Technical Support Report for Regulatory Action

Cost-Effectiveness Analysis of the Proposed Revisions in the Exhaust Emission Standards for New and In-Use Gas Turbine Aircraft Engines Based on EPA's Independent Estimates

by

Richard S. Wilcox
Richard W. Munt

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NOTICE

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air and Waste Management
U.S. Environmental Protection Agency

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INTRODUCTION

To determine the most efficient means of achieving the National Ambient Air Quality Standards (42 CFR §420), the cost effectiveness of various pollution abatement control strategies are compared and the most effective are implemented. This report contains a cost-effectiveness analysis of the proposed revisions in exhaust emission standards for new and in-use aircraft gas turbine engines using EPA's independent cost estimate.

The control strategies analyzed are:

1. Control of newly manufactured gas turbine engines in 1981 for HC and CO only;

2. Retrofit of in-use gas turbine engines in 1985 for HC and CO only (to the same levels as in #1); and

3. Control of newly manufactured gas turbine engines in 1984 for HC, CO, and NOx.

Discrepancies between industry estimates and data from earlier EPA studies (References 1 and 2) made it necessary for the EPA to prepare an independant cost estimate.

This interim report represents EPA's preliminary cost analysis in a continuing effort to expand and update its cost information in a timely manner. Care must be taken in interpreting the results of this analysis. Because of the complexity of the subject matter and the uncertainties which prevail, the choice of simplifying assumptions can have a significant effect on the direction of the results. Every effort has been made to present a realistic scenario of the costs of control. The subsequent final report will be more precise and will incorporate information received during the comment period of the Notice of Proposed Rule Making concerning this regulatory action.

The Discussion section of this analysis is divided into two main portions. Part I was prepared to allow a direct comparison with gas turbine engine manufacturers' estimates as published in TSR AC77-02 (Reference 3), although the cost-effectiveness figures are not directly comparable since this report includes the latest FAA fleet projection (Reference 4) and other modifications. Part II presents an alternative way to compute the cost-effectiveness of the proposed standards. This alternative reflects the uncertainty associated with the promulgation of a NOx standard in 1984. It differs from Part I in that the 1981 NME Standard is projected as the final requirement for all newly manufactured engines. The second part also differs from the first in the method of determining the incremental burden associated with the possibility of NOx control.

In addition, the purpose of this analysis is to present EPA's cost estimates; therefore, the discussion of several important elements presented in TSR AC77-02 is not repeated in detail here.

METHODOLOGY

The procedure used in this analysis consisted of determining the cost increment and the total reduction in fleet exhaust emissions for each control strategy. A portion of the total cost was then applied to each individual pollutant. The resulting HC, CO, and NOx cost-effectiveness factors are defined in terms of dollars spent per ton of pollutant reduced ($/ton). The undiscounted lifetime costs (zero discount rate), expressed in 1976 dollars, are used throughout this analysis.

As previously mentioned, several elements which were detailed in the previous cost-effectiveness report are not repeated in this study. Some of these elements are a part of the methodology and include:

1. The derivation of emissions reduction over an engine's lifetime; and

2. The derivation of fuel savings associated with the proposed standards.

For a detailed discussion of these derivations the reader should refer to TSR AC77-02 (Reference 3).

This analysis includes several engine families which were not part of TSR AC77-02. Recent information indicates that the JT8D-209, CF6-32, and RB211-535 may hold significant shares of the market in compliance with the standards under consideration. The EPA has very little data on the JT8D-209, and no data on the CF6-32 and RB211-535. (The latter engines are clipped fan versions of the CF6-6 and RB211-22B, and are presumed to be in the design phase, therefore, very little information is available.) The assumptions used to derive the statistics necessary to complete the analysis are given in Appendix A. These engines are further discussed in Appendix B, "Fleet Projection and Engine Inventory".

A brief discussion of each part of the methodology used in this analysis is presented in the following sections.

EMISSIONS REDUCTION

The pollution abatement brought about by the use of a low-emission version of an engine is computed by finding the net reduction per landing-takeoff (LTO) cycle and multiplying that figure by an estimate of the total LTO cycles the engine will experience during its useful life.

The number of LTO cycles for each engine are the same as those used in Reference 3, except that those for the B707 and DC-8 retrofit (JT8D and CFM56 engines) have been changed to reflect the long-haul low-LTO-cycle operation of these aircraft (Reference 4, See Appendix A).

The following formulae are used to determine the number of LTO cycles for specific engines based on their representative aircraft type. The inputs come from published CAB data as found in Reference 3 and 4.

$$\text{LTOs/day} = \frac{\text{Daily aircraft utilization in hours}}{\text{Revenue hours/Revenue departures}} \quad (1)$$

or

$$\text{LTOs/day} = \frac{\text{Daily block hours per aircraft}}{\text{Stage length/Block speed}} \quad (2)$$

COST

The incremental cost of each control strategy is conveniently separated into four major components: non-recurring, manufacturing, operating, and maintenance. In most instances, the amounts of each cost component were derived from References 1, 2, 7, 8, and 9. Where costs were incomplete, vague, or incorrect based on more recent knowledge, systematic application of judgment was used to complete the estimate.

Non-recurring. This major component is composed of several elements: development, certification, service evaluation, initial production, and engine dedication. These funds represent the corporate investment associated with the application of demonstrated technology to specific engine families and must be recovered in the engine selling price. Not included are the research and development (R&D) costs of initial design and engine demonstration which were funded through U.S. Government contract and Independent Research and Development (IR&D) money.

Manufacturing. The cost of manufacturing refers only to the increment in engine selling price as a consequence of the increased complexity or more expensive materials found in a low-emission engine. This burden is generally attributed to the combustor and fuel supply system, but may include increased costs to manufacture the pressure casing and equipment bay.

Operating. In this analysis, the operating cost is defined as the increment in fuel consumption between regulated and non-regulated engines. No performance penalties (such as a loss of thrust) are expected from the use of low-emission technology.

Maintenance. Although generally considered an operating expense, maintenance cost is segregated in this study because it includes subject areas for which no estimates are available, or elements which are too abstract to define with any certainty. These expenses, typically incurred by the air carriers, are excluded from this analysis.

FLEET PROJECTION

Having obtained the emissions reduction and cost of control for each engine model, it is necessary to average them over the fleet in order to obtain overall figures. Three fleets are of interest: (1) the fleet of pre-1981 aircraft which is subject to the 1985 Retrofit Standard, (2) the 1981 to 1984 aircraft fleet which is subject to the 1981 NME Standard; and (3) the 1984 and beyond fleet of new aircraft which is subject to the 1984 NME Standard.

The projection used to obtain each fleet mix (Reference 5) is based on the FAA's latest fleet projection (Reference 6) and is discussed in Appendix B.

COST APPORTIONMENT

The costing methodology employed in this analysis is consistent with that used for automobile emission control strategies (Reference 10). For the 1981 NME and 1985 Retrofit Standards which control only HC and CO, no quantitative approach to cost application exists since the same technology controls both species. For this reason, the cost of control is divided equally between the two pollutants.

The 1984 NME Standard regulates NOx in addition to HC and CO. Since the allowable levels for HC and CO are the same as 1981 NME, the same cost of control is assigned to these two pollutants for 1984 NME and any additional burden is attributed to NOx control.

COST EFFECTIVENESS

Part I and II

In both parts of the Discussion section; the cost effectiveness for each of the proposed standards is calculated by first finding the total cost as follows:

$$\text{Total Cost} = \begin{array}{c}\text{Total}\\ \text{non-recurring cost}\end{array} + \begin{array}{c}\text{Total selling}\\ \text{price increment}\end{array} + \begin{array}{c}\text{Total fuel}\\ \text{consumption increment}\end{array} \quad (1)$$

For the 1981 NME and 1985 Retrofit Standards, 50 percent of the total cost is applied to the total reduction in each pollutant (HC and CO) which yields the final cost-effectiveness ratio.

$$\begin{array}{l}\text{Cost effectiveness}\\ \text{for pollutant A}\end{array} = \frac{\text{50\% of equation 1}}{\text{Total reduction in pollutant A}} \quad (2)$$

Part I

The 1984 NME Standard cost-effectiveness ratio for HC and CO is the same as that found by Equation 2 for the 1981 NME Standard. These ratios are then used to determine the NOx cost-effectiveness ratio in the following manner:

$$\text{HC allocation} = (\text{Total reduction in HC for 1984}) \times (\text{Eq. 2 for HC}) \quad (3)$$

$$\text{CO allocation} = (\text{Total reduction in CO for 1984}) \times (\text{Eq. 2 for CO}) \quad (4)$$

$$\text{NOx allocation} = \text{Eq. 1 for 1984 NME} - (\text{Eq. 3} + \text{Eq. 4}) \quad (5)$$

$$\begin{array}{l}\text{Cost effectiveness}\\ \text{for NOx}\end{array} = \frac{\text{Eq. 5}}{\text{Total reduction in NOx}} \quad (6)$$

Part II

The 1984 NME Standard cost-effectiveness ratio for HC and CO is the same as that found by Equation 2 for the 1981 NME Standard.

The total cost of NOx control in 1984 is defined by Eq. 1 where:

1) The non-recurring cost is represented by the non-recurring expenses incurred as a result of developing and implementing 1984 control technology;

2) The selling price increment is equal to the difference between the 1984 NME selling price increment and the 1981 NME selling price increment, multiplied by the number of engines produced under the 1984 standard; and

3) The fuel consumption increment is the difference between consumption increments calculated for the 1984 in-service engines when utilizing either 1984 NME or 1981 NME control hardware.

The cost effectiveness is found by the following equation:

$$\begin{array}{l}\text{Cost effectiveness}\\ \text{for NOx}\end{array} = \frac{\text{Eq. 1}}{\text{Total reduction in NOx}} \quad (7)$$

DISCUSSION

Part I

This portion of the Discussion was prepared to allow a direct comparison with gas turbine engine manufacturers' estimates as published in TSR AC77-02 (Reference 3).

EMISSION REDUCTIONS

The exhaust emission reductions were calculated over the useful life of each engine family. This interval is somewhat arbitrary and was selected to approximate the corporate accounting lifetime. Newly manufactured engines are considered to have a useful life of 15 years. Based on a 15 year aircraft attrition rate, the fleet projection (Reference 5) forecasts that all retrofitted engines except the CF6-50, CFM56, and JT8D-209 will have an average useful life of 8 years remaining. The CF6-50 was introduced on later airplane models and would have expended less of its useful life; therefore, this engine has 11 of its original 15 year lifetime remaining. The CFM56 and JT8D-209 would be retrofitted on older aircraft (e.g., B707) which have an average of 12 years remaining before retirement. For this reason, the useful lives of these engines are also limited to 12 years.

The date of the 1985 retrofit overlaps the 1984 NME Standard by one year. This means that the new-engine retrofit of aircraft which might normally comply with the 1985 standard will be forced to use engines produced under the more stringent 1984 standard. The fleet projection (Reference 5) shows that 204 engines (CFM56 and JT8D-209) for the retrofit of the B707 and DC-8 fleets are involved. This retrofit is dependent on compliance with FAR Part 36 noise regulations which are effective in 1985. The airlines will probably retrofit these aircraft with engines manufactured before 1984 to avoid a mix of engines on their long-haul narrow-bodied aircraft fleets. However, to remain consistent with the fleet projection and the standards as proposed, this analysis accounts for the 204 engines under the 1984 NME Standard as previously stated.

A useful life of 15 years was used for the 204 engines retrofitted under the 1984 standard instead of the shorter value employed for other retrofit engines. A re-examination of the fleet projection showed that as their numbers dwindled, the utilization of the remaining B707 and DC-8 aircraft increased so that a longer useful life was more appropriate.

Tables 1, 2, and 3 summarize the lifetime reductions in gaseous exhaust emissions for each engine family as well as the total reduction for each fleet affected by the 1981 NME, 1985 Retrofit, and 1984 NME Standards, respectively.

The JT8D-17 (representative of all JT8D family members except the dash 209), dominates the total lifetime emission reductions brought about by the 1985 Retrofit Standard (Table 2). The large number of these engines account for about 40% of the HC and 50% of the CO reduction totals.

Table 1

Reduction in Gaseous Emissions
Resulting from the 1981 NME Standards

Model	Tons/Engine/Lifetime[a,b] HC	CO	In-Service[c] Engines	Total Tons/Lifetime (000) HC	CO
JT8D-17	70	204	549	38.4	125.2
JT8D-209[d]	65	130	264	17.2	34.3
JT9D-7	146	264	124	18.1	32.7
JT9D-70	72	242	124	8.9	30.0
CF6-6	87	174	105	9.1	18.3
CF6-50	125	207	226	28.3	46.8
CFM56	42	205	262	11.0	53.7
RB211-22B	386	447	102	39.4	45.6
RB211-524	351	472	102	35.8	48.1
TOTAL			1858	206.2	434.7

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[a] 15 year useful life.

[b] See Reference 3 for derivation.

[c] See Appendix B.

[d] See Appendix A.

Table 2

Reductions in Gaseous Emissions
Resulting from the 1985 Retrofit Standard

Model	Tons/Engine/Lifetime[a,b] HC	CO	In-Service[c] Engines	Total Tons/Lifetime (000) HC	CO
JT8D-17	38	109	2947	112.0	321.2
JT8D-209[d]	29	58	302	8.8	17.5
JT9D-7	78	141	616	48.1	86.9
CF6-6	46	93	399	18.4	37.1
CF6-50[e]	91	152	104	9.5	15.8
CFM56[d]	19	92	302	5.7	27.8
RB211-22B	206	238	399	82.2	95.0
TOTAL	-	-	5069	284.7	601.3

[a] Useful life is 8 years except as noted.

[b] See Reference 3 for derivation.

[c] See Appendix B.

[d] 12 year useful life.

[e] 11 year useful life.

Table 3

Reductions in Gaseous Emissions
Resulting from the 1984 NME Standards

Model	Tons/Engine/Lifetime[a,b] HC	CO	NOx	In-Service[c] Engines	Total Tons/Lifetime (000) HC	CO	NOx
JT8D-209[d,e]	65	130	65	468	30.4	59.4	30.4
	37	71	37	102	3.7	7.3	3.7
JT9D-7	140	220	121	1040	145.6	228.8	125.8
JT9D-70	53	195	63	1040	55.1	202.8	65.5
CF6-6	87	195	87	738	64.2	143.9	64.2
CF6-50	122	225	98	1437	175.3	323.3	140.1
CFM56[d]	42	205	26	468	19.7	95.9	12.2
	24	115	15	102	2.4	11.7	1.5
RB211-22B	386	447	55	738	284.9	329.9	40.6
RB211-524	338	446	95	1085	366.7	483.9	103.1
CF6-32[e]	71	160	71	933	66.2	149.3	66.2
RB211-535[e]	294	341	42	932	274.0	317.8	39.1
JT10D[e]	57	280	36	933	53.2	261.2	33.6
TOTAL				10,030	1541.4	2615.2	726.0

[a] 15 year useful life.

[b] See Reference 3 for derivation.

[c] See Appendix B.

[d] Two different annual LTO cycles used. The higher figure represents the twin-engined narrow-bodied application and the lower figure the B708 and DC-8 retrofit program. See Appendix A.

[e] See Appendix A.

The air quality benefits from controlling the JT8D family in 1984 are significant. As shown in Table 3, the contribution of the JT8D-209 to the emission reduction totals is fairly low. This should not suggest, however, that the engine will be rather unimportant in the 1984 NME fleet. The low in-service population of this engine is a function of the broad assumptions which were necessary to complete the fleet projection. There are indications that the dash 209 may be heavily utilized in the two-engine narrow-bodied fleet if the DC9 Super 80 is placed in production.

In a letter from Pratt and Whitney to the EPA (Reference 11), it is stated that aircraft such as the Super 80 have a market potential of 1000-2000 units by 1990. More specifically, a letter from McDonnell Douglas to the EPA (Reference 12) forecasts "a market for several hundred of the DC-9 Super 80 aircraft and its derivatives." Presumably these are worldwide production figures, but if a significant proportion of these aircraft are used by air carriers operating in the U.S., the dash 209 will be a very significant source of pollutants.

The JT10D was omitted in the 1981 NME and 1985 retrofit fleets (Tables 1 and 2). The engine's production design has not been finalized and no companion airframe exists at this time. For these reasons, it is unlikely that JT10D engines will be produced under the corresponding standards. A more complete discussion of this engine is contained in the section on engine costs.

The retrofit projection (Table 2) omits a separate category for the JT9D-70. The number of these retrofitted engines is expected to be quite small, so rather than venture a guess, the JT9D-70 is included in the JT9D-7 estimate. Although the dash 70 produces twice as much HC, the effect of its inclusion on the total emission reduction is insignificant.

COST

Background

For a more complete understanding of the EPA cost estimate, brief descriptions of the changes to the turbine engine hot section which are necessary for compliance with the exhaust emission standards and the cost components used in this analysis are presented. For a more rigorous discussion of the technology, the reader should refer to Reference 13.

Complexity. The requisite control techniques can be placed into three broad categories of development complexity.

Category 1 - Little or no difficulties encountered in development of the concept on most engines;

Category 2 - Only some minor to moderate difficulty anticipated in the development of the concept for an engine, usually associated with the combustor durability or performance; development is straightforward, although some time is required; and

Category 3 - A number of difficulties must be overcome in developing flightworthy hardware; preservation of other design criteria requires a compromise with the full potential of the emissions control device.

Complexity categories 1 and 2 essentially control HC and CO for the 1981 NME and 1985 Retrofit Standards, while category 3 adds NOx control for compliance with the 1984 NME Standard.

Control Methods

Fuel Sectoring. This method is used to improve the combustion conditions at idle which results in lower HC and CO emissions. Specifically, during the idle mode combustion is quite lean with an attendant low flame temperature; consequently, the combustion efficiency is poor because of inadequate heat to vaporize the fuel and to stimulate the $CO \rightarrow CO_2$ reaction. This problem is resolved by eliminating the fuel flow entirely to a part of the combustor (usually about half) and injecting it with the rest of the fuel into the remaining portion of the combustor. This has two beneficial effects: (1) the atomization of the fuel is improved and (2) the fuel/air ratio is increased (enriched) so that a hotter flame exists, improving vaporization of the fuel and enhancing the $CO \rightarrow CO_2$ reaction.

Minor combustor redesign. This method may consist of rich primary or delayed dilution concepts. With the rich primary concept, reducing primary airflow increases the local fuel/air ratio and hence the primary zone temperature. At low power, this is beneficial since the higher temperature enhances the $CO \rightarrow CO_2$ conversion when O_2 becomes available in the secondary and aids in fuel droplet evaporation, thereby improving the consumption of HC. If the primary zone equivalence ratio is greater than one, smoke becomes a problem requiring complicated air flow patterns and dilution zones in the secondary to consume it.

The delayed dilution concept consists of postponing the introduction of dilution air, producing a longer combustion zone at intermediate temperatures. This increases the residence time of the reactants, which allows the $CO \rightarrow CO_2$ conversion to approach equilibrium and for unburnt hydrocarbons to be consumed. The difficulty lies in adjusting the air flow in the intermediate zone at all power settings so it is hot enough for CO consumption, yet cold enough to prevent NOx, and still achieve flame stability, liner durability, etc.

Air blast. The pressure differential that exists between the compressor and the combustor is employed to produce high velocity air through a venturi system at the combustor inlet. This air is directed toward the fuel nozzle to help break up the fuel droplets, resulting in the elimination of locally rich hot spots and an improvement in combustion efficiency.

The basic concept is relatively simple since it only requires the addition of venturi tubes. However, to achieve the standards in most cases, it usually proves necessary to also optimize the airflow distribution of the liner. For this reason, the concept is placed in the second category of complexity.

Fuel staging. The combustor is divided into two regions, each having its own fuel injection system. These are termed the pilot stage and the main stage. At low power, fuel is supplied only to the pilot stage, thereby allowing a much higher local fuel/air ratio than would be possible if the fuel were distributed throughout the combustor. This mixture is then able to burn hotter, enhancing the $CO \rightarrow CO_2$ conversion and droplet evaporation (reducing HC).

At high power, the fuel is distributed between the two stages in such a way so as to minimize the peak temperature. This aids in preventing NOx production. Staging requires two fuel injection locations which adds to the complexity of the fuel supply system and the fuel control. The combustor liner is also more complex with additional cooling and temperature profile problems.

Table 4 summarizes the low-emission technology which is necessary for compliance with the standards.

Cost component elements. In this analysis the components of cost for each engine family are typically made up of several elements which when combined, account for all of the expenses incurred by the turbine engine manufacturers. Where appropriate these elements also include corporate profit. The main elements within each component are shown in Table 5.

ENGINE COST ESTIMATES

The cost estimates of the control hardware for each engine family are based on industry and NASA technology submittals to the Emission Control Technology Division as of 1 January 1978. A normal development schedule for the modifications is assumed since no major setbacks are expected.

Predicated on the information available at this time and with the knowledge that significant uncertainties exist, the accuracy of the cost estimates for the 1981 NME and 1985 retrofit technology are considered

Table 4

Control Complexity

Control Method		
1981 NME and 1985 Retrofit	1984 NME	Complexity Category
Sector burning		1
Minor combustor redesign		2
Air blast		2
	Fuel staging	3

Table 5

Cost Components and Their Elements

Component	Elements
Development	Design and general laboratory effort General engine hardware Specific modification hardware Various engine tests General engineering support Emission testing
Certification	Engine hardware Specific modification hardware Endurance test Certification test Miscellaneous tests Flight test Emissions test General engineering support
Service Evaluation	Administrative costs Maintenance Inspection Engine hardware
Initial Production	Tool design Tool procurement Initial start up
Engine Dedication	Engines
Non-Recurring Total	Development Certification Service Evaluation Initial Production Engine Dedication
New Engine Increment	Parts Labor
Retrofit	Parts

to be within a factor of 2, while the estimate of the 1984 NME technology is somewhat less reliable. Therefore, the numbers do not represent absolute values and should be interpreted with care.

1981 NME and 1985 Retrofit. The cost estimates for controlling HC and CO are summarized in Table 6. Generally, the differences between engine families of the same manufacturer are attributed to variations in modification complexity and engine size.

In all but one case, it is expected that the retrofit will require new engine parts. However, when production designs become available it may be found that additional parts can be reworked or modified by airline maintenance shops at a substanial savings, as is contemplated under the JT3D smoke retrofit program (Reference 9).

JT10D. This engine is excluded from the 1981 NME analysis because it is a new engine which has not been certified and does not have a companion airframe at this time.

There has been some discussion concerning a growth version of the original engine design being used on the Boeing 7S7 aircraft. However, the Boeing design has not been finalized and no certification date or delivery data has appeared in the literature. As the finalization of design is delayed, the more likely the production JT10D would contain a staged combustor (category 3) to avoid economic and logistic problems. If the EPA receives evidence to dispute the above assumption, the JT10D will be included in the next cost analysis.

(The same basic argument is true for the clipped fan CF6-32 and RB211-535 which are also candidates for the Boeing 7S7 as stated in Reference 14.)

JT9D-7, JT9D-70, and JT8D-209. Air blast is the control method used by these engine families. The JT9D-7 and JT8D-209 are expected to require modifications to the nozzles, nozzle supports, liner, and dome, while the JT9D-70 will require the same changes with the exception of the dome.

The development cost for the JT9D-7 is greater than the JT9D-70, reflecting combustor and carburetor modifications which are more significant departures from production hardware (Table 6).

CF6-6, CF6-50, and CFM56. The control method used by these engine families is sector burning. The hardware modifications are nozzle orifice diameter changes, nozzle support check valves in the primary fuel delivery of the unfueled sector, fuel manifold, and logic control.

Table 6

Engine Costs Associated with the
1981 NME and 1985 Retrofit Standard
(1976 dollars)

	ENGINE FAMILY							
	JT9D-7	JT9D-70	JT8D	CF6-6	CF6-50	CFM56	RB211-22	RB211-524
Development	6.4M	4.5M	2.7M	2.8M	2.8M	2.2M	3.3M	4.1M
Certification	3.5M	3.6M	2.4M	3.0M	3.5M	2.4M	3.1M	3.4M
Service Evaluation	2.0M	1.3M	0.9M	1.4M	1.4M		1.3M	1.3M
Initial Production	0.8M	0.5M	0.3M	0.4M	0.4M	0.3M	0.2M	0.2M
Non-Recurring Total	12.7M	9.9M	6.3M	7.6M	8.1M	4.9M	7.9M	9.0M
New Engine Increment	3.6M	4K	1.5K	5K	5K	3.4K	1K	1K
Retrofit	46K	39K	11K	50K	50K		31K	34K

The CFM56 does not require a service evaluation nor a retrofit kit since it is a new engine without previous field utilization (Table 6).

RB211-22 and RB211-524. These engine families will utilize minor combustor redesign. Changes are required to the dome and liner.

Rolls Royce has indicated that greater difficulties are expected in applying the requisite technology to the dash 524 than the dash 22; therefore, its development cost is somewhat higher (Table 6).

1984 NME. The cost estimate for controlling NOx in addition to HC and CO are summarized in Table 7. As with the 1981 NME and 1985 retrofit, differences between engine families of the same manufacturer are attributed to variations in modification complexity and engine size.

Many of the costs for similar engine families (e.g., CF6-6 and CF6-50) are identical (Table 7). Although the technology is well defined, its application to specific families is limited; therefore, the available data lack sufficient detail to allow discrimination between these families. The greatest variation is expected to occur in the development category. Nevertheless, these price differentials may have a tendency to cancel each other so that the total expenditure by the manufacturer relatively remains as indicated.

The reason one family may have a higher development cost than another family of similar design produced by the same manufacturer is quite obvious, unexpected problems, although the reasons for lower costs are less intuitive. Two of these reasons include: (1) the application of combustor technology to some engine families is partially complete since during its development, NASA contracts produced engine demonstrator hardware; and (2) some degree of commonality exists between similar engine families; therefore, after initial experience is gained, the learning curve for subsequent engines is enhanced.

All of the engines in compliance with the NOx standard will require essentially the same changes: liner, dome, fuel nozzle, fuel supports, fuel manifold, swirlers, and logic control.

JT9D-7, JT9D-70, JT10D, and JT8D-209. These engine families are expected to utilize Pratt and Whitney's Vorbix design. This is considered the most complex staged combustor and is reflected in the higher levels of most cost components (Table 7).

The JT10D is having its design work done after emission standards were promulgated. This means the staged comgustor will be incorporated with much less expense than if the engine design was finalized. Furthermore, at this point many of the costs associated with developing and manufacturing a new engine have not been incurred. For these reasons, the price increment for low-emission versus conventional hardware was estimated.

Table 7

Engine Costs Associated with 1984 NME Standard
(1976 dollars)

	ENGINE FAMILY								
	JT9D-7	*JT9D-70*	*JT10D*	*JT8D-209*	*CF6-6*	*CF6-50*	*CFM56*	*RB211-22*	*RB211-524*
Development	12.9M	12.9M	5.1M	10.7M	9.6M	9.6M	7.6M	10.3M	10.3M
Certification	7.8M	7.8M		5.2M	6.2M	6.2M	4.3M	6.2M	6.2M
Service Evaluation	5.3M	5.3M		3.7M	4.2M	4.2M	2.9M	4.2M	4.2M
Initial Production	4.2M	4.2M	1.6M	3.2M	3.8M	3.8M	2.9M	3.8M	3.8M
Engine Dedication	3.2M	3.6M		1.8M	3.2M	3.6M	2.2M	3.2M	3.6M
Non-Recurring Total	33.4M	33.8M	6.7M	24.6M	27M	27.4M	19.9M	27.7M	28.1M
New Engine	29K	29K	23K	19K	22K	22K	15K	22K	15K

CF-6, CF6-50, and CFM56. General Electric's Double Annular design will be used by these engine families.

RB211-22 and RB211-524. Information on the type of control technology is lacking for Rolls Royce engine families. This manufacturer has not participated in the initial technology development under the Experimental Clean Combustor Program. Since initial work has not predisposed them to a specific design, it seems likely that the less complex double annular combustor would be their choice. Therefore, this design is assumed with an additional increment for development since Rolls Royce will benefit less from NASA programs than did General Electric or Pratt and Whitney. The extent to which they may have been aided by the British government's National Gas Turbine Establishment is unknown.

ENGINE COST SUMMARY

Within this section engine costs are separated into non-recurring and recurring categories. Recurring costs are represented by the selling price increment per engine which reflects increments in the (1) manufacturing complexity and (2) hardware costs. Neither the selling price increment nor the retrofit unit cost include pro-rated non-recurring expenses.

The reader is reminded that important cost elements have been excluded from this analysis. These include probable maintenance penalties associated with hot section durability degradation and other expenses to the airlines as discussed in TSR AC77-02. Therefore, the results of this section should be regarded only as accounting for a significant share of the impact brought about by the proposed standards.

Tables 8, 9, and 10 summarize the costs associated with the 1981 NME, 1985 Retrofit, and 1984 NME Standards, respectively.

To derive a more accurate estimate of the total selling price increment, a 20 percent increase in the in-service fleet numbers (Appendix B) is used to develop cost information. These extra units reflect the spare parts inventory of the airlines.

As shown in Table 9, additional non-recurring expenses are not incurred under the 1985 retrofit since the same hardware is used to meet the 1981 NME Standard.

OPERATING COSTS

The only operating expense identified as a consequence of the control schemes is the increment in fuel consumption between regulated and non-regulated engines. This increment may take two forms. First, although no weight penalty results from the 1981 NME and 1985 Retrofit Standards, there is a 200-300 pound per engine penalty associated with

Table 8

The Costs Associated with the 1981
NME Standard (Category 1 and 2 Technology)

(In thousands of dollars)

Model	Non-Recurring Costs	Selling Price Increment/Engine	Total Engines	Selling Price Increment/Family
JT8D-17	a	1.5	659	989
JT8D-209	6,300	1.5	317	476
JT9D-7	12,700	3.6	149	536
JT9D-70	9,900	4.0	149	596
CF6-6	7,600	5.0	126	630
CF6-50	8,100	5.0	271	1355
CFM56	4,900	3.4	314	1068
RB211-22B	7,900	1	122	122
RB211-524	9,000	1	122	122
TOTAL	66,400			5,894

[a]Essentially the same combustor as the dash 209, therefore, no additional non-recurring.

Table 9

The Costs Associated with the 1985 Retrofit Standard
(Category 1 and 2 Technology)

(In thousands of dollars)

Model	Retrofit Unit Cost	Total Engines	Retrofit Cost/Family
JT8D-17	11	3536	38,896
JT8D-209[a]	1.5	362	543
JT9D-7	46	739	33,994
CF6-6	39	479	18,681
CF6-50	50	125	6,250
CFM56[a]	3.4	362	1,230
RB211-22B	31	479	14,849
TOTAL			114,443

[a] This is a new engine price increment instead of a retrofit kit price.

Table 10

The Costs Associated with the 1984 NME Standard
(Category 3 Technology)

(In thousands of dollars)

Model	Non-Recurring Costs	Selling Price Increment/Engine	Total Engines	Selling Price Increment/Family
JT8D-209	24,600	19	684	12,996
JT9D-7	33,400	29	1248	36,192
JT9D-70	33,800	29	1248	36,192
CF6-6	27,000	22	886	19,492
CF6-50	27,400	22	1724	37,928
CFM56	19,900	15	684	10,260
RB211-22B	27,700	22	886	19,492
RB211-524	28,100	15	1302	19,530
JT10D[a]	6,700	23	1120	25,760
CF6-32[a]	b	22	1120	24,640
RB211-535[a]	c	22	1118	24,596
TOTAL	228,600			267,078

[a] See Appendix A.

[b] Same core as CF6-6, therefore, no additional non-recurring.

[c] Same core as RB211-22B, therefore, no additional non-recurring.

the use of staged combustors to meet the 1984 NME Standard. The additional weight is expected to manifest itself as an increase in the aircraft's fuel consumption at cruise. The EPA is presently analyzing this problem to determine its magnitude, therefore, no quantitative expression of the penalty is included in this study. Second, to meet the proposed standards, manufacturers will improve the combustion efficiency of their engines, resulting in an idle specific fuel consumption (SFC) reduction for most engines.

A re-evaluation of the incremental fuel useage figures published in TSR AC77-02 on an engine-by-engine basis concluded that the estimates were excessive. Most engines will experience a 3 percent decrease in idle fuel consumption rather than a 5 percent decrease. No discrepancy was found in the 1 percent improvement claimed for the JT8D.

The fuel penalties associated with the General Electric engines in compliance with the 1981 NME and 1985 Retrofit Standards were also erroneous. The use of sector burning (category 1) by these engines causes a 8 percent decrease in component efficiency (instead of the 10 percent previously used), which coupled with the 3 percent benefit in combustion efficiency (instead of the 5 percent previously used), yields a 5 percent overall penalty in idle SFC.

Recent information concerning the CFM56 reveals that the CO emission standards can only be met by an increase in idle thrust from 4 to 6 percent. The EPA estimtes this will result in a 19.6 percent increase in idle fuel consumption in addition to any other fuel usage increment brought about by combustion efficiency changes or the use of sector burning.

The fuel consumption increments associated with the 1981 NME, 1985 Retrofit, and 1984 NME Standards are summarized in Tables 11, 12, and 13, respectively, in 1976 dollars.

General Electric's use of sector burning overwhelms the fuel savings from other engine families and causes a significant net fuel consumption increase for the 1981 NME Standard (Table 11). The penalty associated with GE's sector burning is also significant for the 1985 Retrofit Standard, although the net effect of the standard is an overall fuel savings (Table 12). The reduction in fuel consumption for each JT8D-17 engine in the 1985 retrofit fleet is small, but the number of in-service engines is so large that most of the GE penalty is offset. The total fuel savings for the 1985 Retrofit Standard is considered insignificant.

As shown in Table 13, a substantial fuel savings is brought about by the fleet in compliance with the 1984 NME Standard. The effect of the CFM56 idle power increase is reflected by a lifetime fuel penalty of $90,000 per engine.

Table 11

The Fuel Consumption Increment Associated with the 1981 NME Fleet

Model	In-Service[a] Engines	\$ Saved/Engine[b] ($x 10^{-3}$)	\$ Saved/Family ($x 10^{-6}$)
JT8D-209	264	9[c]	2.4
JT8D-17	549	9	4.9
JT9D-7	124	16	2.0
JT9D-70	124	16	2.0
CF6-6	105	-20	-2.1
CF6-50	226	-20	-4.5
CFM56	262	-144	-37.7
RB211-22	102	18	1.8
RB211-524	102	19	1.9
TOTAL			-36.7

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[a]See Appendix B.

[b]See Reference 3 for derivation.

[c]See Appendix A.

Table 12

The Fuel Consumption Increment Associated with the 1985 Retrofit Fleet

Model	In-Service[a] Engine	\$ Saved/Engine[b] ($\times 10^{-3}$)	\$ Saved/Family ($\times 10^{-6}$)
JT8D-17	2947	5	14.7
JT8D-209	302	7	2.1
JT9D-7	616	9	5.5
CF6-6	399	-11	-4.4
CF6-50	104	-15	-1.6
CFM-56	302	-65	-19.6
RB211-22	399	10	4.0
TOTAL			0.7

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[a] See Appendix B.

[b] See Reference 3 for derivation.

Table 13

The Fuel Consumption Increment Associated with the 1984 NME Fleet

Model	In-Service[a] Engines	$ Saved/Engine[b] ($x 10^{-3}$)	$ Saved/Family ($x 10^{-6}$)
JT8D-209[c]	468	9[c]	4.2
	102	5	0.5
JT9D-7	1040	16	16.6
JT9D-70	1040	16	16.6
CF6-6	738	12	8.9
CF6-50	1437	12	17.2
CFM-56[c,d]	468	-90	-42.1
	102	-51	-5.2
RB211-22	738	18	13.3
RB211-524	1085	19	20.6
CF6-32[d]	933	10[b]	9.1
RB211-535[d]	932	14[b]	13.1
JT10D[d]	933	17[b]	15.9
TOTAL			88.7

[a] See Appendix B.

[b] See Reference 3 for derivation.

[c] Two different annual LTO cycles used. The higher figure represents the twin-engined narrow-bodied application and the lower figure the B707 and DC-8 retrofit program. See Appendix A.

[d] See Appendix A.

COST EFFECTIVENESS

The overall cost effectiveness for each of the standards under consideration is presented in Table 14. The HC and CO cost-effectiveness figures for the 1981 NME and 1985 retrofit combination are comparable, contrary to what would be expected. Primarily, by adding the retrofit and 1981 NME fleets, the non-recurring costs are amortized over a greater number of engines, reducing the unit cost and increasing the emission reductions which substantially enhances the cost effectiveness of the control strategy. However, the benefit is eroded by fuel penalties accompanying sector burning.

As pointed out earlier, the cost-effectiveness figures calculated in this analysis (Table 14) and those presented in TSR AC77-02 (Table 15) are not directly comparable. However, the difference in magnitude between the two NOx cost-effectiveness numbers requires some explanation. First, there are significant variations between EPA and industry cost estimates of the control hardware necessary to meet the proposed standards. Based on the information accumulated at this time, the EPA is unable to account for the gross differences in both the non-recurring costs and selling price increments. It is expected that information received during the comment period of the NPRM concerning the proposed standards will help explain these discrepancies.

Second, the FAA fleet projection used in this analysis (Appendix B), forecasts 3676 more in-service engines for the 1984 NME fleet than was used in the preceeding analysis. (Part of this increase is also accounted for by the use of a 15 year production period instead of the 10 year period used in AC77-02). This allows the non-recurring costs of control to be amortized over a greater number of engines, thereby substantially reducing the cost per engine while increasing the amount of the pollutants abated and the incremental fuel savings.

The above factors, acting in concert, offset reductions in the fuel saved by each engine (as discussed in Operating Costs), and substantially augment the cost effectiveness of the standards under consideration.

The control of HC from aircraft turbine engines in 1981 and 1985 is more cost effective than that for most other control strategies under consideration, while the cost effectiveness of controlling NOx emissions from aircraft turbine engines in 1984 is substantially better (Tables 14 and 16).

Table 14

The Overall Cost-Effectiveness of the Standards Under Consideration ($/Ton)

Pollutant	1981 NME	1985 Retrofit in addition to 1981 NME	1984 NME
HC	260	230	260[a]
CO	125	110	125[a]
NOx			-450

[a] The HC and CO values are the same as for 1981 NME.

Table 15

The Overall Cost-Effectiveness of the Standards Under Consideration Based on Industry Submittals[a] ($/Ton)

Pollutant	1981 NME	1985 Retrofit in addition to 1981 NME	1984 NME
HC	560	390	560[b]
CO	220	170	220[b]
NOx			1316

[a] TSR AC77-02 (Reference 3).

[b] The HC and CO values are the same as for 1981 NME.

Table 16

The Overall Cost-Effectiveness of Other Control Strategies Under Consideration ($/Ton)

Strategy	HC	NOx[a]
Stationary Engines (75% control)		340
LDV (1.0 g/mile)		450
Utility Boilers (90% control)		1200
LDV (0.41 g/mile)		2300
Gasoline Handling, Stage 1	100[a]	
Gasoline Handling, Stage 2	700[a]	
LDV (0.41 g/mile)	470[a]	
LDV (IM)	420[b]	
Neighborhood Dry Cleaners	770[b]	

[a] Reference 10.

[b] Reference 15.

Part II

This portion of the Discussion was prepared to present an alternative cost-effectiveness analysis of the proposed standards. The basis of each data element used in this alternative is the same as that described in Part I; therefore, the discussion of these fundamentals is not reiterated.

The cost-effectiveness determination described in this part has two principle components. First, the consequences of promulgating the 1981 NME Standard as the final requirement for all newly manufactured engines are examined, i.e., 1981 to 1999. Second, since the HC and CO standards for 1981 NME and 1984 NME are equivalent, the incremental burden of NOx control is quantified by determining the costs and benefits accrued beyond those encountered by controlling these two pollutants in 1984 with 1981 technology.

EMISSION REDUCTIONS

The reductions in gaseous emissions for the 1981 NME and 1985 Retrofit Standards are shown in Table 17. The HC and CO lifetime savings brought about by each standard are combined in this table which reflects the fact that it is unlikely either standard would be promulgated separately. This approach is followed throughout the remainder of the analysis.

Table 18 shows the effect of the 1984 NME Standard on NOx emissions. It is assumed that the lifetime reductions per engine for HC and CO brought about by the 1981 NME and 1984 NME Standards are equivalent. In reality, a difference exists between the ability of 1981 and 1984 hardware to reduce these two pollutants (Table 1 and 3, respectively). It may be argued that these differences represent additional increments of control effectiveness and should be allocated to the costs of 1984 technology. However, a preliminary review of this variability found the total reductions achieved by the two technologies differed by less than 3 percent in each case. This is well within the uncertainty of the analysis; therefore, the simplification has no measurable impact on the final results, and NOx control is retained as the only increment being analyzed.

ENGINE COST SUMMARY

Table 19 is a summary of the costs associated with the control of HC and CO. The incremental cost burden for NOx control is summarized in Table 20. This burden includes the 1981 versus 1984 new engine selling price differential.

Table 17

Reductions in Gaseous Emissions
Resulting from the 1981 NME and 1985 Retrofit Standards

	1981 NME					1985 Retrofit						
				A					B		A + B	
	Tons/Engine/Lifetime		In-service	Total Tons/Lifetime(000)		Tons/Engine/Lifetime		In-Service	Total Tons/Lifetime(000)		Total Ton(000)	
	HC	CO	Engines	HC	CO	HC	CO	Engines	HC	CO	HC	CO
JT8D-17	70	204	549	38.4	125	38	109	2947	112.0	321.2	150.4	446.2
JT8D-209	65	130	732	47.6	95.2	29	58	404	11.7	23.4	59.3	118.6
JT9D-7	146	264	1164	169.9	307.3	78	141	616	48.1	86.9	218.0	394.2
JT9D-70	72	242	1164	83.8	281.7	NA	NA	NA	NA	NA	83.8	281.7
CF6-6	87	174	843	73.3	146.7	46	93	399	18.4	37.1	91.7	183.8
CF6-50	125	207	1663	207.9	344.2	91	152	104	9.5	15.8	217.4	360.0
CFM56	42	205	730	30.7	149.7	19	92	404	7.7	37.2	38.4	186.9
RB211-22B	386	447	840	324.2	375.5	206	238	399	82.2	95.0	406.4	470.5
RB211-524	351	472	1187	416.6	560.3	NA	NA	NA	NA	NA	416.6	560.3
JT10D[a]	57	279	933	56.6	260.3	NA	NA	NA	NA	NA	56.6	260.3
CF6-32[a]	71	143	933	66.2	133.4	NA	NA	NA	NA	NA	66.2	133.4
RB211-535[a]	293	340	932	273.1	316.9	NA	NA	NA	NA	NA	273.1	316.9
Total				1788.3	3096.2				289.6	616.6	2077.9	3712.8

[a] See Appendix A

Table 18

Incremental Reductions in Gaseous Emissions
Resulting from the 1984 NME Standard

Model	Tons/Engine/Lifetime[a] NOx	In-Service Engines	Total Tons/Lifetime (000) NOx
JT8D-209[b]	65 37	468 102	30.4 3.7
JT9D-7	121	1040	125.8
JT9D-70	63	1040	65.5
CF6-6	87	738	64.2
CF6-50	98	1437	140.1
CFM56[b]	26 15	468 102	12.2 1.5
RB211-22B	55	738	40.6
RB211-524	95	1085	103.1
CF6-32[c]	71	933	66.2
RB211-535[c]	42	932	39.1
JT10D[c]	36	933	33.6
TOTAL		10,030	726.0

[a] HC and Co reductions are considered to be equivalent to the 1981 NME Standard's.

[b] Two different annual LTO cycles used. The higher figure represents the twin-engined narrow-bodied application and lower figure the B708 and DC-8 retrofit program. See Appendix A.

[c] See Appendix A.

Table 19

The Costs Associated with the 1981 NME and 1985 Retrofit Standards (Category 1 and 2 Technology)

(In thousands of dollars)

	1981 NME				1985 Retrofit			
				A			B	A + B
Model	Non-Recurring Costs	Selling Price Increment/Engine	Total Engines	Selling Price Increment/Family	Retrofit Unit Cost	Total Engines	Retrofit Cost/Family	Total Recurring Costs
JT8D-17	a	1.5	659	989	11	3536	38,896	39,885
JT8D-209	6300	1.5	1001	1502	1.5[f]	362	543	2045
JT9D-7	12,700	3.6	1397	5029	46	739	33,994	39,023
JT9D-70	9900	4.0	1397	5588	NA	NA	NA	5588
CF6-6	7600	5.0	1012	5060	39	479	18,681	23,741
CF6-50	8100	5.0	1995	9975	50	125	6250	16,225
CFM56	4900	3.4	998	3393	3.4[f]	362	1230	4623
RB211-22B	7900	1	1008	1008	31	479	14,849	15,857
RB211-524	9000	1	1424	1424	NA	NA	NA	1424
JT10D	b	b	1120	0	NA	NA	NA	0
CF6-32[c]	d	4	1120	4480	NA	NA	NA	4480
RB211-535[c]	e	1	1118	1118	NA	NA	NA	1118
TOTAL	66,400			39,566			114,443	154,009

[a] Essentially the same combustor as the dash 209, therefore, no additional non-recurring.

[b] New engine design negligible impact on cost.

[c] See Appendix A.

[d] Same core as CF6-6, therefore, no additional non-recurring.

[e] Same core as RB211-22B, therefore, no additional non-recurring.

[f] This is a new engine price increment instead of retrofit kit price.

Table 20

The Costs Associated with the 1984 NME Standard for NOx
(Category 3 Technology)

(In thousands of dollars)

Model	Non-Recurring Costs	Selling Price Differential/Engine	Total Engines	Selling Price Differential/Family
JT8D-209	24,600	18	684	12,312
JT9D-7	33,400	25	1248	31,200
JT9D-70	33,800	25	1248	31,200
CF6-6	27,000	17	886	15,062
CF6-50	27,400	17	1724	29,308
CFM56	19,900	12	684	8,208
RB211-22B	27,700	21	886	18,606
RB211-524	28,100	14	1302	18,228
JT10D[a]	6,700	21	1120	23,520
CF6-32[a]	b	18	1120	20,160
RB211-535[a]	c	21	1118	23,478
TOTAL	228,600			231,282

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[a] See Appendix A.

[b] Same core as CF6-6, therefore, no additional non-recurring.

[c] Same core as RB211-22B, therefore, no additional non-recurring.

OPERATING COSTS

The fuel consumption increments associated with the 1981 NME and 1985 retrofit fleets are shown in Table 21, while the fuel differential associated with the 1984 standard is shown in Table 22. When the use of 1981 control technology is extended, the fuel penalty associated with General Electric's sector burning concept becomes very significant because of the large production volume associated with the standard. This not only manifests itself by increasing the cost of controlling HC and CO, but provides an additional fuel savings when 1984 technology is introduced.

The net fuel penalty associated with the 1985 retrofit is considered insignificant relative to the uncertainty of the analysis (Table 21). Primarily, the fuel saved by the large number of JT8D engines in the fleet offsets most of the fuel consumption increase brought about by General Electric's use of sector burning.

COST EFFECTIVENESS

The overall cost effectiveness for each of the proposed standards under consideration is presented in Table 23. As expected, a very significant reduction in the 1981 NME and 1985 retrofit control strategy cost-effectiveness ratios for HC and CO has resulted. By lengthening the production time interval of the 1981 standard by 15 years (in reality the standard is infinite), the non-recurring costs are amortized over more engines, reducing the unit cost while increasing the reductions in gaseous emissions. These benefits overwhelm the accompaning fuel penalty which accounts for about one-fourth of the total HC and CO control cost.

Also as expected, the cost-effectiveness ratio of the NOx control strategy increased substantially over the -$450 derived in Part I (Table 14). This increase is a consequence of applying the entire burden of 1984 NME technology to NOx control.

As shown in Tables 23 and 16, controlling HC emissions by a single newly manufactured engine standard in 1981 and a retrofit standard in 1985 is more cost effective than any of the other proposed control strategies. Furthermore, the cost effectiveness of controlling NOx emissions from aircraft engines is comparable to the most cost effective control strategies under consideration.

Table 21

The Fuel Consumption Increment Associated with the 1981 NME and 1985 Retrofit Fleets

Model	1981 NME			1985 Retrofit			
			A			B	A + B
	In-service Engines	\$ Saved/Engine $(x\ 10^{-3})$	\$ Saved/Family $(x\ 10^{-6})$	In-Service Engine	\$ Saved/Engine $(x\ 10^{-3})$	\$ Saved/Family $(x\ 10^{-6})$	Total \$ Saved $(x\ 10^{-6})$
JT8D-209	732	9	6.6	3049	5	15.3	21.9
JT8D-17	549	9	4.9	302	7	2.1	7.0
JT9D-7	1164	16	18.6	616	9	5.5	24.1
JT9D-70	1164	16	18.6	NA	NA	NA	18.6
CF6-6	843	-20	-16.9	399	-11	-4.4	-21.3
CF6-50	1663	-20	-33.3	104	-15	-1.6	-34.9
CFM56	730	-144	-105.1	404	-65	-26.3	-131.4
RB211-22	840	18	15.1	399	10	4.0	19.1
RB211-524	1187	19	22.6	NA	NA	NA	22.6
CF6-32[a]	933	-16	-14.9	NA	NA	NA	-14.9
RB211-535[a]	932	14	13.1	NA	NA	NA	13.1
JT10D[a]	933	17	15.9	NA	NA	NA	15.9
TOTAL			-54.8			-5.4	-60.2

[a] See Appendix A.

Table 22

The Fuel Consumption Differential Associated with the 1984 NME Fleet

Model	In-Service Engines	1984 NME Baseline		1981 NME Baseline		Differential
		$ Saved per Engine ($\times 10^{-3}$)	A $ Saved per Family ($\times 10^{-6}$)	$ Saved per Engine ($\times 10^{-3}$)	B $ Saved per Family ($\times 10^{-6}$)	A + B $ Saved per Family ($\times 10^{-6}$)
JT8D-209[a]	468	9	4.2	9	4.2	0
	102	5	0.5	5	0.5	0
JT9D-7	1040	16	16.6	16	16.6	0
JT9D-70	1040	16	16.6	16	16.6	0
CF6-6	738	12	8.9	-20	-14.8	23.7
CF6-50	1437	12	17.2	-20	-28.7	45.9
CFM-56[a]	468	-90	-42.1	-144	-67.4	25.3
	102	-51	-5.2	-81	-8.3	3.1
RB211-22	738	18	13.3	18	13.3	0
RB211-524	1085	19	20.6	19	20.6	0
CF6-32[b]	933	10	9.1	16	-14.9	24.0
RB211-535[b]	932	14	13.1	14	13.1	0
JT10D[b]	933	17	15.9	17	15.9	0
Total			88.7		-59.8	122.0

[a] Two different annual LTO cycles used. The higher figure represents the twin-engined narrow-bodied application and the lower figure the B707 and DC-8 retrofit program. See Appendix A.

[b] See Appendix A.

Table 23

The Overall Cost-Effectiveness of the
Standards Under Consideration ($/Ton)

Pollutant	1985 Retrofit in addition to 1981 NME	1984 NME
HC	70	70
CO	40	40
NOx	-	470

Table 16

The Overall Cost-Effectiveness of Other
Control Strategies Under Consideration ($/Ton)

Strategy	HC	NOx[a]
Stationary Engines (75% control)		340
LDV (1.0 g/mile)		450
Utility Boilers (90% control)		1200
LDV (0.41 g/mile)		2300
Gasoline Handling, Stage 1	100[a]	
Gasoline Handling, Stage 2	700[a]	
LDV (0.41 g/mile)	470[a]	
LDV (IM)	420[b]	
Neighborhood Dry Cleaners	770[b]	

[a] Reference 10.

[b] Reference 15.

CONCLUSIONS

The cost-effectiveness information presented in this report was prepared from existing EPA cost data. Important uncertainties exist at this time; therefore, any conclusions must be interpreted with care.

In most cases, the differences between industry and EPA cost estimates of the requisite control hardware are significant and unaccounted for. It is expected that information received during the comment period of the NPRM concerning the proposed revisions in the standards will help explain these discrepancies.

The consequences of alternative control strategies and cost accounting methods were analyzed. The impact of the proposed standards on incremental fuel usage at idle varied under the two alternatives examined, although the results were generally consistent.

A significant overall fuel consumption penalty was calculated for engines in compliance with the 1981 NME Standard. The 1985 Retrofit Standard typically had an insignificant net effect on fuel consumption. A substantial fuel savings was associated with the 1984 NME Standard.

Depending on the method of determination, controlling HC emissions from gas turbine aircraft engines to the levels prescribed by the 1981 NME Standard or in conjunction with the 1985 Retrofit Standard was found to be more cost effective than all, or most of the other control strategies under consideration. The cost effectiveness of NOx control under the 1984 NME Standard was substantially better than, or comparable to the most cost effective of the other proposed control strategies for mobile and stationary sources.

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APPENDIX A

The following information is necessary to complete the derivation of emissions reduction and fuel savings as presented in Appendix B of TSR AC77-02.

Engine Parameters

JT8D-209:

1. Rated thrust is 18,500 pounds;

2. Impulse over the cycle is 1684 pound-hours;

3. Baseline EPAPs based on fuel flow and pressure ratio corrections from JT8D-17 data are HC 2.3, CO 8.5, and NOx 6.4 pounds per 1000 pound-hours impulse over the LTO cycle; and

4. Regulated EPAPs are HC 0.2, CO 4.4, and NOx 4.3 pounds per 1000 pound-hours impulse over the LTO cycle; and

5. $\dot{M}_f$ at idle is 1090 lbms/hr.

CF6-32:

1. All the necessary information is based on derivations for the CF6-6, which has the same core, by using a correction factor based on the rated thrust of the engines (CF6-32 at 32,000 lbs ÷ CF6-6 at 39,000 lbs = 0.82).

RB211-535:

1. Same method as used for the CF6-32 above, only the correction factor is based on the RB211-22B, which has the same core as the RB211-535 (32,000 lbs ÷ 42,000 lbs = 0.76).

JT10D:

1. Same method as used for the CF6-32 above, only correction the factor is based on the CFM56 without the penalties associated with sector burning and increase idle power. Both engines are a low emission design (30,000 lbs ÷ 22,000 lbs = 1.36).

CFM56:

1. The baseline $\dot{M}_f$ idle has been increased to 714 lbs/hr from the 600 lbs/hr published in TSR AC77-02. To achieve the CO level under each standard, the idle thrust must be increased from 4% to 6%, resulting in a corrected M_f idle of 854 lbs/hr. The use of sector burning to comply with the 1981 NME and 1985 Retrofit Standards has an associated 5% penalty in addition to that brought about by the thrust idle increase.

LTO Cycles

A re-evaluation of the LTO cycle figures used in TSR AC77-02 to represent the number of operations an engine experiences in its useful life found that the figure used to reflect the retrofit of the B707-DC-8 fleet was inappropriate. The long-haul operational nature of these aircraft precludes a high number of LTOs. Therefore, a review of the CAB data necessitated a change from 2455 to 1380 LTOs per year for the engines used in the B707 and DC-8 retrofit fleet (JT8D-209 and CFM56).

APPENDIX B

Fleet Projection and Engine Inventory

There are three aircraft fleets of interest, each associated with one of the three dates of the standards: 1981 (NME: HC, CO), 1984 (NME: NOx), and 1985 (Retrofit for pre-1981 engines to 1981 NME levels). The associated engine inventories are obtained from Reference 1, Table VII. The derivation of this inventory projection contains certain important assumption that are worth noting here:

(1) The original fleet projection comes from an unpublished forecast made by the FAA (to the year 2000), which apparently was derived from the same study that produced Reference 2;

(2) The introduction of new aircraft models are accounted for in the following manner: the 1981 NME fleet includes the DC-9-S80 and B737-300, and the 1984 NME fleet includes 2 and 3-engined versions of the B7S7, L1011-600, and Twin DC-10;

(3) The B707 and DC-8 will remain in the fleet in declining numbers, but will be re-engined by 1985 with the CFM56 and JT8D-209 equally to meet environmental regulations;

(4) The all new B7S7 will be powered by the "clipped fans" engines, CF6-32 and RB211-535, and by the JT10D (this mix reflecting the state of uncertainty at this time); and

(5) Aircraft are expected to be in service 15 years, regardless of category or type, this corresponding roughly to the depreciation period.

In addition, there is the difficulty of specifying an inventory for the 1984 standard which is indefinite in duration. For the purposes of costeffectiveness estimating, it is postulated that a reasonable number of engines to consider are those over which the R & D, certification, and intital tooling costs (i.e., the fixed costs) would be amortized. Beyond this number, the cost would be reduced and the cost effectiveness increased unless, of course, those engine types are replaced by newly certification engine for which some of the fixed cost burden is repeated.

It is assumed here that the write-off period of the fixed costs constitutes 15 years of production (i.e., to 1999). It may be argued that this is an unlikely long period inasmuch as most of the engines in question were originally configured in the 1960s. Nonetheless, the high cost of development, the refinement of technology, and the timing of new technology (e.g., the NASA Energy Efficient Engine program) suggest that the present engines and their derivatives will be around for a long time. Thus, 15 years is used.

Table B-1 presents the projection of the engine inventory.

Table B-1

Engine Inventory

Engine	Standard: 1985 Retrofit	1981 NME	1984 NME
JT8D-17	2947	549	0
JT8D-209	302	264	570[a]
JT9D-7	616	124	1040
JT9D-70	0	124	1040
JT10D	0	0	933
CF6-6	399	105	738
CF6-50	104	226	1437
CF6-32	0	0	933
CFM56	302	262	570[a]
RB211-22B	399	102	738
RB211-524	0	102	1085
RB211-535	0	0	932

[a] These numbers include 102 engines newly built in 1984 to be retrofitted onto the B707 and DC-8 fleet for compliance with the 1985 Retrofit Rule. Although these engines exceed the requirements specified by the rule, their date of manufacture forces them to comply with the more stringent standard.

References

(Appendix B)

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