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NOISE CONTROL TECHNOLOGY EVALUATION FOR SUPERSONIC TRANSPORT CATEGORY AIRCRAFT

July 1980

Prepared for:

U.S. Environmental Protection Agency
Office of Noise Abatement and Control

Under Contract No. EPA 68-01-4488

This report has been approved for general availability. The contents of this report reflect the views of the contractor, who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of EPA. This report does not constitute a standard, specification, or regulation.

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16. ABSTRACT

Noise control technology applicable to supersonic transport (SST) category aircraft is evaluated in view of the restraints of the Noise Control Act of 1972, which restricts both the EPA and the FAA to noise regulations that meet considerations of "safety, economic reasonableness, technological practicability, and appropriateness to type of aircraft." The effect of such constraints on the design goal for second-generation SSTs is considered.

The report contains five sections. Section 2 develops a basic perspective on the noise of subsonic and supersonic aircraft and the general relationships between their airframe and engine performance characteristics, noise certification standards, and noise impact. Section 3 summarizes the status of individual elements of noise control technology including engine, aerodynamics, and operational procedures. Section 4 reviews some of the integrated airframe-engine noise integration studies, and Section 5 attempts to summarize where noise and the SST stand with respect to technology.

This report is based on information developed and made available prior to Fall 1978.

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SUMMARY

The assessment of technology related to the noise of future Supersonic Transport Category Aircraft is a most difficult and complex task. The difficulties result from the plethora of data and opinions which have come from a wide variety of groups addressing an equally wide variety of engine and airframe design concepts and design time frames. The only consensus of opinion and evidence appears to be that the Concorde and its forseeable derivatives cannot be expected to meet the FAR Part 36 Stage 2 noise limits.

For new designs initiated in the near future, opinions diverge, although much of the opinion of USA technical personnel is that the Stage 2 noise limits can be met, perhaps with only a small economic penalty. However, there is concern relative to the adequacy of the design margins required to insure meeting of guaranteed or certificated noise performance requirements.

For new designs initiated in the mid 1980's there appears little doubt that the Stage 2 noise limits can be met, again with a small economic penalty, although the vehicle would have much better overall economic potential than either Concorde or the best new design initiated in the near future. Such new designs incorporate "future" or "Class 2 and 3" technology which offer significant improvements in overall vehicle aerodynamic, engine, and noise performance.

There is only a small amount of evidence and opinion that new designs of the mid 1980's could meet the Stage 3 noise limits. This lack of evidence and positive opinion results primarily from three factors:

1) The majority of the design and conceptual development studies have focused on Stage 2 limits as either a goal or constraint, and only a few studies have examined the implications of meeting Stage 3 limits. Stage 3 limits impose relatively more difficulty on SST category aircraft than on the subsonic category aircraft, whose aerodynamic performance and engine exhaust velocity requirements are more condusive to quieter operation.

2) The Stage 3 limits and test requirements, as currently stated, are based on the performance characteristics (aerodynamic, engine, and noise) of subsonic aircraft with high bypass engines. Their intent is to constrain the noise of aircraft, not only within the measurement boundary, but beyond, as well, to a much larger area when the majority of the noise impact is experienced. However, because of their origin they do not necessarily provide an appropriate design constraint to minimize total noise impact of an aircraft category that has rather different performance characteristics.

3) There appears to be no generalized conceptual noise goal for supersonic transport category aircraft which relates SST noise performance (or impact) and its probable operational time frame with the needs of the airports from which it might operate.

Each of these three factors should be addressed, as appropriate, in the various R & D programs which are related to supersonic cruise vehicles. The goal of this effort should be to produce the information necessary to develop noise rules which lead towards optimization of the design performance of supersonic transport category aircraft with respect to the environmental needs.

Unless these factors are addressed in a timely fashion, the possibility of initiation of an aircraft design that will only meet Stage 2 limits is increased. The result could easily be the development of an aircraft which begins operation in the 1990's with a noise impact considerably in excess of any other new aircraft of its time frame. Operation of such an aircraft could not only negate much of the progress made in reducing the impact of aircraft noise on airport neighbors, but also could provide an obvious focal point for the public's concern for noise reduction. This possible outcome could lead to operational restrictions that would severely penalize the economic and public transport service potential of the aircraft.

1. INTRODUCTION

This report has been developed in response to an Environmental Protection Agency (EPA) task order requesting an evaluation of noise control technology applicable to Supersonic Transport (SST) category aircraft. To date, SST category aircraft have tended to be noisier than subsonic aircraft when operating in the vicinity of an airport, particularly during takeoff. The Federal Aviation Administration (FAA) has recently amended its noise regulations to include the existing fleet of 16 Concorde SSTs under many of its provisions and to control the noise of any future new aircraft of that type to the levels of the original rule for subsonic aircraft [192-194].

It is generally agreed that the design goal for second generation SSTs be to make them compatible with contemporary future subsonic aircraft, but the means for stating this goal quantitatively and in regulatory framework are elusive and without consensus. Under the Noise Control Act of 1972, EPA has the responsibility to recommend regulatory actions to the FAA for its consideration [187], and the FAA also has the responsibility to develop regulations that will minimize aircraft noise for the benefit of public health and welfare. However, both organizations are constrained by the Act's admonition that any noise regulations be subject to considerations of "safety, economic reasonableness, technological practicability, and appropriateness to type of aircraft." Some of these constraints are particularly difficult to consider with respect to future SSTs.

First, many people question the economic viability of the existing SSTs and those that were proposed in the past. The imposition, through regulation, of any additional economic penalties or risks could have a disproportionate significance in the event that the SST design was in fact economically marginal; or could be a significant factor in preventing the initiation or continuation of a truly viable SST program.

Second, technological practicability is often demonstrated in full-scale flight certificable hardware. Such a full-scale demonstration is difficult with SST noise control technology, primarily because of the absence of a hardware development program, either civil or military. Consequently, much of the proven practicable technology appropriate to SST aircraft is constrained to be that already in service. Proof of newer technology will require a hardware-oriented program for its development and test.

These constraints make it difficult to translate the noise objectives for future SSTs into regulatory language. But unless some way is found, there can be no guarantee that the next SST design will produce an aircraft that will be compatible with other aircraft at its time of entry into service.

1.1 Background

In the late 1950s, the United Kingdom and France initiated design studies for a civil SST aircraft. In 1962, they formally merged their efforts and by 1965 had finalized the design of the Concorde. The first prototypes flew in 1969 and the production aircraft entered airline service in 1976. Sixteen aircraft have been produced and no more are believed to be planned for construction. The Concorde carries up to 128 passengers over a transatlantic range of up to 3450 nautical with a cruise Mach number slightly in excess of 2.0 [188].

During the 1960s, developments were undertaken in both the USSR and the USA. The USSR effort resulted in the design of the TU-144 aircraft, which has entered limited service within the USSR. This aircraft is similar to the Concorde in its general size and performance characteristics [188].

The US effort to develop a civil SST aircraft began in 1963 and was terminated in early 1971 by the Congress, for a combination of reasons including:

- potential destruction of upper atmosphere ozone layer which protects the earth from ultraviolet radiation
- uncertainty of the economic viability of the design when put in service
- concern over the precedent of Federal participation and subsidy of a commercial venture
- airport noise and sonic boom.

At the time the program was cancelled, the prototype aircraft (Boeing B2707-300) was into final design design stages and some hardware had been constructed. The design was intended to carry 270 passengers over a range of 3550 nautical miles at a cruise speed of Mach 2.7.

Some of the technology development items from the US SST program were carried forward by the FAA, together with NASA and industry. In 1972, NASA developed a formal advanced Supersonic Technology (AST) program, now called Supersonic Cruise Aircraft Research (SCAR). Its overall objectives were to provide:(67)

Note: For additional information on Concorde and SST programs see references 14,15,17,1825,31,46,50,137,165,172,203 and 207.

- expanded technology base for future civil and military supersonic aircraft
- data needed to assess environmental and economic impacts on the US of present and future foreign supersonic transport aircraft
- a sound technical basis for any future consideration that may be given by the US to the development of an environmentally acceptable and economically viable commercial SST.

This program has generated a large number of interrelated system studies by both industry and NASA in the fields of propulsion (including noise) stratospheric emissions impact, structures and materials, aerodynamic performance, and stability and control. [40,136,151,152,205] The propulsion and aerodynamic studies are of particular relevance to technology assessment of SST noise control technology.

The noise goals for the Concorde aircraft development were to *not create a noise exceeding the level then accepted for the operation of subsonic aircraft,* a resolution of the International Civil Aircraft Organization (ICAO) in 1962 [177]. It did not meet this generalized goal, and, consequently, for takeoff it is the noisiest aircraft in the civil fleet. Further, by the time it entered service in 1976, new subsonic aircraft with high bypass ratio engines were demonstrating significant noise reductions over the subsonic aircraft of 1962. Thus, the Concorde, by comparison, appears relatively even noisier than anticipated or intended.

The noise reduction demonstrated by the new subsonic jets was a result of the technology advances in the 1960s and the promulgation in 1969 by the FAA of the first noise standards for the aircraft type certification for subsonic aircraft [186]. These standards were applied to the last version of the US SST in 1970 by recommendation of the SST Noise Advisory Committee. Their imposition necessitated a major redesign of the aircraft to ensure compliance.

The 1969 standards, now called Stage 2 noise limits, were superceded in 1977 by even more stringent limits, called Stage 3 limits, for new subsonic turbojet aircraft applying for type certification after November 1975 [195]. Recently, the FAA has promulgated a regulation which includes the existing Concordes under several provisions and applies the Stage 2 noise limits to all other civil SST aircraft [194].

The US is actively working with the ICAO Committee on noise and its working group E to develop internationally acceptable standards for future design SSTs. Working group E has defined a "common case" SST design objective for which the member nations will conduct noise and economic tradeoff studies for both current and future assumed technology. This information is of major relevance to this report [72-122].

It is recognized that if design of a new SST aircraft were initiated now, it would not enter service until 1990. At such time, an SST meeting Stage 2 noise limits would be noisier than the aircraft now in production, and much noisier than the aircraft meeting Stage 3 limits expected to be in production in the early 1980s. Therefore, the current regulation does not ensure that the noise characteristics of future design SSTs will be compatible with contemporary aircraft at the date of entry into service.

1.2 Frame of Reference for Technology Definition

These are two sets of definitions for the time frame availability which are used in this report, one used by the EPA and the other developed by ICAO CAN working group E for its studies.

The EPA definitions give three categories of technology; current, available, and future. Their definitions are:

- *Current technology* includes "shelf item" hardware and commonly known (state of the art) techniques and procedures which have been used effectively by most manufacturers for many applications.
- *Available technology* includes "shelf items" hardware and commonly known (state of the art) techniques and procedures which have been used effectively by some manufacturers for some applications. Also included are the results of RD&D which have not been put into practice but are available for implementation. Some performance testing may still be necessary but this technology has been certified for airworthiness or, by adequate ground and/or flight testing, determined to be capable of being certified.
- *Future technology* represents the outcome of RD&D programs now in progress which have not been verified but the results to date indicate high potential to a reasonable degree of confidence. Included are

present RD&D programs which are being conducted with sufficient resources of manpower, funding, and time to carry to programs to conclusion. Definitive results are expected in the relatively near future for acoustical and operational performance, economics, and flight safety. The nature of the expectations is positive because predictions of nonviable results would have been cause for earlier termination of the RD&D programs.

The ICAO-CAN-WG-E definitions give three classes of technology which are specified by the time frame that the technology would be expected to be available for use in initial design [78]. The classes are defined as:

- The Class I technology is the technology which is considered as established such that a manufacturer might rely on it to start design and development of a supersonic aircraft between 1977 and 1980. For some items, qualification is needed and will be given in the text.
- The Class II technology is the technology which is likely to be established (if the ongoing works confirm today's expectations) such that a manufacturer might rely on it to start design and development of a supersonic aircraft between 1980 and 1985.
- The Class III technology is that which will probably not be established before 1985 to the extent that a manufacturer could rely on it for design and development start of a supersonic aircraft.

A preliminary assessment by the working group gave the following interpretation to power plant and aerodynamic technology items relevant to this report (see Table 1-1).

A comparison of the EPA and ICAO definitions indicates approximately that "current" technology would be contained in Class I; available technology in Class I or II, depending on the time status of the item; and future technology in Class II or III, again depending on time status. It should be recognized that the assessment of any item of technology depends to some extent on the subjective viewpoint of those making the assessment. For example, a manufacturer is likely to be much more conservative in his assessment of availability and performance of an item if his assessment is to be used in developing a regulation or performance guarantee. Conversely, a design analyst conducting a system tradeoff to optimize the potential of a new design is less likely to be conservative, because excess safety margins inconsistently scattered among design elements tend to result in optimization trends which may be misleading; consequently, the "best estimate" is often used uniformly throughout the study process.

1.3 Organization and Time Frame of the Report

There are five sections in the body of this report. Section 2 develops a basic perspective on the noise of subsonic and supersonic aircraft and the general relationships between their airframe and engine performance characteristics, noise certification standards, and noise impact. Section 3 summarizes the status of individual elements of noise control technology including engine, aerodynamics, and operational procedures. Section 4 reviews some of the integrated airframe-engine noise integration studies, and Sec. 5 attempts to summarize where noise and the SST stand with respect to technology.

This report is based on information developed and made available prior to Fall 1978. Because the research effort for improved supersonic cruise aircraft is continuing, additional new findings may be anticipated, many of which may be expected to provide improved potential performance relative to that of "available" or Class 1 or 2 technology.

TABLE 1.1. PRELIMINARY ASSESSMENT OF SELECTED ITEMS OF TECHNOLOGY FOR SST BY CLASS (FROM ICAO CAN WGE [78]).

	Class I (1977-1980)	Class II (1980-1985)	Class III (Beyond 1985)
A. Powerplant			
1. Engine cycle and other items			
- Turbojet/fan	Low bypass ratio		Duct burning, variable cycle engine
- Turbine entry temperature (in cruise)	1450/1500°K	1500/1600°K	> 1600°K
- Improved compressor/turbine aerodynamic efficiency	Continuous Improvements		
- Variable geometry	Available for nozzle or stator components	Extension of the concept	Advanced as needed for VCE
- Nozzle efficiency	Continuous Improvements		
2. Engine noise reduction			
- Compressor design criteria	Continuous Improvements		
- Acoustical treatments (low temperature)	Continuous Improvements		
- Turbine design criteria	Some improvement	Further Improvements	
- Combustion noise reduction	N/A	N/A	Available
- Acoustical treatments (high temperature)	Limited	Increased Use	
- Jet noise:			
a. Opening primary nozzle	Available	Available	Available
b. Flows mixing	Marginal	Increased	
c. Retractable silencers	N/A	Available	Available
d. Coannular flows	N/A	N/A	Available
- Engine installation	N/A	N/A	Available
- Air intake acoustical treatments	Continuous Improvements		
B. Aircraft Aerodynamic Performances			
- Higher L/D (in cruise and at T.O.	Continuous Improvements		
- Movable L/E slats	Continuous Improvements		
- Low drag pods	Continuous Improvements		
- CCV concepts	Continuous Improvements		
- Improved design methods	Continuous Improvements		
- Variable sweep wings	N/A	N/A	N/A
- Moustaches (Canards)	Continuous Improvements		
- T/E flaps	Continuous Improvements		
- Eddy generated lift	Continuous Improvements		

2. PERSPECTIVE: SUPERSONIC VS. SUBSONIC AIRCRAFT PERFORMANCE AND AIRPORT NOISE

The performance and noise characteristics of aircraft designed for supersonic cruise differ in many aspects from the characteristics of aircraft designed for subsonic cruise. This section summarizes some of the most significant differences.

2.1 Performance

The aerodynamic and propulsion characteristics of supersonic aircraft are primarily dictated by the requirements for supersonic cruise. An SST aircraft, such as the Concorde illustrated in Fig. 2-1, has a slender fuselage and a highly swept wing of quasi triangular or delta planform. In comparison to the subsonic B-747, illustrated in Fig. 2-1, the Concorde has a much lower aspect ratio (wingspan $\div \sqrt{\text{wing area}}$). It does not have leading edge flaps for increased low speed lift as does the B-747. Its engines are afterburning turbojets which have very high speed jet exit velocity whereas the B-747 has high bypass ratio turbofan engines with a relatively low jet exit velocity. These differences, resulting from both mission and design date of technology, directly affect the noise characteristics of these aircraft.

The lift-drag ratio (L/D) (lift force ÷ drag force) of selected subsonic and supersonic cruise aircraft is illustrated in Fig. 2-2a. In the subsonic regime the subsonic aircraft have significantly better values than does the Concorde. Through the transonic region (Mach 0.9 - 1.1) the L/D of Concorde drops by about one-third because of the wave drag associated with transonic and supersonic flight. The result of the variation of L/D with Mach number is that the cruise L/D of Concorde is less than one-half the value obtained by an advanced subsonic design such as the B-747 and

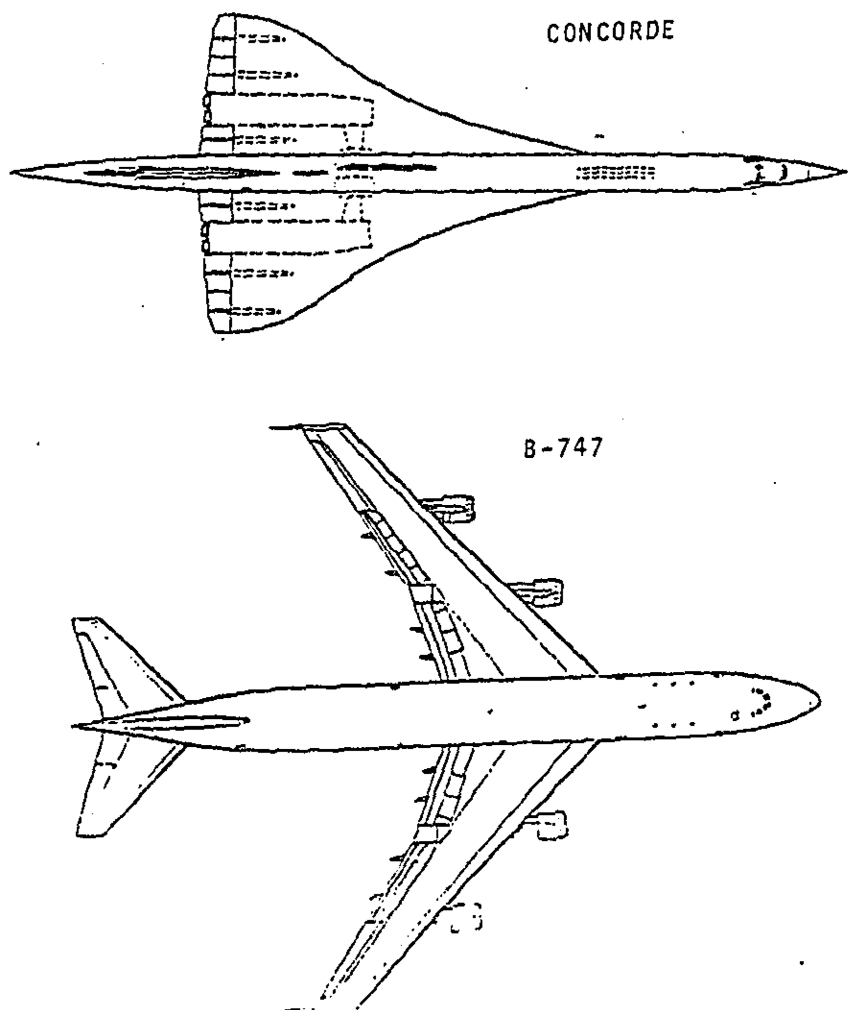


FIG. 2.1 PLANFORMS OF SUPERSONIC CONCORDE AND SUBSONIC BOEING 747 AIRCRAFT.

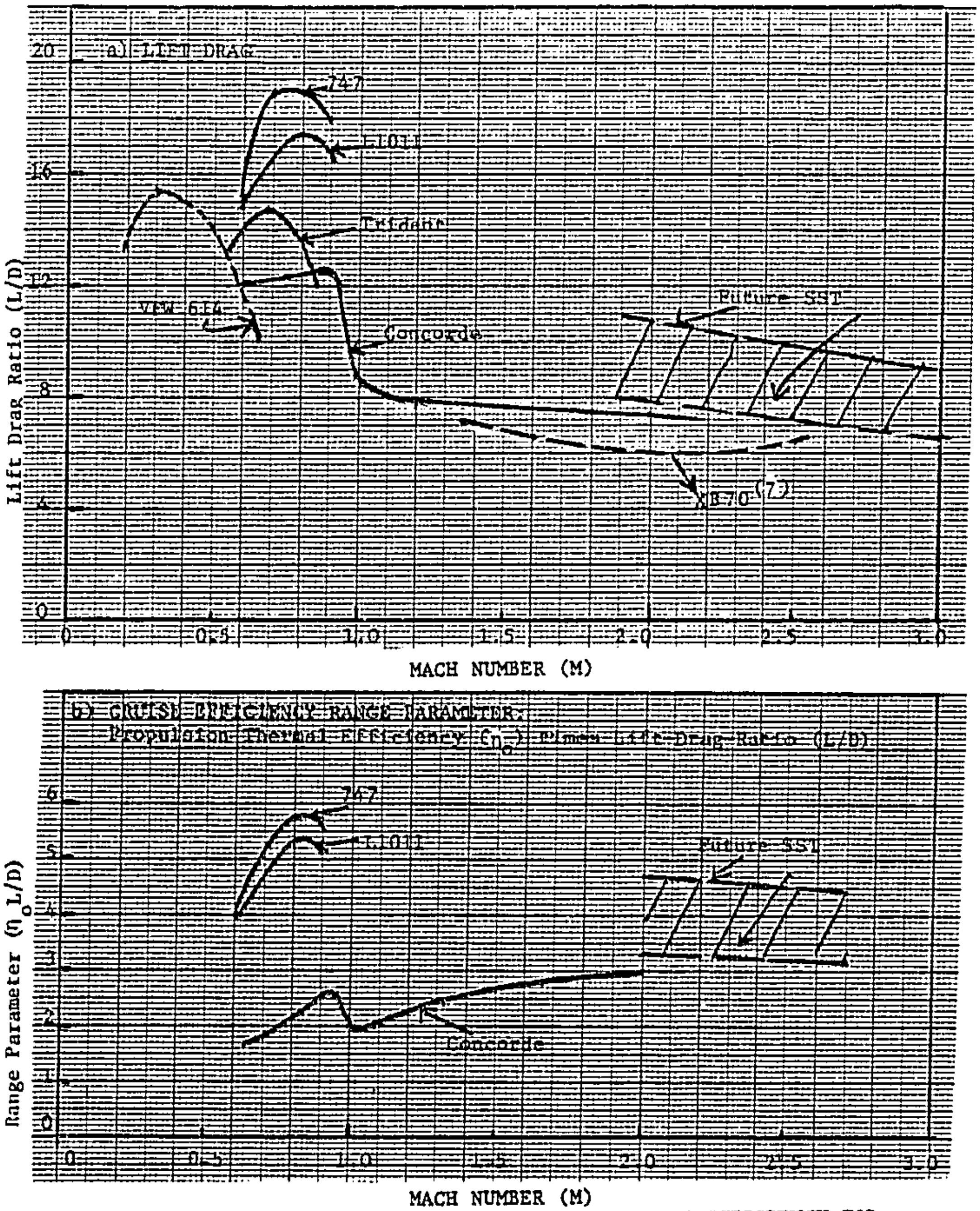


FIG. 2.2 COMPARISON OF THE LIFT DRAG RATIO AND CRUISE EFFICIENCY FOR SELECTED SUBSONIC AND SUPERSONIC AIRCRAFT. (Refs. 7,28 & 29)

L-1011. Thus, at cruise the Concorde requires over twice the propulsive net thrust per unit aircraft weight than that required by an advanced subsonic aircraft.

The thermal efficiency of the Concorde engine is higher than that of an advanced subsonic turbofan engine, 41% vs. 33%. This increase of power plant efficiency mitigates somewhat the poorer L/D of the Concorde in determining the amount of fuel required to achieve a stated mission range. Figure 2-2b illustrates the range parameter, which is the thermal efficiency times the L/D ratio, for some of the aircraft in Fig. 2-2a. Although the Concorde's range parameter performance is considerably below that of advanced subsonic aircraft, the potential performance of "future" supersonic cruise aircraft is estimated to be much closer to that of the advanced subsonic aircraft [28].

For its design range of 3150 nautical miles (n.m.), Paris to New York, the Concorde's fuel load is about 50% of its 400,000 lbs. takeoff weight. Of this 50%, 9% is reserve and 41% is consumed. The passenger and baggage payload is 25,000 lbs or 6% of takeoff weight (TOW) and the operating empty weight is 44% of TOW. An early model 747 which had a maximum TOW of 775,000 lbs could carry a full passenger and baggage payload of 80,000 lbs (10% of TOW) for 5400 n.m. The fuel carried is approximately 42% of TOW, and the operating empty weight is 48% of TOW. If the payload of this model B-747 is increased to 20% of TOW, the range is reduced to 4200 miles, and the total fuel carried to 32% of TOW.

These comparisons clearly show the overall performance penalty to the Concorde relative to the 747 that results from Concorde's lower value of L/D. Additionally, for a transatlantic mission Concorde's payload is very sensitive to any addition of weight to the aircraft. For example, a 1% addition to TOW caused by an increase in either operating empty weight or fuel carried would reduce the payload from 6% to 5% of TOW, a reduction of 17% in payload.

Table 2.1 summarizes values of lift-drag and thrust-weight (F/W) ratios for takeoff and cruise for the Concorde, B-747 and L-1011 aircraft. The Concorde requires a higher F/W for takeoff and has a much lower L/D than either subsonic aircraft. Both of these factors tend to increase noise, i.e. a larger power plant and a lower angle of climb. The ratio of cruise to takeoff thrust for the Concorde is about twice that of either of the two subsonic aircraft. This difference implies that the optimum engine cycles could be expected to differ significantly between the two types of aircraft.

Examples of engine performance as a function of bypass ratio for supersonic and subsonic cruise are presented in Fig. 2-3. The specific thrust (net thrust ÷ mass flow) for the supersonic cruise mission at a zero bypass ratio is about 63% of that for the subsonic engine, and at a bypass ratio of five is about 47%. The specific fuel consumption (SFC) (fuel weight consumption per hour ÷ net thrust) for the subsonic engine decreases with increasing bypass ratio. This decrease of SFC is the major reason for the use of high bypass ratio engines (4 to 5) on subsonic jets. However, for supersonic cruise, the SFC has a slight minimum at a bypass ratio of 1.3 and increases for higher values of bypass ratio. Thus, for supersonic cruise, only bypass ratios in the range of zero to 1.3 warrant design consideration — the optimum determined after considering the increase in engine weight with increased by-pass ratio and the savings of fuel weight and other factors.

TABLE 2.1

COMPARISON OF LIFT TO DRAG (L/D) AND THRUST TO WEIGHT (F/W) RATIOS FOR THREE AIRCRAFT

AIRCRAFT	Max Gross Weight (1000 lbs)	TAKEOFF			CRUISE			THRUST RATIO
		Mach No.	L/D	F/W *	Mach No.	L/D	F/W	Cruise / Takeoff
Concorde	400	0.30	4.0	0.38	2.0	7.4	0.14	0.36 (0.42 w/o A/B)
L1011	430	0.24	9.8	0.29	0.85	17.0	0.06	0.20
B747	775	0.24	9.0	0.25	0.85	18.5	0.05	0.22

*Takeoff thrust is sea level static (SLS); cruise thrust is actual required net thrust.

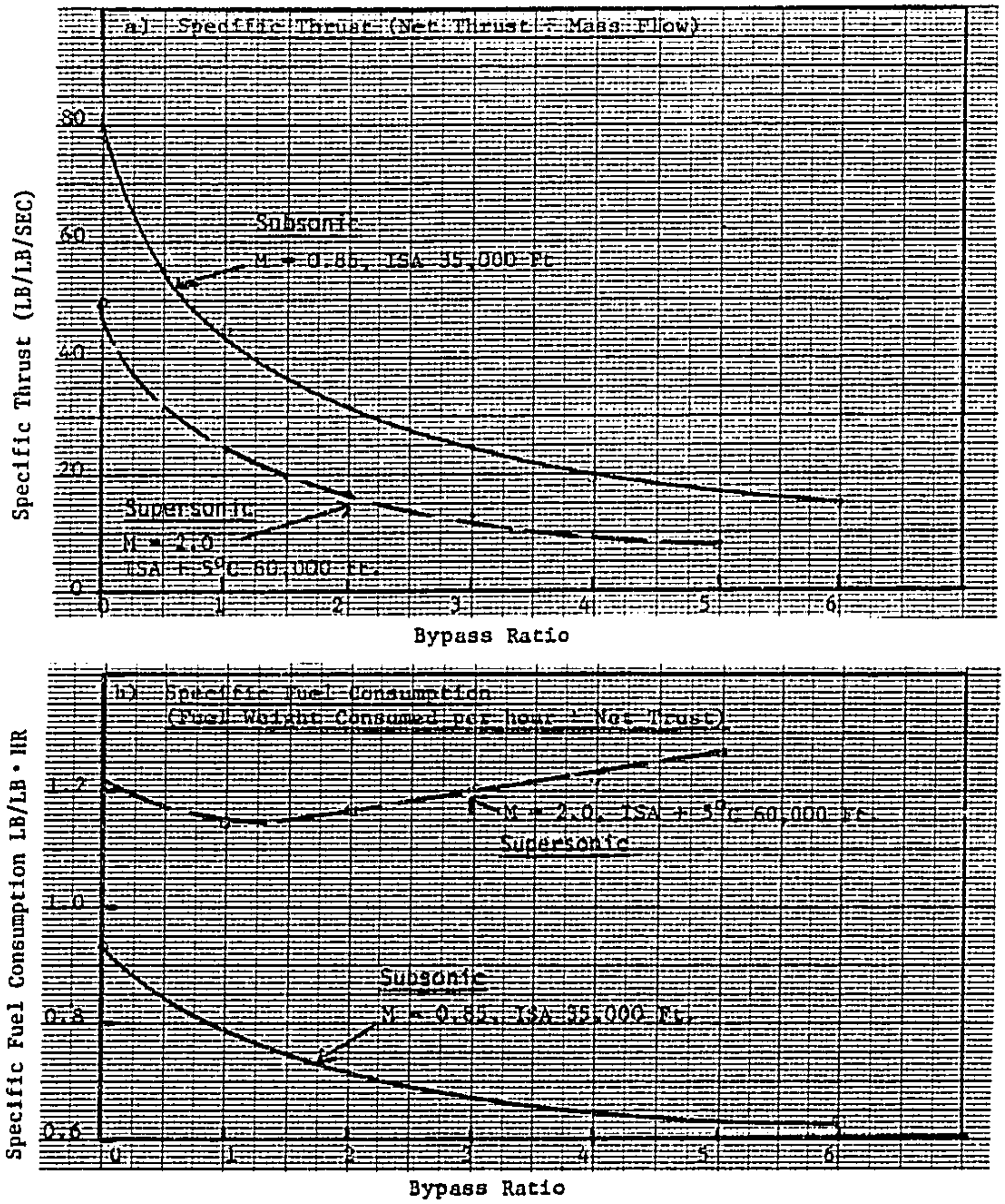


FIG. 2.3 COMPARISON OF SPECIFIC THRUST AND SPECIFIC FUEL CONSUMPTION FOR SUPERSONIC MIXED DUCTED FLOW ENGINES AND SUBSONIC UNMIXED DUCTED FLOW ENGINES WITH TURBINE INLET TEMPERATURE OF 1500°K. (From Ref. 29)

2.2 Noise

Current supersonic aircraft are powered with zero bypass ratio jet engines that have afterburning capability. When an afterburner is used during takeoff the jet exit velocity is very high, generally resulting in the highest noise levels per pound of thrust developed by an aircraft jet propulsion system.

Table 2.2 gives comparative noise values at a slant distance of 1000 feet between the observer and the aircraft for three supersonic aircraft and four subsonic civil aircraft. The 747-200 and DC-10, which have high bypass ratio engines, are quieter than the older design aircraft, 707-320 B and 727-200, that have low bypass ratio engines. All of the subsonic aircraft tend to be quieter than the supersonic aircraft when compared at grossly similar weights and thrust. The most striking example is the comparison of the Concorde with the DC-10; the Concorde is 22-25 dB noisier at maximum takeoff power and 13 dB noisier at approach power.

The noise differential between Concorde and subsonic aircraft is not limited to maximum power engine noise in the immediate vicinity of the airport. Its noise differential extends far from the airport, after engine power has been cut back. Figure 2-4 illustrates th noise of several aircraft measured directly under the flight path at distances up to 85,000 feet from the beginning of takeoff roll. If the Concorde cuts back to the engine power appropriate to a 3% climb gradient close to the airport, its noise under the flight path is decreased from that of full power, but then becomes larger at greater distances from brake relaease. For example, at 30,000 feet from brake release, Concorde with a 3% climb gradient is 28 dB noisier than the DC 10-30, and at 60,000 feet it is 30 dB noisier, see table 2-3. If it does not cut back

TABLE 2.2. COMPARISON OF TAKEOFF AND APPROACH NOISE (EPNL) FOR SELECTED AIRCRAFT AT A 1000 FOOT SLANT RANGE.

Aircraft	Max Gross Weight (1000 lbs)	Engine No./Thrust (1000 lbs)	Takeoff Condition		Approach	Ref.
			With Afterburner	Max Dry		
Supersonic						
B-1	390	4/30.0	128	115	113	174
Concorde	400	4/38.5	127	124	111	189
SR-71	140	2/32.5	120	113	98	174
Subsonic						
707-320B	328	4/18.0	NA	115	108	16
727-200	173	3/14.5	NA	111	100	16
747-200	775	4/48	NA	108	99	16
DC10-10	430	3/39	NA	102	98	16

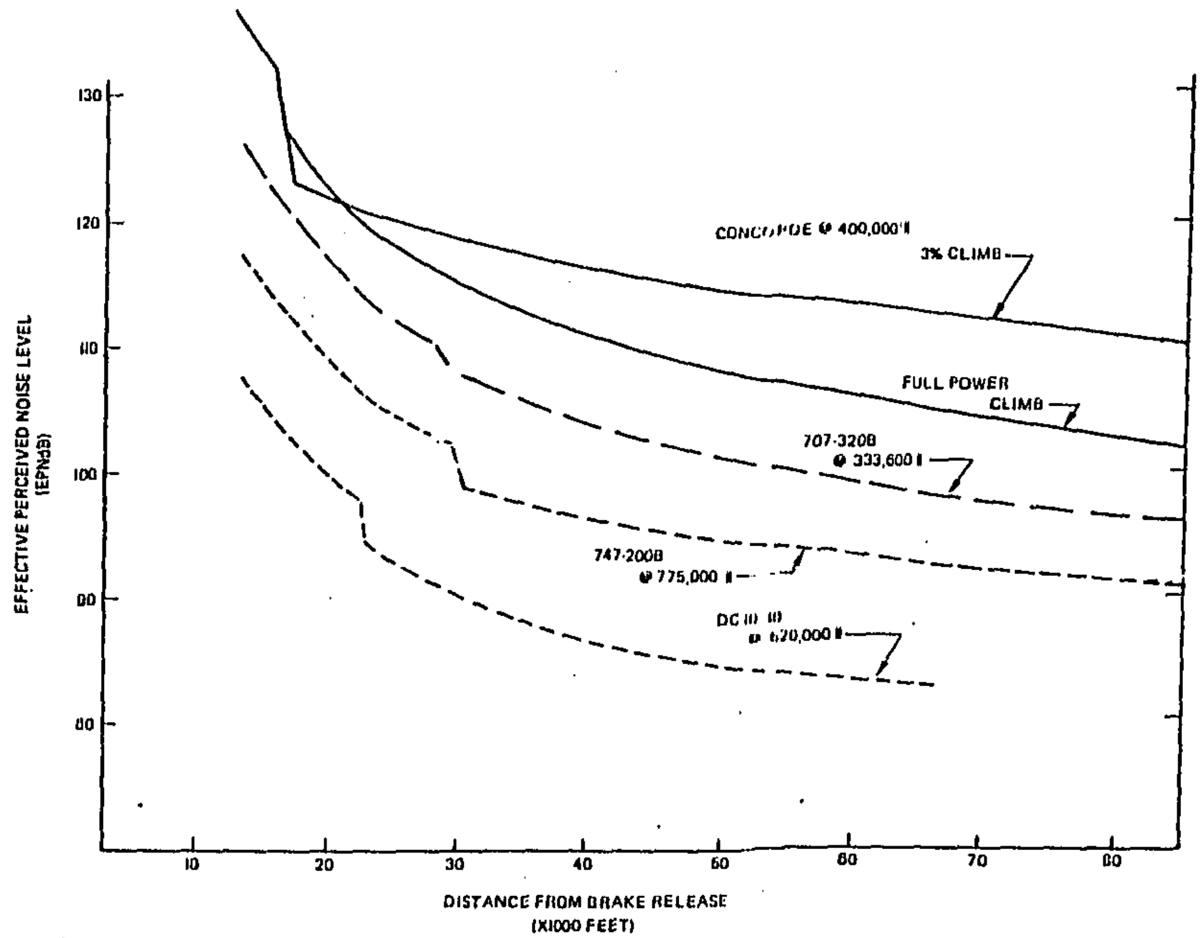


FIGURE 2-4 NOISE LEVELS UNDER TAKEOFF PATHS FOR COMPARATIVE AIRCRAFT. (From Ref. 189)

TABLE 2.3 TAKEOFF NOISE (EPNL) DIRECTLY UNDER THE FLIGHT PATH AT 30,000 AND 60,000 FEET FROM BRAKE RELEASE AND AREA ENCLOSED BY THE 100 EPNL CONTOUR FOR AIRCRAFT IN FIG. 2.3. (From Ref. 189)

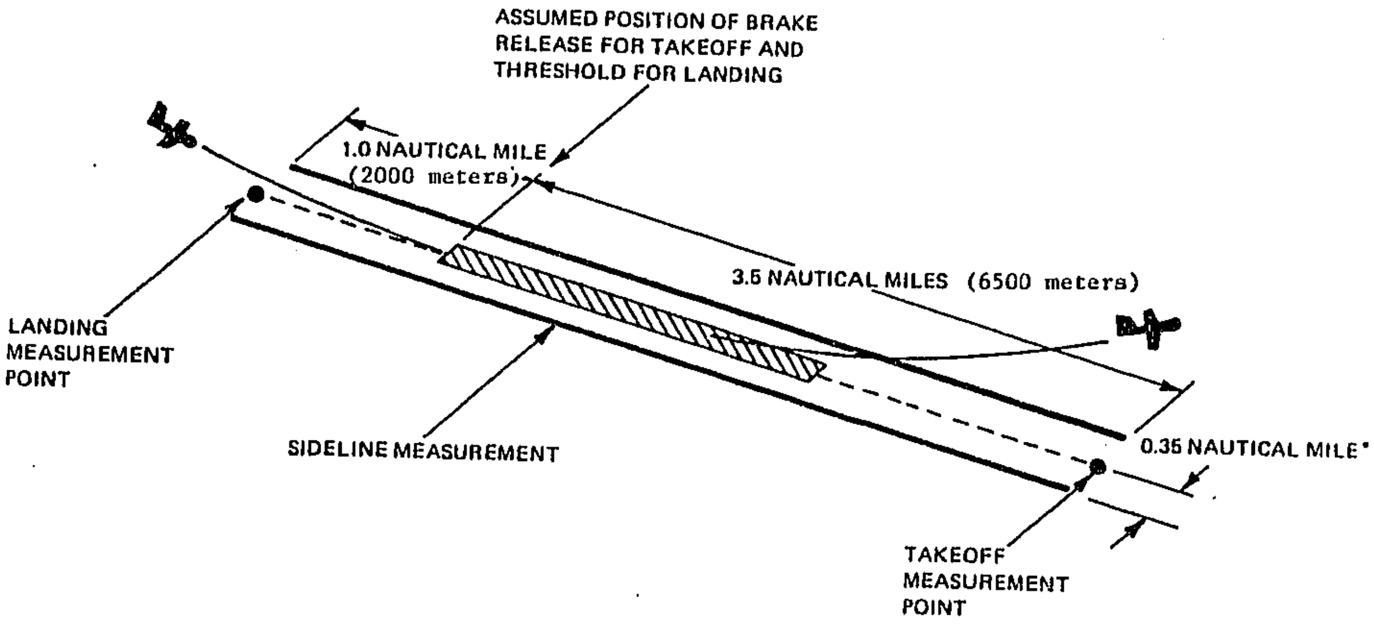
Aircraft	Weight (1000 lbs)	Distance From Brake Release: 30,000 Ft EPNL (dB)	30,000 Ft ΔEPNL Re Concorde @ 3% (dB)	60,000 Ft EPNL (dB)	60,000 Ft ΔEPNL Re Concorde @ 3% (dB)	Area Within 100 EPNL Contour (Sq.N.Mi.)
Concorde (@ 3% climb)	400	119	0	113	0	Not Available
Concorde (@ Full Power)	400	115	- 4	105	- 8	54.3
B707-320B	334	108	-11	99	-14	7.5
B747-200B	775	99	-20	93	-20	2.9
DC10-30	520	91	-28	83	-30	1.0

power and climbs more rapidly, it is 24 dB greater than the DC 10-30 at 30,000 feet and 22 dB greater at 60,000 feet. At its best, full power takeoff and maximum takeoff gross weight, Concorde's area within the 100 EPNL contour is estimated to be over 7 times that of a B-707-320B and over 50 times that of a DC-10-30. Concorde's relative noise performance during takeoff shows the combined effects of its high velocity jet noise, and its low lift-drag ratio in the takeoff speed range.

In 1969 the FAA began to certify aircraft for noise under FAR Part 36 [186]. This regulation has been amended several times to increase its coverage, make technical improvements and reduce the maximum allowable noise levels. Three measurements are specified: approach, sideline, and takeoff. The measurement configuration is illustrated in Fig. 2-5 with both the original 1969 distances and the most recent amended metric distances. The regulation specifies maximum allowable noise levels for each location as a function of maximum gross takeoff weight, and for some locations as a function of number of engines. The rule allows for trading of a maximum of 3 dB among the three locations with no more than 2 dB at a single location. Thus an aircraft that was 2 dB over at one location, 1 dB over at a second location, and 3 or more dB under at the third location would comply.

Examples of the maximum allowable noise levels are given in Table 2-4 for 4-engine aircraft at 3 selected maximum gross takeoff weight. The Stage 2 Limits are the limits originally promulgated in 1969. The Stage 3 Limits were promulgated in 1977-8

The Stage 2 Limits apply to the *operation* of supersonic cruise aircraft, except for the 16 Concorde aircraft that have flight time prior to 1980. However, there is no certification rule per se for new design supersonic cruise aircraft. The Stage 2 Limits apply



*For 4-Engine Aircraft (0.25 NM for 2- and 3-engine aircraft and for 4-engine aircraft in stage 3) (450 meters)

FIGURE 2-5 FAR 36 NOISE CERTIFICATION MEASURING POINTS. (From Refs. 195 and 201)

(Note: Original nautical mile distances have been amended to new metric distances except for Stage 1 and 2 4-engine aircraft.)

TABLE 2.4

COMPARISON OF FAR PART 36, STAGE 2 AND 3 NOISE STANDARDS FOR AIRCRAFT TYPE CERTIFICATION OF 4-ENGINE AIRCRAFT AT SELECTED GROSS WEIGHTS (EPNL in dB) [186, 195]

MEASUREMENT/ FLIGHT CONDITION	STAGE	DISTANCE	MAXIMUM GROSS TAKEOFF WEIGHT 400,000 lbs	600,000 lbs	800,000 lbs
Sideline	2	0.35 NMiles	106.8	108.0	108.0
	3	450 Meters	98.6*	100.1*	100.1*
Δ(2-3)			8.2	7.9	7.9
Takeoff	2**	6500 Meters	105.1	108.0	108.0
	3	6500 Meters	101.6	104.0	105.6
Δ(2-3)			3.5	4.0	2.4
Approach	2**	2000 Meters	106.8	108.0	108.0
	3	2000 Meters	103.5	104.9	105.0
Δ(2-3)			3.3	3.1	3.0

*Corrected to 0.35 nautical miles by subtracting 1.5 dB.

**ORIGINAL FAR PART 36 1969 had the distances for takeoff and approach at 3.5 and 1.0 nautical miles, respectively.

to all civil airline type aircraft currently produced for use in the United States, and in the 1980s will apply to those in airline use requiring, for example, retrofit to Stage 2 limits or disposal of old aircraft not certified under FAR part 36.

The Stage 3 limits apply to subsonic aircraft for which an application for an air worthiness certificate was made after November 1975.

The numbers in Table 2.4 show that for 4-engine aircraft the most significant reduction between Stage 2 and 3 limits is about 8 dB, at the sideline location. This comparison is made at the original 0.35 n.m. distance by adjusting the Stage 3 limits by 1.5 dB to approximate the expected difference. The reductions at the other two locations are of the order of 3 dB, varying with aircraft weight.

The noise levels at the certification locations for Concorde and three subsonic aircraft are given in Table 2.5 together with the Stage 2 and 3 levels appropriate to a 400,000 and 800,000 lb aircraft. To meet Stage 2 requirements, the Concorde's noise would have to be reduced by 5-14 dB, depending on location, and to meet Stage 3, the reductions would have to be 13-18 dB. Such an aircraft would be 4-5 dB noisier than an L-1011 on takeoff, but be the same on approach. Further, it would average about the same noise levels as does the 727-200.

An 800,000 lb supersonic cruise aircraft that met the Stage 2 noise limits would be about 10 dB noisier than a B-747 on sideline and 1-2 dB noisier at the other 2 locations. If it were to meet the Stage 3 limits, it would average to slightly less noise than the B-747.

TABLE 2.5

COMPARATIVE VALUES OF NOISE AT FAR PART 36
4-ENGINE AIRCRAFT NOISE MEASUREMENT POINTS
FOR SELECTED AIRCRAFT IN THE POST 1985 FLEET
(From Refs. 186, 195, 196 and 197)

AIRCRAFT	Max Gross Weight 1000 lbs	Takeoff	Sideline*	Approach
Concorde	400	119.5	112.0	116.5
Stage 2 SST**	400	105.1	106.8	106.8
Stage 3 SST**	400	101.6	98.6	103.5
L1011-1	430	97.0	93.5	103.4
727-200	208	102.4	102.7	100.4
747 200B	770	107.4	97.8	106.2
Stage 2 SST**	800	108.0	108.0	108.0
Stage 3 SST**	800	105.6	101.1	105.0

*Sideline Data for 3-engine aircraft and for Stage 3, 4-engined aircraft corrected to a constant reference distance of 0.35 nautical miles by subtracting 1.5 dB.

**Hypothetical aircraft with assumed noise requirements for comparison with other aircraft.

Therefore, if a design goal of an 800,000 lb transatlantic supersonic cruise aircraft were to be "compatibility with the existing fleet," the B-747 would probably be an appropriate reference aircraft, leading to a certification goal intermediate between Stage 2 and Stage 3 subsonic limits. However, if the design goal were to be "compatibility with other new aircraft entering service in the same time frame", say 1990, then the certification goal for takeoff would be *at least* 5 dB lower than Stage 3 since the L-1011 which represents the best current technology has already achieved this result.

The problems of achieving Stage 2 certification levels for a 700,000-800,000 lb supersonic cruise aircraft are significant, but are shown later to appear technically feasible. The solution depends upon improved engine cycles, improved low-speed aerodynamic characteristics, improved throttle-flap managemnt control devices, together with application of noise control technology to engine-nacelle design. However, the difficulty in meeting Stage 3 limits (or 5 dB better) is much greater and the probability of success cannot be stated with any degree of certainty.

3. TECHNOLOGY APPLICABLE TO NOISE CONTROL

The design of a supersonic cruise aircraft to accomplish a given mission — range, speed and payload — at an acceptable cost involves the optimization of a large number of variable factors. Many of these factors either directly or indirectly affect the noise characteristics of the aircraft when it approaches or departs from an airport.

For example, improvements in mission L/D enable reductions in engine thrust requirements and aircraft size and weight, thus increasing the payload fraction of the total aircraft weight. This reduction in engine size may lead directly to noise reduction, and/or the increase in payload fraction may enable additions of weight for noise suppression without accruing as severe a penalty as with a lesser L/D. Improvements in low speed L/D for approach enable a reduction in thrust during approach and a direct lowering of noise. For departure, the improvement in low speed L/D leads to the ability to climb at a higher gradient at given thrust, decreasing the noise through a greater distance; or to lower cutback thrust, and hence noise, while maintaining the same climb gradient.

Development of complex variable engine cycles that approach optimum performance for takeoff, subsonic climb and cruise, transonic acceleration and supersonic cruise tend to reduce fuel requirements and engine drag, again leading to a smaller and lighter aircraft for the given mission. This optimization in cycle also gives possibilities for reducing aircraft noise in the vicinity of the airport, because to optimize the subsonic engine performance it is necessary to maximize the bypass ratio, which then enables direct noise reduction.

Thus, the technology applicable to noise control includes not only direct noise control technology, e.g., jet suppressor, duct lining and configuration, blade spacing, engine/airframe configuration, etc., but also includes many of the fundamental technologies applicable to the overall design, e.g., aerodynamic, structural and propulsion. This section summarizes the following technologies as applicable to noise:

- aerodynamic performance
- structural design and materials
- propulsion system and noise performance
- propulsion system noise control
- control of propulsion/flight parameters
- aerodynamic (airframe) noise.

3.1 Aerodynamic Performance

The L/D for supersonic cruise for an aircraft designed today would probably be in the vicinity of 9-10, approximately 30% better than achieved in the Concrode.[28,40] Part of this improvement results from improvement in wing planform, as shown by some examples in Fig. 3.1. Part comes from more sophisticated detailing, such as optimized camber and twist [40] and wing body aerodynamic blending [22,118,169] illustrated in Fig. 3.2. These, and other improvements resulting from aerodynamic research are often made practicable by concurrent developments in materials and structural design concepts.

The subsonic L/D for optimum supersonic cruise aircraft will generally be less than that of optimum subsonic aircraft because of both the high sweep angle and the typically low aspect ratio of the supersonic aircraft. (See, for example, Fig. 3.3.) Some

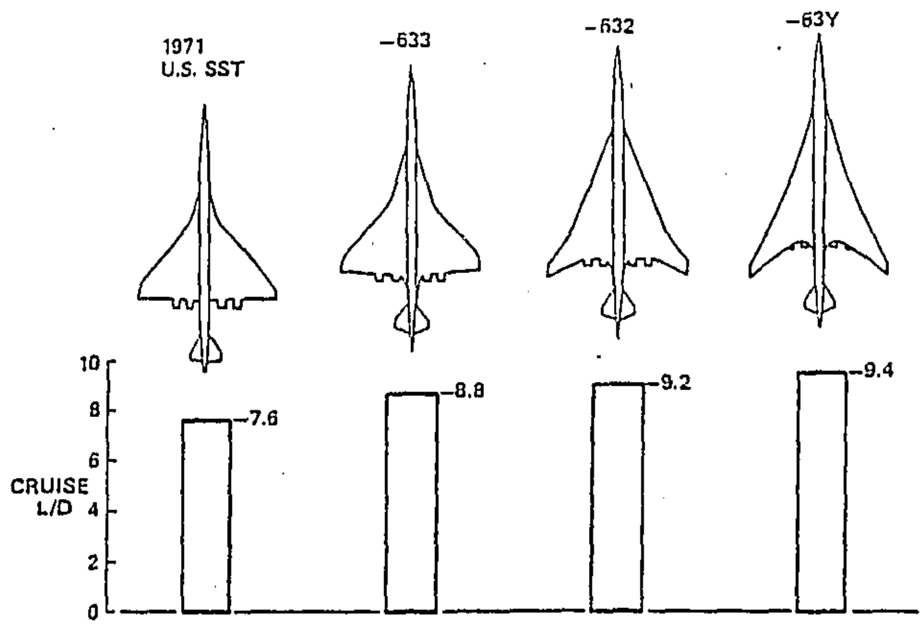


FIG. 3.1 EFFECT OF WING PLANFORM ON SUPERSONIC CRUISE LIFT/DRAG RATIO. (From Ref. 118)

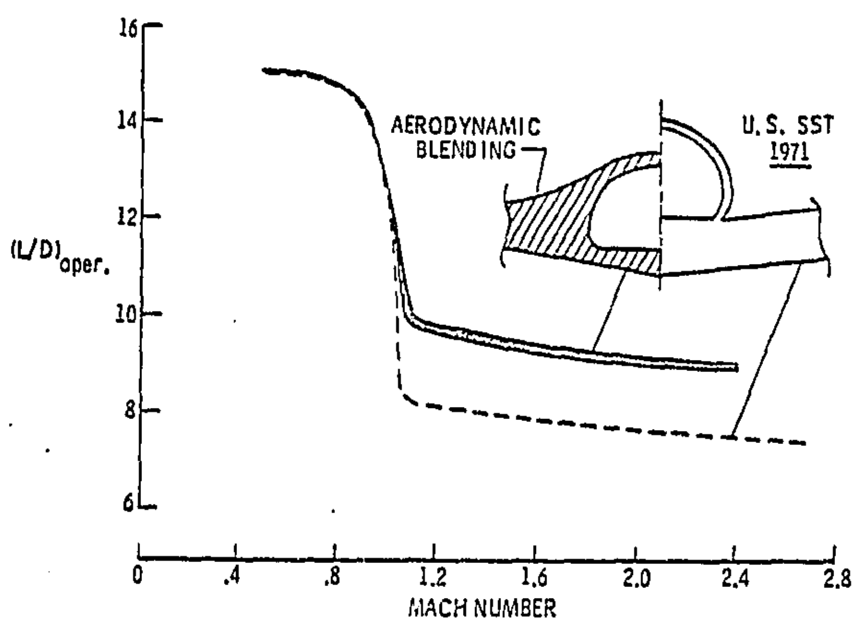


FIG. 3.2 ADVANTAGES OF AERODYNAMIC BLENDING. (From Ref. 118)

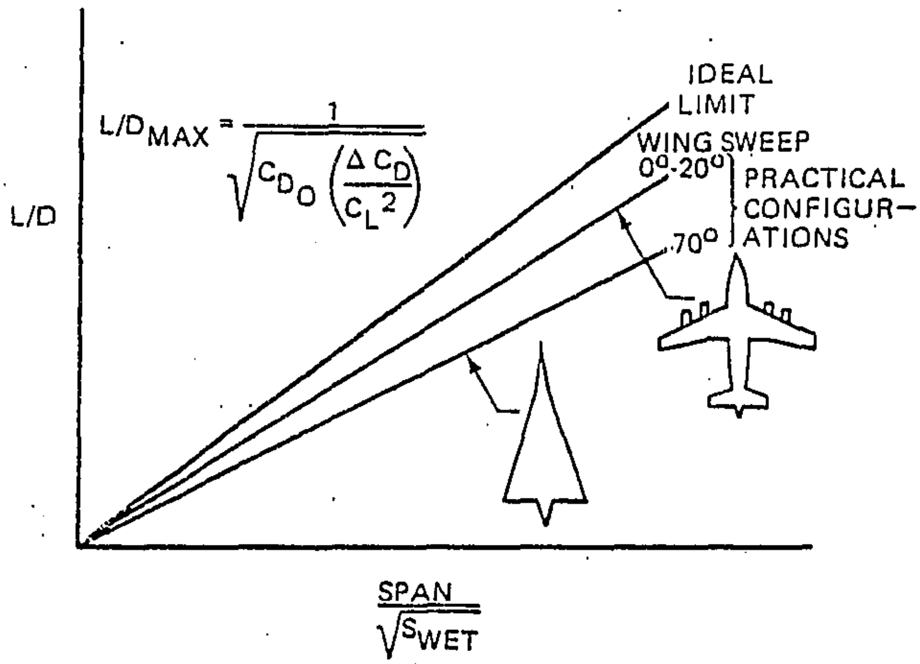


FIG. 3.3 AIRPLANE DESIGN PARAMETERS FOR HIGH SUBSONIC L/D. (From Ref. 118)

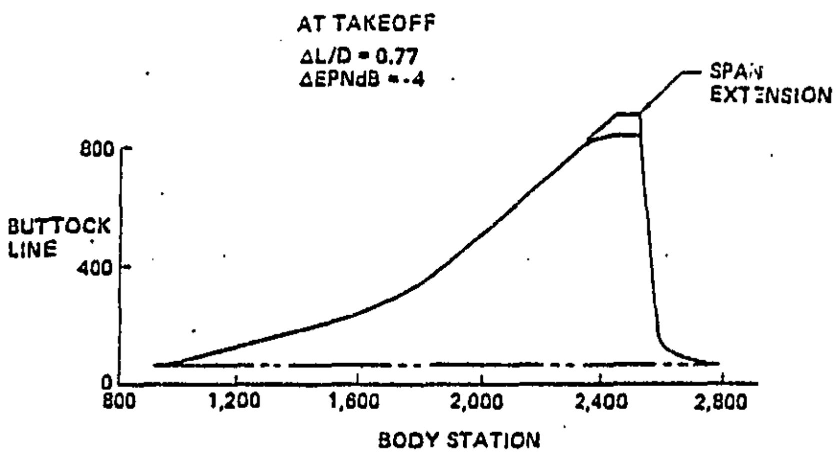


FIG. 3.4 WINGSPAN EXTENSION. (From Ref. 118)

improvement is possible by extending the wingspan to a maximum value consistent with the basic wing planform as illustrated in Fig. 3.4. However, such extensions may lead to complex structural and flutter problems.

One of the most promising ways of improving the low-speed subsonic performance near the aircraft is the development of variable contour leading edge flaps. A design such as that shown in Fig. 3.5 achieves an increase in wing camber, hence lift, at a constant angle of incidence. It also enables an increase in leading edge radius. from the fairly sharp entry optimum for supersonic flight at low angles of incidence to a more blunt edge which is less susceptible to separation at the higher angles of incidence required for low speed flight.

The degree of improvements for two designs are illustrated in Fig. 3.6. The results indicate a potential low speed L/D of about 10 with optimized leading edge flaps. This is a significant improvement over Concorde which has an L/D of 4 during takeoff.[28] The potential for noise reduction relative to Concorde is very significant, since the change from about 7 to 10 for the delta wing example of Fig. 3.6 represents a potential reduction of 10 dB under the takeoff flight path. [118]

There are other possible improvements for the takeoff and low speed flight regimes currently under study. These include:

- extendable wing tips with active controls to improve aspect ratio; [123]
- variable geometry landing gear and center of gravity management with active controls to improve lift coefficient at takeoff; [118]
- control surface refinements;

- boundary layer control over flaps;
- upper surface blowing for increased lift [33,118], and possible installation of engine above the wing [170].

It is clear that the results demonstrated above offer significant improvement in noise for a future design supersonic cruise aircraft relative to Concorde and the former U.S. SST, the B-2707.

Footnote: For additional information see references 3,7,9,11,13,21,33,41, 47,64,143,144,145,146,151,163 and 171.

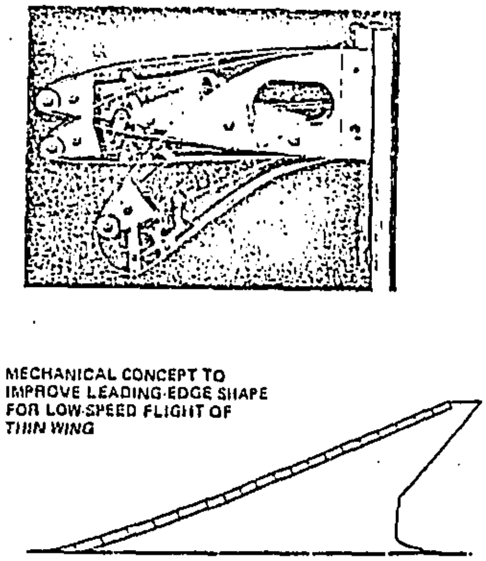
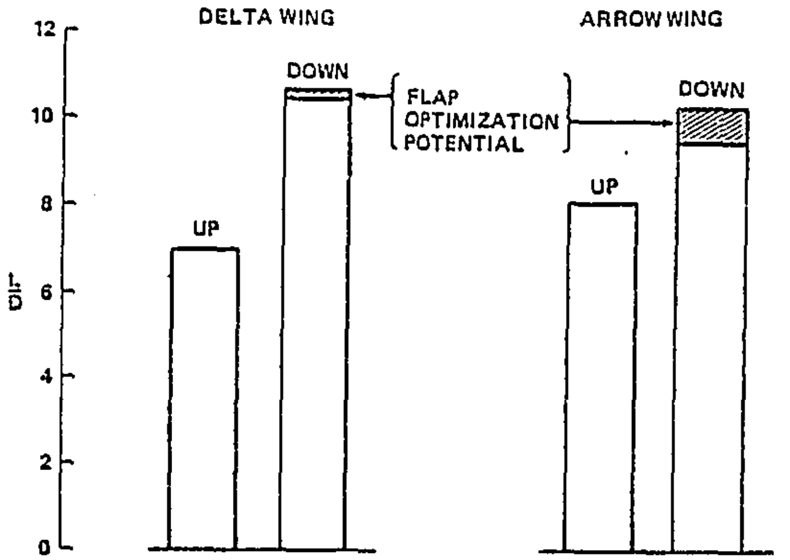


FIG. 3.5 LEADING-EDGE DESIGN TO REDUCE COMMUNITY NOISE. (From Ref. 118)



$\Delta \frac{L}{D}$ OF 3 IS WORTH ABOUT 10 EPNdB JET NOISE AT COMMUNITY

FIG. 3.6 EFFECT OF LEADING EDGE FLAP DESIGN (CLIMB OUT). (From Ref. 118)

3.2 Structural Designs and Materials

The technology for designing aircraft structure has advanced significantly with the development of finite element modeling techniques that utilize large high-speed computers. The analysis process, including static and dynamic loads with consideration of static strength, fatigue and flutter can now be accomplished in a week, 5-10% of the time formerly required. [40]

An example of a finite element model for an arrow wing supersonic cruise aircraft is given in Fig. 3.7. The aircraft is a Boeing derivative of the NACA SCAT 15F series that was designed for a maximum takeoff gross weight of 750,000 lbs., a payload of 49,000 lbs. (230 passengers) and a cruise mach of 2.7.

Table 3.1 compares two independent weight estimates for this aircraft; one by Boeing [19,20] which assumes 1975 materials technology, the other by Lockheed [168] which assumes 1980 technology. The 1980 technology structural weight is estimated to be about 9% less than that representing 1975 technology. In the example, the resulting weight gain was translated into increased fuel weight and a 200 mile, or 5%, increase in range.

Some of the weight savings of 1975 technology relative to earlier designs result from the use of these finite element programs which enable optimization of weight and strength throughout the structure. Additional savings are possible through improved methods of defining aerodynamic loads, both steady-state pressure distribution and nonsteady pressure fluctuations due to turbulence [35]. Further, potential exists by reducing landing and runway loads, using hydraulic actuators to provide active control for the landing gear. [40]

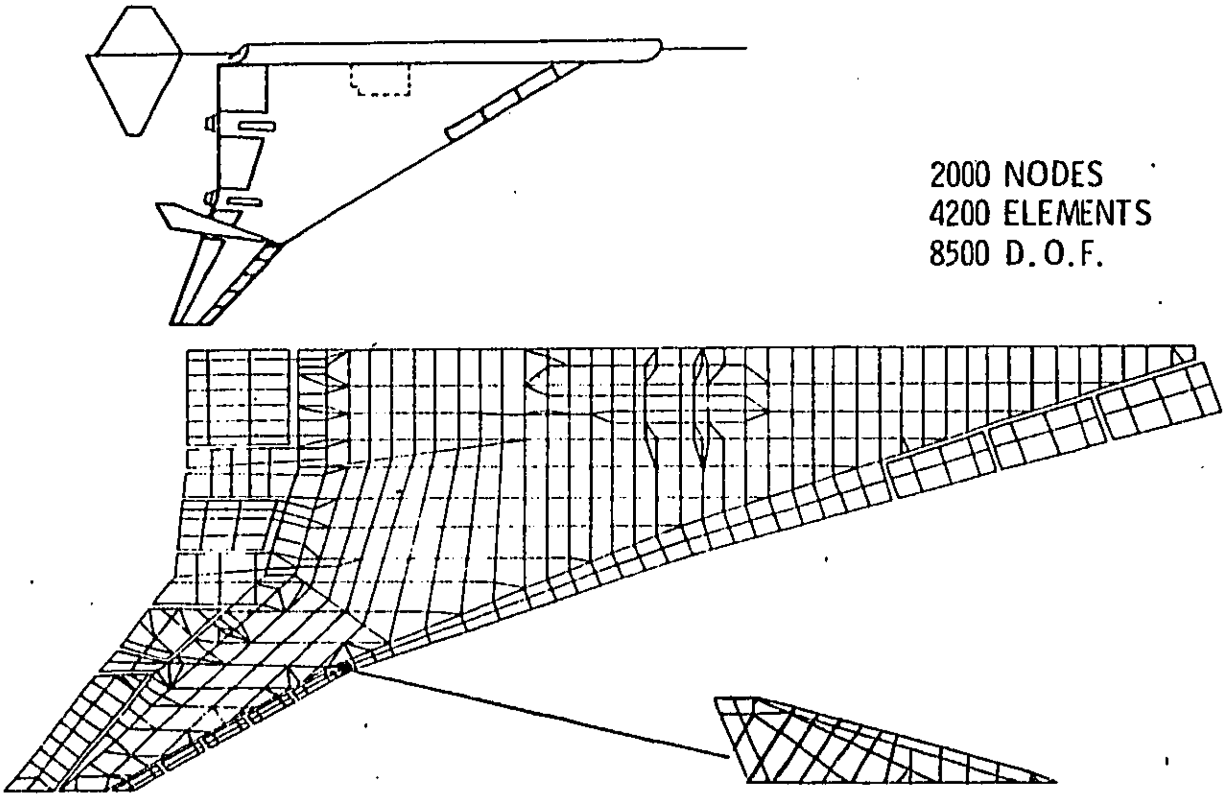


FIGURE 3.7 FINITE ELEMENT MODEL OF AN ARROW-WING SUPERSONIC CRUISE AIRCRAFT-BOEING CO. (From Ref. 34)

TABLE 3.1 WEIGHT ESTIMATES FOR 750,000 LB., 230 PASSENGER, MACH 2.7 NASA ARROW-WING SUPERSONIC CRUISE AIRCRAFT. (From Ref. 34)

ARROW-WING GROUP MASS STATEMENT IN lb_m.						
ELEMENT	Boeing (1975 Technology)			Lockheed (1980 Technology)		
	Weight (lbs)		% GTOW	Weight (lbs)		% GTOW
Structure		224,400	29.9		201,300	26.8
Wing	95,800			90,600		
Horizontal tail	6,500			7,900		
Vertical tail	5,800			5,400		
Fuselage	56,100			42,000		
Main gear	37,300			27,400		
Nose gear	3,800			3,000		
Nacelle	19,100			24,900		
Propulsion		56,800	7.6		58,100	7.8
Systems		77,100	10.3		54,400	7.2
OEW		358,300	47.8		313,800	41.8
Payload (held constant)		49,000	6.5		49,000	6.5
Fuel		342,700[1]	45.7		387,200[2]	51.7
GTOW (held constant)		750,000	100		750.000	100

[1]Range of 4000 n.mi. [2]Range of 4200 n.mi.

The principal factor for the improvement in the weight of 1980 technology relative to that of 1975 technology in Table 3.1 results from the increased use of composite materials. [34,35,60] Figure 3.8 illustrates some of the advanced structural concepts for the 1980 technology study, and figure 3.9 illustrates weight savings which can be achieved with composites. Some of these composites were developed in the B-1 program [169], as illustrated in figure 3.10. Another promising development of the B-1 program [169] is a diffusion process for bonding titanium to fabricate structural assemblies which have weight, strength, fatigue and cost advantages for many parts such as those illustrated in figure 3.11.

The combination of improved design analysis computational methods for both loads and structure, active control devices to reduce loads, and increased utilization of advanced composite structures could result in an 8-10% reduction in operating empty weight. [40] These potential weight reductions can be translated into increases in range and/or payload; or for the same range and payload provide weight margins for the addition of noise control devices and/or margins for the reduction of engine thrust and size requrements.

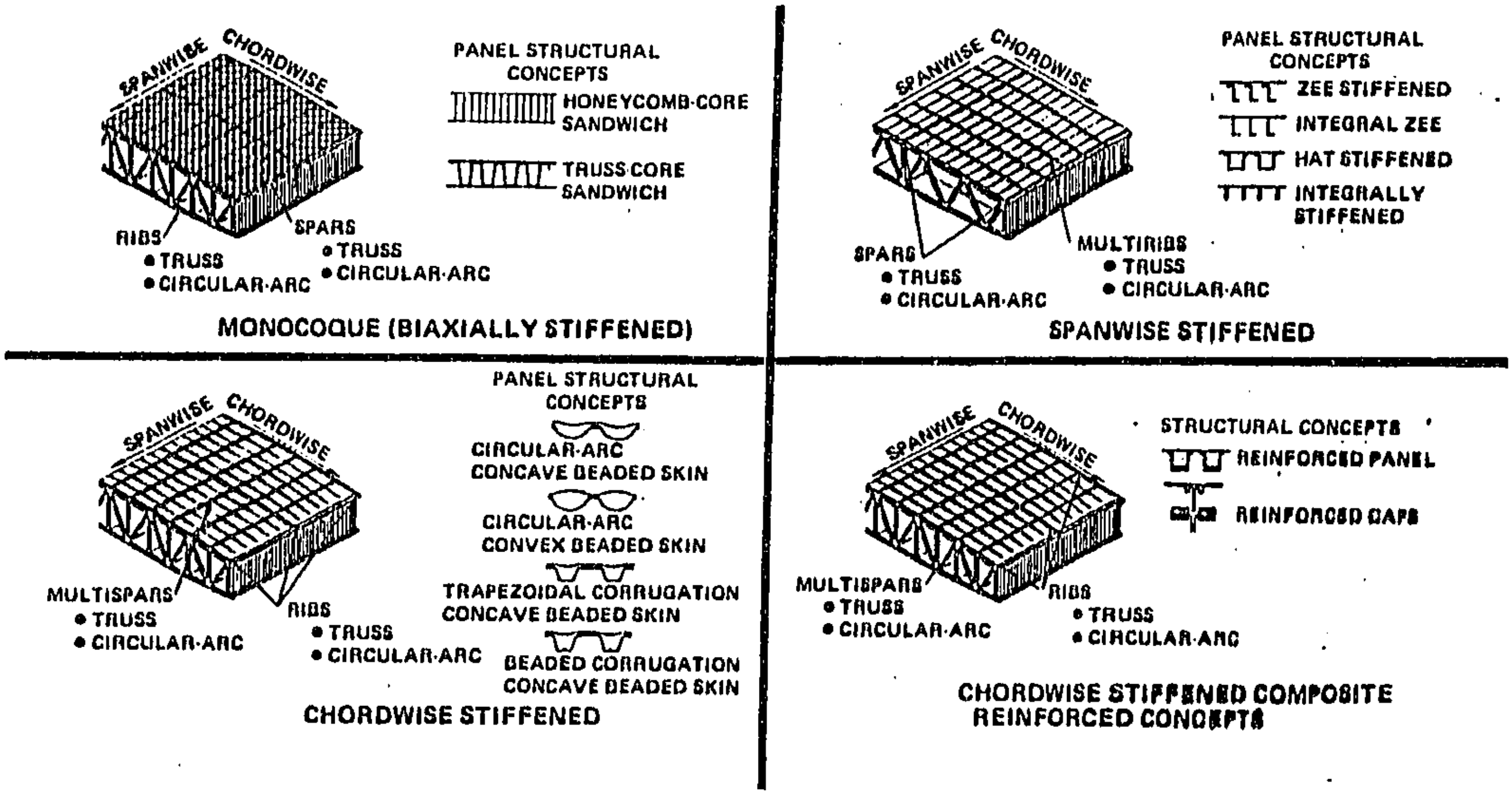


FIGURE 3.8 STRUCTURAL CONCEPTS FOR AN ARROW-WING SUPERSONIC AIRCRAFT-LOCKHEED CO. (From Ref. 34)

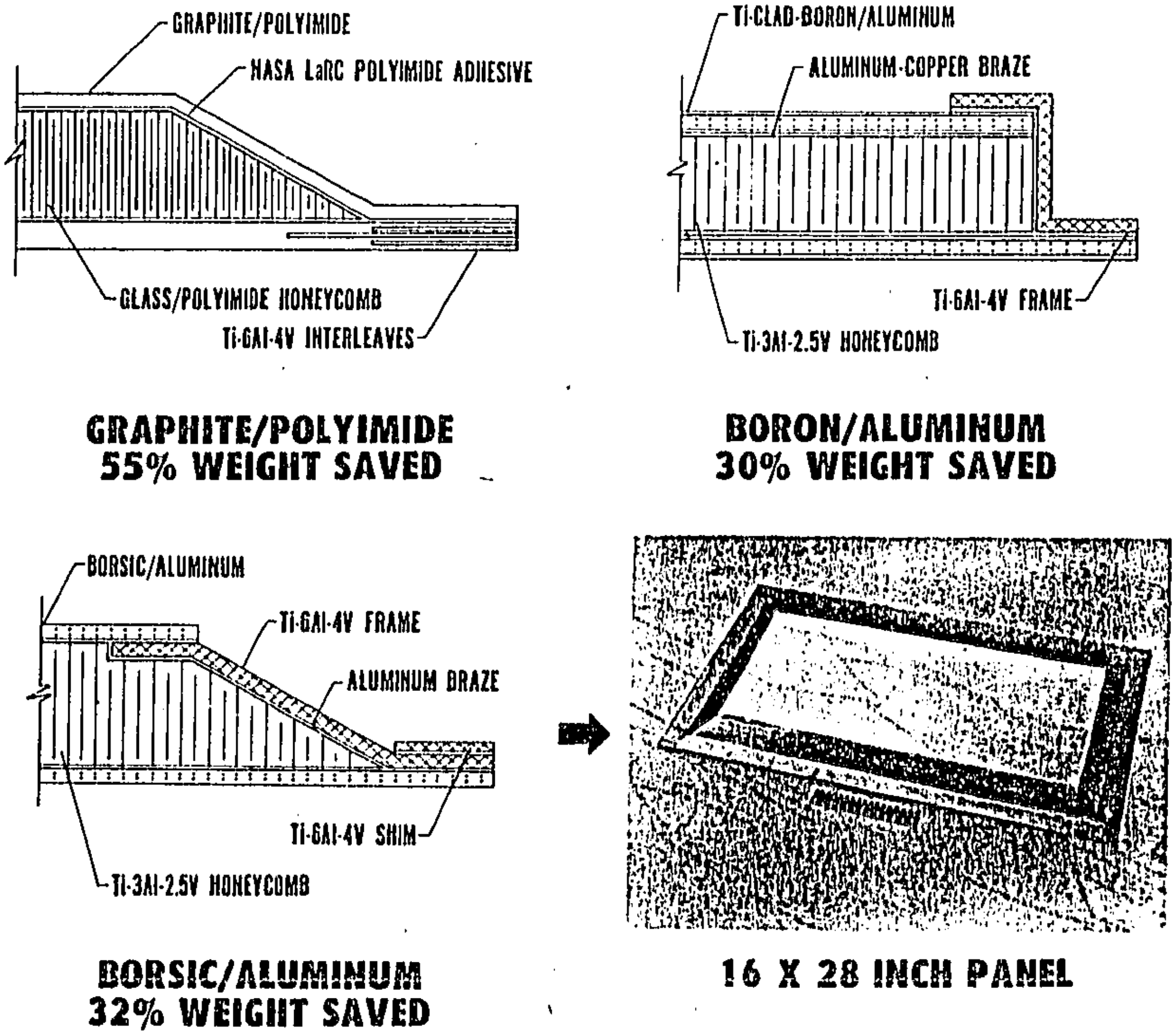


FIGURE 3.9 COMPOSITE PANELS FOR SUPERSONIC AIRCRAFT. (From Ref. 34)

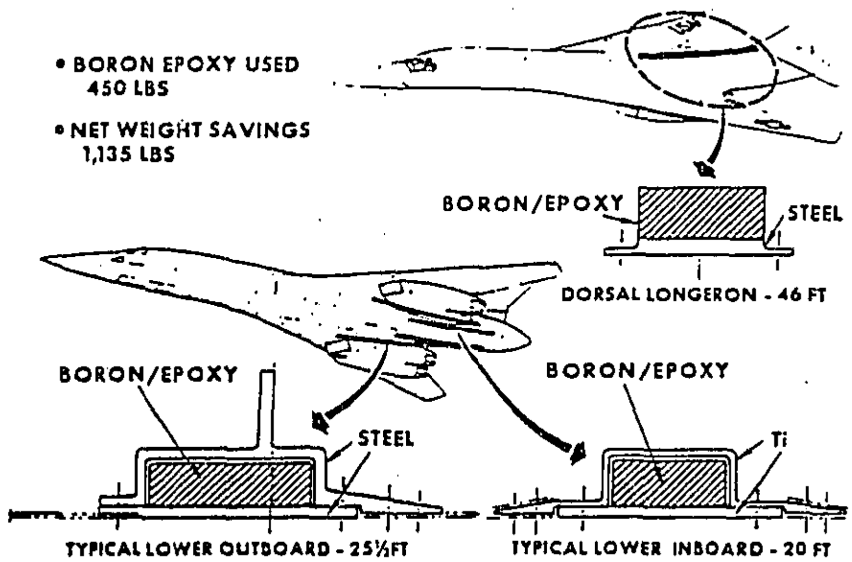


FIG. 3.10 EXAMPLES OF BORON/EPOXY-REINFORCED LONGERONS. (From Ref. 169)

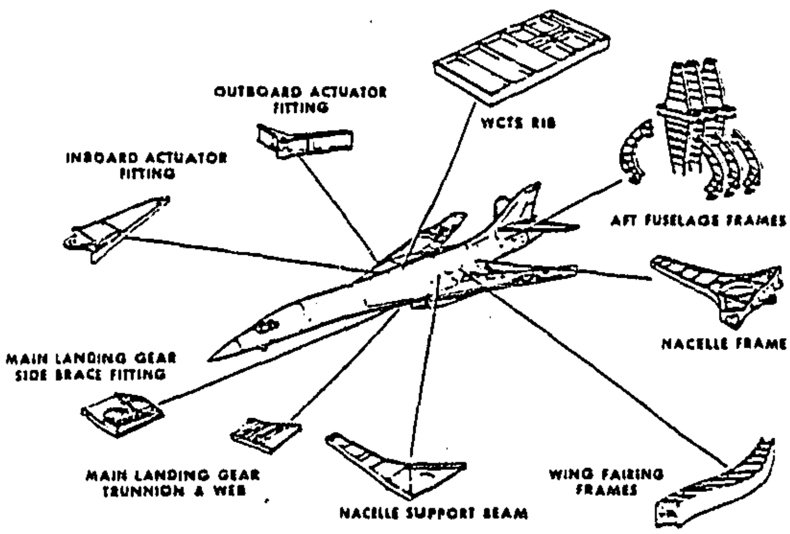


FIG. 3.11 TYPICAL B-1 DIFFUSION-BONDING APPLICATIONS. (From Ref. 169)

3.3 Propulsion System Performance and Noise

The optimization of an engine for a supersonic cruise aircraft involves the complex balancing of many factors, some of which are in conflict. These factors include engine weight and size, subsonic and supersonic specific fuel consumption, and takeoff and landing noise. The design thrust depends on reequirements for takeoff field length, noise, climb and transonic acceleration, and supersonic cruise. Considerable progress has been made in the SCAR program, [204,205,211], primarily through studies by Pratt and Whitney [68,69,167] and General Electric [4,5,179] towards developing new advanced engine concepts that begin to optimize the various requirements. These new concepts are generally based on 1980-1990 technology for design certification in the early 1990's. Existing engines based on 1965-1975 technology are more limited.

The Rolls Royce Olympus engine [28-30] which powers the Concorde is a very advanced design straight turbojet with afterburner. Its thrust is sized for supersonic cruise without afterburner, and the afterburner is used to provide the additional thrust required for transonic acceleration and takeoff. The U.S. SST prototype B-2707 aircraft was at one time designed to use the GE-4-J5 series afterburning turbojet engine. It too utilized afterburner for both takeoff and transonic acceleration, and, in addition, required partial afterburner during supersonic cruise. In the last year of the prototype program, the engine was resized so that the B-2707 could achieve FAR 36 Stage 2 noise limits with 8-12 dB noise suppression. To decrease the jet velocity (noise) the engine airflow was increased from 633 to 890 lbs/second, and the afterburner was eliminated. [129,151] (See Table 3.2 for other comparisons among these engines.)

Footnote: For additional information on engines see references 2,10,23,52, 150,182,183,208 and 210.

TABLE 3.2

COMPARISON OF SELECTED CONVENTIONAL TURBOJET ENGINES FOR SUPERSONIC CRUISE AIRCRAFT

FACTOR	Rolls Royce Olympus	General Electric GE4J5	General Electric GE4J6H
Status	In Service	Prototype Tested	Scaled "paper" engine
Application	Concorde	Boeing B2707	Boeing B2707-300
Cycle	Afterburning Turbojet	Afterburning Turbojet	Turbojet
Mass flow SLS(lbs/sec)	425	633	890
Thrust SLS (lbs)	38,200	70,000	73,900
Weight (lbs)	6,750	13,243	17,670 approx.
SFC Subsonic Cruise	0.93	1.08	NA
(lbs/hr/lb F)	@ M.85	@ M.9	--
SFC Supersonic Cruise	1.19	1.44	NA
(lbs/hr/lb F)	@ M2.0	@ M.262	
Turbine Inlet Temp (^{o}F)	2236	2300	2520
References	28	129,147	5,129

The weight increase, occuring with the change from the J-5 to the J6H, was approximately 18,000 lbs for the four engines. This translated into weight increase for the B2707 aircraft of many times 18,000 lbs, so that its range and payload could be maintained, albeit at greater cost. Later it was stated that the availability of a variable cycle engine would have enabled a weight reduction equivalent to the entire payload. [178] Such an engine would combine the following idealized characteristics:

- For Takeoff: high mass flow for low jet velocity and hence low noise, providing the thrust required for the field length objective,
- For subsonic cruise: higher mass flow to attain lower SFC's associated with turbofan engines,
- For supersonic cruise: operation as a straight turbojet low bypass turbofan designed to minimize spillage, bypass and boat tail drag.

These characteristics would lead to minimum jet noise while operating near an airport and near minimum fuel consuption when optimized for a mission containing both subsonic and supersonic requirements.

In the early 1970's jet model tests indicated that noise reduction was possible with a co-annular exhaust nozzle in which the outer flow had a greater velocity than the inner flow. A full-scale test was made in the Ames Wind Tunnel using a modified JT8D engine with an air inverter which ducted the fan bypass flow towards the center and the hot flow towards the periphery of the engine. These tests demonstrated the ability to increase the mass flow up to 70%, varying the bypass ratio from 1.1 to 3.5, and reducing the noise by 4 dB [118, 126], as shown in figures 3.12 and 3.13.

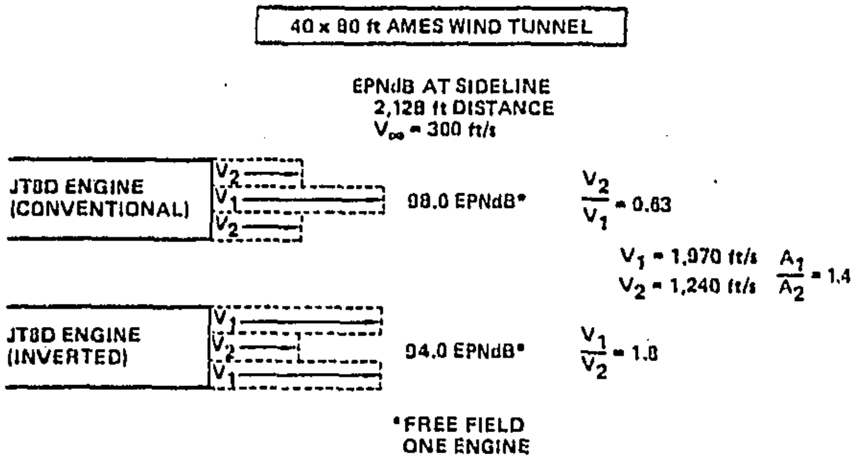


FIG. 3.12 INVERTED FLOW TEST RESULTS, FULL-SCALE JT8D (From Ref. 118).

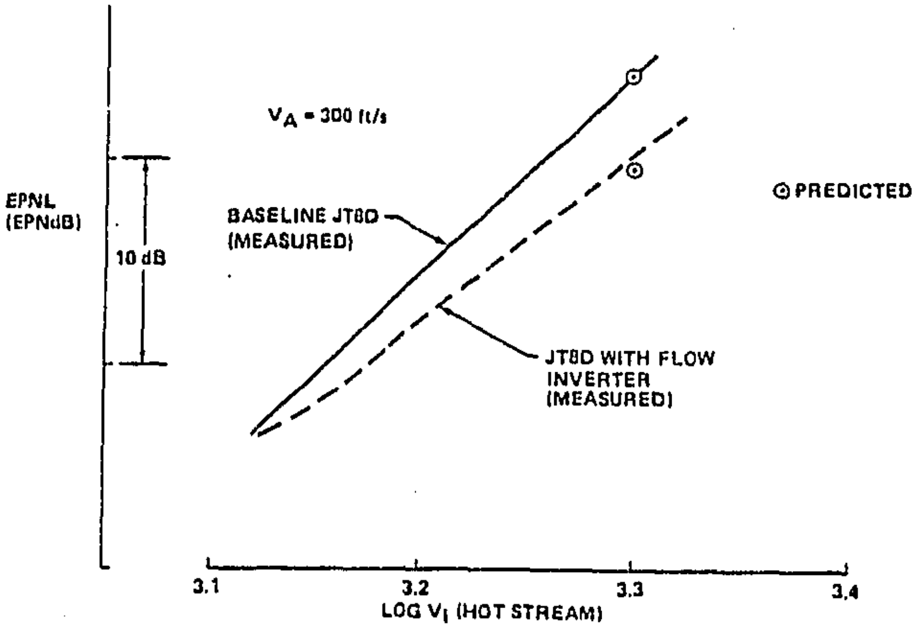


FIG. 3.13 INVERTED FLOW TEST RESULTS FOR FULL-SCALE JT8D. (From Ref. 118)

Several programs (see, for example, Refs. 61,71,128,131 and 155) developed an experimental basis for predicting the magnitude of the co-annular effect. The potential range of the noise reduction relative to a conical nozzle is on the order of 3-7 PNdB for a range of possible configurations, as illustrated in figure 3.14. Higher reductions are often quoted, but their reference condition is the old SAE prediction method of synthesis [173 (1965)] in which the noise of the inner and outer flows were computed separately on the basis of equivalent area conical nozzles and then summed. This method tended to over-predict the noise of all co-annular flows, as well as over-predicting the noise of a single conical nozzle having the same thrust and mass flow as does the co-annular nozzle. Consequently, noise reductions based on "synthesis" yield higher values than those based on an equivalent single conical nozzle as may be seen in comparing figures 3.14 and 3.15.

The fundamental mechanism of the co-annular nozzle noise reduction is the rapid mixing accomplished by the higher speed outer flow, much as in the case of the daisy multilobe noise suppressors [43]. Because of this mixing, the axial velocity decays rapidly with axial distance, and the low and medium frequency noise generated in the major portion of the jet flow (axial distances greater than 2 diameters) is much less. Model data comparing the axial velocity as a function of axial distance for several configurations is shown in figure 3.16. Because the flow is inverted, e.g., the high speed primary is in the outer annulus, the equivalent downstream jet is probably slower than it would be if the flow were not inverted and the noise generation correspondingly lower than in a conventional bypass engine with the same area and velocity rations [43].

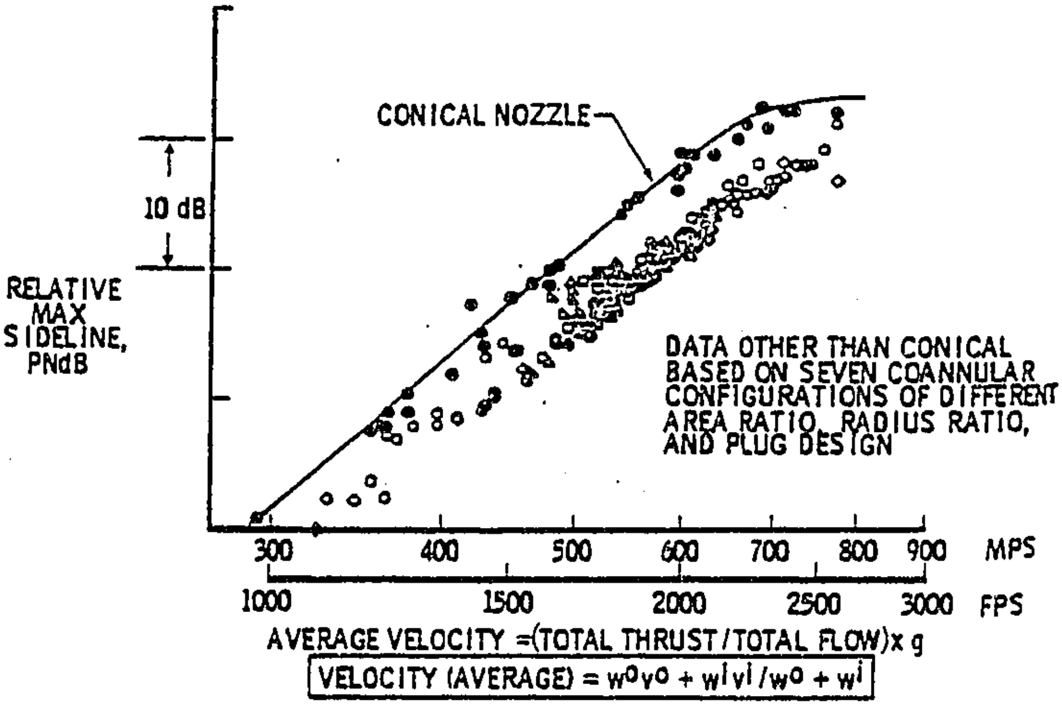


FIG. 3.14 COANNULAR NOZZLE MAXIMUM PERCEIVED NOISE LEVEL (PNdB) CORRELATION. PNdB NORMALIZED FOR JET DENSITY AND THRUST (IDEAL); 732m (2400 ft) DISTANCE; .33m² (513 in²) NOZZLE AREA. (From Ref. 131)

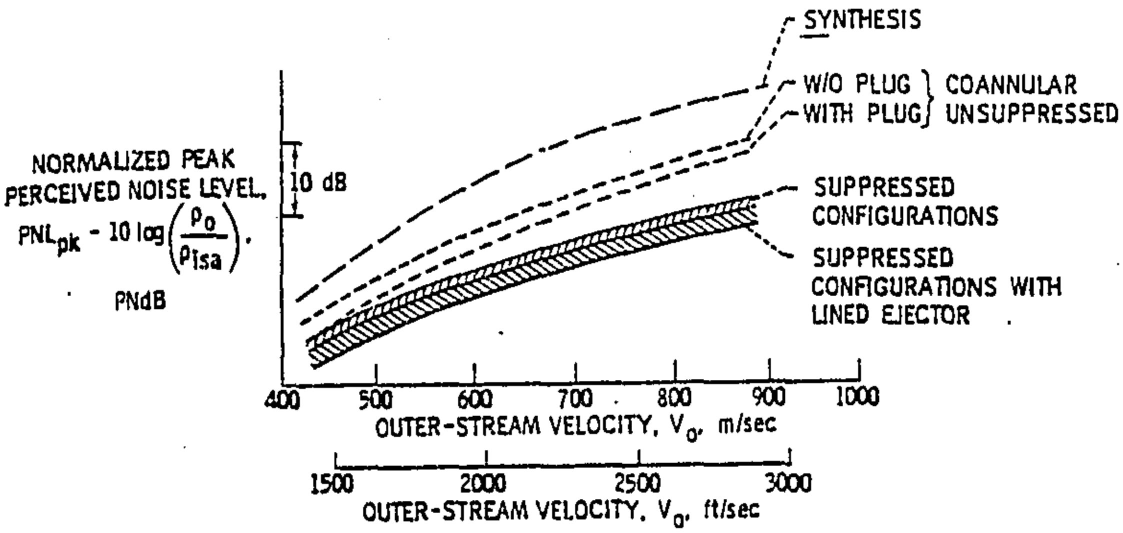


FIG. 3.15 PEAK NOISE LEVEL AS FUNCTION OF OUTER-STREAM VELOCITY FOR TYPICAL INVERTED-VELOCITY-PROFILE COANNULAR NOZZLES. SIDELINE DISTANCE, 649m (2128 ft); ALTITUDE, 366m (1200 ft); $V_o \geq 1.5\ V_i$. (From Ref. 61)

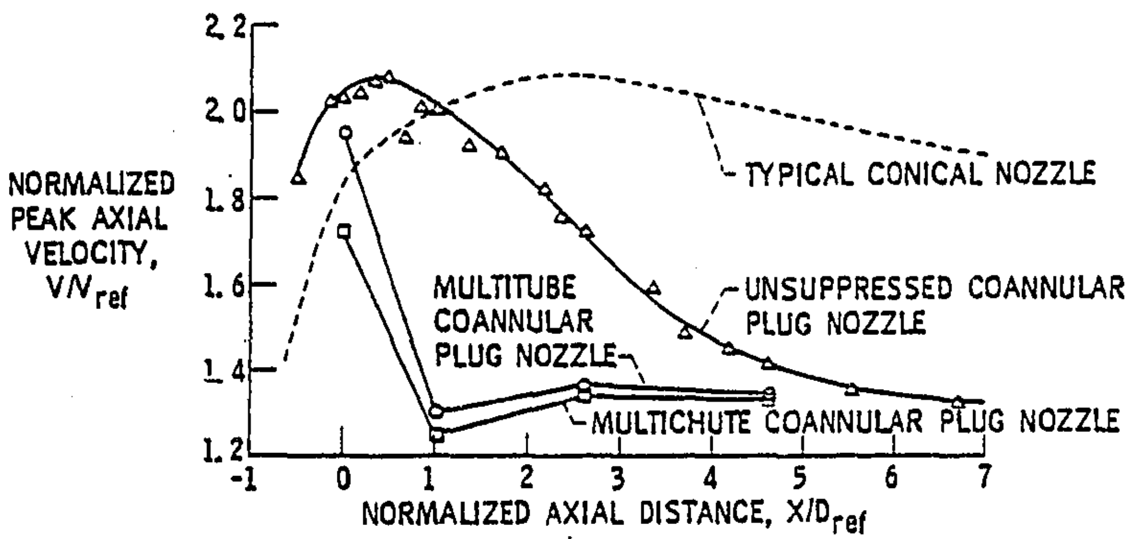


FIG. 3.16 VARIATION OF PEAK AXIAL VELOCITY FOR SUPPRESSED AND UNSUPPRESSED COANNULAR PLUG NOZZLES. TOTAL PRESSURE RATIO: INNER STREAM, 1.5; OUTER STREAM, 2.86. TOTAL TEMPERATURE: INNER STREAM, 812 K; OUTER STREAM, 784 K. REFERENCE VELOCITY, 304.8 m/sec (1000 ft/sec); REFERENCE DIAMETER, 15.23 cm (6 in.). (From Ref. 61.)

The "coannular noise reduction effect" was subsequently utilized in the design of several types of variable cycle engines (VCE) which were intended to explore the possibility of meeting the objectives stated above, using advanced technology variable geometry components and materials with turbine inlet temperatures of 2800°F. Two concepts of VCE's which can utilize the coannular effect are illustrated in figures 3.17 and 3.18 The duct burning turbofan heats the outer fan flow with a duct burner to provide additional thrust and control the relative velocity of the two streams. The double bypass variable cycle engine uses flow inverting passages to direct the slower stream to the center.

The General Electric engine [5,129] is termed a double bypass engine because the fan is separated into two blocks with an outer bypass between the blades and the normal bypass after the second block [129]. This arrangement, together with variable inlet guide vanes and overspeeding the front fan, enables the engine to have increased airflow (high flow) through the oversized front fan block and auxiliary inlet to meet takeoff thrust and noise requirements without oversizing the entire engine. The detailed section of this engine in figure 3.19 illustrates two variable area bypass injectors (VABI). The forward VABI has partial control of the amount of air in the primary stream relative to the bypass stream. This control is used to achieve the desired thrust-velocity-noise relationship during takeoff, optimize engine SFC during subsonic cruise, and provide maximum air during transonic accelleration and supersonic cruise. The rear VABI allows independent variations of high and low pressure rotor speeds, and together with the forward VABI, varies the MACH number in the stream to the correct value for the mass flow and

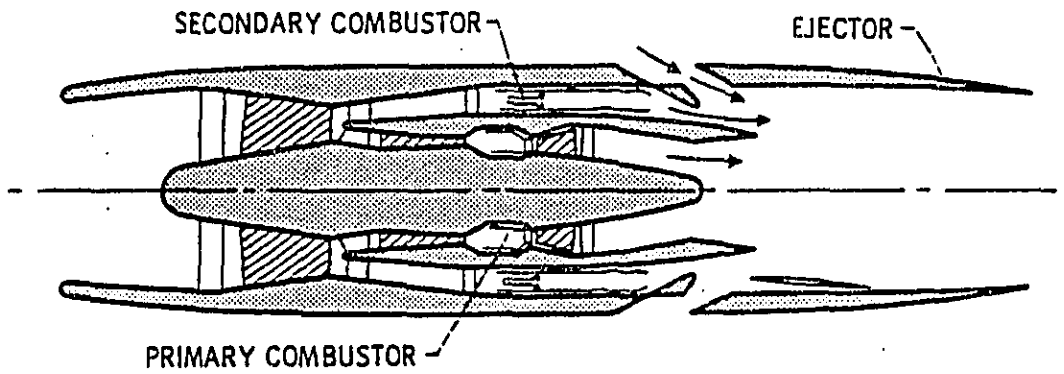


FIG. 3.17 PRATT AND WHITNEY LOW-BYPASS TURBOFAN CONCEPT — DUCT-BURNING TURBOFAN (from Ref. 62).

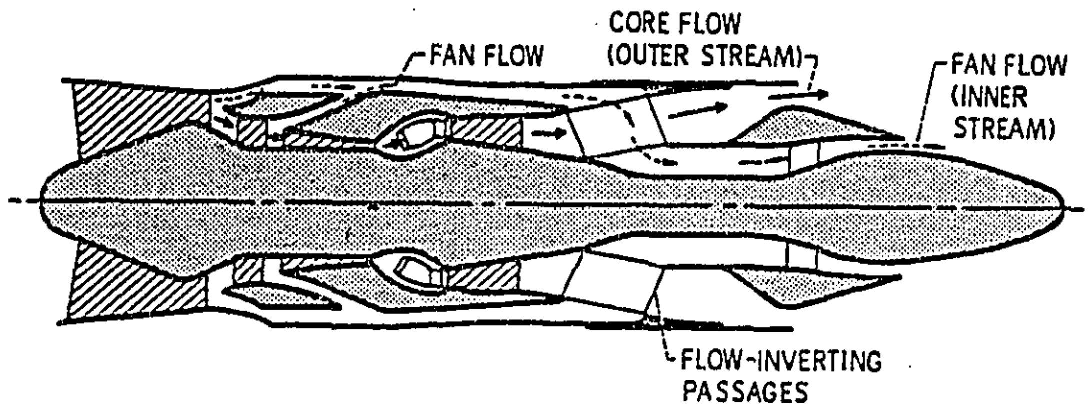


FIG. 3.18 GENERAL ELECTRIC LOW-BYPASS TURBOFAN CONCEPT — DOUBLE-BYPASS, VARIABLE-CYCLE ENGINE (From Ref. 62).

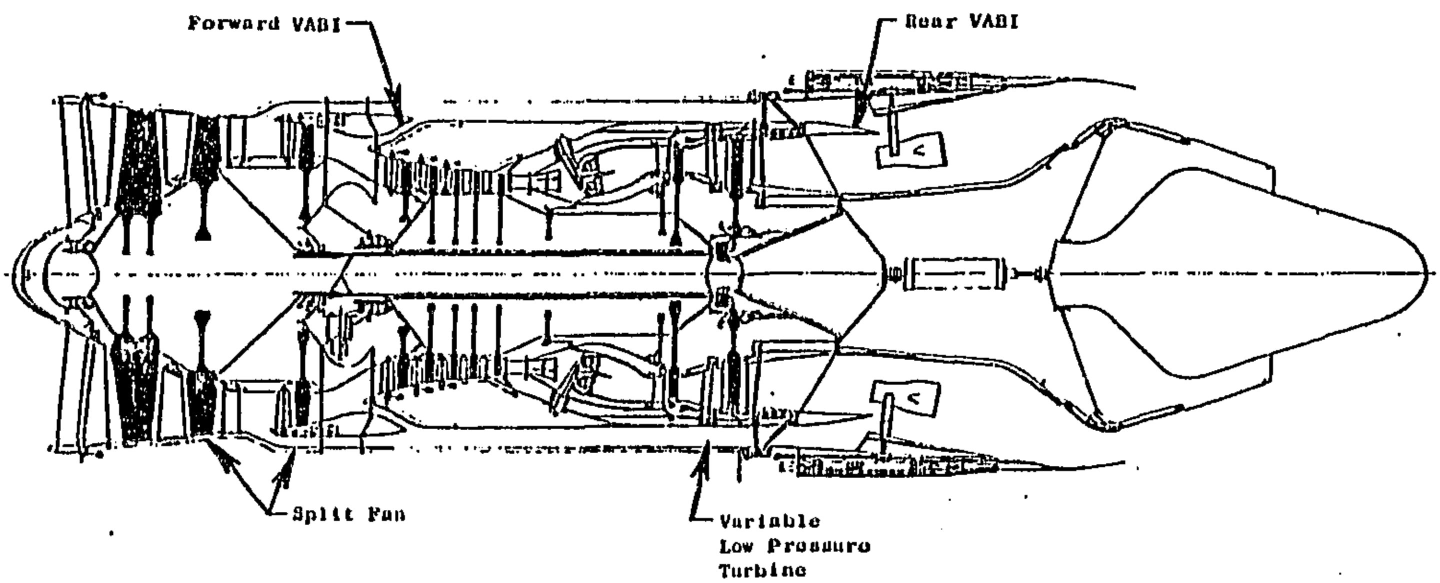


FIG. 3.19 GENERAL ELECTRIC GE 21 SERIES DOUBLE BYPASS VARIABLE CYCLE ENGINE (from Ref. 5).

total pressure to obtain the required pressure balance for mixing the flows. The variable area low pressure turbine increases flexibility in variation of shaft speeds and accommodates the large varieties in power required by the forward fan block. An augmenter is provided for transonic acceleration and climb.

Parametric analysis of a wide range of double bypass VCE's were accomplished [5] using the 1973 NASA reference advance supersonic technology aircraft [134] and the mission profile illustrated in Fig. 3.20. Figure 3.21 shows the variation of range and noise which results from "high flowing." (The percentage of high flowing is defined relative to 100% RPM for the front fan with the nominal inlet area without auxiliary inlet.) The presumed coannular noise reduction effect was the only suppression assumed.

For this example, the range is maximum for an engine with approximately 700 lbs/second airflow which is well matched to the supersonic cruise requirement. As air flow is increased by increasing engine size (and weight) to 900 lbs/second, the range decreases – in the supersonic mission from about 4050 NM to 3900 nautical miles, and in the mixed mission from about 3960 to 3730 NM. If the increased airflow is obtained by high-flowing the engine, the loss in range is much lower, because the weight increase is less, the airflow during supersonic cruise is better matched to the thrust requirement, and the SFC in subsonic cruise is better.

An approximate scale of sideline noise level relative to FAR Part 36, Stage 2 requirements is also shown on Figure 3.21. It ranges between 4 dB greater than the limit at 900 lbs/second to 1 dB less than the limit at 1170 lbs/second. For a given noise limit, and, hence in this analysis a given airflow, the increase

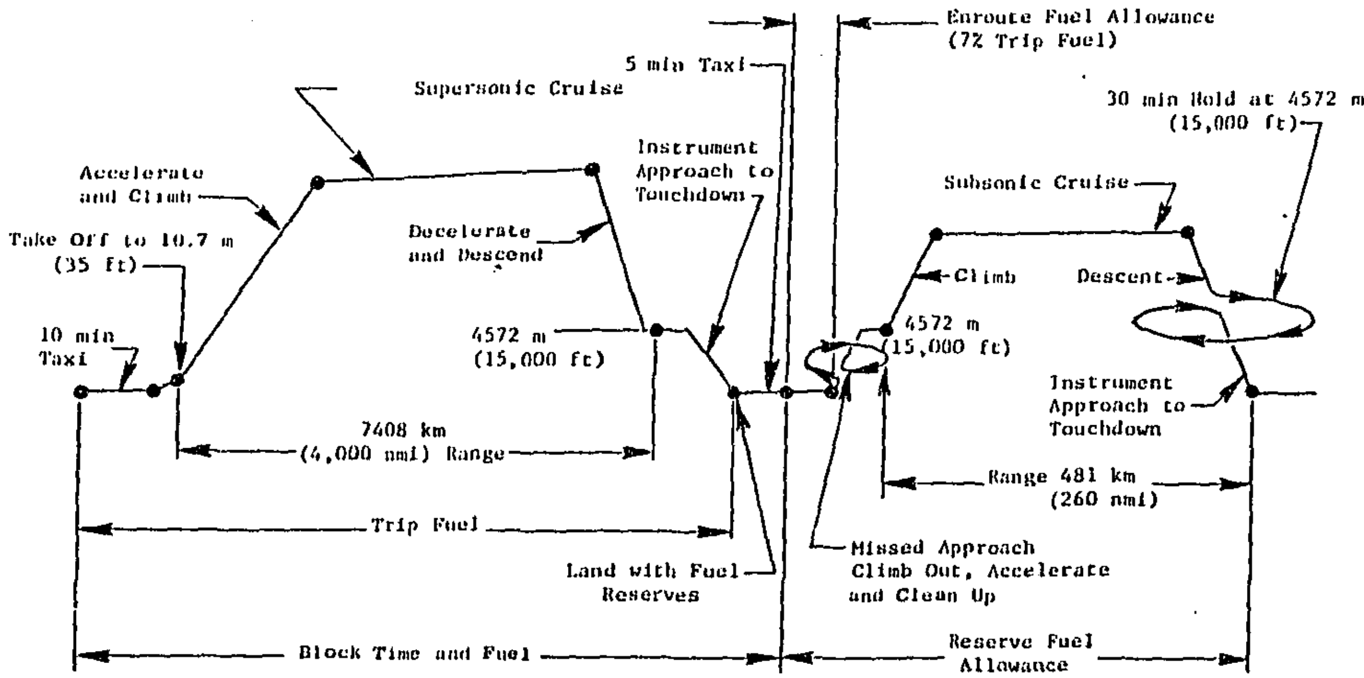


FIG. 3.20 MISSION A PROFILE FOR AST 1973 REFERENCE AIRCRAFT, TOGW 762,000 LBS MACH 2.4. MISSION B PROFILE IS SIMILAR EXCEPT FOR THE INCLUSION OF A 600 N.M. SUBSONIC LEG AND A REDUCTION OF SUPERSONIC CRUISE. (From Ref. 5)

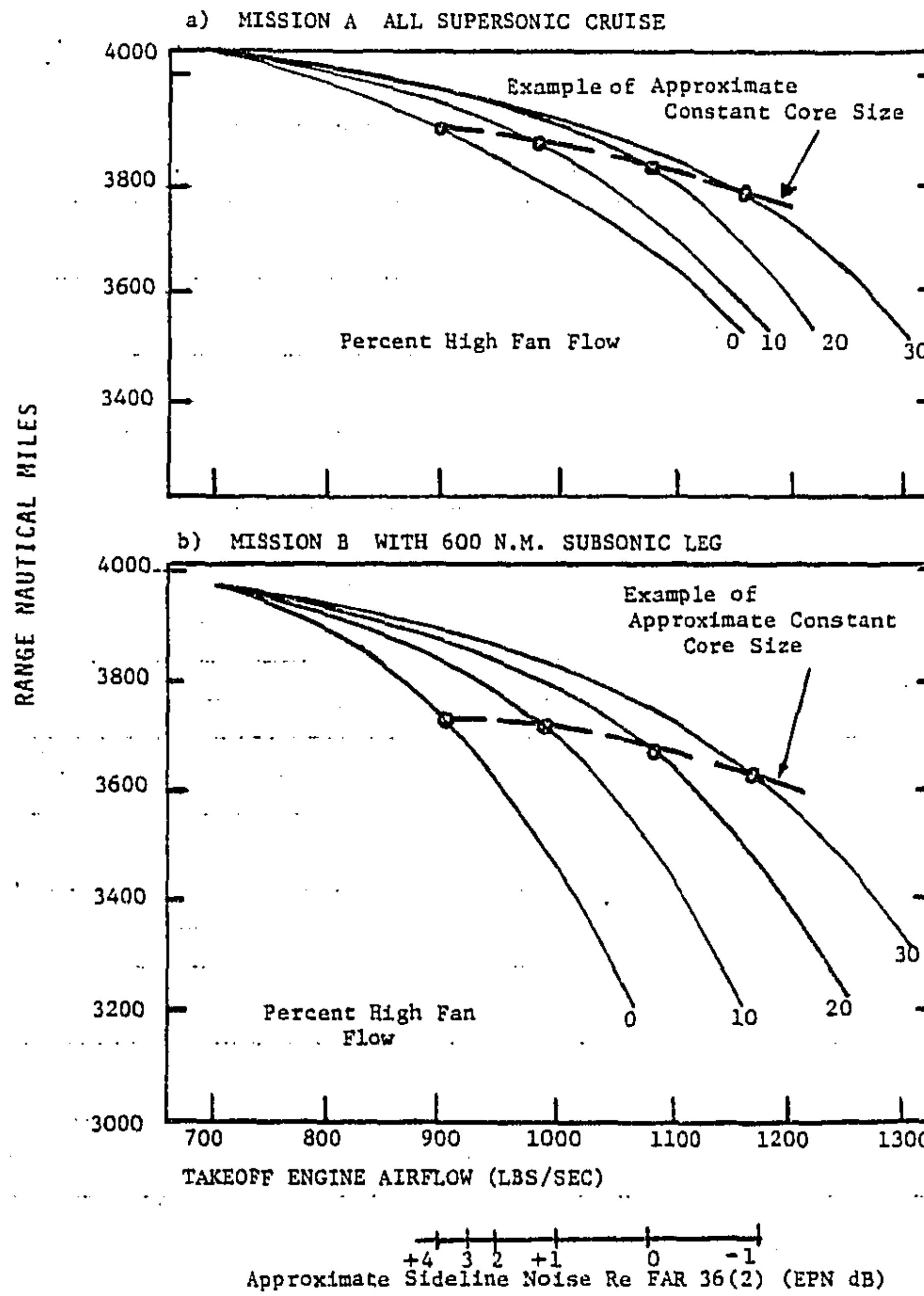


FIG. 3.21 EFFECT OF HIGH-FLOWING GE 21 SERIES ENGINE ON RANGE OF NASA 1973 REFERENCE AIRCRAFT AND SIDELINE NOISE FOR TWO MISSION PROFILES (CRUISE M2.32, INSTALLED THRUST AT M 0.35L IS 57,000 LBS.) (From Ref. 5)

of range with percentage high-flow is significant, particularly in the mixed mission. Also, for a constant core size, the reduction of noise as a function of high-flow is significant with little range loss, e.g. 5 dB in the example shown for a change in percent high-flow from 0 to 30 and a range loss of about 3%. Table 3.3 gives some typical values of engine parameters for the mixed mission.

TABLE 3.3
EXAMPLE FROM FAN HIGH-FLOW STUDY FOR MIXED MISSION B
(From Ref. 5)

Engine Performance Factors at Rotation	% Fan High-Flow		
	10%	20%	30%
Airflow $W\sqrt{\theta}/\delta$ (lb/sec)	990	1080	1170
Primary $W_{jet\ hot}$ (lb/sec)	806	690	637
Primary $V_{jet\ hot}$ (ft/sec)	2460	2420	2430
Secondary $W_{jet\ cold}$ (lb/sec)	194	405	541
Secondary $V_{jet\ cold}$ (ft/sec)	1570	1530	1510
Velocity ratio $V_{j\ cold}/V_{j\ hot}$	0.64	0.63	0.62
Air Flow Ratio $W_{j\ cold}/W_{j\ hot}$	0.24	0.59	0.85
Installed Thrust (lbf)	57,250	56,860	57,500
Noise Level Relative to FAR 36 Stage 2	+1.5 dB	0	-1.0 dB
Range (nmi)	3700	3670	3610

Pratt and Whitney carried three engines into the Phase 3 SCAR engine concept study. [69] They are the Variable Stream Control Engine (VSCE-502B), the Rear Valve Cycle Engine (VCE-112C) and a non-augmented Low Bypass Turbojet (LBE-430). The first two of the above are variable cycle engines, the third is a reference engine with the same level of technology.

The VSCE 502B, [70] illustrated in Fig. 3.22 contains a variable geometry fan and compressor and both a primary and duct burner. The fan is driven by the low pressure turbine and the compressor by the high pressure burbine, both turbines driven by the primary flow. Its capability to independently vary the temperature and velocity of the bypass and primary streams is used to maximize the "coannular noise reduction effect" during take-off and nearly match optimum flow conditions for subsonic and supersonic cruise requirements (see Fig. 3.23 for nozzle velocity profiles for various conditions).

The rear valve engine [70] differs from the VSCE in that the low pressure turbine which drives the variable geometry fan is split into two sections; the rear section being driven by either the heated bypass duct flow when the rear valve is inverted, or by the mixed flow when the rear valve is in the mixing position. Thus this engine is capable of two distinct cycles, a "twin turbojet" mode and a "turbofan" mode as depicted in Fig. 3.24. For takeoff it is operated in the "twin turbojet" mode with the primary burner and peripheral exhaust stream at maximum temperature and the duct burner at intermediate temperature to control the inner exhaust stream. However, because the peripheral airflow for this rear valve engine is a smaller percentage of the total, as compared to the VSCE 502B in Fig. 3.25, the "coannular noise reduction effect" is much lower than that estimated for the VSCE 502B.

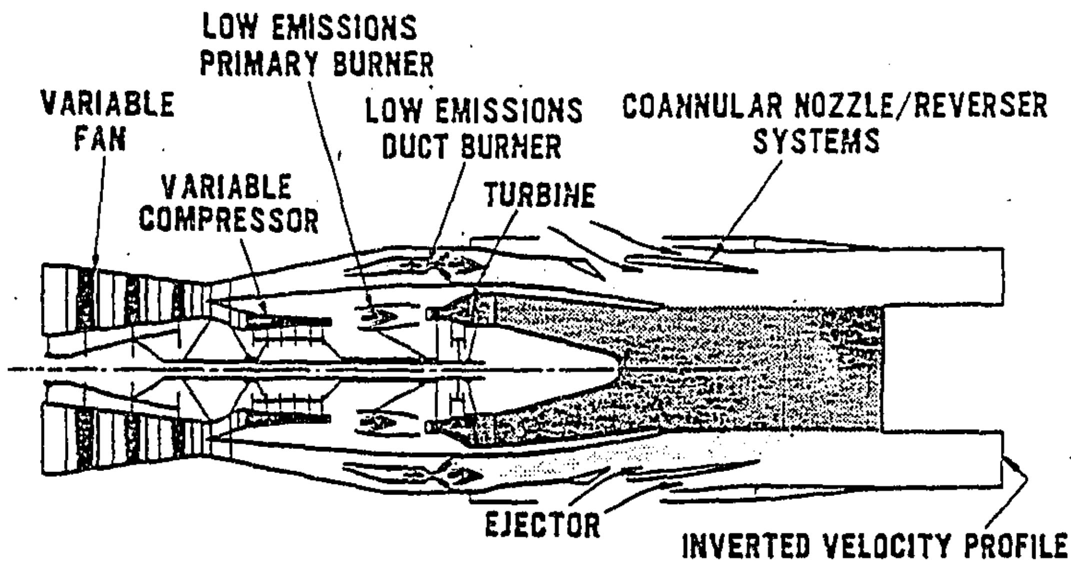


FIG. 3.22 PRATT & WHITNEY VARIABLE STREAM CONTROL ENGINE (VSCE 502) (From Ref. 71).

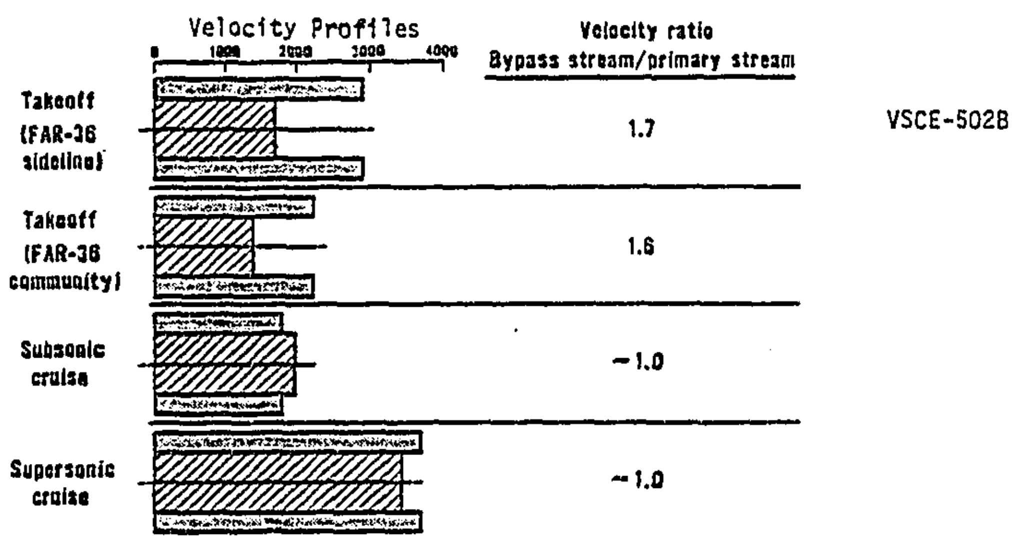


FIG. 3.23 VARIABILITY OF EXHAUST CONDITIONS FOR THE VSCE-502B. (From Ref. 69).

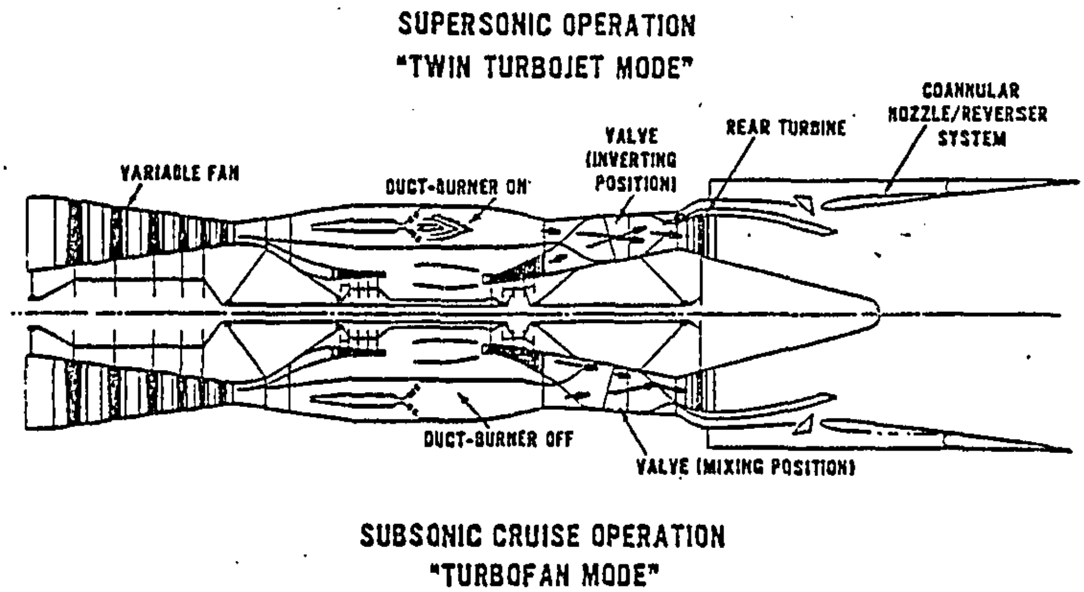


FIG. 3.24 PRATT & WHITNEY REAR-VALVE CYCLE ENGINE (VCE 112) (From Ref. 70).

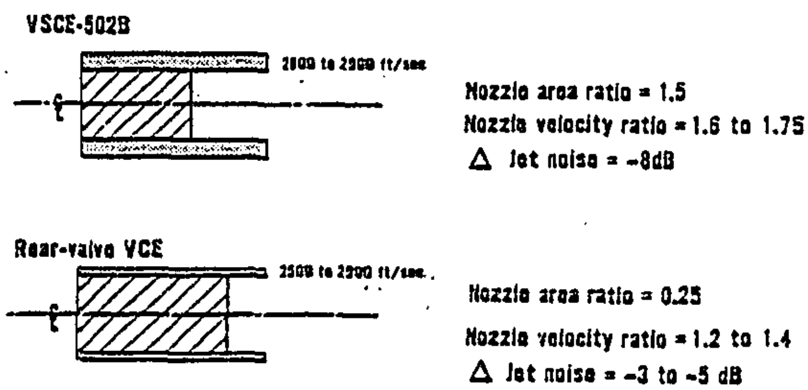


FIG. 3.25 TAKE-OFF EXHAUST VELOCITY PROFILE COMPARISON OF VSCE AND VCE (From Ref. 69).

The specific fuel consumption of these three engines is compared in figures 3.26 and 3.27 for supersonic and subsonic cruise, respectfully. The low bypass turbojet is slightly better than the variable cycle engines for supersonic cruise and slightly worse for subsonic cruise; and the VSCE-502B is slightly better than the VCE 112C for both conditions. Figures 3.28-3.31 illustrate the range potential for these engines as a function of the sideline noise relative to the FAR Part 36 Stage 2 noise limits for the missions described in Figure 3.20 and for two values of thrust to weight ratio. These range results are probably not directly quantitatively comparable with those of figure 3.18 because assumptions and prediction methodology probably vary between the two studies. However, the basic trends are similar; increasing range with increasing sideline noise on takeoff.

The VSCE Study [69] also showed that approximately 4 dB additional reduction could be obtained by high-flowing an oversized fan and inlet. This reduction is the same as that found by General Electric for an engine of similar size shown in the curve labeled "example of approximate constant core size" in Figure 3.21

It is clear from these parametric studies that variable cycle engines with advanced technology appropriate to certification in the early 1990's offer improved performance relative to current technology turbojets, as well as the advanced technology LBE, in terms of both aircraft range and takeoff noise [65]. The range improvement comes from a more efficient matching of airflow and fuel flow to the various thrust requirements for the engine. This improvement in range is more significant in the mixed mission B than in the all-supersonic mission A because the variable-cycle engine's improved subsonic SFC gives a greater range potential. The improved noise performance of the VCE is dependent upon its ability

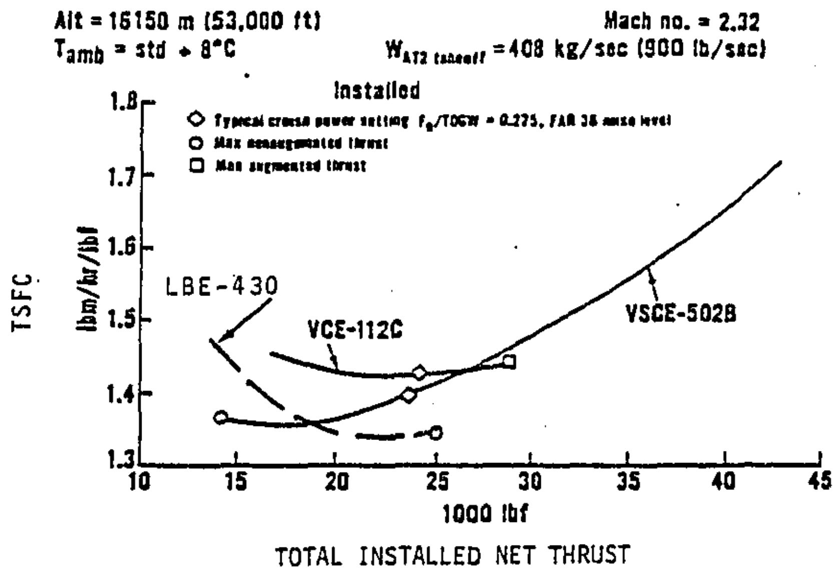


FIG. 3.26 SUPERSONIC CRUISE PERFORMANCE COMPARISON OF PRATT & WHITNEY PHASE III VARIABLE CYCLE ENGINES WITH UNSUPPRESSED LOW BYPASS ENGINE (From Ref. 69).

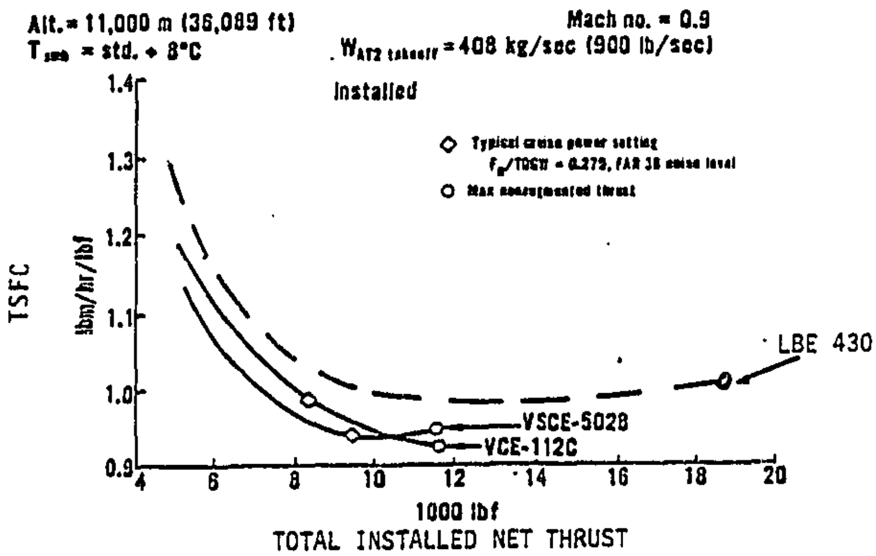


FIG. 3.27 SUBSONIC CRUISE PERFORMANCE COMPARISON OF PRATT & WHITNEY PHASE III VARIABLE CYCLE ENGINES WITH UNSUPPRESSED LOW BYPASS ENGINE (From Ref. 69).

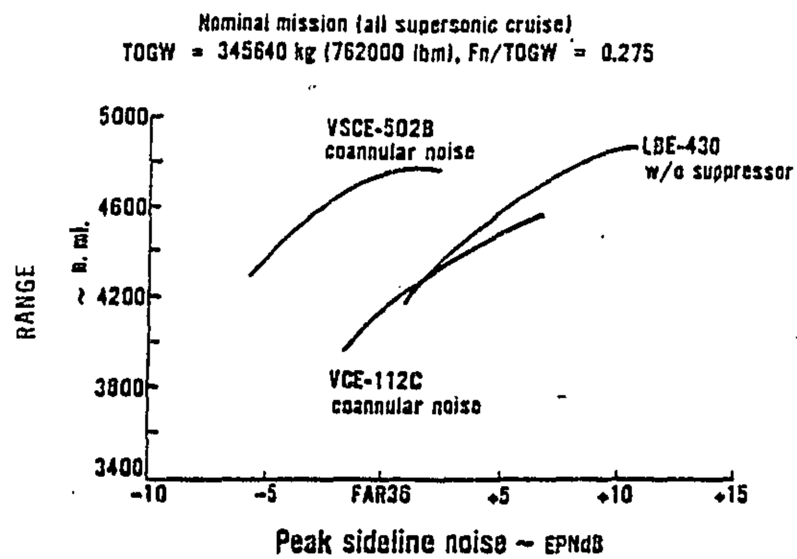


FIG. 3.28 MISSION A RANGE COMPARISON FOR PRATT & WHITNEY PHASE III REFINED ENGINES (From Ref. 69).

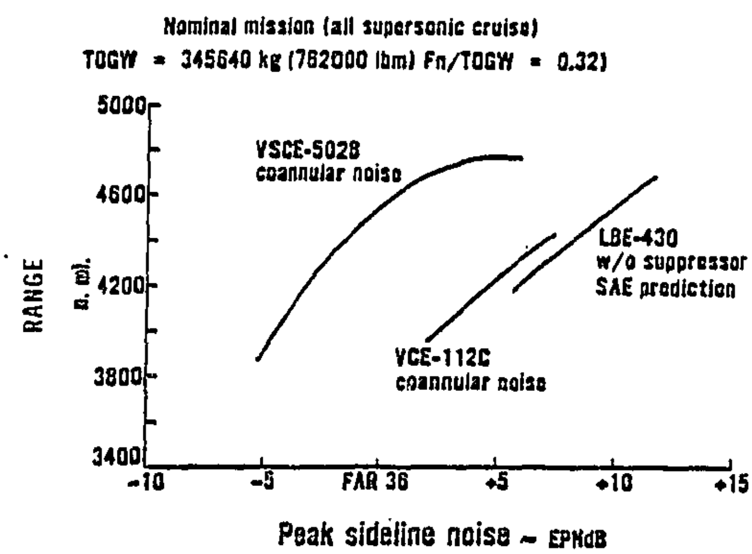


FIG. 3.29 MISSION A RANGE COMPARISON FOR PRATT & WHITNEY PHASE II REFINED ENGINES (From Ref. 69).

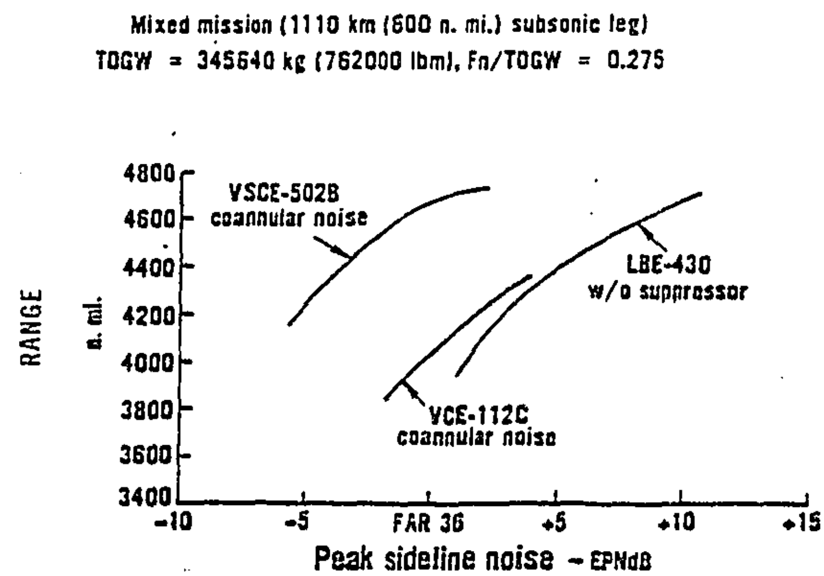


FIG. 3.30 MIXED MISSION B RANGE COMPARISON FOR PRATT & WHITNEY PHASE III REFINED ENGINES (From Ref. 69).

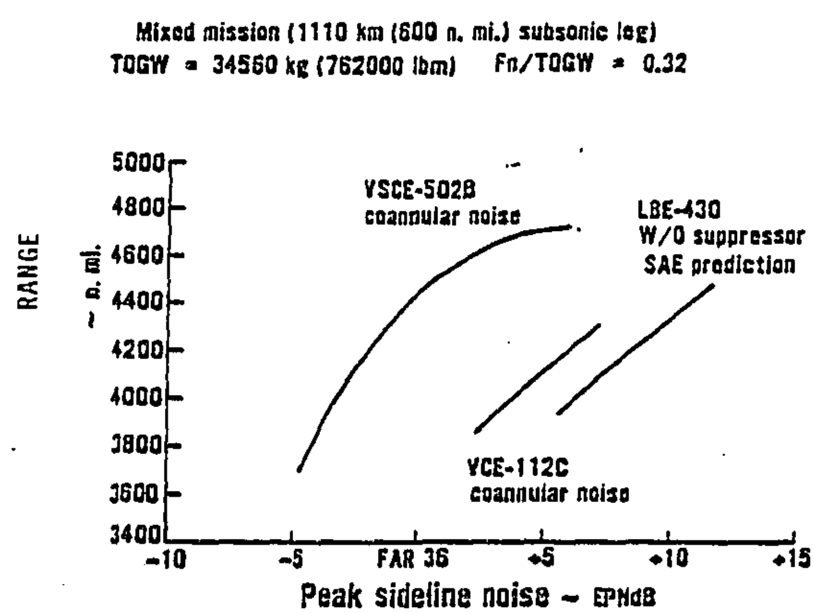


FIG. 3.31 MIXED MISSION B RANGE COMPARISON FOR PRATT & WHITNEY PHASE III REFINED ENGINES (From Ref. 69).

to take advantage of the "coannular effect" together with its ability to have a higher airflow (hence less noise per lb. of thrust) for no significant weight penalty.

3.4 Propulsion System Noise Control

Propulsion system noise is generated by many sources, including: jet mixing, turbulence-shock-interaction, combustion, fan (both forward and aft radiation) and turbine. The fan and turbine generate noise comprised largely of a series of discrete tones; the other sources generate noise that has primarily broad band random noise spectra. The jet mixing and shock turbulence interaction occur in the flow behind the engine and are determined by flow parameters and nozzle geometry. The other sources are inside the engine and can be controlled by a combination of design for minimum noise generation and application of sound attenuation technology.

For engines considered for supersonic cruise, noise from jet mixing and shock turbulence interaction generally dominates during takeoff, whereas a more complex combination of propulsion sources, as well as airframe noise, are important for the noise at the lower power settings associated with landing.

Prediction of the noise during aircraft operations is a very sophisticated, but inexact, art. There are a wide range of methods used in industry both in the U.S. and abroad as illustrated in Table 3.4. An example developed by an ICAO subcommittee on SST noise prediction methods [106] of the variation of results amongst these methods is given in Table 3.5. This example is for 100% power where jet and shock noise dominate. Greater variation in the total EPNL occurs at part power where the greater variability of prediction of the other sources has more effect on the total noise, see Table 3.6. The "reference - modified strawman"

TABLE 3.4

PREDICTION METHODS USED BY MEMBER STATES AND INDUSTRY FOR SST EVALUATION
(From Reference 106)

	JET	SHOCK	COMBUSTOR	FAN FORWARD	FAN AFT	TURBINE	AIRFRAME
NASA-ANOPP* (USA)	ARP 876 + own modified Bush SAE flight exponent	SAE draft. TANNA - Fisher Harper-Bourne	NASA Method TMX-71627	TMX 71763	TMX 71763	No approved method	FINK FAA RD-77-29
SNECMA (FRANCE)	ARP 876 + own modified Bush SAE exponent	Own method (SAE circulated) TNA 5502/74	SAE draft proposal (GE-MATTA-Envelope) FAA RD-74-125	TMX 71763 1st stage only	TMX 71763 1st stage only	GE-MATTA FAA RD-77-4	None
SAG (UK)	ARP 876 (pre-publication) + SAE Bush proposal	SNECMA method	SAE draft	Smith and House with tones	None Ratified	GE method at present. Smith and Bushell for back-up	FINK
BOEING	ARP 876 + own flight exponent	Not included	Own but similar to SAE draft	JT3D and JT9D based, similar to NASA CR-114649		JT3D-JT9D static data base	–
DOUGLAS	Own method	Not included	Not included	Modified Smith and House with tones		Modified Smith and Bushell with tones	
LOCKHEED	Modified ARP 876	SAE Draft	SAE Draft	Own method	Own method	GE method	Own unpublished method
P & W	ARP 876 + near average Bush and Bushell flight exponent	SAE draft proposal	Assumed low in SST	JT3D based method and no inflight	Proprietary on bypassed "clean-up"	Own, Matthews (modified)	
GE (for Concorde evaluation)	ARP 876 + SAE + Bushell flight exponent	SAE draft proposal	SAE draft proposal (GE method)	(Estimated from measured spectra)			Not considered
RR	ARP 876 + modified Bush flight exponent	SAE draft proposal	SAE draft proposal and modified spectra and field shape	Own method based on NGTE fans		Own method	FINK

NOTES: (i) *Sutherland Absorption used, whereas ARP 866A is normally used by Industry for certification purposes.

(ii) For forward speed effects on sources other than jet mixing a 4th power Doppler amplification is used generally.

TABLE 3.5

EXAMPLE OF APPLICATION OF VARIOUS PREDICTION METHODS TO AN SST TYPE ENGINE AT 100% POWER. (From Ref. 106)

REVIEW OF SST TRIAL ENGINE

CASE 100 % POWER AT 1000 ft Altitude

FREEFIELD PREDICTIONS ISA+10% 70% RH

Date

Chart No. 2

ORGANISATION (or method)	EPNL	PEAK PNL of SOURCE						COMMENTS
		JET	SHOCK	CORE	FAN fwds	FAN rwds	TURBINE	
'STRAWMAN'	[113]	111¾	112½	95	[85]	((110¾))	((66½))	No fan tones.
NASA ANOPP	113½	113	112½	96	110	102	–	PNL(T).
UK (BAC)	[114]	111	114	95	85	(115)	96¼	Fan rearwards doubted.
FRANCE (SNECMA)	112½	111	113½	96¾	106¾	91	(72½)	Turbine low.
USSR	110¾	111	–	101	100	102¼	89½	
BOEING	[111½]	111¼	[110]	96½	97½	90½	77	Shock assessed.
McDAC	112	112	–	99	107	93	101	
LOCKHEED	[113]	111	114	96	109	–	–	
GE	114½	116	113¼	95¾	109¼	–	70	Close spaced IGV fan assessed.
RR	113½	109¾	113¼	101½	100¾	97¾	80½	EPNL includes 1.2 metres ground reflection.
P&W	112¾	112¼	–	–	110½	110½	74½	
(REFERENCE)	113½	115½	114¼	97	107¾	102¾	[90½]	

LEGEND

( ) = not included in total

[ ] = assessed, not accurately predicted

[ ] = no tones included in estimate

TABLE 3.6

SUMMARY OF APPLICATION OF VARIOUS PREDICTION METHODS TO AN SST TYPE ENGINE AT VARIOUS POWER SETTINGS. (From Ref. 106)

TRIAL SST SUMMARY

		Freefield EPNL	Freefield source Predictions – Peak PNL					
			Jet	Shock	Combustor	Fan (forward)	Fan (Aft)	Turbine
100% power at 1000 ft	Industry/Agency Average‡	113 ±1½	112	113	97¼	106½	101	86
	"STRAWMAN" – Methods of July 1977	113	111¾	112½	95	(85)	(110¾)	(66½)
	"Reference"* – modified Strawman as per Annex II	113½	115½	114¼	97	107½	102¾	90½
66% power at 1000 ft	I/A Average ‡	105½ ±5	102	91	94	103½	102¼	85
	Strawman	103	101¼	95¾	90¾	84¼	(110½)	(69)
	Reference*	104½*	104	94	92½	107	101¾	90
25% power at 400 ft	I/A Average ‡	108 ±5	93	–	94½	100¼	109½	99
	Strawman	111	93¼	–	92¾	94	119½	79½
	Reference*	107*	94½	–	95½	110	110	106

* Computed by BAe (Weybridge), where Reference Procedure is programmed

‡ Would increase by ½ dB approximately if all participants estimated all sources.

( ) Figures not included in EPNL

prediction procedure [106] together with the current SAE procedure [173] appear to represent the current consensus for predicting propulsion system noise for supersonic engines.

The primary noise condition of concern for SST design is takeoff, because it is generally considered that the noise control potential for noise during landing is sufficient for FAR 36 Stage 2 requirements, and the control potential probably is sufficient for Stage 3 requirements as well. The variable inlet geometry required for supersonic flight offers potential of using a near sonic throat [59] to reduce all forward radiated fan noise during landing, and the sophisticated aircraft control system enables optimization of a decelerating approach, as has been proved to be effective by the Concorde [190]. Airframe noise which provides a threshold during landing is discussed later, as is the relative noise at the sideline and takeoff noise measurement locations which are affected by how the aircraft is operated.

The amount of noise generated in the jet flow, as well as its frequency and directional characteristics is primarily a function of nozzle geometry in combination with the spatial distribution of flow (pressure, temperature and velocity) in or near the effective nozzle plane. In the development of new engine concepts, previously discussed, noise control was considered and integrated in the selection of engine cycle, bypass ratio, flow inversion, stream velocities for coannular effect, fan high flow for takeoff, etc.; all together with cruise and climb performance requirements. If additional noise reduction is required for the design, it may be obtained by altering nozzle geometry, i.e., a noise suppressor with or without an acoustically treated exhaust ejector, or by resizing the engine to attain the required thrust with higher airflow and lower combustion temperatures, thus reducing exit

Footnote: For additional information on noise generation, see references 1,12, 24,27,32,36,45,55,56,57,58,66,124,127,130,132,133,135,138,140,141, 142,148,149,156,157,158,159,169,175,176,180 and 181.

velocity. These two techniques have been applied in integrated airframe-propulsion studies to the various candidate engine families developed in the SCAR program for the purpose of studying the tradeoffs between various performance parameters, such as noise and range. (See Section 4.) Additionally, up to 3 dB reduction can be attained by configuring the aircraft so that the engines are over the wing; or, as in the case of the Lockheed study [110, 212], in an over under configuration, so that the lower jet shields (or refracts) the noise of the upper jet from observers under the aircraft.

Noise suppressors for turbojet engines were developed in the 1950's. The early B-707s had the circular conical nozzle replaced with 21 smaller tubes; the early DC-8 had a multilobed daisy nozzle with retractable ejector. These suppressors effectively spread the jetstream over a larger circular area, reducing its downstream velocity and low and middle frequency noise, but increasing slightly its high frequency noise generated by the initial mixing of the smaller jets on the periphery of the flow [43]. The thrust losses with the better early suppressors were typically of the order of 1% per PNdB.

Little improvement in technology occurred until the late 1960's when Boeing and General Electric attempted to reduce the noise of the afterburning GE4J5 engine which was developed for the B2707 SST. Considerable progress was made, both in maximization of suppression and in minimization of thrust losses through better base ventilation. This work was continued after the cancellation of the U.S. SST program with development of hardware that could be tested in flight, and led to a major FAA program with General Electric to investigate almost all aspects of high velocity jet noise suppression [119].

The performance of a suppressor is affected by the nozzle flow conditions, pressure ratio and velocity, and by the flight conditions. Figure 3.32 illustrates the effect of flight speed on the suppression characteristics of several model nozzles evaluated in the Ames 40 x 80 ft wind tunnel, and includes two B727 flight test points. In all of these test configurations the suppression decreases with an increase in forward velocity, as found for the Concorde spade suppressors [63].

Figure 3.33 illustrates the suppression characteristics of a 32 spoke-plug and a 12 chute-plug nozzle over a range of jet velocities, both static and in low speed flight. In both cases, the suppression increases with jet velocity tending to reach a maximum at the nozzle design condition. For these examples, the peak PNL tends to decrease in flight relative to its static condition. The installed gross thrust coefficient for the 12 chute-plug nozzle was about 0.93 when measured statically, and 0.89-0.92 when in flight at nozzle pressure ratios in excess of 2.0. The installed gross thrust coefficient for the 32 spoke nozzle was approximately 0.89-0.92 statically, and 0.81-0.84 in flight at nozzle pressure ratios over 2.0 [24].

Examples of suppressor configurations studied in the FAA high velocity jet noise suppression program [119] are illustrated in figures 3.34 and 3.35. Simulated flight data for a 40 shallow chute dual stream suppressor and a 32 chute single stream suppressor are given in figure 3.36. The noise reduction in the forward quadrant is thought to result from the suppression of shock noise as illustrated in figure 3.37a. The EPNL suppression for the 32 chute single stream suppressor is estimated to be 10 EPNdB for a weight penalty of approximately 1150 lbs, and a thrust loss of 6% (see Fig. 3.37b). For the 40 shallow chute coannular plug nozzle the reduction is 8.5 EPNdB for a weight

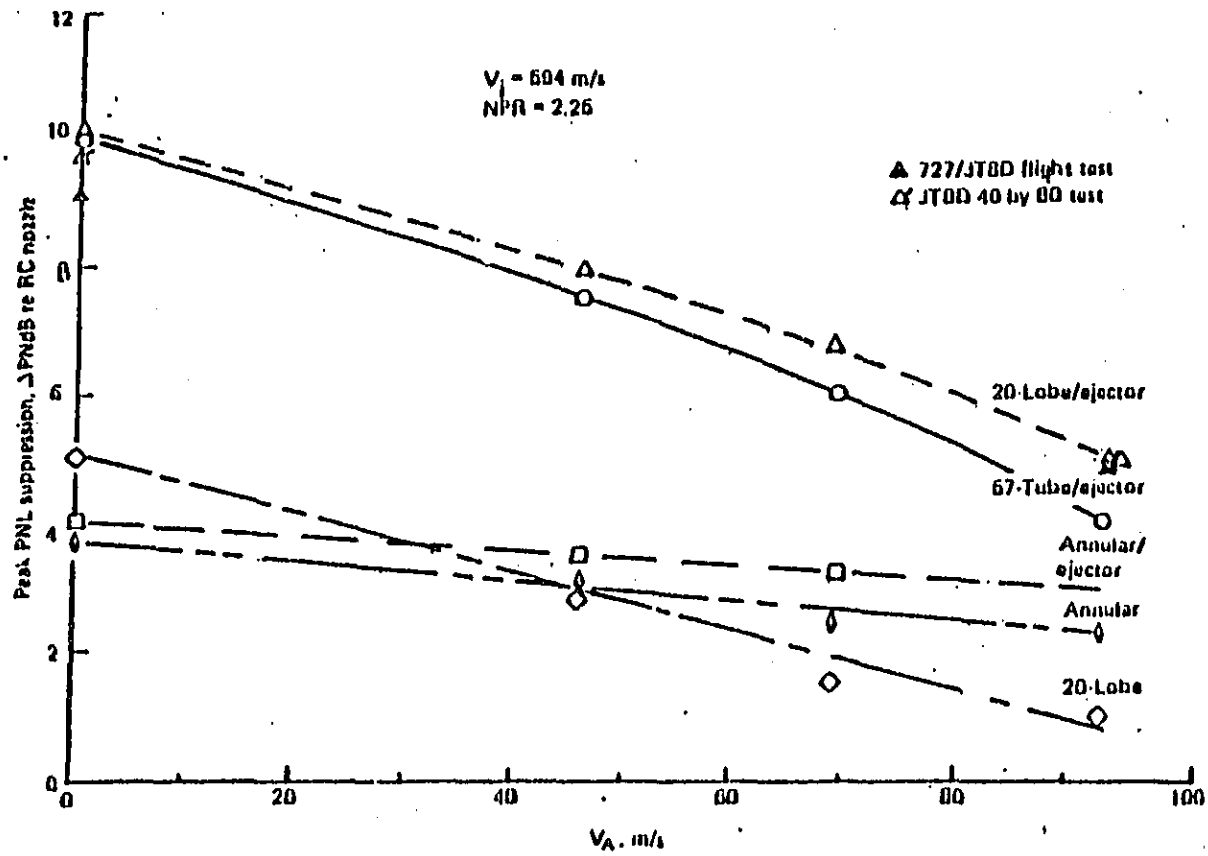


FIG. 3.32 FLIGHT EFFECT ON SEVERAL MODEL SUPPRESSORS AS MEASURED IN THE 40 X 80 FT WIND TUNNEL. (From Ref. 102)

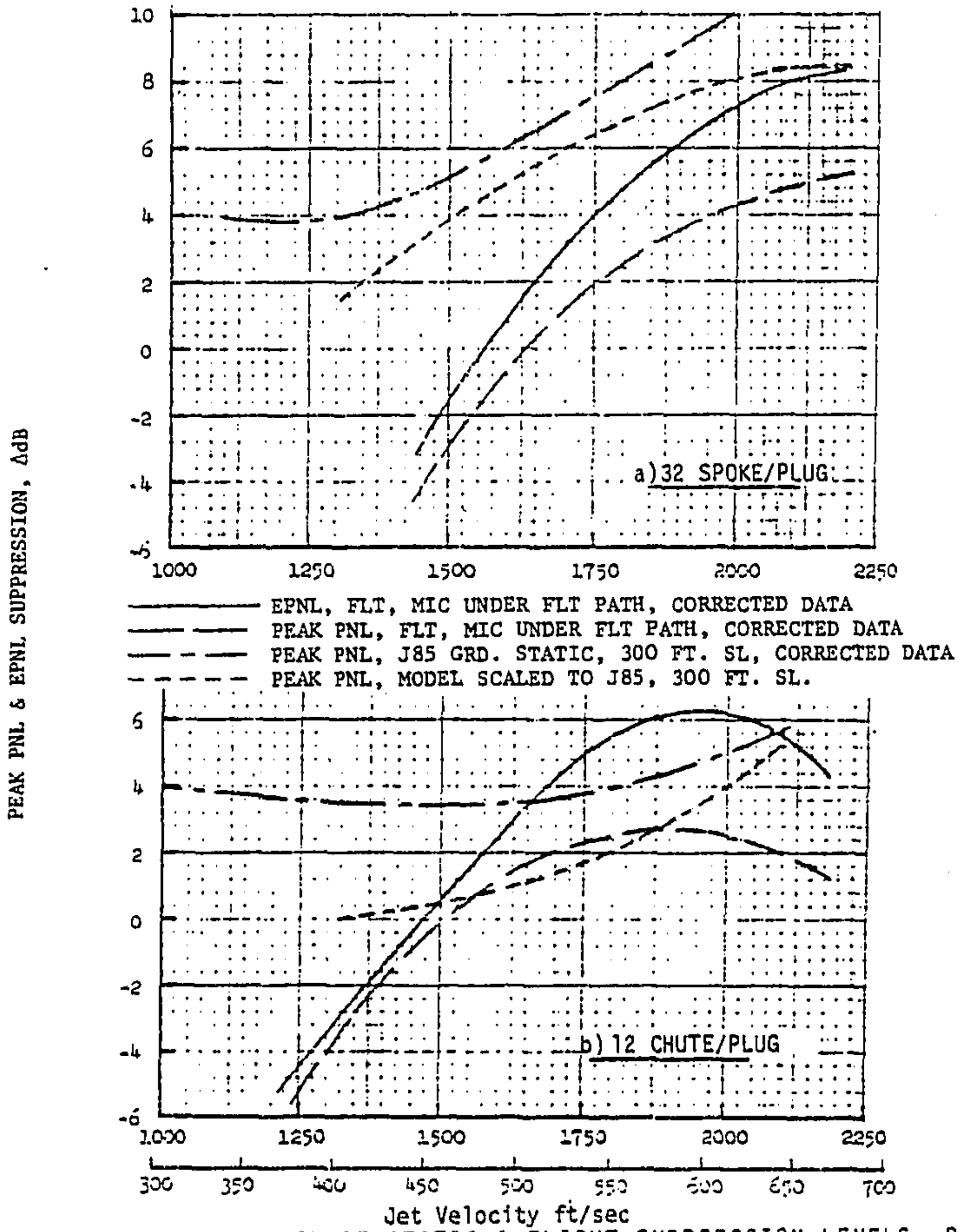


FIG. 3.33 COMPARISON OF STATIC & FLIGHT SUPPRESSION LEVELS, PEAK PNL & EPNL USING J85 ENGINE ON F106 AIRCRAFT. (From Ref. 24)

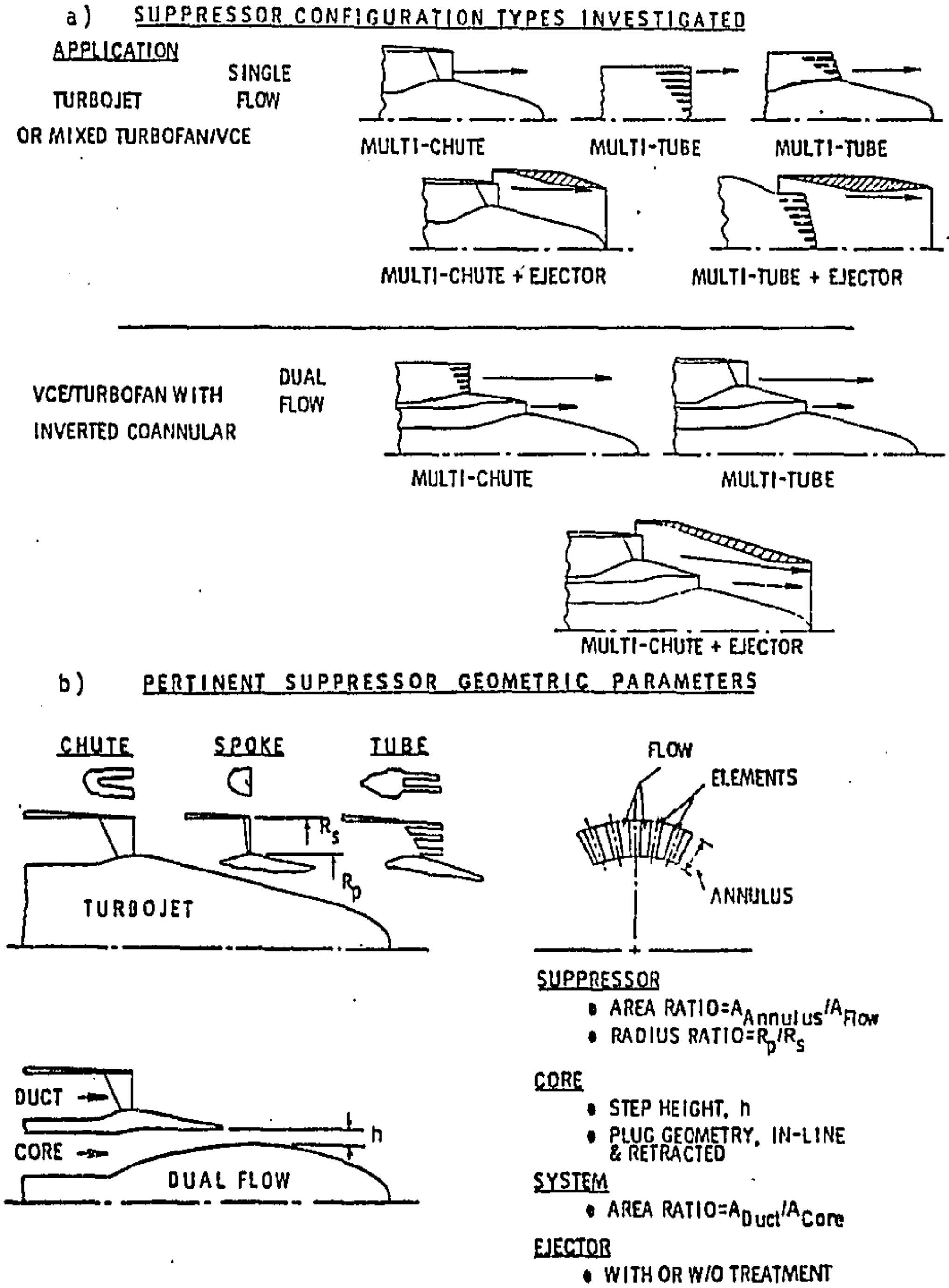


FIG. 3.34 SUPPRESSOR CONFIGURATIONS AND GEOMETRICS IN FAA-GE PROGRAM. (From Ref. 119)

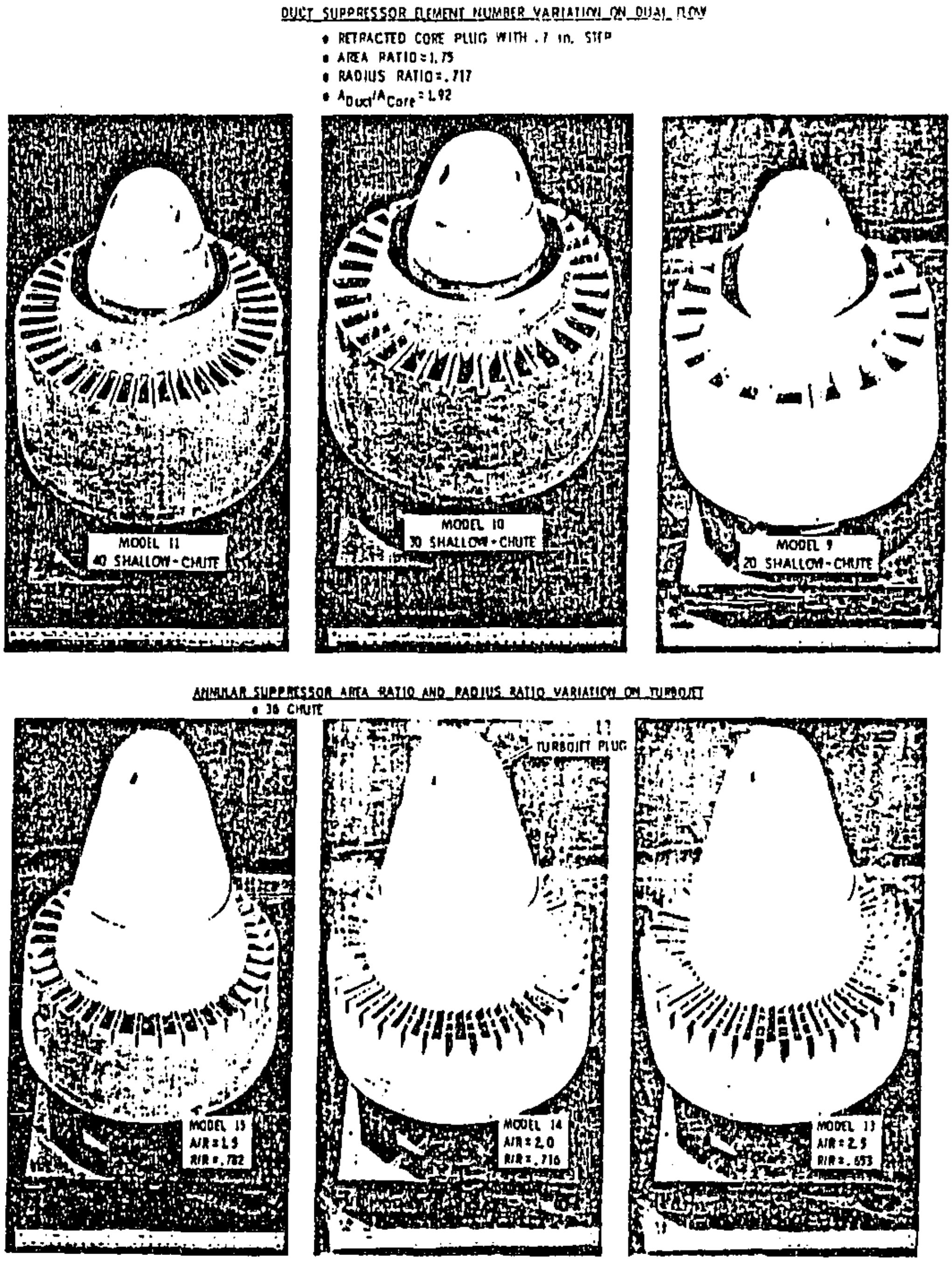


FIG. 3.35 EXAMPLES OF CHUTE TYPE SUPPRESSORS FOR SINGLE AND DUAL FLOW PLUG NOZZLES.

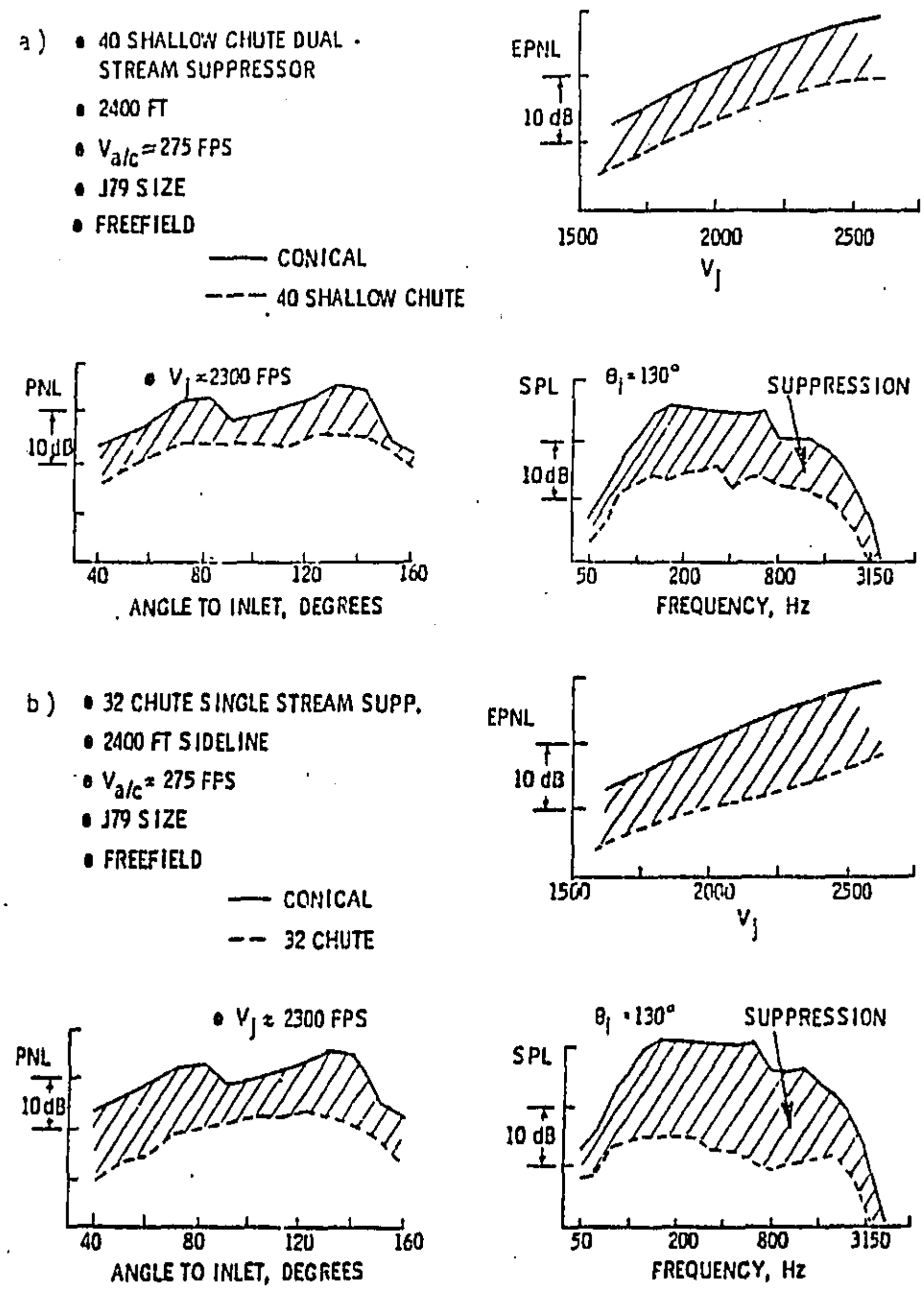
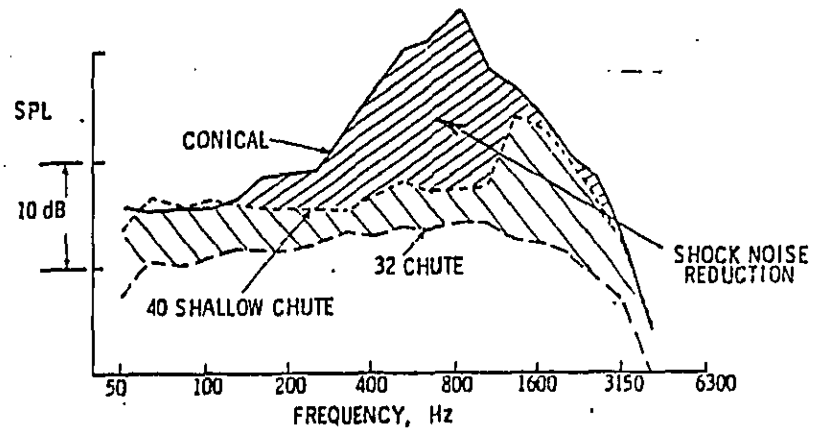


FIG. 3.36 NOISE SUPPRESSION IN SIMULATED FLIGHT (FREE JET FACILITY) FOR TWO TYPES OF CHUTE SUPPRESSORS. (From Ref. 119)

a) SHOCK NOISE REDUCTION BY SUPPRESSORS

- $\theta_j = 50°$
- $V_j \approx 2300$ FPS, NOZZLE PR = 3.2
- 2400 FT SIDELINE
- J79 SIZE



b) SUPPRESSOR IN-FLIGHT ACOUSTICS, AERO PERFORMANCE & ESTIMATED WEIGHTS

		SINGLE STREAM	DUAL STREAM
• SUPPRESSION (re: CONICAL)		• 32 CHUTE/PLUG	• 40 SHALLOW CHUTE/ COANNULAR PLUG
• 2128' SL, 1000' ALT.			
• $V_j \approx 2300 - 2400$ FPS			
J79 SIZE	ΔEPNL	11.5	9.5
	ΔPNL_{peak}	13.0	12.0
AST SIZE	ΔEPNL	10.0	8.5
	ΔPNL_{peak}	12.0	10.5
• WEIGHT CHANGE DUE TO SUPPRESSOR			
• AST SIZE - Δ WEIGHT		~1150 LBS(1)	~550 LBS(2)
• THRUST DEGRADATION (re: CONICAL)			
• .36 MACH - ΔC_{F_G}		~ 6%	~8%

(1) REF. TO BASELINE PLUG NOZZLE; 770 LBS/SEC FLOW SIZE

(2) REF. TO BASELINE COANNULAR PLUG NOZZLE; 840 LBS/SEC FLOW SIZE

FIG. 3.37 SELECTED CHARACTERISTICS OF TWO EXAMPLES OF CHUTE NOISE SUPPRESSORS. (From Ref. 119) penalty of approximately 550 lbs and a thrust loss of 8%. The factors influencing the thrust loss for a typical chute suppressor the shown in Fig. 3.38a and for the base pressure losses of a tube suppressor in Fig. 3.38b.

This FAA program has not only investigated systematically a large range of designs for suppressors, but has also developed more sophisticated analytical methods for predicting their performances. One example of predicting the detailed noise performance of a 104 tube suppressor in flight is illustrated in figure 3.39. The agreement is very close. The comparison of measured and predicted in-flight EPNL over a variety of suppressor types is illustrated in figure 3.40. The data have a correlation coefficient of 0.98, 80% confidence of prediction within ± 2.1 EPNdB, 95% confidence of prediction within ± 3.2 EPNdB.

Table 3.7, prepared for ICAO CAN Working Group E [102], summarizes the suppression characteristics of several types of suppressors applicable to the high jet velocities applicable to engines for supersonic cruise aircraft. Configurations such as the 32 chute-plug and the 57 tube treated ejector are shown to give static suppression of 12 and 15 dB, respectively, with less than 1/2% thrust loss (flight) per dB suppression (static).

For these data, the amount of flight suppression tends to be equal or less than the amount of static suppression, as illustrated in figure 3.41, with some of the multi-tube suppressors showing maximum promise of good flight performance. As might be anticipated, the number of PNdB reduction (static) per % thrust loss (static) is highly variable, varying from 5:1 to 0.5:1 in the data illustrated on figure 3.42 Even greater variability can be found in comparing the number of PNdB reduction in flight with the thrust loss in flight as illustrated in figure 3.43.

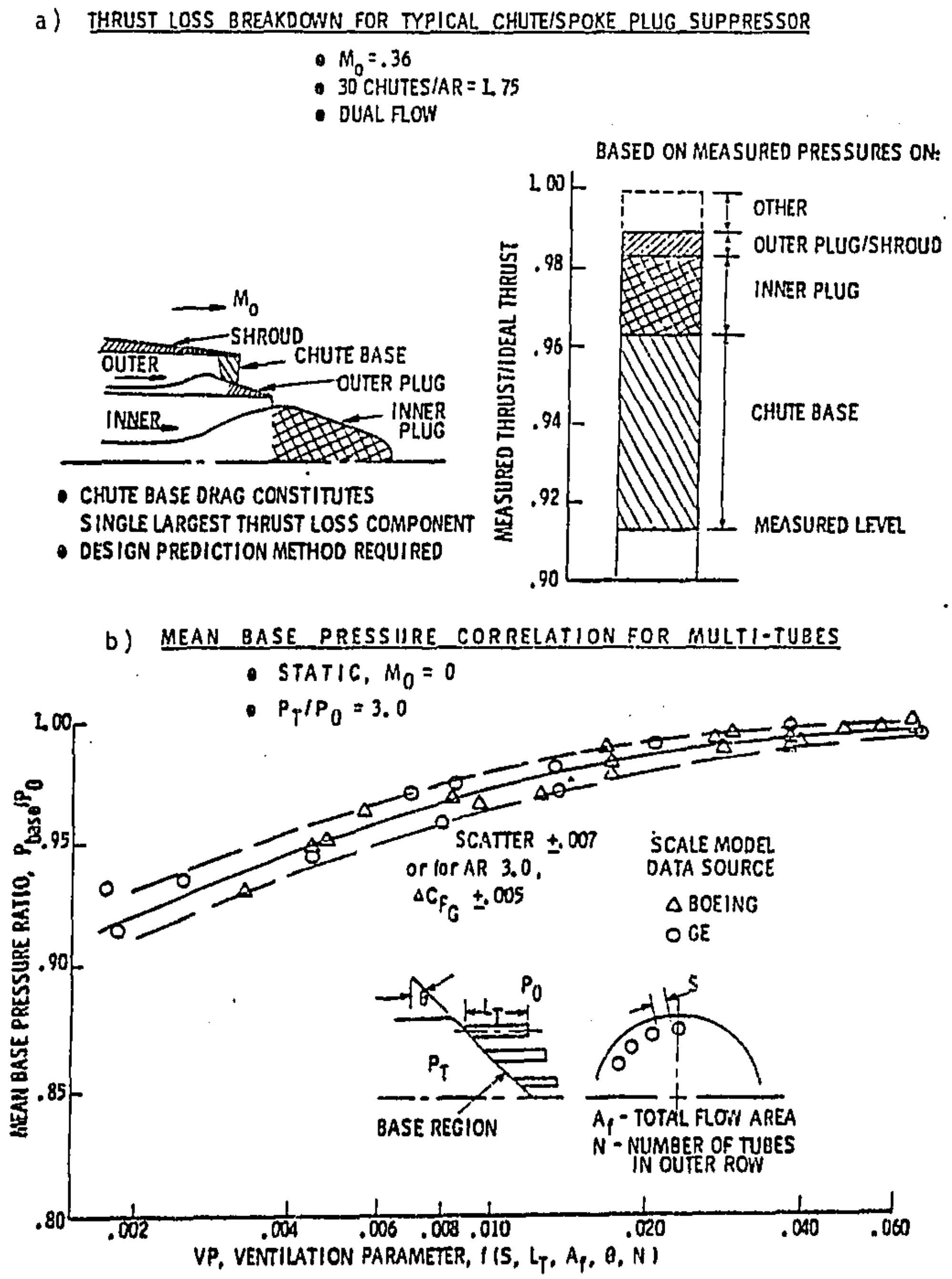


FIG. 3.38 FACTORS INFLUENCING THRUST LOSSES OF TWO TYPES OF SUPPRESSORS. (From Ref. 119)

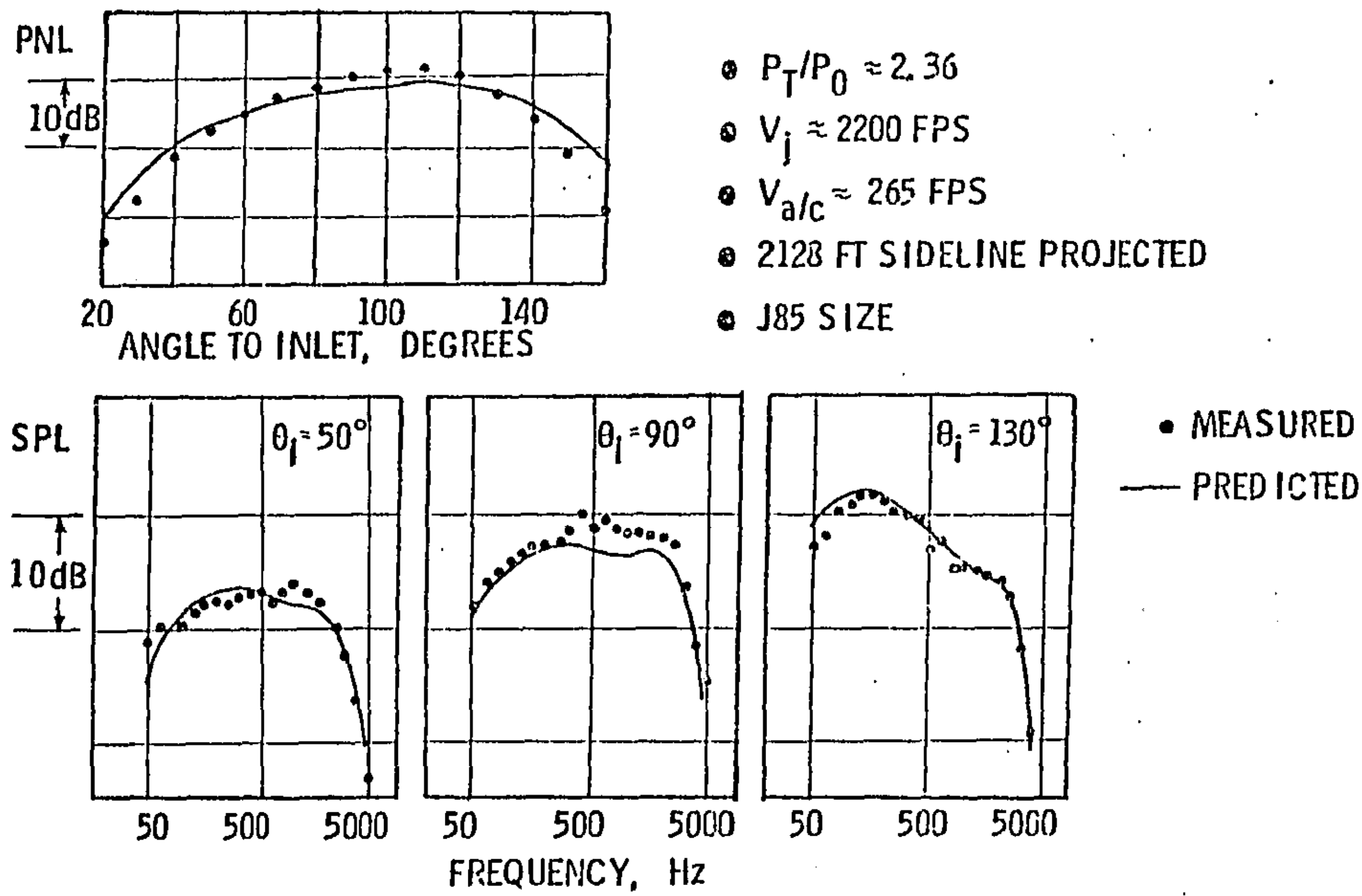


FIG. 3.39 COMPARISON OF MEASURED AND PREDICTED NOISE CHARACTERISTICS OF 104 TUBE SUPPRESSOR IN "AEROTRAIN," FLIGHT. (From Ref. 119)

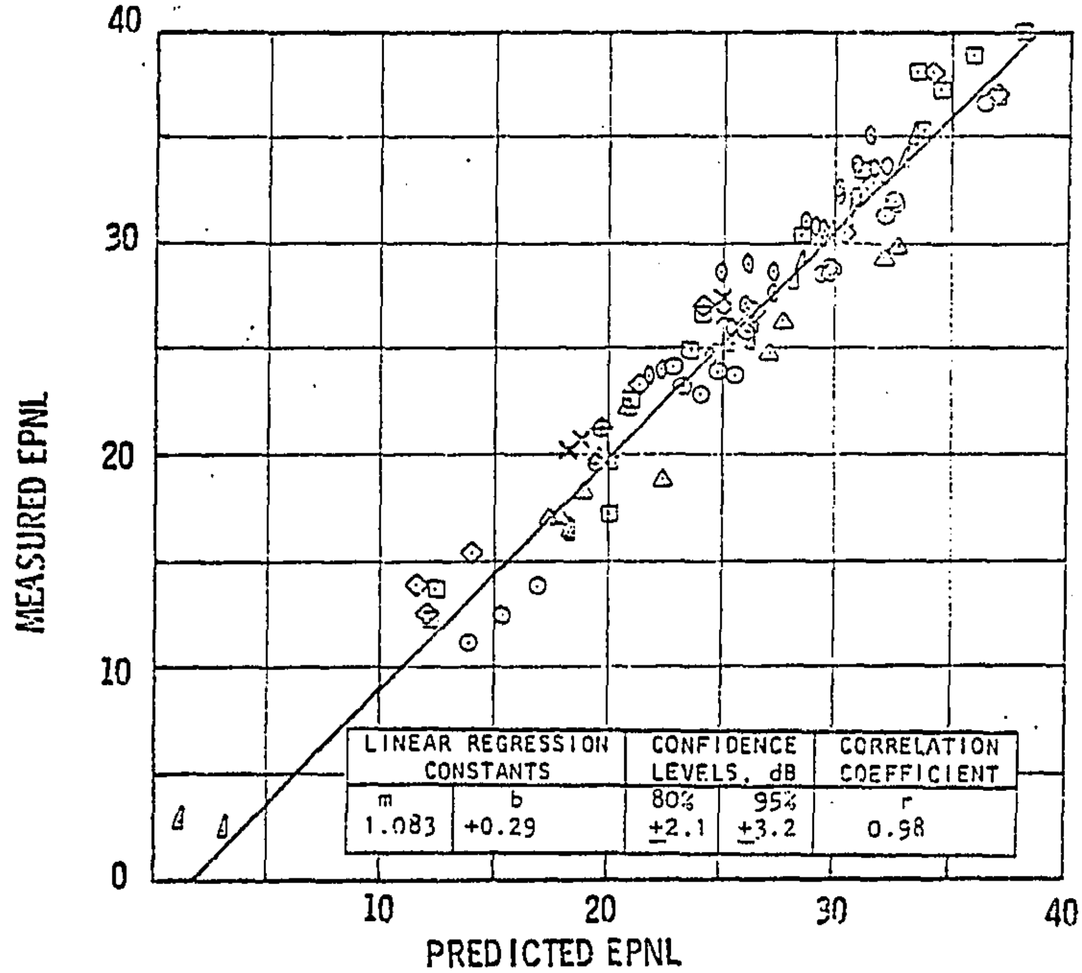


FIG. 3.40 CORRELATION BETWEEN MEASURED AND PREDICTED EPNdB FOR ALL TYPES OF SUPPRESSORS INVESTIGATED UNDER FLIGHT CONDITIONS. (From Ref. 119)

TABLE 3.7 NOISE SUPPRESSION/AERO PERFORMANCE POST SST STATUS (From Ref. 102) SHOWING TYPICAL SIDELINE ΔPNL'S RE CONICAL STATIC AND THRUST COEFFICIENT (C_{F_g}) @ $V_{a/c}$ = 240 KNOTS

SUPPRESSOR TYPE	MASS AVERAGED VELOCITY, fps	ΔPNL (Static)	$\Delta PNL/\Delta C_{F_g}$ (Flight)
Turbojet/Mixed Flow Turbofan Single Flow			
8 Lobe Daisy	~2200	~ 5.7	~ .9
32 Chute/Plug	~2500→2550	~12.0	~ .4
48 Spoke/Plug	~2500→2550	~16.0	~ .8
57 Tube/Treated Ejector	~2500→2550	~15.8	~2.2
85 Tube/Treated Ejector	~2500→2550	~20.8	~1.2
104 Tube	~2200	~13.2	~1.1
Annular Plug/High Radius Ratio	~2400	~ 2.0	~3.3
Low Bypass/Dual Flow			
Coannular Nozzle with Plug	~2200	~5 - 6	~2.9

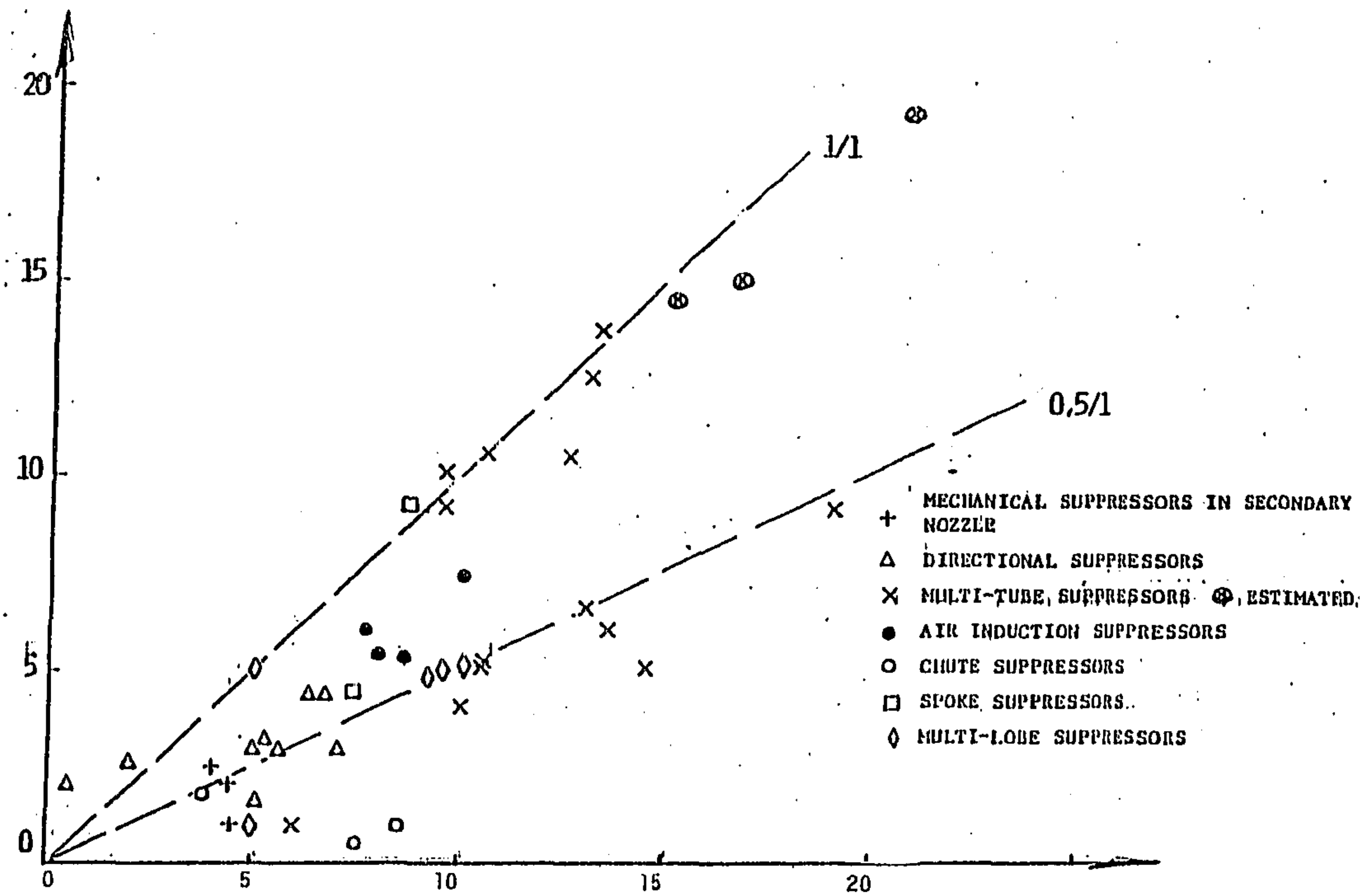


FIG. 3.41 STATIC VS FLIGHT NOISE SUPPRESSION FOR MANY SUPPRESSOR FAMILIES WITH FLIGHT SPEED 230-400 FT/SEC. (From Ref. 102)

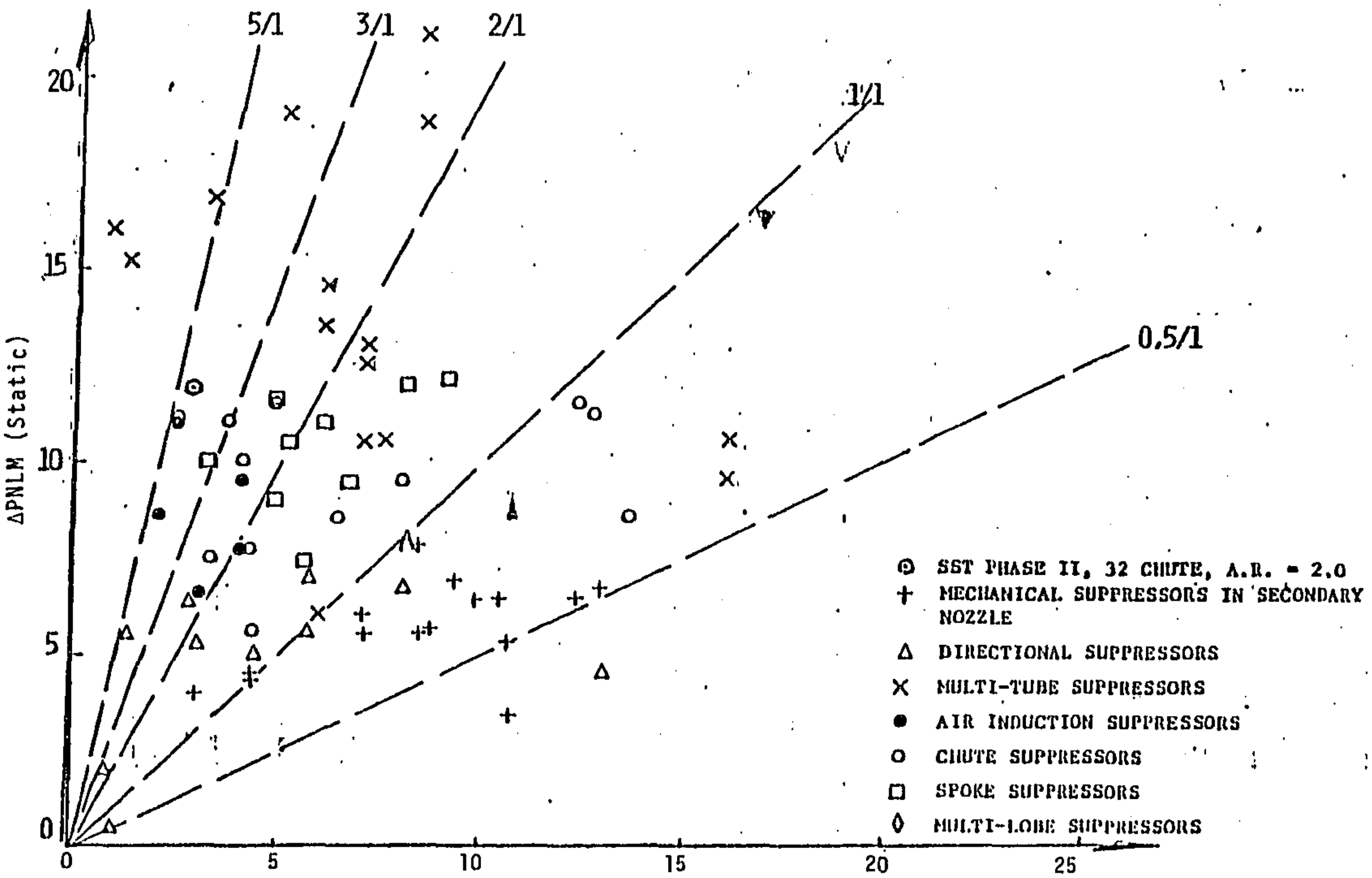


FIG. 3.42 STATIC NOISE SUPPRESSION VS STATIC THRUST LOSS FOR MANY SUPPRESSOR FAMILIES. (From Ref. 102)

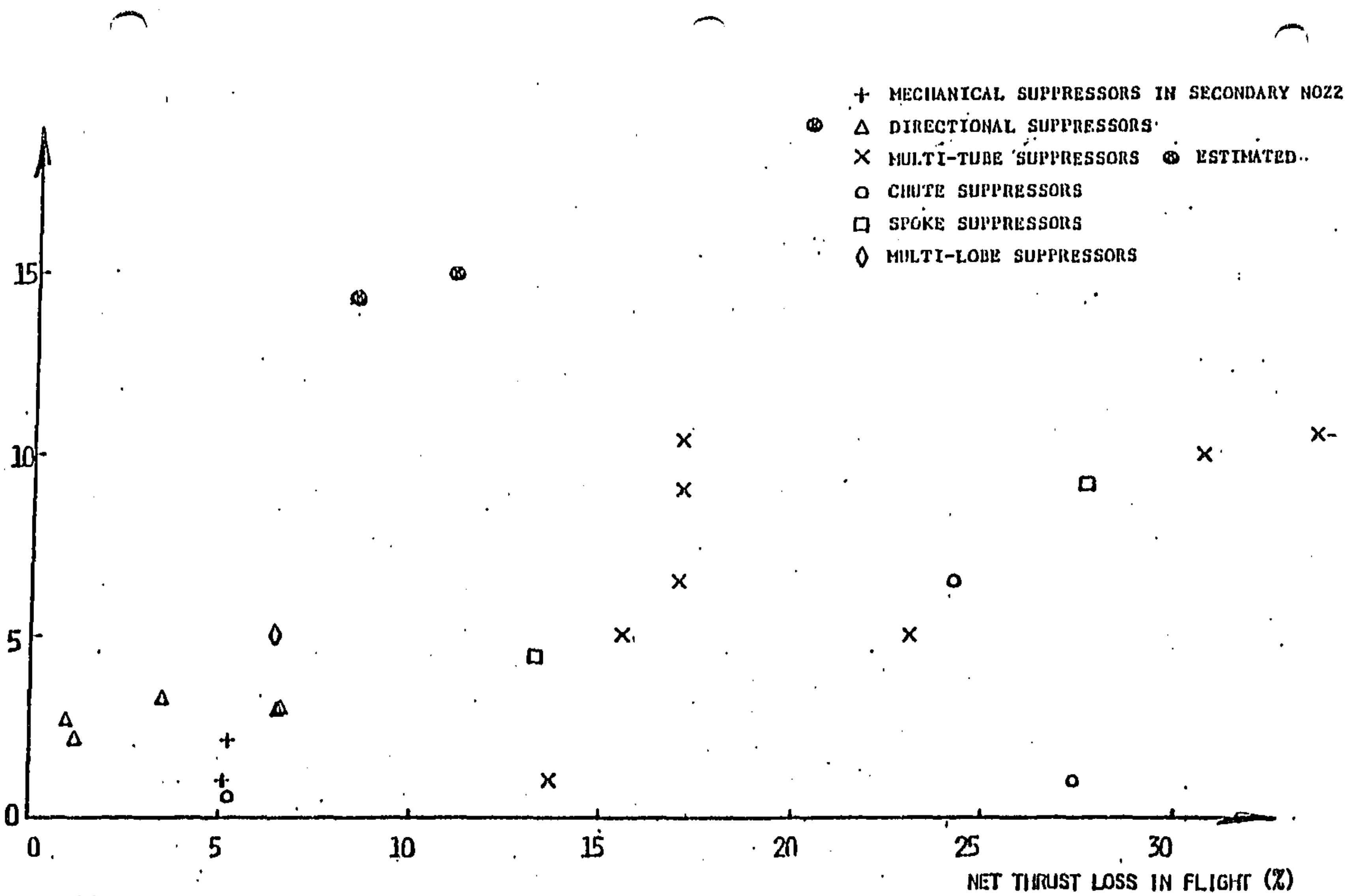


FIG. 3.43 SUPPRESSION VS NET THRUST LOSS OF DIFFERENT SUPPRESSOR FAMILIES (FLIGHT SPEEDS OF 250 TO 400 FT/SEC). (From Ref. 102)

These data summaries illustrate that there have been many suppressors designed that have exhibited a wide range of performance characteristics with regard to both noise and thrust in both flight and static conditions. Some have very useful characteristics; others are unsatisfactory in one or more aspects. Although many of the devices tested were undoubtedly designed to explore the range of individual parameter variations, there have been many designs which were thought to be promising for noise suppression which have failed in flight noise suppression performance. As a result, test facilities, free jet, aerotrain, flight test bed and wind tunnel, have been developed for use in testing suppressor performance. The use of these facilities, together with the advanced prediction methodologies developed in the FAA program [119] and elsewhere, should enable the design for supersonic cruise aircraft of practical suppressors in the 8-12 EPNdB reduction range at modest thrust penalties.

Footnote: For additional information on suppression see references 26,37, 38,44,125,139 and 166.

3.5 Control of Propulsion/Flight Parameters

A supersonic cruise aircraft is expected to have a very sophisticated computer flight control system which may be programmed to continuously vary both aircraft and engine controls during landing and takeoff. Consequently, it is anticipated that both engine thrust and aircraft control surfaces can be managed to achieve a variety of flight conditions which would not be conceivably under manual control within the normal cockpit workload limitations.

Figure 3.44a illustrates a Boeing concept [118] of the range of possibilities that deviate from existing FAR 36 rules. The range of tradeoffs for this example indicate as much as 9 EPNdB reduction of community noise when controls are used to minimize community noise, or a 4 EPNdB reduction in both sideline community noise when controls are used to minimize sideline noise.

If the aircraft engine is oversized for noise or other flight conditions, a programmed thrust reduction during takeoff will enable the aircraft to use maximum thrust when ground attenuation is high, and decreased thrust after becoming airborne. Figure 3.45 illustrates the potential of this technique on a Lockheed study aircraft [121]. The results in this example are a 2.7 EPNdB reduction in sideline, 0.7 EPNdB reduction in community noise for a 1.8 dB reduction in traded noise.

The acoustic considerations used by Pratt and Whitney [69] in developing optimized programmed thrust during takeoff are illustrated in Fig. 3.46. When the aircraft is on the runway the combination of shielding and excess ground attenuation is estimated to be 13 PNdB at the sideline distance. The excess ground attenuation reduces with altitude, becoming zero PNdB at 600 ft

a) Advanced Takeoff Systems and Procedures

SYSTEM/ PROCEDURE	APPLICATION	PURPOSE	ADVANTAGES
PROGRAMMED THROTTLES	AUTOMATIC THROTTLE MODULATION DURING TAKEOFF AND CLIMB	TAKE ADVANTAGE OF GROUND SHIELDING	LOWER TAKEOFF FIELD LENGTH HIGHER COMMUNITY ALTITUDE OR HIGHER L/D AT COMMUNITY
PARTIAL FLAP RETRACTION	AUTOMATIC PARTIAL FLAP RETRACTION DURING INITIAL CLIMB	IMPROVE CLIMBOUT LIFT/DRAG RATIO	HIGHER COMMUNITY ALTITUDE HIGHER L/D AT COMMUNITY
CLIMB ACCELERATION	TRADE CLIMB CAPABILITY FOR ACCELERATION	IMPROVE L/D AT THE EXPENSE OF COMMUNITY ALTITUDE	HIGHER L/D AT COMMUNITY
AUTOMATIC PERFORMANCE RESERVES (APR)	AUTOMATIC INCREASE IN THRUST (10%) AFTER ENGINE FAILURE	MEET LEVEL FLIGHT ENGINE-OUT REQUIREMENT WITH APR	LOWER COMMUNITY CUTBACK POWER SETTINGS

b) Noise Levels

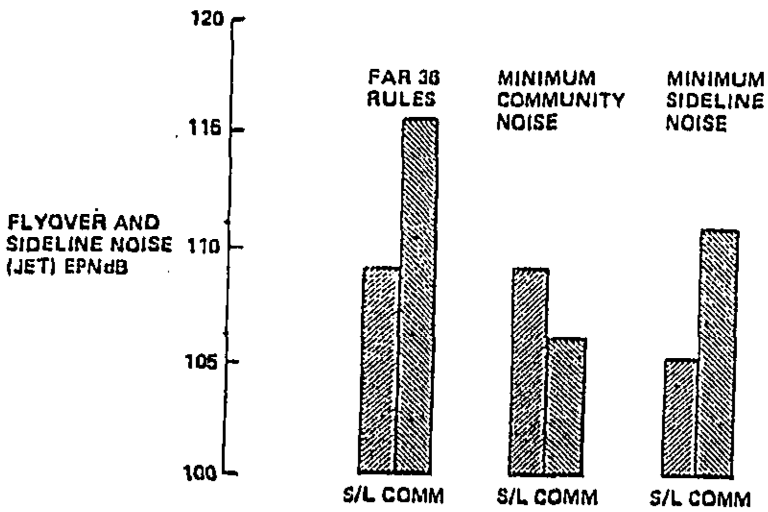
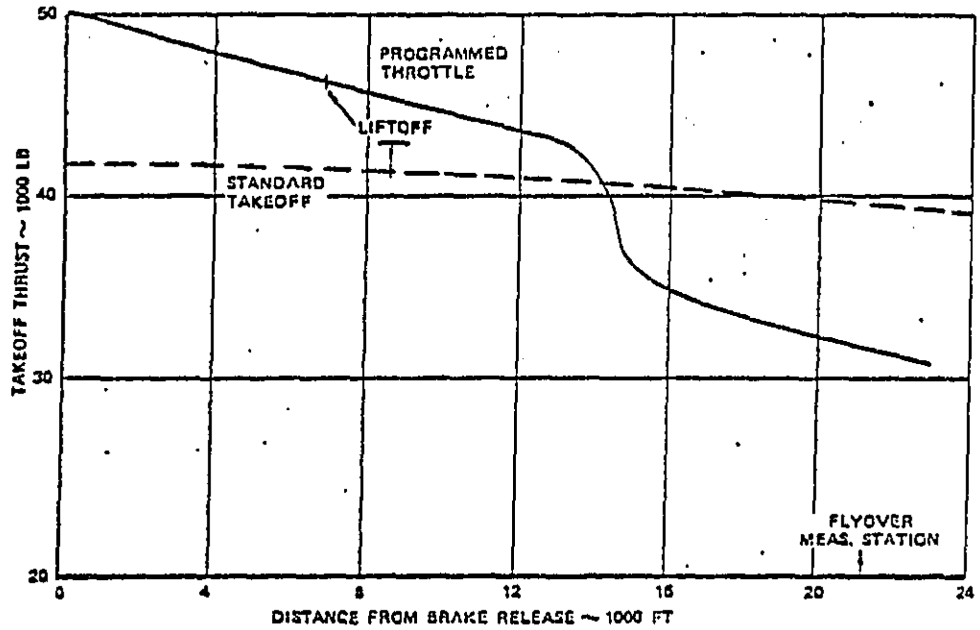


FIG. 3.44 NOISE REDUCTION POTENTIAL OF ADVANCE TAKEOFF SYSTEMS AND PROCEDURES. (From Ref. 118)

a) Takeoff Thrust Comparison



b) Noise Level Comparison

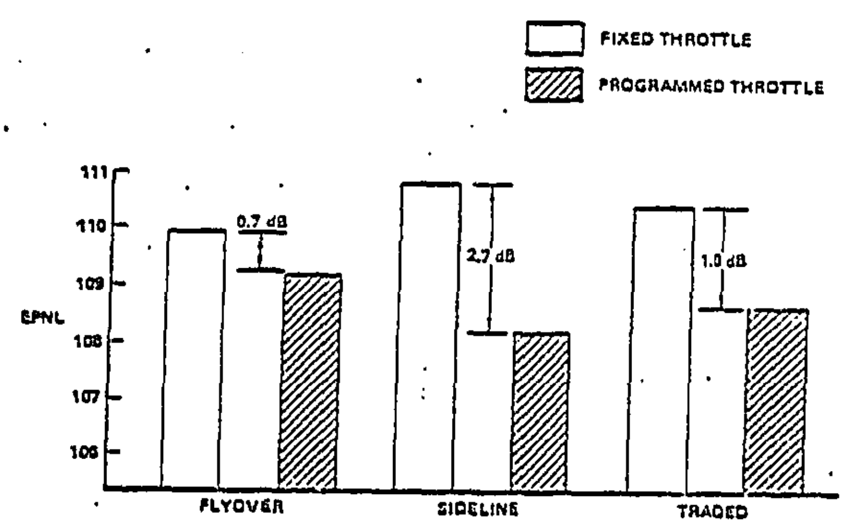
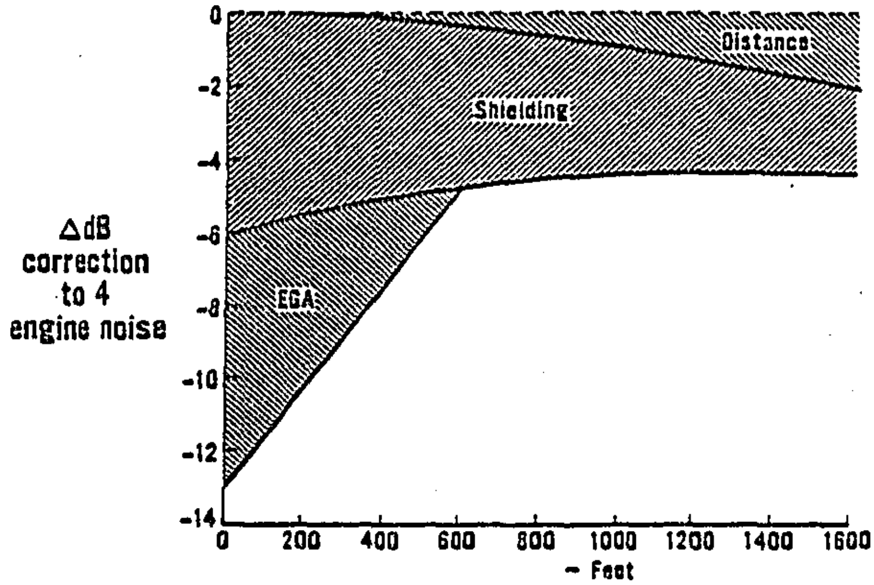


FIG. 3.45 COMPARISON OF FIXED AND PROGRAMED THROTTLE AND NOISE LEVELS WITH CL1611-1 AIRCRAFT AND VSCE 516 ENGINE. (From Ref. 121)



Altitude

FIG. 3.46 EFFECT OF ALTITUDE ON SIDELINE NOISE.
(From Ref. 69)

altitude. For higher altitudes the combined effect of shielding and increased distance is estimated to provide approximately 5 PNdB reduction.

The range of throttle schedules investigated for two examples of programed throttle is compared with constant throttle in Figure 3.47, together with the sideline noise estimates for each example. For the constant throttle case, the thrust weight ratio (F_n/TOGW) required for the field length of 10,500 ft is 0.275 prior to cutback where it is reduced to 0.20. For the programed throttle cases, the entire available F_n/TOGW of 0.328 is utilized for the ground roll, and is reduced consistent with sideline noise requirements as the aircraft gains altitude. Because of the higher thrust during ground roll, the aircraft can attain a higher velocity with its associated improvement in L/D such that the cutback thrust weight ratio can be 0.17, less than that possible in the constant throttle case.

Examples of climb profiles with programed throttles are compared with the constant throttle case in Fig. 3.48. In this example the engine is sized (mass flow 780 lbs/sec) to achieve with constant throttle 108 EPNdB at both sideline and community (108/108). The possible tradeoffs between community and sideline noise are illustrated in Fig. 3.48. Throttle schedule B enables achievement of a 5 EPNdB reduction at the community measurement point when holding 108 EPNdB along the sideline. Throttle schedule C keeps both community and sideline levels equal, but 3.5 dB less than the 108 associated with the constant throttle schedule A. The range loss estimated for throttle schedule C is approximately 40 nautical miles (approximately 1%), as illustrated in Fig. 3.50.

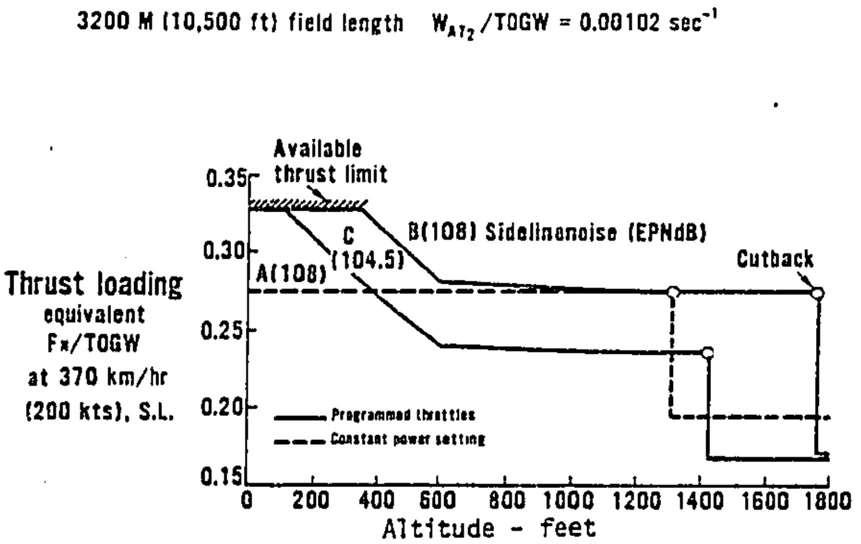


FIG. 3.47 TYPICAL THROTTLE SCHEDULES FOR THE VSCE-502B FOR CONSTANT SIDELINE NOISE. (From Ref. 69)

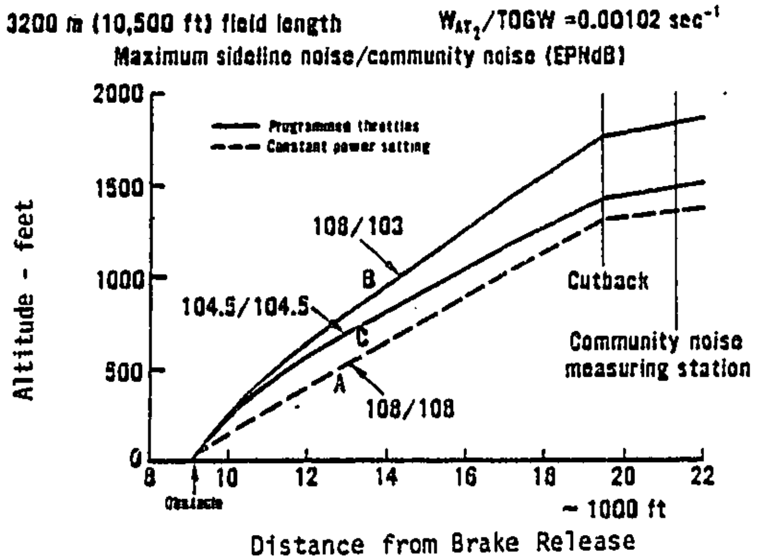


FIG. 3.48 CLIMB PATHS WITH TYPICAL PROGRAMMED THROTTLE SCHEDULES. (From Ref. 69)

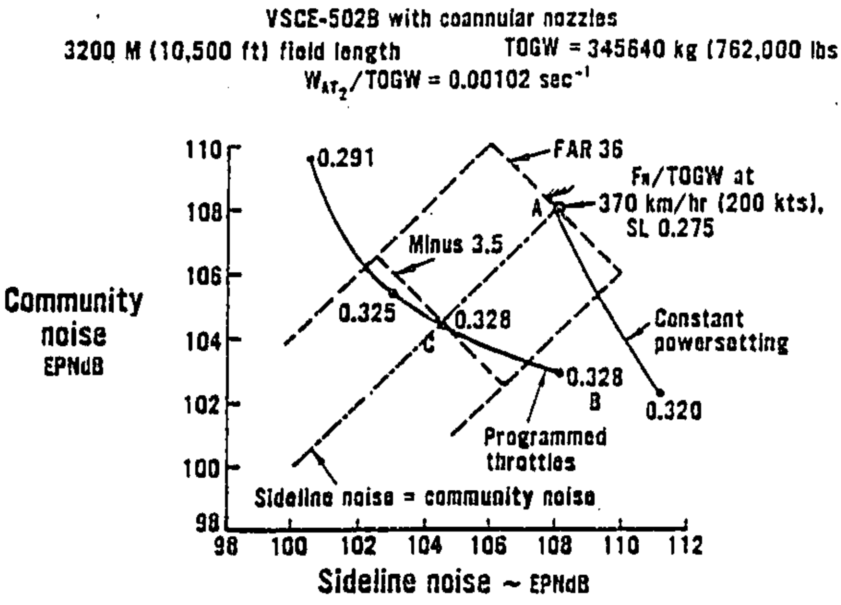


FIG. 3.49 COMMUNITY/SIDELINE NOISE TRADES. (From Ref. 69)

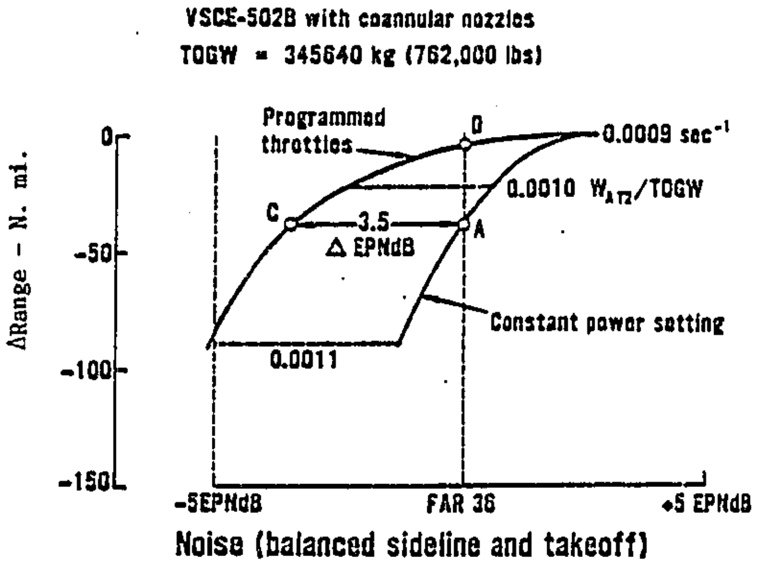


FIG. 3.50 EFFECT OF PROGRAMMED THROTTLE SCHEDULE ON RANGE/NOISE LEVEL TRADES. (From Ref. 69)

Thrust management can be used to increase range for constant noise as well as reducing both range and noise, as shown in a tradeoff study on the GE dual bypass engine [5]. Table 3.8 illustrates the potential for increasing range by reducing engine size (airflow) and weight, keeping sideline noise constant at 110 EPNdB through application of programed throttles. In this example the increase in jet velocity, required for constant thrust at takeoff with smaller engines, results in both lower altitude and higher jet velocities at cutback. Consequently, the noise over the community is higher during climbout after cutback resulting in larger footprint areas, yet still meeting the same certification requirements.

TABLE 3.8 NOISE CHARACTERISTICS FOR ENGINE SIZED FOR TAKEOFF (From Ref. 5)

	Effects of Varying Exhaust Jet Velocity and Varying Amount of Thrust Management			
Exhaust Jet Velocity, V_J - ft/sec	2442	2500	2550	2600
Airflow for 61400 lbf 7.0 Thrust - lb/sec	1164	1077	1029	994
Peak Sideline Noise (Constant throttle climbout) EPNL dB	110.0	110.7	111.5	112.6
Peak Sideline Noise (Power Management) EPNL dB	110.0	110.0	110.0	110.0
ΔRange (Mission A) N.mi.	(base)	+150	+200	+220
ΔRange (Mission B) N.mi.	(base)	+180	+230	+270
Estimated Altitude at Community Point, ft.	1870	1843	1782	1716
Estimated Community Noise (Cutback Thrust) EPNL dB	101.9	102.8	103.6	104.3
Traded Noise EPNL dB	108.0	108.0	108.0	108.0

3.6 Aerodynamic (Airframe) Noise

The turbulence created by the aerodynamic flow of air over an aircraft and the wakes beyond the aircraft structure radiate noise often referred to as airframe noise. The absolute magnitude of the total airframe noise radiated is approximately the same during both takeoff and landing, the noise increase due to the higher speed during takeoff approximately offset by the noise radiated from the landing gear, doors and wheel wells during landing. However, since the propulsion system noise is much greater during takeoff than during landing, airframe noise is of importance only in landing.

Some of the sources of airframe noise are illustrated in Fig. 3.51, and a comparison of measured and calculated noise for two configurations of the B747 is shown in Fig. 3.52. For this case, the extension of landing gear adds about 3 dB to the broadband noise of the aircraft with only flaps down. The comparison between FAA prediction and measurement [48] seems relatively good for this case.

The basic prediction method [48] is based on summing the noise of the clean airframe together with the noise generated by individual components, e.g., flaps, spoilers, landing gear, etc. The noise of the clean airframe follows the fifth power of velocity for a wide variety of aircraft types as shown in Fig. 3.53. In these data the clean F-106 delta wing fighter aircraft may be seen to follow the lower line of quieter configurations. However, its noise is not as well predicted by the FAA method as by the NASA ANOPP drag element method; compare Figs. 3.52 and 3.54.

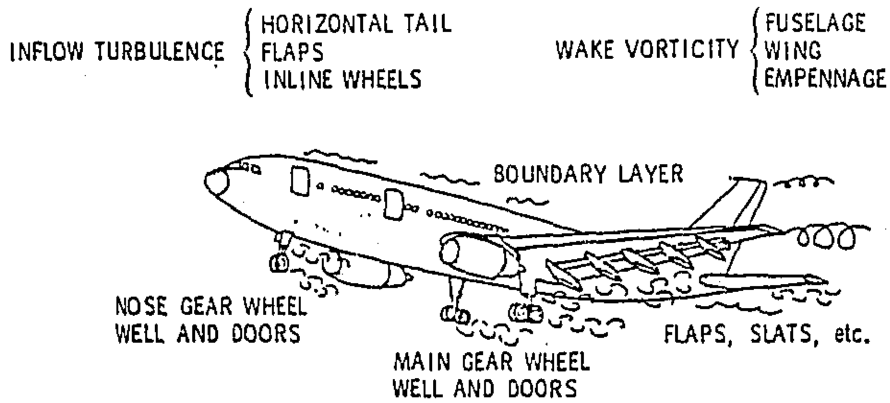


FIG. 3.51 SCHEMATIC DIAGRAM ILLUSTRATING POTENTIAL SOURCES OF AIRFRAME NOISE. (From Ref. 62)

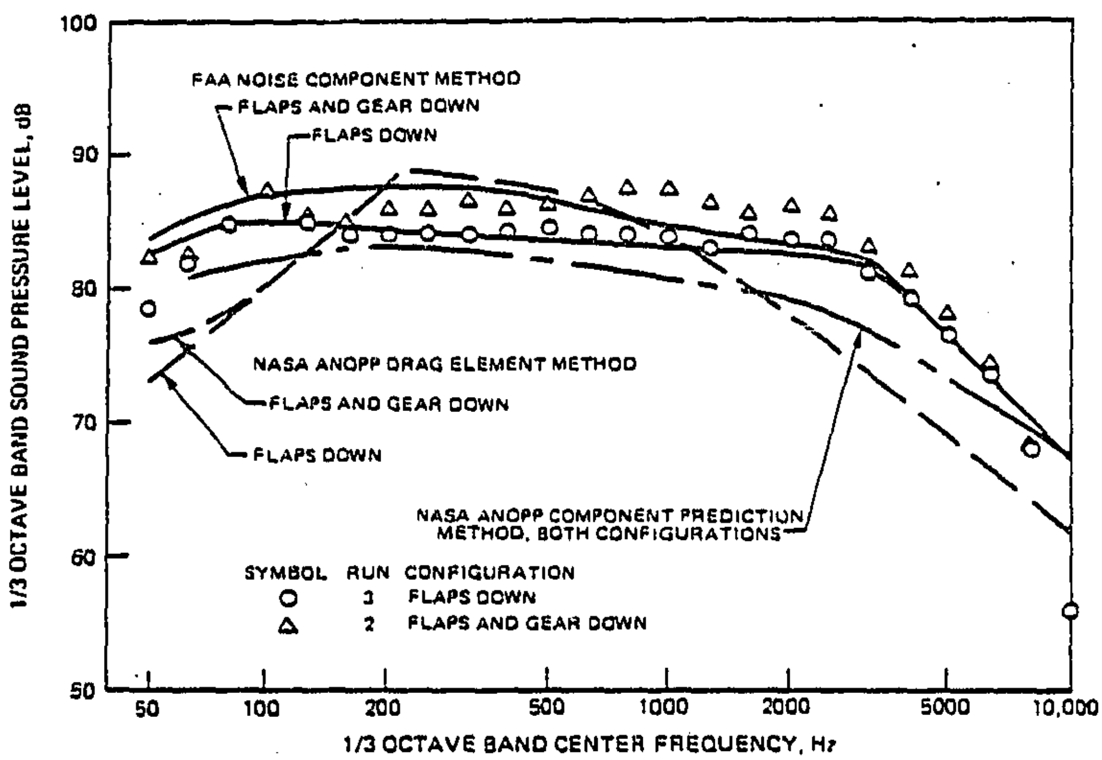


FIG. 3.52 COMPARISON OF MEASURED & CALCULATED FLYOVER NOISE SPECTRA FOR BOEING 747 WITH TRAILING EDGE FLAPS EXTENDED, & WITH FLAPS & LANDING GEAR EXTENDED, AT 204 KNOTS AIRSPEED. (From Ref. 48)

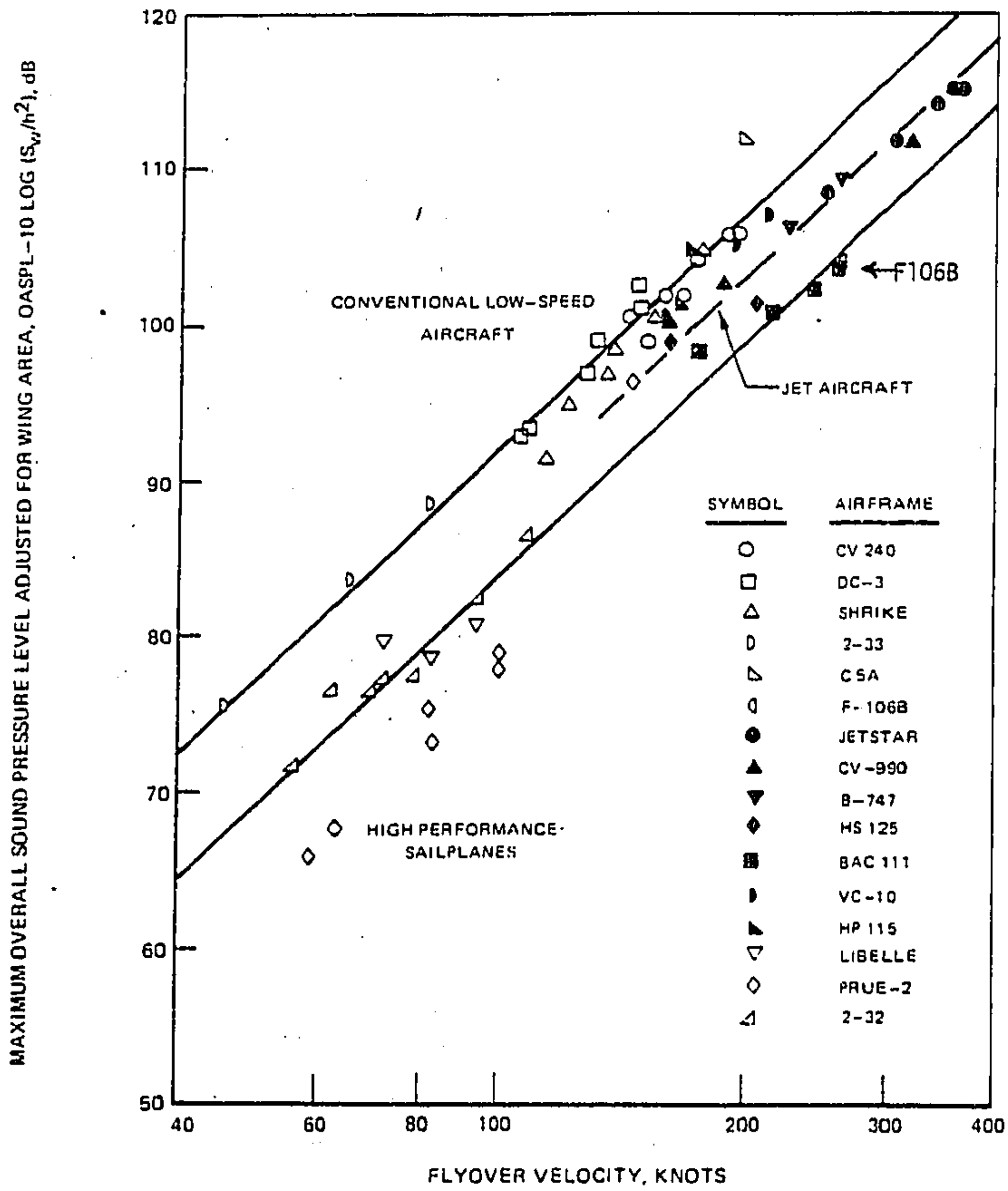


FIG. 3.53 MAXIMUM OVERALL SOUND PRESSURE LEVEL FOR CLEAN AIRFRAMES, NORMALIZED WITH RESPECT TO WING AREA, (From Ref. 48)

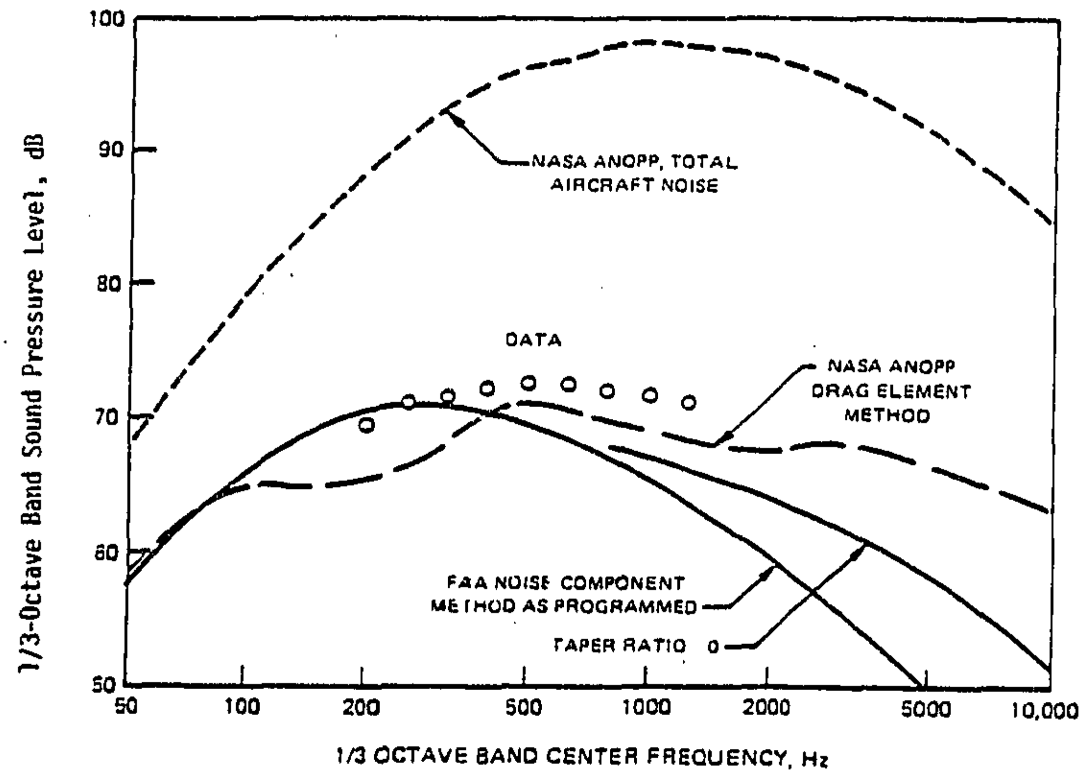


FIG. 3.54 COMPARISON OF MEASURED AND PREDICTED FLYOVER NOISE SPECTRA FOR CONVAIR F-106B IN CLEAN CONFIGURATION AT MACH NUMBER 0.4. (From Ref. 48)

The increase in noise for the VC10 aircraft, "dirty" vs. "clean", is shown in Fig. 3.55, together with the engine noise and its compressor tone at 2.5 kilohertz. The estimated contribution of leading edge slats, flaps at various angles, landing gear, landing gear doors are shown in Fig. 3.56. The combination of all of these factors adds 11 dB to the overall sound pressure level of the noise radiated by the "clean aircraft."

An 0.015 scale model of the AST 100 was tested in the Langley freejet anechoic facility [162] to determine its airframe noise. The model was tested at several speeds in both a clean and an approach flaps (without landing gear) configuration. The data shown in Fig. 3.57 show good agreement with prediction for the clean configuration. The data for the approach flaps condition are about 2-3 dB below the prediction for landing configuration, which might be expected because no landing gear were included in the model. An approximate scaling of these data to full-scale, 170 knot approach at 1 nautical mile altitude and conversion to PNL by adding 7 dB to the OASPL [48] gives an EPNL of 88 EPNdB for the "clean" configuration and 98 EPNdB for the approach flap condition.

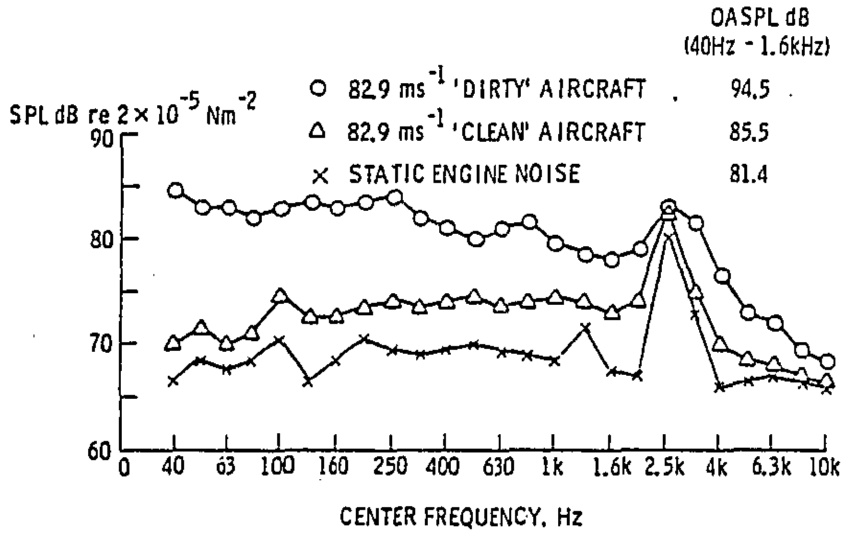


FIG. 3.55 COMPARISON OF 1/3-OCTAVE BAND AIRFRAME NOISE SPECTRA FOR DIRTY & CLEAN CONFIGURATIONS OF VC10 AIRCRAFT FLYING OVERHEAD AT 183 m ALT. (From Ref. 62)

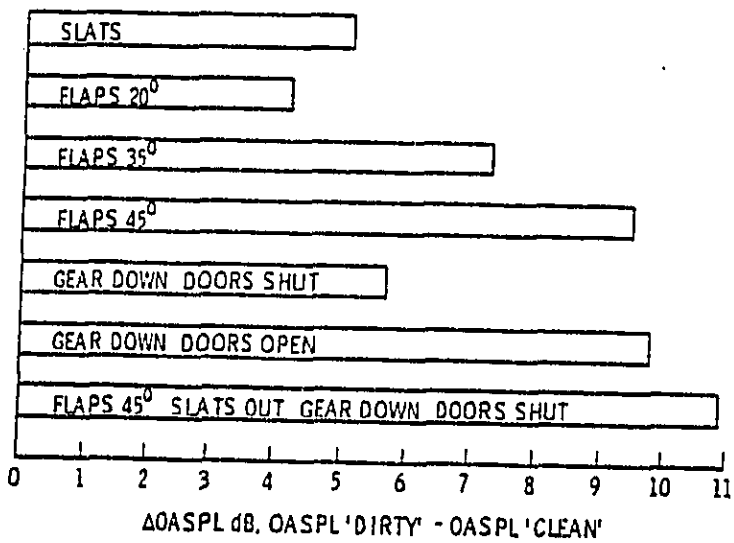


FIG. 3.56 ESTIMATED NONPROPULSIVE NOISE INCREASE DUE TO CHANGES FROM THE CRUISE CONFIGURATION FOR THE VC10 AIRPLANE. (From Ref. 62)

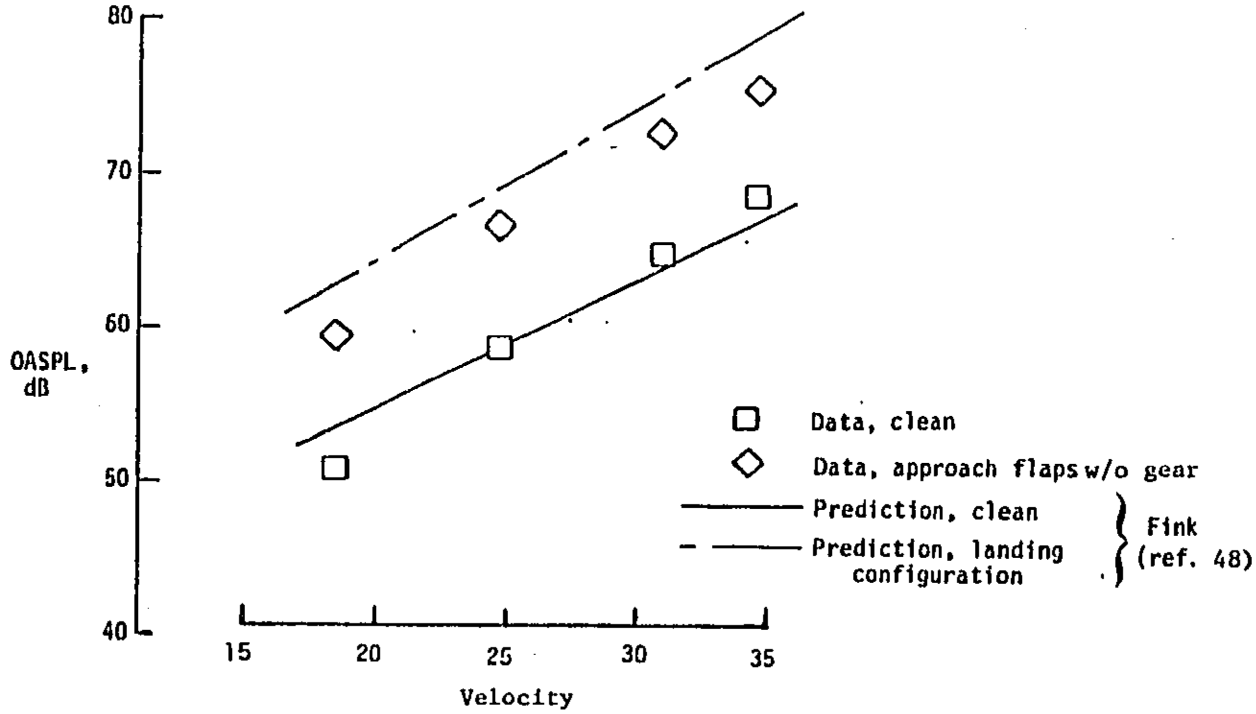


FIG. 3.57 VARIATION OF OVERALL SOUND PRESSURE LEVEL (OASPL) WITH VELOCITY FOR VARIOUS CONFIGURATIONS OF A 0.015 MODEL OF AST/00 IN A FREE JET ANECHOIC FACILITY AT A DISTANCE OF 4.33 FT. (From Ref. 162)

These results are consistent with the estimates by Lockheed [116] for various weights and models of its CL 1611 advanced supersonic transport. The CL 1611 series data given in Table 3.9 show predicted airframe noise ranging between 96.7 and 99 EPNdB and total estimated approach noise ranging between 103.1 and 105.9. For this example all of the configurations meet the FAR-36 Stage 2 limits, and some meet the Stage 3 limits. However, assuming that the airframe noise predictions are correct, and of the order of 99 EPNdB, to achieve a reduction of the total noise to 102 EPNdB would require the total propulsion noise (fan and jet) to be no greater than 99 EPNdB, and to achieve a total noise of 100 EPNdB would require total propulsion noise to be no greater than 93 EPNdB.

TABLE 3.9 APPROACH NOISE LEVELS OF LOCKHEED CL 1611 SERIES (Preliminary Results) (From Ref.)

DESCRIPTION	-1 MIN. DOC	-1 MIN. DOC	-3 MIN. DOC	-4 MIN. DOC	-1 MIN. NOISE	-7 MIN. DOC	-9 MIN. DOC
Landing Weight (lbs)	375,000	395,000	397,000	406,000	400,000	416,000	400,000
Thrust Required (lbs) (4 Engines)	42,268	48,660	41,325	49,797	49,148	47,798	48,852
Jet Noise (EPNdB) (No Credit for Mechanical Suppressor)	101.7	99.6	102.4	100.6	101.5	94.9	93.9
Fan Noise (EPNdB)	97.0	93.3	97.3	93.8	97.4	96.4	98.4
Airframe Noise (EPNdB)	96.7	98.6	96.2	98.7	98.8	99.0	98.6
Total Approach Noise (EPNdB)	104.8	104.2	106.9	104.8	105.9	103.5	103.1

4. AIRFRAME-PROPULSION INTEGRATION AND NOISE

The NASA SCAR program has utilized a series of reference aircraft designs to provide a basis for evaluating the overall effectiveness of technological developments in improving AST performance [40]. Table 4.1 summarizes some of the characteristics of three versions of the NASA reference AST, together with the reference designs of McDonald Douglas and Lockheed, and the Concorde and the prototype Boeing 2707 which was cancelled in 1970.

The five U.S. reference designs have a design range of 3850 to 4400 nautical miles. A nominal 4000 nautical mile range satisfies the requirements for many key city pair routes, as shown on figure 4.1. It covers the major North Atlantic routes, including New York-Rome. Arguments have been forwarded for design ranges up to 6500 n. miles [46] which would include most of the routes amongst the industrialized nations. An estimate of the traffic on overseas routes in the year 2000 [51] indicates that a range of 3500 n. miles would satisfy 53% of the world overwater route; a range of 4000 n. miles would satisfy 77%, and a range of 4500 would satisfy approximately 85%, including San Francisco-Tokyo. Additionally, a range of 4000 n. miles would give one stop service amongst 95% of the world's population [46].

Figure 4.2 indicates three specific markets for an advanced SST which require ranges between approximately 3300 and 4500 n. miles, and it illustrates the kind of range — payload tradeoff — which might be anticipated in a family of aircraft for two values of takeoff gross weight. The aircraft described in Table 4.1 essentially cover this range of markets.

TABLE 4.1 CHARACTERISTICS OF SELECTED 4-ENGINE SUPERSONIC AIRCRAFT DESIGNS*

CHARACTERISTIC	AIRCRAFT: U.K.-France Concorde	Boeing B2707 (1970) Prototype	NASA (Ref. AST (1973)	NASA AST-100 (1976)	NASA 1976 AST 102 (1976)	McDonald Douglas AST (1975)	Lockheed AST (1975)
Technology	Current	Current	Cert. in 1990s	Cert. in 1990s	Cert. in 1990s	Start des. late 1970s	Start des. early 1980s
Takeoff Gross Weight (1000 lbs)	400	750	762	718	718	750	592
Number of Passengers	108	261	292	292	292	273	290
Cruise Mach No.	2.02	2.7	2.2-2.7	2.7	2.7	2.2	2.55
Range (nautical miles)	3150	3650	4000	3968	4400	4400	3850
Engine (reference)	Rolls Royce Olympus	Gen. Elec. Turbojet & A/B	Gen. Elec. Turbojet (Ref.)	Gen. Elec. Turbojet (Ref.)	Gen. Elec. Turbojet (Ref.)	Gen. Elec. Turbojet (Ref.)	Pratt & Whitney VSCE (Ref.)
S.L. Static thrust (1000 lbs)	38.0	67.8	73.5	66.0	55.7	74.7	
S.L. Liftoff Net Thrust (1000 lbs)	33.6	52.5	54.5			54.3	44.0
Static Thrust-Weight Ratio	0.38	0.36	0.39	0.37	0.31	0.40	
Aero Efficiency Max Cruise L/D	7.4	7.95	8.7	9.1	9.1	9.6	9.0
Noise Estimates (EPNL):		Goals	Goals	Goals			
Sideline	112.2	119.5*(112)	*111.6 (108)*	*109.5 (108)	*Not-Constrained	*105	Meets FAR 36
Takeoff	119.5	108. (108)	*119.7 (108)	*109.5 (108)		108	
Approach	116.7	109 (108)	*108.5 (108)	*108 (108)		107	
References	26,63	51.147	8,134	8	49	53	54,213
FOOTNOTES: *These study designs may be found in many versions and mated with many engine designs	Intended to be no more noisy than B-707 & DC8 aircraft	*Later version was calculated to meet FAR-36	*Requires 11.7 dB suppression to meet FAR 36.	*With 4.9 dB suppression requires 1.5 more for a total of 6.4 dB suppression	*Would require suppression to meet FAR 36	*Employs MDC suppression system to meet FAR 36	

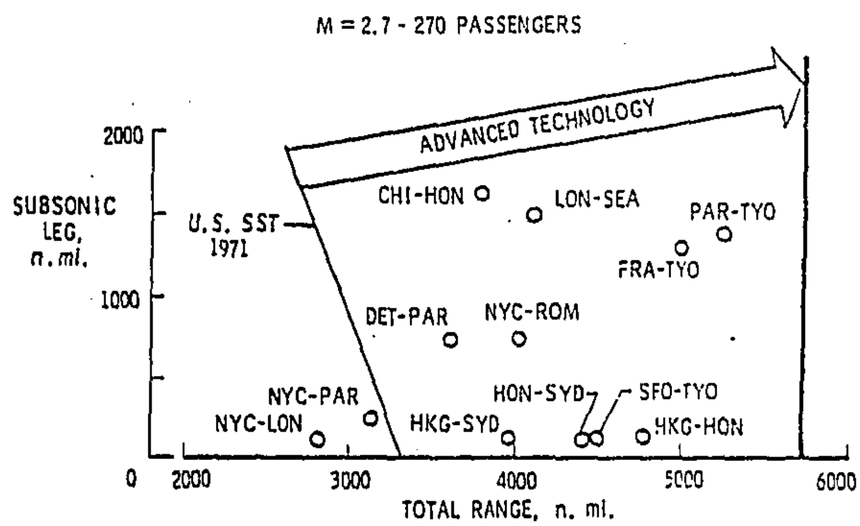


FIG. 4.1 POSSIBLE RANGE IMPROVEMENTS FOR SUPERSONIC TRANSPORTS. (From Ref. 22)

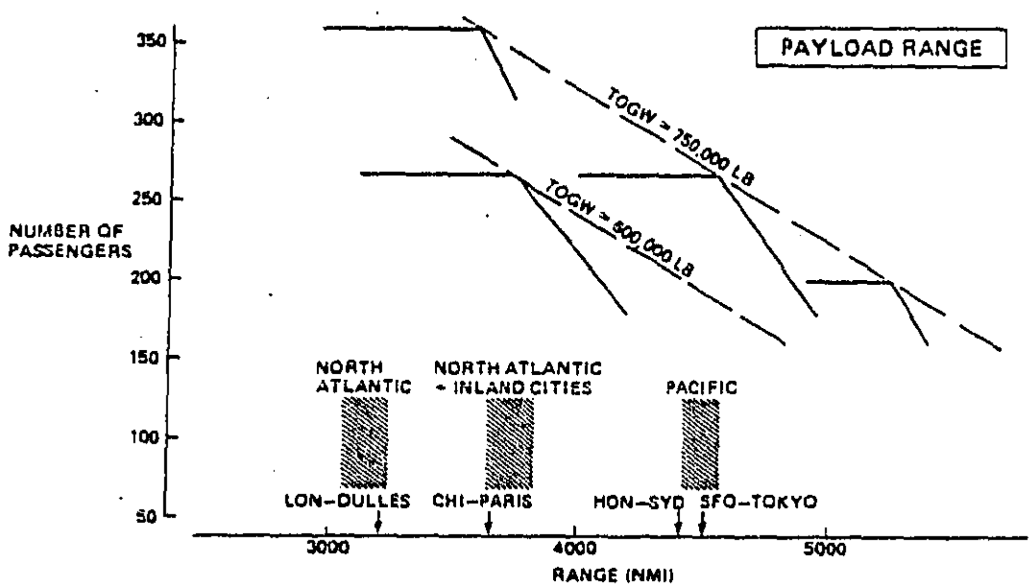


FIG. 4.2 MARKET AREAS FOR NEXT SST. (From Ref. 60)

The cruise design mach number for the aircraft in Table 4.1 varies between 2.0 and 2.7. The Concorde utilized a mach number slightly above 2.0, enabling it to be constructed primarily of aluminun. McDonald Douglas [50] selected a cruise mach number of 2.2, as appropriate for an aircraft intended for immediate initiation of detailed design, because of its reduced technical risk, lower operating costs and increased range. Lockheed [54] selected a cruise mach number of 2.55 for an aircraft intended for detailed design initiation in the early 1980s and for considerable use of composite structures. The NASA Reference AST, intended for certification in the 1990s, was utilized for a variety of tradeoff studies in the mach number range of 2.2-2.7. However, its derivative aircraft, the AST 100 and 102 were optimized for mach 2.7.

The sea level static thrust-weight ratio for these aircraft designs varies between approximately 0.3 and 0.4 with the higher values in some of the U.S. study designs resulting partially from oversizing the engines to attain takeoff thrust requirements at lower jet exit velocity and noise. The AST-102 represents an iteration of the AST100, optimized for range at fixed TOGW and payload, without a noise constraint.

The aerodynamic efficiency (L/D at cruise) is between 9 and 10 for the U.S. study designs, considerably greater than the 7-8 range of the earlier aircraft. This aerodynamic improvement is a major factor in the range increases shown.

The AST study aircraft and the B2707 have been used for the development of many derivative designs, specialized for particular study objectives. Their performances are variously quoted, depending upon the specific study in which the data are derived, its assumptions, methods, and constraints. This statement applies particularly to the estimated noise levels, the earlier studies utilizing a variety of assumptions and methods, some of which are at variance with current practice. Therefore, the quoted noise levels should be considered as those believed at the time by the developing organizations, and not necessarily comparable amongst organizations or currently validated.

The following subsections examine some of the aspects of the NASA AST reference designs, the noise studies accomplished with both NASA and airframe manufacturers designs, and the relationship between potential impact and noise levels at certification measurement locations.

4.1 NASA Reference Aircraft Designs

Aircraft Characteristics

The 1973 NASA Reference AST [134] was derived from earlier Boeing study aircraft which evolved from the B2707 and the NASA development of aerodynamically advanced AST concepts with arrow wing planforms. The propulsion system parameters were based on scaled data from the GE4 engine series designed for the U.S. SST program [129]; but without afterburner, and with improved component technology, including an increase of 450°F in turbine inlet temperature. Similarly, the weight estimates for the reference AST were based on design data from the U.S. SST program, and later verified by Boeing in a detailed structural analysis [19,20].

The NASA reference AST was refined and updated in early 1976 by the development of the AST-100 design [8], which is illustrated in Fig. 4.3. Some of its characteristics and design mission performance are summarized in Table 4.2. Its improvement in maximum L/D relative to the reference aircraft, see Fig. 4.4, enabled

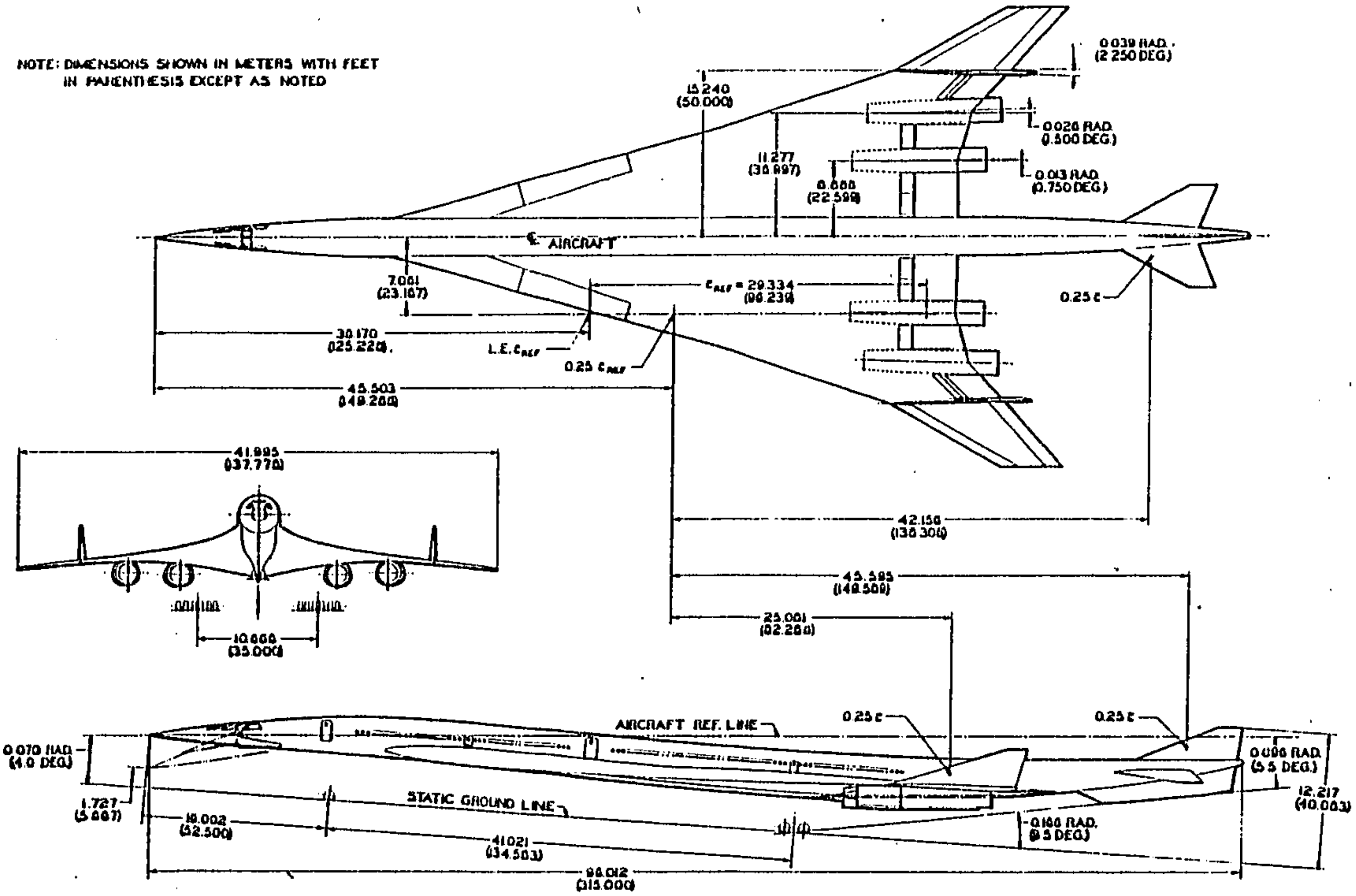


FIG. 4.3 GENERAL ARRANGEMENT OF AST-100. (From Ref. 8)

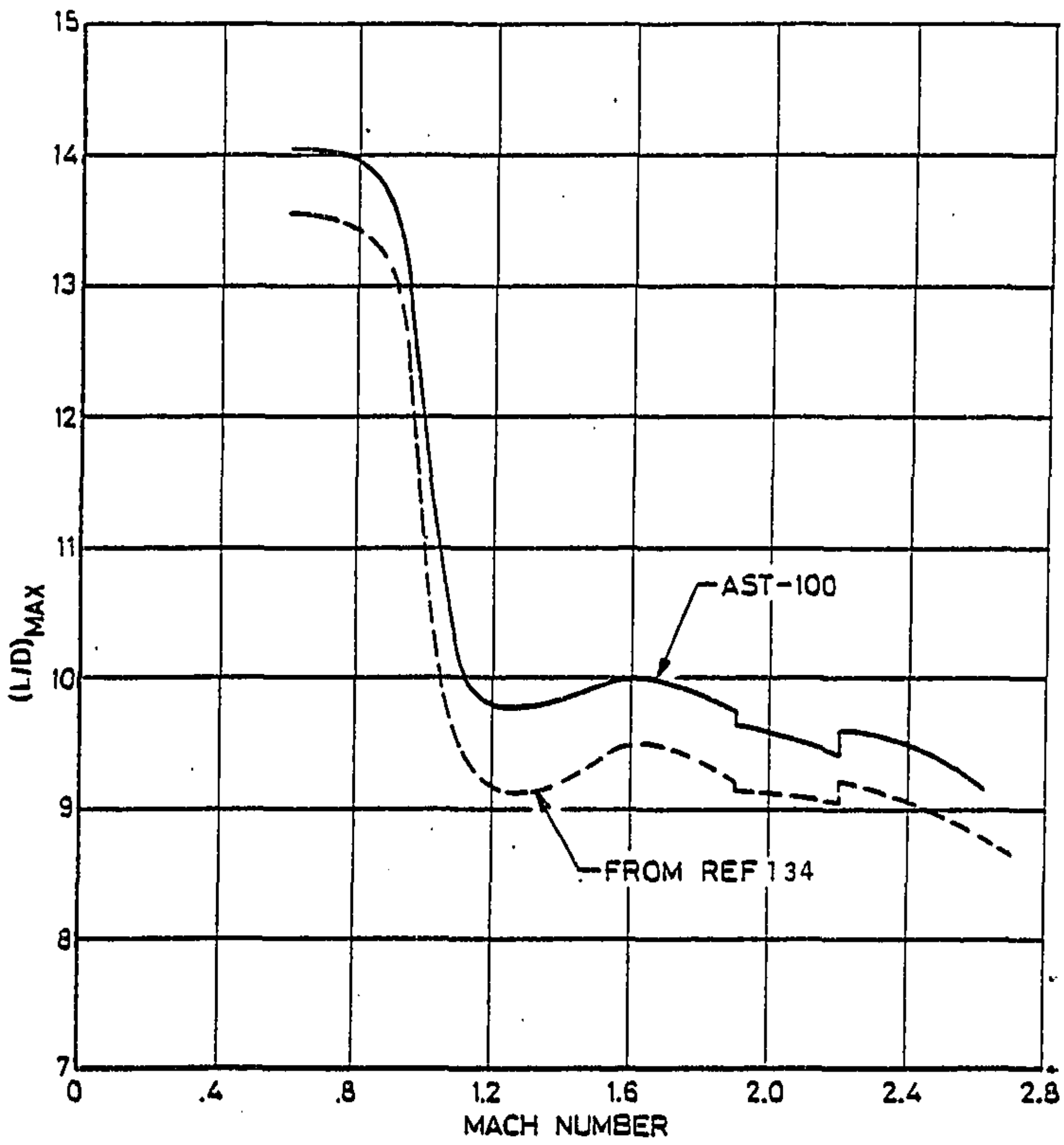


FIG. 4.4 MAXIMUM LIFT-TO-DRAG RATIO VARIATION WITH MACH NUMBER. (From Ref. 8)

TABLE 4.2 AIRCRAFT CHARACTERISTICS AND MISSION PERFORMANCE OF NASA AST-100 FROM REF. 8

AIRCRAFT CHARACTERISTICS

Takeoff gross weight	lbm	718000
Operating weight empty	lbm	329476
Payload-No. Passengers		292
Cargo		0
Total Weight	lbm	61028
Wing area - reference	ft^2	9969
- actual	ft^2	10996
S.L. static installed thrust per engine (std. day + 8°C),	lbf	65978
Initial installed thrust to weight ratio		.37
Initial wing loading - reference	lbm/ft^2	72.0
- actual,	lbm/ft^2	65.3
Takeoff field length	ft	10,500

INITIAL CRUISE CONDITIONS

Lift Drag Ratio	8.91
Specific Fuel Consumption (lbs/hr/lb	1.355
Altitude (feet)	62000

DESIGN MISSION SUPERSONIC CRUISE MACH 2.62 (2.7 Std. Day)

	OPERATING WEIGHTS	Δ FUEL lbm	Δ RANGE n.m.	Δ TIME min.
Takeoff	718000	9600	0	11
Start Climb	708400	63769	337	22
Start Cruise	644631	186081	3431	134
End Cruise	458550	3550	200	20
End Descent	455000	2578	0	5
Taxi-In				
Block Fuel & Time		265578		192
Reserve Fuel		64491		
Trip Range			3968	

NOTES: 1. Taxi-in fuel taken out of reserves at destination.

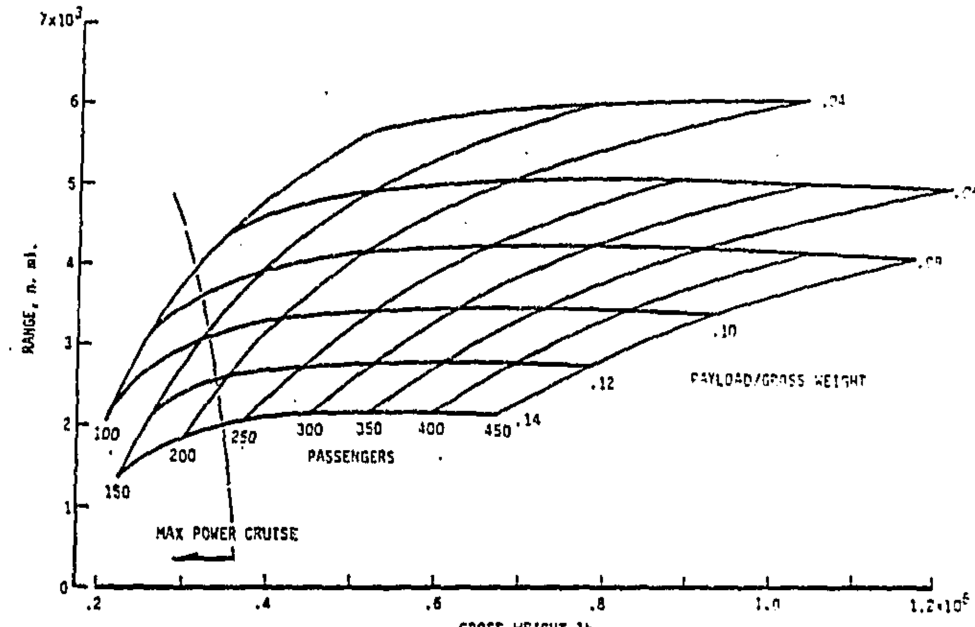
2. C.A.B. range corresponding to block time and fuel equals trip range minus traffic allowances as will be specified for supersonic aircraft.

a reduction in engine size and fuel consumption leading to a reduction of aircraft takeoff gross weight from 762 to 718 thousand lbs., while still achieving the same payload and range performance capability.

The range capability for various combinations of takeoff gross weight and payload for aircraft with the AST-100 thrust-weight and wing loading values is illustrated in Fig. 4.5. The values to the left of the maximum power cruise line are not possible because of insufficient or inefficient engine thrust. The results show that the payload-gross weight fraction is a decreasing function of range and size and that for a constant passenger payload the aircraft size increases approximately proportional to aircraft range.

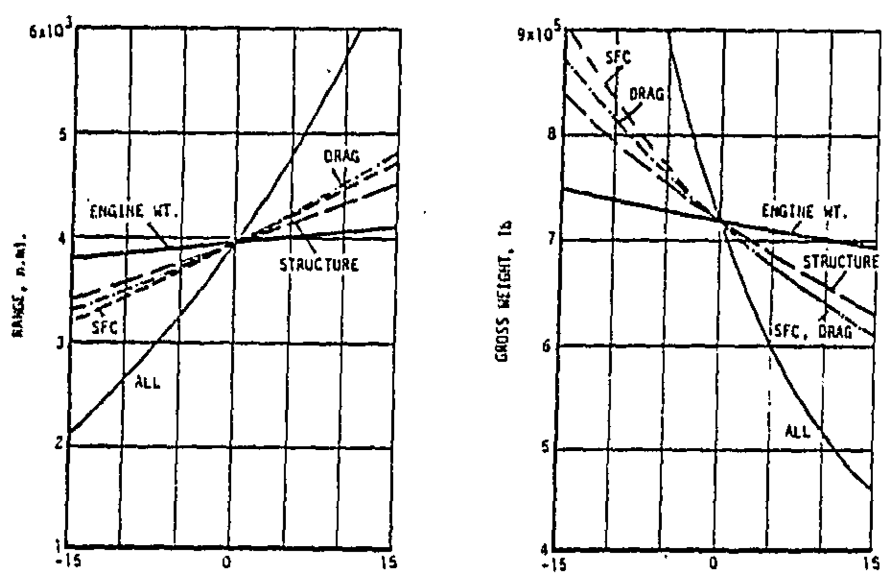
The effect of technology improvements (+) (regressing (-)) on both range (for fixed takeoff gross weight) and takeoff gross weight (for fixed range) are shown in Fig. 4.6. Drag and specific fuel consumption are the most important terms, followed by structural and total engine weight. Thus small changes in engine weight, such as a stowable suppressor, would not necessarily have great significance, as long as they did not cause penalties in either drag or specific fuel consumption.

Subsequent to the development of the AST-100 NASA applied a new design sizing and performance optimization program to a family of AST derivative aircraft with the same takeoff gross weight, passenger payload, mission and cruise mach number as that of the AST-100. The independent variables for this optimization were wing loading (W/S in lbs/sq.ft.) and sea level static installed thrust weight ratio (F/W). The object of the optimization was to maximize range, subject to a set of fixed constraints



(a) F/W = .367; W/S = 72 psf.

FIG. 4.5 RANGE CAPABILITY AT VARIOUS PASSENGER AND GROSS WEIGHT COMBINATIONS. (From Ref. 49).



(A) TOGW = 718,000 lb (b) Range = 3966 n.mi.

FIG. 4.6 TECHNOLOGY IMPROVEMENTS IN RANGE AND GROSS WEIGHT FOR AST-100 AIRCRAFT. (From Ref. 49).

derived from other considerations; such as takeoff field length of 10,500 ft; cruise and climb thrust margins of 0.1 and 0.2, respectively, and takeoff speed not exceeding 200 knots.

The results of this study are presented in Fig. 4.7 which shows contours of constant range vs. F/W and W/S, together with superimposed constraints. The allowable region is on the side of the constraint lines that is away from the shading. The optimum aircraft, neglecting constraints, has a range of 4861 n. miles, a wing loading of 110 lbs/sq ft and a thrust weight ratio of 0.25. Such an aircraft has a relatively small wing, with minimum structure and engine empty weight, enabling a reduction of thrust requirements for part of cruise, and an increase in the amount of fuel carried for fixed gross takeoff and payload weights. This increase in fuel weight carrying potential is the primary reason for its range potential. However, such an aircraft design would probably not have the physical volume to store the allowed fuel weight. Further, its takeoff field length is estimated at over 16,000 feet, takeoff speed is about 225 knots, and climb thrust margin is about 0.06; all three factors violating the fixed constraints.

The aircraft that does meet all constraints (except fuel) is designated as the AST-102. This aircraft was found to have a range potential that is approximately 13% greater than that of the AST-100, after modifying the design of the wing so that it can carry the required fuel. However, its noise problem would be greater than that of the AST-100 because its takeoff thrust margin is less (lower F/W) and its low speed climb capability is lower (less wing area for same TOGW and approximately similar L/D). Consequently during takeoff, its engine must be operated nearer to maximum thrust; i.e. maximum jet velocity and noise.

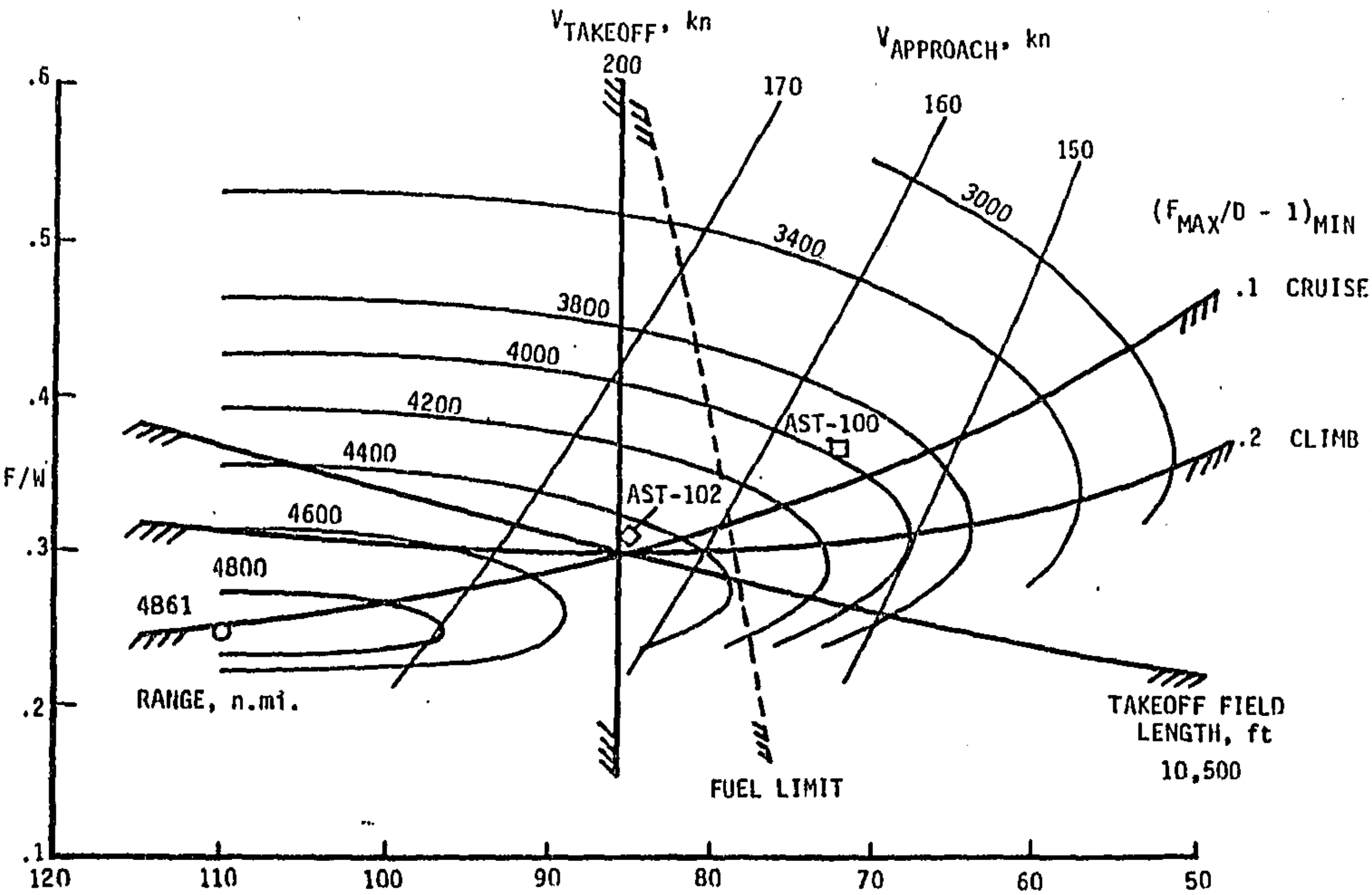


FIG. 4.7 AST-102 THUMBPRINT WITH TOGW = 713,000 lb.; M_c = 2.62; PASSENGERS = 292; STANDARD + 8°C DAY; FLAP ANGLE + 20° AND NO NOISE CONSTRAINT. (From Ref. 49)

Low-Speed Aerodynamics and Noise

The low-speed aerodynamic L/D performance of the AST-100 is summarized in Fig. 4.9 for approach, takeoff and initial climb with 20° flaps, and climb out with 5° flaps. The effect of various flap angle settings on L/D is shown in Fig. 4.10. For takeoff and climbout, the L/D of the AST-100 is about 0.82 greater than that estimated for its predecessor reference aircraft as shown in comparing the data given in Table 4.3. The improvement for approach L/D is about 0.26. These improvements in L/D are attributed to updated test data and the application of newly discovered leading edge scaling effects [8,33]. The resulting takeoff-climb values of 7.5-8.5 are considerably in excess of the Concorde's L/D of 4.0 [28]. This improvement, about doubling the Concorde's low-speed aerodynamic performance, means that an AST has significantly improved *potential* for climbing over the community at noise levels significantly lower than those of the Concorde.

The noise analysis of the AST-100 [8] indicated that suppression would be required because the tradeoffs between oversizing the engine for noise and range were less attractive than those between suppression and range. They also indicated that it was desirable to accelerate the aircraft prior to cutback for the 3.5 n. mile takeoff measurement location, such that the flaps could be reduced from 20 to 5 degrees in accordance with the reduced C_L requirement associated with the higher speed. The solution found, was a takeoff at approximately 209 knots with an acceleration to 241 knots at 700 ft altitude (minimum allowed altitude for cutback for FAR-36 certification) 19,500 feet from start of takeoff roll. Note that this speed is just below the 250 knot FAA maximum speed limit for operation below 10,000 feet altitude. With this profile, the C_L required is reduced from 0.44 to 0.38 and the $L/_D$ for climbout is increased from 8.63

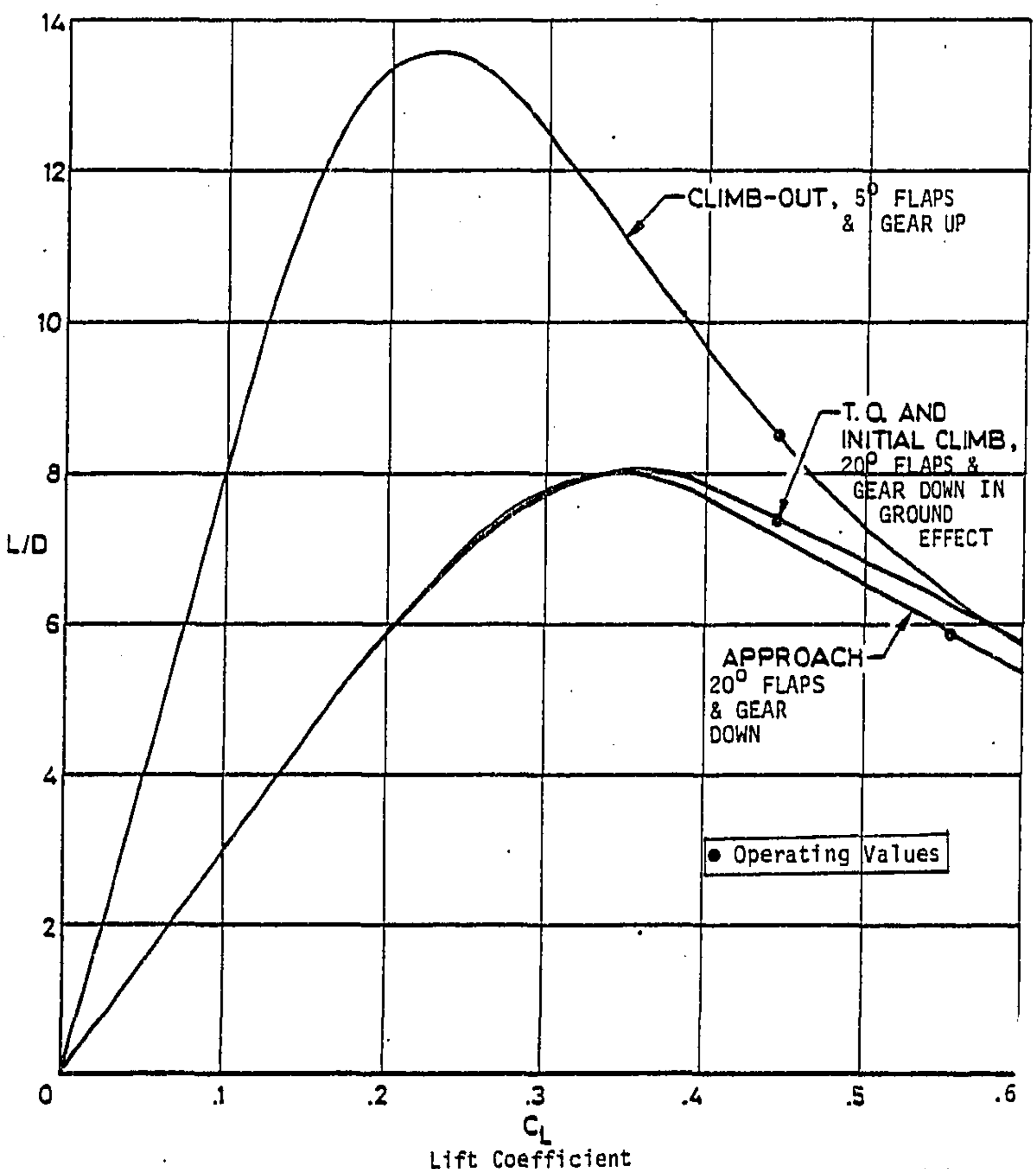


FIG. 4.9 LIFT TO DRAG RATIO VARIATION WITH LIFT COEFFICIENT OF AST-100 WITH AIRCRAFT TRIMMED (C_L FOR TAKEOFF IS 0.44 AND FOR APPROACH IS 0.55). (From Ref. 8)

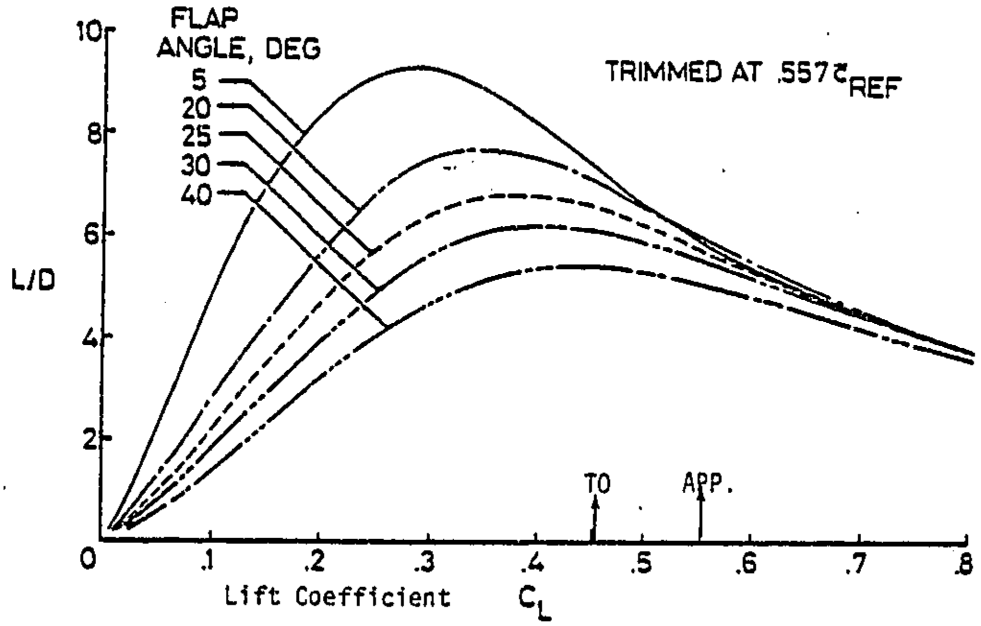


FIG. 4.10 PRELIMINARY LOW SPEED LIFT-DRAG RATIO OF AST-100 OUT OF GROUND EFFECT WITH GEAR DOWN AT VARIOUS FLAP SETTINGS (C_D GEAR IS 0.00849). (From Ref. 147)

TABLE 4.3 COMPARISON OF LOW SPEED LIFT-DRAG OF REFERENCE (1973) AST WITH AST-100. (From Ref. 8)

FIG.	FLIGHT CONDITION	CONFIG.	FLAP ANGLE	GEAR	C_L	GRD. EFFECT	L/D AT C_L	MAXIMUM L/D
1	Takeoff & Initial Climb (Approx 208 Knots)	Reference	20^o	DN	.44	In	6.70	6.75
		AST 100	20^o	DN	.44	In	7.52	8.09
2	CLIMBOUT* (Approx. 220 knots)	Reference	5^o	UP	.44	Out	7.80	10.87
		AST 100	5^o	UP	.44	Out	8.63	13.53
3	APPROACH (Approx. 159 knots)	Reference	20^o	DN	.55	Out	5.75	6.75
		AST 100	20^o	DN	.55	Out	5.91	8.00

*Note: Climbout condition developed for AST-100 optimum noise takeoff profile was at a speed of 241 knots a C_L of approximately 0.38 and an L/D of 10.1.

to 10.1 (see Fig. 4.9). Because of the higher L/D in climbout the engines could be throttled back in cutback by a greater amount, leading to reduced noise while meeting the 4% climb gradient and one engine out level flight requirements of FAR Part 36 certification regulations [186].

The engine was sized for cruise thrust, which for this design, gave it an ample thrust margin for meeting the desired 10,500 ft takeoff field length and attaining 700 feet altitude prior to cutback. Consequently, it was possible to operate the engine at constant part power thrust during the takeoff roll and initial climbout. The thrust was chosen by finding an engine jet velocity (within the allowable thrust range) at which both the sideline and takeoff noise suppression requirements were thought to be equal, see Fig. 4.11. This condition occurred with a 2470 ft/sec jet exit velocity and a thrust of 50,433 lbs on a standard +10^{o}C Day. This thrust is only 77% of the available engine thrust and provides an operating thrust to weight ratio of about 0.28. Note: for this design the application of an advanced controlled throttle takeoff procedure (section 3.5) would probably increase significantly the altitude of the aircraft prior to cutback, and enable its acceleration to 250 knots, both outcomes reducing the community noise under the takeoff path.

The suppression requirement found in this analysis was 4.9 dB, allowing for a +1.5 dB trade at *both* sideline and takeoff measurement locations using the margin of at least 3 dB presumably achieved relative to the approach requirement. The estimated unsuppressed EPNL values along the centerline and sideline are shown in Figs. 4.12 and 4.13, respectively.

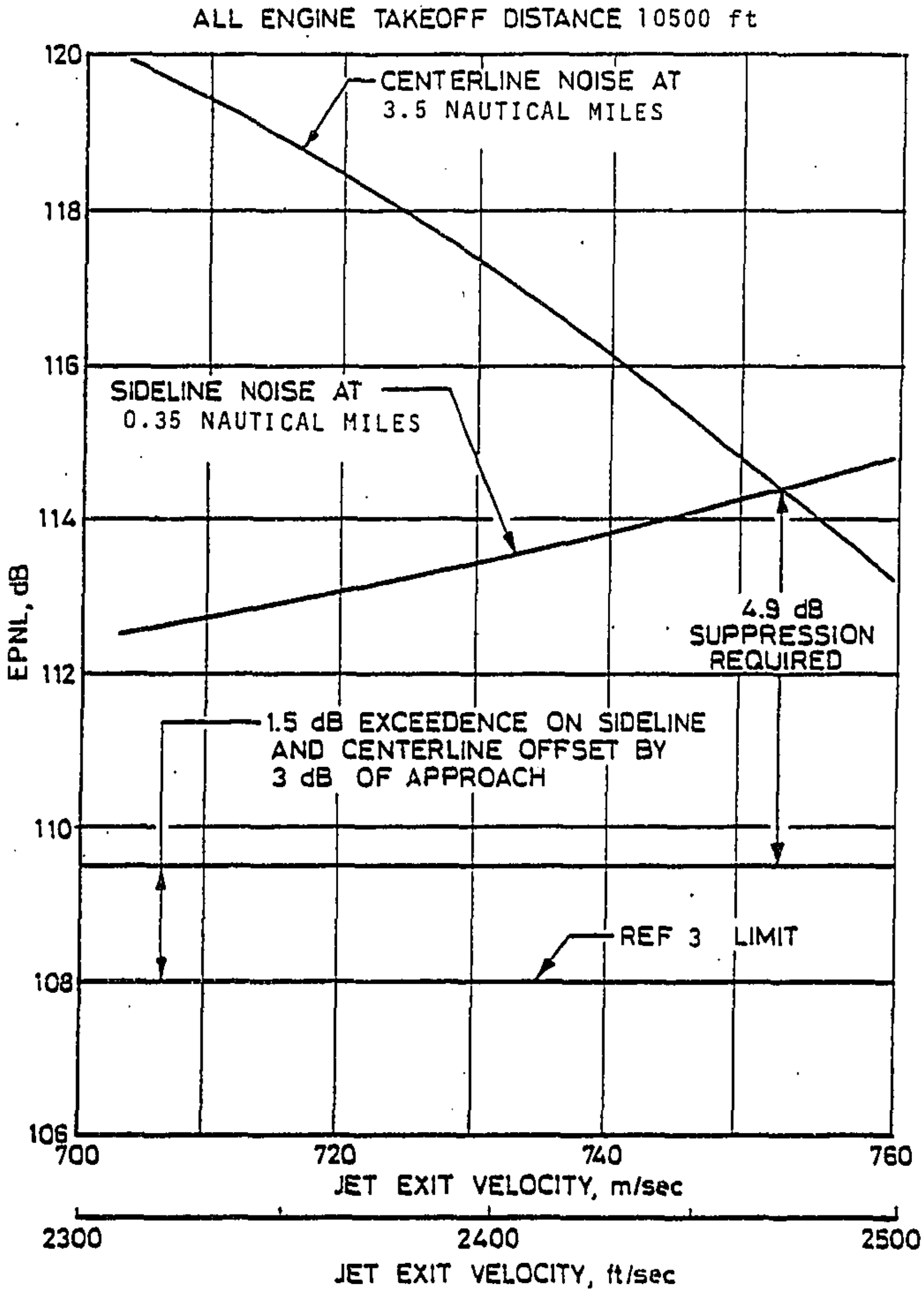


FIG. 4.11 VARIATION OF EFFECTIVE PERCEIVED NOISE LEVEL WITH JET VELOCITY FOR AST-100 AIRCRAFT. (From Ref. 8)

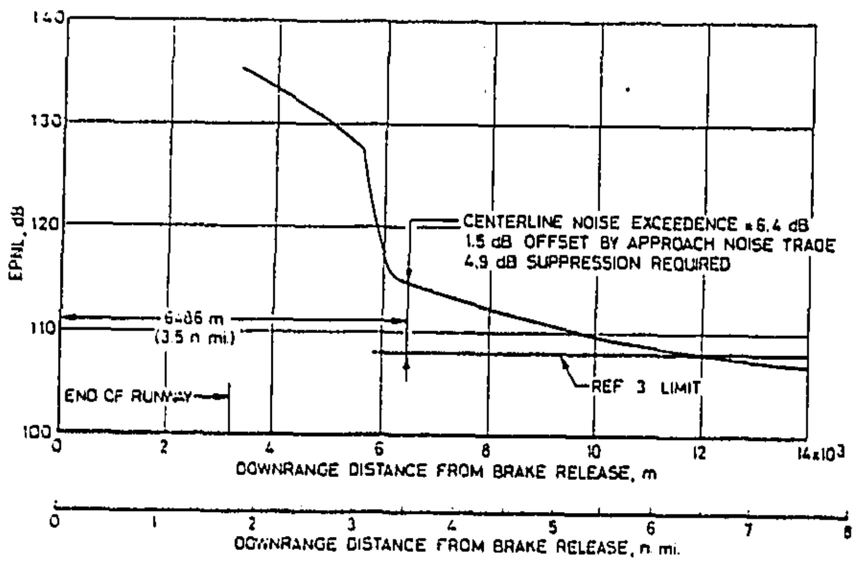


FIG. 4.12 AST-100 EFFECTIVE PERCEIVED NOISE LEVEL WITHOUT SUPPRESSION ALONG RUNWAY CENTERLINE DURING TAKEOFF. (From Ref. 8)

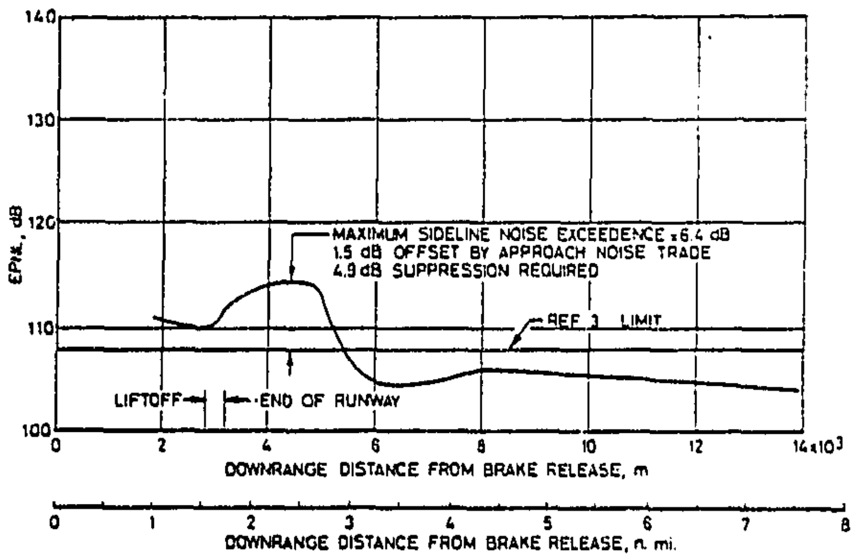


FIG. 4.13 AST-100 EFFECTIVE PERCEIVED NOISE LEVEL WITHOUT SUPPRESSION ALONG SIDELINE DURING TAKEOFF. (From Ref. 8)

4.2 Integrated Airframe-Propulsion Noise Studies

FAR Part 36 (1969)

The design optimization program used to evolve the AST-102 was applied to analysis of the range changes resulting from imposition of noise constraints on the range of the AST, when it is equipped with one of four engine type [147]. The engines studied were:

- GE-4 turbojet with afterburner from US-SST program
- Pratt and Whitney variable stream control engine (VSCE) in 502 series
- Pratt and Whitney rear valve engine (RVE) in 112 series
- General Electric double bypass variable cycle engine (DBE) in GE 21 series.

For each engine design the aircraft thrust-weight ratio (engine size) and wing loading were selected to maximize range, holding gross takeoff weight and payload at 718 and 61 thousand pounds, respectively, and cruise mach number at 2.62.

The five cases investigated included the no constraint case together with four cases that included the constraints on field length, takeoff and approach speed, and climb and cruise thrust margin utilized in the AST-102 study, together with

- no noise constraint
- 108 EPNL without suppression (assumes co-annular effect unknown)
- 108 EPNL with suppression
- 108 EPNL with suppression and 12500 ft fielding.

The noise was calculated in accordance with the methods of Reference 8 with the following suppression allowances:

GE4 - 8 dB mechanical suppressor (5% thrust loss and 7% increase in engine weight).

VSCE - up to 10 EPN dB coannular effect at maximum throttle

RVE - up to 5 EPN dB coannular effect at maximum throttle

DBE - up to 9 EPN dB coannular effect at maximum throttle.

The takeoff was generally constrained to initiate cutback and flap retraction to 5° at 700 ft altitude and 19,500 feet from start of roll, after accelerating to maximum speed consistent with this profile, the other constraints and the available takeoff thrust margin. For each noise constraint case the sideline and takeoff EPNL was calculated as a function of absolute partial power thrust used and an engine scale factor (ESF), see the example in Fig. 4.14. The partial thrust and ESF values that were estimated to result in meeting the 108 EPNL requirements at each of the two measurement locations were then compared to determine the values of both partial power takeoff thrust and ESF which uniquely meet both requirements, see example in Fig. 4.15.

The resulting engine size for the configurations is an engine whose maximum installed sea level takeoff thrust on a standard +10°C day is the value of the derived engine scale factor times the full power thrust associated with an ESF of 1.0. For the example shown in Figs. 4.14 and 4.15, the selected ESF is 0.90, and the engine is sized at 57,887 lbs (0.90 x 64,319 lbs reference for ESF = 1.0).

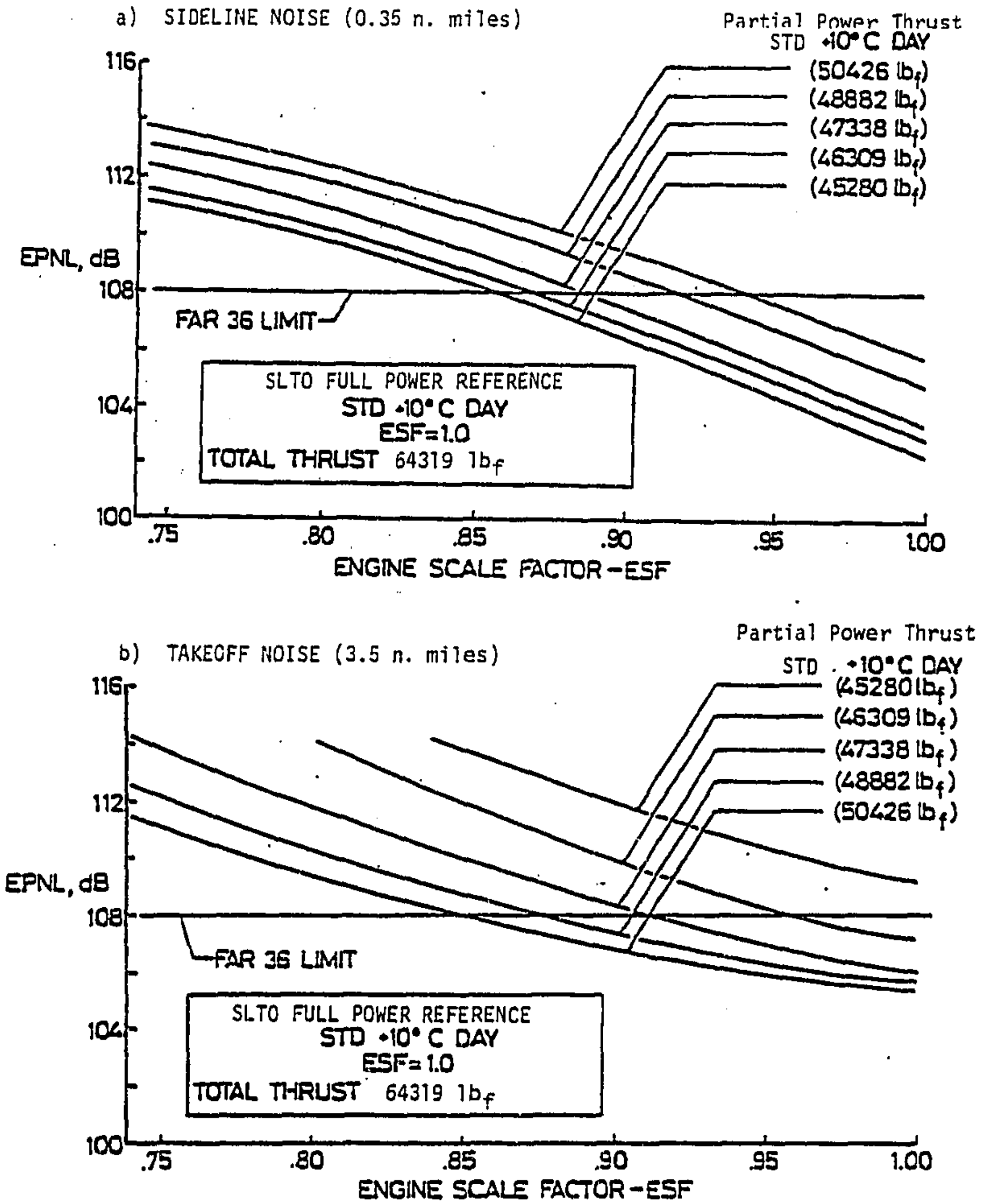


FIG. 4.14 VARIATION OF SIDELINE AND TAKEOFF CENTERLINE EPNL WITH ENGINE SCALE FACTOR FOR AST-100 FAMILY AIRCRAFT, 12,500 FT FIELD LENGTH, AND P & W VSCE ENGINE WITHOUT SUPPRESSION. (From Ref. 147).

The variation of sideline noise at constant partial power thrust as a function of ESF in Fig. 4.14a represents the effect of the change in jet exit velocity with a change in the ratio of partial thrust to installed thrust (ESFX reference thrust). Thus, at a constant partial power thrust, the noise decreases as ESF increases because the required jet exit velocity required to attain the constant partial thrust decreases.

The variation of takeoff noise at constant partial power thrust as a function of ESF shown in Fig. 4.14b behaves in the same manner as that on the sideline. However, unlike the sideline case, higher values of constant thrust result in lower noise levels. The higher values of constant thrust during the initial takeoff enable a greater aircraft speed at cutback, hence lower C_L requirement, higher L/D and a resulting lower value of thrust after cutback with its lower value of noise.

The engine sizes chosen from these analyses are shown on the thumbprints for each engine type shown in Fig. 4.16. The optimum ranges for an all supersonic mission are summarized in Table 4.4. These results indicate a significant range penalty to meet the 108 EPNL requirement for the older afterburning GE-4 engine, particularly when noise control is accomplished by oversizing the engine to reduce jet velocity rather than including a suppressor. *For the assumption of this study* the results suggest that the imposition of a 108 EPNL FAR Part 36 (1969) rule impose little or no penalty in range for the AST-100 family aircraft derivatives when powered with advanced technology variable cycle engines. A similar conclusion can be drawn from a McDonnell Douglas study [117] of various 1978-82 technology engines in their study AST aircraft. The aircraft is configured to carry 225 passengers at a cruise mach number of 2.2 over ranges in excess of 4000 n. miles with a takeoff gross weight of 705 thousand lbs.

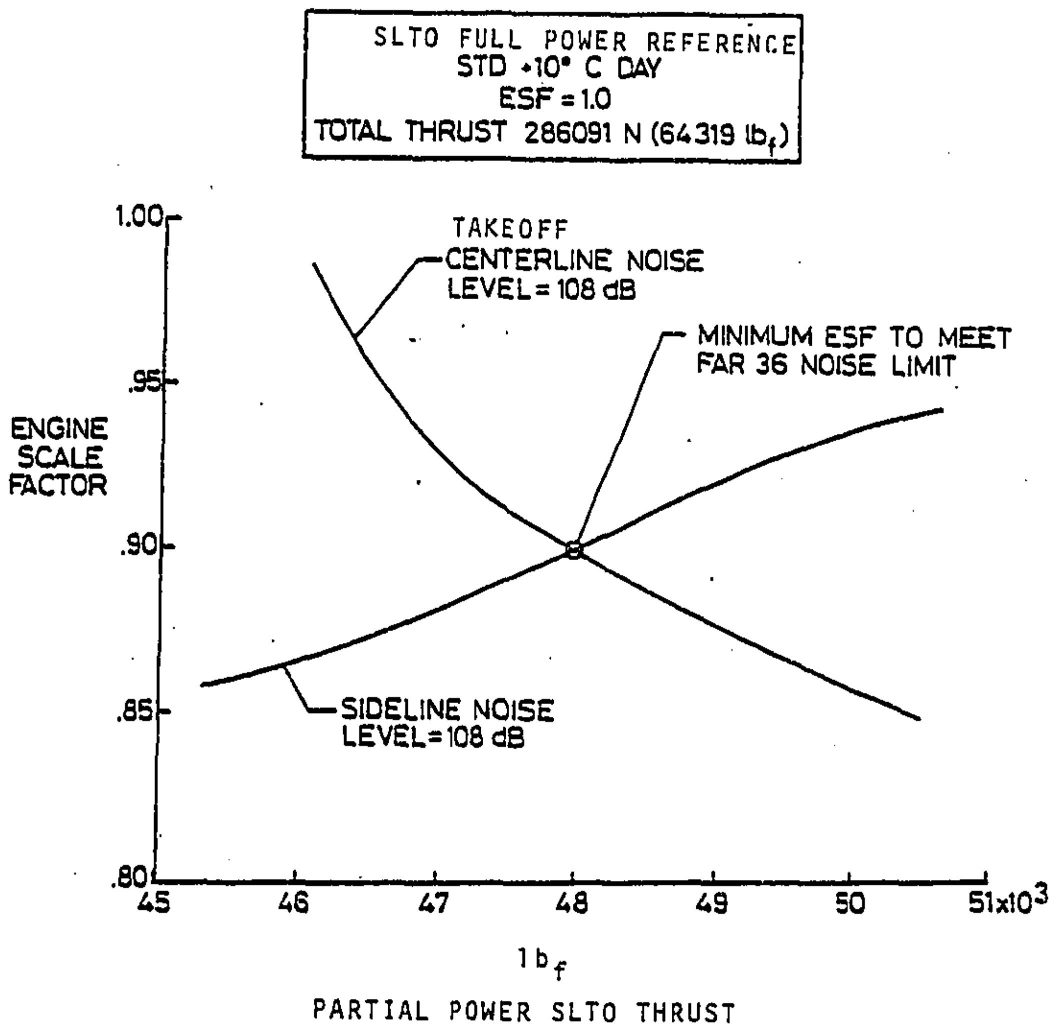


FIG. 4.15 VARIATION OF ENGINE SCALE FACTOR WITH TAKEOFF THRUST FOR AST-100 FAMILY AIRCRAFT, 12,500 FT FIELD LENGTH, AND P & W VSCE ENGINE WITHOUT SUPPRESSION. (From Ref. 147).

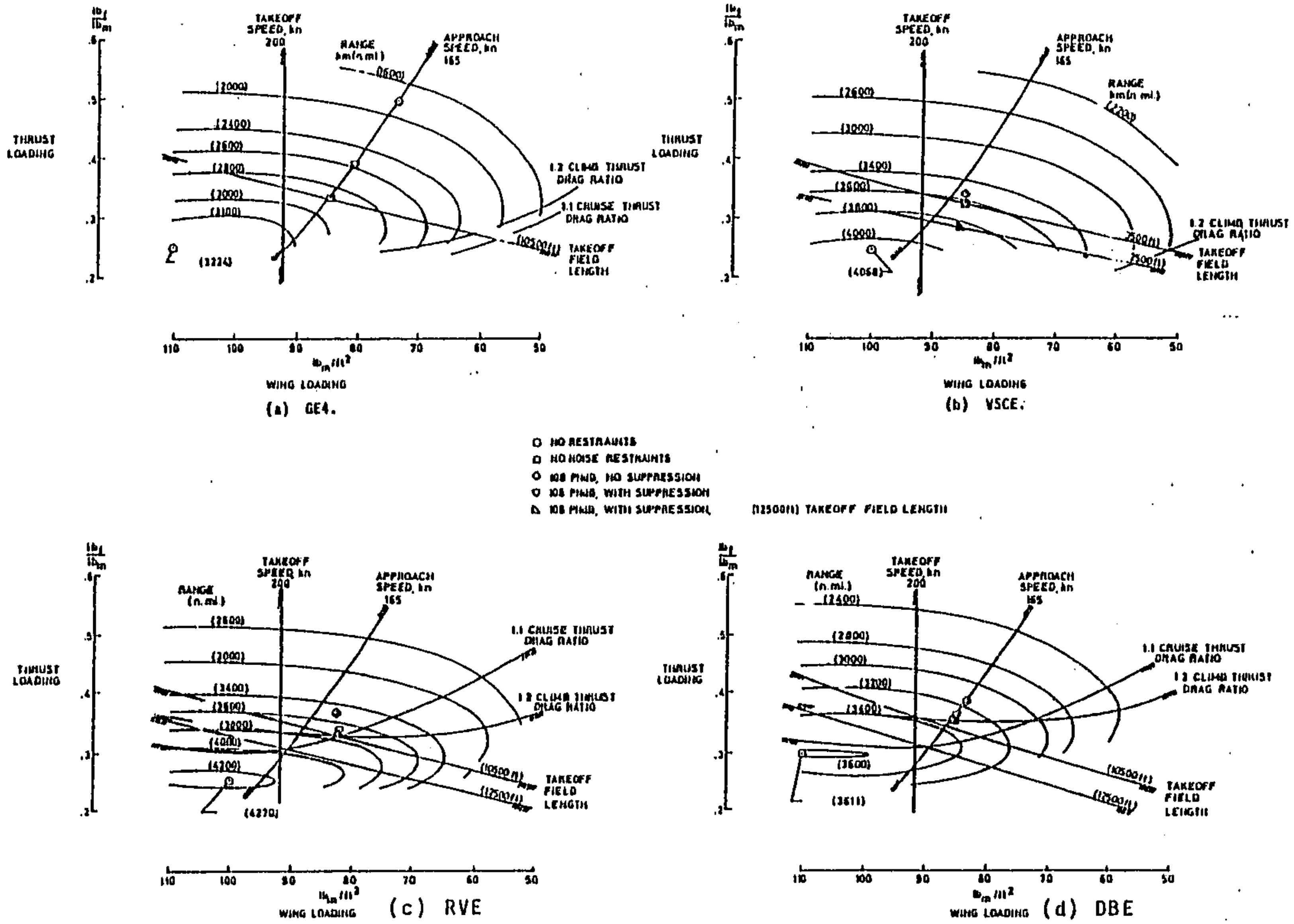


FIG. 4.16 ENGINE STUDY THUMBPRINT SUMMARY. (From Ref. 147)

TABLE 4.4 RANGE SUMMARY - ENGINE STUDY ALL SUPERSONIC MISSION (From Ref. 147)*

Condition	Cruise Thrust Margin	Climb Thrust Margin	Field Length Restraint	GE4	VSCE	RVE	DBE
No Restraint	None	None	None	3224	4067	4270	3611
No Noise Restraint	1.1	1.2	(10500 ft)	3002	3625	3752	3329
108 EPNdB, No Suppression	1.1	1.2	(10500 ft)	1969	3543	3490	3109
108 EPNdB, With Suppression	1.1	1.2	(10500 ft)	2601	3625	3714	3247
108 EPNdB, With Suppression	1.1	1.2	(12500 ft)	N/A	3812	3/52	3329
108 EPNdB, With Suppression	None	None	(12500 ft)	N/A	3812	3934	3475

*For the VSCE, RVE and DBE engines the "suppression" is the coannular noise reduction and the "no suppression" is based on the calculated noise, assuming the coannular effect were unknown.

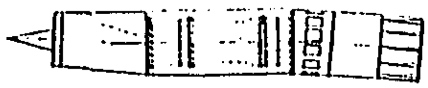
The engines used in the study are shown in Fig. 4.17; the 1978 engines are mini or low bypass turbojets. The 1982 engines include the 1978 engines uprated to an assumed 1982 technology status, and two variable cycle engines derated from nominal 1985-9 technology to assumed 1982 technology. The noise estimates were based on manufacturers' suppressed and unsuppressed data, except that where the MDC suppressor was utilized it was assumed to provide a peak suppression of 13 PNdB.

Figure 4.18 presents the range vs engine size summary with the selected size for each engine indicated with a symbol. The symbol used indicates the controlling constraint; either takeoff field length of 11,000 ft, climb thrust-drag ratio of 1.1 or maximum range. These results indicate that while all objectives can be met with 1978 technology engines, significant range improvements are anticipated with later technology engines.

The noise levels predicted for sideline and cutback positions for these six cases are given in Table 4.5. The P & WA LBE 435 (1978) engine has a margin of 6 dB on sideline and 2 dB at cutback, both relative to the FAR 36 (1969) requirement of 108 EPNdB. However, it does not quite meet the FAR 36 Stage 3 requirements of approximately 100 EPNdB on sideline and 105 EPNdB at cutback.

1978 TECH

GE MINI BYPASS GE21/J10B3	
AIRFLOW 760 LB/SEC	
WEIGHT (ENGINE AND NOZZLE)	16,101 LB
LENGTH (INTAKE FACE TO NOZZLE)	283.5 IN.
MAX DIAMETER	80.3 IN.
SLS THRUST	67,069 LB



1978 TECH

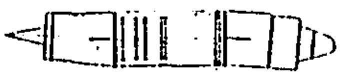
P&WA LBE 435	
AIRFLOW 767 LB/SEC	
WEIGHT (ENGINE AND NOZZLE)	16,264 LB
LENGTH (INTAKE FACE TO NOZZLE)	335.0 IN.
MAX DIAMETER	81.3 IN.
SLS THRUST	65,718 LB

1982 TECH

GE MINI BYPASS GE21/J10B4	
AIRFLOW 657 LB/SEC	
WEIGHT (ENGINE AND NOZZLE)	12,067 LB
LENGTH (INTAKE FACE TO NOZZLE)	260.3 IN.
MAX DIAMETER	74.3 IN.
SLS THRUST	53,727 LB

1982 TECH

P&WA LBE 431	
AIRFLOW 720 LB/SEC	
WEIGHT (ENGINE AND NOZZLE)	14,170 LB
LENGTH (INTAKE FACE TO NOZZLE)	320.5 IN.
MAX DIAMETER	70.2 IN.
SLS THRUST	62,909 LB



1982 TECH

GE DB/VCE GE21/J11B16	
AIRFLOW 816 LB/SEC	
WEIGHT (ENGINE AND NOZZLE)	11,360 LB
LENGTH (INTAKE FACE TO NOZZLE)	274.7 IN.
MAX DIAMETER	73.0 IN.
SLS THRUST	63,532 LB

1982 TECH

P&WA VSCE 511D	
AIRFLOW 760 LB/SEC	
WEIGHT (ENGINE AND NOZZLE)	12,200 LB
LENGTH (INTAKE FACE TO NOZZLE)	240.0 IN.
MAX DIAMETER	80.3 IN.
SLS THRUST	60,751 LB

FIG. 4.17 DESCRIPTION OF ENGINES USED IN McDONNELL DOUGLAS STUDY. (From Ref. 117)

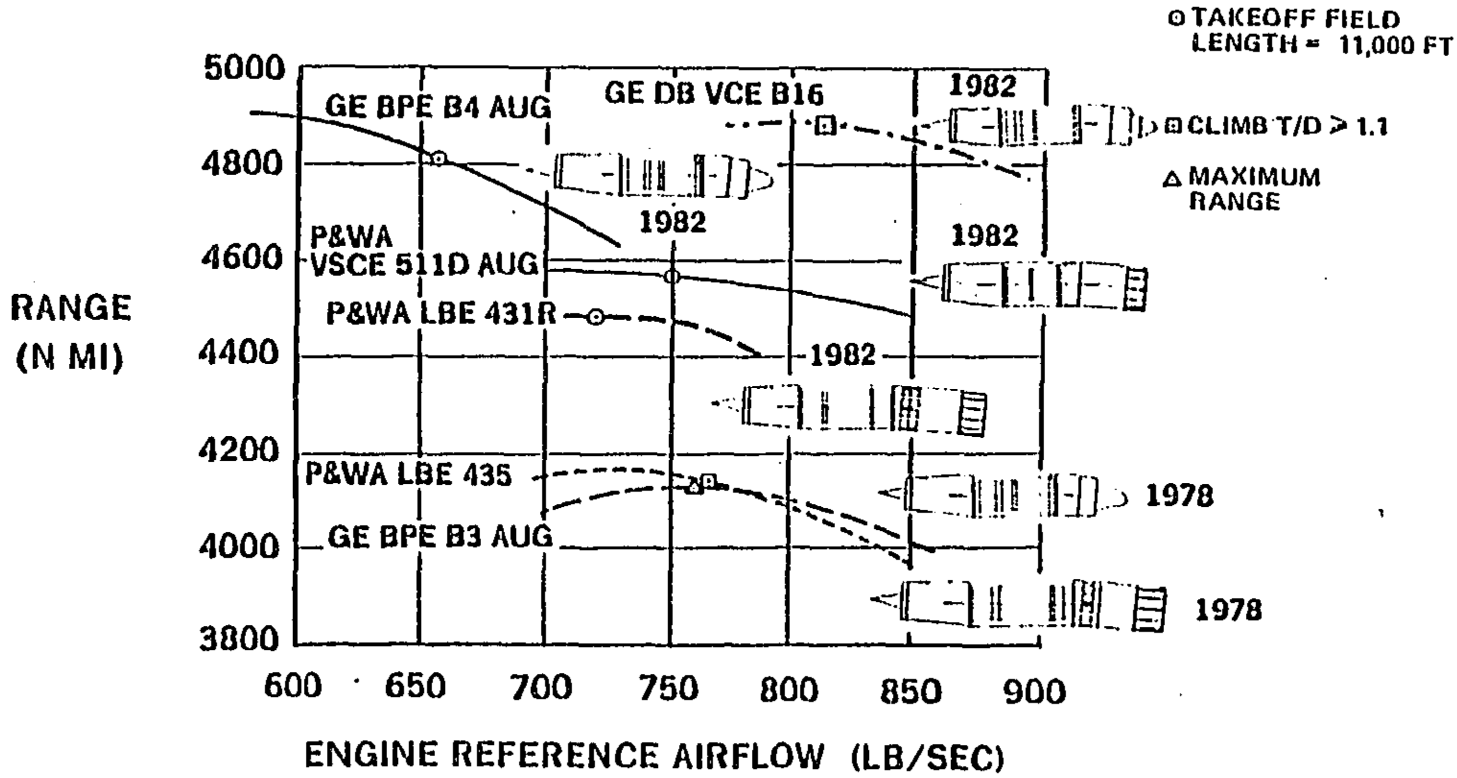


FIG. 4.18 SUMMARY OF RANGE VS ENGINE REFERENCE AIRFLOW FOR ENGINES IN McDONNELL DOUGLAS STUDY FOR A MACH 2.2 AIRCRAFT WITH A 225 PASSENGER (46,000 LB) PAYLOAD, 705,000 TAKEOFF GROSS WEIGHT MEETING FAR Part 36(1969) TAKEOFF NOISE REQUIREMENTS. (From Ref. 117)

TABLE 4.5 PREDICTED TAKEOFF NOISE LEVELS (EPNdB) AT FAR PART 36 MEASUREMENT LOCATIONS FOR McDONNELL DOUGLAS STUDY WITH MACH 2.2, 705,000 LB AST WITHOUT TOLERANCES FOR AIRCRAFT PERFORMANCE OR NOISE. (From Ref. 117)

ENGINE	ASSUMED TECHNOLOGY DATE	SIDELINE	CUTBACK	ALTITUDE AT 3.5 NAUTICAL MILES (Feet)
GE21/J10B3	1978	108	108	1391
GE21/J10B4	1982	106	110	1168
P&WA LBE 435	1978	102	106	1234
P&WA LBE 431R	1982	104	106	1165
GE21/J11B16 (DB VCE)	1982	106	110	1378
P&WA VSCE 511D	1982	106	107	1192

Reducing Noise to FAR 36 - 5 EPNdB

The SCAR program objectives in noise included investigating the effect of two assumed possible goals: FAR Part 36 (1969) and FAR Part 36 (1969) - 5 EPNdB. The engine manufacturers' studies [4,5,68 and 69] developed engine and noise data for integrated airframe-engine designs to assess the effects of various noise goals and these data were also applied by NASA to various aircraft designs [208, 211].

A 1976 NASA study [208] assessed the effect of varying FAR takeoff field length and sideline noise goals on the range performance of the NASA reference AST aircraft [134] and a derivative of the Boeing 2707-300 aircraft for four engine types. Pertinent aircraft and engine characteristics are given in Tables 4.6 and 4.7. The two aircraft were chosen to represent the range between "optimistic" advanced design (Reference AST) and conservative "older" design (B-2707). The engines were from the Phase II study results [4,68], but without the manufacturers' normal margins in quoting performance and weight.

The effect of engine sizing without either field length or noise constraints is given in Fig. 4.19. As would be expected, the "older" conservative aircraft design exhibited less range than that of the advanced design, regardless of engine type. The low bypass engine (LBE 405B) showed poorer range than the three variable cycle engines because of its greater weight, poorer subsonic SFC and more conservative assumed technology. In general, the optimum SLS corrected airflow was near 700 lbs/second, which would yield relatively low thrust to weight ratios on takeoff with consequent long field lengths and high velocity jets and noise.

TABLE 4.6 MAJOR AIRPLANE CHARACTERISTICS FOR FIELD LENGTH/SIDELINE NOISE STUDY. (From Ref. 208)

Characteristic	Airplane	
	NASA/LANG. LTV 1973 Reference	Boeing B2707-300 Derivative
Takeoff gross weight, lb	762 000	750 000
Number of passengers	292	273
Payload, lb	61 028	57 057
Reference wing area, ft^2	9969	7700
Operating empty less podded propulsion weight, lb	259 913	271 920
Lift-off C_L	0.55	0.70

TABLE 4.7 ENGINE CYCLE, WEIGHT, AND DIMENSIONAL CHARACTERISTICS FOR FIELD-LENGTH/SIDELINE NOISE STUDIES (PHASE II PERFORMANCE [4, 68]. (From Ref. 208)

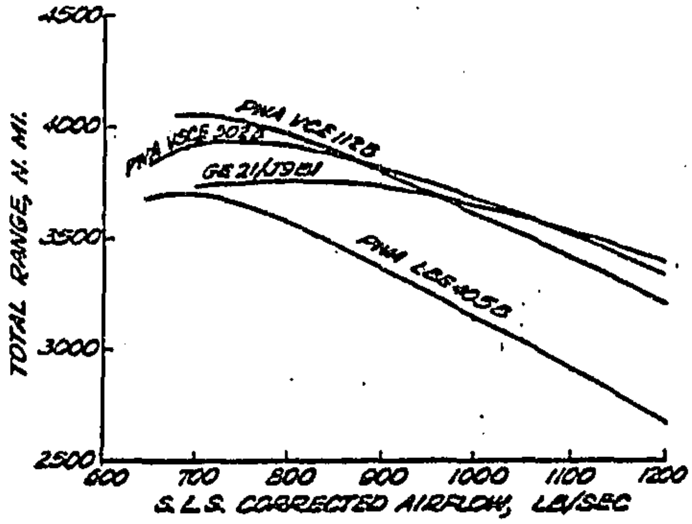
Characteristic	P&WA LBE 405A	P&WA VSCE 502B	P&WA VCE 112B	GE21/J9 Study B1
Fan pressure ratio	4.1	3.3	5.0	3.1/4.0
Bypass ratio	0.1	1.3	2.5	0.7/0.4
Overall pressure ratio	17	20	25	22.4
Max. combustor exit temperature, F	2600	2800	2800/1900	2826
Total corrected airflow, lb/sec	900	900	900	900/740
Adjusted engine weight, including nozz./rev., lb	15 200	13 085	13 156	13 250
Total weight per pod, lb	20 960	18 725	19 086	17 690

Figures 4.20 and 4.21 show the effect of the two takeoff field length and noise constraints on the Boeing and NASA AST reference aircraft. The ranges are less than the maximum values found for the unconstrained designs of Fig. 4.19, reflecting the higher values of corrected airflow required to meet the constraints. The same reason explains the reduction of range resulting from reducing the field length at constant noise.

The percentage reduction in range for a 5 EPNdB reduction for each field length constraint and aircraft and engine type are summarized in Table 4.8. These percentage range reductions are, in most cases remarkably consistent between the two airplane designs. They are higher with the 10,500 ft field length, probably because this shorter field length requires higher takeoff thrust, and thus more inherent noise. The principal variation in these reductions occurs among engines with the GE21 double bypass showing the least effect (0 to 5.4% reduction) and the low bypass engine the greatest effect (6.6-10.8% reduction).

The results of a more recent study [211] which compared the ranges for several engine types and an AST-100 type aircraft are given in Fig. 4.22. These results indicate that the variable cycle engines, 502B, DBE and DCE, have significantly more promise than the turbojets, CTJ and GE4, in providing useful range while meeting the combined constraints of 10,500 ft field length and sideline noise of FAR 36-5 EPNdB. Unfortunately, the effect of the 5 dB reduction in noise cannot be separated from the combined effect of the two constraints to compare directly with the previous study data given in Table 4.8.

a) Boeing (TOGW 750,000 lbs and 273 Passengers



b) NASA Reference AST (TOGW 762,000 lbs and 292 Passengers

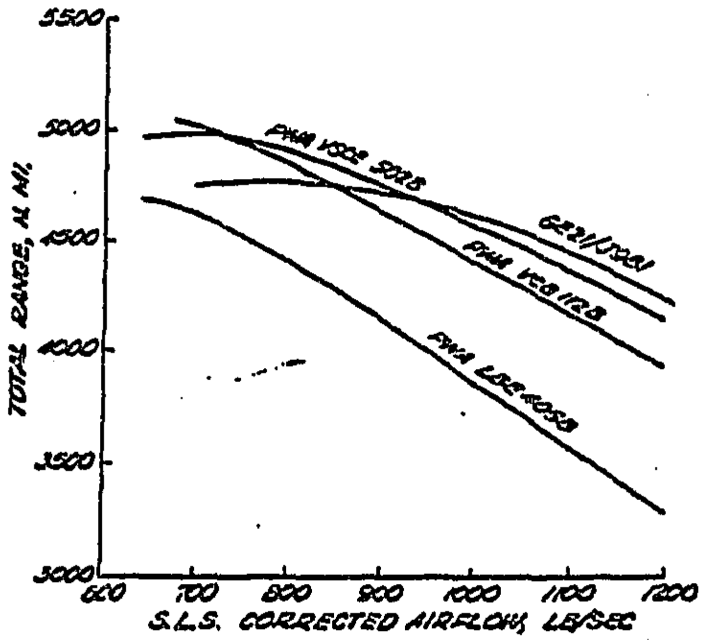


FIG. 4.19 EFFECT OF ENGINE SIZE ON RANGE FOR A MACH 2.32 AIRPLANE. (From Ref. 208)

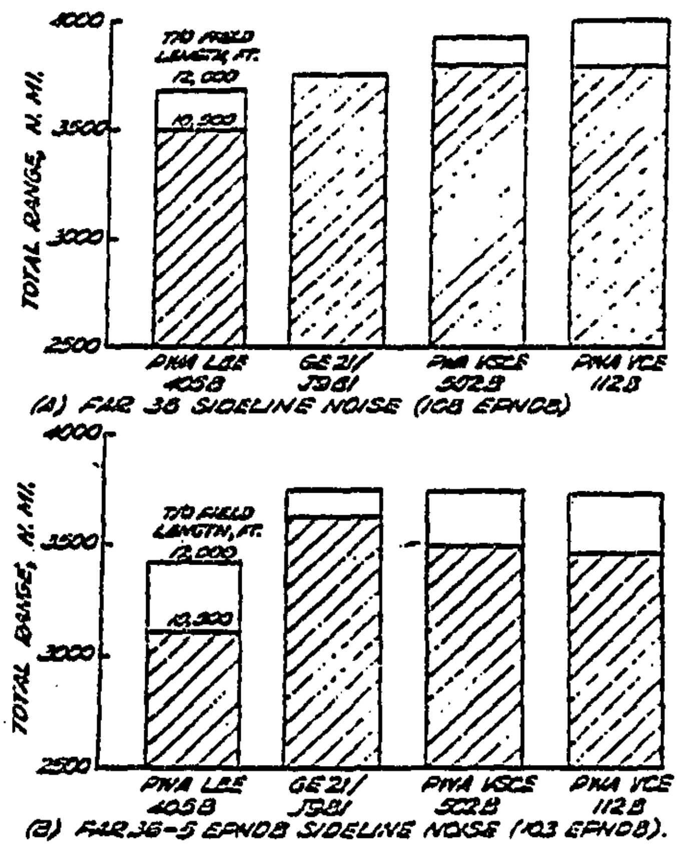


FIG. 4.20 EFFECT OF F.A.R. TAKEOFF FIELD LENGTH AND SIDELINE NOISE LEVEL ON RANGE OBTAINED WITH VARIOUS ENGINE TYPES INSTALLED IN THE BOEING MACH 2.32 AIRPLANE. TAKEOFF GROSS WT. 750,000 LBS, 273 PASSENGER PAYLOAD.

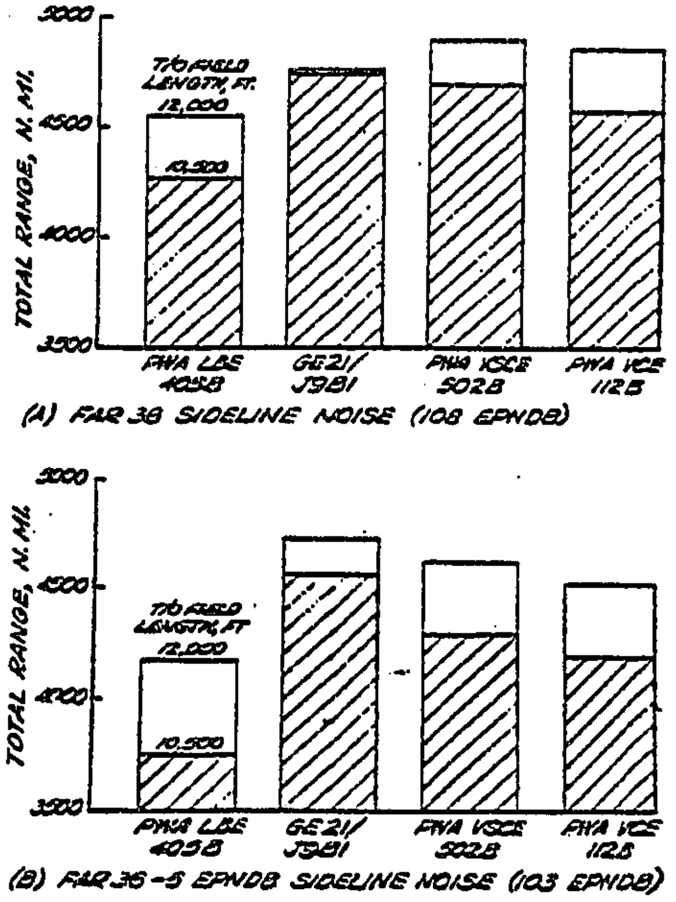


FIG. 4.21 EFFECT OF F.A.R. TAKEOFF FIELD LENGTH AND SIDELINE NOISE LEVEL ON RANGE OBTAINED WITH VARIOUS ENGINE TYPES INSTALLED IN THE NASA REFERENCE AST MACH 2.32 AIRPLANE. TAKEOFF GROSS WEIGHT, 762,000 LBS, 292 PASSENGER PAYLOAD. (From Ref. 208)

TABLE 4.8 PERCENTAGE REDUCTION IN RANGE RESULTING FROM REDUCING SIDELINE NOISE FROM 108 TO 103 EPNL FOR TWO VALUES OF TAKEOFF FIELD LENGTH, TWO AIRCRAFT AND 4 ENGINE TYPES. (From Ref. 208).

AIRPLANE	TAKEOFF FIELD LENGTH			
	12000 Feet		10500 Feet	
	NASA*	Boeing**	NASA	Boeing
Takeoff Gross Weight (1000 lbs)	762	750	762	750
Cruise Mach Number	2.32	2.32	2.32	2.32
Passenger Payload	292	273	292	273
ENGINE TYPE				
P&W LBE 405B	6.6	6.8	10.2	10.8
GE21/J9B1	1.1	0	3.2	5.4
P&W VSCE 502B	5.1	3.8	8.0	6.7
P&W VCE 112B***	6.7	6.3	7.7	7.9

* NASA Reference AST with Arrow Wing, most Advanced AERO ±1341, Range: 3750-4725

** Boeing Derivative of 2707, most conservative AERO, Range: 3400-3975

*** The noise estimates may be quite overoptimistic for this engine because of coannular effect assumption. [208].

a) Pratt & Whitney Engine Comparison

b) General Electric Enigne Comparison

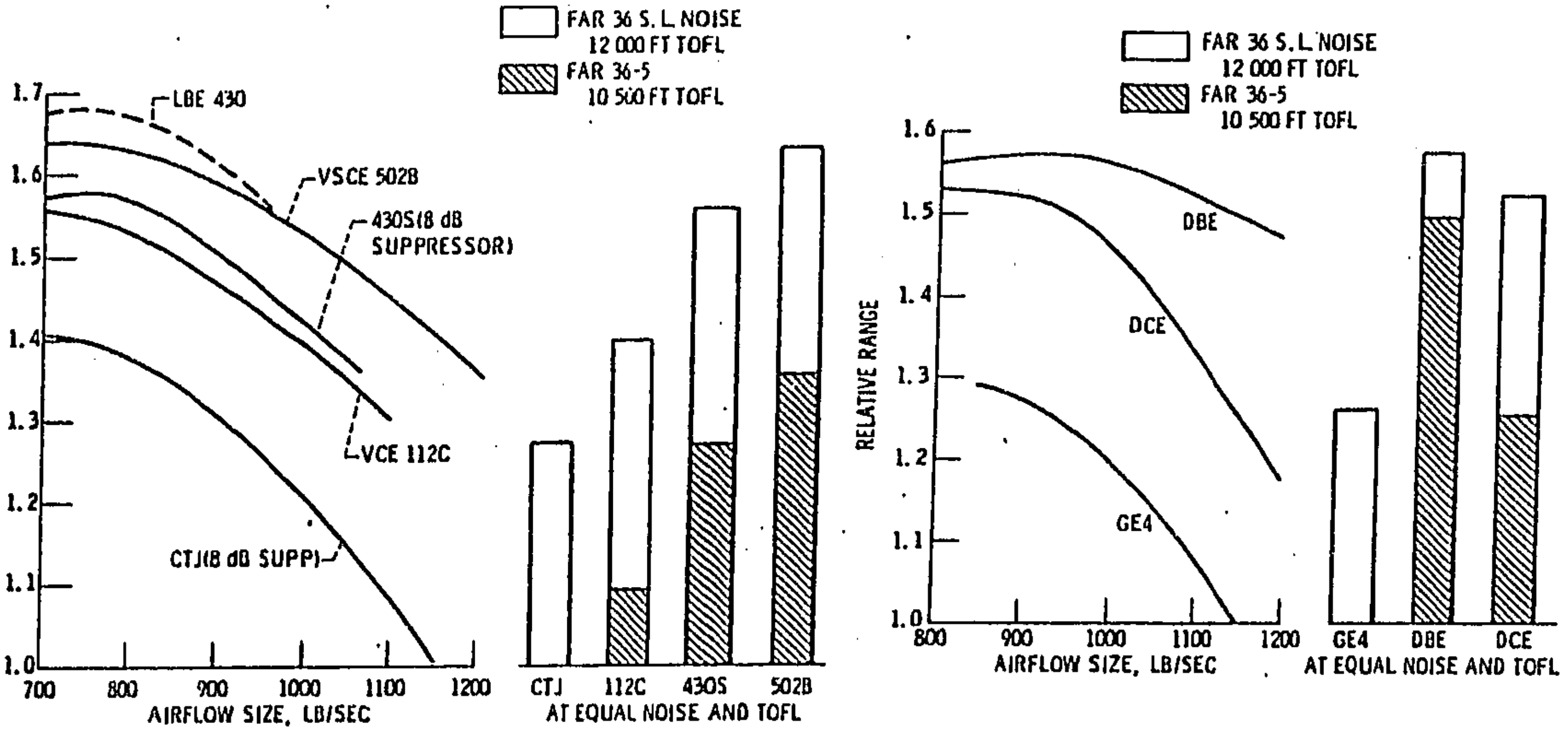


FIG. 4.22 RELATIVE RANGE COMPARISONS FOR VARIOUS ENGINES IN AST-100 TYPE AIRCRAFT AS A FUNCTION OF ENGINE AIRFLOW, TOGETHER WITH THE EFFECT OF COMBINED FIELD LENGTH AND SIDELINE NOISE CONSTRAINTS. (From Ref. 211)

A summary [119] of the predicted tradeoffs between range and noise of the NASA reference AST [134] and a post 1985 version of the G.E. double bypass engine is shown in Fig. 4.23. The AST was operated at a cruise mach number of 2.4. For the study the payload remained constant while the nominal gross takeoff weight of 762,000 lbs and range varied with engine configuration. The results indicate that mechanical suppressors offer good potential in reducing noise at a low cost in range. Their use at a constant range of 4000 miles produces benefits of 5-9 EPNdB depending upon complexity. Alternatively, attaining 5dB reduction at the sideline for the two unsuppressed engines costs a range penalty of approximately 11%.

The unsuppressed coannular nozzle just meets the 1969 sideline requirements at a 4000 mile range and is almost 2 dB in excess of the requirement at cutback. With the most complex suppression analyzed, the sideline level can be reduced about 6 EPNdB below the requirement and the cutback level about 4 EPNdB below the requirement, not quite meeting the FAR 36 Stage III requirements.

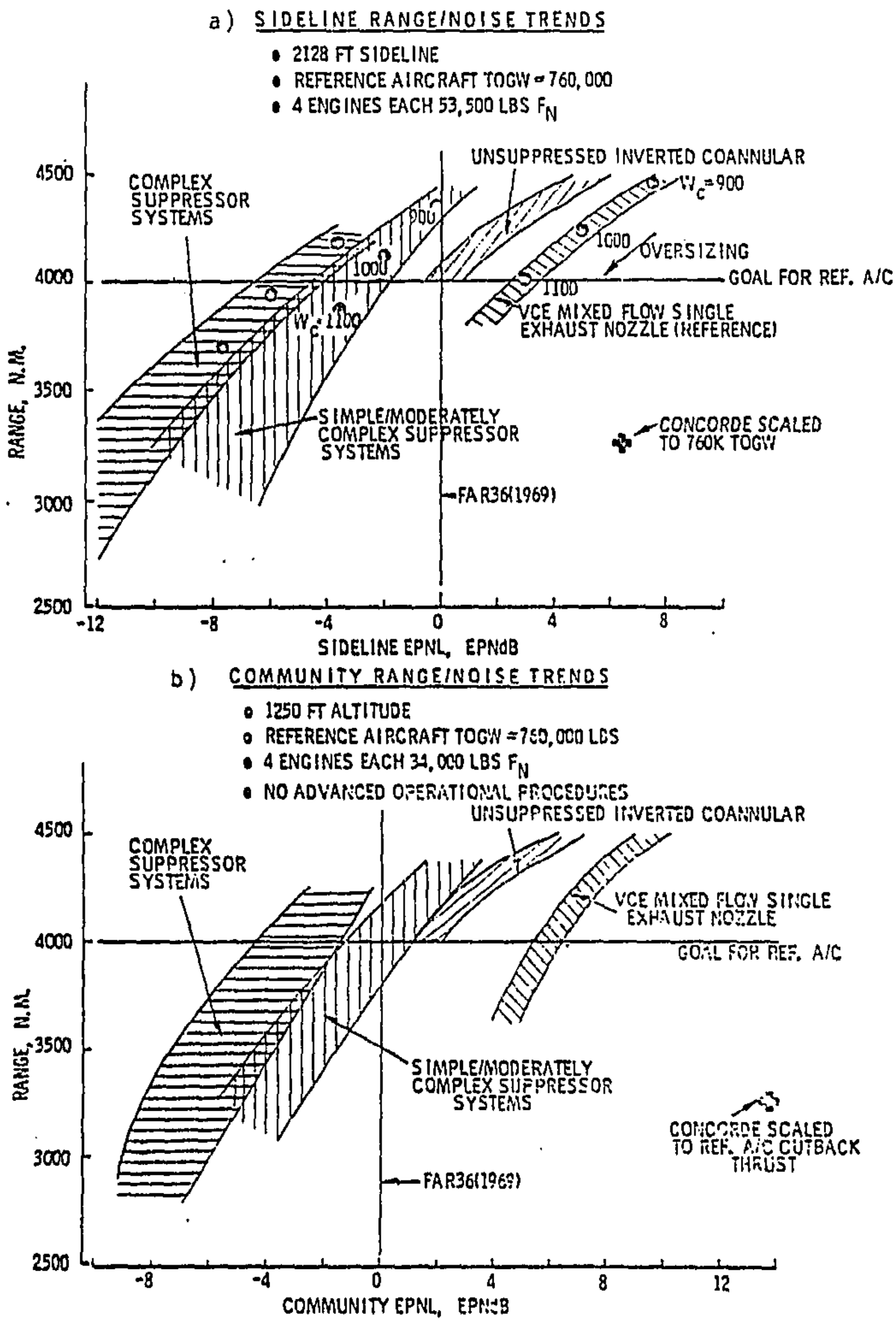


FIG. 4.23 ESTIMATE OF TRENDS OF NOISE LEVELS VS RANGE FOR ADVANCED GE21 ENGINE WITH VARIOUS NOZZLE & FLOW CONFIGURATIONS & WITH 1985 TECHNOLOGIES FOR NASA REFERENCE AIRCRAFT WITH A CRUISE MACH NUMBER OF 2.4. (From Ref.119)

4.3 Potential Impact vs. Flight Procedures

The basic noise certification procedures in FAR Part 36 apply to subsonic transport category aircraft. Both the flight procedures and the certification levels have resulted from detailed study of the performance characteristics of subsonic aircraft. If the certification procedures were to be revised to include supersonic transport aircraft, they would probably incorporate some new procedures appropriate to the performance characteristics of such aircraft. However, the exact form of these possible changes is not known at this time.

Supersonic aircraft have a higher thrust-to-weight ratio, and poorer lift drag ratio than subsonic aircraft, and more sophisticated computer control capability. Furthermore, their engines are designed for continuous operation at high power settings, whereas engines for subsonic aircraft are designed for only short durations at full power. These differences have significant implications for the relationship between the noise level under the flight path, the levels at the certification locations and the procedures used to fly the aircraft.

McDonnell Douglas studied [39] the effect of various procedures on the noise characteristics of the MDC AST. All employed constant throttle prior to cutback, and did not include the additional potential possibly available from programed throttles (see Sec.3.5). The variation of noise level directly under the flight path is illustrated for several procedures in Figure 4.24 for a turbojet engine with MDC's stowable suppressor. In four of the cases [3,4, 6 and 7] the full suppressed power is resumed shortly after passing the takeoff monitor so that the cutback is for a short duration. With this procedure, the certification levels may be attained, but the noise subsequently increases further down the flight path.

However, because of the short duration of cutback, there is not much loss of altitude relative to a full suppressed power takeoff, and the levels at greater distances down the path become comparable to those for the full power takeoff, Case 1. When cutback is maintained and climb proceeds at a 4% gradient, Case 2, the noise level monotonically decreases with distance after cutback along the flight path. But, because of the slow climb rate and the higher drag associated with speeds less than 250 knots, the noise level beyond approximately 30,000 ft. from start of roll is greater than that associated with a full suppressed power takeoff. This result is similar to that shown for Concorde in Fig. 2.4. The 90, 100 and 110 EPNL contours associated with the procedures studied for both takeoff and approach are illustrated in Fig. 4.25.

Table 4.9 presents the areas associated with the seven contour sets for takeoff and the estimated certification levels for each of the procedures. From this study it is clear that there is no absolute relationship between certification levels and contour areas. However, there is a suggestion that an inverse relationship may exist, i.e., higher certification levels (no cutback) produces the smallest contour area. Compare the results for Cases 1 and 2. Table 4.9 also presents similar data for the three approach procedures studied.

The study results for takeoff indicate the desirability of accelerating to 250 knots (maximum allowable climb speed below 10,000 ft) as soon as possible so that flaps can be retracted as appropriate, and their drag minimized. If cutback is utilized to achieve the 3.5 n. mile takeoff levels, power should be reapplied gradually with a programed throttle schedule designed to ensure that the noise does not increase after the takeoff measurement location point, and to minimize the length and area of the contours and thus, the probable magnitude of the impact.

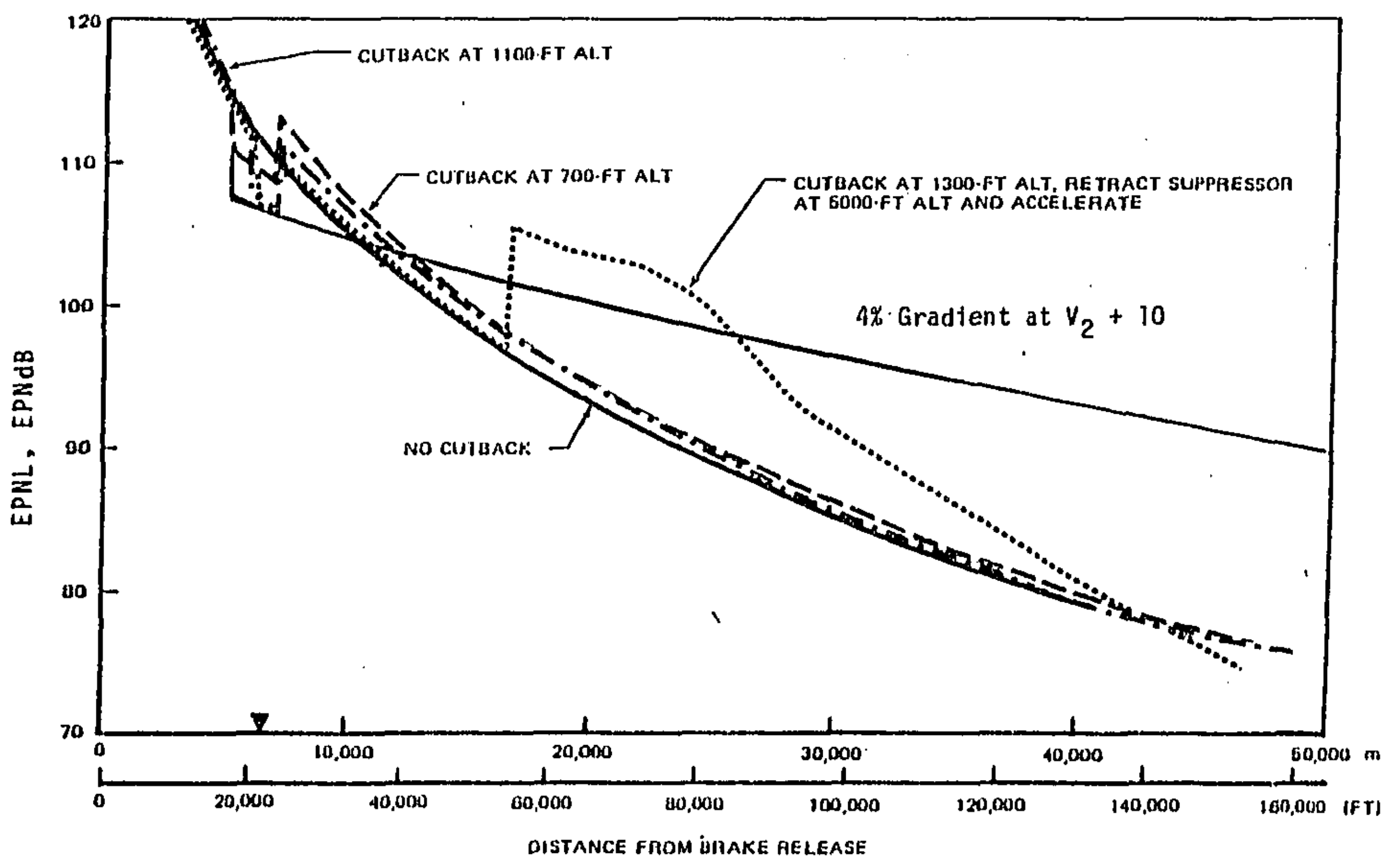


FIG.4.24 ESTIMATED TAKEOFF CENTERLINE NOISE LEVELS-
MDC TURBOJET AIRCRAFT. (From Ref. 39)

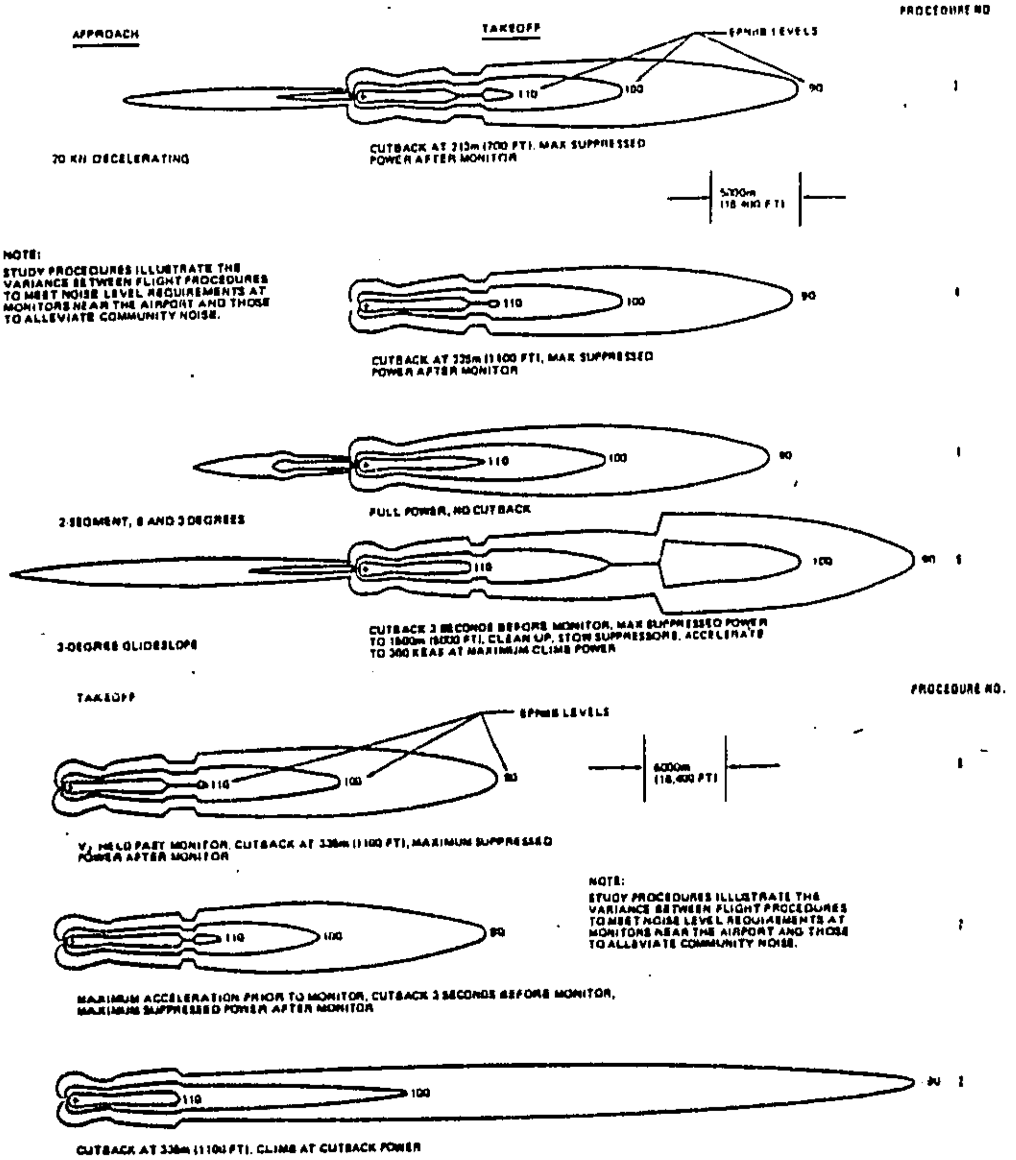


FIG. ESTIMATED COMMUNITY NOISE CONTOURS FOR SEVERAL TAKEOFF FLIGHT PATHS — MDC TURBOJET AIRCRAFT. (From Ref. 39)

TABLE 4.9 SUPERSONIC CRUISE CONFIGURATION TAKEOFF CONTOUR AREAS (SQ.N.MI.) AND ESTIMATED CERTIFICATION LEVELS FOR VARIOUS TAKEOFF AND APPROACH PROCEDURES, WITH MDC-AST, (from Ref.39)

PROCEDURE NUMBER	PROCEDURES	AREA (SQ. N.Mi.)			CERTIFICATION NOISE in EPNdB	
		90 EPNdB	100 EPNdB	110 EPNdB	Sideline 0.35 N.Mi.	Takeoff 3.5 N.Mi.
	TAKEOFF					
1	Full Suppressed Power	21.94	6.25	1.24	104	112
2	Cutback at 1100 ft, Speed at V_2+10 knots, climb at 4% gradient at cutback power	35.96	6.34	1.15	104	107
3	Cutback at 700 ft, Climb at max. suppressed power after monitor	22.88	6.65	1.21	103	110
4	Cutback at 1100 ft., climb at max. suppressed power after monitor	22.88	6.59	1.17	104	107
5	*Cutback at 1300 ft, Suppressor retracted at 5000 ft, climb at max. unsuppressed power after monitor	36.40	11.26	1.22	104	107
6	Cutback at 1100 ft, with aircraft speed held at V_2, climb at maximum unsuppressed power after monitor	23.08	6.83	1.13	104	107
7	*Cutback 3 sec. before monitor, aircraft speed max. prior to monitor [V_2+37 knots], climb at max. suppressed power after monitor.	21.17	5.96	1.34		
	APPROACH				CERTIFICATION in EPNdB Approach 1 N.Mi.	
1	Standard (3°)	6.74	0.73	.04	108	
2	*2 Segment (6°) & (3°)	2.56	0.67	.04	107	
3	*20 KEAS Decelerating Approach	3.65	0.46	.02	107	

*Not in conformance with Part 36 Procedures.

5. CONCLUSIONS

The noise design goal that has received the greatest attention in the NASA program is the FAR 36 Stage 2 certification requirements. The preponderant evidence in this report from the NASA program and the engine and airframe manufacturers is that this goal is achievable. The technology required for a Mach 2.2 AST meeting this noise goal with an immediate initiation of detailed design (Class 1 technology by ICAO definition), is primarily "current" and "available" by the EPA definition, although some might be considered "future."

For an initiation of detailed design in the mid 1980s, a Mach 2.55-2.7 AST could be developed, utilizing primarily Class 2 and 3 or "available" and "future" aerodynamic, structure, engine cycle and noise control technologies. Such an aircraft would be expected to have higher performance margins, and lower risk in terms of meeting the Stage 2 noise limits. However, if it were to just meet the Stage 2 noise limits it would be noisier than new subsonic aircraft introduced in a comparable time period. Such subsonic aircraft would be expected to meet at least the Stage 3 noise limits. Airframe manufacturers [55,60] recognize that this situation may not be tolerable, and that Stage 3 or more restrictive noise certification limits might have to be faced in the 1980s in the design of an acceptable AST.

The FAR Part 36 certification regulations were developed for subsonic category aircraft. Their certification flight test procedures and noise limits were based on the performance characteristics of subsonic aircraft. Consequently, they do not necessarily serve as an appropriate design goal for an AST, and were never intended for such use. However, because they exist they become the de facto AST design guidelines and constraints.

Their application to AST design, as shown in some of the studies reported here, often led to oversizing engines to operate at part power takeoff and a climbout profile that has a minimum climb gradient which, in effect, stretches the noise contours for much greater distances along the flight track than those of subsonic aircraft of comparable size and range. Thus, the potential impact on people of the AST is often greater than that of the subsonic aircraft even when it meets the same certification limits.

Because of its inherent design requirements an optimum AST will probably have a greater noise potential than a comparable subsonic aircraft. However, it will also probably have the capability to accelerate to the 250 knot speed limits in a relatively short distance after rotation and to thereafter climb in a clear aerodynamic configuration. This potential capability would be enhanced if it is allowed to use optimum power management during takeoff [40]. The use of these potentially available positive noise control characteristics should be encouraged to achieve an optimized minimum noise impact AST.

In order to promote the design of an environmentally acceptable AST a set of goals should be established for the designers. These goals should be stated in terms of impact potential, such as footprint areas and tolerances on the gross dimensions of specific contours [39,55], rather than the levels at the current measurement locations. The numbers assigned to the goals should be selected to obtain a desired level of compatibility between supersonic and subsonic aircraft of comparable size, route structure and time of entry into service. Further, the goals should allow a maximum latitude in developing takeoff and landing flight and power management procedures, consistent with proper flight and air traffic control safety requirements.

With the development of design goals that relate directly to environmental impact potential, and the relaxation of subsonic derived flight procedures, it should be possible for the designer to optimize AST design for the real world environmental requirements, as well as for range, payload and economic viability.

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