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ADVANCED SUPERSONIC TECHNOLOGY PROPULSION SYSTEM STUDY

Final Report

by

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GENERAL ELECTRIC COMPANY

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16. Abstract The Advanced Supersonic Propulsion System Technology Study had the objectives of determining the most promising conventional and variable cycle engine types and the effect of design cruise Mach number (2.2, 2.7 and 3.2) on a commercial Supersonic Transport; effect of advanced engine technology on the choice of engine cycle and effect of utilizing hydrogen as the engine fuel. The technology required for the engines was defined and the levels of development required to ensure availability of this technology in advanced aircraft propulsion systems were assessed.

No clearcut best conventional or variable cycle engine was identified in the study. The dry bypass turbojet and the duct burning turbofans were initially selected as the best conventional engines, but later results, utilizing augmentation at takeoff, added the mixed-flow augmented turbofan as a promising contender. The modulating airflow, three-rotor variable cycle engine identified the performance features desired from VCE concepts (elimination of inlet drag and reduction in afterbody drag), but was a very heavy and complex engine.

The study identified Mach 2.2 and 2.7 cruise Mach numbers as being feasible, but aircraft gross weights required for Mach 3.2 were considered impractical [greater than 1,000,000 lb (453,592 kg)].

Advanced (1980) engine component and material technology showed a small mission improvement over 1975 technology levels. The major technology improvement was the advanced exhaust jet suppressor which reduced noise levels substantially. The use of these advanced suppressors in conjunction with takeoff augmentation in the duct burning turbofan (both conventional and modulating airflow, three-rotor VCE) and the mixed-flow augmented turbofan, resulted in smaller engines (higher specific thrust at takeoff) which better match the AST airplane mission performance.

The use of hydrogen fuel resulted in a 40% reduction in airplane takeoff gross weight, but the high hydrogen fuel costs and high operating weight empty (OWE) gave poorer economics than conventional fuel.

The major technology items requiring work prior to incorporation in advanced propulsion studies were:

- Integrated exhaust nozzle, sound suppressor and advanced technology suppressor
- Material development to decrease engine weight and cost
- VCE unique component development and technology work

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Advanced Technology Sound Suppressor
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INTRODUCTION

NASA is studying the application of Advanced Supersonic Technology to the areas of supersonic commercial transport aircraft and supersonic military aircraft. These studies are being sponsored to define the technology areas required and assess the levels of development necessary to ensure availability of advanced technology for incorporation in the propulsion system design of future advanced aircraft projects.

The propulsion system study effort had the objectives of determining the most promising engine types and the effect of design cruise Mach number; the effect of advanced technologies on the choice of type and the effect of utilizing hydrogen as the fuel for the engine. While economics of the system and aircraft relative takeoff gross weight (TOGW) were the basic measuring parameters of the study, the traded FAR noise levels were also integrated into the work because of the impact on the results.

The outlined work was accomplished through the investigation of a series of engines at the specified design cruise Mach numbers utilizing the supplied aircraft performance and mission ground rules. Consistency in engine design was maintained through the use of a parametric engine cycle computer program that incorporated a technology level, aero-thermal, aeromechanical and mechanical constraints in addition to noise calculation procedures, weight and dimension models. The output from this program was used as input for mission analysis yielding aircraft weight and economic factors.

This effort drew heavily on the experience gained from the previous SST effort in which the contractor was deeply involved. The last technology levels used in that effort were used as the basis for this AST study with the incorporation of technology advancements estimated to be available for development in 1975.

RESULTS AND DISCUSSION

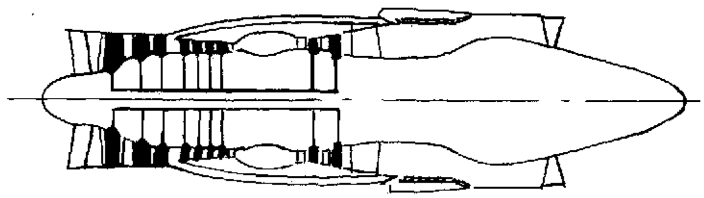
Engines studied during the Advanced Propulsion System Technology Study fell into two basic categories: Conventional cycles and several variable cycle engine (VCE) concepts. The conventional engine cycles studied in Task I were:

- Dry and augmented bypass turbojets - Figure 1a and b
- Duct burning turbofans - Figure 1c
- Mixed flow augmented turbofans - Figure 1d

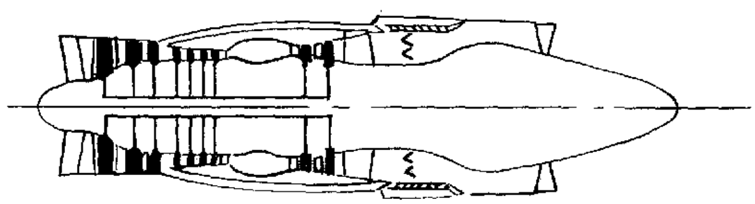
The variable cycle concepts studied in Task II can be placed in four different groups:

- Dual Inlet Engines - Those requiring auxiliary inlets to match series/parallel flow requirements.
  - Turbo augmented cycle engine (TACE) - Figure 2a
- Supplementary Takeoff Airflow Engines - Concepts which supplement the takeoff airflow of the main propulsion engines.
  - Fan-in-wing - Figure 2b
  - Augmentor wing - Figure 2c
- Convertible Engines - Turbofan characteristics during subsonic operation and turbojet characteristics in supersonic flight.
  - Flex cycle - Figure 2d
  - Modulating Airflow - 2 rotor engine - Figure 2e
- Modulating Airflow Engines - Capability to vary rotor speed and airflow over the operating range to minimize installation losses.
  - Modulating Airflow Engine - triple rotor - Figure 2f

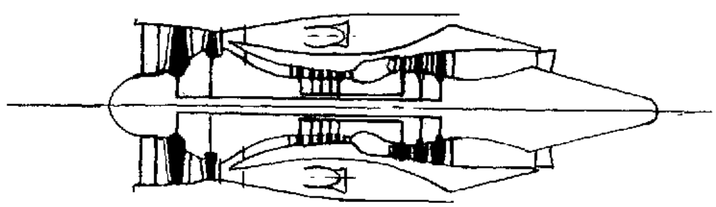
The 1975 technology conventional engines were analyzed in Task I and the VCE concepts in Task II to select the most promising types within the ground rules established for each Task. The selected types were further analyzed with advanced technology (1980), hydrogen fuel and with takeoff augmentation in Tasks III, IV, and V. After completion of the individual Tasks, further effort refined the results obtained and established the direction for possible follow-on work.



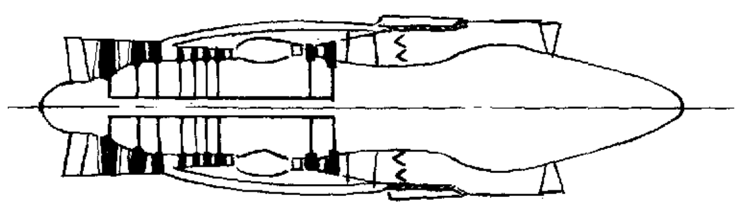
a. Dry Bypass Turbojet



b. Augmented Bypass Turbojet

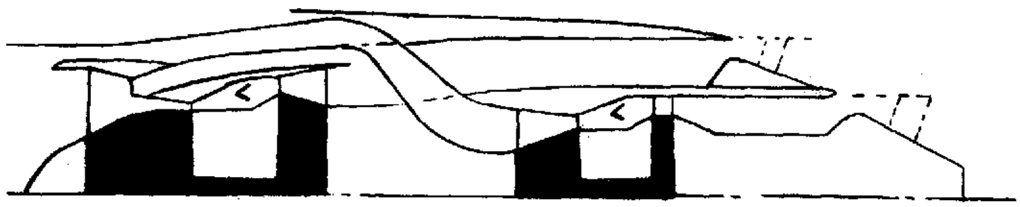


c. Duct Burning Turbofan

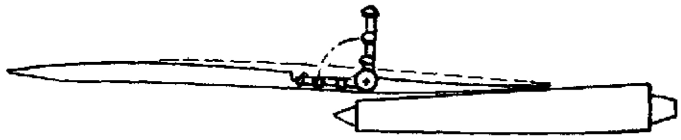


d. Mixed-Flow Augmented Turbofan

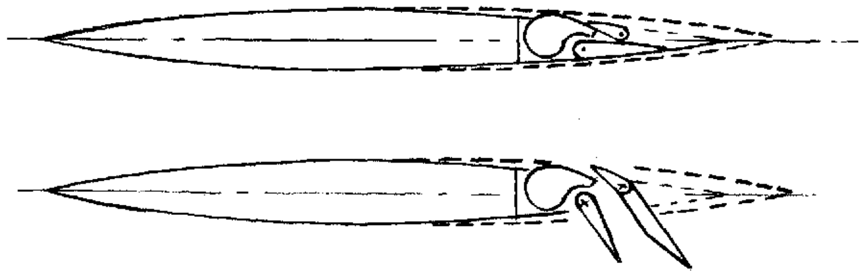
Figure 1. Task I Study Engines.



a. Turbo Augmented Cycle Engine



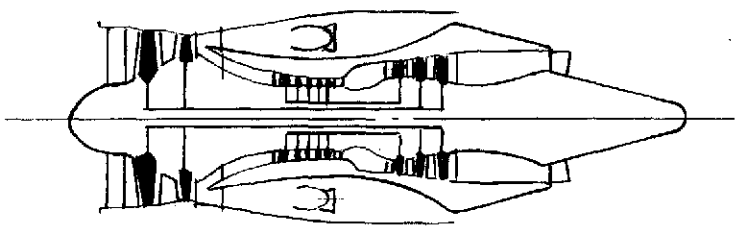
b. Fan-In Wing



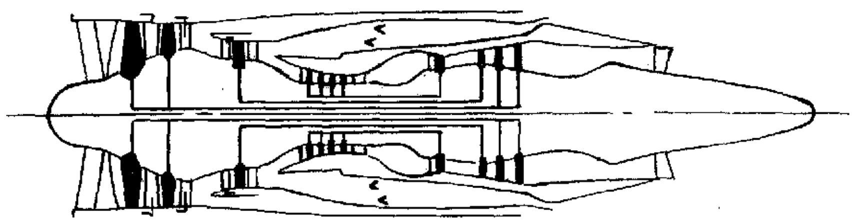
c. Augmented Wing

Figure 2. Task II Study Engines.

d. Flex Cycle



e. Modulating Airflow - Two Rotor



f. Modulating Airflow - Three Rotor

Figure 2. Task II Study Engines (Concluded).

The most important results of each task and a brief discussion of these results are given in the following section. A comprehensive review of each task is given in the attached Appendices A through F.

TASK I - CONVENTIONAL ENGINES, 1975 TECHNOLOGY

1. Specific Objectives

The objectives of Task I were to study the selected engine types, with cycle variations, to obtain the effect of operation at the three specified Mach numbers (M2.2, 2.7, and 3.2), and select the most favorable engine types on the basis of range in the baseline AST mission and economics (DOC, ROI).

2. Approach/Ground Rules

The selected baseline conventional cycles (Figure 1) were sized for noise, takeoff and mission requirements and flown through the AST baseline mission. Gross weight and economics (Direct Operating Cost, Return on Investment) were calculated. Cycle variations (P/P, β, turbine inlet temperature) were performed and the engine types with the longest mission range were selected for further effort in Tasks III and V.

The general ground rules used in Task I for the airplane, mission engine are given in detail in Appendix A, Task I. The most important engine ground rules were:

- 53,300 lb (237,000 N) thrust at rotation [12,400 ft (3775 m) balanced field length and nominal, 750,000 lb (340,000 kg) airplane].
- FAR 36 noise levels, 2500 ft/sec (763 m/sec) exhaust velocity with 10 PNdB sound suppressors on core for duct burning turbofans and on full stream for bypass turbojets and mixed flow turbofans.
- No takeoff augmentation.

3. Major Results

- The conventional cycles which had the lowest takeoff gross weight (TOGW) for the 4000 NMi (7410 km) AST mission and the best economics were (see Figure 3):
  - Dry burning turbofan
  - Dry bypass turbojet

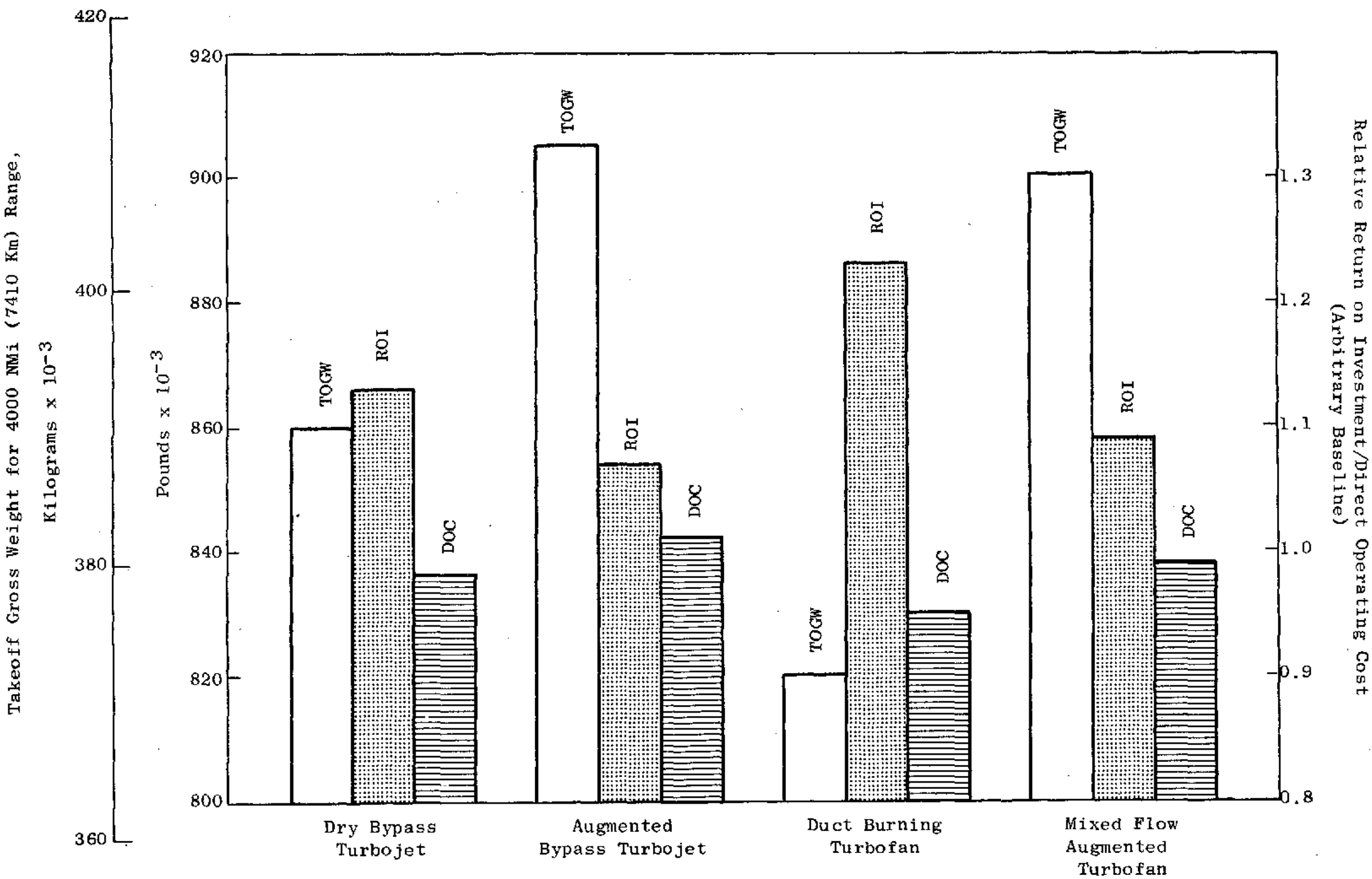


Figure 3. Task I TOGW and Economics Test Results, M = 2.7, FAR 36 Noise Levels.

- 2.2 cruise Mach number showed the best economics and the lowest TOGW for all engine types, with 2.7 Mach number poorer in economics and TOGW. Mach 3.2 did not give reasonable results and was eliminated from the study (See Figure 4).

4. Discussion

Figure 3 shows the Task I results for the four major engine types studied. The results can be summarized using the duct burning turbofan as the base:

- Duct burning turbofan
  - TOGW - Base
  - ROI - Base
  - DOC - Base

- Dry bypass turbojet
  - TOGW - 1.05
  - ROI - .92
  - DOC - 1.03

- Mixed flow augmented turbofan
  - TOGW - 1.1
  - ROI - .89
  - DOC - 1.04

- Augmented bypass turbojet
  - TOGW - 1.1
  - ROI - .87
  - DOC - 1.06

The duct burning turbofan showed up best in the analysis because its low propulsion system weight and good subsonic fuel consumption more than offset its supersonic fuel consumption deficiency.

The dry bypass turbojet is the next best. It is desirable because of its relative simplicity, and its performance is considered competitive with the duct burning turbofan, because its supersonic cruise fuel consumption partially offsets a higher propulsion system weight and high subsonic fuel consumption. The dry bypass turbojet also suffers from a long transonic climb and acceleration time and distance (poor range factor) which reduces the supersonic cruise distance (good range factor).

The mixed-flow augmented turbofan studied had good subsonic cruise performance and propulsion system weight, but had very poor supersonic cruise fuel consumption. The initial engine ranking resulted in study concentration on the duct burning turbofan and the dry bypass turbojet as the best candidate AST conventional engines, and the mixed-flow cycles were not exercised further in Tasks I-VI. Subsequent effort conducted in preparation for the Phase II AST contract did show, however, that using techniques from Task V (takeoff augmentation) could result in competitive mixed-flow augmented turbofan engines. The changes in philosophy resulting from this re-evaluation will be discussed later.

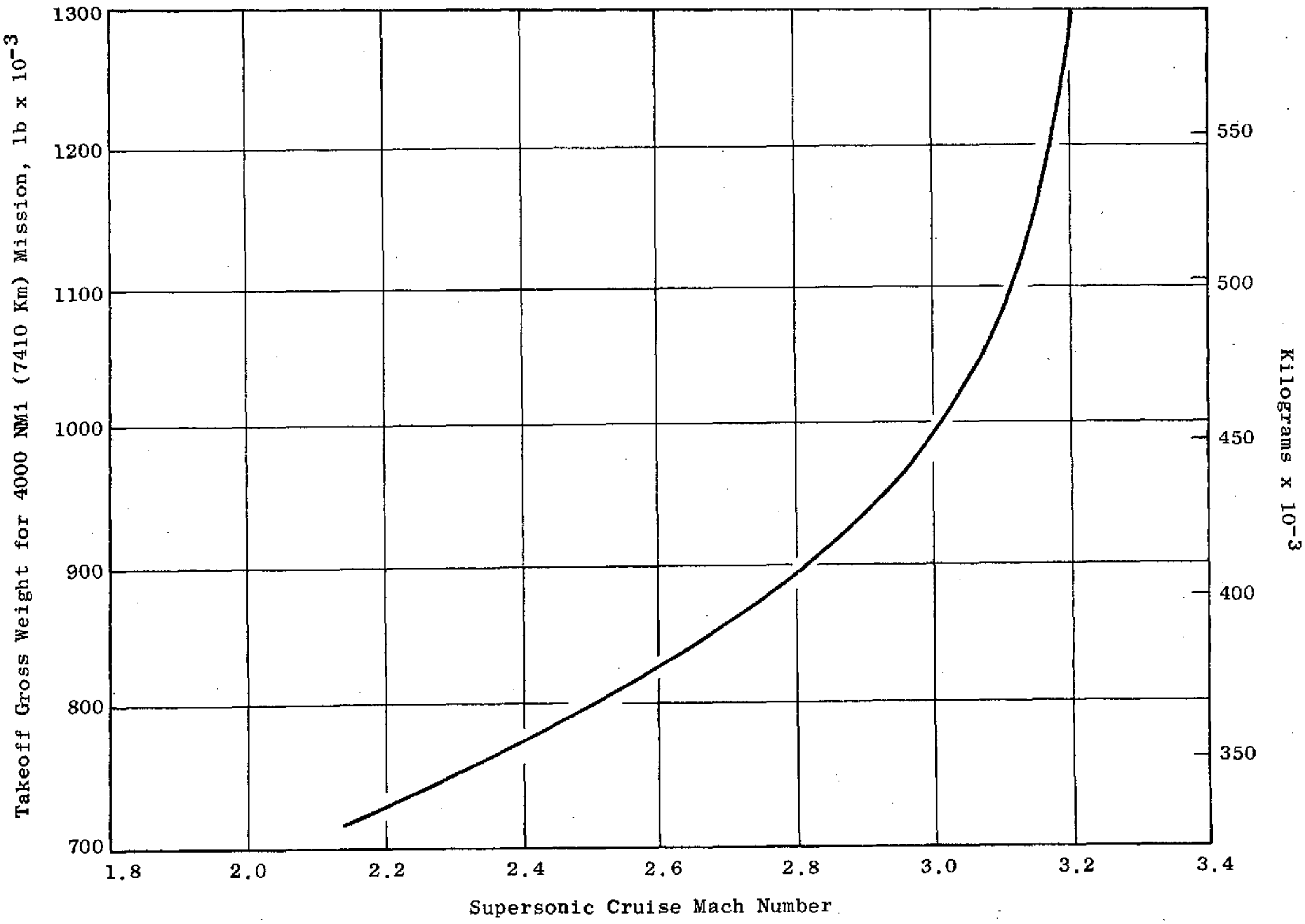


Figure 4. TOGW Vs. Supersonic Cruise Mach Number for Dry Bypass Turbojet, Task I Study Results, FAR 36 Noise Levels.

The augmented bypass turbojet engine suffered from high propulsion system weight (addition of an augmentor) and a higher loss cycle which had slightly poorer subsonic and supersonic fuel consumption than the dry bypass turbojet. The improved transonic climb and acceleration performance did not offset these penalties. Since Task I did not use augmented takeoff, the engine could not be scaled down to take full advantage of the augmentation available (See Task V results).

Figure 4 shows typical results of increasing cruise Mach number from 2.2 to 3.2. All engine types had similar trends to the dry bypass turbojet results shown in the figure. The increase in Mach number results in:

- Higher propulsion system weight (large engines)
- Higher supersonic and subsonic cruise fuel consumption
- Increased Supersonic Cruise L/D
- Increased time and distance during transonic climb and acceleration

The poorer installed performance and increased propulsion system weight more than offset the improved aircraft L/D and result in higher takeoff gross weight for increasing cruise Mach number. This indicates there is little incentive to increase the cruise Mach number beyond 2.7.

TASK II - VARIABLE CYCLE ENGINES, 1975 TECHNOLOGY

1. Specific Objectives

The objectives of Task II were the same as Task I except it utilized selected Variable Cycle Engine Concepts.

2. Approach/Ground Rules

The approach for Task II was similar to Task I, but a minimum of cycle variations were studied because of the complexity of most of the variable cycles.

The airplane and mission ground rules were the same as Task I, except that TOGW was the only criterion considered. The variable cycle engine ground rules were:

- FAR 36-10 EPNdB noise level
- Equal exhaust stream velocities on dual stream engines for takeoff, with exhaust velocity set at the maximum for the desired noise level [1960 ft/sec, (598 m/sec) 10 PNdB suppressors].

3. Major Results

- In terms of takeoff gross weight, no variable cycle concept showed a clear advantage over the best Task I conventional engines, and in fact, only one could be called competitive. (See Figure 5)

- The modulating airflow, triple-rotor engine equaled the Task I M2.7 TOGW of the dry bypass turbojet engine at a reduced noise level of FAR-36-10 PNdB. M2.2 range of the VCE was 400 NMi (741 km) less than the best Task I engines.

- The supplementary takeoff airflow engines (fan-in-wing and augmentor wing) met FAR-36-10 PNdB noise levels with no exhaust jet suppressors, but required major aircraft structural changes which could not be evaluated in this study.

4. Discussion

Figure 5 shows the takeoff gross weight required to meet the 4000 NMi (7410 km) range objective in the AST airplane and baseline mission. The modulating airflow - 3-rotor engine required a TOGW of 860,000 lb (390,000 kg) which is the same as required for the Task I Mach 2.7 dry bypass turbojet. This means that fuel economy of the 3-rotor engine was good enough to offset the approximately 20,000 lb (9070 kg) (4 engines) penalty in propulsion system weight. The other variable cycle concepts suffered from a combination of high propulsion system weight and poor supersonic cruise performance.

- Modulating Airflow - 3-rotor engine

  - Excellent subsonic cruise performance especially for hold and divert. This is because of the ability of this engine to hold airflow constant down to 50% maximum dry thrust with a resulting reduction in inlet drag (additive and bypass drag) and afterbody drag.

  - Fuel savings at constant TOGW imply superior DOC compared to conventional engines.

  - Supersonic performance slightly worse than the dry bypass turbojet engine.

  - High propulsion system weight.

  - Relatively complex engine structure and subsystems.

- Fan-in-Wing

  - Cruise fan thrust augmentation at takeoff enabled the augmented bypass turbojet to be scaled down to minimum size at rotation.

  - Low propulsion system weight (result of small gas generator size).

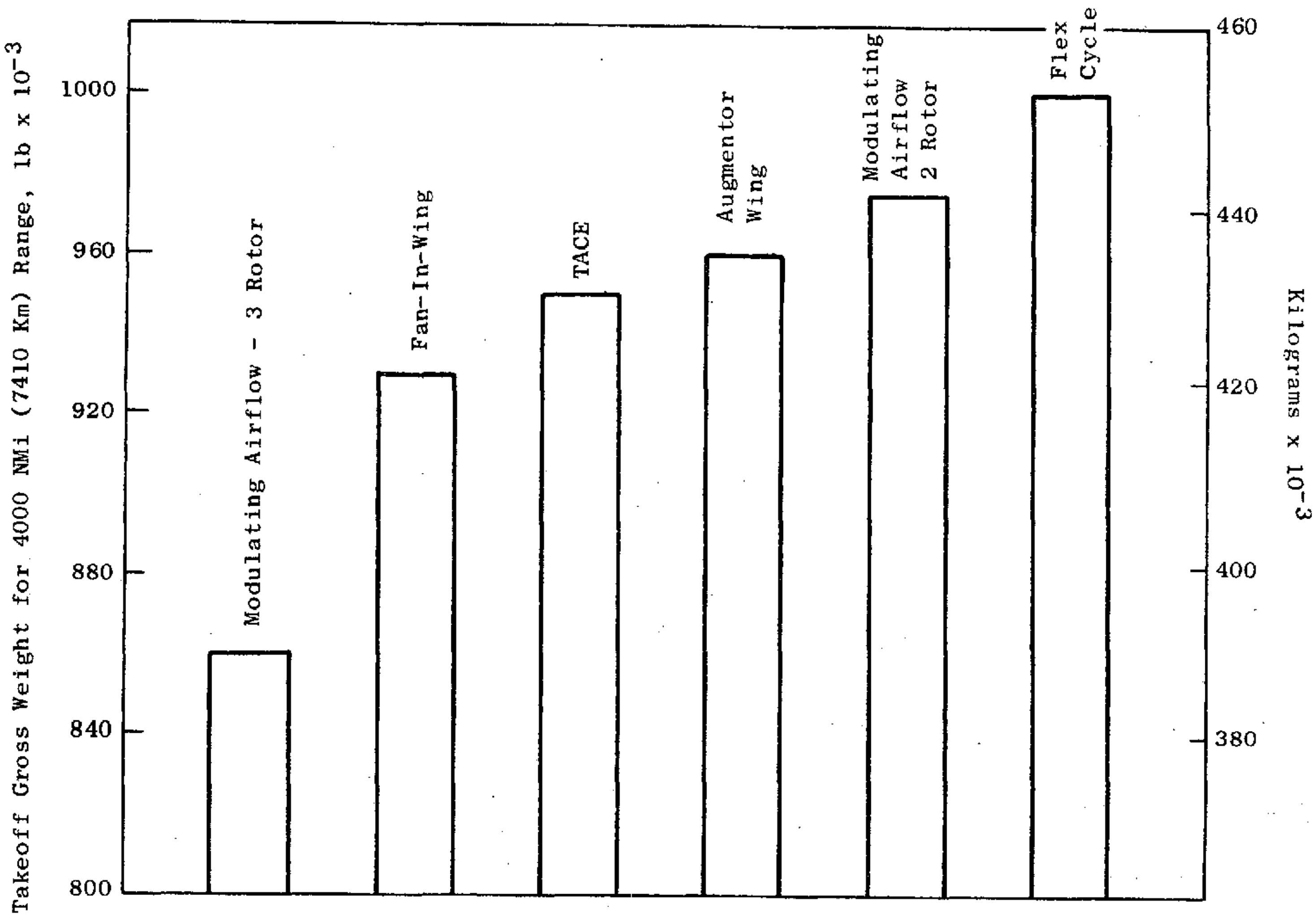


Figure 5. TOGW Required to Meet 4000 NMi (7410 km) Range for Task II Study Engines, FAR 36 - 10 PNdB Noise Levels.

- Poor supersonic cruise fuel consumption because of high augmentation required.

- Slightly poorer subsonic performance than dry bypass turbojet.

- Cost and complexity of fans, ducting, valving and associated controls.

- A presumed requirement to increase wing thickness to accommodate the retractable fans and associated ducting, and airplane structural penalties for large hot gas ducting through wing spars, neither of which could be analyzed in this study.

- Turbo Augmented Cycle Engine (TACE)

  - High propulsion system weight.

  - System and structural complexity.

  - Good subsonic cruise performance.

  - Good supersonic cruise performance.

  The TACE concept has the capability to reduce installation losses similar to the 3-rotor engine, but its propulsion system weight is too high to be offset by the slightly better overall performance. TACE also requires auxiliary inlets with inlet pressure recovery as good as the main engine inlet during subsonic cruise in order to reduce installation losses.

- Augmentor Wing

  - High propulsion system weight.

  - Good subsonic cruise performance.

  - Poor supersonic cruise performance.

  - The same aircraft structural penalties as fan-in-wing.

  The augmentor wing concept does not have a large enough takeoff augmentation (1.1:1 assumed) to allow the engine size to be scaled down as far as the fan-in-wing. The addition of the augmentor flaps and actuating mechanism and hot gas ducting raises the overall propulsion system weight much higher than the fan-in-wing and the low subsonic fuel consumption does not result in improved mission performance.

- Modulating Airflow - 2 rotor (VAPCOM)

  - Very high propulsion system weight.

- Complex structure and subsystems.

- Good subsonic cruise performance.

- Competitive supersonic cruise performance.

- Poor transonic climb acceleration performance.

The 2-rotor engine also has the capability to reduce installation losses during subsonic cruise and transonic climb acceleration, but does not compensate for the extremely high propulsion system weight.

- Flex Cycle

  - Very high propulsion system weight.

  - Complex structure and subsystems.

  - Good subsonic cruise performance.

  - Competitive supersonic cruise performance.

  The very high propulsion system weight, caused by high turbomachinery weight and the additional LP turbine, cannot be offset by the good subsonic performance, and results in high takeoff gross weight.

The Task II variable cycle concepts were not studied in depth to define optimum cycle parameters because of the complexity of each of the concepts. Further cycle optimization could improve the results shown here, but this would probably not change the relative standings. The cycle parameters actually used in this study for each concept were chosen by:

- Previous cycle studies

  - Flex cycle

  - Modulating airflow - 2 rotor (VAPCOM)

- Parallel work on military missions

  - Turbo Augmented Cycle Engine (TACE)

  - Modulating airflow - 3 rotor

- Adaptation of Task I parametric analysis

  - Fan-in-wing

  - Augmentor wing

TASK III - CONVENTIONAL AND VARIABLE CYCLES - 1980 TECHNOLOGY

1. Specific Objectives

Identify and incorporate in the best Task I and Task II engines advanced technology (see Appendix C) available for development in 1980. Identify the technology advances with the largest payoff (range improvement, DOC, etc.).

2. Approach/Ground Rules

There were no changes in airplane or mission ground rules for Task III. The engine ground rules were:

- Introduce technology improvements in the best way to improve engine specific thrust, reduce cruise SFC and reduce weight.
- Utilize engine technology to reduce engine size which leads to better mission performance.

3. Major Results

- Improved exhaust jet suppressor technology shows the largest payoff for
  - reduced engine size at the same noise level
  - reduced engine noise at the same engine airflow
- Improved materials for lower engine weight is the next most important technology payoff.
- Other advanced component technology used did not show appreciable improvements in engine weight or mission performance.

4. Discussion

Figure 6 shows the results of advanced technology introduced in the three Mach 2.7 Task I and II engines studied. The advanced technology with the largest effect is improved jet suppressors.

- Dry Bypass Turbojet
  - The major effect on this cycle is a reduction in FAR 36 noise level of 5 PNdB due to the increased suppression levels.
  - Improving the cycle with advanced technology provided small performance improvements which offset the added suppressor weight and higher engine airflow and resulted in a slight reduction in TOGW.

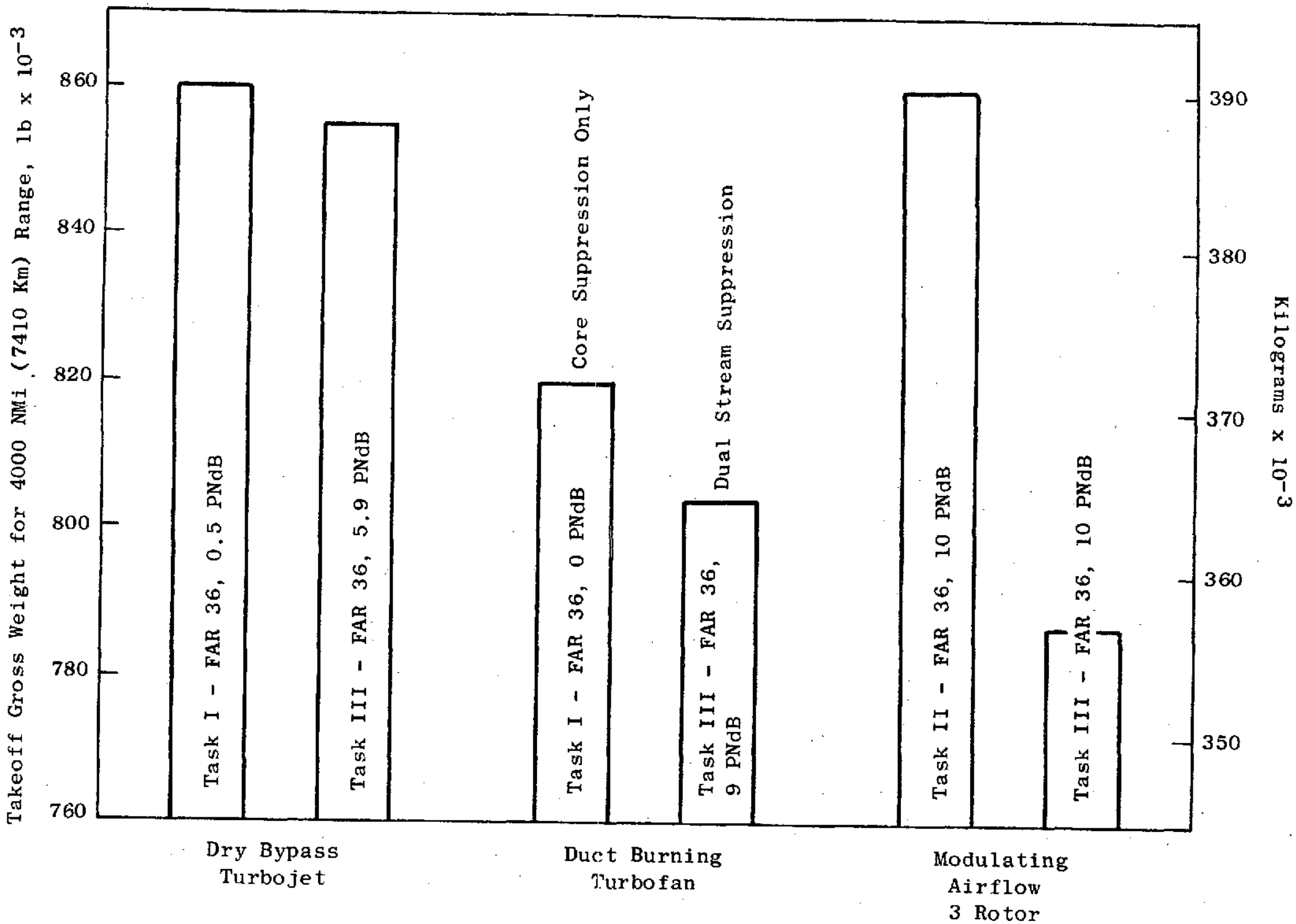


Figure 6. Task III Study Results for the Three Mach 2.7 Engines.

- Duct Burning Turbofan

  - The addition of advanced suppression to only one stream resulted in very small changes in noise level, but the addition of advanced suppressors on both the fan and core streams reduced the traded FAR 36 noise level by 9 PNdB.

  - Other advanced technologies applied to the engine cycle improved performance slightly and resulted in a reduction in TOGW of approximately 2%.

- Modulating Airflow - 3 rotor engine

  - The approach taken on this cycle was different than the others Since the Task II 3-rotor engine was designed to have FAR 36-10 PNdB noise levels, cycle improvements were used to increase the exhaust jet velocity of both streams to the maximum that would keep traded FAR noise level constant with advanced suppressors. The increase in specific thrust from higher exhaust velocity allowed a reduction in engine airflow to maintain rotation thrust levels. This resulted in a reduction of engine airflow from 1136 lb/sec (515 kg/sec) (Task II) to 996 lb/sec (452 kg/sec) with the engine noise levels remaining essentially constant.

  - The reduction in airflow size (and propulsion system weight) resulted in a reduction in TOGW of approximately 8 percent.

After completion of the Task III effort, model test results on various suppressor configurations reduced peak suppression level estimates for advanced technology suppressors by 3 PNdB (see Figure 8). The effect of this reduction on the Task III engines is:

- Reduction of traded FAR 36 noise levels by approximately 3 PNdB.

- A negligible effect on TOGW or range.

TASK IV - CONVENTIONAL AND VARIABLE CYCLES - 1980 TECHNOLOGY, HYDROGEN FUEL

1. Specific Objectives

Utilizing the engines from Task III using liquid hydrogen as the fuel, evaluate the engine size, takeoff gross weight, noise, and economics in the NASA hydrogen configured airplane.

2. Approach/Ground Rules

Changes were made to the Task III engines to reflect the use of liquid hydrogen fuel and the resulting engines were sized to meet mission sizing points. The engines were evaluated in the mission and economics were analyzed.

Ground rules for Task IV were:

- NASA Aircraft drag polar and structural fractions.
- Available hydrogen heat sink was only used for engine oil cooling.

3. Major Results

- High aircraft operating weight empty (OWE) of the hydrogen airplane plus high hydrogen fuel costs results in poorer economics compared to conventional fuels.
- Hydrogen-fueled aircraft results in a 40% reduction in takeoff gross weight.

TASK V - ADDITIONAL STUDIES - 1975 TECHNOLOGY

1. Specific Objectives

- Continued airframe contractor support.
- Further analysis of the selected conventional engine types (duct burning turbofans and bypass turbojets) to improve mission performance.
- Investigate the effect of mission changes on the relative performance of selected engines.
- Analysis of noise footprints of the selected engine types.
- Military applicability of variable cycle engines.

2. Approach/Ground Rules

Aircraft and basic mission ground rules remain the same as Tasks I through IV. Engine ground rules were essentially the same as Tasks I and II with the addition of takeoff augmentation to scale down engine size.

3. Major Results

- For all engine types considered, takeoff augmentation to exhaust velocities compatible with maximum exhaust jet suppression is the most effective way to reduce takeoff gross weight and improve mission performance.
- Duct burning turbofans with suppression on the fan stream only result in higher airflow than fully suppressed engines for the same noise level (down to FAR 36-10 PNdB) and takeoff thrust.
- Maximum suppressed engines can yield noise footprint areas (100 EPNdB contour) equal to current wide-body transports of similar configuration and TOGW.

4. Discussion

Figure 7 compares the Mach 2.7 duct burning turbofans of Tasks I, III, and V, and illustrates the reduction in engine airflow and airplane TOGW with maximum suppression levels and no augmentation (Task III) and takeoff augmentation and maximum suppression levels (Task V). (Similar results for the bypass turbojet are not illustrated.) At the same time the engine noise level has been reduced from FAR 36-0 PNdB (Task I) to FAR 36-9 PNdB (Tasks III and V). The augmentation is used to increase the duct exhaust velocity to the level required by the maximum capability of the suppressor to meet a required noise level. This results in the smallest engine (maximum specific thrust) that meets both noise and mission requirements. In a two-stream engine, both streams should be at maximum exhaust velocity and suppression capability. Bypass turbojet and mixed-flow turbofan engines can also be reduced to minimum size by the same method.

The reduction in peak suppressor levels, discussed under Task III, will reduce the noise level of the Task V engines by 3 PNdB with negligible effect on TOGW.

Duct burning turbofans with suppression on the fan stream only can be reduced in airflow by the same method. The two-stream maximum suppressed engine, however, will have a lower airflow for the same takeoff thrust, since its average jet exhaust velocity (specific thrust) will be higher than the fan only suppressed engine. The propulsion system weight trade-off will depend on several factors related to the specific cycles studied. The fan-only suppressed duct burner will usually have a higher bypass ratio, which will make the engine weight lower for a given airflow. It will also have a higher airflow than the fully suppressed engine, which will increase its weight. The fully suppressed engine weight will be penalized by the higher suppressor weight required. All of these factors must be traded against mission performance. The Task V effort did not analyze fully the bypass turbofan with fan stream suppression only, and a direct comparison cannot be made.

The AST baseline mission was changed to evaluate the effect of subsonic cruise length. As expected, increasing the subsonic distance favors the turbofan engines, while decreasing the subsonic distance favors the turbojets.

The airplane L/D at supersonic cruise was varied to evaluate the effect on TOGW. A reduction in supersonic L/D (one unit) resulted in an increase of approximately 20% in TOGW for the nonaugmented engines and about 15% for augmented engines. An increase in supersonic L/D (one unit) results in a reduction of 7% in TOGW for all cycles studied.

The modulating airflow, 3-rotor engine was exercised in a typical military penetrator bomber mission and showed the potential of an 8-10% improvement in range over a conventional engine baseline. A smaller improvement ($\sim$3%) was achieved in a typical fighter bomber mission. The improvement possible is dependent on the inlet and afterbody drag assumptions, since the modulating airflow, 3-rotor engine can reduce the installation drags substantially. High installation drag assumptions will result in the largest mission range improvements with the variable cycle engine.

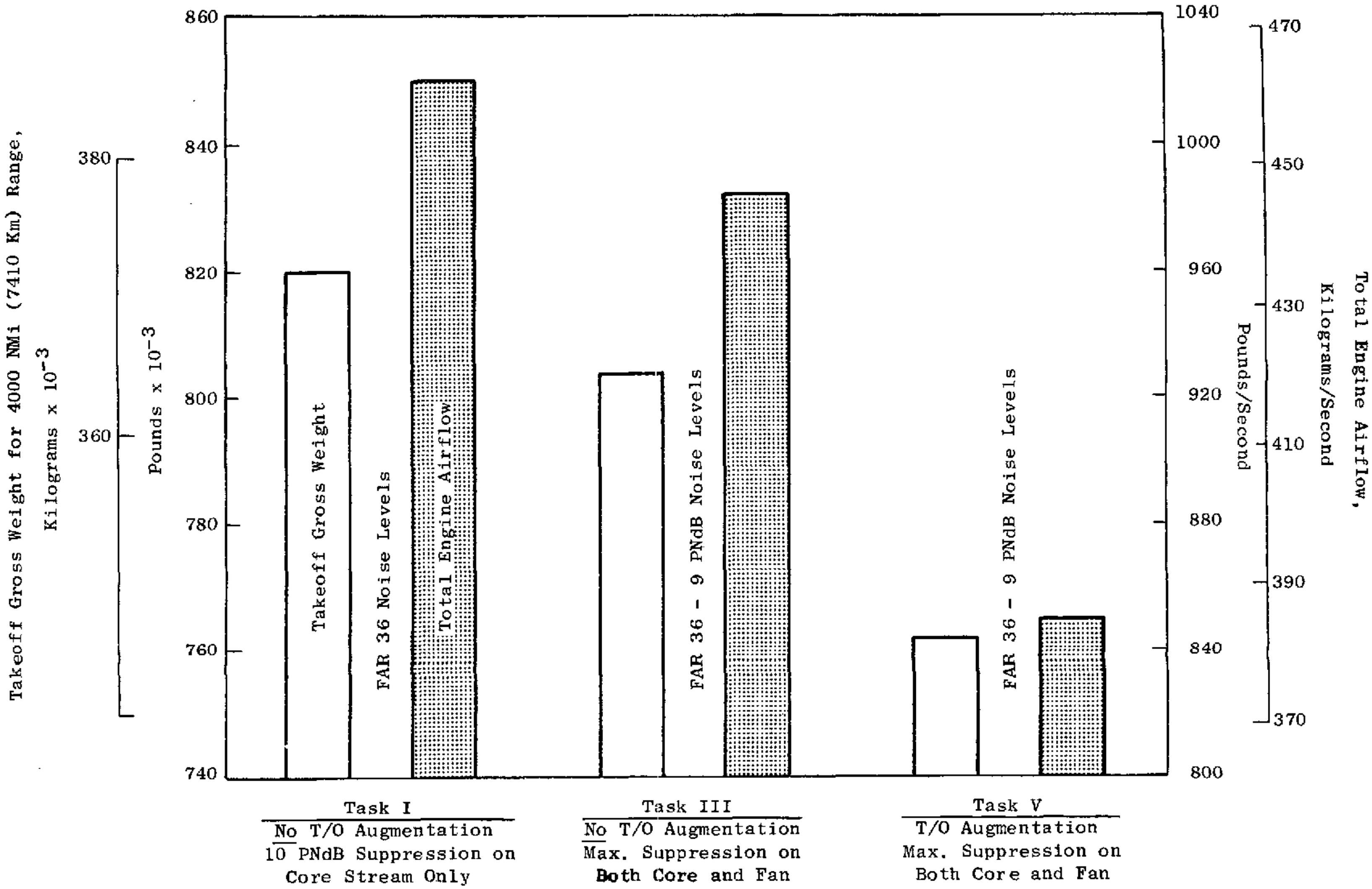


Figure 7. Task V Study Results, Comparison of Mach 2.7 Duct Burning Turbofans of Tasks I, III, and V.

TASK VI - TECHNOLOGY EVALUATION

1. Specific Objectives

The engine technology trades were reviewed and specific areas of technology improvement shown most needed for AST propulsion systems identified.

2. Approach/Ground Rules

Only the technology areas that are specific AST requirements were identified. Other technology areas (High T4, component improvement, etc.) available from other development programs (Military engines, ATEGG, IR&D, etc.) were not considered for recommended AST technology development.

3. Major Results

Several major technology areas need development work to be available for AST propulsion systems:

- Engine acoustical suppression technology and integration of compressors with exhaust system.
- Material and structural design improvements to decrease engine weight and cost.
- VCE unique component development and technology work such as modulating flow multistage fan and LPC and variable LP turbine.
- Combustor and augmentor low emission technology.
- Long life, high performance (2800° F, 1538° C) combustor and turbine technology.

Post Task VI Effort

At the conclusion of the AST definitive Task I-VI study effort, further work was accomplished to examine some of the aerodynamic and mechanical concepts needed to verify that the engines in Tasks IV and V were feasible. These results are reported here to provide a transition to subsequent study effort. In this same time period, the results of studies done in the Acoustics area indicated that exhaust jet suppression level for 1980 technology was too optimistic and should be reduced to a maximum of 15 PNdB at 2500 ft/sec (762 m/sec) exhaust velocity (see Figure 8). This was factored into preliminary design studies of the single- and two-stream exhaust nozzle/suppressor/reverser systems to verify the feasibility of actuating and stowing the sound suppressors and the weight estimates used in the parametric cycle deck. The single-nozzle exhaust system (bypass turbojets, mixed-flow turbofan) study verified the weights used for these engines in Tasks I-V, but the dual-stream suppressed exhaust systems were much more complex and resulted in higher weight than previously estimated. This caused a major impact on the propulsion system weight of the maximum suppressed duct burning turbofan, and therefore on its mission performance in the baseline AST airplane.

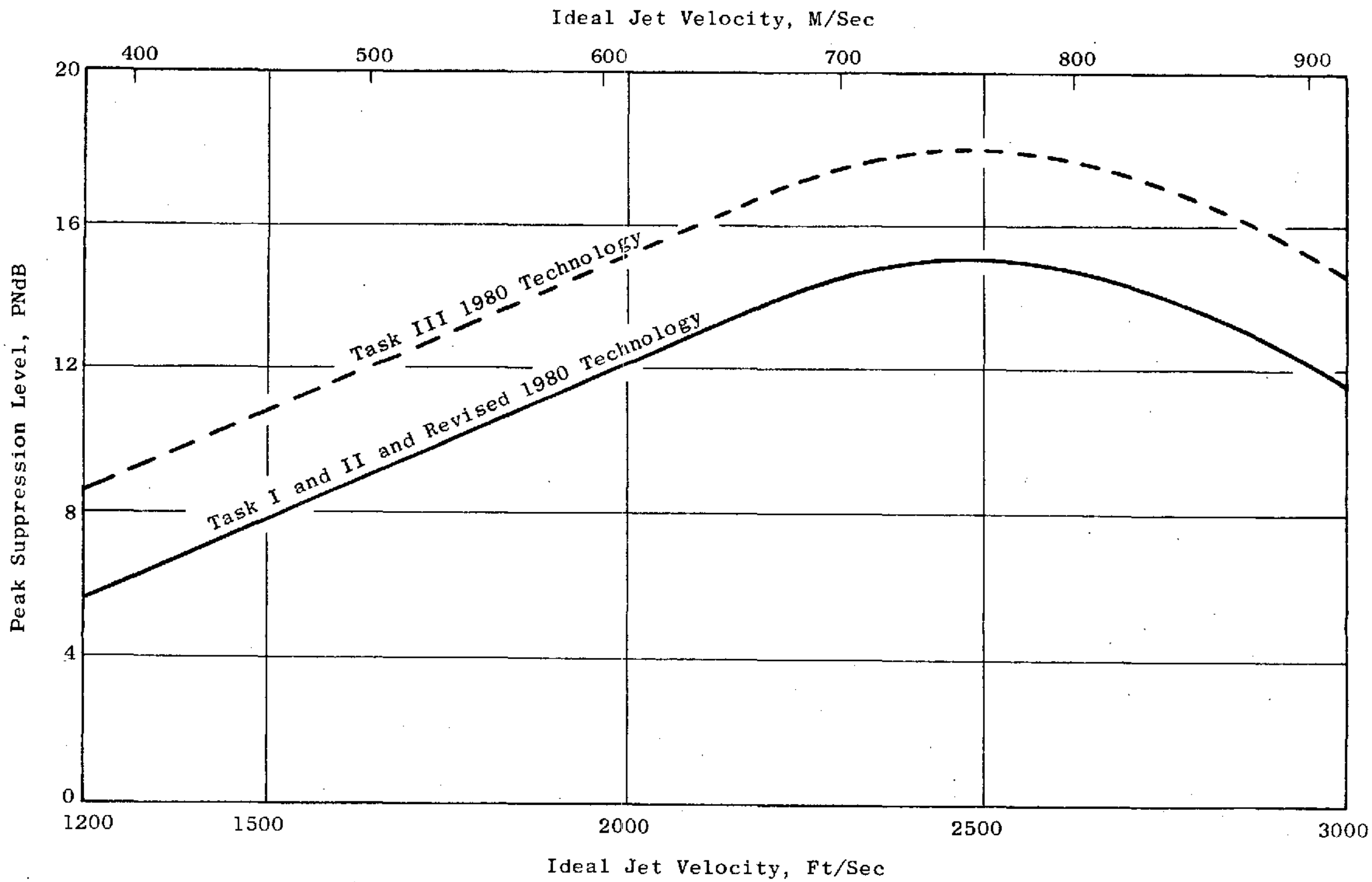


Figure 8. Post Task VI Study Effort, Jet Noise Suppression Technology, M = 0.3.

The effect of the lower peak jet suppression level and increased exhaust system weight for duct burning turbofans was factored into the previous Task I-V results and more effort was applied to the mixed-flow augmented turbofan cycle previously eliminated in the Task I study. All of the M2.7 engine types from Task I, and selected variable cycle concepts were studied (see Table I) using revised peak jet sound suppression levels and exhaust system weights combined with takeoff augmentation (where mission sizing allowed) to give the smallest, lightest engines of each type which met all mission sizing criteria. The engines were sized to give traded FAR 36-3 to 5 PNdB noise levels where possible. The result of this work is shown on Figures 9 and 10 which compare propulsion system weight, range, and noise level of the selected engines. These figures are presented primarily for illustrative purposes and are not intended to show a "best" engine.

The addition of a maximum exhaust jet sound suppressor combined with takeoff augmentation to reduce engine size, at a traded FAR 36-5 PNdB noise level, indicates that the mixed-flow augmented turbofan (engine 23 on Figures 9 and 10) is a competitive engine with the duct burning turbofan and dry bypass turbojet.

Task II variable cycle engine work did not identify a clear "best" VCE concept when looked at from a complexity, weight and mission performance standpoint. It did, however, identify the VCE performance features desired from a variable cycle engine. The modulating airflow, triple-rotor engine did exhibit performance advantages that made up for its high propulsion system weight, but its complexity and risk were considered very high.

The modulating airflow triple-rotor engine has the capability to match the aircraft inlet airflow characteristics and greatly reduce the installation drag. If this same reduction in installation drag could be accomplished on a less complex engine with one exhaust nozzle, suppressor, and reverser system, the advantages of reduced weight, better reliability and lower risk would be gained.

The analysis of the mixed-flow augmented turbofan engine with takeoff augmentation and maximum jet sound suppression showed good performance characteristics over the AST mission profile, except for low subsonic power conditions (subsonic cruise, divert and hold) where the low thrust required is obtained by a reduction in engine airflow. This reduction in airflow results in increased installed specific fuel consumption (inlet spill drag, afterbody drag). The mixed-flow cycle has a minimum capability to reduce thrust at a constant airflow over a small decrement in thrust, which is limited by the constraint of the static pressure balance in the tailpipe. The separated-flow cycle provides relief from this constraint and allows a further reduction in thrust at constant airflow. The triple-rotor VCE provides a variation in thrust, at constant airflow, to about 50% of maximum dry power by maintaining fan speed and airflow, slowing down the intermediate rotor to desupercharge the high pressure compressor, and bypassing the excess fan flow through a relief duct between the fan and intermediate rotor. In a two-rotor, separated-flow cycle, the same result can be obtained by separating the fan stages, opening a relief duct between the stages, and throttling the flow in the last fan stage (or stages) with variable

Table I. Post Task VI - Study Engines.

			Airflow Lbs/Sec (Kg/Sec)	LPCPR	BPR	ΔT Aug $^{o}F(^{o}C)$		Supp Level		Sizing Point
						T.O.	Sup. Cr.	PNdb	Streams	
	1	Dry BPTJ	882(400)	3.48	0.4	-	-	15	Jet	Dry Sup. Cr. T/O Noise
△	1C	Aug BPTJ	850(385)	3.48	0.4	540(282)	0(-18)	14.1	Jet	Dry Sup. Cr. T/O Noise
	2A	MF Aug TF	840(381)	3.1	0.8	600(315)	300(149)	14.7	Jet	Dry Sub. Cr. T/O Noise
	5	DBTF	887(402)	3.6	1.0	890(477)	540(279)	15	Both	Dry Sub. Cr. T/O Noise
	13	DBTF	850(385)	3.6	1.0	1080(582)	540(279)	15	Both	Dry Sub. Cr. T/O Noise
	14	DBTF	840(381)	3.6	1.5	1100(597)	800(427)	15	Both	Dry Sub. Cr. T/O Noise
□	4b	DBTF	900(408	3.6	1.8	1300(704)	730(484)	15	Duct	Dry Sub. Cr. T/O Noise
	17	DBTF	1065(483)	3.6	2.0	1300(704)	500(260)	13.8	Duct	Dry Sub. Cr. T/O Noise
	18	DBTF	1090(494)	3.2	2.0	1340(726)	500(260)	13.6	Duct	Dry Sub. Cr. T/O Noise
	19	DBTF	930(422)	3.2	2.2	1340(726)	800(427)	14.8	Duct	Dry Sub. Cr. T/O Noise
	6	MAF	890(404)	4.75	1.25	880(471)	500(260)	15	Both	Dry Sub. Cr. T/O Noise
	7	Dry TJ to TF	1390(630)	3.0	1.8	-	-	0	Both	Dry Sup. Cr. T/O Noise
VCE	11	MAF	1136(515)	4.75	1.25	0(-18)	500(260)	10	Both	T/O Noise
	12	MAF	996(452)	4.75	1.25	700(379)	400(204)	14	Both	T/O Noise
	21	Aug T/O TJ to TF	1150(521)	3.0	1.8	1400(760)	0(-18)	10	Duct	Dry Sup. Cr. T/O Noise
	22	TACE	1336(606)	3.1	1.4	-	-	10	Both	Dry Sup. Cr. T/O Noise
△	23	MF Aug TF	700(317)	4.0	.28	110(61)	300(149)	15	Jet	Dry Sup. Cr. T/O Noise

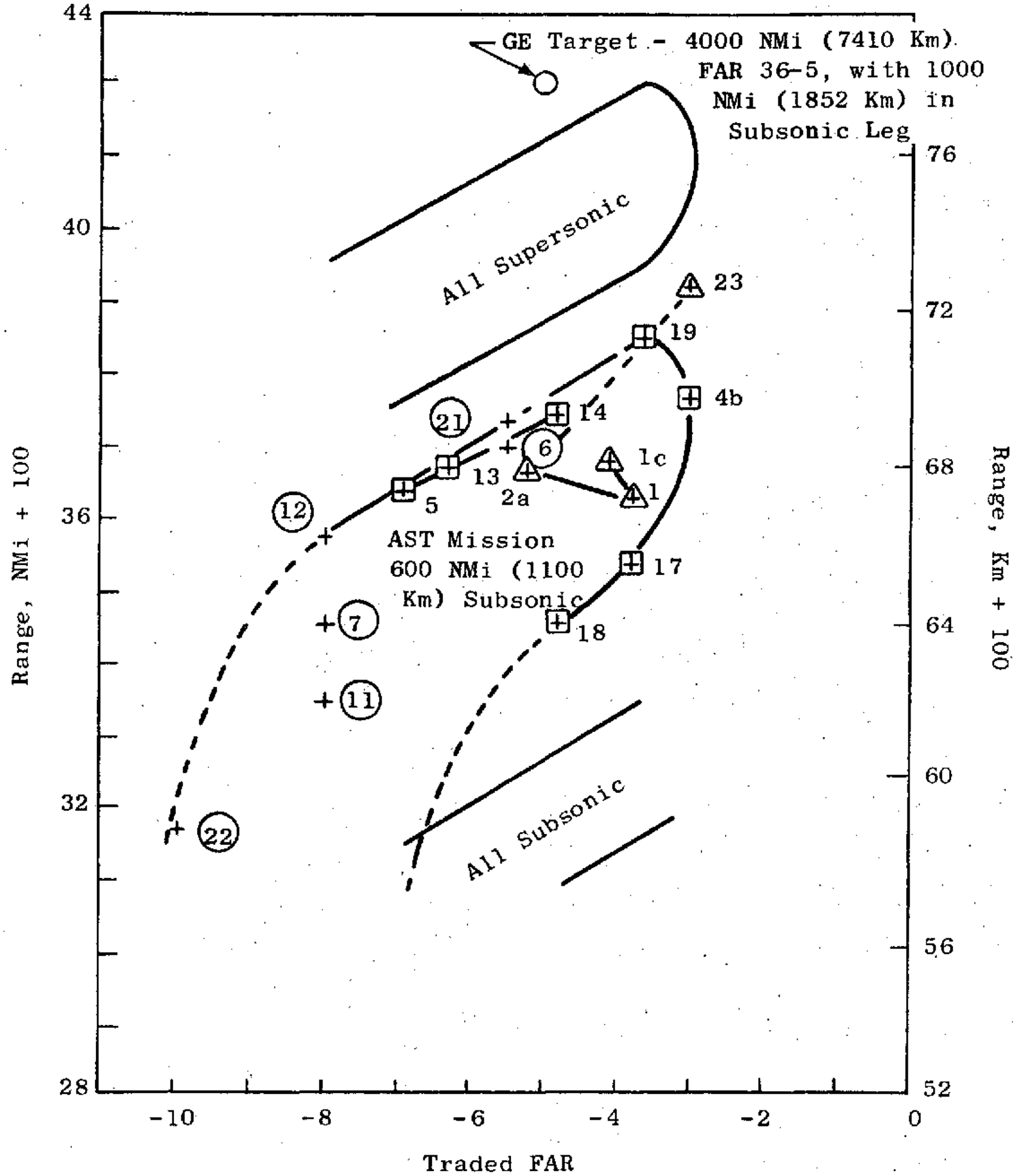


Figure 9. Noise - Range Summary with Revised Suppression M = 2.7, AST Baseline Airplane, 750,000 lb (340,000 kg) TOGW.

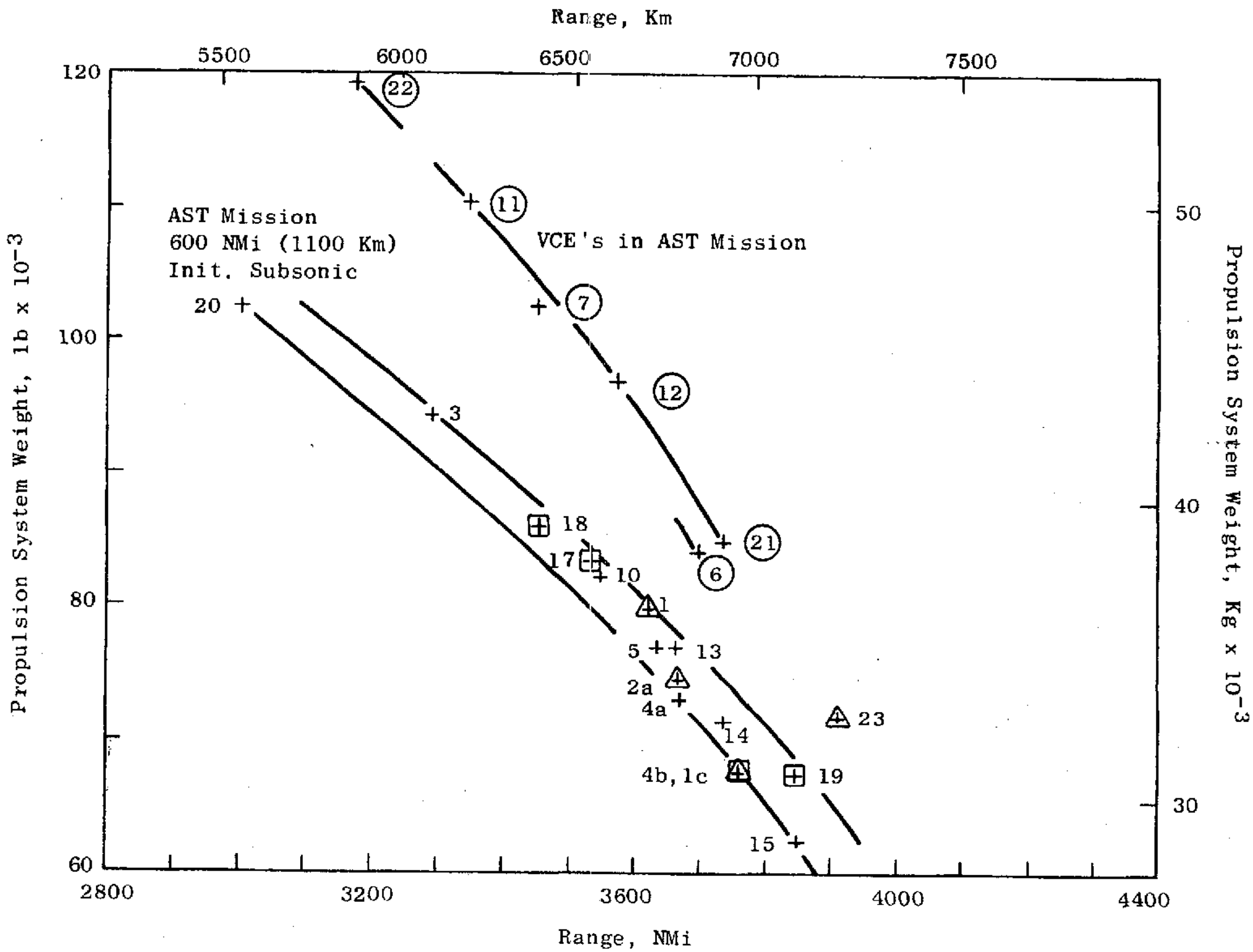
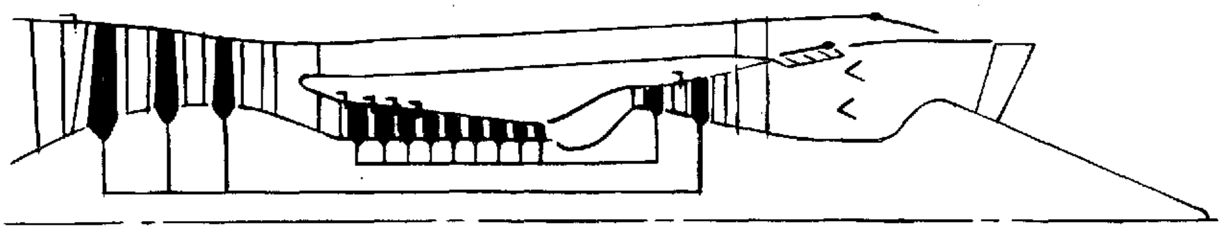


Figure 10. TOGW - Range Summary, M = 2.7, AST Baseline Airplane, 750,000 lb (340,000 kg) TOGW.

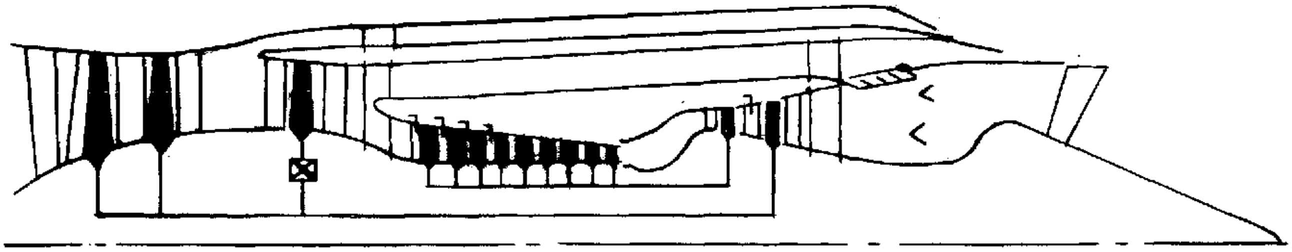
stators and outlet guide vanes, or by introducing a variable pitch fan stage. This configuration will probably require a variable low pressure turbine stator. The addition of a diverter in the tailpipe to allow the fan flow to mix with the core stream, or to be bypassed through a separate exhaust nozzle, results in a variable cycle engine concept that is termed the double bypass dual cycle engine (see Figure 11). This concept is a mixed-flow engine for take off, high power subsonic cruise, transonic climb and acceleration and supersonic cruise, and is changed to a separated-flow engine with two bypass streams during low power subsonic operation at cruise, divert, and hold conditions. Cycle improvements may also be possible by separating the flow at other flight conditions to provide independent control of fan and core speed. This engine concept also may show to advantage in some military missions with the requirement for extended low power subsonic cruise and supersonic dash capability, and for VTOL applications where one exhaust nozzle can provide the ability for vectored takeoff thrust.

The combination of improved mixed-flow cycles with takeoff augmentation and the new variable cycle engine concept, the double-bypass, dual-cycle engine, opens up a new direction for AST follow-on studies. Figure 12 shows some of the benefits that further work on these cycles are expected to achieve.

Table II, AST Summary and Trends, gives a concise summary of the results of the Phase I AST trends, and the indicated direction for follow-on study.



Dual Cycle Engine



Double Bypass Dual Cycle Engine

Figure 11. Dual Cycle and Double Bypass Dual Cycle Engines.

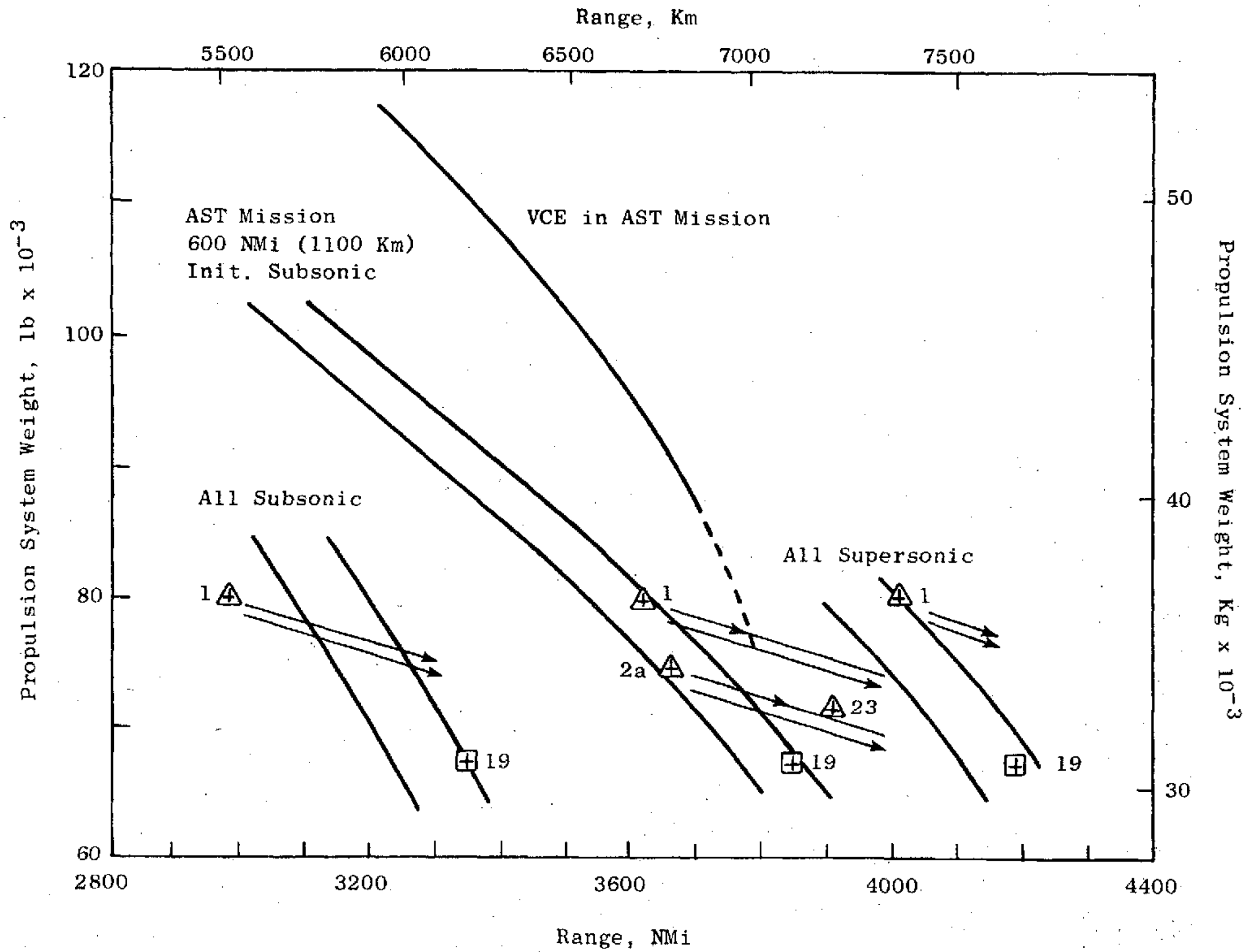


Figure 12. Mixed-Flow Engines and Goals for Phase II.

Table II. AST Summary and Trends.

General Comments

- Range increases with...
  - Decreasing propulsion system installed weight
  - decreasing supersonic and subsonic installed fuel consumption
- Propulsion system installed weight decreases with...
  - decreasing airflow
  - increasing bypass ratio (in .4-2.2 range)
- Installed supersonic SFC decreases with...
  - decreasing bypass ratio and dry operation
- Installed subsonic SFC decreases with...
  - increasing bypass ratio
  - reduced throttle - dependent drags (inlet matching, nozzle base drag)
- Noise decreases with...
  - Increasing airflow and bypass ratio (decreasing specific thrust)
  - increasing jet suppression
- Takeoff...
  - Augmentation gives more thrust for shorter ground roll and less deceleration and nose-down pitch-over before the community measuring station - or higher altitude.
  - Lower noise footprints result when the augmentor is turned off for climb-out.
- Limitations
  - Practical adv. jet suppressors have a maximum of 15 PNdB effect.
  - Suppressors have 1700° F gas temperature limit.
  - Dual stream, ventilated, chute suppressors for DBTF and MAF VC are considerably heavier and more complex than single-stream suppressors for DBTF duct or bypass TJ.
  - Increasing bypass ratio is limited by dry subsonic cruise requirements and increasing supersonic installed SFC and T/O suppressor temperature limits (augmented T/O).
  - Emissions of mixed flow and duct burner augmentation systems used at takeoff, climb, cruise for all engines of β > .4 may prove a limitation.
  - Excessive complexity of some engines is a serious concern.
  - Component efficiencies, losses, and cooling flows limit SFC gains.
- M2.7 Trends
  - No engine meets GE target of 4000+ mi and FAR-36-5. Engines are 5-10% deficient in range.
  - All leading engine contenders in FAR-36-2 to -5 noise category are within approx. 5% range of one another in three missions of interest- All supersonic (about 400 NMi for dry bypass turbojet) - 600 NMi initial subsonic cruise (about 3600 NMi for dry bypass turbojet) - all subsonic (about 3000 n. mi. for dry bypass turbojet).
  - All engines have bypass streams. (.4-2.2 bypass)
  - Bypass ratios above .4 require augmentation (incl. T/O) in order to improve range.
  - Maximum range in noise category of FAR-36-2 to -5 was attained with bypass ratios of approx. 1.5-2 with duct burners and duct stream jet suppressors.
  - No superior variable-cycle engine has been identified yet.
  - The single-rotor dry bypass TJ scores highest on commercial transport virtues of least complexity, risk, cost and emissions. Higher bypass cycles are better on AST mission range, subsonic flexibility and noise footprint areas.
  - M2.7 appears to hurt range, economics, and contains too many unsolved aircraft problems and engine/aircraft risks.
- Where do we go from here
  - M2.4, 4000+ mi, FAR-36-5
  - Higher cycle P/P, strive for dry cruise, use 15 PNdB chute suppressor.
  - Improved SFC, more payoff from high T_4, reduction of throttle dependent drags, higher supersonic turbomachinery flow.
  - Can we meet weights in 1973 AST studies?
  - Improved mission flexibility.
  - Simpler engines: Commercial transport standards of reliability, durability.
  - Baseline -- Dual Rotor bypass TJ, β .4-1.0, P/P 20.
    VCE -- dual cycle version (mixed/separate flow).
    VCE -- double bypass dual cycle version
  - Analyze Boeing multicycle.
  - Use NASA AST, Boeing improved 2707, Douglas and Lockheed aircraft characteristics. Identify different effects on engine selection.
- Key technology needs for M2.4
  - Modulating flow multistage fan/LPC
  - Variable LP turbine technology
  - Long life, high performance 2800° T_4 combustor and turbine technology
  - Integrated high performance nozzle/15 PNdB suppressor/VCE exhaust features.
  - Low emissions, high efficiency augmentor
  - Lightweight technology $\}$ adv. materials and processes
  - Lower cost

APPENDIX A

TASK I - CONVENTIONAL ENGINES, 1975 TECHNOLOGY

GENERAL APPROACH

In order to preclude omission of a potentially attractive AST engine type, this task of the program defined 11 baseline engines of four basic types around which perturbations of salient engine parameters were made, embracing the three design cruise Mach numbers specified. These types were the augmented bypass turbojet, nonaugmented bypass turbojet, mixed-flow augmented turbofan, and duct burning (separated flow) turbofan. With engine performance, weight, size, and noise data generated from a parametric engine computer program, mission analyses were run to evaluate each of these engines as to their ability to perform the prescribed mission within the specified ground rules. Noise level of the engine was incorporated in the study as an independent parameter with no specified value for which to design.

Evaluation in terms of relative TOGW and simplified economics were the bases in defining the "best" engine as shown in the Figure 13 flow chart.

GROUND RULES

Succintly stated, Table III, in conjunction with Figure 14, summarizes the ground rules used through the entire program utilizing the NASA specified "arrow wing" aircraft polars.

TECHNOLOGY DEFINITION

Levels of performance for each of the major engine components were defined as being consistent with a detail design initiation of 1975. Generally, this included turbomachinery operating at higher tip speeds and loading levels, fewer number of stages throughout the engine, advanced design concepts and materials to yield higher thrust-to-weight ratios. The levels incorporated were advanced relative to the earlier SST offerings.

Turbine entry temperatures were significantly increased to the 2750° to 2800° F (1510° to 1538° C) regime reflecting the advances achieved in development programs conducted in recent years. Although representing a challenge to design and achieve the required life in the complex blading configurations inherent with this temperature operation, the thermodynamic advantages [200° F (93° C) reduction in T_{41} is equal to an approximate 150 mile (278 km) decrease in range] were considered to overshadow the mechanical/life complexity.

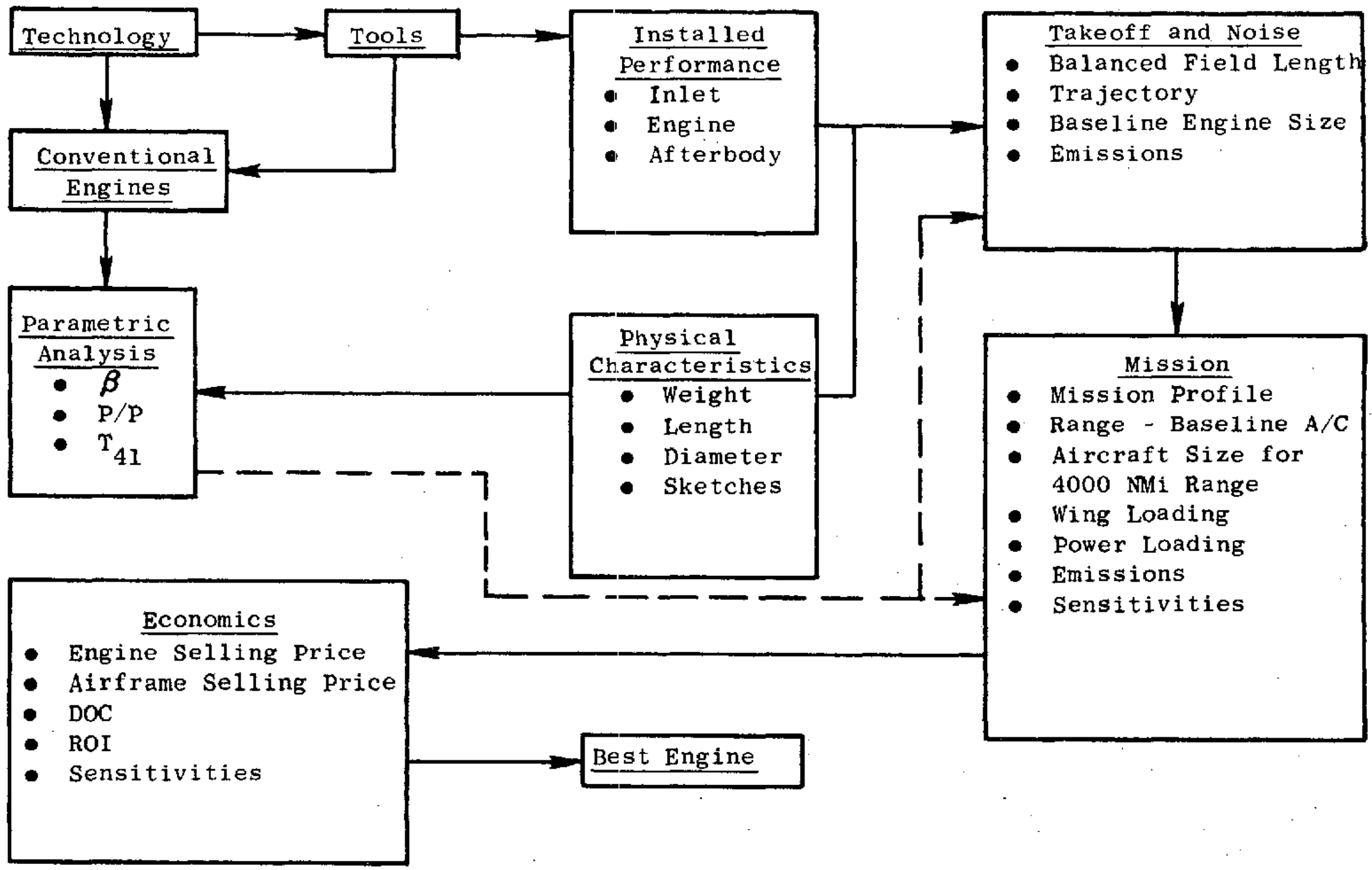


Figure 13. Task I Study Approach.

TABLE III. STUDY GROUND RULES.

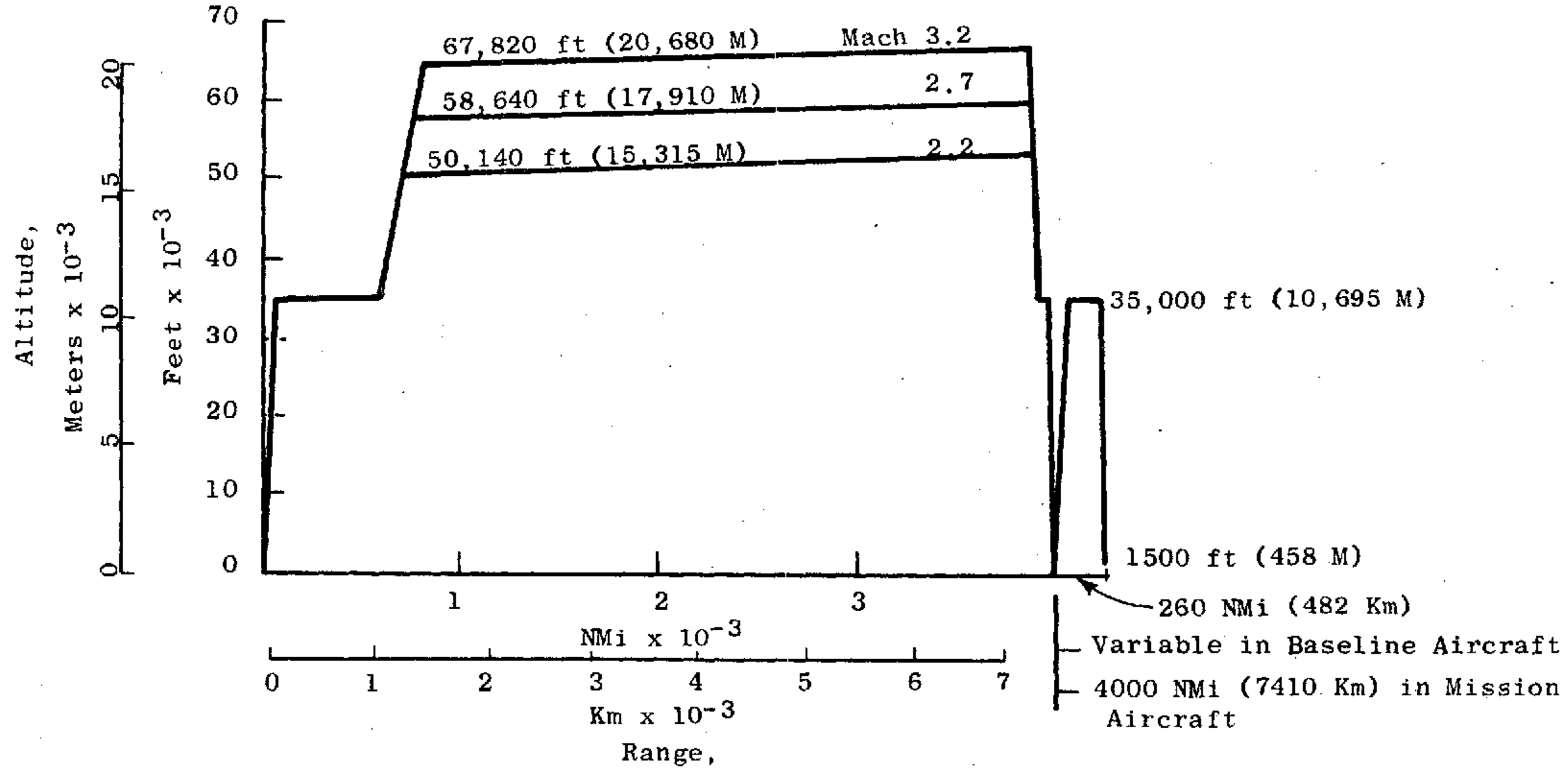
- BASELINE AIRCRAFT - SAME AIRFRAME FOR THREE DESIGN CRUISE MACH NUMBERS: 2.2, 2.7, 3.2
- PAYLOAD - 236 PASSENGERS (48,096 LB) (21,810 KG)
- CONFIGURATION - ARROW WING WITH NASA POLARS

  - 4 ENGINES UNDERWING
- WEIGHT - BASELINE 750,000 LB (340,000 KG) TOGW, 75 LB/FT^2 W/S (3585 Pa)
- TAKEOFF - BALANCED FIELD LENGTH 12,400 FT (3775 M)

  - FAR-36 and FAR-36-0 EPNdB NOISE LEVELS (ALSO IN APPROACH)
- CLIMB/ACCEL - 20% THRUST MARGIN TO SUPERSONIC CRUISE
- RESERVES - FAR-121.648
- ECONOMICS - NASA COST FOR OWE LESS ENGINES

  - ATA FORMULA FOR DOC
  - LOCKHEED FORMULA FOR ROI

• Mission



• Mission Aircraft

W/S - "Best" for Takeoff Noise and Minimum TOGW

TOGW - Scale to 4000 NMi (7410 Km)
NASA Weight Rule for OWE - Propulsion Weight

Figure 14. Task I Study Ground Rules.

Major technology features were:

- High tip speed turbomachinery
  - compressors - 1500 to 1600 ft/sec (458 to 488 m/sec)
  - turbines - 1800 to 1900 ft/sec (549 to 579 m/sec)
- High stage loading turbomachinery
  - compressors - 0.4 to 0.6 hub loadings
  - turbines - 0.7 to 1.1 stage loading
- High turbine temperature
  - turbojets - 2750° F @ cruise (1785° K)
  - turbofans - 2800° F @ cruise (1810° K)
- Jet suppressor effectiveness - 10 ΔPNdB
- High performance annular plug exhaust nozzle

Component performance in greater detail than stated was used in the definition of the study engines.

DEFINITION OF PARAMETRIC BASELINE ENGINES

The choice of the baseline engines to be evaluated and perturbed represents a starting point for the engine types. Table IV exhibits these engines with their important thermodynamic design parameters. Also mentioned is the fact that in this task, a maximum jet exhaust suppression level of 10 ΔPNdB was applied to the primary or core streams of each engine. In conjunction with this constraint was the exhaust velocity of the suppressed stream being designed to a value of 2500 ft/sec (762 m/sec) to take maximum advantage of the suppressor effectiveness. This parameter is tabulated along with the exhaust velocity of the fan stream of the duct burning turbofans. A third ground rule was imposed during this task that no augmentation would be utilized during takeoff. This was applied since at the time this work was initiated, the EPA imposed pollution levels were so stringent that it was felt that there was no means by which augmentors would be capable of meeting the standards at takeoff. Augmentation was utilized during climb and supersonic cruise on the engines having that capability.

Applying these parameter definitions and constraints, engine designs and performance could be generated on an uninstalled basis.

Table IV. Baseline Engine Description (All Engines have 10 PNdB Maximum Suppression in Hot Stream).

DESIGNATION	TYPE	MO	CPR	LPR	MAX CRUISE MAIN-AUG.	TEMP -° F β	ROTOR	JET VEL AT TAKEOFF CORE	DUCT
GE21/J3A1	NON-AUGMENTED TURBOJET-TJ	2.2	25	4.9	2750(1510° C)	.3	2	2425(740 m/sec)	-
GE21/J3B1	AUGMENTED TURBOJET-TJA	2.2	25	4.9	2750(1510° C)	.3	2	2488(759 m/sec)	-
GE21/F2B1	MIXED FLOW AUG. TURBOFAN MFATF (.8)	2.2	25	4.0	2800(1538° C)	.8	2	2479(756 m/sec)	-
GE21/F2B2	MIXED FLOW AUG. TURBOFAN-MFATF (2.5)	2.2	25	2.5	2800(1538° C)	2.5	2	1690(515 m/sec)	-
GE21/F3B2	DUCT BURNING TURBOFAN - DBTF (1.5)	2.2	25	3.2	2800(1538° C)	1.5	2	2493(760 m/sec)	1842(561 m/sec)
GE21/J2A1	NON-AUGMENTED TURBOJET-TJ	2.7	15	3.9	2750(1510° C)	.3	1	2473(754 m/sec)	-
GE21/J2B1	AUGMENTED TURBOJET - TJA	2.7	15	3.9	2750(1510° C)	.3	1	2486(758 m/sec)	-
GE21/F1B1	MIXED FLOW AUG. TURBOFAN-MFATF (.8)	2.7	15	3.1	2800(1538° C)	.8	1	2299(700 m/sec)	-
GE21/F3B1	DUCT BURNING TURBOFAN-DBTF (1.5)	2.7	15	3.2	2800(1538° C)	1.5	2	2502(763 m/sec)	1810(552 m/sec)
GE21/J2A3	NON-AUGMENTED TURBOJET-TJ	3.2	9	3.2	2750(1510° C)	.3	1	2094(639 m/sec)	-
GE21/F3B3	DUCT BURNING TURBOFAN DBTF (1.2)	3.2	10	2.6	2800(1538° C)	1.2	2	2475(755 m/sec)	1715(523 m/sec)

INSTALLATION CONSIDERATIONS

To enable meaningful mission analyses to be conducted on each of the baseline engines and subsequent perturbations thereof, installed performance of each of the engines was generated considering the drags associated with a typical inlet and afterbody during operation over the flight regime of the engine. Figure 15 exhibits the items considered in the calculation of the throttle dependent drags associated with the engine. Afterbody drag estimates were made on the assumption of an isolated nacelle. Any interference effects of nacelle placement on throttle dependent drags were not considered, since this is dependent on specific airplane design and beyond the scope of this study.

These drag calculation procedures were incorporated in the computer deck through parametric representation of inlet airflow characteristics using a designed inlet as the basepoint for the airflow variations at each Mach number.

NOISE

Because of the large number of engines to be analyzed in this program, it was decided that the most consistent and expeditious procedure of noise evaluation would be through incorporating a calculation procedure in the performance deck. A procedure was written by the contractor's acoustic personnel and after appropriate checking and analyzing, it was compiled into the engine performance program.

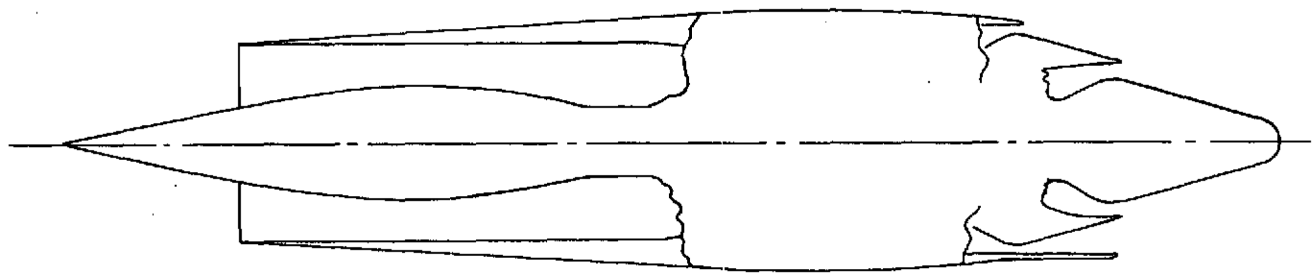
This procedure considered all the major noise sources of an engine, calculated the noise levels from each of five sources for each of three aspect angles, applied the specified acoustical treatment (suppression for each component), and summed logarithmically the output of each source to determine the noise level of the engine in terms of PNdB. Conversion to EPNdB was done as a function of the flight condition and aspect angle; sideline, community, or approach. By trading these values per the prescribed manner in FAR Part 36, the traded FAR number was determined.

Figure 16 exhibits the noise calculation flow chart used throughout the AST program.

SIZING

The program ground rules, in conjunction with the supplied aircraft polars, dictate certain installed thrust requirements for the engines. Upon analyzing these ground rules relative to each of the baseline engine installed thrust levels, the sizing criterion for each was determined. Table V exhibits the sizing point for each of the baseline engines.

The flight condition at which the engine is sized for the mission is determined by the thrust lapse characteristics of the engine type in conjunction with the aircraft thrust requirements. Therefore, significant in this



Engine

- Ram Recovery
- Customer Air Bleed - 1.0 lb/sec (0.45 kg/sec)
- Customer Power Extraction - 200 HP (149.2 Kw)

Inlet

- Different Inlet for Each Mo
  - 2-D Mixed Compression @ 2.2
  - Axisymmetric, Mixed Compression @ 2.7
  - Axisymmetric, Mixed Compression @ 3.2
- Inlet/Engine Airflow Matching
  - Hot Day Supersonic Cruise
  - Maximum Engine Airflow
  - Cruise Cycle Temperature
  - Maximum Compressor Disch Temp.

  Simultaneously Where Possible
- Installation Drag
  - Spillage Drag (Throttle Dependent)
  - Boundary Layer Control Drag
  - Bypass Drag

Afterbody

- Maximum Nacelle Diameter
  - Nozzle
  - Augmentor
  - Over Turbine
  - Compressor Inlet
- Installation Drag
  - External Flow Effects Included in CFG
  - Afterbody Drag

  $FDAB = C_{DAB} \cdot A_{MAX} \cdot q_o$

  C_{DAB} is a Function of $\frac{A_{MAX}}{A_{9.1}}$, Mo

Nacelle

- Friction and Wave Drags are in the Aircraft Polar

Figure 15. Task I Installation Considerations.

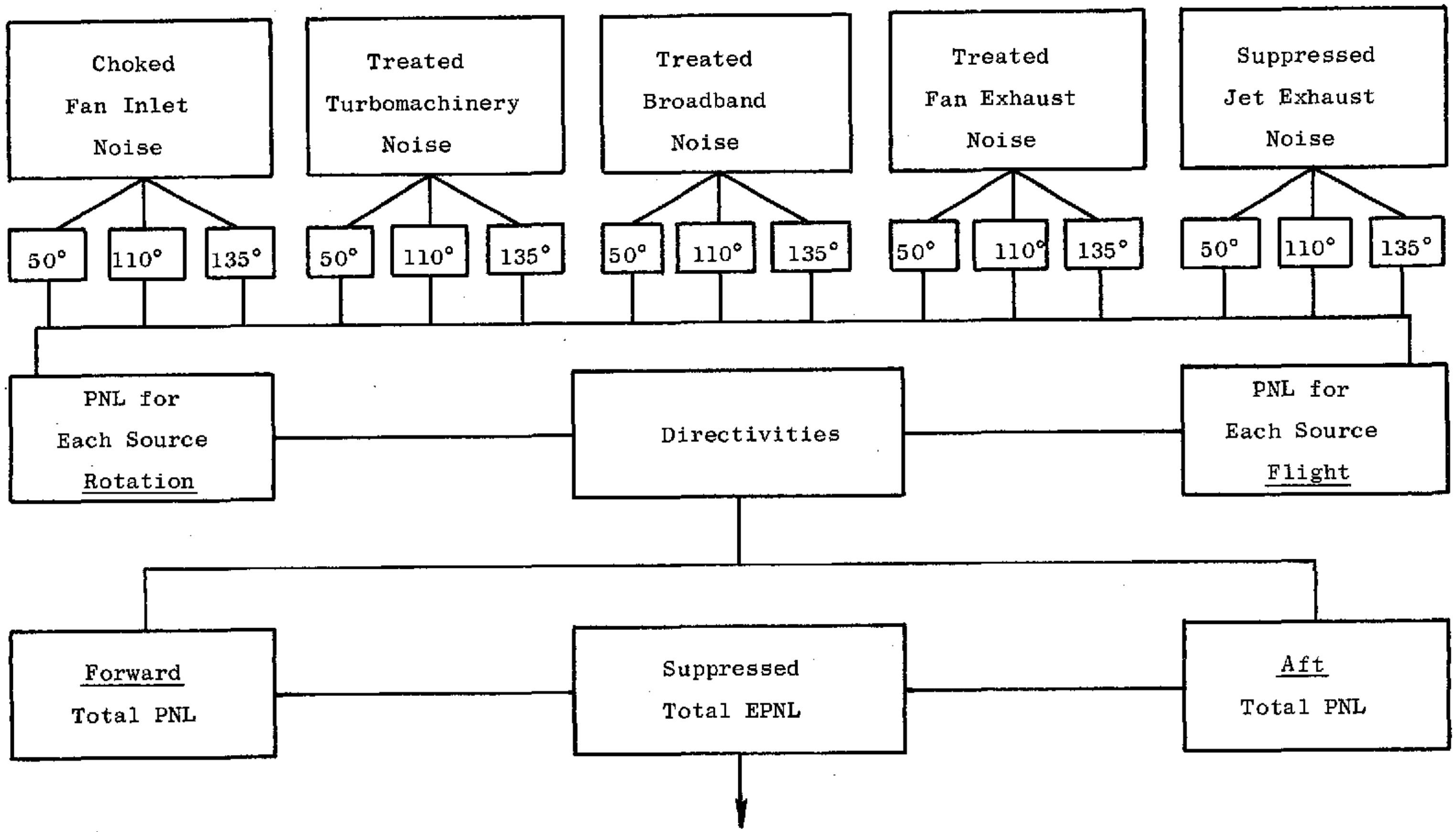


Figure 16. Noise Calculation Flow Chart.

Table V. Engine Sizing in Baseline Aircraft.

DESIGN CRUISE MACH	2.2					2.7				3.2	
DESIGNATION	J3A1	J3B1	F2B1	F2B2	F3B2	J2A1	J2B1	F1B1	F3B1	J2A3	F3B3
TYPE (β)	TJ	TJA	MFATF (.8)	MFATF (2.5)	DBTF (1.5)	TJ	TJA	MFATF (.8)	DBTF (1.5)	TJ	DBTF (1.2)
FIELD LENGTH	X	X	X		X			X	X	X	X
FAR-36 NOISE LEVEL							X				
SUBSONIC CRUISE				X							
SUPERSONIC CRUISE						X					
AIRFLOW SIZE LB/SEC (KG/SEC)	880 (399)	860 (390)	930 (421)	1560 (707)	1120 (507)	850 (385)	850 (385)	940 (426)	1100 (498)	1020 (462)	1130 (512)

*BASELINE AIRCRAFT DEFINED AS 750000 LB (340000 KG) TOGW, 75 LB/FT^2 (3585 Pa) W/S table is the fact that eight of the 11 engines were sized by the balanced field length requirement and met the FAR 36 traded noise level of 108 EPNdB. This is because of two factors:

1. The stringent thrust requirement imposed by the balanced field length dictates engines large enough as to meet the other flight thrust levels.

2. The 10 ΔPNdB suppression level applied to these engines yielded low enough noise levels to just meet FAR 36-0.

In the case of the high bypass ratio, mixed-flow turbofan (GE21/F2B2), installation drags associated with an engine so large in diameter reduced installed thrust sufficiently to require sizing to be at the subsonic cruise condition.

The nonaugmented bypass turbojet at Mach 2.7 (GE21/J2A1) is supersonic cruise sized due to its thrust characteristics and the aircraft drag level. Consequently, its up sizing made it large enough to meet the balanced field length criterion and also just meet the FAR 36 traded noise level.

The augmented bypass turbojet (GE21/J2B1), because of having augmentation available at supersonic cruise, could potentially be reduced in size. However, the traded noise level of FAR 36-0 requires its size be the same as the nonaugmented bypass turbojet.

RESULTS

All this basic information was put into the mission analysis utilizing the baseline aircraft at 750,000 lb (340,000 kg) TOGW and 75 lb/ft^2 (3585 Pa) wing loading. Each engine was "flown" with range being the fallout or measure of merit. Table VI summarizes the result of this phase of Task I and exhibits:

- The best performing engines in each design cruise Mach number category are the nonaugmented bypass turbojets.
- The duct burning turbofans exhibit essentially equal range to their turbojet counterparts.
- Aircraft range at 2.7 cruise Mach number is approximately 10% less than at Mach 2.2 while 3.2 cruise Mach number range is unacceptably low.
- The nonaugmented bypass turbojet at Mach 2.2 exhibits the best range value reaching the goal level.
- The high bypass ratio, mixed-flow turbofan grossly fails to meet the mission range due to the mismatch of engine size and the high afterbody drag losses associated with a large diameter, low exhaust pressure ratio engine.

Table VI. Baseline Aircraft Noise Summary.

DES	TYPE	MO	AIRFLOW LB/SEC	AIRFLOW (KG/SEC)	NOISE EPNdB SIDE	NOISE EPNdB COMM.	NOISE EPNdB APP.	NOISE EPNdB FAR-36 MARGIN	RANGE NMI	RANGE (KM)
J3A1	TJ	2.2	880	(399)	108.3	108.5	102.5	-1.1	4046	(7500)
J3B1	TJ(A)	2.2	860	(390)	108.7	109.4	102.5	-0.4	3847	(7140)
F2B1	MFATF (.8)	2.2	930	(421)	107.8	108.3	103.4	-1.4	3436	(6360)
F2B2	MFATF (2.5)	2.2	1560	(707)	103.9	104.9	101.4	-4.6	1763	(3265)
F3B2	DBTF (1.5)	2.2	1120	(507)	107.1	107.8	102.7	-2.1	3915	(7250)
J2A1	TJ	2.7	850	(385)	108.4	108.7	105.7	-0.4	3498	(6485)
J2B1	TJA	2.7	850	(385)	108.4	108.7	105.7	-0.4	3380	(6260)
F1B1	MFATF (.8)	2.7	940	(426)	106.8	107.2	103.4	-2.2	3310	(6145)
F3B1	DBTF (1.5)	2.7	1100	(498)	107.0	107.7	102.7	-2.1	3418	(6340)
J2A3	TJ	3.2	1020	(462)	104.2	106.4	101.1	-3.6	2655	(4950)
F3B3	DBTF (1.2)	3.2	1130	(512)	106.2	106.5	101.4	-3.1	2477	(4590)

- All engines meet the FAR 36 requirement with the turbofans being slightly lower in noise level because of higher airflow (lower specific thrust).

Further analysis of the baseline aircraft performance is shown on Figure 17 which ranks the engines from left to right in order of descending range. Shown on the figure is the propulsion system weight and the portion it removes from the available fuel.

Generally, the better performing engines have the lowest propulsion system weight (most fuel) and therefore the longest range. Also of note is that the "best" three engines (highest range values) are Mach 2.2 design cruise engines.

Comparing the "best" turbofans and turbojets at Mach 2.2 and 2.7 showing the breakdown of the major components of the aircraft, of particular interest is the fuel breakdown exhibited on Figure 18. Generally, the increased propulsion weight of the Mach 2.7 engines in addition to their slightly higher installed SFC (higher reserves) leaves less fuel for the supersonic cruise portion of the mission where nautical miles/lb of fuel is highest. Consequently the range is slightly lower (~10%) than for the Mach 2.2 design cruise aircraft. The companion plot exhibits the range as a function of weight showing the distance covered for each leg of the mission and the fuel burned off and the resulting reduced range.

The goal range set down in the ground rules was 4000 NMi (7410 km) which was met by only one engine type - the nonaugmented bypass turbojet at Mach 2.2. To reach this goal range, the remaining aircraft/engine combinations required scaling as shown on Figure 19. This exhibits the level to which the baseline aircraft [@ 75 lb/ft^2 (3585 Pa) wing loading] must be scaled to reach 4000 NMi (7410 km). Three of the engine combinations indicate a characteristic that would yield no logical answer. The remaining engines indicate being able to meet the goal range at a TOGW of under 1,000,000 lb (453,592 kg). On the other end of the scale is the nonaugmented bypass turbojet of Mach 2.2 which requires some small amount of scaling down in size because of its exceeding the range in the baseline aircraft.

All of the preceding data and comment is centered around the baseline aircraft at 75 lb/ft^2 (3585 Pa) wing loading. However, the studies indicated that some advantage in TOGW could be made through the variation of wing loading. Consequently, to round out this task, the aircraft wing loading was varied to the best value and the engine/aircraft sized to yield the lowest TOGW and meet FAR 36 with no margin (108 EPNdB) simultaneously. Table VII exhibits the important parameters resulting from this effort.

No appreciable change in the order of merit came about from this analysis. However, the study did indicate that wing loadings of less than 75 lb/ft^2 (3585 Pa) offered some advantage in reducing TOGW at the expense of engine noise level.

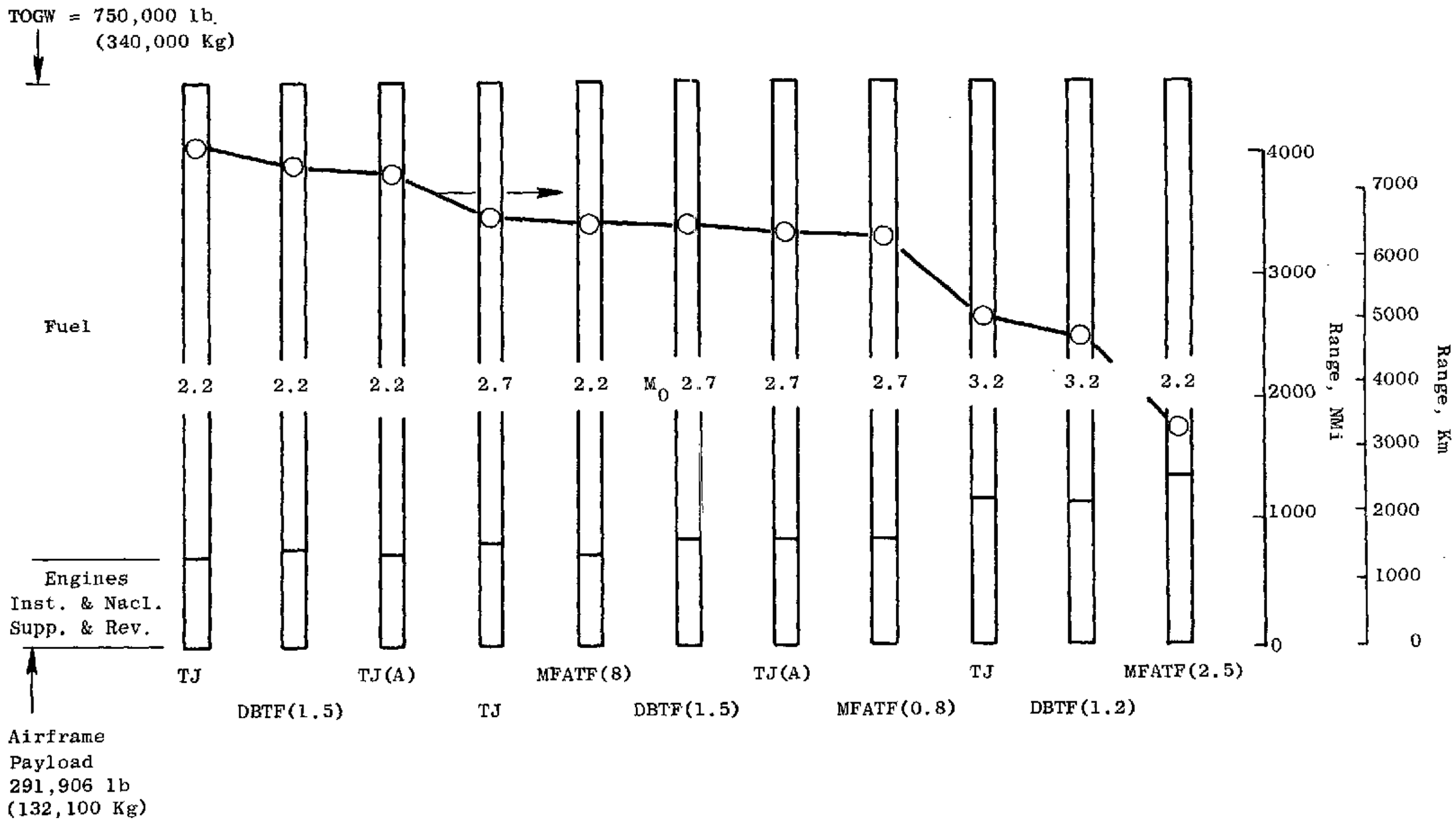


Figure 17. Task I Engine Fuel Weight and Range in the Baseline Aircraft.

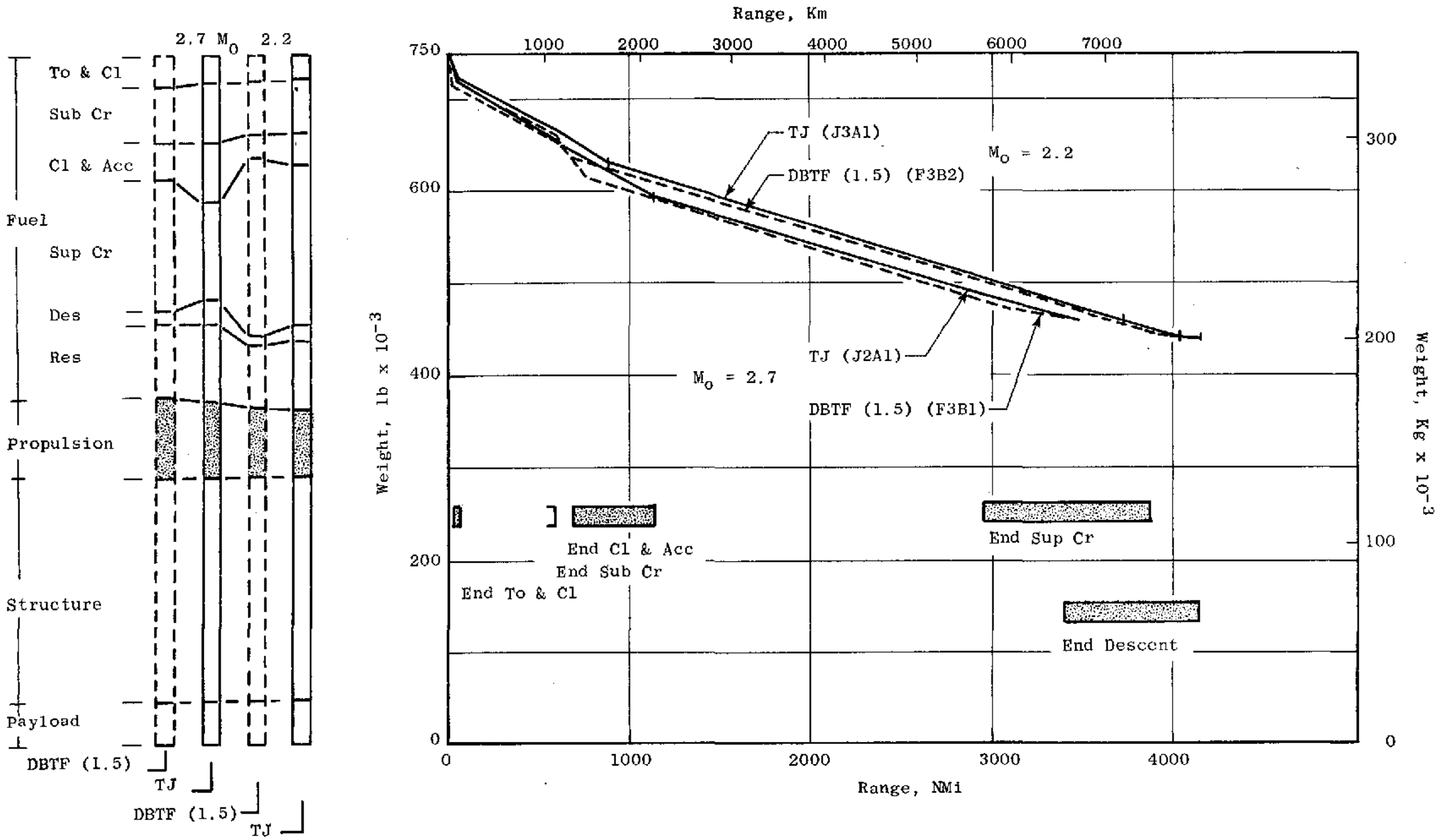


Figure 18. Task I, Weight and Range Breakdown "Best" Engines in Baseline Aircraft.

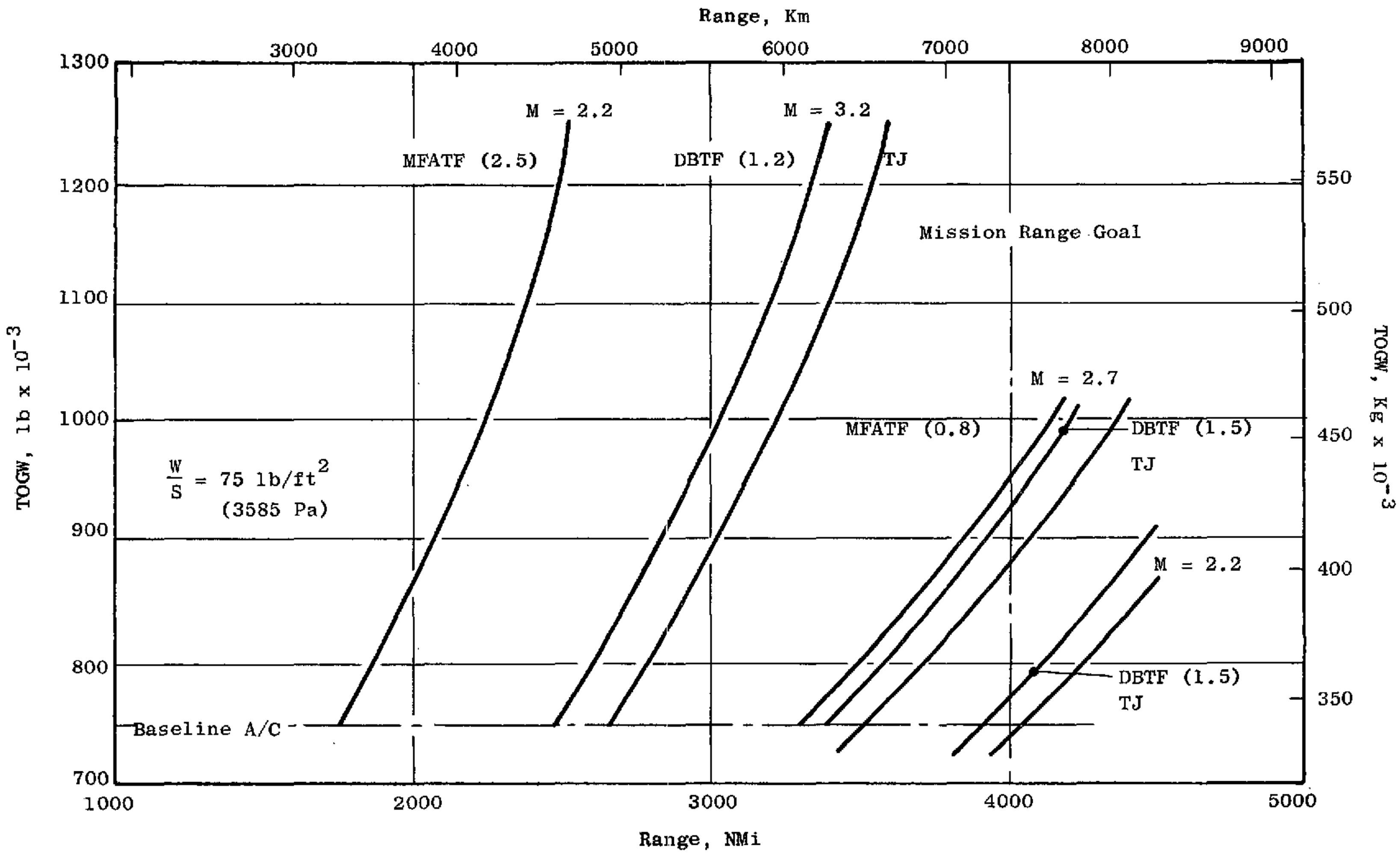


Figure 19. Task I Aircraft Growth Characteristics.

Table VII. Mission Aircraft Summary.

RANGE = 4000 NMI (7410 KM)									NOISE*			
			TOGW		W/S		AIRFLOW					FAR-36
DES.	TYPE	MO	LBx10^3	(KGx10^3)	PSF	(Pa)	LB/SEC	(KG/SEC)	SIDE	COMM	APP	MARGIN
J3A1	TJ	2.2	731	(331)	70	(3345)	806	(376)	108.5	110	101.3	0
J3B1	TJA	2.2	778	(352)	70	(3345)	848	(384)	108.9	110	101.4	0
F2B1	MFATF(.8)	2.2	860	(389)	60	(2870)	966	(438)	108.4	108.4	101	0
F2B2	MFATF(2.5)	2.2	OMITTED BECAUSE OF HIGH TOGW									
F3B2	DBTF(1.5)	2.2	735	(332)	66	(3155)	990	(449)	107.6	110	101.3	0
J2A1	TJ	2.7	860	(389)	67.5	(3225)	975	(441)	108.6	110	103.4	0
J2B1	TJA	2.7	910	(411)	71	(3395)	950	(430)	108.6	110	103.4	0
F1B1	MFATF(.8)	2.7	900	(407)	67.5	(3225)	1045	(474)	107.1	109	101.2	-1
F3B1	DBTF(1.5)	2.7	835	(378)	60	(2870)	1045	(474)	107.6	110	101.4	0
J2A3	TJ	3.2	1300	(588)	50	(2390)	1355	(614)	104.5	110	100.6	0
F3B3	DBTF(1.2)	OMITTED BECAUSE OF HIGH TOGW										

*DOES NOT INCLUDE EFFECT OF CHOKED INLET OPERATION (SEE FIGURE 21)

Considering the economic aspects of this Task I study, calculations of "relative ROI" were made for these "best" 4000 NMi (7410 km) aircraft. Figure 20 is the first of these plots exhibiting the relationship between TOGW and "relative ROI" for the 2.2 and 2.7 Mach number engines. As indicated, the lowest TOGW aircraft yields the highest "relative ROI" with the Mach 2.2 design cruise engines yielding the highest values. These Mach 2.2 engines, because of having TOGW values essentially equal, yield "relative ROI" values that are also equal. This is because the formula used in the "relative ROI" calculations makes no distinction in engine type with regard to maintenance, etc. Refinements in the analytical method should be strived for to adequately assess the complexity in the manufacture and maintenance of different engine types.

The aircraft engine combinations discussed have all had traded noise levels in the range of FAR 36-0 to -1. Since a noise level for the SST has not been specifically stated, an investigation of reduced levels are in order. Two approaches are possible. One, scaling both aircraft and engine up holding payload constant is in effect oversizing the engine and then retarding the throttle to maintain the thrust level and reducing exhaust velocity. The other is by the addition of a more effective jet suppressor.

These two approaches are shown on Figure 21 with the rapidly rising lines indicating the scaling approach and the horizontal sliding of the points indicating the addition of an additional 5 ΔPNdB in the suppressor with no penalty in weight or nozzle performance. The scaling procedure increases TOGW rapidly while additional suppression reduces noise for essentially no penalty in TOGW. In actuality, a small penalty is envisioned in TOGW as suppressor effectiveness is increased.

To sum up, this task indicates:

- Bypass turbojet and duct burning turbofan engines are essentially equal in performance.
- Mach 2.2 design cruise is economically better than Mach 2.7 by approximately 10%.
- Additional jet suppressor effectiveness is the most economical means of reducing propulsion system jet noise.

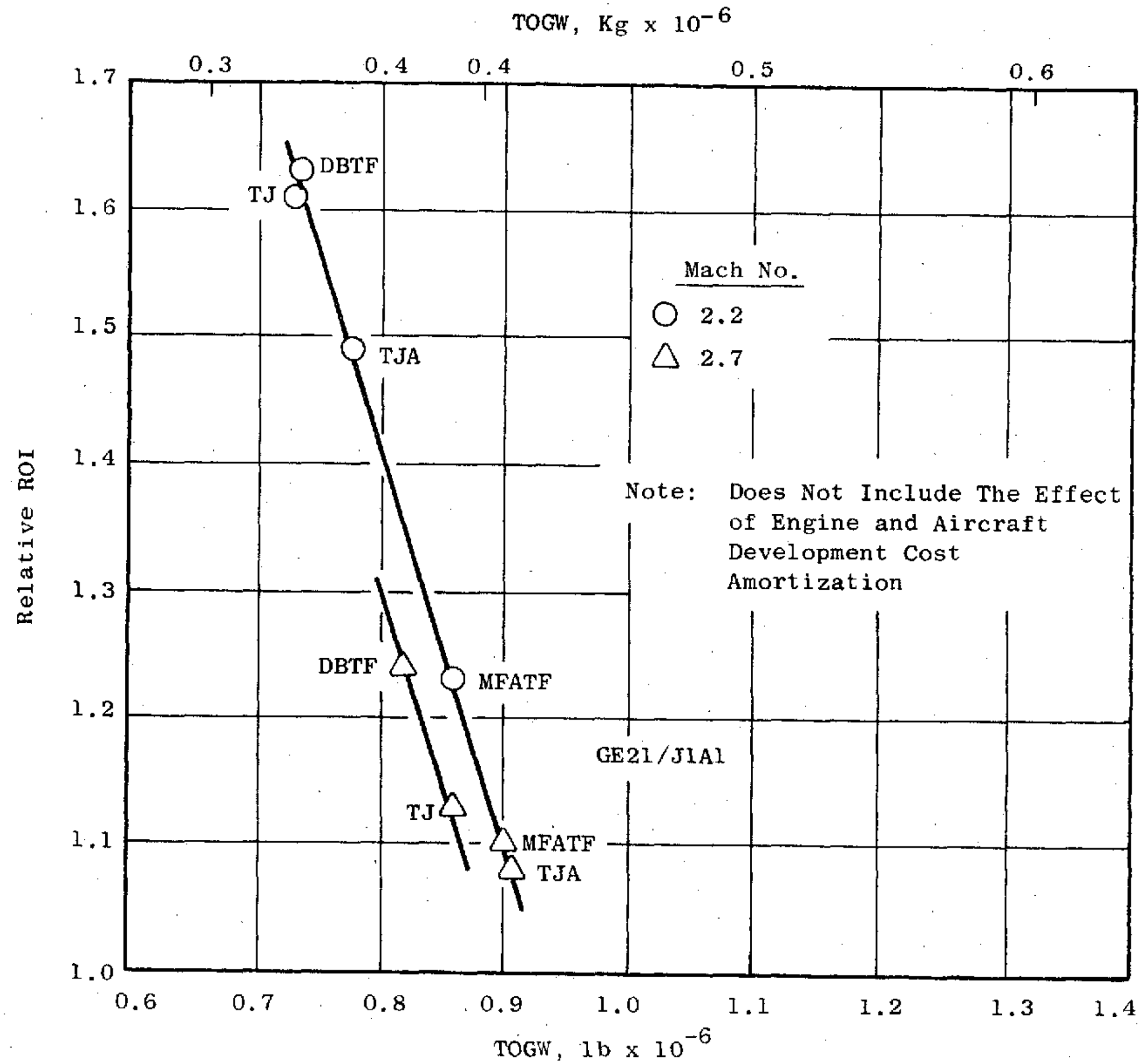


Figure 20. Task I, TOGW Vs. Relative ROI, "Best" Aircraft for 4000 NMi (7410 km) Range.

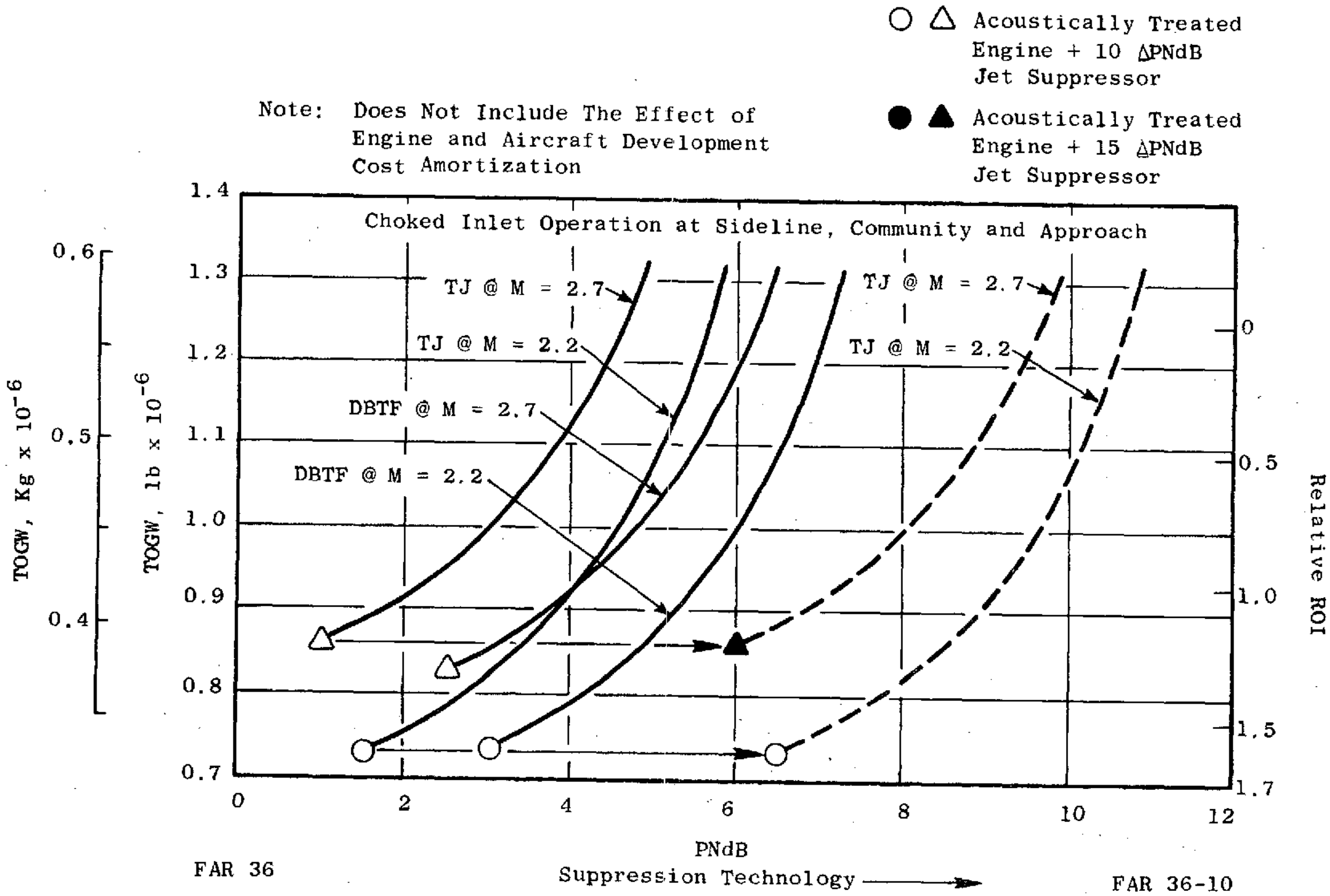


Figure 21. Task I Study, TOGW and Relative ROI for FAR 36-10.

APPENDIX B

TASK II - VARIABLE CYCLE ENGINES, 1975 TECHNOLOGY

GENERAL APPROACH

The variable cycle concept, irrespective of its configuration, is a very complex system because of the many degrees of freedom inherent in the design. Consequently, integration to a suitable inlet and nacelle to maximize the installed performance of such a propulsion system presents a significant challenge, while being the area of greatest potential advantage.

This task was oriented toward the analysis of several of these complex propulsion systems that were different in concept and operation and were evaluated through essentially the same procedures as applied in Task I. Relatively little optimization of these propulsion systems was performed due primarily to the large number of variables available for perturbing.

The ground rules for this task were the same as those used in Task I except emphasis was placed on attaining noise levels of FAR 36-10.

OPERATIONAL OBJECTIVES

Variable cycle engines have been conceived in an effort to improve propulsion system performance through either better inlet matching, improved internal engine performance, reduced installation drags or combinations of all. These means of performance improvements are applicable throughout the flight regime of the aircraft but greater advantage is exhibited at some conditions over others.

Combining these potential performance improvements the variable cycle engine objectives approach the favorable features of turbojets and turbofans. These are shown graphically on Figure 22 and are:

- Low takeoff noise through designing with low jet velocities and using 10 ΔPNdB suppression.
- Low subsonic installed SFC from good matching of the cycle to the required thrust plus low installation drags due to the airflow handling capabilities of the concept.
- High climb/accel installed thrust through high exhaust velocities similar to turbojet operation made possible through cycle variability due to mechanical capability built in the concept.
- Low supersonic SFC coming from reduced installation drags in addition to cycle variability approaching turbojet operation.

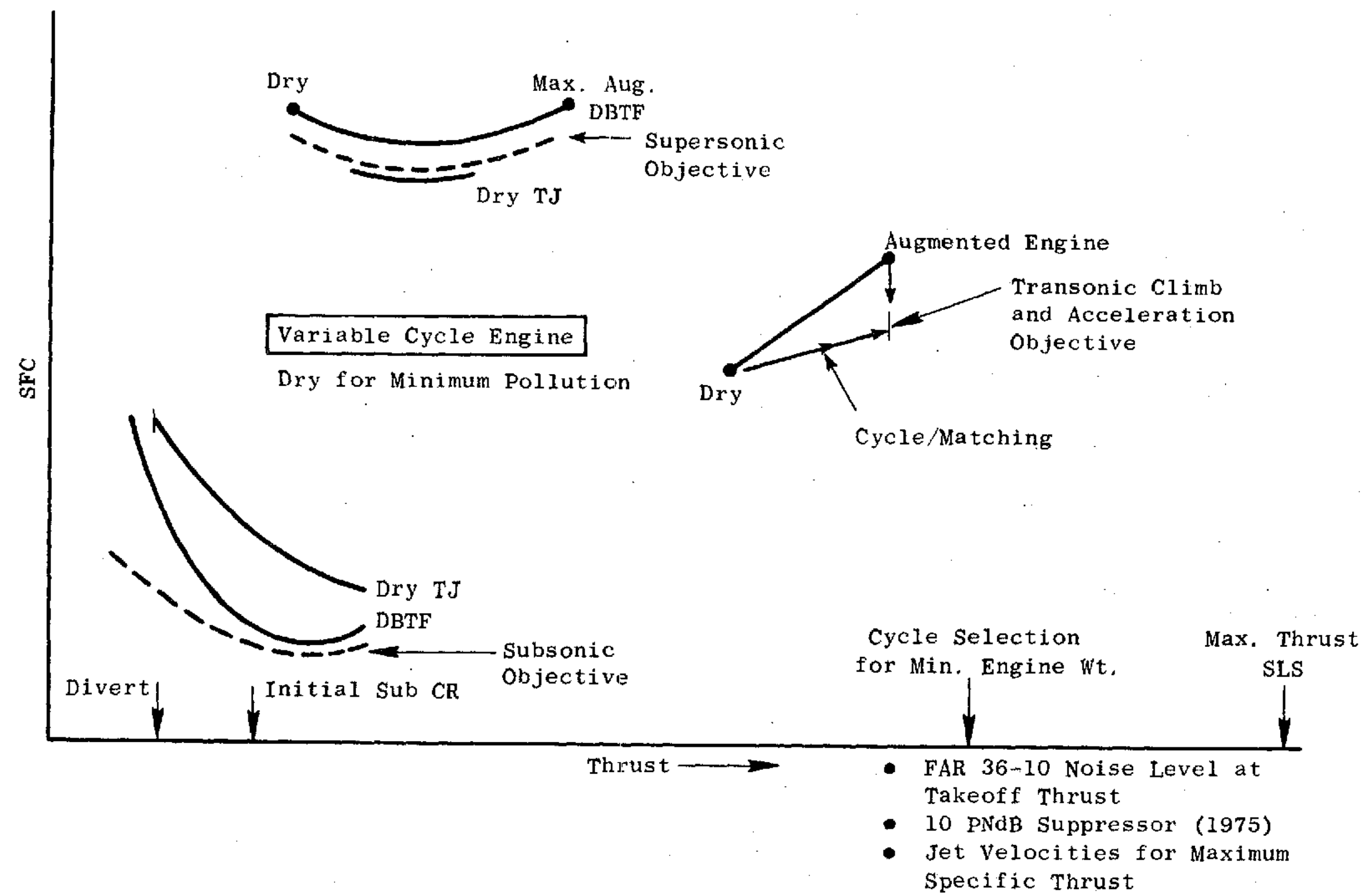


Figure 22. Task II Performance Objectives, Variable Cycle Engines.

With these set down as objectives to achieve, many different variable cycle concepts become candidates for analysis, each exhibiting advantages at some of the important mission flight conditions. Consequently, the task becomes one of defining the variable cycle that best satisfies the total requirements while not necessarily excelling in any one or more parts of the mission.

Figure 23 exhibits the installed performance objectives for the VCE through the reduction of drags from both the inlet and afterbody. With additional flow handling capability incorporated in the concept, the objective for the variable cycle engine is to eliminate the inlet drags by swallowing all the airflow accepted by the capture area streamtube. Additionally, by increasing the exhaust jet plume area, the Amax/Ajet plume ratio decreases, thereby decreasing the afterbody drag. Ajet plume is increased by high flowing of the engine which fills out the base or by increasing exhaust nozzle pressure ratio allowing flow expansion to larger base areas or by combination of both.

Figure 24 graphically shows the relationship between sideline noise, exhaust jet velocity and relative airflow (engine) size. Since all Task I and II engines were tailored to a maximum exhaust velocity with 10 PNdB suppression of 2500 ft/sec (762 m/sec), this would yield a sideline noise level of 108 EPNdB at a relative airflow level of 1.0 to achieve FAR 36-10 EPNdB, additional airflow must be taken on board to maintain constant thrust. An approximate 40% increase in airflow must be realized to meet this 98 EPNdB noise level.

Figure 25 relates design bypass ratio (β) to relative SFC, relative thrust and relative weight. These parameters are very important to mission performance since each impacts directly on mission fuel or range.

Variations in each parameter are shown as a function of design bypass ratio over a range of zero (turbojet) to approximately 1.6 for both the bypass turbojet and the duct burning turbofan engines. These data were developed from the Task I studies and were used as trends in determining the basic cycle parameters of the investigated concepts.

DEFINITION OF ENGINES

For the study of variable cycle engines, the concepts selected could be categorized into four different types:

- Dual Inlet Engines - Those requiring auxiliary inlets to accommodate series-parallel flow operation.

- Supplementary Takeoff Airflow - Concepts utilizing means by which airflow supplementary to the main propulsion engines is used during the takeoff portion of the mission.

- Convertible Engines - Types that have the capability of turbofan operation during subsonic flight and turbojet characteristics while in supersonic flight.

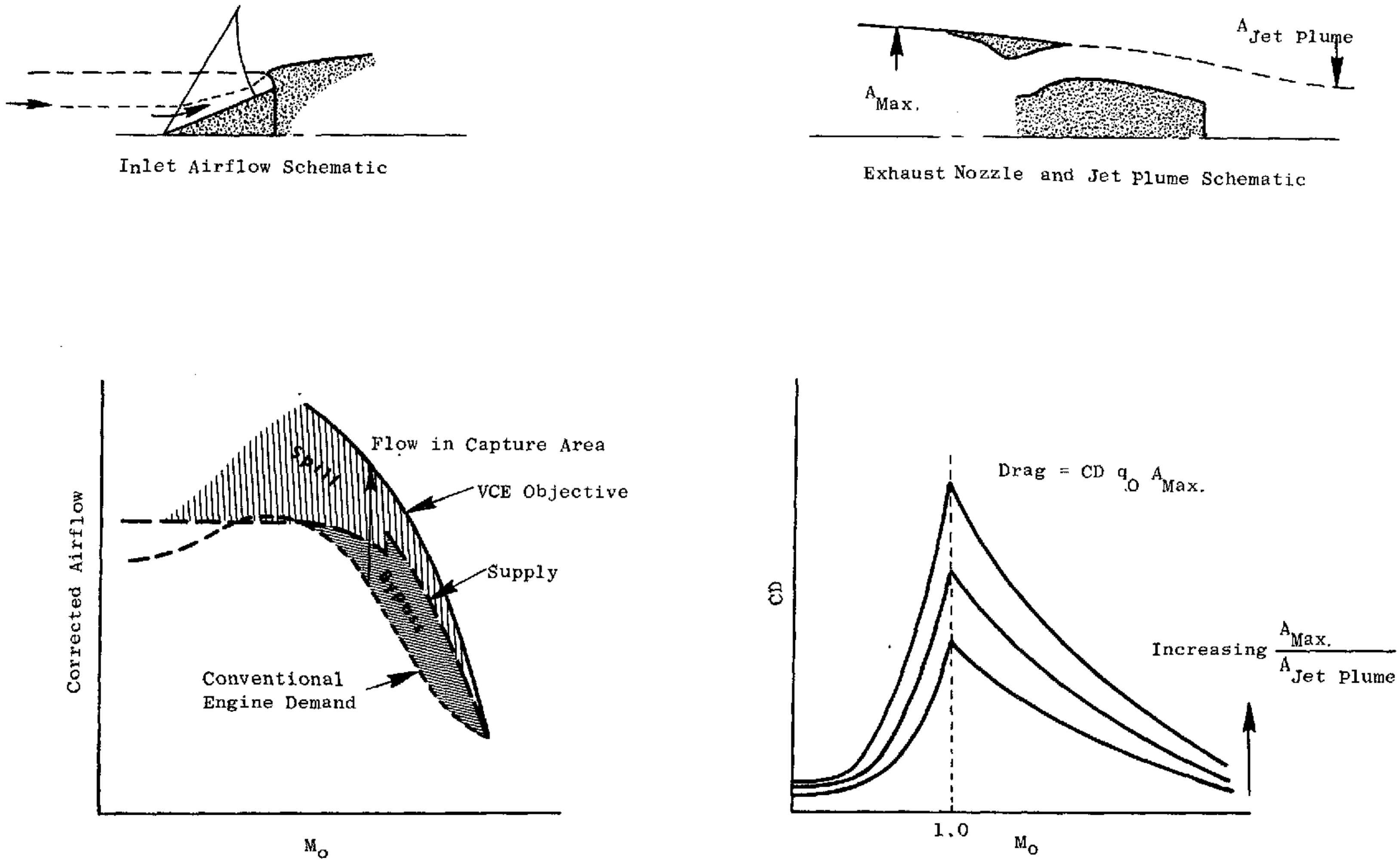


Figure 23. Task II Installed Performance Objectives.

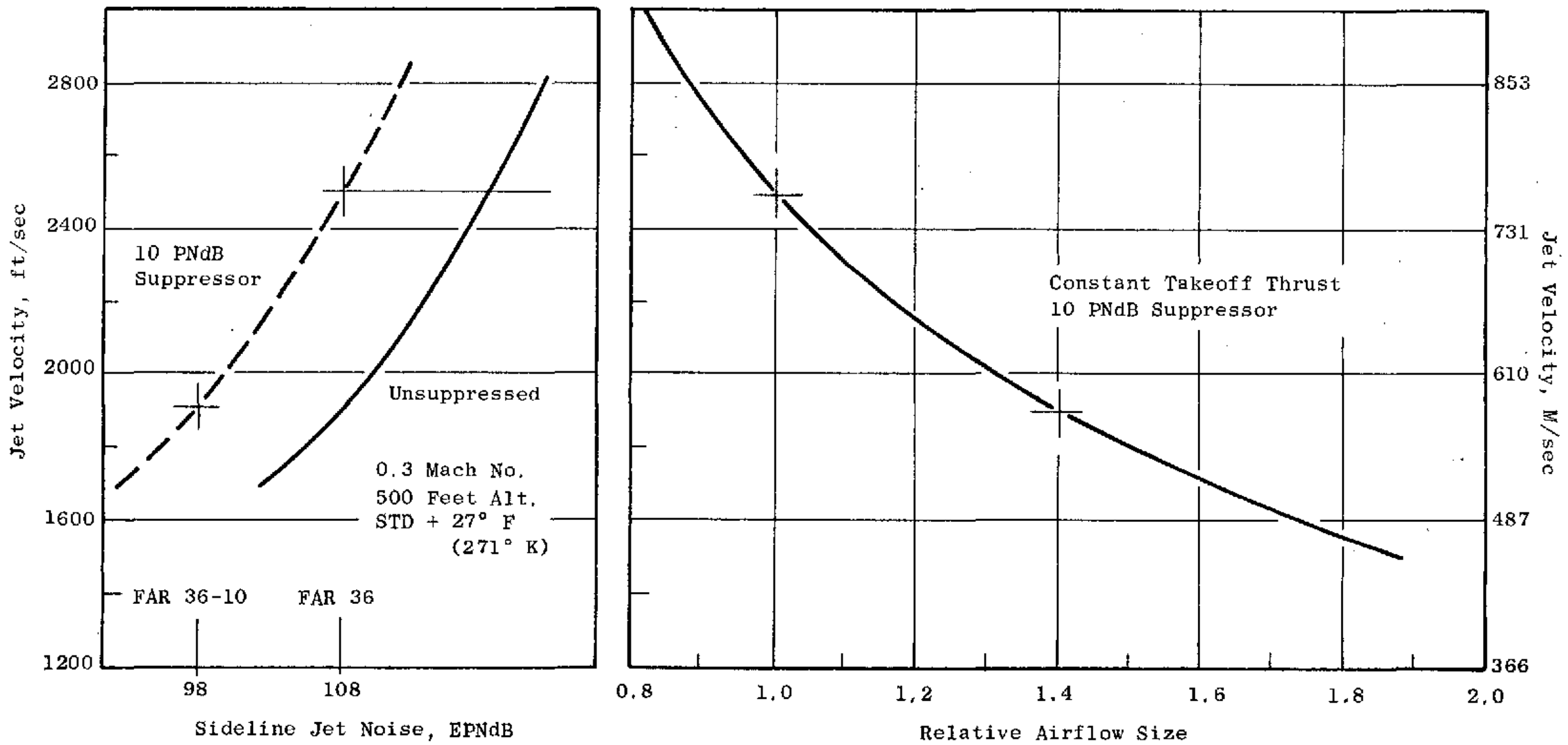


Figure 24. Task II, Variable Cycle Engine Sizing for Noise.

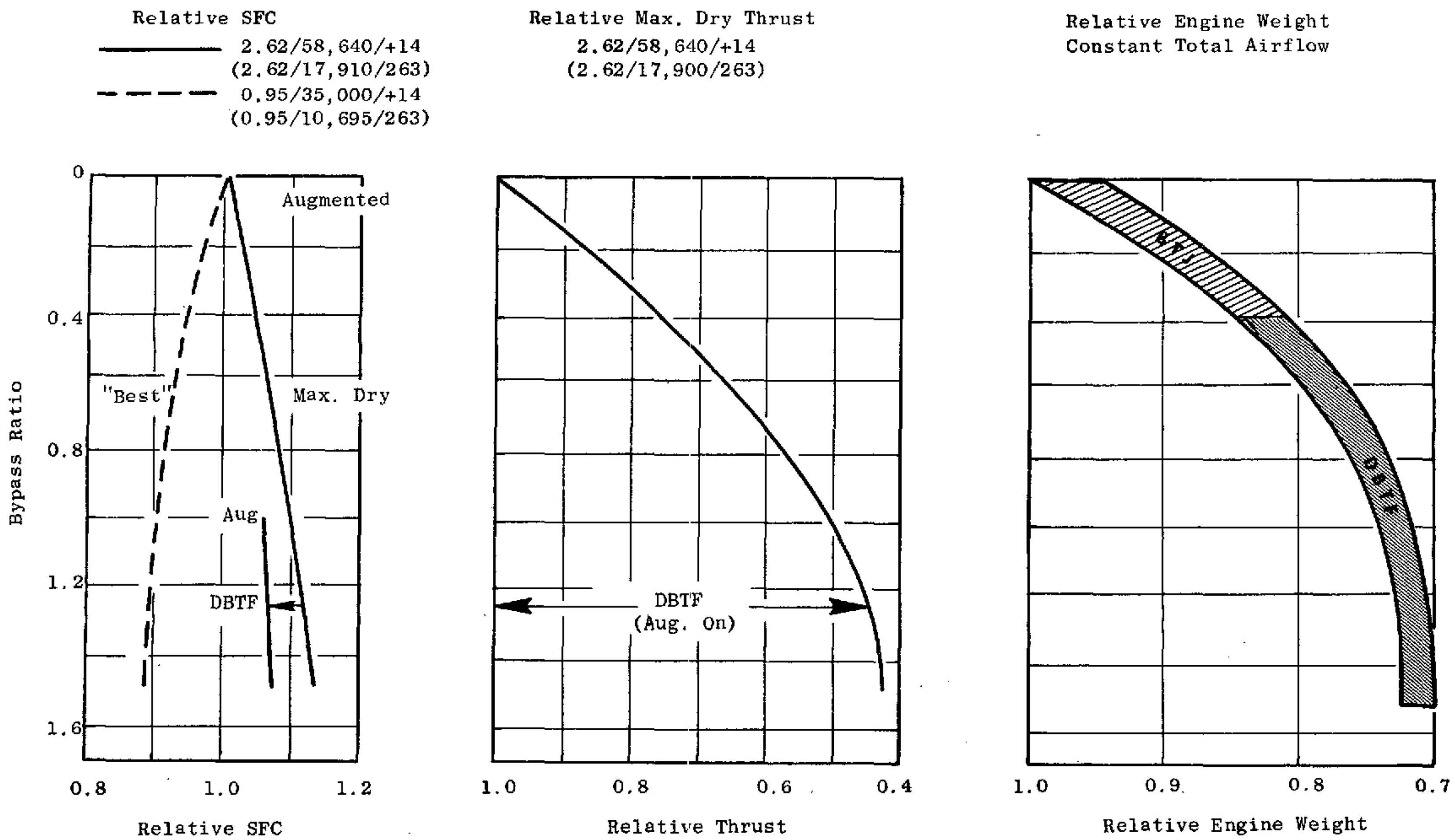


Figure 25. Task II, Variable Cycle Engine Sizing for Performance and Weight.

- Modulating Airflow Engines - Having the capability of speed and airflow variation throughout the flight regime to maximize installed performance.

A total of six engine concepts in these four categories were analyzed at Mach 2.7 cruise and these are exhibited schematically along with the salient parameters of each on Figures 26 through 31. Weight and performance for each of these engines were generated to conduct the mission analysis, based on the operational characteristics devised to yield best performance.

OPERATIONAL CHARACTERISTICS

These engine concepts were chosen because each offered some unique feature that could possibly yield mission performance that was superior to the conventional bypass turbojet or duct burning turbofan. Consequently, the operational characteristics of each concept require brief discussion so that their unique features may be emphasized.

Dual Inlet Engine

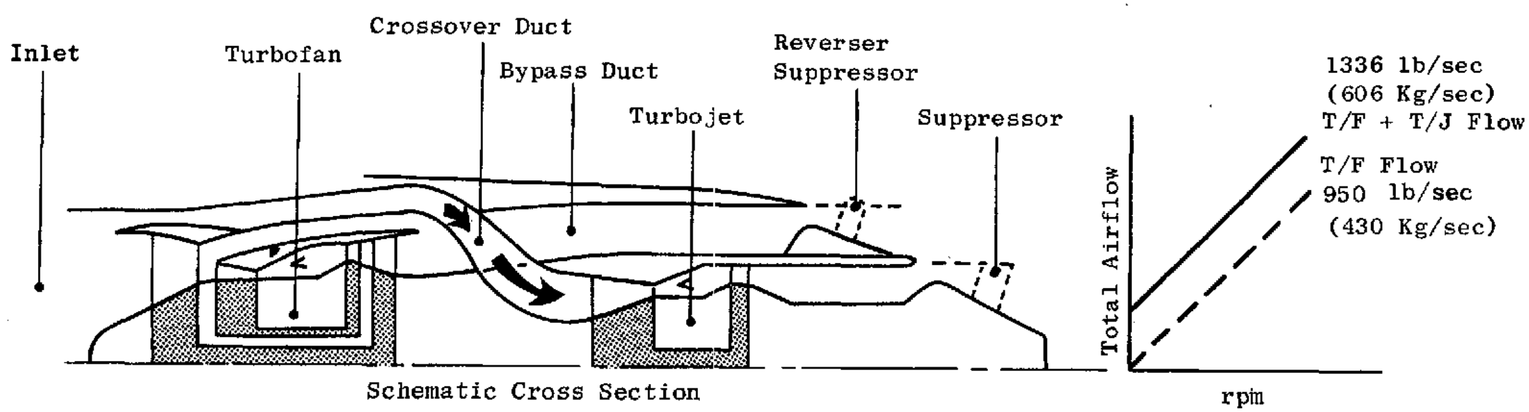
This engine is in actuality a turbofan and a turbojet in tandem operating independently of each other but with operation integrated to yield superior mission performance.

At takeoff - The turbofan operates at full RPM with the fan and core streams mixed and exhausting through the outer annular nozzle. The turbojet is taking air from an auxiliary annular inlet around the outside of the turbofan and runs at a condition to yield an exhaust velocity approximately equal to the turbofan exhaust velocity. The operation of these engines was scheduled such that exhaust conditions coupled with 10 PNdB suppressors on both streams would yield noise levels approaching FAR 36-10.

At Subsonic Cruise - The turbojet is shut down and the auxiliary annular inlet is closed off. Operation of the propulsion system is totally on the turbofan mode with the mixed exhaust flowing through the outer annular nozzle. Modulation of the turbofan rotor speeds was used to vary the thrust levels.

At Climb/Accel - During this operational mode, maximum thrust is required from the propulsion system. This is achieved through operation of both engines simultaneously. Since the climb/accel is up to supersonic cruise Mach number, the auxiliary annular inlet is not used. The turbofan is operated at maximum, with speed variation to match the inlet supply characteristic. The exhaust of both streams of the turbofan is mixed and, through the use of a crossover duct, is guided into the inlet of the turbojet. The turbojet is running at maximum speed, swallowing the discharge flow of the turbofan. Any flow that the turbojet cannot swallow is bypassed around the turbojet and discharged through the outer annular nozzle.

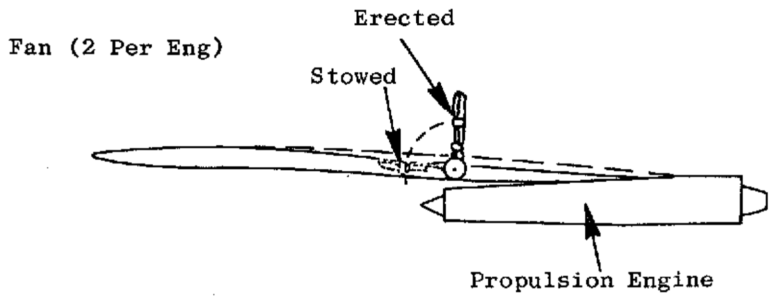
At Supersonic Cruise - Operation during supersonic cruise is primarily with the turbojet and is very similar to the climb/accel operation except the turbofan is operating at reduced speed so as to swallow the flow to match the inlet characteristic. Thrust modulation is by variation of this throat area of the turbojet.

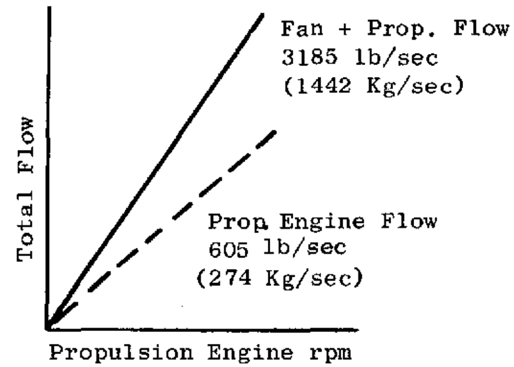


Important Parameters

	Turbofan	Turbojet	Total Engine
Number of Rotors	2	1	3
Airflow at Takeoff - lb/sec (Kg/sec)	950 (430)	386 (175)	1336 (605)
Bypass Ratio	0.8	0.3	
LP Pressure Ratio	3.1	3.9	
Core Pressure Ratio	4.84	3.85	
Overall Pressure Ratio	15	15	
Exhaust Velocity - ft/sec (M/sec)	1820 (555)	1870 (570)	
Suppressor Effectiveness - PNdB	10	10	

Figure 26. Task II Study, Dual Inlet Engine, Turbo Augmented Cycle Engine (TACE), GE21/F9A1.

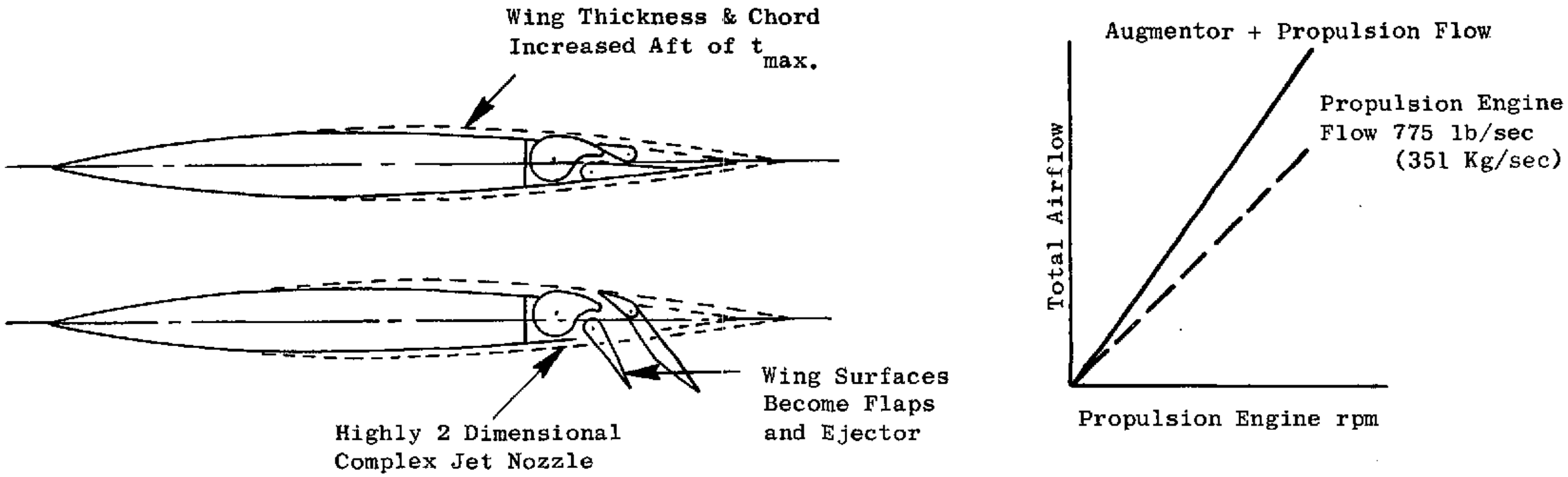




Important Parameters

	Propulsion Engine (Turbojet)	Fan	Total Engine
Number of Rotors	1	2	3
Airflow at Takeoff - lb/sec (Kg/sec)	605 (274)	1250 ea. (584)	3185 (1442)
Bypass Ratio	0.3	4.3	
LP Pressure Ratio	3.9	1.4	
Core Pressure Ratio	3.85	---	
Overall Pressure Ratio	15	---	
Exhaust Velocity - ft/sec (M/sec)	1180 (360)	875 (287)	
Suppressor Effectiveness - PNdB	No Suppressors Used		

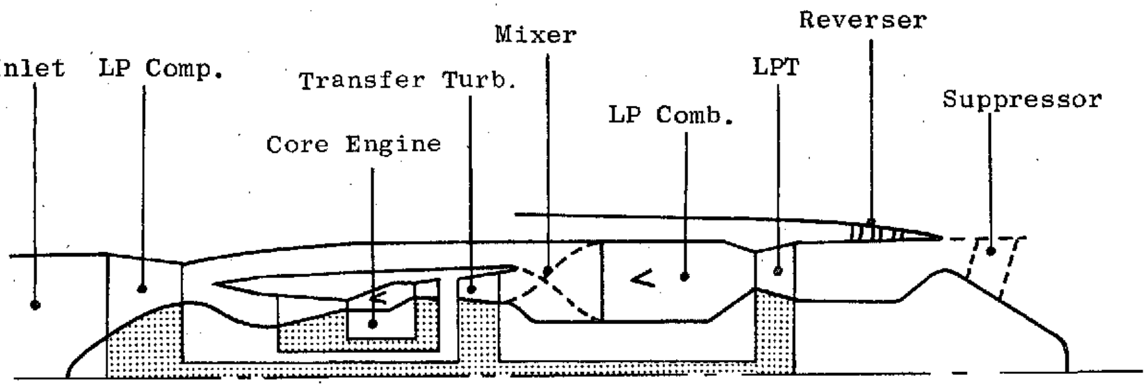
Figure 27. Task II Study, Supplementary Airflow Engine, Fan-In Wing, GE21/J6E1.



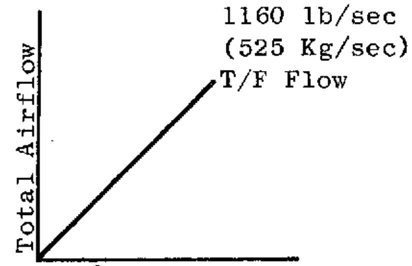
Important Parameters

	Propulsion Engine (Turbojet)	Augmentor
Number of Rotors	1	None
Airflow at Takeoff ~ lb/sec (Kg/sec)	775 (351)	---
Bypass Ratio	0.3	---
LP Pressure Ratio	3.9	---
Core Pressure Ratio	3.85	---
Overall Pressure Ratio	15	---
Exhaust Velocity - ft/sec	Mixed with Augmentor Flow	
Suppressor Effectiveness	No Suppressors Used	

Figure 28. Task II Study, Supplementary Airflow Engine, Augmentor Wing, GE21/F7B1.



Schematic Cross Section

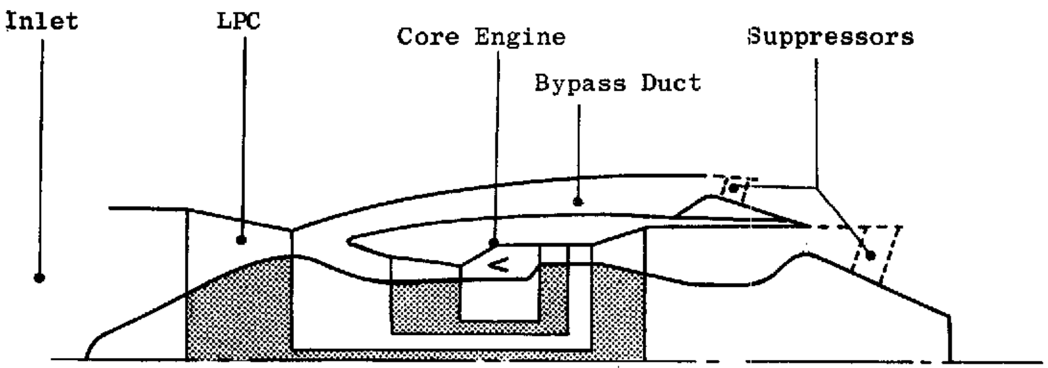


Airflow Schematic

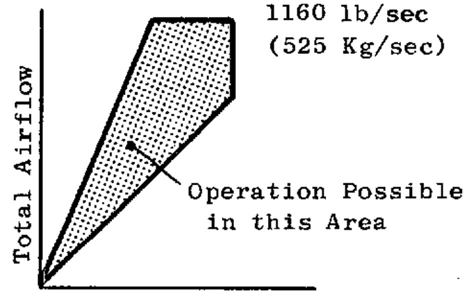
Important Parameters

Number of Rotors	2
Airflow at Takeoff - lb/sec (Kg/sec)	1160 (525)
Bypass Ratio	0.7
LP Pressure Ratio	6.0
Core Pressure Ratio	4.25
Overall Pressure Ratio	25.5
Exhaust Velocity - ft/sec (M/sec)	1960 (596)
Suppressor Effectiveness - PNdB	10

Figure 29. Task II Study, Convertible Engine, Flex Cycle, GE21/F10A1.



Schematic Cross Section

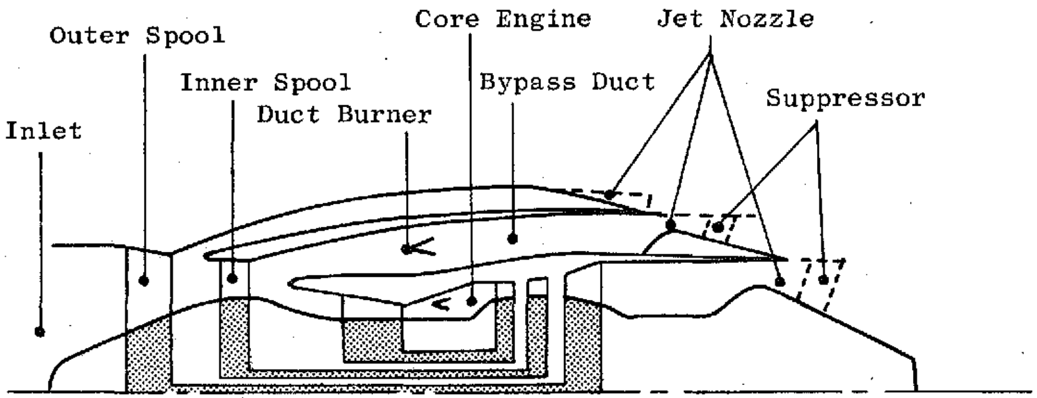


Core rpm
Airflow Schematic

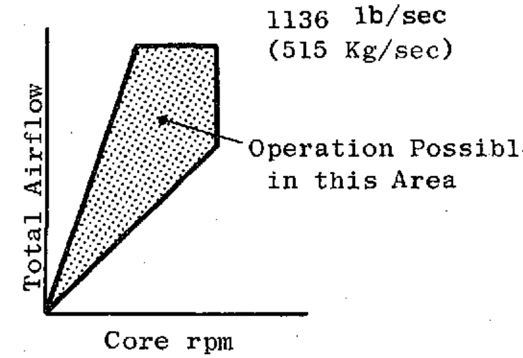
<u>Important Parameters</u>

Number of Rotors	2
Airflow at Takeoff - lb/sec (Kg/sec)	1160 (525)
Bypass Ratio	0.75
LP Pressure Ratio	4.75
Core Pressure Ratio	3.15
Overall Pressure Ratio	15
Exhaust Velocity - ft/sec, Core/Duct (M/sec)	1960/1960 (596/596)
Suppressor Effectiveness - PNdB, Core/Duct	10/10

Figure 30. Task II Study, Convertible Engine, VAPCOM, GE21/F10A1.



Schematic Cross Section



Airflow Schematic

Important Parameters

Number of Rotors	3
Airflow at Takeoff - lb/sec (Kg/sec)	1136 (515)
Bypass Ratio	1.25
LP Pressure Ratio	2.8
Intermediate Pressure Ratio	1.7
Core Pressure Ratio	3.15
Overall Pressure Ratio	15
Exhaust Velocity - ft/sec, Core/Duct (M/sec)	1970/1970 (600/600)
Suppressor Effectiveness - PNdB, Core/Duct	10/10

Figure 31. Task II Study, Modulating Airflow Engine, Triple Rotor, GE21/F10B1.

Supplementary Airflow Engine

Operation of the two engines in this category is basically the same during climb/accel, subsonic cruise, and supersonic cruise since the main propulsion engines are turbojets and operate in a conventional manner during these flight conditions.

Takeoff operation is different because of the configurations and these will be discussed.

Fan-in-Wing at Takeoff - The turbojet exhaust gases are diverted through ducts into the wing section to the scroll sections of tip turbine driven fans. These are rotated from horizontal, buried positions in the wing to upright, vertical positions during takeoff. In this position, eight fans, each handling 1290 lb/sec (584 kg/sec) airflow (2 fans per propulsion engine), supply the thrust for takeoff. During the climbout after the community noise measuring point, the system transists to propulsion on the turbojet engines for the remainder of the mission.

Augmentor Wing at Takeoff - Similar to the fan-in-wing, exhaust gases from the turbojet propulsion engines are diverted to spanwise ducts in the wing for distribution of this flow over flaps to induce flow in an augmenting configuration utilizing the Coanda effect. By virtue of these augmentor flaps having to be wing surfaces when retracted, the augmentor configuration is something less than optimum and yields an augmentation ratio of slightly greater than 1.0. During the climbout, the flaps of the augmentor are slowly retracted while the flow from the propulsion engine is reduced until the total propulsive effort is being generated by the turbojet. Flight throughout the remainder of the mission is on turbojet power.

Convertible Engine

This concept, named the flex cycle, is basically a turbofan engine which is capable of nearing turbojet operation characteristics through the use of variable geometry and an additional special low pressure turbine stage downstream of a low pressure combustor. The mode of operation briefly is:

At Takeoff - Operation is on the "turbofan" mode in that energy is being supplied only in the high pressure burner and engine operation is similar to that of a mixed flow turbofan.

At Subsonic Cruise - Operation is identical to takeoff with thrust variation through rotor speed modulation.

At Climb/Accel - For high specific thrust operation, energy is supplied in both high pressure and low pressure burners. Variable turbine geometry in the special low pressure turbine enables rotor speeds to be maintained while high thrust levels are generated to supersonic cruise conditions.

At Supersonic Cruise - Operation at this condition is similar to a low pressure ratio turbojet. The high pressure burner ΔT is reduced to near idle levels while the low pressure burner supplies the majority of the energy. The high pressure rotor slows down and the low pressure rotor speed is held constant and is scheduled to match the inlet supply. Thrust modulation is achieved through nozzle area variation.

A second convertible engine concept, VAPCOM, is basically a very low bypass ratio turbojet that approaches turbofan operation through exhaust nozzle and low pressure turbine variability. This flexibility features near optimum relative rotor speed enabling near optimum matching of airflow and thrust requirements. Operational modes are:

At Takeoff - Operation is in the "turbofan" mode with increased low pressure rotor speed and "high" bypass ratio through the opening of the bypass exhaust nozzle.

At Subsonic Cruise - Operation identical to takeoff with thrust variation through rotor speed modulation.

At Climb/Accel - To generate maximum thrust, the low pressure rotor speed is scheduled to match the inlet characteristic while the bypass exhaust nozzle is closed down to raise the fan pressure ratio which lowers the bypass ratio. Consequently, turbojet operation is approached.

At Supersonic Cruise - Operation continues in the same manner as during climb/accel with thrust modulation accomplished through scheduling of the variable geometry features to maintain airflow while changing specific thrust.

Modulating Airflow Engine

This engine concept is conceived to use a large amount of turbomachinery variability in a basic separated flow, duct burning turbofan to enable greater variation in its airflow handling characteristics. This would allow a reduction in installation drags and improve mission performance. The operational characteristics of this concept are:

At Takeoff - With three rotors and three exhaust nozzles, this engine potentially exhibits a broad range of operational capability. The low pressure rotor is run to maximum speed for maximum airflow swallowing capability. The intermediate and high pressure rotors operate at maximum speed also with no burning in the duct burner. Speeds and pressure ratios are scheduled to yield equal exhaust velocities at levels that approach FAR 36-10 noise levels with 10 PNdB effectiveness jet suppressors in both streams, fan, and core.

At Subsonic Cruise - The low pressure rotor is operated at essentially constant speed over the thrust range. This is to match the inlet and preclude drag penalties associated with part throttle operation of a conventional engine (bypass, spillage). The intermediate and high pressure rotor speeds are varied to modulate thrust. Airflow discharged from the low pressure compressor not accepted by the intermediate compressor is bypassed around the duct burner and exhausted through the outer annular nozzle. This flow fills the exhaust plume area minimizing the afterbody drag. Consequently, installed performance is maximized over the thrust range with greatest benefit occurring at the divert condition, i.e., lowest thrust.

At Climb/Accel - Maximum speeds for all the rotors are utilized in this mode of operation with modulation of the low pressure rotor speed to match the inlet characteristic, minimizing the inlet bypass and spillage drags and thereby maximizing installed performance. Flow exhausts through the inner two annular nozzles with augmentation utilized in the duct burner.

At Supersonic Cruise - The rotor speeds are modulated at supersonic cruise to approach as closely as possible turbojet operation. Consequently, the intermediate and high pressure rotors are running at high speed to reduce bypass ratio. Thrust modulation is achieved through duct burner temperature variation.

RESULTS

Analysis of the mission performance of these engines was made and comparison was made to the bypass turbojet engine as defined in Task I. Because of special features of some of these concepts, some airframe oriented areas affected by these features could not be evaluated. Consequently, these items are noted in the results as not being accounted for.

In evaluating the results, each concept was exercised in a manner similar to the conventional engines relative to size, weight and performance. Table VIII highlights the more important parameters of each concept relative to the non-augmented bypass turbojet and enables a cursory system assessment of each engine to be made while Figure 32 exhibits the overall relative performance results in terms of range. This analysis, from which these results came, yields:

- No concept met all the operational objectives.
- All concepts were sound in approach but were more complex than the conventional engines of Task I.
- Fan-in-wing and augmentor wing systems required gross aircraft structural and aerodynamic changes that could not be evaluated in this study.
- The three rotor modulating airflow engine yielded the best mission performance and was the concept chosen for analyses in Tasks III, IV, and V.
- To approach FAR 36-10, additional airflow was required which was reflected in increased propulsion system weight. With 10 PNdB suppressors (1975 technology), the three-rotor modulating airflow engine resulted in:

Table VIII. Summary of Variable Cycle Engine Characteristics Relative to Bypass Turbojet.

	TACE	Fan-in-Wing	Augmentor Wing	Flex Cycle	Modulating 3 Rotor	VAPCOM 2 Rotor
Inlet Matching	Complex*	Conventional				
Augmentation ΔT						
Takeoff	---	---	---	---	---	---
Climb/Accel	---	1030	1030	---	1550	---
Supersonic Cruise	---	500	125	---	525	---
Suppressor Effectiveness Level - PNdB Core/Duct	10/10	0/-	0/-	0/-	10/10	10/10
Traded FAR-36 Number	98			100		
Δ% SFC						
Subsonic Cruise	-5	-6	-3	-10	-14	-3
Supersonic Cruise	-1	+12	+6	+2	+2	+2
Δ Weight of Four Propulsion Systems-lb (kg)	+29500 (13400)	-6500 (2945)	+4700 (2135)	+47600 (21600)	+20100 (9100)	+2380 (1080)
Nacelle Cross Section Area Δ%	+7	---	---	+7	+7	+4
Aircraft Modification	None	Wing*	Wing*	None		

*Modifications to inlet or wing required; additional drag not included in analysis.

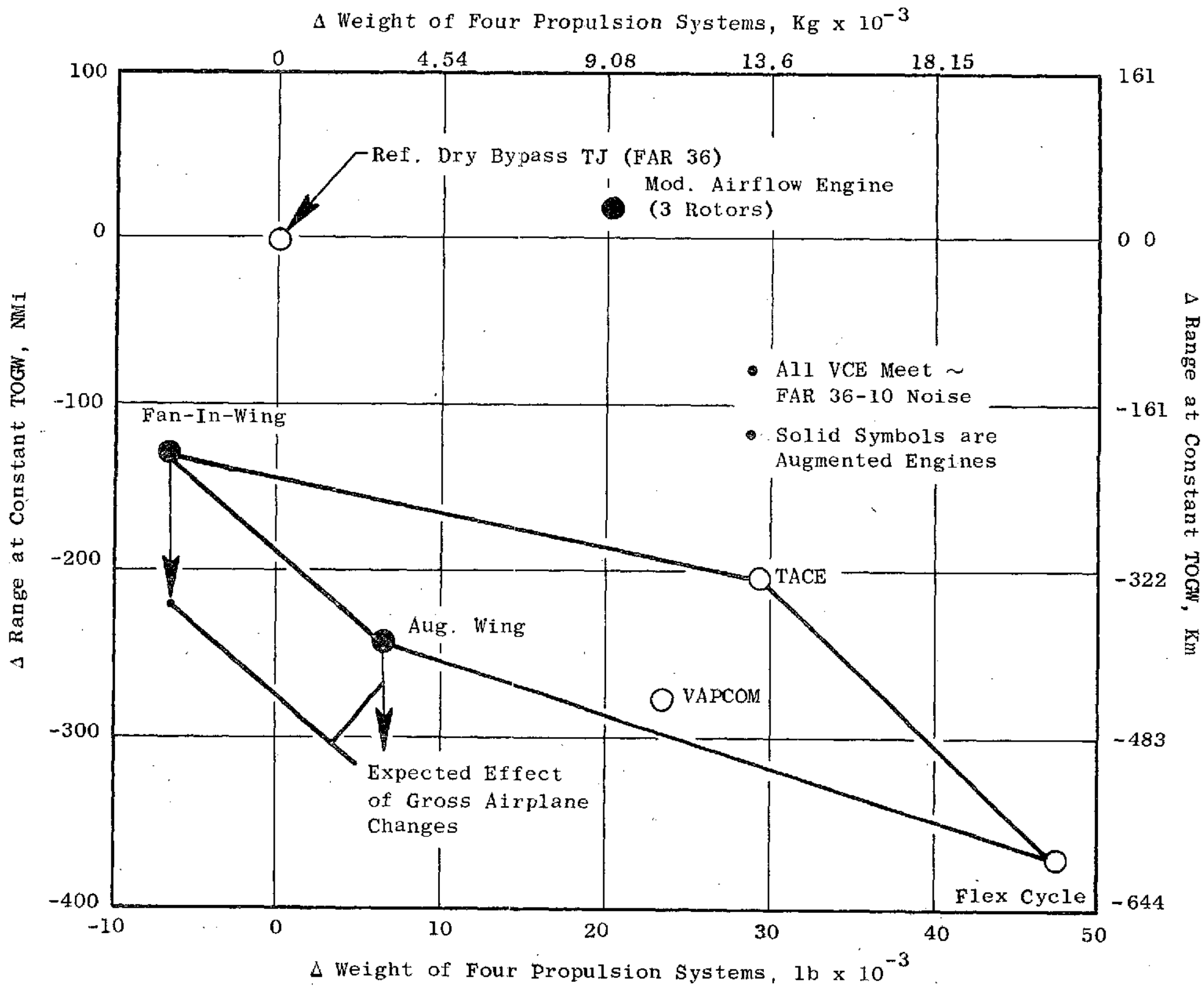


Figure 32. Task II Summary of Results, M = 2.7, Baseline Airplane.

- At Mach 2.7 no penalty in range compared to the bypass turbojet at FAR 36-0.

- At Mach 2.2 a 400 NMi (741 km) penalty in comparison to the Mach 2.2 bypass turbojet at FAR 36-0.

APPENDIX C

TASK III - CONVENTIONAL AND VARIABLE CYCLES - 1980 TECHNOLOGY

GENERAL APPROACH

Technology level, achieved through research and development expenditures, is a key factor in the study of any propulsion system and especially so in the Advanced Supersonic Technology area. With primary study emphasis centered around a commercial long range transport with a payload-to-TOGW fraction in the order of 6.5%, the importance of technological advances are even greater with passenger safety and operating economics being prime in the airline's thinking.

Consequently, as part of the propulsion studies of the Advanced Supersonic Technology program, Task III was involved with the state of the art beyond the Task I and II technology level. This technology level was designated "1980", although it is not necessarily 5 years beyond Task I and II levels. It was applied to the "best" performing engines resulting from the Task I and II studies, conventional and variable cycles, respectively.

With the "best" Task I and II engines selected, the objectives of Task III were threefold:

1. Identify the component design, performance and or material advances available. Not all Task III engine components have exhibited improvements in performance or advancements in design.

2. Utilizing the identified improvements, define the engine design which yields the greatest mission performance/noise benefits. By virtue of the improvements associated with Task III technology, some change to the engine cycles was required to best use these improvements.

3. Calculate the mission performance levels and determine the gains available due to the predicted technology advancements.

TECHNOLOGY ADVANCES AND ENGINE DESCRIPTION

As stated, the technology advancements designated Task III were applied to the "best" engines resulting from the Task I and II effort. These technology advances, succinctly stated, are in five areas:

- Higher jet suppressor effectiveness - An advanced design to yield levels up to 18 PNdB of in-flight suppression at jet velocities of 2500 ft/sec (762 m/sec). In conjunction with this suppressor design, additional sound treatment of the other major noise sources is required in order to suppress the total engine noise.

- Improved exhaust nozzle performance - Both internal and installed performance levels exhibit potential improvement. A projected 0.2%

improvement in thrust coefficient is included in addition to an approximate 25% reduction in transonic afterbody drag at Mach 1.0.

- Advanced materials - Research and development in the materials area is being conducted continuously since this discipline has been a key item pacing the development of turbine engines. These material advances are manifested in both lighter weight engines and higher metal temperature operation.

  A review of the impact of advanced materials through the engine has led to a reduction of engine weight of 4% plus a reduction in internal coolant flows. The material advances have been utilized in allowing metal temperatures to rise approximately 200° F (93° C), significantly reducing the cooling flow requirements in the engine.

- Improved duct burner efficiency - Burner development has been accelerated by the new emphasis on combustion emissions. This has resulted in a twofold benefit - reduced emissions and improved combustion efficiency. For the AST duct burning turbofan, a 1% efficiency improvement has been predicted for Task III technology.

- Improved LP compressor efficiency - Predicted improvements in both efficiency and flow-speed relationships have been incorporated in the Task III technology engine definition. The improvements in the LP compressor are approximately an overall 0.5% efficiency increase in addition to an approximate 6% increase in corrected airflow in the mid corrected speed regime.

These improvements, when considered individually, tend to improve the specific thrust of the engine (reduced cooling flows, higher LP compressor efficiency, better nozzle CFG), reduced SFC (better duct burner efficiency, reduced nozzle afterbody drags) or reduced weight (advanced materials), all leading to improved mission performance in the form of lower TOGW.

In combination; these advances in technology were incorporated in the Task III engines by a change in the cycles to maximize the mission performance and is best illustrated in Table IX.

BYPASS TURBOJET ANALYSIS

With no change in jet suppressors, the application of the technology improvements to the turbojet cycle was done to increase the mission performance. Previous analyses had indicated that bypass ratios of approximately 0.4 would yield close to minimum TOGW for the design mission of 4000 NMi (7410 km). Consequently, it was determined that, to hold a 0.4 bypass ratio and T41, the LP compressor pressure ratio was increased while holding the design overall pressure ratio.

As a result, the specific thrust potential of the engine was increased. However, to achieve maximum jet suppression, the exhaust velocity of the engines were maintained at 2500 ft/sec (762 m/sec), precluding any size reduction from the increased specific thrust. This is summarized below.

Table IX. Engine Description.

"BEST" TASK I & II						"BEST" TASK III				
BTJ	DBTF	BTJ	DBTF	MOAF		MOAF	DBTF	BTJ	DBTF	BTJ
2.2	2.2	2.7	2.7	2.7	MACH NO.	2.7	2.7	2.7	2.2	2.2
850 (385)	970 (441)	850 (385)	1020 (462)	1136 (515)	AIRFLOW SIZE - LB/SEC (KG/SEC)	996 (451)	1013 (459)	888 (402)	983 (445)	897 (406)
25	25	15	15	15	CYCLE P/P	15	15	15	25	25
.4	.4	.4	1.0	1.25	BYPASS RATIO	1.25	1.0	.4	.4	.4
3.7	3.6	3.5	3.6	4.75	LP P/P	4.75	4.1	3.8	4.1	4.1
2750 (1510)	2800 (1538)	2750 (1510)	2800 (1538)	2800 (1538)	MAX CRUISE T41 - ° F (° C)	2800 (1538)	2800 (1538)	2750 (1510)	2800 (1538)	2750 (1510)
2	2	1	2	3	NO. ROTORS	3	2	1	2	2
2500 (762)	2500 (762)	2500 (762)	2500 (762)	1970 (600)	JET VELOCITY - FT/SEC (M/SEC)	2220 (676)	2500 (762)	2500 (762)	2560 (780)	2500 (762)
-	1990 (606)	-	1890 (576)	1970 (600)	DUCT VELOCITY - FT/SEC (M/SEC)	2220 (676)	1910 (581)	- -	1960 (597)	- -
10	10	10	10	10/10	SUPPRESSION LEVEL*	16.5/16.5	18/14	18	18/14	18
13800 (6250)	15300 (6830)	13950 (6310)	14200 (6440)	20400 (9425)	WEIGHT LB (KG)	18800 (8515)	15200 (6890)	15700 (7110)	16100 (7285)	14200 (6435)
108	107	107	106	100	TRADED NOISE LEVEL**	98	99	101	101	102
YES	YES	YES	YES	YES	DRY T.O.	NO	YES	YES	YES	YES
YES	NO	YES	NO	NO	DRY CRUISE	NO	NO	YES	NO	YES
YES	NO	YES	NO	NO	DRY CLIMB	NO	NO	YES	NO	YES

** Noise level is traded at the three measuring points, takeoff, community and approach, per FAR rules.

* Dual valued tabulation indicates suppressors on both streams, core/duct. BTJ - bypass turbojet, DBTF - duct burning turbofan, MOAF - modulating airflow variable cycle engine.

BTJ - Task I			BTJ - Task III	
2.2	2.7	Mach No.	2.7	2.2
10	10	Suppression Level	10	10
850 (385)	850 (385)	Airflow Size - lb/sec (kg/sec)	840 (381)	848 (384)
0.4	0.4	Bypass Ratio	0.4	0.4
3.7	3.5	LP Comp. P/P	3.8	4.1
2500 (762)	2470 (752)	Exhaust Velocity - ft/sec (m/sec)	2500 (762)	2500 (762)
108	107	Traded Noise Level	107	108
13800 (6250)	13950 (6310)	Weight - lb (kg)	14100 (6380)	12800 (5800)
1.0	1.0	Relative TOGW	0.98	0.96

The Mach 2.7 bypass turbojet weight increased slightly when advanced technology was used, primarily because bypass ratio and turbine inlet temperature were held constant, and fan pressure ratio was allowed to increase. The higher fan pressure ratio increased the weight because an additional fan stage was required, and fan case, frame, etc. are subjected to higher loads and their weights went up accordingly.

The Mach 2.2 bypass turbojet was affected to a lesser extent, since the increased fan pressure ratio did not require an additional fan stage.

Small reductions in relative TOGW are available due to technology changes throughout the engine, with essentially no change in noise level.

At this point, a jet suppressor with an effectiveness of 18 PNdB was substituted for the original 10 PNdB suppressor on the engine.

As jet suppression level increased, other engine noise sources became dominant requiring further treatment to levels beyond those used in Task I. As both jet and engine suppression was increased, the engine traded noise levels were reduced. However, the increased weight of the suppressor, in conjunction with the poorer nozzle thrust coefficient due to the suppressor, imposed a penalty requiring an increased engine airflow size as compared below.

BTJ (10 PNdB)			BTJ (18 PNdB)	
2.2	2.7	Mach No.	2.7	2.2
10	10	Suppression Level	18	18
848 (384)	840 (381)	Airflow Size - lb/sec (kg/sec)	888 (402)	897 (406)
0.4	0.4	Bypass Ratio	0.4	0.4
4.1	3.8	LP Comp. P/P	3.8	4.1
2500 (762)	2500 (762)	Exhaust Velocity - ft/sec (m/sec)	2500 (762)	2500 (762)
108	107	Traded Noise Level	101	102
12800 (5800)	14100 (6380)	Weight - lb (kg)	15700 (7110)	14200 (6435)
1.0	1.0	Relative TOGW	.995	1.0

The result of the bypass turbojet analysis is exhibited on Figure 33 and concludes that:

1. The application of advanced technology to the bypass turbojet with 10 PNdB suppressor yields only modest reductions in relative TOGW.

2. The addition of increased suppressor effectiveness in conjunction with additional noise treatment has a significant effect on engine noise level with only small change in relative TOGW.

DUCT BURNING TURBOFAN ANALYSIS

Low Bypass Ratio

A similar approach was taken with the duct burning turbofan as with the bypass turbojet in the application of the Task III technology. Bypass ratio was held constant while fan pressure ratio was increased. Consequently, the specific thrust was increased while holding the core jet velocity at 2500 ft/sec (762 m/sec). The engine size was reduced for constant jet suppression level and relative TOGW was also reduced. Summarized below are the engine/mission improvements.

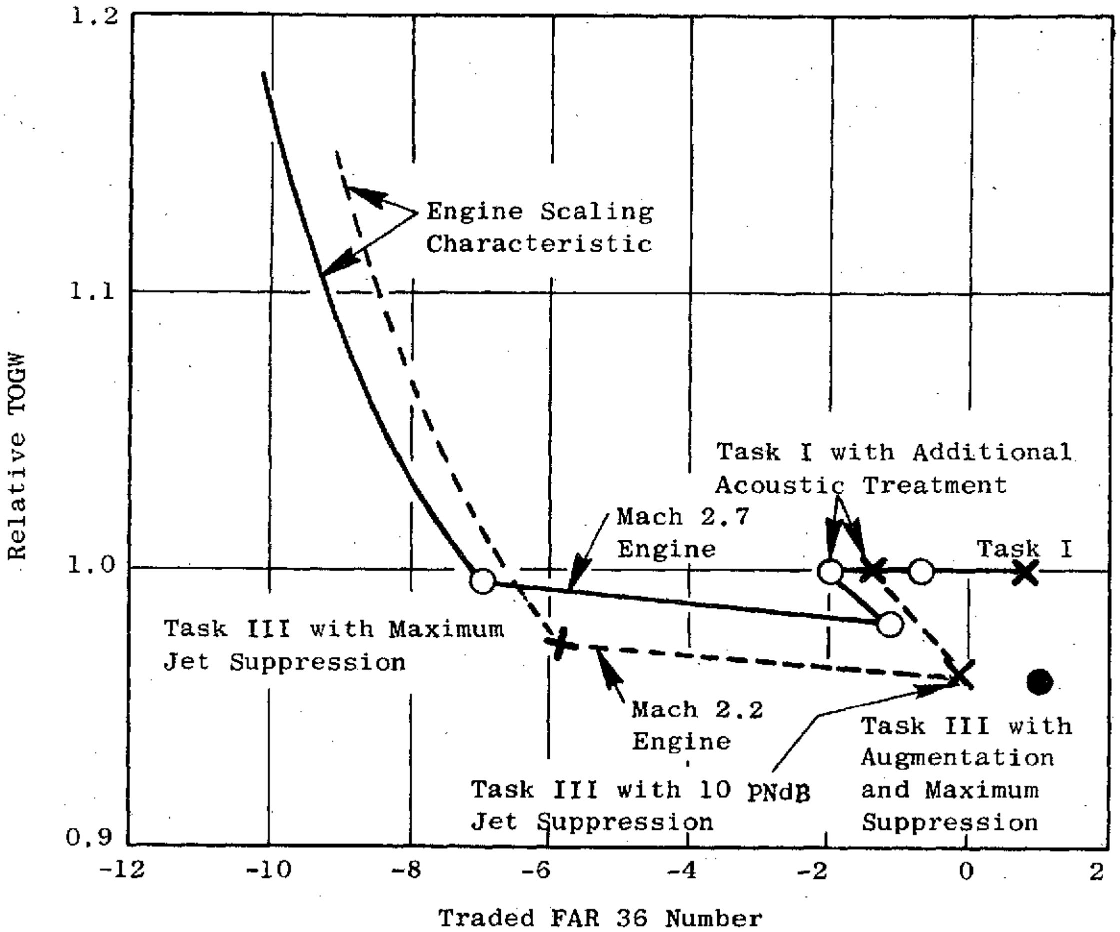


Figure 33. Task III Bypass Turbojet Engine Analysis.

DBTF - Task I			DBTF - Task III	
2.2	2.7	Mach No.	2.7	2.2
10	10	Suppression Level	10	10
970 (440)	1020 (462)	Airflow Size - lb/sec (kg/sec)	984 (445)	948 (429)
0.4	1.0	Bypass Ratio	1.0	0.4
3.6	3.6	LP Comp. P/P	4.1	4.1
2500 (762)	2480 (756)	Jet Exh. Velocity - ft/sec (m/sec)	2500 (762)	2500 (762)
1990	1890	Duct Exh. Velocity - ft/sec (m/sec)	1910	1960
107	106	Traded Noise Level	108	107
15300 (6930)	14260 (6450)	Weight - lb (kg)	14100 (6390)	15000 (6800)
1.0	1.0	Relative TOGW	0.90	0.90

By virtue of the reduced engine size resulting from the higher specific thrust, noticeable reductions in relative TOGW were available with essentially no change in noise level.

As was done with the bypass turbojet, an 18 PNdB suppressor was applied to the core exhaust.

Treatment of other noise sources was applied as was done with the bypass turbojet with a resulting reduction in traded noise.

A quick analysis indicated that the noise improvement achieved was not equivalent to the levels seen in the bypass turbojet. This is caused by the fan since no suppressor has been incorporated in that stream. The jet velocities coming from the fan duct are of such a magnitude that duct suppression would have a pronounced effect on the overall traded engine noise.

With maximum suppression applied to the fan stream, summarized below is the effect of this addition on total noise and relative TOGW.

DBTF (Core Supp. Only)			DBTF (Duct & Core Supp.)	
2.2	2.7	Mach No.	2.7	2.2
10	10	Suppression Level*	18/14	18/14
948 (429)	984 (445)	Airflow Size - lb/sec (kg/sec)	1013 (459)	983 (445)
0.4	1.0	Bypass Ratio	1.0	0.4
4.1	4.1	LP Comp. P/P	4.1	4.1
2500 (762)	2500 (762)	Jet Exh. Velocity - ft/sec (m/sec)	2850 (869)	2650 (807)
1960 (597)	1910 (581)	Duct Exh. Velocity - ft/sec (m/sec)	1810 (551)	1710 (521)
107	108	Traded Noise Level	99	101
15000 (6800)	14100 (6390)	Weight - lb (kg)	15200 (6890)	16100 (7295)
0.90	0.90	Relative TOGW	0.98	0.97

* Dual values indicate suppression on both streams - core/duct.

Large gains in total engine noise are available by the addition of duct suppression with the engines approaching FAR 36-8 PNdB on a traded basis with only small penalties in relative TOGW. These trends are exhibited on Figure 34.

High Bypass Ratio

An additional group of duct burning turbofans was investigated that can be generically classed as "high bypass ratio". Since high specific thrust cycles yield high noise levels, the trend of AST engine design has been to types with moderate specific thrust levels and the employment of jet suppressors plus acoustic treatment to keep noise levels within acceptable limits. The duct burning turbofans previously analyzed fell in this category; however, analysis of higher bypass ratio engines with no jet suppressors was necessary to effectively assess the total AST turbofan regime. Three cycles were chosen for analysis, and no attempt was made to vary cycle parameters. Further optimization of fan pressure ratio and bypass ratio could show further gains, but would not give as low a TOGW as the dual suppressed turbofans at the same takeoff noise levels.

Three turbofan engines at Mach 2.7 were devised to investigate this area of interest. These were:

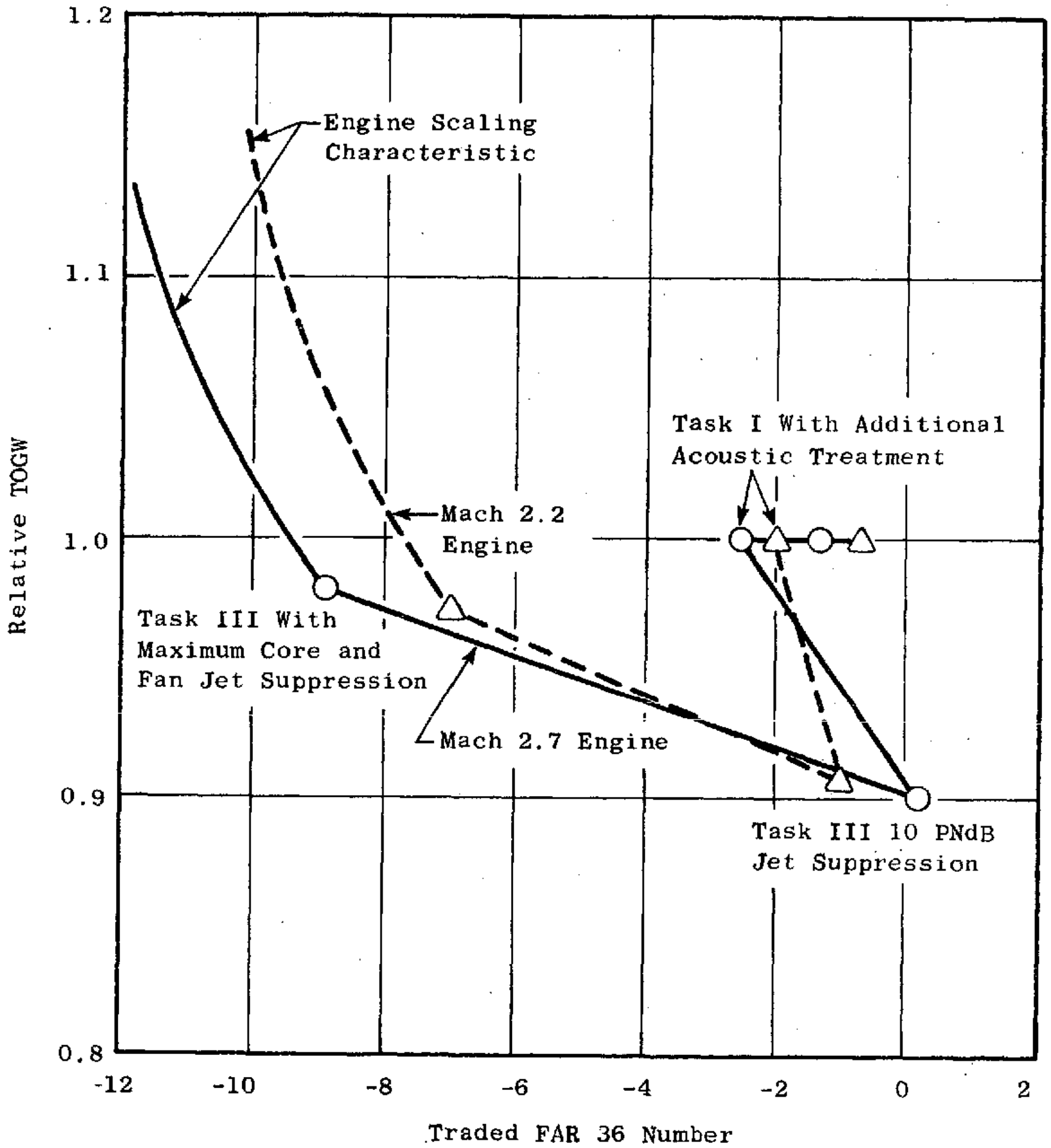


Figure 34. Task III Duct Burning Turbofan Analysis.

1. A duct burning turbofan with equal generated sound levels in both streams, low enough such that suppressors were not required to meet FAR 36.

2. A second turbofan, similar to number 1 with a small amount of duct burning used on takeoff [approximately 800° F (427° C)] ΔT including a low level of suppression to maintain the noise at FAR 36.

3. A third turbofan similar to number 2 except with low fan pressure ratio such that with duct burning on takeoff, the jet velocity was low enough precluding suppression to maintain the noise level.

These three engines were defined and configured utilizing Task III component technology with the NASA baseline aircraft for the 4000 NMi (7410 km) mission. Because of the high thrust lapse rate with increasing flight Mach number for high bypass ratio turbofans, it was determined that the engines were sized by the subsonic cruise requirement. They are sized to operate dry during subsonic cruise. The following summary exhibits the characteristics of these engines.

Engines	1	2	3
Mach No.	2.7	2.7	2.7
Suppression Level Core/Duct	0/0	0/10	0/0
Airflow Size - lb/sec (kg/sec)	1226 (555)	930 (421)	1313 (595)
LP Comp. P/P	3.2	3.2	2.1
Bypass Ratio	2.2	2.2	3.2
Cycle Pressure Ratio	15	15	15
Core Exhaust Velocity - ft/sec (m/sec)	2000 (610)	2000 (610)	1850 (564)
Duct Exhaust Velocity - ft/sec (m/sec)	1850 (564)	2390 (729)	1830 (557)
Augmentor ΔT at TO ° F (° C)	0 (-18)	860 (460)	570 (299)
Traded Noise Level	106	106	108
Weight - lb (kg)	15424 (7000)	11516 (5215)	16391 (7425)
Relative TOGW*	1.022	.937	1.282

* Values are related to Task I duct burning turbofan

Engine No. 1 relative TOGW is essentially equal to the Task I duct burning turbofan indicating that the increase in airflow size to reduce noise increases the engine weight and trades favorably with the weight saving associated with having no noise suppressors on the engine. However, no advantage is indicated.

Engine No. 3 is an extension of No. 1 in that the LP compressor pressure ratio is decreased sufficiently that augmentation of the bypass stream is utilized to increase the fan jet velocity to equal that of the primary stream approximately 1850 ft/sec (564 m/sec). Mission analysis indicates that performance of this engine is inferior to No. 1 due primarily to high installation losses and poor matching of the mission thrust requirements.

Engine No. 2 with a high fan jet velocity [∿2400 ft/sec (731 m/sec)], through augmentation of the bypass stream, requires a 10 PNdB suppressor to meet FAR 36. This engine, by virtue of the augmented takeoff, can be reduced significantly in size, better matching subsonic cruise thrust and exhibits a significant reduction in relative TOGW, approximately 10%.

Applying takeoff augmentation to the GE21/F4 Study B1 yielded results similar to those observed with engine No. 2 above. Airflow size was reduced in the mission to approximately that of the bypass turbojet. Relative TOGW was also reduced significantly.

Figure 35 summarizes the bypass ratio variation analysis.

The analysis of duct burning turbofans results in:

1. For the duct burning turbofan, fan jet suppression is required in addition to core suppression to efficiently reach traded engine noise levels below FAR 36-2.

2. Utilizing maximum jet suppression does not penalize the aircraft TOGW relative to Task I levels.

3. Moderately high bypass ratio engines ($\beta \sim 1.8$ to 2.2) without jet suppression yield performance in the regime of the Task I engines with 10 PNdB suppressors.

4. High bypass ratio engines ($\beta > 2.2$) without jet suppression result in high relative TOGW due primarily to the installation losses associated with the large diameter, low pressure ratio characteristics of high bypass ratios.

5. With a duct burner designed to meet acceptable pollution standards, augmented takeoff offers potential in significantly reducing relative TOGW.

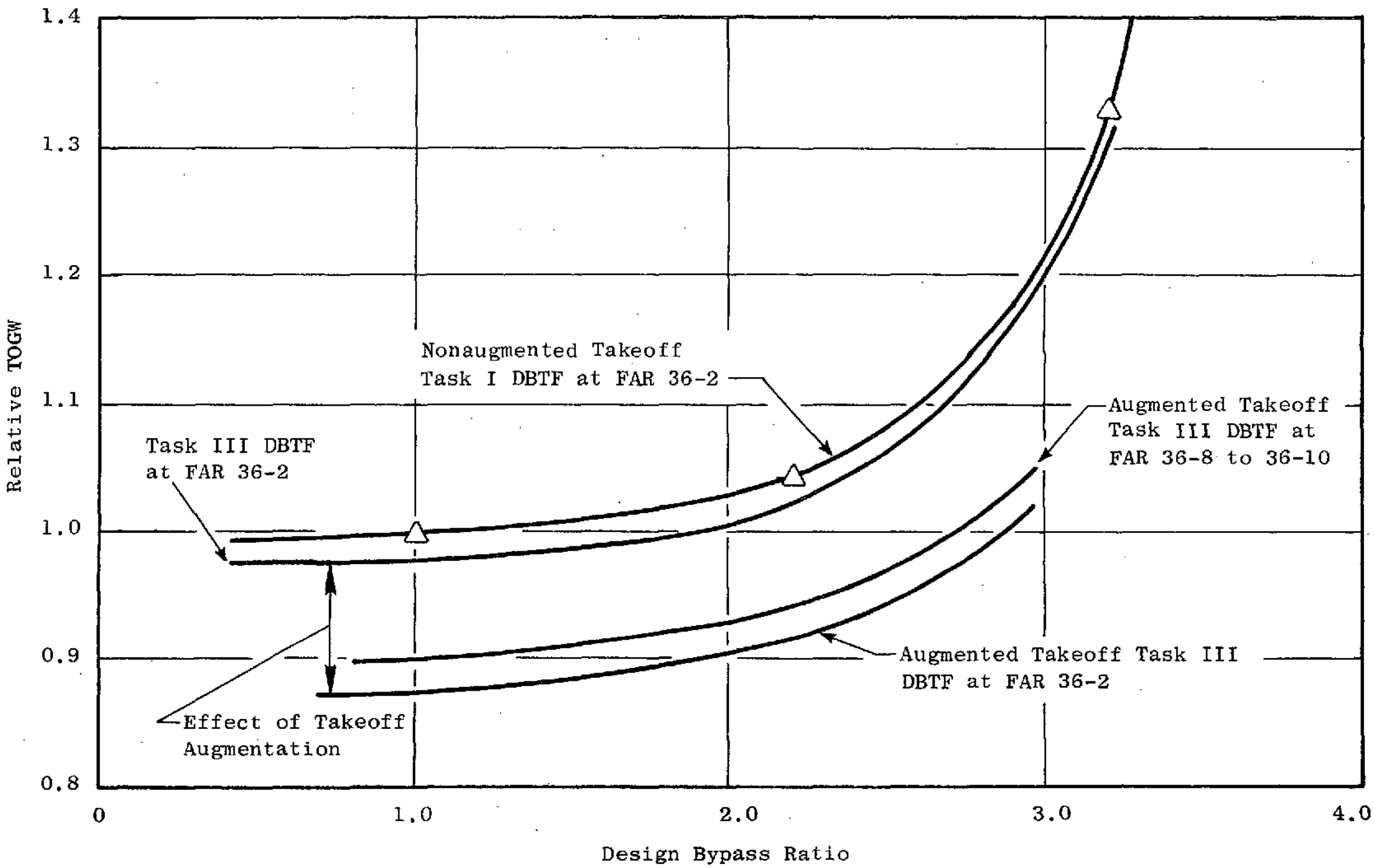


Figure 35. Task III, Design Bypass Ratio Vs. Relative TOGW, Mach 2.7 Duct Burning Turbofan.

VARIABLE CYCLE ENGINE ANALYSIS

The application of Task III component technology to the variable cycle engine can be made through several possible combinations of the five improvement areas. The approach taken was considered to yield the greatest payoff based on these observations:

- Task I results show that ROI and DOC improve rapidly with increasing mission range and decreasing airplane TOGW. Every opportunity should be taken to improve these parameters.

- FAR 36-10 PNdB noise levels are adequate and range payoffs are now more important than future noise reductions, although Task III suppressor technology could be used to obtain slightly lower noise levels than FAR 36-10.

- Task II component technology levels preclude further substantial cycle gains resulting from compressor, turbine, and burner efficiency gains or from reduction of installation drags.

- The only way to increase the range of the baseline aircraft with an engine of given cycle is to reduce propulsion system weight.

The results from applying Task III component technology to a modulating airflow, variable cycle engine have a direct effect on the TOGW of the 4000 NMi (7410 km) aircraft. Excluding maximum jet suppression, these are:

- <u>Duct Burner Efficiency</u> - Fuel saved in climb and acceleration is used to reduce TOGW, thereby permitting the engine to operate at higher altitude and better L/D.

- <u>Exhaust Nozzle Efficiency</u> - Reduced afterbody drags and improved thrust coefficients yield gains in installed specific thrust during climb, acceleration, and cruise which are equivalent to SFC improvements or fuel savings.

- <u>Low Pressure Compressor (Fan) Efficiency</u> - Increased efficiency has been used to increase core corrected speed and reduce low pressure turbine work, resulting in slightly higher specific thrust/ improved SFC.

- <u>Advanced Materials</u> - This item has resulted in improvements in two areas: reduced weight and reduced engine cooling flows due to higher allowable operating metal temperatures. The weight reductions work directly on aircraft TOGW while reduced cooling air results in higher specific thrust, therefore, improved SFC.

The summation of these items of improvement are shown on Figure 36, retaining the 10 PNdB suppression on both jet streams. By virtue of the improved engine specific thrust and resulting reduction in engine size [from 1136 lb/sec (515 kg/sec) to 996 lb/sec (451 kg/sec)] while maintaining thrust, the engine

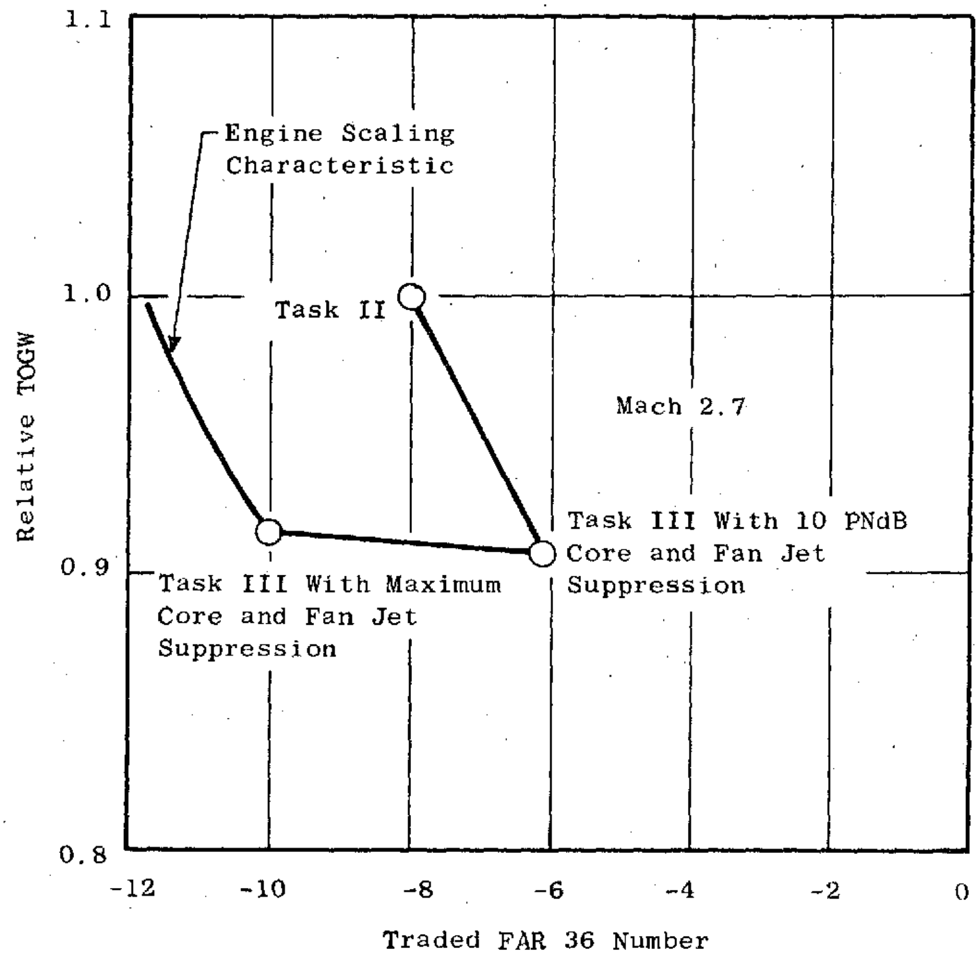


Figure 36. Task III, Modulating Bypass Engine Analysis.

noise level has increased approximately 2 PNdB. Addition of increased suppression on both streams yields the engine total noise levels lower than Task II levels.

- Increase Jet Suppression - The component improvements have increased the core jet velocity from 1970 ft/sec (600 m/sec) to 2220 ft/sec (676 m/sec). Fan jet velocity was increased to the same level by augmenting that stream approximately 250° F (121° C). Consequently, to achieve a constant FAR 36-10 noise level, jet suppressor effectiveness was increased from 10 to 16.5 PNdB. This required a weight addition for the jet suppressors and also supplemental acoustic treatment to maintain the FAR 36-10 PNdB noise level.

The following tabulation summarizes the change in the engine relative to the Task II engine.

MOAF (Task II)		MOAF (Task III)
2.7	Mach No.	2.7
10/10	Suppression Level	16.5/16.5
1136 (515)	Airflow Size - lb/sec (kg/sec)	996 (451)
1.25	Bypass Ratio	1.25
4.75	LP Comp. P/P	4.75
1970 (600)	Jet Exhaust Velocity - ft/sec (m/sec)	2220 (676)
1970 (600)	Duct Exhaust Velocity - ft/sec (m/sec)	2220 (676)
100	Traded Noise Level	98
1.0	Relative TOGW	0.92
20400 (9425)	Weight - lb (kg)	18800 (8515)

A result from Task II showed the modulating airflow engine (3 rotors) having no advantage over a conventional cycle engine at Mo = 2.2. The application of Task III component technology to the modulating airflow engine will improve its capability, as shown for the Mo = 2.7 engine, but its relative standing versus a conventional cycle engine at Mo = 2.2 will not change with equal technology changes in both types of cycles.

TASK RESULTS

Considerable effort has been expended in the discharging of this task, done to predict the applicable technology advances and done to ensure consistency between the tasks. This effort has yielded several significant results:

1. Application of Task III technology to both conventional and variable cycle engines indicates that the duct burning turbofan requires suppression in the duct to get the greatest benefit from maximum suppression. All other things being equal, the duct burning turbofan noise level can be reduced approximately 6 PNdB with the application of a duct suppressor.

2. Advanced technology does not change the relative economic ranking of engine type and cruise Mach number for the Task I or Task II engines.

3. The application of advanced suppression to these engines results in propulsion systems capable of traded noise levels in the range of FAR 36-7 to -10 without using augmentation on takeoff. Figure 37 exhibits the relative relationship of these Task III engines. At FAR 36-10, the variable cycle and the duct burning turbofan (β = 1.0, augmented with 2 suppressors) have equal relative TOGW while the bypass turbojet has an approximately 10% higher TOGW. At FAR 36-5, the three engine types appear to be essentially equal in TOGW.

4. Relative TOGW values for the maximum suppression engines did not change appreciably from Task I. Consequently, the economics (DOC and ROI) of the aircraft system remained at essentially the same levels of Task I.

5. These are very high risk engines. The duct burning turbofan and modulating bypass engines are very complex especially with the incorporation of jet suppressors on two streams. Much more in-depth study is required to determine the best engine type.

6. Augmentation on takeoff of the duct burning turbofan and the variable cycle engine offers a potential ($\sim$5 to 15%) reduction in relative TOGW due to effecting a better match to the thrust requirements. Figure 37 exhibits this effect and indicates an advantage for the duct burning turbofan with suppressors on both streams. A duct burning turbofan with fan suppression only exhibits an advantage at FAR 36-5 of approximately 4% over the bypass turbojet.

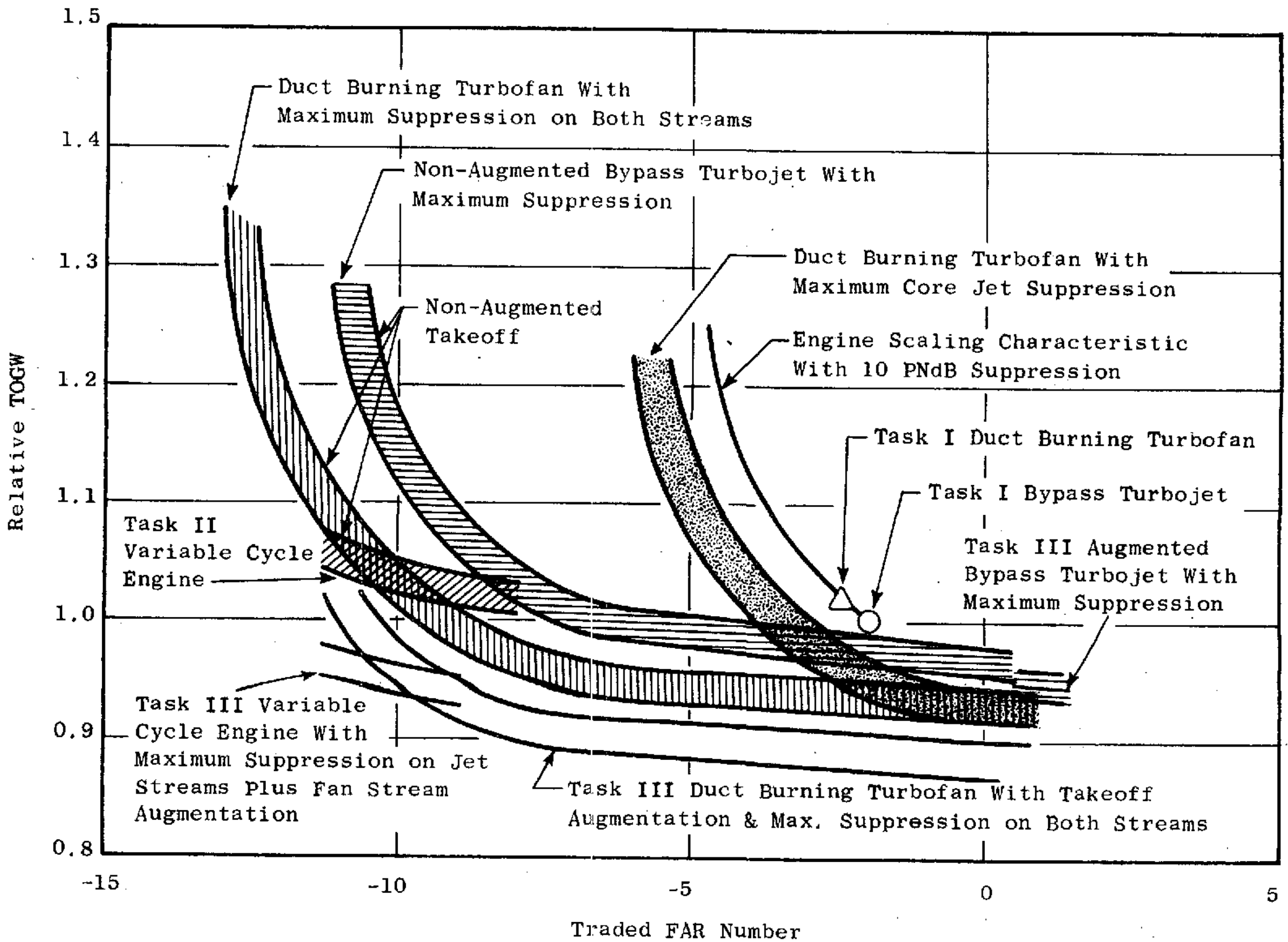


Figure 37. Task III, Noise Vs. Relative TOGW for Mach 2.7 Engines.

APPENDIX D

TASK IV - CONVENTIONAL AND VARIABLE CYCLES - 1980 TECHNOLOGY, HYDROGEN FUEL

GENERAL APPROACH

The predictions of dwindling world fossil fuel reserves by the year 2000 at which time an advanced commercial supersonic transport fleet would be operational has caused NASA to direct that a portion of the AST Propulsion System Study investigate hydrogen as a fuel for this application. This study was conducted utilizing Task III level of technology as defined and analyzed in that task.

The engines studied in this task are the same as the Task III engines with the exception of using hydrogen as the energy source.

Consequently, the objectives of this task were:

1. Utilizing the NASA aircraft configured for hydrogen, evaluate the changes in engine size, TOGW, noise and economics for hydrogen operation.

2. As a result of the change in the aircraft, investigate the effect of the different aerodynamic characteristics on engine type.

GROUND RULES

Through the use of hydrogen fuel in this task, certain ground rules were used that differed from the other JP fuel tasks. These were:

- No use of the available hydrogen heat sink was made other than its use in cooling the oil in the engine.

- The hydrogen was considered to be used throughout the engine in liquid form, with vaporization occurring in the combustor.

- NASA supplied aircraft polars were used in the mission analysis that depicted the aircraft performance.

- Hydrogen was used at a lower heating value of 51,800 Btu/lb (120,200,000 j/kg)

BYPASS TURBOJET ANALYSIS

Due to the different gas properties of hydrogen, slight changes were made to the engine cycles to maximize mission performance. These changes were similar to those of Task III in that bypass ratio and T41 were held constant and LP compressor pressure ratio allowed to increase. This resulted in a cycle with higher specific thrust potential but held to 2500 ft/sec (762 m/sec) jet velocity to be consistent with the previous task engines. The following table compares the base Task III engines with the hydrogen fueled Task IV engines.

BTJ(JP)			BTJ(H2)	
2.2	2.7	Mach No.	2.7	2.2
18	18	Suppression Level	18	18
897 (406)	888 (402)	Airflow Size - lb/sec (kg/sec)	888 (402)	897 (406)
0.4	0.4	Bypass Ratio	0.4	0.4
4.1	3.8	LP Comp. P/P	4.0	4.3
2500 (762)	2500 (762)	Exhaust Velocity - ft/sec (m/sec)	2500 (762)	2500 (762)
102	101	Traded Noise Level	102	103
14200 (6440)	15700 (7110)	Weight - lb (kg)	15900 (7205)	14460 (6550)
Base	Base	Supersonic Cruise ΔSFC	-61%	-61%
Base	Base	Subsonic Cruise ΔSFC	-63%	-63%

Upon conducting the mission analysis, it became readily apparent that the lower L/D at supersonic cruise increased the thrust requirement and sized the engine at that condition. Consequently, the engines were sized approximately 30% oversize from the JP case. The summary below compares the engines as sized for flying the aircraft the required 4000 NMi (7410 km). Significant is the marked reduction in aircraft TOGW due to the reduced fuel weight stemming from installed SFC levels of approximately 0.9.

BTJ(JP)			BTJ(H2)	
2.2	2.7	Mach No.	2.7	2.2
18	18	Suppression Level	18	18
897 (406)	888 (402)	Airflow Size - lb/sec (kg/sec)	940 (426)	951 (431)
2500 (762)	2500 (762)	Exhaust Velocity - ft/sec (m/sec)	1925 (586)	1850 (564)
102	101	Traded Noise Level	99	100
14200 (6440)	15700 (7110)	Weight - lb (kg)	17000 (7700)	15400 (6885)
0.973	0.995	Relative TOGW*	0.675	0.655

* Relative TOGW are based on Task I results.

The 20% thrust margin requirement, in conjunction with lower supersonic L/D of the H_2 fueled aircraft, requires the nonaugmented turbojet to be sized approximately 30% above the next sizing point, i.e., takeoff. It, therefore, becomes advantageous to redesign the engine with approximately 25% thrust augmentation through afterburning which would allow a 20% reduction in engine size and have the engine operate at supersonic cruise 5% below max dry thrust and match acceptably at takeoff. The following table compares the nonaugmented bypass engine with the augmented engine and exhibits the reduction in TOGW through the incorporation of augmentation.

Nonaugmented BTJ(H2)			Augmented BTJ(H2)	
2.2	2.7	Mach No.	2.7	2.2
18	18	Suppression Level	18	18
951 (431)	940 (426)	Airflow Size - lb/sec (kg/sec)	752 (341)	760 (344)
1850* (564)	1925* (586)	Exhaust Velocity - ft/sec (m/sec)	2400 (731)	2300 (701)
100	99	Noise Level	100	101
15400 (6885)	17000 (7700)	Weight - lb (kg)	13000 (5890)	11800 (5345)
0.655	0.675	Relative TOGW	0.61	0.60

* Reduced exhaust velocities reflect oversize condition of the engines.

Figure 38 exhibits these changes in curve form progressing from the Task I base point to the augmented H_2 aircraft. Results from this analysis are:

1. Based on the aircraft configuration, characteristics and mission ground rules furnished, hydrogen fueled aircraft offer marked reductions in TOGW relative to their JP fueled counterparts.

2. Because of reduced supersonic aircraft aerodynamic efficiency (L/D), some degree of augmentation was very beneficial in reducing the size of the engine and TOGW.

3. Noise levels are essentially unchanged from the Task III level.

DUCT BURNING TURBOFAN ANALYSIS

Hydrogen gas properties have allowed a change in the duct burning turbofan cycle and were handled in the same manner as Task III. Bypass ratio was held constant, fan pressure ratio was allowed to rise and the duct burner efficiency, by virtue of burning hydrogen, is approximately 1% higher than the comparable JP burner.

The hydrogen separated flow turbofan cycle resulted in a higher specific thrust cycle; however, the engine was configured to yield the same exhaust velocity and therefore the same noise level. A slight increase in engine weight was required in the hydrogen fueled engines because of additional control and accessory hardware. The table below compares the base Task III engines with the hydrogen fueled Task IV.

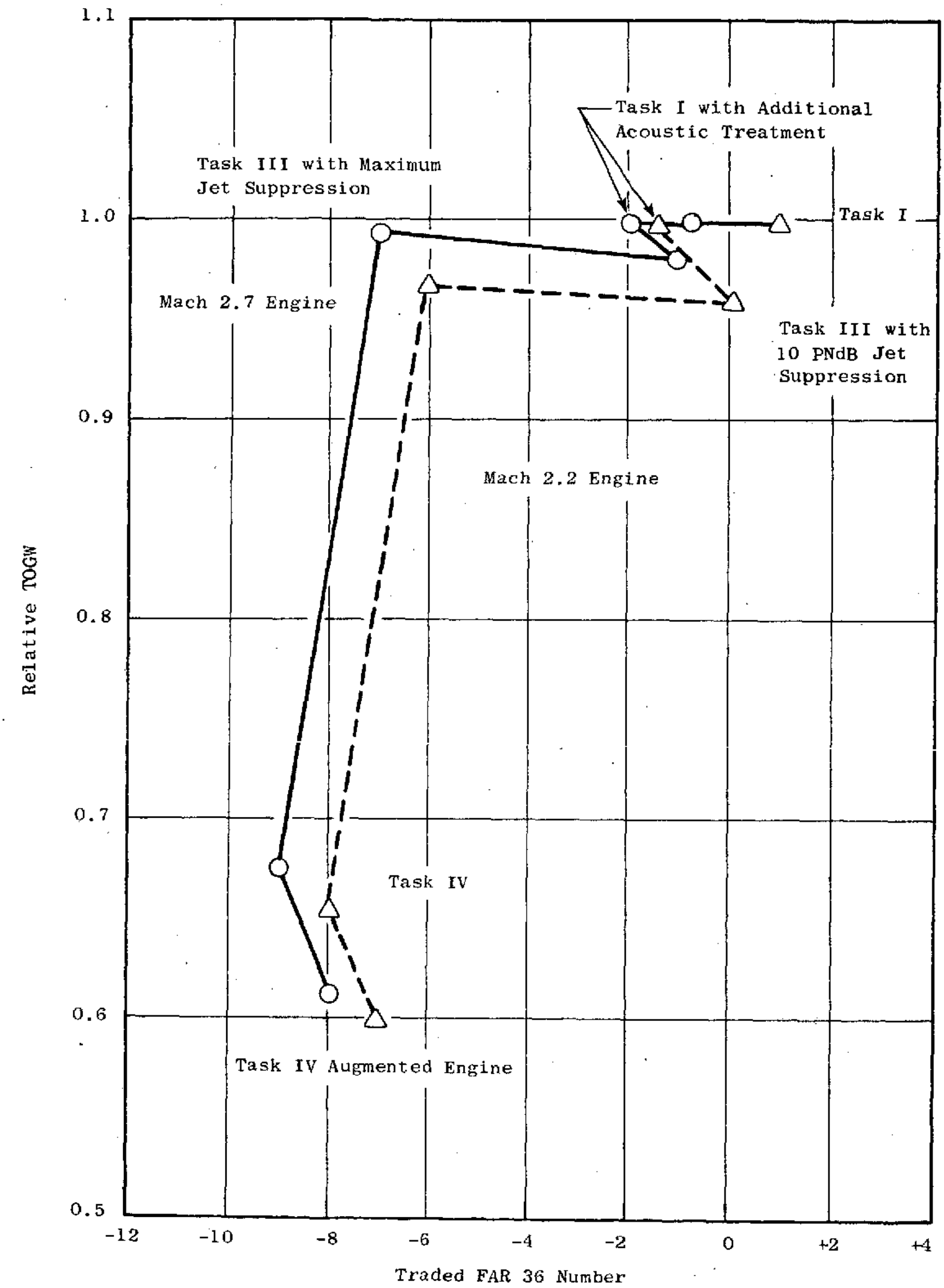


Figure 38. Task IV Bypass Turbojet Engine Analysis, H_2-Fueled Aircraft.

DBTF(JP)			DBTF(H2)	
2.2	2.7	Mach No.	2.7	2.2
18/14	18/14	Suppression Level*	18/14	18/14
983 (445)	1013 (459)	Airflow Size - lb/sec (kg/sec)	1013 (459)	983 (445)
0.4	1.0	Bypass Ratio	1.0	0.4
4.1	4.1	LP Comp. P/P	4.3	4.3
2650 (807)	2650 (807)	Jet Exh. Velocity - ft/sec (m/sec)	2650 (807)	2650 (807)
1710 (521)	1810 (551)	Duct Exh. Velocity - ft/sec (m/sec)	1810 (551)	1710 (521)
101	99	Noise Level	99	101
16100 (7295)	15200 (6890)	Weight - lb (kg)	15500 (7020)	16400 (7435)

* Dual values indicate suppression on both streams - Core/Duct

Since the duct burning turbofan employs augmentation during supersonic cruise, it continues to be sized at the takeoff condition, thereby resulting in a low TOGW aircraft. At 4000 NMi (7410 km) range, the hydrogen-fueled aircraft has a significantly lower TOGW than the JP-fueled version. Summarized below are the size and weight reductions of these engines.

DBTF(JP)			DBTF(H2)	
2.2	2.7	Mach No.	2.7	2.2
18/14	18/14	Suppression Level	18/14	18/14
983 (445)	1013 (459)	Airflow Size - lb/sec (kg/sec)	686 (311)	665 (302)
2650 (807)	2650 (807)	Jet Exhaust Vel. - ft/sec (m/sec)	2650 (807)	2650 (807)
1710 (521)	1810 (551)	Duct Exhaust Vel. - ft/sec (m/sec)	1810 (551)	1710 (521)
101	99	Noise Level	98	100
16100 (7295)	15200 (6890)	Weight - lb (kg)	9700 (4400)	10200 (4628)
0.97	0.98	Relative TOGW	0.59	0.57

As with the bypass turbojet, the application of hydrogen fuel provides very significant reductions in aircraft TOGW. Figure 39 graphically exhibits the trend of noise and TOGW change from Task I through Task IV for both Mach 2.2 and 2.7 aircraft and engines. Results of the analysis of the turbofans are:

1. As with the bypass turbojet, large reductions in TOGW are available by using hydrogen as the fuel in a duct burning turbofan powered aircraft.

2. Noise levels are essentially the same as those of the Task III engines.

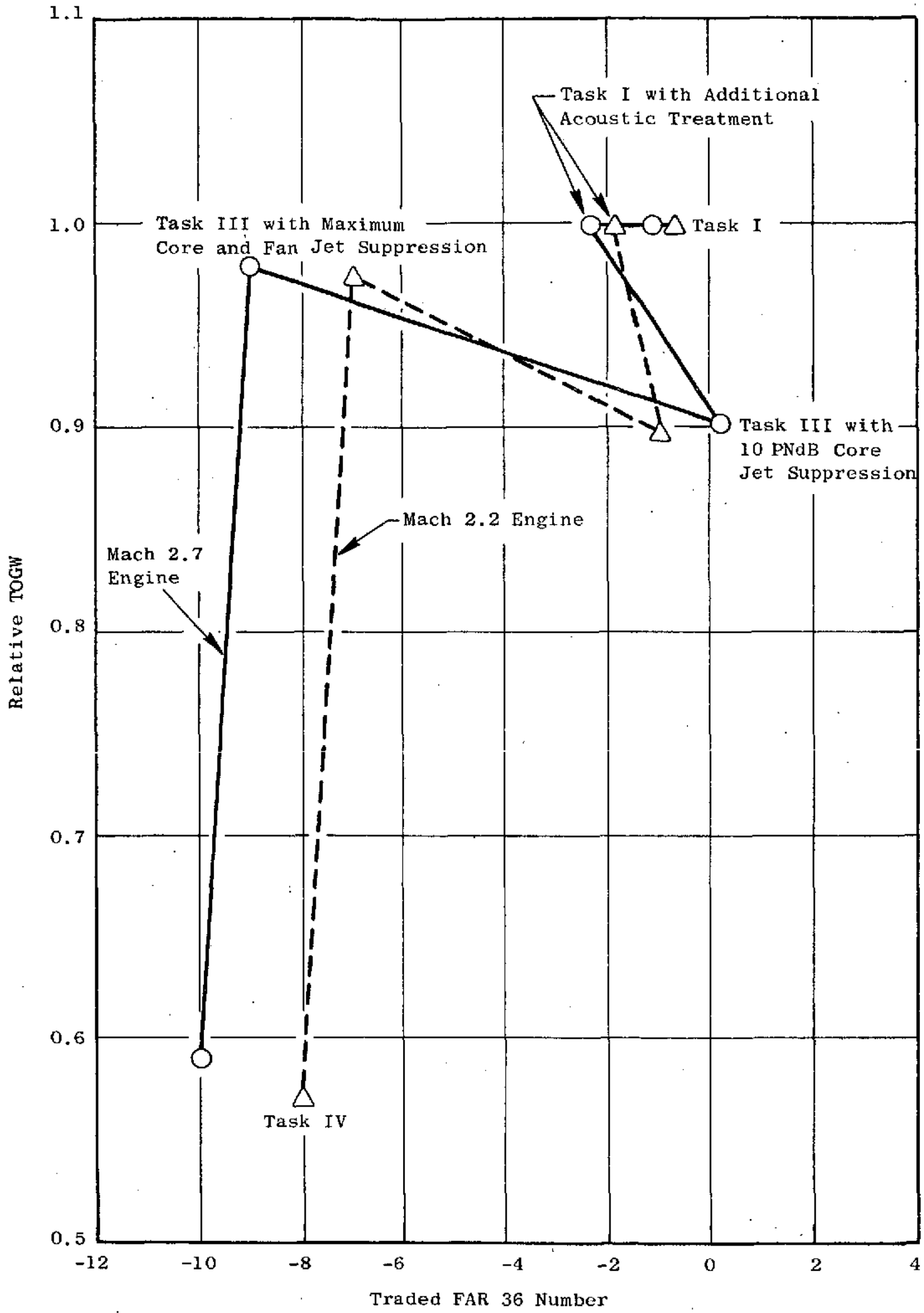


Figure 39. Task IV Duct Burning Turbofan Analysis, H_2-Fueled Aircraft.

VARIABLE CYCLE ENGINE ANALYSIS

The modulating airflow engine cycle was not modified when operated on hydrogen other than reducing turbine inlet temperature to yield the same thrust as the JP version. This resulted in engine performance identical to the Task III version except for the difference in SFC.

In applying these data to mission analysis, the engine weight was increased approximately 1% to reflect the modifications necessary to accept hydrogen as fuel. This was primarily in the pumping and metering functions of the engine. A summary of the engines along with effect of hydrogen on the size and aircraft relative TOGW follows. Figure 40 presents these results graphically.

MOAF(JP)		MOAF(H2)
16.5/16.5	Suppression Level	16.5/16.5
996 (451)	Airflow Size - lb/sec (kg/sec)	649 (294)
2220 (676)	Jet Exh. Velocity - ft/sec (m/sec)	2220 (676)
2220 (676)	Duct Exh. Velocity - ft/sec (m/sec)	2220 (676)
98	Traded Noise Level	97
18800 (8540)	Weight - lb (kg)	11400 (5160)
1.0	Relative TOGW	0.55

Results from this analysis are:

1. The reduction in TOGW for the variable cycle engine operating on hydrogen is a significant value; very close to the duct burning turbofan because of their similarity in basic design and operation.

2. The variable cycle engine is potentially capable of yielding attractive TOGW levels in conjunction with traded noise values of approximately FAR 36-10 PNdB, depending on amount of suppression applied.

RESULTS

Utilizing the new characteristics and dynamics of the hydrogen-fueled aircraft supplied by NASA, a detailed evaluation of the aircraft system was completed. This involved slight adjustments to the engines to most efficiently utilize the properties of hydrogen as the fuel. This analysis yielded several significant results:

1 Hydrogen-fueled aircraft offer approximately a 40% reduction in TOGW due primarily to reduced fuel weight.

2. Noise levels of approximately FAR 36-6 to 8 are exhibited for the bypass turbojet and duct burning turbofan while FAR 36-8 to 10 appears feasible for the modulating airflow engine.

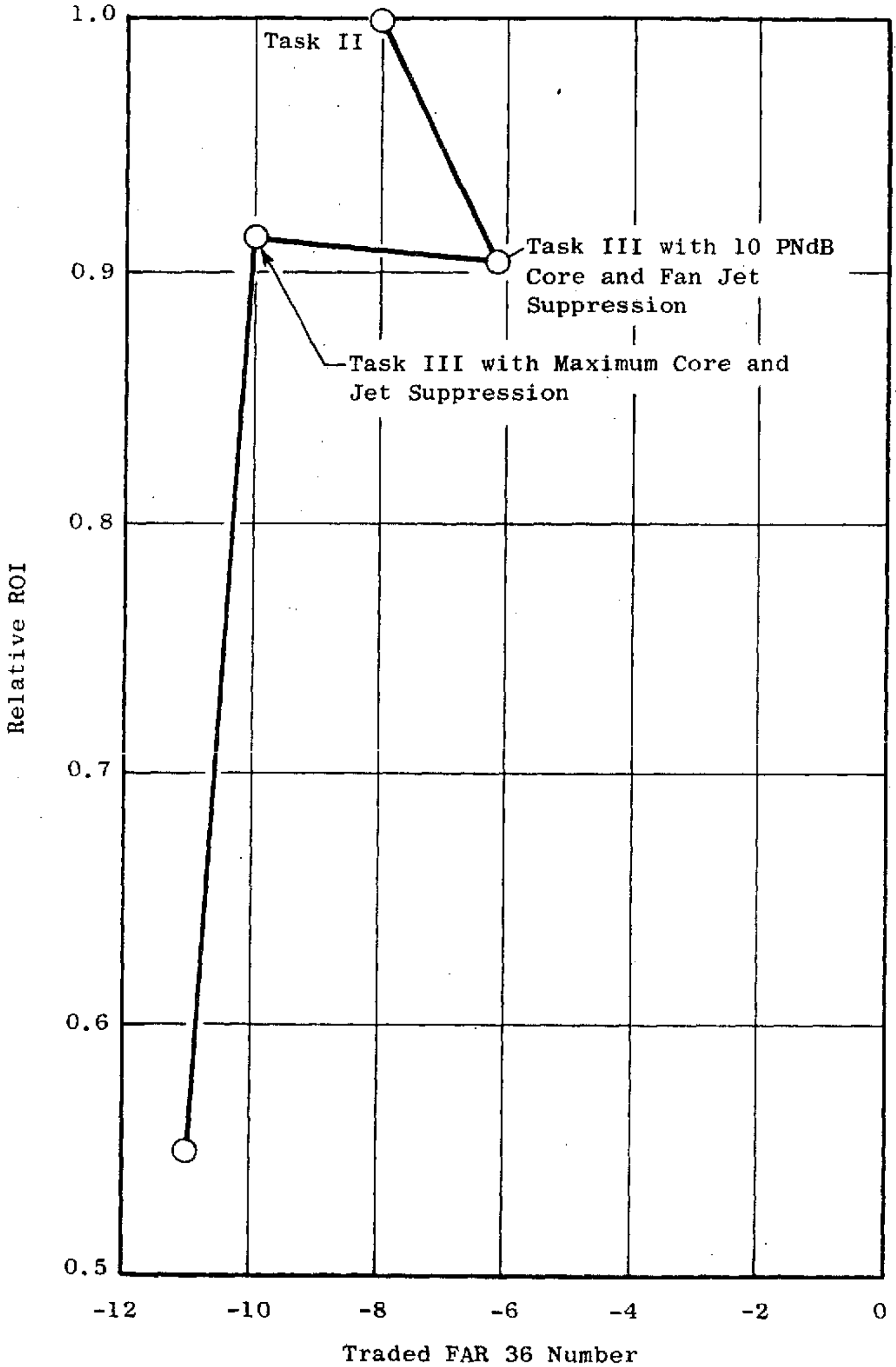


Figure 40. Task IV Modulating Airflow Engine Analysis, H_2-Fueled Aircraft.

3. Even with low TOGW levels, in the 500,000 lb (226,500 kg) regime for the 4000 NMi (7410 km) mission, attractive economics are precluded because the operating weight empty (OWE) of the aircraft is similar in level with a comparable JP aircraft. This aircraft cost in conjunction with fuel costs, approximately 2.3 times JP on Btu basis, yields low levels of "relative ROI" as summarized on Figure 30.

4. Figure 41 compares the "relative ROI" levels of the Task I, II, and III engines with that of a hydrogen-fueled aircraft at a fuel cost of 13¢/lb (28.6¢/kg) as specified. As stated, the "relative ROI" is not attractive, however, as the hydrogen fuel cost approaches that of JP on a unit energy basis or approximately 6¢/lb (13.2¢/kg) vs. 2¢/lb (4.4¢/kg) for JP, the "relative ROI" then becomes slightly in favor of the hydrogen fuel.

5. Employment of hydrogen as a fuel has a significant effect on emissions in that CO, smoke, hydrocarbons, and sulphur compounds do not exist in the exhaust of turbine engines operating on that fuel. NO_x emissions, however, do exist at approximately the levels of JP-type fuels but advanced combustors, designed to take advantage of the wide operating fuel-air ratio capability of hydrogen , can operate the primary zones of these combustors at very low fuel-air ratios, reducing NO_x emissions.

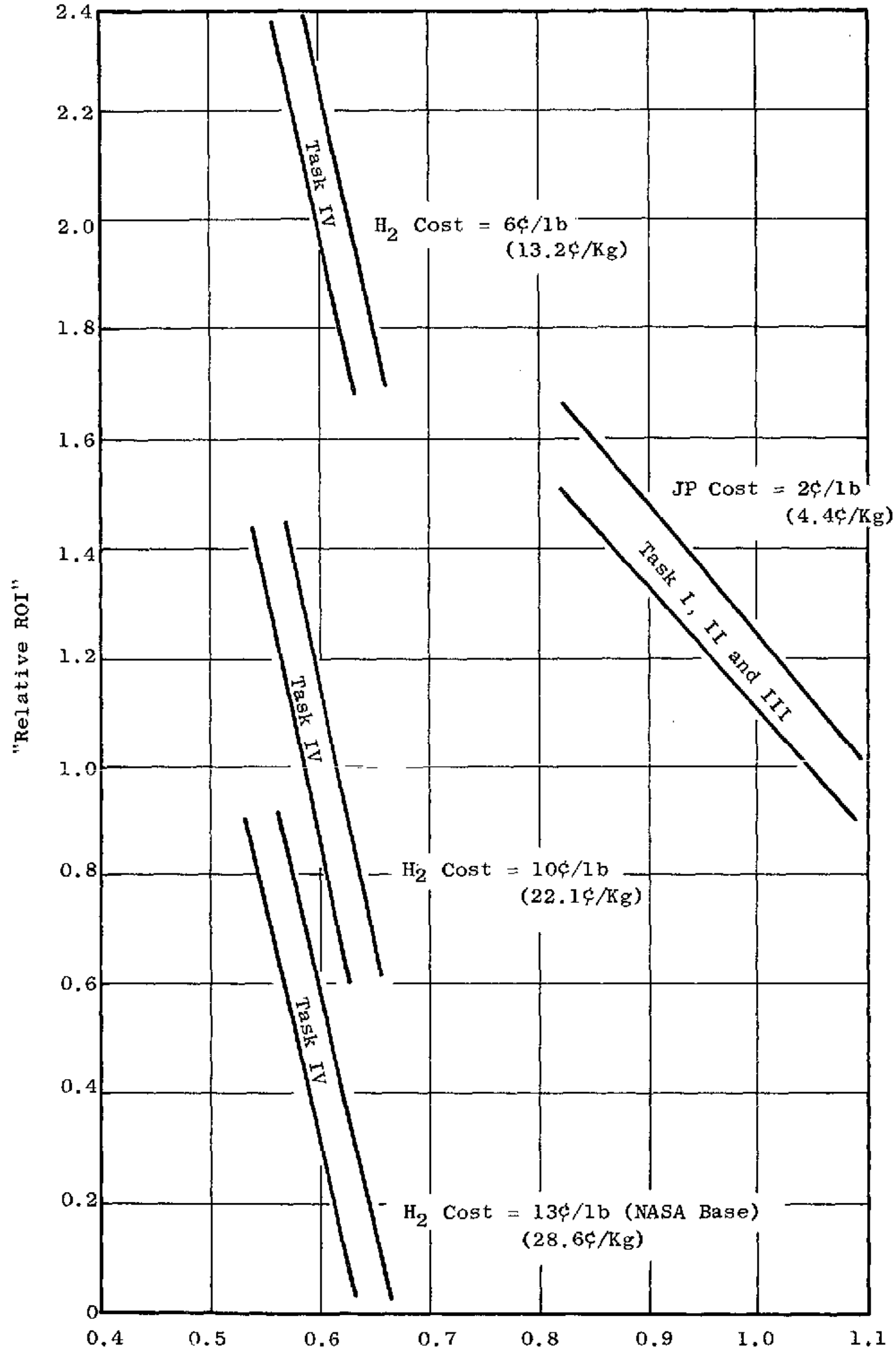


Figure 41. Economic Comparison Between Task I, II, and III JP-Fueled Engines and Task IV H_2-Fueled Engines.

APPENDIX E

TASK V - ADDITIONAL STUDIES-1975 TECHNOLOGY

INTRODUCTION

The foregoing tasks in the AST effort have dealt with determining the "best" engine type for both conventional and variable cycle engines utilizing different levels of technology and also examining hydrogen as a possible fuel in the event fossil fuels become scarce. Complementary to the previous work, Task V was structured to utilize the engine choices of the previous tasks in a combination of efforts to explore possible trends that could accrue from influences external to the engine. Additionally, other applications of the variable cycle engine and the area of combustor emissions were investigated.

OBJECTIVES

In discharging this task, five objectives were defined while primarily utilizing 1975 (Task I & II) technology:

1. Continued support of the aircraft manufacturers to refine the engine offerings for a better match with the aircraft.

2. Additional analysis of each engine type to investigate possible changes that would yield improved mission performance.

3. Investigation of the effect of mission changes on the mission performance of each engine.

4. Generation and analysis of noise footprints of each engine type.

5. Military applicability of the variable cycle engine in penetrator and fighter roles.

AIRCRAFT MANUFACTURER SUPPORT

In the course of the various tasks, engine data have been distributed to the Langley contractors in brochure form, providing sufficient information to permit engine cursory mission analyses to be made.

Prior to the beginning of Task V, the aircraft contractors were contacted for their requirements regarding data content and format to permit them to conduct mission analyses to a degree of detail consistent with their preliminary design effort. Response was in the form of a data matrix from each airframer with the method of data transmittal generally being the engine performance data punched on electronic data processing cards in specific fields.

The three data matrices were combined into one which yielded essentially all the information each Langley contractor requested, plus extra data peculiar to the other contractors. This matrix totaled approximately 900 data points consisting of approximately 400 points used for noise analysis and 500 for mission analysis. These data were transmitted in card form and also in a brochure. For the "best" Task I bypass turbojets and duct burning turbofans, these were:

ENGINE	GE21/J3A1	GE21/F3B2	GE21/J2A1	GE21/F3B1
Design Mach No.	2.2	2.2	2.7	2.7
Airflow Size - lb/sec (kg/sec)	850 (385)	970 (440)	850 (385)	1020 (462)
Cycle Pressure Ratio	25	25	15	15
Bypass Ratio	0.4	0.4	0.4	1.0
Cruise Turbine - Temp °F (°C)	2750 (1510)	2800 (1538)	2750 (1510)	2800 (1538)
Traded FAR Number -EPNdB	108	107	107	107
Core Suppression ΔPNdB	10	10	10	10

None of these engines employed augmentation on takeoff.

A large effort was expended in Task II, the study of variable cycle engines. Several different concepts were investigated at both Mach 2.2 and 2.7. The engine systems analyzed at a design cruise Mach number of 2.2 were all inferior to the conventional engines due primarily to:

- Higher propulsion system weight than a comparably thrusted conventional engine.
- The operating times where variable cycles were superior to conventional engines, i.e., direct and climb/accel, were shorter at Mach 2.2, thus reducing the improvement to the mission.

Consequently, the variable cycle engine that exhibited the greatest potential was for Mach 2.7 design cruise and featured the capability of modulating airflow through the judicious scheduling of three rotors. Although not optimized, this engine definition was chosen for a publication of a limited scope study data brochure for cursory evaluation by the Langley contractors. This engine, the GE21/F10B2, has the following characteristics:

Airflow Size - lb/sec (kg/sec)	1136 (315)
Cycle Pressure Ratio	15
Cruise Turbine Temperature - °F (°C)	2800 (1538)
Bypass Ratio	1.25
Traded FAR Number - EPNdB	98
Suppression (both streams) - ΔPNdB	10

Augmentation on takeoff was not utilized.

Upon completion of Task I, reviews with each of the Langley contractors were held to discuss contract progress and direction. In the course of discussion with Douglas personnel, a desire for a nonaugmented turbojet at temperatures and operating pressure ratios lower than offered from the Task I study was indicated. Consequently, a turbojet for a design cruise Mach number of 2.2 was designed with minimum cross section area in response to their desires. Brochure data for mission analysis were generated and delivered to Douglas for this engine, the GE21/J3A2, as follows:

Airflow Size - lb/sec (kg/sec)	725 (328)
Cycle Pressure Ratio	18
Bypass Ratio	0.1
Traded FAR Number - EPNdB	107
Suppression - ΔPNdB	10
Cruise Turbine Temperature - °F (°C)	2400 (1316)

ADDITIONAL ENGINE ANALYSIS

With the extensive number of engines to contend with in Tasks I and II, little investigation of engine design variations was done. This section of Task V dealt primarily with the duct burning turbofan in an effort to evaluate several variations. Four areas of variation were analyzed:

- Higher Bypass Ratio
- Duct Augmentation on Takeoff
- Variable Turbine Geometry
- Variation of Jet Suppressor Effectiveness Including Dual Annular Suppressors.

Higher Bypass Ratio

The Task I analysis of engines indicated that low bypass ratios (0.4 to 1.0) for the duct burning turbofan yielded the "best" mission performance. The only investigation of high bypass ratio in Task I was a mixed-flow, augmented, β=2.5 turbofan (GE21/F2B2) whose performance was inferior to other turbofans. The Task I analysis was conducted utilizing no augmentation on takeoff.

However, it was recognized that there was a group of higher bypass ratio turbofans that could meet FAR 36 without jet suppressors that had not been analyzed. Consequently, two engines with higher bypass ratios were defined and run through the mission analysis. Compared to the "best" Mach 2.7 Task I duct burning turbofan, these were:

Engine	GE21/F3B1		
Bypass Ratio	1.0	2.2	3.2
LP Pressure Ratio	3.6	3.2	2.1
Core Jet Velocity - ft/sec (m/sec)	2500(762)	2000(610)	1850(564)
Fan Jet Velocity - ft/sec (m/sec)	1890(575)	1850(564)	1830(557)
Suppression Level, Fan/Core - ΔPNdB	0/10	0/0	0/0
Traded FAR Number - EPNdB	106	106	106
Airflow Size - lb/sec (kg/sec)	1020(462)	1225(555)	1310(594)
Mission Sizing Point	T.O.	T.O.	Sub. Cruise

These engines yielded mission performance as shown on Figure 42, leading to the following results:

- In the mission defined, low bypass ratios (~0.4) yield "best" system performance.
- Deleting all jet suppression by exhaust velocity reduction (cycle change to β=2.2) allows the meeting of FAR 36 but with an approximate 3% penalty in relative TOGW.
- Utilizing bypass ratios above approximately 2.5 yields unacceptable TOGW levels. This is because the afterbody drags associated with high bypass ratio are large due to large nacelle diameters and low exhaust plume diameters (low nozzle pressure ratio). Also, this engine does not match the aircraft/mission thrust requirements and consequently is oversized for takeoff and supersonic cruise.

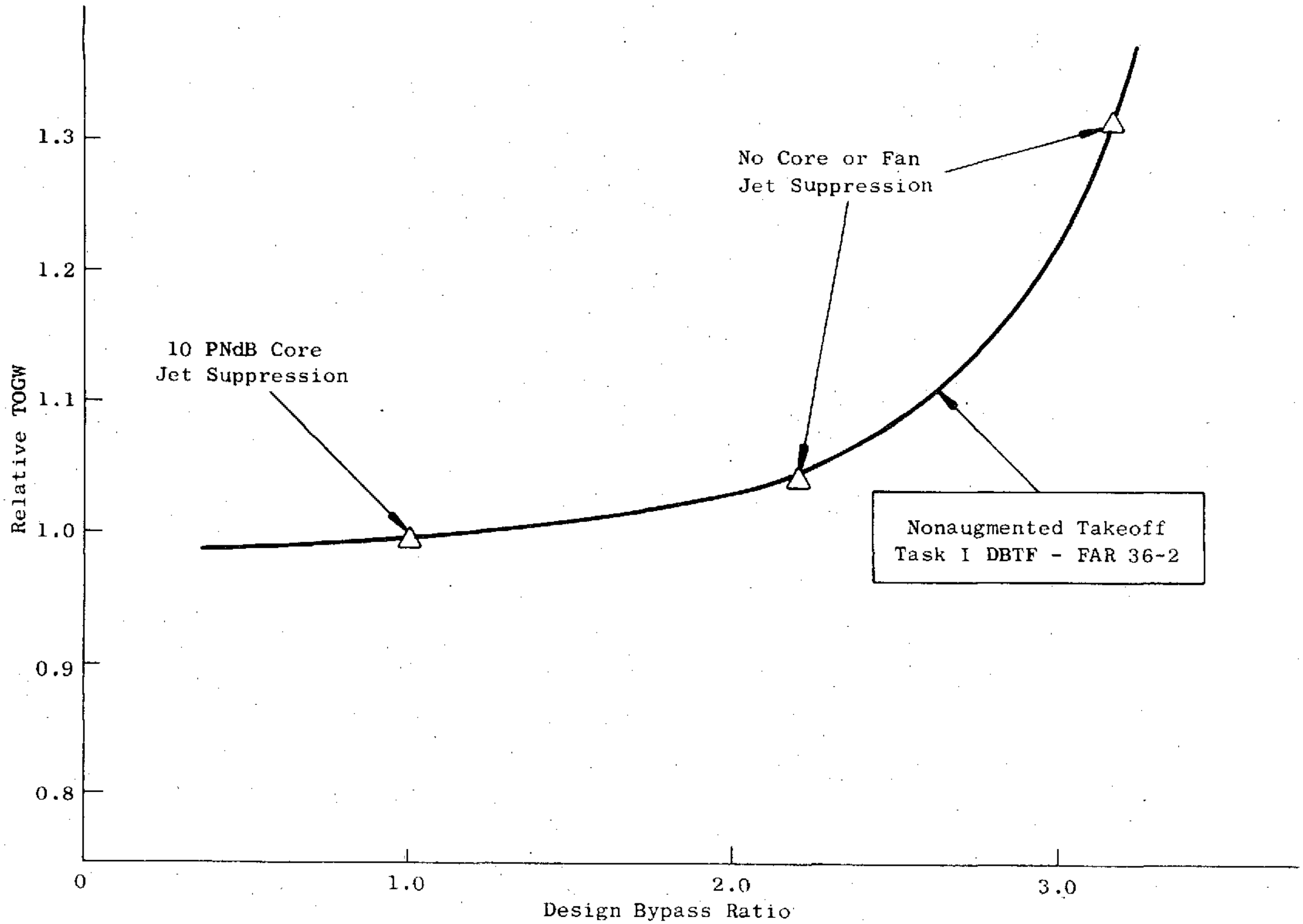


Figure 42. High Bypass Ratio Turbofan Performance.

Duct Augmentation on Takeoff

In the Task I studies, a basic ground rule was made that no augmentation would be used on takeoff. At that time, it was felt that augmentors could not be designed to simultaneously meet the operational requirements and the pollution levels. However, augmentation on takeoff may be possible at some later date at pollution levels acceptable to the EPA and attainable through duct burner development.

Applying takeoff augmentation to the Task I duct burning turbofan from the previous subtask affords an interesting comparison as tabulated below:

Engine	GE21/F3B1	
	Task V	Task I
Bypass Ratio	1.0	1.0
LP Press Ratio	3.6	3.6
Core Jet Velocity - ft/sec (m/sec)	2500(762)	2500(762)
Fan Jet Velocity - ft/sec (m/sec)	2640(805)	1890(575)
Augmentor $\Delta T°R$ (°K)	1080(600)	-
Suppression Level, Fan/Core - ΔPNdB	18/18	0/10
Traded FAR Number - EPNdB	99	106
Airflow Size - lb/sec (kg/sec)	850(385)	1020(462)
Mission Sizing Point	T.O.	T.O.

Graphically, Figure 43 represents the relative performance of these engines compared to their counterparts with takeoff augmentation resulting in:

- Takeoff augmentation exhibits an improvement of approximately 7% relative TOGW at constant noise levels due primarily to improved matching of the engine to the aircraft thrust requirements.
- Increasing levels of fan suppressor effectiveness are required as takeoff augmentation is utilized and is dependent upon the level of traded FAR noise desired.
- At constant traded FAR noise levels, the degree of core suppressor effectiveness required decreases with increasing bypass ratio.
- The lower bypass ratio engines exhibit slight mission advantage both with and without takeoff augmentation.

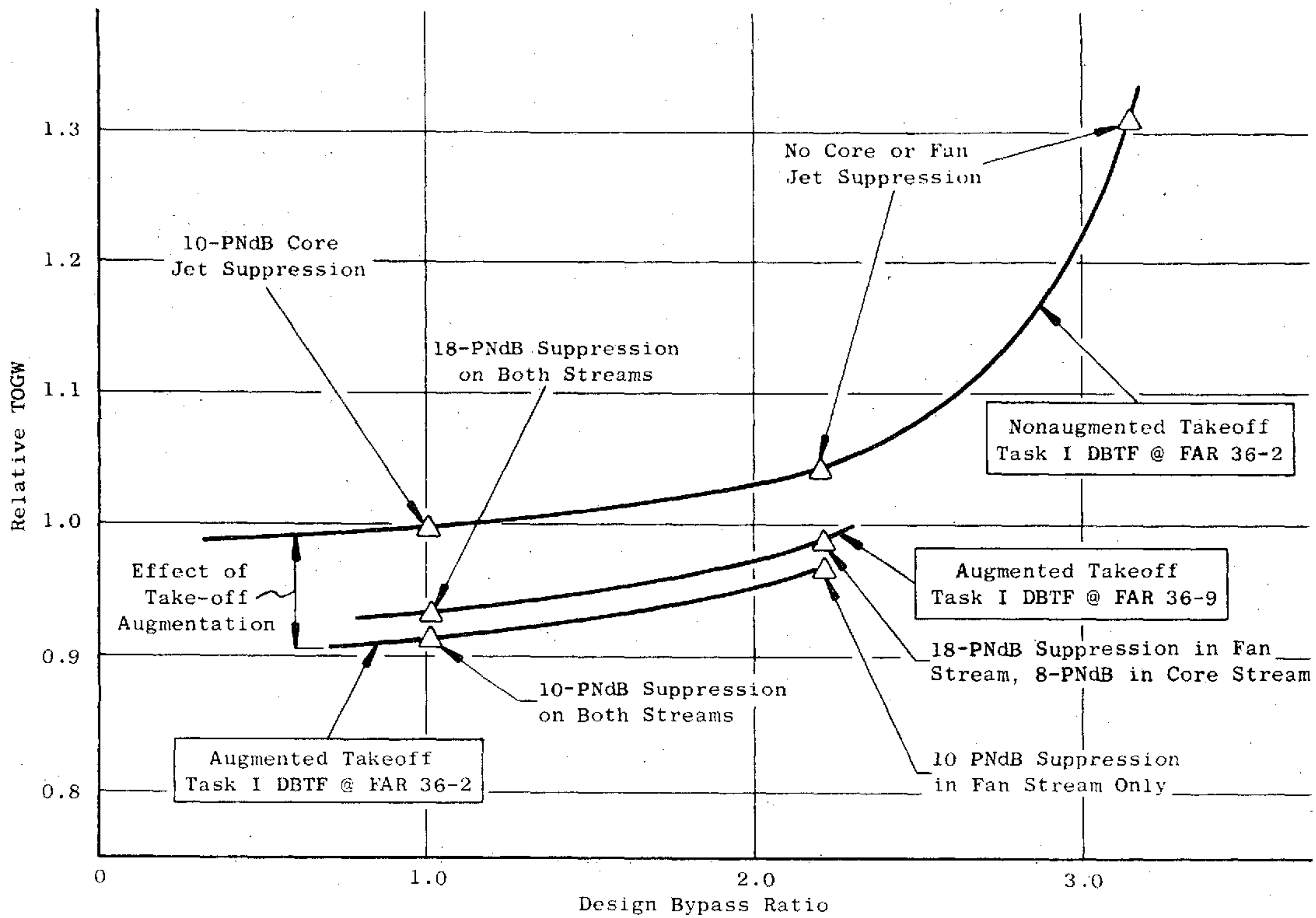


Figure 43. Duct-Burning Turbofan Performance, Effect of Take-off Augmentation.

Variable Turbine Geometry

The efforts on the variable cycle engines during Task II indicated that, for the three-rotor modulating airflow engine, variable turbine geometry was a necessity in the high and low pressure rotors to maximize the installed performance of the engine. Additional analysis of the variable cycle engine indicated that the greatest area variation required was approximately +10% to -30% in the low pressure turbine. With this information, it was decided to investigate the applicability and performance advantage associated with variable geometry in both high pressure and low pressure turbines of duct burning turbofans. This analysis was conducted on the GE21/F3B1, the Mach 2.7 duct burning turbofan.

The study investigated three flight conditions, i.e., 0.95M/35,000 feet (10,695m) subsonic cruise, 1.6M/41,300 feet (12,600m) climb/accel, and 2.62M/58,600 feet (17,910m) supersonic cruise. Figure 44 compares the thrust ratios of the variable cycle engine with the duct burning turbofan, both with and without variable turbine and exhaust nozzle geometry. It is shown that the divert flight condition is the primary point at which an improvement can be made. This results from the ability of the engine to swallow a greater percentage of the inlet air as the thrust requirement is reduced, thereby reducing the additive drag of the inlet (see Figure 45). Figure 46 exhibits the SFC advantage that the turbofan can potentially have with variable geometry. This is compared to the variable cycle engine and the duct burning turbofan and indicates that, at low thrust levels (below 60% max dry), an installed SFC improvement of approximately 8% is available. The major improvement is caused by varying the exhaust nozzle area as thrust is reduced. The GE21/F3B1 engine operates at a fixed exhaust nozzle area at subsonic cruise operating conditions.

The overall results of this study are:

- Incorporation of variable geometry in the duct burning turbofan has the potential of reducing relative TOGW approximately 1%.

- Variable geometry in the low pressure turbine yields a slight improvement, while variable geometry in the high pressure turbine offers essentially no additional improvement.

Variation of Jet Suppressor Effectiveness

The Task III analysis included increased jet suppressor effectiveness as part of an advanced technology evaluation. This effect, however, was not evaluated as a function of jet exhaust velocity. This analysis evaluated three levels of effectiveness, i.e., 0, 10, and 20 ΔPNdB, while considering the associated weight and performance loss of increased suppressor effectiveness. Figures 47 and 48 present these effects relative to jet exhaust velocity for the bypass turbojet and duct burning turbofan respectively, yielding the following result:

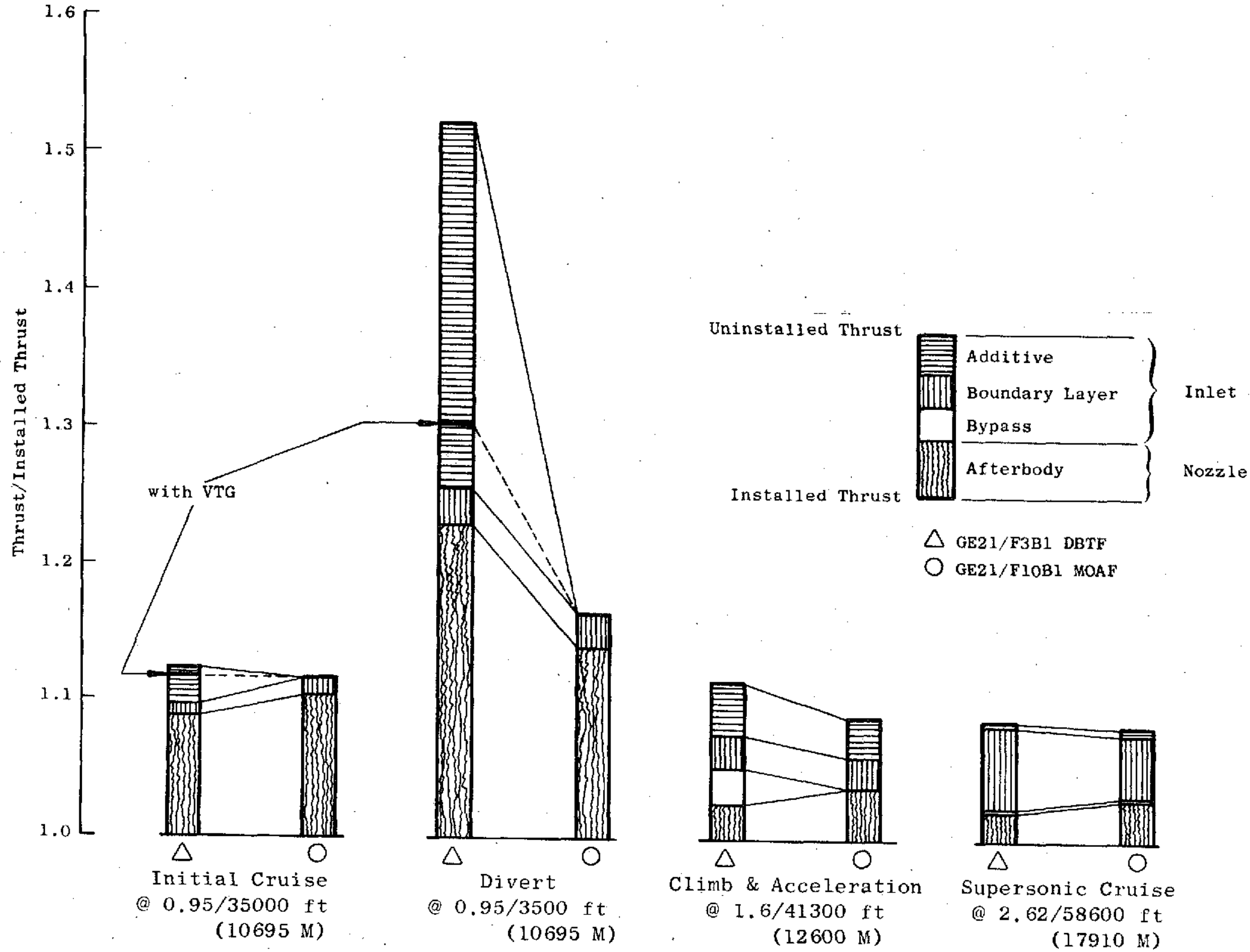


Figure 44. Effect of Variable Turbine Geometry on Installation Losses.

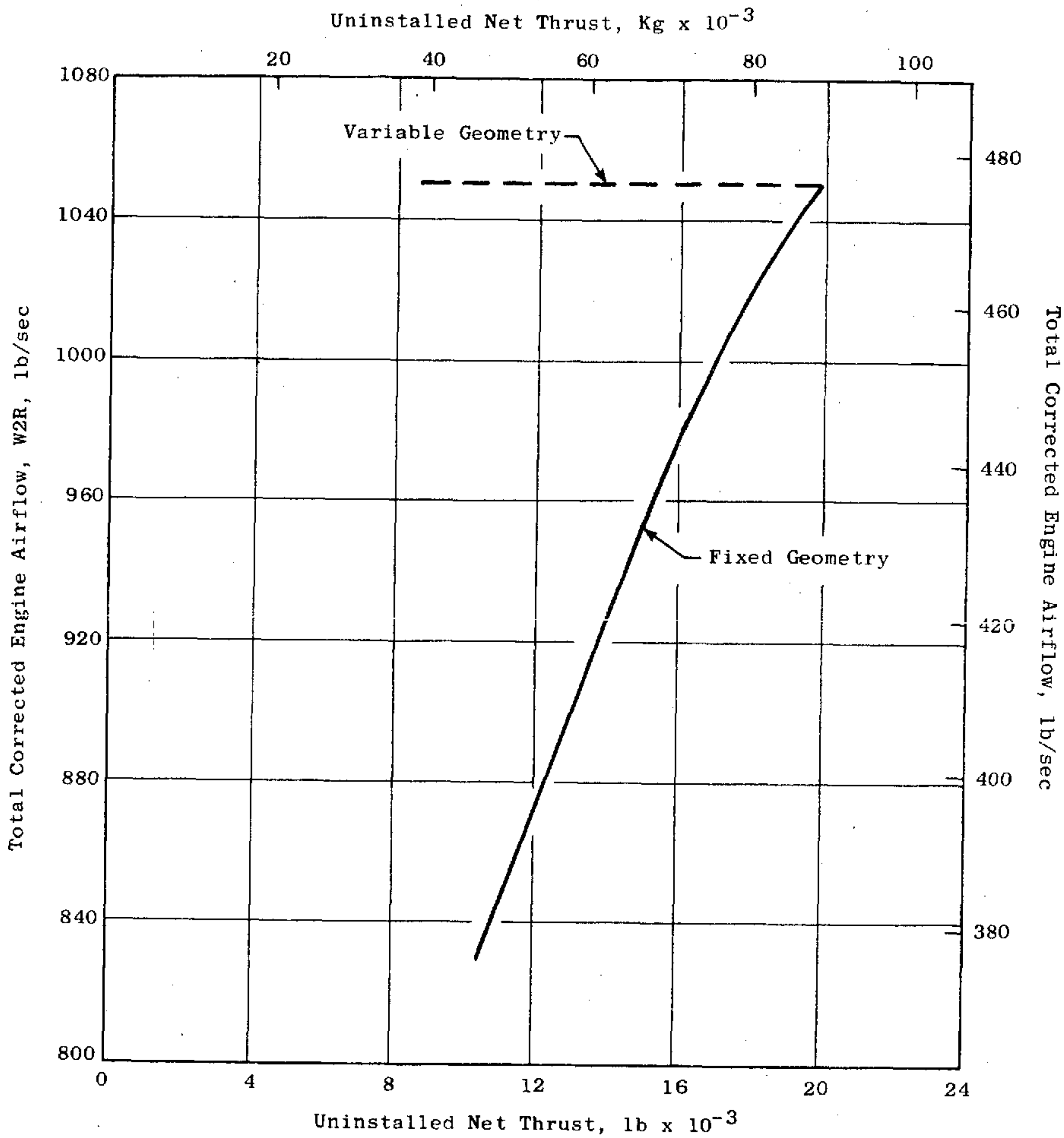


Figure 45. Effect of Variable Turbine Geometry, Total Corrected Engine Airflow Vs. Uninstalled Net Thrust, M = 0.95, 35,000 Ft (10,695 M).

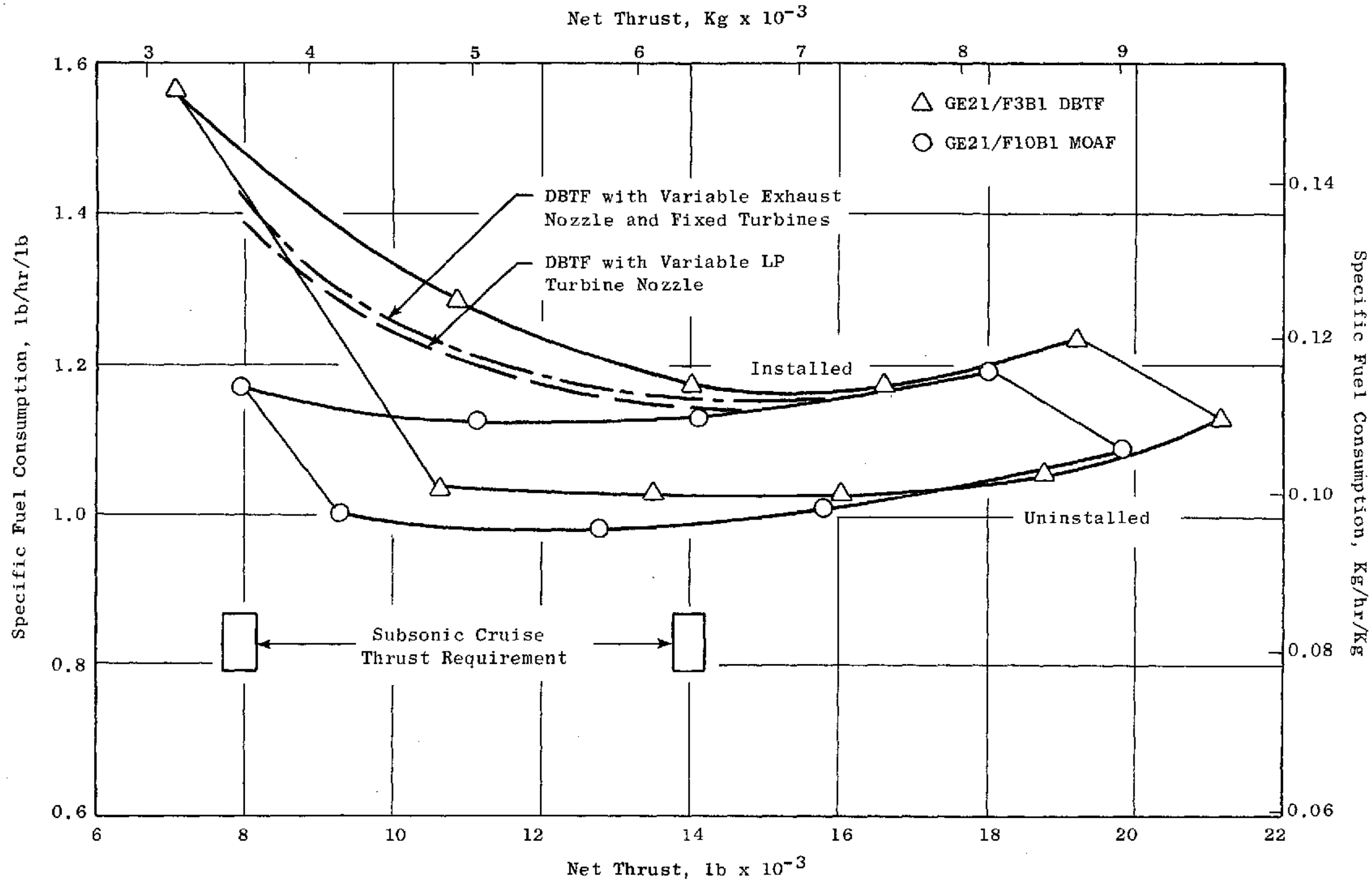


Figure 46. Effect of Variable Turbine Geometry at M_o = 0.95/35,000 ft (10,695 M).

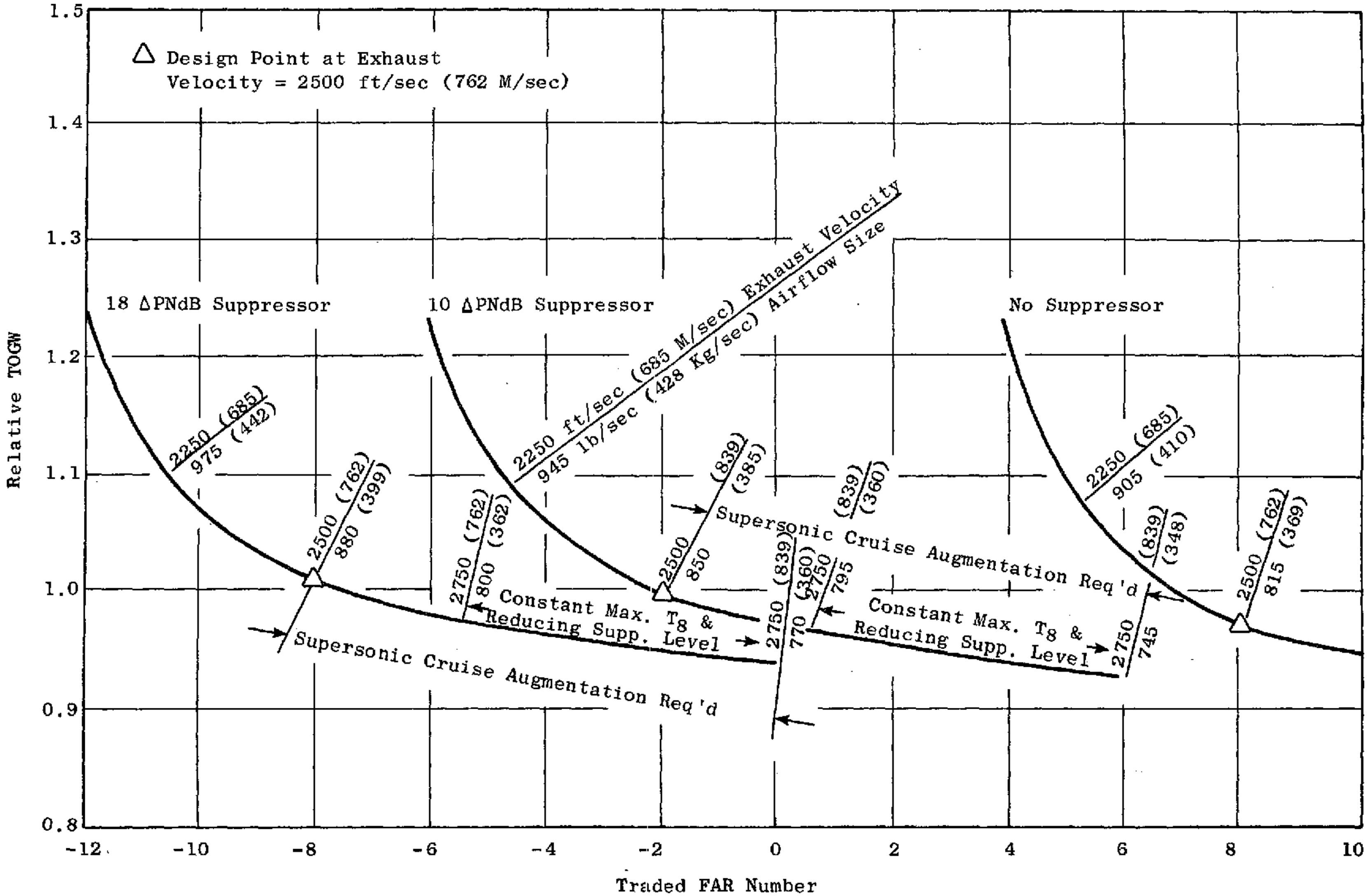


Figure 47. Effect of Jet Suppression on Relative TOGW, Augmented Bypass Turbojet, M_o = 2.7 Design Cruise.

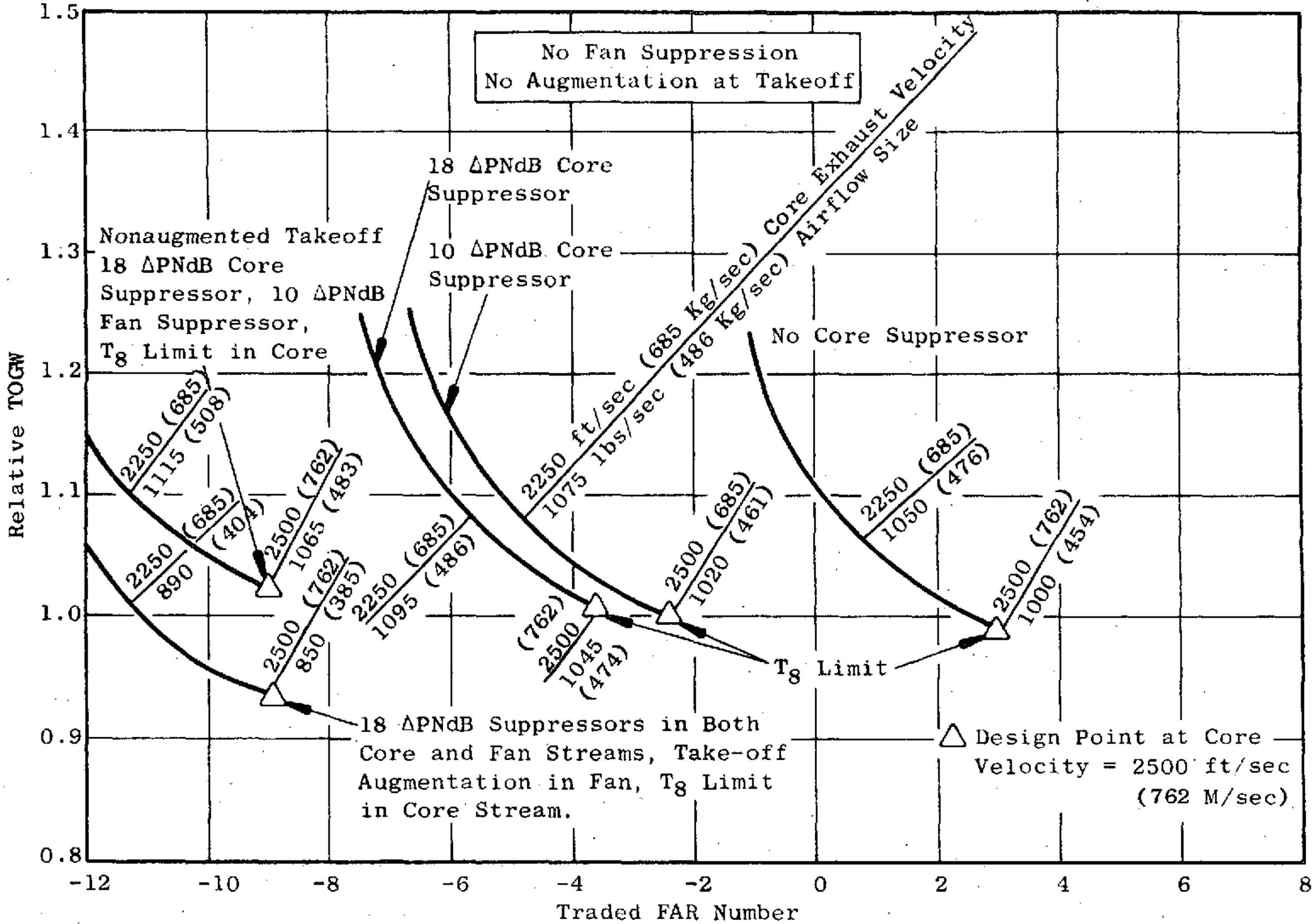


Figure 48. Effect of Jet Suppression on Relative TOGW Duct-Burning Turbofan, Mo = 2.7 Design Cruise, β = 2.0, Augmentation Utilized During Supersonic Cruise.

- For the bypass turbojet:
  - For a given noise level, the use of jet suppression is a much more efficient means of achievement than by exhaust velocity reduction which requires engine/aircraft scaling.
  - The derivative per percent of relative TOGW for the use of jet suppression is approximately 1/4% per EPNdB of traded FAR number while the exhaust velocity reduction process yields a derivative of approximately 4% per EPNdB of traded FAR number.
- For the duct burning turbofan:
  - Core only suppression is most effective up to approximately FAR 36-2. To efficiently achieve lower noise levels, fan suppression must be incorporated. Noise/suppression derivatives are similar to turbojet values.
  - With suppression on both streams, takeoff augmentation allows an engine size reduction without sacrificing noise level. The installation of a fan suppressor of higher effectiveness (to -18 PNdB) maintains the same noise levels at exhaust velocities approximately equal to the core exhaust velocity.

MISSION SENSITIVITIES

An important aspect of the AST studies is the evaluation of the effects of mission perturbations on the propulsion system and, more specifically, the engine type. Although cursory in depth, these studies offer information useful in the selection of the final engine for the SST mission. These studies included:

- Effect of subsonic leg length
- Effect of Supersonic L/D
- One engine out mission performance

Although many additional aspects of the mission could be surveyed, these were considered to be important and representative of the mission changes that could evolve.

Effect of Subsonic Leg Length

With a subsonic cruise leg specified to be 600 NMi (1111 km) in length, evaluations of the mission performance of the bypass turbojet and the duct burning turbofan at Mach 2.7 in the baseline aircraft [750,000 lb (340,000 kg) TOGW] indicated a range potential of approximately 3600 NMi (6660 km). The effect on range of varying the subsonic leg length to eliminate it totally (except for the subsonic portion of the climb/accel) and, the other extreme, on all subsonic cruise mission, is shown on Figure 49. The following conclusions are appropriate:

- Elimination of the subsonic leg increases range approximately 14% to about 4000 NMi (7410 km) for the bypass turbojet.

- An all subsonic mission for the bypass turbojet reduces total range to approximately 2800 NMi (5190 km) to about 80% of the baseline value.

- The turbofan and variable cycle powered aircraft would have similar performance exhibiting a smaller increase in range (~12%) for the all supersonic mission and a greater range (~83% relative range) for the all subsonic mission. This is due primarily to the poorer installed supersonic SFC and better installed subsonic SFC of the turbofan and variable cycle engines relative to the bypass turbojet.

Effect of Supersonic L/D

As aircraft are developed, the performance objectives are usually compromised to some degree as a result of pressures from other design considerations such as structural constraints, volumetric limitations or configuration changes. Consequently, the modified aircraft aerodynamic performance impacts on the mission performance such that TOGW is changed for the constant range aircraft. For the supersonic transport, supersonic L/D as a single item probably has the greatest impact on aircraft mission performance. Consequently, this parameter was chosen to be the variable in investigating the mission effect with different engine types. Figure 50 exhibits the changes for the duct burning turbofan, variable cycle engine and the bypass turbojet at Mach 2.7 design cruise utilizing Task I & II technology.

As supersonic L/D was varied, the engines were changed as required to meet the sizing requirements to maintain the 4000 NMi (7410 km) range. This analysis resulted in the following conclusions:

- At the design level of L/D, the bypass turbojet enjoys a small (~2%) relative TOGW advantage over the duct burning turbofan. This is consistent with Task I results.

- As supersonic L/D is decreased, the relative TOGW for the nonaugmented bypass turbojet increases at a more rapid rate (approximately 10%) than the duct burning turbofan. This results from the fact that the turbojet is sized supersonically and requires scaling up to meet the increased thrust requirement or reduced L/D.* The turbofan has the capability of increasing thrust through increasing augmentation levels in the duct burner, therefore requiring no size change. SFC increases with increased augmentation level cause the TOGW to increase.

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* Addition of tailpipe augmentation to the bypass turbojet would reduce the curve slope to essentially that of the duct burning turbofan.

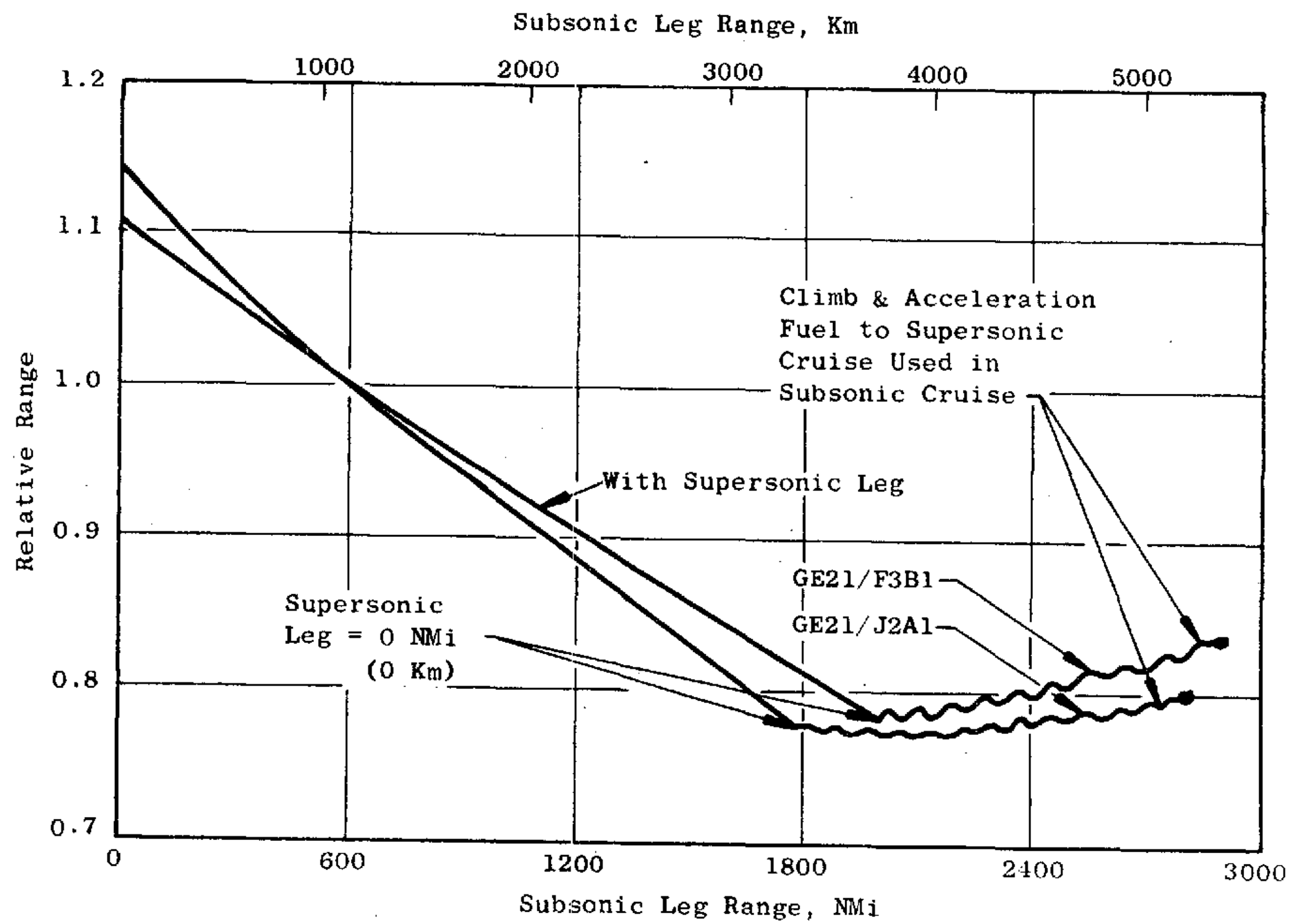


Figure 49. Effect of Varying Subsonic Leg Range, TOGW = 750,000 lb (340,000 kg) Standard + 8° C Day.

- Task I Engine, GE21/J2A1 Bypass Turbojet with 10 ΔPNdB Suppression (FAR 36-1)
- Task I Engine, GE21/F3B1 Duct-Burning Turbofan with 10 ΔPNdB Core Suppression (FAR 36-2)
- Task II Engine, GE21/F10B1 Three-Rotor Variable Cycle with 10 PNdB Suppression Both Streams (FAR 36-8)

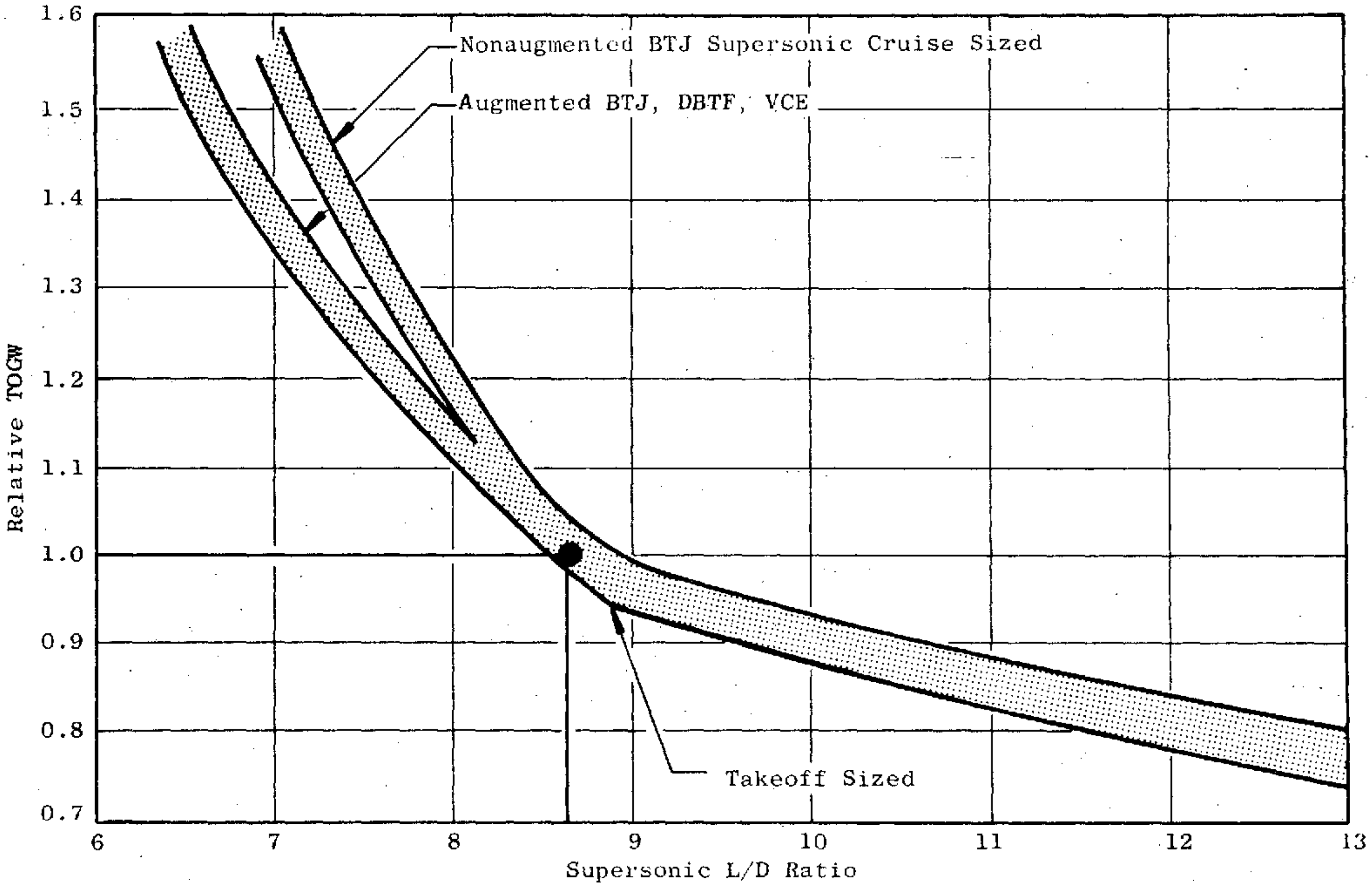


Figure 50. Effect of Supersonic L/D at Mach 2.7.

- As supersonic L/D increases, the relative TOGW of the bypass turbojet decreases, scaling the engine down to the point where the sizing is effected simultaneously at supersonic cruise and takeoff. The characteristic slope changes to reflect a takeoff engine sizing and throttling back at supersonic cruise to match thrust. The turbofan characteristic is the same, reflecting a change in SFC due to the change in augmentation level.

One Engine Out Mission Performance

An operational item to be considered for the SST is an engine failure during supersonic cruise. Such a mission was analyzed utilizing the following assumptions:

- Mach 2.7 design cruise
- Turbojet powered aircraft
- New York to Paris mission
- Failure occurs on outboard engine, at mid-point between Gander, Newfoundland and Shannon, Ireland
- Subsonic flight required after failure
- Reserves maintained for 15 minutes hold plus landing
- Asymmetric aircraft drags considered

The results of this analysis are shown graphically on Figure 51 and are:

- Paris can be reached under the assumptions made.
- Subsonic cruise at 0.95 Mach is more efficient than at 0.5 Mach in that Paris is reached with more margin at the higher Mach number.

NOISE FOOTPRINTS

The various tasks performed in this contract have dealt with engine noise levels based on community, takeoff, and approach flight conditions and traded per FAR Part 36. This yields a "traded FAR number" requiring 108 EPNdb as a maximum. While representing a benchmark to categorize engines at noise levels, an additional aspect must be considered, namely the noise footprint generated by these engines. This subtask has evaluated eight different engines, embracing both Task I & II and Task III technology levels, as to the footprints generated.

Tables X and XI describe the engines, the technology levels, the suppression levels, and the noise levels at the noise monitoring points, as well as the traded FAR numbers for each engine.

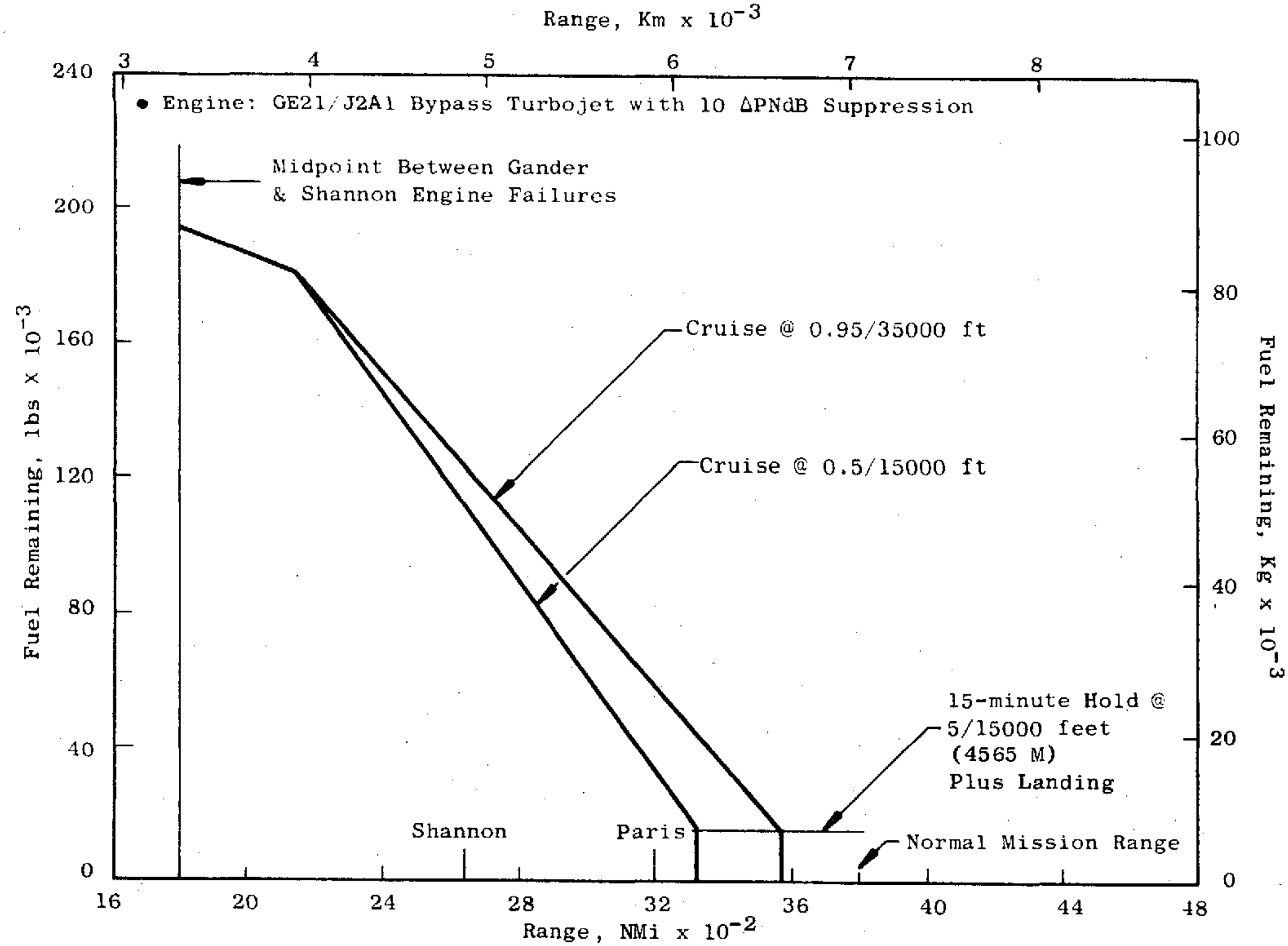


Figure 51. Effect of a One Engine Failure on Mach 2.7 Mission.

Table X. Noise Footprints.

- FOOTPRINTS GENERATED WITH AND WITHOUT CUTBACK ON TAKEOFF
- 90 & 100 EPNdB CONTOURS SHOWN WITH NOISE BARCHART
- ENGINES ANALYZED:

	DESIGNATION GE21	TECHNOLOGY	SUPPRESSION CORE	SUPPRESSION FAN	TRADED FAR
BTJ	J2A1	TASK I	10	-	- 0
	J421	TASK III	18	-	- 6
	F3B1	TASK I	10	0	- 0
	F4B1	TASK III	18	0	- 0
DBTF	F4B1	TASK III	18	14	- 6
	F4B1 (T.O. Aug.)	TASK III	18	18	- 6
	HIB (T.O. Aug.)	TASK III	18	18	- 8
VCE	F11B1 (T.O. Aug.)	TASK III	17	17	- 10

- COMPARED TO SUBSONIC INTERCONTINENTAL AIRCRAFT:

AIRCRAFT	CLOSURE DISTANCE - NMI (KM) 90 EPNdB CONTOUR	CLOSURE DISTANCE - NMI (KM) 100 EPNdB	AREA - SQ. NMI (SQ.KM) 90 EPNdB CONTOUR	AREA - SQ. NMI (SQ.KM) 100 EPNdB
707-320B WITH CUTBACK				
WITHOUT CUTBACK	18.1(33.6)	8.6(15.9)	45.2(155.7)	9.6(33.0)
747-200 WITH CUTBACK	11.4(21.2)		9.3(32.0)	
WITHOUT CUTBACK	10.7(19.9)	5.0(9.3)	12.5(43.0)	2.3(7.9)

Table XI. Engine Noise at Monitoring Points.

		* SIDELINE NOISE	COMMUNITY NOISE (T.O. POWER)	* COMMUNITY NOISE (CUTBACK)	* APPROACH NOISE	TRADED FAR (USING * ITEMS)	RELATIVE TOGW	JET SUPPRESSION LEVEL- ΔPNdB FAN CORE
	FLT.COND.	.3M/SL	.34M/1574' (480 M)	.30M/1500' (457 M)	.221M/370' (113 M)			
	S/L DIST		0	0 -	0			
ENGINE [β]	THR. REQT	T.O.	T.O.	30000	14000			
J2A1(P4)BTJ [0.4]		109	111	108	105	107	1.0	0/10
J4A1 BTJ [0.4]		101	103	102	104	102	1.02	0/18
F3B1(P15)DBTF [1.0]		109	111	108	105	107	1.02	0/10
F4B1 DBTF [1.0]		108	110	107	106	107	.99	0/18
F4B1 DBTF [1.0]		100	102	100	102	101	1.01	14/18
F4B1 REV. DBTF [1.0]		102	104	101	102	102	.90	18/18
HI β DBTF [2.2]		100	102	97	98	98	.95	18/18
F11B1 [1.25]		99	100	98	98	98	1.0	17/17
CONCORDE		115	114	-	112	113		
707-320B		108	115	114	128	116		
747-200		98	107	105	106	104		

Figure 52 shows the flight path and flight Mach number of the takeoff trajectory used in the footprint generation, while Figures 53 through 60 exhibit the 90 and 100 EPNdB contours, with the upper half of the footprint being without cutback and the bottom half with cutback.

These plots lead to the following results:

- 90 EPNdB footprints of the Task I technology engines are approximately 20% larger than the 707-320B and 350% larger than the 747-200.
- Application of Task III technology to these same engines reduces the footprints such that they are approximately 50% smaller and 25% larger than the 707-320B and 747-200, respectively.
- Duct burning turbofan augmentation on takeoff, although allowing an approximate 13% reduction in airflow size for the turbofan, increased the footprint area approximately 20% relative to not using augmentation on takeoff for the same traded FAR level.
- Maximum 18 PNdB suppression on both streams of a high bypass ratio (~2.2) duct burning turbofan using augmentation on takeoff yields an engine with a 90 EPNdb footprint approximately the size of a 747-200 footprint.
- The relative relationship of the contours with and without cutback is the same for the engines analyzed with the choice of trading closure distance (with cutback) for sideline width (without cutback). In general, the without cutback footprints are approximately 10 to 20% larger in area than the cutback footprints at either noise level.

MILITARY APPLICABILITY OF VARIABLE CYCLE ENGINES

The majority of effort in the AST program has been directed toward commercial application of the supersonic transport. Defined during this effort has been a bypass turbojet, duct burning turbofan and a three-rotor, modulating airflow, variable cycle engine. Analyses have exhibited that the variable cycle engine is inherently capable of reducing installation losses (inlet and afterbody drags) due to the operational flexibility derived from variable geometry in the turbine systems. Consequently, another logical application of the variable cycle engine would be in typical military missions.

This subtask investigated the three rotor-modulating bypass engine in simulated military missions of the penetrator and fighter type. Figure 61 exhibits these typical missions compared to the civil AST mission, while Figure 62 indicates graphically the relative SFC advantages potentially available by utilizing the variable cycle engine relative to the optimized conventional engines for the missions. Table XII compares the salient cycle definitions of the engines for this subtask with the AST cycle.

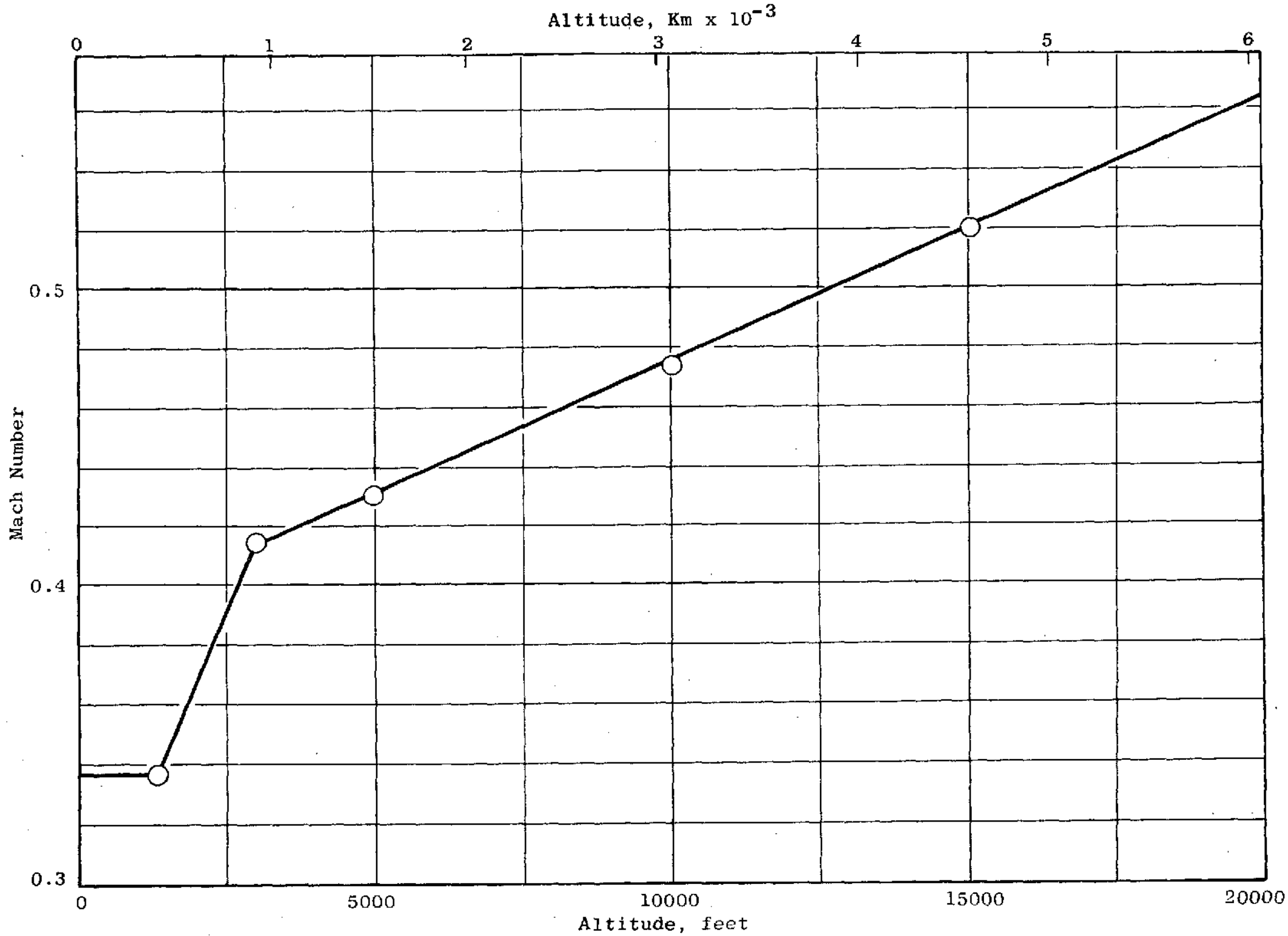
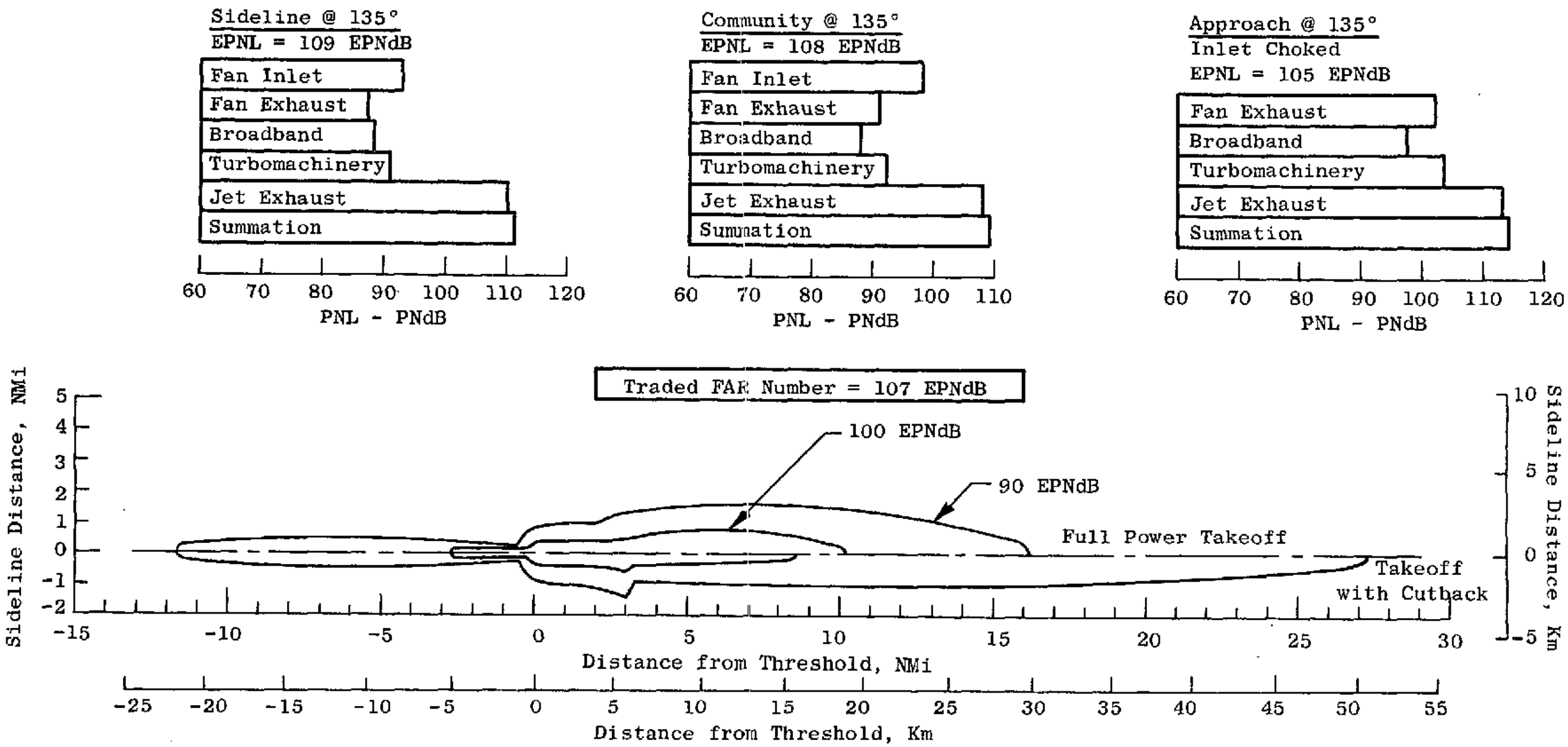


Figure 52. Takeoff Trajectory Mach Number Variation with Altitude, Full Power and Cubtack Takeoff.

- Engine: GE21/J2A1 Bypass Turbojet, Task I Technology.
- Suppression Level: 10 EPNdB in Core Stream.

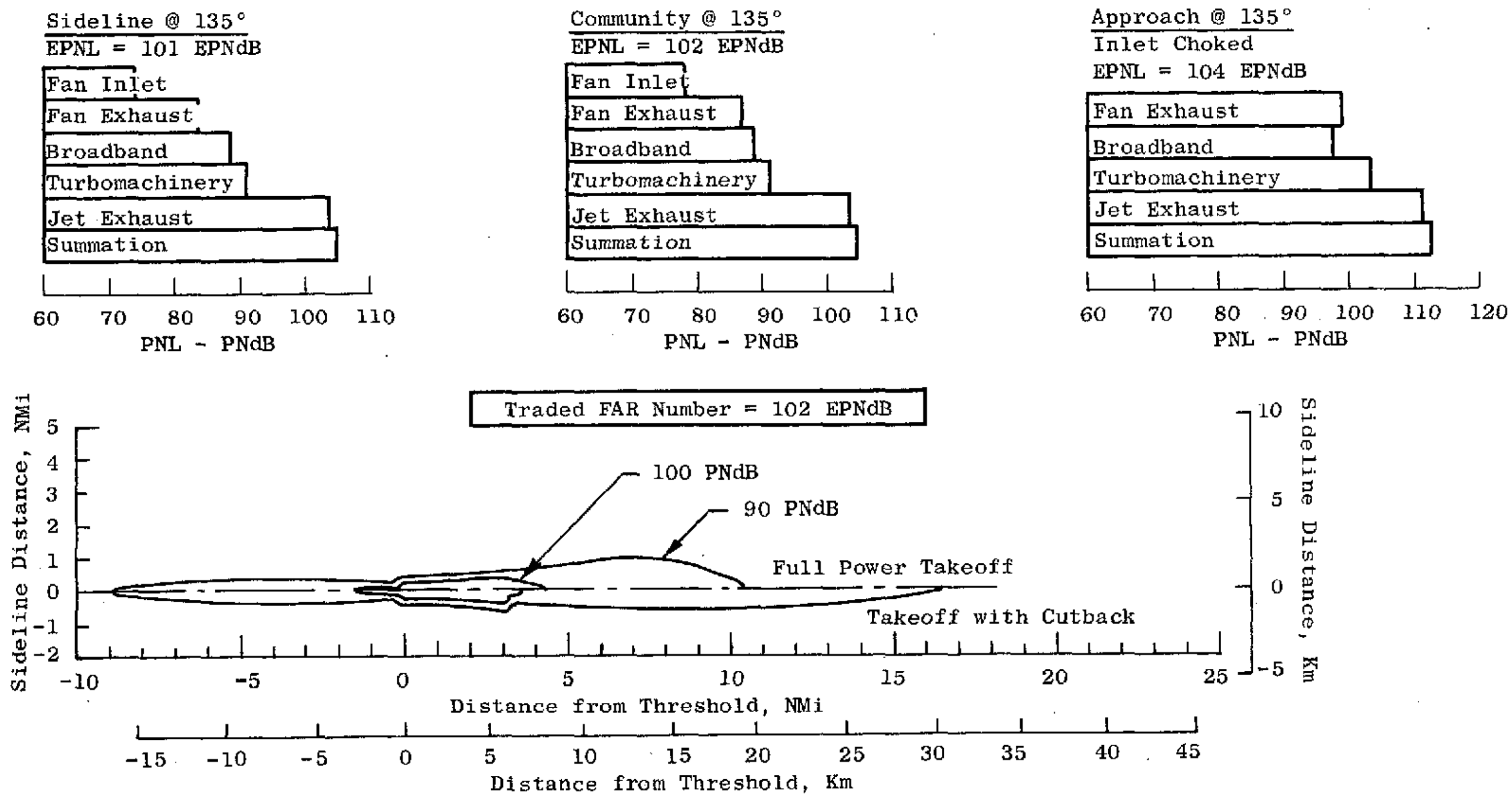


Noise Level at Monitoring Points, EPNdB	
Sideline, 0.3 M/Sea Level	= 109
Community, TO Power @ 0.34 M/570' (174 M)	= 111
Community, with Cutback @ 0.3 M/1400' (426 M)	= 108
Approach, 0.22 M/370' (113 M)	= 105

Footprint Total Contour Area, Sq NMi (Sq Km)	EPNL	Takeoff	Approach	Total
Without Cutback	100	8.9 (30.5)	0.6 (2.1)	9.5 (32.6)
With Cutback	100	5.8 (19.9)	0.6 (2.1)	6.4 (22.0)
Without Cutback	90	41.1 (141.2)	9.9 (34.0)	51.0 (175.2)
With Cutback	90	46.0 (158.0)	9.9 (34.0)	55.9 (192.0)

Figure 53. AST Footprint, GE21/J2A1, Suppression Level = 10 PNdB in Core Stream.

- Engine: GE21/J4A1 Bypass Turbojet, Task III Technology.
- Suppression Level: 18 PNdB in Core Stream.

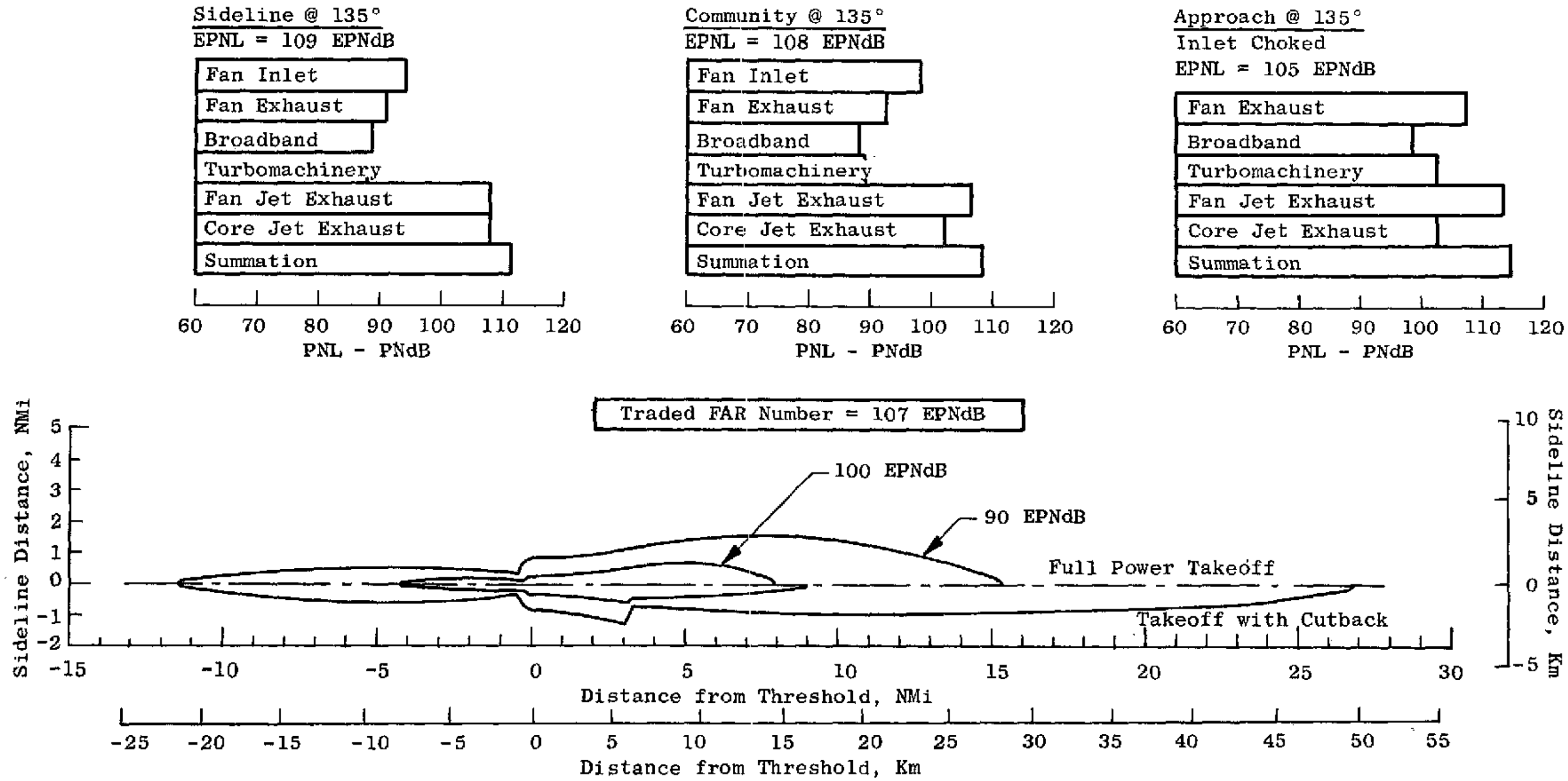


Noise Level at Monitoring Points, EPNdB	
Sideline, 0.3 M/Sea Level	= 101
Community, TO Power @ 0.34 M/570' (174 M)	= 103
Community, with Cutback @ 0.3 M/1400' (426 M)	= 102
Approach, 0.22 M/370' (113 M)	= 104

Footprint Total Contour Area, Sq NMi (Sq Km)	EPNL	Takeoff	Approach	Total
Without Cutback	100	2.0 (6.9)	0.2 (0.7)	2.2 (7.6)
With Cutback	100	1.5 (5.1)	0.2 (0.7)	1.7 (5.8)
Without Cutback	90	14.4 (49.5)	5.8 (19.9)	20.2 (69.4)
With Cutback	90	17.4 (58.8)	5.8 (19.9)	23.2 (79.7)

Figure 54. AST Footprint, GE21/J4A1, Suppression Level = 18 PNdB in Core Stream.

- Engine: GE21/F3B1 Duct-Burning Turbofan, Task I Technology.
- Suppression Level: 10 PNdB in Core Stream, None in Fan Stream.



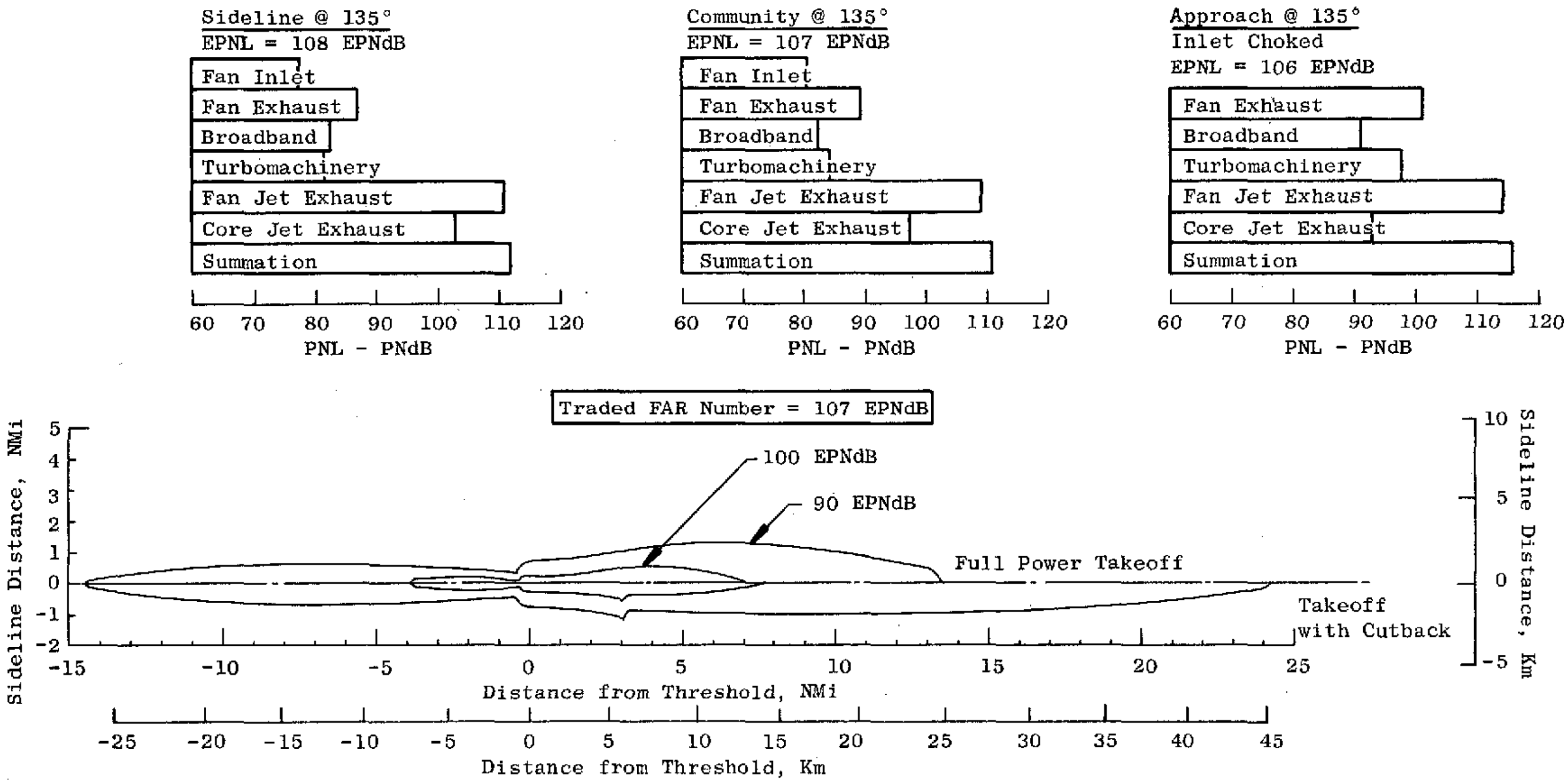
Noise Level at Monitoring Points, EPNdB	
Sideline, 0.3 M/Sea Level	= 109
Community, TO Power @ 0.34 M/570' (174 M)	= 111
Community, With Cutback @ 0.3 M/1400' (426 M)	= 108
Approach, 0.22 M/370' (113 M)	= 105

Footprint Total Contour Area, Sq NMi (Sq Km)

	EPNL	Takeoff	Approach	Total
Without Cutback	100	8.0 (27.5)	0.5 (1.7)	8.5 (29.2)
With Cutback	100	6.0 (20.6)	0.5 (1.7)	6.5 (22.3)
Without Cutback	90	35.9 (123.4)	9.4 (32.3)	45.3 (155.7)
With Cutback	90	43.9 (151.0)	9.4 (32.3)	53.3 (183.3)

Figure 55. AST Footprint, GE21/F3B1, Suppression Level = 10 PNdB in Core Stream.

- Engine: GE21/F4B1 Duct-Burning Turbofan, Task III Technology.
- Suppression Level: 18 PNdB in Core Stream, None in Fan Stream.

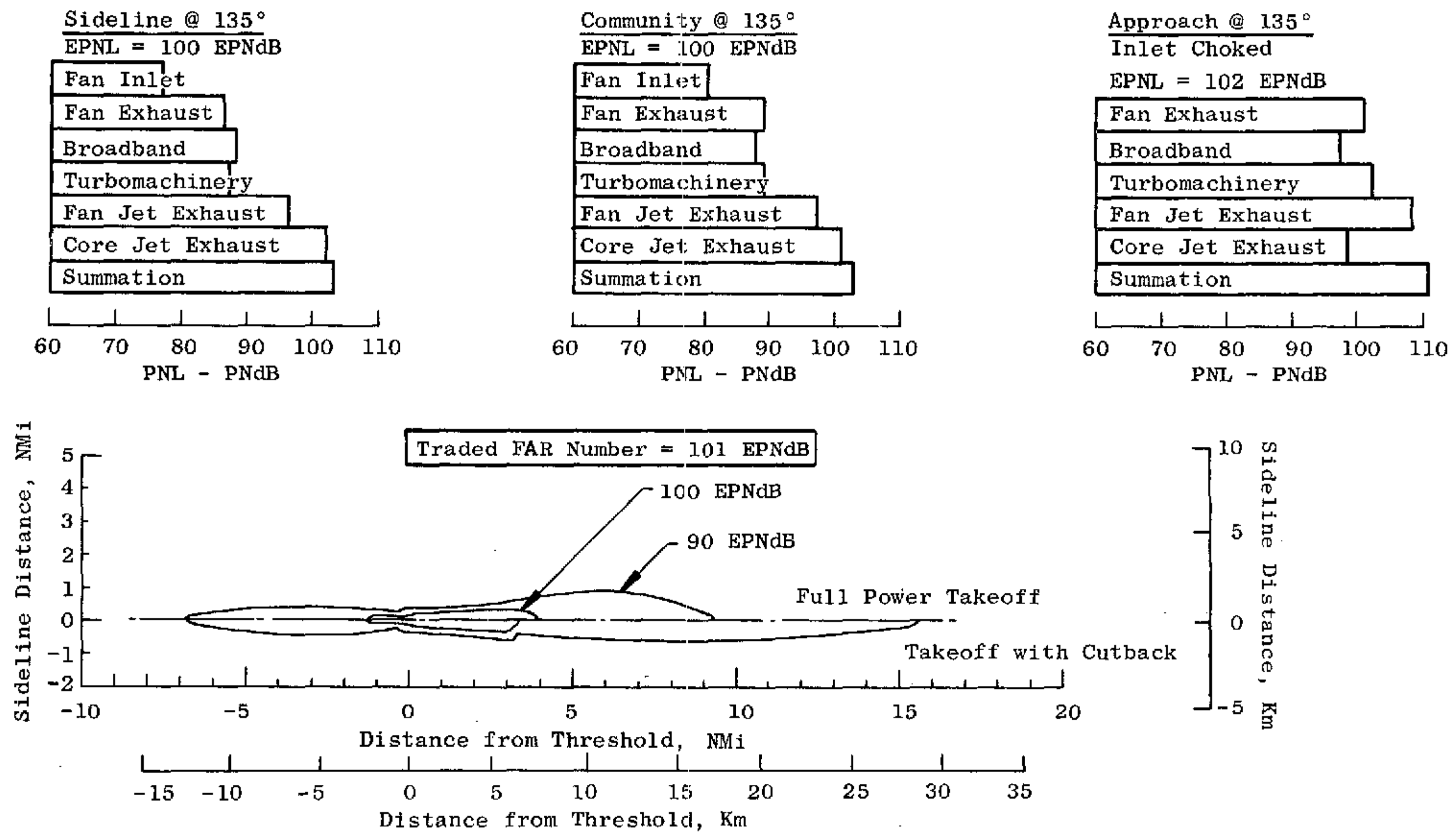


Noise Level at Monitoring Points, EPNdB	
Sideline, 0.3 M/Sea Level	= 108
Community, TO Power @ 0.34 M/570' (174 M)	= 110
Community, with Cutback @ 0.3 M/1400' (426 M)	≈ 107
Approach, 0.22 M/370' (113 M)	= 106

Footprint Total Contour Area, Sq NMi (Sq Km)	EPNL	Takeoff	Approach	Total
Without Cutback	100	5.9 (20.3)	1.1 (3.8)	7.0 (24.1)
With Cutback	100	4.8 (16.5)	1.1 (3.8)	5.9 (20.3)
Without Cutback	90	27.8 (95.5)	14.8 (50.8)	42.6 (146.3)
With Cutback	90	36.6 (125.8)	14.8 (50.8)	51.4 (176.6)

Figure 56. AST Footprint, GE21/F4B1, Suppression Level = 18 PNdB in Core Stream.

- Engine: GE21/F4B1 Duct-Burning Turbofan, Task III Technology.
- Suppression Level: 18 PNdB in Core Stream, 14 PNdB in Fan Stream.

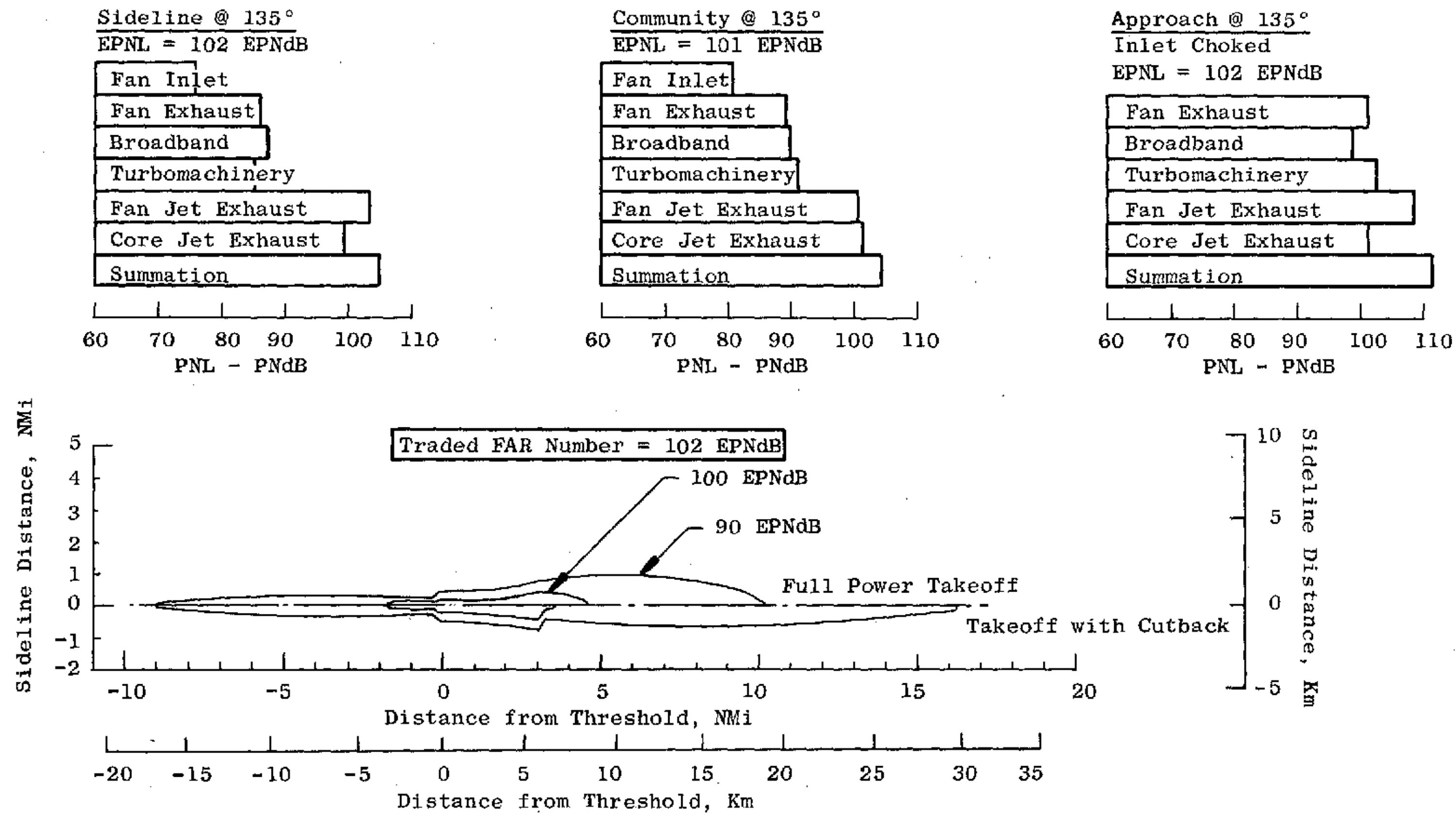


Noise Level at Monitoring Points, EPNdB	
Sideline, 0.3 M/Sea Level	= 100
Community, TO Power @ 0.34 M/570' (174 M)	= 102
Community, with Cutback @ 0.3 M/1400' (426 M)	= 100
Approach, 0.22 M/370' (113 M)	= 102

Footprint Total Contour Area, Sq NMi (Sq M)	EPNL	Takeoff	Approach	Total
Without Cutback	100	1.6 (5.5)	0.1 (0.3)	1.7 (5.8)
With Cutback	100	1.3 (4.5)	0.1 (0.3)	1.4 (4.2)
Without Cutback	90	11.5 (39.4)	3.6 (12.4)	15.1 (51.8)
With Cutback	90	15.0 (51.5)	3.6 (12.4)	18.6 (63.9)

Figure 57. AST Footprint, GE21/F4B1, Suppression Level = 18 PNdB in Core Stream and 14 PNdB in Fan Stream.

- Engine: GE21/F4B1 Duct-Burning Turbofan with Augmentation on Takeoff, Task III Technology.
- Suppression Level: 18 PNdB in Both Fan and Core Streams.

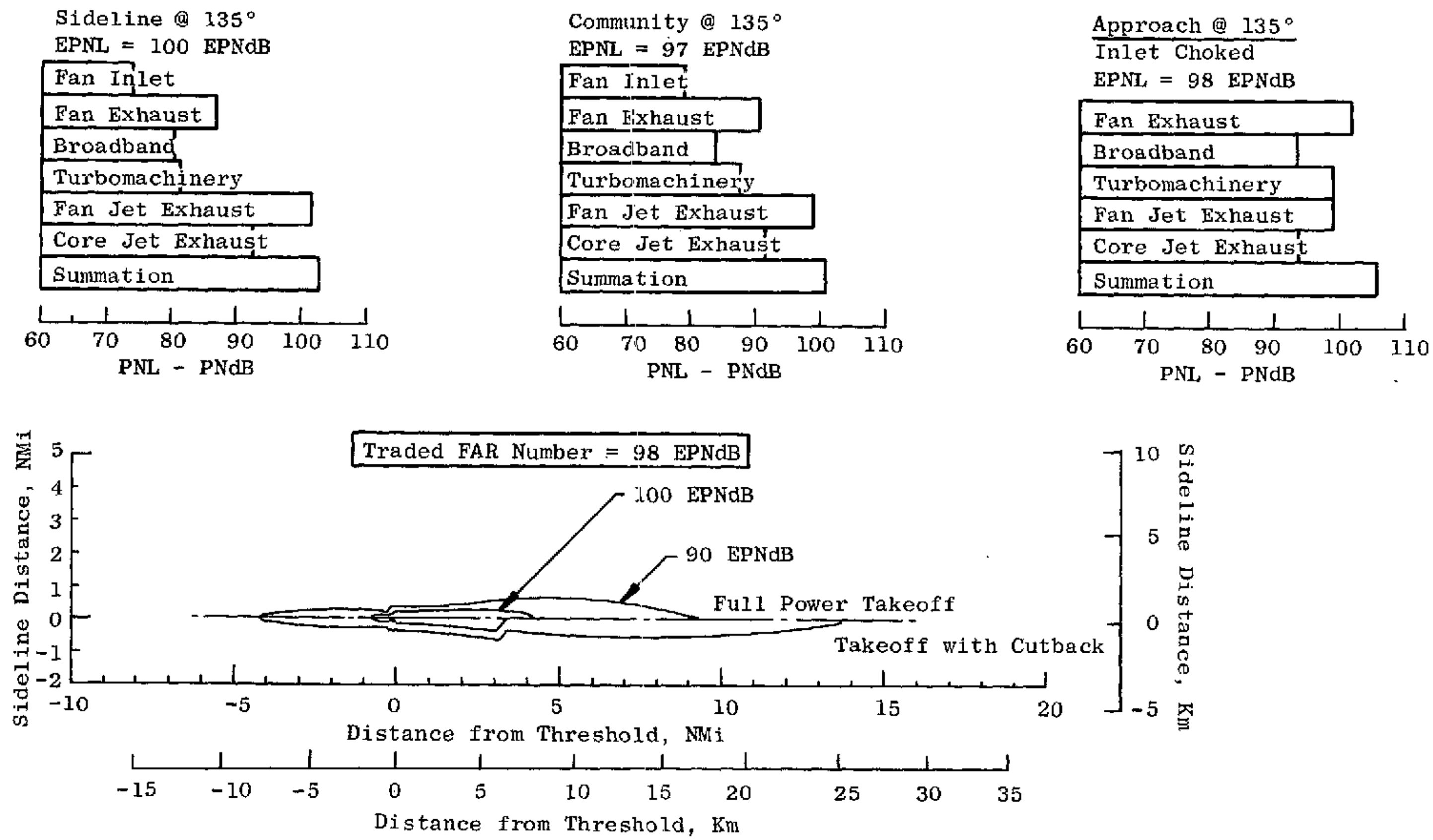


Noise Level at Monitoring Points, EPNdB	
Sideline, 0.3 M/Sea Level	= 102
Community, TO Power @ 0.34 M/570' (174 M)	= 104
Community, with Cutback @ 0.3 M/1400' (426 M)	= 101
Approach, 0.22 M/370' (113 M)	= 102

Footprint Total Contour Area, Sq NMi (Sq Km)	EPNL	Takeoff	Approach	Total
Without Cutback	100	2.3 (7.9)	0.2 (0.7)	2.5 (8.6)
With Cutback	100	1.6 (5.5)	0.2 (0.7)	1.8 (6.2)
Without Cutback	90	14.6 (50.1)	5.7 (13.6)	20.3 (69.7)
With Cutback	90	16.7 (57.4)	5.7 (13.6)	22.4 (77.0)

Figure 58. AST Footprint, GE21/F4B1, Suppression Level = 18 PNdB in Both Fan and Core Stream.

- Engine: High Bypass Ratio Duct-Burning Turbofan with Augmentation on Takeoff, Task III Technology.
- Suppression Level: 18 PNdB in Both Fan and Core Streams.

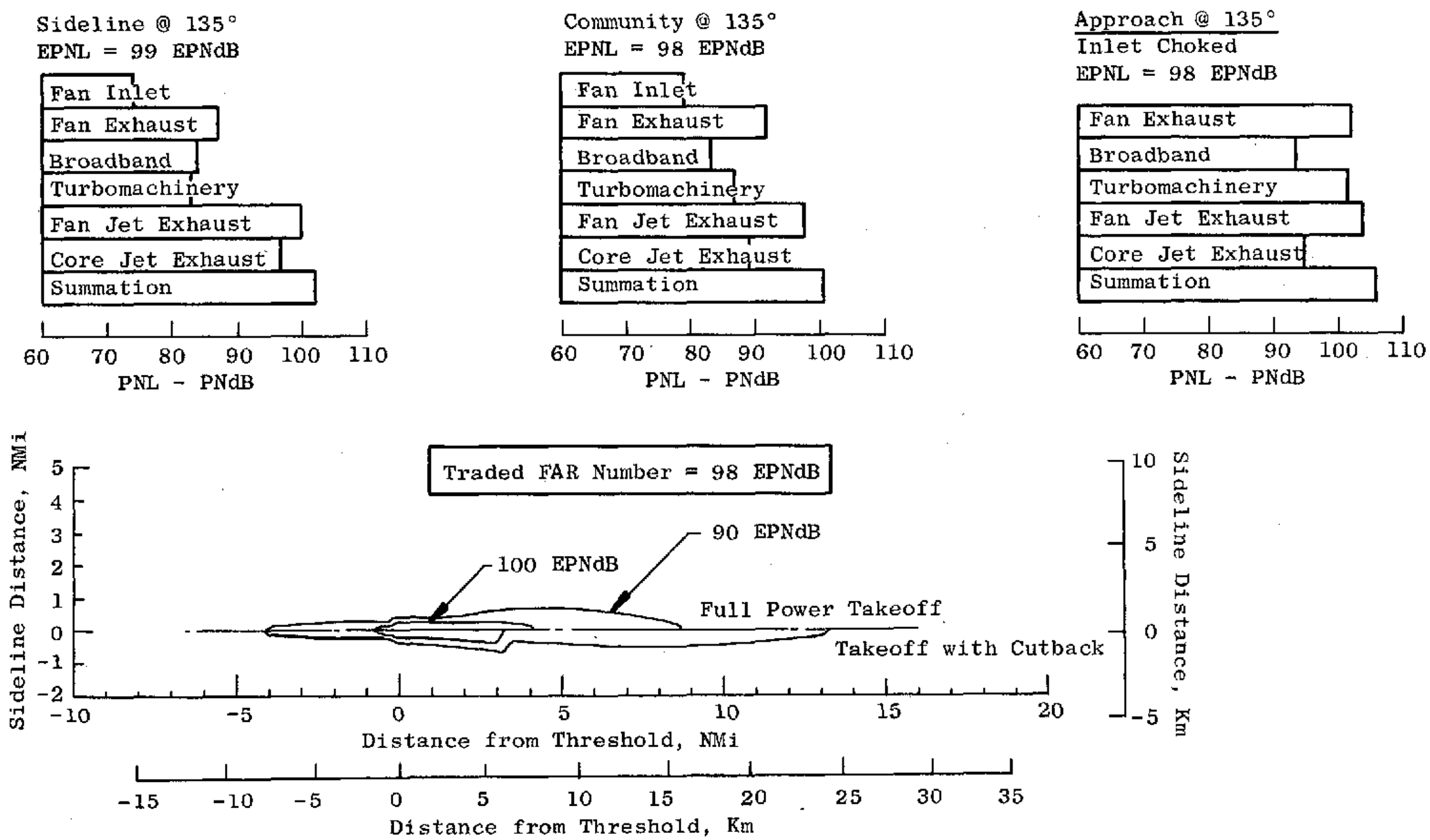


Noise Level at Monitoring Points, EPNdB	
Sideline, 0.3 M/Sea Level	= 100
Community, TO Power @ 0.34 M/570' (174 M)	= 102
Community, with Cutback @ 0.3 M/1400' (426 M)	= 97
Approach, 0.22 M/370' (113 M)	= 98

Footprint Total Contour Area, Sq NMi (Sq Km)				
	EPNL	Takeoff	Approach	Total
Without Cutback	100	1.7 (5.8)	0.1 (0.3)	1.8 (6.1)
With Cutback	100	1.3 (4.5)	0.1 (0.3)	1.4 (4.8)
Without Cutback	90	11.6 (39.8)	1.4 (4.8)	13.0 (44.6)
With Cutback	90	12.4 (42.6)	1.4 (4.8)	13.8 (47.4)

Figure 59. AST Footprint, High-Bypass Ratio, Duct Burning Turbofan Task III Technology. Suppression Level = 18 PNdB in Both Fan and Core Streams.

- Engine: GE21/F11B1 Modulating Airflow Engine with Augmentation on Takeoff, Task II Technology.
- Suppression Level: 18 PNdB in both Fan and Core Streams.



Noise Level at Monitoring Points

Sideline, 0.3 M/Sea Level	=	99
Community, TO Power @ 0.34 M/570' (174 M)	=	100
Community, with Cutback @ 0.3 M/1400' (426 M)	=	98
Approach, 0.22 M/370' (113 M)	=	98

Footprint Total Contour Area, Sq NMi (Sq Km)

	EPNL	Takeoff	Approach	Total
Without Cutback	100	1.7 (5.8)	0.1 (0.3)	1.8 (6.1)
With Cutback	100	1.3 (4.5)	0.1 (0.3)	1.4 (4.8)
Without Cutback	90	11.6 (39.8)	1.4 (4.8)	13.0 (44.6)
With Cutback	90	12.4 (42.6)	1.4 (4.8)	13.8 (47.4)

Figure 60. AST Footprint, GE21/F11B1, Suppression Level = 18 PNdB in Both Fan and Core Streams.

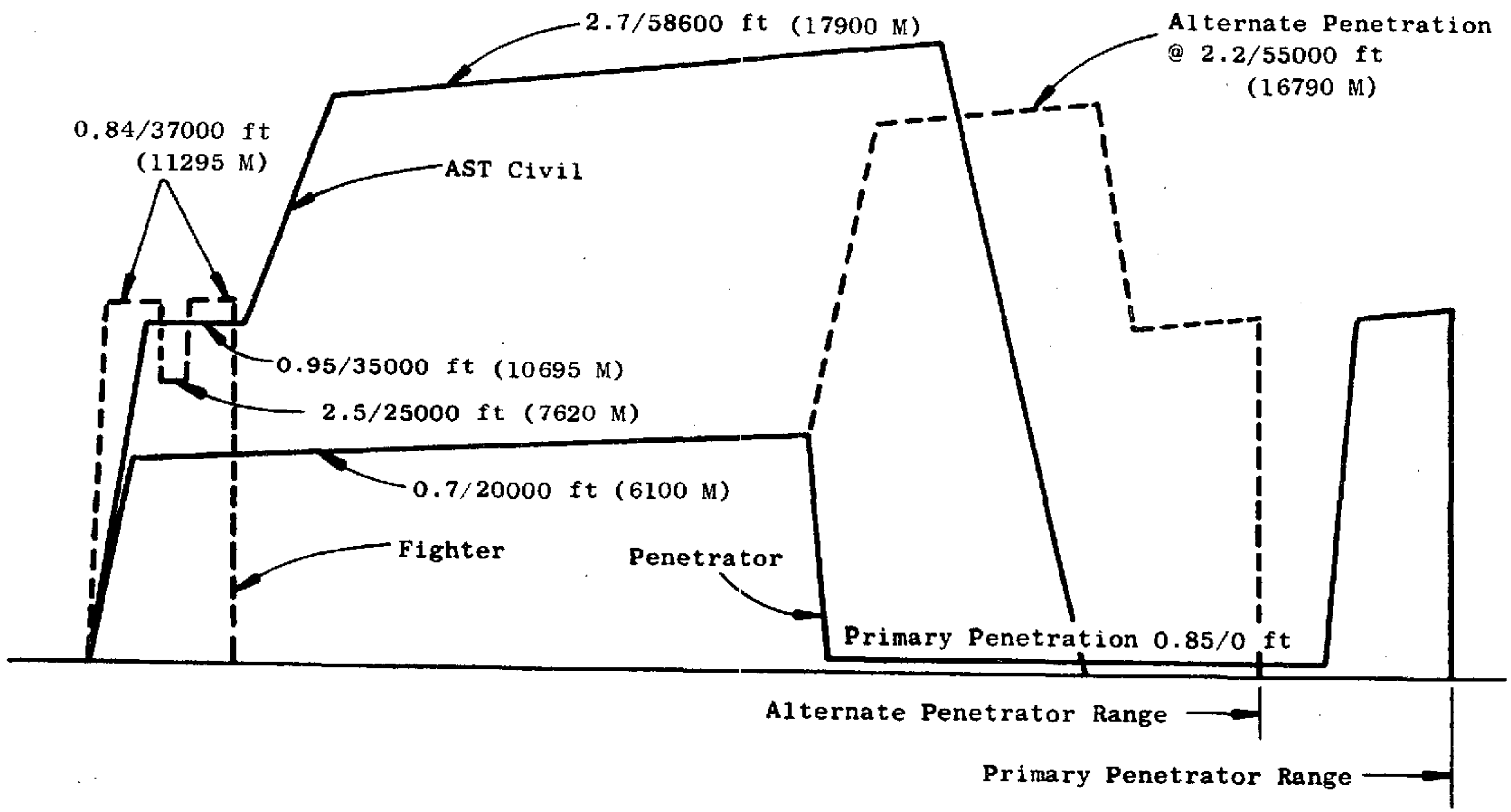


Figure 61. Military Applicability of Variable Cycle Engines, Civil and Military Missions.

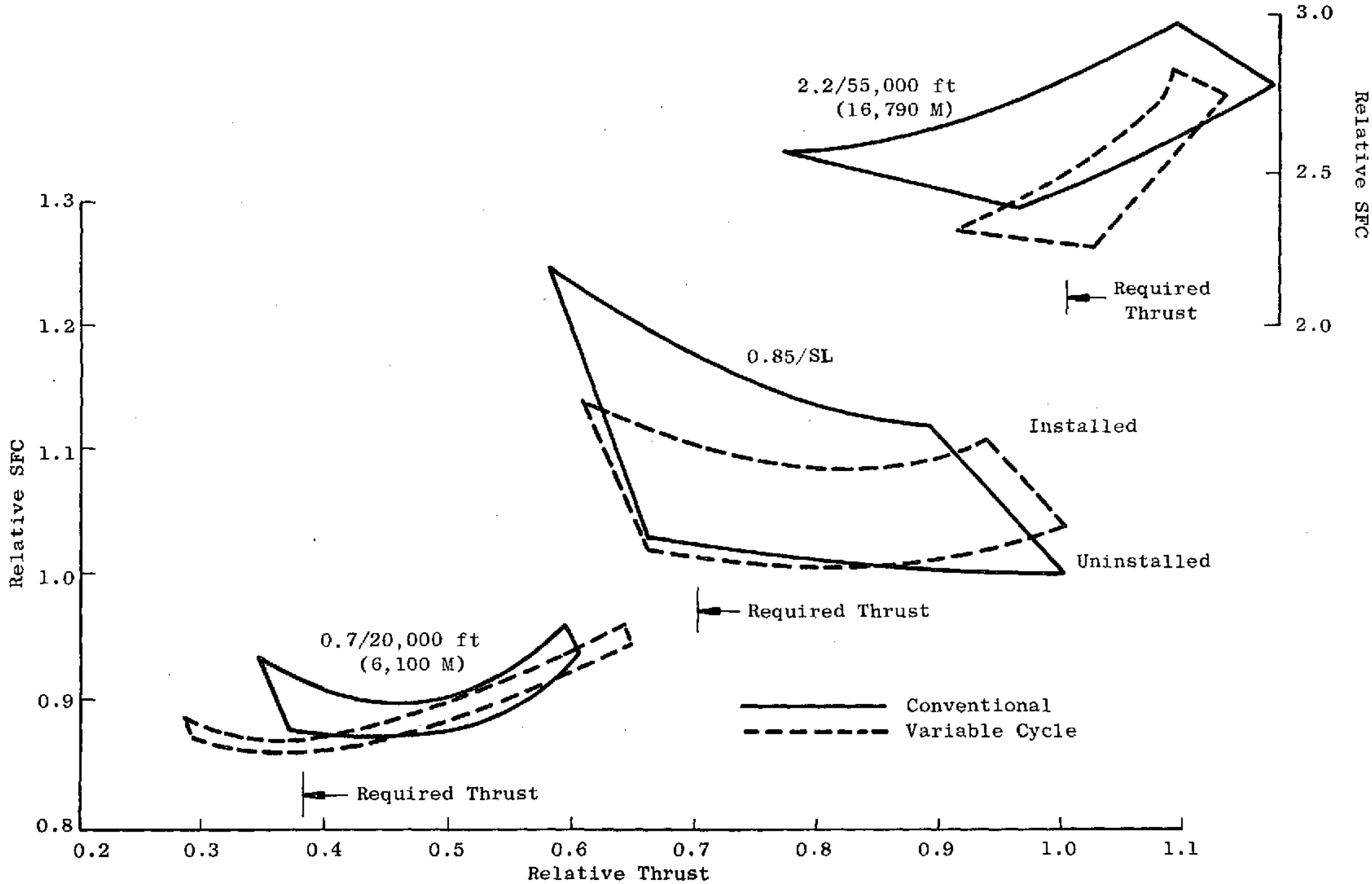


Figure 62. Military Applicability of Variable Cycle Engine, Penetrator Performance.

Table XII. Military Applications of VCE.

COMPARISON OF CIVIL AND MILITARY ENGINES

Mission	Engine Type	P/P (LP)	P/P (OA)	β	T_{41} °F (°C)	M_o Max.	Airflow %	Engine Wt. %	Engine Dia. %
Penetrator	Mixed Flow A/B TF	2.2	26	2.0	2400 (1316)	2.2	100	100	100
Penetrator	Mod. Air -3R	3.6	36	2.7	2850 (1566)	2.2	110*	113	105
AST	Mod. Air -3R	4.83	15	1.25	2800 (1538)	2.7			
Fighter	Mixed Flow A/B TF	4.0	24	1.25	3200 (1760)	2.5	100	100	100
Fighter	Mod. Air	4.4	25	1.25	3200 (1760)	2.5	107	110	103.5

* SIZED FOR SAME SUPERSONIC RANGE AS MIXED FLOW A/B TF (BASE ENG.)

Analysis of this effort has led to the following results:

- In the penetrator, an approximate 3-8% range improvement depending on drag is possible with the variable cycle compared to the mixed-flow turbofan in the primary (subsonic) mission. Slightly higher gains are potentially possible in the alternate (supersonic) mission through additional tuning of the cycle, with no loss in performance in the primary mission.

- Indications are that similar gains in mission performance are potentially possible for the fighter.

- The SST engine size required is approximately three times that of the military engines.

Estimated Emissions Levels

Exhaust emissions estimates for some AST study engines have been prepared; first with existing combustor technology, then assuming advanced combustor technology (from the NASA Experimental Clean Combustor and other programs).

Exhaust emissions estimates with existing technology are based upon the combustor inlet conditions in Table XIII and measured emissions of the F101 engine which represents the best GE state-of-the-art with respect to low emissions, mixing combustor design technology. These estimates are tabulated in Table XIV with the AST emissions goals for comparison. None of the three engines meet all of the goals. The high pressure ratio engine very nearly meets the idle emissions goals, but exceeds the takeoff and cruise goals. The lower pressure ratio engine meets the takeoff (nonaugmented) and cruise (augmented) goals, but exceeds the idle emissions goals. Thus new technology is needed for these engines.

During the past several years, GE-AEG has been continuously conducting programs and investigations to develop technology for the design of combustors which have reduced levels of objectionable exhaust emissions. As a result of these efforts, advanced engines with virtually nonvisable smoke levels at all operating conditions have been designed and developed, and are in service. Also, considerable progress has been made in the development of combustors with lower levels of the gaseous emissions of concern. Currently, General Electric is engaged in conducting the NASA Experimental Clean Combustor Program (Contract NAS3-16830). Figure 63 compares the current state-of-the-art emissions levels for oxides of nitrogen with the reduced emission level goals for this experimental program. Thus, while the AST exhaust emissions goals are not expected to be met using current design technology, advanced technology is being developed to design combustors which will meet these goals. With this new technology, it is estimated that the emissions levels tabulated in Table XV can be achieved. These emissions estimates assume that much of the recent results and design approaches which are discussed below will be applied.

Table XIII. AST Main Combustor Inlet Conditions.

	Engine Design Overall Pressure Ratio	15	25
Idle	P_3 psia (Pa)	44.3(305500)	69.2(477000)
	T_3 °F (° C)	297(149)	418(214)
	WFD/WFT	0	0
Takeoff	P_3 psia (Pa)	207.9(1431500)	341.5(2354000)
	T_3 °F (° C)	758(403)	961(516)
	WFD/WFT	0	0
Cruise	P_3 psia (Pa)	111.2(1613000)	169.3(2456000)
	T_3 °F (° C)	1116(602)	1151(622)
	WFD/WFT	0.327	0.256
	P_{15} psia (Pa)	36.4(251000)	30.0(206800)
	T_{15} °F (° C)	680(360)	505(263)

Table XIV Estimated AST Exhaust Emissions Levels*
Standard Day, Kerosene Fuel

Engine Design Overall Pressure Ratio	15	25	Goal
Emission Index lb/1000 lb fuel (kg/1000 kg)			
CO @ Idle	45	23	20
HC @ Idle	6	2	4
NO_x Supersonic Cruise-Nonaugmented	19	26	15
Augmented	14	20	
NO_x @ Takeoff - Nonaugmented	8	20	10
SAE Smoke No. @ T/O	12	26	10

*Best current design technology level, no CD air bleed at idle.

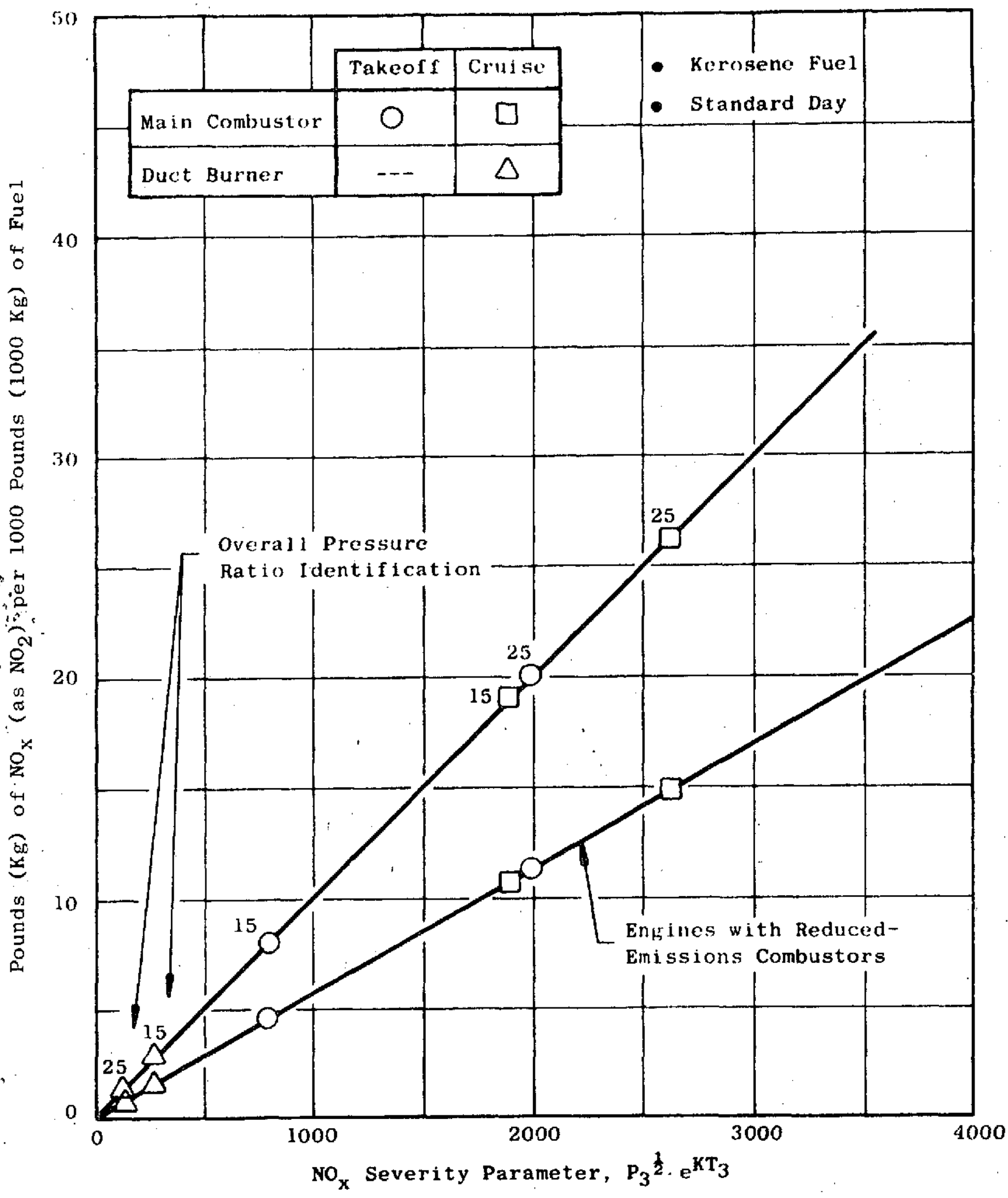


Figure 63. Predicted NO_x Emissions Characteristics of Reduced-Emissions Combustors.

Table XV Estimated AST Exhaust Emissions With New Combustor Technology Standard Day, Kerosene Fuel.

Engine Design Overall Pressure Ratio	15	25	Goal
Emission Index, lb/1000 lb Fuel (kg/1000 kg)			
CO @ Idle	20	20	20
C_xHt @ Idle	4	4	4
NO_x @ Takeoff (dry)	5	11	10
NO_x @ Supersonic Cruise			
Dry	11	15	--
Augmented	8	11	15
SAE Smoke No. @ T/O	10	10	10

Carbon Monoxide and Hydrocarbon Emissions at Idle

Carbon monoxide (CO) and hydrocarbon (HC) emissions are the result of inefficient combustion. The levels of these emissions are highest at idle power and decrease rapidly as power is increased. Typical trends are shown in Figure 64. The CO and HC levels at idle are high because the inlet temperature and pressure are low, the fuel-air ratio is low and the fuel atomization is relatively poor. High pressure ratio engines invariably have lower idle emissions than do low pressure ratio engines simply because the combustor inlet temperatures and pressures are more favorable. This trend is reflected in the estimates in Table XIV. Another clear trend is that combustor designs which incorporate carbureting fuel injection systems (such as the F101) have lower idle emissions levels than do the more conventional pressure atomizing fuel nozzle systems. Thus, carbureting fuel injection systems are included in virtually all advanced designs.

Conventional combustors are designed to have approximately a stoichiometric fuel-air ratio in the primary zone at full power. At idle, the primary zone fuel-air ratio is typically less than 0.6 of the stoichiometric value. Significant changes in idle emissions have been found when the primary zone stoichiometry was altered. One method of changing the idle stoichiometry is to bleed the engine at the compressor discharge. Figure 65 summarizes the effects of the bleed on the idle emissions of several advanced GE engines. With 12 percent bleed, HC and CO emissions are about 40 and 75 percent respectively of the non-bleed levels. Thus the AST idle hydrocarbon emissions goals could be achieved on both engines simply by incorporating CD bleed. Additional techniques would however be required to achieve the CO goals with these engines.

In combustor component tests, primary zone fuel-air stoichiometry has been varied over wider ranges than are obtainable by CD bleed. Typical results are shown in Figure 66. These data indicate that the AST idle CO goal could be achieved in even the lowest pressure ratio engine if the primary zone fuel-air ratio were increased 60 percent. This change would be implemented by incorporating either a variable geometry or a staged combustor design (Figures 67, 68 and 69). These concepts are currently being built up for test in the Experimental Clean Combustor Program.

Carbon Monoxide and Hydrocarbon Emissions at Takeoff

Main combustors have been developed to a high degree of combustion efficiency for operation at the favorable conditions of high pressure and high combustion inlet temperature that exist at takeoff. Consequently, the emissions of carbon monoxide and unburned hydrocarbon are negligible compared with the idle condition. The engines evaluated in Table XIII were sized to provide adequate takeoff thrust without using any burning in the fan duct. In the past, fan burners have primarily been low efficiency designs, and a significant level of carbon monoxide and hydrocarbon emissions exist and would result at takeoff. However, it has been identified that it may be possible to develop fan burners with the same low level of emissions that can be achieved with main engine burners at idle. The inlet pressures and temperatures of the fan burners at takeoff conditions are

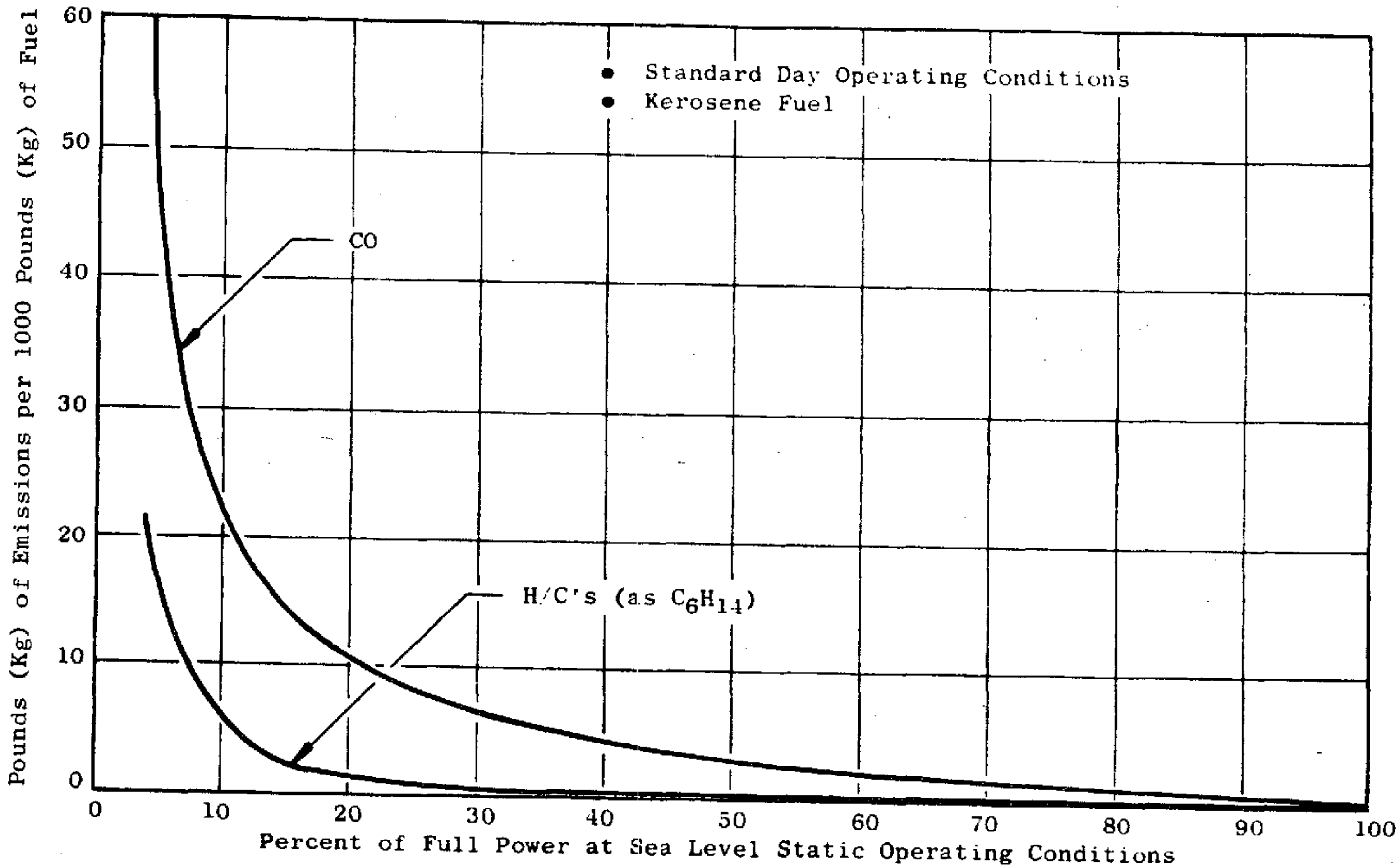


Figure 64. Typical Exhaust Emissions Characteristics.

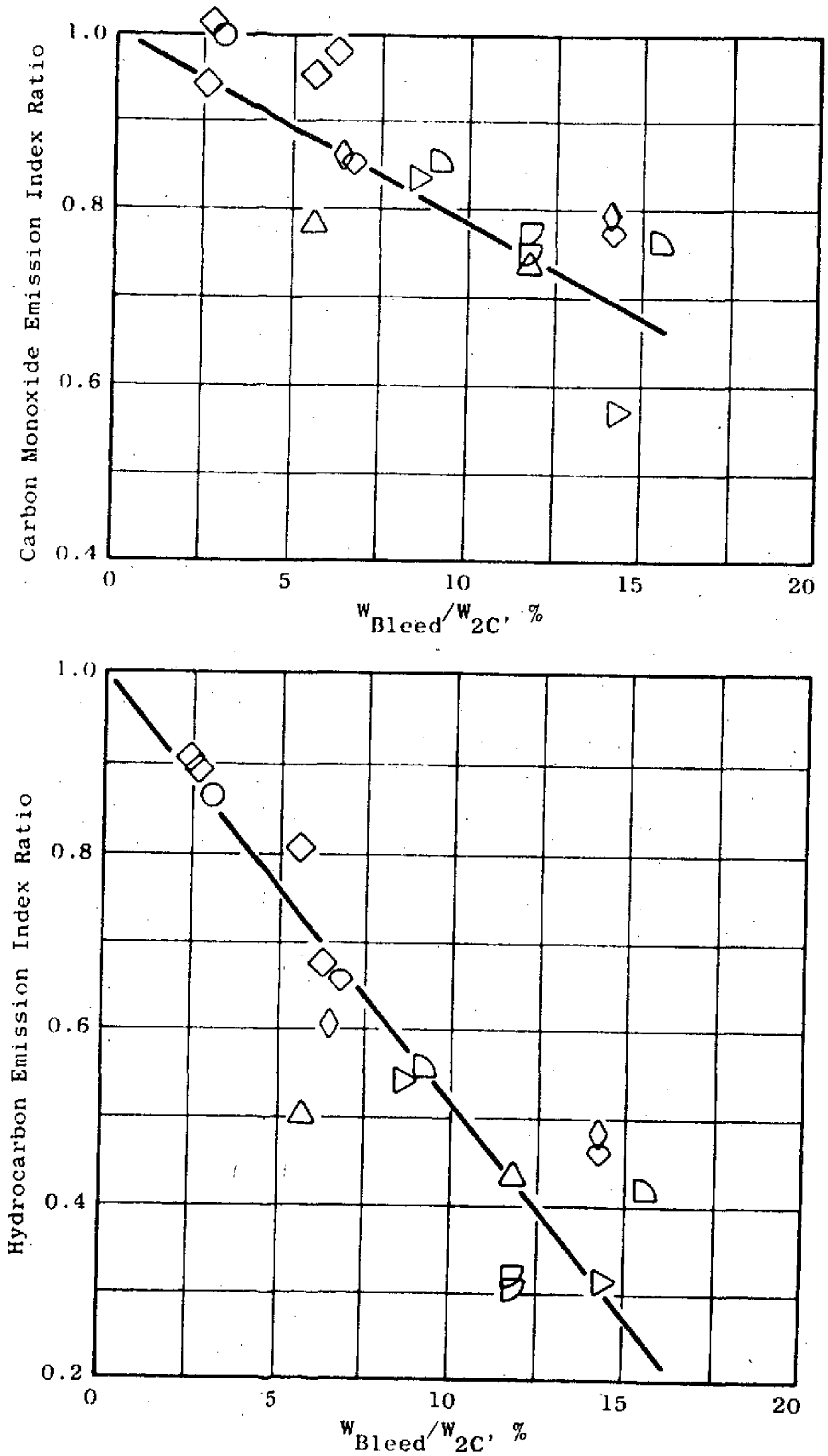


Figure 65. Effect of Compressor Discharge Air Bleed on Exhaust Emissions at Idle, Engine Test Results.

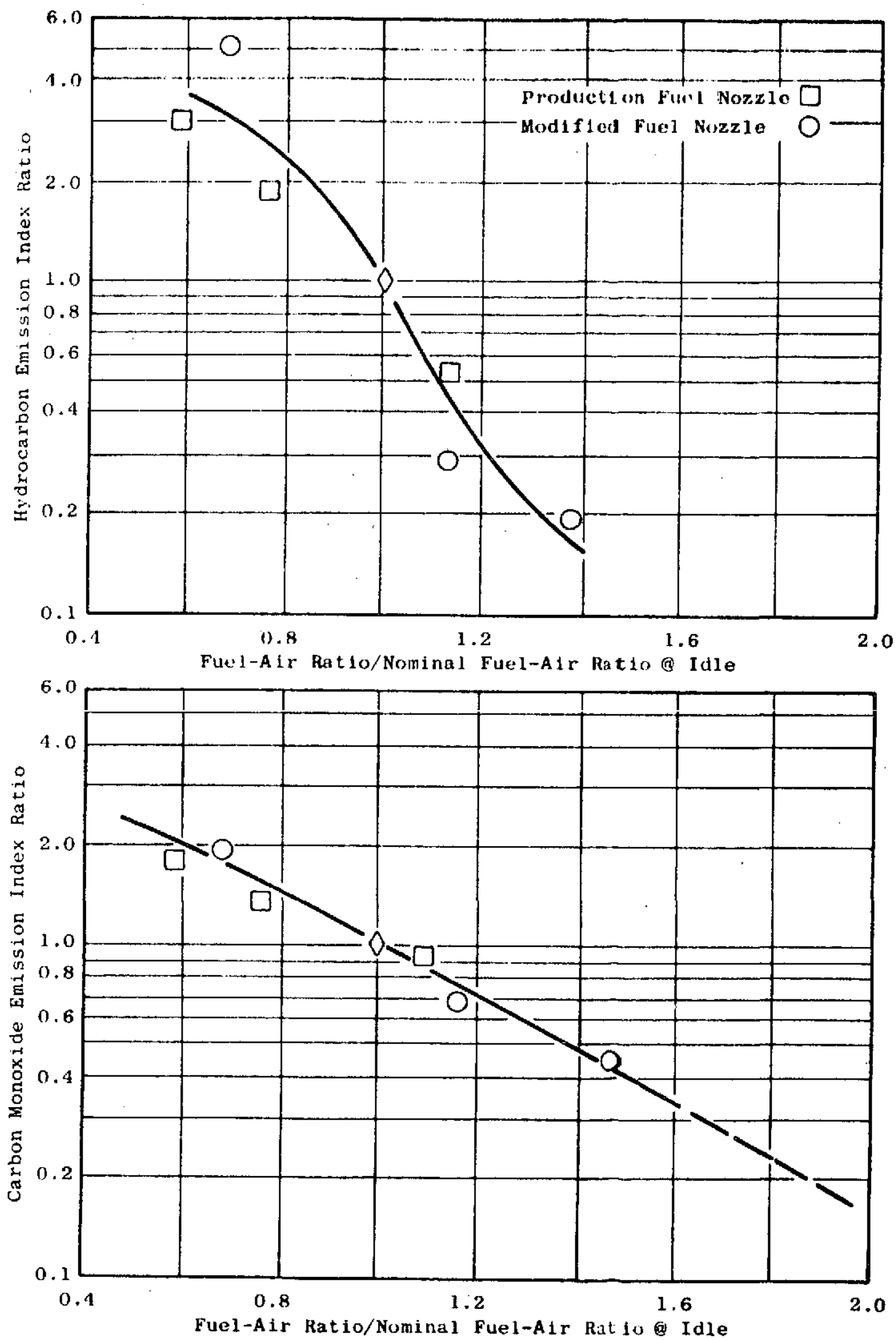


Figure 66. Effect of Fuel-Air Ratio on Exhaust Emissions at Idle Combustor Inlet Conditions, Advanced Combustor Component Test Results.

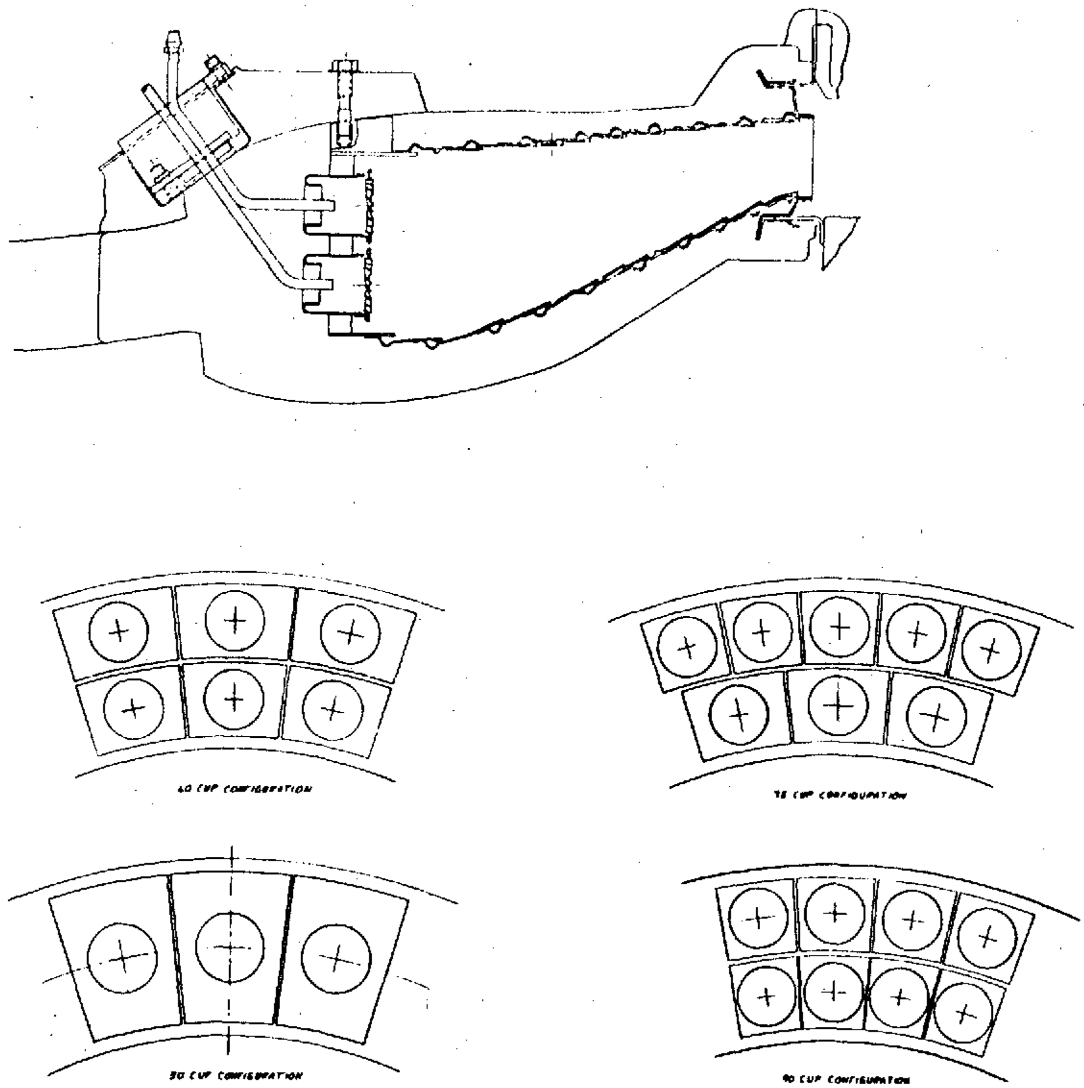


Figure 67. NASA Swirl-Can-Modular Combustor, Baseline Configuration.

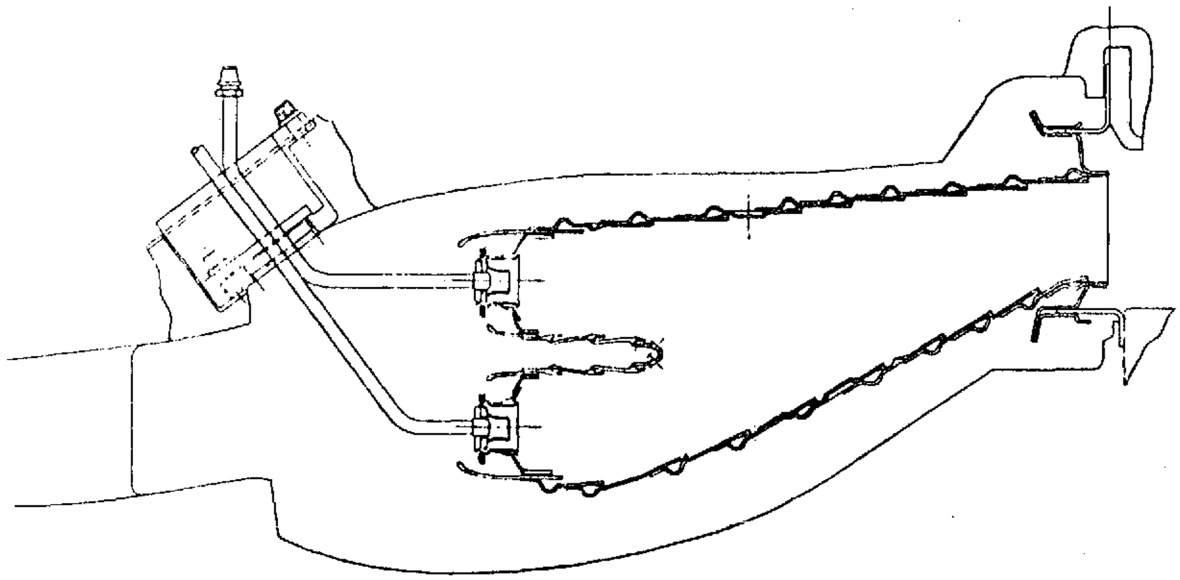


Figure 68. Double-Annular Dome Combustor, Conceptual Design.

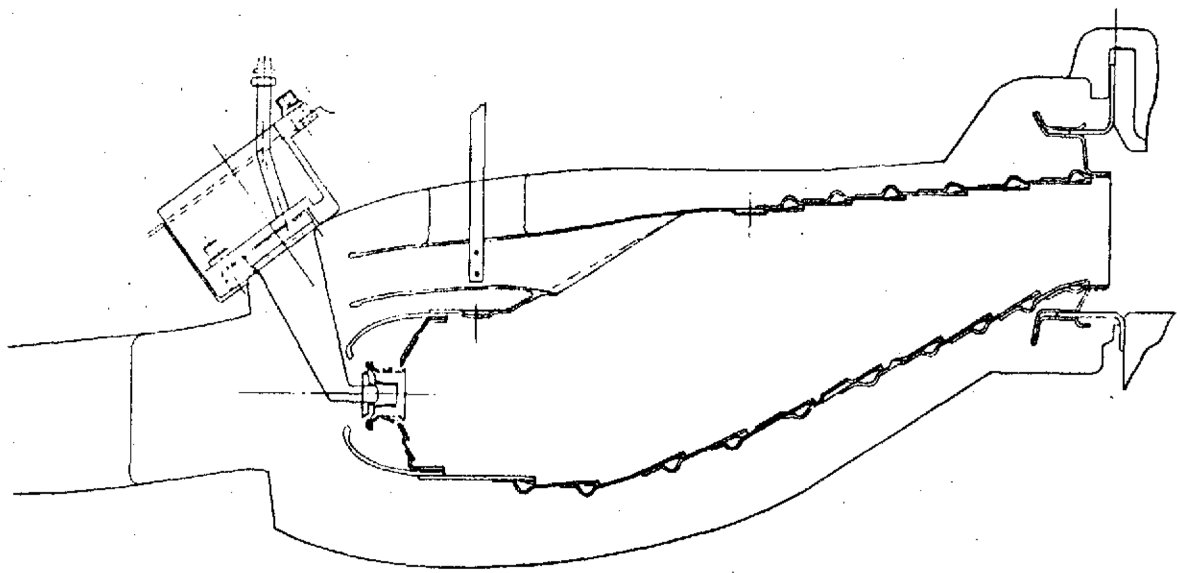


Figure 69. Radial/Axial Staged Combustor, Conceptual Design.

close to those of the main burner at idle. Furthermore, because noise requirements limit the temperature rise at takeoff to moderate levels it is possible to achieve this augmentation temperature rise in only part of the total airstream, using essentially main burner design features optimized for emission control in this burner stage. Higher temperature levels can be obtained in a second burner stage.

Achieving idle level emissions in the fan burner at takeoff would not meet the present EPA 1979 standards written for nonaugmented engines. Those standards utilize integrated emission levels for a specific mission near the airport. Hence, any carbon monoxide or hydrocarbon emissions produced at takeoff by the fan burner beyond the very small contribution from the main burner, would require that the main burner emissions at idle be reduced to compensate for these additional emissions. Engines for supersonic transport applications were specifically excluded from the present EPA standard, recognizing the probable need for an alternate standard for these engines. An additional allowable emission quantity of carbon monoxide and hydrocarbon at takeoff, equivalent to that now allowed for idle would be the type of modification to the present standard that would be consistent with the projected state of the art in emission technology.

If the advanced emission technology for main burners is successfully introduced into fan burners for takeoff, they would be able to set a modified standard as suggested above, specifically for augmented engines for the supersonic transport application.

It is interesting to note that the NO_x produced at takeoff in a main burner type of fan burner is very low and would help reduce the overall NO_x level of the engine. For a smaller fan burning version, the high pressure ratio configuration shown in Table XII, the NO_x level would be reduced at takeoff.

NO_x Emissions

Whereas CO, HC, and smoke are products of inefficient combustion, oxides of nitrogen (NO_x) are an equilibrium product of high temperature combustion. The formation rates are highly sensitive to flame temperature and fuel-air ratio. Thus NO_x reduction concepts involve altering the fuel-air ratio distribution and/or residence time within the combustor.

An atmospheric sector test program was conducted in 1972 in which combustor airflow distribution was systematically varied and NO_x emissions levels of the various combustor configurations were measured. The key results of these tests are shown in Figure 70.

As shown, reductions in NO_x emissions levels of 25 percent were obtained by increasing the primary zone equivalence ratio to values of 2.0 or more. However this approach would be expected to result in increased smoke levels. Operation with increased primary zone equivalence ratios apparently results in a shift of the NO_x formation zones from the primary combustion zone to the downstream dilution zones. In addition reductions of approximately 25 percent were obtained by using a quick quench design approach in which the liner

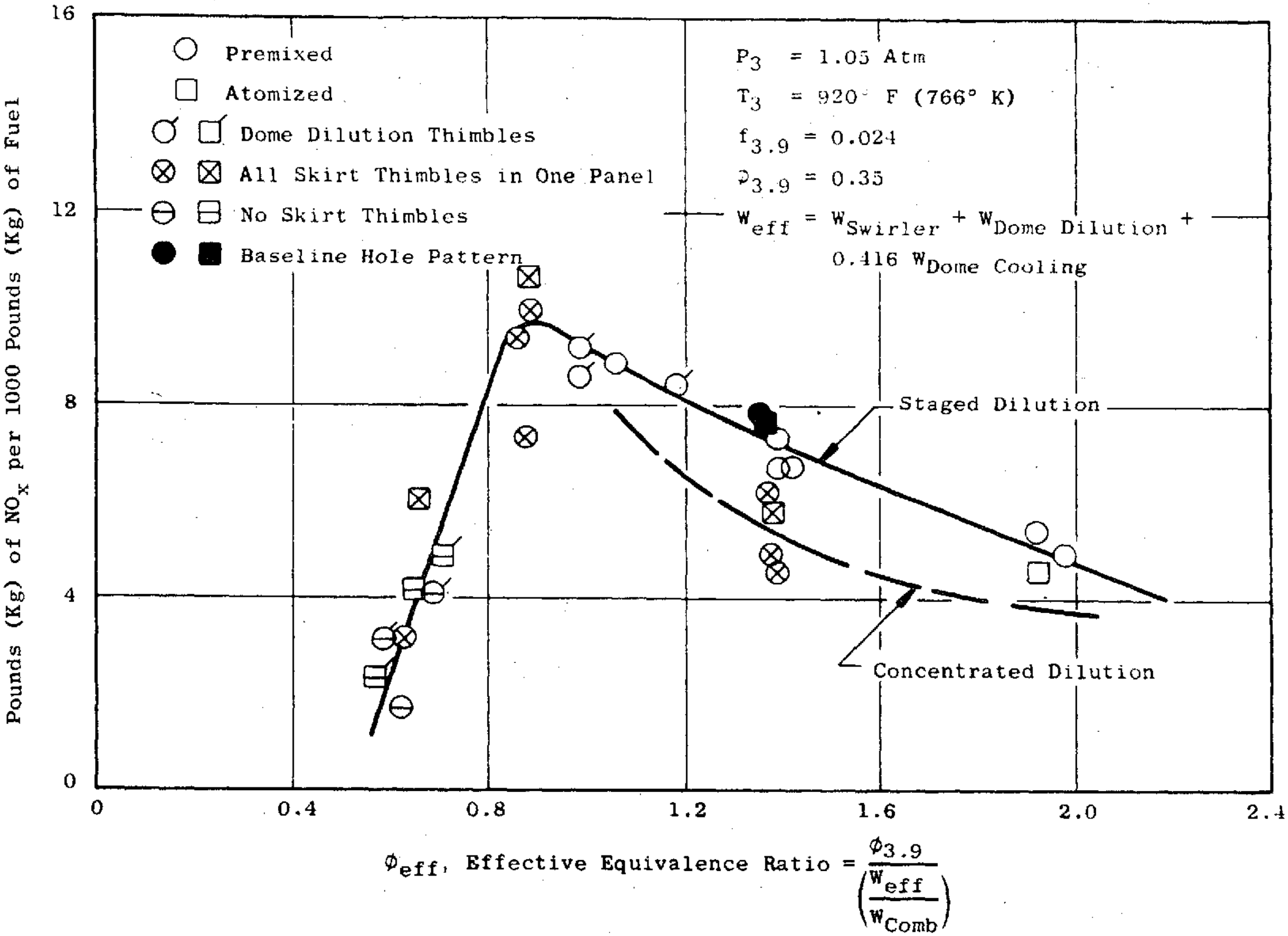


Figure 70. Effect of Primary Zone Equivalence Ratio on NO_x Emissions Levels.

dilution holes were concentrated in one panel, rather than staging them along the combustor liner. Large reductions of up to about 75 percent were obtained with lean primary zones. This lean dome design approach appears to be effective, because it results in reduced flame temperatures everywhere in the combustor.

Based on these results, four full annular TF39 combustor configurations, with various airflow splits, were tested in a high pressure test rig. The NO_x emissions level results of these tests are shown in Figure 71. These results verified the trends obtained in the atmospheric sector tests. Based on these results, all of the test configurations being designed in the NASA Experimental Clean Combustor Program incorporate the lean dome concept, since this appears to be the only approach available for obtaining the needed large reductions in NO_x emissions levels without the use of water injection techniques.

Four main approaches are being designed:

1. <u>NASA Swirl-Can-Modular Combustor</u>

   This concept shown in Figure 67 incorporates two annular rings of carburetor/flameholder devices. The number of fuel injection points will be 2 to 3 times that of current combustors. Various flameholder and swirler designs will be evaluated. At light-off and idle probably only one ring or sectors will be fueled.

2. <u>Single-Annular Simulated Variable Geometry Combustor</u>

   This concept will be sized so that at full power the effective equivalence ratio in the dome will be about 0.5. However, in actual application variable geometry would be used to divert much of the dome flow at idle.

3. <u>Double Annular Combustor</u> (Figure 68)

   This design also incorporates the lean dome concept, but to avoid the use of variable geometry, only one annulus will be fueled at idle.

4. <u>Radial/Axial Staged Combustor</u> (Figure 69)

   This design incorporates a primary stage sized specifically for optimum fuel-air ratio at idle. At higher power, the second (premixed) stage is fueled. Mixed-flow augmentor technology is utilized. While it is a radical departure from current main combustor design concept, it is expected to provide significant reductions in all emissions.

Testing of these concepts will begin in the fourth quarter of 1973.

Thus, a great deal of insight into the characteristics of exhaust emissions has been obtained, and new concepts have been developed. It is expected that one or more of these design approaches will allow the AST exhaust emissions goals to be achieved.

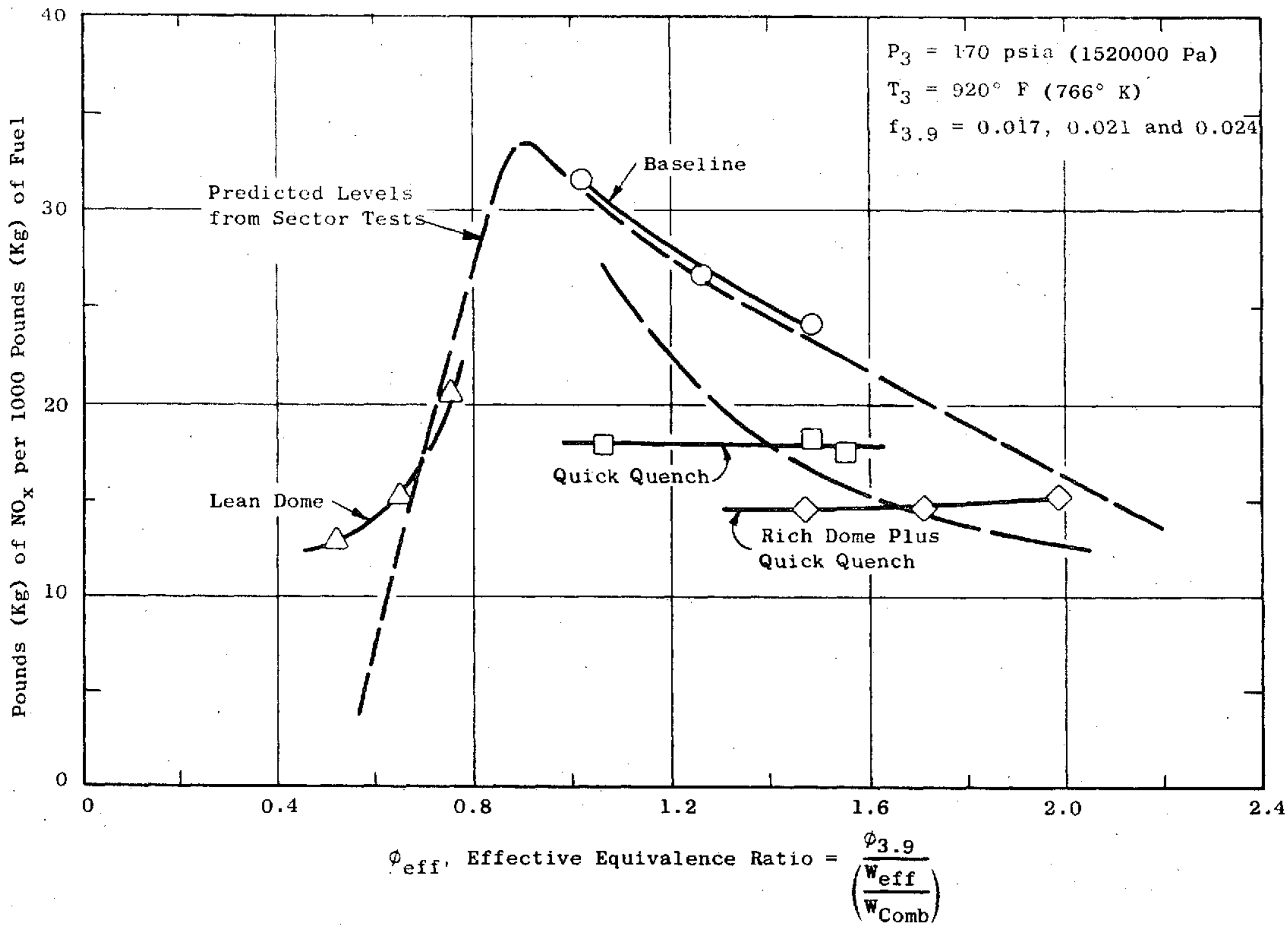


Figure 71. Comparison of Full-Annular and Sector Test Results.

RESULTS

A broad range of items have been investigated in an effort to identify system performance trends resulting from engine refinements, mission changes and noise footprints. Additionally, the military applicability of the variable cycle engine has been briefly assessed. This effort has resulted in the following observations.

- Duct burning turbofans with low bypass ratios (β = 0.5 - 1.0) yield lower relative TOGW than higher bypass ratio turbofans.

- Bypass ratios greater than approximately 2.5 result in mission relative TOGW levels that are unacceptable.

- Increasing the bypass ratio of the turbofan to approximately 2.0 to meet FAR-36-0 noise levels without jet suppression yields a small (~3%) increase in relative TOGW relative to the core suppressed baseline, low bypass ratio turbofan at comparable noise levels.

- The use of augmentation on takeoff for the duct burning turbofan offers a potential improvement of approximately 7% over the nonaugmented type at equal noise levels.

- Augmented takeoff requires jet suppression in the fan stream to maintain noise levels. The level of suppressor effectiveness is dependent upon the desired FAR level.

- The incorporation of variable turbine geometry in the duct burning turbofan has the potential of reducing relative TOGW approximately 2% with the majority of the improvement coming from the variability in the low pressure turbine.

- Jet exhaust suppression in the AST engines is the most efficient means of reducing noise level. For the bypass turbojet, 1 PNdB of suppressor effectiveness is equal to approximately 1 PNdB of traded FAR number below 10 PNdB of suppression. Above 10 PNdB of suppression, 1 PNdB of suppression yields approximately 0.63 PNdB traded FAR. For the turbofan utilizing suppression on both streams with equal efficiency, the effectiveness derivative would be essentially the same as the turbojet. The same is true for the three rotor, modulating airflow, variable cycle engine as for the turbofan.

- Variation of subsonic cruise leg length yields expected results in mission performance in that the turbojet range increases (~14%) with decreasing subsonic distance and improves to a greater degree than does the turbofan. Increasing subsonic leg length has the reverse effect in that the turbofan yields greater range values than the turbojet. Specific fuel consumption of the engines, subsonically and supersonically, is the primary cause for the trend. The turbojet, in all subsonic mission, would have its design range reduced approximately 20% while the turbofan range would be reduced approximately 16%.

- As supersonic L/D is reduced below design level, the trend for augmented engines is to increase relative TOGW approximately 15% per unit L/D and is due primarily to the need to increase thrust through augmentation. For a nonaugmented turbojet requiring upsizing to meet the thrust levels, relative TOGW would increase approximately 20% per unit L/D. As supersonic L/D is increased above the design level, relative TOGW reduces approximately 7% per unit L/D. This results from the reduction in augmentation temperature to coincide with the reduction in thrust requirement.

- In the event of an engine failure at the mid point of a New York to Paris mission, subsonic operation is assumed for the remainder of the flight which can be completed. Analysis indicates that subsonic cruise at the 0.95/35000 ft (10695 m) condition yields a greater range than operation at 0.5/5000 ft (1640 m).

- Noise footprint evaluations (90 EPNdB contour) have revealed that use of maximum jet suppression (~ 18 PNdB) on nonaugmented engines will yield footprints that are approximately 50% smaller than the 707-320B and 25% larger than the 747-200. 100 EPNdB contours exhibit approximately 75% smaller and equal areas respectively to the two aircraft. Using augmentation on takeoff in the duct burning turbofan increases the footprint area approximately 20% over the nonaugmented engine at the same traded FAR noise level. Increasing bypass ratio (to ~2.2) in conjunction with takeoff augmentation yields a 90 EPNdB footprint approximately the area of a 747-200. This is because of the larger engine airflow having a lower exhaust velocity. Footprints without cutback are approximately 15% larger than those with cutback due to the higher thrust levels.

- Military application of the modulating airflow, variable cycle engine in typical fighter and penetrator roles indicates an approximate 3 to 8% range improvement is possible and is dependent on base drag levels. These military engines would be approximately one-third the size of the AST engine.

- Utilizing combustor technologies being developed under research programs, the AST engines are predicted to be capable of meeting NASA emissions standards. With duct burners having inlet characteristics similar to those of main combustors at idle power, emission levels during augmented takeoff preclude meeting the NASA or EPA standards. Consequently, a new standard will have to be formulated or significant progress on augmentor low emission if augmented takeoff is to be used.

APPENDIX F

TASK VI - TECHNOLOGY EVALUATION

TECHNOLOGY TRENDS

The preceding five tasks of the AST Program have dealt with a wide range of engines at two technology levels. These engines have been evaluated through mission analysis to assess the effects of aircraft performance, mission profile change, and technology improvement on the type and relative performance on the engines. These Task efforts have yielded indications in the choice of engine design parameters in addition to trends in component and discipline technology. It must be stressed that these are indicators or trends and are generally applicable to required technology for the SST. Significantly additional analysis is required in all aspects of this study effort before a viable, attractive SST propulsion system can be identified which will necessarily require further advances in technology and design.

As in the previous national SST program, the major consideration and goal was a viable, economical aircraft capable of efficient operation over a prescribed mission with a given payload. The supersonic transport in the AST program has the same goals with two additional systems constraints imposed; an acceptable noise level of FAR Part 36 or below and an engine emission level compatible with standards proposed by the EPA for SST aircraft. From the engine viewpoint, technology advancements are required for most of major engine disciplines including technology levels for noise and emission to meet standards whose levels have not yet been specifically set. Figures 72 through 85 graphically illustrate some trends of salient engine technologies which are considered generally compatible to the AST generated designs. AST "interest areas" are superimposed on these General Electric Technology Planning Curves indicating the relationship of these areas to those of GE experience and advanced preliminary designs. Figures 86 and 87 exhibit similar information relative to noise and pollutant emission standards illustrating the need for additional development in these areas.

EVALUATION OF DISCIPLINES

The preceding curves yield some preliminary conclusions with regard to the readiness of the various major technical disciplines vital to the development of a propulsion system for an advanced SST. Many parameters either approach or meet the state of the art projected for the AST engine. However, much more development work must be accomplished to meet the required levels of weight, efficiency, life, reliability, cost necessary for an economically viable, civil SST for the 1980 time period. Figure 88 exhibits a graphical evaluation of these major disciplines corroborating the trends in that the noise and pollution (duct burner) emission technologies require significant development levels to meet the anticipated standards. Other technology items requiring development to support the engine design are in areas of high turbine temperature, advanced materials, nozzle performance, nozzle/thrust reverser/ suppressor design. One other salient item not discussed earlier is the technology

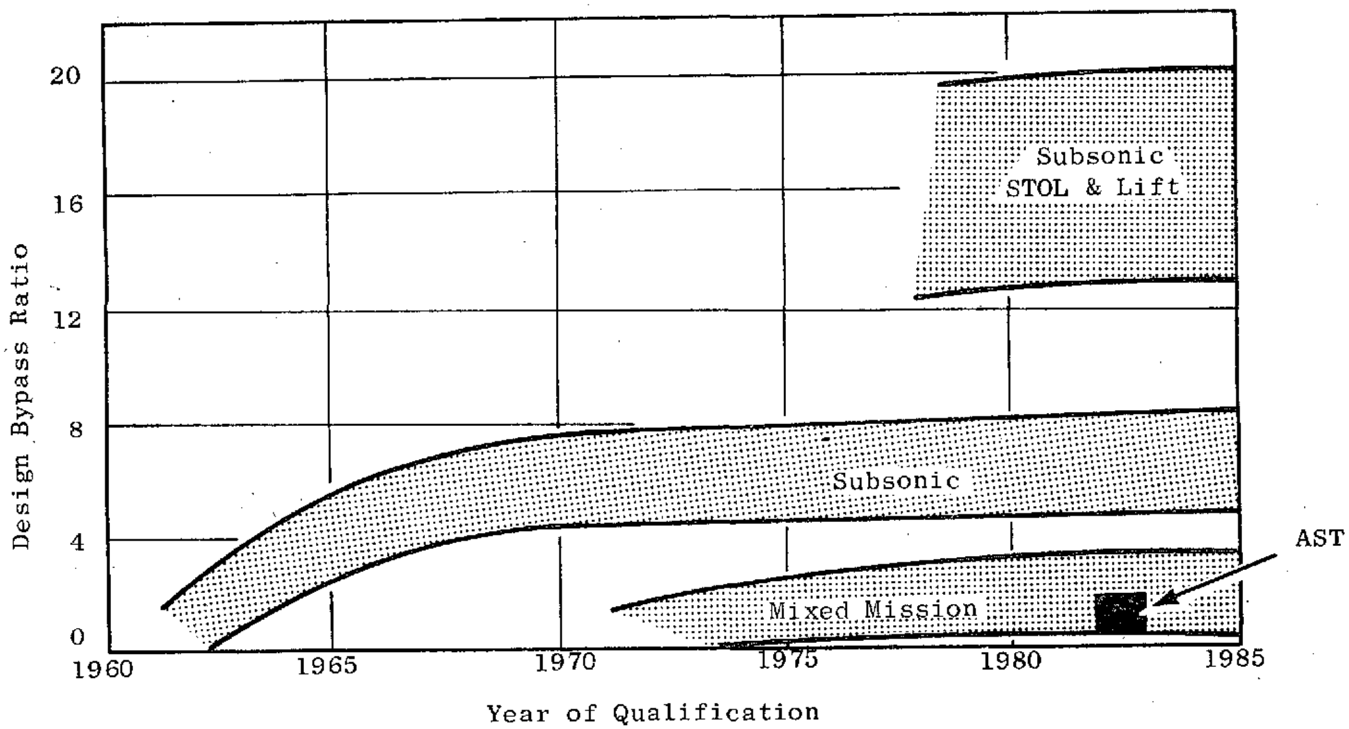


Figure 72. Technology Trends, Design Bypass Ratio.

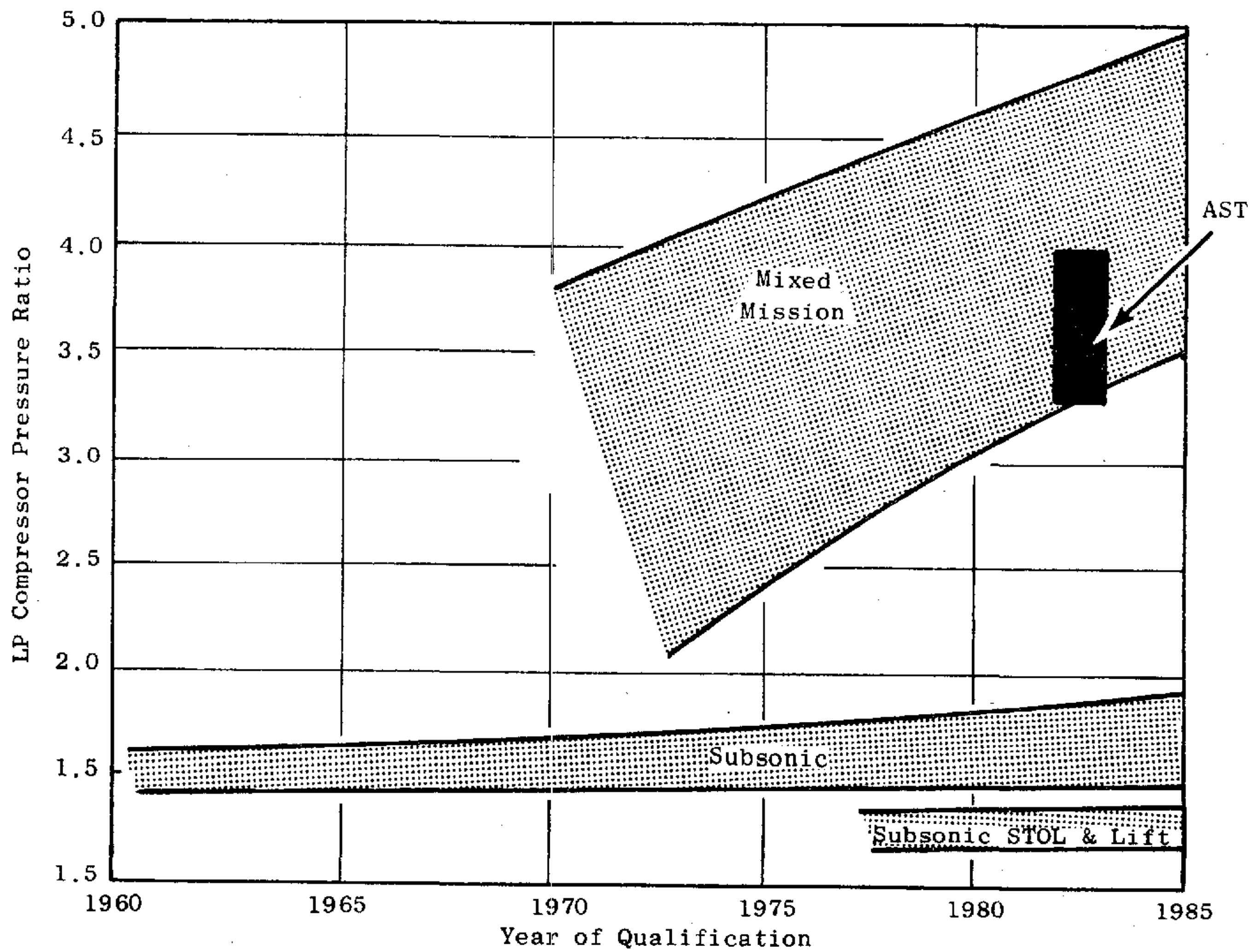


Figure 73. Technology Trends, Low Pressure Compressor Pressure Ratio.

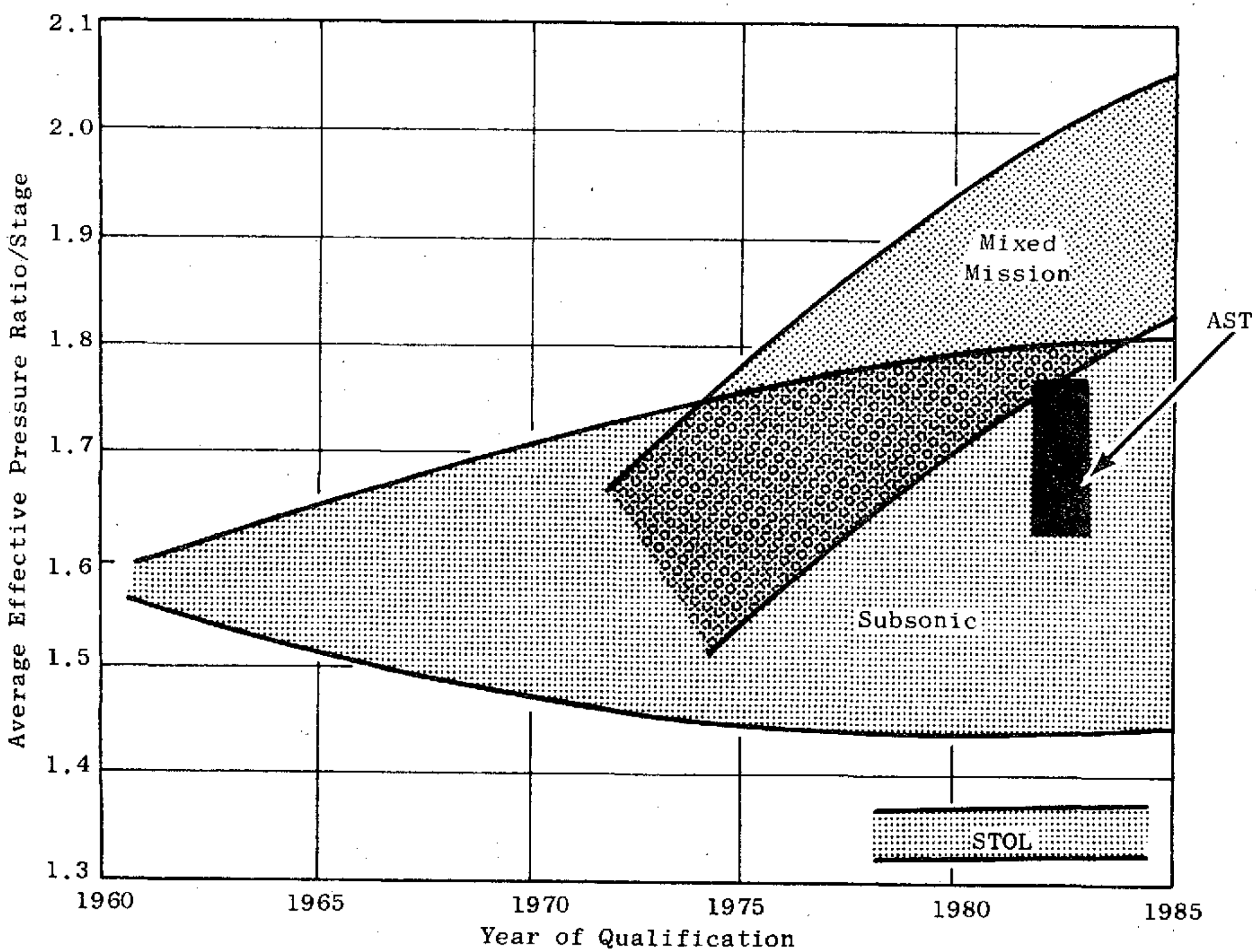


Figure 74. Technology Trends, Low Pressure Compressor Aerodynamic Performance.

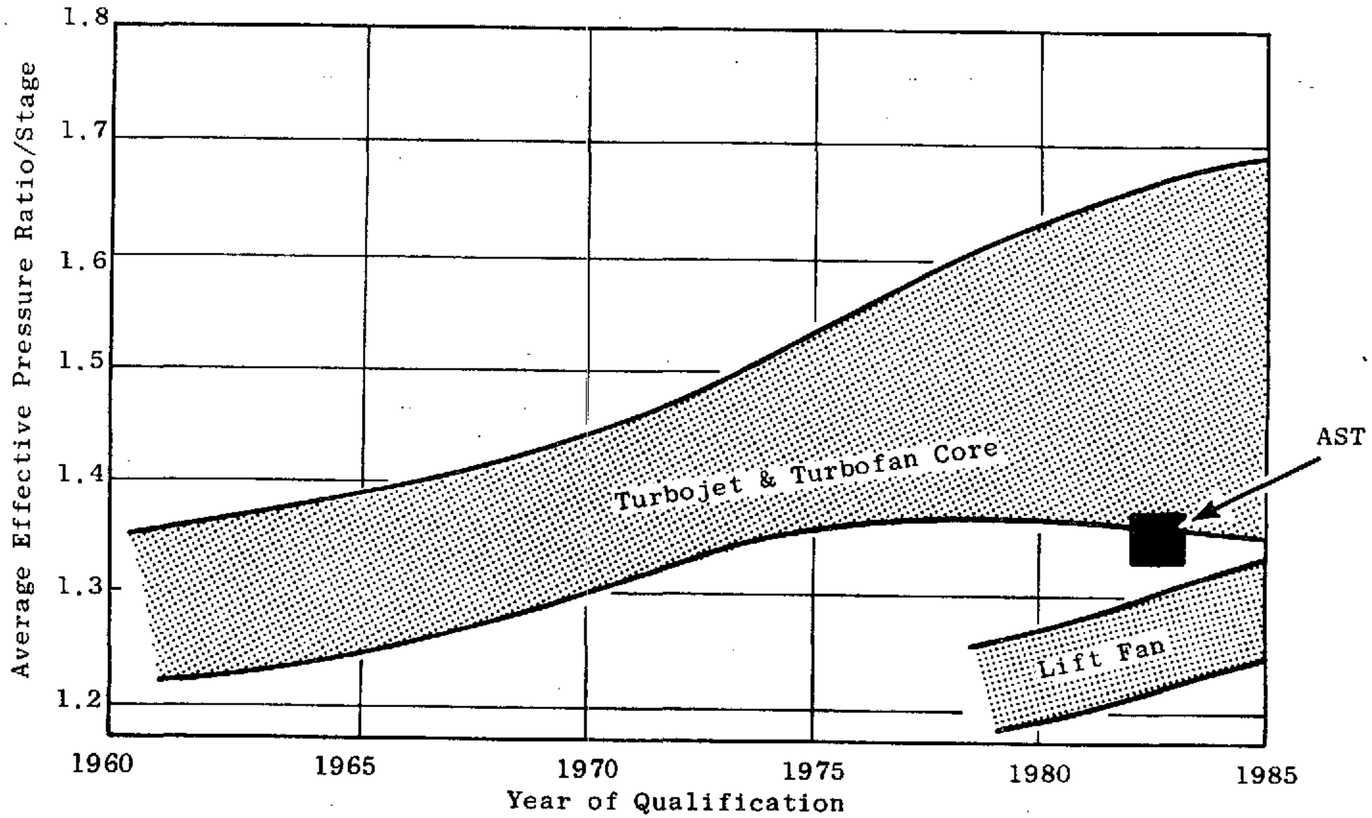


Figure 75. Technology Trends, High Pressure Compressor Aerodynamic Performance.

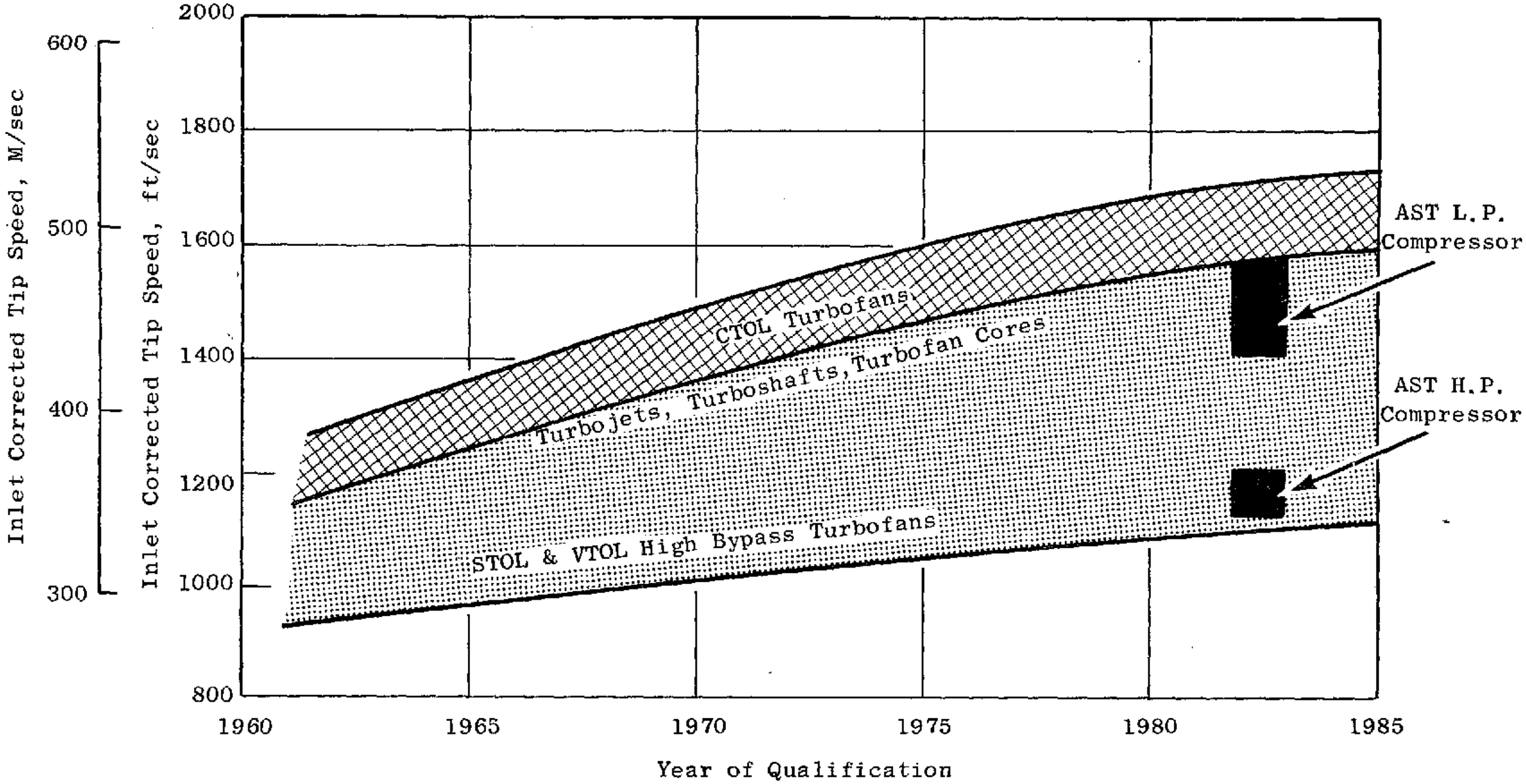


Figure 76. Technology Trends, Low Pressure and High Pressure Compressor Tip Speed.

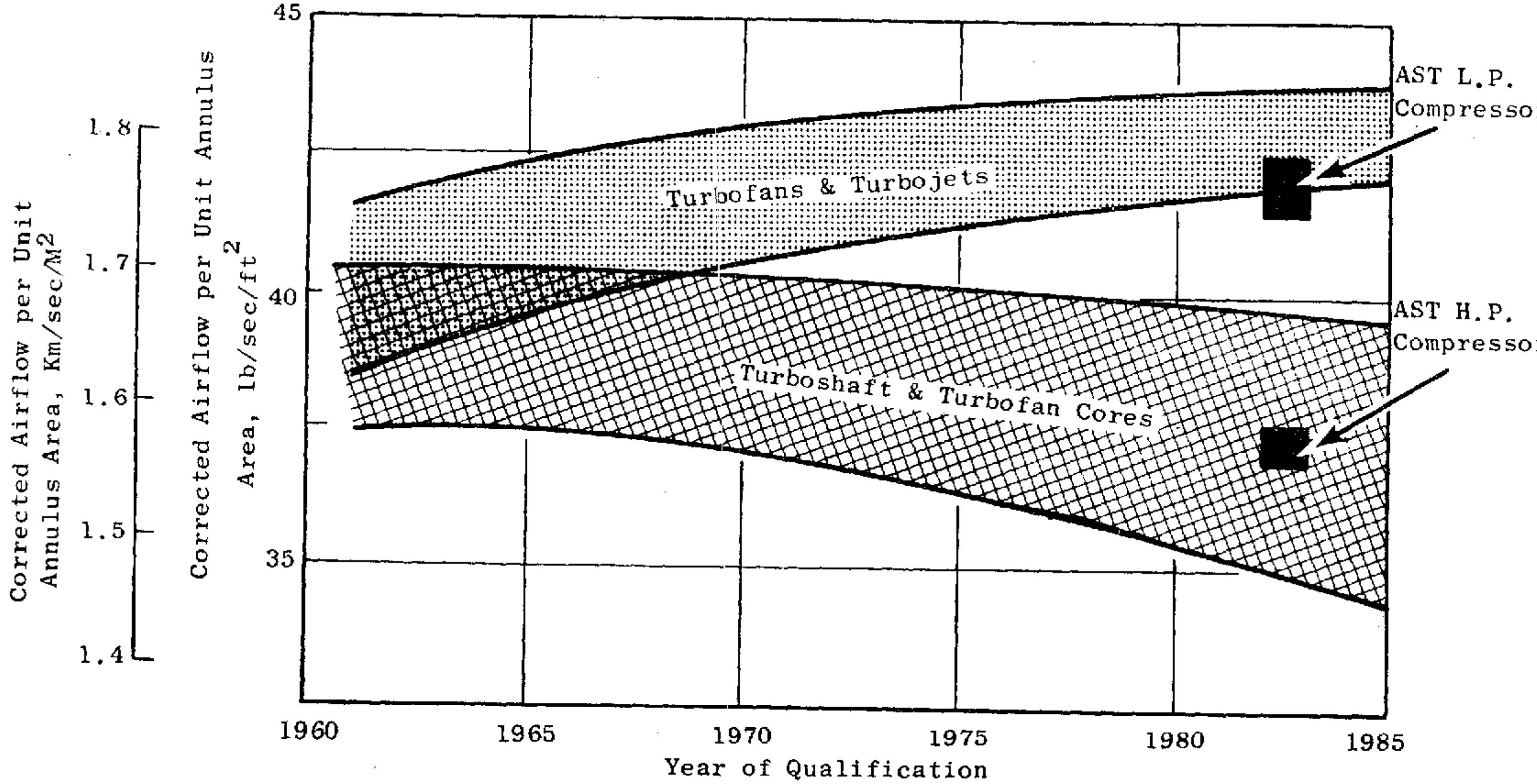


Figure 77. Technology Trends, Low Pressure and High Pressure Flow Per Unit Annulus Area.

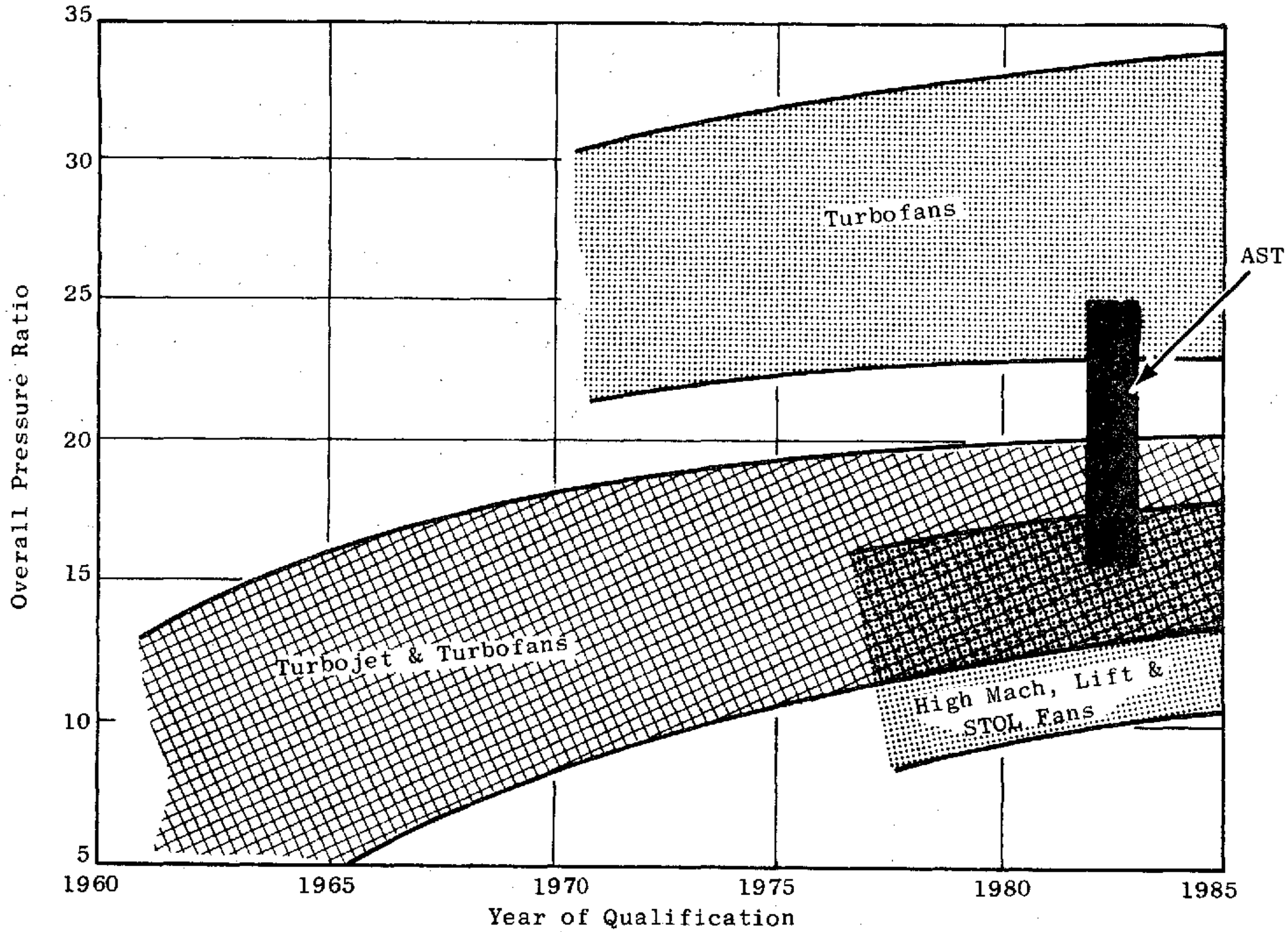


Figure 78. Technology Trends, Overall Pressure Ratio.

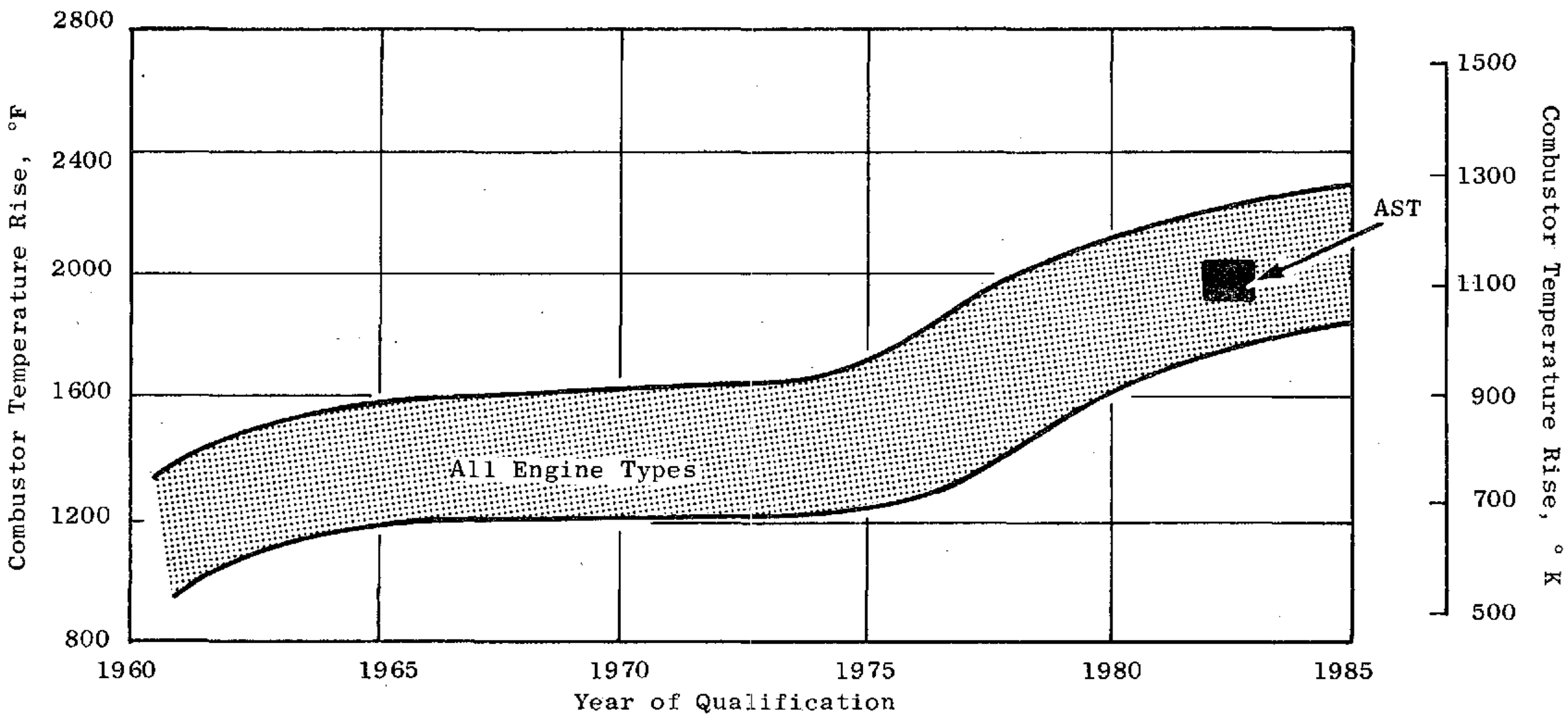


Figure 79. Technology Trends, Combustor Temperature Rise.

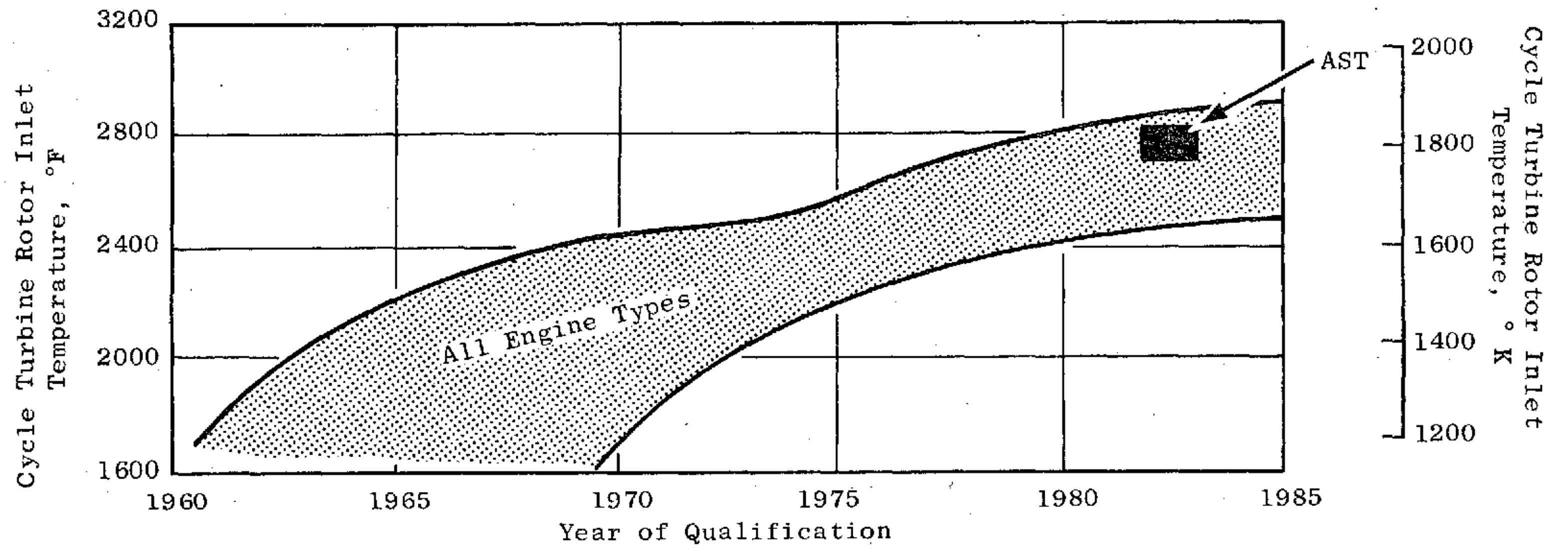


Figure 80. Technology Trends, Turbine Rotor Inlet Temperature.

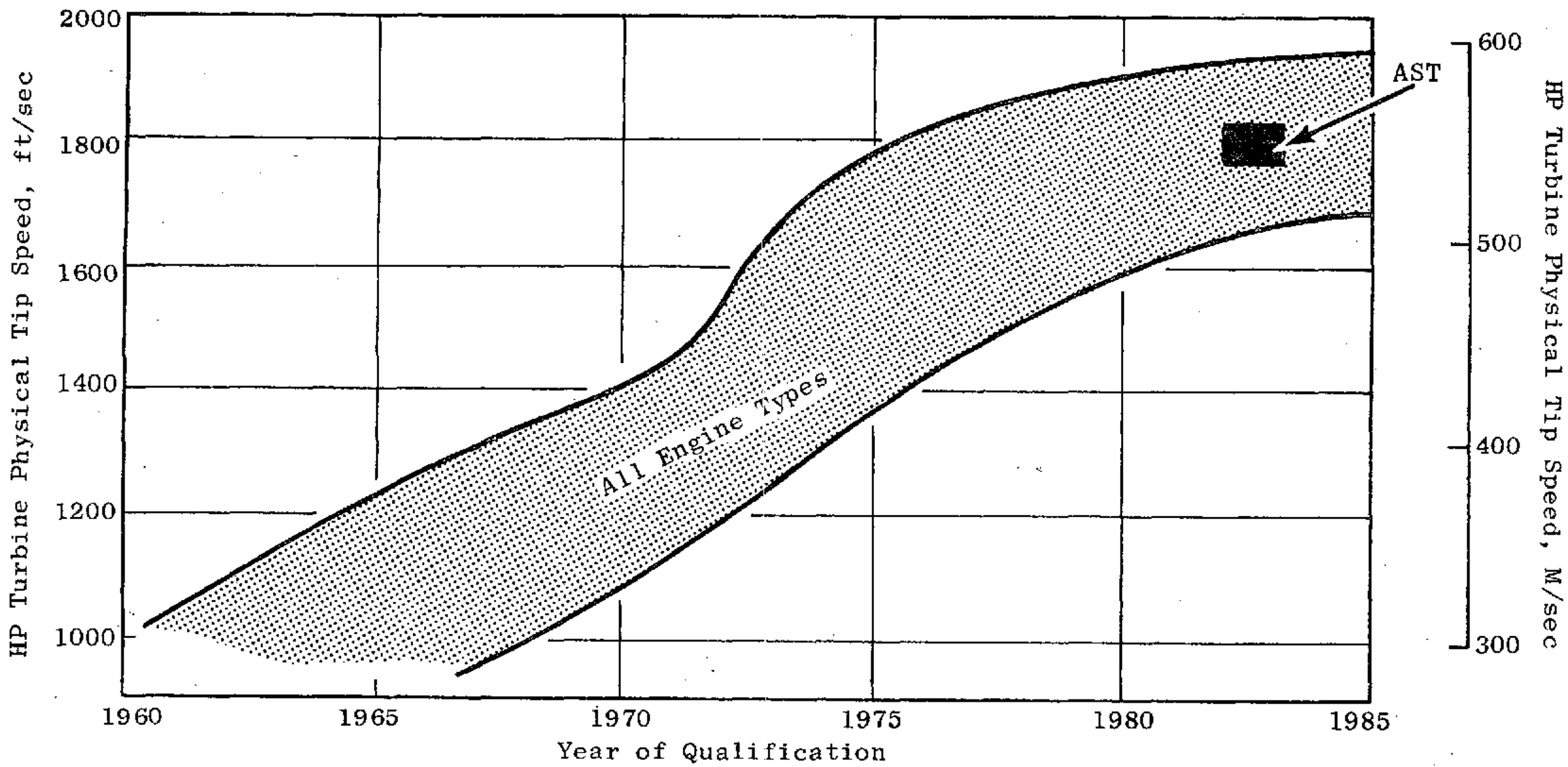


Figure 81. Technology Trends, High Pressure Turbine Tip Speed.

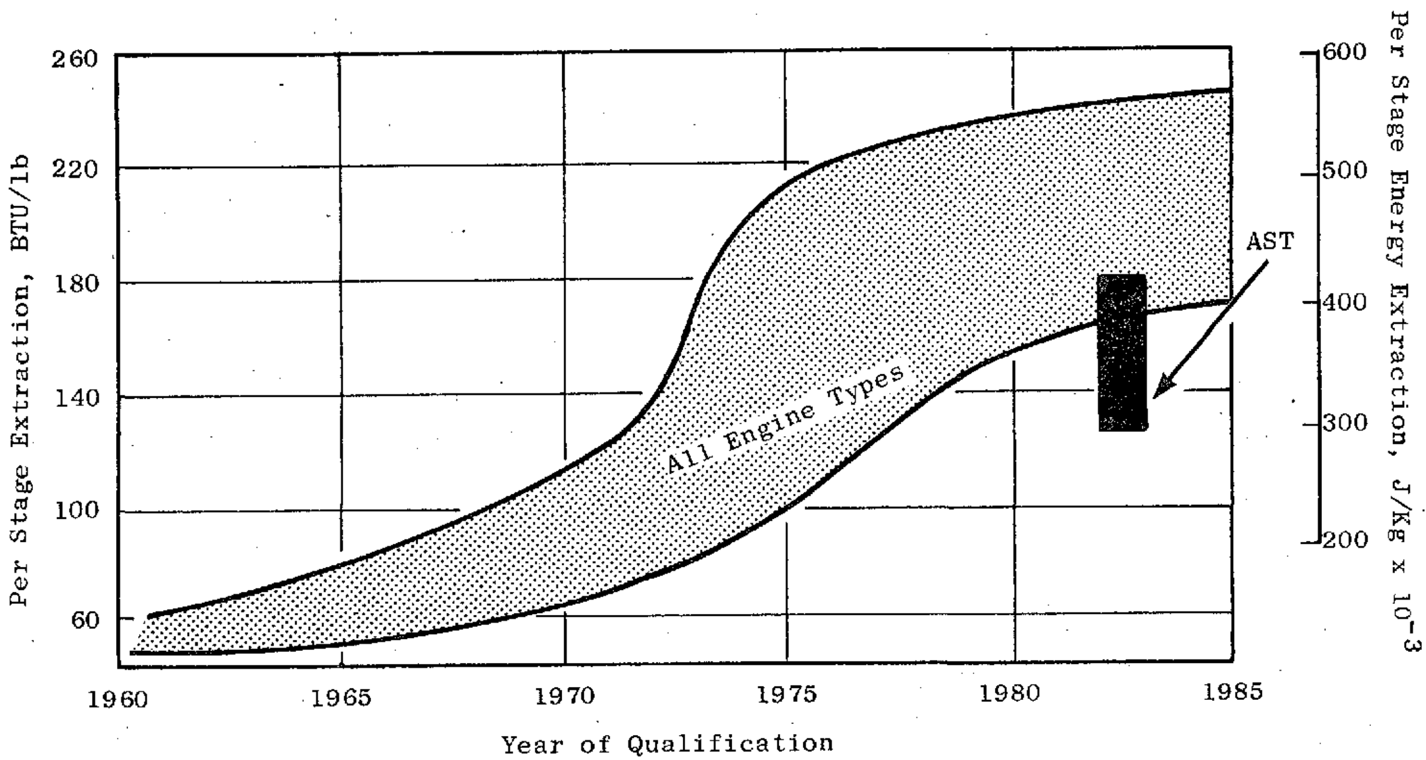


Figure 82. Technology Trends, Per Stage Energy Extraction.

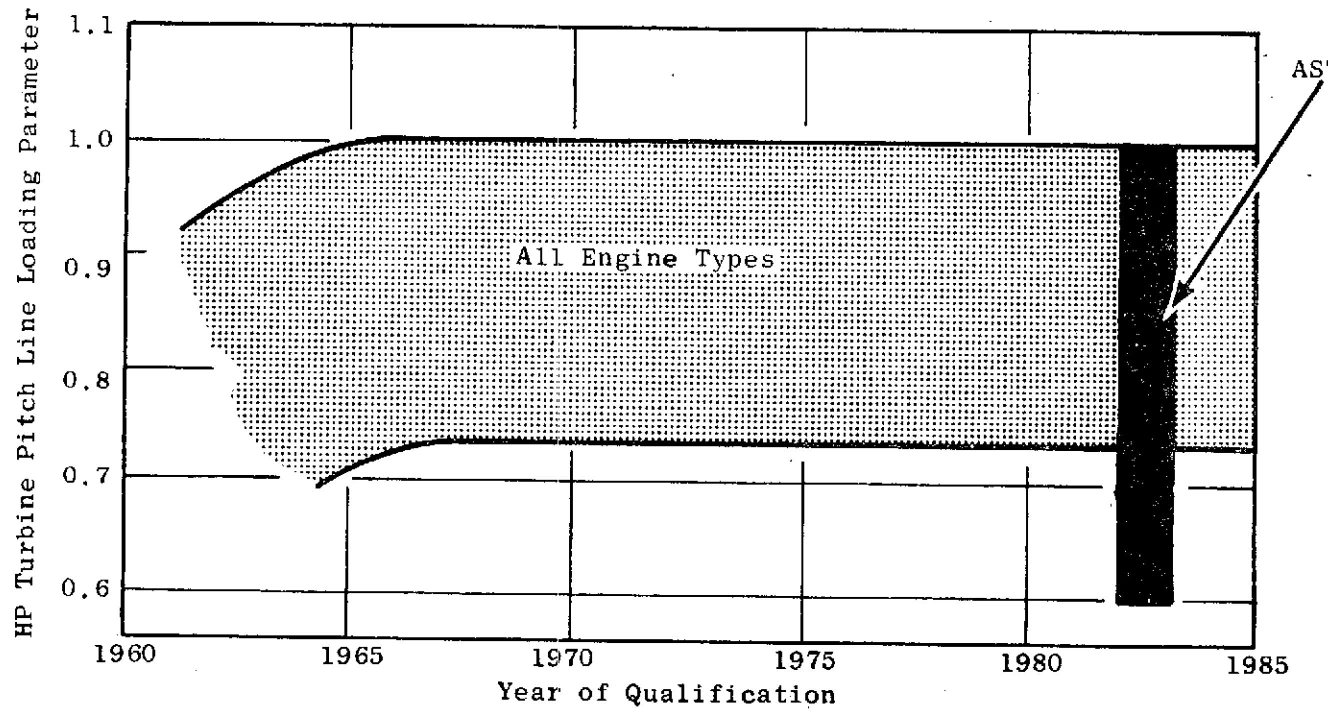


Figure 83. Technology Trends, High Pressure Turbine Pitch Line Loading Parameter.

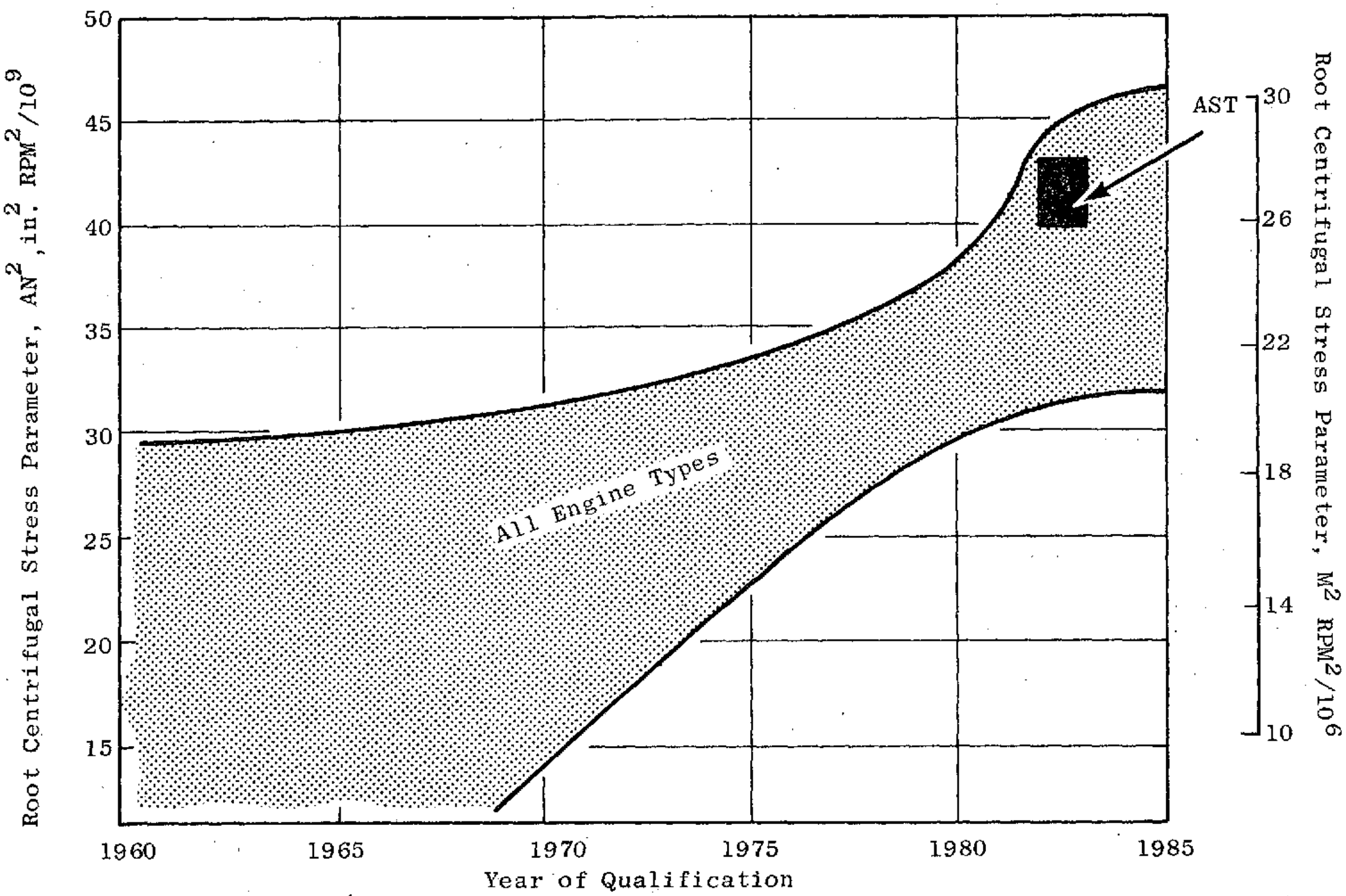


Figure 84. Technology Trends, Turbine Root Centrifugal Stress.

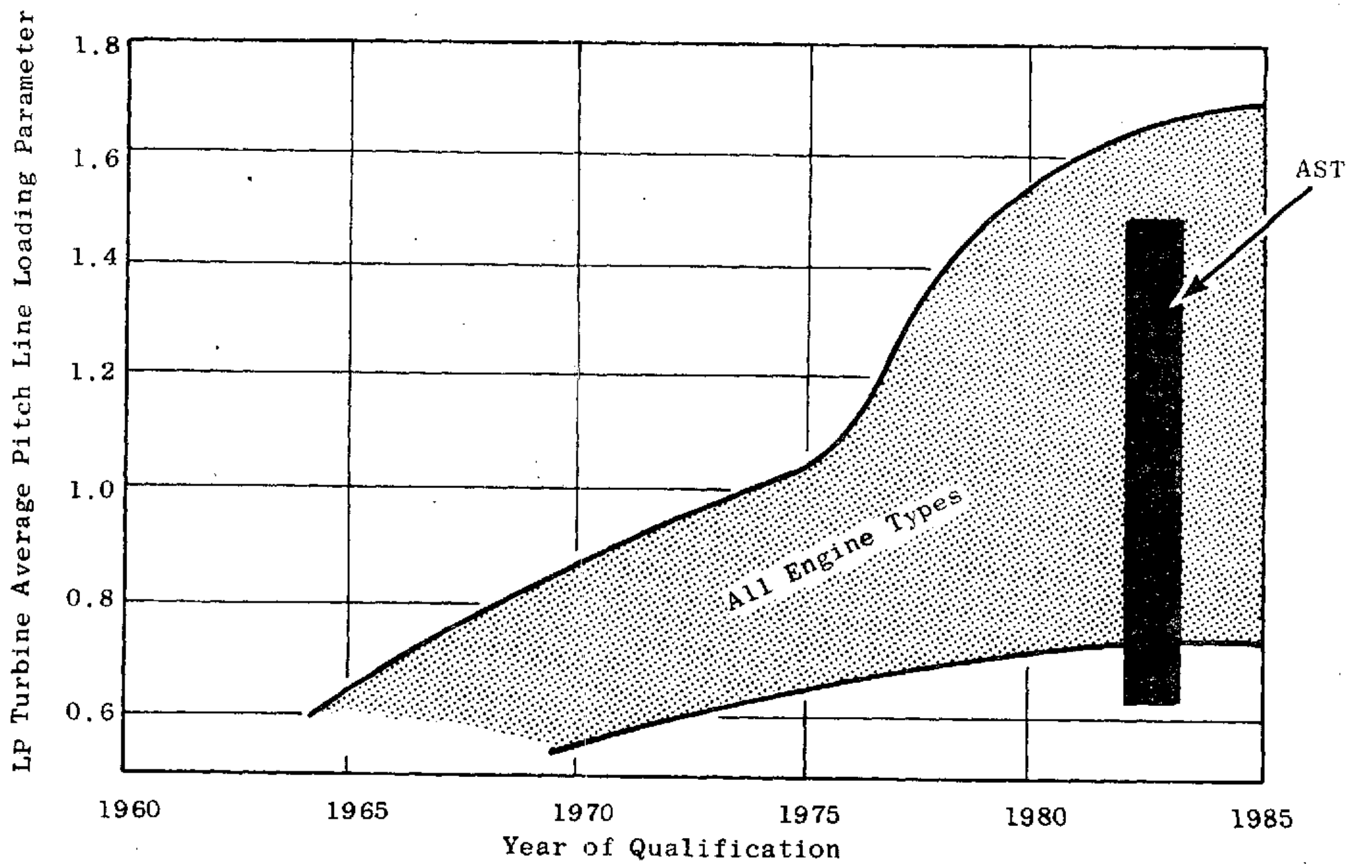


Figure 85. Technology Trends, Low Pressure Turbine Average Pitch Line Loading Parameter.

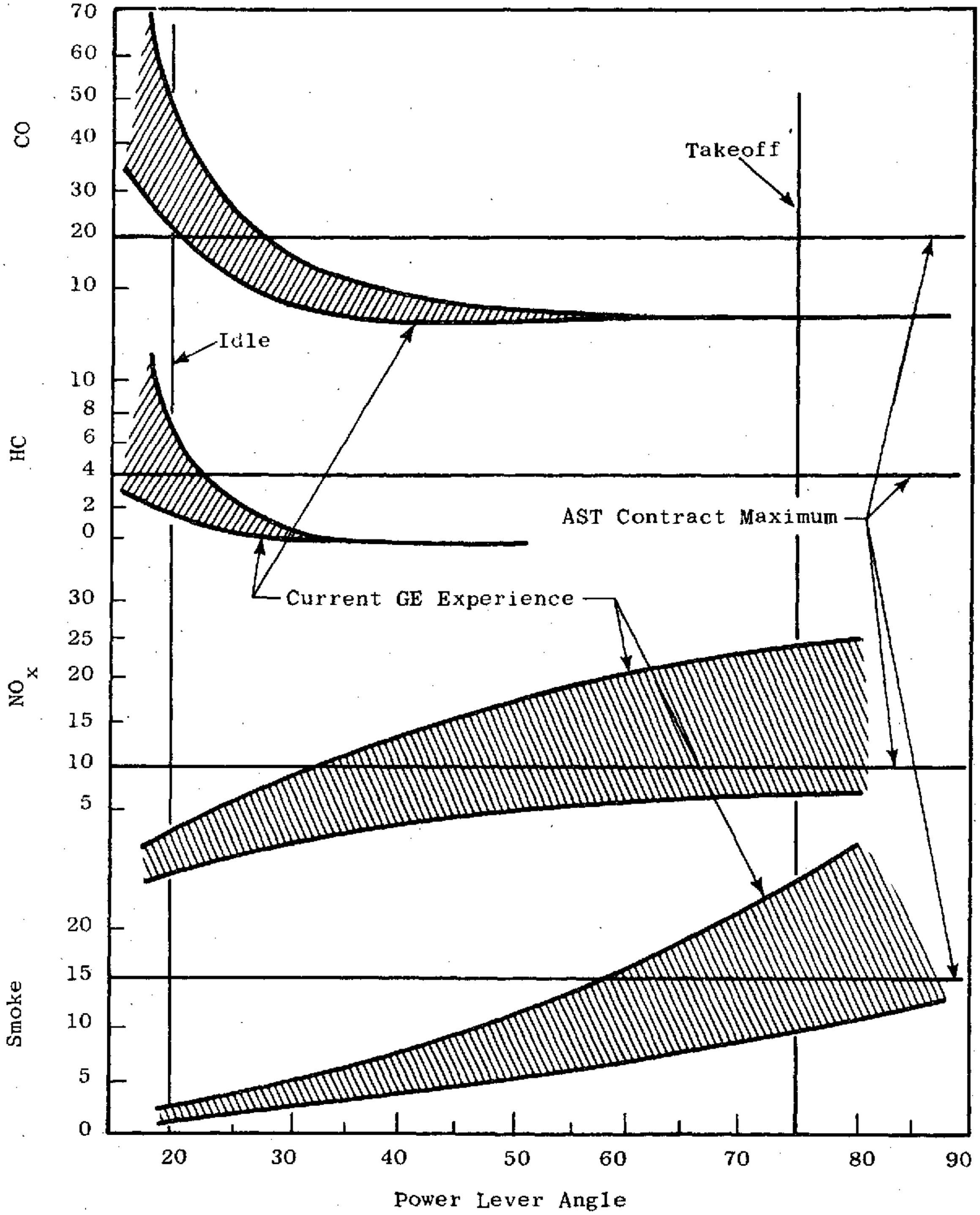


Figure 86. Technology Trends, Combustion Emissions.

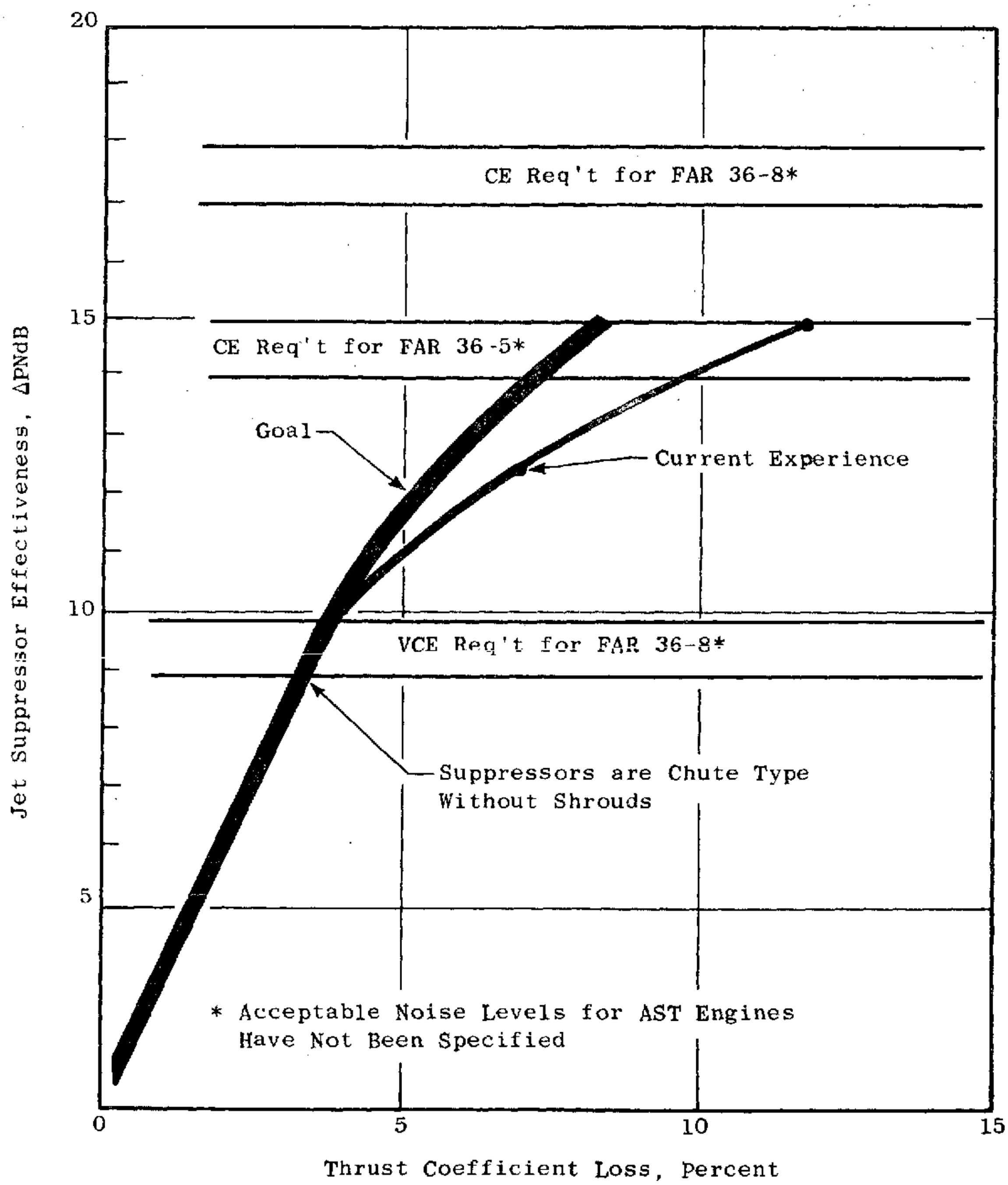
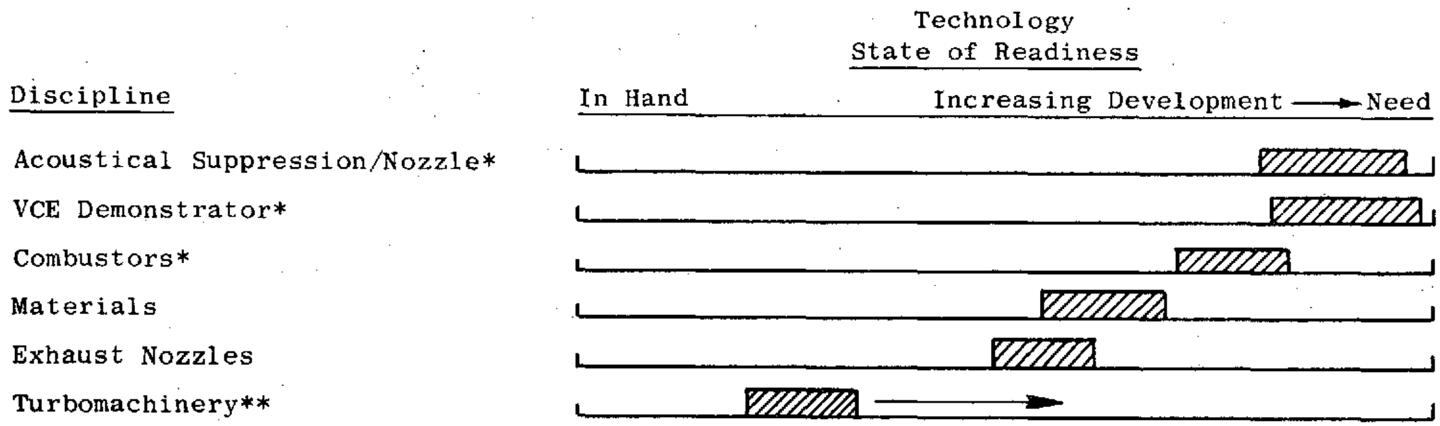


Figure 87. Technology Trends, Inflight Jet Suppressor Effectiveness.



* Development Items Specifically Required for AST

** Choice of VCE for AST Development Would Increase Emphasis on This Technology Item

Figure 88. Evaluation of Technical Disciplines of Primary Need for Commercial SST.

required to demonstrate the variable cycle concept and is indicated as an area requiring major development. This is predicated on the possibility that a variable cycle engine of some type becomes the preferred means of AST propulsion.

Consequently, as indicated on Figure 88, noise suppression, combustion emissions, and variable cycle demonstration are the items requiring primary development effort that apply specifically to the AST engines. Additional critical development items were stated previously. The remaining disciplines, also requiring significant levels of development, are considered to be available in the time period proposed for initiation of engine design. Additional comment is required on turbomachinery.

Dependent upon the type of variable cycle engine concept chosen for AST development, the turbomachinery discipline could conceivably increase in development importance. Studies indicate that the better performing variable cycle concepts require variable geometry throughout the design requiring consideration of variable low pressure compressor stators and variable stators in the turbine area, both high and low pressure. Additionally, a three-rotor system may also require consideration.

RECOMMENDED DEVELOPMENT

The preceding comments and discussion have presented the considerations and needs in the area of AST technology/disciplines and enable recommendations to be made with regard to development of these disciplines.

Itemized below are the items of primary need and recommended for development with specific areas under each requiring attention. In order of priority:

- Acoustical Suppression
  - Jet suppressors, aero and acoustical performance
  - Integration of suppressor to nozzle concept
  - Suppression of the remaining engine noise sources

- VCE Demonstration
  - Variable turbine geometry
  - Three-rotor systems
  - Triple-flow annular exhaust nozzle

- Combustors
  - Duct burner, thermal performance and emissions
  - Main combustor emissions

- Materials
  - Eutectic
  - Composite
  - High temperature

The first three items yield benefits specifically for the AST program while the last technology area, being applicable generally to all engine types, will benefit the AST engine development appreciably. Programs, adequately funded and strategically timed, should be initiated to assure having the necessary information at the time of engine detail design inception.

Other technology items requiring development for the assurance of a viable commercial SST propulsion system were stated previously and are reiterated to emphasize the need for these additional disciplines in the propulsion system design.

PRELIMINARY PROGRAM PLAN

To assure having the required technology, both discipline and degree, development programs designed to accomplish this end must be initiated and funded. Resulting from the earlier discussion, three major AST programs and several minor ones are required that are considered vital to the development of a viable SST engine. These in addition to the related programs that are underway and expected to be continued in the near future are exhibited in Figure 89.

At this point in time, these estimates are considered to be crude at best and should include the additional discipline development programs mentioned earlier. Better estimates of program timing and cost are precluded until a propulsion system that would lead to an economically viable SST is identified. Definition of the "best" engine system is not possible within the earlier time frame stated by NASA and is noted as such on Figure 89.

The benefits accruing from these programs are significant in terms of reduced aircraft TOGW and traded FAR noise levels. However, in relation to the overall program costs, the expenditure for these technologies cannot be accurately assessed since this is dependent upon the engine type chosen.

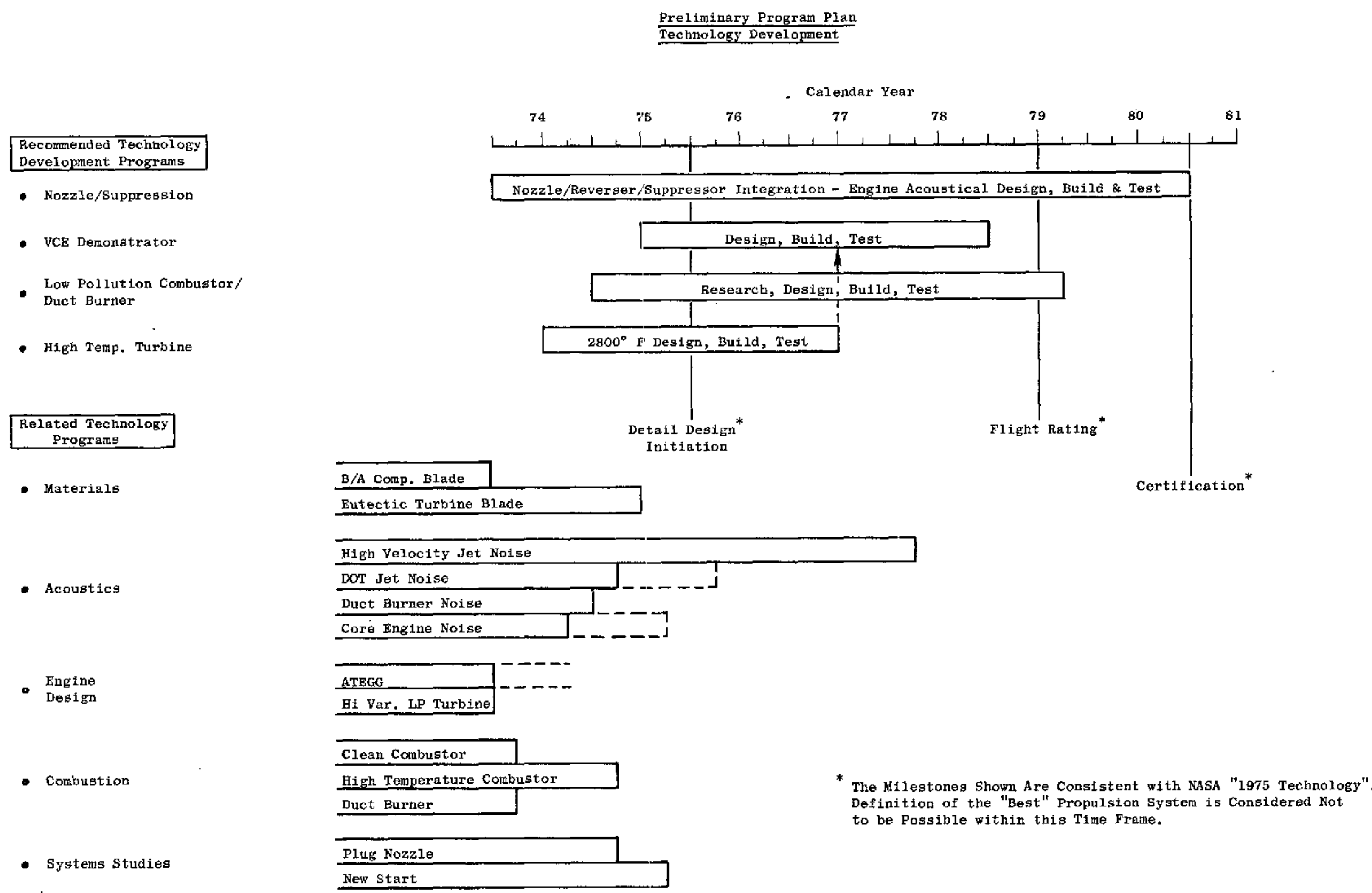


Figure 89. Preliminary Program Plan, Technology Development.