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NASA CR-134495

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A STUDY OF ENGINE VARIABLE GEOMETRY SYSTEMS FOR AN ADVANCED HIGH SUBSONIC LONG RANGE COMMERCIAL AIRCRAFT

by

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GENERAL ELECTRIC COMPANY

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS3-15544

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-134495		

4. Title and Subtitle	5. Report Date
A Study of Engine Variable Geometry Systems for an Advanced High Subsonic Long Range Commercial Aircraft.	October 1973
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
M.A. Compagnon	R73AEG185
	10. Work Unit No.
9. Performing Organization Name and Address	
Aircraft Engine Group General Electric Company Cincinnati, Ohio 45215	11. Contract or Grant No. NAS3-15544
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address	
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

Several variable geometry high Mach inlet concepts, aimed at meeting a system noise objective of 15 EPNdB below FAR part 36, for a long range, Mach 0.9 advanced commercial transport are assessed and compared to a fixed geometry inlet with multiple splitters. The effects of a variable exhaust nozzle (mixed exhaust engine) on noise, inlet geometry requirements, and economics are also presented. The best variable geometry inlet configuration identified is a variable cowl design which relies on a high throat Mach number (<0.8) for additional inlet noise suppression only at takeoff, and depends entirely on inlet wall treatment for noise suppression at approach power. Relative economic penalties as a function of noise level are also presented.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Turbofan Engines Subsonic Aircraft Advanced Technology Variable Geometry Inlets Noise	UNCLASSIFIED - LIMITED

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
UNCLASSIFIED	UNCLASSIFIED	104	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This study was performed for the National Aeronautics and Space Administration, Lewis Research Center under Modification 1 to Contract NAS3-15544. Mr. Robert J. Antl was the NASA Program Manager for this effort and Mr. W.R. Collier served as the General Electric Program Manager. This report was prepared by M.A. Compagnon, the Technical Project Manager, with contributions from J.J. Frantz, N.J. Biesik, D.E. Parker, J.R. Martin, H.D. Sowers and other General Electric personnel.

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SUMMARY

Several variable geometry high Mach inlet concepts aimed at meeting a system noise objective of 15 EPNdB below FAR part 36 for a long range, Mach 0.90 advanced commercial transport are assessed and compared to a fixed geometry inlet with multiple splitters. The objective of the study was to determine if inlet noise could be reduced with less of an economic penalty with a variable geometry inlet that is practical, reliable, and safe than is incurred with a fixed geometry inlet with multiple splitters. The significant results and conclusions reached are summarized below:

- The best inlet configuration that meets the specified noise objective of 15 EPNdB below FAR 36 relies on a combination of wall treatment and high inlet throat Mach number [(<0.8) for inlet noise suppression at take-off sideline and over the community (3.5 nautical mile point)] and only on wall treatment to suppress inlet noise at approach (hybrid inlet).

- The most attractive variable geometry concept evaluated in this study is a variable cowl concept with fixed external cowl and a variable internal surface.

- In conjunction with a variable exhaust nozzle area, this configuration requires only a 10% smaller inlet throat area than the cruise design value. Without a variable exhaust nozzle, a 20% inlet throat area variation is required.

- The maximum noise reduction potential of variable geometry inlets is limited by the maximum throat Mach number judged to be practical and realistic. This value will have to be established experimentally for a specified inlet geometry, considering the range of operating conditions to be encountered.

- If a throat Mach number of 0.85 were found to be acceptable and used at approach as well as at high power settings, a noise level of approximately 18 EPNdB below FAR 36 could be achieved with additional fan exhaust noise suppression of about 5 dB.

The effects of a variable exhaust nozzle (mixed exhaust engine) on noise, inlet geometry requirements, and economics are also presented:

- A low area ratio C-D nozzle was selected because of its superior flow capacity at low nozzle pressure ratios compared to a convergent nozzle, which leads to significantly smaller physical area change to achieve the same effective area change.

- Based on the host airplane requirements at the FAR noise measuring stations and especially over the community (1300 feet/396 meters, 80% take-off thrust), a variable exhaust nozzle is required to reduce a jet noise to meet FAR 36 -15. With a fixed exhaust nozzle, approximately 13.5 EPNdB below FAR 36 can be obtained. The economic penalties of a variable exhaust nozzle are significant: 0.9% in TOGW, 1.1% higher DOC, and 0.8% lower ROI.

Economic penalties as a function of noise level are summarized for the inlet configurations of most interest.

- The mission performance penalty for the hybrid inlet configuration is ~30% less than the TOGW penalty for a fixed geometry inlet with multiple splitters (acoustic baseline inlet) that meets the noise objective. This corresponds to about 2% lower TOGW, 1.8% lower DOC, and 1.2% higher ROI relative to the fixed geometry acoustic baseline inlet. These gains must be balanced against the increased complexity and risk that are introduced with any variable geometry element, no matter how well implemented, and compared with the liabilities of an inlet with multiple splitters.

- It must be emphasized that the economic penalty associated with a noise level of FAR 36 -15 EPNdB compared to FAR 36 -10 EPNdB is still quite high: 3.2% higher DOC for the hybrid inlet compared to a 5% increase in DOC for the fixed geometry acoustic baseline inlet.

- A fixed exhaust nozzle does not significantly affect the mission performance advantage that the selected hybrid inlet configuration (which does not require high throat Mach number at approach power) has over a fixed geometry inlet with multiple splitters. However, a variable geometry hybrid inlet (which depends on high Mach number at approach as well as at high power settings for additional inlet noise suppression) requires a variable area exhaust nozzle to achieve the appropriate inlet Mach number/cycle flexibility relationships.

INTRODUCTION

NASA is currently studying the application of advanced technologies to long range, high subsonic, commercial transport aircraft. Propulsion system optimization studies conducted by the General Electric Company in 1971-72 under the direction of the NASA-Lewis Research Center are presented in Reference 1. These studies identified, within specified noise constraints, the most desirable propulsion system characteristics over the speed range of Mach 0.90 to 0.98 with emphasis placed on the higher end of this range. Two advanced, mixed exhaust turbofan engines utilizing a high pressure ratio single stage fan were defined based on the findings of the parametric engine study phase. Engine No. 1 was based on technology judged compatible for commercial operation in the late 1970 time period; engine No. 2 used a more advanced technology level associated with the mid-1980 time period.

Based on the results of these studies, additional cycle studies (other than conventional fixed-geometry turbofan cycles) were indicated. This report presents the results of these additional studies, using the results of the prior propulsion system studies to the maximum possible extent. The studies were conducted within the guidelines provided by NASA, as follows:

- Emphasis was placed on the lower end of the flight speed range studied earlier, namely Mach 0.90 rather than Mach 0.95 to 0.98.
- The studies utilize the Boeing 767-640, Mach 0.90 trijet ATT study airplane as the host vehicle to define engine size, engine power levels, and flight conditions for noise evaluation.
- Engine cycles and characteristics for a 1985 commercial engine certification (as defined in the earlier studies, reference 1) were used.
- Variable geometry features which are productive in reducing noise were emphasized.

Studies of variable geometry inlets and variable exhaust nozzles, aimed at reducing noise at less cost than with a fixed geometry inlet with multiple splitters, are presented herein. The characteristics of the ATT Mach 0.90 host airplane were used to estimate noise levels and assess the relative economics of the various configurations studied.

STUDY APPROACH

SCOPE

This Contractor concentrated on those variable features that appeared to have promise of significant reductions in noise with less penalty than achievable by other methods, although the original scope of the study requested by NASA was intended to consider additional engine cycles on a broad front involving other than conventional fixed geometry turbofan cycles and different engine configurations including aft fans, geared fans, and three-spool engines. Approaches which aim at improving off-design sfc have previously been studied by General Electric for long range subsonic (Mach 0.8 to 0.9+) commercial transport applications without any significant advantages being identified. The reason is simply that most of the fuel is used at near-design point conditions of the turbomachinery (cruise, climb, and takeoff). Even at off-design conditions (such as hold), no clear cut improvement by variable geometry (such as variable turbine nozzles) has been identified. Regarding alternate turbomachinery arrangements, General Electric studies of three-spool, aft fan, and geared turbofans have shown that these have no payoff and, in some cases, have major disadvantages for this high subsonic Mach application. In the context of the engine cycle identified in Reference 1 for the ATT aircraft, which involves a high fan pressure ratio (1.8+) with a single stage fan, variable fan rotor blades are not mechanically practical.

The two dominant noise sources for the ATT engine cycle are the fan noise and the jet exhaust noise. The variable geometry system studies address these noise sources by focusing on variable geometry inlet and exhaust systems.

Since thrust is very closely tied to the fan operating conditions, fan excursions at constant thrust are the only variations that will have an impact on fan noise; the simplest manner in which these excursions can be obtained is by varying the single exhaust nozzle area in the mixed exhaust engine configuration recommended in Reference 1. Similar excursions can be obtained in more complex ways by introducing variable geometry turbines which could alter the core operating conditions at the same time. However, the impact of core operating conditions on noise is not presently well understood. Furthermore, once suppressed to the degree required to meet the noise objective, core-generated noise variations are believed to be small enough that they would be masked by the other major noise sources.

OBJECTIVE

The objective of the variable geometry inlet study was to determine if inlet noise could be reduced by means of a variable geometry inlet (that must also be practical, reliable, and safe) with less of an economic penalty than is incurred with a fixed geometry inlet with multiple splitters. The primary focus was on a noise level of FAR 36 -15, but the possibility of lower noise also was examined.

AIRCRAFT CHARACTERISTICS

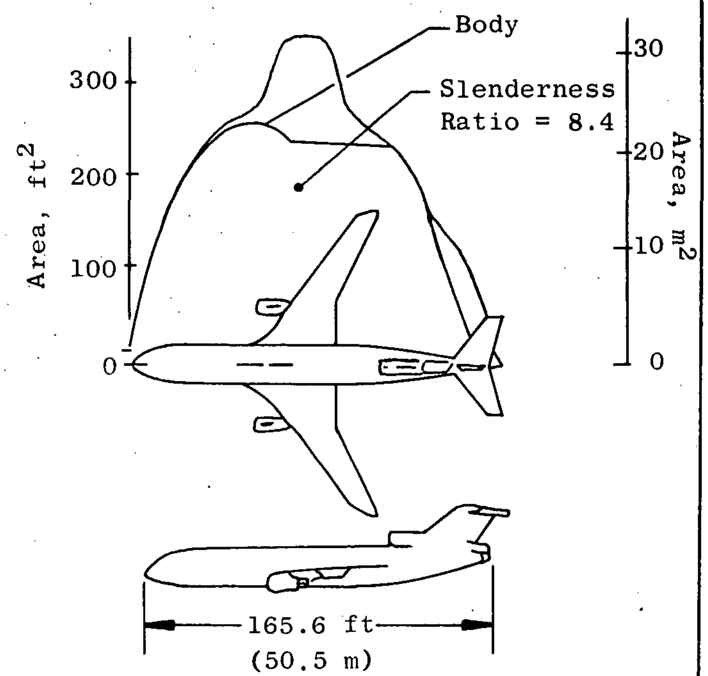
The Boeing 767-640 Mach 0.90 ATT study aircraft shown in Figure 1 was used as the host vehicle to define engine size, engine power levels, and flight conditions for noise evaluation (as shown in Table I) and to assess the relative economics of the configurations studied.

Note in Table I that the engine study size is larger than required by the airplane. For convenience, this study was done in the same size as the earlier studies reported in Reference 1, assuming the engine could be scaled as necessary. However, noise estimates are presented for the engine size required by the airplane, and the mission sensitivity factors have been adjusted appropriately to account for the change in size.

It should also be noted that the most severe condition from a noise standpoint, as will be shown in the noise discussion, is take-off community noise, even with the power cutback which has been assumed for all noise estimates. The primary reason for this situation is the relatively low altitude achieved by this aircraft at the 3.5 nautical mile noise measuring point. Consequently, the take-off community noise point sets the suppression requirements in this study instead of the approach point which was controlling in earlier studies.

ENGINE CYCLE AND CONFIGURATION

The engine cycle was redefined to accommodate the lower flight speed (Mach = 0.90), as directed by NASA, instead of the higher speed (Mach 0.98) that was emphasized in preceeding studies. The revised engine cycle, denoted ATT No. 3 in Table II, retains the technology level defined for the ATT No. 2 (1985 certification date). The significant change between the two cycles is the lower specific thrust (higher bypass ratio) selected for ATT No. 3 for optimum performance at the lower cruise Mach number. The lower specific thrust calls for a lower fan pressure ratio which allows the fan aerodynamic design to be consistent with the fan being designed, and to be procured and tested, under another NASA program. A smaller core size then evolves to achieve the proper energy extraction for the mixed exhaust cycle. The fan turbine loading, which increases because of the lower wheel speed and smaller core flow, has been upgraded based on recent results from a four-stage, highly loaded fan turbine program also sponsored by NASA. A schematic cross section of the ATT No. 3 engine showing the general turbomachinery arrangement is presented in Figure 2.



Boeing 767-640 Payload = 40,000 lbs (18,144 kg) Design Range = 3000 n mi (5556 km)	
TOGW, lbs (kg) OEW, lbs (kg)	303,700 (137,756) 159,550 (72,371)
Thrust/Engine, T_{SLS}, lbs (kN)	31,300 (139.2)
Wing Area, S_W, ft^2 (m^2) Sweep, degrees Aspect Ratio	2,260 (210) 36.5 7.6
Performance TOFL (1000 ft/90° F - 305 m/32° C) ft (m) ICA, ft (m) V_{App}, kn (m/sec)	 8,300 (2,530) 35,800 (10,912) 135 (69.4)

Figure 1. ATT No. 3 Aircraft Characteristics, Mach 0.90 Design.

Table I. Airplane Requirements Based on the Boeing 767-640[1] (Mach = 0.90) ATT Airplane.

Condition	Altitude ft (m)	Mach No.	T_{am}, °F (°C)	Thrust, lbs (kN)		% Take-off Thrust at Specified Flight Condition
				767-640	Engine Study Size	
Engine Sizing	1000 (304.8)	0.18	90 (32)	25,000 (111.2)	35,000 (155.7)	100
Approach						
(3° Glide Slope)	Sea Level	0.22	---	6,380 (28.4)	8,940 (39.8)	26
Take-off (Noise)						
No Cutback	1350 (411.5)	≈0.22	---	24,000 (106.8)	33,530 (149.1)	100
With Cutback	1280 (390.1)	≈0.22	---	19,100 (85.0)	26,800 (119.2)	80

(1) Trijet (2 Wing-mounted, 1 Tail-mounted); 40,000-pound (18,143 kg) Payload; 3,000 Nautical Mile (5,556 km) Range; Design Cruise Mach No. = 0.90; Take-off Gross Weight = 304,000 lbs (137,892 kg)

Table II. Advanced Technology Engines, 1985 Certification.

Parameter	ATT No. 2	ATT No. 3
Cruise Match Point (Aero Design Point)		
Mach Number	0.98	0.90
Cycle (Cruise Match Point)		
Overall Pressure Ratio	37.2	37.2
T_4 Cruise - Std + 18° F	2820	2820
° C	1549	1549
Takeoff - Std + 31° F	3000	3000
° C	1649	1649
Bypass Pressure Ratio (BPR)	5.6	6.2
Specific Thrust - Fn/W_2, lbs/pps	19.8	18.9
N/kg/sec	1941	1853
Fan		
$(W\sqrt{\theta}/\delta)_2$ - Study Size, lbs/sec	1414	1414
kg/sec	641	641
P/P (Bypass Flow)	1.85	1.8
$W\sqrt{\theta}/\delta$ X Annulus Area, lbs/sec-ft^2	44	44
kg/sec-m^2	214.8	214.8
Inlet Radius Ratio	0.34	0.38
U_2/θ_2, ft/sec	1750	1650
m/sec	533.4	502.9
D_T, inches	81.6	83.0
meters	2.07	2.11
Boosters		
No. Stages	2	2
P/P, Including Fan Hub	2.71	2.71
Core, Study Size		
$(W\sqrt{\theta}/\delta)_{2c}$, lbs/sec	95.3	86.9
kg/sec	43.2	39.4
Fan Turbine		
No. Stages	4	4
Pitch Work Coefficient, $\psi_p = gJ\Delta h/2\Sigma U_p^2$	1.2	1.7

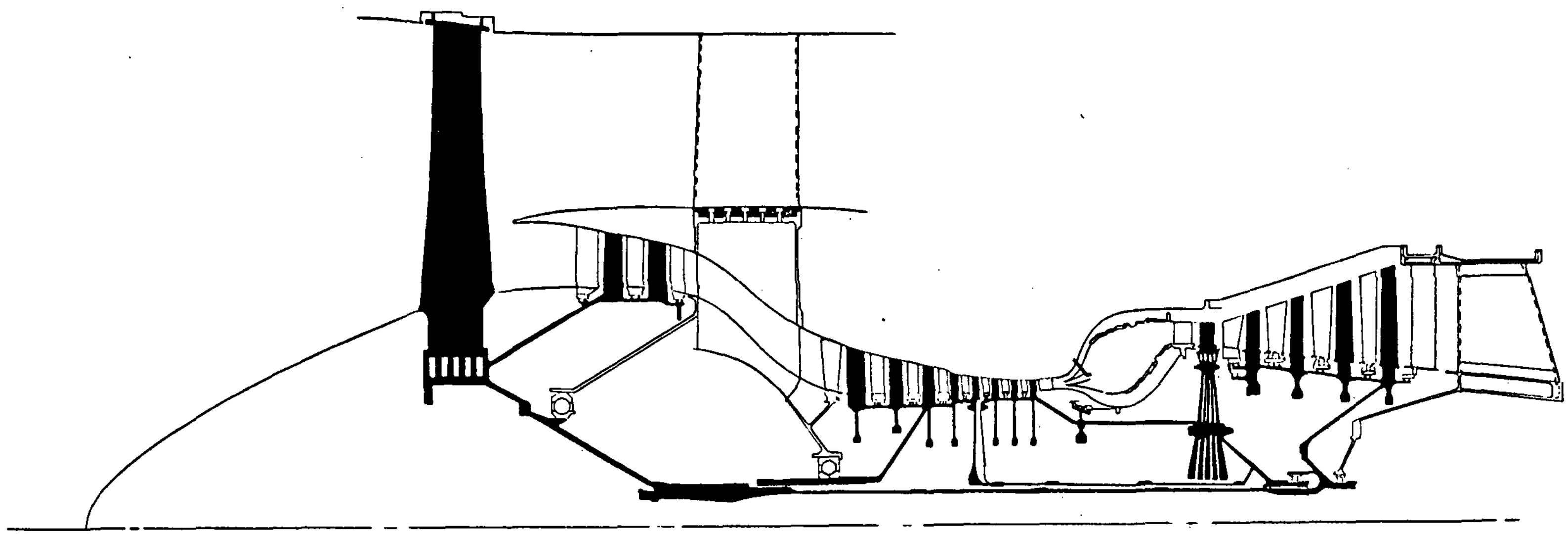


Figure 2. ATT No. 3 Bare Engine Cross Section Schematic.

INLET SYSTEM REQUIREMENTS

INLET FLOW VARIATION

Figure 3 shows the variation in inlet throat Mach number (one-dimensional basis) as a function of fan inlet corrected airflow for a fixed geometry inlet designed for a throat Mach number of 0.7 at cruise. Take-off, power cutback (80% take-off thrust), and approach (26% take-off thrust) flows are spotted on this curve to show the broad range of flows over which a high Mach inlet must be designed to operate. Opening the common exhaust nozzle area is very effective in increasing the flow at constant thrust, as indicated in Figure 3. Figure 4 shows the migration of the operating points on the fan map. At take-off power, the amount of exhaust area variation that is acceptable is limited by the loss of take-off thrust which occurs at rated turbine inlet temperature. It is strongly dependent on the rate at which fan efficiency diminishes as pressure ratio is decreased below the normal steady-state operating line. With the fan matched at its aerodynamic design point at cruise, a conventional turbine temperature differential between cruise and take-off ratings, and considering normal off-design fan efficiency characteristics, it can generally be expected that a 5% to 10% increase in A_8 can be used with little or no thrust loss. At power cutback conditions (80% take-off thrust), the maximum A_8 increase that can be contemplated is usually set by the fan exhaust Mach number before a maximum climb temperature limit is reached. A 25% increase in A_8 was established on this basis. At approach power, the fan exhaust Mach number eventually becomes the controlling factor, but an exhaust area increase of 40% relative to cruise A_8 was used as a limit for practical exhaust configurations.

INLET THROAT DESIGN MACH NUMBER

The effectiveness of noise suppression increases dramatically, as has been amply demonstrated experimentally, as the inlet nears choking. It therefore is desirable to set the throat Mach number as high as possible from a noise suppression standpoint. Practical design considerations (tolerances, steady-state flow fluctuations, inlet diffuser performance, Mach number measurements under crosswind and angle of attack, control stability, and the risk of inlet choking at critical operating conditions) will dictate the throat Mach number that can be used. This level is not now known and will have to be established experimentally for each inlet design. For the purpose of this study, a throat Mach number of 0.8 was selected. As shown in Figure 5, an average or one-dimensional Mach number of 0.8 results in a design which is only 3.7% from full choke, whereas a 0.9 Mach number design is only 1% away from choking the inlet on an idealized basis.

It should be noted that the inlet geometry layouts which follow are not grossly affected by the choice of a different design Mach number since the change in throat area that the variable geometry inlets would have to negotiate would be small. For instance, between Mach 0.80 and 0.85 the change in throat area variation would be +1.7%.

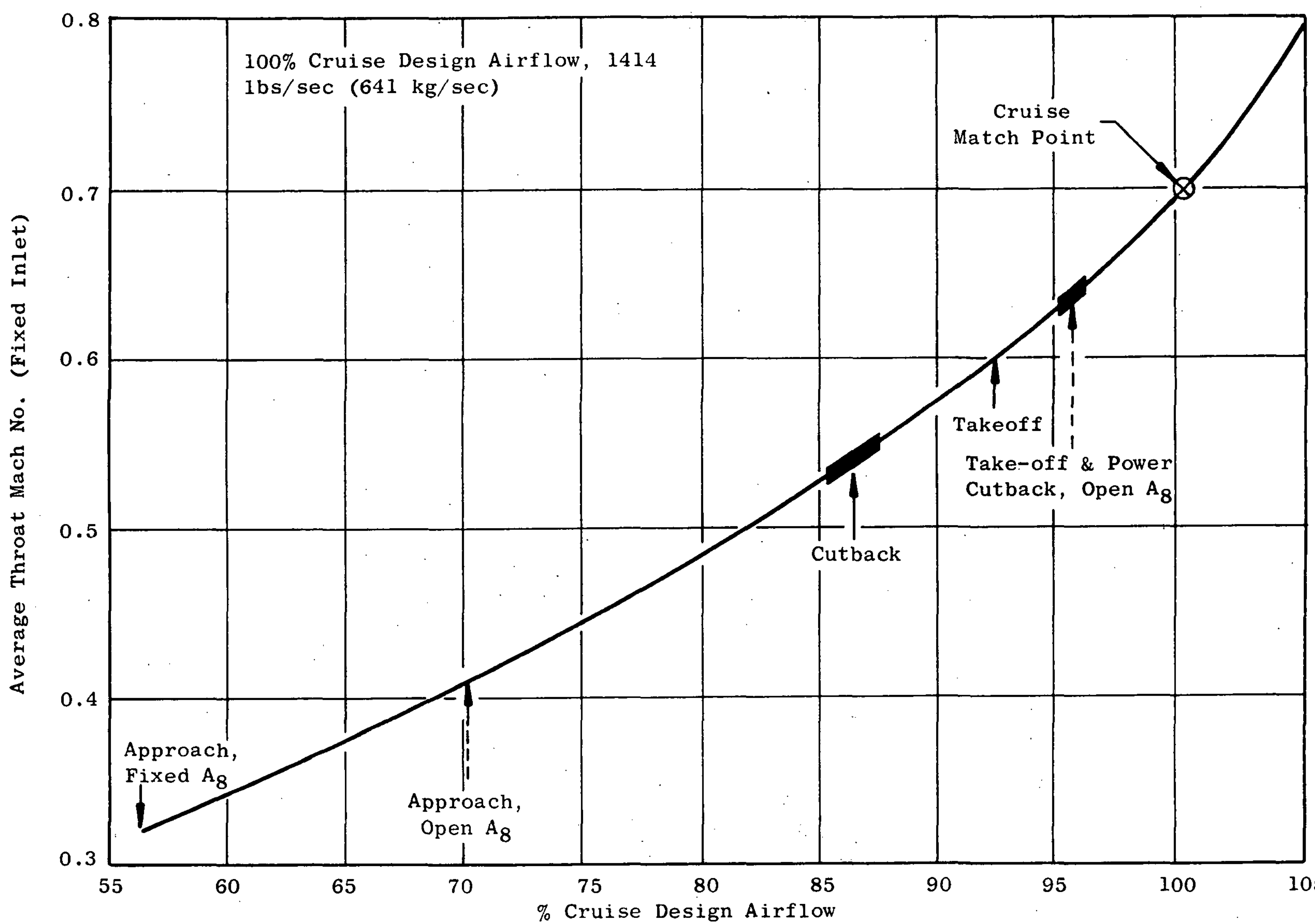


Figure 3. ATT No. 3 Throat Mach No. Variation, Fixed Inlet, Cruise Design Throat Mach No. = 0.70.

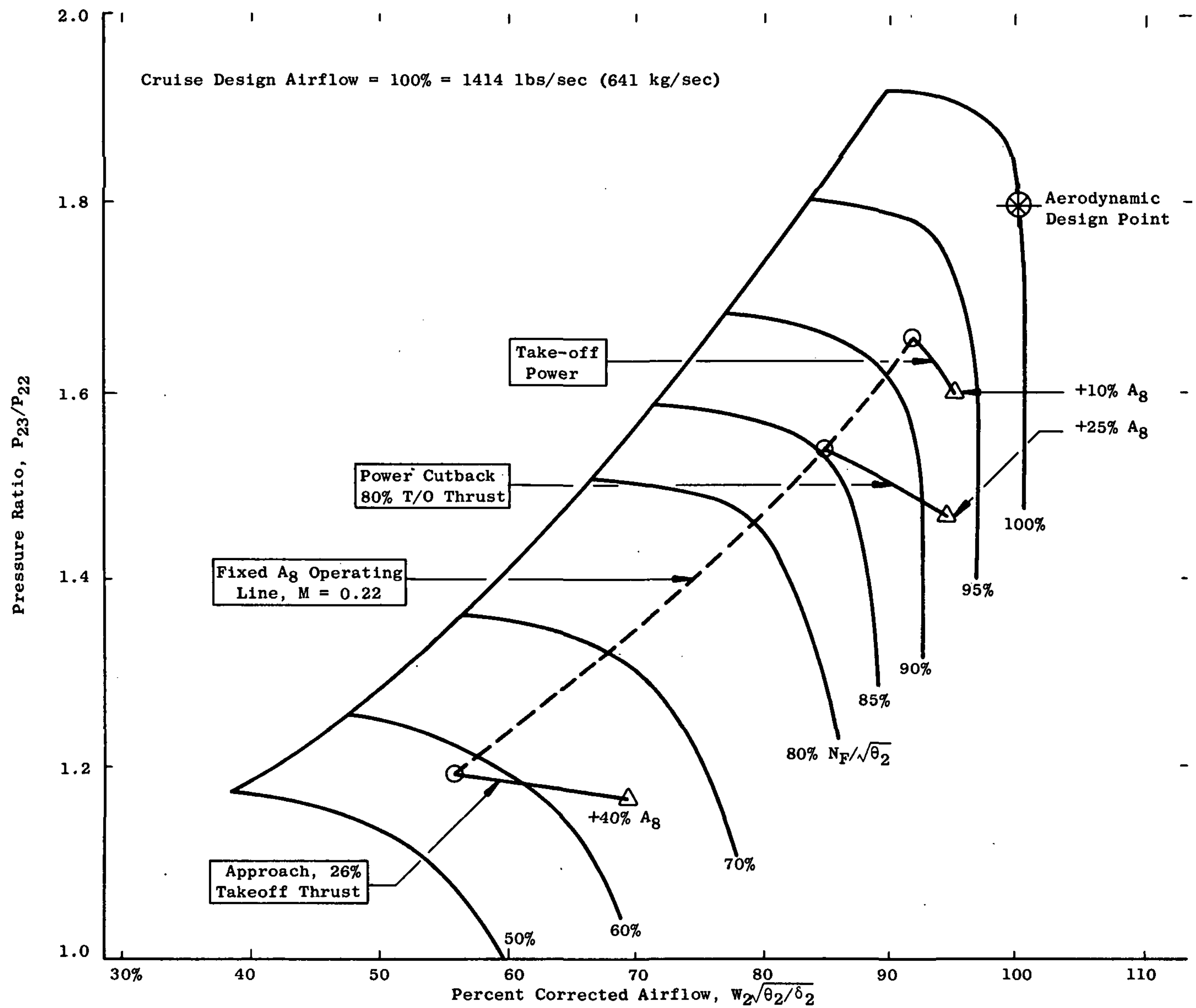
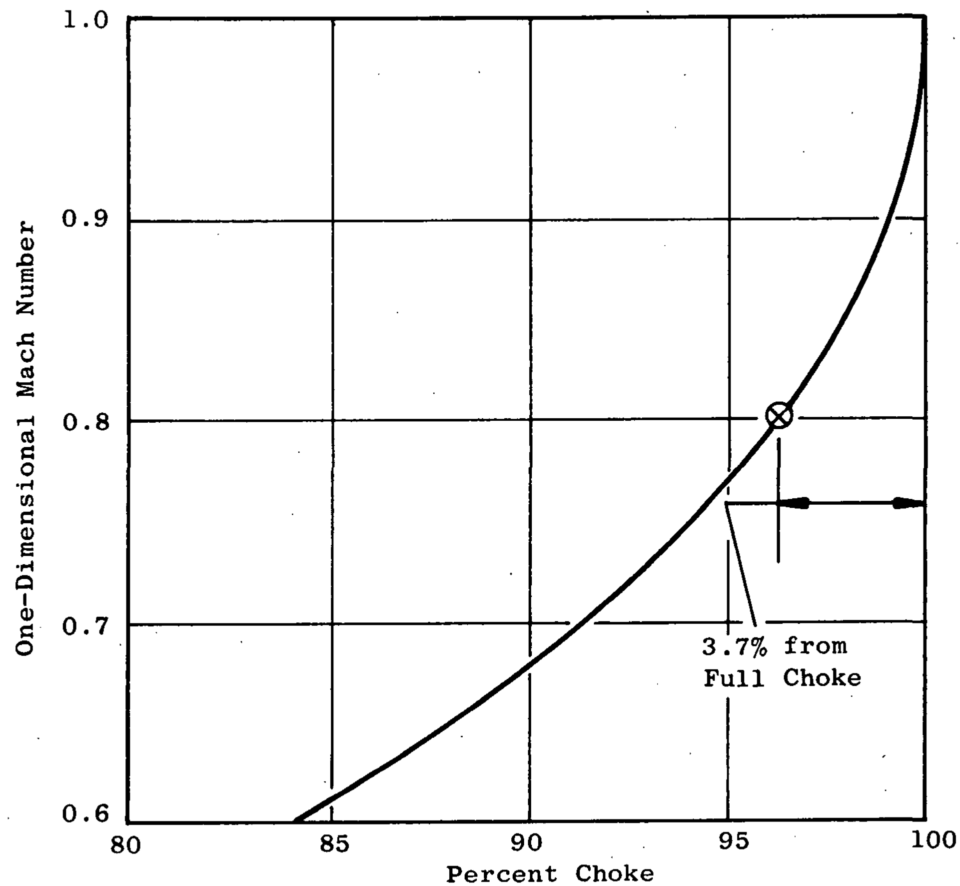


Figure 4. ATT No. 3 Fan Operating Conditions with Variable Exhaust Nozzle.



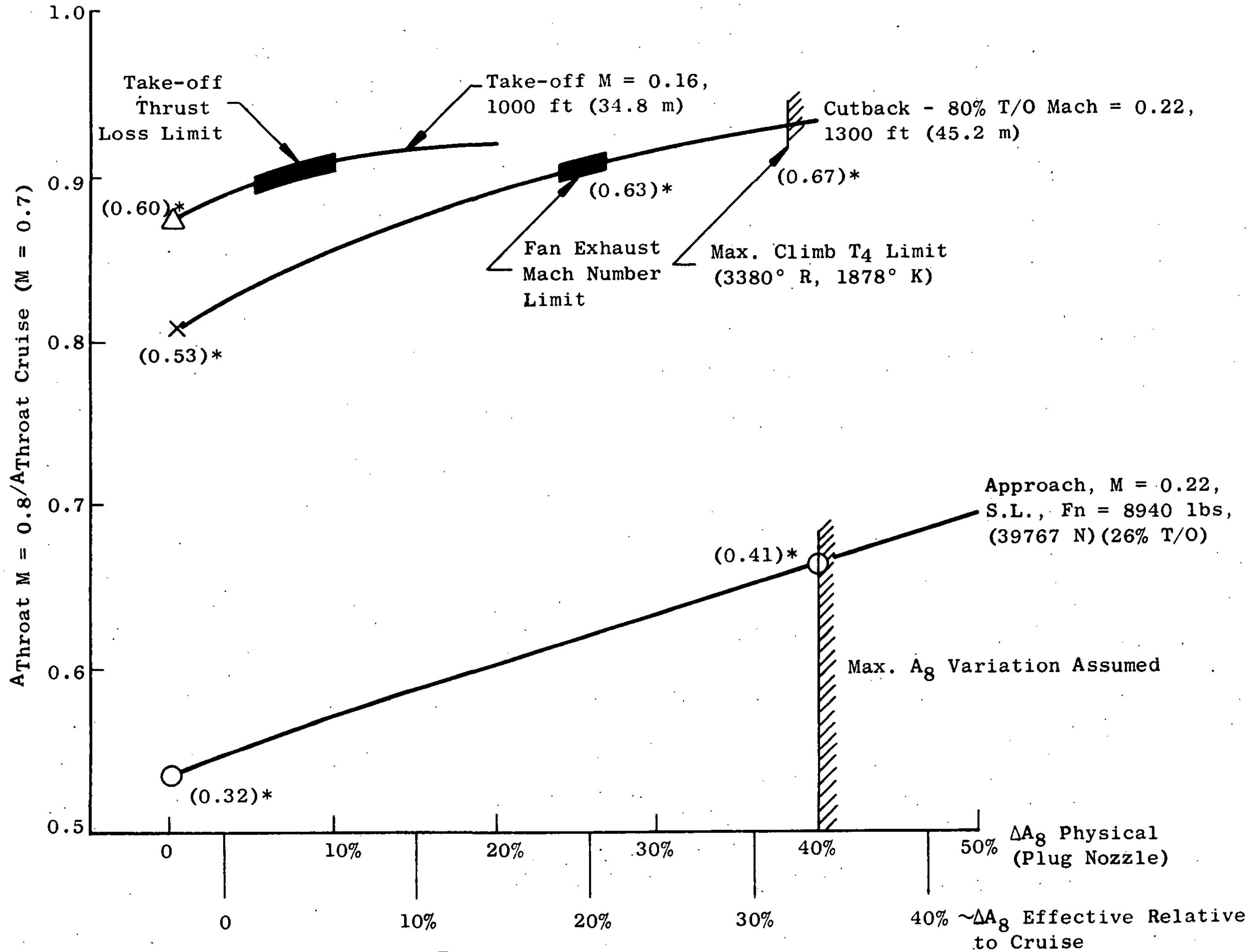
- Nominal Inlet Throat Mach Number of 0.8 Selected to Minimize Aerodynamic Risk in Inlet Diffuser.
- At Higher Mach Numbers (>0.8), Control Aspects and Tolerances Also Become a Concern.

Figure 5. ATT No. 3 Inlet Throat Mach Number.

INLET GEOMETRY REQUIREMENTS

The inlet throat area variation needed to maintain an inlet throat Mach number of 0.8, as a function of exhaust nozzle area, is presented in Figure 6 as a fraction of the throat area at cruise for the three FAR noise conditions (i.e., take-off sideline, take-off over the community with power cutback, and approach). For the exhaust area schedule selected, the inlet geometry requirements are significantly reduced, compared to the requirements that prevail with a fixed exhaust nozzle as shown in Table III.

Note that the inlet diffuser requirements, which determine the inlet length to avoid separation for the variable cowl and centerbody inlets considered, are less severe with a high fan inlet specific flow of 44 lb/sec-ft^2 (1.85 kg/sec-m^2) at the cruise design point than would otherwise be the case.



(*) Inlet Throat Mach No. with Fixed Inlet.

Figure 6. ATT No. 3 Effect of A_8 Variations on Inlet Throat Area Requirements for M_{Throat} = 0.8.

Table III. Inlet Geometry Requirements for Throat Mach No. = 0.8.

	Take-off Sideline		Power Cutback		Approach	
Exhaust Nozzle Area	Fixed	Variable (+7%)	Fixed	Variable (25%)	Fixed	Variable (+40%)
Δ Throat Area (Relative to Cruise)	-12.5%	-10%	-19%	-10%	-47%	-34%
Diffuser Area Ratio, A_{Fan}/A_{Throat}	1.17	1.14	1.27	1.14	1.93	1.55
Diffuser Velocity Ratio, $V_{Fan\ Face}/V_{Throat}$	0.74	0.78	0.67	0.78	0.41	0.52

VARIABLE GEOMETRY INLET SCREENING STUDIES

GENERAL APPROACH

A literature survey was conducted from which several variable geometry inlet concepts were identified. The various concepts can be categorized into variable cowl, variable centerbody, and variable blockage systems (or combinations of these). The initial selection of concepts to be screened was governed by the desire to evaluate at least one approach in each of the above categories in the specific context of this application in order to gain a meaningful perspective of the characteristics, advantages, and shortcomings of these fundamental approaches. Those considered in the initial screening are listed in Table IV.

The concepts were selected to meet the specific requirements discussed above using consistent aerodynamic ground rules established for the nacelle and inlet diffuser, as well as noise-imposed constraints. This aerodynamic screening study was then followed by preliminary mechanical design studies of seven concepts to assess their feasibility. These were carried out sufficiently far to obtain reasonable weight estimates and to at least identify possible solutions to the problems uncovered in each case. In addition to the variable geometry concepts investigated, approaches to retract splitters were also studied and one approach was selected for evaluation.

The relative economics (ΔDOC and ΔROI) of these eight configurations were then compared to the fixed geometry acoustic baseline inlet with multiple splitters at the noise objective level of FAR 36 -15 EPNdB. The best variable geometry concept identified was then further optimized, leading to a recommended configuration that best meets the low noise objective of 15 EPNdB below FAR 36 on a traded basis.

BASELINE INLETS

A fixed geometry inlet as shown in Figure 7, was evolved without any restrictions for acoustic reasons. A fixed inlet with two splitters was laid out to achieve the FAR 36 -15 noise level as shown in Figure 8. The former was used to illustrate the penalties of achieving the FAR 36 -15 noise level; the latter was used as the base in comparing the variable geometry schemes at the FAR 36 -15 noise level.

VARIABLE CENTERBODY INLETS

A variety of variable centerbody inlets was laid out for the screening study. Figure 9 shows three translating internal plug types with various area ratios. Figure 10 shows a refined version of this approach. Figure 11 shows an external translating plug inlet and Figure 12 presents a collapsing plug inlet. Figure 13 shows a translating and collapsing plug inlet. This variety was narrowed down to two cases for the mechanical feasibility studies; i.e., the translating internal plug (Figure 10) and the collapsing plug (Figure 12).

Table IV. Aerodynamic Screening Study Cases.

Category	Description	Exhaust Nozzle			
		Fixed A_8		Variable A_8	
		Inlet Area Variation		Inlet Area Variation	
		0%	-47%	-34%	-10%
Fixed Inlets	Aerodynamic Baseline	X	---	---	---
	Acoustic Baseline	X	---	---	---
Variable Centerbody Inlets	Translating Internal Plug	---	X	X	X
	Translating External Plug	---	X	X	---
	Expandable Centerbody	---	X	X	---
	Translating & Expandable C/B	---	X	X	---
Variable Cowl Inlets	Translating Cowl	---	X	X	X
	Hinged Lip	---	X	X	X
	Double Lip	---	X	X	---
	Inflatable Lip	---	---	---	X
Variable Blockage Systems	Variable Stagger Vanes	---	X	X	---
	Double Row Articulated Vanes	---	X	X	---
	Retractable Vanes	---	X	X	---
	Translating 2 & 3 Vane Rows	---	X	---	---
	Translating C/B + 2 Vane Rows	---	X	---	---
	Expandable Vanes (1 Row)	---	X	X	---

$X/D_{Max.} = 0.61$

$D_{HL}/D_{Max.} = 0.91$

$A_{HL}/A_{Th} = 1.25$

$A_O/A_{HL} = 0.735$

	Throat Mach No.
Max. Cruise	0.70
Max. Climb	0.78
Takeoff	0.60

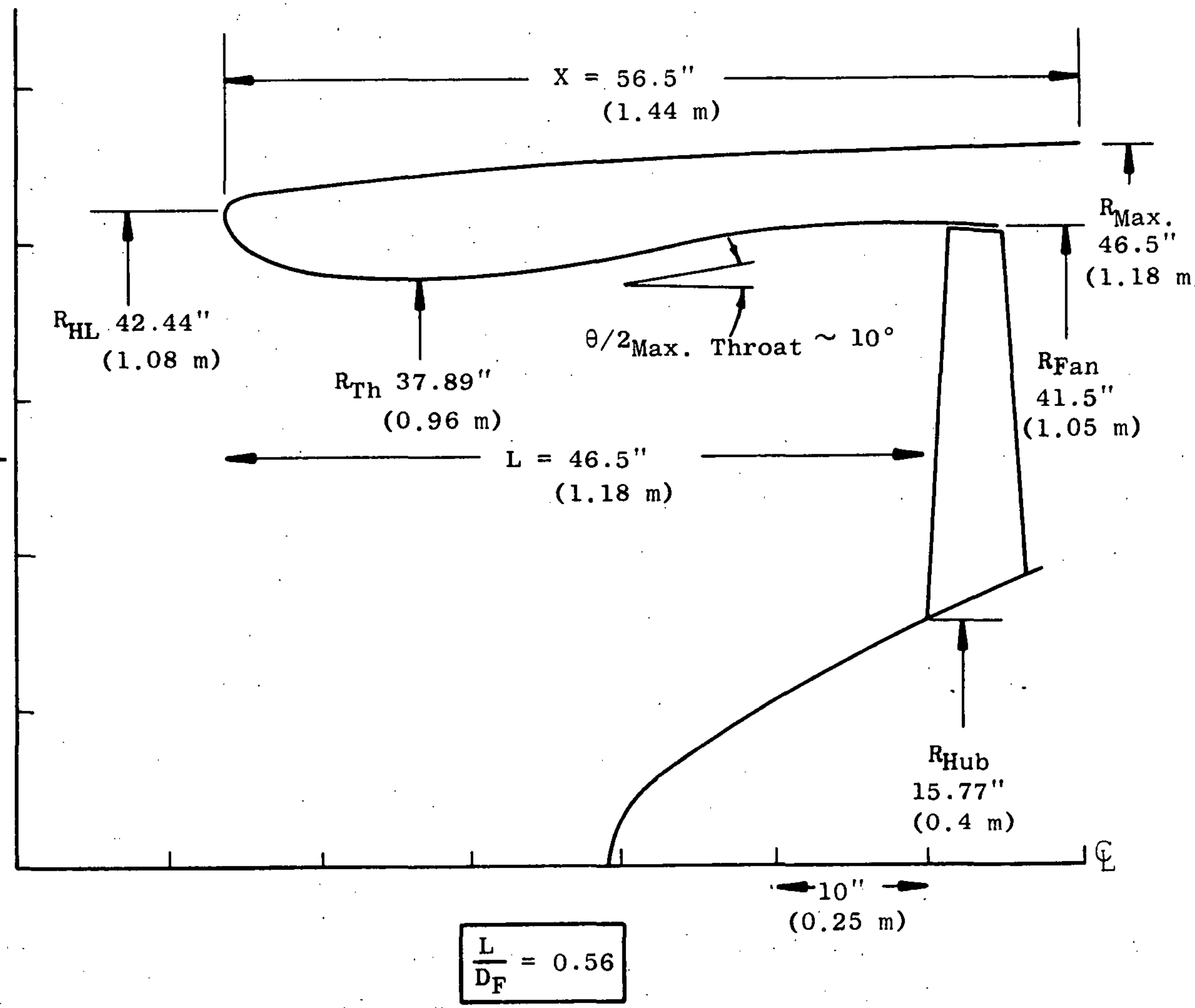


Figure 7. ATT No. 3 Aerodynamic Baseline Inlet for M = 0.90 (No Acoustic Restrictions Imposed).

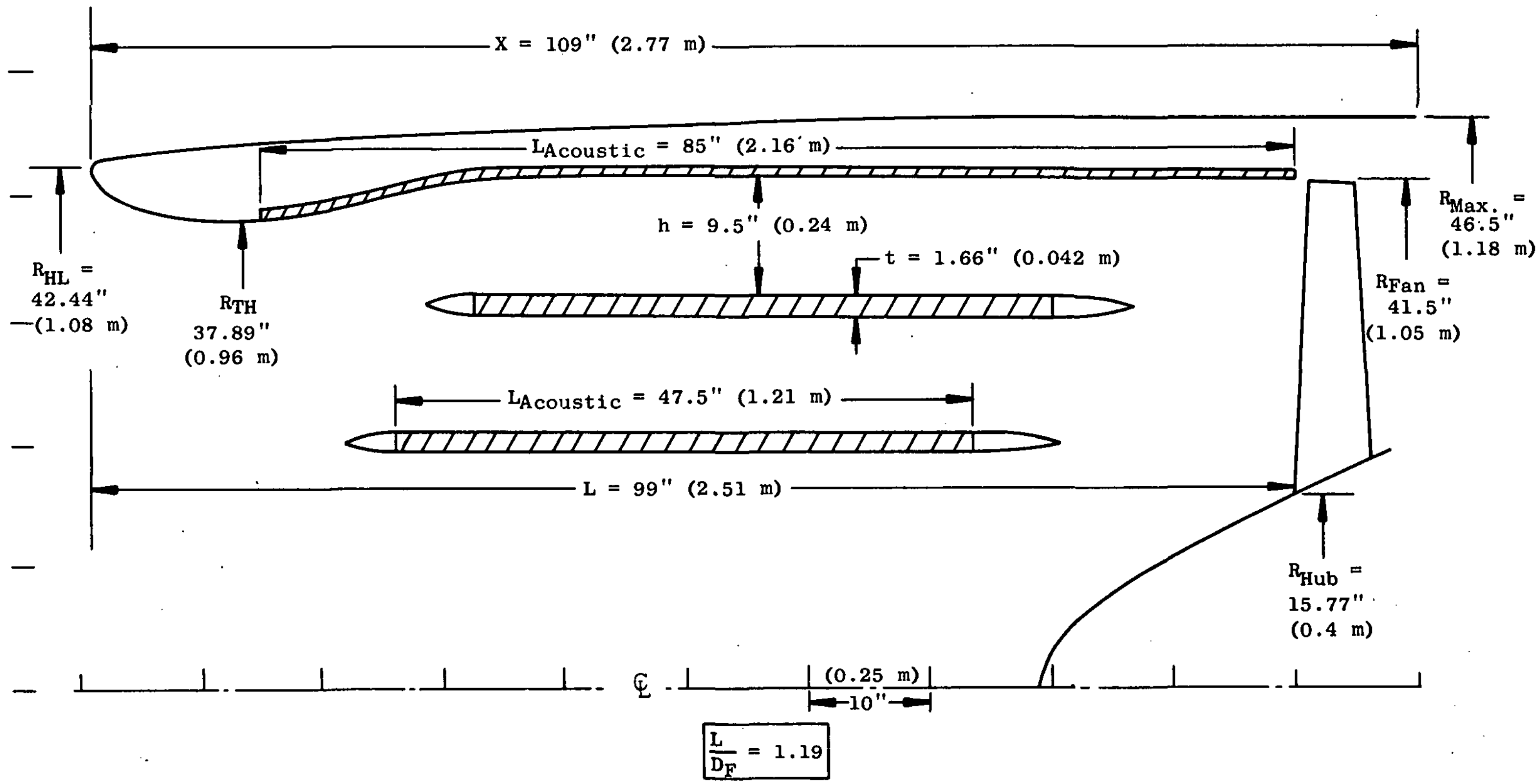


Figure 8. ATT No. 3 Acoustic Baseline Inlet for FAR 36 -15.

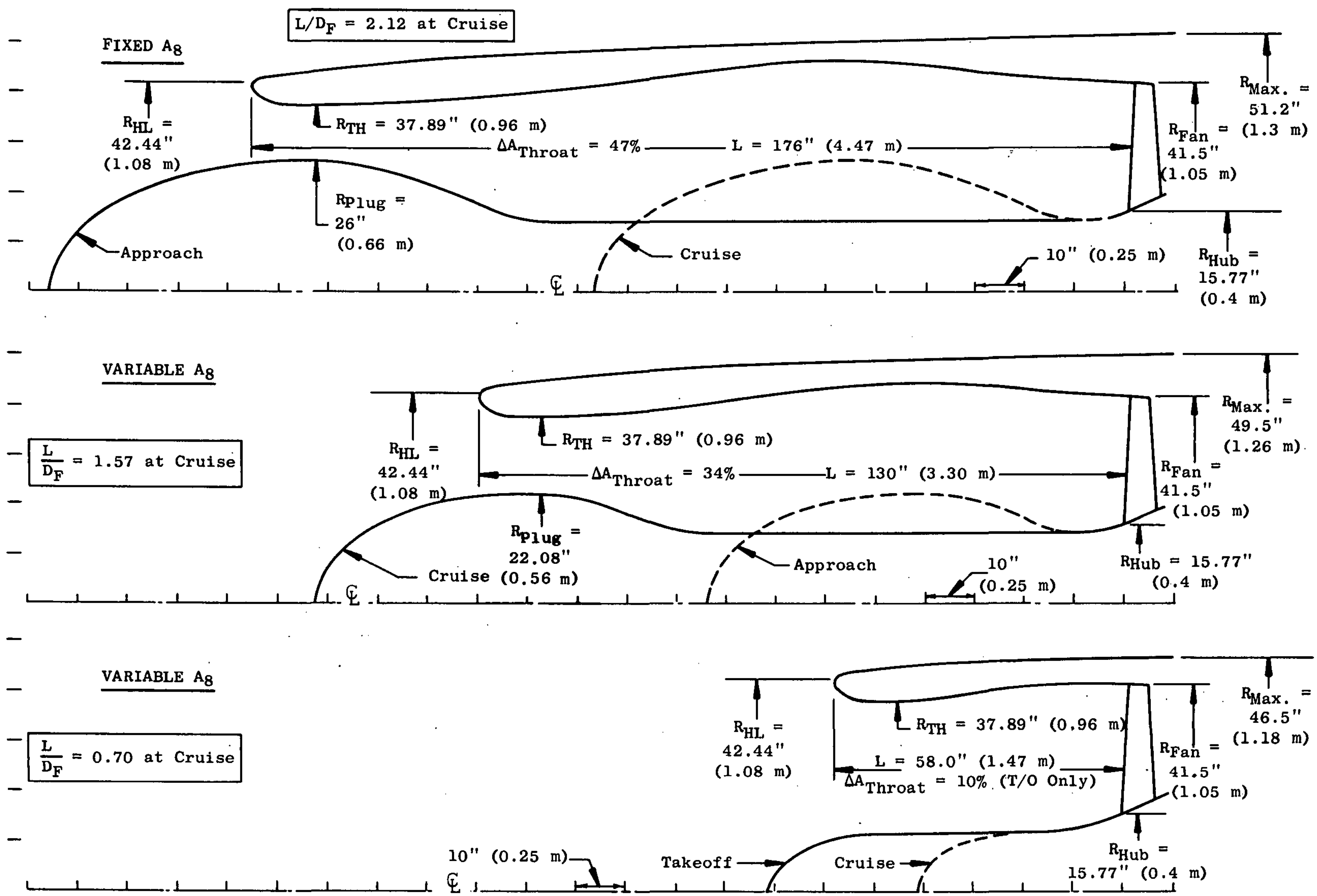


Figure 9. ATT No. 3 Internal Translating Plug Inlets.

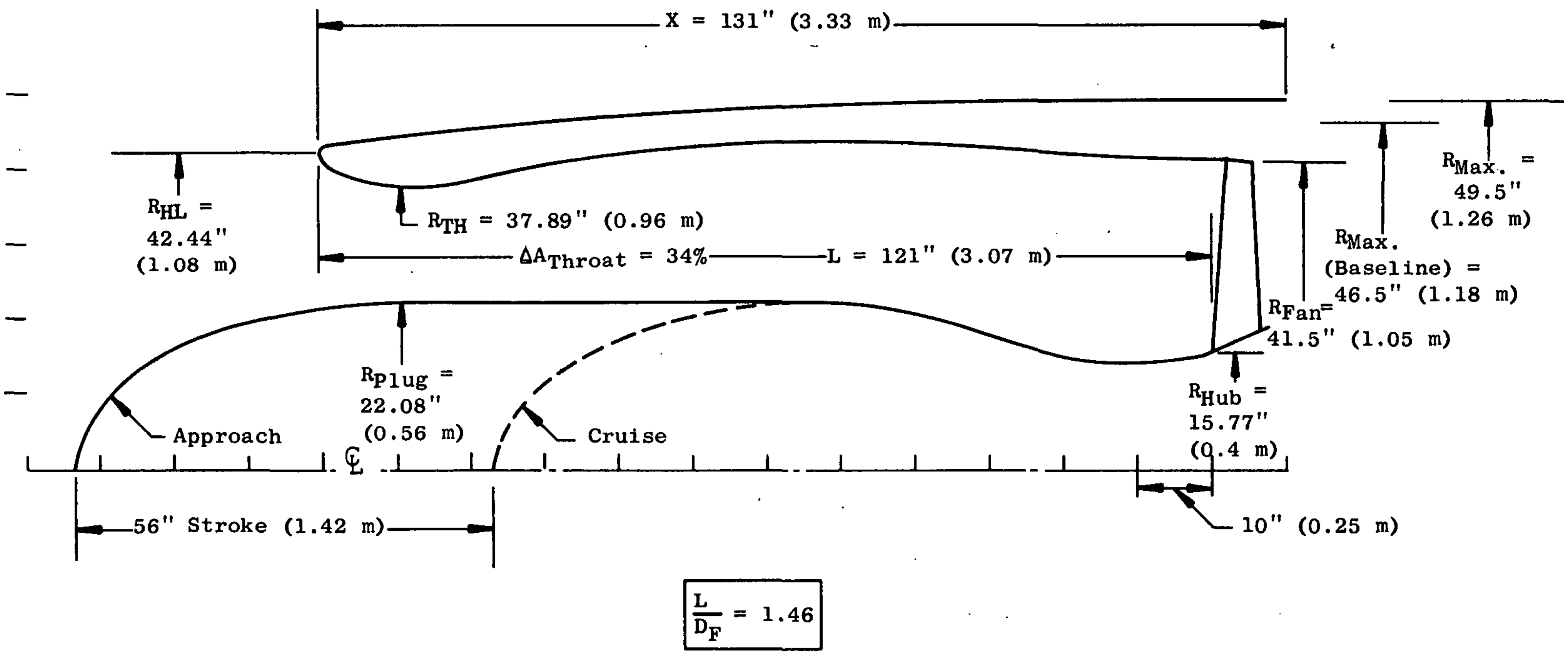


Figure 10. ATT No. 3 Internal Translating Plug Inlet, Variable A_8.

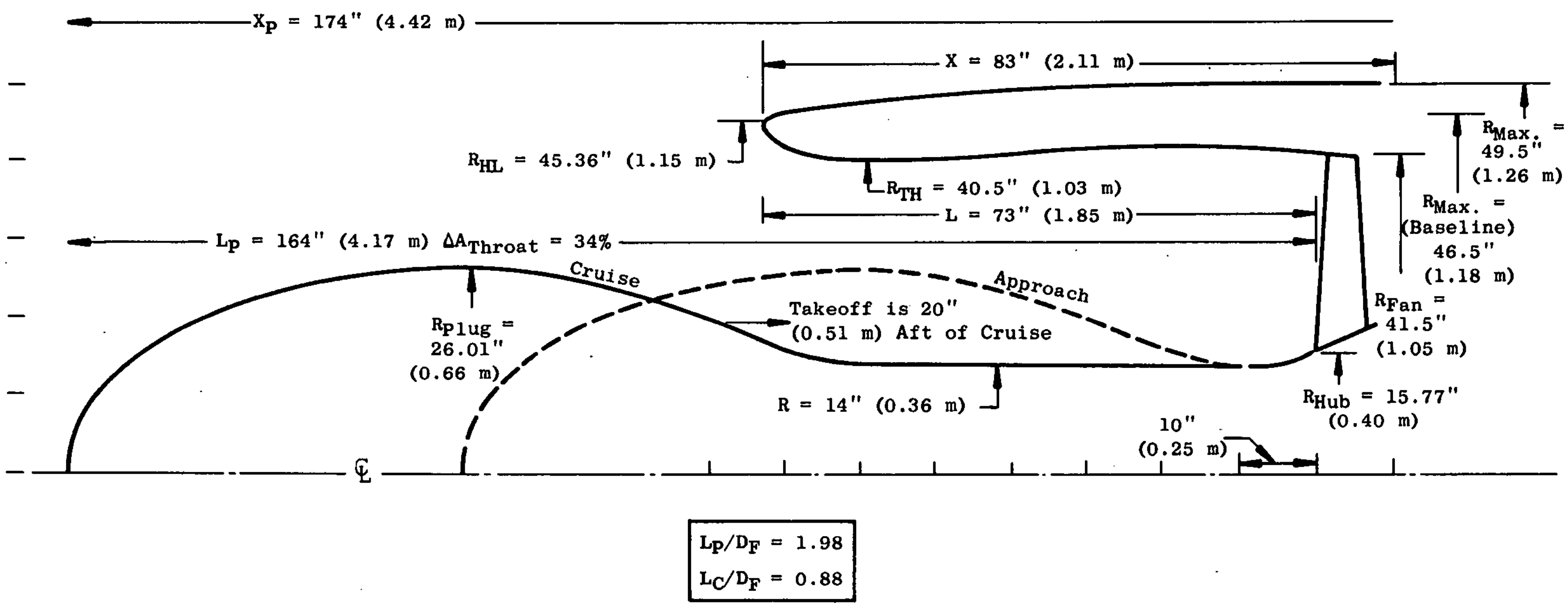


Figure 11. ATT No. 3 External Translating Plug Inlet, Variable A_8.

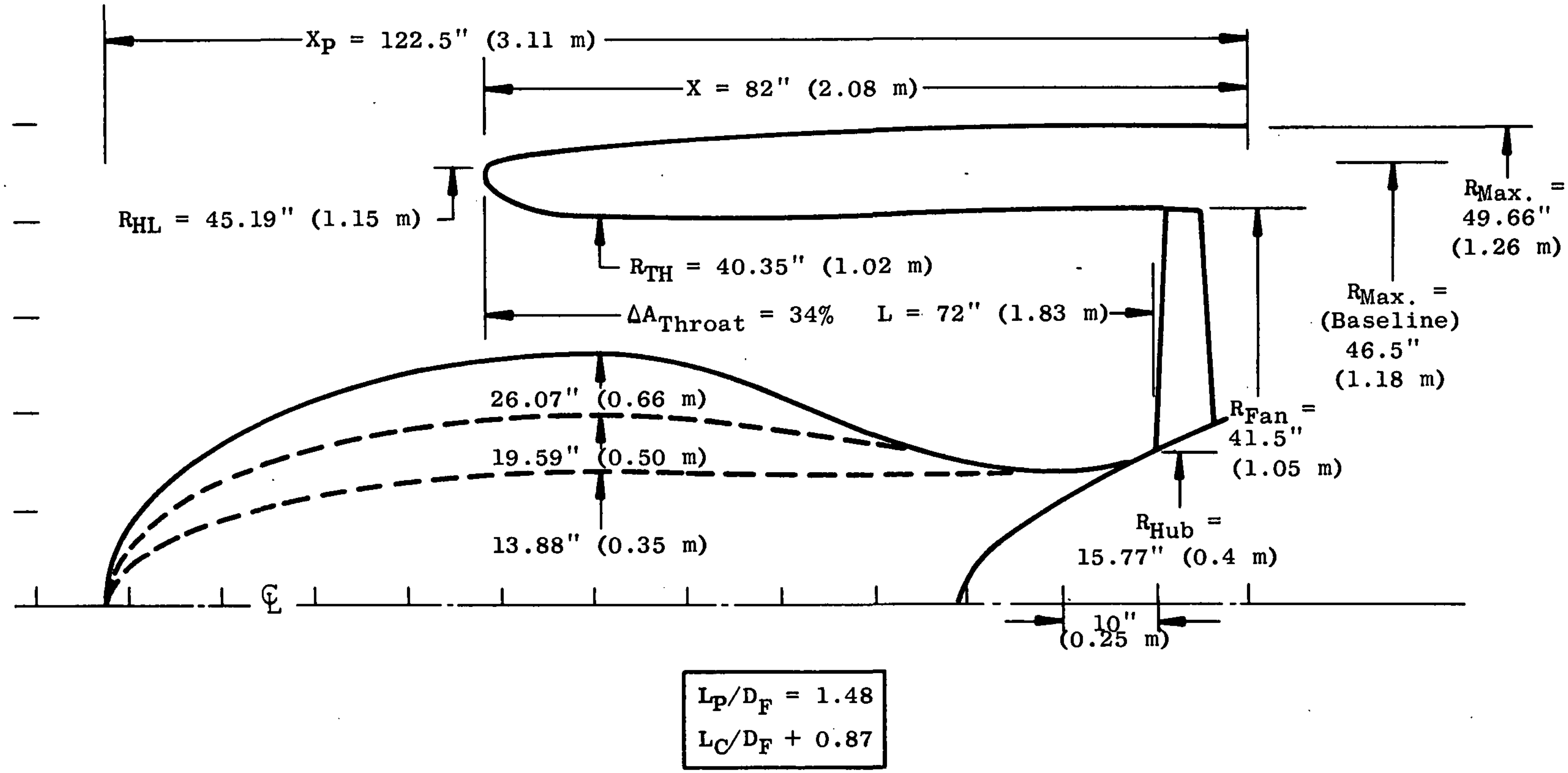


Figure 12. ATT No. 3 Collapsing Plug Inlet, Variable A_8.

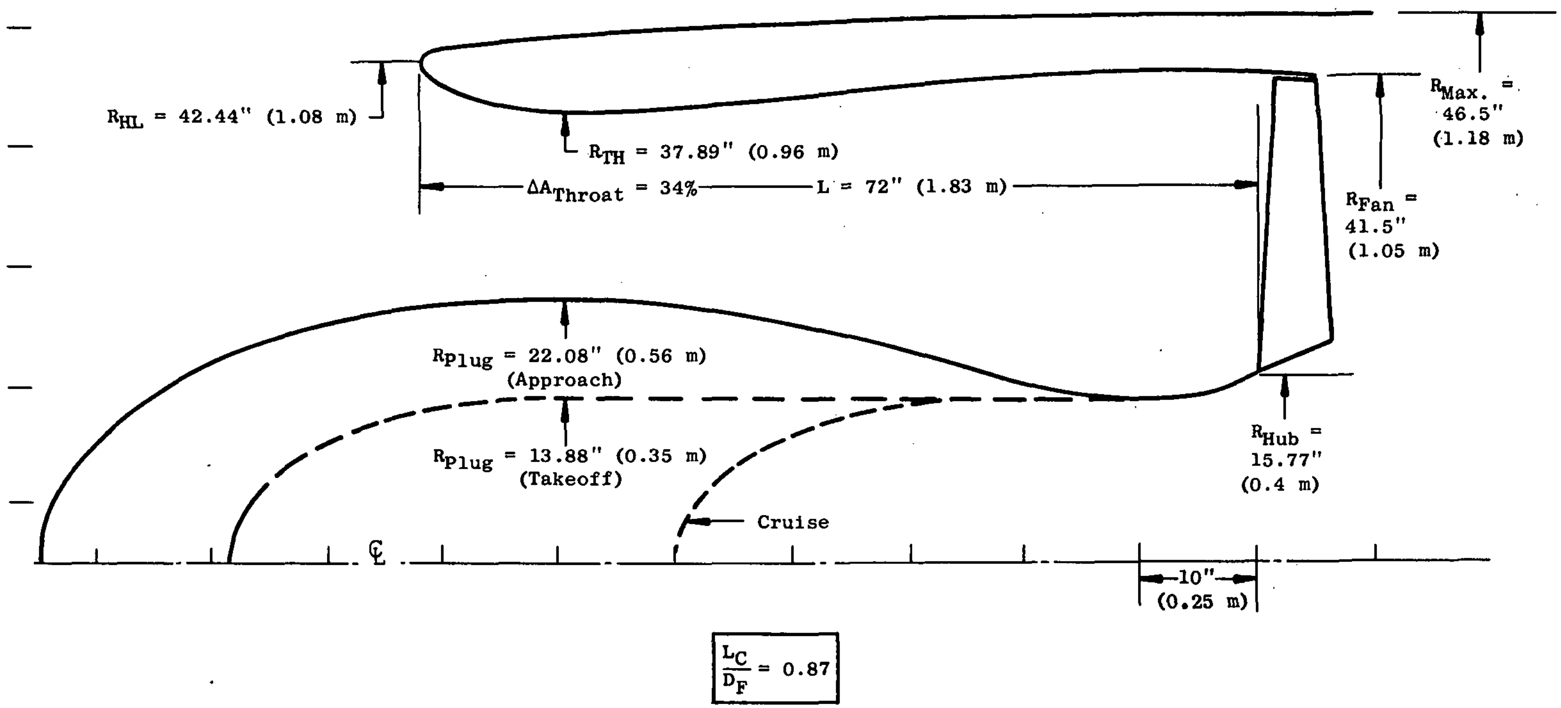


Figure 13. ATT No. 3 Translating and Collapsing Plug Inlet, Variable A_8.

VARIABLE COWL INLETS

Several variable cowl inlets were evolved for the screening study. Figure 14 illustrates the variable cowl geometry desired for the different conditions of interest. Figure 15 shows the hinged lip concept for two conditions, and Figure 16 shows a double-lip inlet concept. The latter two were selected for further evaluation.

VARIABLE BLOCKAGE SCHEMES

A variety of approaches which change the blockage in the inlet or just ahead of the fan was considered. Conventional variable stagger inlet guide vanes were considered, as illustrated in Figure 17. This approach was discarded because of several adverse effects upon fan operation for the large angle changes implied by high throat Mach number levels. Specifically, closure in the direction of fan rotor rotation will not produce choke without significant fan overspeed, and significant closure in the opposite direction of rotation reduces the fan stall line substantially.

Figure 18 shows a double row articulated vane concept, and Figure 19 presents the retractable vane approach. Figures 20 and 21 illustrate translating radial vane approaches. Figure 22 shows a translating vane plus centerbody approach. Figure 23 shows the expandable vane approach. There are various means of accomplishing the geometry change as illustrated in Figures 24 and 25.

Table V summarizes total pressure losses estimated for the variable blockage schemes. Three concepts - retractable vanes, expandable vanes, and tandem articulated vanes - were selected for further evaluation.

CONFIGURATIONS SELECTED

A cursory assessment of the relative attractiveness of the various approaches was made considering performance, weight, and mechanical complexity. The geometric aspects of the various inlets are summarized in Figure 26. The length and diameter have a major impact on weight while diameter affects the external drag. The configurations selected for further evaluation are summarized on Table VI. Although it is not a high throat Mach number concept, it was decided to include a retractable splitter approach as shown in Figure 27.

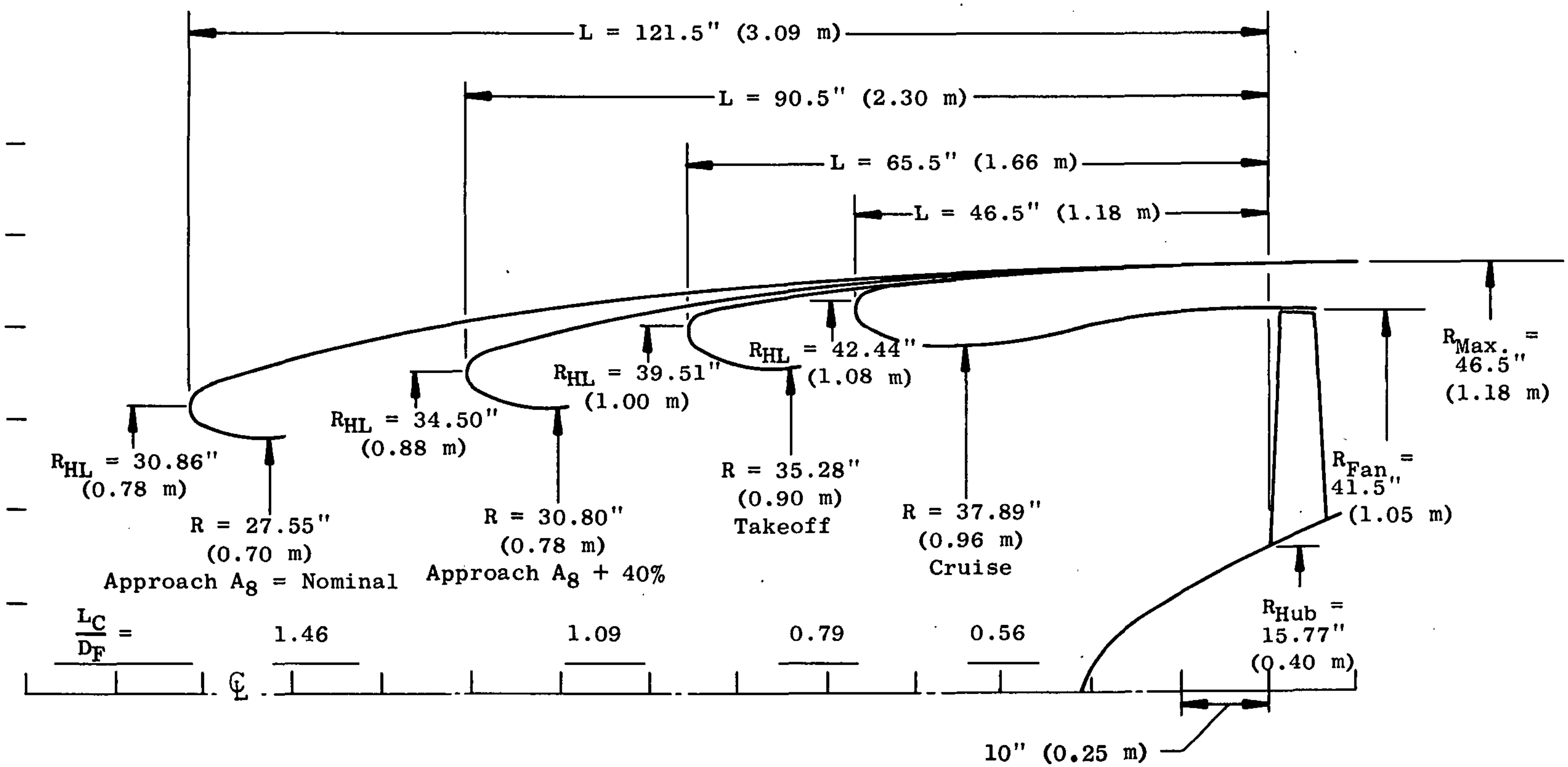


Figure 14. ATT No. 3 Variable Cowl Inlet Geometry, Point Design Comparisons.

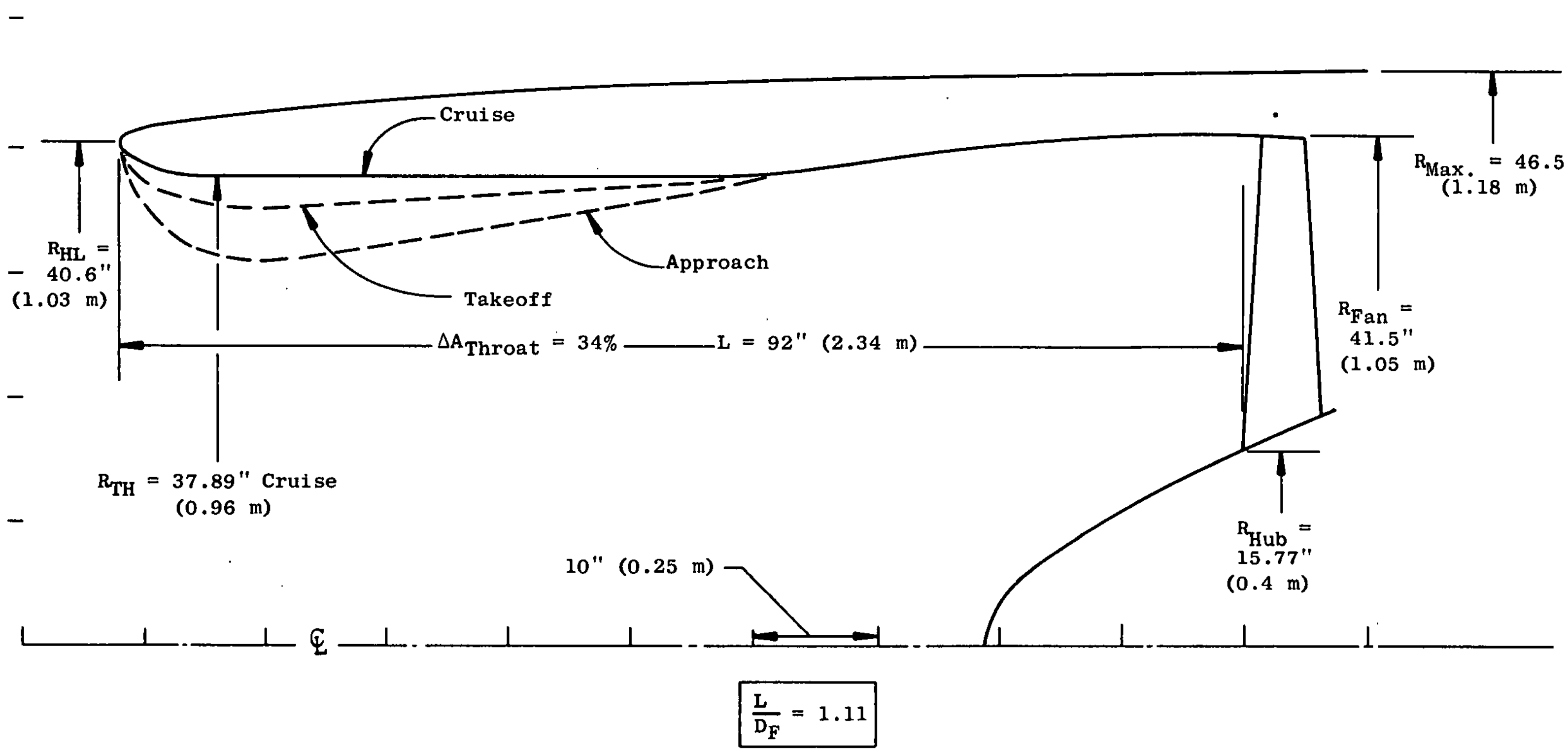
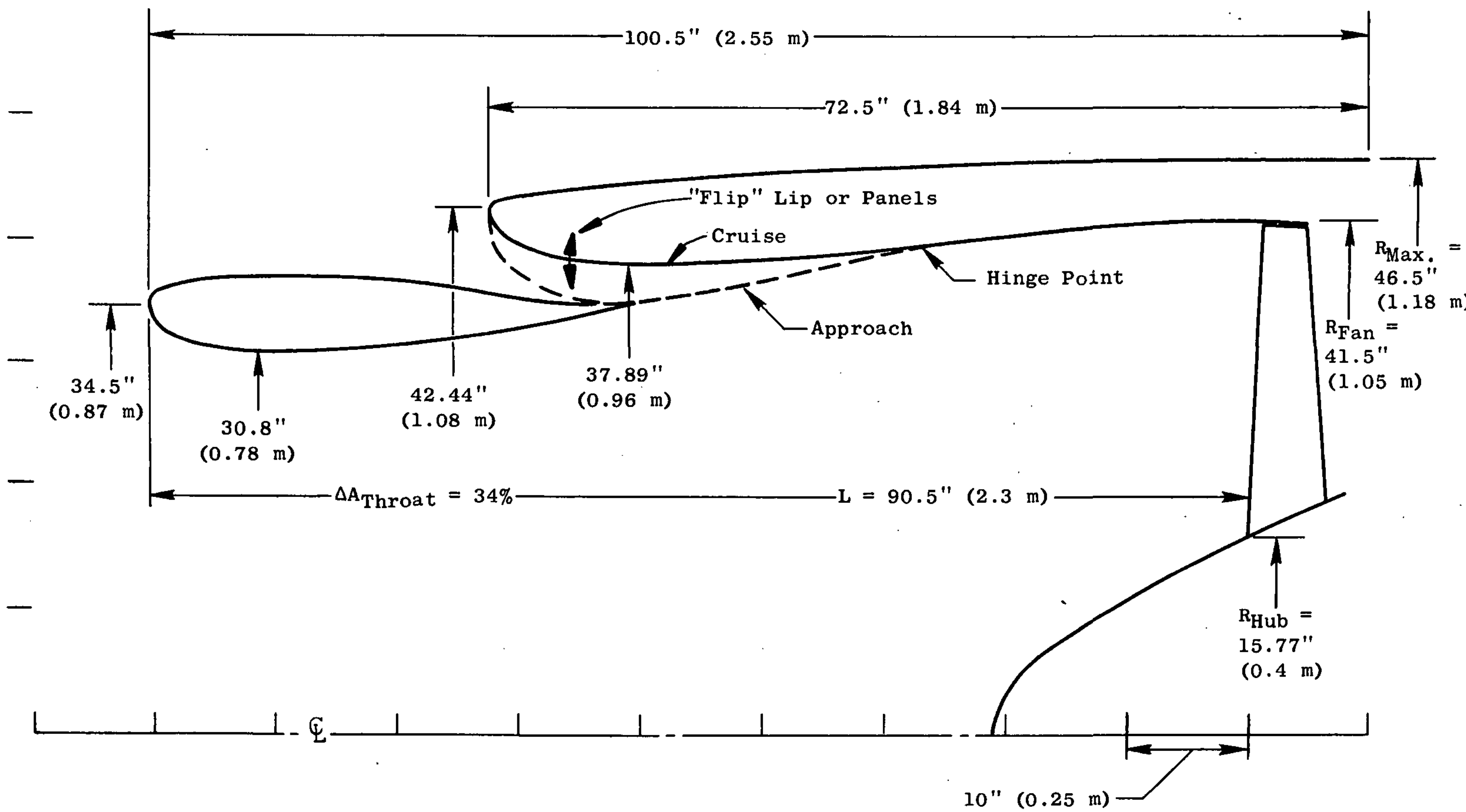


Figure 15. ATT No. 3 Hinged-Lip Inlet No. 2, Variable A_8.



$\frac{L}{D_F} = 1.09$

Figure 16. ATT No. 3 Double-Lip Inlet, Variable A_8.

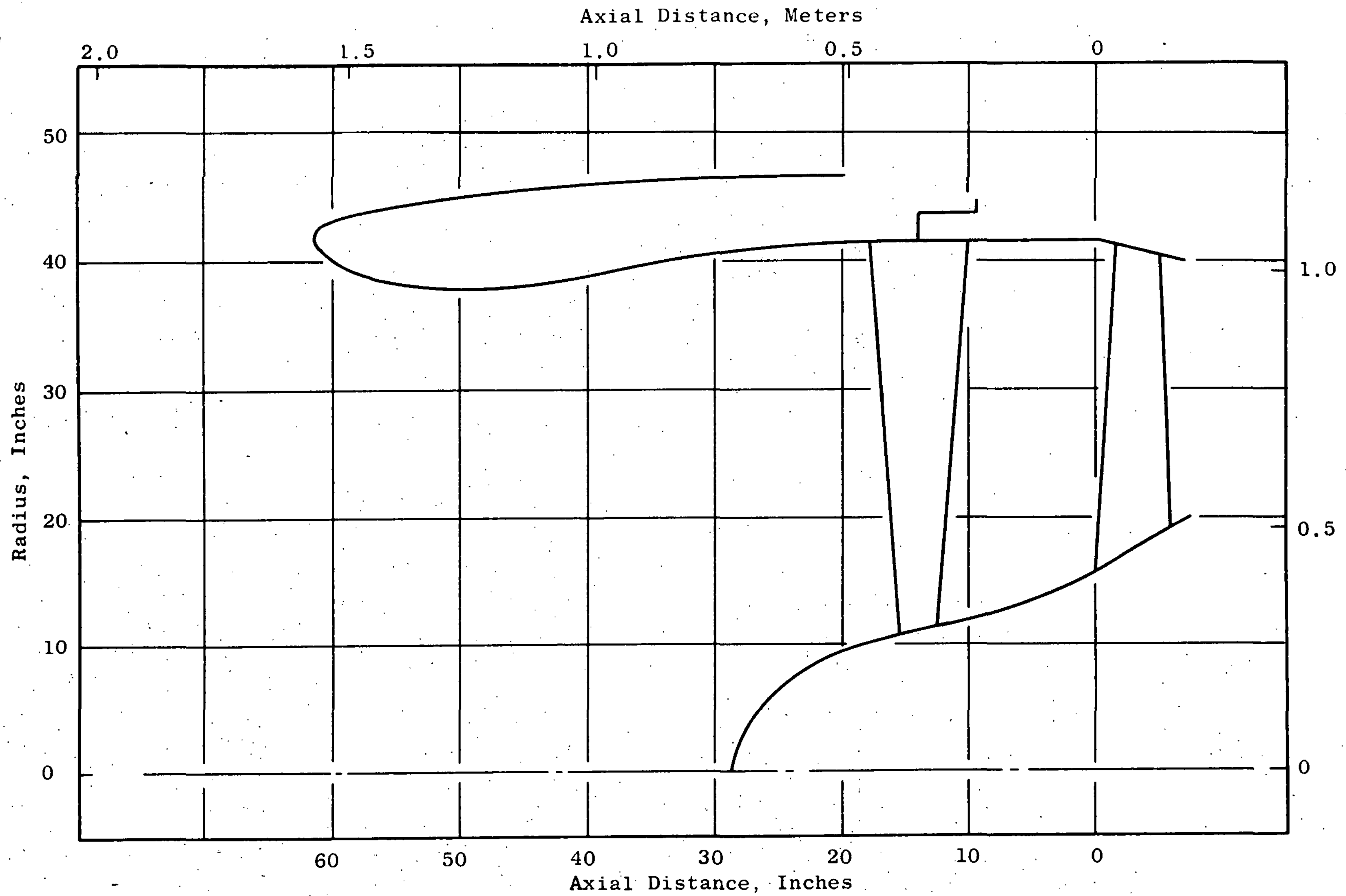


Figure 17. Variable Stagger Inlet Guide Vanes.

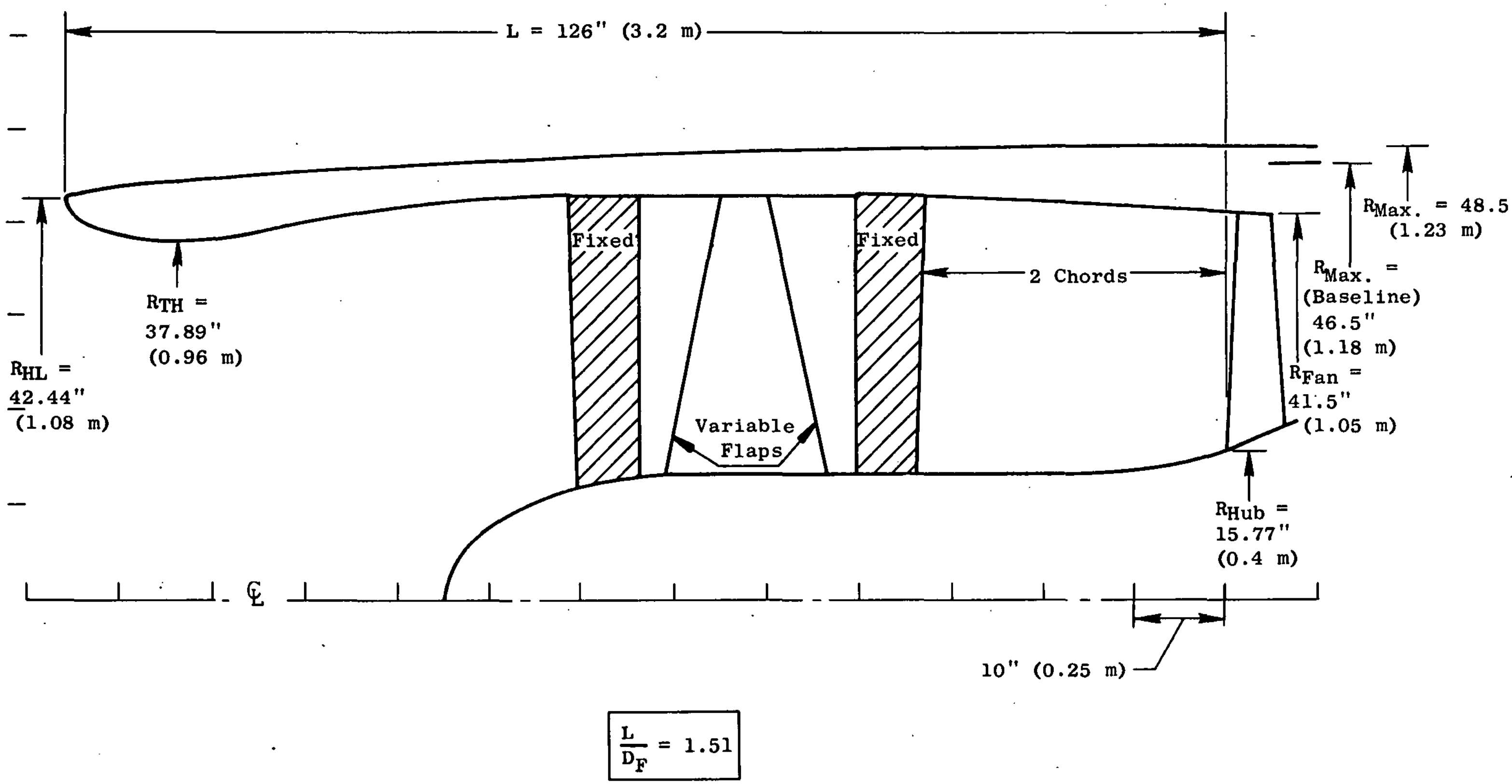


Figure 18. ATT No. 3 Double-Row Articulated Vanes, Variable A_8.

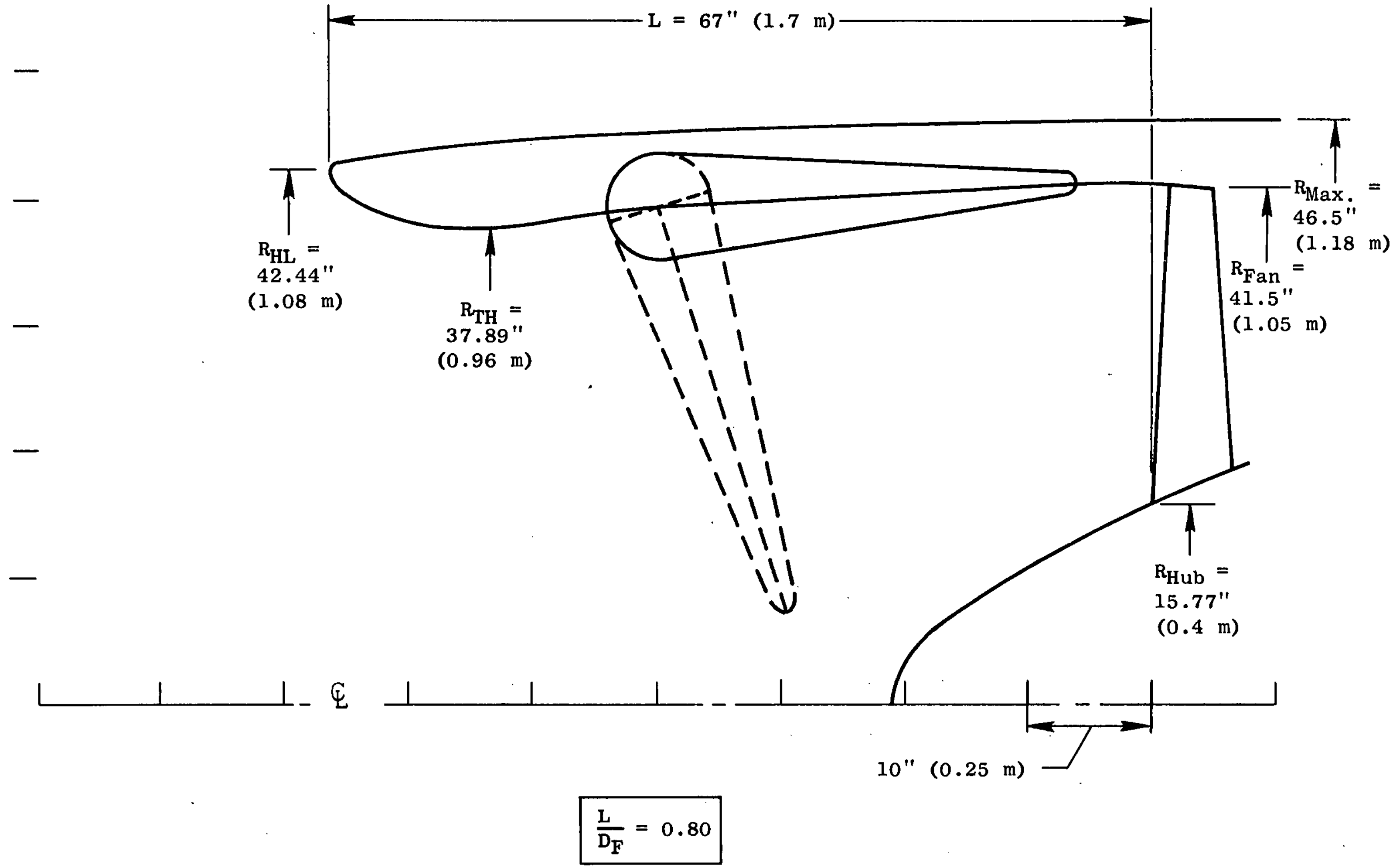


Figure 19. ATT No. 3 Retractable Vanes, Variable A_8.

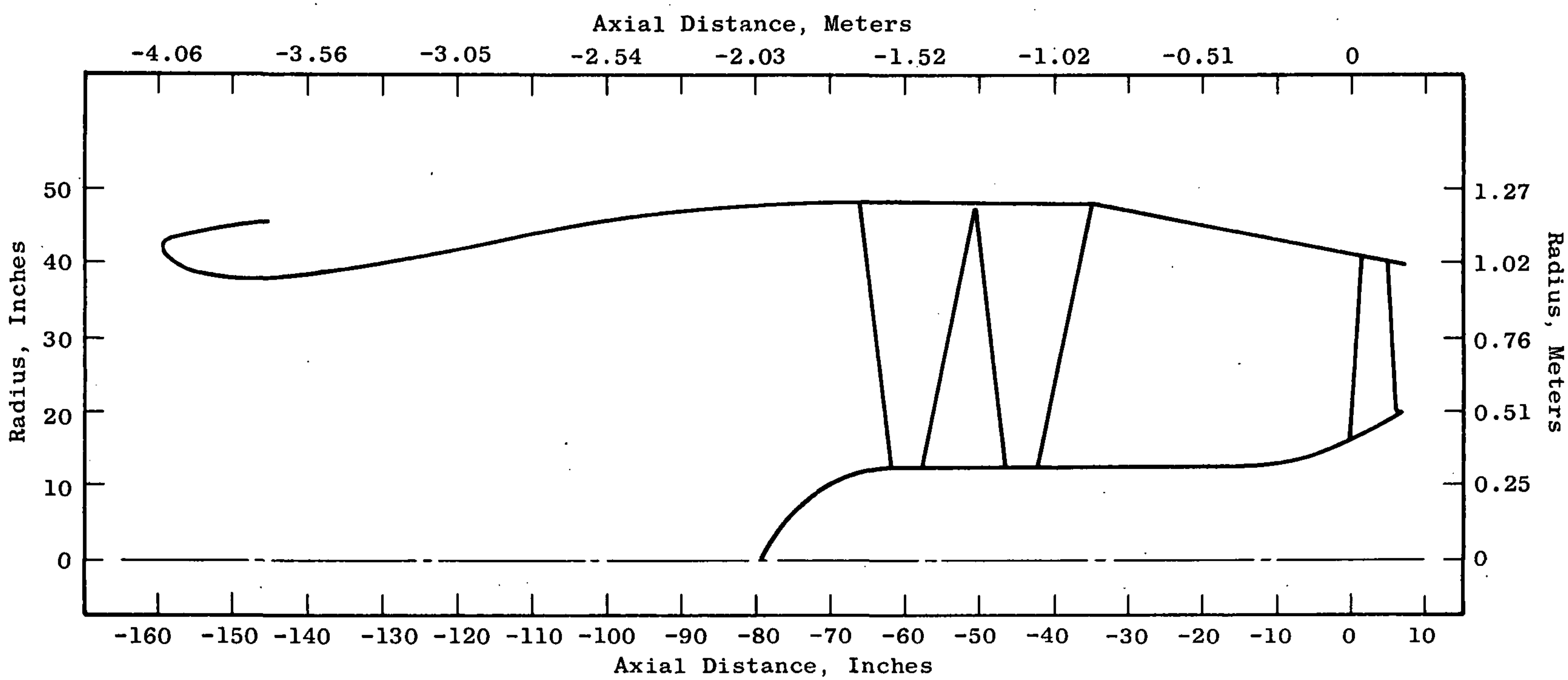


Figure 20. Double-Row Translating Vanes.

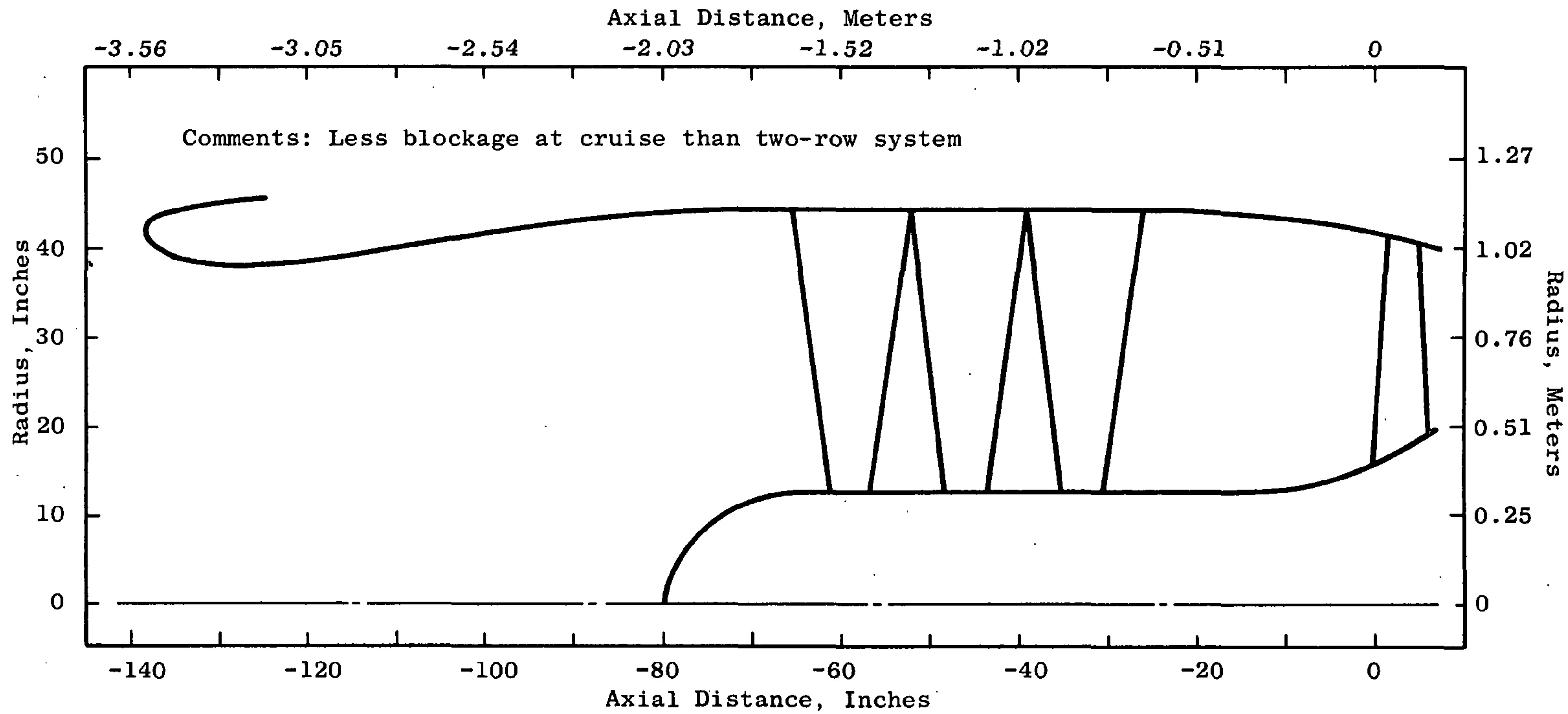


Figure 21. Triple Translating Radial Vanes.

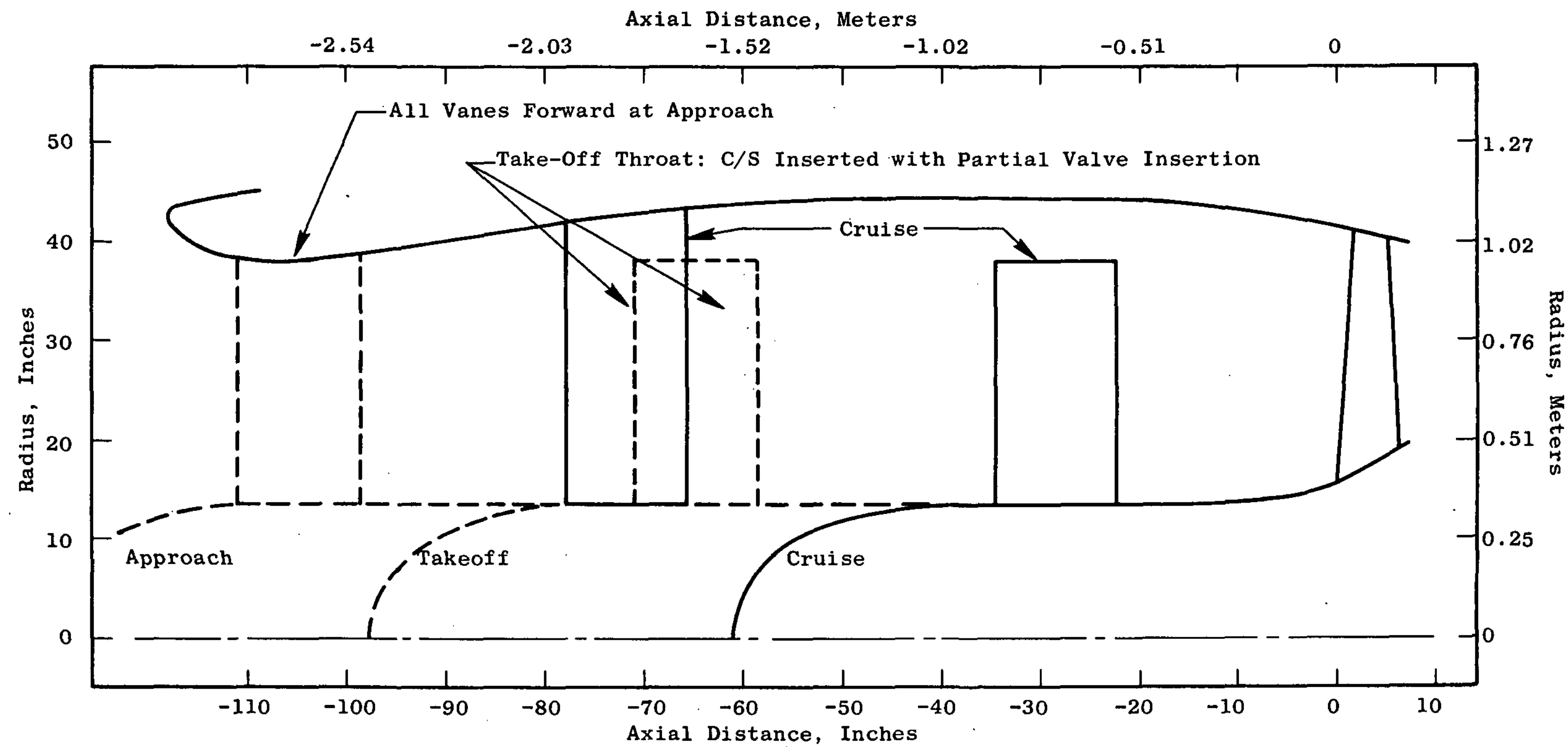


Figure 22. Translating Vanes and Centerbody.

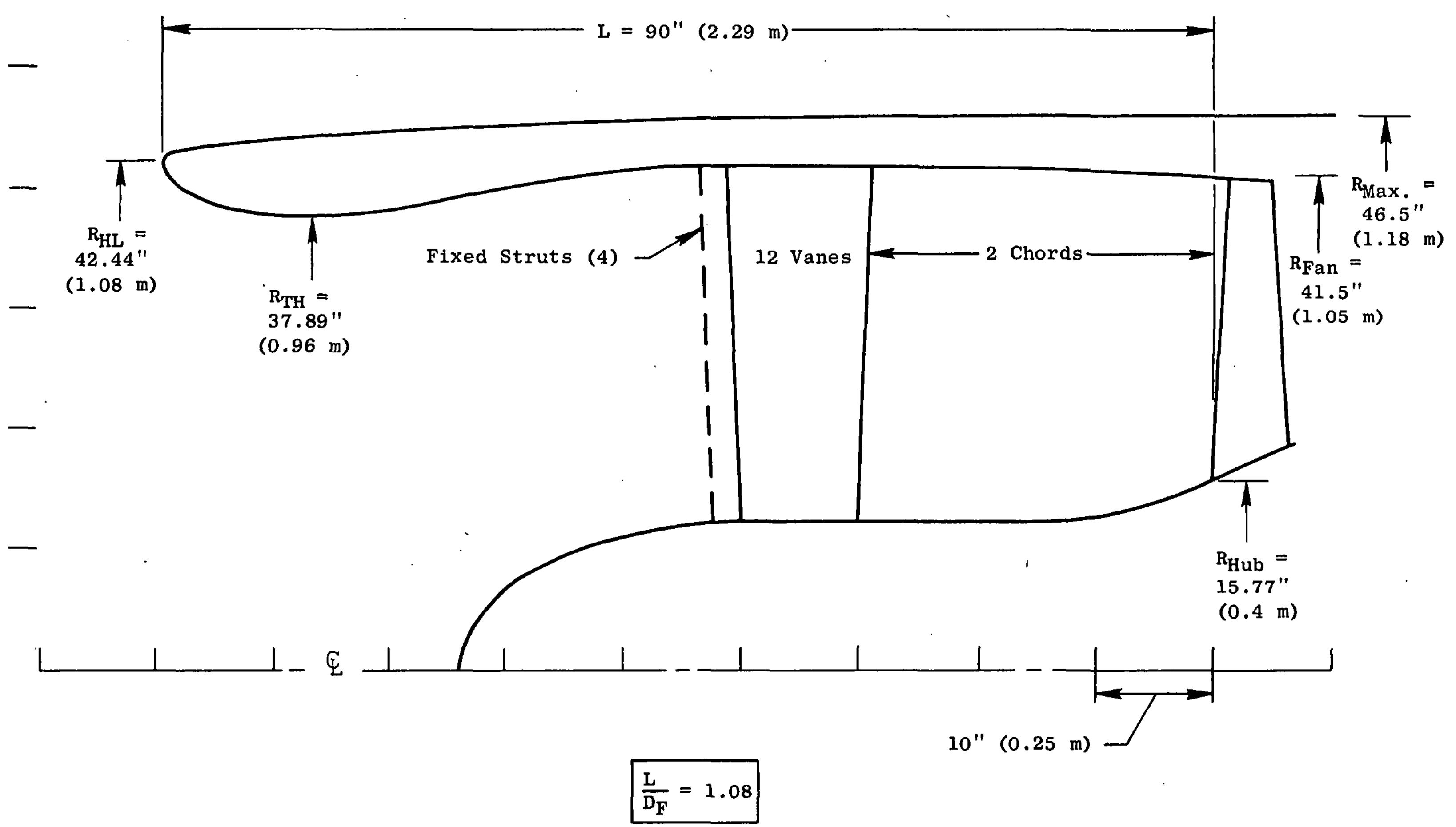


Figure 23. ATT No. 3 Expandable Vanes, Variable A_8.

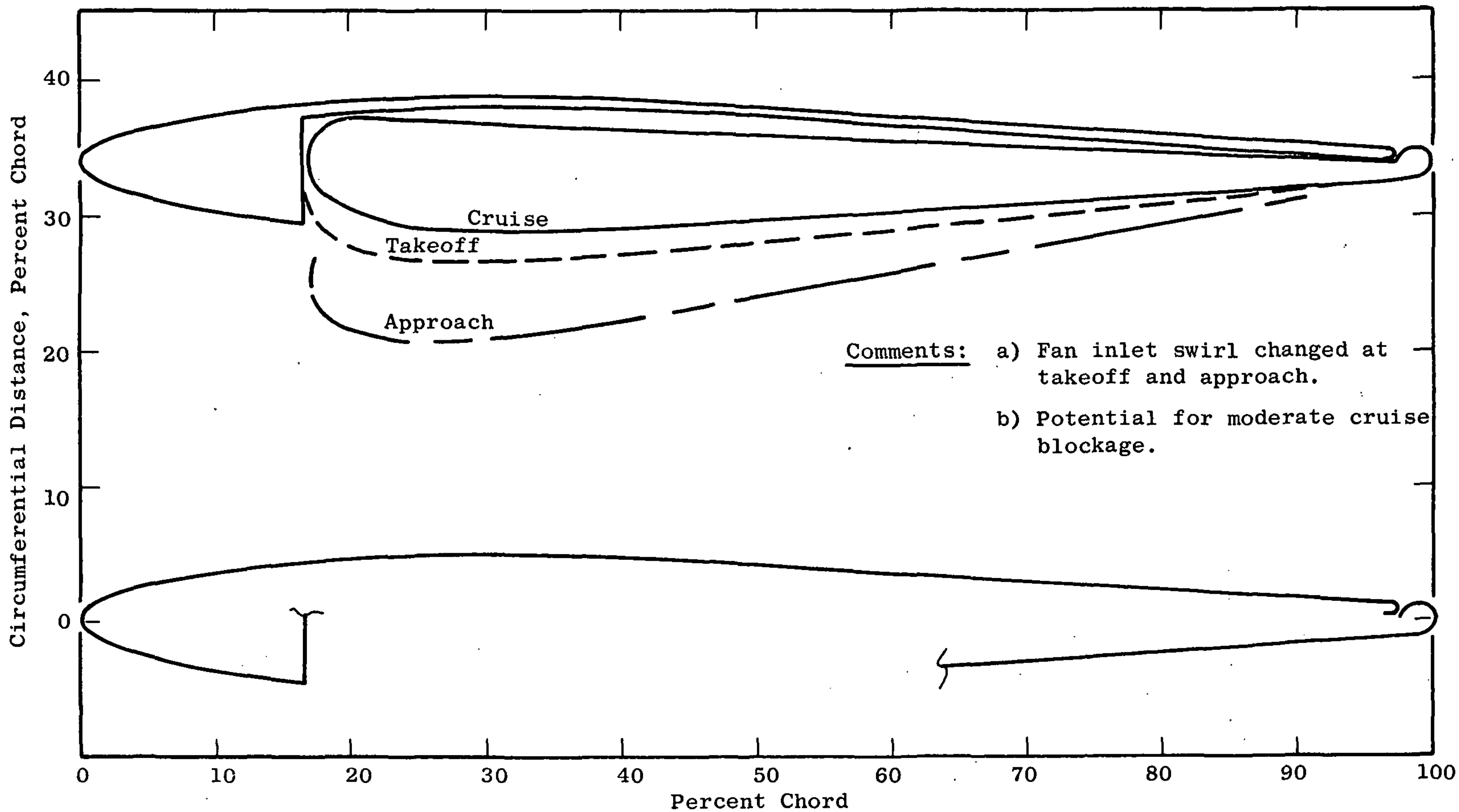


Figure 24. Expandable Vanes, Variable Surface.

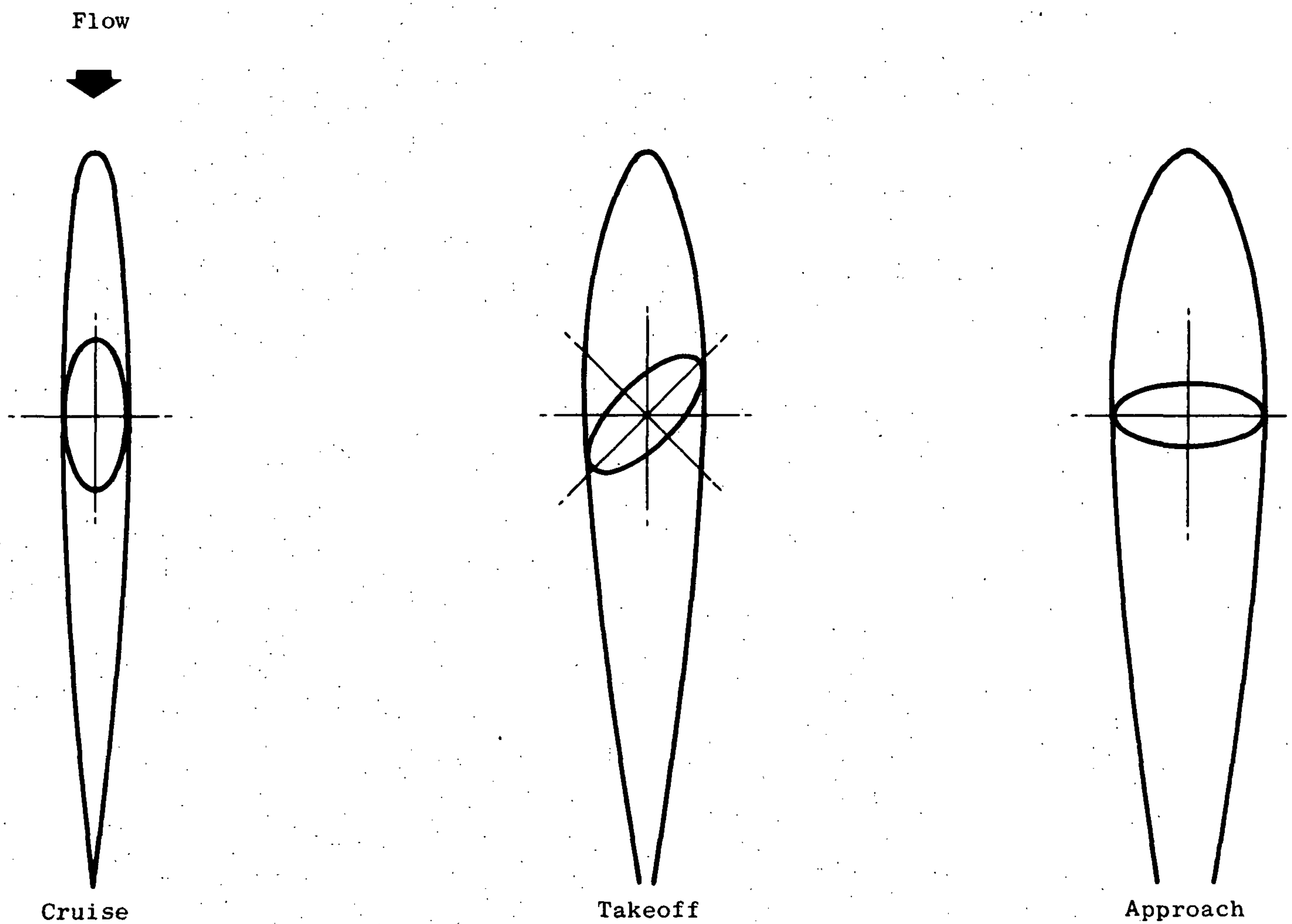


Figure 25. Expandable Vanes, Internal Cams.

Table V. Inlet Pressure Loss Estimates for Variable Blockage Systems.

Concept	Approx. Total Pressure Loss, %			Approx. Cruise Annulus Blockage %	Approx. Required Increase In O.D. Radius Over Rotor Tip, Inches (Meters)
	Cruise	Takeoff	Approach		
Variable Stagger - IGV	←	Impractical	→	---	---
Tandem Articulated IGVs	1.5	5.0	9.7	10	1.3 (0.033)
Retractable Vanes	0	1.0	4.6	0	0
Translating Vanes and Centerbody	2.2	2.5	3.5	15	2.4 (0.061)
Triple Translating Vanes	2.7	4.0	7.5	16	2.6 (0.066)
Double Row Translating Vanes	3.6	3.7	10.0	27	5.0 (0.127)
Expandable Vanes - Variable Surface	2.2	3.2	8.0	15	2.4 (0.061)
Expandable Vanes - Internal Cam	1.9	2.9	7.5	15	2.4 (0.061)

Above losses are for screening purposes only. The losses are strongly influenced by the details of the execution of the concept.

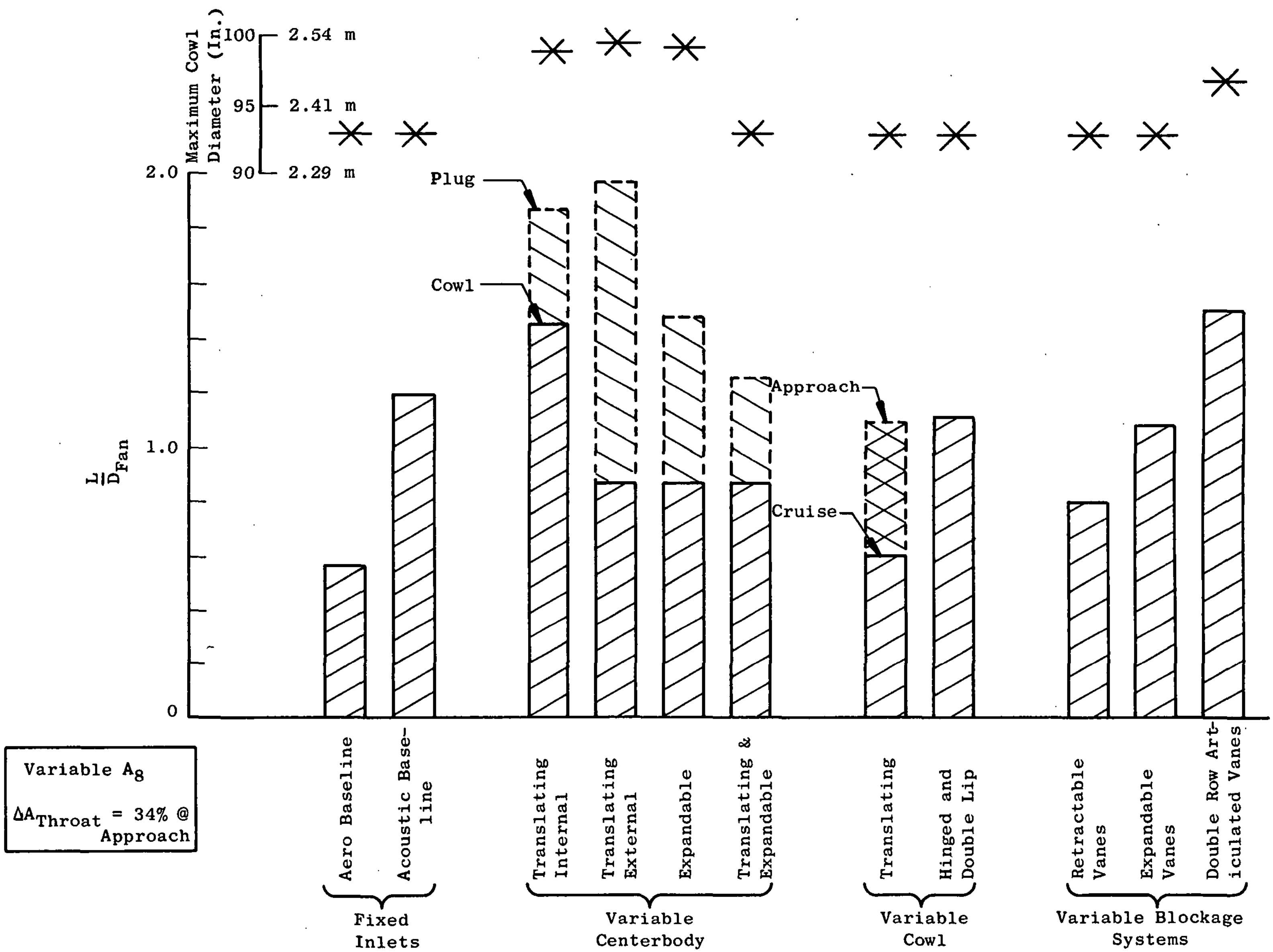


Figure 26. ATT No. 3 Geometry Summary.

Table VI. Configurations Selected for Preliminary Mechanical Design Studies.

I. Variable Cowl Inlets

- Hinged Lip
- Double Lip

II. Variable Centerbody Inlets

- Translating Internal Plug
- Expandable Plug

III. Variable Blockage

- Retractable Vanes
- Expandable Vanes - with Partial Dump at Approach
- Double Row Articulated Vanes

IV. Retractable Splitters

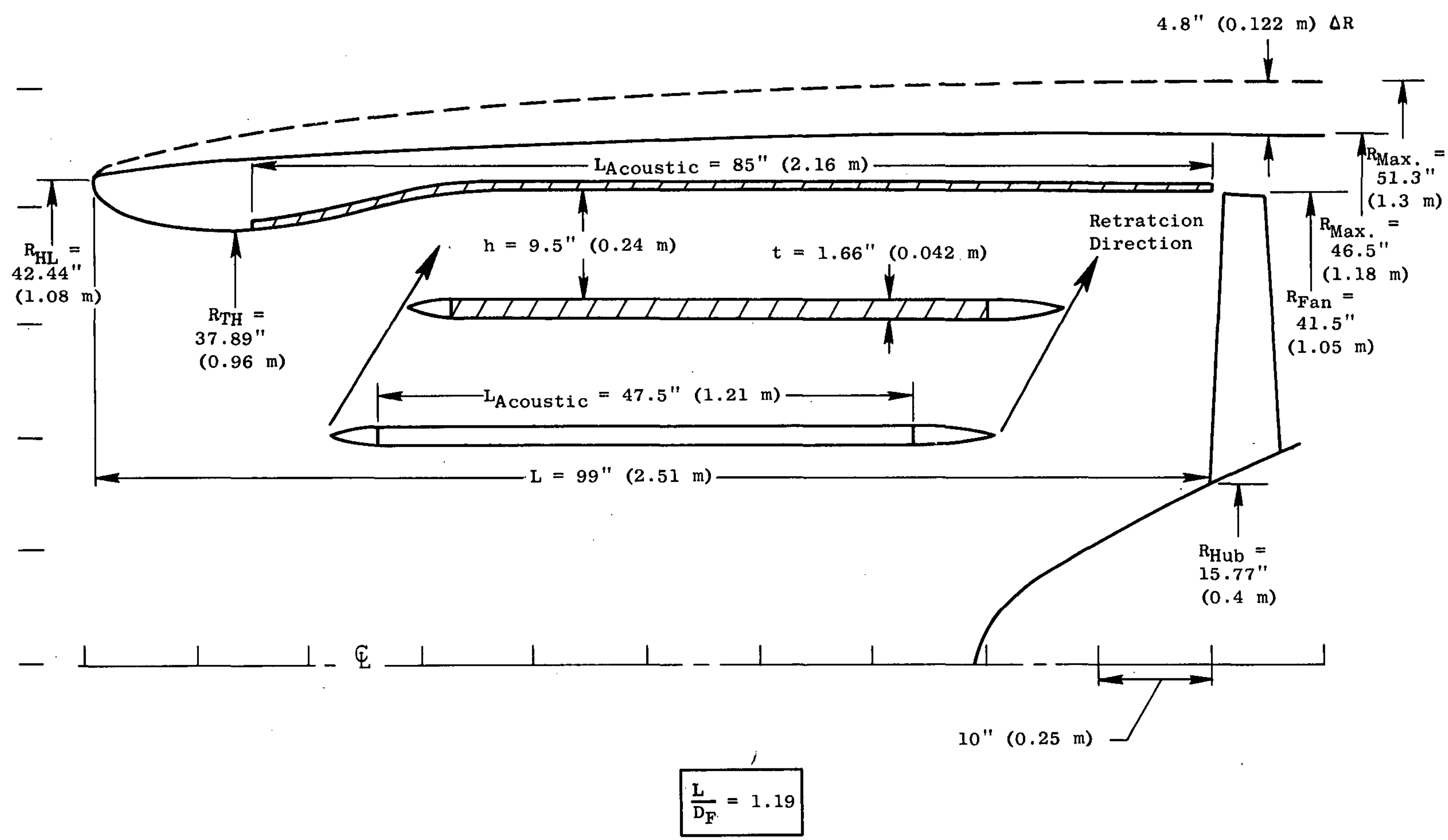


Figure 27. ATT No. 3 Acoustic Baseline with Retractable Splitters.

MECHANICAL FEASIBILITY STUDIES

GENERAL APPROACH

Variable geometry inlets can be classified into three general categories: 1) variable blockage inlets, 2) variable centerbody inlets, and 3) variable cowl inlets. Although of a different family, a retractable splitter concept was also studied. The variable blockage inlets accomplish the required area reduction through the introduction of retractable stator vanes or the rotating or expanding of vane cascades which are constantly in the air stream. The presence of a centerbody is optional, depending on the configuration. The second variable geometry concept utilizes changes in centerbody diameter relative to a stationary cowl diameter. A system of stationary struts comprising a frame is required to support the centerbody. The variable cowl inlets require no centerbody and achieve changes in effective throat diameter by means of translating or flipping the cowl.

Following an initial screening process, seven specific configurations were selected as candidates for a preliminary mechanical design investigation. The mechanical design studies were pursued to the point of being able to determine feasibility, identify problems, and make weight estimates. None of the configurations represents a complete mechanical design. Cowling design details, not directly connected to the variable portions of the assembly, have been omitted. The weight of these omitted portions has been established from the nacelle weights of a similar size existing engine, the CF6.

The axial positions of stationary struts and stator vanes, relative to the fan inlet, have been established by acoustic requirements. A two-strut chord spacing between the strut trailing edge and the fan rotor face is the governing criterion.

The mechanical design studies have evolved several factors of interest. The size of the cowl and centerbody are by far the largest contributors to the total assembly weight. The mechanism and actuators constitute only 10% to 20% of the total inlet weight. It can be concluded, therefore, that, even if the design effort were extended to achieve an optimum actuation system, the impact upon the assembly weight would not be controlling.

All of the configurations are scalable. The evaluation of the inlets on a relative basis would remain unchanged if the engine size were changed. The same conclusion would not be valid for differences in required area variation. Some of the concepts, such as the translating internal plug and the expandable centerbody, would become more attractive for smaller area variations on a relative basis.

VARIABLE BLOCKAGE INLETS

The first major category of choked inlets, the variable blockage inlets, includes three configurations: 1) double row articulating vanes, 2) expandable vanes, and 3) retractable vanes.

The double row articulating vane concept (Figure 28) utilizes two tandem vane cascades. The forward airfoil, consisting of a stationary leading edge and a variable flap trailing edge, provides the required area variation. The aft airfoil, which consists of a variable flap leading edge and a stationary trailing edge, turns the flow back to axial prior to its entrance to the fan. The stationary components of the airfoils lead the flow into and out of the flaps and support the centerbody which is included to enhance vane stability.

The double vane row represents a simple mechanical design which can be configured to offer easy maintenance and excellent life potential. It does, however, require a long, large diameter cowl. The large nacelle results in a heavy assembly despite the assumed inclusion of hollow titanium airfoils. The only factor that would reinstate this configuration as a strong candidate would be a sufficient reduction of the required area variation to allow the utilization of a single-flap-strut pair.

The second variable blockage concept, the expandable vanes, makes use of variable thickness struts to achieve the reduced flow area. Design criteria include minimum blockage at cruise, a radial blockage variation of less than 15% at any flight condition, and axial positioning of the vanes two chord lengths ahead of the rotor. The requirement for complete diffusion through the vane cascade has been relaxed for this configuration in order to minimize chord length and overall inlet length. Vane chords have been established to produce ideal diffusion through the cascade and to limit dump losses off the trailing edge to 1/2% in the take-off position. Additional dump loss is allowed during approach.

The diameter of the centerbody was chosen based on the following considerations. The diameter must be less than or equal to 25 inches (0.64 m) in order to lead the flow properly into the fan. A significantly smaller diameter produces only a slight reduction of the cowl diameter while it forces a larger variation in vane thickness between ID and OD. A smaller centerbody allows less room for mounting actuators internal to the centerbody if required. Since the disadvantages of a small centerbody diameter outweigh the advantages, the largest possible diameter, 25 inches (0.64 m), was chosen.

The number of vanes selected is influenced by several factors. Practical mechanical design dictates a minimum acceptable thickness for the vane at cruise. Large numbers of vanes, therefore, result in high solidity, large blockage at cruise, and relatively high cascade weight. Large numbers of vanes do have the advantage of reducing the amount of vane thickness expansion required for the take-off and approach modes and, therefore, reducing the linkage problems internal to the vanes. The external linkage naturally becomes more complex because of the additional vanes. Small numbers of vanes are mechanically attractive for those configurations that do not require internal linkage.

Since each unit of chord length results in three units of inlet length, because of the two-chord spacing acoustic requirement, it is important to

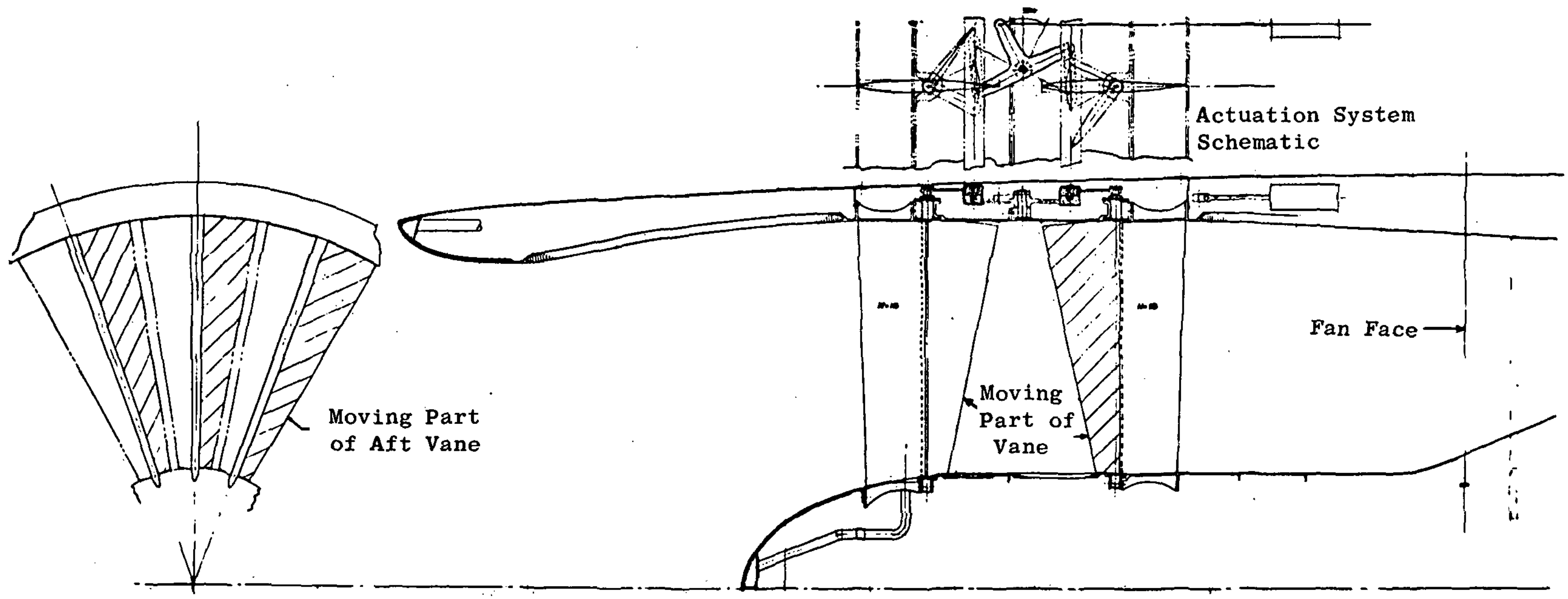


Figure 28. Double-Row Articulating Vanes, Variable Blockage Inlet.

minimize the vane chord. The total chord length is the result of two requirements. First, the length from the airfoil maximum thickness point to the trailing edge is established as the necessary distance to yield complete diffusion and then is shortened until the dump losses approach 1/2%. The distance from the leading edge to the maximum thickness is chosen as the required length to give a reasonably shaped lead into the maximum thickness point at the take-off and approach conditions.

The selected expandable vane concept (Figure 29) utilizes 12 variable thickness vanes. Four stationary struts support a centerbody which is included to promote vane stability. The chord of the struts has been made slightly longer than the chord of the vanes to provide additional stiffness for support of the centerbody. The configuration utilizes two ring assemblies. The stationary ring assembly consists of 360° outer and inner shells connected by 12 intermittent panels which form the aft diffusion portion of the second wall of the variable thickness vanes. The rotating ring is positioned within the fixed structure by one preloaded roller bearing and three preloaded ball bearings. The ring is driven by actuators located in the outer cowling. The vane panels of the two ring assemblies are connected together by four hinged panels which form the leading edge of the variable thickness vane. Flow area variation is accomplished by rotation of the movable ring assembly which in effect changes the thickness of the vane. An additional set of hinged panels could be added to the aft end of the rotating panels to minimize or eliminate the dump at take-off and approach conditions if the wakes resulting from the airfoil dump proved detrimental to operation of the fan. The additional panels, however, would increase the overall length requirement of the inlet.

The fairly complicated nature of this design concept and the large numbers of associated variables suggest that a more detailed analysis of the system and its components is required before any final assessment can be made. The pseudo vane is essentially comprised of long narrow sandwich panels which must be checked for normal operational strength and stability and for vulnerability to foreign object damage. The large number of parts could present assembly and maintenance problems. The assumed radial blockage variation results in a smaller blockage at the outer diameter where the largest amount of fan noise is generated. Wakes resulting from the trailing edge dumps could present aeromechanical problems to the fan. It is not clear what mode position the system will assume in the event of an actuation system failure. All of these factors make the expandable vane concept somewhat of an unknown quantity.

The retractable vane concept (Figure 30) provides the required flow area variations by inserting vanes into the flow at takeoff and approach and rotating them up out of the flowpath at cruise. During takeoff, one half of the vanes are inserted. The vanes do not rotate to a fully radial position in order to maintain the capability for a larger-than-nominal blockage. At approach both cascades are rotated into the flow stream. As with the expandable vanes, chords of the take-off vanes have been established to produce ideal diffusion through the cascade with a 1/2% dump loss off the trailing edge permitted. The chord of the second set of vanes, those in the flow at approach but not at takeoff, is equal to the chord of the take-off vanes.

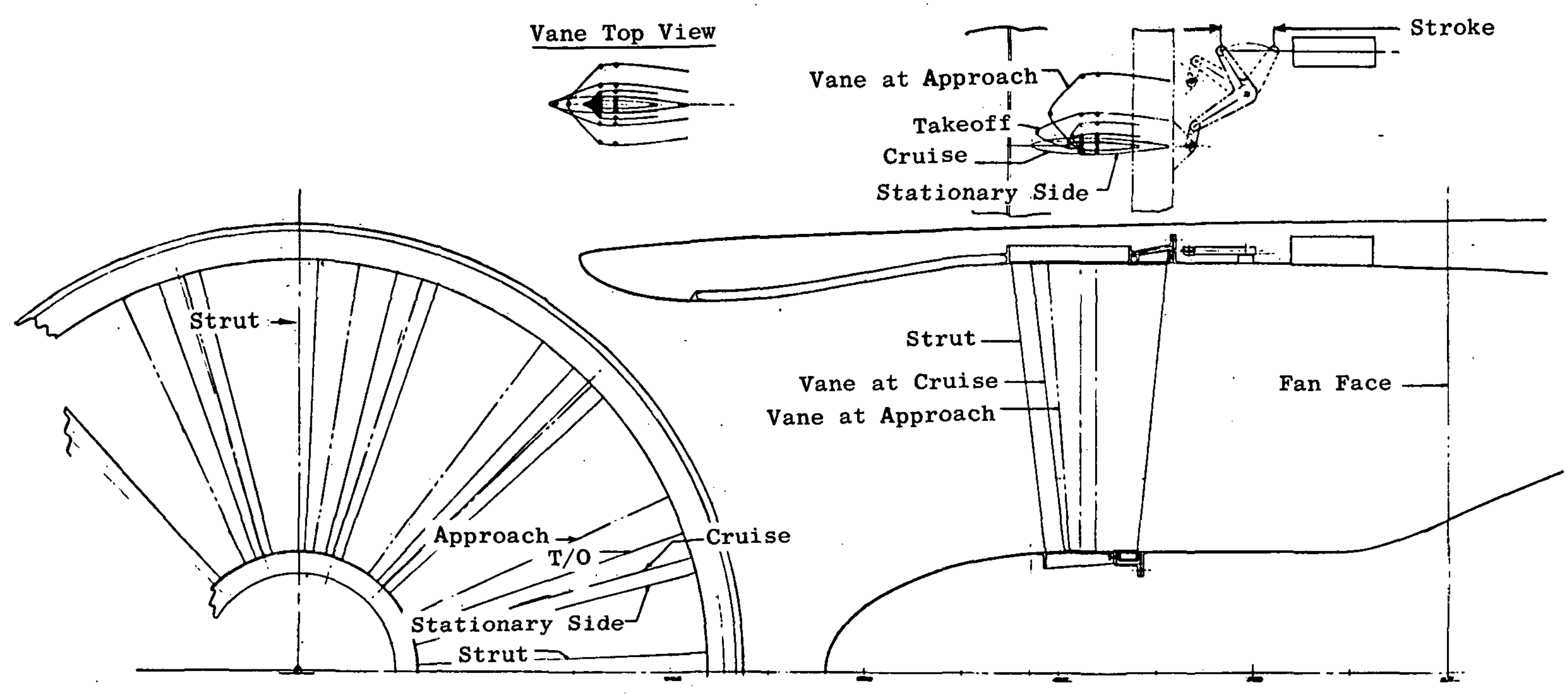


Figure 29. Expandable Vanes, Variable Blockage Inlet.

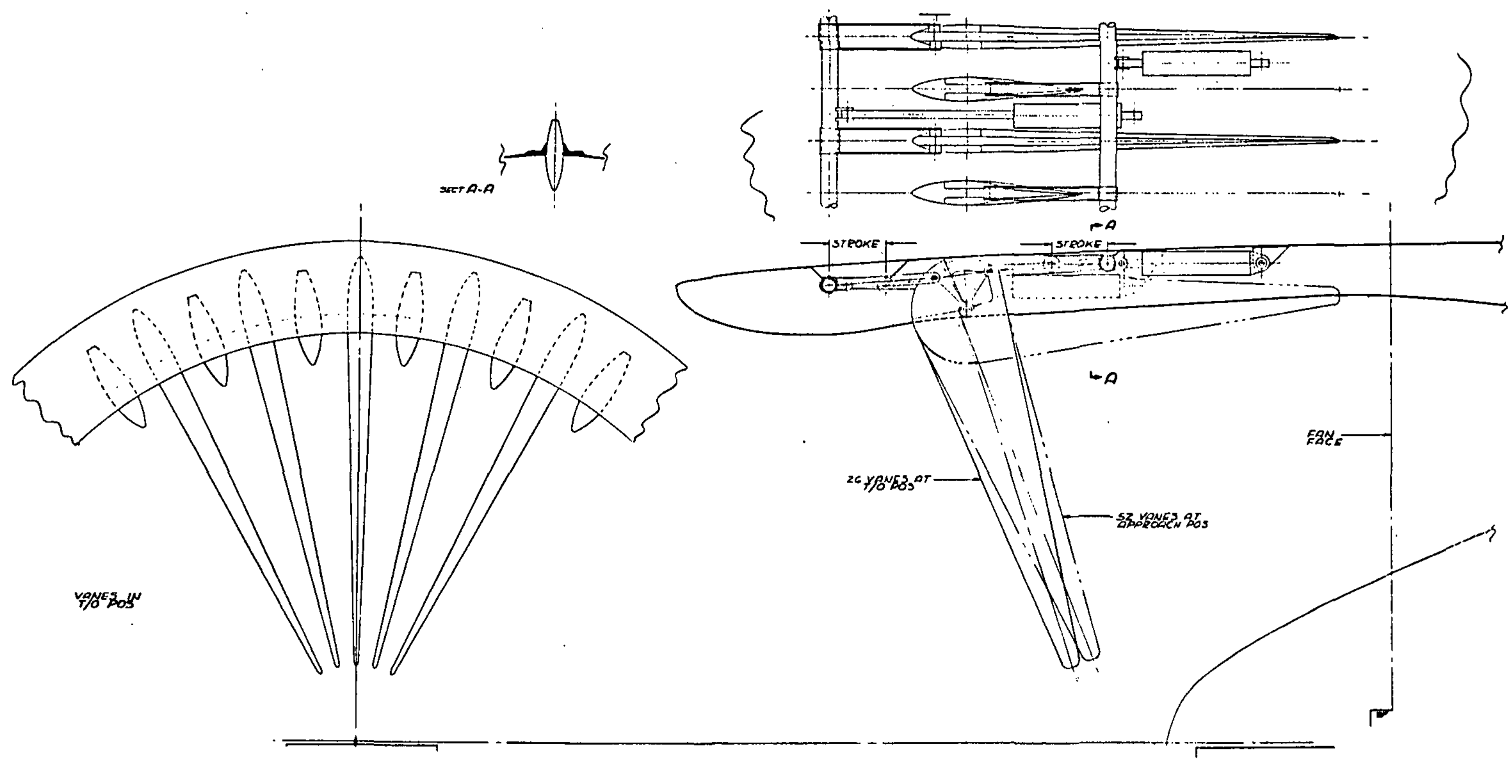


Figure 30. Retractable Vanes, Variable Blockage Inlet.

The shape of the vanes was defined to maintain stable diffusion to the trailing edge where a dump loss higher than 1/2% was permitted. The radial blockage variation was restricted to 10%, and a five inch (0.13 m) clearance was maintained between the fan rotor and the retracted vanes. An increased blockage at the OD increases the vane stability and results in a less abrupt blockage change at the ID. The estimated first flexural frequency of the vanes was maintained at 10% above 1/rev at maximum physical speed. The reduced velocity parameter, a measure of torsional stability, was limited to 1.0, thus assuring stability.

The number of vanes was chosen to satisfy both mechanical stability and aerodynamic diffusion requirements. A parametric study was performed to arrive at the optimum number of vanes. For each selected number of vanes, the thickness was defined by blockage requirements and the chord by diffusion considerations. The number of vanes was then chosen as the minimum number which is mechanically stable. Flexural stability was the limiting factor with torsional stability presenting no problem.

The initial retractable vane configuration included a centerbody supported by stationary struts to produce a more uniform radial blockage and to provide support for the vanes in the extended position. Since, however, the vanes must have the capability of remaining stable while rotating, the stability provided by the centerbody means much less than originally appears. The centerbody, therefore, was eliminated from this configuration in order to avoid the additional cruise blockage and its resulting nacelle diameter increase, to eliminate the struts and their losses at cruise, and to reduce anti-icing air requirements.

The vane chord requirement of this configuration results in an airfoil too large to stow in the preferred cowl thickness. One alternative is to completely stow the vanes and to increase the outer diameter of the cowl as much as necessary. This results in a significant drag increase. A second option is to maintain the basic cowl outer diameter at its preferred size and bubble the nacelle locally over each of the vanes. This concept results in a smaller drag increase, but produces a complicated, unattractive actuation system. The selected design requires neither increases of the cowl OD nor blisters on the outer cowl surface. The vanes retract only to their maximum thickness and the leading half remains extended into the fan flow at cruise. The seal blocking the cowl void produced by the vacated vane is envisioned as a flexible, tapered, rubber-like component capable of sealing the vane slots with the vanes in either of their extreme positions. If this configuration should prove unsatisfactory, a slip type, spring loaded, sheet metal seal activated by the vane actuation system could be considered as an alternate design.

Two actuation systems including actuators, rings, and links are required to actuate independently the two sets of airfoils. The anti-icing system would include a separate flexible line linking the air manifold to each individual vane. Air would enter the vane through the supporting pin or through a fitting inserted in the vane base.

The retractable vane configuration is a short cowl, lightweight design concept. It is easily maintained and readily permits rotor inspection and maintenance. Sealing could be a problem. Its greatest objection, however, is the presence of cantilevered airfoils, vulnerable to foreign object damage, located in the engine inlet.

VARIABLE CENTERBODY INLETS

The variable centerbody inlets consist of the translating plus and the expandable plug. Stationary struts, spaced two chord lengths ahead of the fan rotor, support the central plug and actuation system in each concept.

The translating plug configuration (Figure 31) utilizes a plug that is aft of the throat in the cruise condition and actuates forward into the throat at take-off and approach conditions. The minimum cowl thickness and the minimum plug diameter immediately ahead of the rotor were defined by mechanical considerations while the remainder of the dimensions was established by aerodynamic requirements. The large blockage of the centerbody in the cruise position forces out the cowl OD to a point where the maximum nacelle diameter is approximately six inches (0.15 m) larger than the acceptable value for the majority of the other studied concepts.

The original design investigation centered around an assembly using a central, stationary, cylindrical plug with a translating nose piece at its forward end. The design had minimum mechanical complexity even though sealing around the struts was an unsolved problem. The major stumbling block was the long inlet length required for ideal, complete diffusion. The chosen configuration shortens the diffusion length, but increases mechanical complexity. This concept utilizes several telescoping shells which are positioned by a single, long-stroke actuator.

The proposed design requires additional stability analysis. The distance between support rollers in the extended position may be too small relative to the plug diameter. Vulnerability to excessive system vibration of the entire strut-centerbody assembly is another potential problem. An increase in the chord length of the struts or the number of struts may be required to increase stability. The actuation stroke is long, and the very small unlubricated rollers may have a life problem under the velocities imposed by the long travel distance and the short actuation time.

The expandable centerbody concept (Figure 32) accomplishes the required area reduction by increasing the centerbody diameter at the inlet throat through a series of umbrella-like linkages. A series of hinged panels and lap-type seals form the centerbody flowpath. The flowpath of this concept deviates farther from the ideal than in any of the other studied configurations. The number of links, however, can be increased in order to produce a more ideal flowpath with a corresponding weight and complexity penalty. Since the circumference of the centerbody in the approach mode is approximately double the circumference in the cruise mode, the limit of lap-type seals has been reached.

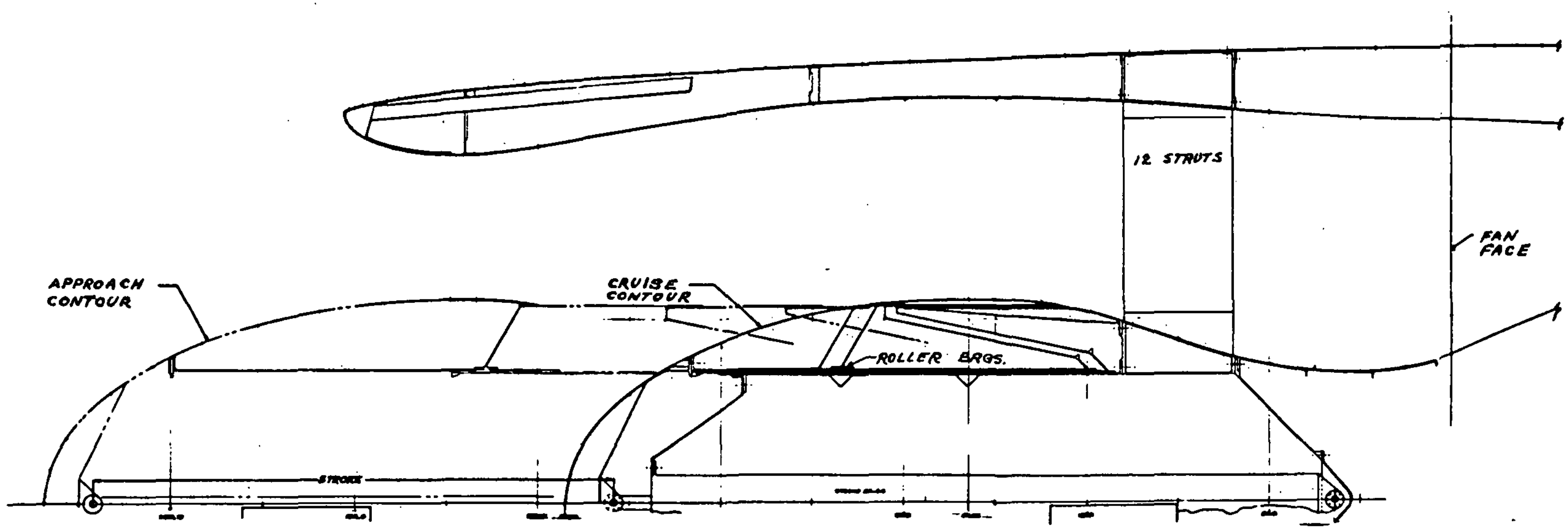


Figure 31. Translating Internal Plug, Variable Centerbody Inlet.

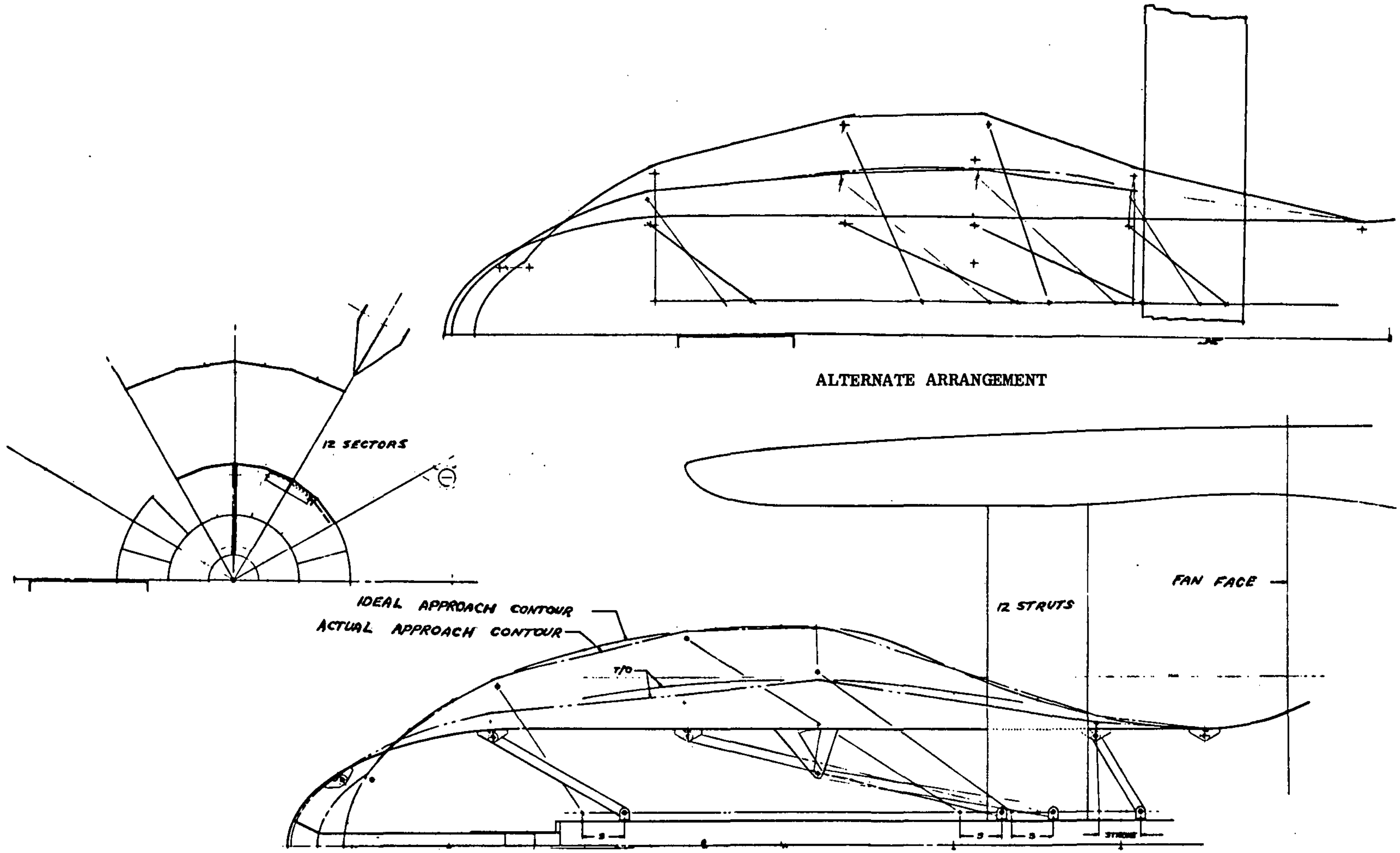


Figure 32. Expandable Centerbody Inlet.

Although there are a few attractive features of this design, such as ease of rotor inspection, there are major problems associated with it. The inlet is heavy, and the nacelle maximum diameter is four inches (0.10 m) larger than most of the other concepts studied. The mechanical complexity of the depicted assembly, without any increase in the number of links, indicate maintenance problems and short life potential.

VARIABLE COWL INLETS

The various variable cowl concepts evolved into two candidate mechanical designs, the hinged lip and the double lip.

The hinged lip (Figure 33) consists of a stationary outer component and a variable inner fairing which changes diameter to effect the required area reduction. The location of the throat in the cowl of the hinged lip does not change during actuation; i.e., the throat diameter at cruise simply decreases to the required take-off and approach values. The inlet length and diameters are established by purely aerodynamic considerations.

Three variations of the variable cowl concept were investigated before a design was chosen. Both a flipping cowl and a translating cowl were evaluated along with the chosen hinged-lip configuration. In the flipping cowl concept, the entire cowl thickness is divided into a series of panels which rotates about a hinge point at the aft end of the panel. Since the entire cowl is movable, the gust loading is transferred directly to the actuators. The size of the loads is multiplied by the fact that the large area variations force the actuation ring to be far aft in the inlet, resulting in a poor mechanical advantage linkage system. The net result of these two factors is abnormally large requirements for the actuators. Sealing between panels is another design problem of this configuration.

In the translating cowl concept, the entire cowl moves forward and inward. The required diameter change is the same as for the flipping cowl, causing the same problems and difficulties inherent in the flipping cowl concept. The additional advantage of a shorter inlet at cruise is more than offset by the stowage problem produced by the fact that the nacelle must store in the area above the rotor which will be filled with containment structure and anti-icing lines.

When the major problems of the two specified designs (flipping cowl and translating cowl) are studied, the evolution to the chosen configuration (hinged lip) is quite natural. In order to avoid transferring external gust loads to the actuation system, the outer portion of the nacelle will remain stationary and absorb the gust loads through its structure, while only the inner portion remains movable to accomplish the required area reductions.

Sealing between the panels is greatly simplified by inserting stationary, wedge-shaped bodies between the panels to fill the gap between them. In this manner, only the constant-width space between a panel and a wedge has to be sealed instead of the widely varying space between adjacent panel segments. The resulting design is very attractive from many standpoints; i.e., it is

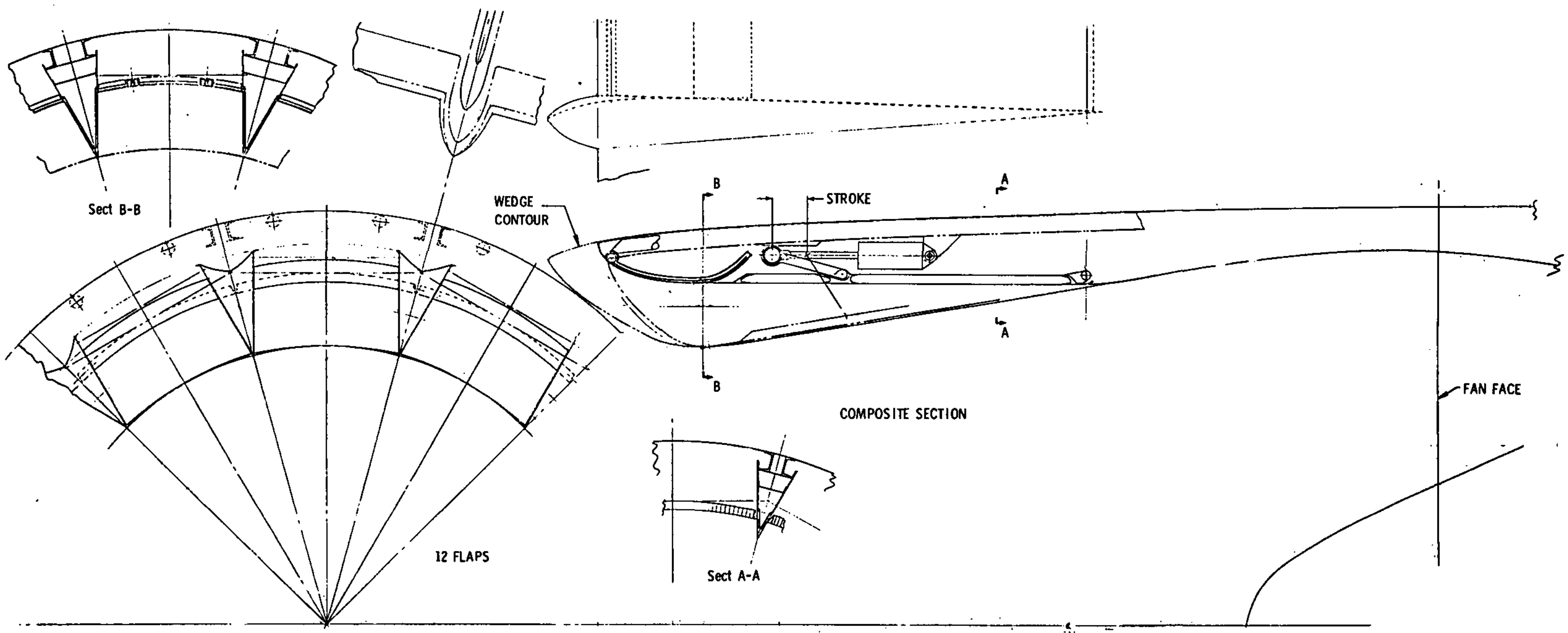


Figure 33. Hinged-Lip, Variable Cowl Inlet.

mechanically simple, lightweight, safe from FOD, and permits easy rotor inspection. One critical area in the design requiring further attention is the joint between the forward panels which lead the air into the throat, and the aft panels which diffuse the air. This joint has to be designed to minimize the necessary slots in the flowpath and the resulting step in the flowpath between forward and aft panels, to enable anti-icing air to pass, and to have good wear characteristics.

The area to be anti-iced and, therefore, the heating airflow required is small when compared to that of the other concepts. However, the hinges, as discussed above, and the forward panel section that is sometimes on the flowpath and other times inside the cowl, make it somewhat difficult to route the anti-icing air to the proper locations. An electrical system might be worth consideration as an alternate to the conventional type system.

The cavity inside the cowl will be vented to the throat since it has the lowest pressure available in the inlet. In the event of an actuation system failure, the panels will then tend to retract to the maximum flow area position. A spring will be needed to assist, however. The venting feature will reduce the size requirement of both the spring and the actuator and linkage system.

The double-lip configuration (Figure 34) includes a forward cowl, or lip, which separates the flow into two annuli for a short axial distance. The area reduction is accomplished by the aft cowl moving in some manner to reduce the outer annulus flow. The throat of the double lip configuration does not stay in the same position, as it did in the hinged lip; the throat is in the aft cowl in the cruise position, and in the forward cowl in the approach position. The aft cowl does not have to undergo as large a diameter change as that required in the hinged lip configuration. The cowl diameters and lengths of this configuration were again established by aerodynamic requirements and not by mechanical considerations.

The double lip followed much the same evolution as the hinged lip. A flipping outer cowl with its seal problems and gust load problems was investigated. The only advantage over its hinged lip counterpart was a somewhat better mechanical advantage in the linkage because of the smaller required diameter changes. A translating outer cowl still displays the same undesirable characteristics of the hinged lip translating cowl configuration; i.e., gust loads, stowage, and seal problems.

The factors influencing the mechanical design are essentially identical to those associated with the hinged lip; therefore, the design assumes a similar configuration. The inner portion of the cowl is movable with intermediate stationary wedges to provide structure and to aid sealing. In comparison with the hinged-lip configuration, the double-lip concept is a more complex assembly with no significant mechanical advantages.

The hinged-lip configuration emerges as the preferred variable throat approach based on mechanical design feasibility. No major mechanical obstacles have been identified. It is a lightweight design and has relatively

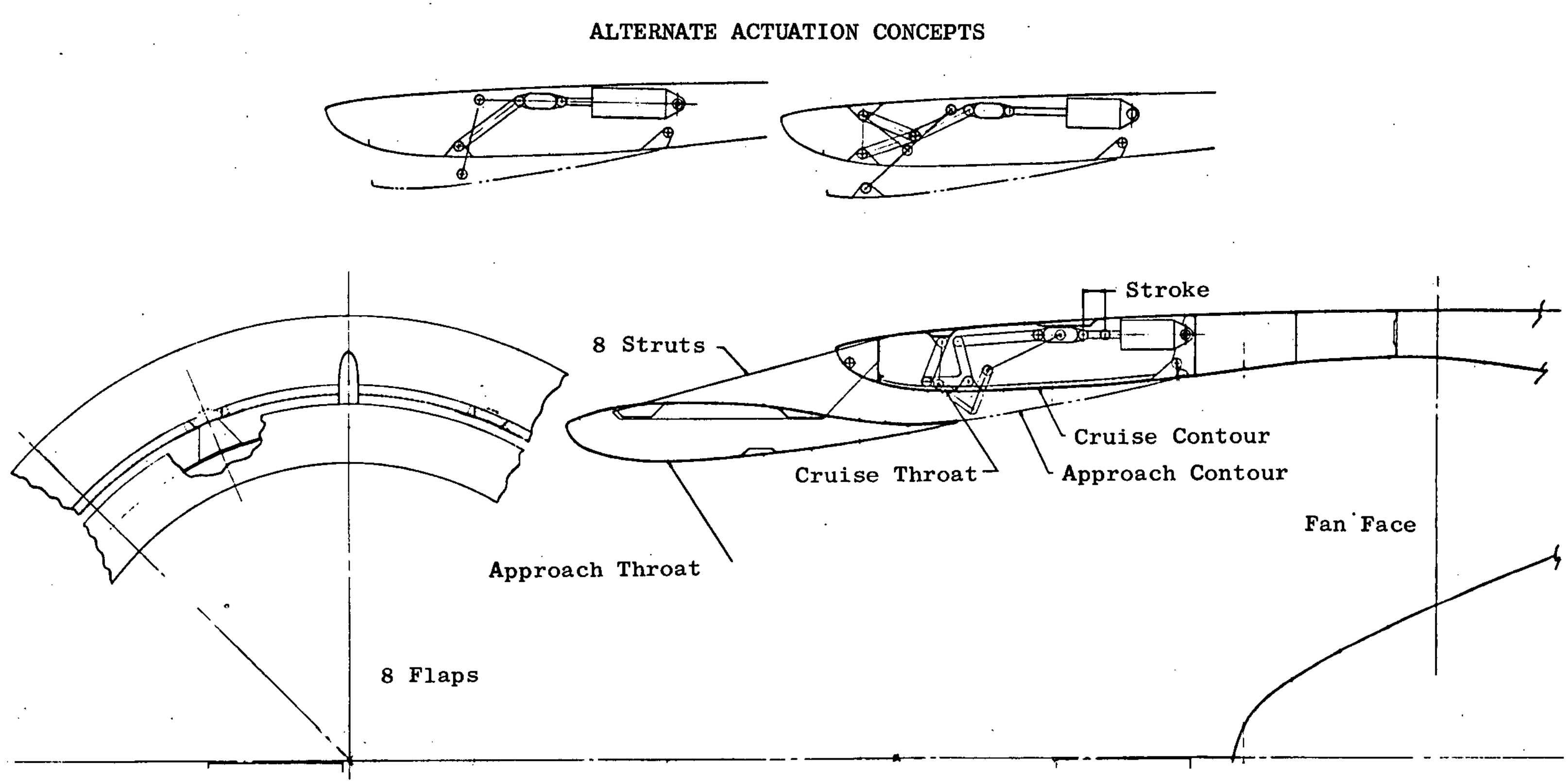


Figure 34. Double-Lip, Variable Cowl Inlet.

low risk from the foreign object damage standpoint. It affords a clean, unobstructed inlet which results in low losses at cruise and excellent access for fan inspection and maintenance.

RETRACTABLE SPLITTERS

The inlet losses associated with fixed multiple splitters are an incentive to devising a retractable splitter mechanism. In addition, such a device permits access and inspection of the fan rotor.

Several approaches to retractable systems were considered on the basis of the following factors:

1) Flowpath should be reasonably smooth when splitters are deployed or stored.

2) Splitters should be parallel to a streamline at all times; i.e., being deployed and reemployed.

3) Storage of thick acoustic splitters should be as compact as possible.

4) The design must be sturdy enough to take ice and bird strikes.

In order to minimize the space required for storage, a concentric splitter was ruled out, and splitters having the radius of curvature of the cowling were selected. This means that, when stored, the splitter thickness alone is the limiting item; and, when deployed, the splitters form a slightly polygonal shape. The design selected is shown in Figure 35. This design uses the same acoustic design as a baseline splitter case with only those modifications necessary for the retractable feature.

The splitters are split so that they form two types. The inner splitter is divided into four segments and the outer splitter into four segments of the same width. The wall suppression is also divided into segments of the same width. All of these segments are supported by four bar linkages on each side, which are kinematically the same at the forward and aft end. This permits the struts to be small and the structure to be rugged at the same time. It also keeps the panels parallel to a streamline. The remaining outer splitter segments and a wall segment of the same width form the second type of segment. Four bar linkages fore and aft and on each side are again used, and they function as for the previous type. This leaves a fixed portion of the cowl between each retractable segment. The actuation linkage, structure, anti-icing ducts, etc., are housed in the fixed-cowl portions. The constant-width retractable sectors are easy to seal. It should be noted that this approach involves more movable panels than splitters, because the wall has to move out of the way. The suppression thickness of the wall and splitters 1 and 2, plus the clearance and structure of the cowling, sets the minimum cowling thickness; the requirements of the linkage and actuation system do not control. The mechanical linkages can be designed, however, so that they are not the limiting items in space requirements.

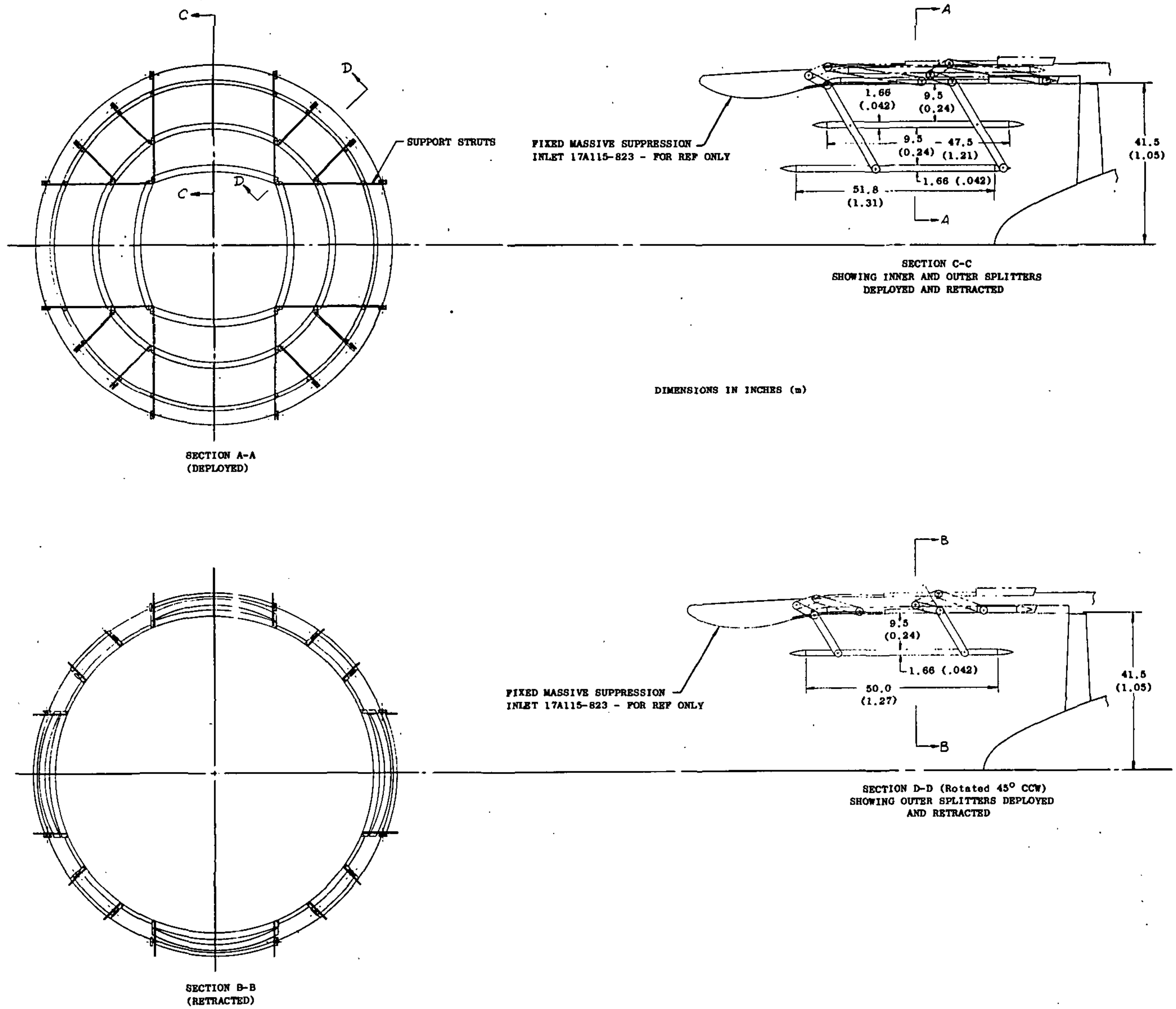


Figure 35. Retractable Splitters.

For the particular installation under study, the nacelle is quite thin, since it is designed for Mach 0.9 application. There is very little storage space in the reference design, and the nacelle maximum diameter for the retractable splitter design therefore increases from 93" to 102" (2.36 m to 2.59 m). This is the major disadvantage of the retractable splitter concept.

VARIABLE EXHAUST NOZZLE

NOZZLE SELECTION

Several approaches to the variable exhaust were considered before the low area ratio C-D nozzle illustrated in Figure 36 was selected. The translating plug design would be an excellent choice for a low area ratio requirement but becomes geometrically impractical for the magnitudes of 20% or more selected for this study. The translating cowl approach has a similar area limitation. A variable flap conical nozzle is very similar to the selected approach but requires more change in physical area to achieve a given effective area variation. The terminal fairing nozzle incorporates fixed terminal fairings to serve as the sealing surface and to house the actuators. This approach was not pursued because of performance considerations. The C-D approach was selected primarily because of its large flow capacity for a given geometry at low nozzle pressures.

NOZZLE AREA VARIATION

The nozzle operates over the range of conditions as shown in Figure 37. At cruise, the nozzle is in the closed position, with the area ratio selected to give good performance for the nozzle pressure ratio level or approximately 3.0. At takeoff, the nozzle is still relatively closed but the effective area, as indicated by the nozzle thrust coefficient (CF8) on Figure 37, is increased. At cutback, the physical area is opened somewhat more and the effective area is further increased. At approach, the physical area is increased 23% to achieve an effective area increase of 34%. Also shown in Figure 37 is the physical variation required of a plug-type nozzle to achieve the effective area variation required by the cycle.

NOZZLE MECHANICAL DESIGN

Several approaches to actuating the external nozzle segments were studied, two of which are shown in Figure 38.

One approach is to actuate each segment externally by its own linkage and actuator. To keep the actuator size down, the number of leaves and actuators should be large. This also minimizes the geometry mismatch between leaves. The actuator locations form local bumps as shown on the lower right of Figure 38. Mechanically this system is "springy" and relatively complicated.

Another approach is to use a yoke-type linkage that actuates the linkage by effectively changing the circumference. This approach has been used effectively in other nozzles. It results in a low actuator force, large travel, and low hysteresis. It does require some integration device in the control.

Considered Several Approaches:

- Translating Plug
- Translating Cowl
- Variable Flap Conical
- Terminal Fairing Nozzle
- Low-Area-Ratio C-D Nozzle

Selected Low-Area-Ratio C-D Nozzle Because of Superior Flow Capacity at Low Pressure Ratios.

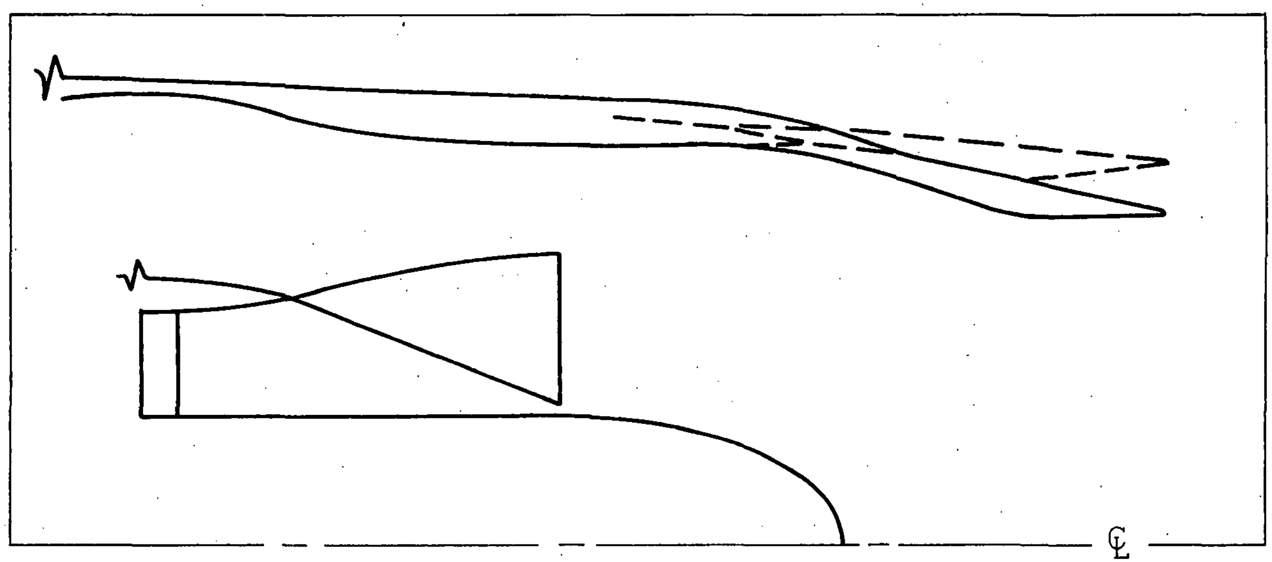
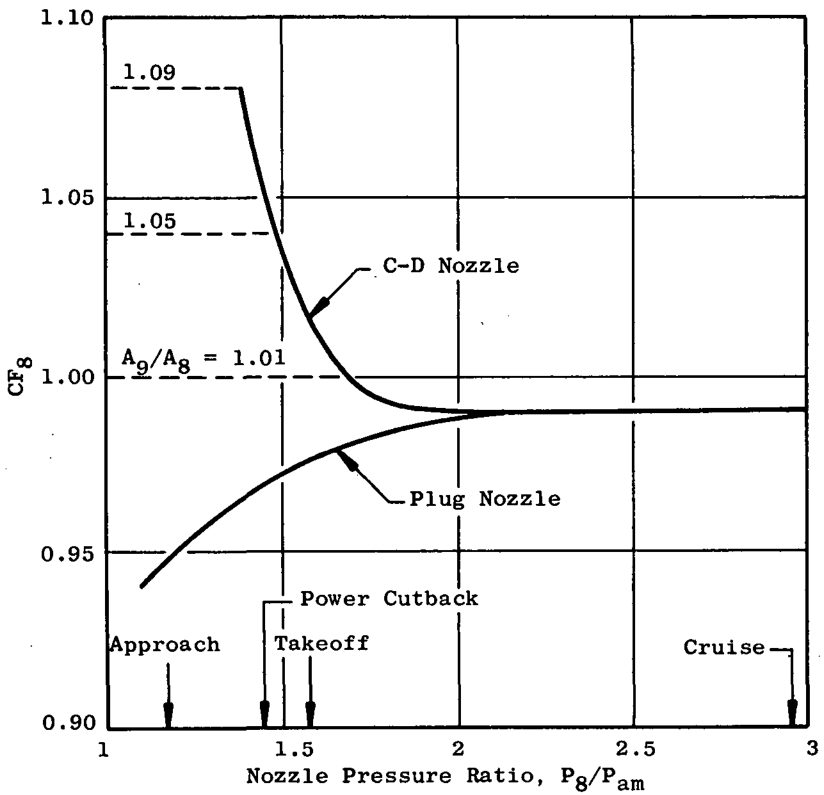


Figure 36. ATT No. 3 Variable Exhaust Nozzle Studies.



Flight Conditions	Takeoff	Power Cutback	Approach
Representative Effective Area Schedule	+8%	+22%	+34%
Nozzle Pressure Ratio	1.57	1.45	1.16
C-D Nozzle A_9/A_8 Schedule	1.01	1.05	1.09
<u>Physical Area Change</u>			
• Plug Conical Nozzle	+10%	+25%	+40%
• C-D Nozzle	+3%	+16%	+23%

Figure 37. ATT No. 3 Typical Nozzle Flow Coefficients.

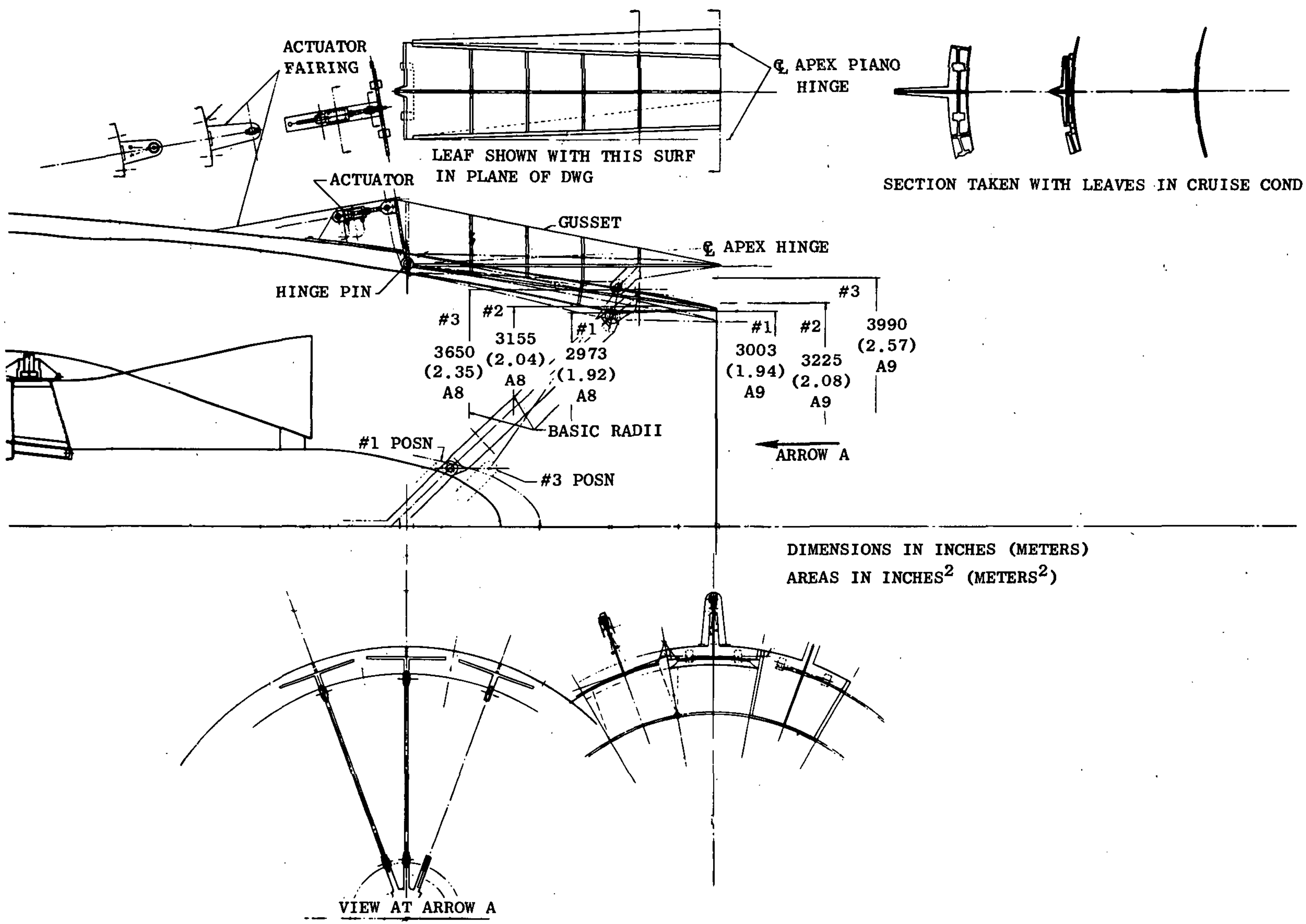


Figure 38. External Nozzle Actuation.

The same segment geometry can be used and actuated by an umbrella-type linkage which goes to a single actuator located in the tailcone as shown on the lower left of Figure 38. This eliminates any bulge for linkage at the O.D. It has lower actuator forces and does not require any unison ring or control unification. This system is positive and direct and offers no complication due to hysteresis or springback. Segment construction is lighter and simpler than the externally actuated cases. The linkage is located in the main flowpath, but the links are small and the losses low. Weight and cost for this approach are potentially lower than for other alternatives.

NOISE ESTIMATES

APPROACH

To attain noise goals of FAR 36 -15 to FAR 36 -20, extensive fan inlet suppression is required which, if obtained in the usual manner by the application of acoustic treatment, results in multiple splitters. These splitters have several features which are undesirable from both mechanical and aerodynamic view points, such as:

- Large weight increase
- Increased inlet internal loss
- Structural support and anti-icing requirements
- Reduced fan accessibility for inspection and maintenance
- Possible effect of wakes on aft noise

The purpose of this study was to define alternate inlet configurations, which will attain the same level of suppression.

Each inlet studied had suppression potential from one or more of the following:

1. Wall treatment
2. Centerbody treatment
3. Splitters
4. Increased inlet throat Mach number

To define an inlet without splitters with the same suppression level, it is necessary to trade items 3 and 4. Both inlets, with splitters and without, may utilize items 1 and 2.

When an increased inlet throat Mach number is used to obtain inlet suppression at takeoff, the throat area must be adjustable to obtain an acceptable Mach number at cruise and to maintain the increased throat Mach number at the other noise rating points (community and approach), where the thrust or engine power setting is reduced. The engine flow requirements at the take-off, community, cruise points determine the amount of area variation required. The biggest variation is required to meet the approach flow, since the approach power setting is very low. The flow differences between take-off, community (with power cutback), and cruise points are small and can be satisfied with inlets having small variable geometry capability. Thus, by not using Mach number as a suppression device at approach, the complexity of the inlet may be minimized. For these inlets it is necessary to provide sufficient wall treatment to satisfy the approach noise goals, resulting in levels that are higher than those of inlets having variable geometry at approach. To maintain the same traded level of noise, it is necessary to increase the suppression at the take-off and community points by increasing the inlet Mach number. Thus, a trade of approach noise suppression with increased inlet Mach number at the take-off and community points is possible.

Three inlets were defined to demonstrate the potential design differences discussed above:

1) Baseline inlet - 2 acoustic splitters

2) Hybrid variable geometry - variable geometry to provide high Mach number suppression at take-off and community points. Wall treatment suppression only used at approach.

3) Variable geometry - variable geometry to provide high Mach number suppression at take-off, community, and approach points.

All of the inlets were evaluated with the following assumptions:

1) Fixed fan exhaust suppression

2) Maximum inlet throat Mach number of 0.8.

3) Inlet wall treatment length equal to one fan diameter

In addition to a comparison of the inlets, the noise at approach was evaluated to determine the effect of approach power setting on the inlet design, operational procedures, and thrust spoiling.

DESIGN REQUIREMENTS

FAR 36 requirements were used as a basis for the study with an objetive of attaining FAR 36 - 15. The potential of reaching FAR 36 - 20 also was determined. Table VII shows the noise levels required to meet FAR 36 with a 300,000 lb (136078 kg) aircraft and specifies the three noise rating points. Also given is an example of trading noise levels to meet the FAR 36 level. Note that the maximum level at any of the three points cannot be more than 2 EPNL above the desired level. Thus, to attain FAR 36 - 15, the maximum level at any one point is FAR 36 - 13. Also shown in Table VII are the aircraft altitude, speed, thrust, and nozzle area at the three noise rating points.

The nozzle areas were selected after the suppressed noise levels were calculated at each point for the baseline two-splitter inlet. These results are shown in Figure 39. At the take-off sideline point, increasing the nozzle area has no effect for the unsuppressed configuration because the aft

Table VII. Noise Levels Required to Meet FAR 36 with a 300,000 lb (136078 kg) Aircraft and the Three Noise Rating Points.

FAR 36 Requirements	300000 lbs (136078 kg) Aircraft
T/O at 0.25 n mi (463 m) Sideline	106 EPNL
T/O under Flight Path at 3.5 n mi (6482 m) from Brake Release	103 EPNL
Approach under Flight Path at 1.0 n mi (1852 m) from Touchdown	106 EPNL

Traded Levels

Maximum of +2 at any Point

Maximum of +3 Total

Total Above Balanced by Levels Below

Example

	EPNL		
	Calculated	Objective	Traded
T/O Sideline	105	106	-1
T/O Community	105	103	+2
Approach	105	106	-1
			Sum 0

Noise Rating Point Conditions

	Alt.	S.L.	M	Thrust	Area (A_8)
T/O Sideline, ft	800	1500			
m	243.8	457.2	0.24	Takeoff	+10%
T/O Community, ft	1300	0			
m	396.2	0	0.24	80%	+15%
Approach, ft	370	0			
m	112.8	0	0.22	26%	Nominal

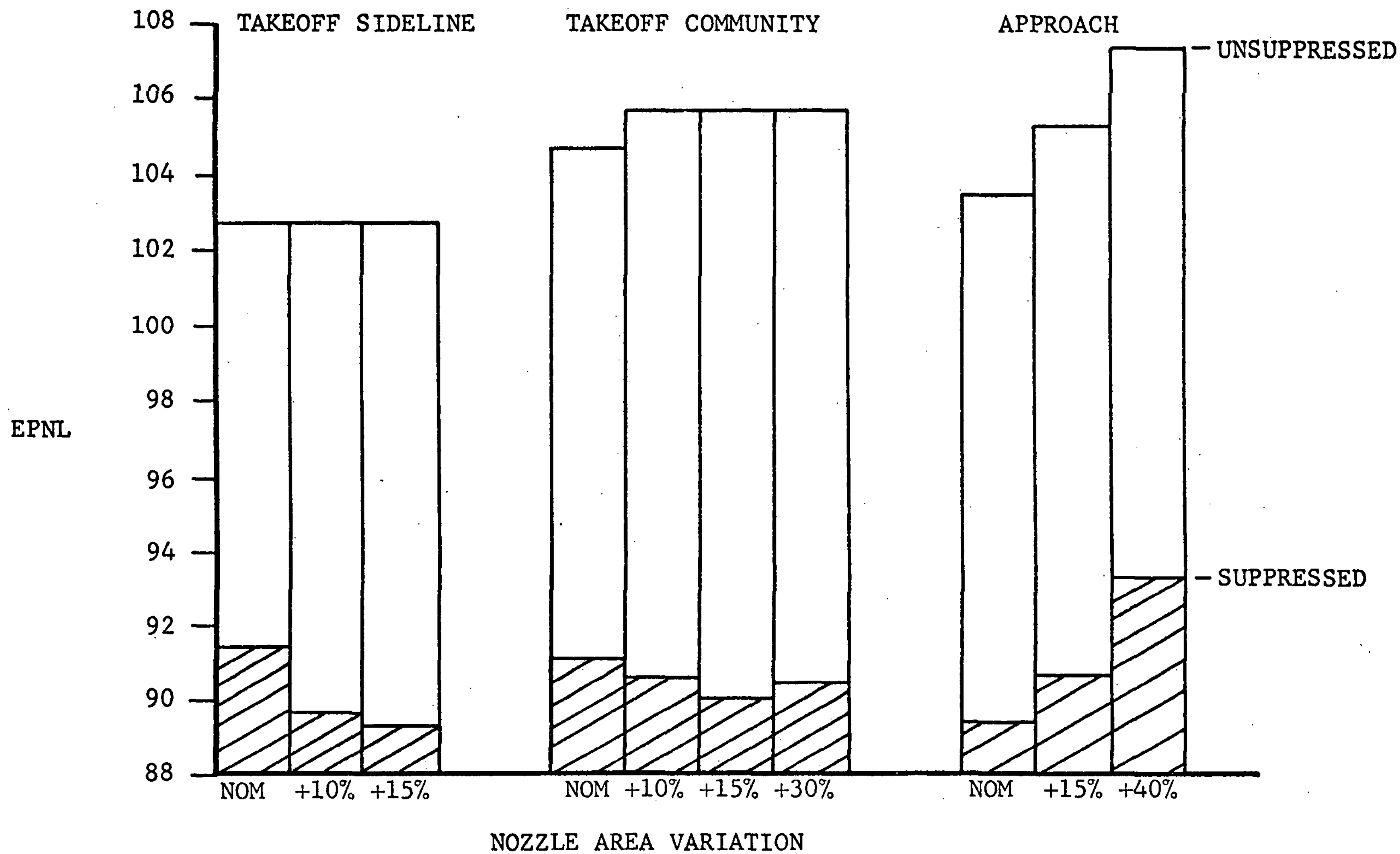


Figure 39. Effect of Nozzle Area at Rating Point (Baseline Inlet).

and forward radiated fan noise levels are dominant. With suppression, the increased area results in decreased jet noise which is now contributing significantly to the overall noise.

At the take-off community point, with power cutback, increasing area also increases fan tip speed, since the engine speed rpm must increase to maintain constant thrust. Associated with the increased tip speed is a decrease in fan pressure ratio due to the larger exit area. Thus unsuppressed, the noise initially increases and then remains constant as the fan inlet noise increases and the exhaust noise decreases. Suppressed noise has a minimum at 15% area as a result of the interaction of several noise sources: increasing inlet noise, decreasing exhaust noise, and decreasing jet noise. From the nominal to 15% area conditions, the jet noise is contributing; and, thus, the overall noise decreases due to the decreased jet velocity. Above 15% area, the jet noise is not significant and the inlet noise is becoming dominant; thus, the overall noise increases.

At approach, the effect of area is much like the community power cutback condition above 15%. The jet noise is not significant, thus increasing the area and increasing rpm results in higher fan inlet noise. The reason for the rather large effect is that the fan tip speed is in the range where multiple pure tones are varying significantly.

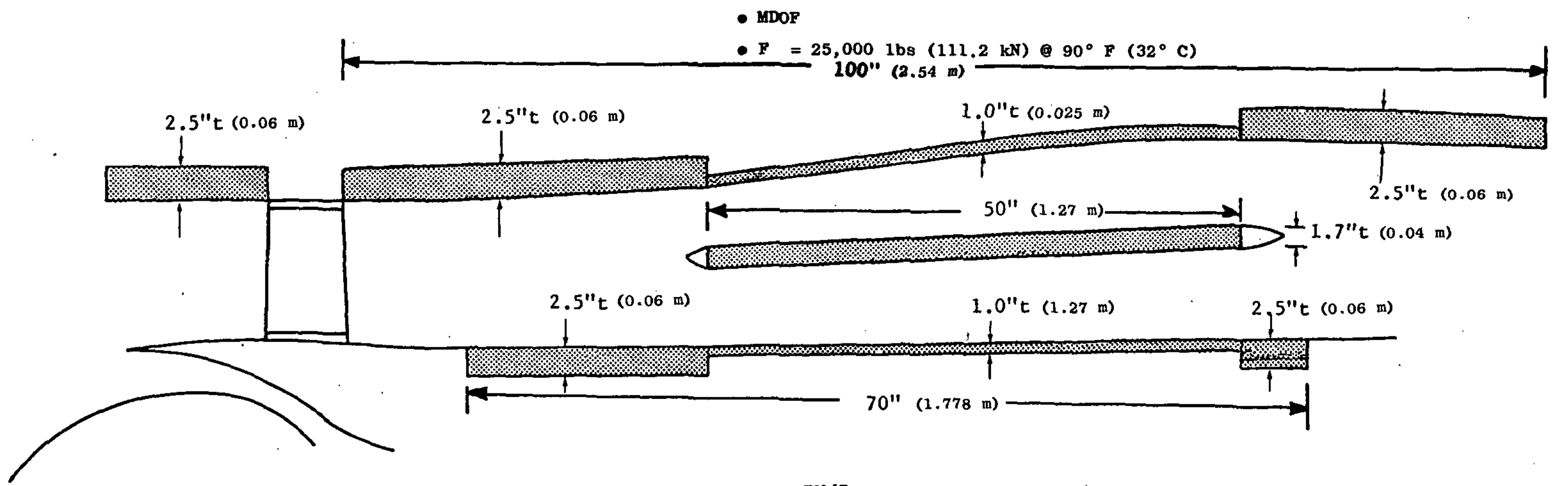
From Figure 39, the three areas of 10% at takeoff, 15% at community power cutback, and nominal at approach were selected. Note that at takeoff a larger area would be advantageous acoustically. However, engine thermodynamic limits are encountered above 10%.

SUPPRESSED INLET AND EXHAUST DESIGNS

Three basic suppression designs were defined, one exhaust and two inlets, as shown in Figures 40, 41, and 42. Figure 40 shows the exhaust treatment used for all FAR 36 -15 cases. Figure 41 represents the baseline two-splitter inlet configuration. Figure 42 represents the suppression for both the hybrid inlet without variable geometry at approach and the fully variable geometry inlet.

Exhaust suppression, Figure 40, was designed to provide both high frequency and low frequency suppression. Experience from tests of highly suppressed exhaust configurations on the TF34 and Quiet Engine Program engines has shown the need for a very broad suppression spectra which will reduce the fan-generated broadband noise. In addition to the fan broadband noise, there is low frequency broadband noise generated by the acoustic splitters; thus, thick wall treatment is shown aft of the splitter to reduce this type of noise. Estimates of the suppression due to the configurations are shown on Figure 40 as 14 to 16 PNL. The variation in suppression is a result of the changing source noise spectrum and the relative contribution of puretone and broadband noise to the unsuppressed PNL levels.

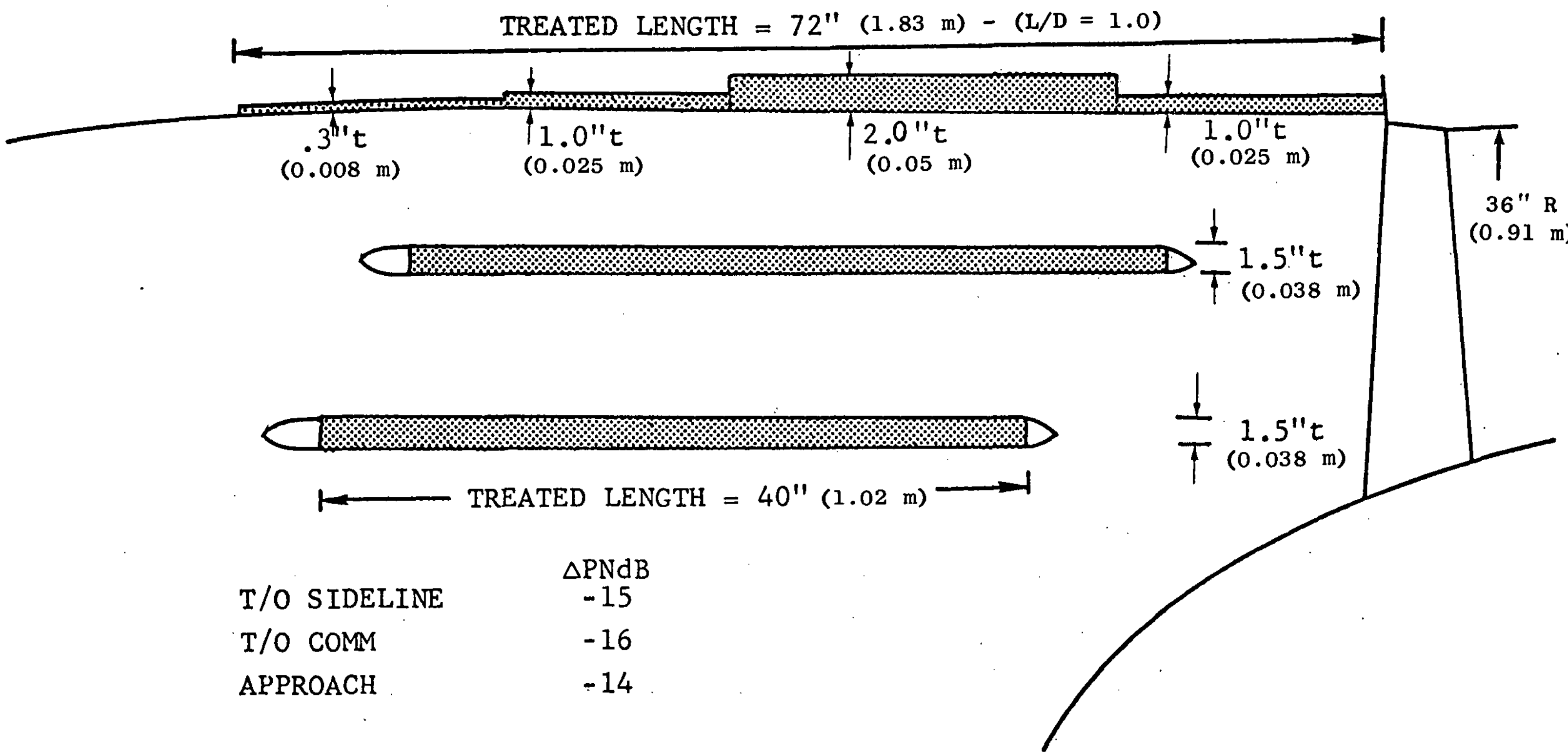
Treatment design for the baseline inlet, Figure 41, was based on results of tests on the TF34 and Quiet Engine Program engines. A combination of thick



	ΔPNdB
Takeoff Sideline	-14
Takeoff Community	-16
Approach	-15.5

Figure 40. Baseline Exhaust Treatment.

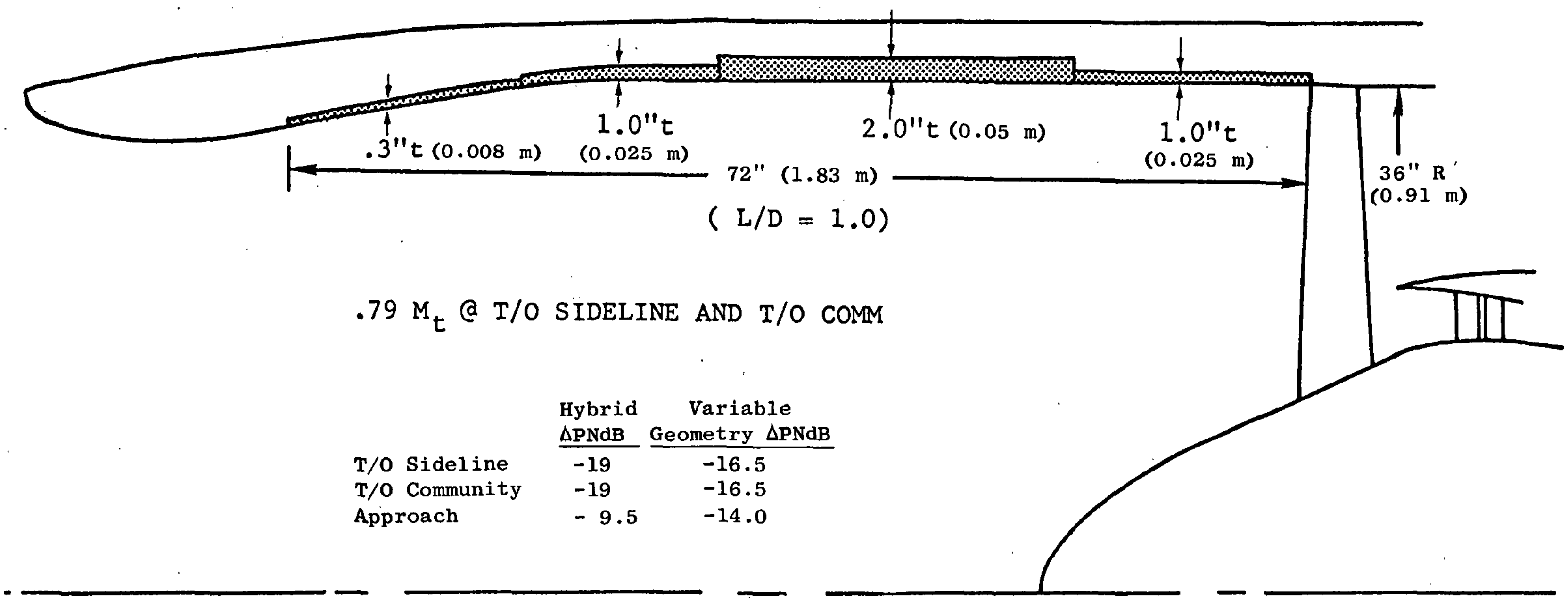
- MDOF
- F_N = 25,000 lbs (111.2 kN) @ 90°F (32°C)



	ΔPNdB
T/O SIDELINE	-15
T/O COMM	-16
APPROACH	-14

Figure 41. Baseline Inlet Acoustic Design.

- MDOF
- F_N = 25,000 lbs (111.2 kN) @ 90°F (32°C)



.79 M_t @ T/O SIDELINE AND T/O COMM

	Hybrid ΔPNdB	Variable Geometry ΔPNdB
T/O Sideline	-19	-16.5
T/O Community	-19	-16.5
Approach	- 9.5	-14.0

Figure 42. Variable Geometry Inlet Acoustic Design.

and thin treatment is utilized, as in the exhaust duct, to provide broadband suppression. The thinner treatment is designed to suppress the relatively high frequency noise from the fan, while the thick treatment is designed to suppress low frequency broadband noise. The thick treatment is also very effective in reducing multiple puretone noise wiich is associated with high fan tip speeds at takeoff. Two splitters were selected on the basis of the fan annulus height, so that the proper ratio of passage height between splitters to design frequency wave length (H/λ) is maintained.

For the variable geometry inlets, Figure 42, the same inlet wall treatment was used as that of the baseline inlet, but the splitters were removed. For the hybrid inlet, this results in reduced suppression at approach. In order to still meet FAR 36 -15 with the higher approach noise, the suppression levels at takeoff and community are increased. The suppression at these two points is accomplished by removing the splitters and increasing the inlet throat Mach number. For the variable geometry inlets, the suppression is held constant at all three points by replacing the splitter suppression with increased throat Mach number suppression. Suppression for the hybrid inlet is lower at approach than takeoff and community since there is no Mach number benefit at that point.

CONSTITUENT NOISE LEVELS

A detailed summary of the individual noise constituents is given in Table VIII. Both the baseline and hybrid inlets will meet FAR 36 -15 on a traded basis, which is a reduction of 15.7 EPNL from the unsuppressed configuration.

At the take-off sideline, the suppressed configurations have reached the point where fan noise suppression is becoming ineffective due to the presence of the jet noise. This is particularly true in the aft quadrant where the jet noise is higher than the fan exhaust noise. Core noise, which includes both low frequency broadband noise from the combustor and turbine as well as high frequency turbine machinery noise, would also be a dominant source if it were not suppressed 10 PNL. Although the core noise and its suppression were not considered in detail, its impact on the overall noise must be noted and considerable design effort will be required to incorporate a 10 PNL suppressor in the core exhaust system.

At takeoff community, with power cutback to 80% thrust, the jet noise is not as significant in either the forward or aft quadrants; however, it is still contributing 0.5 to 3 PNL to the overall noise. The baseline inlet, which is not as suppressed as the hybrid inlet, has slightly less contribution due to jet noise in the forward quadrant. For this rating point, the forward and aft noises are balanced, due primarily to the reduction in aft noise with power cutback and lower jet noise. The take-off community point has the limiting noise level relative to FAR 36 -15 for both inlet designs. It has the maximum allowable traded level, FAR 36 -13, for the baseline inlet.

Table VIII. ATT Constituent Noise Levels.

- 3 Engines
- 25,000 lbs Thrust (111.2 kN)

Constituent	Forward PNL				Aft PNL				EPNL	ΔFAR 36, EPNdB
	Fan	Jet	Core	Total	Fan	Jet	Core	Total		
Takeoff, Sideline (0.25 nautical miles/463 m & 800 ft/244 m altitude)										
Unsuppressed	102.1	80.5	82	102.2	99.3	86.5	88	100.2	102.6	-3.4
Baseline Inlet	87.1	80.5	72	88.6	85.3	86.5	78	89.3	89.8	-16.2
Hybrid VG Inlet	83.1	80.5	72	85.8	85.3	86.5	78	89.3	89.1	-16.9
Takeoff, Community (1300 ft/396 m)										
Unsuppressed	106.2	78.6	83.6	106.3	102.2	84.6	89.2	102.8	105.7	+2.7
Baseline Inlet	90.2	78.6	73.6	90.8	86.2	84.6	79.2	89.5	90.0	-13.0
Hybrid VG Inlet	87.2	78.6	73.6	88.4	86.2	84.6	79.2	89.5	88.9	-14.1
Approach (370 ft/113 m)										
Unsuppressed	106.3	68.7	85.8	106.3	109.3	74.7	91.8	109.3	103.9	-2.1
Baseline Inlet	92.3	68.7	75.8	92.3	93.8	74.7	81.8	94.5	89.3	-16.7
Hybrid VG Inlet	96.8	68.7	75.8	96.8	93.8	74.7	81.8	94.5	91.8	-14.7
Traded Noise Level, EPNdB										
Unsuppressed, FAR	+0.7									
Baseline, "	-15									
Hybrid VG, "	-15									

Noise levels at approach are dominated by the inlet- and exhaust-radiated fan noise since the jet noise is quite low at the approach power setting of 26% thrust. Although the fan noise is dominant, it is interesting that the core noise is louder than the jet noise even with 10 PNL core suppression. Fan exhaust noise is dominant for the baseline inlet since the inlet treatment with two splitters is quite effective. The hybrid configuration, however, is dominated by inlet-radiated noise since the Mach number suppression is lost and only wall treatment is effective.

EFFECT OF INLET DESIGN ON OVERALL EPNL LEVEL

At each of the three noise rating points (takeoff, community, and approach), inlet suppression will result in overall noise reduction until a floor from other sources is reached. Beyond this point, the increase in inlet suppression is ineffective with little or no payoff in overall noise reduction. This effect is shown in Figure 43 at each of the rating points using the baseline exhaust suppression. There are two sets of critical noise levels on Figure 43: (1) the levels of 93 and 91 EPNL at takeoff and approach, which are the maximum allowable levels to meet FAR 36 -15 traded and FAR 36 -15; and (2), the levels of 90 and 88 EPNL at community which are the maximum allowable levels to meet FAR 36 -15 traded and FAR 36 -15. Thus, the minimum suppression at any rating point is equal to that required to meet the corresponding maximum allowable noise level. On a traded basis, only one rating point may be at the maximum, and the other two points must be a corresponding amount below the required level.

For the baseline inlet, shown by the square symbols on Figure 43, the community point is the highest noise level; thus, suppression is provided to meet the maximum allowable level of 90 EPNL at this point. This occurs at an inlet suppression level of 16 PNL. Thus, treatment then is sufficient to keep the noise levels at takeoff and approach below the FAR 36 -15 point of 91 EPNL. The net result is a traded level of FAR 36 -15.

When the design is modified to a hybrid configuration, there is a change in the inlet suppression at each of the three rating points. This is shown on Figure 43 by the triangular symbols. At approach the inlet suppression is less but still sufficient to keep the noise level below the maximum allowable level of 93 EPNL. To compensate for the increased noise, the take-off and community levels are reduced by increasing the suppression. At these high suppression levels, the other noise sources make it necessary to put in 3 additional PNL inlet suppression while obtaining a decrease of only 2 EPNL on an overall basis when compared to the baseline inlet.

From these two examples of inlet design change, it can be seen that there is little flexibility in the suppression requirements at the level of FAR 36 -15. The overall levels are fluctuating only +3 and -1 EPNL, with inlet suppression requirements falling in the 16 to 20 PNL range. The least flexibility exists for the community point, since it is the loudest rating point level and has the lowest required noise level. The effect of approach noise is also evident from Table VIII which is critical to the application of approach power setting changes and/or operational procedures.

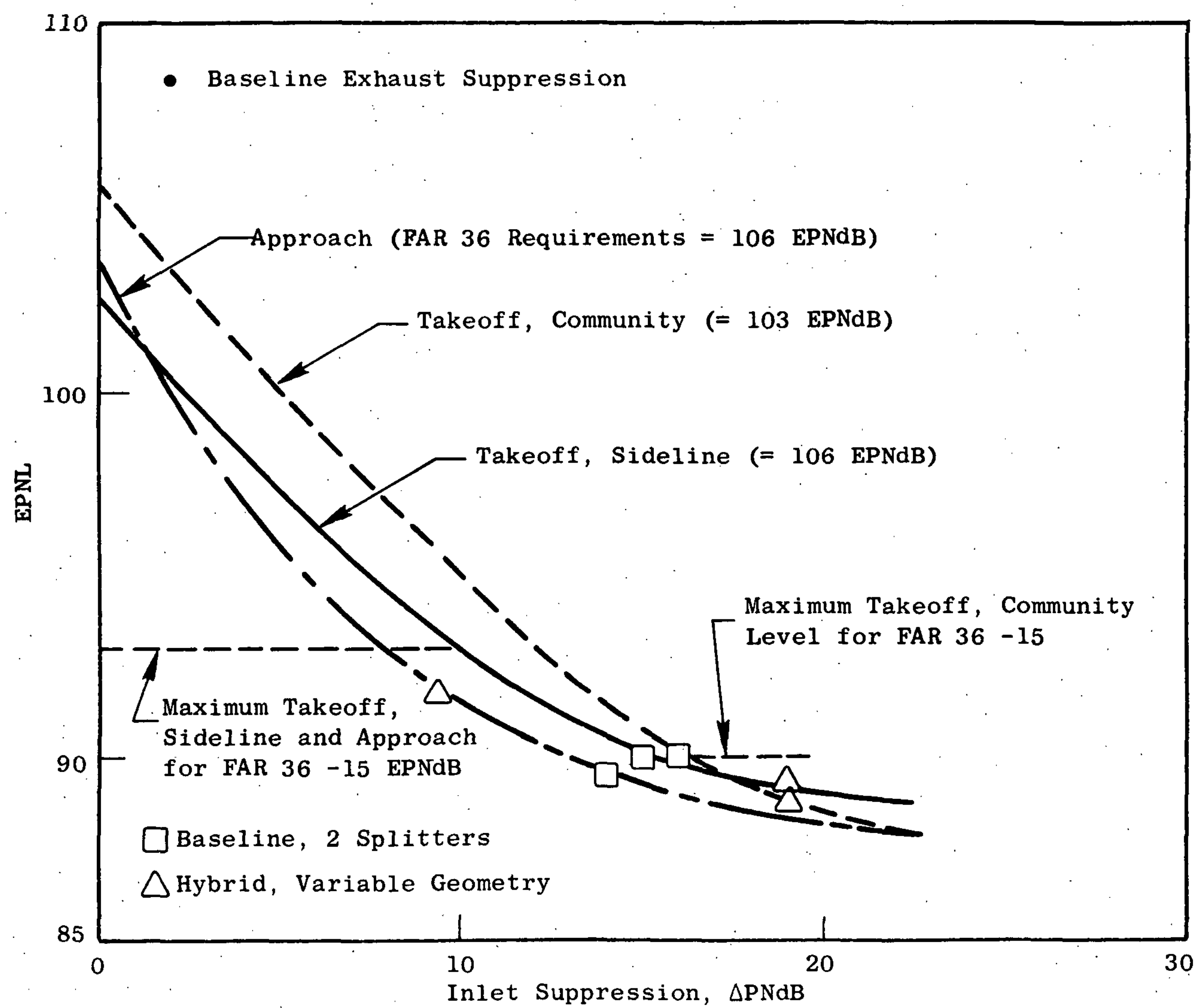


Figure 43. Variation in FAR Rating Point Noise with Inlet Suppression.

Figure 44 presents the effect of using high inlet Mach number as a means of obtaining inlet suppression. The ordinate is the traded noise level relative to FAR 36, and the abscissa is the suppression obtained from high inlet Mach number. Suppression for an inlet wall treatment length equal to one fan diameter is also applied in addition to the Mach number suppression. A second scale is given on the abscissa to indicate the level of Mach number required to obtain the indicated suppression. For the variable geometry inlets, the inlet Mach number is assumed to be equal at all three rating points; and, for the hybrid inlets, the Mach number is assumed equal at takeoff and community, but no suppression is taken at approach beyond that obtained from the wall treatment.

The baseline inlet, which has no suppression due to high Mach number and meets FAR 36 -15, is shown on the extreme left of Figure 44. This design was then altered, as shown previously on Figure 43, by letting the approach noise increase and further reducing the take-off and community noise levels. To achieve this level of suppression, an inlet Mach number of 0.79 is required at takeoff and community as indicated by the triangle on Figure 44. If a variable geometry inlet is utilized with high Mach suppression at approach, then (remembering Figure 43) the required noise suppression at takeoff and community is reduced and the Mach number is reduced. This is indicated on Figure 44 at 0.72 Mach number. This is the inlet Mach number required at all three of the rating points. The system benefit, therefore, for a fully variable inlet is 0.72 inlet throat Mach number instead of 0.79 for constant noise of FAR 36 -15.

The variable geometry inlet also was used to determine the effect of increasing suppression at each of the three rating points. This is shown by the two lines on Figure 44. As the inlet Mach number and suppression increase, the benefit relative to FAR 36 becomes quite small since other noise sources are becoming dominant. Initially, the fan exhaust noise is critical and, if suppressed an additional 5 PNL, would result in a traded noise level decrease of approximately 2 EPNL. This additional 5 PNL increase in aft suppression would represent a difficult acoustic design problem. With core noise and jet noise becoming increasingly significant, and fan exhaust noise requiring major increases in suppression, this study indicates a level of FAR 36 -18 to be the minimum recommended goal for the cycle selected in this study.

Although the FAR 36 criterion is of prime importance at the present time, the effect of inlet design on an exposure or noise footprint basis is also of interest. Figure 45 shows the 90 EPNL contours for the baseline and hybrid inlet designs. Relative to the unsuppressed configuration, both inlets result in a significant reduction in exposure area. A reduction of approximately 90% is attained in both cases. The hybrid design has a slightly lower exposure even though the approach noise is higher by 6 PNL. The small reduction in take-off and community noise more than compensates for the increase at approach on an acreage basis. This is discussed further in a later section.

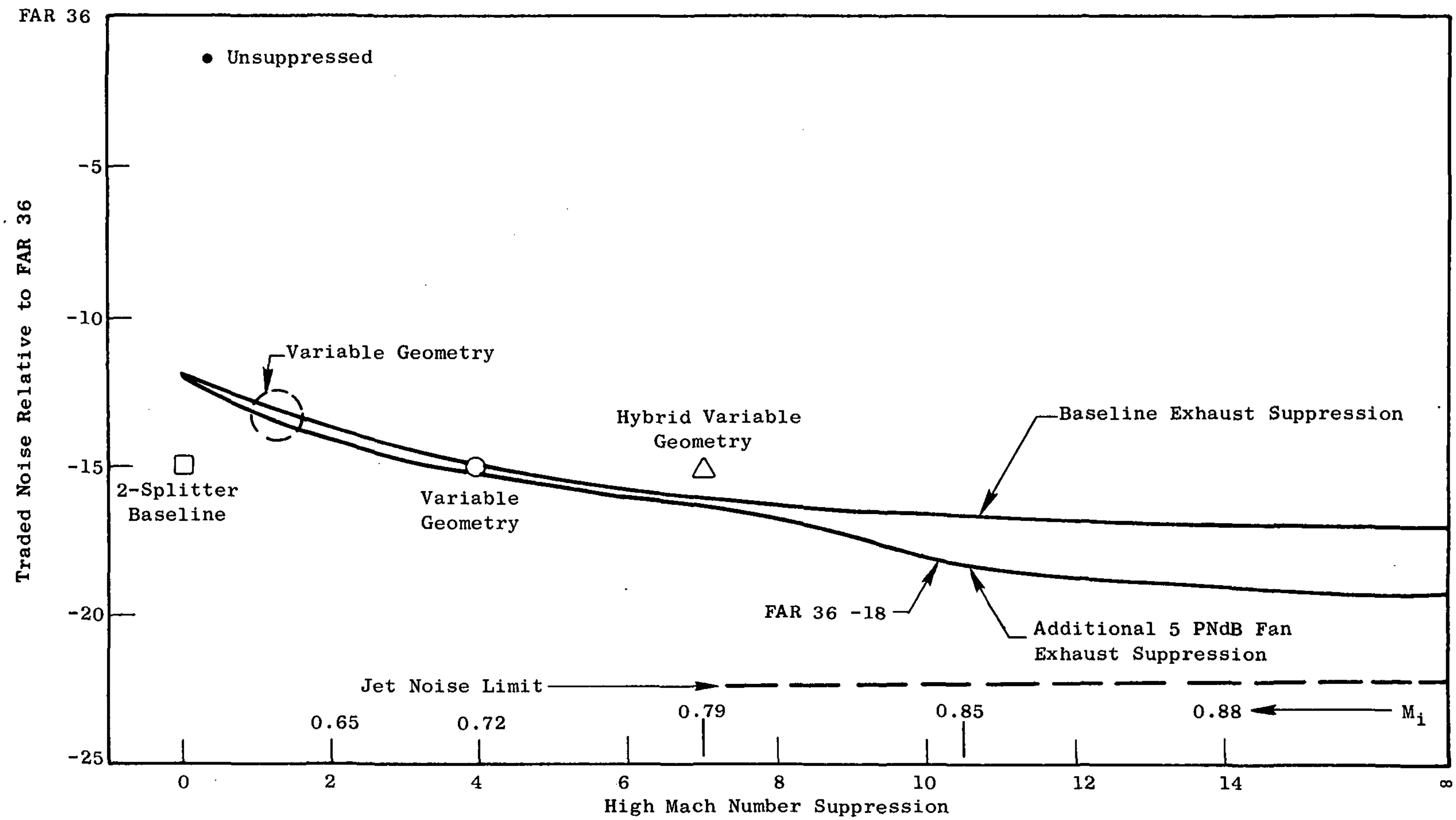


Figure 44. Effect of Inlet Mach Number on FAR Objectives.

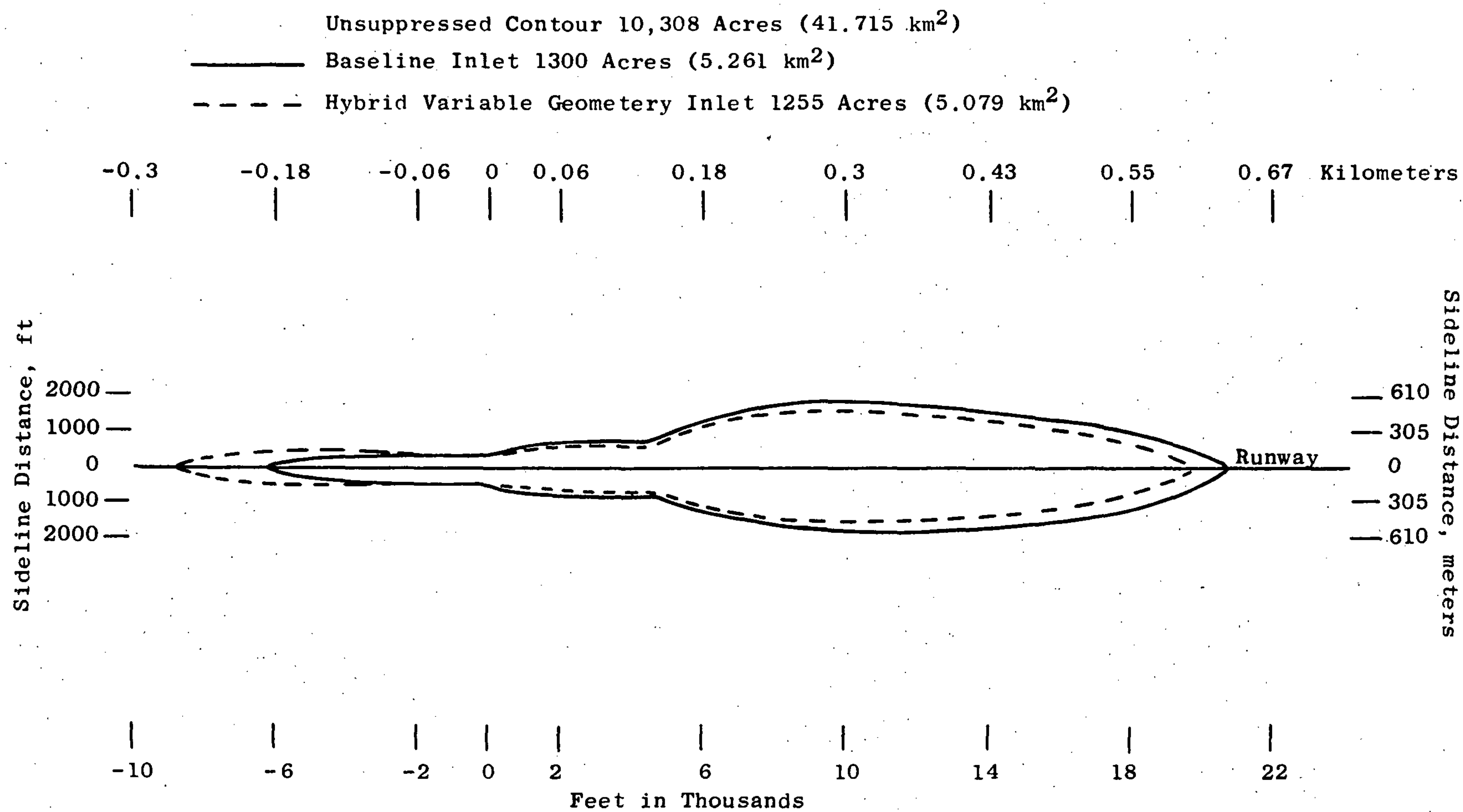


Figure 45. Effect of Inlet Design on 90 EPNL Contours.

EFFECT OF OPERATIONAL PROCEDURES AT APPROACH

At approach, there are available several aircraft operational procedures that have an effect on the noise rating point level. These variations will affect the noise levels or exposure area to a different degree for different inlet designs. To determine these effects, various inlet configurations were evaluated with the following:

1) Variation in approach power setting

2) Change in aircraft approach glide slope

3) Use of thrust spoilers

The change in approach EPNL with engine power setting is shown in Figure 46 for both the hybrid and baseline inlet configurations. Noise levels presented previously had assumed an approach power setting of 26% take-off thrust as shown in Figure 46. For lower power settings, the approach noise will decrease for the hybrid and baseline inlets since the only suppression mechanism assumed is treatment suppression. The FAR 36 levels will not change appreciably, since the other noise levels (take-off and community) will become limiting. As power setting increases, there is a limit of 93 EPNL which cannot be exceeded if the total system is to meet FAR 36 -15. The baseline inlet may increase to 37% take-off thrust with the same suppression, while the hybrid inlet can only increase to 30%. Also shown in Figure 46 is the effect of combining added treatment with increasing thrust. Comparison of the 15 PNL and 20 PNL suppression lines shows the very small effectiveness of increased inlet suppression. Thus, increasing thrust at constant noise would require extensive additional treatment for small increases in thrust.

If a variable geometry inlet is used at approach, changes in power setting will result in changes in airflow, inlet throat Mach number, and corresponding suppression. Figure 47 shows the effect of changing approach thrust for this type of inlet. The design point thrust was set at 26% for two inlet Mach number designs, 0.72 and 0.85. Also shown is the hybrid inlet which has the same acoustic treatment as the other inlets. As thrust decreases, the noise of the variable geometry inlets begins to approach that of the hybrid inlets since all of them are providing only suppression from acoustic treatment. Thus, the advantage of the variable geometry is lost. At higher power settings the two variable geometry inlets reach a suppression level of -20 PNL which represents the point at which additional suppression is not effective. This results in an overall approach noise increase, even though the inlet suppression is increasing.

Thrust spoiling may also be used at approach as a means of keeping increased engine speed for quick response while holding the approach thrust at a low level. Figure 48 shows the approach noise levels for the baseline and hybrid inlets at an engine power setting of 50% with thrust spoiled to a net value of 26%, as compared to an equal approach net thrust without thrust spoiling. Both inlets with thrust spoiling exceed the maximum allowable EPNL value of 93.

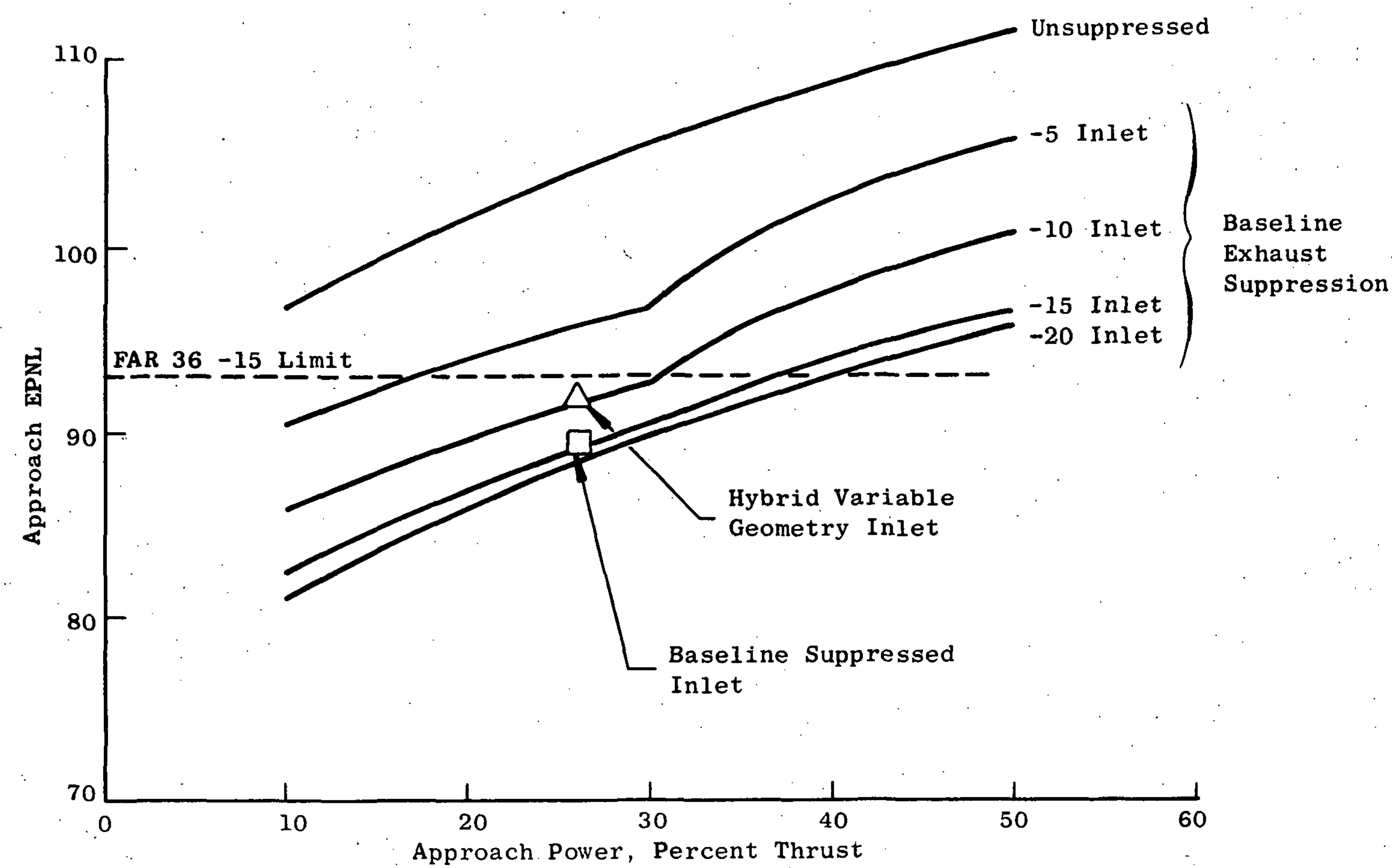


Figure 46. Effect of Thrust on Approach Noise.

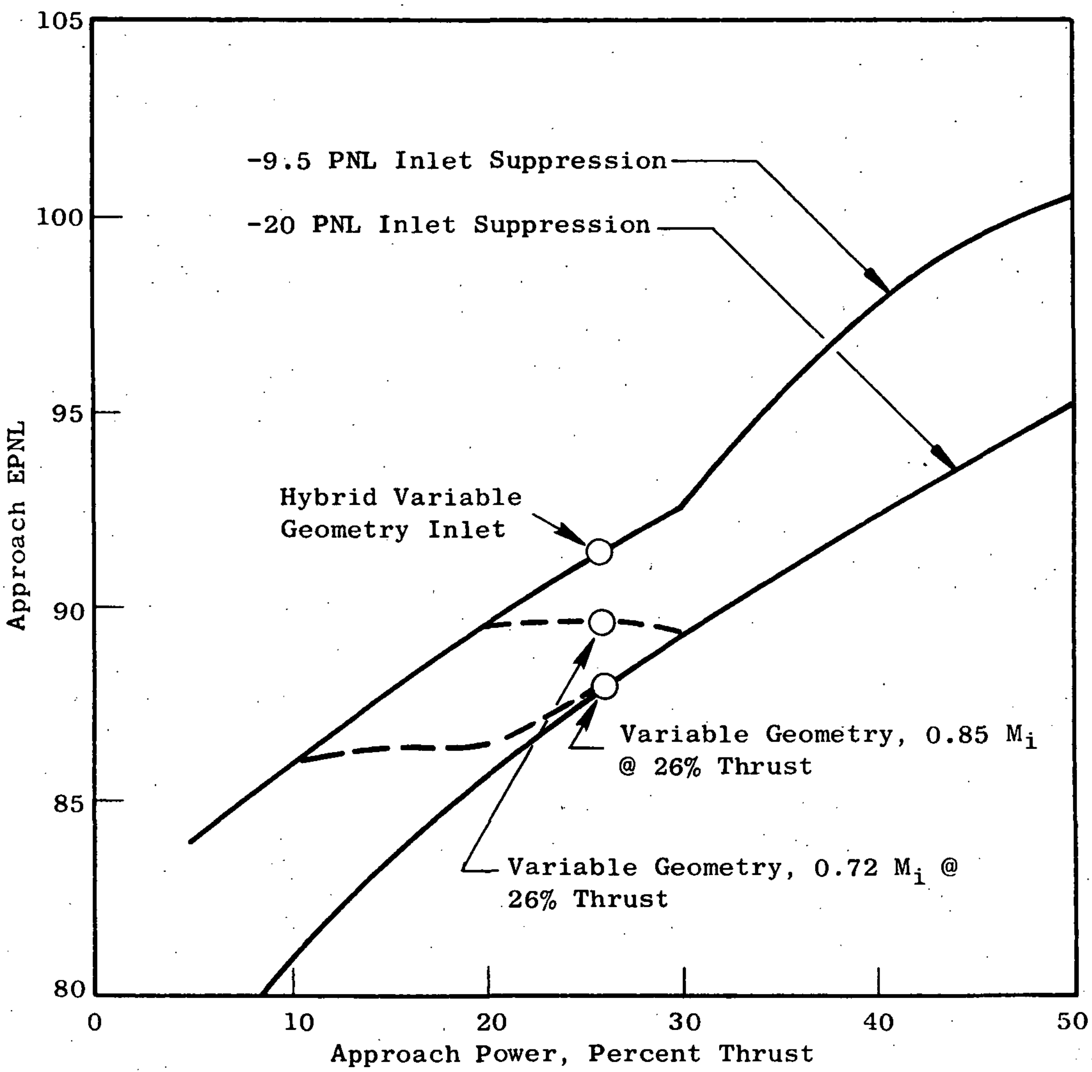


Figure 47. Effect of Approach Power Setting for Different Inlet Designs.

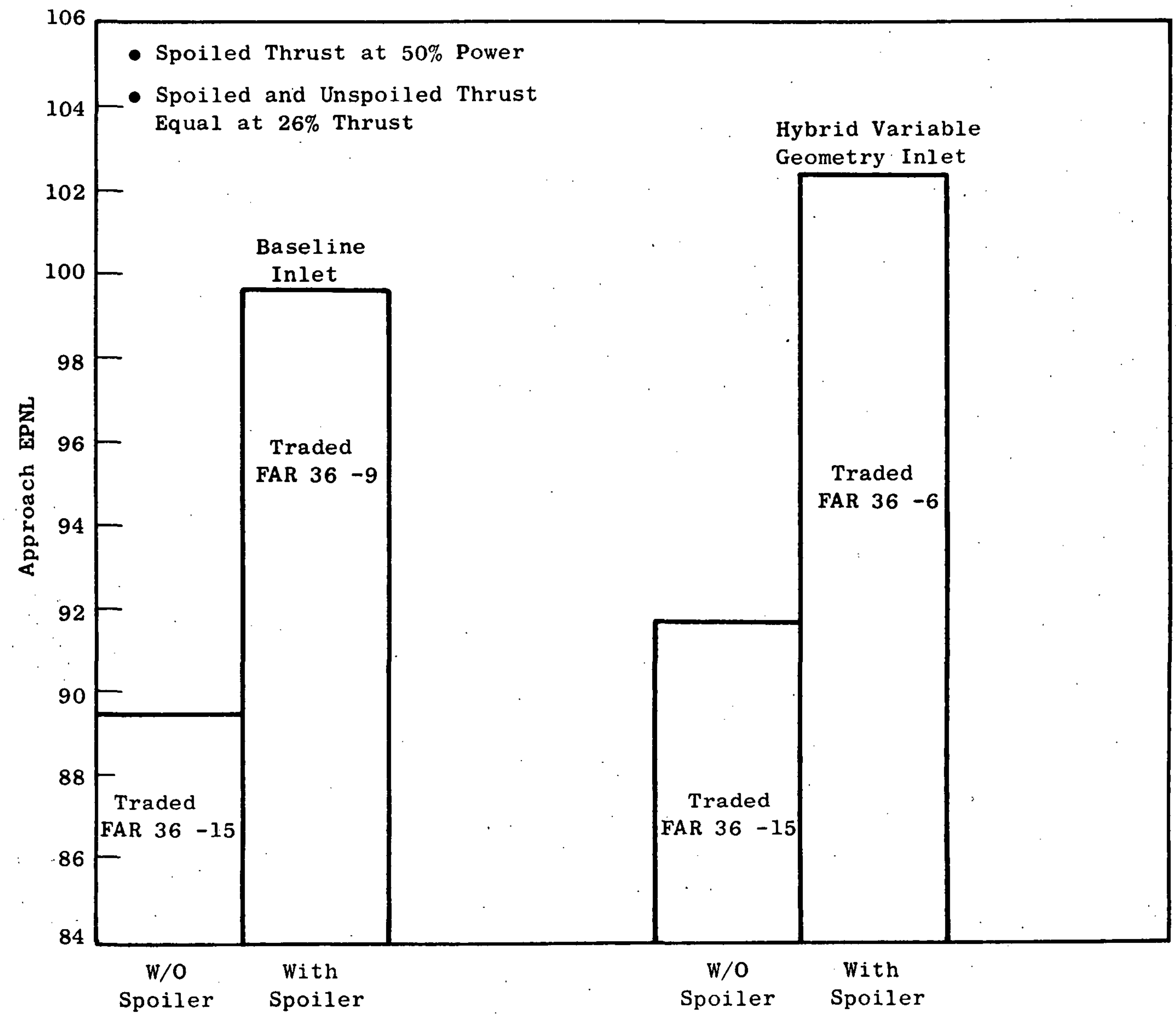


Figure 48. Effect of Thrust Spoiling on Approach Noise.

The change relative to FAR 36 would be from FAR 36 -15 to FAR 36 -9 for the baseline inlet and from FAR 36 -15 to FAR 36 -6 for the hybrid inlet. Both the jet and spoiler noise sources are contributing to the overall level, since the jet noise alone increases approximately 21 PNL. The fan inlet and fan exhaust noises, however, are of equal value to the jet noise since the engine tip speed and pressure ratio have increased in accordance with the engine power setting change from 26% thrust to 50% thrust.

In addition to the FAR approach rating point noise level, community exposure may be affected by aircraft approach operating procedures. Two methods which may be used to evaluate exposure area are:

1) Maintain constant total exposure area but balance the take-off and approach contributions.

2) Decrease the approach area by varying thrust and approach glide-path angle.

The potential change in approach noise with the first method is demonstrated in Figure 49. Approach exposure area is approximately 1/12 of the take-off area for an exposure level of 90 EPNL and a noise level at approach and takeoff of 90 EPNL. This large difference is due to the approach noise being evaluated with an aircraft altitude of only 370 feet (113 m), as compared to a take-off community altitude of 1300 feet (396 m). Since both points have the same noise criteria on the ground, the approach source noise must be lower to compensate for being closer. By decreasing the noise at takeoff, a decrease in area is obtained which, if balanced by a corresponding increase in area at approach, would allow an appreciable change in approach noise. This increased approach noise could be used to allow higher approach power settings or to decrease the suppression requirements. The latter benefit is shown in Figure 50. This curve shows the increase in approach noise versus the decrease in take-off noise which holds the 90 EPNL area constant. Small changes in take-off noise allow large increases in approach noise. For the hybrid inlet, which was designed with a 0.79 inlet Mach number at takeoff and a treated length of one fan diameter (L/D = 1.0), the inlet length was decreased 23% to L/D = 0.77 as a result of the higher approach noise and corresponding lower suppression. To attain the decreased take-off noise, the inlet Mach number must be increased from 0.79 to 0.85. Although the FAR 36 -15 level is not met due to the higher approach noise levels, the total exposure area is constant and there has been a significant decrease in inlet length which may result overall in an improved system.

The second method of evaluating exposure area is to decrease the approach area by changing the glide-slope angle, thereby yielding a benefit in reduction in the total area. As shown in Figure 51, the available change in approach area is small. To obtain decreased exposure, the approach glide path was changed from 3° and 26% thrust to a two-segment method consisting of a 6° slope at 10% thrust down to an altitude of 400 ft. (122 m) then a final 3°, 26% thrust segment. Since the approach noise level at an altitude of 370 feet (113 m) is in the 90 EPNL range, there would be little or no change in a 90

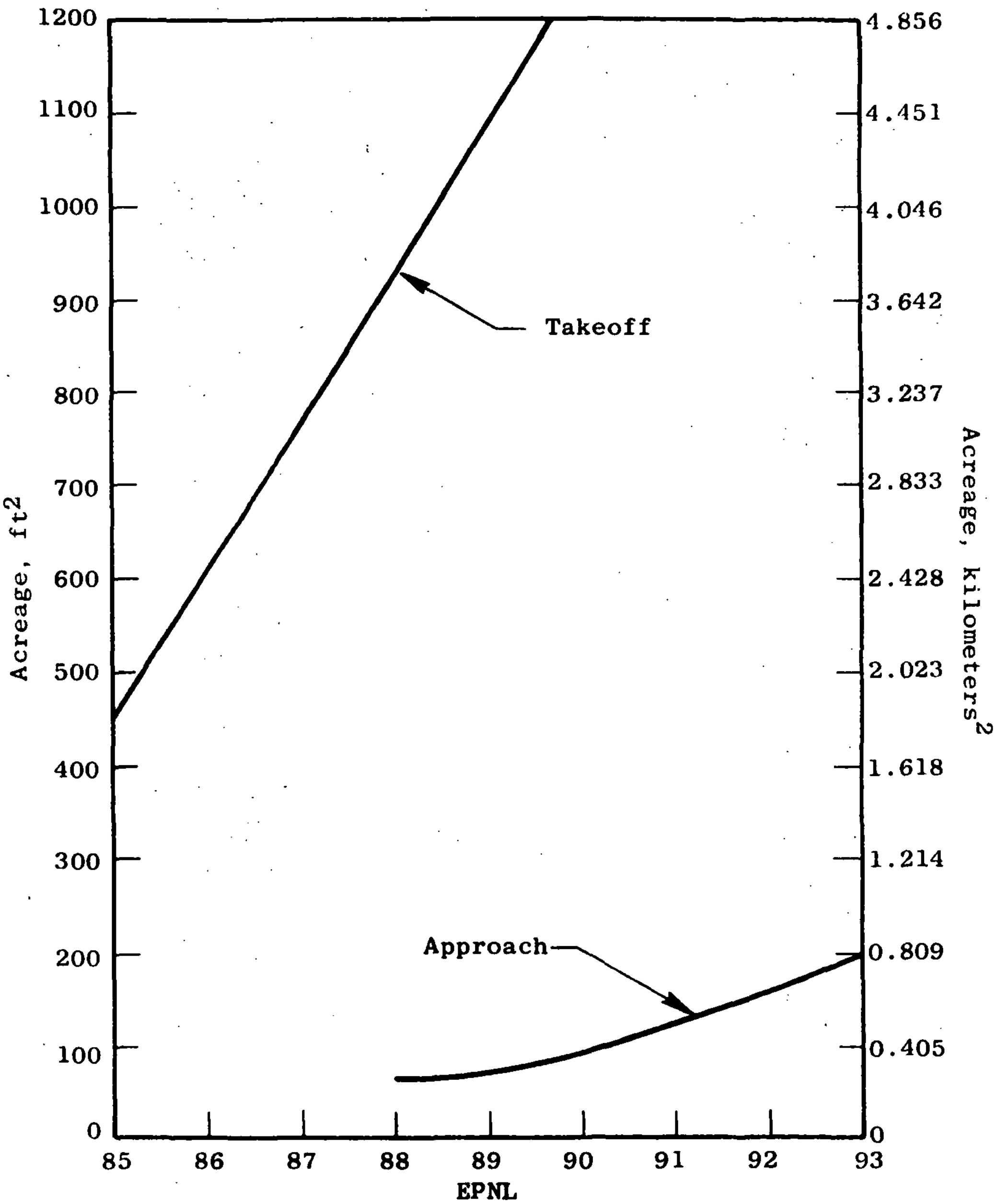


Figure 49. 90 EPNL Contour Acreage.

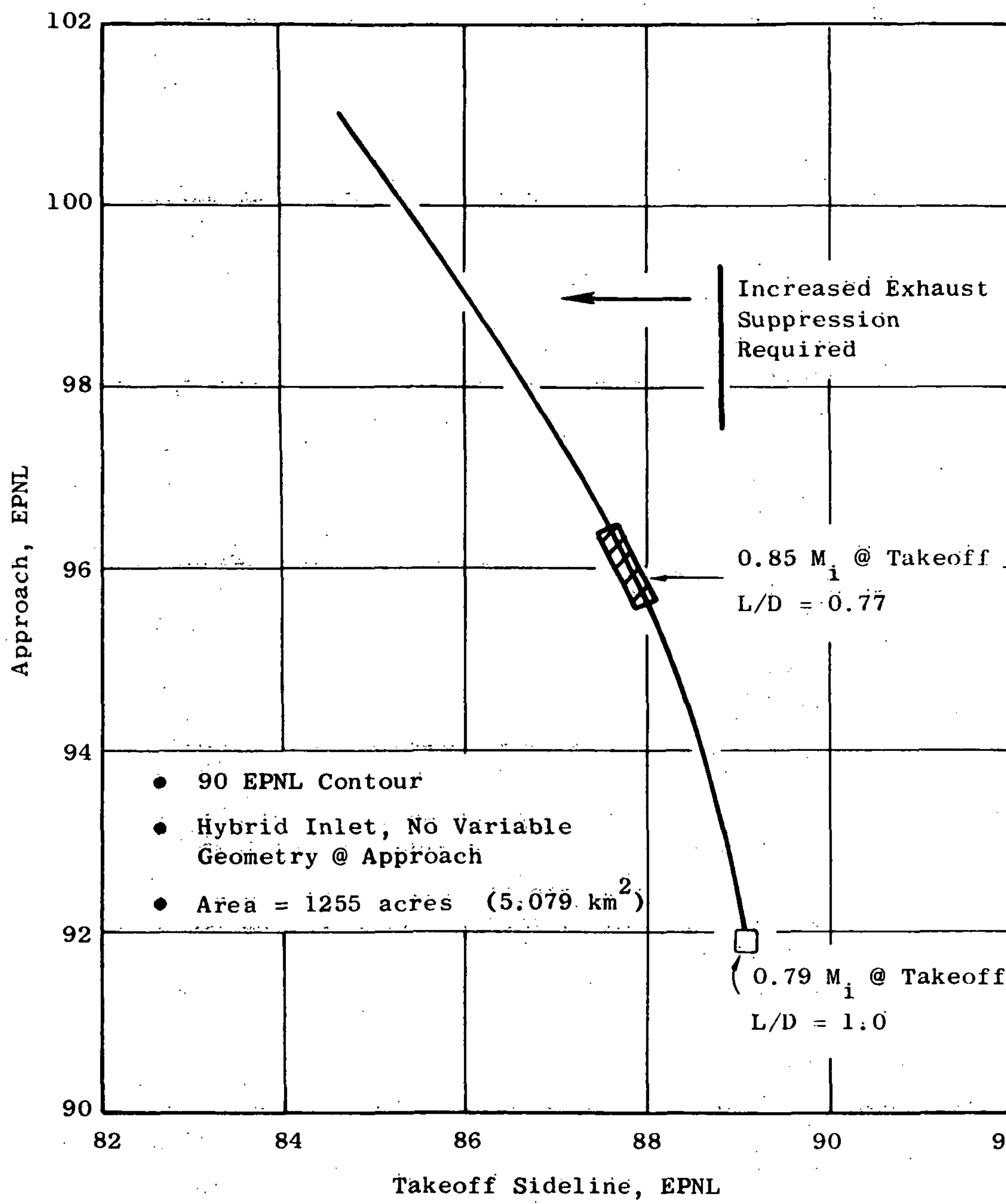


Figure 50. Effect of Increasing Approach Noise at Constant Exposure Area.

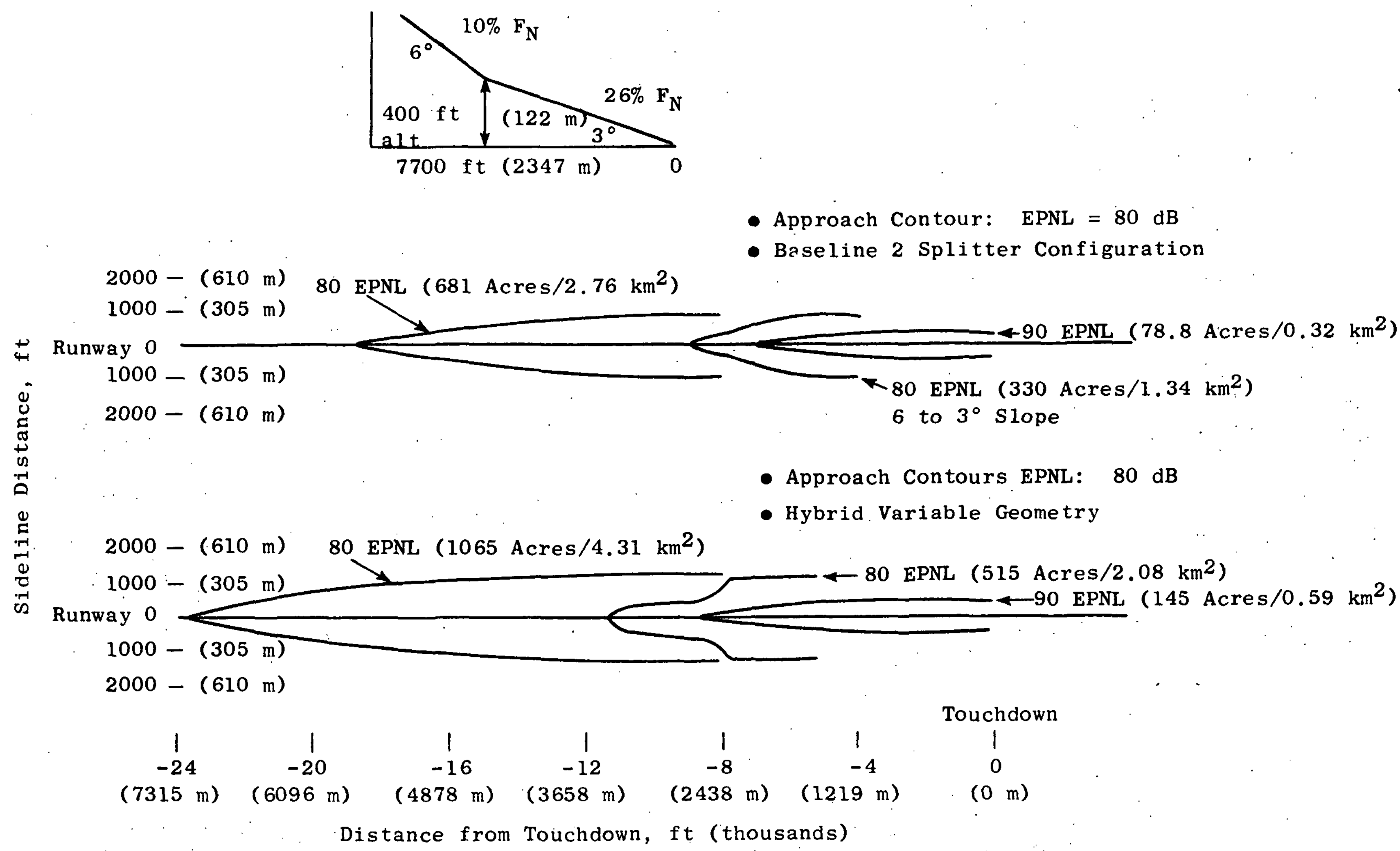


Figure 51. Effect of Operational Procedures on Approach.

EPNL contour between the two different approach paths. For this reason, an 80 EPNL contour was used to show the area change due to the operational procedures. Figure 51 shows the result of changing the approach path as described for both the hybrid and baseline inlets. The effect expressed in percent is about the same for both inlets, but the absolute decrease in area is greater for the hybrid inlet because the reference area is larger. As discussed previously, the 90 EPNL contour is small for both inlets and is located primarily in the region after the transition from a 6° to a 3° glide slope. These data indicate that evaluation of operational procedures and their benefits acoustically are dependent upon the initial noise level. Configurations with high noise levels will show very significant changes in area due to operational procedures, while low noise configurations will show little or no value at levels comparable to FAR 36 -15.

CONCLUDING REMARKS

- A hybrid variable geometry inlet with a throat Mach number of 0.79 at takeoff and community can attain FAR 36 -15 for the ATT No. 3 cycle.

- FAR 36 -20 tends to be beyond that possible for the ATT No. 3 cycle with FAR 36 -18 being a more reasonable limit. The required level of suppression would involve an extensive noise evaluation program due to the many potential noise floors that may be encountered.

- Both the baseline two-splitter and hybrid inlet configurations result in an 87% reduction of the 90 EPNL contour from the unsuppressed configurations.

- Approach thrust is limited to approximately 30% to 35% to attain FAR 36 -15 with the baseline and hybrid inlet configurations.

- The benefit of variable geometry at approach is sensitive to change in approach power setting.

- Trading increased approach exposure area with take-off area can result in significant reductions in inlet treatment length requirements.

- Operational procedures at approach which change glide-path angle and thrust are more effective for high noise configurations. Low noise configurations (FAR 36 -15) will be effective for the 80 EPNL contour but show no change for the 90 EPNL contour.

EVALUATION OF RESULTS

The weight, performance (both internal and external effects), and relative cost of the various inlet concepts were evaluated by simplified but consistent procedures suitable for a comparative study of this type. The results are shown in Table IX in which the dimensional characteristics are shown at the top and the changes in nacelle drag (expressed as percent of thrust level), inlet and exhaust pressure losses, weight, and price are shown below using the fixed aerodynamic baseline inlet as a reference case. Also shown are the mission merit results discussed below. Note these are inlet-related effects only and do not include what may be necessary in the exhaust to achieve a given engine noise level. These penalties are summarized in Table X.

The mission trade factors shown in Table XI were updated from those presented in Reference 1. These were then applied to the various inlets considered in this report. Figure 52 summarizes the merit of the various FAR 36 -15 inlets in terms of TOGW using the fixed-geometry, two-splitter inlet as a base. The contributions of inlet losses at both cruise and takeoff, nacelle drag, and weight are shown by the cross-hatched bars; the combined effect is shown by solid bars. Figure 53 then summarizes the changes in TOGW, DOC, and ROI for these same inlets. The only cases with an appreciable advantage are the two hinged-lip inlets. As discussed earlier, they also happen to be the least undesirable of any of the variable geometry concepts. The expandable plug and retractable vane also show a moderate improvement over the splitter inlet but are less desirable mechanically.

Table XII summarizes the overall impact of reducing noise from that of the untreated aerodynamic baseline including whatever is required in the exhaust to achieve the stated noise level. Note there are some refinements that would be applied, since the high Mach inlet that uses high Mach at approach needs to make more use of the two-position nozzle than do the other cases.

The hybrid hinged-lip inlet (high Mach not used at approach) is believed to be the best alternate to the multiple splitter inlet design for noise levels in the FAR 36 -15 range. In addition to having the lowest economic penalty of the inlets studied, it is believed to have lower aerodynamic risk than other variable geometry approaches; it is simpler; mechanically, it makes the engine accessible for maintenance; it does not result in wakes that might affect aft noise; anti-icing is not difficult; and, it does not represent anything unusual from the foreign object damage standpoint. It still has the control and operational complexity of a variable geometry inlet, but the consequences of failure are believed to be less than other types with greater area variation, particularly since most failures will be to the open position.

The use of a variable-geometry, high-Mach inlet will require control features added to the engine with appropriate consideration given to operational factors. A preliminary review of this area was made, and the main

Table IX. Summary of Penalties Associated with Alternate Inlets, Inlet-Related Effects Only.

Parameter	Aerodynamic Baseline, Fixed	Acoustic Baseline, Fixed, FAR 36 -15 EPNdB	Hinged Lip	Double Lip	Translating Internal Plug	Expandable Plug	Retractable Vanes	Expandable Vanes	Double-Row Articulated Vanes	Hybrid Hinged Lip	FAR 36 -10 EPNdB, Fixed	Retractable Splitters
Maximum Diameter, Inches	93	93	93	93	99	99.3	93	93	97	93	93	102.6
Meters	2.36	2.36	2.36	2.36	2.51	2.52	2.36	2.36	2.46	2.36	2.36	2.61
Cruise Inlet												
L/D_F (Cowl)/Plug	0.56	1.19	1.11	1.09	1.46	0.87/1.48	0.80	1.08	1.51	1.16	1.19	1.19
$\Delta D/Fn$ Cruise, %	0	0.40	0.40	0.40	1.1	0.80	0.20	0.40	0.90	0.40	0.40	1.3
Inlet $\Delta P/P$, %												
Cruise	0.3	1.9	0.7	1.6	0.8	0.6	0.7	1.2	2.0	0.6	0.5	0.7
Takeoff	0.3	1.2	0.8	1.6	0.9	0.7	1.9	3.5	5.4	0.7	0.4	1.4
Inlet $\Delta(\Delta P/P)$												
Cruise	Base	1.6	0.4	1.3	0.5	0.3	0.4	0.9	1.7	0.3	0.2	0.4
Takeoff	Base	0.9	0.5	1.3	0.6	0.4	1.6	3.2	5.1	0.4	0.1	1.1
Δ Weight Total, lbs	0	950	770	770	1210	1000	670	820	1260	630	400	1380
kg	0	431	349	349	549	454	304	372	571	286	181	626
Δ Price, 1000$	0	49	66	67	102	93	61	71	106	51	25	91
Merit Factors												
Δ TOGW, %	0	4.1	2.5	3.6	4.2	3.2	2.9	4.9	8.2	2.1	1.4	5.0
Δ DOC, %	0	3.8	2.4	3.6	4.1	3.2	3.0	5.0	8.3	2.0	1.3	4.8
Δ ROI, %	0	-2.8	-1.9	-2.7	-3.2	-2.5	-2.3	-3.8	-6.3	-1.6	-1.0	-3.6

Table X. Exhaust System Penalties.

	Baseline Inlet	FAR 36 -10 Inlet	FAR 36 -15 Cases
Fan Exhaust Suppression			
Δ P/P, %	Base	0.4	0.7
Δ Weight, lbs.	↓	50	520
kg	↓	22.7	236
Δ Price, $1000	↓	4	22
Variable Exhaust Nozzle			
Δ P/P, %	Base	0	0.1%
Δ Weight, lbs.	↓	0	390
kg	↓	0	177
Δ Price, $1000	↓	0	39
Merit Factors			
Δ TOGW, %	Base	0.4	2.4
Δ DOC, %	↓	0.4	2.5
Δ ROI, %	↓	-0.3	-1.8

Table XI. Mission Trade Factors for 0.90 Mach Number Aircraft.

Change	% Effect Upon TOGW	DOC	ROI (1)
+1% Installed SFC	+0.75	+0.73	-0.46
+500 lb. (227 kg) weight per engine	+0.96	+0.61	-0.39
+$10,000 basic engine price	---	+0.14	-0.12
+$10,000 reverser price	---	+0.08	-0.09
+$10,000 other installation	---	+0.07	-0.09

Note: All engines scaled to a cruise thrust of 8,700 lbs (38.7 kN) at 40,000 ft. (12.2 km), Mach 0.90 (study engine size). Trade factors assume aircraft and engine resized to hold payload and range.

(1) ROI - A 1% change in ROI represents an absolute change as from 25% to 26%.

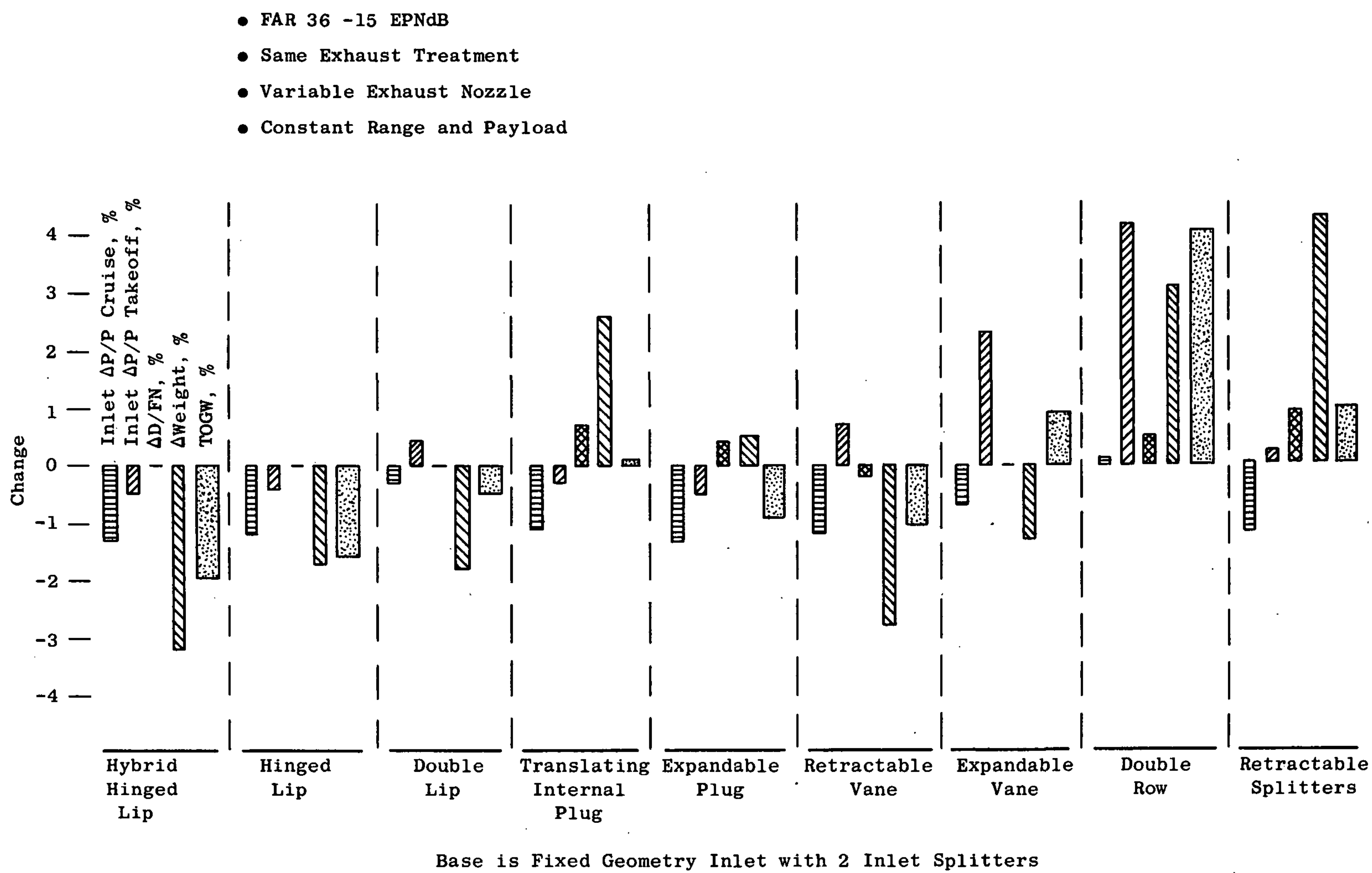


Figure 52. Summary Results, TOGW.

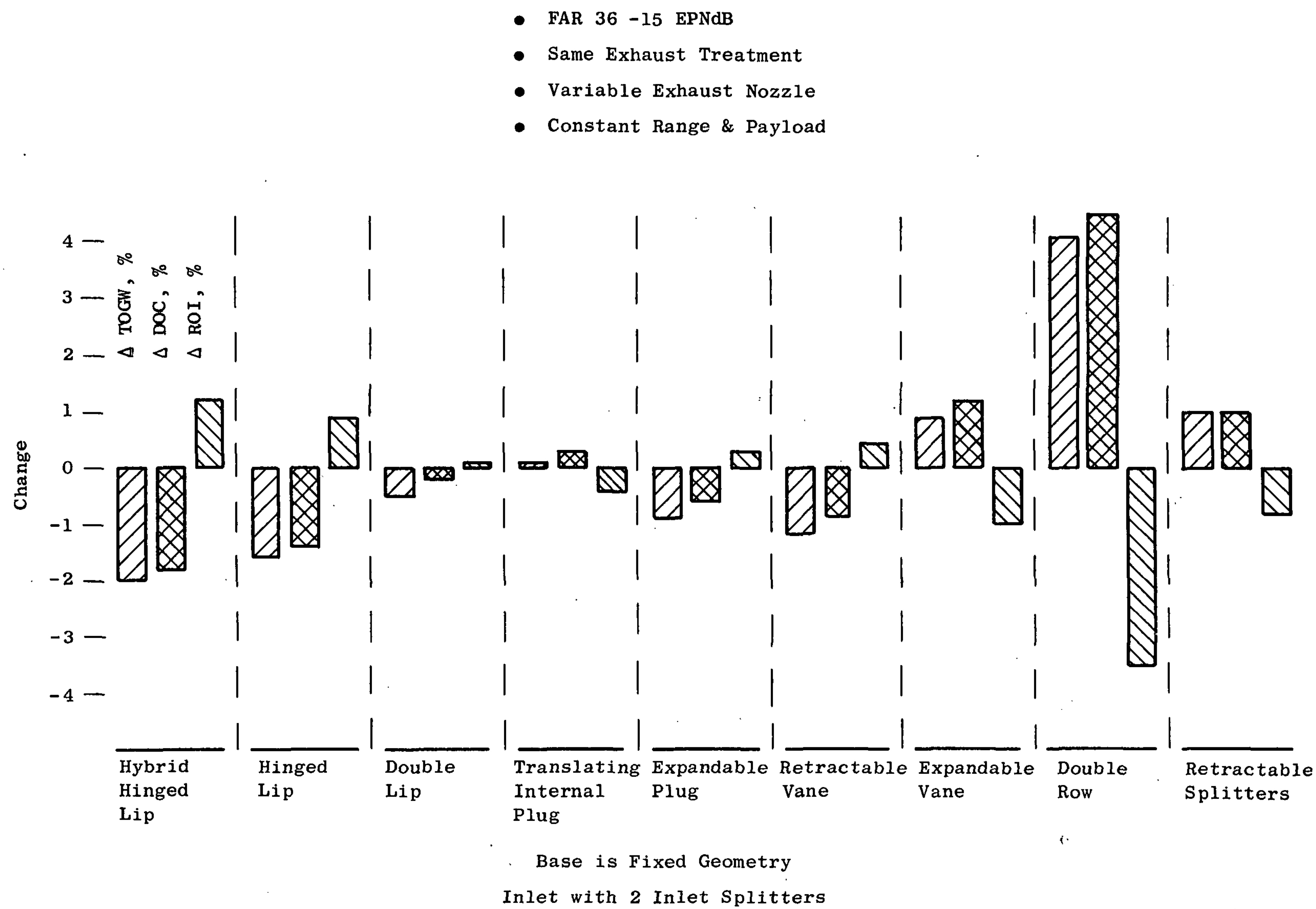


Figure 53. Summary, Changes in TOGW, DOC, and ROI.

Table XII. Summary Results, Overall Impact of Reducing Noise from Untreated Aerodynamic Baseline.

	Fixed Geometry Inlets			Best Variable Geometry Inlet	
	Untreated Aero. Baseline	Treated			
Traded Noise Relative to FAR 36 →	+0.7	-10	-15	-15	-15
<u>Noise Treatment</u>	Unsuppressed	---	---	---	---
Wall L/D_F Treatment	0	1.0			
Inlet Splitters	0	0	2	0	0
Exhaust Splitters	0	0	1	1	1
High Mach	No	No	No	T/O Power Cutback	All Conditions
Throat Mach No.	---	---	---	0.79	0.72
Inlet Throat Area Variation, %	---	---	---	10	34
Variable Nozzle	No	No	Yes	Yes	Yes
*Δ TOGW, %	Base	+1.8	+6.9	+4.9	+5.3
*Δ DOC, %	Base	+1.7	+6.7	+4.9	+5.3
*Δ ROI, %	Base	-1.3	-4.9	-3.7	-4.0

*Constant Range & Payload

points are summarized in Tables XIII and XIV. Table XIII indicates the major requirement of the control of a variable-geometry, high-Mach inlet. Of particular importance is the necessity of avoiding large thrust losses due to failure of control or variable geometry system. There are several possible methods of arranging the control, but the most straightforward is to have the pilot select the low noise mode and then have the control maintain the desired level of throat Mach number. A direct variation of inlet area, or a variation of flow by means of the variable jet nozzle, are options for doing this. The significant operational factors of a variable geometry inlet and its control are summarized in Table XIV. Design and development effort will be required to take these things into account.

Table XIII. Variable Geometry Inlet Control Considerations.

Requirements

- Provide automatic scheduling of variable geometry inlet to maintain selected inlet throat Mach number when in noise abatement mode.
- Must avoid inlet choking to prevent large thrust loss.
- Must be fail-safe so that nearly full thrust can be obtained at important conditions.
- Must protect engine - avoid stalling fan.

Sequence of Events

- Pilot selects low noise mode
- Power lever angle ($N_F/\sqrt{\theta}$) schedules nominal variable geometry position (inlet and exhaust)
- Closed loop control modulates areas to maintain desired inlet reference Mach no.

Possible Options for Trimming

- Inlet area
- Exhaust nozzle area (subject to jet noise situation)

Table XIV. Control System Operational Considerations.

	Requirement	Reason
1)	Pilot override	To prevent massive thrust loss if control fails with inlet area in minimum position.
2)	Switch over from cruise mode to low noise mode safe from any power setting at any time	Inadvertent pilot selection of low noise mode from cruise mode.
3)	Transient control override	Inlet capability and engine demand must be matched during all transient operations (wave-off in particular).
4)	Take-off abort accommodation	Must prevent inlet area closure with throttle retard to reverse thrust position.
5)	Multiple sensors	Required to provide valid throat Mach number reference within allowable cross-wind and inlet distortion limits.
6)	Multiple or backup schedule	Loss of sensing signal cannot drive inlet closed.

Control Dynamics Considerations

1)	Inlet Mach number level	Must be studied with complete engine dynamic model to find best solution and establish limits.
2)	System response/stability	
3)	Interaction with engine during transients	

CONCLUSIONS

GEOMETRY ASPECTS

- The magnitude of inlet throat area change has a pronounced effect on all variable geometry inlet concepts, but variable cowl concepts tend to be less affected.
- If a high throat Mach number design is used at approach power (26% take-off thrust), a variable exhaust nozzle (to increase fan flow and thereby minimize inlet throat area variation) is required to make most concepts practical.
- Inlets with variable cowl systems tend to be shorter than variable centerbody configurations. Variable cowl inlets have about the same length as a massive suppression inlet for the same noise.
- Variable centerbody systems generally lead to an increase in nacelle diameter in addition to being longer.
- Variable vane blockage concepts tend to be high-loss systems especially at takeoff and approach.
- The best inlet configuration that meets the specified noise objective (15 EPNdB below FAR 36 on a traded basis) relies on a combination of wall treatment and high inlet throat Mach number (<0.8) for inlet noise suppression at the take-off sideline and over the community [3.5 nautical mile point (6.5Km)], and only on wall treatment to suppress inlet noise at approach (hybrid inlet).
- The most attractive variable geometry concept evaluated in this study is a variable cowl configuration with a fixed external cowl and a variable internal surface (denoted "hinged lip").
- In conjunction with a variable exhaust nozzle, the hybrid inlet requires only a 10% smaller inlet throat area than the cruise design value. Without a variable exhaust nozzle, a 20% inlet throat area variation is required to maintain the desired inlet throat Mach number of 0.79.

NOISE

- All variable geometry inlets considered can meet the noise objective (FAR 36 -15) with a combination of inlet wall treatment and high Mach suppression with an inlet throat Mach number of less than 0.8.

- Variable geometry inlets, designed for high Mach suppression at approach power (34% throat area variation) as well as at takeoff, can achieve FAR 36 -16 with the same throat Mach number (0.79) as the recommended hybrid configuration or the same noise (FAR 36 -15) with a lower throat Mach number (0.72).

- Based on the host airplane requirements at the FAR noise measuring stations and especially over the community (1300 ft/396 m, 80% take-off thrust) a variable exhaust nozzle is required to reduce jet noise to meet FAR 36 -15 (all configurations) for the cycle studied. With a fixed exhaust nozzle, approximately 13.5 EPNdB below FAR 36 can be obtained on a traded basis.

- The maximum noise reduction potential of variable geometry inlets is limited by the maximum throat Mach number judged to be practical and realistic (i.e., yields a reliable and safe system). This value is not now known and will have to be established experimentally for a specific inlet geometry.

- If a Mach number of 0.85 were found to be acceptable, and used at approach as well as at high power settings, a noise level of approximately 18 EPNdB below FAR 36 could be achieved with additional fan exhaust noise suppression of about 5 dB.

- Operational procedures at approach, which allow flight idle thrust (10% take-off thrust) to be used on a 6° to 3° two-segment approach with a 400 foot (122 m) altitude intercept, decrease the 80 EPNdB noise footprint area by approximately 50%. Because the 90 EPNdB noise contour is so small for an aircraft that meets FAR 36 -15, it remains essentially unchanged with this procedure.

- The effect of in-flight thrust spoiling (which would allow the engine power setting to be higher at approach and, therefore, would permit a significant improvement in thrust response) results in very large increases in noise at approach.

ECONOMIC ASPECTS

- Several of the variable geometry inlet concepts studied are competitive with the fixed geometry acoustic baseline inlet with multiple splitters. However, except for the variable-cowl/hinged-lip configuration, all were judged unattractive on the basis of mechanical complexity, risk, reliability, and safety aspects.

- The mission performance penalties for the best variable geometry inlet configuration identified (hybrid inlet) are smaller than the penalties obtained for a fixed-geometry inlet with multiple splitters that meets the noise objective (FAR 36 -15). The hybrid inlet yields about 2% lower take-off gross weight, 1.8% lower DOC, and 1.2% higher ROI relative to the fixed geometry acoustic baseline inlet. These gains must be balanced against the increased complexity and risk that is inherently introduced with any variable geometry element, no matter how well implemented, and compared with the liabilities of an inlet with multiple splitters.

- It must be emphasized that the economic penalties associated with a noise level of FAR 36 -15 EPNdB compared to the FAR 36 -10 EPNdB (advanced technology baseline) are nevertheless quite high: 3.2% higher DOC for the hybrid inlet, compared to a 5% increase in DOC for the fixed geometry acoustic baseline inlet.

- A variable exhaust nozzle capable of a 15% to 25% area variation results in substantial penalties compared to the advanced technology baseline (FAR 36 -10): 0.9% increase in TOGW, 1.1% increase in DOC and 0.8% lower ROI.

RECOMMENDATIONS

Results of this exploratory study indicate that the variable cowl hybrid inlet configuration is worthy of further consideration when engines require multiple inlet splitters to meet a given noise objective. Additional effort is particularly indicated in the following areas:

1) Studies to explore the dynamics of the inlet/engine system, to establish the inlet control system requirements and the system limitations based on realistic variations in the indicated inlet throat Mach number and tolerances of the position feedback control.

2) More extensive mechanical design studies.

3) Aero/acoustic tests with a specific inlet design to establish inlet noise suppression as a function of Mach number up to the limiting value as defined by satisfactory inlet recovery and fan performance.

REFERENCES

1. "Propulsion System Studies for an Advanced High Subsonic Long Range Jet Commercial Transport Aircraft," General Electric Company, NASA CR-121016, November, 1972.

APPENDIX

SYMBOL LIST

ATT - Advanced Technology Transport

A_8 - Core Engine Jet Nozzle Area

C-D - Convergent-Divergent

$D_{max.}$ - Maximum Inlet Diameter

dB - Decibels

DOC - Direct Operating Cost

ΔDOC - Change in Direct Operating Cost

EPNdB - Effective Perceived Noise, decibels

EPNL - Effective Perceived Noise Level, Measured in EPNdB

FAR 36 - Federal Aviation Regulations, Part 36

ID - Inside Diameter

L - Inlet Length

L/D_F - Inlet Length divided by Fan Diameter

MDOF - Multiple Degrees of Freedom

OD - Outside Diameter

PNdB - Perceived Noise, decibels

PNL - Perceived Noise Level, measured in PNdB

R_{HL} - Inlet Highlight Radius

R_{hub} - Fan Hub Radius

$R_{max.}$ - Maximum Inlet Radius

R_{TH} - Inlet Thrust Radius

ROI - Return on Investment

ΔROI - Change in Return on Investment

sfc - Specific Fuel Consumption

TOGW - Take-off Gross Weight

VG - Variable Geometry

X - Distance from Inlet Highlight to Inlet Maximum Diameter

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