Technical Support Report for Regulatory Action

Alternative Derivations of the Standards for T5 (Supersonic Transport) Class Gas Turbine Aircraft Engines

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Abstract

This document contains five alternative approaches to the development of standards for emissions from T5 class (supersonic transport) aircraft engines. Four of these approaches attempt to comply with EPA's earlier stated intention to set standards that "will represent the same level of emissions reduction from current supersonic aircraft, through application of the same types of combustor design technology, as will be required of subsonic aircraft,..." (Preamble to Aircraft Standards, FR Vol. 38, No. 136 19088). Three of these approaches are found faulty by not imposing on the T5 class "the same types of combustor design technology, as will be required of subsonic aircraft." The fourth approach satisfactorily imposes the implementation of a common, acceptable technology. A fifth approach is investigated which attempts to set standards which are compatible with the constraint of requiring compliance in 1979 or shortly thereafter.

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Introduction and Summary

At the time of promulgation of the aircraft emissions regulations, EPA established a separate class of engines to include only those engines that were intended for supersonic flight. This was done because of the realization that the special characteristics of supersonic flight required an engine design that would have a large fuel penalty at low speed which would, in turn, produce large emissions. EPA further stated its intent in the preamble to the aircraft regulations to set standards for the T5 class that "will represent the same level of emissions reduction from current supersonic aircraft, through application of the same types of combustor design technology, as will be required of subsonic aircraft, though the absolute hydrocarbon and carbon monoxide levels will be several times higher". (FR Vol. 38, No. 136, 19088)

This report first analyses four approaches which attempt to establish standards for both newly manufactured and newly certified engines which are based upon an equivalent technology between the two classes. One approach is found to satisfactorily comply with EPA's earlier stated intent to establish standards for the T5 class based upon the application of the same combustor technology in both the T5 and T2 classes.

A brief analysis of the leadtime necessary to implement this technology is included in the report as Appendix B. This analysis shows that the sophisticated technology that is characteristic of the solutions to the T2 class emissions problem cannot be incorporated into newly manufactured T5 class engines (in particular, the Olympus 593) until 1982. This delay of three years from the original 1979 deadline (for newly manufactured engines) in the Notice of Proposal Rulemaking (FR Vol. 39, No. 141, P26653, 1974) would severely compromise the usefulness of the standards if the total production of these aircraft does not exceed forty or fifty aircraft as most or all of the aircraft would have been built by the time the standards went into effect. In that event the newly manufactured engine standards, despite their stringency, do not accomplish any useful air quality gain.

The primary reason for this long leadtime is that without the benefit of a fixed goal (standards) the manufacturers have been directing their efforts for newly manufactured engines (NME) towards the development of a simple and inexpensive, but relatively effective fix (insofar as hydrocarbons and carbon monoxide are concerned). The technology involved in this does not in any way approach the sophistication of the best concepts being pursued for T2 class engines which are very effective in controlling all three gaseous pollutants, hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). As a consequence, the manufacturers would be forced to start all over again if the NME standard were based upon the equivalent technology criterion.

The report then examines an alternative approach which is to consider promulgating NME standards consistent with that development already being pursued by the manufacturers. Because this work has always been directed towards the T5 engine and because it involves simple modifications which result in easier optimization, simple tooling changes, and simple qualifications, it is likely to be available by 1979 or 1980. This would then result in air quality benefit despite the lessening of the standards for newly manufactured engines because they would affect some aircraft even if the total production run were as few as forty or fifty. The standards for newly certified engines (NCE) would be those found to be consistent with the equivalent technology criterion and would be therefore the most rigorous that can be satisfied through adoption of the best technology expected for those engines. This is the approach that is recommended.

Discussion

I. Issue of Equivalent Technology

The T5 class (supersonic commercial transport aircraft) was created in recognition of the special characteristics of supersonic flight which create significant problems in the development of an engine for such aircraft which is both economically acceptable and clean enough to meet the T2 class (subsonic commercial transport aircraft) emissions standards as promulgated in 40 CFR part 87.

The special characteristics which give rise to the emissions problem of supersonic transports (SST) can be seen in the following discussion. The standard used to describe aircraft engine emissions may be interpreted as comprised of two multiplicative terms, one representative of the combustor performance (in terms of mass of pollutant per mass of fuel), and the other descriptive of the fuel consumption efficiency of the engine (in terms of mass of fuel per level of useful output), both terms being weighted over the prescribed landing-takeoff cycle:

standard = (combustor performance) x (fuel consumption performance)

or

$$\text{standard} = \frac{\text{mass of pollutant}}{\text{mass of fuel}} \times \frac{\text{mass of fuel}}{\text{useful output}}$$

= (Emissions Index or "EI") x (Specific Fuel Consumption or "SFC")

or, simply,

$$\text{standard} = \frac{\text{mass of pollutant}}{\text{useful output}} \text{ (called "EPAP")}$$

Compliance with the standard can thus be approached in two ways, (1) by improvement of the combustor performance, and (2) by improvement of the fuel consumption efficiency at lower speeds. The latter approach is accomplished principally by modification of the thermodynamic cycle of the engine, that is, modification of the compressor pressure ratio and the fan bypass ratio, and in the T5 class, especially, the degree of afterburning.

However, high speed flight (supersonic, especially) conditions require additional considerations for optimal fuel economy. The optimum thermodynamic cycle for an engine is a function of the aircraft's cruise speed, its aerodynamic efficiency, and its mission (design range) such that the cycles that promote high speed fuel efficiency are generally at odds with those that promote low speed fuel efficiency. The following brief discussion will expand upon this. The overall efficiency of the engine (the ratio of the useful power to the rate of energy input into the engine through the fuel, can be written as[1]

$$\eta_o = \frac{(U_{ex} - U_\infty)\, U_\infty}{fQ_R} \qquad \text{or} \qquad \frac{\text{Thrust x flight velocity}}{\text{heat release rate}}$$

where

U_{ex} = average velocity of the exhaust gases

U_∞ = flight speed

fQ_R = heat release rate of the fuel (a constant at the design point of the engine)

This efficiency is zero at a zero flight speed (no useful power is being developed), zero again at $U_\infty = U_{ex}$ (thrust has gone to zero), and a maximum at $U_\infty = U_{ex}/2$. At high subsonic speeds, optimum efficiency is achieved through the use of a large fan which produces a low exhaust velocity (U_{ex}). Further, at low subsonic speeds, a propeller is used (turboprop) which produces a very low exhaust velocity thereby keeping the efficiency high. For supersonic speeds, on the otherhand, the U_{ex} produced by a large fan is too low compared to the flight speed (U_∞) to give high efficiency. In fact, if $U_\infty \rightarrow U_{ex}$, the thrust of the engine goes to zero because, roughly,

$$\text{Thrust} \simeq \dot{M}a\ (U_{ex} - U_\infty)$$

($\dot{M}a$ = air mass flow rate through engine)

This, of course, is the reason that the efficiency goes to zero also at this point ($U_\infty = U_{ex}$). It is therefore imperative that at supersonic speeds, the exhaust velocity (U_{ex}) be increased. This is done by reducing

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[1] See, e.g., "Mechanics and Thermodynamics of Propulsion," by P.G. Hill and C. R. Peterson, Addison-Wesley, 1965, pp. 143-145.

the fan size (perhaps to zero, a pure turbojet) and relying instead upon the hot core flow for thrust where U_{ex} is much greater. This is the primary reason for reducing or eliminating a fan for supersonic flight. Secondarily, the size and weight of the fan offer large drag penalties at flight speeds in excess of Mach 1.

The second significant thermodynamic problem at high speed is that as the ram compression heats the air in addition to the compressor heating, the point would be reached that the air entering the combustor is already at the maximum allowable turbine inlet temperature, thereby permitting no fuel to be added. It is necessary, therefore, to reduce the amount of compression from the compressor to reduce the combustor inlet temperature enough to permit proper energy addition from the fuel.

The disparity between the high and low speed design conditions becomes greater as the spread between the high speed and the low speed widens: For supersonic flight the loss of high speed efficiency with the use of a subsonic cycle (high pressure ratio, high bypass ratio) is of such a magnitude (at best, a JT9D engine operating at Mach 2 is only 56% as efficient in terms of specific fuel consumption as an Olympus 593 engine designed specifically for Mach 2; this large and heavy engine would also cause aerodynamic problems) that there is little room for compromise and, the high speed cruise condition wherein the bulk of the fuel is consumed essentially dictates the engine design. On the other hand, the use of a good supersonic cycle (moderate pressure ratio, low or no bypass ratio) performs with mediocre efficiency at low subsonic speeds (at take-off, with afterburner, the efficiency of the SST is one-fourth the efficiency of a B-747) as encountered at or near the airport. This high fuel consumption contributes directly to the high emissions levels of this aircraft. For this reason there is considerable advantage to the variable cycle engine concept which is at this time only in early stages of exploration.

Without the existence in the near future of a variable cycle engine (VCE), a SST engine is necessarily constrained to optimize its engine cycle at or very near its cruise condition. Improvements in its emissions then can be realized only through improvements in its combustor emissions performance. In view of the low speed fuel consumption penalty experienced by SST engines (when compared with subsonic engines), such improvements in the combustor performance would have to be much greater than that necessary for subsonic engines if both supersonic and subsonic engines had to meet the same standard. This would imply the use of a much more sophisticated control technology on the part of the SST engine.

There is, however, one critical factor which weighs against the imposition of too sophisticated an emission control technology for the T5 class: There is a practical limit to which one can go in utilizing advanced technology in an existing system (speaking now of the standards for newly manufactured engines). Radical innovations may not mate well with the existing system, causing degradation in performance or major renovation of large parts of the engine. Such radical advances in emissions technology belong more reasonably in totally new engines or engines for which major features are being redesigned. This is the intent behind the separate standards for newly certified engines.

The philosophy first considered is to determine the SST standards based upon the application of a common, available and acceptable combustion system technology applicable to all large engines. This satisfies the requirement of the technical limitations imposed by the systems. This philosophy is also expounded in the preamble to the T5 class NPRM:

> "These standards will represent the same level of emissions reduction from current supersonic aircraft, though application of the same types of combustor design technology, as will be required of subsonic aircraft, though the absolute hydrocarbon and carbon monoxide levels will be several times higher ...."

There remains then, the question of what standards for the T5 class best represent the "application of the same types of combustor design technology." There are four readily identifiable strategies for computing standards for the T5 which are based on some sense of equivalency. These will be discussed individually below.

Alternative I

Set T5 standards identical to the T2 standards.

This approach assumes the argument that the two types of aircraft, commercial subsonic and supersonic, perform the same function, are directly competitive, and hence ought to meet the same standards. Referring to 40 CFR part 87.21 (d) and (e), the standards are then:

EPAP $\frac{\text{mass of pollutant}}{\text{useful out}}$ *

	HC	CO	NOx
NME**	0.8	4.3	3.0
NCE***	0.4	3.0	3.0

* pounds of pollutant per 1000 pounds-thrust x hours per LTO cycle LTO = Landing-Takeoff)

** Newly Manufactured Engines - date of implementation discussed in Appendix B.

*** Newly Certified Engines - date of implementation discussed in Appendix B.

TABLE I

However, this approach totally fails to recognize the existence of the T5 class. The issue of fuel consumption and combustor performance differences between the T2 and T5 classes are ignored entirely. It is therefore, technically unacceptable from the start.

Alternative II

- Require the same Emission Indices (lbs. of pollutant/1000 lbs. of fuel) for supersonic engine combustors as are expected to be found in future subsonic engines and set the T5 standards accordingly, accounting for the increased fuel consumption characteristics of the SST type engines that result from the requisite thermodynamic cycle. Add after-burner contribution separately.

By this approach, for the main burner,

$$\overline{EI(T5)} = \overline{EI(T2)}$$

The bars over the values indicate values averaged over the LTO cycle. Then, as the standard can be written as

$$EPAP = \overline{EI} \times \overline{SFC},$$

the T5 standards would be

$$EPAP(T5) = EPAP(T2) \times \frac{\overline{EI(T5)}}{\overline{EI(T2)}} \times \frac{\overline{SFC(T5)}}{\overline{SFC(T2)}}$$

or, because of the equality indicated by equation (1),

$$EPAP\ (T5) = EPAP\ (T2) \times \frac{\overline{SFC(T5)}}{\overline{SFC(T2)}}$$

The LTO weighted SFC will differ from engine to engine, being a function of individual engine characteristics (e.g., idle speed) and the thermodynamic cycle of the engine (i.e., pressure ratio and bypass ratio), and can be represented approximately by an empirical expression valid for a large range of turbine engines (offered by Rolls Royce),

$$\overline{SFC}_{\text{(LTO cycle)}} = \frac{1}{0.47 + 0.039 \times PR + 0.19 \times BR} \qquad (2)$$

where

BR = Bypass ratio, PR = Pressure ratio.

Considering the JT9D as representative of modern T2 class engines, having BR = 5.2 and PR = 22.3, and taking the Olympus 593 as the T5 class engine, having BR = 0 (a pure turbojet) and PR = 15, the T5 SFC will be 2.20 times the value of the T2 SFC. It is worth reiterating here the discussion at the beginning that the cycle differences between the T5 class which lead to this SFC problem are fundamental to the design goals of the two classes: One engine (T2) is optimized for subsonic cruise, the other (T5) supersonic cruise. If the EPAP value for each of the three gaseous pollutants of the T2 standard is then multiplied by 2.20, a T5 standard results. That is, the T2 1979 and

1981 standards are

EPAP (T2)

	HC	CO	NOx
1979 (NME)	0.8	4.3	3.0
1981 (NCE)	0.4	3.0	3.0

which when multiplied by 2.20 gives for the T5 class:

EPAP (T5) (less afterburner contribution)

	HC	CO	NOx
NME*	1.8	9.5	6.6
NCE*	0.9	6.6	6.6

*Date of implementation discussed in Appendix B.

TABLE II

However, this calculation has not yet considered the contribution of the afterburner to the emissions. The afterburner is separate from the functioning of the main combustor and therefore must be considered separately.

A certain degree of afterburner (20%) has been assumed for both the 1979 and 1981 standards which is based upon the present Olympus/Concorde System. Without considerable advances in the propulsion system (e.g., variable cycle engine) or in the airframe (e.g., swing wing) such afterburning is reasonable even for the newly certificated engine standards. SNECMA has indicated that the present Olympus 593 afterburner has a combustion efficiency of 98% and that expected improvements should bring this to 99.0% which would be applicable to the newly manufactured engine (NME) standards. A combustion efficiency of 99.5% is believed possible for newly certified engines (NCE) although there has been little technical development for an efficiency above 99.0% at this point. A combustion efficiency less than 100% results in a mixture of hydrocarbons (HC) and carbon monoxide (CO) in the exhaust. The afterburner apparently does not contribute to the formation of NOx because of the leaner burning (less elevated temperatures), lower pressures, and shorter residence times.

Figure 1 (at the back) shows that for any given combustion efficiency a wide range of HC/CO ratios can exist. However, as the data show, there is a reasonably well defined mean. As the entrance conditions to an afterburner are quite hot and partially depleted of oxygen, the CO/HC ratio will be higher than that for a main burner at the same combustion efficiency. The afterburner points used in this analysis and shown on figure 1 reflect this fact. Rolls Royce's own recommendation assumed a

CO/HC ratio of 9.2 (see Alternative V). For afterburners in newly manufactured engines (η_c = 99.0%), a CO/HC ratio of 9.0 was chosen as being most probable. From the circular point on the figure on the η_c = 99.0% line the emission indices are seen to be 3.4 and 30.4 for HC and CO respectively (CO/HC = 9.0) in lbs. per 1000 lbs. of fuel for the afterburner. For the Olympus 593, the afterburner fuel flow rate is 22,000 lbs. per hour for a duration of 1.2 minutes. The total emissions from the afterburner are then

$$EI \times \dot{M}_{fuel} \times time$$

or

$$\text{Mass of HC} = 3.4 \times \frac{22,000}{1,000} \times \frac{1.2}{60}$$

$$= 1.50 \text{ lbs.}$$

and

$$\text{Mass of CO} = 30.4 \times \frac{22,000}{1,000} \times \frac{1.2}{60}$$

$$= 13.4 \text{ lbs.}$$

The total impulse of the engine over the LTO cycle (that is, the useful output referred to in the denominator of the expression for the standard) for the Olympus 593 is 3002 lb-thrust x hours. (Note: the total impulse of the engine, not simply the impulse due to the afterburner operation must be used here so that these terms and the EPAP values found in Table II can be added). Dividing the mass of each pollutant by the total impulse x 10^{-3} gives the afterburner contribution to the EPAP. The same procedure is followed for NCE but with an afterburner combustion efficiency of 99.5% and a CO/HC ratio of 15. The afterburner contribution is:

Afterburner ΔEPAP (NME and NCE)

	HC	CO	NOx
NME	0.5	4.5	0
NCE	0.2	2.5	0

TABLE III

These ΔEPAP values for the afterburner must be added to the EPAP values calculated for the main burner only given in table II. The T5 class standards, then, by this procedure are

EPAP (T5)

	HC	CO	NOx
NME	2.3	14.0	6.6
NCE	1.1	9.1	6.6

TABLE IV

This method, however, must also be rejected as the supposition of technological equivalence of combustor performance between subsonic and supersonic engines cannot be defended in spite of the equating of the Emission Indices. Emission Indices are generally considered to be descriptive of the sophistication of the emission control technique employed on a particular engine. However, the simple comparison of the Emissions Indices found in two different systems is not adequate to make a genuine comparison of the relative merits of the different technologies. The reason for this is that operating conditions as well as technical design affect the pollutant production. If two identical combustors (thereby eliminating technology and size effects) are run at two different operating conditions as reflected primarily by the combustor inlet pressure for the same fuel-air ratio (to simulate the same engine power setting), that combustor which is run at the higher pressure will exhibit lower HC and CO Emission Indicies, but higher NOx Emission Indices. The reason for this is that at higher inlet pressures (and the correspondingly higher inlet temperatures): (1) the greater temperature and pressure increase the chemical reaction rate of hydrocarbon combustion, (2) the greater temperature leads to better fuel evaporation, and (3) the greater pressure drop across the combustor leads to better mixing. These factors reduce the pollutants that result from inefficient combustion, namely HC and CO. On the other hand, the greater temperature and pressure increase that reaction rate of NOx which leads to greater NOx formation.

In the case at hand, therefore, it may be expected that despite the application of equivalent combustor technology, the lower inlet pressure of the SST engine (and the correspondingly lower inlet temperature) would make it more difficult to achieve a combustion efficiency at each power setting comparable to that found in a typical modern high pressure ratio subsonic turbofan (e.g., the Olympus 593 has a pressure ratio of 15, the JT9D, 22). A lower combustion efficiency would mean higher levels of HC and CO (as expressed by the Emissions Index) in the Olympus 593. However, the Olympus 593 has a fairly lengthy combustor residence time at low power compared with other engines. This would allow it to better consume the HC and CO left as a result of the lower combustor pressure. While combustor size (and hence residence time) may be considered an emissions control technique for newly certified engines, it cannot be so construed for newly manufactured engines as the geometrics of such engines are fairly well fixed. Hence, on one hand, the SST has an operating cycle (pressure ratio) that lends itself to poor HC and CO emissions, but on the other hand, its combustor size is favorable to good HC and CO emissions. Requiring equal Emissions Indices for HC and CO between the T2 and the T5 class will not in itself result in equivalent technology.

As far as NOx emissions are concerned, the lower pressure ratio of the engine will contribute to low NOx production and the imposition of equal Emissions Indices for NOx between the two classes is patently favorable to the SST class.

Alternative III

Apply the percentage reductions to the T5 baseline EPAPs that have been demonstrated or are expected to be demonstrated in the near future in other engine applications.

The following emissions reductions have been demonstrated or are expected to be demonstrated shortly in typical modern subsonic engines (newly manufactured engines):

EPAP (T2 NME)

Production	HC	CO	NOx
JT9D	4.8	13.8	5.7
CF6-6	3.4	10.0	7.2
CF6-50	4.3	10.8	7.7
Average	4.2	11.5	6.9
Expected (No water)	0.8	4.3	3.8
% Reduction	80%	60%	55%

These reductions, if not already demonstrated, are expected on the basis of development work, both in-house and public, which is now nearing completion. Typical of this work is the NASA Experimental Clean Combustor Program.

For newly certified engines, the following reductions are anticipated:

EPAP (T2 NCE)

	HC	CO	NOx
Average Production	4.2	11.5	6.9
Expected	0.4	3.0	3.8
% Reduction	90%	75%	55%

Support for the anticipated reductions for newly certified engines comes largely from EPA Report No. 1168-1, Assessment of Aircraft Emission Control Technology and from the present subsonic engine standards for newly certified engines which reflect these anticipated reductions.

Applying these percentage reductions to the baseline Olympus 593, taken as representative of the T5 class engines, gives

EPAP(T5)

	HC	CO	NOx
Baseline (main burner only)	15.2	57.1	8.8
% reduction	80%	60%	55%
NME standard	3.4	22.8	4.0
% reduction	90%	75%	55%
NCE	1.5	14.3	4.0

TABLE V

As with Method 2, however, the afterburner contribution which is not present in the T2 class must be considered separately. This contribution is given in Table III and is discussed in detail in Section 2. Adding the EPAP values from that table to Table V, gives

EPAP(T5)

	HC	CO	NOx
NME*	3.9	27.3	4.0
NCE*	1.7	16.8	4.0

*Date of implementation discussed in Appendix B.

TABLE VI

This method should be rejected, however, because implicit in this procedure is the assumption that the two baselines (subsonic and supersonic) represent equal emissions technology levels. If this is not true and the baseline of either group is founded upon a combustion system technology different from that represented by the other group's baseline, then simple application of percentage reductions would preserve that inequality of technology in the standards set for the T5 class based upon that procedure.

Furthermore, there is no assurance that changes in emission technology are adequately represented by percentage reductions in emissions. That is, if a certain advance in technology yields some percentage reduction in emissions from a representative engine of one group (e.g., subsonic), there is no assurance that this technology, if applied in a representative engine of another class which has markedly different operating environment (e.g., supersonic), will yield the same percentage reduction. Standards based upon this procedure may then implicitly generate a condition of inequality of technical demands on the combustors between subsonic and supersonic engines.

Alternative IV

Identify the best demonstrated or anticipated emissions control technology that would be applicable to the T5 class, determine its emissions performance (i.e., its Emission Indices) when operating in an SST engine type environment (i.e., inlet pressure, air loading parameter, etc.), account for the increased fuel consumption per unit output (specific fuel consumption) due to the SST type thermodynamic cycle (i.e., pressure ratio, bypass ratio) and set the standards accordingly. Add afterburner contribution separately.

This description of the procedure warrants further explanation. The four steps are, in order,

(a) Identify the best emissions control technology, demonstrated or anticipated in any engine (as measured by the Emissions Indices of the combustor subject to the particular operating conditions of the engine), which is applicable to the T5 class.

(b) Determine the emissions performance of that technology concept subject to the particular operating conditions of the representative T5 engine (as measured by the Emissions Indices).

(c) Determine the fuel consumption characteristic of the representative SST engine.

(d) Compute the emissions performance of the basic T5 engine using (b) and (c) (as measured by the EPAP). Add the afterburner contribution separately.

Each step is relatively straightforward and is discussed in detail below.

(a) Identify the best emissions control technology (demonstrated or anticipated).

<u>HC and CO</u>

There is considerable work being done now in support of low emissions in all the classifications of engines for which regulations exist. The work involving the large, commercial subsonic engines is most relevant to the T5 class as the combustor technology is generally transferable. The major efforts here are those programs being conducted by the manufacturers and through the NASA Experimental Clean Combustor Program.

To identify the best available technology, it is insufficient merely to specify the Emissions Indices experienced by test hardware. Emissions Indices for all pollutants are functions not only of the technology incoporated into the design, but also of the operating conditions. This point was alluded to in earlier discussions of the first and second method of calculation and must be analysed further here.

Emissions of hydrocarbons and CO reflect incomplete combustion generally at low power, an off design point. This incomplete combustion occurs because the operating conditions of the combustor (temperature, pressure, and residence time) are not conducive to good combustion. The inlet temperature is too low and the air flow rate too low for good fuel preparation (atomization and evaporation), the pressure drop across the combustor is too low for good turbulent mixing of the fuel and air, and the combustor temperature and pressure are too low for rapid chemical reaction (especially $CO \rightarrow CO_2$). The ability of the combustor to perform well can be described by one of several so-called "air-loading parameters", all of which are empirical and equally good here. The one chosen for use here was offered by Rolls-Royce Corporation in its response to the T5 class NPRM. It is

$$\Omega \text{ (air loading parameter)} = \frac{\dot{M}_a}{P^{1.8}\, V\, f(T)}$$

where

$$f(T) = 10^{(0.00143T)}/3.72$$
V = combustor volume (ft^3)
P = combustor pressure (atm.)
$\dot{M}_a$ = air mass flow rate (lbs/sec)
T = combustion inlet temperature ([K)

Smaller values of Ω are more favorable to good combustion and hence lower emissions of HC and CO. The value of Ω experienced may depend on several factors: (1) power setting (the higher the power setting, the lower the air loading parameter), (2) engine design (a higher pressure ratio engine will have a proportionally lower Ω at all power settings), and (3) combustor design (a larger combustor volume would have a lower air loading parameter). Except for the secondary effect of ambient temperature, the combustor inlet temperature is directly related to the compressor pressure ratio and hence is not an independent variable.

The emissions performance of a combustor can be correlated with the value of the air loading parameter (with some scatter), as shown in Figure 2. In the figure, the emissions performance is measured by the combustion inefficiency ($1-\eta$) which is computable from the Emissions Indices:

$$1-\eta = [\ 0.875\ EI(HC) + .2322\ EI(CO)] \times 10^{-3}$$

where EI(HC) is in terms of CH_4. This correlation holds true for all engines of comparable emissions technology and thus it is a measure of that technology.

While the correlation line of Figure 2 shows the emissions performance for the present day technology, a new correlation line is necessary to measure the performance of an advanced emissions technology. Such a line would be below the present technology line and is shown schematically below:

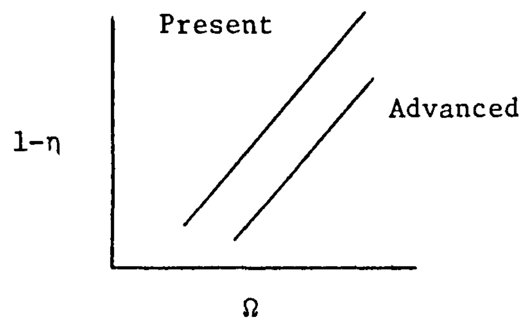
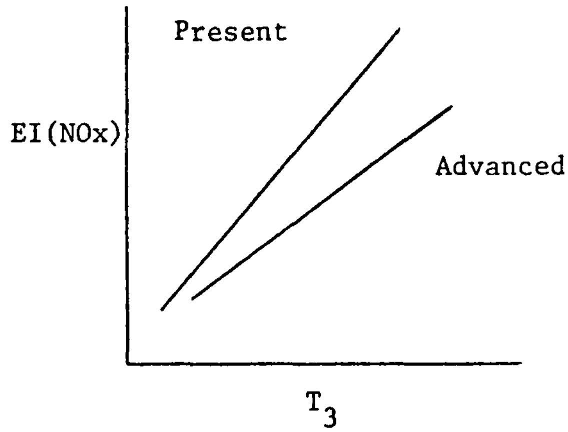


Figure 3 shows the new technology line (labeled "NME") that is emerging as a result of the studies and programs currently underway. This line represents the upper bound of the performance achieved by actual combustor rig tests of the NASA - General Electric double-annular combustor, the present configuration of which has been designed for the CF6-50. It is this demonstrated technology, then, that shall form the basis of the T5 standards calculated here, at least for newly manufactured engines.

Also, shown on Figure 3 is the anticipated technology line applicable to newly certified engines (labeled "NCE"). This is quite advanced technology and, as such, it has not been demonstrated. It is based upon projections of the technology should be applicable to both in the 1980 decade. This technology should be applicable to both subsonic and supersonic engines and is reflected in the T2 standards for newly certificated engines. The EPAP values of the T2 standards for newly certificated engines can be correlated with Emission Indices values and hence combustion inefficiency by properly accounting for engine effects (SFC) and pollutant formation characteristics (i.e., the vast bulk of HC and CO are formed at idle, generally 95-99%). This is discussed in detail in Appendix A.

NOx

NOx production (EI) is closely correlated with combustor inlet temperature for all conventional modern combustors (see Figure 4) according to the work of Lipfert. An advance in NOx control technology may be expected to lower this curve. Improvements at low power will not be as significant as at high power because the greater combustion efficiency at low power (resulting from efforts to reduce HC and CO emissions) will increase the idle temperature (and, therefore, the NOx production rate) enough to largely offset the low NOx characteristics of the combustor. The NOx situation is shown below schematically.



The demonstrated technology for NOx reduction shown in Figure 5 is that which has been surpassed in rig tests in support of subsonic engine emissions reduction. It does not rely on water injection at high power, but relies, rather, on combustor design (lean burning).

Unlike the HC and CO situation, there is no technology line drawn for newly certified engines (NCE) for in parallel with the T2 class standards, the maximum identifiable control of NOx is established in this approach in the newly manufactured engine standards.

(b) Determine the emissions performance expected of the T5 class engine.

This follows quite readily from the results of step (a). For both CO and HC on one hand, and NOx on the other, not only has the emissions performance of the new combustors been identified, but technology lines have been established (Figs 3 and 5). To find the emissions performance of this low emissions technology when applied to SST engines, it is only necessary to identify the operating points of that engine on the abscissa of Figs 3 and 5 and record the associated combustion efficiency and Emissions Index for NOx. To determine the Emissions Indices for HC and CO from the combustion efficiency, refer to Fig 1. The set of Emissions Indices for a given combustion efficiency is not unique (although the converse is) so the most probable relationship, which is also shown on the figure, should be taken.

It is necessary to identify properly the operating points of the T5 class engine. For HC and CO emissions, the operating point is determined by the air loading parameter as discussed earlier. This parameter is to a limited degree an independent variable. That is, given the engine cycle (present ratio) and size (air mass flowrate), the designer is at liberty to select the combustor volume V so as to reduce Ω and thereby improve the emissions performance. However, this freedom is limited by other performance constraints on V, such as altitude relight. Hence, within a band of considerable scatter, the Ω limits of a given engine are determined by the pressure ratio of the compressor (Figure 6). For the Olympus 593 in particular, the present idle value of the air loading parameter, $\Omega = 1.6$, may be taken as representative of what will be found in future versions of it and in new T5 engines (although it should be expected that the designer will take full advantage of what leeway he has in the selection of Ω to reduce emissions).

Reading the combustion efficiency values from the "demonstrated technology" lines for newly manufactured engine (NME) and certified engines (NCE) from Figure 3 and the corresponding Emissions Index values from Figure 1 gives the following results for each of the flight modes of an SST engine:

T5 Class

	Newly Manufactured		Newly Certificated	
Mode	HC	CO	HC	CO
Idle	3.8	19.5	2.1	13.5
Takeoff*	-	0.5	-	-
Climbout	-	1.0	-	-
Descent	1.3	10.0	0.6	6.0
Approach	0.2	3.0	0.1	2.0

* Main Burner only

TABLE VII

For NOx emissions, the operating point is determined by the combustor inlet temperature which for standard day sea level conditions is essentially a unique function of the compressor pressure ratio by

$$T_3 \text{ (combustor inlet temperature)} = T_{ambient} \times \left\{ \left[\left(\frac{P_3}{P_2} \right)^{\frac{\gamma-1}{\gamma}} -1 \right] \frac{1}{\eta_{comp}} + 1 \right\}$$

where η_{comp} = compressor adiabatic efficiency which for large compressors will lie between 0.7 and 0.9, depending on the spread between the design point and the operating point in question. For the Olympus 593 (maximum pressure ratio equal 15), the operating points are shown in Fig 5. The Emissions Indices for the NOx at the various power settings of the LTO cycle are, from Figure 5, T5 Class

Mode	EI(NOx)
Idle	2.1
Takeoff	8.2
Climbout	6.8
Descent	3.1
Approach	4.6

TABLE VIII

(c) Determine the fuel consumption characteristic of the representative SST engine.

This information has been given to EPA by Rolls Royce, the manufacturer:

<u>Olympus 593</u>

Mode	Thrust	Fuel flowrate	SFC	Time in Mode (min.)
Idle	1,800	2,500	1.39	26
Takeoff*	32,000	28,000	0.88	1.2
Afterburner**	6,500	22,000	3.88	1.2
Climbout	25,000	20,000	0.80	2.0
Descent	5,800	5,200	0.90	1.2
Approach	13,100	10,000	0.76	2.3

* main burner only
** on during takeoff

TABLE IX

(d) Compute the emissions performance of the basic engine.

For each pollutant the EPAP can be calculated as follows from the known quantities:

$$EPAP = \frac{\text{total pollutant formation per LTO cycle}}{(\text{total impulse per LTO cycle}/1000)}$$

$$= EPAP_{\text{main burner}} + EPAP_{\text{afterburner}}$$

or

$$EPAP = \frac{\text{total pollutant formation by main burner}}{(\text{total impulse}/1000)}$$

$$+ \frac{\text{total pollutant formation by afterburning}}{(\text{total impulse}/1000)}$$

The total impulse is given by

Σ Thrust x time

where the thrust and time values are given in Table IX. For the Olympus 593, the total impulse is 3002 pound thrust x hours. The numerator of the first term of the EPAP expression, EPAP main burner, is given by

$$\sum_{\text{modes*}} EI \times \frac{\dot{M}_{fuel}}{1000} \times \text{time (hours)}$$

(* takeoff values exclude the afterburner)

Table X summarizes the results for the computation of the numerator. The appropriate Emissions Indices are taken from Tables VII and VIII.

Newly Manufactured Engines (NME)

			Emissions Index			Mass per Mode		
Mode	Fuel flowrate	Time in Mode	HC	CO	NOx	HC	CO	NOx
Idle	2,500 lbs/hr	26 min	3.8	19.5	2.1	4.11	21.12	2.28
Takeoff*	28,000	1.2	0	0	8.2	0	0.28	4.59
Climbout	20,000	2.0	0	1.0	6.8	0	0.28	4.59
Descent	5,200	1.2	1.3	10.0	3.1	0.14	1.04	0.32
Approach	10,000	2.3	0.2	3.0	4.6	0.08	1.15	1.76
					Total	4.33	23.87	13.48

Newly Certified Engines (NCE)

			Emissions Index			Mass per Mode		
Mode	Fuel flowrate	Time in Mode	HC	CO	NOx	HC	CO	NOx
Idle	2,500 lbs/hr	26 min	2.1	13.5	2.1	2.28	14.63	2.28
Takeoff*	28,000	1.2	0	0	8.2	0	0	4.49
Climbout	20,000	2.0	0	0	6.8	0	0	4.53
Descent	5,200	1.2	0.6	6.0	3.1	0.06	0.62	0.32
Approach	10,000	2.3	0.1	2.0	4.6	0.04	0.77	1.76
					Total	2.38	16.02	13.48

* Main burner only

TABLE X

From the total pollutant formation by the main burner given in Table X, division by the total impluse/1000 or 3.002 gives the EPAP values for the main burner (Table XI):

EPAP (Main Burner)

	HC	CO	NOx	NOx + 10%
NME	1.4	8.0	4.5	5.0
NCE	0.8	5.3	4.5	5.0

TABLE XI

Although the calculated NOx EPAP value is 4.5, a 10% margin has been added to account for certain anomolies in the NOx production characteristics of these low HC and CO combustors. At lower power settings (approach and below), the fuel staging which generally is employed in such combustors is operating only on the primary injectors in order to give a hotter flame to consume the HC and CO. This has the effect of increasing the emissions index for NOx at those lower power settings, thus distorting the shape of the technology line (Figure 5). This effect has been examined in CF6-50 case and is roughly 10% of the EPAP value.

The afterburner contribution must now be added to get the total EPAP. This contribution is given in Table III. The total EPAPs and therefore the standards as calculated by this method are:

T5 Class

EPAP

	HC	CO	NOx	Implementation Date*
NME	1.9	12.5	5.0	January, 1982
NCE	1.0	7.8	5.0	January, 1984

* Date of implementation derived and discussed in Appendix B.

TABLE XII

This approach is considered to be the most technically acceptable in that it takes demonstrated or anticipated combustor technology directly and computes its performance in the T5 situation. For the standards for newly manufactured engines (NME), in particular, the presence of demonstrated technology virtually ensures compliance. Furthermore, this approach readily satisfies the earlier criterion set by EPA that the T5 standards "will respresent the same level of emissions reduction from current supersonic aircraft, through application of the same types of combustor design technology, as will be required of subsonic aircraft,..." (Preamble to Aircraft Standards, FR Vol. 38, No. 136 19088).

II. Issue of Expeditious Promulgation of Standards for Newly Manufactured Engines

Alternative V

Set the standards for newly manufactured engines equal to the values recommended by Rolls Royce and set the standards for newly certified engines equal to those values calculated by alternative IV.

As is discussed in Appendix B, the most expeditious approach to controlling the T5 class is to set the T5 standards to be compatible with the development work currently underway by the manufacturers. According to Rolls Royce, one of the two members of the Olympus 593 consortium, its effort has been directed at the following goals which are applicable to their engine (the newly manufactured engine category):

	EPAP		
	HC	CO	NOx
NME	3.9	30.1	9.0

A comparison with the production engine

	EPAP		
	HC	CO	NOx
Production	16.2	66.5	8.8

shows that Rolls Royce is seeking a reduction in HC and CO, but not in NOx. In fact, they are allowing themselves a slight increase in the NOx emissions which makes the job of reducing HC and CO emissions that much easier.

Rolls Royce set its HC and CO goals in a manner similar to the calculation of method 3 using, however, not the average reduction of the main representative T2 engines, but only the JT9D. Their calculation proceeded as follows.

	JT9D	
	CO	HC
Current EPAP	11.3	3.0
1979 T2 standards	4.3	0.8
Reduction required	62%	73%

Olympus 593

Current EPAP	58	15.4 (Main Burner)
Reduction	62%	73%
Goals	22.1	4.1
ΔEPAP	5.5	0.6 (Afterburner)
EPAP Goal	27.6	4.7
Adjusted EPAP*	30.1	3.9

*This increase in the CO level and decrease in the HC level is recommended over that of the initial calculation as it accounts for the decrease in the HC/CO ratio as combustion efficiency is improved (see Figure 1).

Technically this approach suffers the same drawbacks as method 3 with the additional inconsistency that NOx is not treated in the same manner as the other pollutants. Pragmatically, though, this approach would permit standards to be implemented as soon as possible and certainly it is not open to criticism as being unreasonably stringent as Rolls Royce itself recommends these standards.

The fact that Rolls Royce has not been pursuing NOx reduction is worthy of further comment. Their approach to setting goals for HC and CO emissions is certainly not the best as is discussed in method 3 (an approach similar to the Rolls Royce calculation), but it does offer a justifiable rationale. However, the failure to set a NOx goal in the same fashion demonstrates that Rolls Royce in the absence of promulgated standards elected to take the far simpler approach and not pursue the NOx problem.

For newly certified engines there is currently no development underway for such engines which would conflict with the imposition of the most rigorous standards now judged to be technically feasible (NCE standards by alternative IV). The use of this set of standards has the advantage of imposing the greatest control on the second generation of SSTs which would be built only if the class were a commercial success. These later aircraft would be built in larger numbers so that strong control would be much more important.

The set of standards by this approach are then,

EPAP

	HC	CO	NOx	Implementation Date*
NME	3.9	30.1	9.0	January, 1980
NCE	1.0	7.8	5.0	January, 1984

* Date of implementation derived and discussed in Appendix B.

Recommendation

Method one is rejected because it does not recognize the existence of the T5 class at all which is contrary to EPA's stated intent.

Method two is rejected because there is no rationale for imposing equal Emissions Indices in order to force a common technology between the classes. This method fails to recognize that even the best combustor would be affected by the operating conditions characteristic of each engine type.

Method three adopts an acceptable point of view, but may be overly stringent or lenient if the baseline values upon which the percentage reductions are imposed reflect a technology which is already advanced or, alternatively, is obsolete.

Method four carries out its calculations directly referring to the technology available and how well it will perform in the SST environment, as well as accounting for SST fuel consumption characteristics. This is the preferred approach from a technical point of view. Method four, however, can result in an essentially uncontrolled SST fleet because control could not be achieved until January, 1982 at which time the fleet, if produced in only limited numbers, would escape any control.

Method five results in control of SST emissions at the earliest possible date (January 1, 1980) while retaining the strictest possible standards for subsequent generations of SST's. It is thus recommended.

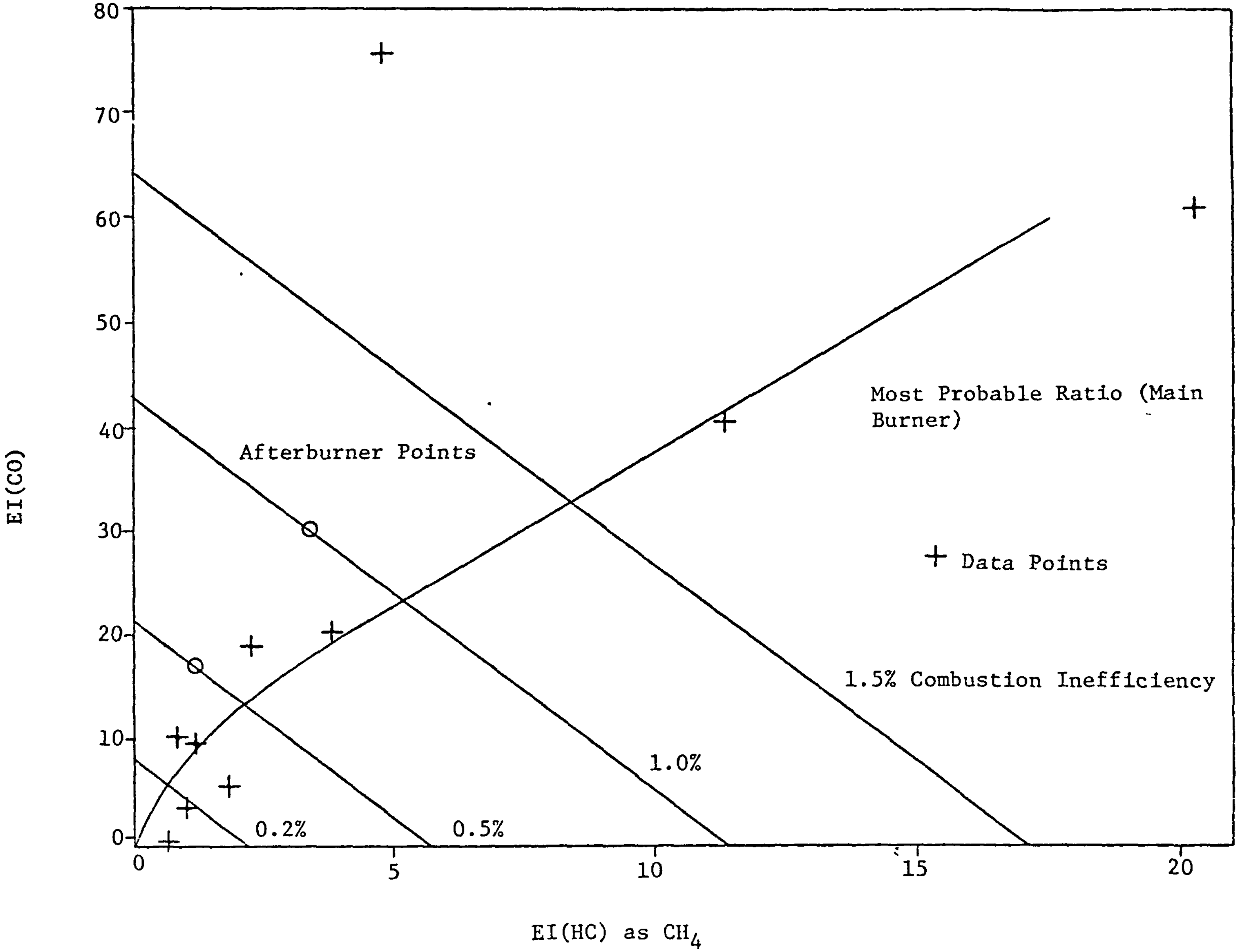

80
70
60
50
40
30
20
10
0
EI(CO)
0
5
10
15
20
EI(HC) as CH_4
Most Probable Ratio (Main Burner)
Afterburner Points
Data Points
1.5% Combustion Inefficiency
1.0%
0.5%
0.2%

Figure 1

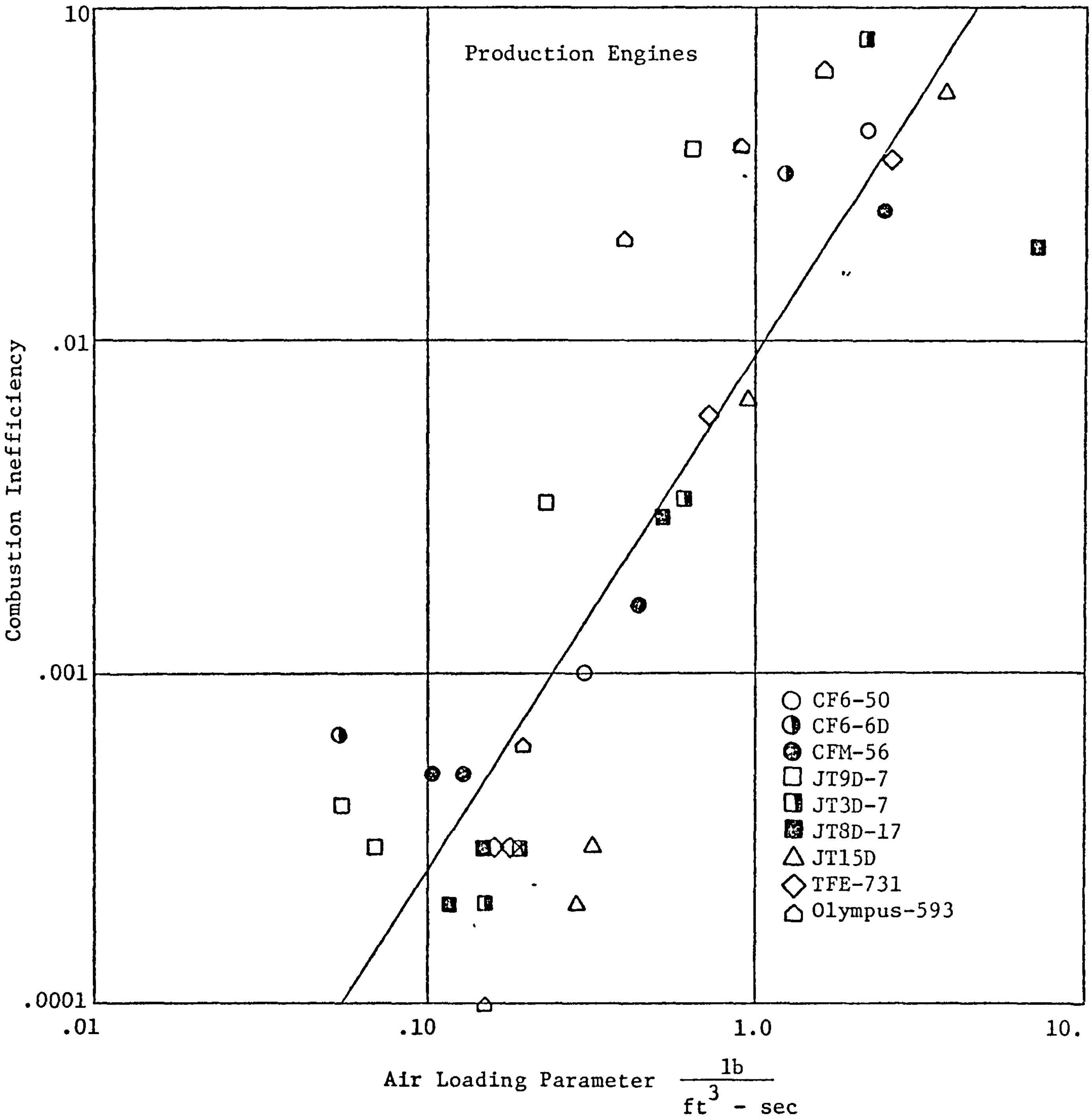

Production Engines
10
.01
.001
.0001
.01
.10
1.0
10.
Combustion Inefficiency
Air Loading Parameter lb / ft3 - sec
CF6-50
CF6-6D
CFM-56
JT9D-7
JT3D-7
JT8D-17
JT15D
TFE-731
Olympus-593

Figure 2

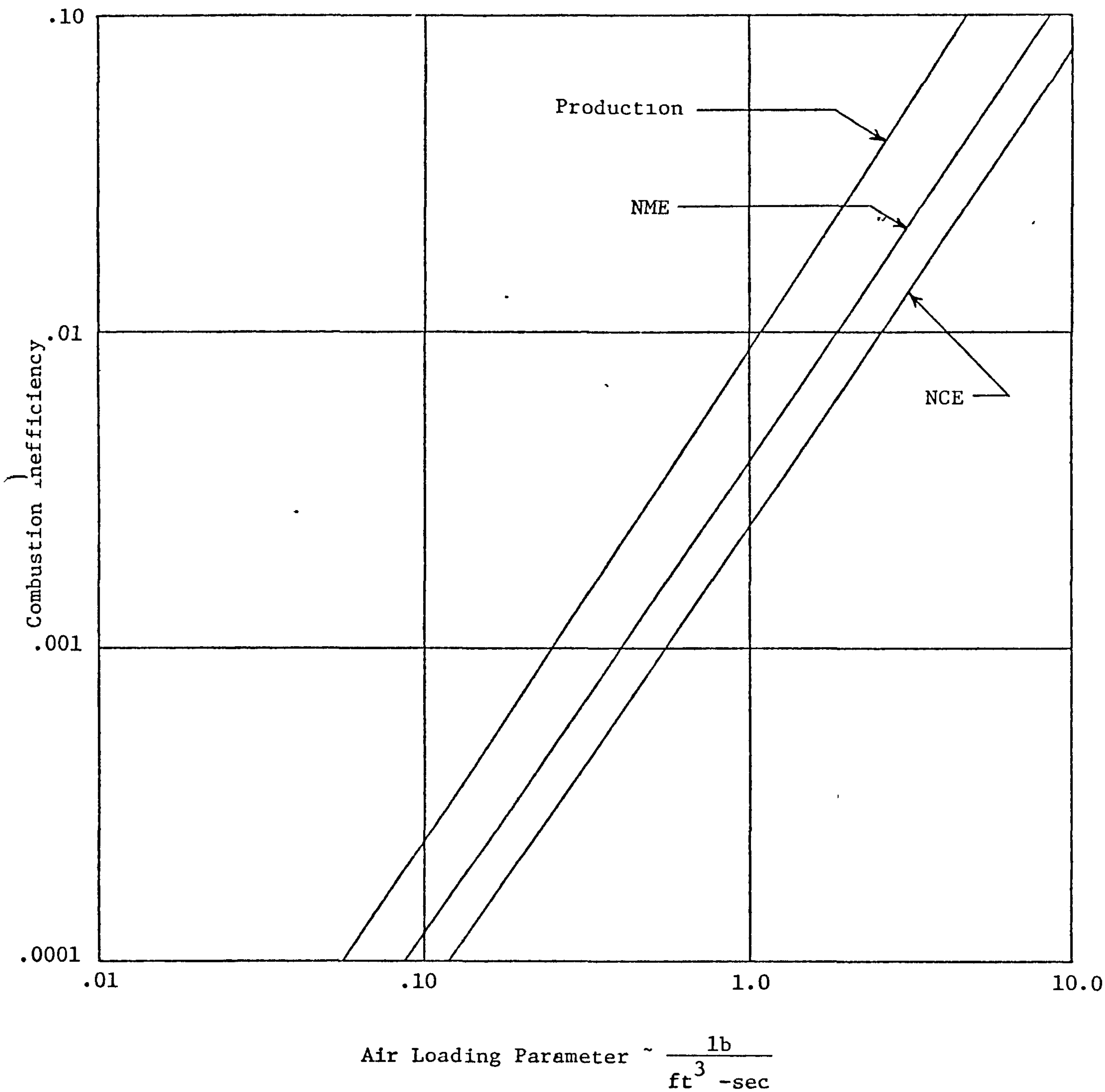

.10
.01
.001
.0001
Combustion Inefficiency
Production
NME
NCE
.01
.10
1.0
10.0
Air Loading Parameter ~ lb / ft3 -sec

Figure 3

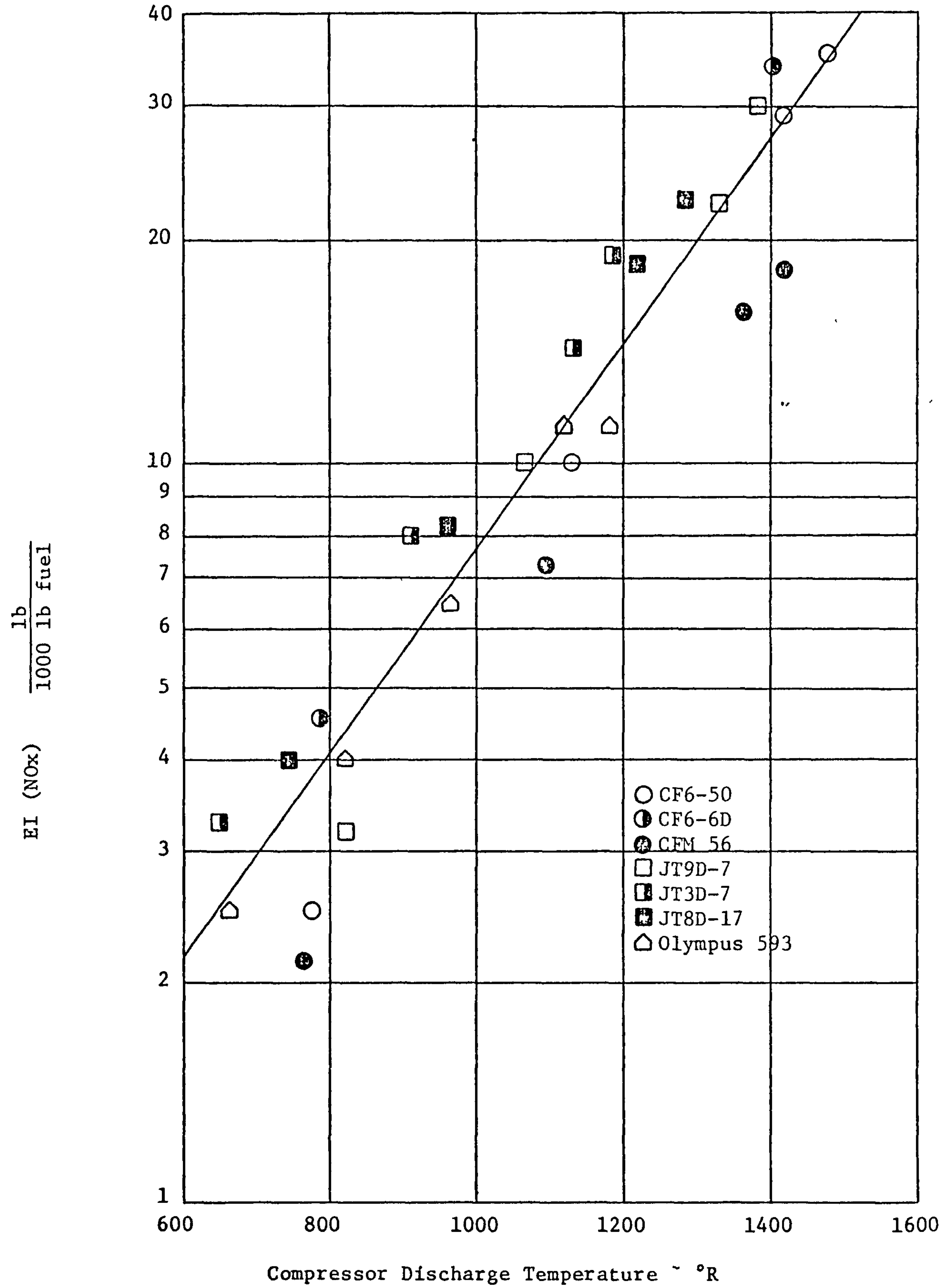

40
30
20
10
9
8
7
6
5
4
3
2
1
EI (NOx) $\frac{lb}{1000\ lb\ fuel}$
600
800
1000
1200
1400
1600
CF6-50
CF6-6D
CFM 56
JT9D-7
JT3D-7
JT8D-17
Olympus 593
Compressor Discharge Temperature ~ °R

Figure 4

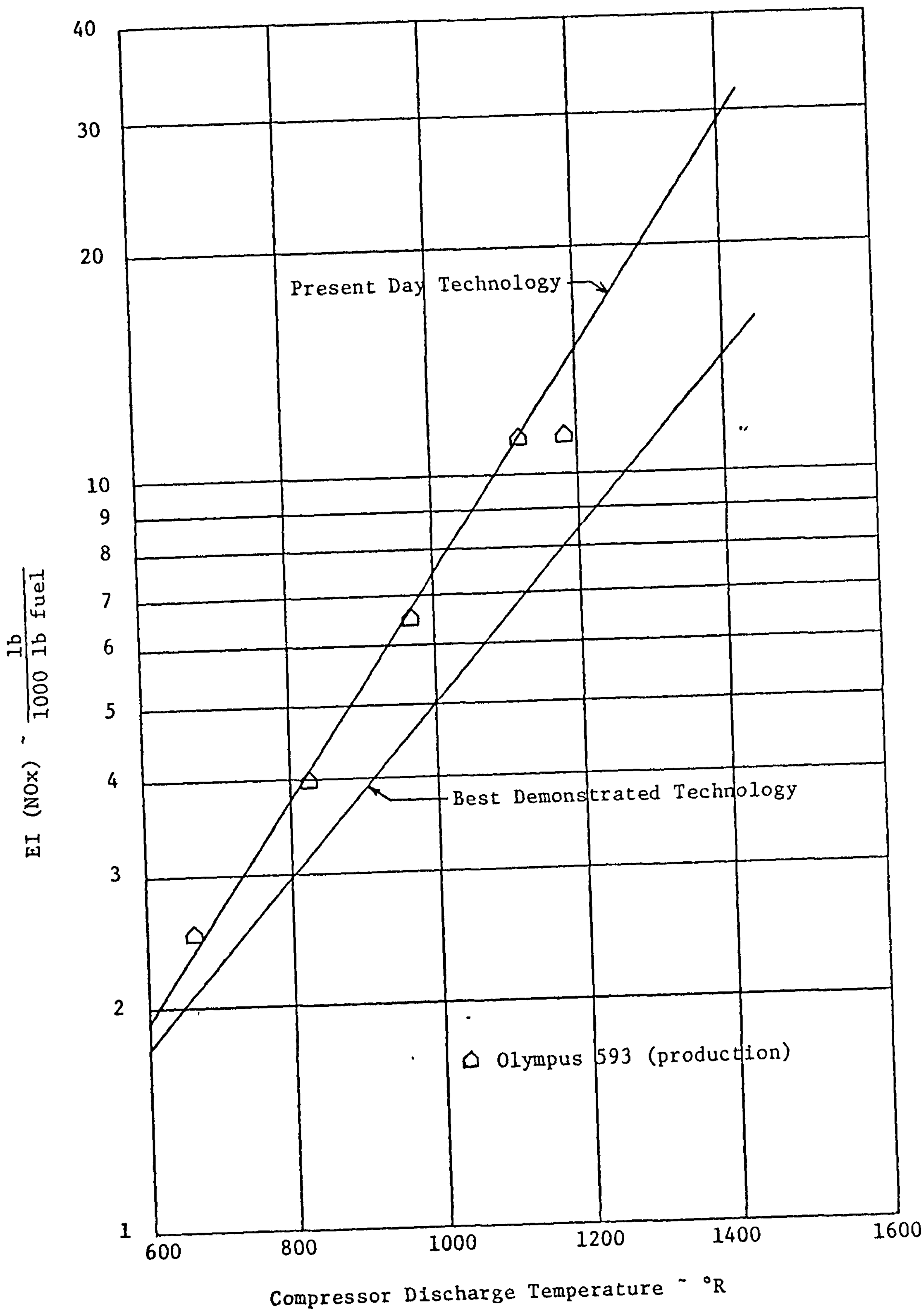
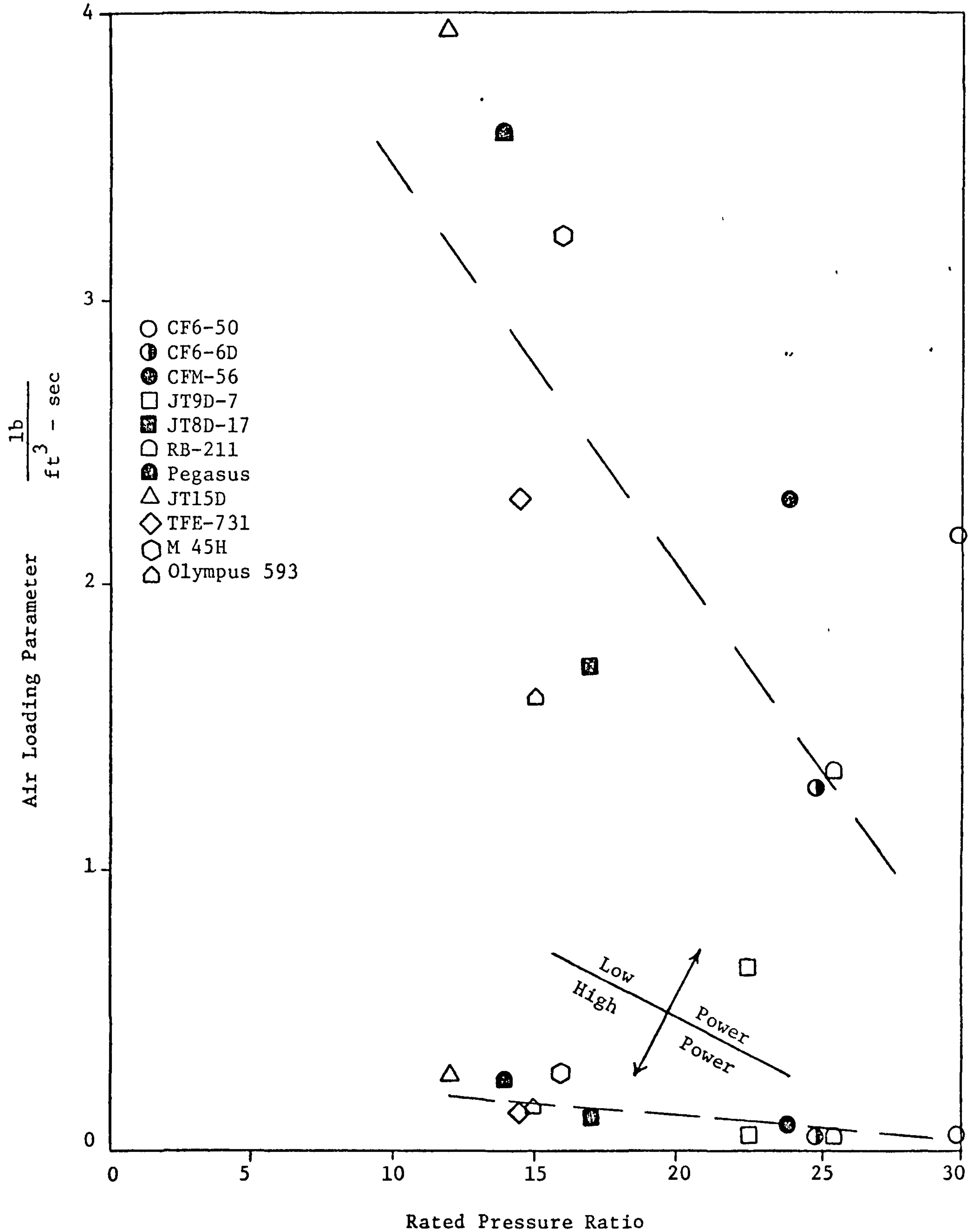

40
30
20
10
9
8
7
6
5
4
3
2
1
EI (NOx) ~ lb / 1000 lb fuel
Present Day Technology
Best Demonstrated Technology
Olympus 593 (production)
600
800
1000
1200
1400
1600
Compressor Discharge Temperature ~ °R

Figure 5



4
3
2
1
0
lb / ft^3 - sec
Air Loading Parameter
CF6-50
CF6-6D
CFM-56
JT9D-7
JT8D-17
RB-211
Pegasus
JT15D
TFE-731
M 45H
Olympus 593
Low
High
Power
Power
0
5
10
15
20
25
30
Rated Pressure Ratio

Figure 6

Appendix A

Calculation of Anticipated Future Combustor Performance

The T2 class standards for newly certified engines are based upon the existence of an emissions control technology that should be common to both supersonic and subsonic engines. In order to derive T5 standards that reflect this commonality, it is necessary to correct the EPAP values in the T2 standards (NCE) to their respective Emissions Indices in order to compute the combustion inefficiency for Figure 2.

For a modern T2 class engine the great bulk of the hydrocarbon and CO is produced during the idle mode (see Table below); hence, to a good approximation it is sufficient to consider the total hydrocarbons and CO to be a result of incomplete combustion of the mass of fuel consumed at idle only.

Mode	HC(lbs)	CO(lbs)	% of Total
Idle	19.5	54.6	94.6
Takeoff	0	.20	0.2
Climbout	0	.41	0.5
Approach	0.39	3.27	4.7
Total	19.89	58.48	100

Emissions for JT9D-7(T2 class)

Roughly, then,

$$\text{EI (HC or CO) Idle} = \frac{\text{Total Emissions (HC or CO)}}{\text{(Mass of fuel consumed at idle/1000)}}$$

where

Total Emissions (HC or CO) Idle = (EPAP Anticipated x Total impulse over LTO cycle/1000)

so that

EI (HC or CO) Idle = Anticipated EPAP x Total Impulse over LTO cycle/Mass of fuel consumed at idle

For subsonic newly manufactured engines, the following EPAP values are expected:

	HC	CO
NME(T2)	0.8	4.3

and for subsonic newly certified engines,

	HC	CO
NCE(T2)	0.4	3.0

These values agree with the percent reductions listed in the discussion of Alternative III.

The CF6-50 may be taken as a representative subsonic engine in order to establish the expected technology lines. For this engines,

total impulse over LTO cycle = 3868 lb-thrust x hrs.

mass of fuel consumed at idle (26 min) = 528 lbs.

Thus, the EIs and the combustion inefficiency can be calculated for NME and NCE to give

	EI(HC)	EI(CO)	$1-\eta$	Ω
NME	5.9	31.5	1.24%	2.18
NCE	2.9	22.0	0.77%	2.18

where the air loading parameter for the CF6-50 is included so that the point can be fixed in figure 3. The technology lines are then drawn perpendicular to the production engine technology line. This last step may be optimistic at the high power points (small Ω), however, as these points contribute little, if anything to the total HC and CO EPAP calculations, the point is moot.

Appendix B

Implementation Data[2]

Introduction

This appendix presents an analysis of the leadtimes necessary to implement the two most acceptable alternatives discussed in the main text. The first analysis here examines the leadtime for Alternative IV which is considered the most acceptable from a strictly technical point of view (It establishes T5 standards that require the use of the best technology thought to be available).

The second analysis examines the leadtime for Alternative V which is the recommended approach because, as the analysis shows, it can be implemented sooner. An early date of effectiveness is desirable because of the liklihood that only a small fleet (less than 60) of SSTs will be built. More control can then be achieved by early enforcement.

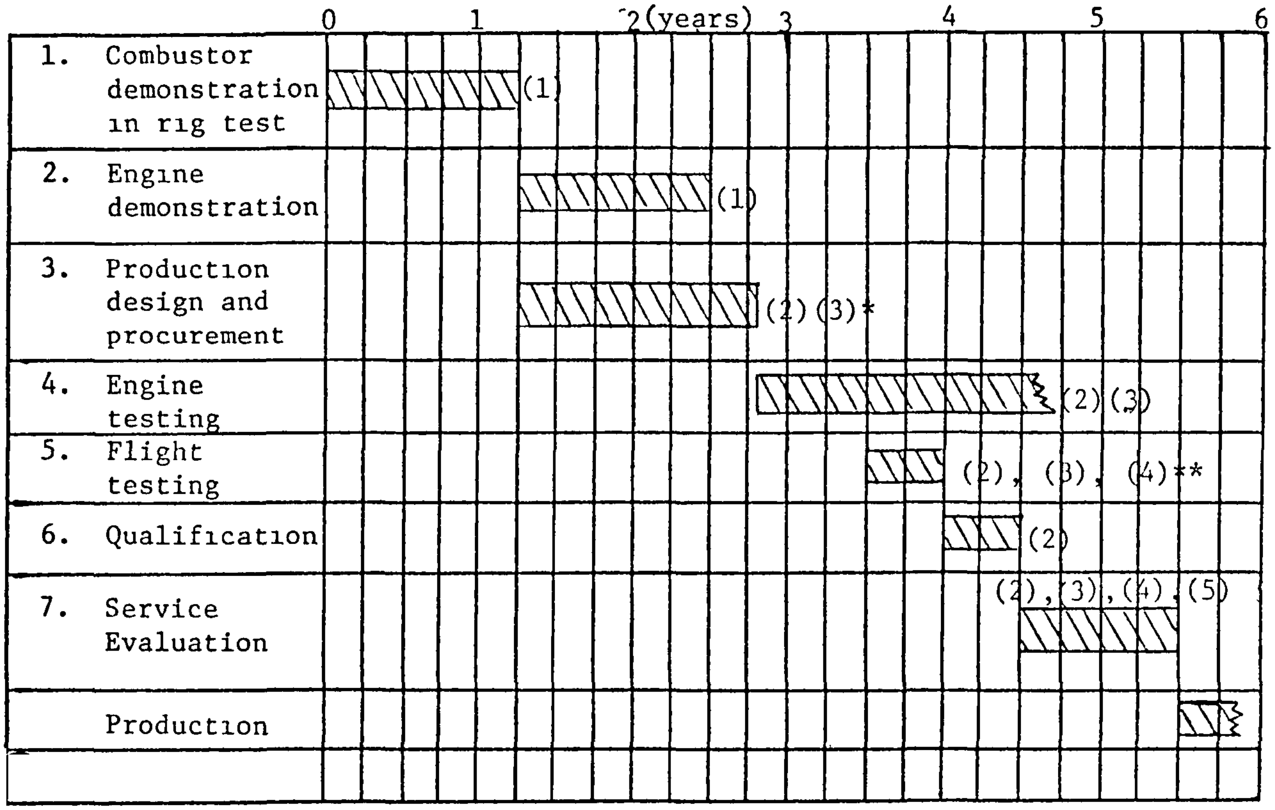
Method Four

Method four represents the technically most stringent standards that can reasonably be imposed on the T5 class. From that point of view it is the preferred approach. The question then must be answered: At what date can these standards go into effect?

The NME standards calculated by method four are based upon the application of combustor technology already demonstrated in rig tests in the United States. The time necessary to implement that technology into production depends on the accomplishment of the tasks listed below in the graph. The EPA estimates of the time required to complete these tasks are derived from the times involved in the NASA Experimental Clean Combustor Program, Phases II and III, communications with General Electric and Pratt and Whitney Aircraft, EPA experience with smoke reduction programs, and explanations in EPA Report No. 1168-1, "Assessment of Aircraft Emission Control Technology", September 1971. The NASA program times are concerned with the demonstration of the technology in rig and engine prototype tests, while the manufacturer and EPA times are concerned with engine certification, checkout, and production preparation times. Some foreshortening of the General Electric time estimates has been assumed and the differences are noted herein.

The tasks are described as follows:

1. Combustor demonstration in rig test. The requisite technology has already been successfully demonstrated in rig tests in the United States as part of the NASA Experimental Clean Combustor Program (ECCP). The operating environment of the tests simulated subsonic engine operating conditions and the geometries were scaled to specify subsonic engines. While that technology is transferable to other engines and other operating



(1) NASA ECCP

(2) GE communication

(3) EPA Report No. 1168-1

(4) P&WA communication

(5) Comparison with other service evaluation programs

* Start of this task advanced 3 months

** Start of this task advanced 6 months

conditions, nonetheless, it must be verified and refined in rig tests prior to engine testing so that the effectiveness of the scheme to control emissions in that application can be proven. Rig testing also permits extensive optimization of the system for safety and reliability. It further permits simulated altitude performance testing (including relight) which otherwise would be very costly in engine tests in altitude chambers, if possible at all. The time allotted for this task is 15 months and is chosen because it is identical to that of Phase II of the NASA ECCP wherein similar work was done.

2. Engine Demonstration. Engine demonstration is necessary first to verify that the combustor, which was optimized in the rig tests, operates satisfactorily in the full engine and second to design the necessary fuel control system to achieve that satisfactory performance. Satisfactory performance here means (1) acceptable steady state performance as evidenced by specific fuel consumption within production specification and acceptable turbine inlet temperature profile and (2) acceptable transient performance as evidenced by acceleration/deceleration times within FAA requirements with sufficient surge margin. The time allotted for this effort is again 15 months and is identical to that of Phase III of the NASA ECCP wherein similar work is being accomplished.

3. Production Design. This task involves the design and manufacturer (in limited numbers) of all the engine parts modified by the low emissions system and the associated tooling. Such engine parts may include, in addition to the combustor liner itself, the inner and outer casing, diffuser, struts, fuel control, nozzles.

Manufacturing includes the necessary tooling as well as the limited production to supply engines for static and flight testing, qualification, and service evaluation. As reported in EPA Report No. 1168-1, September 1971 and by General Electric in a separate communication this exercise should take a little over 1 1/2 years, much of which can overlap the engine demonstration period as the final configuration is finally identified, thereby requiring only four additional months until engine testing can begin.

4. Engine Testing. This activity involves endurance and cyclic testing necessary first to generate an adequate safety record for later flight testing and engine qualification and second to develop a maintenance and reliability record for airline service. This is a continuous effort throughout the service life of the engine, but only eight months are necessary before sufficient time is accumulated to begin flight tests. General Electric suggested that about fourteen months be given to ground testing before flight testing begins. Through a more intensive test schedule this can be shortened to eight months, saving six.

5. Flight Testing. This is done primarily to investigate engine performance at altitude. It is usually done on a corporate owned experimental aircraft or an available military aircraft neither of which are subject to the FAA requirements of certification. Included in the

engine performance criteria are thrust, specific fuel consumption, relight, and transient behavior. Environmental factors such as icing, etc., may be investigated as necessary. General Electric and Pratt and Whitney generally allocate about six months to flight testing prior to start of qualification.

6. Qualification. This step involves obtaining the necessary type certificate, supplemental type certificate, or engineering approval for the low emissions engine. The amount of effort involved here is largely dependent upon the type of certification necessary. In any case, FAA certification here involves mostly paperwork as a large part of the necessary testing has already been done. Following the recommendation of the manufacturers, six months is delegated to this task.

7. Service Evaluation. Once an engine has the necessary FAA certification or approval, it is, strictly speaking, available for public use. Nonetheless, another stage of testing, that of service evaluation, has developed as a matter of industry policy prior to full production. The procedure in service evaluation is to have a limited number of engines installed on fleet aircraft (one per plane) for a long enough period of time to judge their performance, reliability, and maintainability in actual airline use. While reliability may be considered a safety issue (the FAA considers service evaluation a vital supplement to its own required testing for certification), it is intended primarily to prove the economics of the engine in service. The length of time of the service evaluation depends upon the rate at which flight time and landing-takeoff cycles are accumulated in service and the extent to which the new system differs from the old (an exotic system will be scrutinized more thoroughly for reliability). A system which has had a history of difficulty in development will command a longer service evaluation.

General Electric has indicated that a one year service evaluation would be adequate for its engines. This is a fairly short time, giving a high time of perhaps 3500 hours and 1400 cycles. This is supported also by EPA Report No. 1168-1, referenced earlier. However, it should be pointed out that some service evalutions take longer, for instance the JT3D and JT8D smoke retrofit programs took 1 and 1/2 to 2 years to complete. However, both represented attempts to install advanced technology in quite mature engines (canannular combustors) and both experienced a history of development problems.

Totally then (steps 1 through 7), 4-1/2 years should be sufficient to implement the demonstrated technology into a production T5 class engine. In comparison, the staff of Rolls Royce, Derby Division (not involved in the T5 class) suggested a six year leadtime is necessary from the definition of a concept (rig test) to production (steps 2 through 7). This analysis calls for 4-1/4 years and an analysis based upon General Electric's unmodified estimates calls for 5 years for the same set of tasks (steps 2 through 7).

A 5-1/2 year leadtime from July 1976 would mean that the T5 standards for newly manufactured engines (by Alternative IV) would go into effect January 1, 1982. Following the patterns set by the T2 class standards, a two year interval from the implementation of the standards for newly manufactured engines to the standards for newly certificated engines would establish the advanced standards on January 1, 1984. Further extension of the deadline for newly certificated engines is not warranted in this case as these standards (Alternative IV) do not presume the development of a variable cycle engine which may be some distance in the future.

Method Five

For newly manufactured engines, this method is nothing more than Rolls Royce's own target values which, in November 1974, they felt confident in meeting by January 1, 1979. While it is possible that they and their partner, SNECMA, have been continuing to pursue development directed towards their original target, it may well be that because of the roughly one year delay in the promulgation of the standards, Rolls Royce and SNECMA have been delaying further work pending redefinition of their goals. If this is the case, then a one year delay is likely to be necessary.

Their concepts for both the main burner and the afterburner have been identified and, at least for the main burner, demonstrated in an engine (the status of the afterburner is not known). This fact, coupled with the fact that the burner changes involved are sufficiently minor that only a minimal qualification effort is necessary, supports the notion that the low emissions engine may be ready by January 1, 1979 and certainly by January 1, 1980.

As the NCE standards for method 5 are nothing more than those of method 4, it follows that the implementation date aimed at above for method 4 is adequate, namely, January 1, 1984. An alternative approach which gives essentially the same date is to first presume that most development work for newly certified engines will be done for the T2 class and that for a newly certified T5 engine the necessary technology will have to be transferred, an activity which involves rig verification and refinement and engine demonstration. Such activities closely follow the work done in Phases II and III of the current NASA Experimental Clean Combustor Program. That work requires 30 months or 2 1/2 years to account for unforseen difficulties in the technology transfer, then it may be concluded that implementation of the T5 standards for newly certified engines would be about three years behind that for the T2 class, giving again January 1, 1984 (adding three years to January 1, 1981, the implementation date for the T2 standards for newly certified engines).