PERFORMANCE AND BENEFITS OF AN ADVANCED TECHNOLOGY SUPERSONIC CRUISE AIRCRAFT

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SUMMARY

The results of four years research on technology are synthesized in an advanced supersonic cruise aircraft design. Comparisons are presented with the former United States SST and the British-French Concorde, including aerodynamic efficiency, propulsion efficiency, weight efficiency, and community noise. Selected trade study results are presented on the subjects of design cruise Mach number, engine cycle selection, and noise suppression. The critical issue of program timing is addressed and some observations made regarding the impact that timing has on engine selection and minimization of program risk.

INTRODUCTION

Since 1972, McDonnell Douglas (MDC) has been conducting systems studies for NASA Langley, coupled with extensive Company-funded efforts, to identify technology requirements for an economical, environmentally satisfactory, supersonic cruise commercial airplane. These efforts were unencumbered by preconceived notions of what should be a proper design. A configuration evolved, based on extensive trade studies, that represents all the advanced technologies deemed applicable to a second generation supersonic passenger airplane.

In order to understand how technology has progressed in the last four years, comparisons are shown with the former U.S. SST design and with the world's first operational supersonic transport, the British-French Concorde. Updating of earlier published data is included.

In addition, important data on several trade studies are presented to enable others to participate in the design selection process. Cruise speed selection and engine cycle selection are both controversial issues at present. At McDonnell Douglas, the cruise speed trade studies seem to confirm the results found separately in over twenty-two years of continuous design, development, and production of military supersonic aircraft. The engine cycle trade studies and important data results are shown. The issue of noise-suppression variations between coannular and mechanical suppression is presented inasmuch as understanding these relationships is so critical to eventual engine cycle selection.

The results presented reflect comprehensive analysis, utilizing extensive computer and detail design iterations, capabilities only recently validated for use in the preliminary design process.

MDC BASELINE DEFINITION

The early research at NASA Langley on the former U.S. SST program identified the fact that a large increase in the aerodynamic efficiency of a supersonic transport could be realized. This was validated in 1965 by the tests of SCAT 15F, a mid-wing design with an arrow wing identified by a notch cutout of the trailing edge of the wing planform. Unfortunately, at that time, satisfactory solutions could not be found for the structural aeroelastic and flutter questions or for the passenger requirements for the fuselage with its impact on fuselage wing intersections. The arrow wing was dropped.

In 1972, following the demise of the U.S. SST, a fresh look at the arrow wing was undertaken. McDonnell Douglas wing planform trade studies, unencumbered by previous design selections, showed that the early delta-wing designs, typical of the Concorde and the former U.S. SST (fig. 1), were not optimum. By keeping a large subsonic leading-edge inner panel, a rather small supersonic leading-edge outer panel, and utilizing a moderate notch in the trailing edge, a result was found that was optimum for minimum operating cost. Some small penalties were paid in aerodynamic cruise efficiency to satisfy the structural demands for strength, aeroelasticity, safe-life, fatigue, damage tolerance, and flutter. Fortunately, improved computer-aided design techniques had become available which were not available in the mid-sixties; thus, much could be done to understand a specific airplane design. The result is that the structural stiffness and flutter questions, which hurt the competitiveness of arrow-wing designs in the late 1960's, can now be allayed and efficient arrow wings designed with confidence.

The four engines were located under the wing, aft of the rear spar and separate from the fuselage based on careful optimization trade studies involving complete airplane structural modeling, detail nacelle design, aerodynamic wave drag, and including even the impacts of changes in landing-gear length as required for engine ground clearance during rotation. Studies indicated that the tail could be reduced in size to match neutral static stability requirements, but that reducing the tail size further was not consistent with the low risk demanded for the other airplane variables.

The McDonnell Douglas baseline airplane that resulted is a 340 200 kg (750 000 lbm) design, with a 929 m^2 (10 000 ft^2) wing (table I). As compared to the last U.S. SST, the design cruise speed has been selected at 2.2 Mach number. The resulting range is 4590 nautical miles, a 48 percent improvement over the last U.S. SST, most of which is from the increase in aerodynamic cruise efficiency, lift to drag (L/D), which improved 34 percent. This then is the big difference in SST design between 1971 and 1976, a 34-percent increase in aerodynamic efficiency.

Much has been written about the advancements required for the propulsion system to make a supersonic airplane viable. There was nothing wrong with the cruise propulsion efficiency of the 1971 engine on the U.S. SST. The big problem was the noise. Thermodynamics is a well-known subject and the ideal engine cycle for cruise has not changed much. The component efficiencies of the 1971 engines were high; thus improvements have not come easily. The big advancements made in the recent NASA-funded U.S. engine studies have been in noise and in weight. Much of the weight improvement results from increased turbine temperatures and improved materials. The challenge really has been to meet or exceed the community noise requirements without losing supersonic cruise propulsion efficiency and this challenge has been met by the engine manufacturers.

One other interesting result is that the structure optimizes with titanium wherever elevated temperatures and highly loaded conditions exist. This is because of the long range payload sensitivity of the supersonic airplane design. On the other hand, studies show that lower cost aluminum is more cost effective on all secondary structures, or on components that have no temperature problem or are lightly loaded.

Two trade studies on cruise speed have been completed, one in 1973, and a more sophisticated second analysis in 1975 (table II). The 1975 results show a slight penalty in gross weight required at 2.2 Mach as compared with 2.0 Mach although the range factor is actually higher at 2.2 Mach. A large penalty is shown for designing for the higher Mach number of 2.4. The designs have all been configured to carry 273 passengers for 7408 kilometers (4000 nautical miles). There are small variations in aerodynamic cruise efficiency and in propulsion efficiency; however, the large variations that result are in the cruise engine thrust requirement. Because the 2.4 Mach number design has to cruise both higher and faster, a significant increase in engine thrust is required. The engine thrust also has to be increased due to a higher take-off speed, and lower climbout lift-drag ratio, whereas the FAR noise requirement remains constant. The structural design for each airplane has been analyzed in detail, including considerations for temperature and thermal stress where appropriate. The weights reflect all these conditions.

The 1975 study results make the case even stronger for selecting a moderate design cruise speed as compared with a higher cruise speed design.

For over twenty-two years McDonnell Douglas has been in continuous design, development, and production of supersonic fighter aircraft (fig. 2). Steady pressure by the customers has been applied over these many years, to try to justify supersonic aircraft with higher speeds like Mach 2.7 or Mach 3.0 but with no success. The latest McDonnell Douglas fighters, the F-18 and the F-15, reflect the results of extensive trade studies on the optimum solution for design speed. (They are more equivalent to 2.2 Mach cruise supersonic transport designs than to 2.5 Mach.) Higher speeds do not seem to be proven to be cost effective. Similar studies on early B-1 designs have shown the same type results. At McDonnell Douglas, no justifiable case can be made for designing an airline transport for a cruise speed above about 2.2 Mach number. At the same time, at McDonnell Douglas it is recognized that much of the technical knowledge gained from these U.S. military programs can be applied to the development of a 2.2 Mach advanced supersonic cruise commercial airplane.

A comparison with the Concorde shows a few additional items of importance (table III). Here, in addition to improvements in aerodynamics and noise, improvements in payload and in cruise speed can be shown, both of which are powerful variables in the economics equation. All hourly operating costs are divided by speed and by payload to obtain operating costs per passenger mile, and of course, tickets are priced by cents per passenger mile. Compared with the Concorde, the 9-percent increase in speed and the 150-percent increase in payload offer dramatic improvements in economy, equivalent to a 60-percent reduction in direct operating costs due to these two parameters alone.

The Concorde today is doing an outstanding technical job, except it is noisy (fig. 3). In the future, any second generation supersonic passenger aircraft must meet society's needs regarding noise. The McDonnell Douglas baseline design meets or exceeds FAR Part 36 noise requirements. Two additional items are of significance. By designing the supersonic airplane for 8334 kilometers (4500 nautical miles), the actual noise will be reduced significantly for most average missions as the gross weight will be lower, and the take-off performance much improved. Also there is good reason to believe that current emphasis on jet noise research is proving to be the most rewarding and further reductions in noise can be envisioned for supersonic designs. Fortunately, for supersonic designs, variable area nozzles are required for thrust recovery at cruise, which means that the variability is already available; there are possibilities for future clever designs for noise suppression at take-off nozzle positions.

The payload range of an airplane is all important for International airlines. The payload range that results for the MDC baseline shows that 273 passengers can be flown 8445 kilometers (4560 nautical miles) in an all metal design utilizing a 1980 state-of-art mini-bypass engine cycle (fig. 4). For a 1980 go-ahead, prudent use of graphite epoxy composite secondary structure is reasonably insured. For a 1985 go-ahead, the state of the art may well allow use of additional composites to reinforce the metal airframe in critical areas, probably in uniaxial loading type applications. Also, for a 1985 go-ahead, the variable cycle engine can be considered applicable and the resulting range of such a design becomes 10,649 kilometers (5750 nautical miles), equivalent to the very longest of the routes being considered today by airlines for subsonic operations. It looks as if a second generation supersonic cruise airplane inherently should possess good growth potential and not be range limited.

The ability to fly long ranges and open up the Pacific to supersonic travel will do much to save unproductive travel time. Such service should stimulate much travel.

A derivative of the Rolls-Royce Olympus is shown, based upon utilizing present core developments coupled with an additional turbine driving a low pressure compressor and fan. Such an engine is marginal for the 273 passenger size McDonnell Douglas design, but for a slightly smaller version it offers much promise. Further work here is active today both in England and at McDonnell Douglas.

The engine cycle selection is critical as engine development time from go-ahead to certification is the pacing item for a supersonic cruise airplane program, as the airplane development actually can take less time. Accordingly, the specific engine cycle and size must be selected early, and this requires selection by the airlines. This means airlines will have placed initial orders, specific engines will have been offered, airplane detail specifications will have been defined, and firm prices will have been established. This process does not come easily. Pacing all these conditions may well be the results of forward-flight tests on coannular and/or mechanical sound suppressors.

The variations in airplane range that result from engine technology readiness dates are shown (fig.5). The 1975 technology engine would require a relatively heavy multi-tube flow breakup nozzle with an acoustically lined ejector for meeting FAR Part 36 noise levels. The 1980 engine also incorporates a mechanical noise suppressor, although lighter. The 1985 technology designs utilize the inherent noise reduction benefits predicted for the coannular jet exhausts which are unique to the variable cycle engine designs. The weight variations between the engines tend to be the dominant reason for the range variations shown.

At present, it is not possible to narrow the engine selection process as the important variables of timing and noise suppression cannot be defined accurately. A comparison of the existing noise suppressor variations between coannular and mechanical suppressor as used by McDonnell Douglas is shown (fig. 6). As compared with conventional unsuppressed nozzles, mechanical suppressors are competitive, especially as the jet velocity is reduced. It can be shown that both mechanical suppressor and coannular suppressor airplane designs can result in airplane noise levels below the 108 EPNdB of FAR Part 36 if the jet velocity can be held low.

NASA could do the industry a great service if they would adequately fund validation testing of large-scale noise-suppression tests of both competitive design approaches that would accurately portray noise-suppression levels corrected for forward flight.

There are engine considerations being given additional study (table IV). The weight variations that result from the McDonnell Douglas engine sizing studies are as shown, with the VSCE showing a 14 515 kg (32 000 pound) advantage in operating empty weight. In addition, the VSCE shows a reduction in fuel reserve of 9 545 kg (21 000 lbm), which is significant, but has only a secondary effect on reducing direct operating costs. It is interesting that the Double Bypass and VSCE engines both optimize for designs that result in long climb schedules relative to more conventional cycles. The analysis includes optimizing the augmentation schedule as well as varying engine size. The average range factors vary more than by differences in specific fuel consumption. This is because most augmented-engine cycle-powered airplane designs optimize for flight at or near the altitude for maximum lift-drag ratio, whereas nonaugmented cycle designs seem to optimize for a slightly smaller engine size and cruise at an altitude that results in a slightly reduced lift-drag ratio.

The engine results show rather significant variations in direct operating costs. These are preliminary results only, uncorrected for changes such as 1976 fuel costs. Further efforts are required to better understand the trades between technology readiness dates, range, and direct operating costs. Airline guidance is needed in this area.

CONCLUDING REMARKS

Four years of systems studies, coupled with important validation wind-tunnel test results of an airline design, indicate that the technology is in-hand to develop an economical, environmentally satisfactory supersonic cruise commercial airplane (table V). No inventions are required. The extensive twenty-two years of continuous design, development, and production of McDonnell Douglas supersonic fighter designs including present F-4, F-15, and F-18 aircraft provide credibility to the McDonnell Douglas baseline supersonic cruise aircraft design. Selection of a 2.2 Mach number for cruise comes from this background of supersonic experience and offers low-risk improved airline economics and lower development costs. Program timing will dictate engine cycle selection and noise testing may also impact on engine selection. Inasmuch as no actual aircraft experience exists in the United States for (1) supersonic performance of arrow wings, (2) brazed titanium honeycomb and skin/stringer primary structures, or (3) flight effects for engine noise suppression, such tests will pace a U.S. second generation transport. Extensive validation testing is required to minimize the inordinately high risk that these areas represent. Only then can a low-risk production program be initiated. Should the U.S. government move out on these tests in FY 1978, then an engine selection is possible in 1980-81 and an economical, environmentally sound advanced supersonic aircraft can be in airline service in 1986.

TABLE I.- SUPERSONIC TRANSPORT TECHNOLOGY COMPARISON

	SST (1971)	MDC BASELINE (1976) *	IMPROVEMENT
SPEED	MACH 2.7	MACH 2.2	
RANGE	5741 km (3100 N MI)	8500 km (4590 N MI)	48% FARTHER
PASSENGERS	261	273	5% MORE
ENGINE	TURBOJET WITH AFTERBURNER	MINI-BYPASS TURBOJET — DRY	
PROPULSION EFFICIENCY (M/SFC)	1.74	1.74	NO CHANGE
AERO EFFICIENCY (L/D)	7.2	9.6	34% INCREASE
STRUCTURAL WEIGHT EFFICIENCY	100% TITANIUM 216°C (420°F)	70% TITANIUM + 30% ALUMINUM 116°C (240°F)	4% BETTER
TAKEOFF AND LANDING NOISE	112 EPNdB AVERAGE	105 EPNdB AVERAGE	BETTER THAN FAR PART 36

* 1980 GO-AHEAD

TABLE II.- CRUISE SPEED STUDY SUMMARY

$$R = K \frac{L}{D} \frac{M}{SFC} \ell g \frac{W_{TO}}{W_L}$$

R = 7408 km (4000 N MI)

	2.0M	2.2M	2.4M
L/D MAX	9.74	9.49	8.97
L/D CRUISE	9.73	9.33	8.86
SFC UNINSTALLED	1.23	1.27	1.33
SFC INSTALLED	1.32	1.38	1.49
M/SFC	1.52	1.59	1.61
L/D x M/SFC (RANGE FACTOR)	14.8	15.0	14.3
W_{TO}* kg (LB)	311,909 (686,200)	321,636 (707,600)	373,182 (821,000)
W_L kg (LB)	182,798 (403,000)	189,874 (418,600)	214,368 (472,600)
SLS THRUST/ENGINE kN (LB)	287.4 (64,600)	302.9 (68,100)	376.3 (84,600)

* MATERIAL SELECTION AND ALLOWABLES INCLUDE TEMPERATURE AND THERMAL STRESS CONSIDERATIONS

REF: NASA MDC 1975 STUDIES

TABLE III.- SUPERSONIC TRANSPORT TECHNOLOGY COMPARISON

	CONCORDE	MDC BASELINE (1976) *	IMPROVEMENT
SPEED	MACH 2.02	MACH 2.2	9% FASTER
RANGE	5834 km (3150 N MI)	8500 km (4590 N MI)	46% FARTHER
PASSENGERS	108	273	2.5 TIMES
ENGINE	TURBOJET WITH AFTERBURNER	MINI-BYPASS TURBOJET — DRY	
PROPULSION EFFICIENCY (M/SFC)	1.70	1.74	2% INCREASE
AERO EFFICIENCY (L/D)	7.6	9.6	26% INCREASE
STRUCTURAL WEIGHT EFFICIENCY	ADVANCED ALUMINUM 93°C (200°F)	70% TITANIUM + 30% ALUMINUM 116°C (240°F)	4% DECREASE
TAKEOFF AND LANDING NOISE	116 EPNdB AVERAGE	105 EPNdB AVERAGE	BETTER THAN FAR PART 36

* 1980 GO-AHEAD

TABLE IV.- ENGINE CONSIDERATIONS

	TECHNOLOGY READINESS	Δ OWE kg (LB)	Δ FUEL RESERVE[1] kg (LB)	Δ T. O. AND CLIMB[2] kg (LB)	Δ RANGE FACTOR	Δ DOC[3]
BASELINE WITH MECHANICAL SUPPRESSOR (MDC)	1975	REF	REF	REF	REF	REF
MINI-BYPASS WITH MECHANICAL SUPPRESSOR (GE)	1980	−5,910 (−13,000)	−4,545 (−10,000)	−3,182 (−7,000)	+1%	−5-1/2%
DOUBLE BYPASS VCE	1985	−5,000 (−11,000)	−5,910 (−13,000)	+5,000 (+11,000	+6%	−6-1/2%
VCE 112C	1985	(−8,636 (−19,000)	−6,364 (−14,000)	+455 (+1,000)	+2%	−2-1/2%
VSCE 502B	1985	−14,545 (−32,000)	−9,545 (−21,000)	+9,545 (+21,000)	+6%	−7%

(1) CORRECTED FOR SAME RANGE
(2) SAME TAKEOFF WEIGHT
(3) 1973 COSTS

TABLE V.- CONCLUSIONS

- 2.2 MACH DESIGN SEEMS OPTIMUM (VERSUS 2.4)
  - MORE CURRENT STATE OF THE ART (F-15, F-18, F-4, ETC)
  - SMALLER ENGINE
  - SMALLER AIRPLANE
  - LOWER DIRECT OPERATING COST
  - LOWER CAPITAL INVESTMENT
- PROGRAM TIMING DICTATES ENGINE SELECTION
  - CRUISE PERFORMANCE SAME
  - COMMUNITY NOISE
  - VCE ADVANTAGES MOSTLY IN LIGHTER WEIGHT
  - VCE REQUIRES 400°F INCREASE IN TURBINE TEMPERATURE (8 YEARS?)
- VALIDATION OF NOISE SUPPRESSION CRITICAL TO ENGINE SELECTION

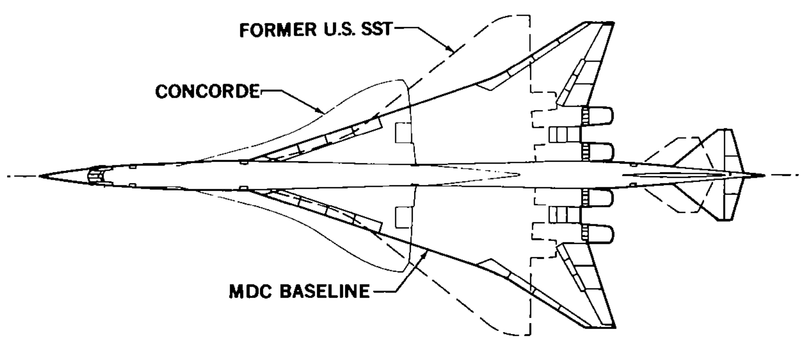

Figure 1.- McDonnell Douglas baseline.

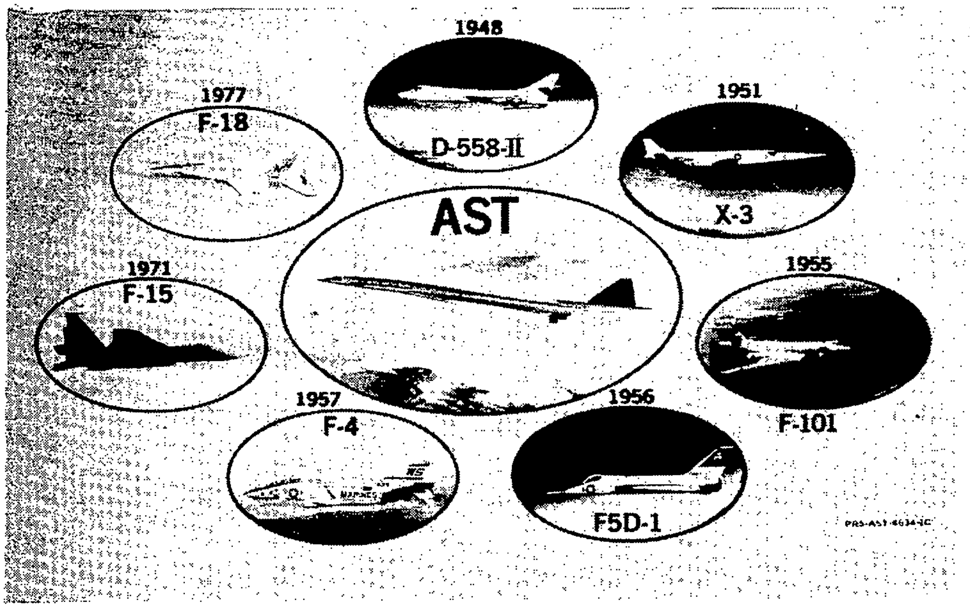

Figure 2.- MDC supersonic aircraft.

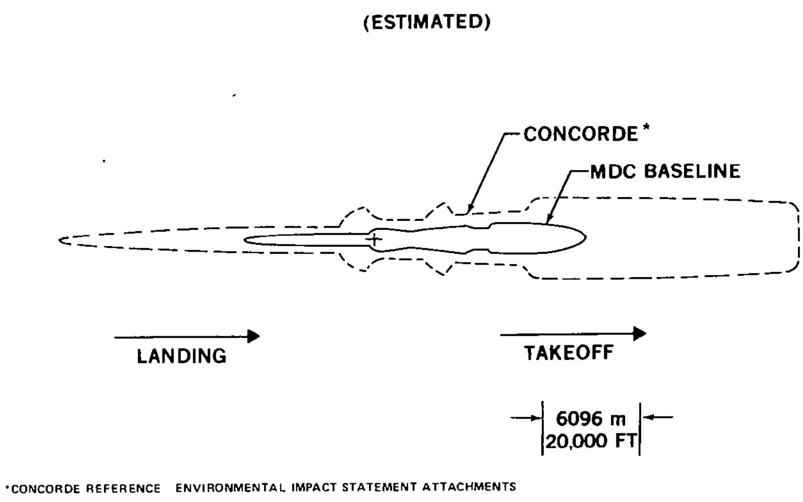

Figure 3.- Comparison of MDC baseline and
Concorde 100-EPNdB contours.

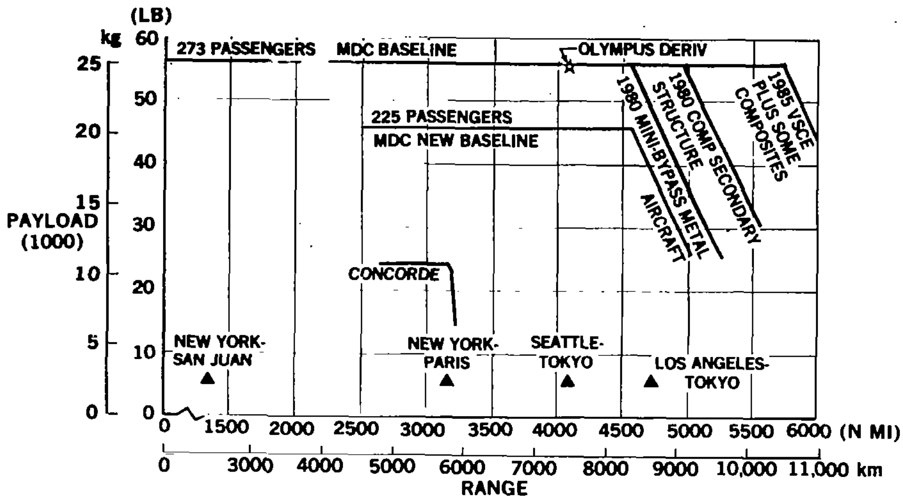

Figure 4.- Payload - range curves.

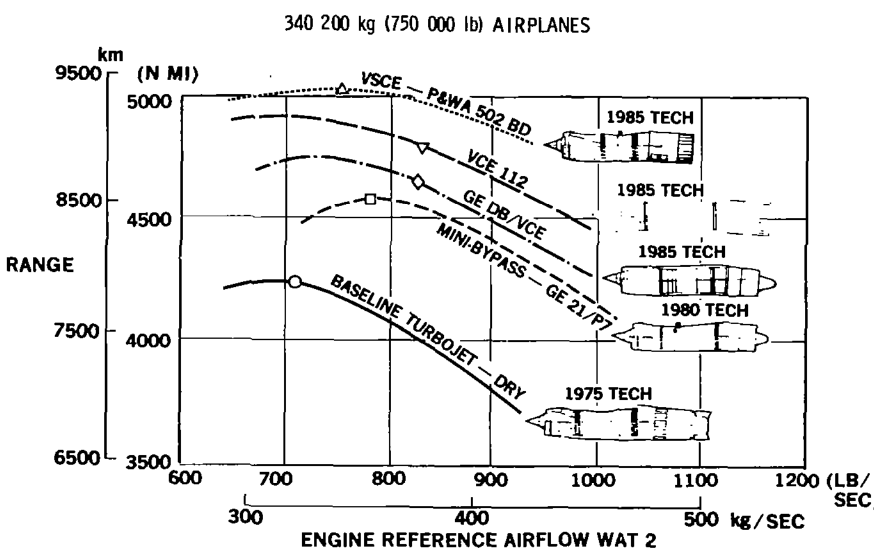

Figure 5.- Engine cycle selection.

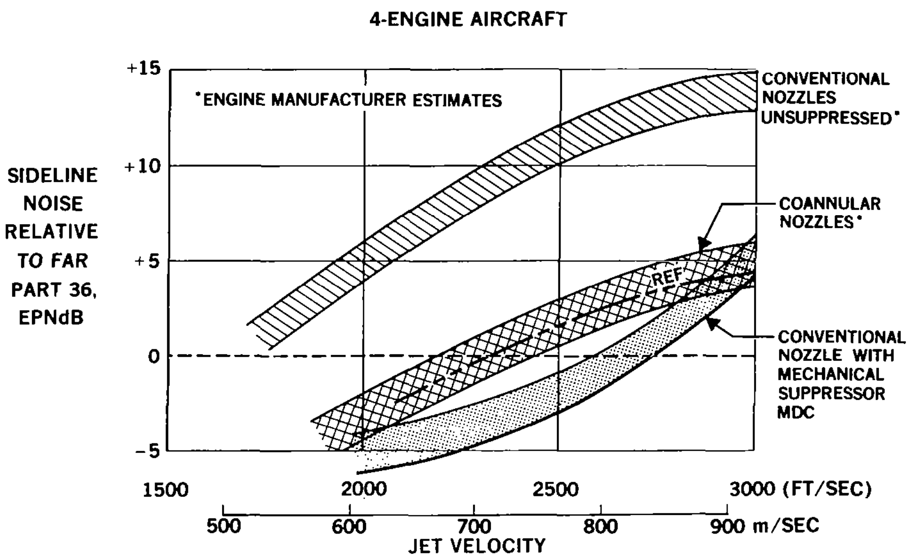

Figure 6.- Noise suppression comparisons.