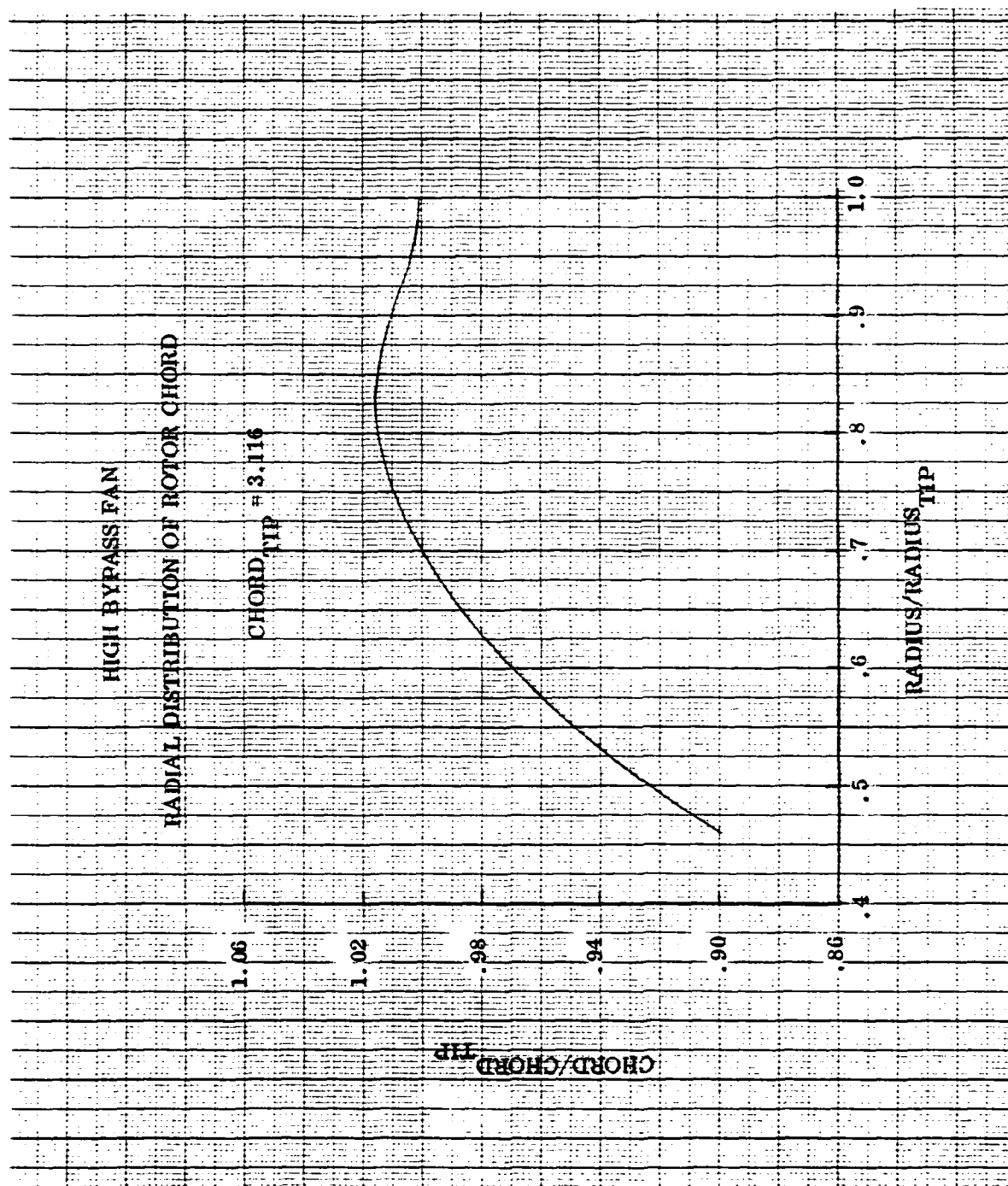
Figure 50. Radial Distribution Rotor Chord

HIGH BYPASS FAN
RADIAL DISTRIBUTION OF ROTOR SOLIDITY
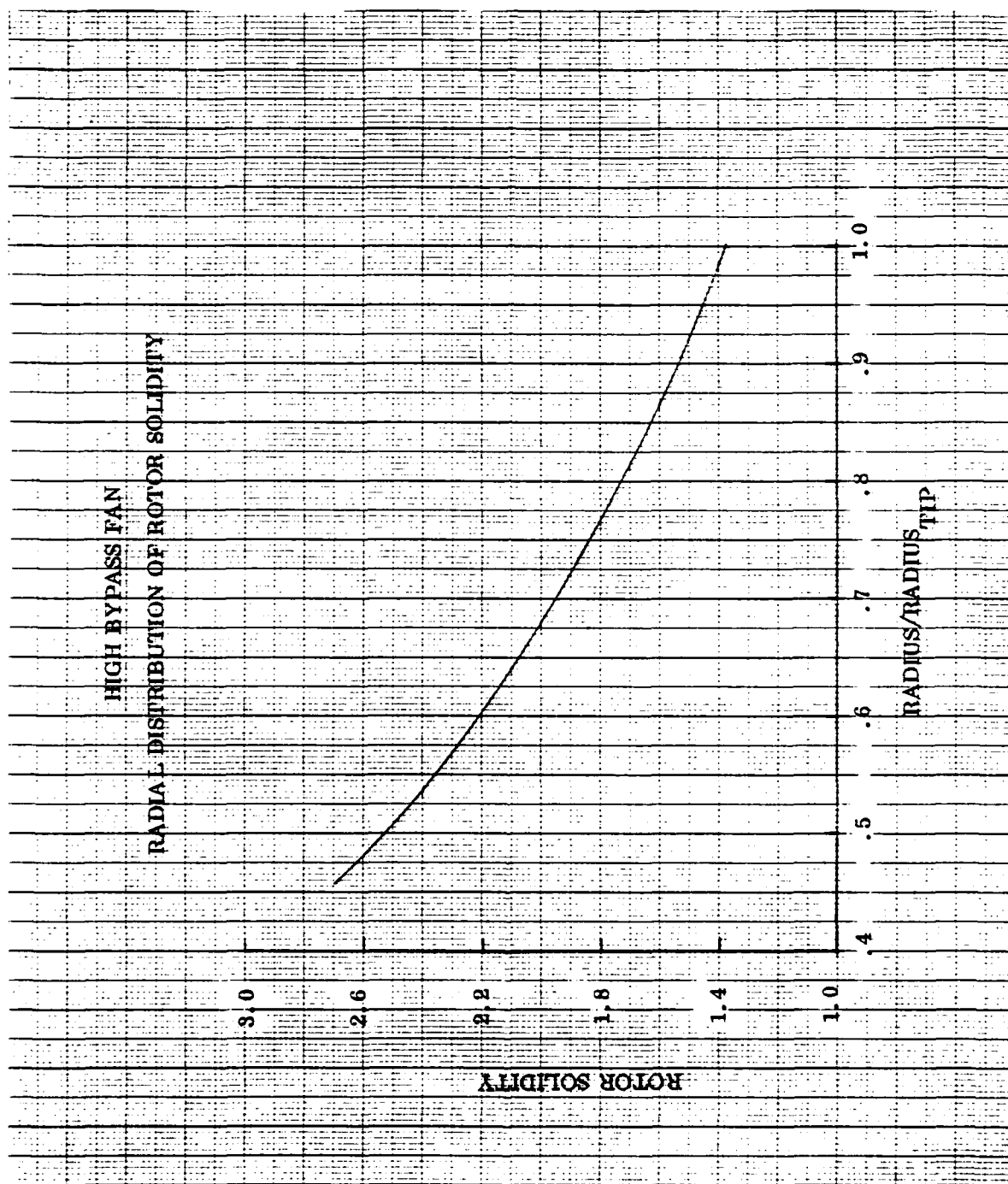
Figure 51. Rotor Solidity Radial Distribution

ROTOR SOLIDITY

RADIUS/RADIUS$_{TIP}$

HIGH BYPASS FAN

RADIAL DISTRIBUTION OF STATOR CHORD

$CHORD_{TIP} = 1.397$

CHORD/CHORD$_{TIP}$

RADIUS/RADIUS$_{TIP}$

Figure 52. Stator Chord Radial Distribution

HIGH BYPASS FAN

RADIAL DISTRIBUTION OF STATOR SOLIDITY
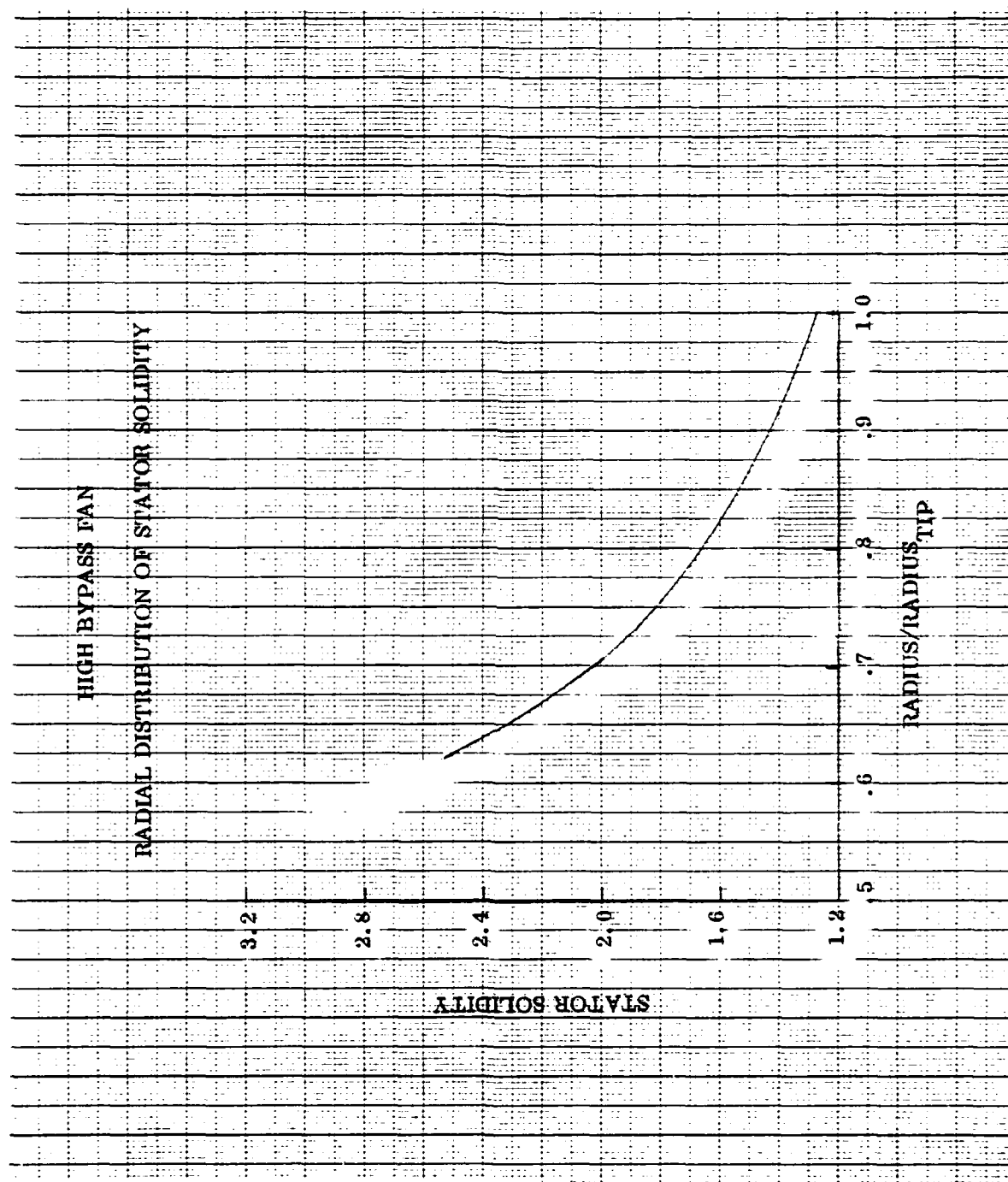
Figure 53. Stator Solidity Radial Distribution
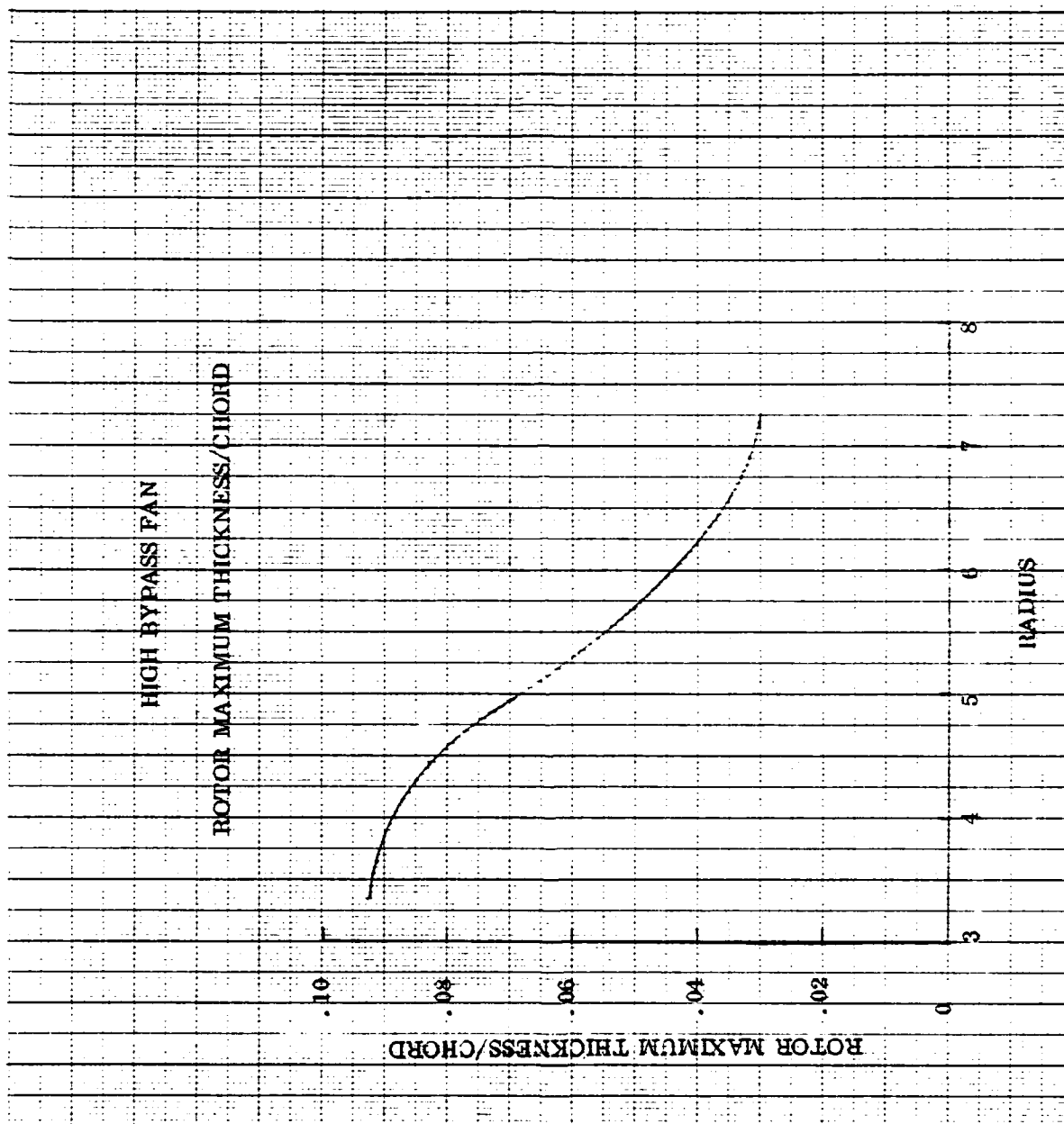
Figure 54. Rotor Maximum Thickness/Chord Radial Distribution

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AIRCRAFT ENGINE GROUP
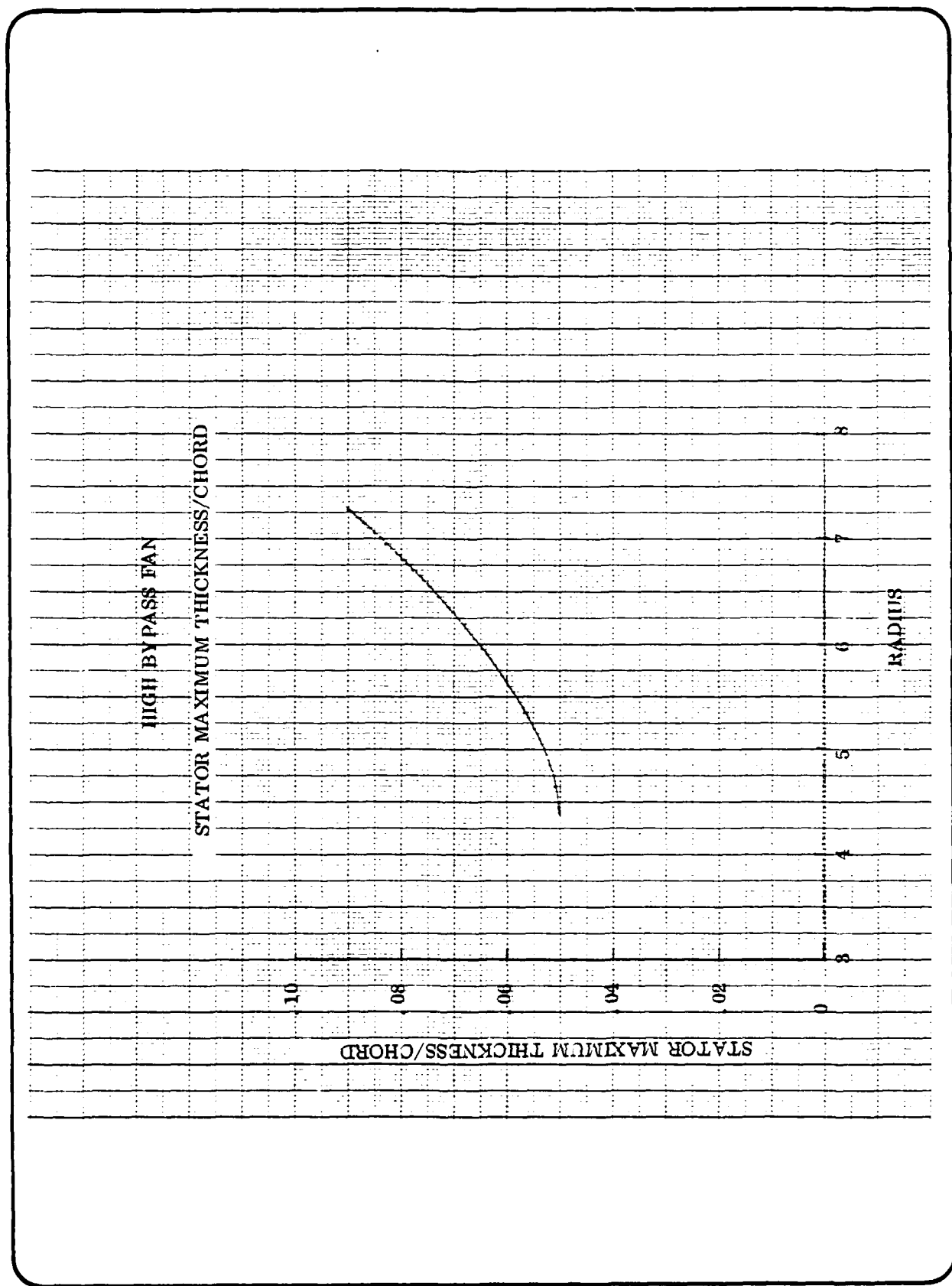
Figure 55. Stator Maximum Thickness/Chord Radial Distribution

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

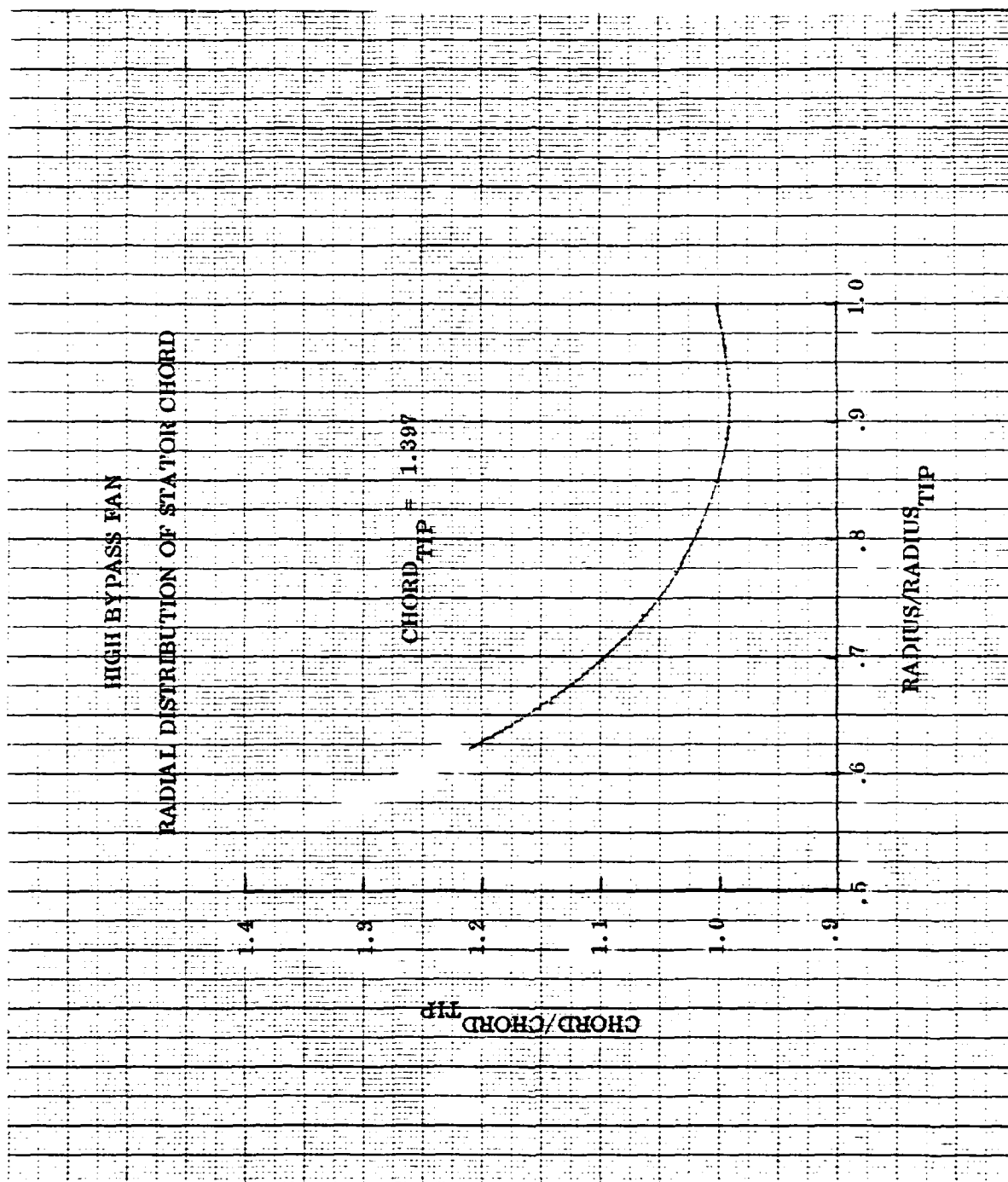Figure 56. Rotor Incidence Angle Radial Distribution

199

Figure 57. Stator Incidence Angle Radial Distribution

Figure 58. Rotor Deviation Angle Radial Distribution
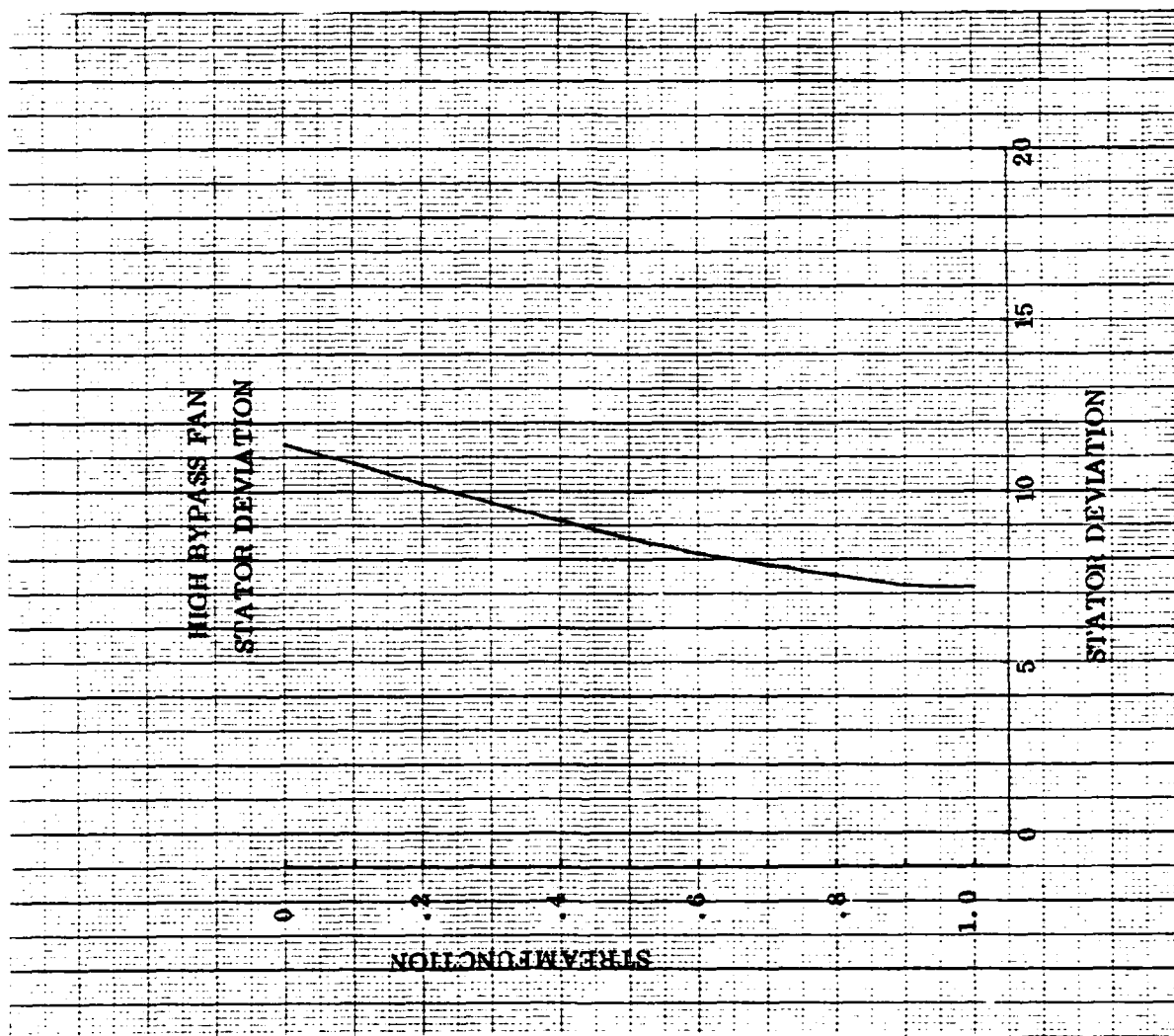
Figure 59. Stator Deviation Radial Distribution

HIGH BYPASS FAN

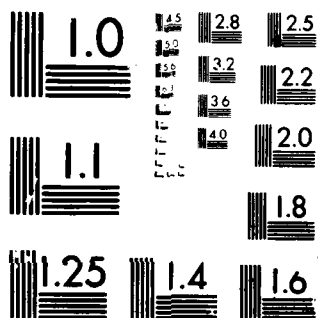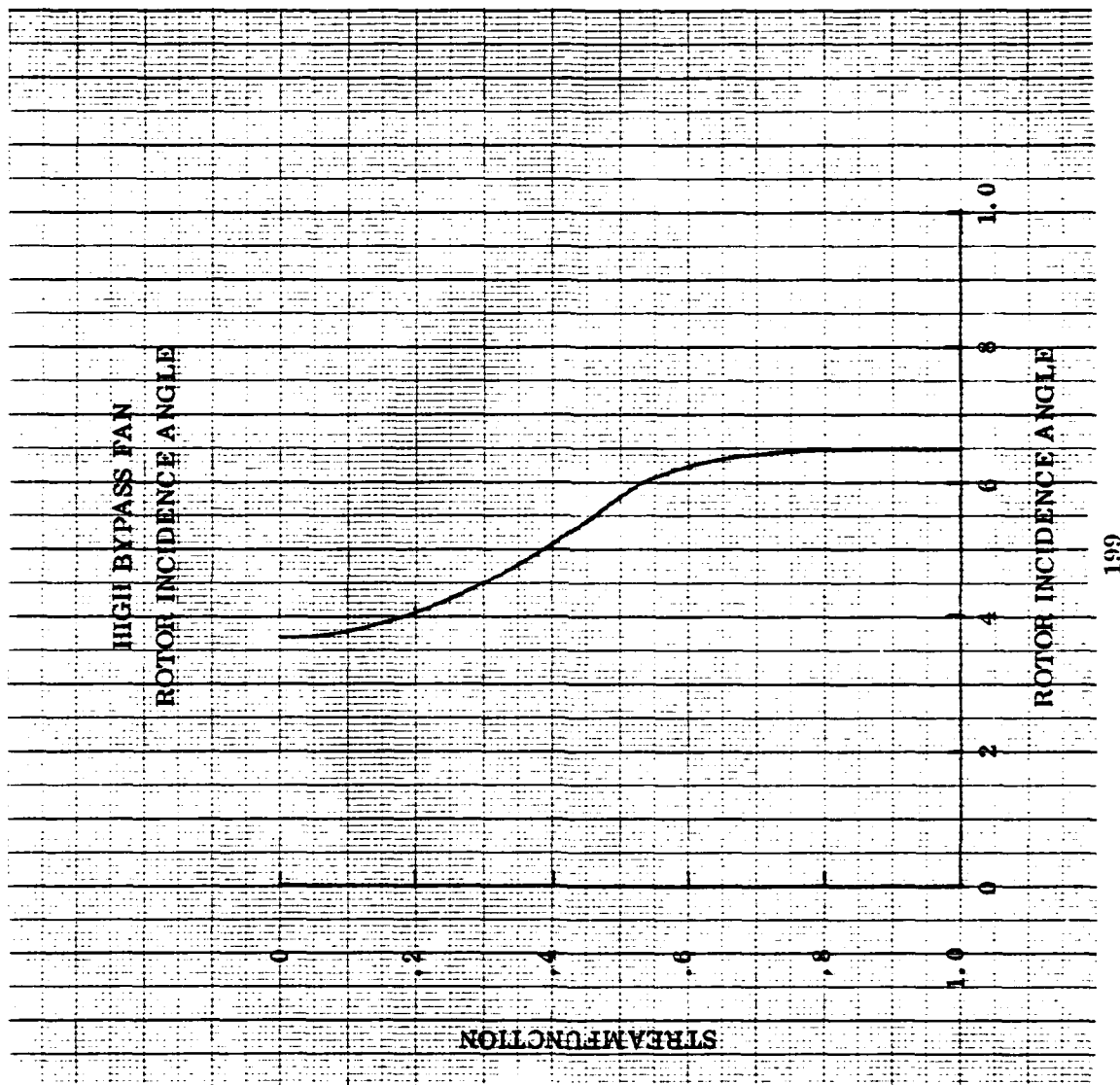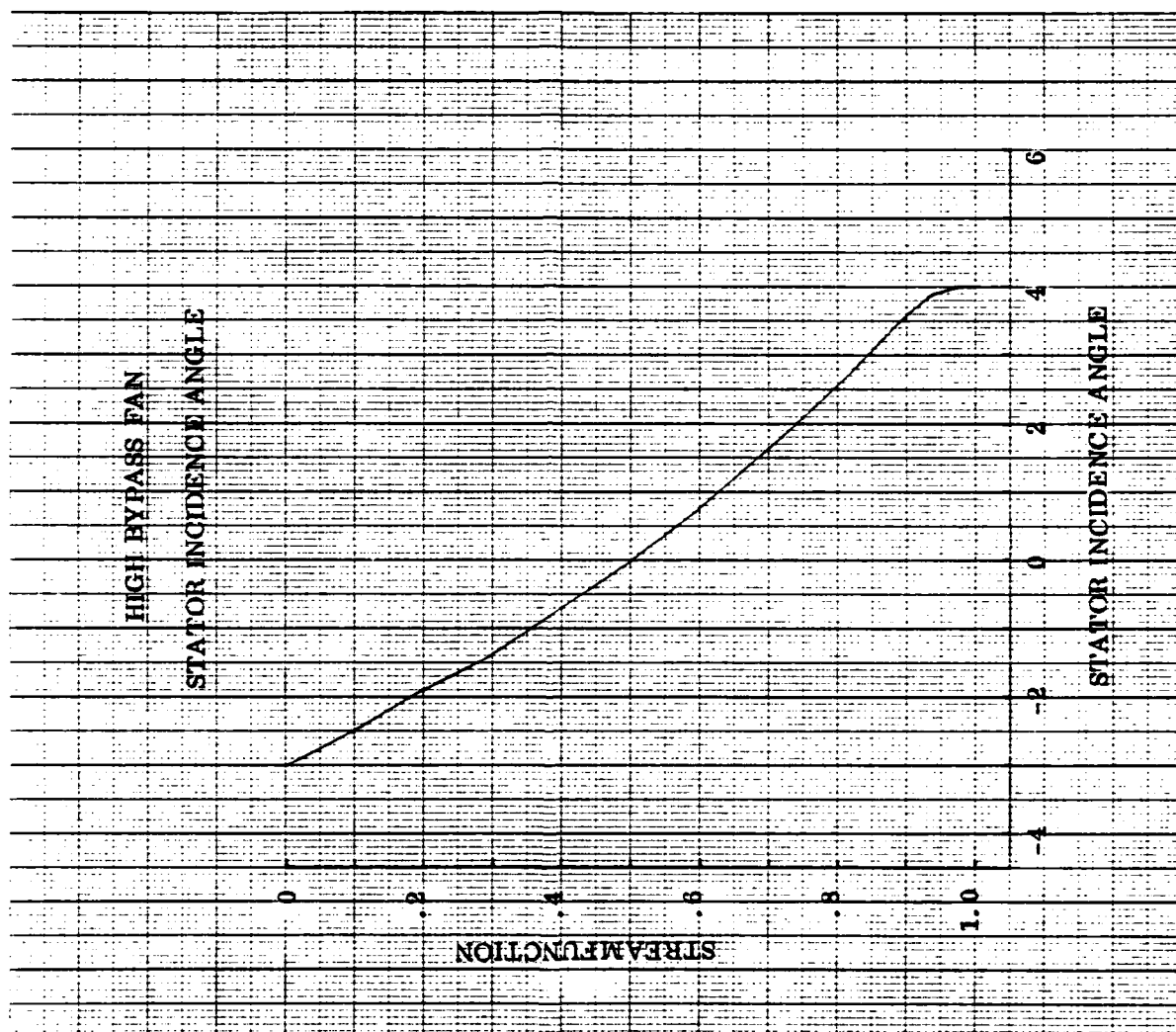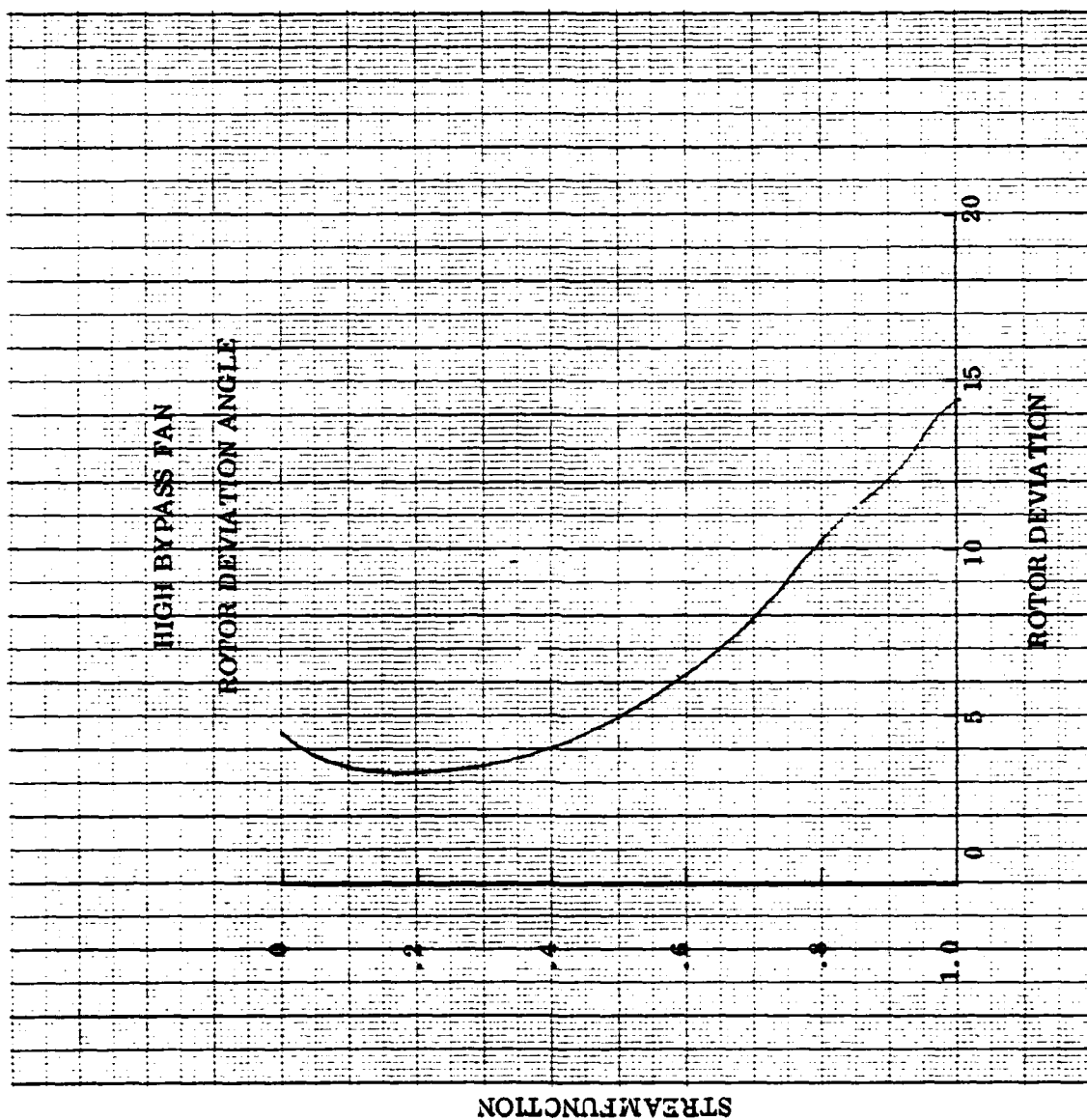## ROTOR MEANLINE METAL ANGLES
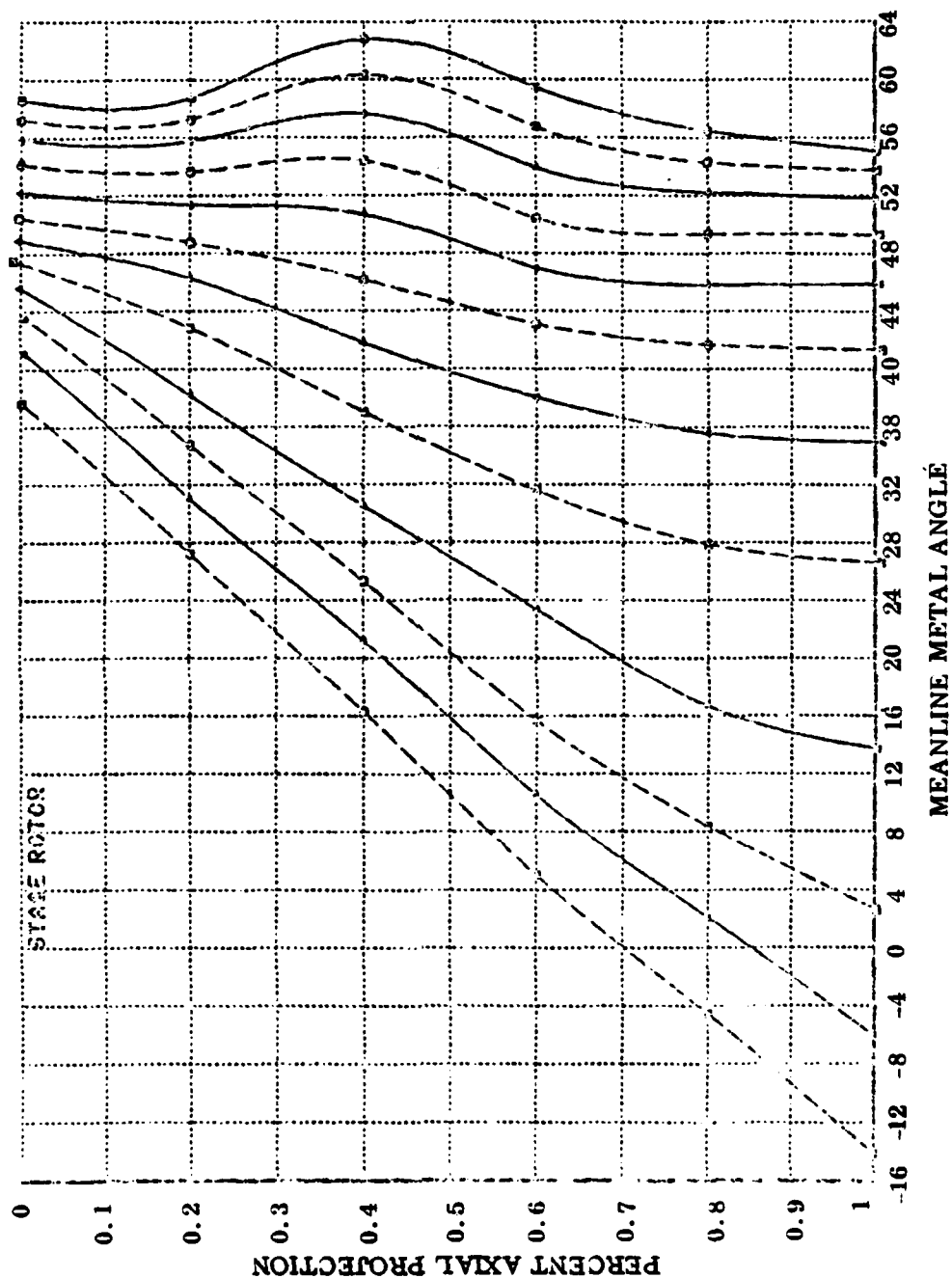
Figure 60. Meanlene Metal Angles

stagger are shown as a function of stream function in Figure 61. The streamline values of camber and stagger will differ from stagger and camber used for aeromechanical analysis and manufacturing which are defined on plane sections cut through the stacking axis. The rotor streamline blade-to-blade passage shapes are shown for tip pitch and hub in Figures 62, 63, and 64, respectively. The rotor blade passage area ratios are shown in Figure 65. The ratio AT/AI to that for normal shock at M1 indicates throat margin. The ratio AT/AM vs MM is blade passage internal contraction and indicates whether the shock structure can operate in the started mode. The ratio AT/AD vs MD indicates whether the blade will provide the desired work input. The rotor suction surface incidence angle is shown in Figure 66.

The stator meanline metal angles are shown as a function of percent axial projection for each streamline in Figure 67. Stator streamline camber and stagger are shown as a function of stream function in Figure 68. The stator tip streamline blade-to-blade passage shapes are shown to OD, pitch and ID in Figures 69, 70, and 71.

The vane passage throat to inlet area ratio is shown in Figure 72 as a function of inlet Mach No. and indicates throat margin.

HIGH BYPASS FAN

ROTOR STREAMLINE CAMBER AND STAGGER
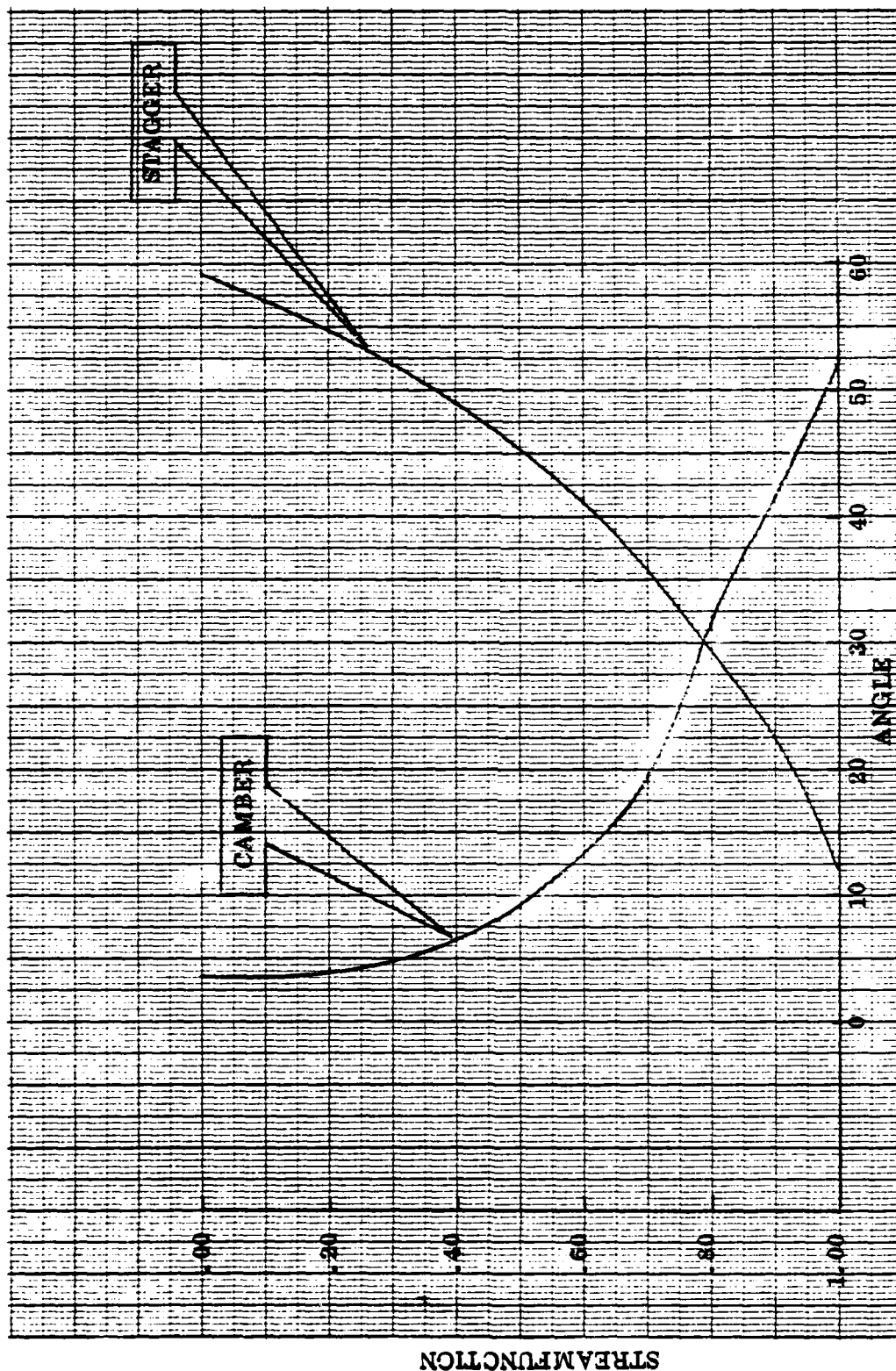
Figure 61. Rotor Streamline Camber And Stagger Angles Distribution

HIGH BYPASS FAN

ROTOR TIP BLADE-TO-BLADE PASSAGE SHAPE

SUCTION SURFACE

PRESSURE SURFACE

THROAT

PRESSURE SURFACE NEXT BLADE

AXIAL LOCATION

TANGENTIAL LOCATION
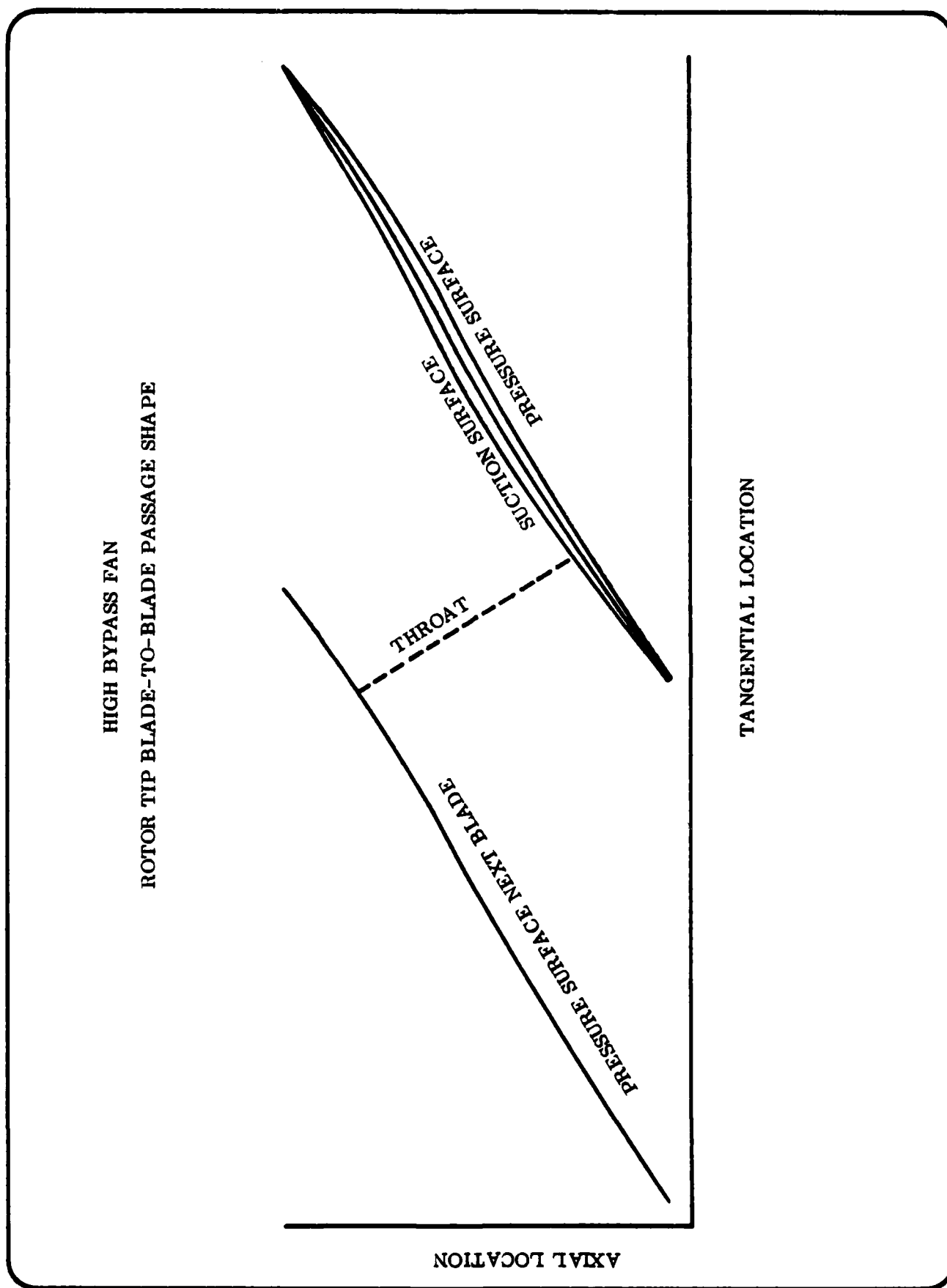
Figure 62.   Rotor Tip Blade-to-Blade Passage Shape

HIGH BYPASS FAN

ROTOR PITCH BLADE-TO-BLADE PASSAGE SHAPE

SUCTION SURFACE

PRESSURE SURFACE

THROAT

PRESSURE SURFACE NEXT BLADE
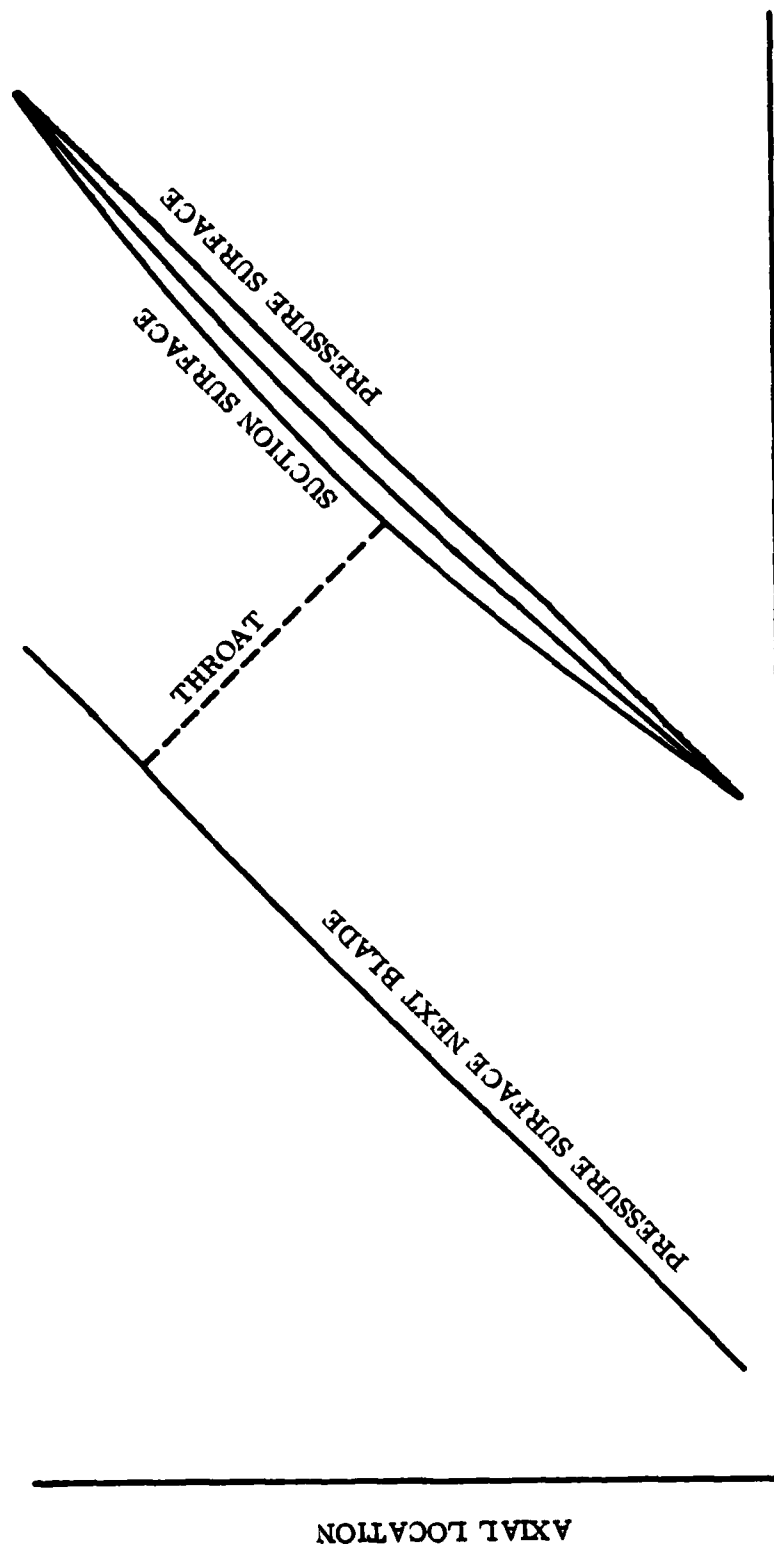
AXIAL LOCATION

TANGENTIAL LOCATION

Figure 63.   Rotor Pitch Blade-to-Blade Passage Shape

HIGH BYPASS FAN

ROTOR HUB BLADE-TO-BLADE PASSAGE SHAPE

THROAT

PRESSURE SURFACE

SUCTION SURFACE

PRESSURE SURFACE NEXT BLADE

TANGENTIAL LOCATION

AXIAL LOCATION
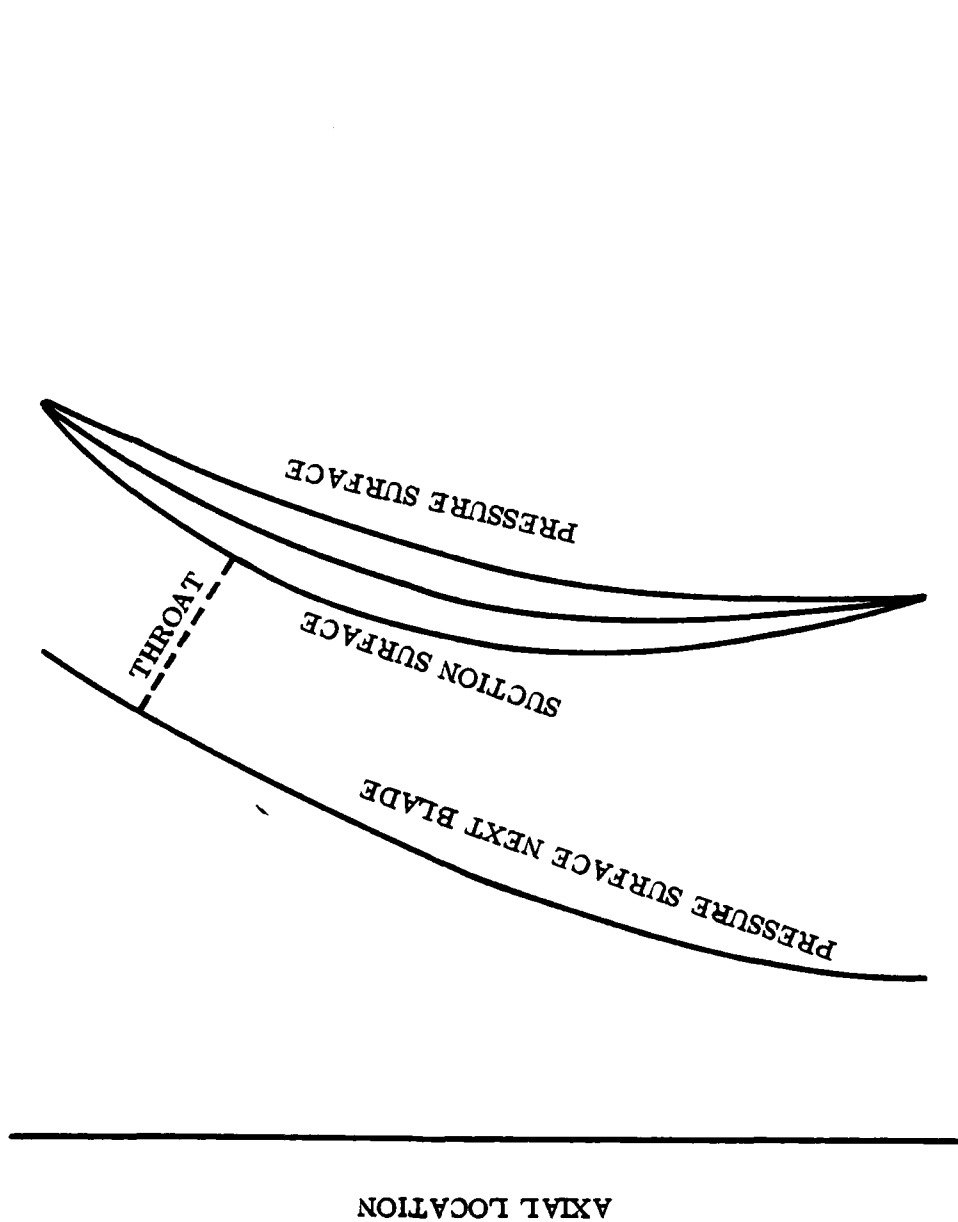
Figure 64. Rotor Hub Blade-to-Blade Passage Shape
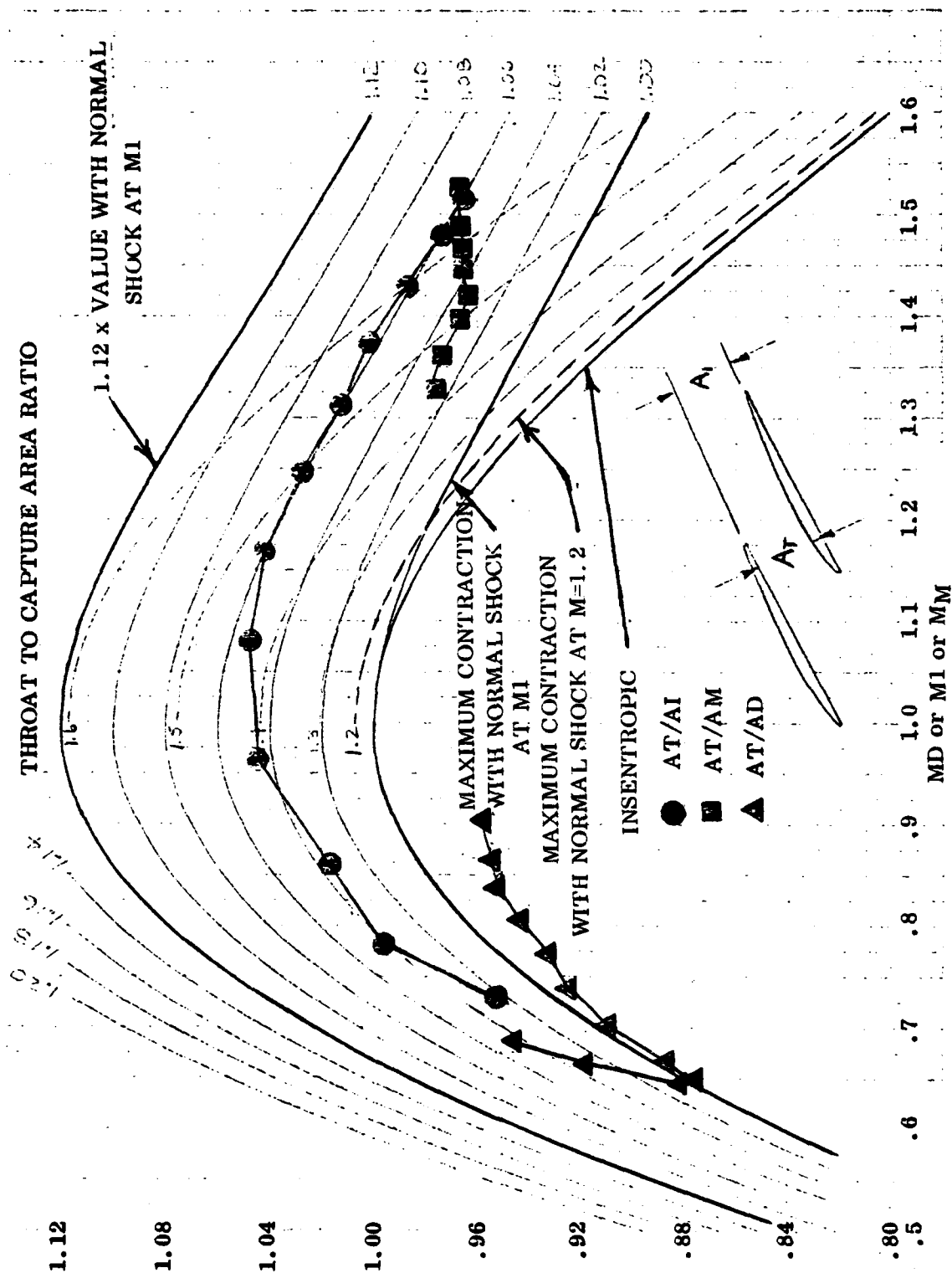
Figure 65. Rotor Blade Passage Area Ratios

HIGH BYPASS FAN

ROTOR SUCTION SURFACE INCIDENCE

ROTOR INLET RELATIVE MACH NO.
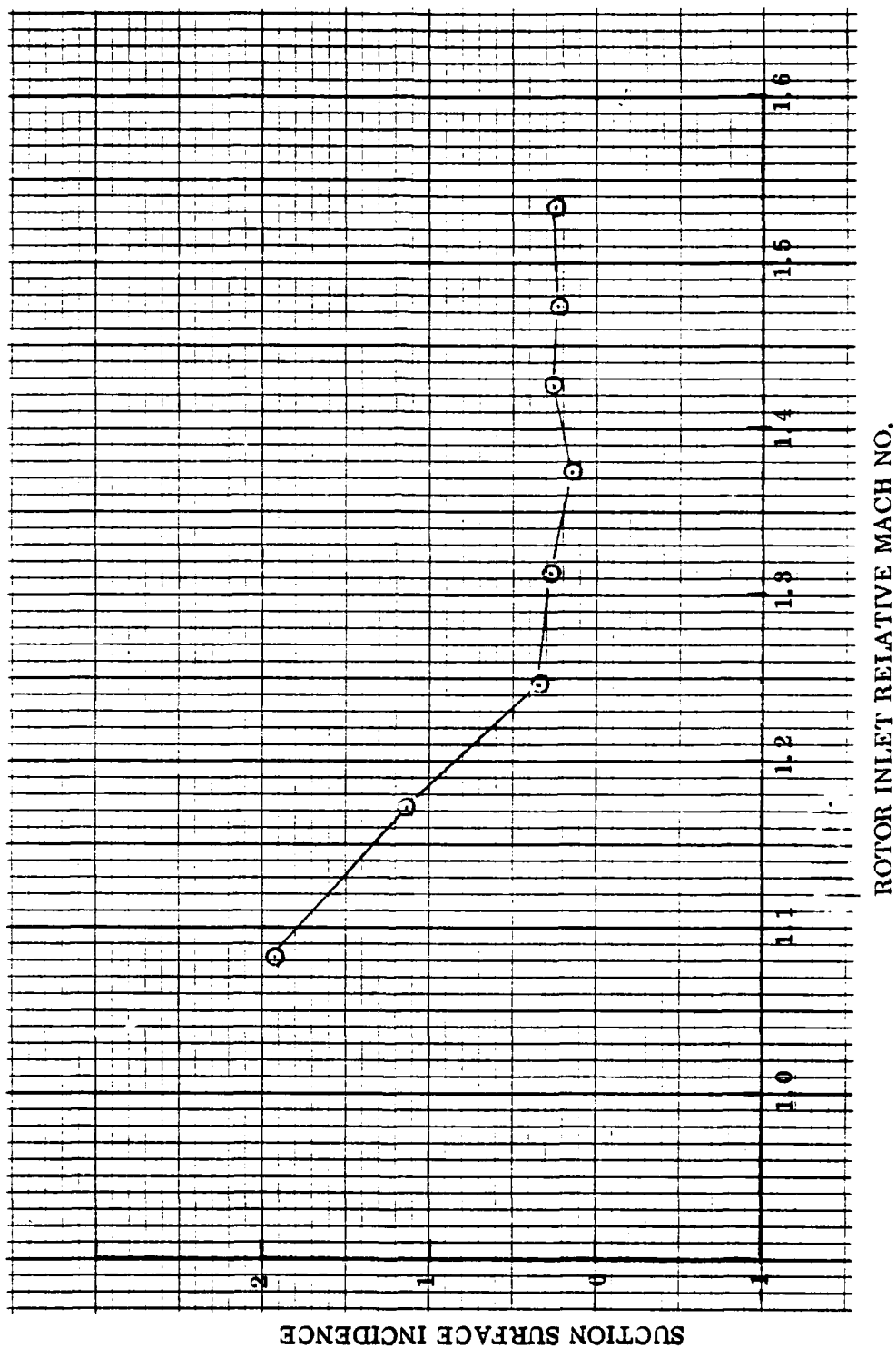
Figure 66. Rotor Suction Surface Incidence Angle

HIGH BYPASS FAN

STATOR MEANLINE METAL ANGLES
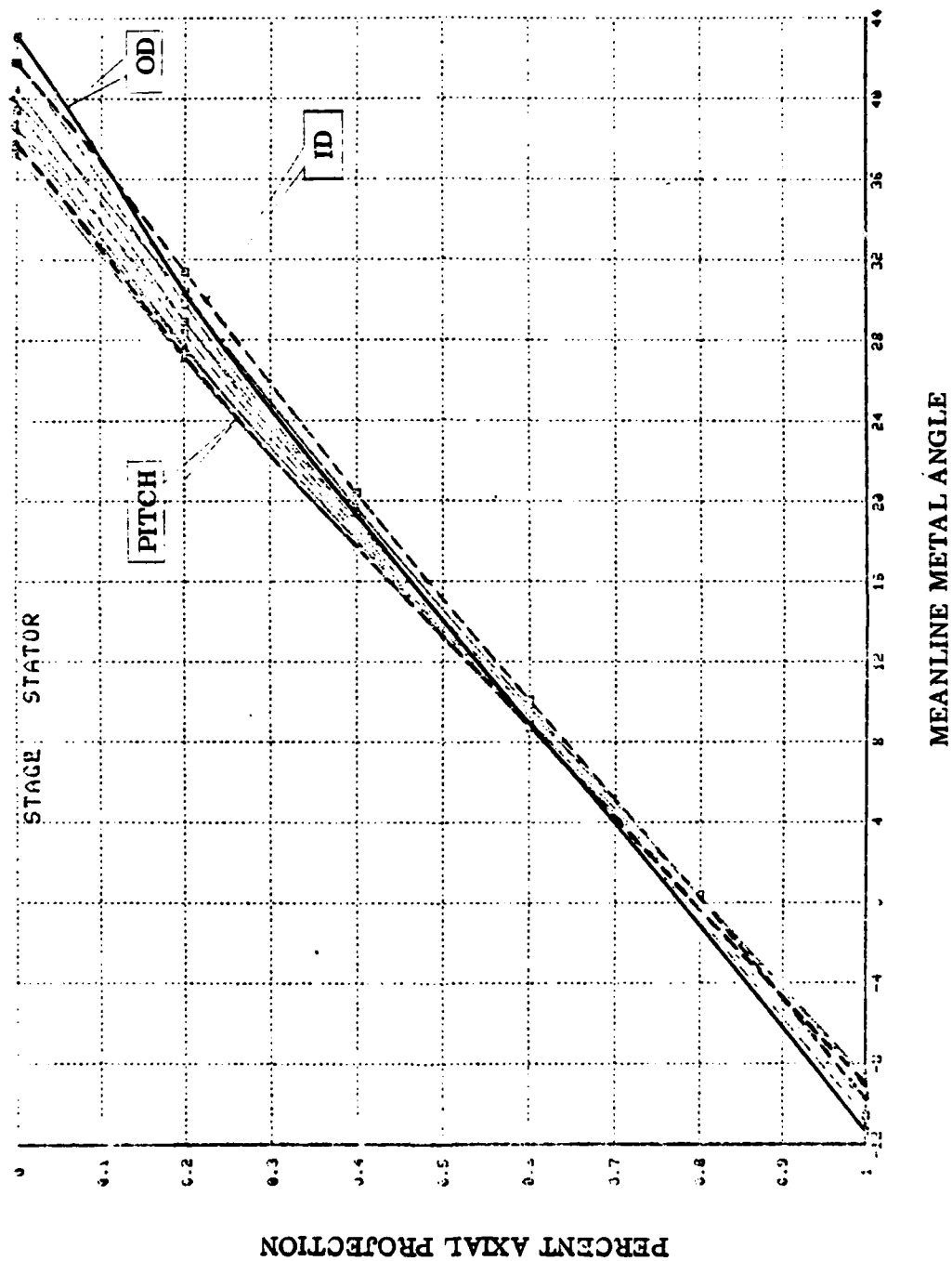
Figure 67. Stator Mealine Metal Angles

HIGH BYPASS FAN

STATOR SCHEDULE CAMBER AND STAGGER
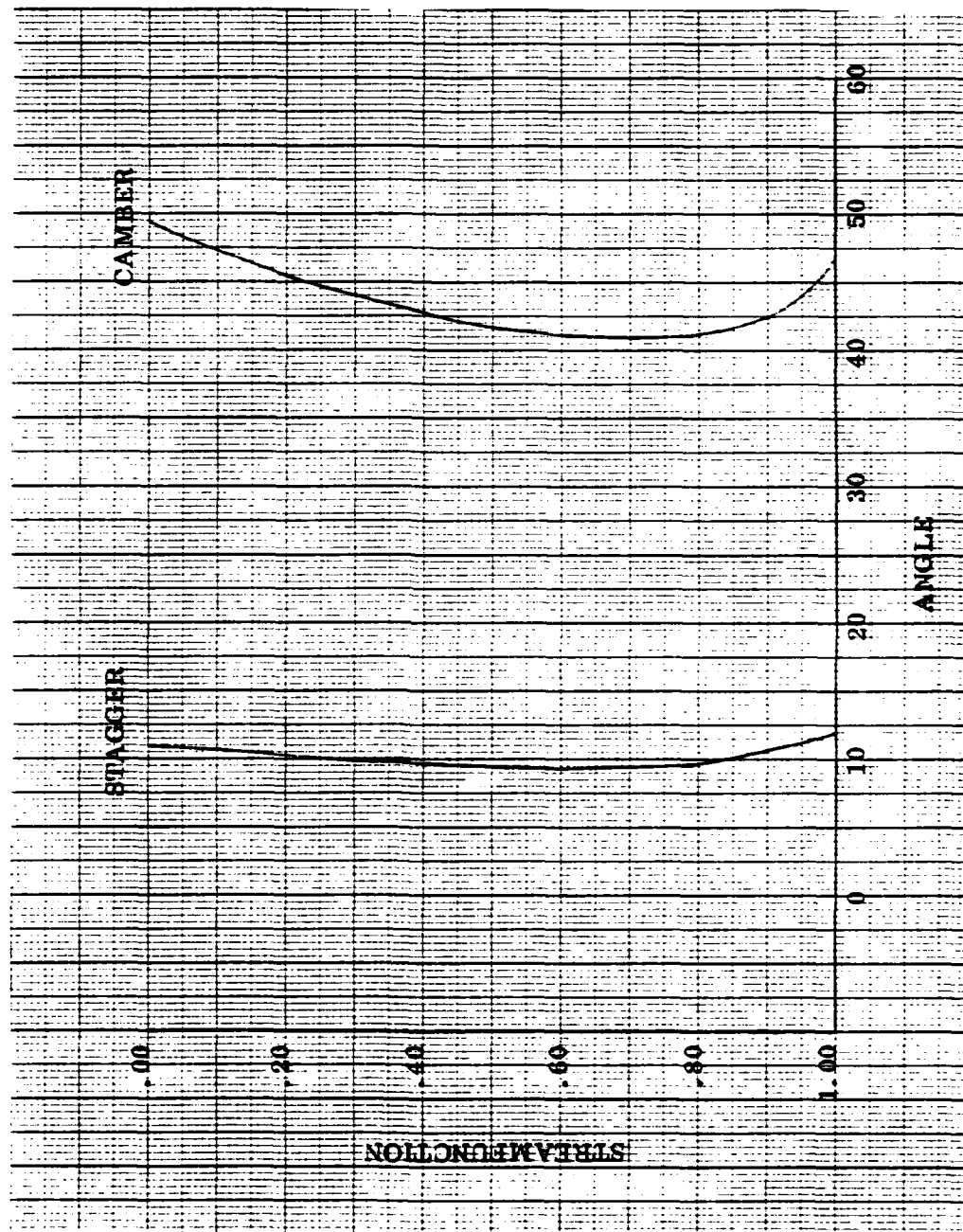
Figure 68. Stator Streamline Camber And Stagger Angles

Figure 69. Stator OD Blade-to-Blade Passage Shape

HIGH BYPASS FAN

STATOR PITCH BLADE-TO-BLADE PASSAGE SHAPE
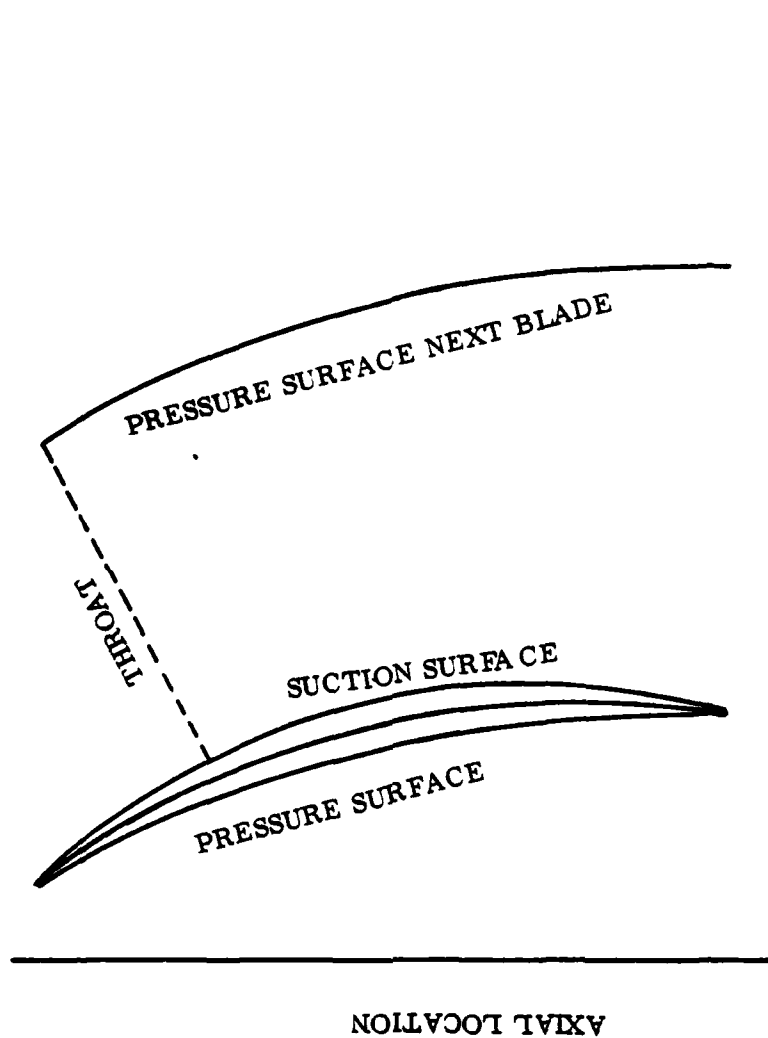
Figure 70. Stator Pitch Blade-to-Blade Passage Shape

HIGH BYPASS FAN

STATOR ID BLADE-TO-BLADE PASSAGE SHAPE
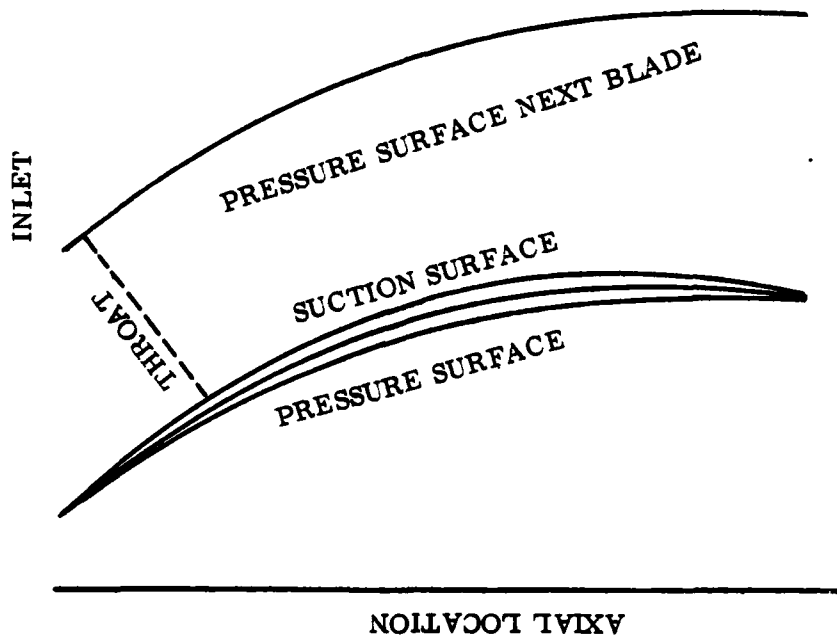
Figure 71. Stator ID Blade-to-Blade Passage Shape
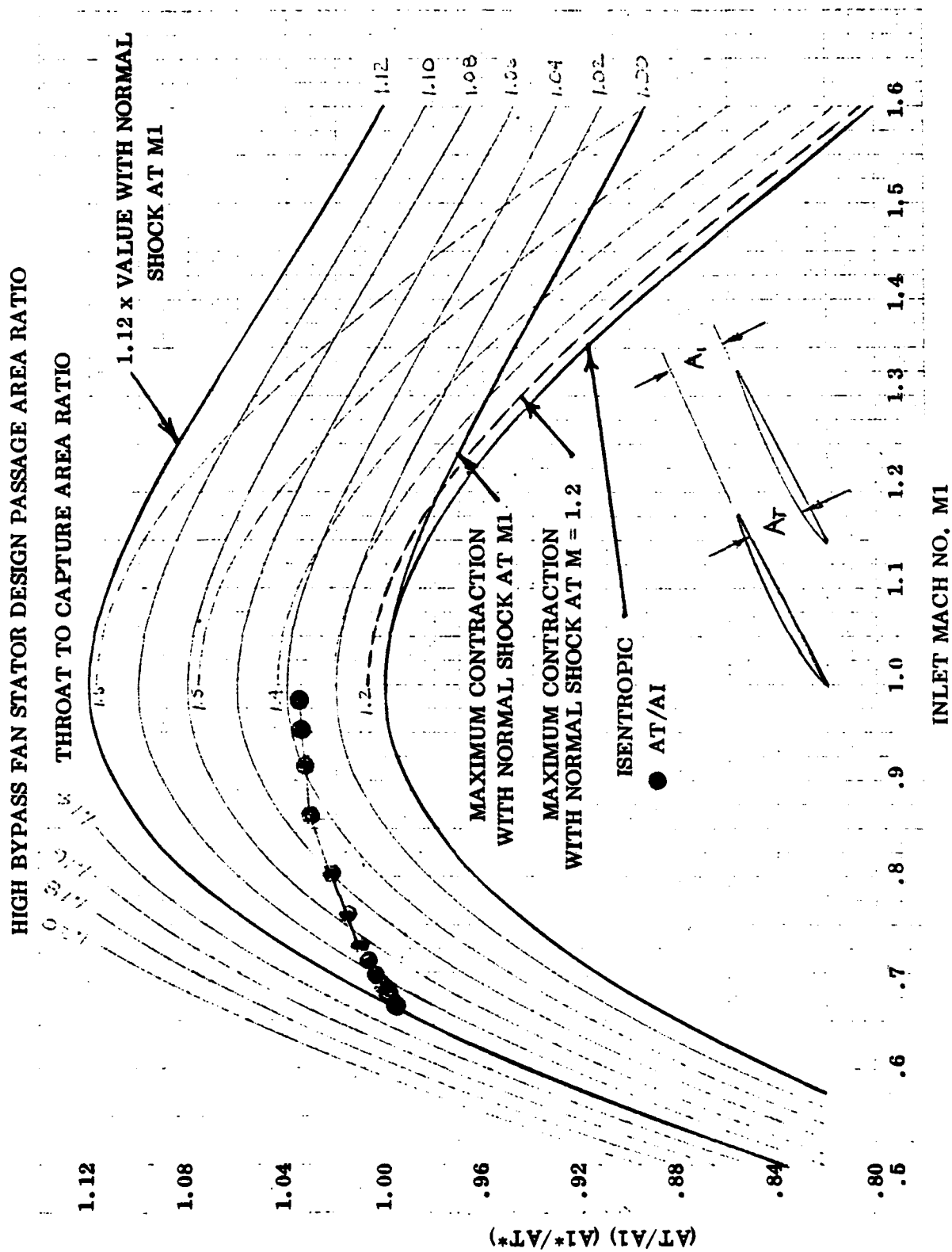
Figure 72. Stator Passage Throat to Inlet Area Ratio

3.4   FAN AEROMECHANICAL ANALYSIS

This subsection describes the detailed aeromechanical design-analysis
procedure essential to provide a basis for the selection of a final fan design
which simultaneously satisfies the prime aerodynamic (aeromechanical/mechanical
design objectives including MIL-E-5007D. The detailed analytical results and
trade-offs involved in the selected final fan design are presented.

3.4.1   Fan Rotor Design Analysis

Having proceeded through the iteration/parametric cycle and arrived at
a mutually satisfactory aerodynamic/aeromechanical/mechanical design, a
detailed design analysis was conducted for the rotor airfoil. This analysis
identified the stress, vibration, stability characteristics and the bird impact
tolerance of the chosen airfoil design. It also determined the airfoil geometry
modifications necessary to achieve the design objectives imposed upon the design.
A description of the airfoil, in terms of pertinent aerodynamic parameters and
geometry plots, is shown in Figure 73. The frequency, stability and stress
characteristics are shown in Figures 74, 75, and 76, respectively. In addressing
to the FOD tolerance of a fan blade, a fundamental approach is to insure that the
leading edge is close to or in compression due to centrifugal effects. This maxi-
mizes the ability of damaged edges to absorb stress risers and minimizes crack
growth rates. Since tangentail tilt can be incorporated to place the leading edge in
compression, Figure 76 shows the implications of incorporating airfoil tilt.
While the tangential tilt helps the leading edge, i.e., place more of the leading
edge in compression, it increases the root convex stress to an undesirable level.
For this reason, tilt was not considered to be an effective ingredient in the airfoil
design.

Evaluation of the airfoil design for bird impact tolerance, Figure 77, suggests
that ingestion of a 4 oz. bird impacting the blade tip area at takeoff conditions
satisfies the design intent. Specifically, the bird impact would be expected to
develop shear stress levels (τmax) no greater than the material shear strength
capabiltiy (τcrit). This suggests the avoidance of having airfoil fragments punched
out of the airfoil. As the engine is throttled back or the bird speed is increased,
(cruise type flight conditions) the bird impact problem becomes less severe as shown
by the lower developed shear stress levels. Since a 4 oz. bird is expected to reside
over 40% of the blade span, placing the bird centroid at 80% span implies that the
bird footprint extends radially from the blade tip to 60% blade height - thus, the
notation of bird impact at 80% span for the 4 oz. bird fragmentation problem. Also
noted is the number of blades (as a percentage of 20) expected to be impacted. The
significance here is that a great many blades could undergo severe damage/deforma-
tion. For a given size engine, as the bird weight is increased, the impact problem
shifts from one of preventing loss of airfoil fragments to one of avoiding loss of
entire airfoils. For the GE26/F4 design, this is the situation when addressing to
ingestion of 2 lb. vs. 4 oz. bird sizes. Because the 2 lb. bird is expected to reside

GE26/F4 FAN ROTOR 3-D FINTE ELEMENT MODEL
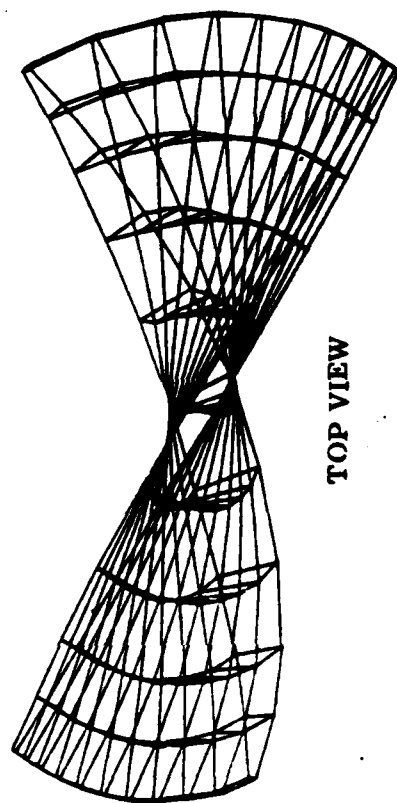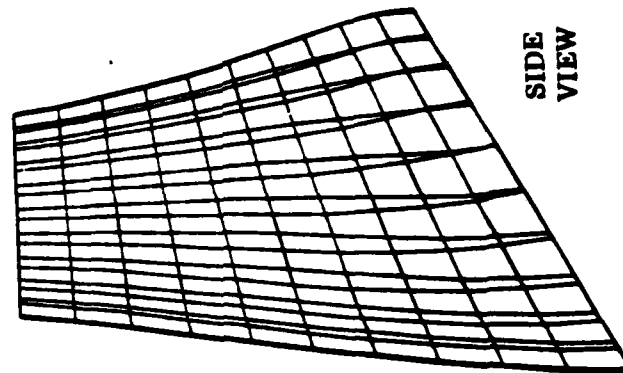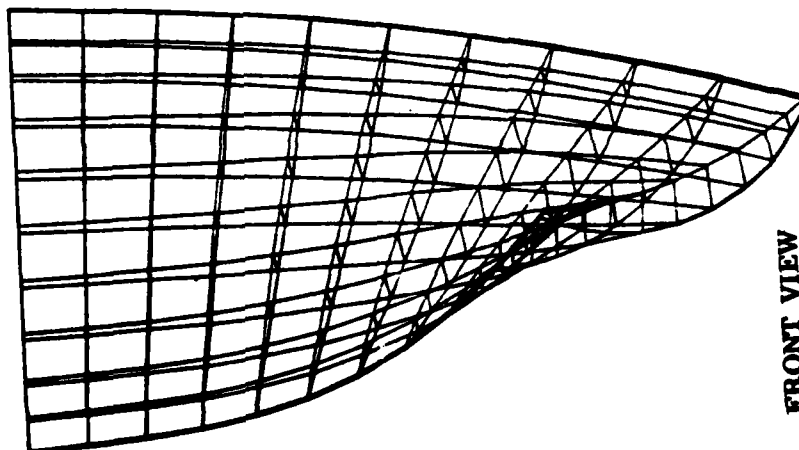
TOP VIEW

Number of Blades	20
W$\sqrt{\theta}$ /δ (pps)	41.6
W/A (Annulus) (pps/ft^2)	41.5
P/P (Hub/Tip)	1.8/1.75
Tip M$_{REL}$	1.53
Tip Speed, U$_T$ (fps)	1440
Tip Diameter (in.) avg.	14.5
Inlet Radius Ratio	.360
Avg. Radius Ratio	.46
Root Aspect Ratio	1.43
Solidity: Tip	1.36
Hub	2.65
Tm/c: Tip	.030
Hub	.093
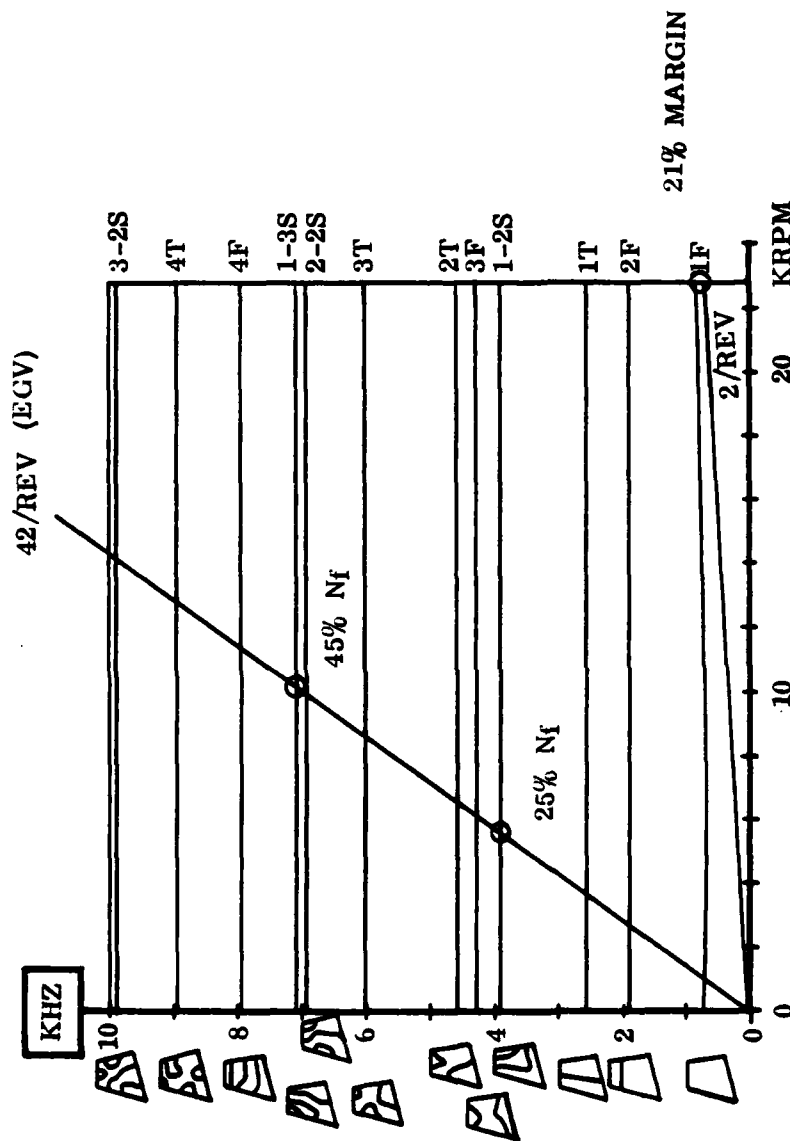
SIDE VIEW

FRONT VIEW

Figure 73. Rotor Airfoil Aerodynamic And Geometric Description

Figure 74. Rotor Airfoil Frequency Characteristics
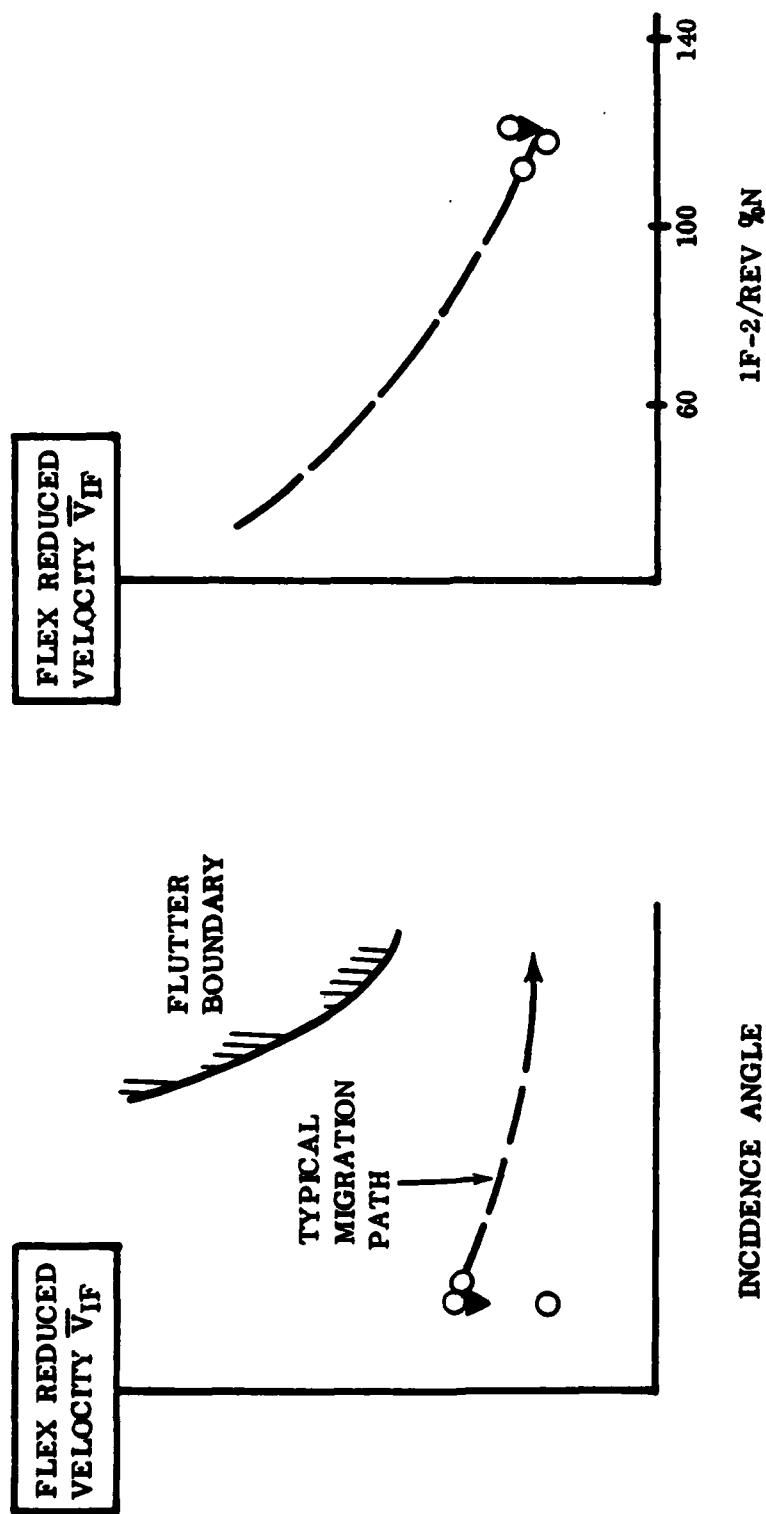
Figure 75. Rotor Airfoil Stability Margin

GE26/F4 FAN, ROTOR AIRFOIL STRESS

-25

0

25

75

100

50

25

0

25

50

75

CVX

0

25

30

75

30

25

0

-25

CCV
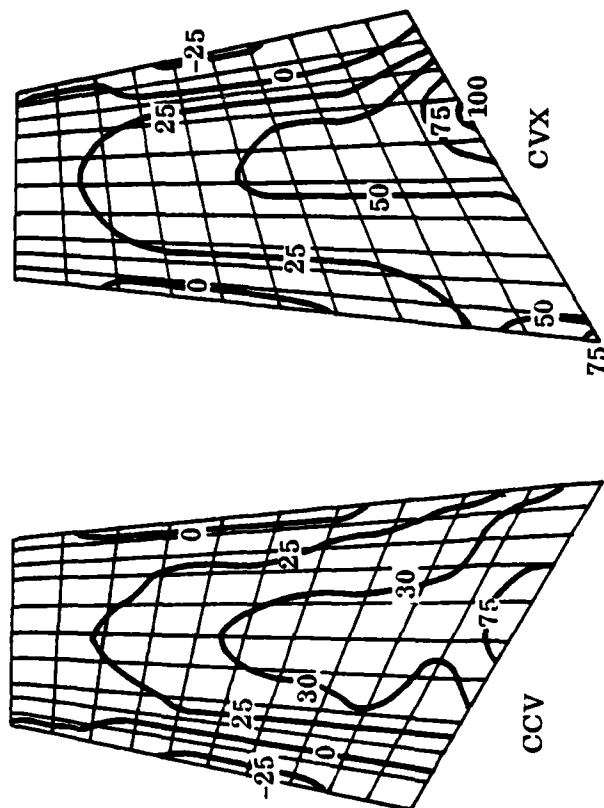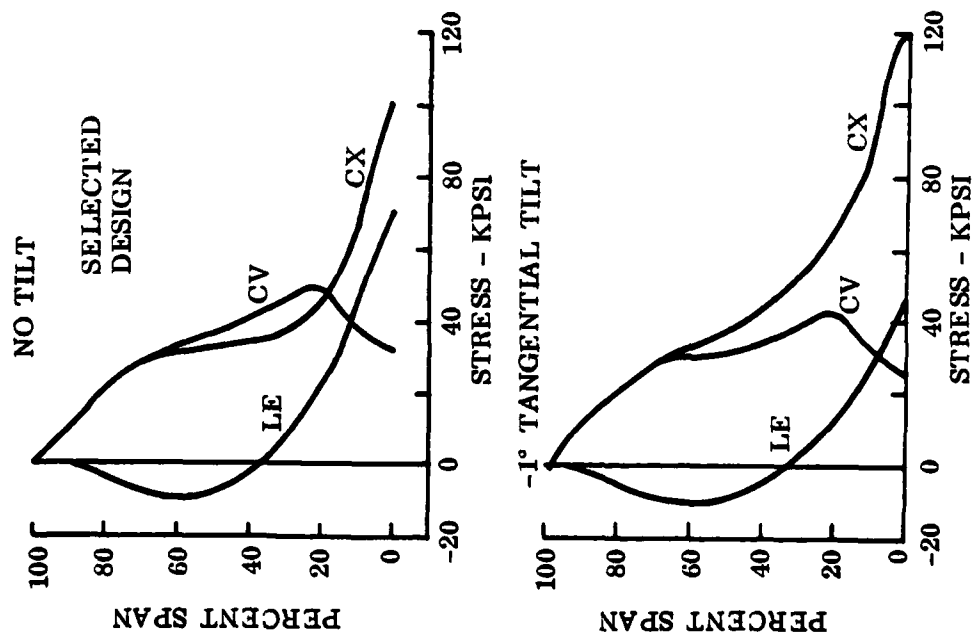
- Design for balanced stress: for F.O.D. resistance, lead-ing edge compressive stress desirable.
- Steady state stress levels consistent with production engine experience.

NO TILT

SELECTED
DESIGN

CX

CV

LE

STRESS – KPSI

120

80

40

0

-20

PERCENT SPAN

100

80

60

40

20

0

-1° TANGENTIAL TILT

CX

CV

LE

STRESS – KPSI

120

80

40

0

-20

PERCENT SPAN

100

80

60

40

20

0

Figure 76.   Rotor Airfoil Stress Characteristics

110

BIRD INGESTION CAPABILITY/EVALUATION

FRAGMENTATION

- AIRFOIL AS DESIGNED MEETS FRAGMENTATION REQUIREMENTS
  ...4 OZ IMPACT @ 80% SPAN
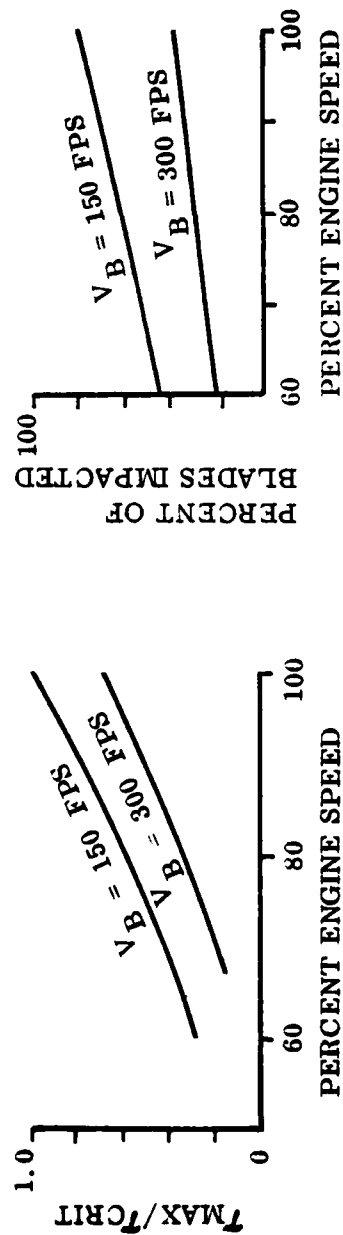
FRACTURE

- AIRFOIL AS DESIGNED MEETS FRACTURE REQUIREMENTS
  ...2 LB IMPACT AT 60% SPAN
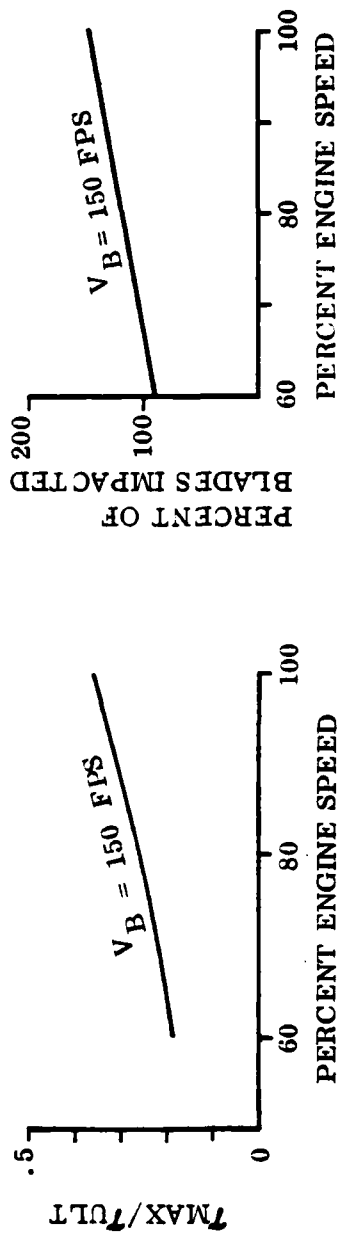
Figure 77. Rotor Airfoil Bird Impact Tolerance Capability

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over 80% of the blade span, this suggests a fracture (loss of entire airfoil) rather than a fragmentation problem. As such, Figure 77 also presents the results of the fracture analysis suggesting that the developed shear stress (τ max) remains lower than that needed for fracture (τ ult). Once again, the concern is the number of blades impacted with some blades undergoing multiple hits from the same bird, i.e., it takes more than one wheel revolution to ingest the whole bird. The large number of blades impacted combined with the relatively large footprint size raises the spectre of very severe airfoil damage/deformation. The fan blades may remain intact but be incapable of sustaining very much of a flow pumping capability. The rationale then for designing small engines for ingestion tolerance to large birds may be counter-productive - that is, severe weight/performance penalties are required to contain fan airfoil damage to a level where reasonable post strike flow pumping capabilities exist. Even then, experimental data would be the key ingredient since the analytical evaluation procedure would be questionable at best.

3.4.2 Fan Stator Design Analysis

The main ingredient in the design evolution of the fan stator is the avoidance of forced vibration problems through frequency/stimulus control. As such, fewer iterations are required to identify a mutually satisfactory design. A description of the vane airfoil in terms of pertinent aerodynamic parameters and geometry plots is shown in Figure 78 with the resulting frequency characteristics shown in Figure 79. The design objective for the selected vane configuration is to avoid fundamental mode resonances excited by the rotor passing frequency (20/rev) in the high engine speed region, and to insure that the fundamental bending and torsion modes are uncoupled. The uncoupling of the modes indicated will be done by insuring that the mechanical construction of the vane attachment has sufficient foundation flexibility so as to suppress the airfoil bending mode frequency while at the same time, rendering the torsion mode frequency unaltered. Design of the vane attachment scheme is still underway, but no problems are expected.

GE26/F4 FANSTATOR 3-D FINITE ELEMENT MODEL
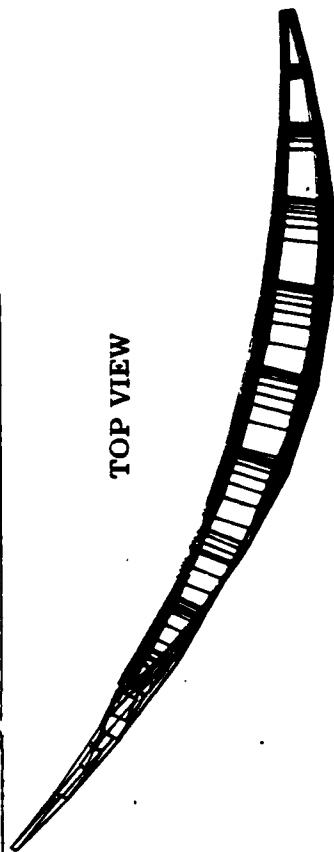
TOP VIEW
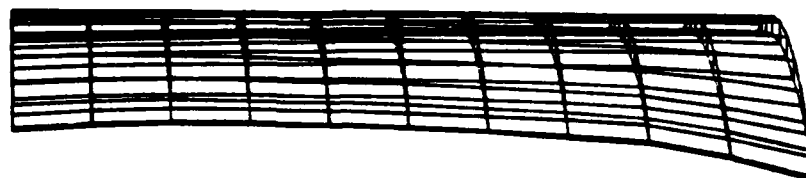
SIDE VIEW

FRONT VIEW

NUMBER OF VANES	42
INLET RADIUS RATIO	.59
AVERAGE RADIUS RATIO	.62
PITCH ASPECT RATIO	1.93
SOLIDITY – OD	1.29
– ID	2.50
TM/C – OD	.099
– ID	.046
CHORD – OD	1.40
– ID	1.69
MATERIAL	A286
ATTACHMENT	FIXED OD / ID
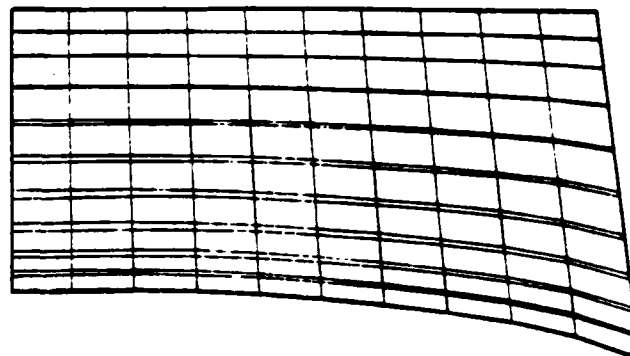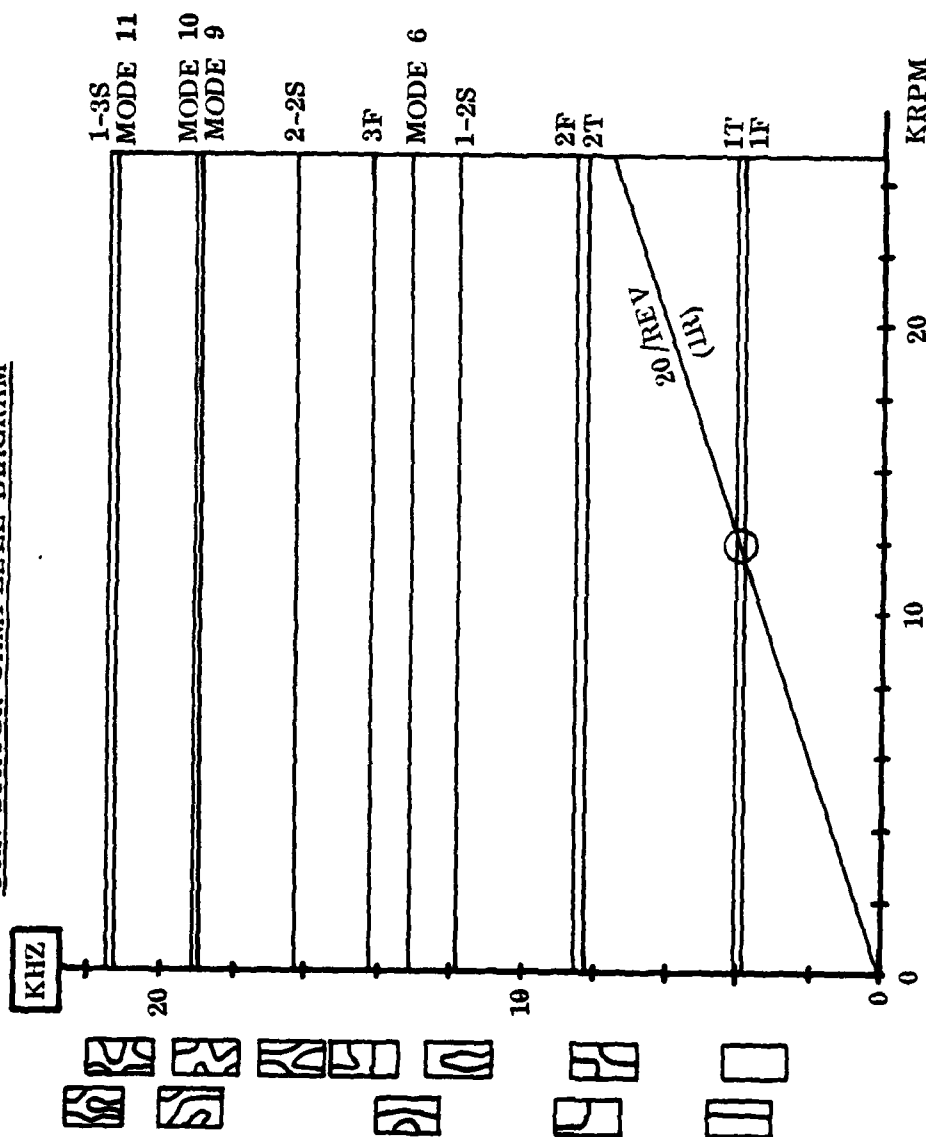
GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Figure 78. Stator Airfoil Aerodynamic And Geometric Description

Figure 79. Stator Airfoil Frequency Characteristics

3.5 FAN MECHANICAL DETAIL DESIGN

3.5.1 Fan Blisk Overall Design

A full scale cross section of the high bypass turbofan blisk is shown in Figure 80. The disk design takes advantage of the fact that absence of blade dovetails allows the blisk rim to carry substantial circumferential stresses. Thus the disk bore diameter could be increased significantly resulting in a lightweight design.

Torque transfer from the drive shaft into the blisk occurs via a bolted flange using ten 1/4" high strength hook bolts.

The blisk was designed to represent flight type hardware. The requirement of instrumentation lead routing in the component vehicle dictates a slightly different aft flange configuration. However the flange can be reworked to update the demonstrator fan blisk into a flight type engine part. Figure 81 shows the similarity between demonstrator and flight type designs. Detail blisk drawing number 17A138-297 has been issued for procurement purposes in Phase III.

3.5.2 Fan Blisk and Spinner Stress Levels

The high bypass turbofan blisk stress analysis was performed using the following guidelines:

o   Rim load distribution non uniform in axial direction. Load distribution from aeromechanical design calculations uprated to 103% NG.

o   Blisk in combination with spinner modeled for finite element stress analysis. Boundary condition in zero axial movement at rear bolt circle.

o   Large bore radius chosen to load up rim and thus to keep weight down. Design is not limited by bore stresses but by overspeed requirements.

o   Blisk/spinner fit was chosen such that interference increases with increasing speed.

The results of the stress analysis are summarized in Figure 82. Conclusions are:

o   Stresses are well within the capabilities of the chosen material (see Para. 3.5.3).

o   Interference fit at blisk/spinner interface plus loads introduced into the spinner result in acceptable stresses in the spinner.

HIGH BYPASS TURBOFAN BLISK DESIGN

FULL SCALE CROSS SECTION
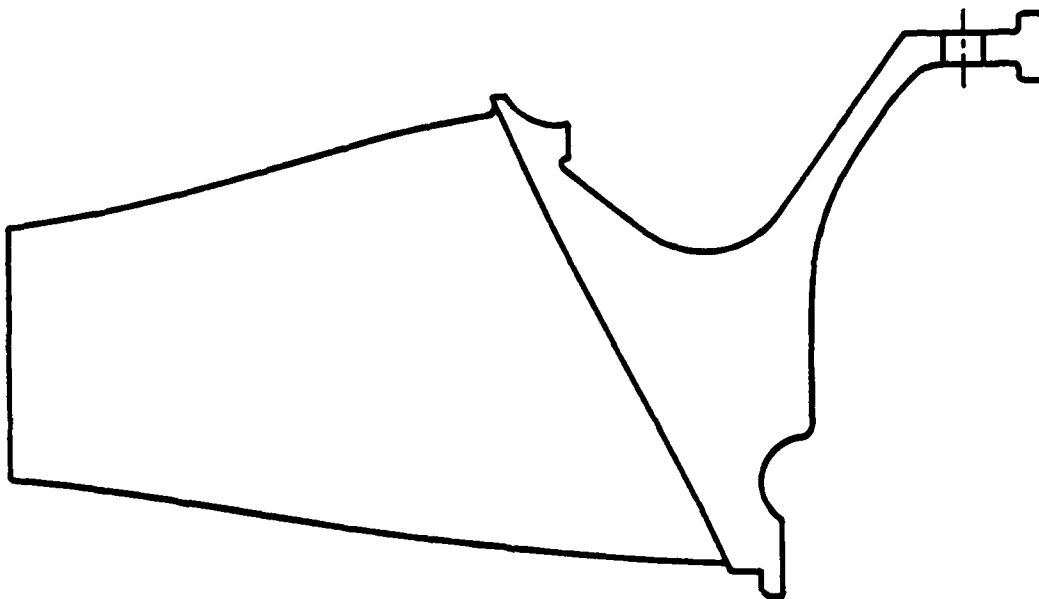
Figure 80.   Fan Blisk Full Scale Cross Section

SIMILARITY OF DEMONSTRATOR VS. FLIGHT BLISK DESIGNS

ENGINE FAN BLISK DESIGN
(SIMPLER FLANGE MATCHES
ENGINE FAN DRIVE SHAFT)

FAN DEMONSTRATOR BLISK DESIGN
(MOUNTING FLANGE MATCHES FAN
TEST RIG DRIVE SHAFT)
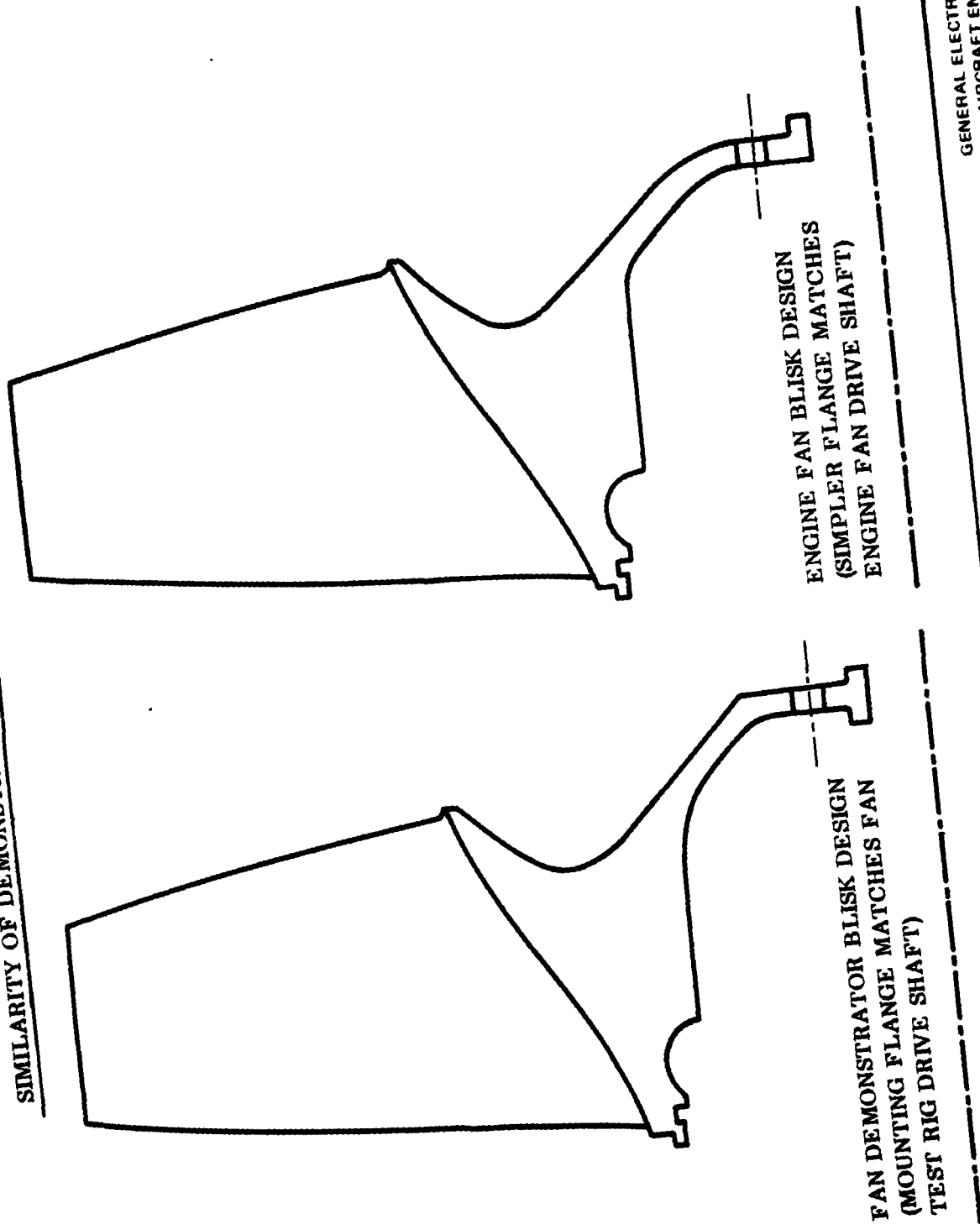
GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP

Figure 81. Comparison Between Demonstrator and Flight Blisks

117
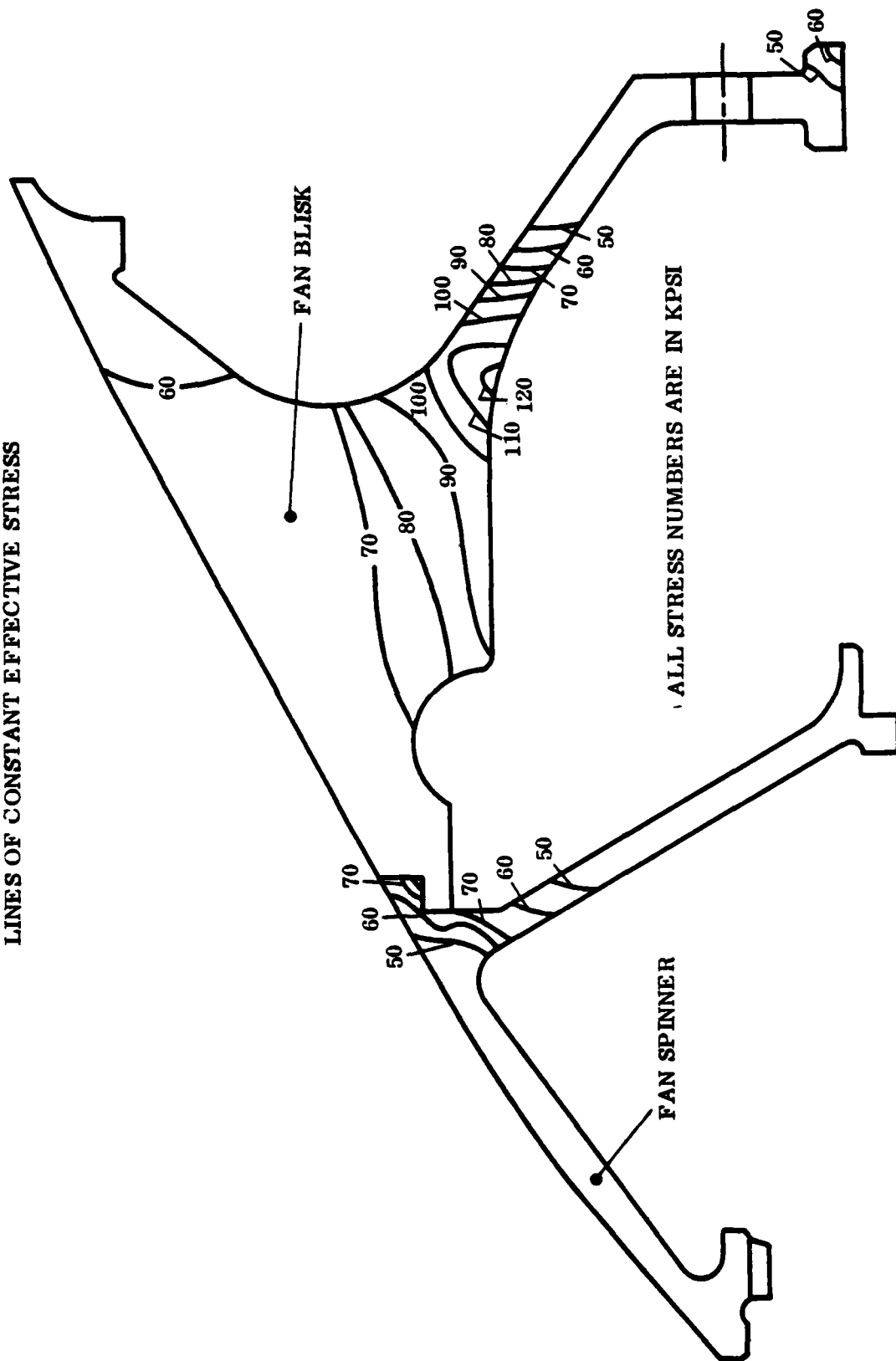
Figure 82. Fan Blisk and Spinner Stress Distribution

3.5.3 Fan Blisk Material Selection

Selection of the high bypass turbofan blisk material was based on the following criteria:

o   cost

o   weight

o   fatigue strength

o   material and process availability

o   FOD and corrosion resistance

o   sand erosion resistance.

With these criteria in mind four material candidates were evaluated, a summary of this study is shown in Table 20.

GE AM355 was selected because it possesses the best balance of the desired criteria and is predictably available from several reliable vendors.

3.5.4 Fan Exit Guide Vane Overall Design

The fan exit guide vane airfoils which resulted from the aeromechanical analysis were integrated into an assembly which becomes a part of the test rig.

The overall design of the exit guide vane assembly is shown in Figure 83. The assembly consists of 42 individually machined vanes with integral outer and inner platforms. The vanes are assembled with .004 nominal gaps all around. Mating surfaces of select exit guide vanes will be ground until the cylindrical aero outer flowpath is met. After final assembly and tack welding the part will be brazed to yield a full 360° vane ring. Design advantages of the chosen design are shown in Figure 83. Detail fan exit guide vane drawing number 17A 138 - 325 has been issued.

3.5.5 Fan Exit Guide Vane Material Selection

The airfoil material selection process followed the same general procedure as that described for the blade (Table 20). The major ingredients, however, in the selection process were high cycle fatigue (HCF) and overstress capability. For this reason the choices involved INCO 718 and A286. The choice of A286 was arrived at considering cost and machineability.

3.5.6 Fan Weight

The total fan weight was estimated in the Phase I preliminary design report to be 43 lbs. The weight calculation of the proposed design shows this estimated weight to be correct.

HIGH BYPASS TURBOFAN FAN BLISK

MATERIAL CANDIDATES:

MATERIAL	FABRICATION PROCESS	PRELIMINARY EXTIMATE OF COST OF 250TH BLISK, $	EST. WEIGHT, LBS	ADVANTAGES/DISADVANTAGES
GE AM355	MACHINED	6000.-	23	GOOD BALANCE BETWEEN COST, WEIGHT, DESIGN INTEGRITY AND FOD/EROSION RESISTANCE. GOOD MATERAIL PROPERTIES OF LARGE FORGINGS
CUSTOM 450	CAST	4000.-	23	PROPERTIES COMPARABLE TO AM 355. NEEDS PROCESS DEVELOPMENT. $2000 COST REDUCTION ANTICIPATED.
TI 6-4	MACHINED	8000.-	13	HIGH PROCUREMENT COST, LOWEST, WEIGHT. EROSION AND FOD RESISTANCE POORER THAN STEEL. POOR MATERIAL PROPERTIES OF LARGE FORGINGS.
INCO 718	MACHINED	10000.-	23	BEST DESIGN INTEGRITY AND FOD/EROSION RESISTANCE. POOR MACHINEABILITY AND HIGHER MATERIAL COST THAN AM355.

MATERIAL SELECTED

GE AM355 WAS SELECTED FOR THE DEMONSTRATOR PROGRAM AND FOR PRODUCTION UNTIL CUSTOM 450 PROCESS IS READY FOR PRODUCTION.

OVERALL EXIT GUIDE VANE MECHANICAL DESIGN (PARTIAL VIEW OF 360° ASSEMBLY)

Typical – O.D. Braze
Joint (Provide 3-5 Mils
Gap Prior to Brazing)

Typical – I.D. Braze
Joint (Provide 3-5 Mils
Gap Prior to Brazing)
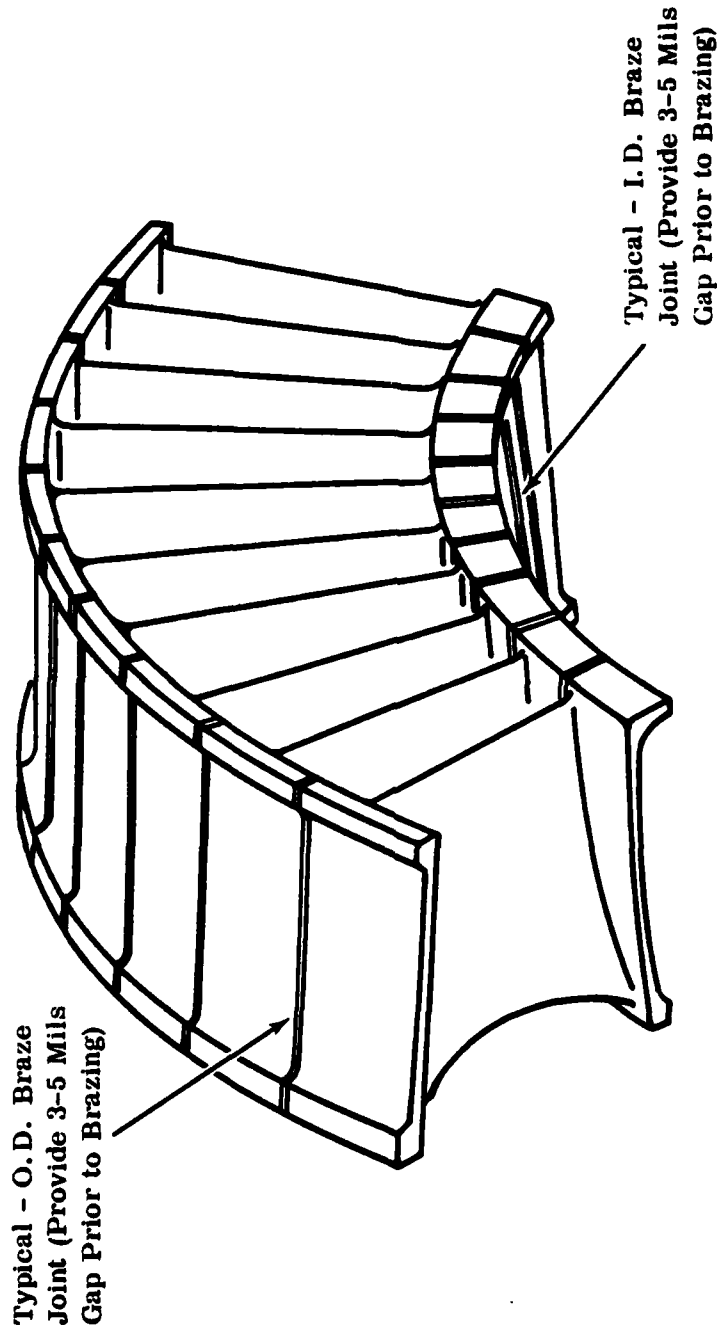
Design Advantages

- Good Dimensional Control.
- Good Control Over Fillet Radii.
- Brazing Joints are Easily Accessible for Good Cleanup.
- Design Allows "Soft" Inner and Outer Supports.

Figure 83. Exit Guide Vane Assembly Overall Design

3.5.7 Compliance with MIL-E-5007 Requirements

Several major MIL-E-5007 requirements, applicable to the high bypass turbofan design are listed in Table 21. According to this table all listed requirements are met.

TABLE 21. KEY MIL-E-5007D REQUIREMENTS EVALUATION

TURBOFAN MECHANICAL DESIGN

RELATIVE TO MIL-E-5007D REQUIREMENTS

1) BIRD INGESTION   AIRFOIL MEETS FRAGMENTATION AND FRACTURE REQUIREMENTS

2) LCF LIFE

    REQUIREMENT: 2 * 12 000 CYCLES

    RESPONSE: DESIGN COMPLIES WITH REQUIREMENT.

3) DISK BURST SPEED

    REQUIREMENT: DISK TO BE ABLE TO RUN SUCCESSFULLY AT 22% ABOVE
                    MAX NG (NG = 1.02*1.22*22719 = 28 270 RPM)

    RESPONSE: DESIGN COMPLIES. DEMONSTRATION IN A SPIN PIT AT
                 28 270 RPM PLANNED.

4) ANTI ICING

    REQUIREMENT: ENGINE MUST BE ABLE TO OPERATE UNDER ICING CONID-
                    TIONS.

    RESPONSE: EXPERIENCE WITH GENERAL ELECTRIC TURBOFAN ENGINES
                 (TF 34-100, CF6-6, CF6-50 AND CFM 56) INDICATES THAT AN
                 ACTIVE HOT AIR ANTI-ICING SYSTEM TO WARM THE BLISK
                 SPINNER OR EXIT GUIDE VANES IS NOT REQUIRED.

3.6 TEST EQUIPMENT INTERFACE AND DESIGN INTEGRATION

3.6.1 Design Philosophy

The fan component test rig is being designed by the Test Facilities Engineering Group using the following guidelines:

o   Use a simple, rugged and inexpensive design without attempting to simulate flight type designs.

o   Use a two bearing design test vehicle similar to the GE26/F2 vehicle which ran very successfully. Bearings consist of a kingsbury thrust bearing in the rear and a roller bearing in the front.

3.6.2 Fan Interface With Test Rig

Figure 84 shows the high bypass turbofan stage as it will be installed in a test rig which will be set-up in an existing, proven fan test facility. The Test Facilities Engineers are supported by the fan design engineers to assure compatibility with the fan and to help achieve design objectives during the component test. The component test rig, currently in its preliminary design phase will satisfy the following ground rules.

o   Meet engine outer and inner flowpath from spinner through EGV

o   Blisk to be per engine configuration. EGV airfoils will be per engine configuration but the EGV assembly will be designed to conform to test rig configuration.

o   Emphasis to be given to aerodynamic simulation and good instrumentation routing.

o   Use existing test facility and rig hardware wherever possible.

3.6.3 Test Rig Design

The front end of the preliminary design is shown in Figure 84. The back end consists of previously used hardware modified for the high bypass turbofan application. The roller bearing is an existing J85 engine bearing. A layout drawing, Number 17A138-274 has been issued to show the blisk and EGV aerodynamic relationship and flowpath.

HIGH BYPASS TURBOFAN STAGE IN COMPONENT RIG

FAN EXIT GUIDE VANE

42 VANES

FAN TEST RIG BEARING/SEAL HOUSING

DRIVE SHAFT (TEST RIG)

10 HOOK BOLT

20 BLADES

FAN "BLISK"

TIE BOLT

LOCK NUT

SPINNER

SPINNER INSERT

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE GROUP
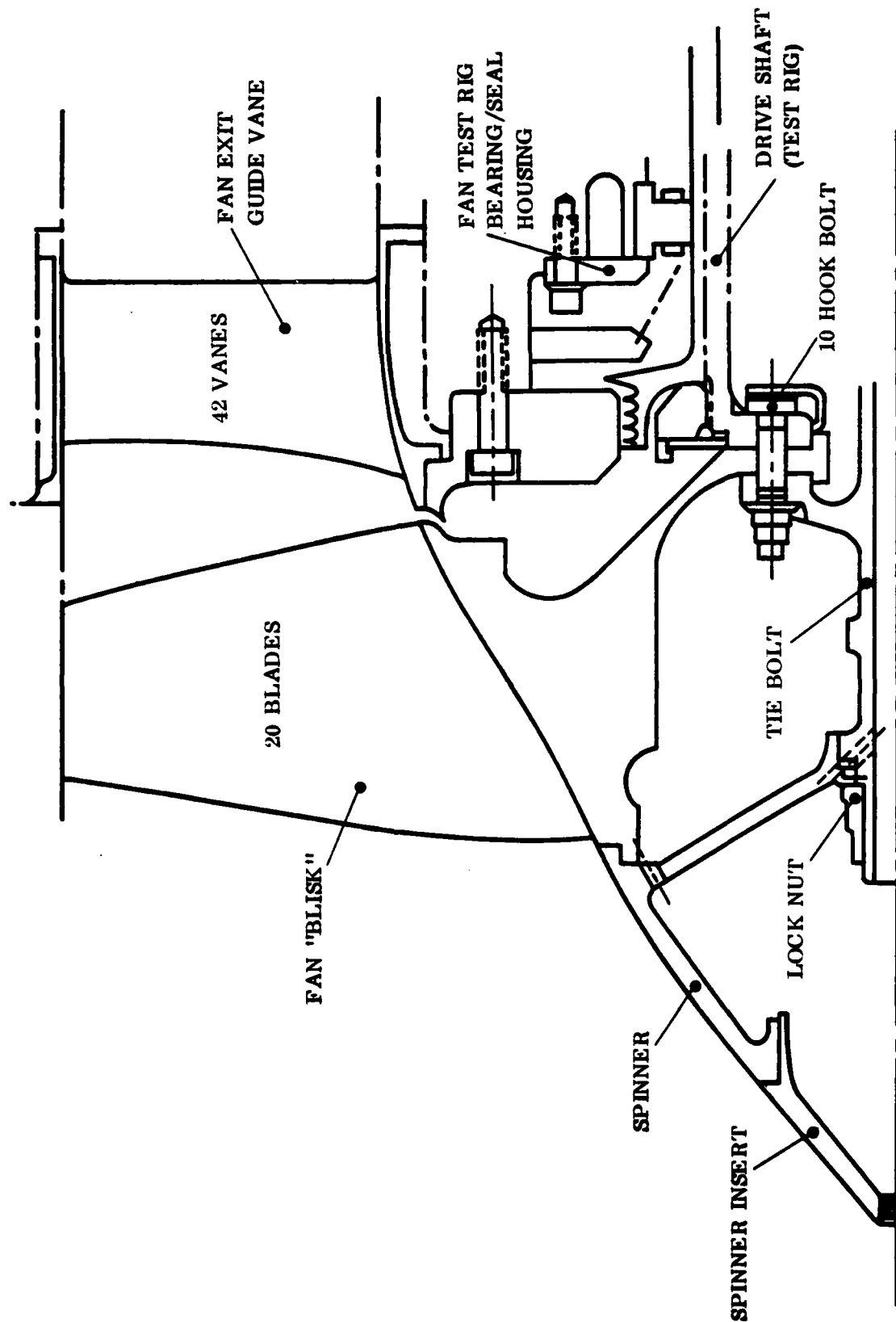
Figure 84. Fan Blisk and EGV Assembled in Test Rig

3.7 RELIABILITY, MAINTAINABILITY, AND SYSTEMS SAFETY

Interim Technical Report #AFAPL-TR-78-109 (Phase I Preliminary Design) concluded that the proposed fan design had satisfactory R&M and Safety characteristics. Since the detailed mechanical design recommended now in this report is essentially the same as the design shown in the Phase I preliminary design report, it is concluded that the R&M and Safety requirements are satisfied. For example, the engine maintainability feature of forward blisk removal without exposure of bearing-sump is included in the component test rig design.

SECTION IV

CONCLUSIONS

The objectives of the Detail Design, Phase II of the Contract Statement of Work, have been met, confirming that the required aerodynamic performance as well as MIL-E-5007D mechanical requirements can both be met simultaneously.

Further, the comparison (in Table 19) of the important design parameters versus those of the originally proposed fan show close agreement.

The High Bypass Turbofan design balanced the aerodynamic and aeromechanical requirements for an operational fan to be used in the engine selected in Phase I so that the original proposed efficiency and stall margin objectives can be met.

SECTION V

RECOMMENDATIONS

The small high bypass fan, designed during Phase II of this contract, meets the aerodynamic and mechanical/life requirements of the Statement of Work, and therefore the Contractor recommends that the Air Force authorize the fabrication and test of the fan stage in accordance with Phase III. (This recommendation was acted upon on 7 May 1979 when the Contractor was authorized to proceed.)

The Contractor recommends that the Air Force consider a critical assessment of the MIL-E-5007D specification of bird strike capability as it applies to relatively small engines.

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AD	=	discharge area
A1	=	inlet area
AM	=	mouth area
AR	=	aspect ratio
AT	=	throat area
β bird	=	relative angle of bird
$\beta 1$	=	inlet relative air angle
$\beta 1^*$	=	inlet relative metal angle
$\beta 2$	=	discharge relative air angle
C_z air	=	axial velocity of air
C_z bird	=	axial velocity of bird
δ	=	corrected pressure
DF_R		rotor diffusion factor
DFS	=	stator diffusion factor
FCW	=	first covered wave
FOD	=	foreign object damage
g	=	gravitational constant
H	=	enthalpy, BTV/lb
HCF	=	high cycle fatigue
i	=	incidence
$\hat{i}$	=	suction surface incidence
ID	=	inner diameter
J	=	778 ft-lb/BTU
LE	=	leading edge
M_D	=	discharge Mach No.
M1	=	inlet Mach No.
M_M	=	mouth Mach No.
N	=	rotational speed, RPM
O/L	=	operating line

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

OD	=	outer diameter
PS1	=	inlet static pressure
PS	=	pressure surface
PT1	=	inlet total pressure
PT2	=	discharge total pressure
RR	=	radius ratio
RT_{in}	=	inlet tip radius
RT_{out}	=	discharge tip radius
SS	=	suction surface
$\sqrt{\theta}$	=	corrected temperature
t_m/C	=	maximum thickness/chord
U	=	wheelspeed, ft/sec
U_T	=	tip wheelspeed, ft/sec
W	=	airflow
W/A	=	airflow/annulus area
W_{air}	=	relative velocity of air
W_{bird}	=	relative velocity of bird
W_{nor}	=	relative velocity component of bird normal to blade