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ADVANCED SUPERSONIC PROPULSION SYSTEM TECHNOLOGY STUDY

PHASE II - FINAL REPORT

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16. Abstract

Variable cycle engines have been identified, based on the mixed-flow low-bypass-ratio augmented turbofan cycle, which has shown excellent range capability in the AST airplane. The Phase II AST Study selected the best mixed-flow augmented turbofan engine, based on range in the AST Baseline Airplane. Selected variable cycle engine features were added to this best conventional baseline engine, and the Dual-Cycle VCE and Double-Bypass VCE were defined. The conventional mixed-flow turbofan and the Double-Bypass VCE were the subjects of engine preliminary design studies to determine mechanical feasibility, confirm weight and dimensional estimates, and identify the necessary technology considered [illegible] yet available. Critical engine components were studied and incorporated into the variable cycle engine design.

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SECTION I

INTRODUCTION

The Phase I Advanced Supersonic Technology Propulsion System Study, reported in Contract NAS3-16950 Final Report, NASA CR-143634, covered a wide range of engine types and cycles to identify the best conventional and variable cycle engine concepts. The depth of the study on any single engine type was restricted by the quantity of engines screened. Three types of conventional engines were identified as being candidate engines for an advanced supersonic commercial transport designed to cruise at Mach numbers of 2.2 to 2.7. Operation at M=3.2 was studied, but the airplane take-off gross weight (TOGW) required to meet the range requirement was not practical. Several variable engine concepts were screened, but none were considered serious candidates for continued effort. These VCE studies did, however, identify desirable engine performance features that would have large payoff if they could be incorporated into less complex, lighter weight engine concepts.

Variable cycle engine features which had these desirable performance benefits were designed to be applied to a low-bypass-ratio augmented mixed-flow conventional engine cycle which had shown excellent range capability in the AST airplane.

The Phase II AST study was designed to select the best conventional mixed-flow augmented turbofan engine by a parametric study, and add selected variable cycle engine features to this conventional engine cycle. These conventional and variable cycle engines were the subject of an engine preliminary design study to determine mechanical feasibility, confirm weight and dimensions, and identify the necessary technology not yet available. Critical engine components also were studied and incorporated into the variable cycle engine design.

This phase of the advanced Supersonic Technology Propulsion System Study has identified a variable cycle engine concept, the double-bypass VCE, which provides high airflow to meet FAR Part 36 noise levels, and at the same time provide the performance advantage of a smaller cruise-size engine which is well-matched to the AST airplane characteristics. This VCE concept also provides the added capability of excellent subsonic installed performance, which makes a mixture of subsonic and supersonic operation a practical consideration.

SECTION II

RESULTS AND DISCUSSION

This phase of the Advanced Supersonic Technology Propulsion Study was made up of two basic parts:

- Definition of best mixed-flow augmented turbofan conventional engine
- Addition of variable cycle engine features to the conventional engine and definition of best variable cycle engine

The mixed-flow augmented turbofan was selected for the baseline conventional engine cycle from the results of the Phase I effort. The variable cycle engine features identified from the study of the modulating airflow three-rotor VCE were added to the conventional engine to make a simple variable cycle engine with much less complexity than the three-rotor VCE. The selected VCE concept retains the high specific thrust and good supersonic cruise specific fuel consumption of the mixed-flow turbofan while providing the added features of:

- High airflow at takeoff for low noise and small takeoff noise footprint area
- Small cruise size for better aircraft performance match
- Excellent installed subsonic SFC from:
  - improved cycle performance
  - elimination of inlet additive drag
  - reduction in afterbody drag

Both the baseline conventional engine and variable cycle engine definition utilized 1985 technology and an intermediate supersonic cruise Mach number of 2.4.

A brief discussion of the results of the Phase II study is given below. A comprehensive review of the study results is given in the General Discussion Section of this report.

A. Baseline Conventional Engine Definition

1. Specific Objectives

Define the best conventional fixed-flow augmented turbofan cycle, measured by range in the AST baseline airplane. Confirm the weight, physical dimensions, and mechanical feasibility of the selected engine by a preliminary design study.

2. Approach/Ground Rules

A matrix of mixed-flow engines was run, varying fan pressure ratio (3.0 to 4.5), bypass ratio (0.33 to 0.85) at an overall pressure ratio of 22.5 and a maximum turbine rotor inlet temperature of 2800° F (1538° C). Mission range)M = 2.4) in the baseline airplane was computed and the best cycle was selected.

The study was started using the following general ground rules:

- AST-1 airplane - 750,000 lbs (340,000 Kg) TOGW
- 53,500 lbs (237,970 n) thrust at rotation
- 12,400-feet (3780 m) balanced field length
- FAR Part 36 -0 to -5 PNdB noise levels with 15 PNdB mechanical jet noise suppressor
- Take-off augmentation limited to 1700° F (927° C)

The baseline conventional engine cycle was defined using the above ground rules. At NASA direction, th airplane definition was changed to AST-2 airplane and balanced field length was reduced. These changes were introduced after the baseline engine definition and at the same time a change in the noise estimating procedure was introduced to be more realistic in computing FAR Part 36 noise levels. The new ground rules were:

- AST-2 Airplane - 762,000 lbs (345,640 Kg) TOGW
- 61,400 lbs (273,107 n) thrust at rotation
- 10,500-foot (3200 m) balanced field length (BFL)
- New noise-estimating procedure

3. Major Results

The best conventional mixed-flow augmented turbofan baseline in the AST-1 airplane, 12,400 foot (3200 m) BFL had the following characteristics:

- 700 lbs/sec (318 Kg/sec) airflow
- 4.0 fan pressure ratio
- 2925 ft/sec (892 m/sec) exhaust velocity
- FAR Part 36 -3 PNdB traded noise level

An engine preliminary design study was completed on this engine which confirmed the feasibility of the mechanical design, and a design report was completed for the NASA-Lewis Research Center.

4. Discussion

Figure 1 compares the all-supersonic range in the AST-1 airplane with the take-off footprint area for the three best conventional cycle engines. The selected engine cycle had the best all-supersonic range of 4350 N.M. (8056 Km) and a 90 PNdB take-off footprint area of 16 square N.M. (30 sq Km). Tables 1 and 2 describe the characteristics of the selected baseline engine and its performance in the baseline AST-1 airplane.

At this point in the AST study, the new airplane (AST-2) and the shorter, 10,500-foot (3200-m) balanced field length were introduced. At the same time the GE noise estimating procedure was revised to reflect more realistic in-flight noise predictions based on up-to-date test data. Table 3 shows the effect of the airplane and balanced field length changes on the airflow size and range of the baseline conventional engine cycle. The take-off thrust requirements have increased by about 15% and the airplane all-supersonic range has been reduced by about 11%. When the revised GE noise estimating procedure was used to predict the noise level of the engine for the new baseline airplane, the traded FAR Part 36 noise level increased from -2.3 PNdB to +5.1 PNdB (see Table 4). Table 5 shows the result of scaling up the engine airflow in order to lower exhaust velocity and lower the noise level. The engine size has increased by 33% to 1070 lbs/sec (485 Kg/sec) and the all-supersonic range has been reduced by 450 N.M. (833 Km). Figure 2 shows the overall effect of:

- AST-1 to AST-2 airplane
- Reduced Balanced Field length
- Revised noise prediction procedure

The baseline engine all-supersonic range has been reduced from 4350 N.M. (8056 Km) to 3470 N.M. (6426 Km), and the 90 PNdB take-off footprint area has increased from 16 square N.M. (555 sq Km) to 19 square N.M. (65 sq Km).

B. Variable Cycle Engine Definition

1. Specific Objectives

Add selected variable cycle engine features to the baseline conventional engine, and evaluate these variable cycle engines, which are identified as:

- Dual-Cycle VCE
- Double-Bypass VCE

2. Approach/Ground Rules

The approach used in this part of the study was to define the specific variable cycle engines and evaluate them based on range in the baseline AST-2 airplane and a 90 PNdB contour take-off footprint area.

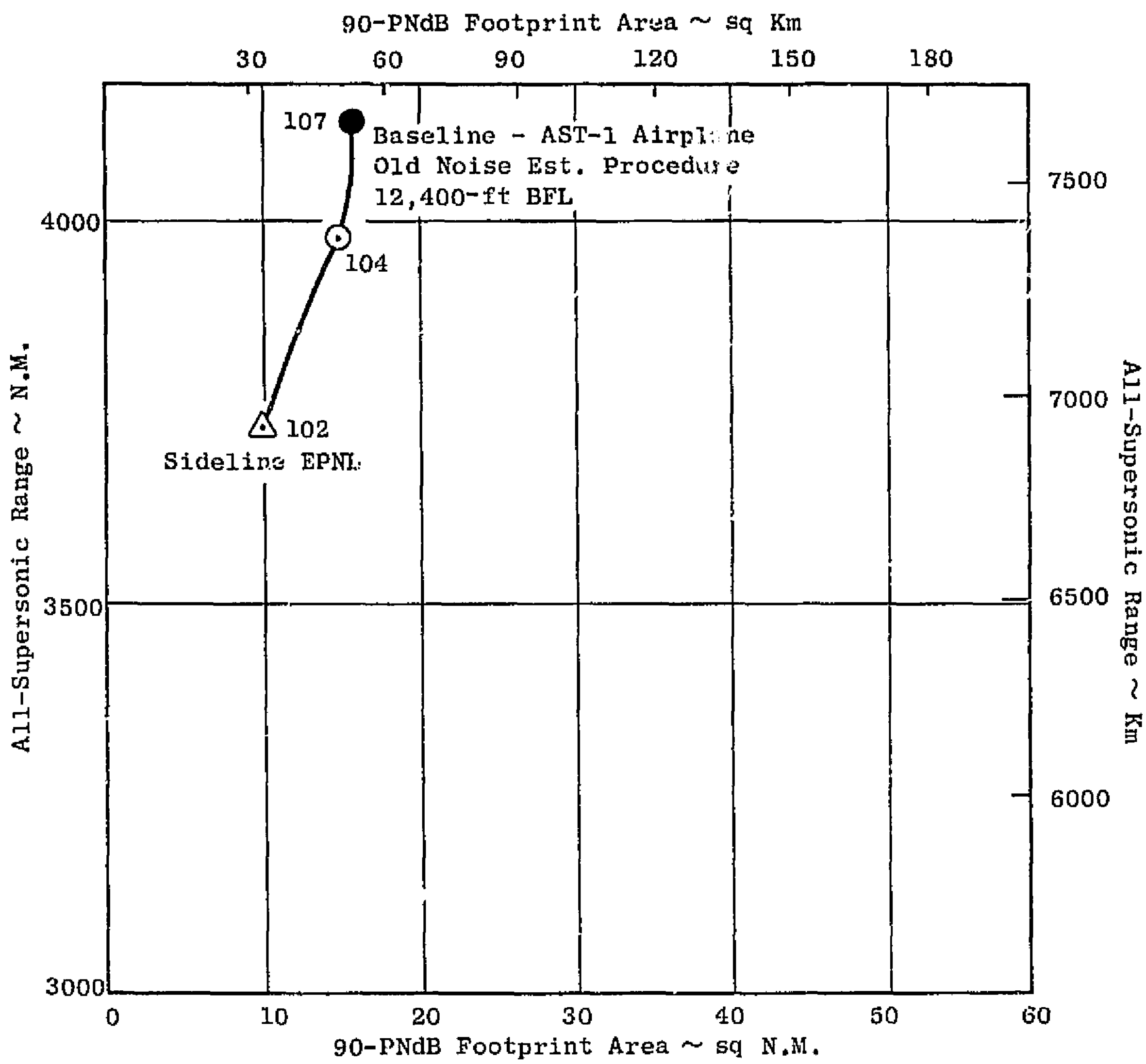


Figure 1. Conventional Cycles Range - Footprints, AST-1 Airplane.

Table 1. GE21/F12 Study B1, Conventional Baseline Engine.

Take-off Thrust, lbs	53,500
N	237,970
W_a, lbs/sec	700
Kg/sec	318
Fan Pressure Ratio	4.0
Overall Pressure Ratio	22.5
Maximum Turbine Inlet Temperature, ° F	2800
° C	1538
Supersonic Cruise Turb. Inlet Temp., ° F	2700
° C	1482
Mechanical Jet Noise Suppression, PNdB	15
Suppressor Design Point, ft/sec	2500
m/sec	762
Take-off Exhaust Velocity, ft/sec	2925
m/sec	892
FAR Part 36 Noise Level, EPNdB	-3
Engine Weight, lbs	13,200
Kg	5990
Maximum Diameter, inches	72.9
m	1.85
Engine Length, inches	301
m	7.65

Table 2. GE21/F12 Study B1, Conventional Baseline Engine, AST-1 Airplane.

Airflow, lbs/sec	700
Kg/sec	318
Take-off Thrust, lbs	53,500
N	237,970
Traded FAR Part 36, EPNdB	-3
90-PNdB Take-off Footprint Area, sq NM	16
sq Km	55
Range:	
All-Supersonic, NM	4350
Km	8056
600-NM Initial Subsonic, NM	4110
Km	7612
All-Subsonic, NM	3420
Km	6334

Table 3. GE21/F12 Study B1, Conventional Baseline Engine, AST-1 and AST-2 Airplanes.

	AST-1 Airplane 12,400-foot (3780-m) BFL	AST-2 Airplane 10,500-foot (3200-m) BFL
Airflow, lbs/sec	700	805
(Kg, sec)	(318)	(365)
Take-off Thrust, lbs	53,500	61,400
(N)	(237,970)	(273,107)
Traded FAR Part 36, EPNdB	-3	-2.3
90-PNdB Take-off Footprint Area, sq NM	19	14.5
(sq Km)	(65)	(26.9)
Range:		
All-Supersonic, NM	4350	3920
(Km)	(8056)	(7260)
600-NM (1111 Km) initial Subsonic, NM	4110	3720
(Km)	(7612)	(6889)
All-Subsonic	3420	3125
(Km)	(6334)	(5788)

Table 4. Revised Relative Velocity Impact on Baseline Engine, AST-2 Airplane.

	Baseline (Old VR)	Baseline (Revised VR)
Airflow, lbs/sec	805	805
(Kg/sec)	(365)	(365)
Take-off Thrust, lbs	61,400	61,400
(N)	(273,107)	(273,107)
Traded FAR Part 36, EPNdB	-2.3	+5.1
90-PNdB Take-off Footprint Area, sq NM	14.5	28
(sq Km)	(50)	(96)
<u>Range</u>:		
All-Supersonic, NM	3920	3920
(Km)	(7260)	(7260)
600-NM (1111-Kg) Initial Subsonic, NM	3720	3720
(Km)	(6889)	(6889)
All-Subsonic, NM	3125	3125
(Km)	(5788)	(5788)

Table 5. Baseline Engine Performance, AST-2 Airplane.

- AST-2 Airplane, 762,000-lb (345,643-Kg) TOGW
- 10,500-ft (3200-m) Balanced Field Length
- Optimized Subsonic and Transonic Climb/Acceleration

	Old VR	Revised VR	(Scaled to Same Sideline EPNL)
Airflow, lbs/sec	805	805	1070
(Kg/sec)	(365)	(365)	(485)
Take-off Thrust, lbs	61,400	61,400	61,400
(N)	(273,107)	(273,107)	(273,107)
Traded FAR Part 36, EPNdB	-2.3	+5.1	-2.5
90-PNdB Take-off Footprint Area, sq NM	14.5	28	18
(sq Km)	(50)	(96)	(62)
Range:			
All-Supersonic, NM	3920	3920	3470
(Km)	(7260)	(7260)	(6426)
600-NM (1111 Km) Initial Subsonic, NM	3720	3720	3170
(Km)	(6889)	(6889)	(5871)
All-Subsonic, NM	3125	3125	2370
(Km)	(5788)	(5788)	(4389)

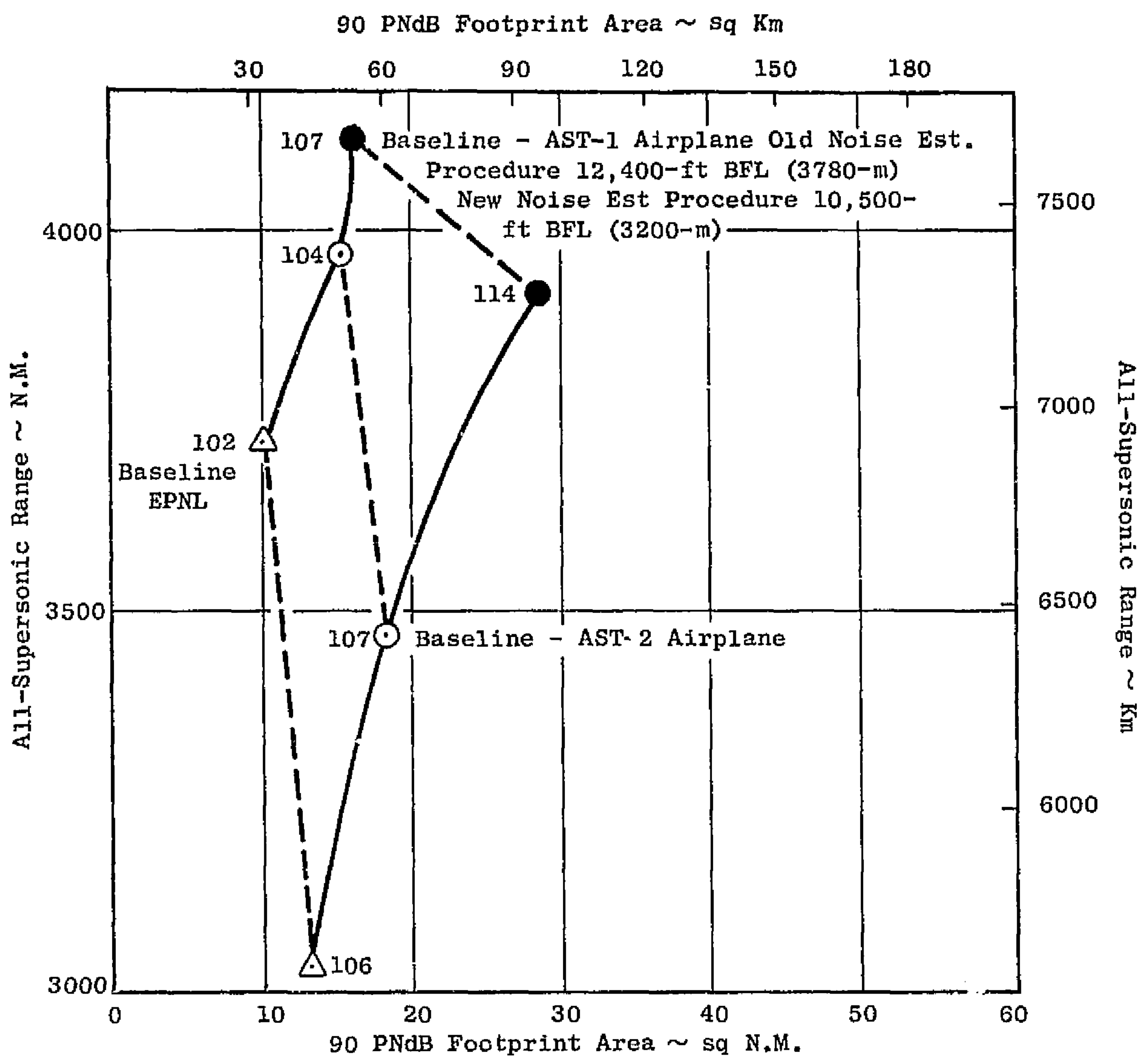


Figure 2. Conventional Cycles Range - Footprints, Includes AST-2 Airplane.

The ground rules used in this part of the study were the same as used in the last part of the conventional engine definition:

- AST-2 airplane
- 10,500-foot (3200 m) balanced field length
- Revised noise estimating procedure

3. Major Results

A variable cycle engine concept, the double-bypass VCE, was defined which provides high take-off airflow for acceptable FAR Part 36 noise levels and take-off footprint areas, while also providing a good performance match with the AST-2 airplane requirements and excellent subsonic installed performance. Table 6 compares the improvements provided by the double-bypass VCE compared to the conventional engine sized for the same noise level.

4. Discussion

The dual-cycle VCE requires minimum change to the conventional engine cycle, which results in a slightly higher engine weight, but provides a substantial improvement in subsonic installed performance. The VCE features also allow high airflow to be maintained at power cutback, for the community noise measuring station, which results in lower noise and a small 90-PNdB contour take-off footprint area. The improvement in subsonic performance saves reserve fuel which can be used for the supersonic cruise segment. This added fuel more than makes up for the small added weight and allows a longer range. Figure 3 shows the small improvement in range and the reduction in take-off footprint area achieved by the dual-cycle VCE.

The dual-cycle VCE does not offer any solution to the take-off noise/airflow size dilemma caused by the short balanced field length and the revised noise estimating procedure. The dual-cycle VCE is sized the same as the conventional engine for take-off noise and thrust, and they both are penalized in flight by a poor match with airplane requirements because of the large engine airflow. The double-bypass VCE provides a solution to this sizing problem by providing a high take-off airflow for desired noise and, at the same time, providing the same good matching of airplane requirements obtained with smaller engines. The double-bypass VCE also provides better subsonic installed performance than the dual-cycle VCE, since it totally eliminates inlet spillage drag, and greatly reduces afterbody drag for the subsonic cruise, divert, and hold flight conditions. The excellent take-off noise footprint areas of the dual-cycle VCE are retained, since both VCE concepts have the ability to maintain high airflow at the power cutback condition. Table 6 shows a comparison of range and take-off footprint areas for the double-bypass VCE compared to the conventional engines sized for the same noise. The all-supersonic range and footprint area are compared to the conventional engines on Figure 4.

Table 6. Double-Bypass/Dual-Cycle VCE Noise and Range.

- AST-2 Airplane, 762,000-lb (345,643-Kg) TOGW
- 10,500-ft (3200-m) Balanced Field Length
- Optimized Subsonic and Transonic Climb/Acceleration

	Baseline (Old VR)	Baseline (Revised VR)	Baseline (Scaled to Same Sideline EPNL)	VCE
Airflow, lb/sec	805	805	1070	900/1093
(Kg/sec)	(365)	(365)	(485)	(408/496)
Take-off Thrust, lbs	61,400	61,400	61,400	61,400
(N)	(273,107)	(273,107)	(273,107)	(273,107)
Traded FAR Part 36, EPNdB	-2.3	+5.1	-2.5	-2.5
90-PNdB Take-off Footprint Area, sq NM	14.5	28	18	13
(sq Km)	(50)	(96)	(62)	(45)
<u>Range</u>:				
All-Supersonic, NM	3920	3920	3470	3675
(Km)	(7260)	(7260)	(6426)	(6806)
600-NM (1111-Km) Initial Subsonic, NM	3720	3720	3170	3560
(Km)	(6889)	(6889)	(5871)	(6593)
All-Subsonic, NM	3125	3125	2370	3170
(Km)	(5788)	(5788)	(4389)	(5871)

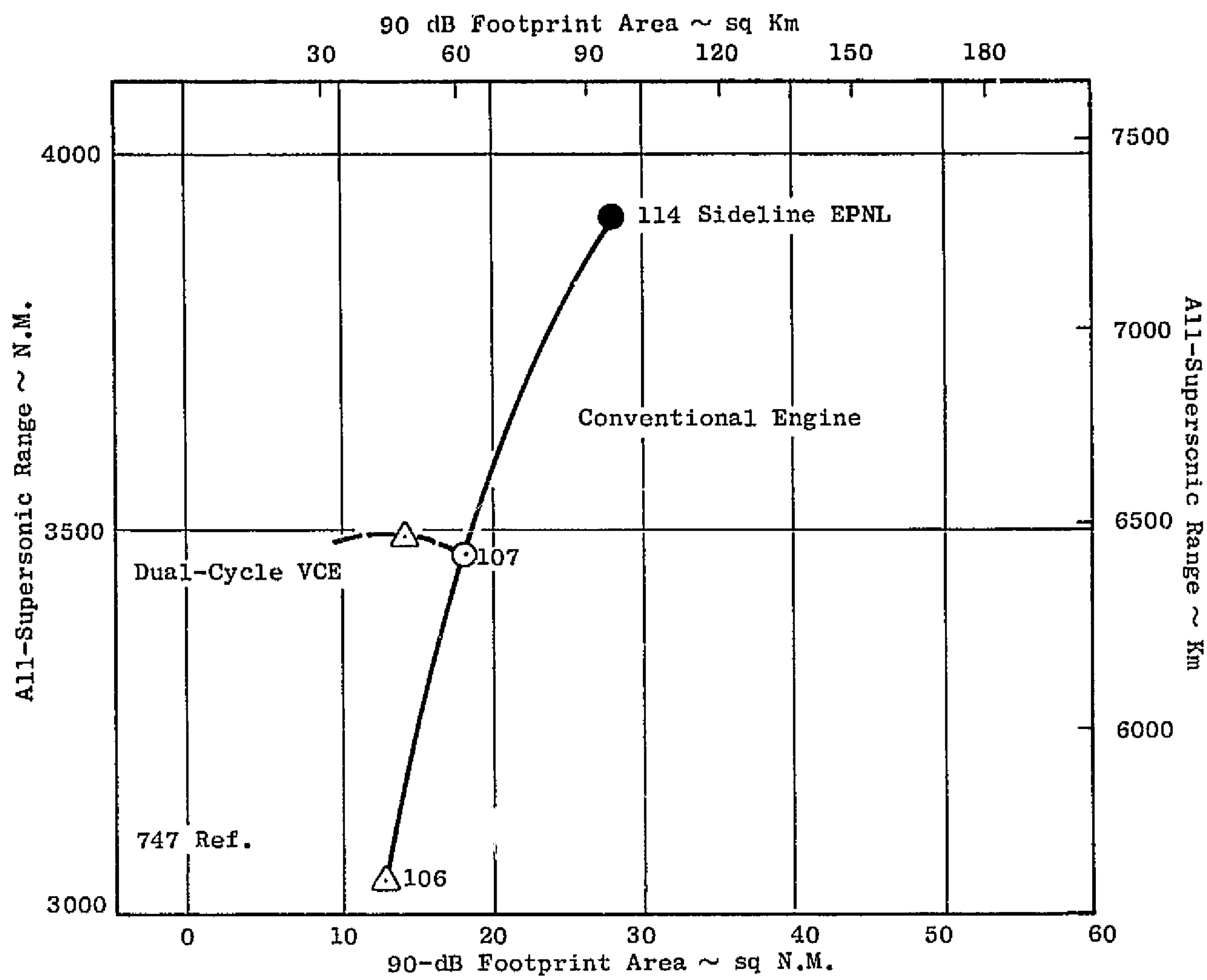


Figure 3. Dual-Cycle VCE Range and Footprint Improvements.

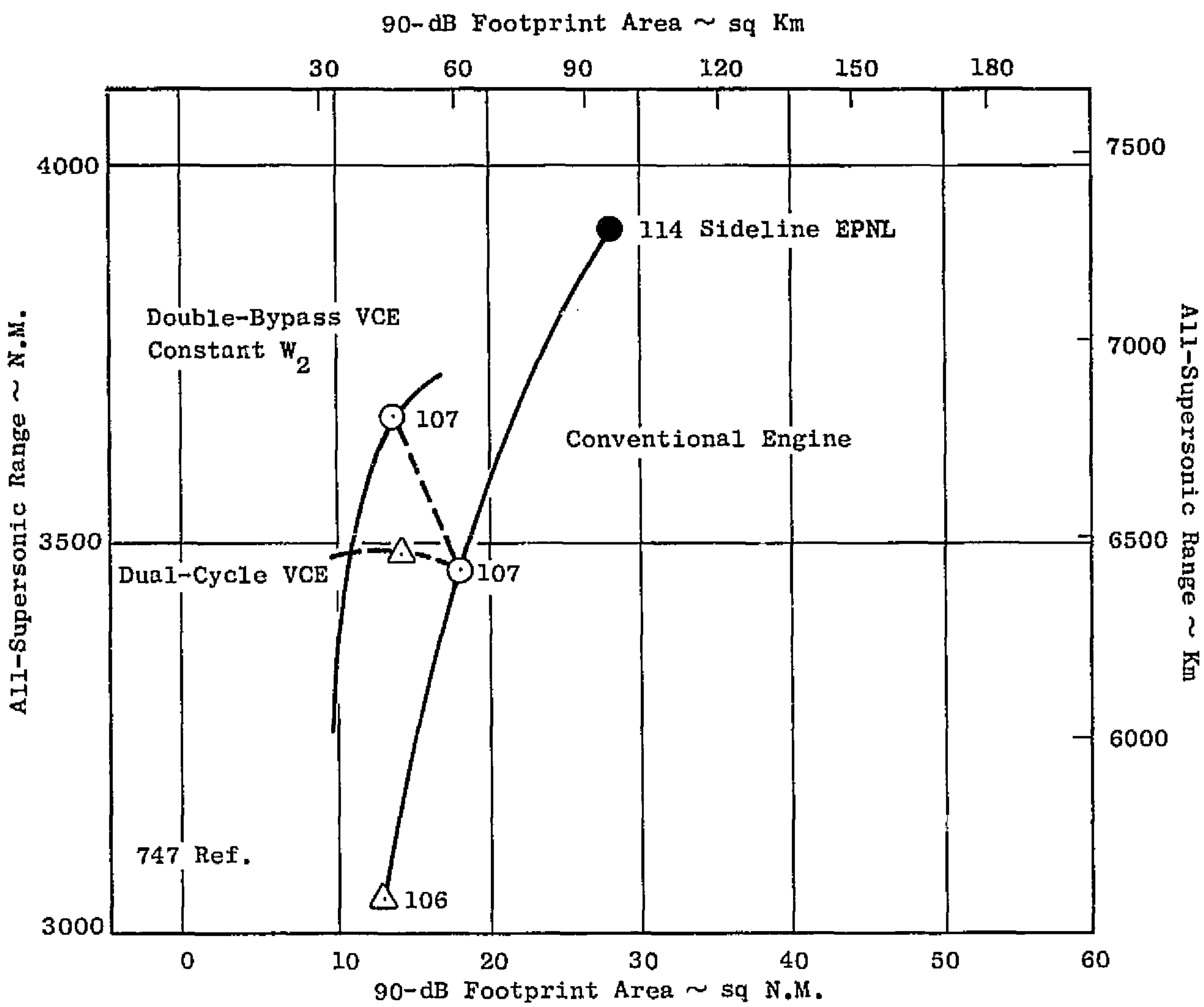


Figure 4. Double-Bypass/Dual-Cycle VCE Range and Footprint Improvements.

Preliminary design studies were completed and provided to the NASA-Lewis Research Center on the double-bypass VCE and selected components considered to be critical. These studies verified the weight, dimensions, and mechanical feasibility of the double-bypass VCE and the critical components.

The double-bypass VCE provides economic advantages over the conventional engines in the AST-2 airplane. Direct Operating Cost (DOC) and Return on Investment (ROI) for the VCE's are compared to conventional engines on Figures 5 and 6. At the selected noise level, the VCE shows a 3.5% improvement in DOC and a 25% improvement in ROI over the conventional engine at the same noise level. A further advantage of the double-bypass VCE is the fuel saving shown on Figure 7. Even in the 4000-N.M. (7408-Km) all-supersonic cruise mission, the VCE provides a fuel saving of 25,000 lbs (11,340 Kg). The addition of subsonic cruise segments provides even larger improvements over the conventional engines.

All of the conventional and VCE concepts defined in this study utilize a mechanical, chute-type, 15-PNdB static jet noise suppressor to suppress the total jet exhaust. The acoustics section (VI) of this report discusses the annular nozzle inherent noise suppression that has been identified in the duct-burning turbofan scale model acoustic testing done under NASA contract. The test results show that substantial jet noise suppression can be obtained in a single-stream exhaust nozzle configuration, very close to the annular plug nozzle utilized in all the current AST study engines, both conventional and variable cycle concepts. This annular suppression could allow the elimination of the mechanical jet exhaust suppressor with its high weight and complexity and provide an improvement in range, complexity, maintainability, and reliability.

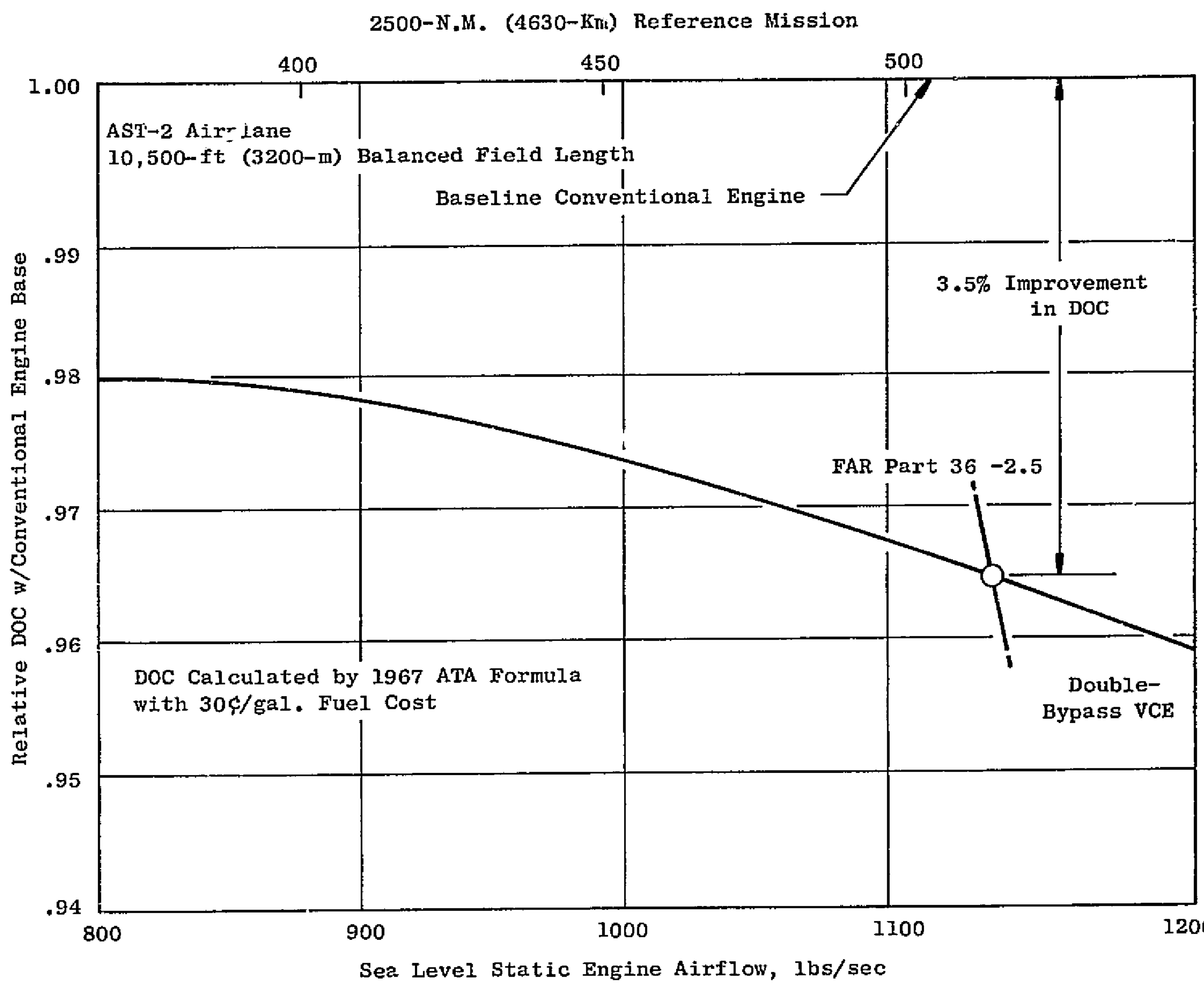


Figure 5. Double-Bypass VCE Improves Operating Cost.

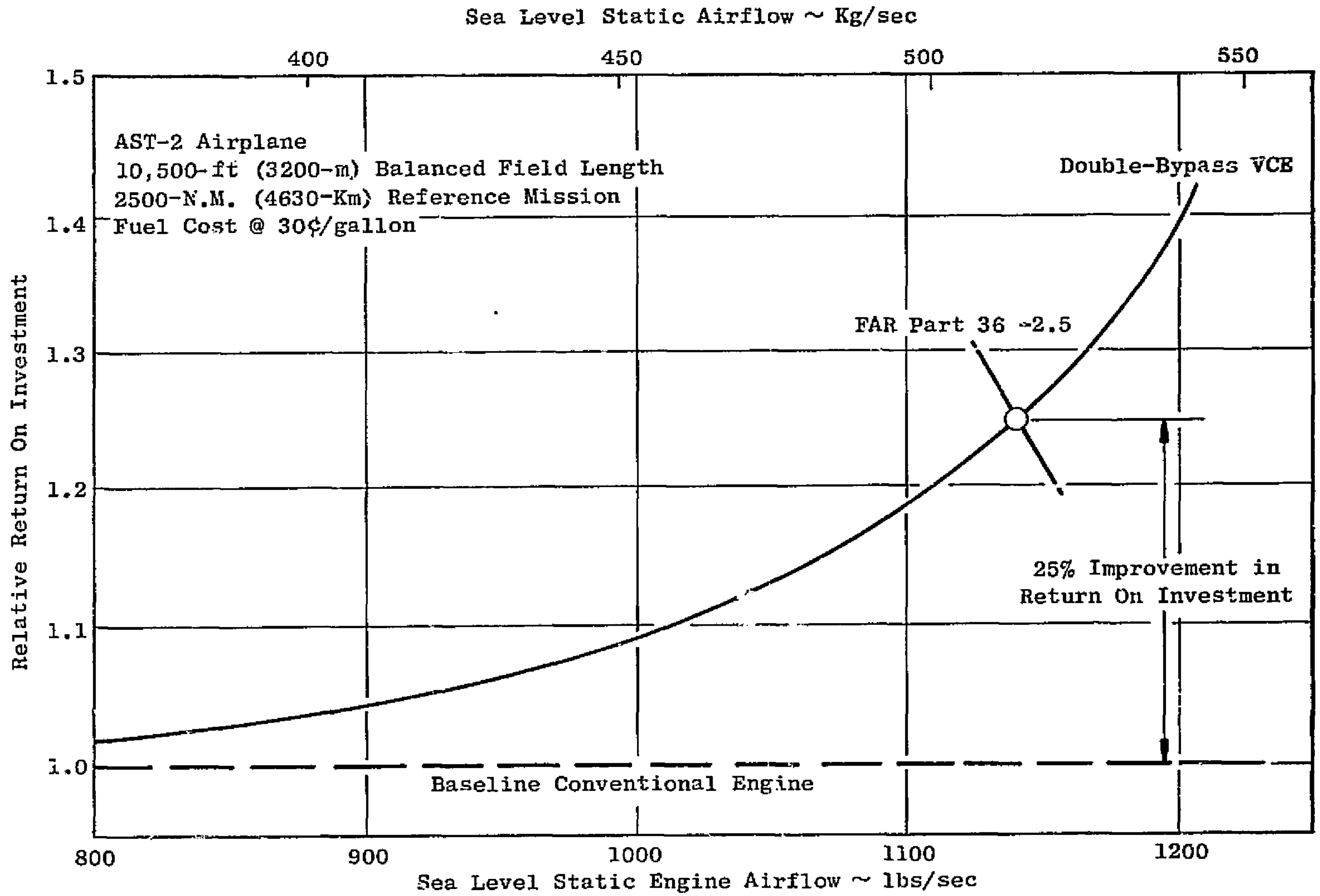


Figure 6. Double-Bypass VCE Improves Return On Investment.

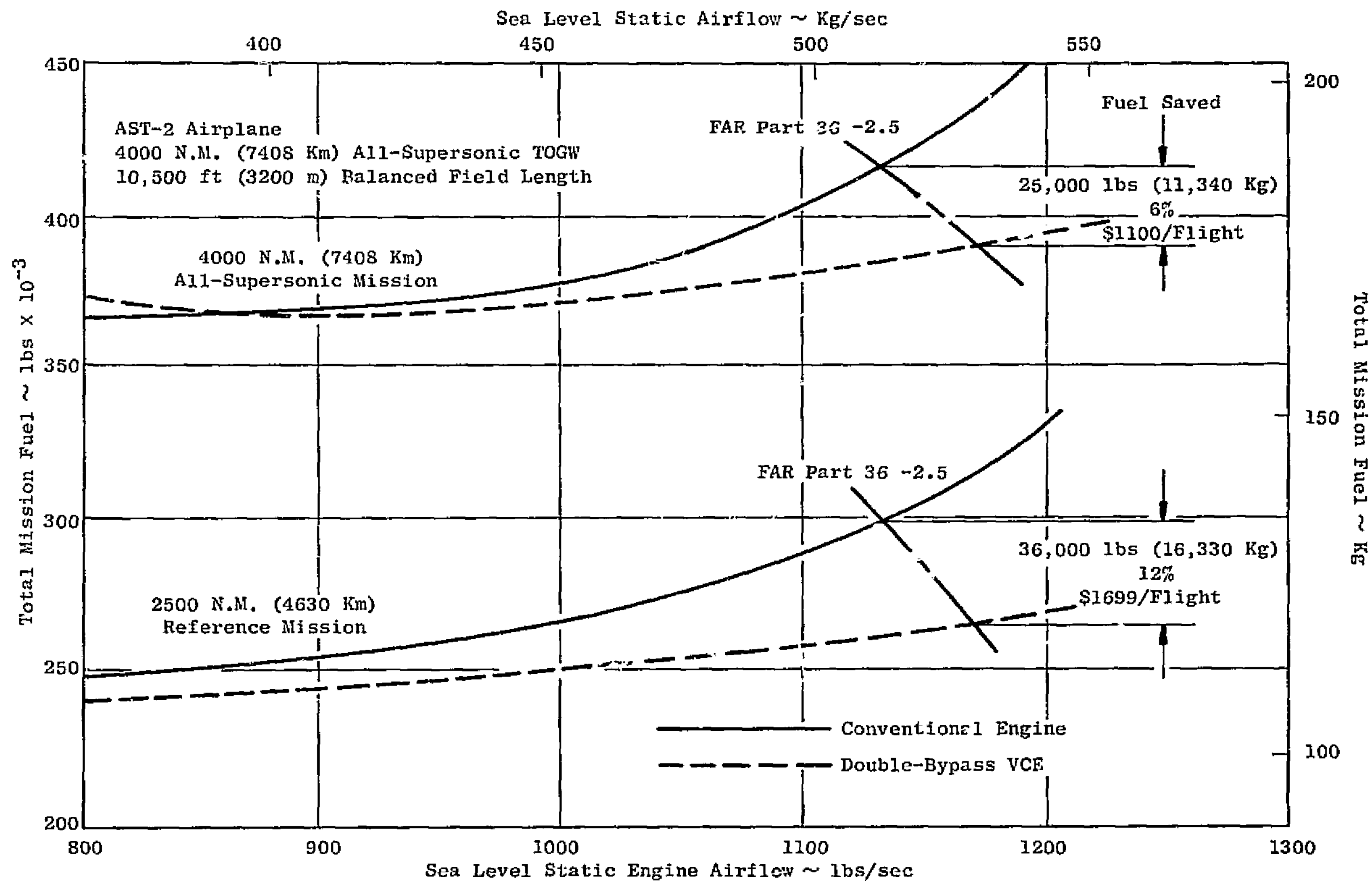


Figure 7. Mission Fuel Saved by Double-Bypass VCE.

SECTION III

GENERAL DISCUSSION - STUDY GROUND RULES

The effort required to balance the AST airplane, mission requirements, and range, in the evaluation of specific propulsion systems, is illustrated in Figure 8. The consideration of balanced field length, airplane definition, regulations, mission, noise, and economics must all be factored into the engine selection procedure.

Some specific ground rules (Table 7) have been set to define some of the possible variables. Many of these ground rules were carried over from the Phase I AST effort (Contract NAS3-16950), and others were introduced during the current Phase II effort (Contract NAS3-16950 Mod. 3). These new ground rules, specifically:

- Revised airplane definition
- Mission reserve definition
- Balanced field length

had an impact on the conventional baseline engine definition and caused a change in engine take-off size requirement and mission range in the baseline airplane. These new ground rules, along with a change to more realistic in-flight noise levels in the General Electric noise prediction procedure, combined to increase engine airflow size from small engines, well-matched to the airplane requirements, to much larger and heavier engines and higher take-off gross weight to perform the baseline 4000 N.M. (7408 Km) all-supersonic mission. These changes, however, did force the definition of variable cycle engine concepts that have high airflow at takeoff for low noise and small cruise size for efficient airplane matching.

A summary of the study ground rules for the Phase I and Phase II AST studies is given on Table 7. The Phase II study effort started, utilizing the Phase I ground rules as noted; and, the change to the newly defined Phase II ground rules was made after the initial baseline conventional engine definition and selection of the best cycle parameters. The remainder of the study used the Phase II ground rules, including all of the variable cycle engine studies.

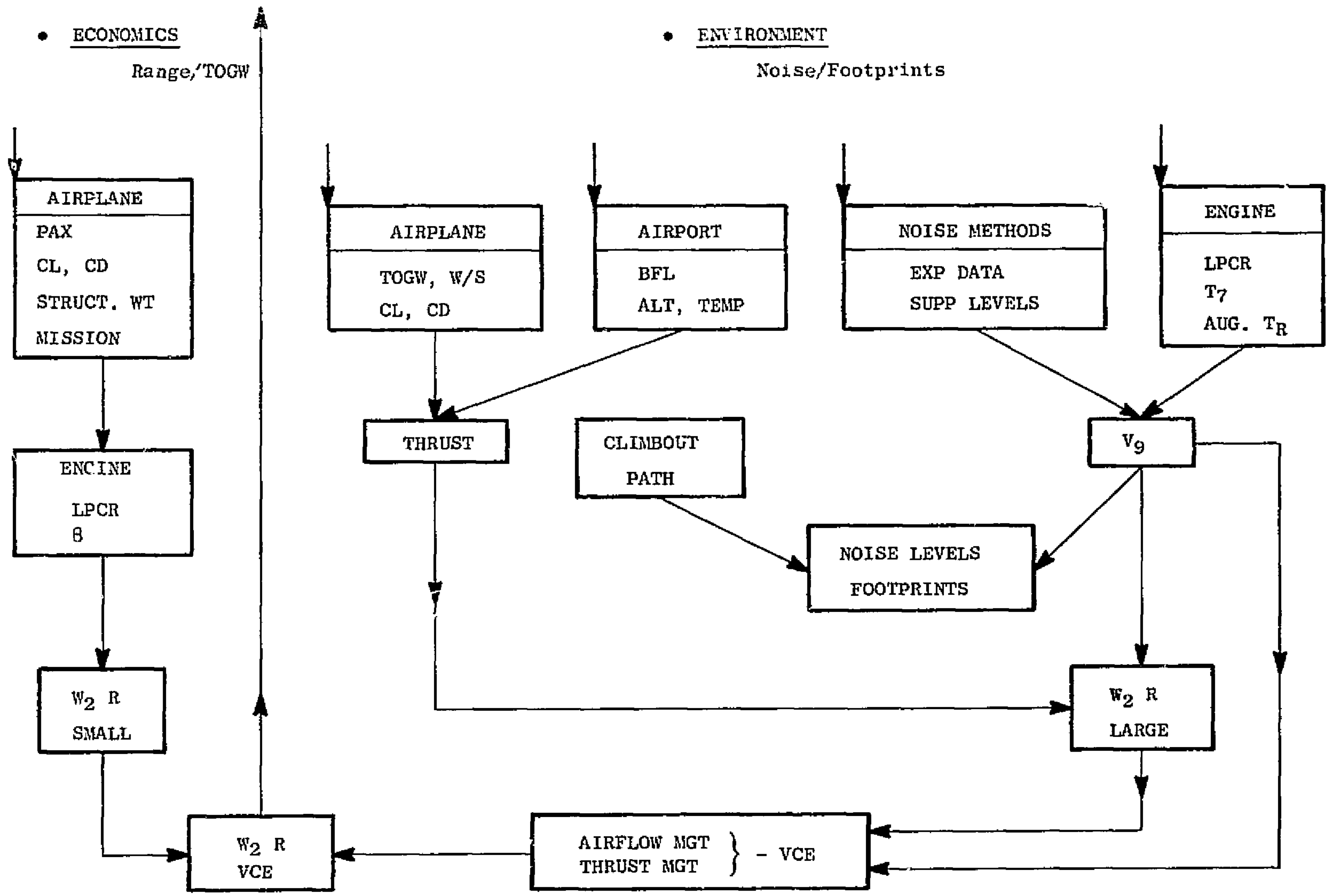


Figure 8. Balancing Economics and the Environment.

Table 7. AST Study Ground Rules.

	Phase I	Phase II NASA CR-132374
AIRPLANE CHARACTERISTICS		
TOGW	750,000 lbs (340,551 Kg)	762,000 lbs (346,000 Kg)
Aspect Ratio	1.7	1.904
S Wing	10,000 ft^2 (935 m^2)	9969 ft^2 (932 m^2)
Passengers	234	292
Payload	48,096 lbs (21,810 Kg)	61,030 lbs (27,700 Kg)
BALANCED FIELD LENGTH	12,400 ft (3780 m)	10,500 ft (3200 m)
MISSION		
Primary	600-NM (1111-Km) Initial Subsonic Cruise	All-Supersonic, 4000-NM (7410-Km)
Alternate	All-Supersonic, 4000 NM (7410 Km)	600-NM (1111-Km) Initial Subsonic Cruise
Economic	---	2500 NM (4630 Km) with 400-NM (741-Km) Initial Subsonic Cruise
RESERVES	FAR-121.648	Lockheed/TWA Report No. LP26133 Except: • 30-Minute Hold at 15,000 ft (4572 m) • Optimized Alt/M for 250-NM (463-Km) Diversion
NOISE GOALS	FAR Part 36 -0 to -10 PNdB	FAR Part 36 -0 to -5 PNdB
CRUISE MACH NUMBER	2.2, 2.7, 3.2	2.4

SECTION IV

CONVENTIONAL BASELINE ENGINE DEFINITION

At the conclusion of the Phase I effort, the low-bypass-ratio mixed-flow augmented engine was identified as having the best range in the Phase I airplane. Even though the propulsion system weight was higher than the duct-burning turbofan, the smaller airflow size and better supersonic performance more than compensated for the weight differential. Figure 9 compares the mission range and propulsion system weight of the three best engines from the Phase I study. The results shown are a Mach 2.7 supersonic cruise, but comparable results were obtained at lower Mach numbers.

The Phase II study was based on optimizing the mixed-flow augmented turbofan cycle and modifying this base conventional engine by adding variable cycle engine features to improve performance. The addition of these variable engine cycle features will add complexity and weight, so these features were measured by the range in the baseline AST aircraft.

A matrix of bypass ratio and fan pressure ratio was set up for conventional cycle engines at a constant overall pressure ratio and turbine inlet temperature (T_{41}). This mixed-flow augmented turbofan matrix covered the following ranges:

- Fan pressure ratio - 3.0 to 4.5
- Bypass ratio - 0.3 to 1.1

The engine performance, weight, and dimensions were obtained from the AST Parametric Engine Computer Program in an 850 lb/sec (386 Kg/sec) airflow size. The results of this constant airflow study are given on Figures 10, 11, and 12, which present engine weight, geometry, and performance as well as the important cycle parameters at the supersonic cruise flight condition. Figure 13 presents the range performance of these engines in the 850 lb/sec (386 Kg/sec) airflow size in the baseline 600 N.M. (1111 Km) initial subsonic cruise mission. The best engines for maximum range are the lowest bypass engines at each fan pressure ratio. In the 850-lb/sec (386-Kg/sec) airflow size, the mission results of the 3.0, 3.5, and 4.0 fan pressure ratios are about the same, but the engines have not yet been scaled to match the airplane requirements. The four base engines (3.0, 3.5, 4.0, and 4.5 fan pressure ratio) were scaled from 850 lb/sec (3.86 Kg/sec) to 680 lb/sec (308 Kg/sec), and the three AST missions were evaluated in the AST baseline airplane (Figure 14). In general, the smallest airflow size engines gave the longest range, regardless of mission type.

The 4.0 fan pressure ratio engine was the overall best, when it was sized at 700 lb/sec (318 Kg/sec) airflow to meet the mission constraints (thrust/drag = 1.2, noise level, subsonic cruise thrust level). The 4.0 fan pressure ratio, 0.43 bypass ratio, 700 lb/sec (318 Kg/sec) airflow size engine was selected as the baseline conventional cycle.

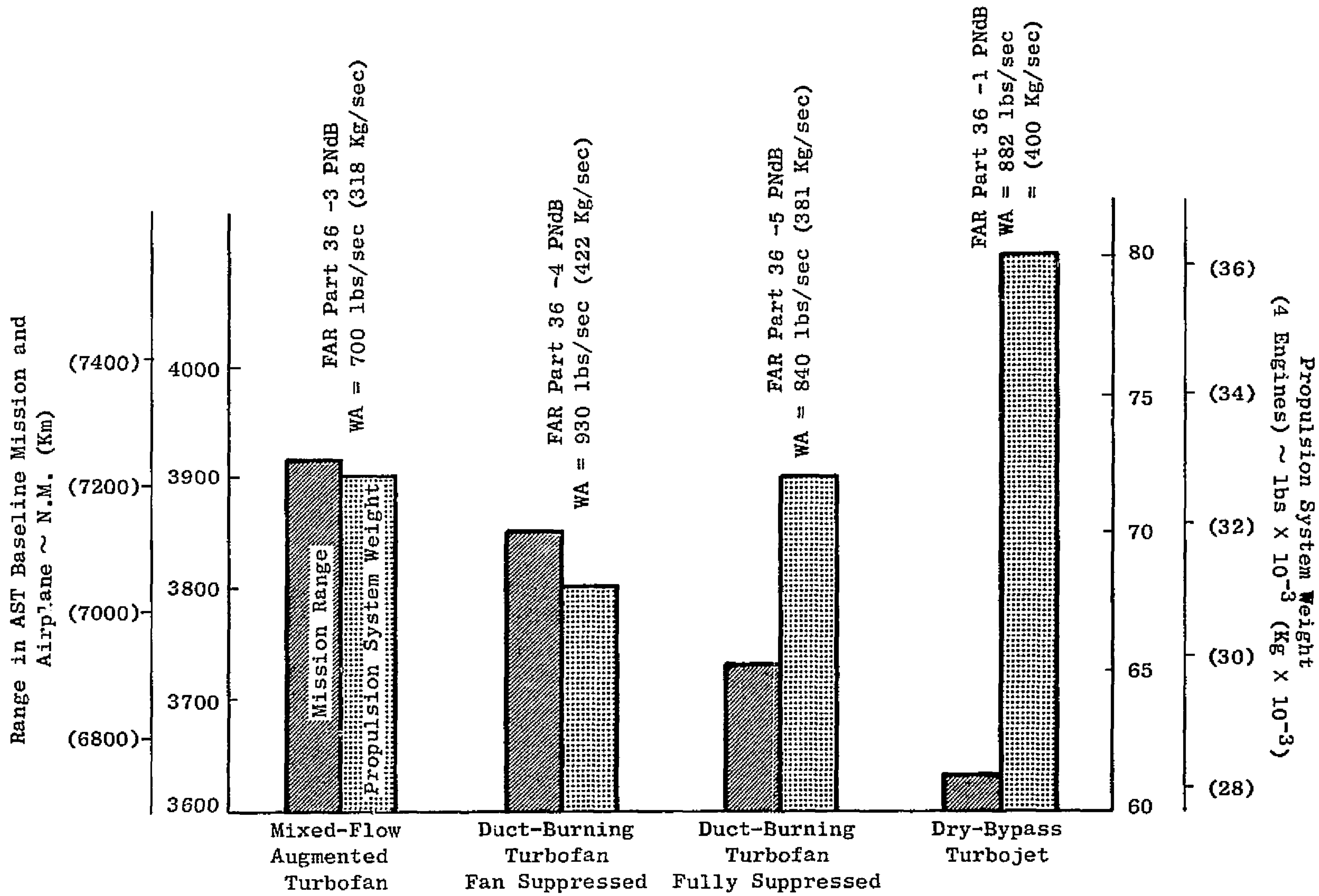


Figure 9. Advanced Supersonic Propulsion System Technology Study, PostTask VI Results, M = 2.7 AST Baseline Mission, 750,000-lb (340,200 Kg) TOGW.

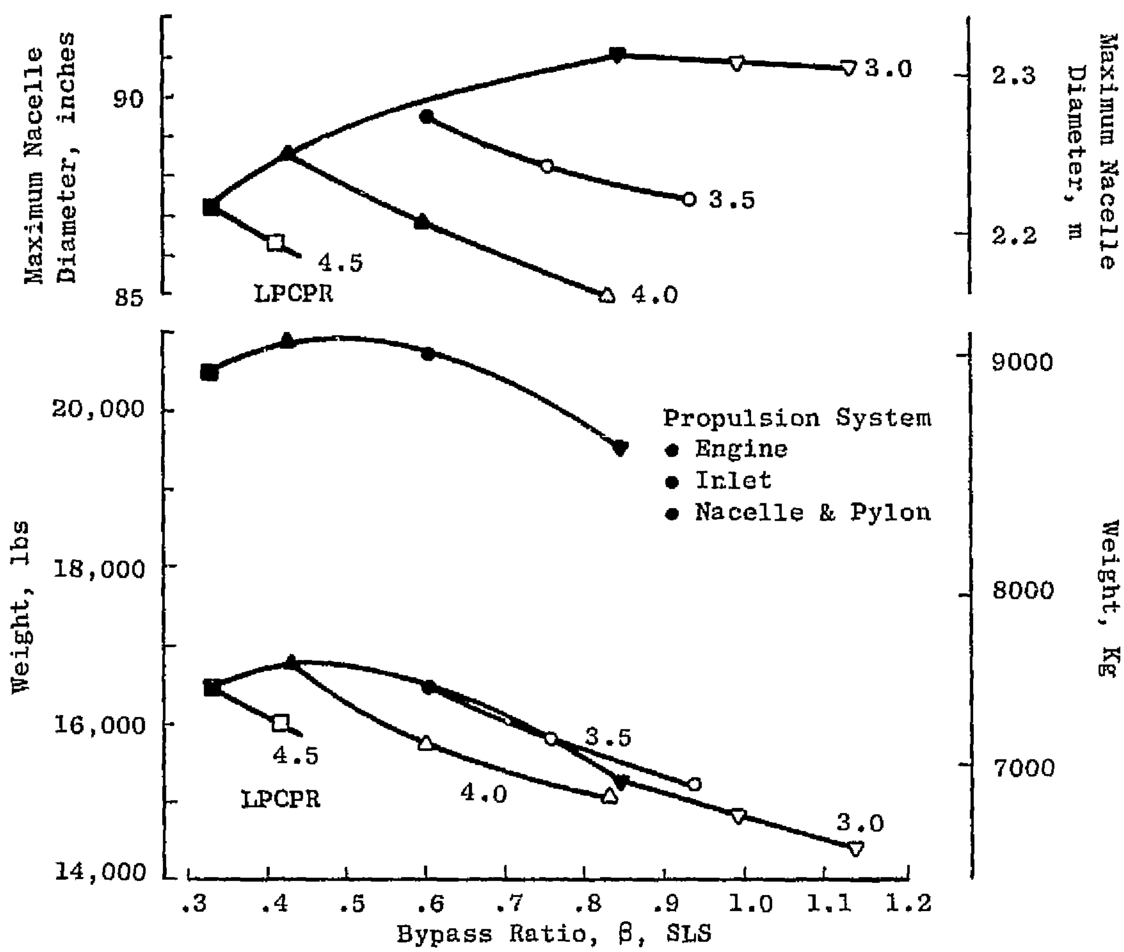


Figure 10. Weights and Dimensions of Mixed-Flow Augmented Turbofans at 850 lbs/sec (386 Kg/sec) Airflow.

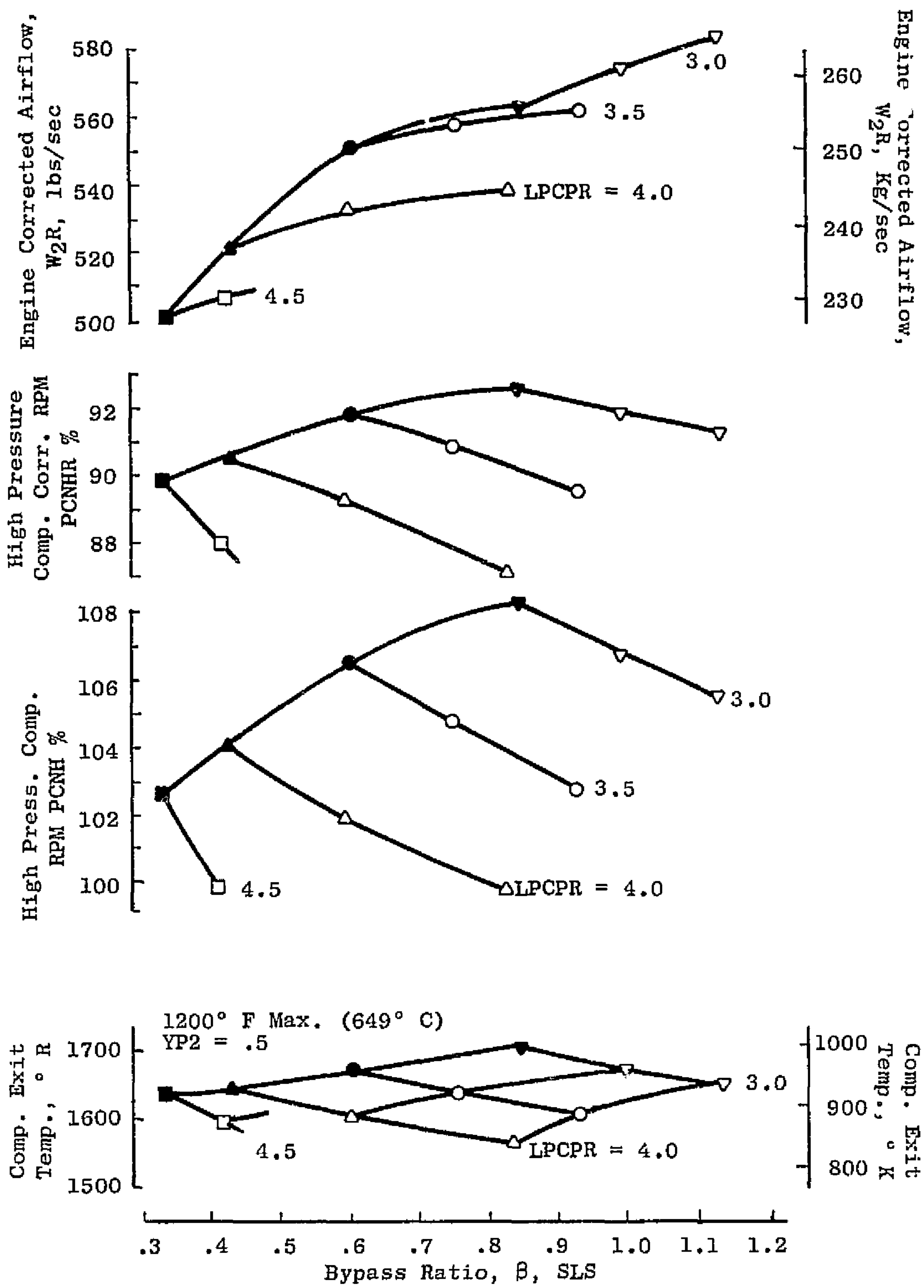


Figure 11. Engine Performance in Supersonic Cruise (M = 2.32).

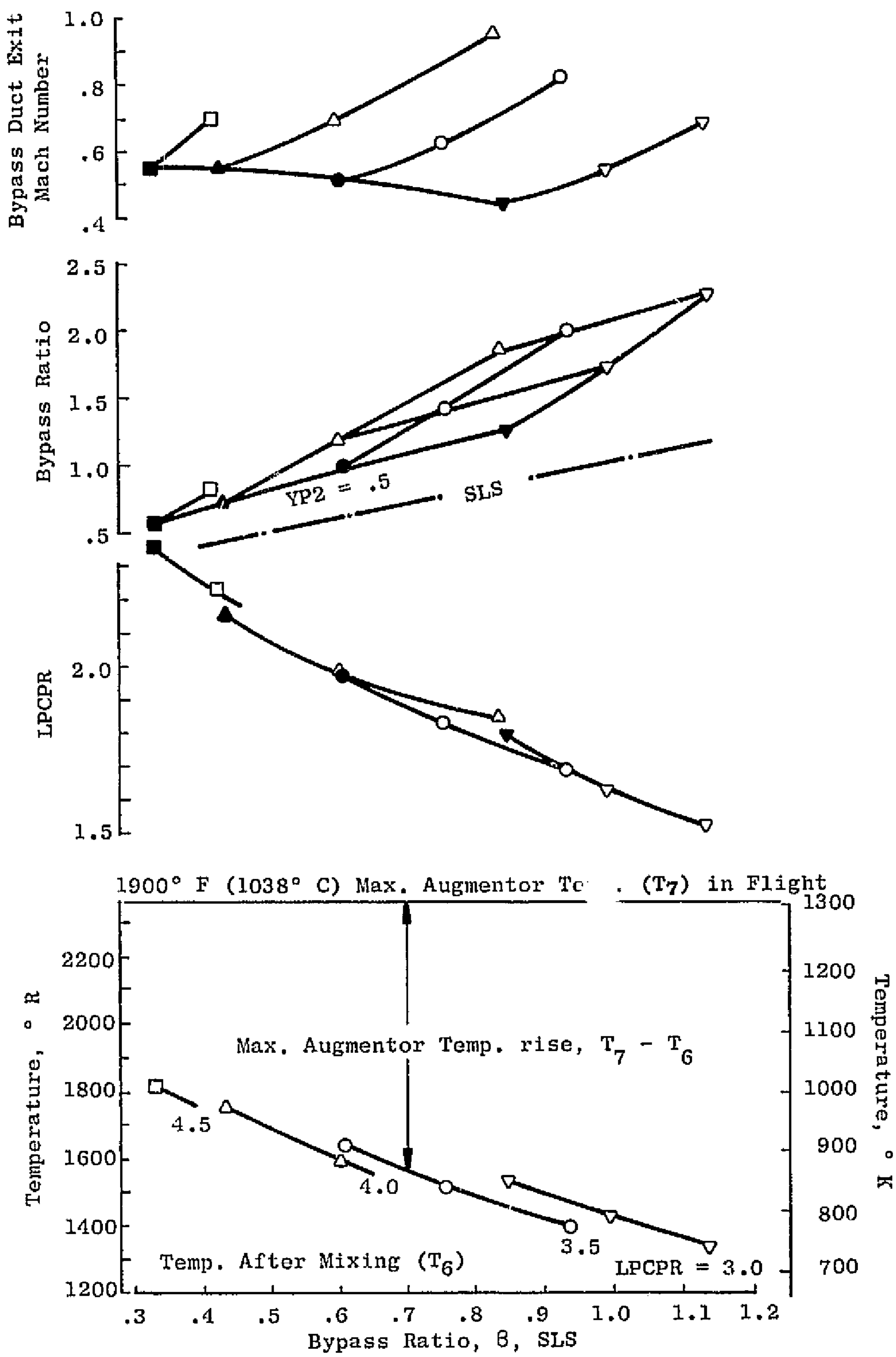


Figure 12. Engine Performance in Supersonic Cruise (M = 2.32).

NOTE:

- SLS Airflow = 850 lbs/sec (386 Kg/sec)
- OPR = 22.5
- Maximum T_{41} = 2800° F (1538° C)
- Supersonic Cruise T_{41} = 2700° F (1482° C)
- T_7 Augmentor = 1900° F Max. (1038° C)

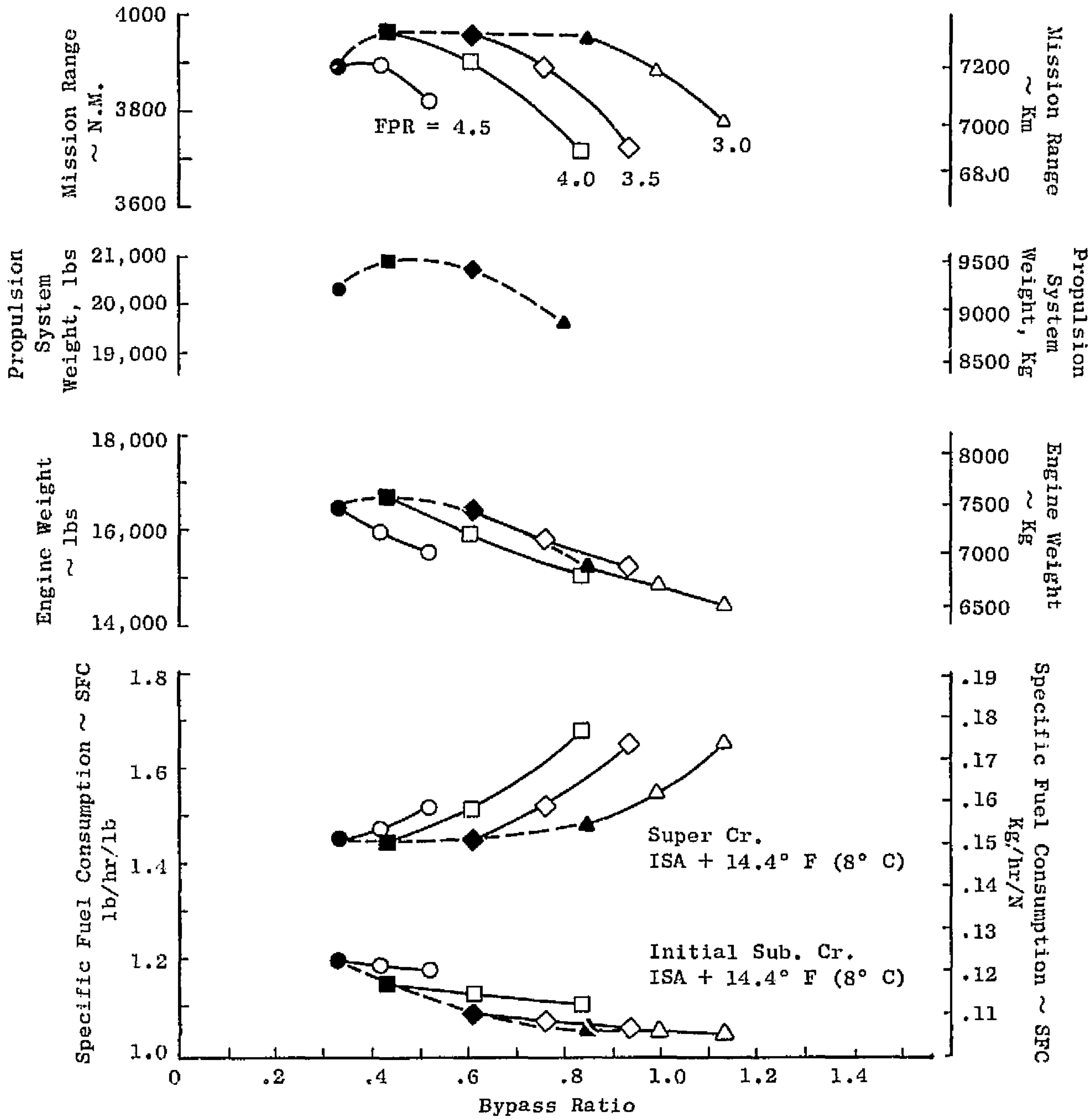


Figure 13. Mach 2.4 Mission Summary, Base Mission 600-N.M. (1111 Km) Initial Subsonic Cruise, Baseline Engines.

ISA + 14.4° F (8° C) Day

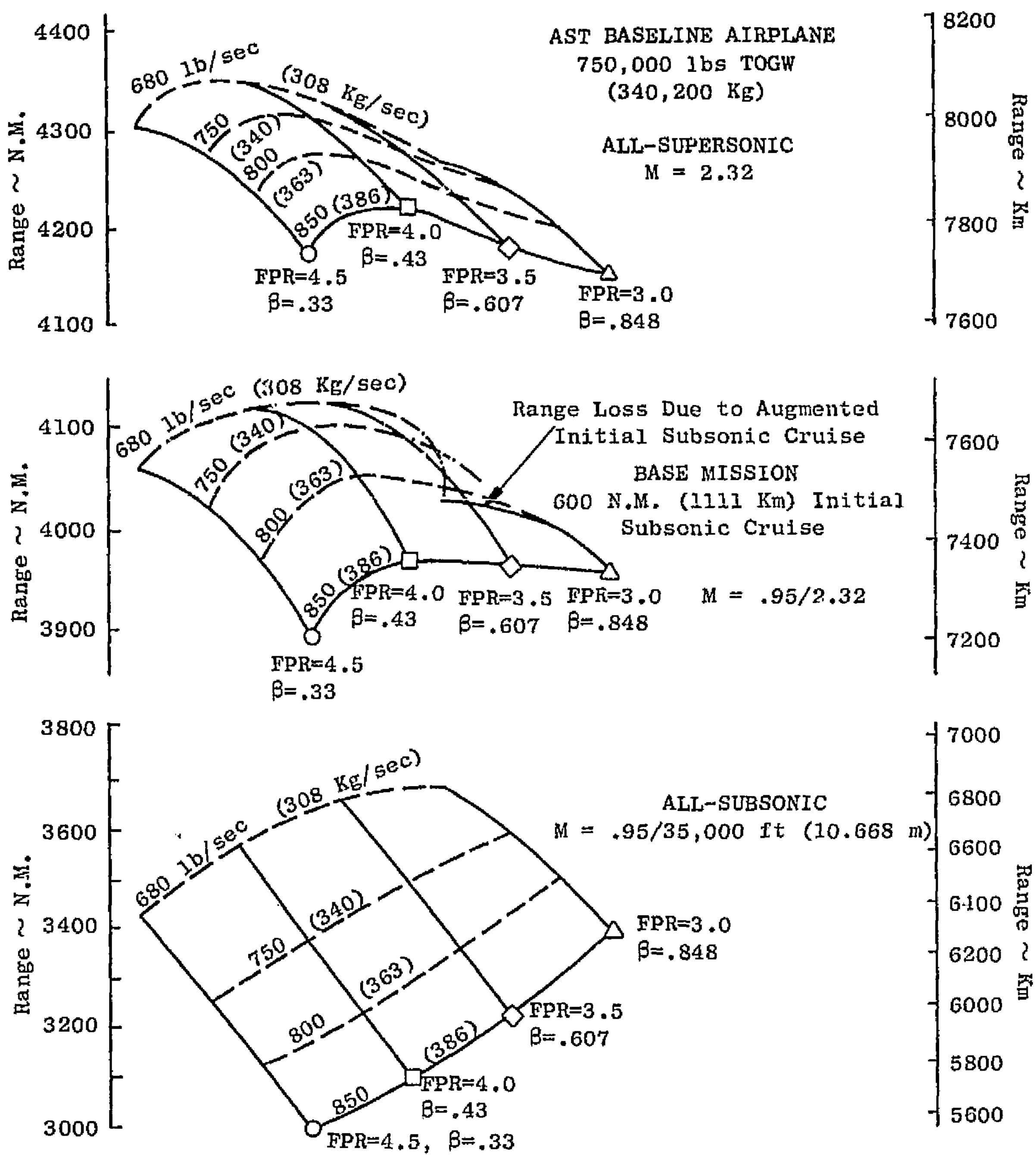


Figure 14. Effect of Engine Cycle and Size on Mission Ranges.

After selection of the baseline conventional engine cycle, a short study was conducted to verify that the selected cycle pressure ratio of 22.5 was correct for this engine. Figure 15 compares thrust and specific fuel consumption at key operating conditions, and the mission range and propulsion system weights at three cycle pressure ratios: 19.0, 22.5, and 25.0. Only very small differences in specific fuel consumption and weight result from the changes in cycle pressure ratio, so the original 22.5 cycle pressure ratio was not changed.

A. Take-off Noise and Footprint Area

The take-off noise and resulting noise footprint area are the major sizing criteria for the AST engines. The jet noise suppressor technology, assumed take-off trajectory, and balanced field length requirements all play a part in the determination of the engine airflow required to meet a noise goal. The noise footprint area is a major consideration, perhaps more important than the overall traded FAR Part 36 noise level. The footprint area is a measure of the number of people subjected directly to the engine noise during the takeoff and landing. For a specified FAR Part 36 noise level, a wide variation in noise footprint area is possible. Figure 16 shows a typical noise footprint which is dominated by the community noise. The contour also is shown for a takeoff with no power cutback, and with power cutback at the community measuring station. In the AST Phase II study, the sideline noise has been made the dominant noise factor, rather than community or approach conditions. As shown on Figure 17, with the sideline the dominant noise source, the traded FAR Part 36 noise level can be determined in different ways. Set "B" has been selected, which means that sideline noise can exceed the desired FAR Part 36 noise level by 2 dB; the approach noise level may be 1 dB above; and, the community must be 3 dB below the desired FAR Part 36 noise level.

The jet noise suppressors on all of the conventional engine cycles covered in this section utilize 15 PNdB jet noise suppressors projected to a 1985 technology level. Testing completed in the past year has demonstrated 13 PNdB static jet noise suppression from a 32-chute suppressor on a J79 engine. The thrust coefficient demonstrated for this suppressor configuration (0.92) has been used in this study, with 2 PNdB additional jet noise suppression (15 PNdB total) assumed to be available by 1980.

Figure 18 shows the jet noise suppressor design point envelope as a function of exhaust gas velocity (V_9). The peak suppression available at any exhaust velocity is given by the design-point envelope. The off-design operation of any point design suppressor is shown by the dashed lines. A suppressor designed for a 2850 ft/sec (869 m/sec) V_9 would have a peak suppression capability of 13.2 PNdB. Its off-design performance at 2000 ft/sec (610 m/sec) would be 6.4 PNdB. If the suppressor were designed for a 2500 ft/sec (762 m/sec) V_9, its off-design performance would be 13.0 PNdB at 2850 ft/sec (869 m/sec) V_9 (about the same as the design point suppressor for that jet velocity); and, at 2000 ft/sec (610 m/sec), its suppression level would be 10.8 PNdB [compared to 6.4 PNdB for the design point at 2850 ft/sec (869 m/sec) V_9]. The proper selection of suppressor design point jet velocity

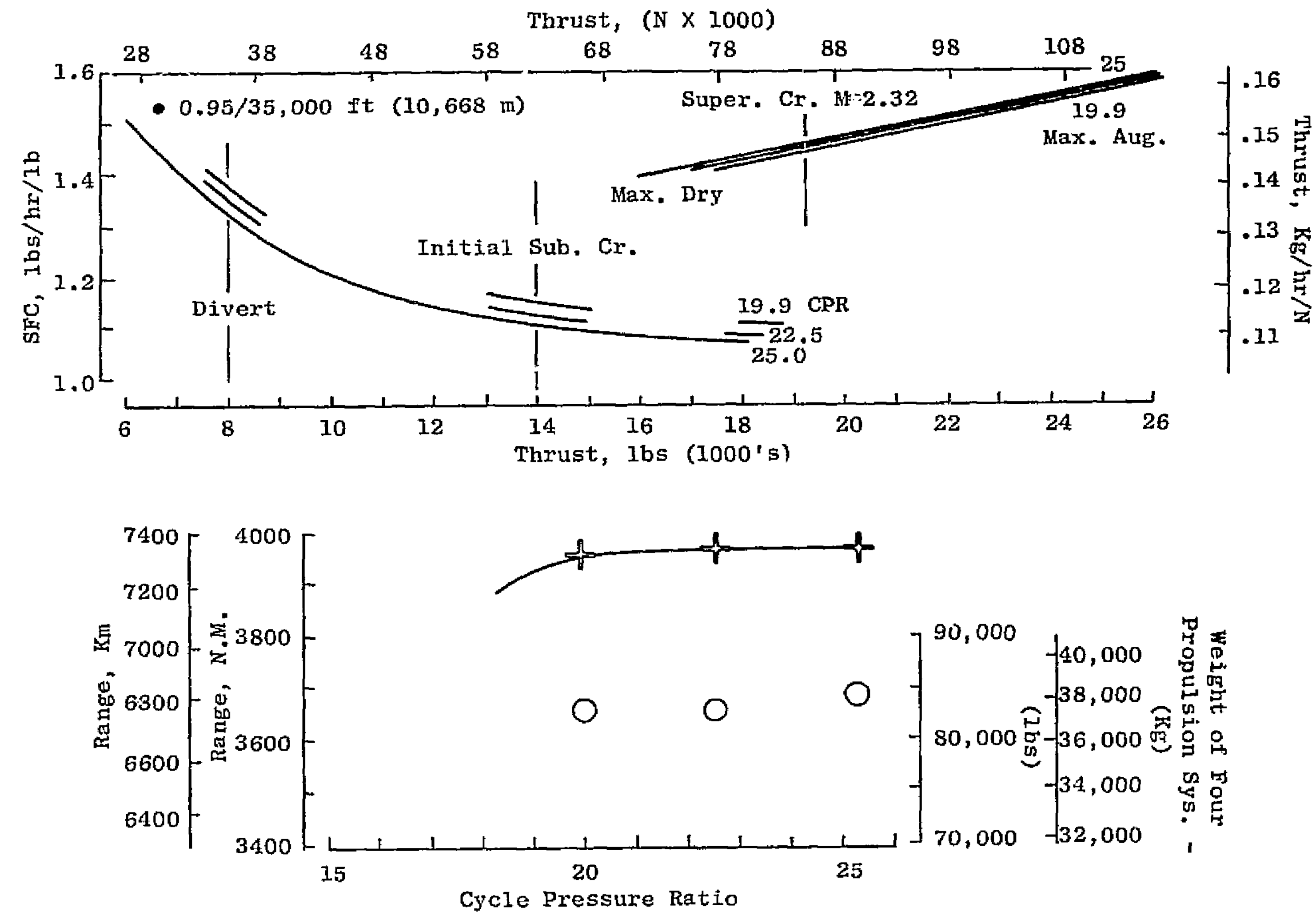


Figure 15. Effect of Cycle Pressure Ratio at M = 2.4 in AST Baseline Airplane, T_{41} Supersonic Cruise = 2700° F, LPCPR = 4.0, BPR = .43.

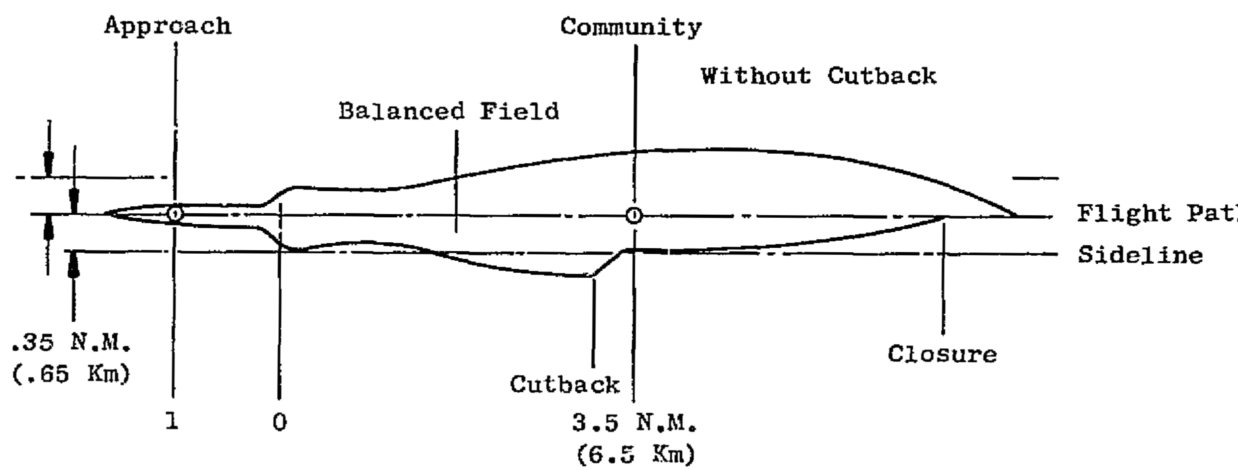


Figure 16. Noise Footprints.

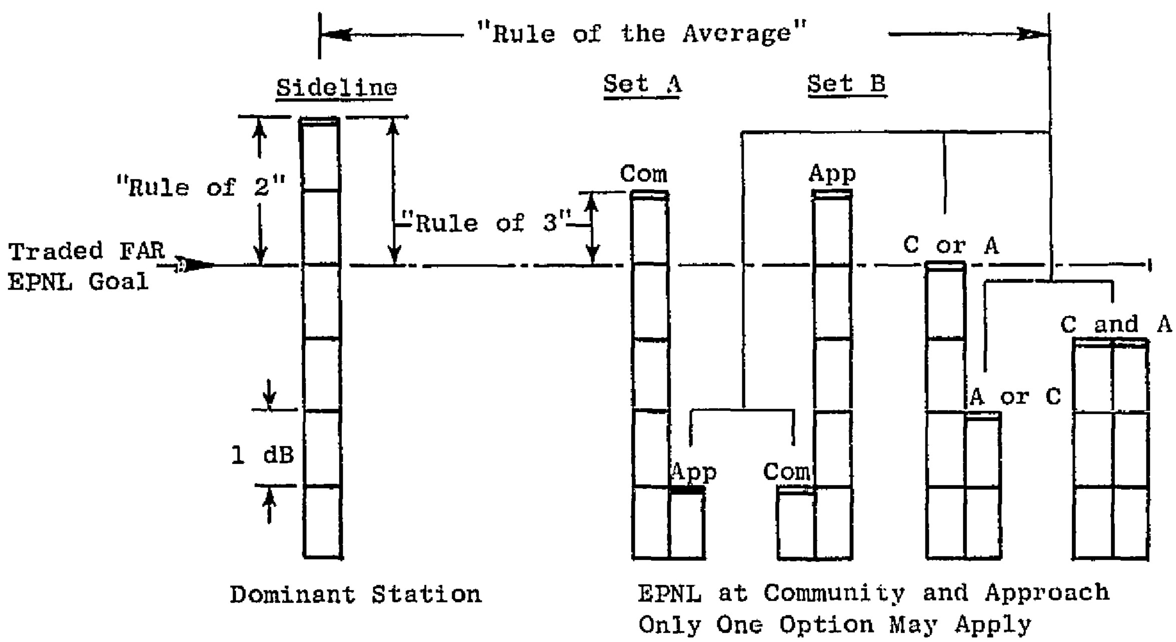


Figure 17. Trading Noise by FAR Part 36 Rules.

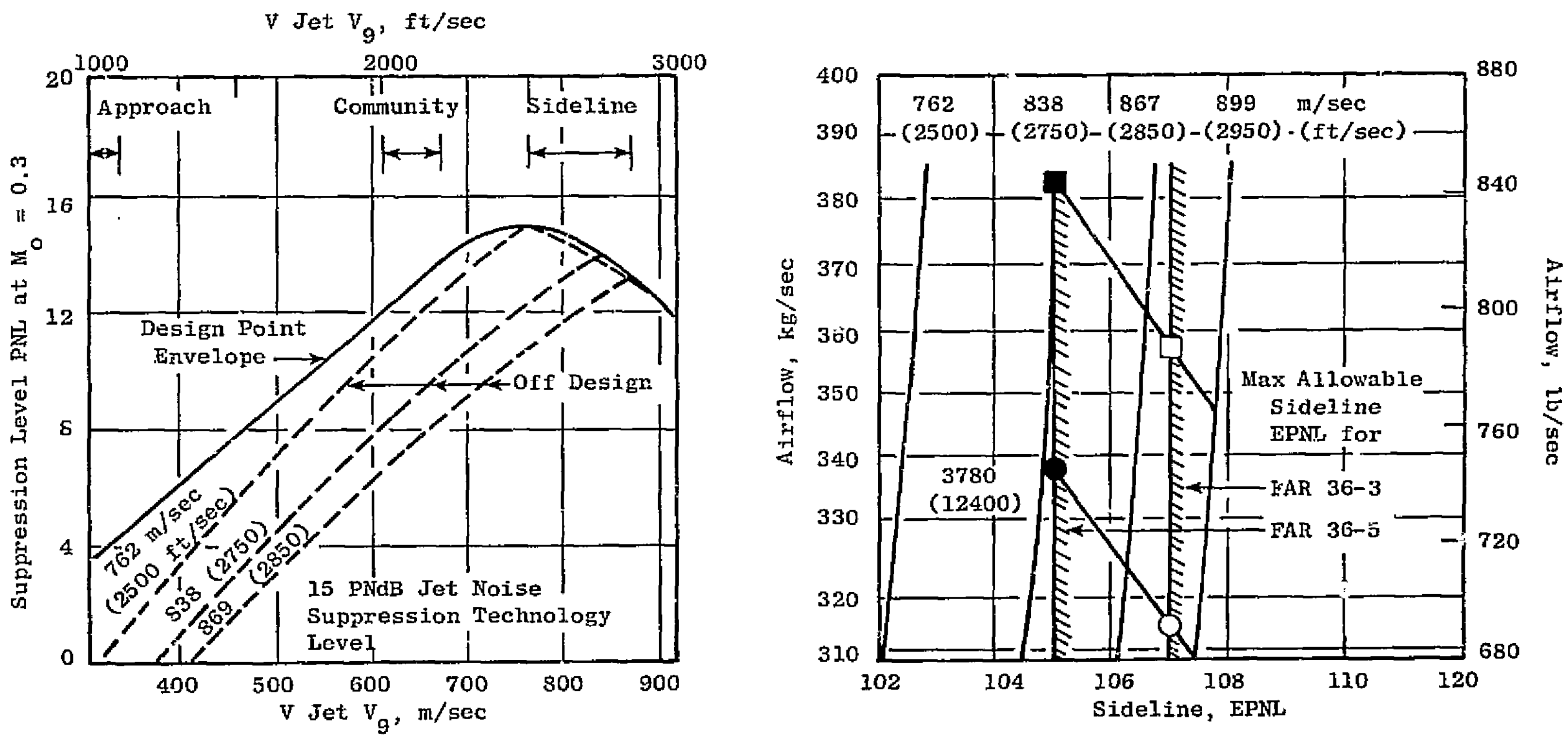


Figure 18. Jet Velocity and Jet Noise Suppressor Options, GE21/F2, 4 P_4. LPCPR = 4.0, β = 0.43, AST Baseline Airplane, TOGW = 750,000 lbs (340,200 Kg).

can have a large effect on the FAR Part 36 noise level and the footprint area.

The right hand curve on Figure 18 presents sideline EPNL as a function of engine airflow, for four scaled baseline conventional engines, sized for:

FAR Part 36 -3 PNdB	-	12,400 ft (3780 m) BFL
		10,500 ft (3200 m) BFL
FAR Part 36 -5 PNdB	-	12,400 ft (3780 m) BFL
		10,500 ft (3200 m) BFL

Figure 19 shows these four engines at takeoff with a balanced field length of both 12,400 ft (3780 m) and 10,500 ft (3200 m), for both the power cutback and no cutback operating conditions. With the jet noise suppressors designed for a 2925 ft/sec (892 m/sec) design point operation, the 12,400-ft (3780 m) balanced field length engines will not meet the FAR Part 36 -3 or -5 PNdB community noise level goal. The 10,500-ft (3200-m) balanced field length engines almost meet the FAR Part 36 -3 PNdB goal, but will not meet FAR Part 36 -5 PNdB. When the suppressor is designed for a 2500-ft/sec (762-m/sec) design point, and operated off-design as shown on Figure 18, for both the sideline and community measuring points, all the 10,500-ft (3200-m) balanced field length engines meet FAR Part 36 -5 PNdB, and the 12,400-ft (3780-m) balanced field length engines meet FAR Part 36 -3 PNdB. With no power cutback, the engines will not meet the community noise goals for either balanced field length.

A similar reduction in 100 PNdB contour footprint area and closure distance is realized by proper selection of the jet noise suppressor design point.

FAR Part 36 -3 to -5 PNdB noise goals and reasonable 100 PNdB contour footprint areas and closure distances can be attained with the proper selection of the jet noise suppressor design point and utilizing power cutback at the community measuring point.

Figure 20 shows a similar analysis for the same engines at the approach operating condition. In this operating condition, the jet noise suppressors are not deployed, since lower exhaust velocity and jet noise can be obtained by maintaining high engine airflow and opening the exhaust nozzle to obtain the required operating thrust. The 12,400-ft (3780-m) balanced field length engines can meet the FAR Part 36 -3 PNdB approach noise goal, and the 10,500-ft (3200-m) balance field length engines can meet the lower approach noise level goal of FAR Part 36 -5 PNdB.

The approach condition could be the limiting noise operating condition if traded FAR Part 36 noise levels lower than FAR Part 36 -5 PNdB are desired. The aerodynamic noise of the airplane with gear and flaps in the landing configuration may set the lowest FAR Part 36 noise level that can be obtained.

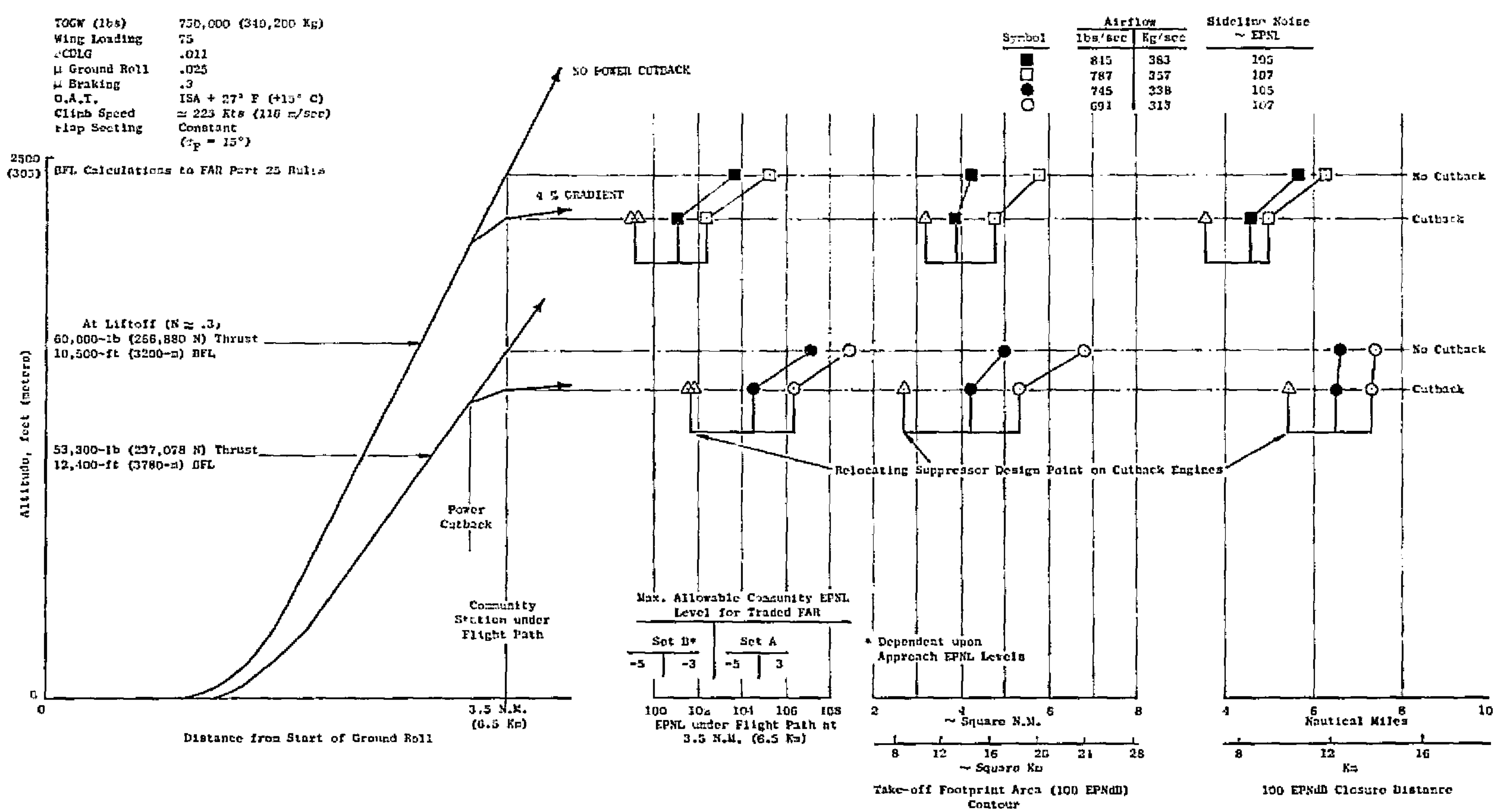


Figure 19. Take-off Balanced Field Length and Climb-out Options with Resultant Noise Characteristics, GE21/F2.4P4, LPCPR = 4.0, β = 0.43, AST Baseline Airplane.

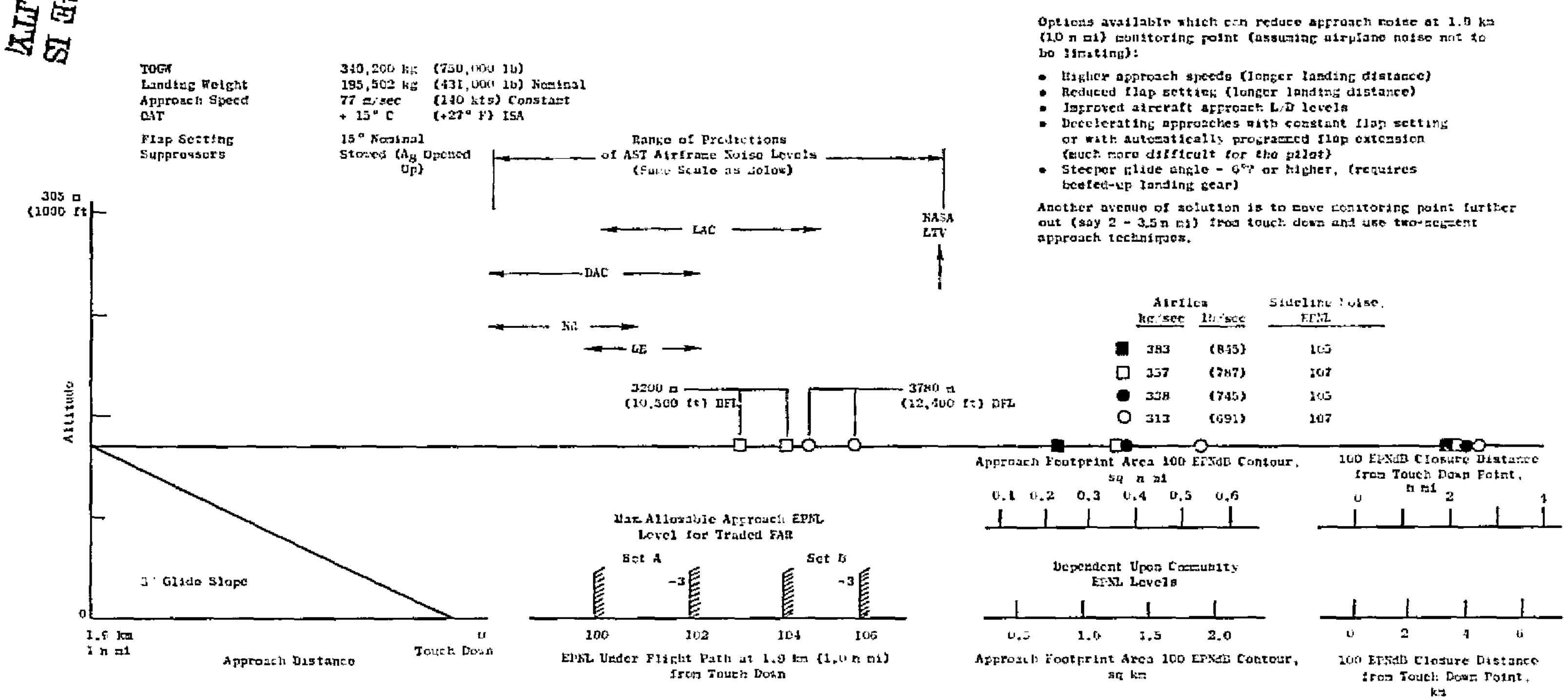


Figure 20. Approach Noise, GE21/F2.4P4, LPCPR = 4.0, β = 0.43, AST Baseline Airplane.

The effect of balanced field length and take-off noise level is primarily a function of engine airflow size and exhaust velocity to give a required thrust level to meet balanced field length and noise levels with a given jet noise suppressor technology. As the airflow varies to meet these constraints, the engine weight and thrust levels at the required operating conditions also vary. Figure 21 presents the AST mission range for varying airflow size, noise level, and balanced field length. The smallest engines (higher noise and longer balanced field length) give the longest range in the AST baseline airplane regardless of mission type. The higher airflow required to meet shorter field lengths and lower noise levels results in reduced range or higher gross weight to meet a required range.

It can be concluded that the engines sized to meet the shorter balanced field length have lower noise levels because they reach a higher altitude over the community noise-measuring station. The higher airflow and weight, however, result in a lower mission range in the baseline airplane.

The final selection of the conventional baseline mixed-flow augmented turbofan engine (GE21/F12 Study B-1) sized for the AST-1 airplane and a 12,400-ft (3780-m) balanced field length is shown on Table 8. The physical characteristics of the selected engine are shown on Table 9.

B. Effect of Ground Rule Changes on Conventional Baseline Engine

At this point in the program, the new AST-2 airplane and the 10,500-ft (3200-m) balanced field length requirement were evaluated, using the selected baseline conventional engine. Table 10 compares the AST-1 and AST-2 airplanes at the same 10,500-ft (3200-m) balanced field length. Since the low speed characteristics of the airplanes are similar, the take-off (rotation) thrust levels are the same for the same balanced field length. The change in balanced field length from 12,400 ft (3780 m) to 10,500 ft (3200 m), however, increased the take-off thrust requirement from 53,000 lbs (237,968 N) to 61,400 lbs (273,107 N) for both airplanes. The combination of the increase in balanced field length and baseline airplane take-off gross weight (TOGW) reduced the range of the AST-2 airplane from that of the AST-1 airplane by a substantial amount. Table 11 gives a direct comparison of the combined effects of the change in baseline airplane definition and balanced field length requirements on the aircraft range. The AST-2 airplane, with the reduced balanced field length, has from 300 to 400 N.M. (556 to 741 Km) less range in all the studied missions than the AST-1 airplane with the longer balanced field length. The impact on economics of this change in ground rules is not that drastic, since the payload (passengers) has been increased by 25% in the AST-2 airplane.

C. Effect of In-Flight Noise Predictions on Engine Size and Aircraft Range

During the AST study, acoustic data became available from many different sources which indicated that the in-flight noise prediction method used in the AST study up to that time was optimistic. Analysis of this flight-type data showed that the impact of a more realistic jet noise prediction method would be from 4 to 6 PNdB higher in-flight noise than previously assumed.

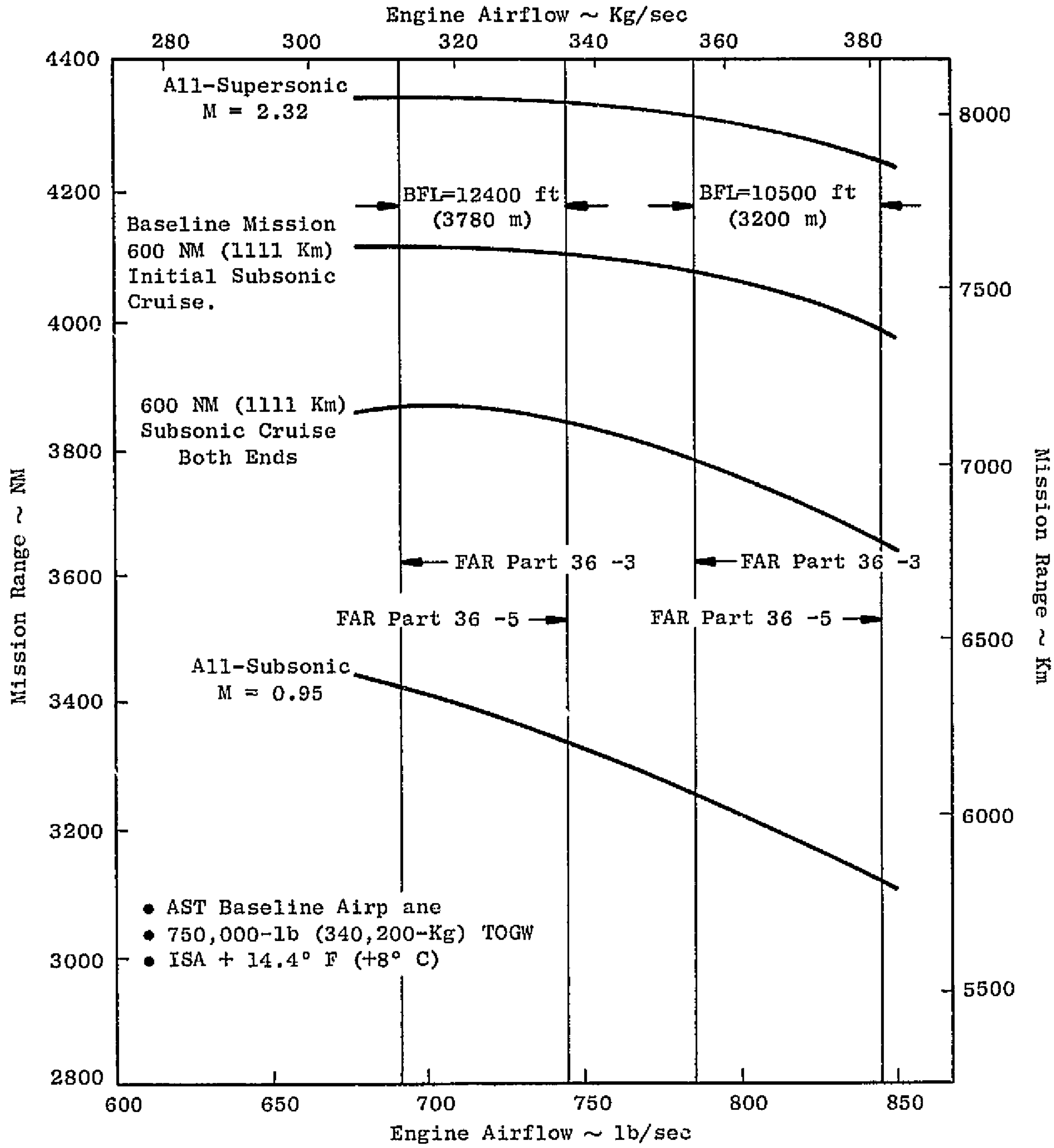


Figure 21. Mission Ranges of GE21/F2.4P4 Engine Sized for Balanced Field Length and Noise Level, LPCPR = 4.0, β = 0.43, AST Baseline Airplane, 750,000-lb TOGW (340,000-Kg), ISA +14.4° F (+8° C).

Table 8. GE21/F12 Study B-1 Conventional Baseline Engine, AST-1 Airplane.

- 750,000-lb (340,200-Kg) TOGW
- 12,400-ft (3780-Km) Balanced Field Length

Airflow, lb/sec	700
(Kg/sec)	318
Take-off Thrust, lbs	53,500
N	237,968
Traded FAR Part 36, EPNdB	-3
90-PNdB Take-off Footprint Area, sq NM	16
sq Km	55
Range:	
All-Supersonic, NM	4350
Km	7612
600-NM (1111-Km) Initial Subsonic, NM	4110
Km	7612
All-Subsonic, NM	3420
Km	6334

Table 9. GE21/F12 Study B-1 Conventional Baseline Engine.

Take-off Thrust, lbs	53,500
N	237,968
W_a, lbs/sec	700
Kg/sec	318
Fan Pressure Ratio	4.0
Overall Pressure Ratio	22.5
Max. Turbine Inlet Temperature, ° F	2800
° C	1538
Supersonic Cruise Turb. Inlet Temp., ° F	2700
° C	1482
Mechanical Jet Noise Suppression, PNdB	15
Suppressor Design Point, ft/sec	2500
m/sec	761
Take-off Exhaust Velocity, ft/sec	2925
m/sec	892
FAR Part 36 Noise Level, PNdB	-3
Engine Weight, lbs	13,200
Kg	5988
Maximum Diameter, inches	72.9
m	1.85
Engine Length, inches	301
m	7.65

Table 10. Comparison of AST-1 to AST-2 Airplanes, 10,500-ft (3200-m) Balanced Field Length.

	AST-1	AST-2
Passengers (234), lbs	48,902	---
(234), Kg	22,182	---
Passengers (292), lbs	---	61,030
(292), Km	---	27,683
Structural Weight, lbs	243,000	259,900
Kg	110,225	117,891
Baseline TOGW, lbs	750,000	762,000
Kg	340,200	345,643
Engine + Fuel Weight, lbs	458,094	440,070
Kg	207,791	199,616
Take-off Thrust, lbs	61,400	61,400
N	273,107	273,107
Community Cutback Thrust Requirement, lbs	30,000	34,000
N	133,440	151,232
Altitude at Community Cutback Point, ft	2100	1850
m	640	564
Transonic Drag	---	Higher

Table 11. GE12/F12 Study B-1 Conventional Baseline Engine, Effect of Airplane Definition and Balanced Field Length.

	AST-1 A/C 12,400-ft (3780-m) BFL	AST-2 A/C 10,500-ft (3200-m) BFL
Airflow, lbs/sec	700	805
Kg/sec	318	365
Take-off Thrust, lbs	53,500	61,400
N	237,968	273,107
Traded FAR Part 36, EPNdB	-3	-2.3
90-PNdB Take-off Footprint Area, sq NM	19	14.5
sq Km	65	50
Range:		
All-Supersonic, NM	4350	3920
Km	8056	7260
600-NM (1111-Km) Initial Subsonic, NM	4110	3720
Km	7612	6889
All-Subsonic, NM	3420	3125
Km	6334	5788

(see Section VI - Acoustics). The revision of the jet noise prediction method to include the more realistic relative velocity (VR) effect is shown on Table 12. The same baseline conventional engine in the AST-2 airplane has increased in noise level by about seven dB, and the take-off footprint area has doubled. In order to meet FAR Part 36 noise levels, the exhaust velocity must be reduced and the engine airflow increased. Figure 22 shows the relationship between jet velocity, fan pressure ratio (LPCPR), and discharge temperature. The original baseline conventional engine was sized to give 2925 ft/sec (892 m/sec) jet velocity and augmentation up to the maximum suppressor temperature of 1700° F (927° C). This sizing gave about 108 EPNL sideline noise with the old noise prediction method. With the new noise prediction method, the velocity must be reduced to the 2500-ft/sec (762-m/sec) range which requires a fan pressure ratio at takeoff of 3 to 3.5. Figure 23 shows that, within a range of exhaust nozzle thrust coefficients of 0.9 to 0.95 for a suppressed configuration, the airflow size required to meet the thrust requirement will be about 1100 lb/sec (499 Kg/sec) with an exhaust velocity close to 2300 ft/sec (701 m/sec). Since a high fan pressure ratio of about 4.0 is desired for range considerations, the fan operating line is lowered for takeoff to obtain the desired low fan pressure ratio. This does have a side benefit of eliminating the need for an augmented takeoff, although the augmentor still is necessary to give best climb/acceleration performance.

The effect of resizing the conventional baseline engine to obtain about the same overall noise level with the new noise-estimating procedure is shown on Table 13. The nominal airflow size has increased from 805 lbs/sec (365 Kg/sec) to 1070 lbs/sec (485 Kg/sec). This increased size and weight has reduced the all-supersonic range by 450 N.M. (833 Km) and the other missions with increased subsonic cruise requirements by up to 750 N.M. (1389 Km).

Figure 24 summarizes, in curve form, the changes in the conventional baseline engine supersonic range and take-off footprint area for the combined effect of:

- AST-1 to AST-2 airplane
- 12,400-ft (3780-m) to 10,500-ft (3200-m) BFL
- Old to new noise-estimating procedure

Table 12. Revised Relative Velocity Impact on Baseline Engine, AST-2 Airplane, 762,000-lb (345,643-Kg) TOGW, 10,500-ft (3200-m) Balanced Field Length, Optimized Subsonic and Transonic Climb/Acceleration.

	Baseline, Old VR	Baseline, Revised VR
Airflow, lb/sec	805	805
Kg/sec	365	365
Take-off Thrust, lbs	61,400	61,400
N	273,107	273,107
Traded FAR Part 36, EPNdB	-2.3	+5.1
90-PNdB Take-off Footprint Area, sq NM	14.5	28
sq Km	50	96
Range:		
All-Supersonic, NM	3920	3920
Km	7260	7260
600-NM (1111-Km) Initial Subsonic, NM	3720	3720
Km	6889	6889
All-Subsonic, NM	3125	3125
Km	5788	5788

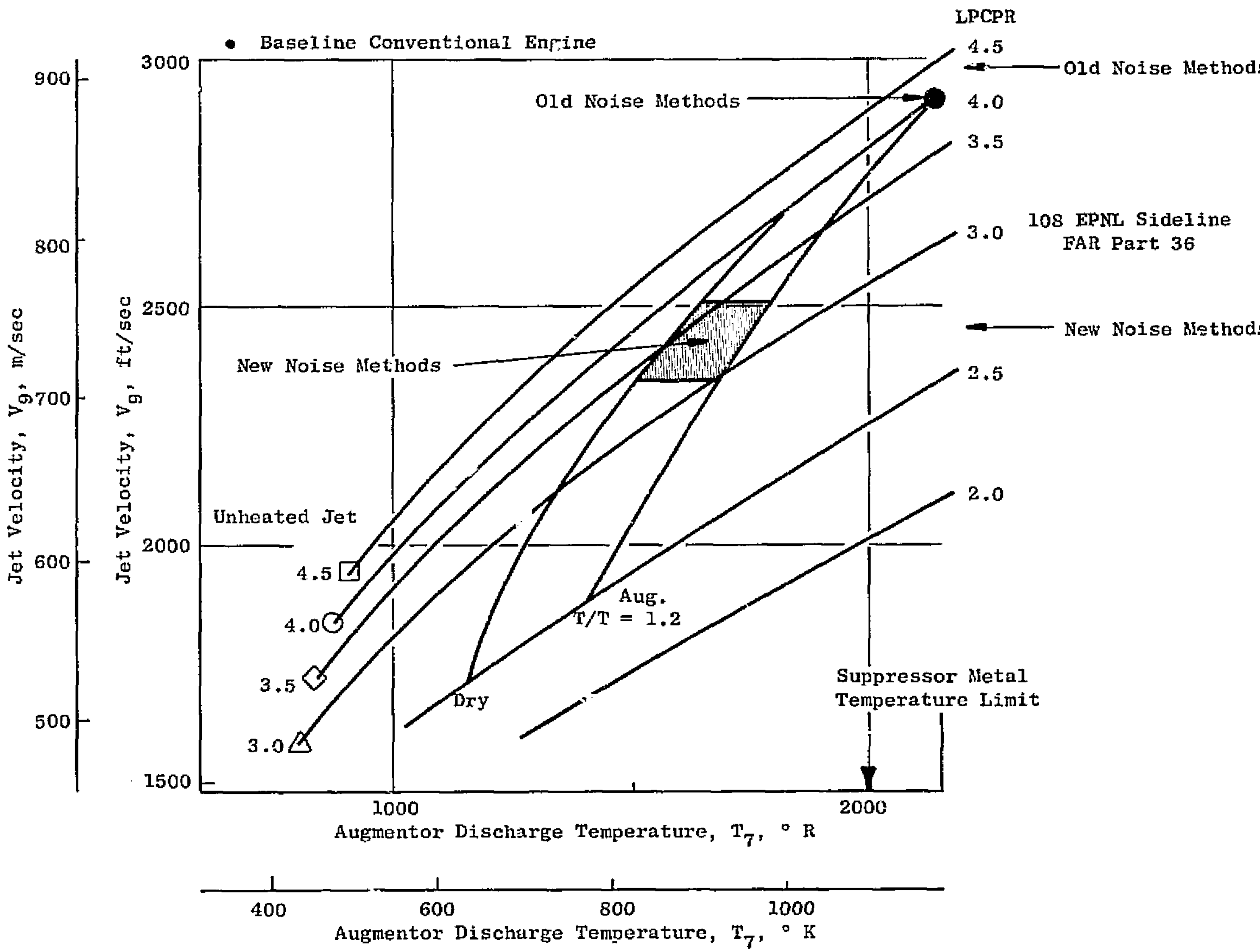


Figure 22. Noise and the Cycle.

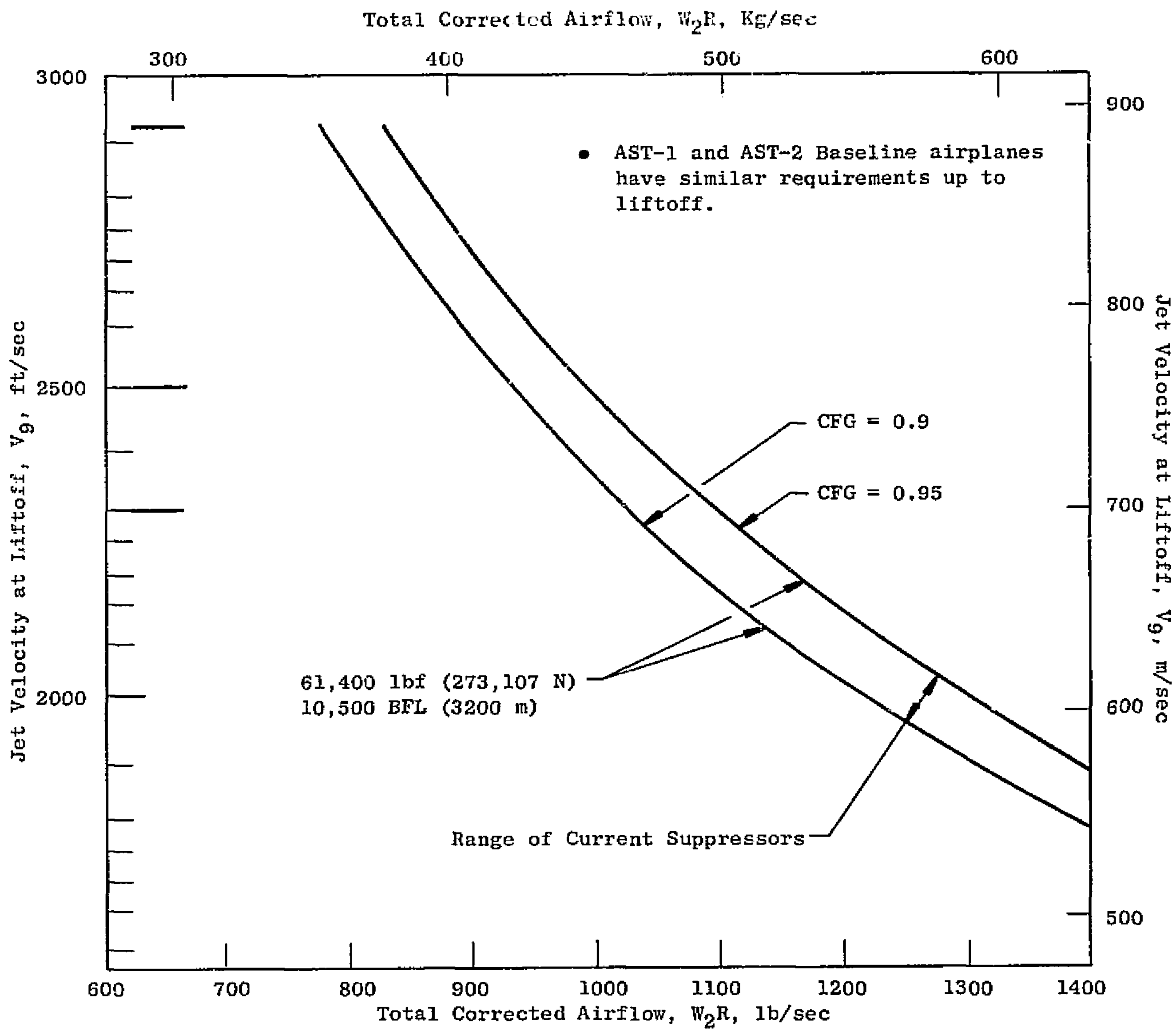


Figure 23. Total Corrected Airflow Versus Jet Velocity at Liftoff.

Table 13. Baseline Engine Performance, AST-2 Airplane, 762,000-lb (345,643-Kg) TOGW.

	Old VR	Revised VR	Scaled to Same Sideline EPNL
Airflow, lbs/sec	805	805	1070
Kg/sec	365	365	485
Take-off Thrust, lbs	61,400	61,400	61,400
N	273,107	273,107	273,107
Traded FAR Part 36, EPNdB	-2.3	+5.1	-2.5
90-PNdB Take-off Footprint Area, sq NM	14.5	28	18
sq Km	50	96	62
Range:			
All-Supersonic, NM	3920	3920	3470
Km	7260	7260	6426
600-NM (1111-Km) Initial Subsonic, NM	3720	3720	3170
Km	6889	6889	5871
All-Subsonic, NM	3125	3125	2370
Km	5788	5788	4389

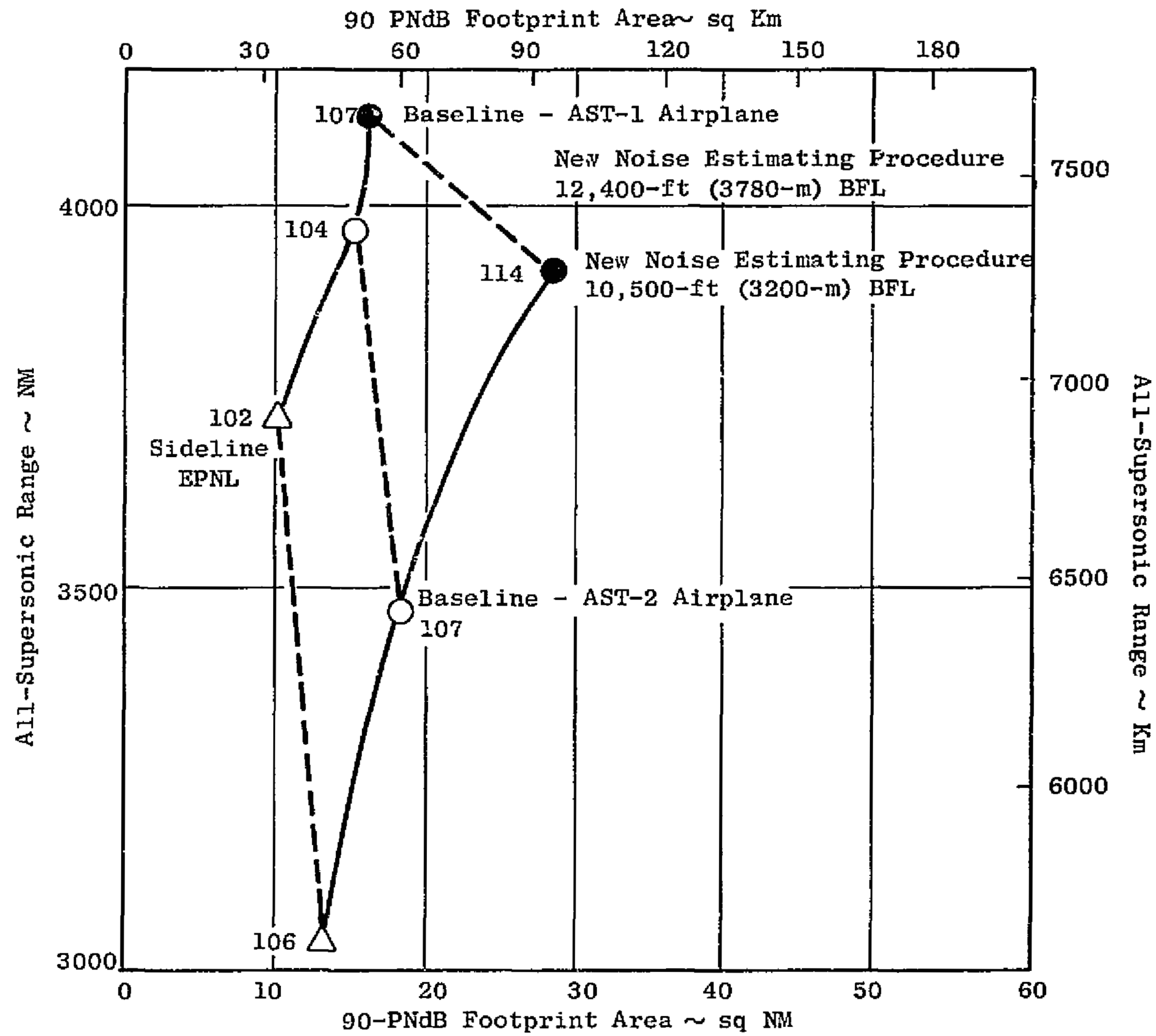


Figure 24. Conventional Cycle Range and Footprints.

SECTION V

VARIABLE CYCLE ENGINE DEFINITION

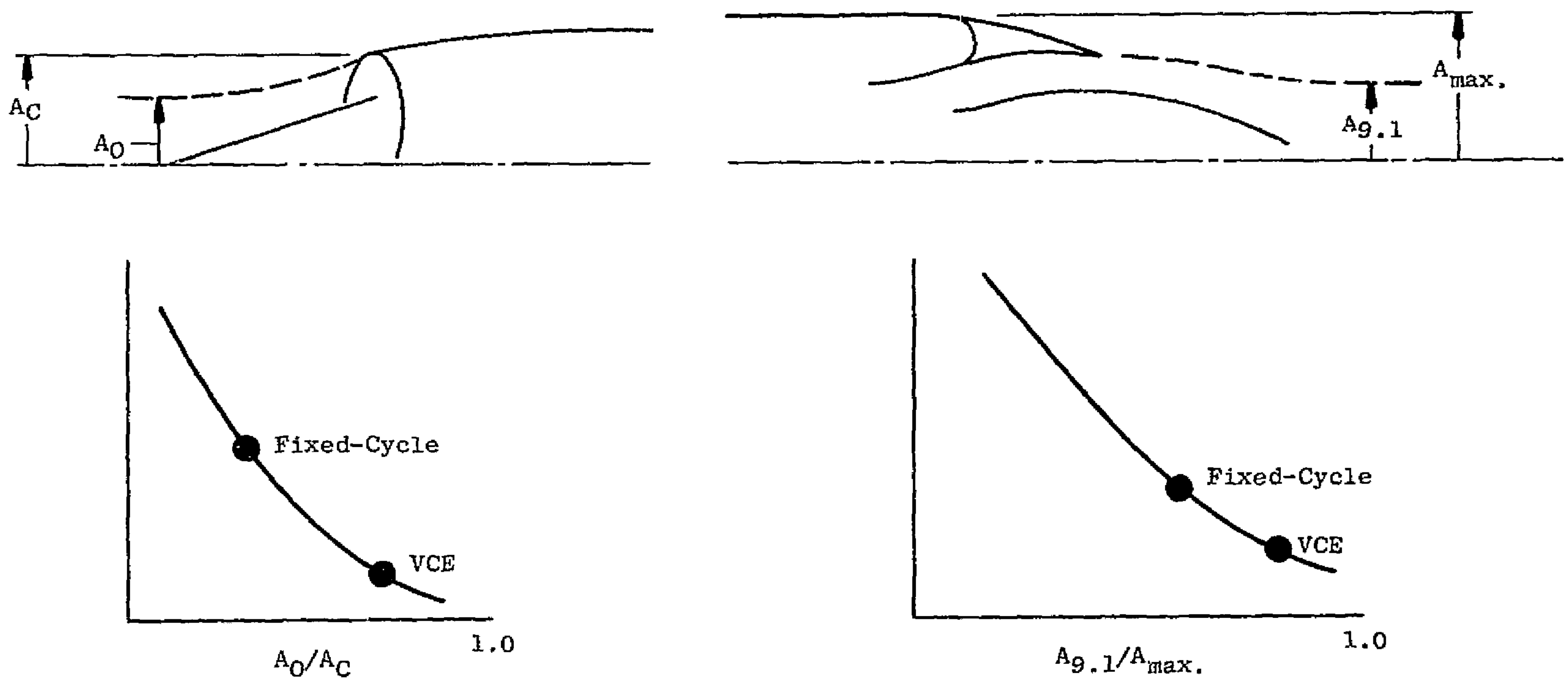
The previous section of this report, covering the definition and selection of the baseline AST conventional engine, illustrated the effect of baseline airplane characteristics, reduction in balanced field length requirements, and realistic exhaust jet noise predictions on engine airflow size. The resulting increase in engine size has caused a poor match with airplane characteristics and large installation penalties in inlet and afterbody drag at part-throttle operation.

The variable cycle engine concepts, based on the conventional baseline mixed-flow low-bypass turbofan, were designed to improve the part-power installed specific fuel consumption by reducing inlet and afterbody drag (see Figure 25). At the same time, the good supersonic performance of the baseline engine was not changed.

A. Dual-Cycle VCE Definition

The Dual-Cycle VCE concept requires minimum additional complexity to the baseline conventional cycle, but it does reduce part-throttle installation losses at only a small engine weight penalty. Figure 26 illustrates the engine airflow/thrust characteristics of the conventional baseline cycle and the Dual-Cycle VCE. The conventional baseline engine matches the inlet at the maximum dry power condition (100%); but, as the engine is throttled back to part-power thrust, the engine airflow is reduced. This reduction in airflow at the required cruise thrust level (A_o/A_c) is representative of the inlet additive drag. Similarly, Figure 27 shows that, as the engine is throttled back, the exhaust nozzle area requirement is reduced and the $A_{9.1}/A_{max.}$ ratio is reduced resulting in high afterbody drag. These same figures also show the dual-cycle VCE characteristics. As the dual-cycle VCE is throttled back to its required part-power thrust requirement, the VCE features allow the inlet flow to remain constant over a substantial range of reduced thrust. At some thrust point, determined by the low pressure turbine operating conditions, the inlet flow must also be reduced. Since thrust is being reduced at a constant airflow, the exhaust velocity is lower than the conventional engine and the exhaust nozzle area is larger at a comparable thrust level. This increases the $A_{9.1}/A_{max.}$ ratio and results in lower afterbody drag. Figure 28 shows the actual variation of inlet and afterbody drag with a reduction in uninstalled thrust (part-power operation) for both the conventional engine and dual-cycle VCE. If the operating thrust requirement was 50% of maximum, the dual-cycle inlet drag would be about one third of the conventional cycle inlet drag, and about three quarters of the afterbody drag. As the subsonic portion of the AST mission increases, this will result in a large fuel saving.

The dual-cycle VCE features do not improve the internal cycle performance at the subsonic flight conditions, as shown on Figure 29. The advantage of the dual-cycle VCE is in the installed performance during subsonic



$$F_{D\ spill} = qo\ C_D\ A_C$$

$$F_{D\ A/B} = qo\ C_D\ A_{max.}$$

Figure 25. Installation Losses.

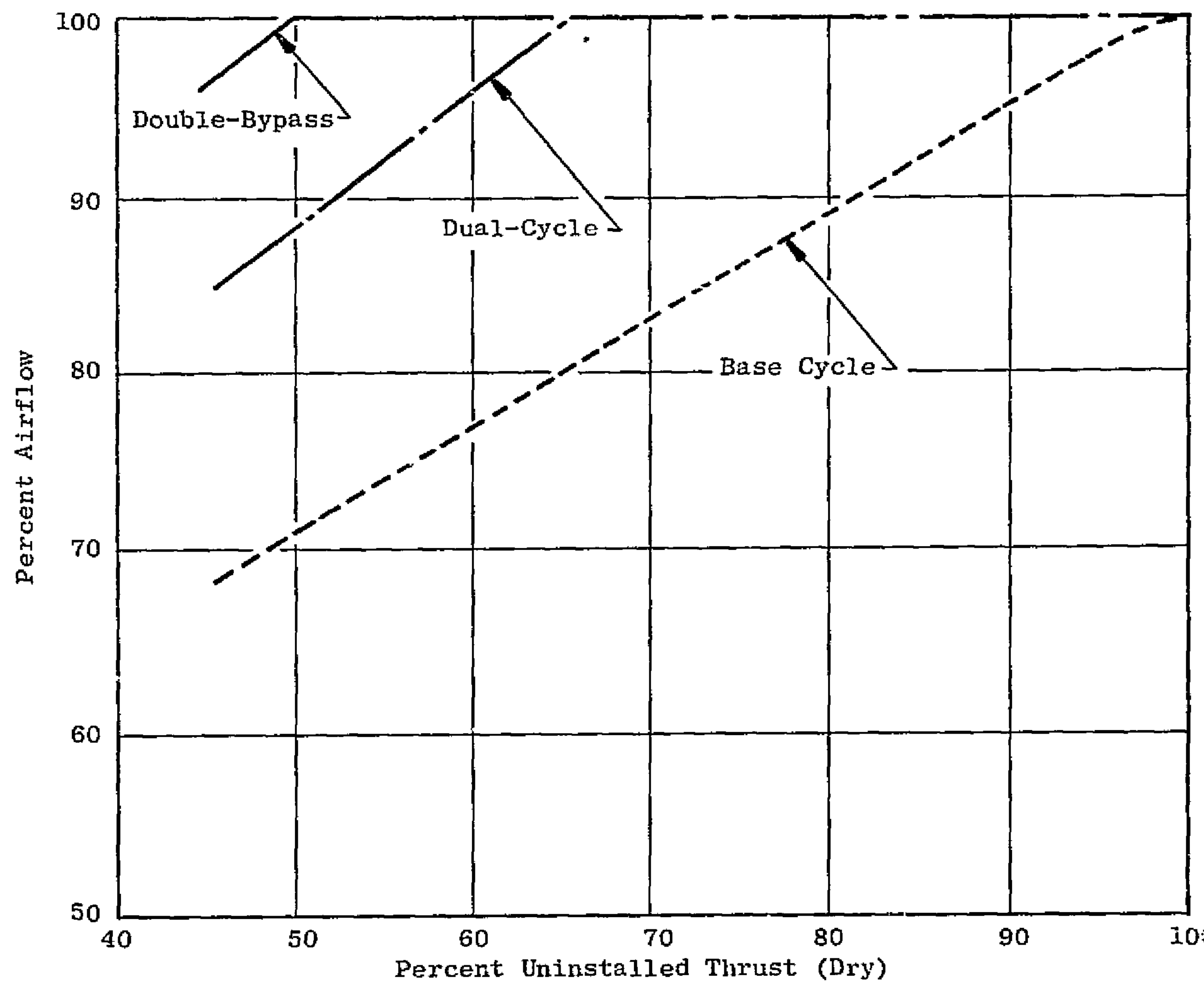


Figure 26. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Engine Airflow/Thrust Relationships at M 0.95/35,000 ft (10,668 m).

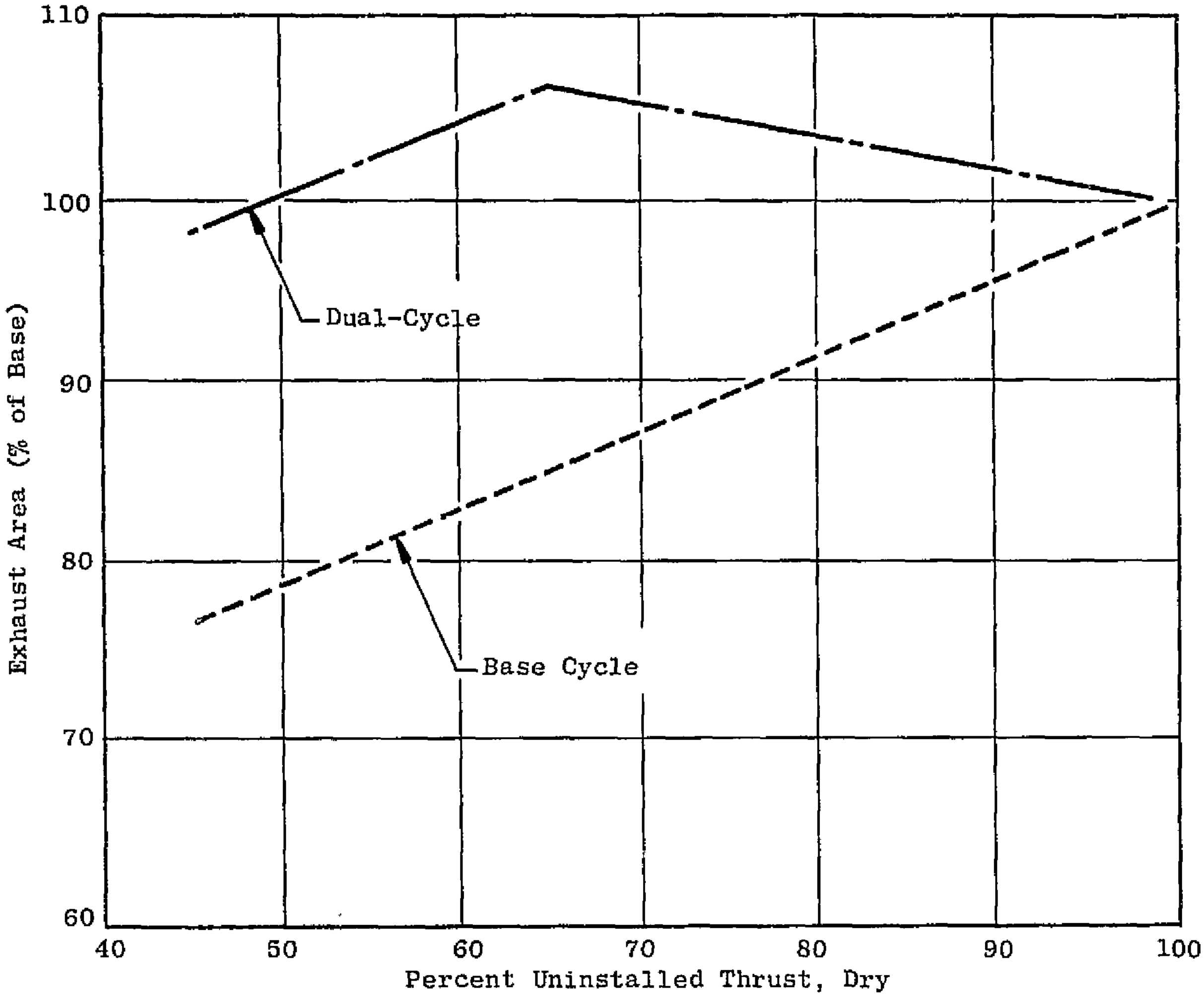
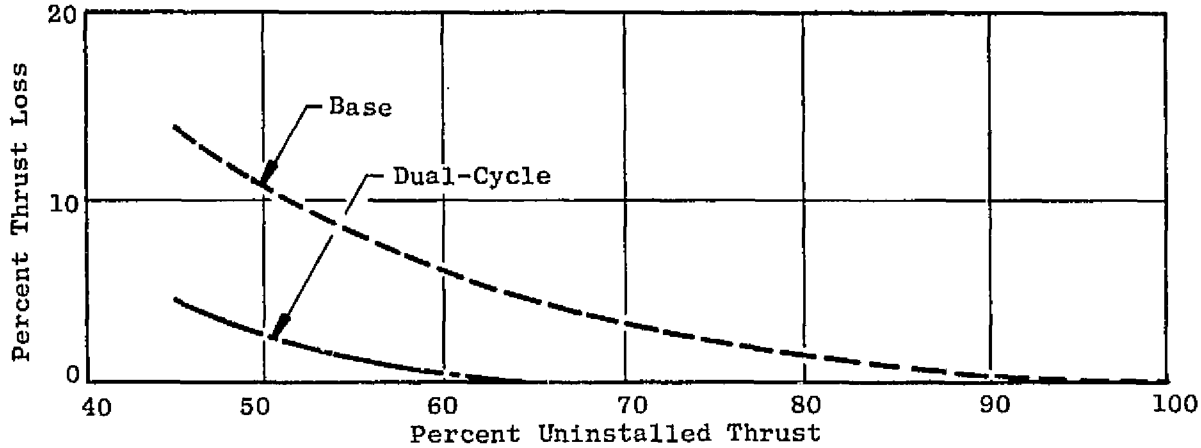
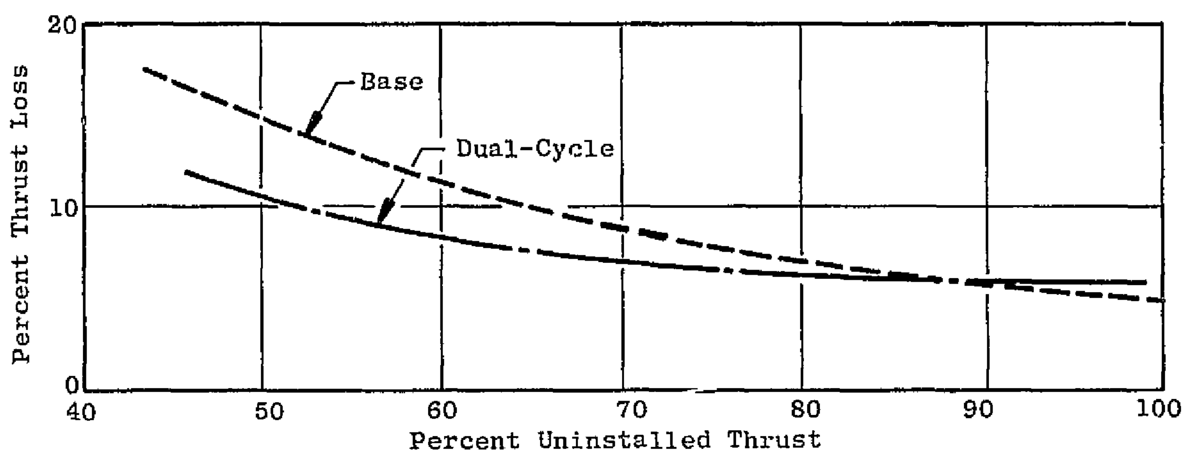


Figure 27. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Relative Exhaust Area/Thrust Relationships at M 0.95/35,000 ft (10,668 m).



(a) Thrust Loss Due to Inlet Spillage



(b) Thrust Loss Due to Afterbody Drag

Figure 28. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Installation Losses at M 0.95/35,000 ft (10,668 m), Hot Day.

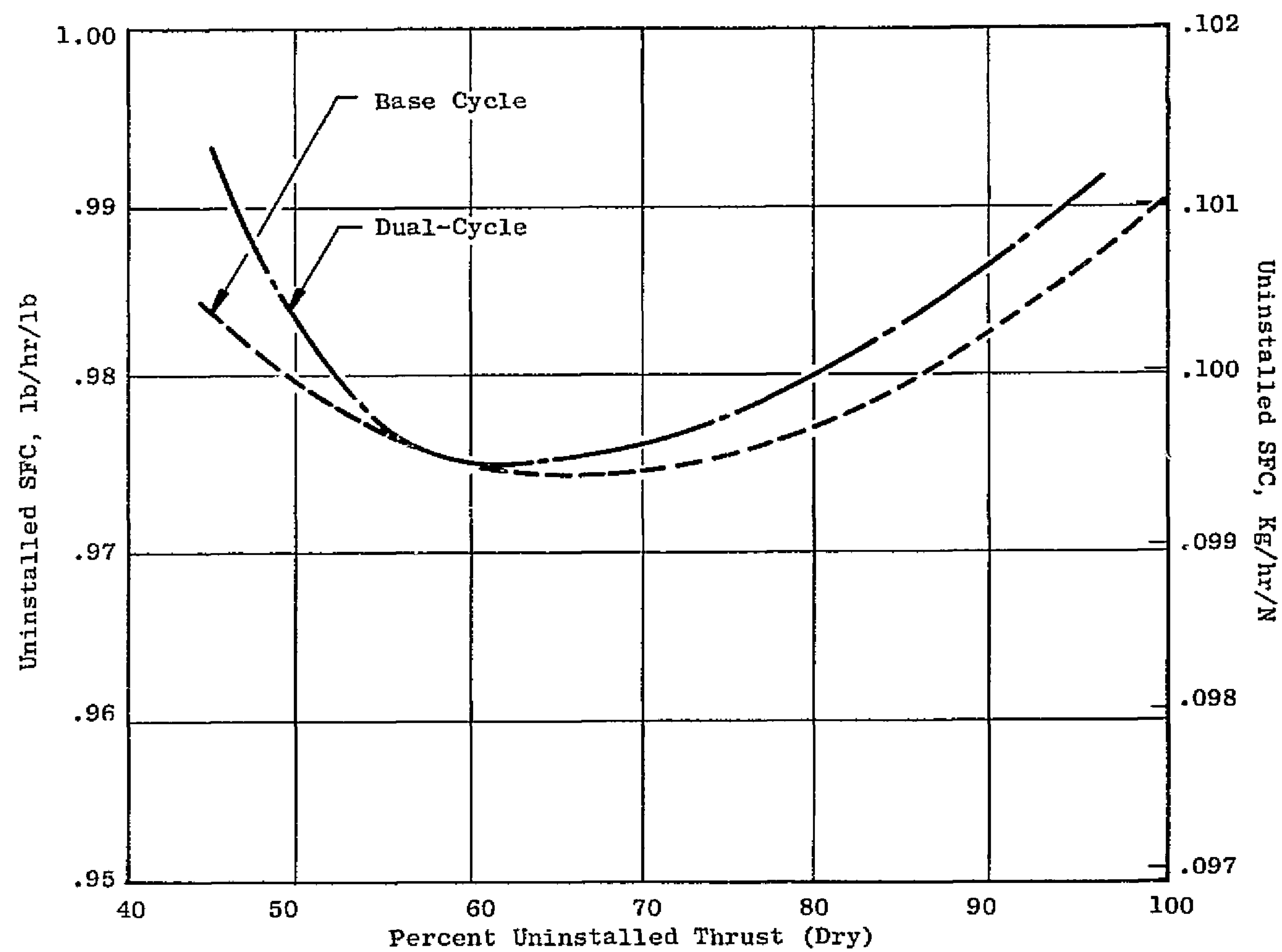


Figure 29. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Uninstalled Performance at M 0.95/35,000 ft (10,668 m), Hot Day.

flight operation as shown on Figure 30. At a 50% installed thrust operating condition, the installed specific fuel consumption is about 8% lower than the same size conventional engine.

The dual-cycle VCE shows a slight improvement in the all-supersonic range over the conventional engine in the AST-2 airplane. The better subsonic performance reduces the reserve fuel requirement and makes more mission fuel available, which makes up for the small weight penalty for the VCE features. Figure 31 compares the all-supersonic range and take-off footprint area of the dual-cycle VCE and the conventional baseline engine. The dual-cycle take-off footprint area is smaller than the conventional engine baseline. This reduction in footprint area is provided by variable cycle features which allow the engine to hold take-off airflow at the community measuring station, which reduces the exhaust jet velocity at the required thrust and gives lower community noise.

The dual-cycle VCE shows slight mission improvements over the baseline conventional engine, but it still requires the same penalty in weight because of the airflow sizing for take-off noise. The double-bypass VCE concept can provide a solution to the high take-off airflow for noise consideration and, at the same time, provide a better match for the aircraft flight characteristics. Physical characteristics of the dual-cycle VCE are shown on Table 14.

B. Double-Bypass VCE Definition

The double-bypass VCE concept provides high take-off airflow to provide the required thrust at acceptable FAR Part 36 noise levels and cruise characteristics that better match the airplane performance requirements. This VCE concept saves approximately 10% in engine weight compared to a conventional engine sized for the same take-off noise level. The double-bypass VCE has the same subsonic advantages as the dual-cycle VCE, but it is effective at even lower subsonic cruise power settings. Figure 32 shows the engine airflow/thrust relationship for the dual-cycle VCE with the double-bypass VCE added. The double-bypass VCE can hold subsonic cruise airflow constant down to approximately 50% maximum dry thrust, which is close to the AST-2 aircraft subsonic cruise requirement. This means that the inlet spillage drag can be eliminated for this flight condition. Figure 33 shows that the exhaust nozzle area also is increasing beyond that of the dual-cycle VCE, and the afterbody drag reduction will be significant. Figure 34 shows the inlet additive drag and afterbody drag reductions that are possible with the double-bypass VCE. At the 50% thrust operating point for subsonic cruise operation, the inlet drag is reduced to zero, and the thrust loss due to afterbody drag is reduced by about one third. These reductions in installation drag can improve the range capability of the AST-2 airplane substantially if an initial subsonic cruise is utilized; even the all-supersonic range is affected, since the good subsonic performance of the double-bypass VCE will reduce the fuel reserves that must be carried. Figure 35 shows that the double-bypass VCE concept improves the internal performance of the cycle about 2% when compared to either the conventional engine or the dual-cycle VCE. At the same airflow size, Figure 36 shows that the improved cycle performance and the reduction in installation losses has resulted in the double-bypass VCE installed specific

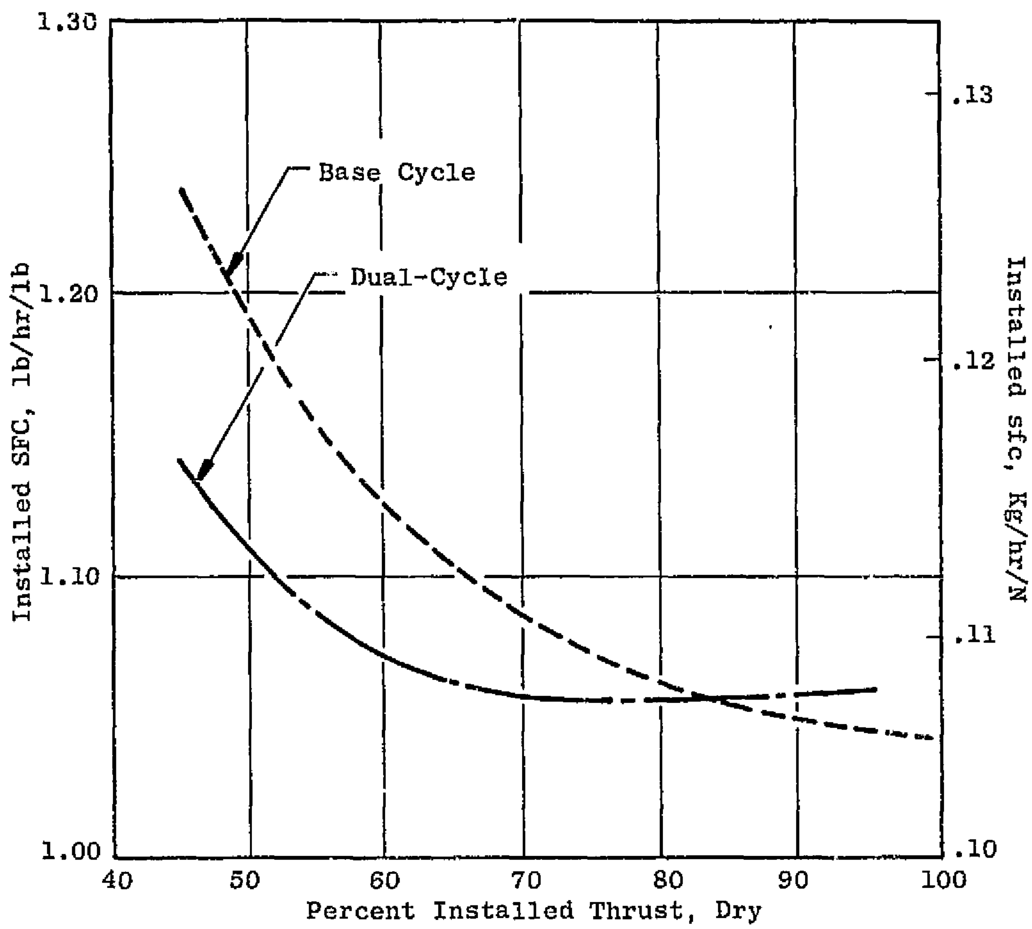


Figure 30. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Installed Performance at M 0.95/35,000 ft (10,668 m), Hot Day.

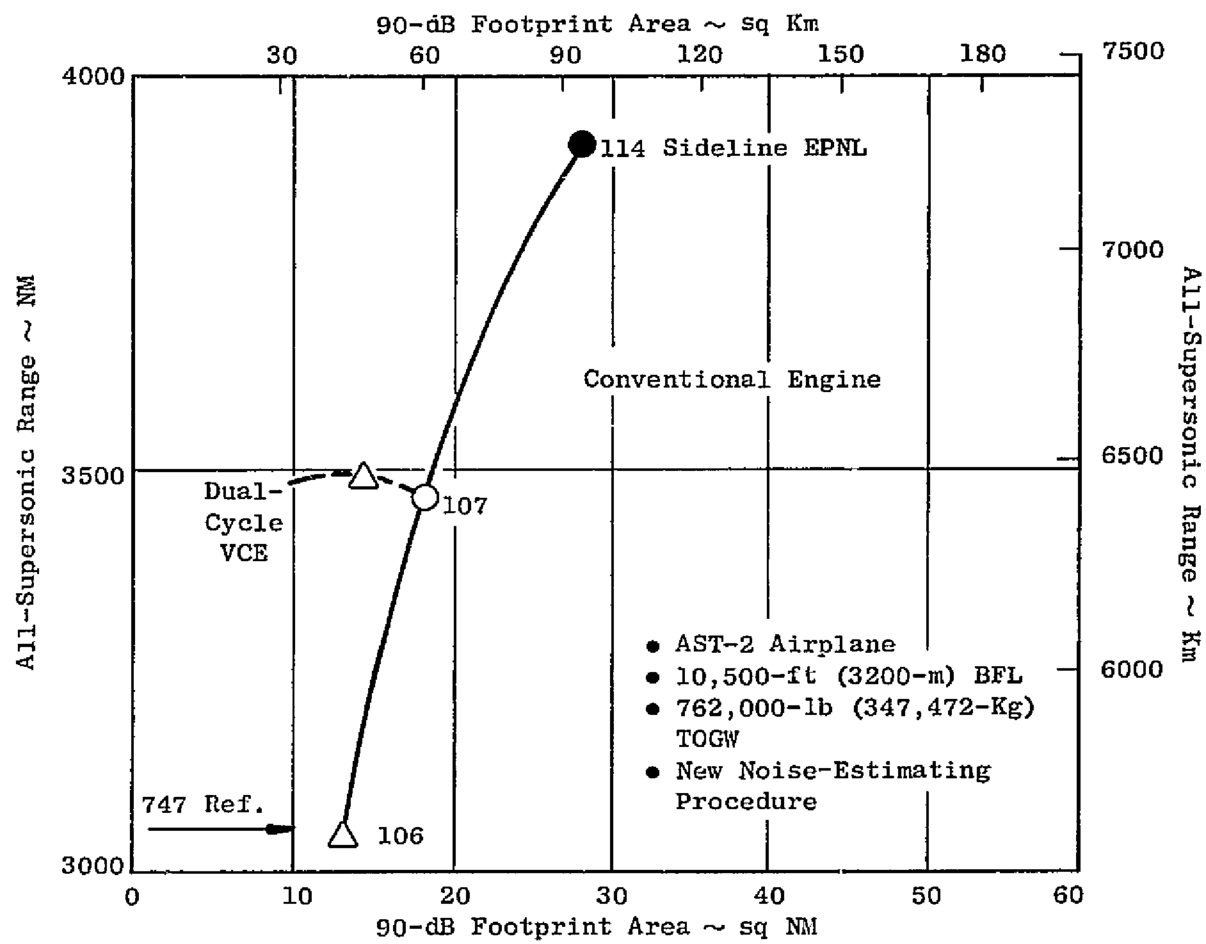


Figure 31. Double-Bypass/Dual-Cycle VCE Range and Footprint Improvements.

Table 14. Variable Cycle Engine Physical Characteristics, Dual-Cycle.

Take-off Thrust, lbs	61,400
N	273,107
W_a, lbs/sec	1070
Kg/sec	485
Fan Pressure Ratio	4.0
Overall Pressure Ratio	22.5
Maximum Turbine Inlet Temperature, ° F	2800
° C	1538
Supersonic Cruise Turbine Inlet Temp., ° F	2700
° C	1482
Mechanical Jet Noise Suppression, PNdB	15
Suppressor Design Point, ft/sec	2500
m/sec	762
Take-off Exhaust Velocity, ft/sec	2500
m/sec	762
FAR Part 36 Noise Level, EPNdB	-2.5
Engine Weight, lbs	21,960
Kg	9961
Maximum Diameter, inches	90
cm	229
Engine Length, inches	320
cm	813

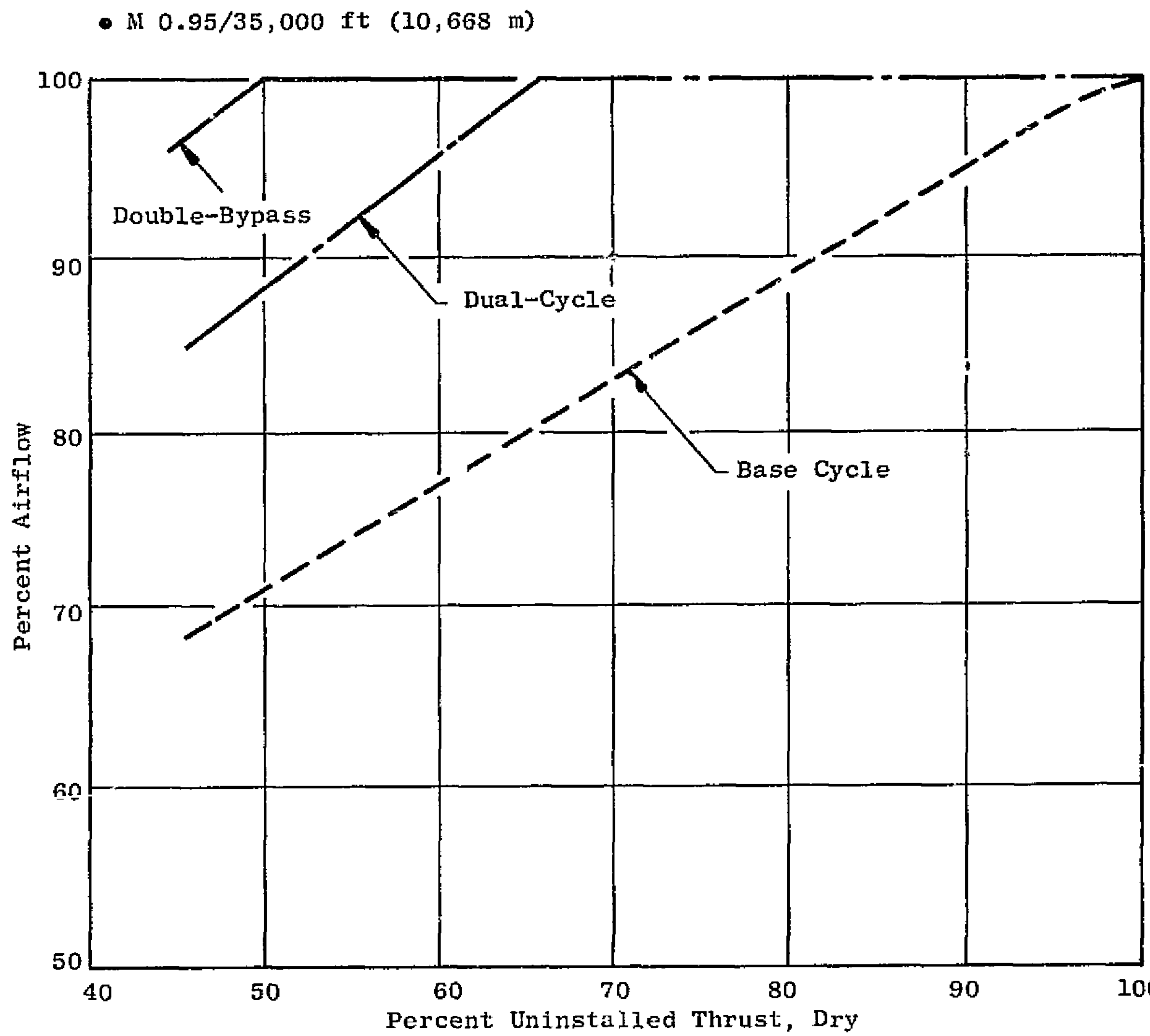


Figure 32. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Engine Airflow/Thrust Relationships at M 0.95/35,000 ft (10,668 m).

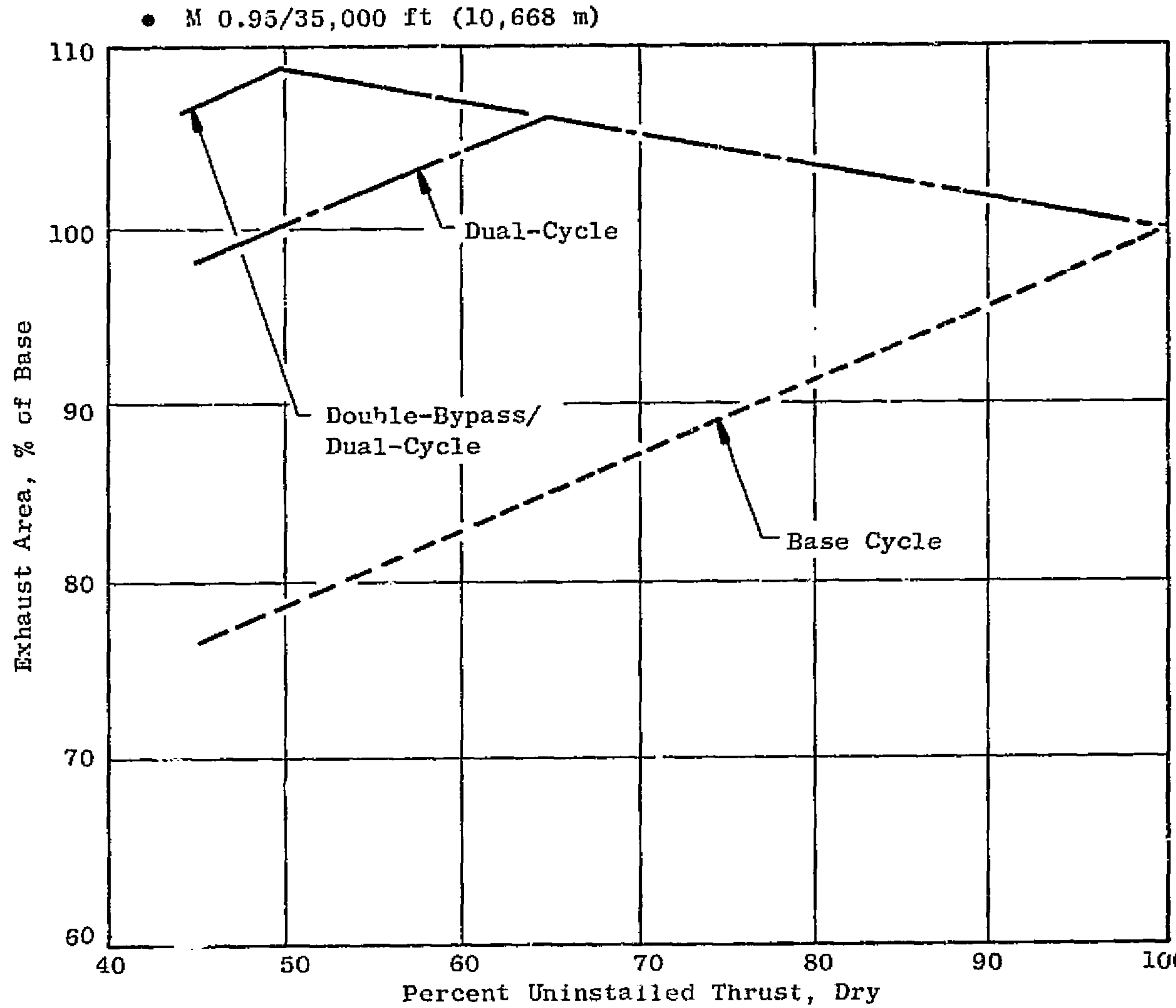
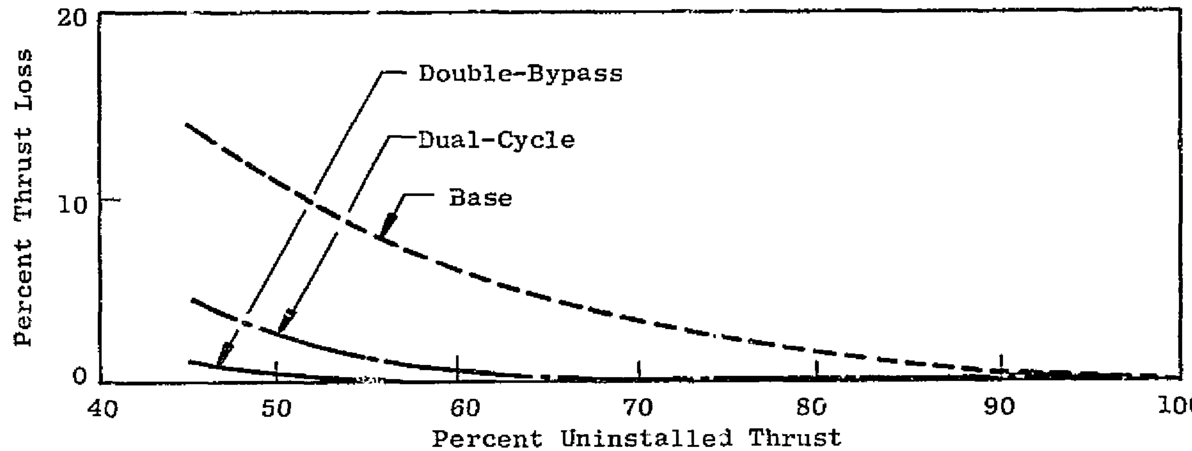
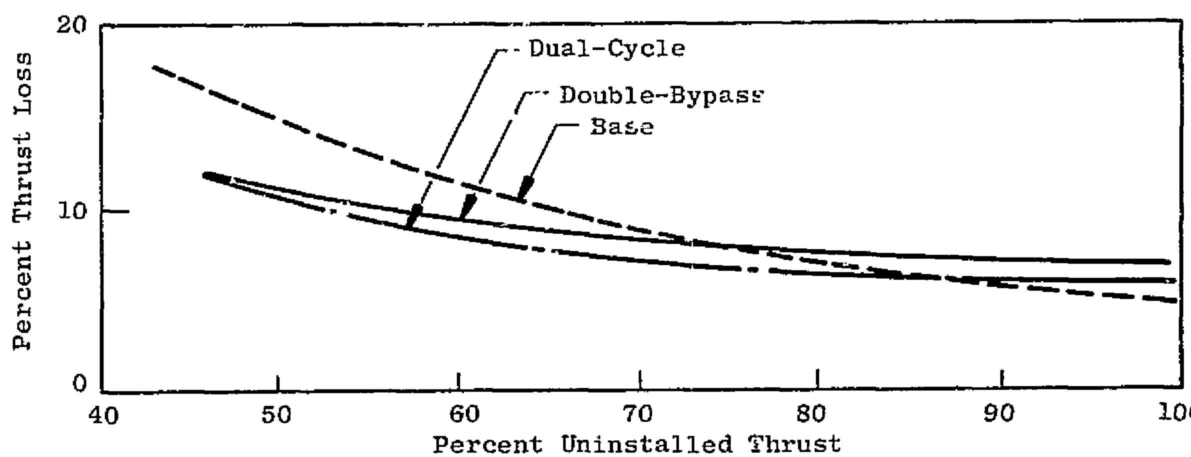


Figure 33. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Relative Exhaust Area/Thrust Relationships at M 0.95/35,000 ft (10,668 m).



(a) Thrust Loss Due to Inlet Spillage



(b) Thrust Loss Due to Afterbody Drag

Figure 34. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Installation Losses at M 0.95/35,000 ft (10,668 m), Hot Day.

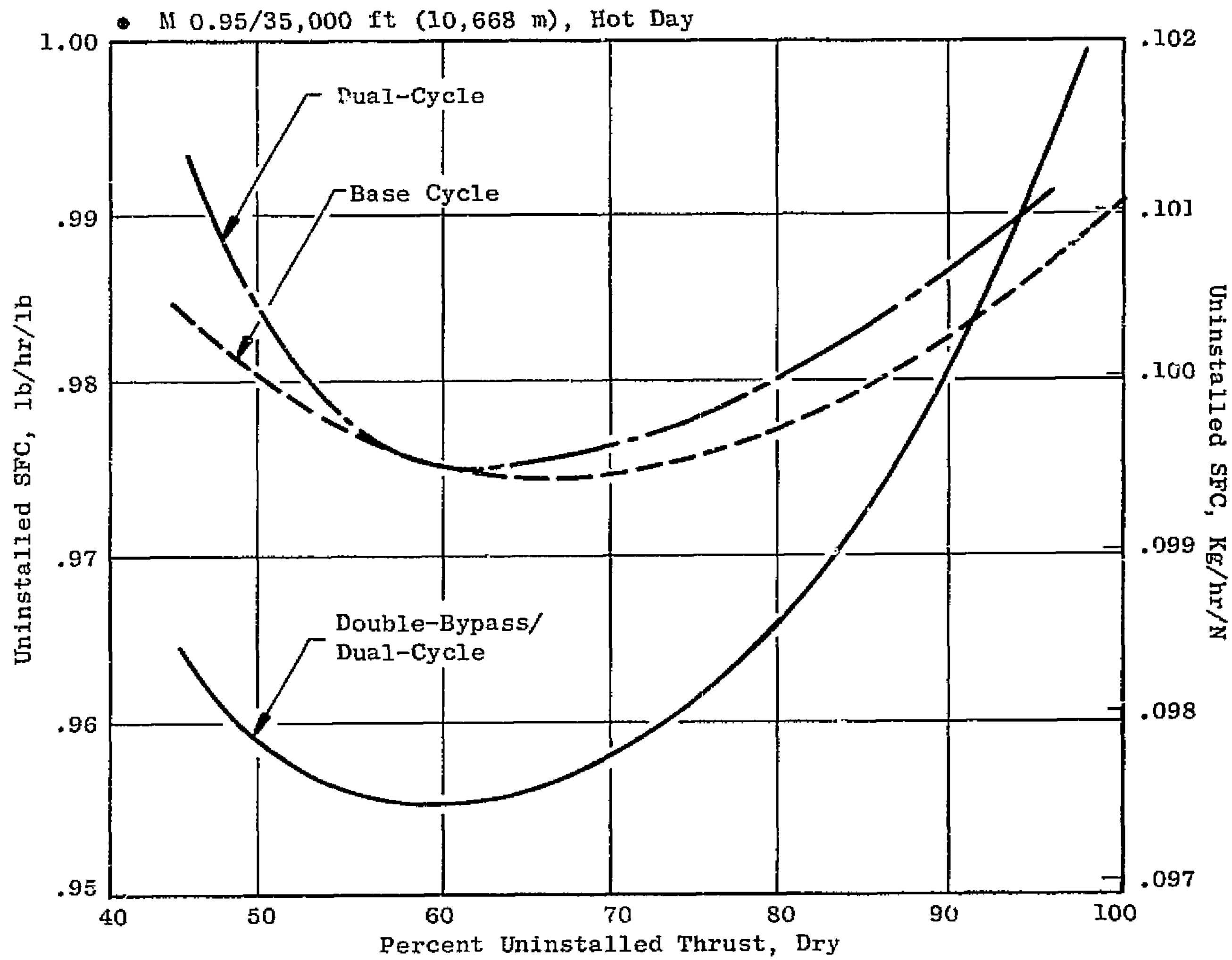


Figure 35. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Uninstalled Performance at M 0.95/35,000 ft (10,668 m), Hot Day.

fuel consumption being about 4% better than the dual-cycle VCE, and about 13% better than the conventional baseline engine. However, when the engines are sized for equal take-off noise (Figure 37), even more improvement is obtained (approximately 16%) since the minimum sfc point for the double-bypass VCE has moved to a lower thrust which is better matched to the airplane requirement. Figure 38 shows that improvement also is obtained at the hold-flight condition, although the very low thrust requirement still requires operation far up the thrust-sfc curve, and the operating sfc is still high. The supersonic installed performance for the double-bypass VCE is shown on Figure 39. This is close to the same performance seen in the conventional baseline engine, but some differences are seen because of a slightly different component match in the double-bypass VCE. Improvements above this have been identified and will be implemented in the next contract phase.

Figure 40 shows a comparison of the all-supersonic range and take-off footprint area for the engine types studied. The double-bypass VCE has a substantial advantage in the all-supersonic range over both the dual-cycle VCE and the conventional engine because of its lower weight for the same take-off noise size. The double-bypass and dual-cycle VCE both have a low take-off footprint area because of their ability to maintain high airflow at the community noise-measuring station. Table 15 shows the evolution of noise prediction methods on the conventional engine airflow size and the improvements offered by the double bypass VCE. The improvement in range, as more subsonic operation is required, becomes very large as the limit of all-subsonic operation is reached.

The double-bypass VCE definition assumed that the conversion of the best conventional engine cycle to the variable cycle engine would not compromise the cycle. To confirm that the match of components in the VCE did not change the installed performance, a study was performed at two different fan pressure ratios [but the same overall pressure ratio (22.5)], and the resulting engines were compared in the AST all-supersonic mission. Figure 41 compares the installed thrust and sfc at supersonic cruise at fan pressure ratios (LPCPR) of 3.7, 4.0 (Base), and 4.5. The highest fan pressure ratio (4.5) has slightly better installed sfc at the required thrust. At subsonic cruise, Figure 42, the 3.7 LPCPR is the best, but the 4.5 LPCPR is poor. Figure 43 shows the effect of fan pressure ratio on take-off gross weight and range for three AST missions. Except for the all-subsonic mission, the variation in fan pressure has about a ±1% effect. However, if we include the take-off 90-PNdB footprint area as a measuring parameter (Figure 44) together with the all-supersonic range in the AST-2 airplane, the 4.0 LPCPR base double-bypass cycle is the best compromise for range and footprint area. Physical characteristics of the double-bypass VCE are shown on Table 16.

C. Economics

Return on Investment (ROI) and Direct Operating Cost (DOC) for both the conventional baseline engine and the double-bypass VCE were calculated in accordance with the Contract Work Statement. The calculation ground rules are given in Table 17, and were used for a series of engine sizes to show the

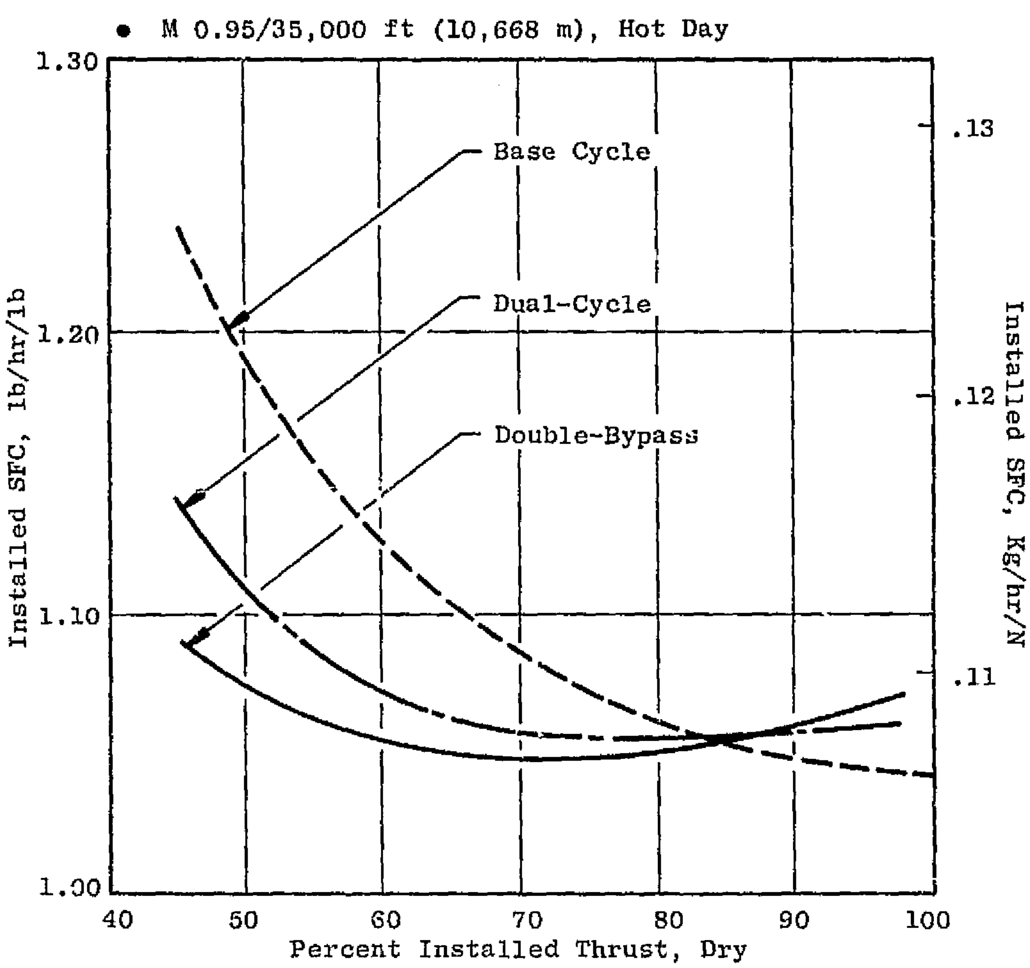


Figure 36. VCE Base Engine Cycle Comparisons, Equal Airflow Size, Installed Performance at M 0.95/35,000 ft (10,668 m), Hot Day.

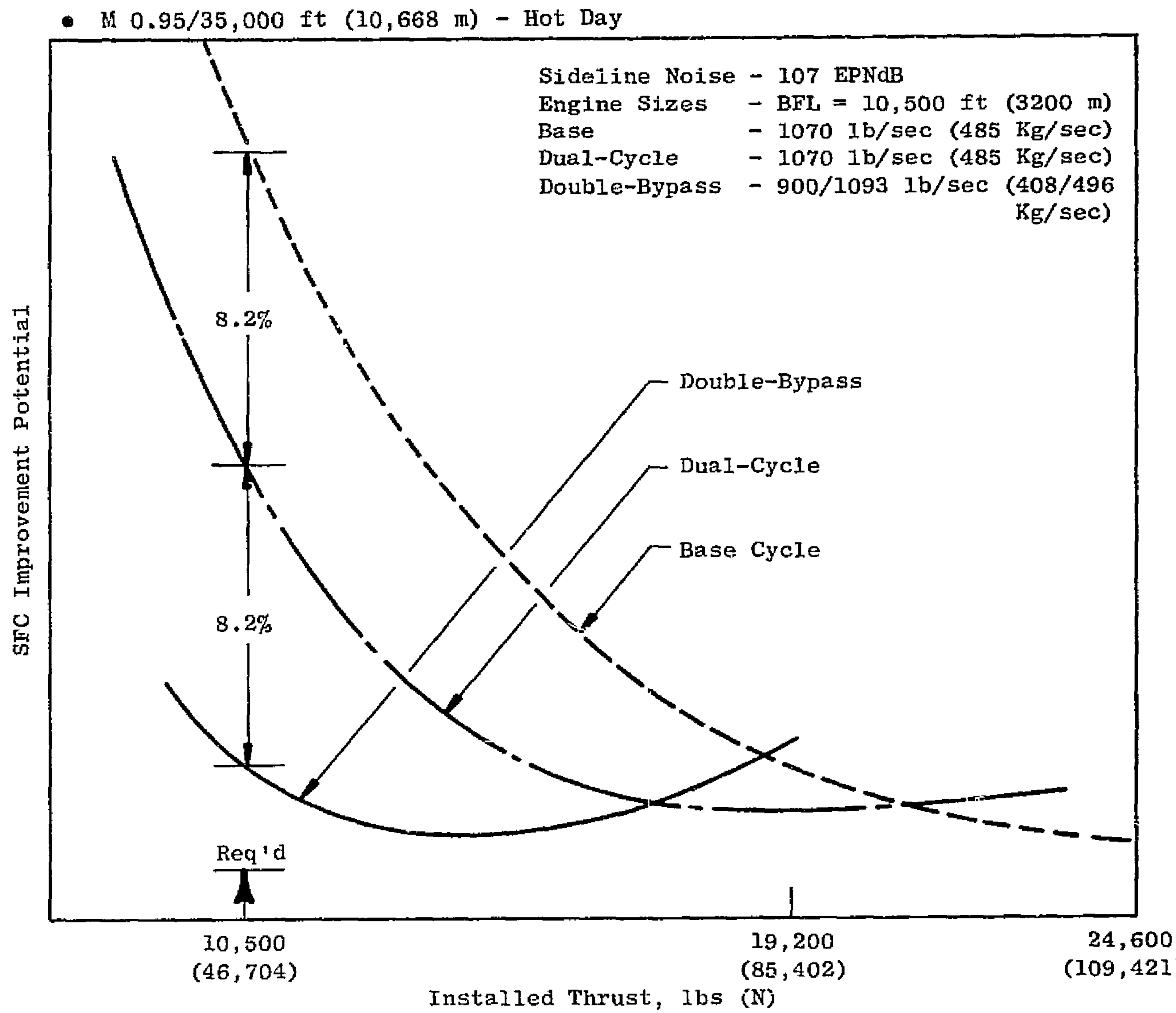


Figure 37. VCE Base Engine Comparisons, Equal Noise Sizing Criteria, Installed Performance at M 0.95/35,000 ft (10,668 m), Hot Day.

• M 0.5/15,000 ft (4572 m) - Hot Day

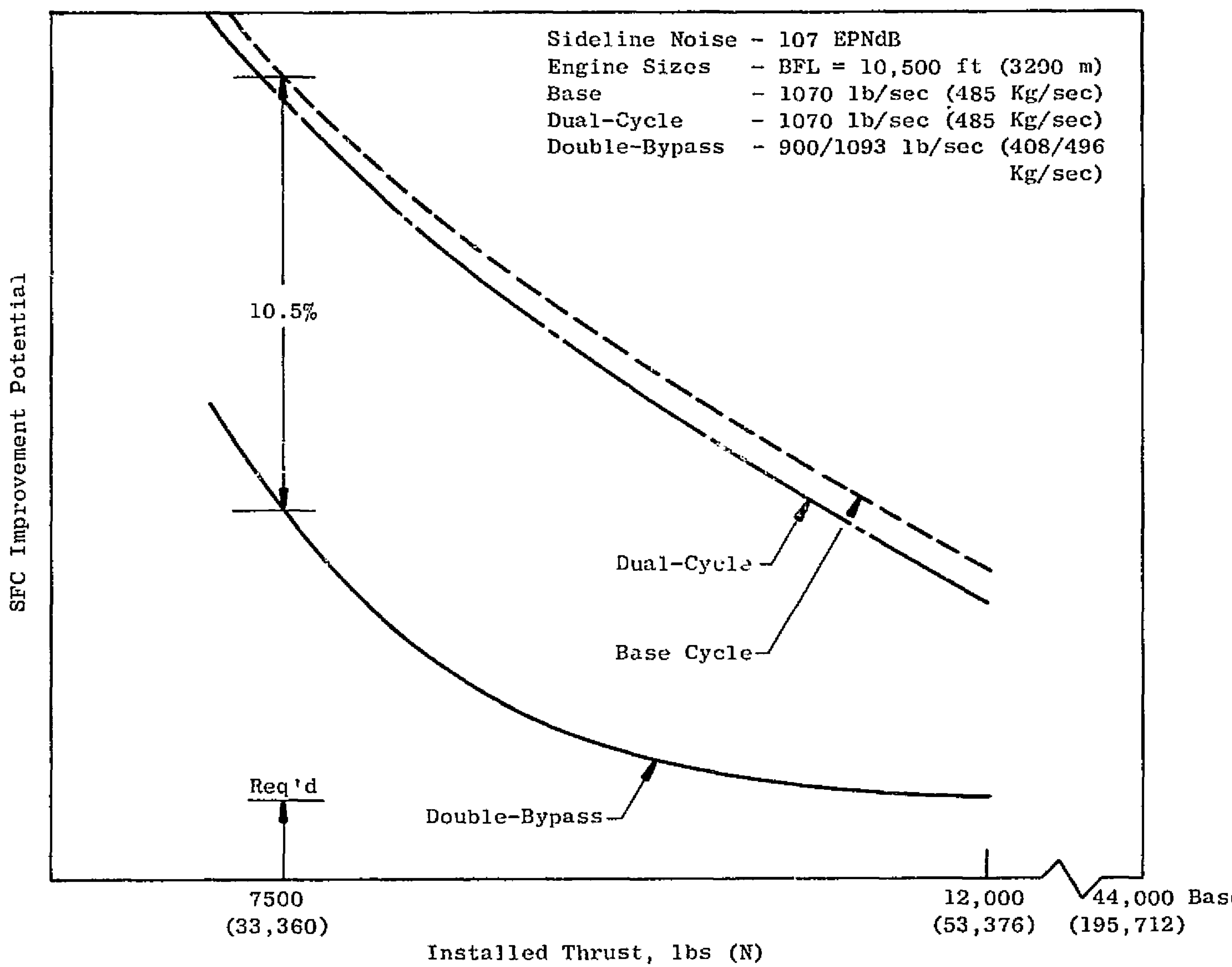


Figure 38. VCE Base Engine Comparisons, Equal Noise Sizing Criteria, Installed Performance at M 0.5/15,000 ft (4572 m), Hot Day.

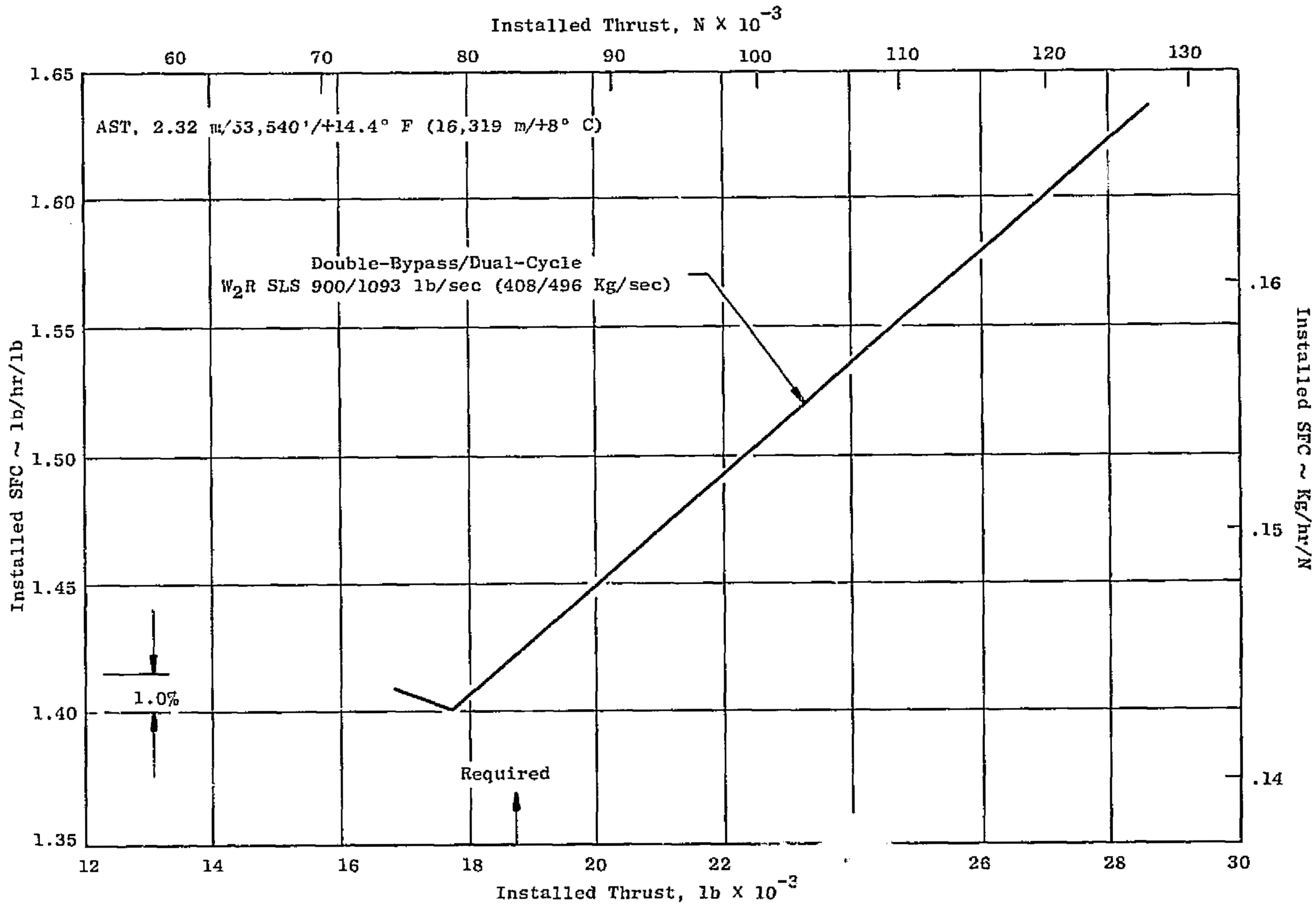


Figure 39. Performance Potential at Supersonic Cruise.

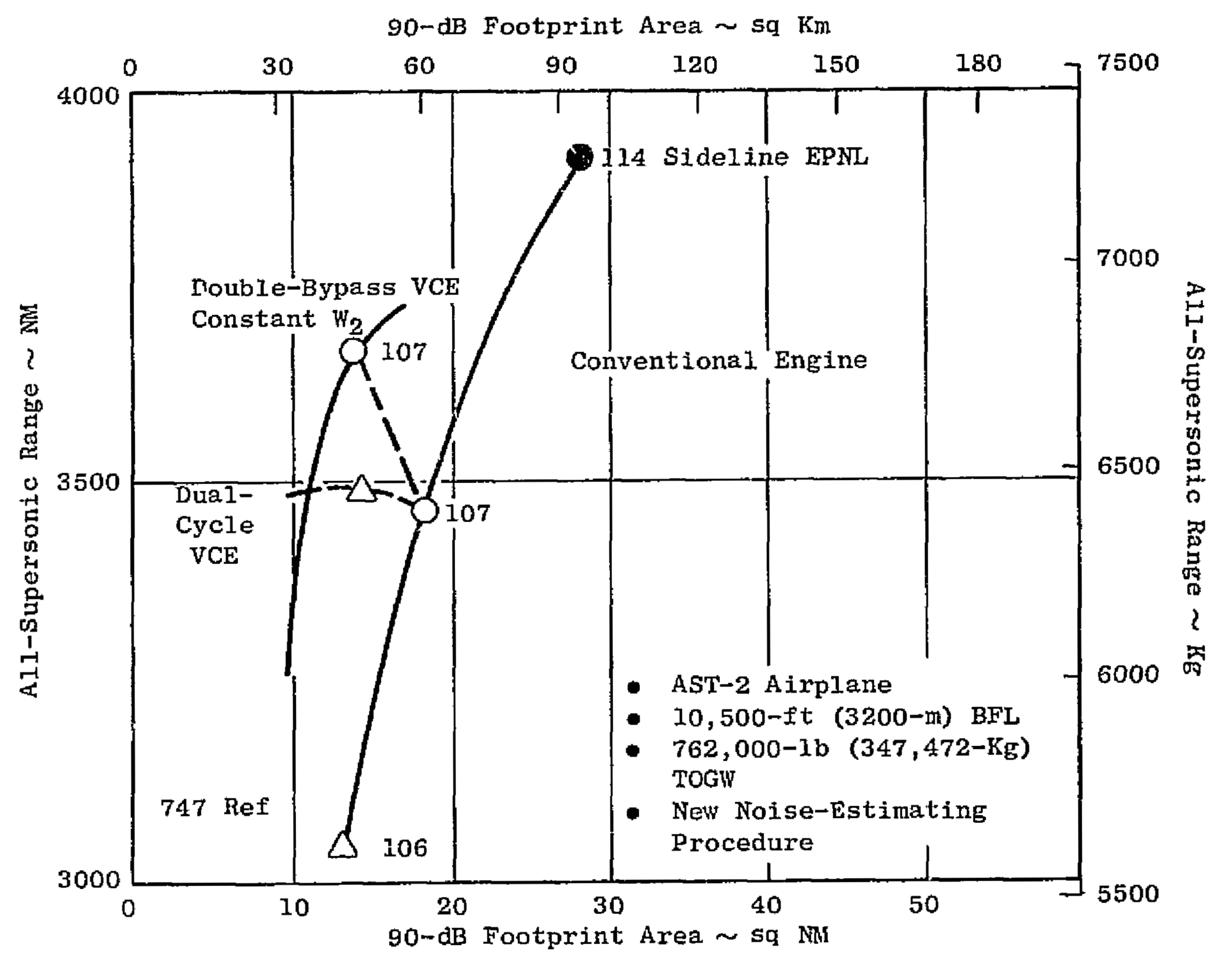


Figure 40. Double-Bypass/Dual-Cycle VCE Range and Footprint Improvements.

Table 15. Double-Bypass/Dual-Cycle VCE Noise and Range.

- AST-2 Airplane
- 762,000-lb (345,643-Kg) TOGW
- 10,500-ft (3200-m) Balanced Field Length
- Optimized Subsonic and Transonic Climb/Acceleration

	Baseline, Old VR	Baseline Revised VR	Baseline, Scaled to Same Sideline EPNL	VCE
Airflow, lbs/sec	805	805	1070	900/1093
Kg/sec	365	365	485	408/496
Take-off Thrust, lbs	61,400	61,400	61,400	61,400
N	273,107	273,107	273,107	273,107
Traded FAR Part 36, EPNdB	-2.3	+5.1	-2.5	-2.5
90-EPNdB Take-off Footprint Area, sq NM	14.5	28	18	13
sq Km	50	96	62	45
Range:				
All-Supersonic, NM	3920	3920	3470	3675
Km	7260	7260	6426	6806
600-NM (1111-Km) Initial Subsonic, NM	3720	3720	3170	3560
Km	6889	6889	5871	6593
All-Subsonic, NM	3125	3125	2370	3170
Km	5788	5788	4389	5871

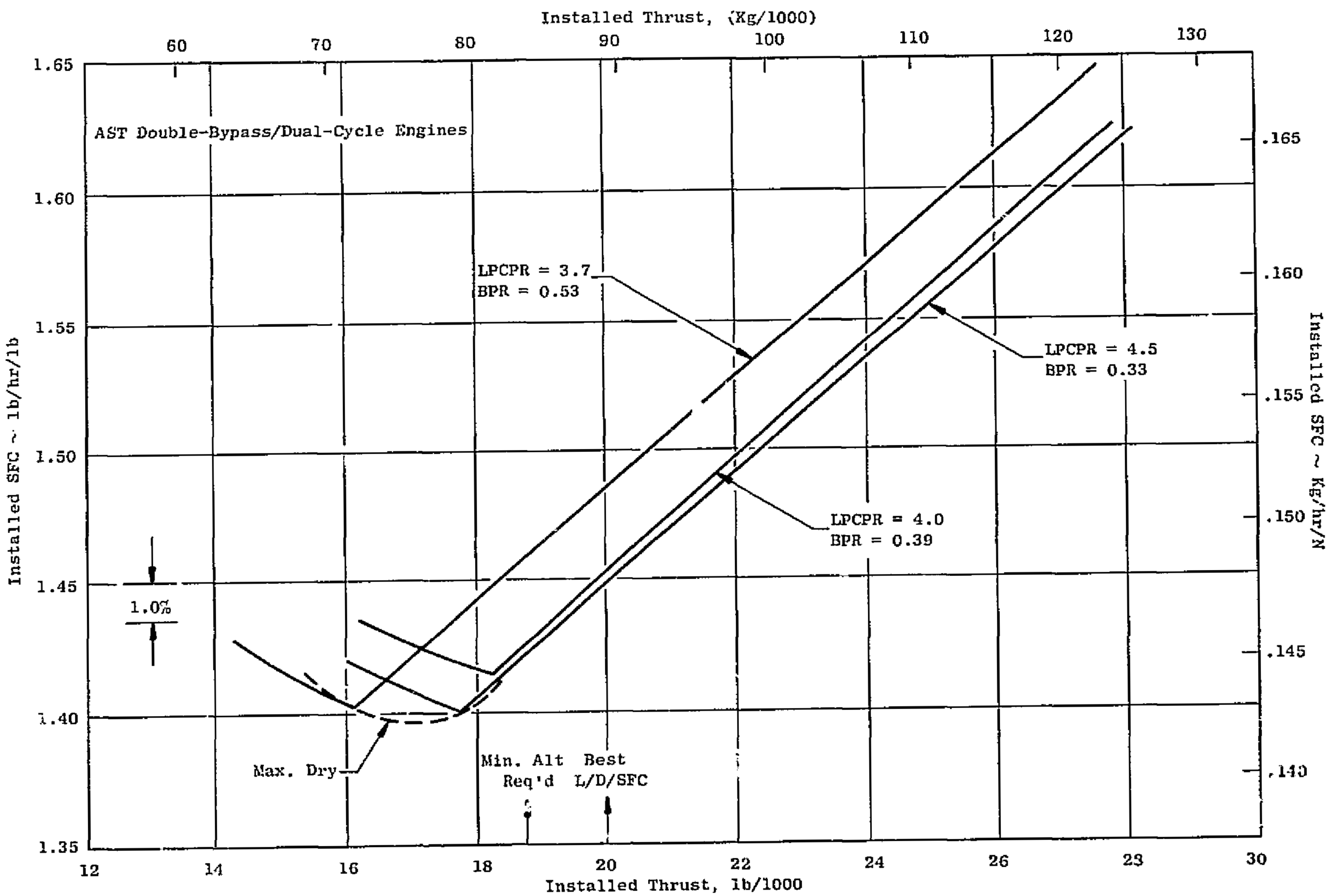


Figure 41. Effect of LPC Pressure Ratio on Supersonic Performance.

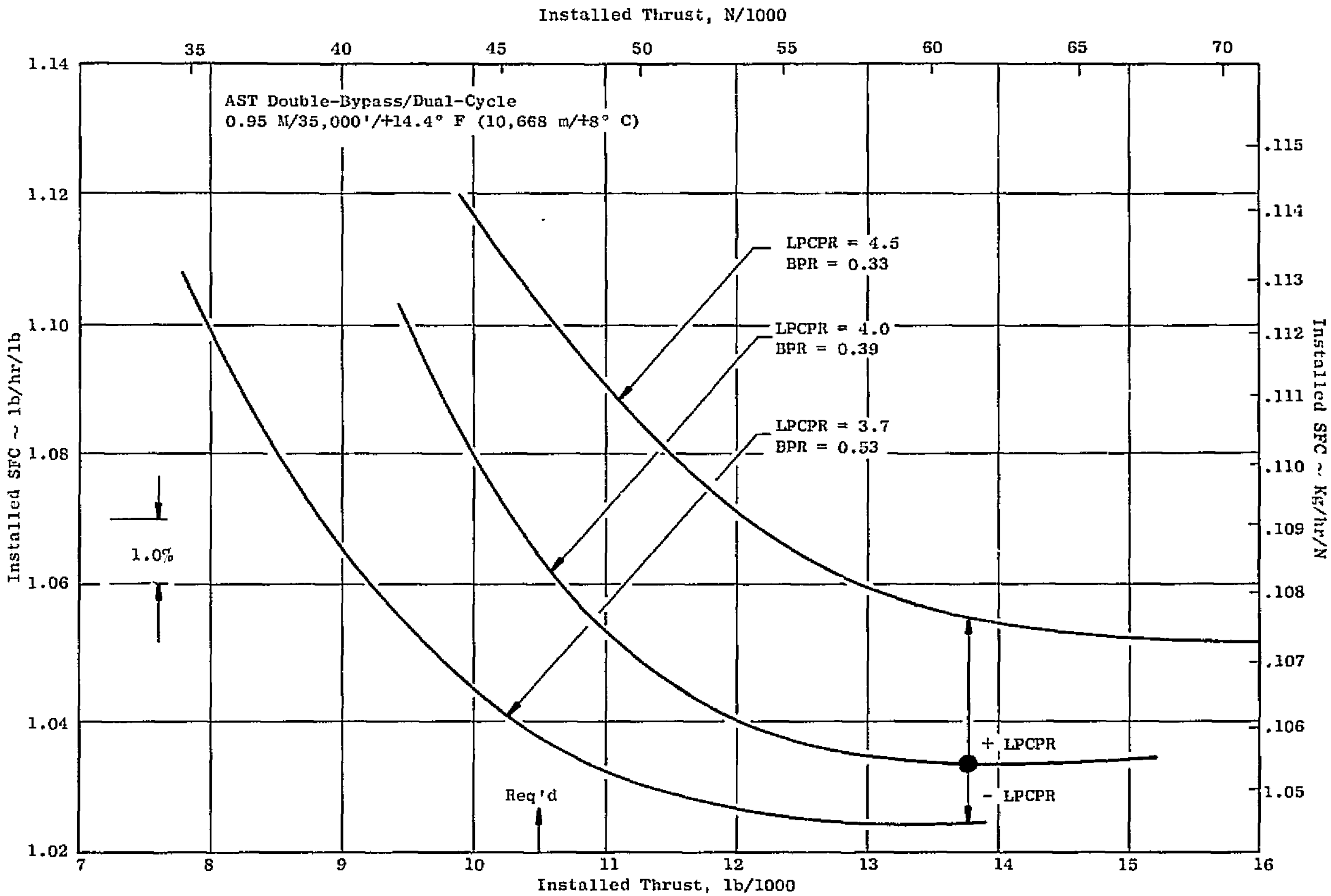
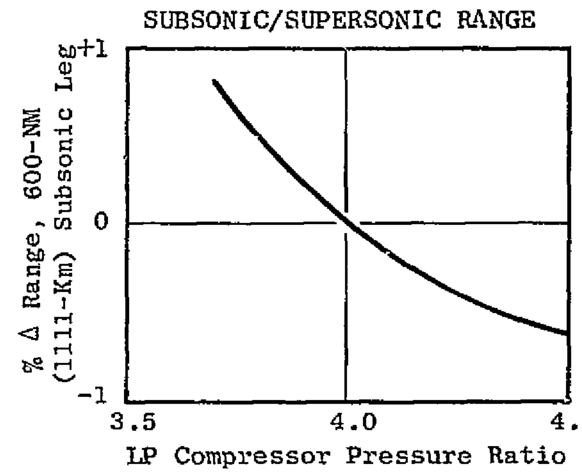
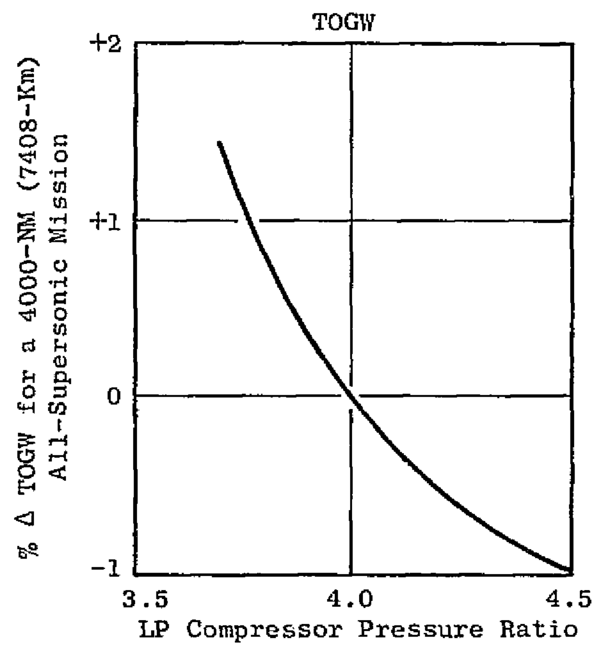


Figure 42. Effect of LPC Pressure Ratio on Subsonic Performance.

When LPCPR Is:	Then the SLS BPR Is:
3.7	0.53
4.0	0.39
4.5	0.33



- 4:1 PR is a reasonable selection



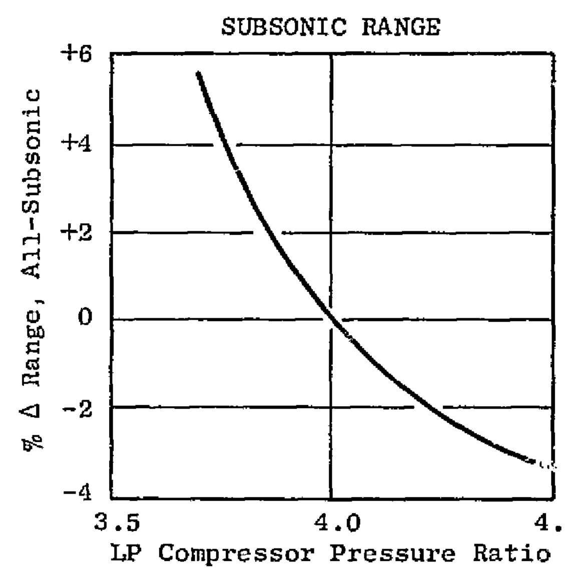


Figure 43. Double-Bypass VCE Cycle Study, Effect of LPC Pressure Ratio on TOGW and Range.

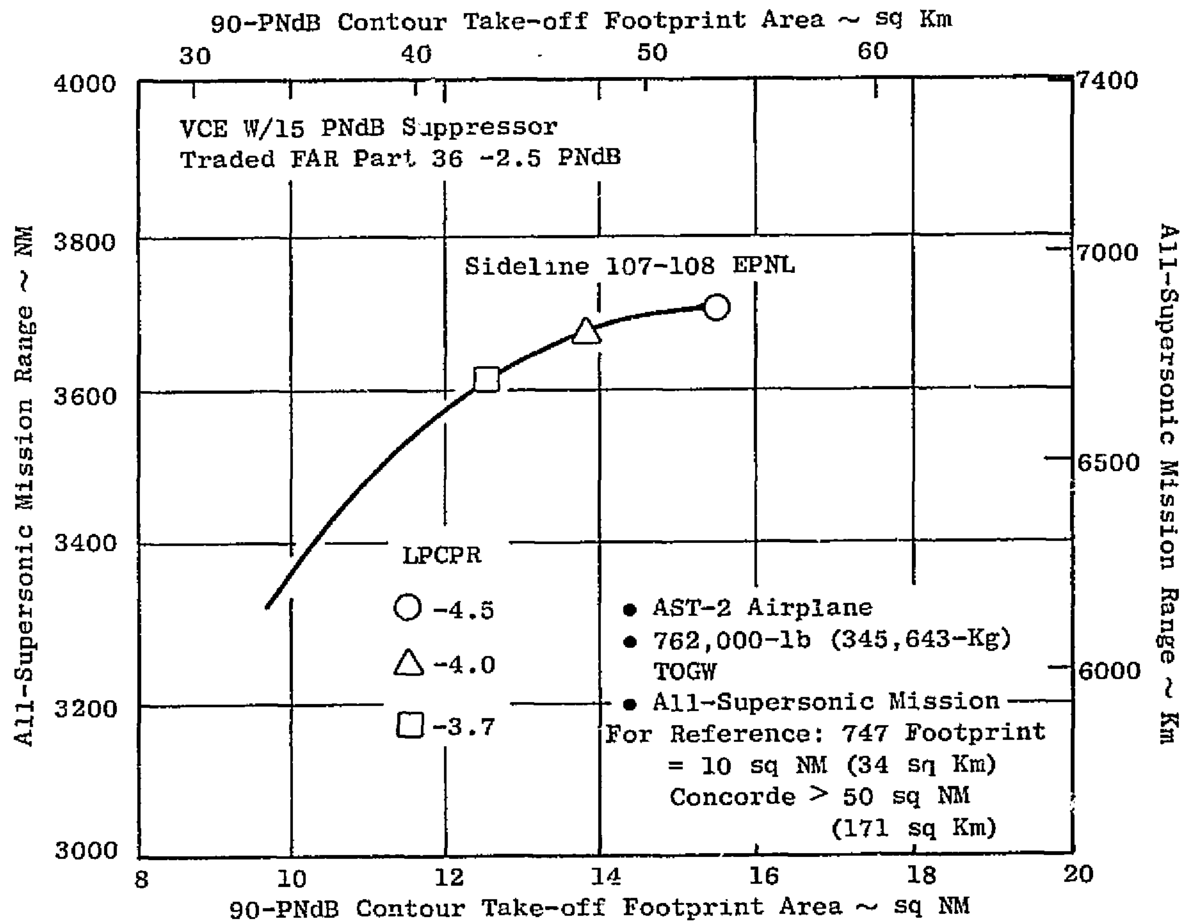


Figure 44. Double-Bypass/Dual-Cycle VCE Range and Footprints.

Table 16. GE21/J9 Study B-1 Double-Bypass Variable Cycle Engine.

Take-off Thrust, lbs	61,400
N	273,107
W_a, lbs/sec	900/1093
Kg/sec	408/496
Fan Pressure Ratio	4.0
Overall Pressure Ratio	22.4
Maximum Turbine Inlet Temperature, ° F	2800
° C	1538
Supersonic Cruise Turbine Inlet Temperature, ° F	2700
° C	1482
Mechanical Jet Noise Suppression, PNdB	15
Suppressor Design Point, ft/sec	2500
m/sec	762
Take-off Jet Velocity, ft/sec	2510
m/sec	765
FAR Part 36 Noise Level, EPNdB	-2.5
Engine Weight, lbs	20,000
Kg	9072
Maximum Diameter, inches	84.4
cm	214.4
Engine Length, inches	320.9
cm	815.1

effect of the engine noise sizing on the AST airplane economics. As shown in the ground rules, the mission for the economic study is 2500 N.M. (4630 Km) with a 400-N.M. (741-Km) initial subsonic segment. The TOGW for each engine size is the TOGW for the 400-N.M. (7408-Km) all-supersonic mission. Figure 45 shows the relative direct operating cost (DOC) of the double-bypass VCE compared to the baseline conventional engine over a range of engine airflow sizes from 800 to 1200 lbs (363 to 544 Kg/sec). At the lower airflow sizes, the VCE provides a 2% improvement in DOC; and, at the airflow size matched to the AST-2 airplane take-off balanced field length and noise levels, it increases to a 3.5% improvement. A similar trend is shown for return on investment (ROI) in Figure 46. At the low airflow, the improvement is very small; but, at the AST-2 take-off conditions, a 25% improvement in ROI is obtained. The double-bypass VCE provides another advantage in using less fuel for a given AST mission than the conventional engine. Figure 47 shows a comparison of total fuel used by the VCE and by a conventional engine in two AST missions. The fuel saved by the VCE is impressive, even in the all-supersonic mission. As subsonic operation is added to the requirement, the percent improvement increases rapidly. The double-bypass/dual-cycle VCE provides a better all-supersonic range, a much better subsonic/supersonic range, and offers large improvements in economic factors, all at a reasonable noise level.

Table 17. AST Economics.

- UNIT COSTS
  - Airframe - NASA Formula
  - Engine - GE Phase I Parametric Estimates

- DIRECT OPERATING COST (DOC)
  - 1967 ATA Formula Modified for 30¢/gallon Fuel Cost and 30% Engine Spares

- RETURN ON INVESTMENT (ROI)
  - NASA Contract NAS3-16950 Work Statement Modified Purchase Price for 30% Engine Spares

- MISSION FOR ECONOMIC STUDY
  - 2500-NM (4630-Km) with 400-NM (741-Km) Initial Subsonic Segment

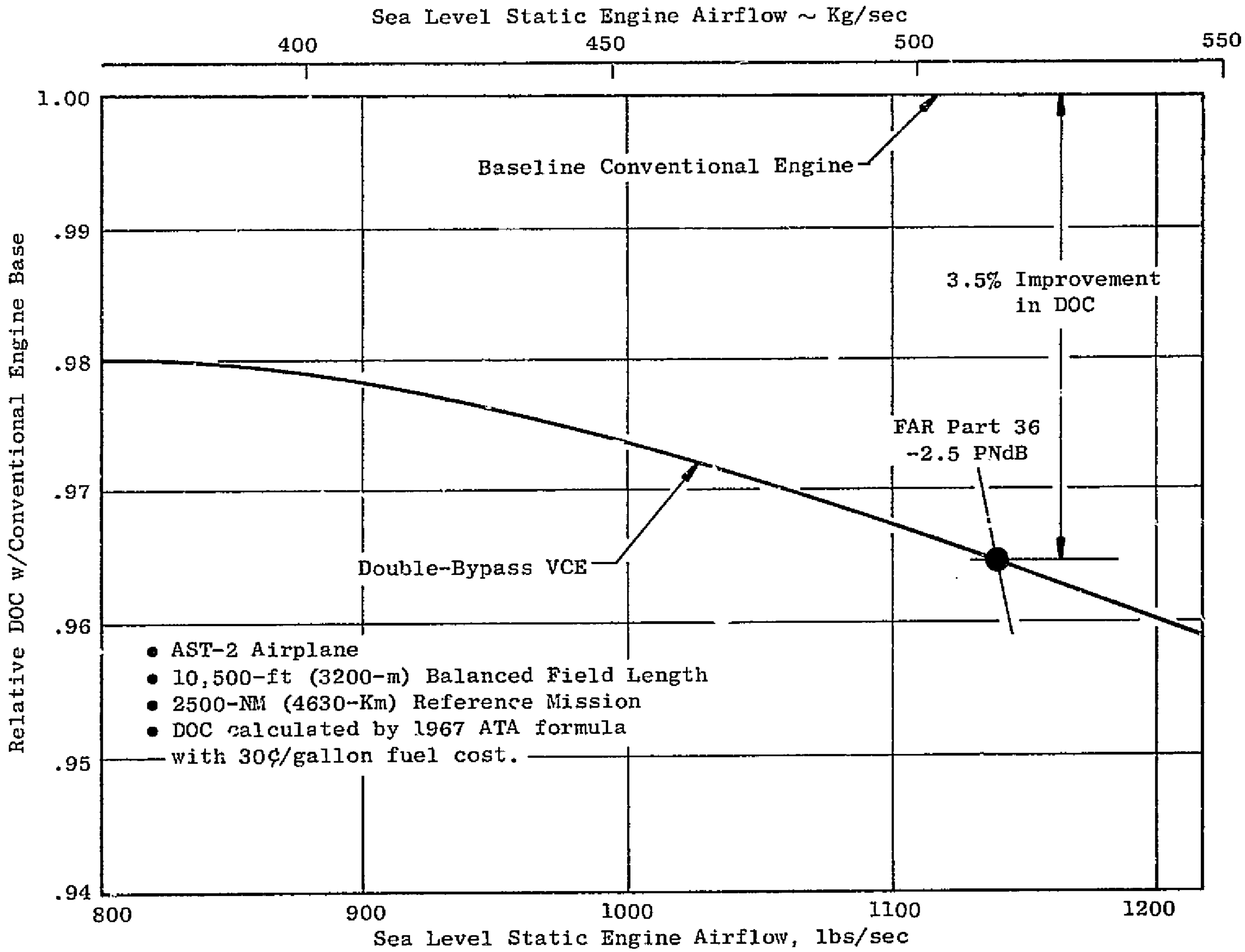


Figure 45. Double-Bypass VCE Improves Operating Cost.

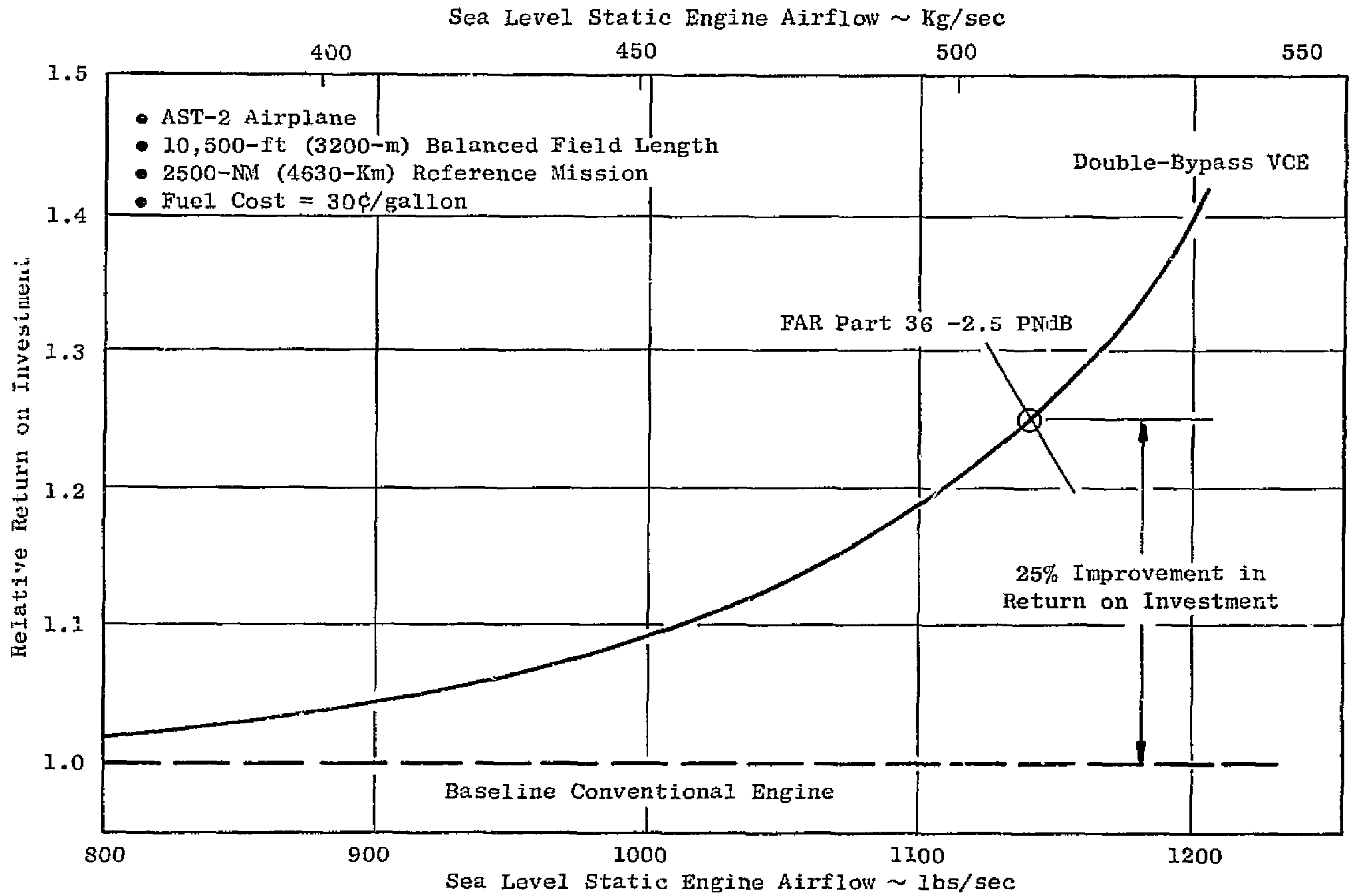


Figure 46. Double-Bypass VCE Improves Return on Investment.

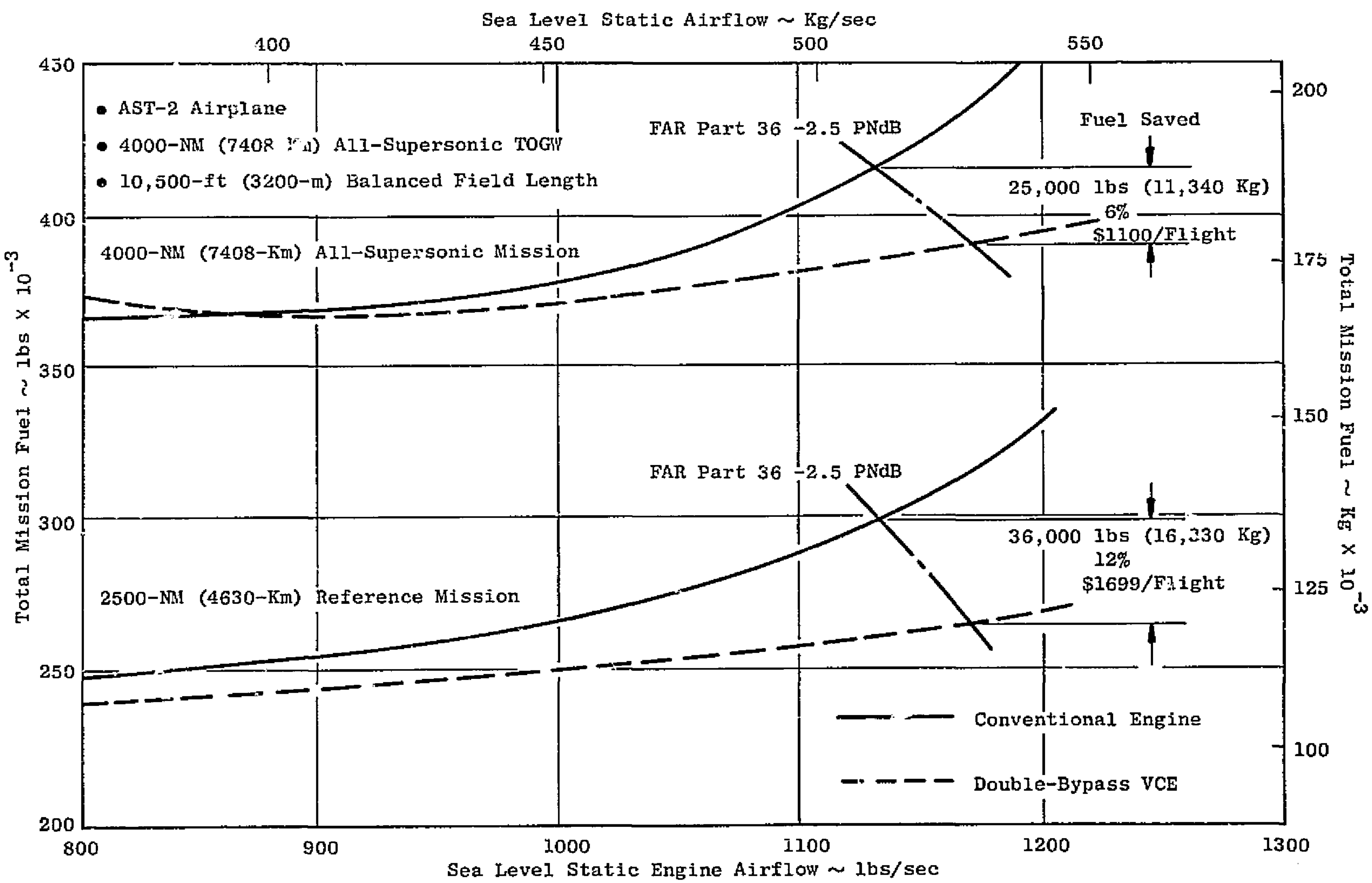


Figure 47. Mission Fuel Saved by the Double-Bypass VCE.

SECTION VI

ACOUSTICS

A. Introduction

As part of the NASA Contract NAS3-16950, various studies were made in acoustics to better define the noise signature of various AST candidate engines as well as to update the AST noise prediction procedure that was used based on the latest available data. These studies included predicting noise contours for AST-engine-powered aircraft, providing approximate predictions based on data not yet included in the AST noise prediction procedure correlations, predicting in detail the noise of the final AST engine (including the predicting of suppression from treatments which could be placed in the engine), and providing acoustic expertise in evaluating unconventional engines and high-risk or highly complex component designs including annular effects.

In updating the prediction procedure, the major changes occurred in the prediction of flight effects and directivity and EPNL determination.

B. Flight Effects

A major study was undertaken to better determine the flight effects on jet noise. Both historic data and recent test results were used including data from the F106, Learjet, Olympus on the VFTB, Bertin Aerotrain, NASA-Ames Wind Tunnel, and the GE/JENOTS Free Jet Facility. The old method used was the SAE method, i.e., predicting jet noise at the relative velocity. This delta was applied to all angles of the static jet directivity. This resulted in an overoptimization of maximum angle PNL and PNL-to-EPNL conversion (see Figure 48). In addition, static jet suppression was applied using the maximum angle delta predicted at all angles (Figure 49).

The new procedure predicts maximum angle flight effects from Figure 50 (1/2 of this value if suppressed), and includes the change in directivity from static to flight for suppressed and unsuppressed cases.

These changes resulted in a 2- to 4-EPNdB increase in predicted noise at sideline unsuppressed, and a 3- to 6-EPNdB increase suppressed.

C. Annular Effects

The AST prediction procedure does not presently differentiate between plug and conical nozzles, and it calculates noise from a coannular system by determining the noise from each stream separately and adding them. Recently, tests were conducted at JENOTS under the Duct-Burning Turbofan (DBTF) Contract with NASA (NAS3-18008). These tests showed dramatic reductions in noise relative to a conical nozzle both with and without suppressors (Figure 51). In addition, it appears that the core flow is not necessary to achieve the suppression (Figure 52). This may indicate substantial reductions from high-radius-ratio, single-flow, plug nozzles; however, this is still under study.

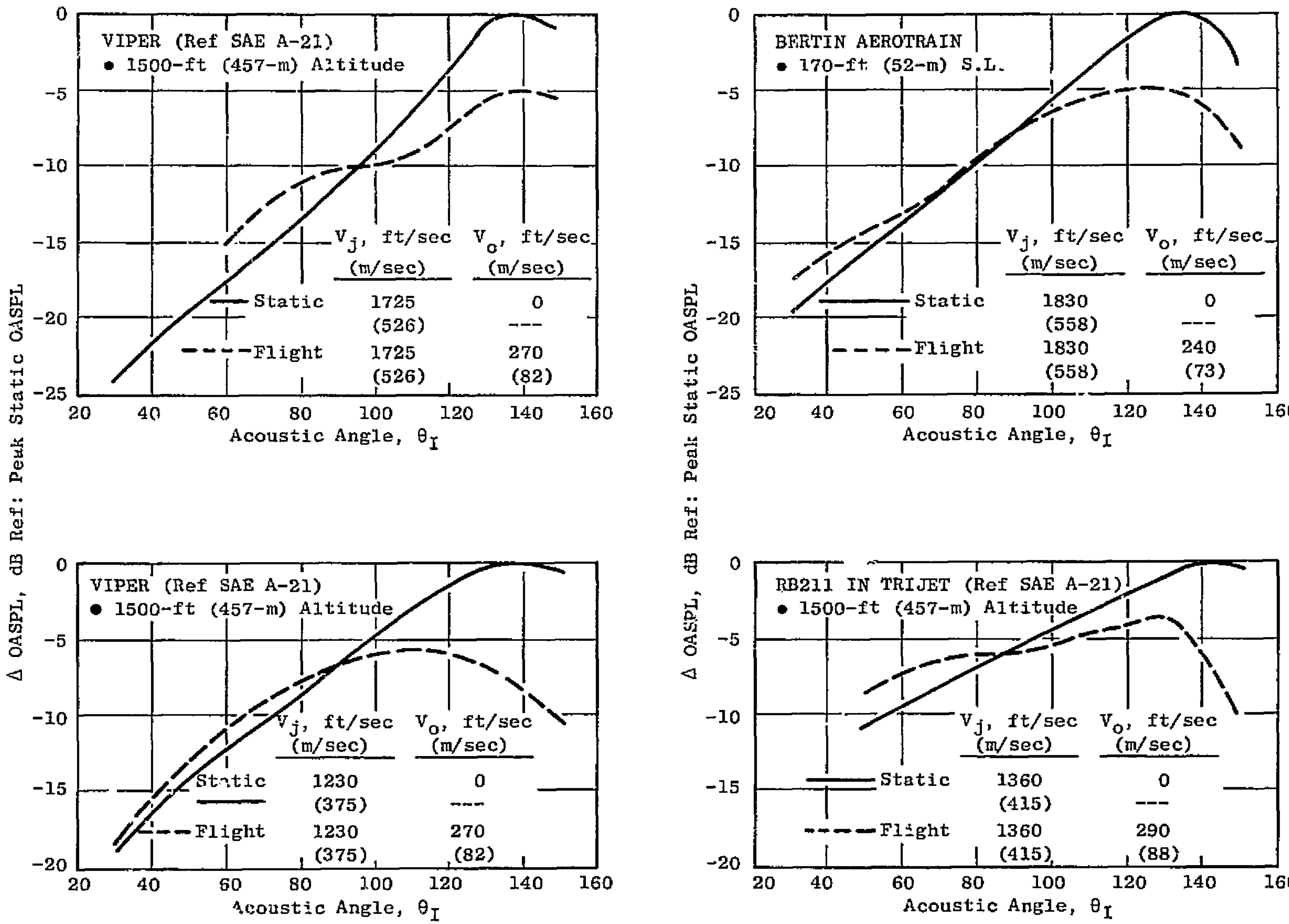


Figure 48. Comparison of Static and Flight Conical Nozzle Noise Characteristics.

AST Jet Noise Prediction - Old Method Vs. New Method

ITEM	NEW	OLD
• Flight Effects	• New Correlation	• SAE Method
• Flight Suppression	• Correct Static by Loss in V_R	• Flight = Static
• Flight Directivity (Suppressor)	• Suppressor D.I. in Flight	• Conical D.I. (Static)

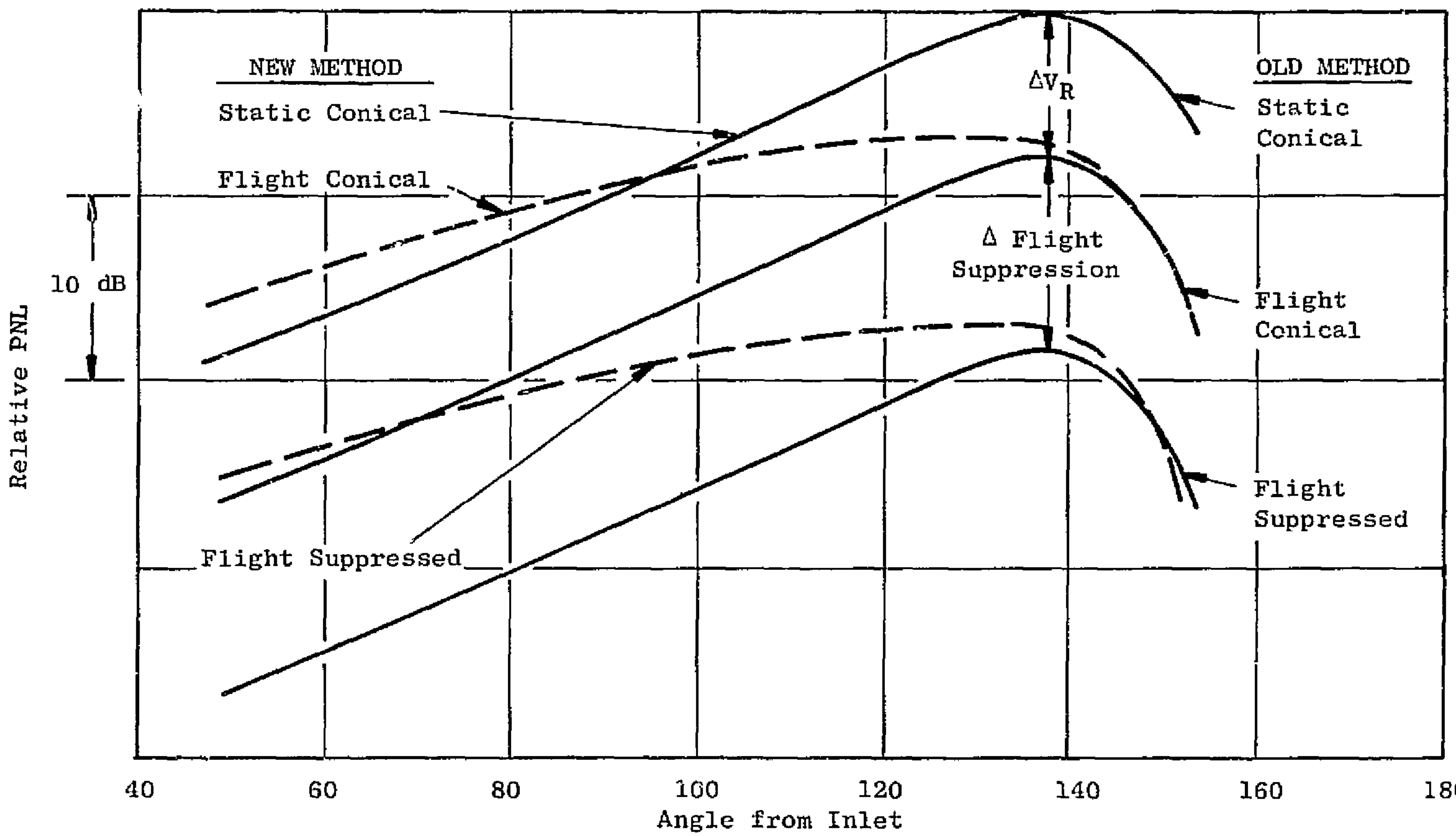
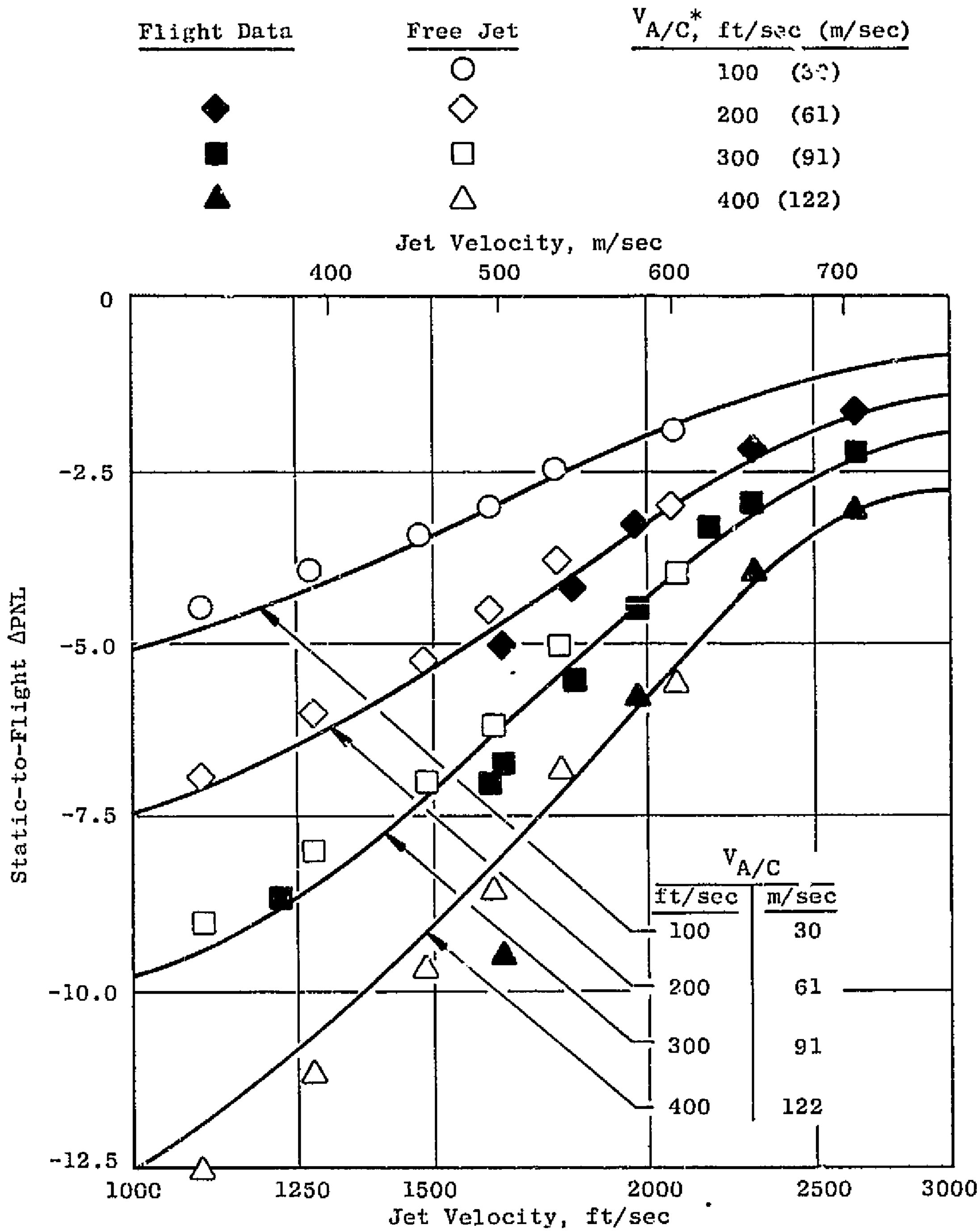


Figure 49. AST Jet Noise Prediction, Old Method Versus New Method.



* Corrected for Dynamic Effect

Figure 50. Unsuppressed Jet Noise Flight Effects at Peak Angle.

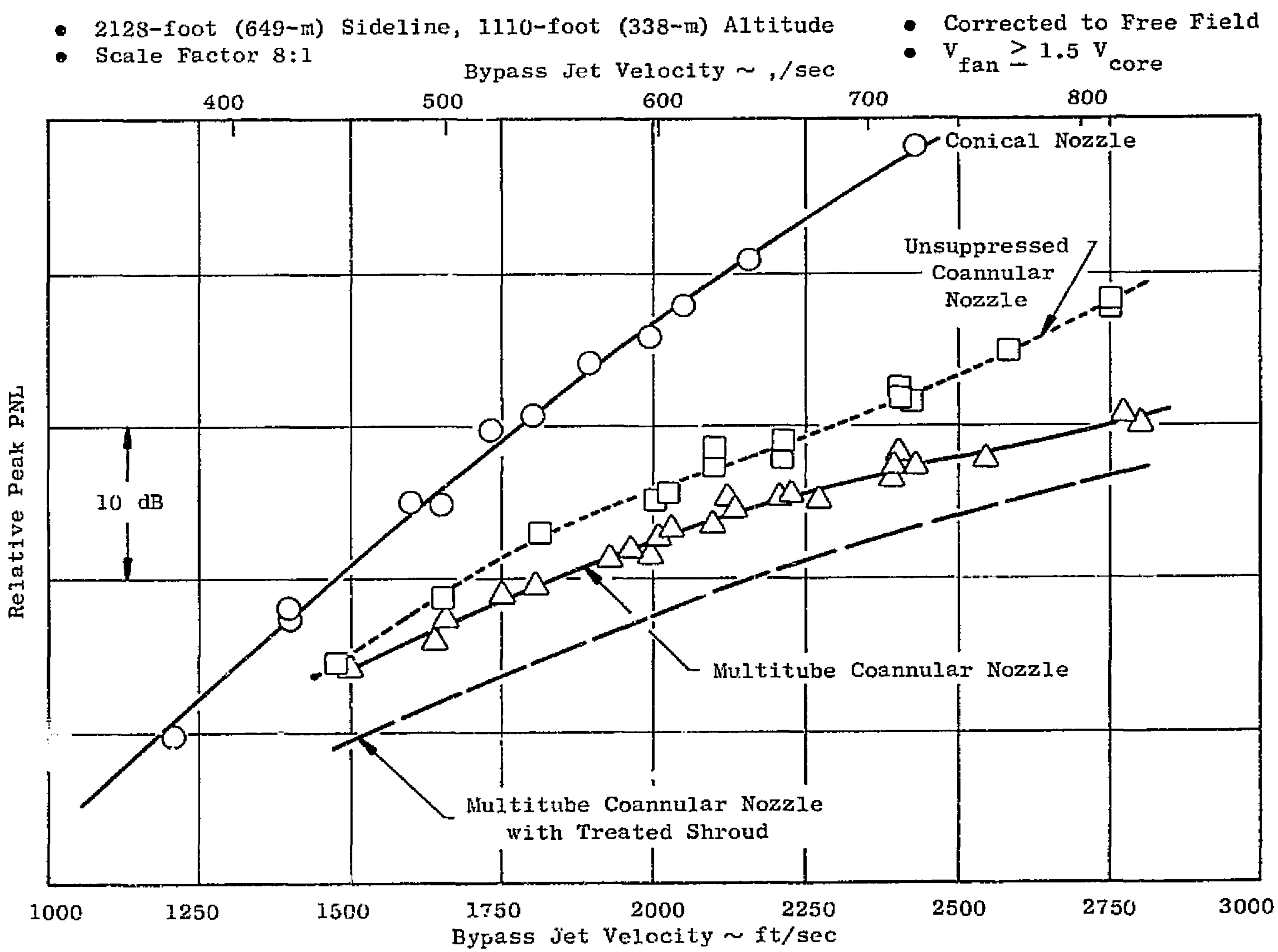


Figure 51. Duct-Burning Turbofan Scale Model Test, Preliminary Results.

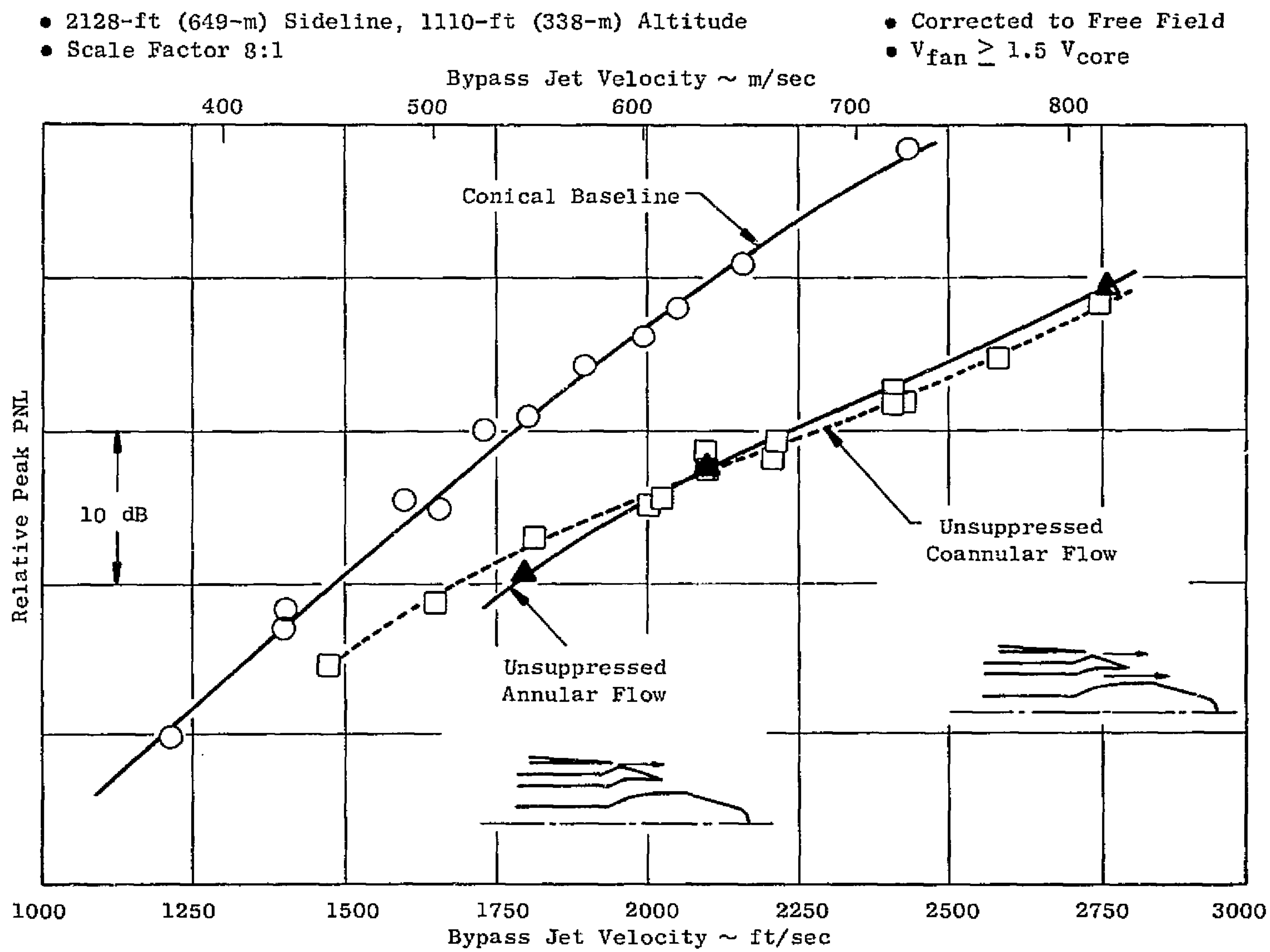


Figure 52. Duct-Burning Turbofan Scale Mcdel Test, Preliminary Results, Effect of Eliminating Core Flow on Unsuppressed Coannular Nozzle.

D. Conclusions and Recommendations

The recent major study undertaken on flight effects increased predicted noise by as much as 6 EPNdB with a jet suppressor; however, this is based on a somewhat limited set of data for the suppressed case. In order to arrive at the best possible prediction for flight effects, analysis will continue on existing data including "Free Jet." The free jet data must have an accurate transformation to flight before they can be used with full confidence. In addition, high velocity jet suppressor data will be taken at JENOTS and on the YF17 to better understand suppressor flight effects.

From the limited data analyzed to date on the DBTF program it appears that significant reductions can be obtained from this type of system. Thrust losses still must be determined for these nozzles, and flight data are necessary to determine flight effects.

Continuing emphasis will be placed on in-flight directivity as well as suppressor nozzle flight effects to achieve the lowest possible noise for AST engines, while still holding a high prediction accuracy. Work will continue on other components to ensure that they remain low as compared to the jet.