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Comparison of Predicted Engine Core Noise with Current and Proposed Aircraft Noise Certification Requirements

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COMPARISON OF PREDICTED ENGINE CORE NOISE WITH CURRENT AND PROPOSED AIRCRAFT NOISE CERTIFICATION REQUIREMENTS

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Abstract

Predicted engine core noise levels are compared with measured total aircraft noise levels and with current and proposed federal noise certification requirements. Comparisons are made at the FAR-36 measuring stations and include consideration of both full and cutback power operation at takeoff. In general, core noise provides a barrier to achieving proposed EPA stage 5 noise levels for all types of aircraft. More specifically, core noise levels will limit further reductions in aircraft noise levels for current widebody commercial aircraft.

Introduction

The need for aircraft noise control can be summarized by the following actions being taken by the local and federal goverments and community groups: (1) air traffic is being effectively curtailed by night curfews at leading airports, (2) noisy aircraft are being assessed extra landing fees, thereby increasing their operating cost, (3) tax monies are being used to provide building insulation for structures near airports, thereby increasing costs to the public, (4) costs to the community for airport development are increased by land-control purchasing of extra land and housing based on noise contours, and (5) increasing numbers of anti-noise law suits are being filed and won by communities and individuals against the airport operators and airlines. Finally a loss of overseas markets can occur due to increasing sensitivity of the population to aircraft noise, if the noise is not reduced to acceptable and competitive levels.

Jet and fan noise are generally considered to be the primary propulsion noise sources for current aircraft that affect the community (fig. 1). As these noise sources are reduced, the core and airframe noise sources provide a barrier to further noise reduction. In particular, core noise is of concern for approach and cutback power settings (refs. 1 and 2).

In general, the main contributor to core noise is considered to be the combustor. In a combustor, the quantities responsible for producing noise are believed to be the fluctuating pressure and temperature. The levels of the fluctuations associated with the combustion process are related to the fuel droplet burning characteristics, combustor geometry, fuel nozzle design and number, etc. Modeling of core noise is still in its infancy. Several correlations of the spectral content and noise level been developed in recent years (refs. 3-5); however, none appear to be completely satisfactory.

In this paper, predicted core noise levels for subsonic CTOL aircraft engines are compared with aircraft noise levels required by present and proposed noise regulations in order to determine whether or not predicted core noise levels comply with these regulations and, if not, by how much the core noise levels must be reduced in order to comply. The predicted core noise levels are also compared with measured total aircraft noise levels obtained during certification flights.

Background

Core Noise

Core noise is considered to consist of the noise generated by the combustor, turbine, support struts, and internal surfaces (fig. 1). Combustor noise is produced by the unsteady combustion in turbine engines (ref. 6). That is, the combustion is unsteady with time varying heat release that in turn produces unsteady pressure fluctuations within the engine. These then propagate downstream from the combustor and give rise to the far-field noise. The sound field generated by the combustion process is partly attenuated by the turbine, depending on the number of stages, and to a lesser degree by the exhaust nozzle.

Reduction of the unsteady flow (turbulence) in a combustor in order to reduce the source noise may not be practical, since the combustion process depends on a high turbulence level for flame stability and burner performance optimization (ref. 6). Consequently, a performance penalty could be expected with reduced combustor noise.

Turbine noise sources are associated with a high frequency generating mechanism. Thus, tailpipe acoustic wall treatment could, in principle, suppress any objectionable turbine tones or noise levels. However, interactions between the turbine generated noise and the turbulent exhaust flow can result in increased overall noise levels (ref. 6).

Strut or obstruction noise is caused by the flow over a solid surface, resulting in a broadband noise source. In general the flow velocities are sufficiently low within the engine boundaries that this noise source is considered a second order source. When strut noise does become apparent, it is generally caused by cross flow or rotating flow over an internal support member.

Current and Proposed Government Subsonic CTOL Aircraft Noise Certification Requirements

The following sections summarize the present flight noise measuring stations and the current and proposed government certification requirements for subsonic CTOL aircraft.

Noise measuring stations. - The conventional FAA noise measuring stations (ref. 7) were used throughout this paper to ascertain the predicted core noise levels. The nominal measuring stations were:

Takeoff: 6486 m from start of roll
Approach: 1853 m from runway threshold
Sideline: 463 m (0.25 n.mi.) from runway centerline (flight path)

The aircraft altitude along the flight path at the takeoff measuring station generally varies with the climb rate of the aircraft, takeoff run, and single-engine out performance requirements. The following altitude ranges at the takeoff station were assumed herein in the prediction of takeoff core noise levels.

Aircraft type	Altitude at takeoff measuring station, m
4-engine commercial	213 - 305
3-engine commercial	305 - 488
2-engine commerical	488 - 670
General Aviation/Business	610 - 915

In the prediction of sideline core noise levels, an altitude of 229 m was assumed for all aircraft. Experience has shown sideline noise is maximized at this altitude.

A 10% reduction in altitude was assumed in the takeoff noise predictions for cutback conditions (85% of maximum fan speed). However, a minimum altitude of 213 m was maintained as a lower limit at the measuring station.

Current and proposed noise rules. - In figure 2, the current FAR-36 (1978) aircraft certification requirements (also called stage 3), in terms of the effective perceived noise level as a function of aircraft gross weight (solid line), are shown for the take-off, sideline, and approach measuring stations (ref. 7). Note that for the takeoff conditions (fig. 2 (a)), three lines are shown for the large commercial aircraft. These lines separate the aircraft by the number of engines, with those aircraft having four or more engines certified at higher noise levels than those having three or two (in descending order).

Also shown in figure 2 are the lower proposed EPA certification requirements (ref. 8), generally referred to as stages 4 and 5. Note that no noise rule differentiation is made with respect to the number of engines on an aircraft for these proposed stages. According to reference 8 the noise levels in EPNdB for the proposed EPA stage 4 noise rule is given by the following relationships:

Takeoff: $7 \log W + 56$
Sideline: $12 \log W + 29$
Approach: $7 \log W + 60$

Similary, the noise levels in EPNdB for the proposed EPA stage 5 noise rule is given by:

Takeoff: $7 \log W + 51$
Sideline: $12 \log W + 25$
Approach: $7 \log W + 57$

These relationships apply to aircraft with takeoff weights from 4530 to 453,000 kg.

Finally, to place the certification requirements in a more complete perspective, the original FAR-36 (1969) noise regulation is shown for comparison with the present and proposed noise rules. The original noise rule is commonly referred to as stage 2, with the unregulated phase referred to as stage 1.

Acoustic Data Base

As part of this study, measured total aircraft noise levels obtained during FAA certification flights are used for comparison with predicted core noise levels and both current and proposed aircraft noise certification requirements (ref. 8). A brief description of the aircraft/engine types included in this paper is given in the following table.

Aircraft		Engine	Number of engines	Nominal aircraft gross weight, kg
B-707	Narrow body	JT3D	4	115-149,600
DC-8	Narrow body	JT3D	4	145,059
B-727	Narrow body	JT8D	3	77,063
B-737	Narrow body	JT8D	2	52,131
DC-9	Narrow body	JT8D	2	49,864
B-747	Widebody	CF6, JT9D	4	317,316
DC-10	Widebody	JT9D	3	276,655
L1011	Widebody	RB211	3	194,923
Learstar 600	General Aviation	YF502*	2	14,506
Cessna 500	General Aviation	JT15D	2	5,213

*Similar to YF102 engine.

Core Engine Characteristics

The nominal full-power core engine characteristics are given in the following table (refs. 9-13):

Engine	Reference	Combustor to-ambient pressure ratio, $P_{3,m}/P_a$	Combustor temperature ratio, $T_{4,m}/T_{3,m}$	Maximum core flow w_m, kg/sec
CF6	9	28	1.96	113.3
RB211	10	28	1.96	95.7
JT9D	11	19	1.95	138.7
JT8D	--	14.5	1.77	65.7
YF102	12	12	2.20	18.1
JT15D	13	7.5	2.30	8.2

In order to provide input into the core noise prediction procedures for less than full-power operation, the preceding core engine parameters were examined for similarity. The combustor-to-ambient pressure ratio, P_3/P_a, and the core flow, w, values were plotted as a function of fan speed based on information available in the appropriate references. The variation of combustor pressure, P_3, and core flow, w, with fan speed is shown in figures 3 and 4, respectively. The solid curves shown in the figures represent mean values for the indicated parameters.

The JT8D core engine data shown in figures 3 and 4 and in the preceding table are unpublished but were made available to the authors for inclusion herein through the courtesy of Pratt and Whitney Aircraft. Similar core data trends with engine parameters were assumed for the JT3D used in the B-707 and DC-8 aircraft.

The variation of thrust with fan speed is shown in figure 5 based on data given in reference 9 for the CF6-50 engine. It is also stated in this reference that during approach, the engine is operated at a thrust level of 30% of maximum, with a corresponding fan speed of 65% of maximum. In the absence of other data, it is assumed herein that all the engines operate at this condition during approach. Furthermore, it is assumed that during cutback at takeoff, all the engines operate at a fan speed of 85% of maximum with a thrust level of 65% of maximum.

In general, the combustor temperature ratio, T_4/T_3, decreases very gradually with a reduction in fan speed over the range of fan speeds of interest. Consequently, herein it is assumed, for convenience, that for the 85% fan speed cutback condition, the T_4/T_3 ratio is the same as that at full power. For approach, on the basis of data in references 9-13, the T_4/T_3 ratio was taken to be 91.5% of that at full power.

Core Noise Prediction

Spectra

The spectral shape used for the prediction of core noise is given in reference 5 and identified as the "spectral envelope." This spectral envelope is a broader spectrum than that frequently ascribed to combustor noise only. The peak of the spectrum is assumed to be at 400 Hz statically and is assumed to be shifted in flight by a Doppler shift in frequency.

Overall Sound Pressure Levels

The predicted noise level statically is obtained from reference 3 and is given by:

$$OASPL_{120^\circ} = K - 20 \log R + 10 \log \left\{ w\left[(T_4 - T_3)(P_3/P_a)(T_a/T_3)\right]^2 \right\} \quad (1)$$

where K, in SI units, is assumed to be 46 for turbofan engines and 56 for turbojet engines. The value of R is the distance from the aircraft to the ground measurement location at each directivity angle. The variation of OASPL with directivity angle taken from reference 3, is given in figure 6; the values shown are dB values relative to the OASPL at $\theta = 120^\circ$, the angle generally considered to be the peak core noise angle.

In order to determine the flight effect from the static values of OASPL, the Doppler factor, $(1-M_o\cos\theta)^{-1}$ was used in reference 1. The resultant inflight OASPL is given as follows:

$$OASPL_F - OASPL_S = -40 \log (1 - M_o \cos \theta)$$

Perceived Noise Levels

Perceived noise levels (PNL) were computed for the appropriate engine power settings at the desired flight conditions. In order to obtain EPNL values, the PNL values, plotted as a function of time, were then integrated between the times when the PNL levels were 10 dB down from the peak PNL.

Predicted core noise levels were adjusted for the number of engines by adding 10 log N to the calculated single engine PNL and EPNL. An arbitrary 3 dB also was added to the calculated PNL and EPNL in order to account for ground reflections inherent in the measured data. In order to account for jet and airframe shielding effects, the following reductions in sideline noise levels were used:

Number of engines	Aircraft type	Nominal sideline Δ dB due to shielding
2	General Aviation, B-737, DC-9	-2
3	B-727, DC-10, L1011	-3
4	B-707, B-747, DC-8	-4

The following nominal flight speeds were assumed in the prediction procedures.

Operational mode	Aircraft type	Number of engines	Percent fan speed	Nominal flight speed, V_o, m/s
Takeoff	Commercial	2, 3	85,100	91.5
	Commercial	4	85,100	102
	General Aviation	All	85,100	82.3, 83.3
Approach	Commercial	All	65	83.8
	General Aviation	All	65	56.4

For the noise prediction calculations, the aircraft attitude during takeoff was assumed to be +15° relative to the flyover plane and 0° during approach.

Comparison of Measured Total Aircraft Noise With Current and Proposed Noise Results

The measured total aircraft noise levels for the aircraft included herein are shown as a function of gross weight in figure 7, together with the current and proposed noise certification requirements (refs. 7 and 8). The aircraft shown cover a range of gross weights for several of the aircraft and the data also indicates successful noise reduction efforts for some of the aircraft. In general, the higher noise levels for a specific aircraft type are for the initial production run while the lower noise levels are for more recently produced models. The later aircraft generally are equipped with engines quieted by the use of acoustic treatment in the engine inlet and/or exhaust ducts. It is also apparent that the total noise signatures of the newer aircraft equipped with engines having bypass ratio greater than 2 (B-747, DC-10, and L1011) all meet the FAA stage 3 noise certification requirements or are below the applicable rule.

Comparison of Core Noise Levels With Current and Proposed Aircraft Certification Requirements

In figure 8, the predicted core noise levels for the aircraft/engine configurations shown previously in figure 7 are compared with various federal noise regulations for the following operational conditions:

(1) Full power takeoff
(2) Cutback (part-power) takeoff
(3) Sideline and
(4) Approach

For each aircraft, predictions were made only for those power settings and operating conditions for which measured noise data were available.

The predicted core engine noise levels for takeoff are shown in figure 8 as vertical bars, with the top of each bare corresponding to the lowest altitude for the specific aircraft category and the bottom of each bar corresponding to the highest altitude for the specific aircraft category. Also shown for reference in the preceding figure are the measured total aircraft noise levels from figure 7.

Pertinent engine and flight parameters for these operational conditions were given in the sections entitled "Core Engine Characteristics" and "Core Noise Prediction."

Takeoff Noise

The comparisons of predicted takeoff core noise levels for full power and cutback (85% fan speed) with the various noise rules are shown in figures 8(a) and 8(b), respectively.

Full power. As shown in figure 8(a), the representative predicted core noise levels for small general aviation/business-type aircraft engines are near the proposed EPA stage 5 certification requirements. The predicted core noise levels and the proposed stage 5 noise rule are generally 5 dB below the measured total aircraft noise levels of current aircraft. However, in order to meet the proposed stage 5 noise rule, all noise sources must be included; consequently, the core noise must be reduced so that the summation of all noise sources will meet the proposed stage 5 noise rule with an adequate margin (generally 1 to 3 dB less than the rule). Current predicted core noise levels for these aircraft are sufficiently low enough so that core noise would not be a factor in determining whether these aircraft are able to meet the proposed EPA stage 4 noise levels.

For the large commercial aircraft, all the predicted core engine noise levels exceed the proposed EPA stage 5 noise. In fact, the predicted core engine noise levels for the high bypass engines used on the widebody L-1011, B-747, and DC-10 type aircraft exceed the proposed EPA stage 4 noise rule. The predicted core noise for these aircraft is very close to the measured total aircraft noise measured during noise certification flights. This indicates that core noise is providing a barrier to further noise reduction for widebody, large commercial aircraft.
Consequently, reductions of other noise sources (fan, jet, etc.) will not produce substantial total noise reductions for these aircraft types.

Cutback. - In order to reduce aircraft noise during takeoff, a cutback in engine power is often used after lift-off and prior to the takeoff measuring station. For the older narrowbody commercial aircraft (B-737, B-727, B-707 and DC-9), the predicted core noise levels with cutback are near or below the proposed EPA stage 5 level (fig. 8(b)). However, the predicted core noise level for the only widebody aircraft (B-747) shown in figure 8(b) is above the proposed EPA stage 4 noise curve and is 6 dB above the proposed EPA stage 5 level. It is expected that the other widebody aircraft (DC-10 and L1011) would show a similar trend; however, because no measured data are available, no predictions were made for these aircraft.

Sideline Noise

The predicted sideline core noise levels shown in figure 8(c) all are calculated for an altitude of 229 m, which experience has shown to give the maximum sideline noise.

The general aviation/business aircraft and narrowbody commercial aircraft predicted core noise levels all are below the proposed EPA stage 5 noise rule by from 2 to 6 dB. However, the predicted core noise levels for the widebody aircraft, as for the takeoff condition, are generally between the proposed EPA stage 4 and stage 5 noise rules. For the widebody aircraft (L1011 and DC-10), the predicted core noise levels are substantially the same as the measured total aircraft noise levels. Thus, core noise for widebody aircraft imposes a barrier to achieving the proposed EPA stage 5 sideline certification requirements.

Approach Noise

The predicted core noise for general aviation/business aircraft and for the older narrowbody aircraft (fig. 8(d)) are up to 8 dB below the proposed EPA stage 5 noise rule. However, the predicted engine core noise levels for the widebody aircraft are near the proposed EPA stage 5 approach noise rule levels. Consequently, core noise again imposes a barrier to achieving the proposed stage 5 approach noise certification requirements when other noise sources are included together with the necessary operations noise margin.

Discussion

The comparisons of the predicted core noise levels with current and proposed federal aircraft noise certification requirements shown in figure 8 indicate that, in general, core noise can provide a barrier to the proposed EPA stage 5 federal noise rules for all aircraft types from general aviation to widebody commercial aircraft. Even for proposed EPA stage 4 noise rules, core noise provides a barrier to achieving this rule for widebody commercial aircraft, with the most severe core noise problem occurring at the takeoff and sideline measuring stations. The question of meeting proposed future noise rules is compounded by the contribution of other noise sources (fan, jet, airframe, etc.) which when coupled with core noise provide a serious obstacle to meeting the proposed EPA stage 5 federal noise rule levels.

Because of the low frequency content of combustor noise, suppression of core noise by lining the tailpipe with reasonable liner thicknesses and weight appears difficult. Advances in bulk liners may offer a possible solution to the low frequency noise suppression problem. However, bulk suppressors could become contaminated with fuel, particularly at engine startup, and create a tailpipe fire hazard.

Reduction of core noise at its source, the combustor, currently is not well understood. Application of available data and analyses generally tend to result in radially larger, heavier, and less efficient combustors that require larger diameter nacelles to house the combustor thereby imposing a drag penalty on the aircraft. In order to provide a viable low core-noise engine, a much improved understanding of the noise generation processes in the core engine, particularly in the combustor, is required.

Examination of the predicted core noise levels compared with measured total aircraft noise indicates that the prediction procedure for core noise needs to be re-examined. The present procedure, while applicable to turbojets and low bypass fan engines, may not be completely suitable for high bypass engines such as the CF6 and RB211 engines. Evidence of this is that of the predicted takeoff core noise level at full power (fig. 8(a)) for the L1011 aircraft (RB211 engines) is greater than the measured total noise level. However, this difference may be erroneous since the exact power setting for the measured noise data was not available and the engines may not have been at the full power setting.

Conclusion

From the results obtained in this study it is obvious that core noise must be reduced in order to meet proposed future federal noise certification requirements, particularly when a certification "margin of safety" is necessary. Because of the interrelationships of core noise and engine performance, the low frequency content of core noise, and physical component limitations, this will be difficult to achieve and requires an extensive and intensive research effort on the part of government and industry.

Appendix - Symbols

c_a	ambient sonic velocity, m/sec
EPNL	effective perceived noise level, EPNdB
K	constant in internally-generated noise prediction, dB re 20 $\mu N/m^2$
M_0	flight Mach number, V_0/c_a, dimensionless
OASPL	overall sound pressure level, dB re 20 $\mu N/m^2$
P	total pressure, N/m^2
PNL	preceived noise level, PNdB
R	source-to-observer distance, m
T	total temperature, K
V_0	flight speed, m/sec
ω	mass flow rate, kg/sec
W	takeoff weight, kg
θ	directivity angle measured from inlet, deg

Subscripts:

a	ambient
F	flight
m	maximum
S	static
120°	evaluation at $\theta = 120°$
3	combustor inlet
4	combustor exit
θ	local directivity angle

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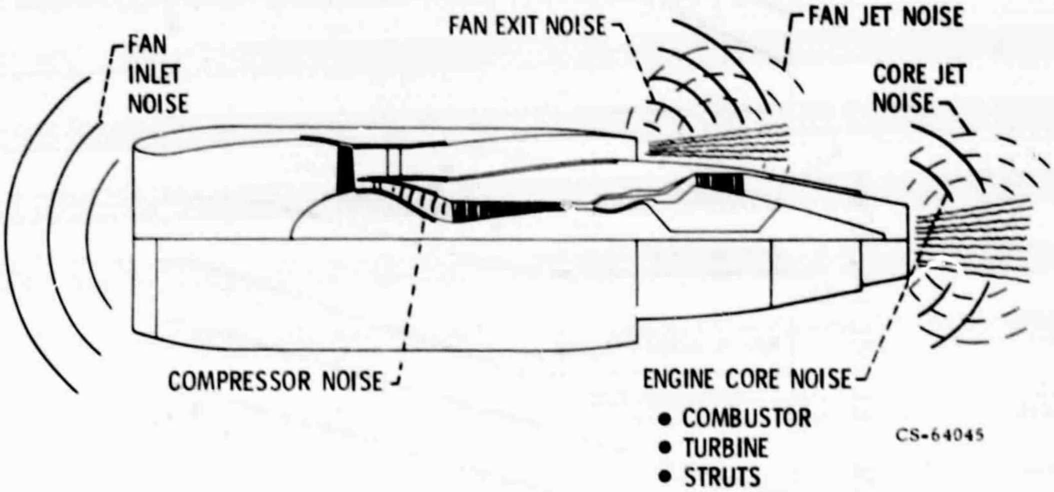


Figure 1. - Engine noise sources.

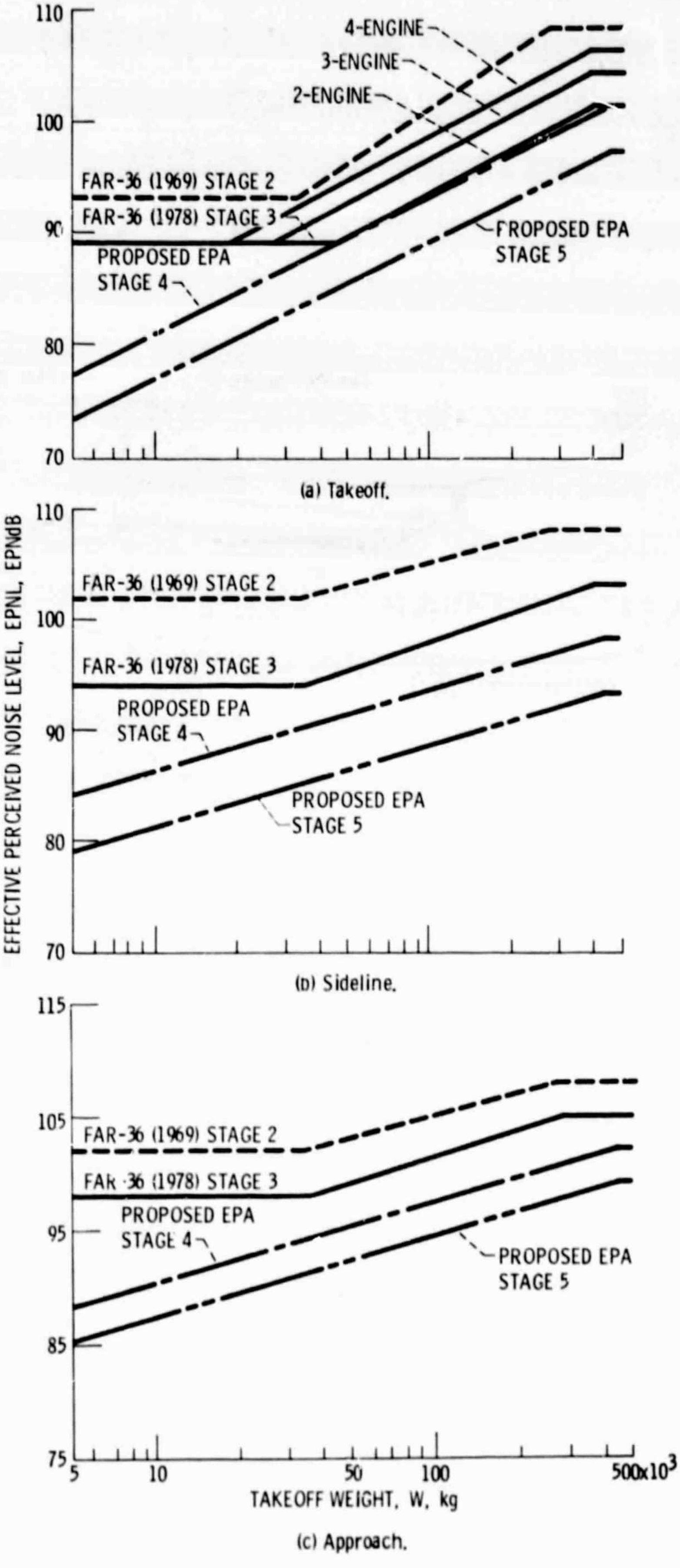


Figure 2. - Summary of past, current, and proposed FAA/EPA aircraft noise certification requirements.

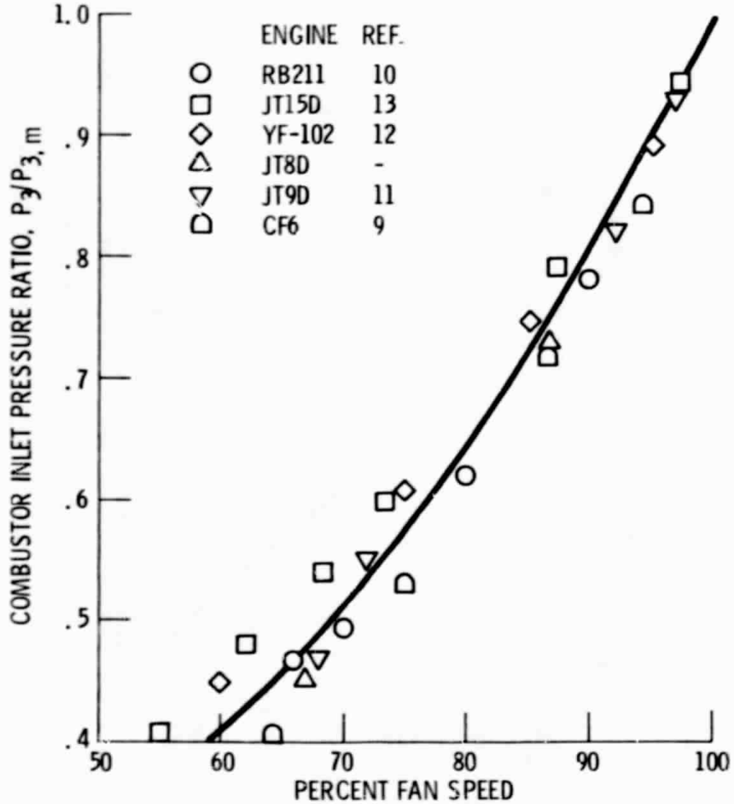


Figure 3. - Variation of combustor inlet pressure ratio with fan speed for turbofan engines.

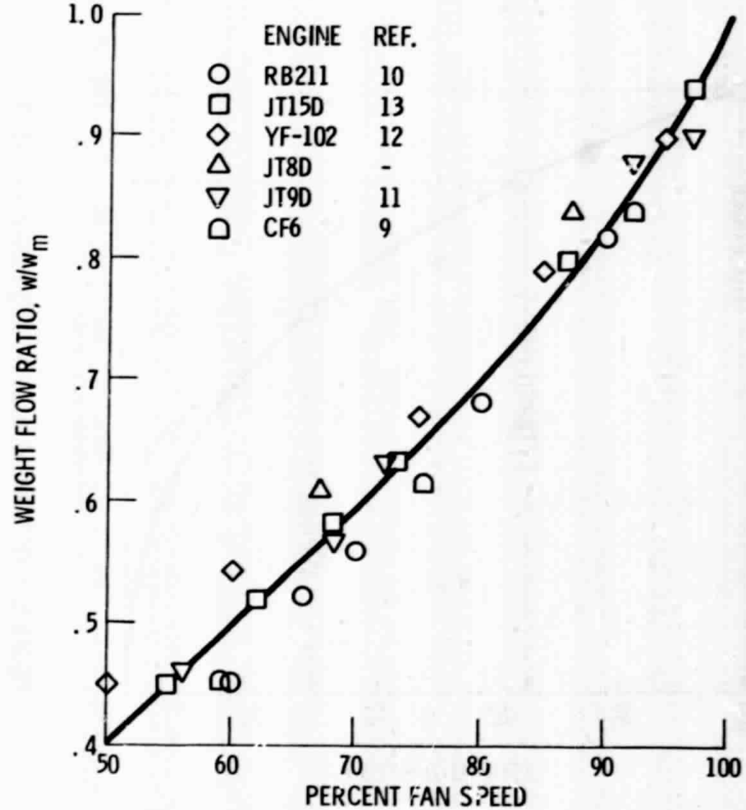


Figure 4. - Variation of weight flow ratio with fan speed for turbofan engines.

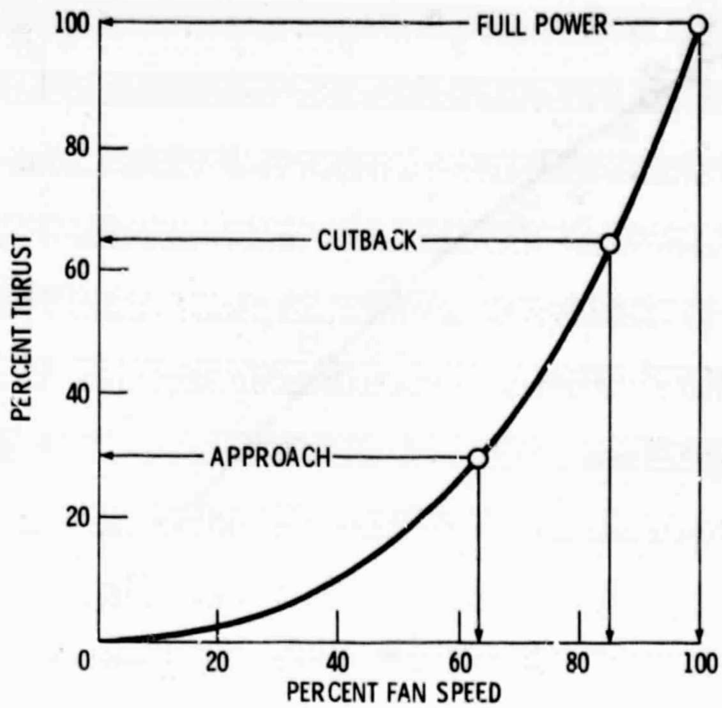


Figure 5. - Variation of thrust with fan speed for CF6-50 engine (ref. 9).

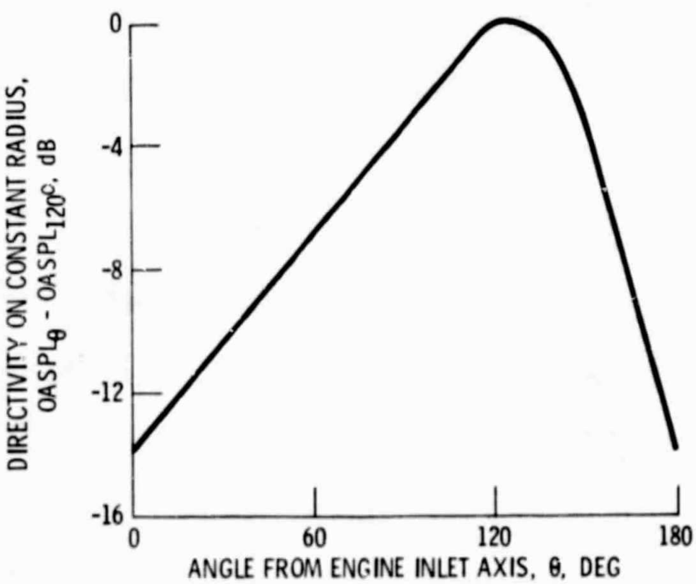
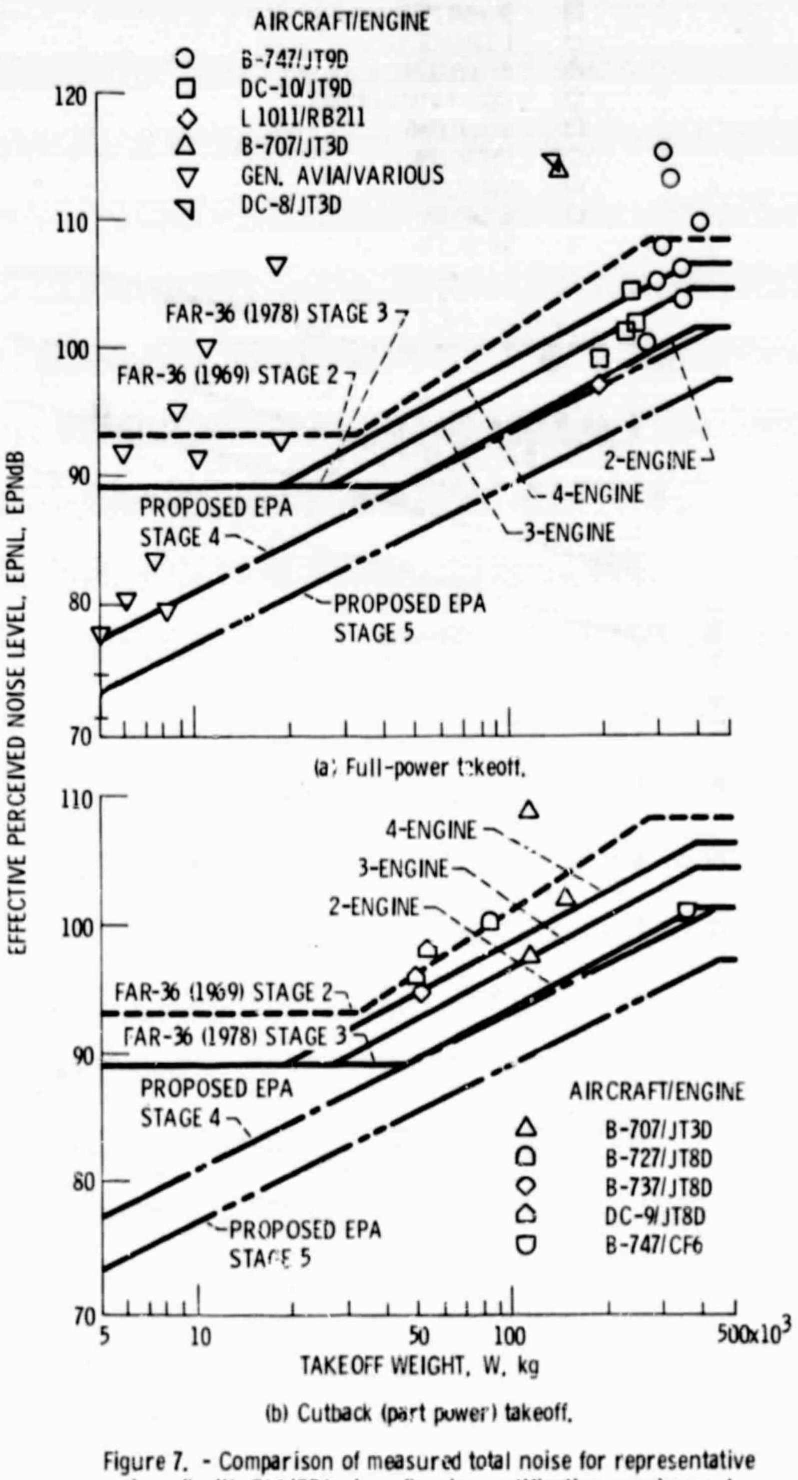


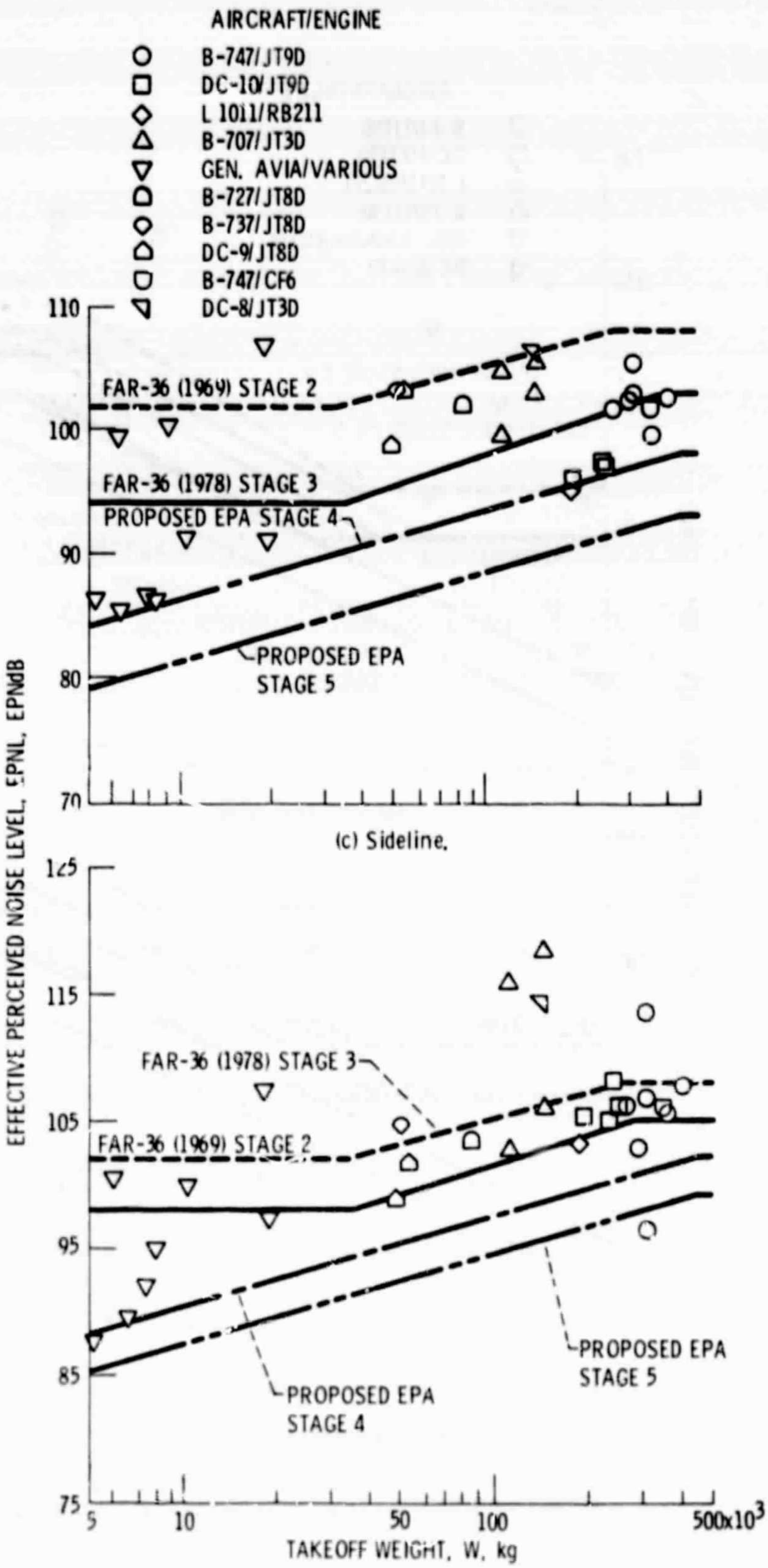
Figure 6. - Core noise static directivity (ref. 3).



(a) Full-power takeoff.

(b) Cutback (part power) takeoff.

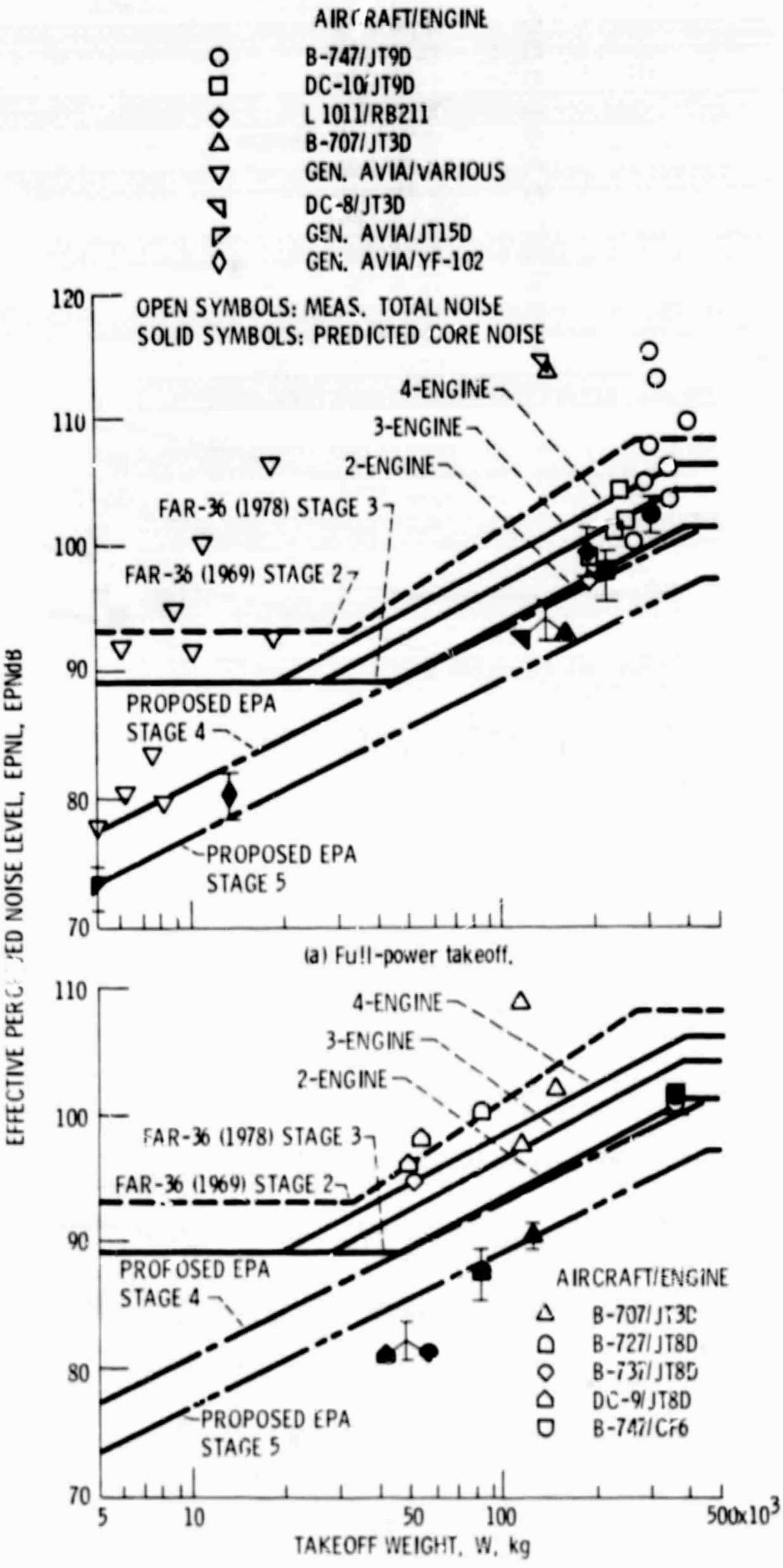
Figure 7. - Comparison of measured total noise for representative aircraft with FAA/EPA aircraft noise certification requirements.



(c) Sideline.

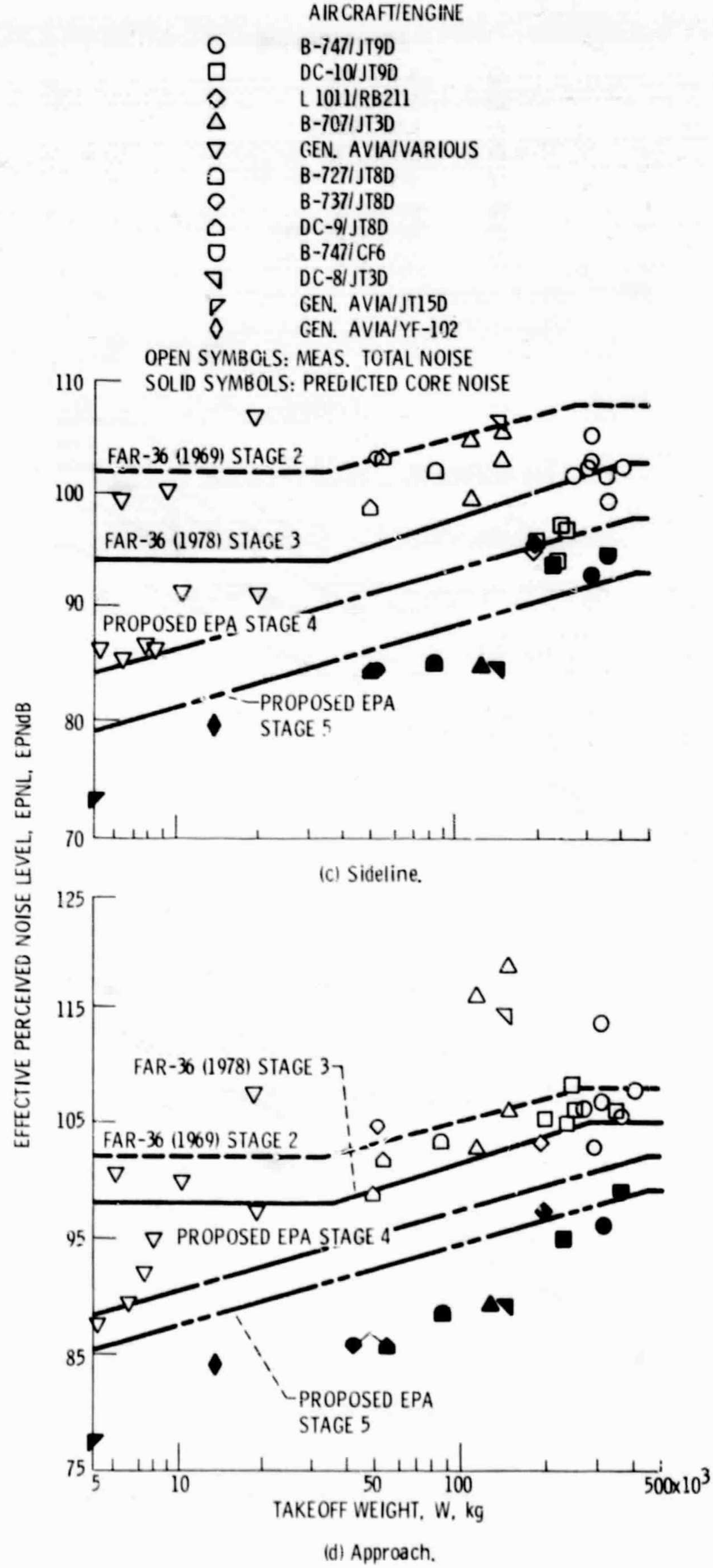
(d) Approach.

Figure 7. - Concluded.



(b) Cutback (part-power) takeoff.

Figure 8. - Comparison of predicted engine core noise level with measured total aircraft noise and FAA/EPA aircraft noise certification requirements.



(c) Sideline.

(d) Approach.

Figure 8. - Concluded.