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COST EFFECTIVENESS OF LARGE AIRCRAFT ENGINE EMISSION CONTROLS

— FINAL REPORT —

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Mobile Source Air Pollution Control
Emission Control Technology Division
Ann Arbor, Michigan 48105

Technical Report

Cost Effectiveness of Large Aircraft Engine Emission Controls

Final Report

by

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

EXECUTIVE SUMMARY

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 strategies is compared and the most effective are implemented. This report contains the final cost-effectiveness analysis of alternative aircraft emission control strategies. It was prepared in support of the current rulemaking action on aircraft engine gaseous exhaust emission standards (43 FR 12615).

The cost effectiveness of promulgating alternative emission standards was determined by evaluating several emission control scenarios which are based on three basic control strategies. The three strategies are:

1. 1982 NME -- Control newly-manufactured commercial gas turbojet or turbofan engines in 1982 for HC and CO;

2. 1986 IUE -- Retrofit in-use commercial gas turbojet or turbofan engines by 1986 for HC and CO; and

3. 1986 NME -- Control newly-manufactured commercial gas turbojet or turbofan engines in 1986 for HC, CO, and NOx.

Cost-effectiveness values were developed for the following emission control scenarios:

1. 1982 NME only;
2. 1982 NME and 1986 IUE only;
3. 1982 NME in conjunction with 1986 NME;
4. 1982 NME and 1986 IUE in conjunction with 1986 NME;
5. 1986 NME only;
6. 1982 NME only, when CF6 engines use an alternative combustor;
7. 1982 NME and 1986 IUE with the CF6 alternative combustor;
8. 1986 NME in conjunction with 1982 standards; and
9. 1986 NME in conjunction with 1982 standards and the CF6 alternative combustor.

The 1986 IUE Standard was not evaluated as a separate control scenario because it would not be implemented without an accompanying newly-manufactured engine standard. The retrofit (1986 IUE) is evaluated, however, as a control strategy to detemine its incremental cost effectiveness as an addition to the 1982 NME Standard.

This report is the result of a comprehensive effort by EPA to accurately assess the cost effectiveness of the proposed aircraft engine emission standards. Consequently all of the major costs of pollution control for large turbine engines were analyzed and documented. A special effort was made to ensure the validity of the economic impact analysis by assembling cost information from several sources. EPA was able to independently judge the accuracy of the cost data used in this study by: 1) gathering cost data from manufacturers in a standardized format to allow comparisons between industry sources; 2) using information from other sources including major airlines, original equipment vendors, independent manufacturers of engine combustion chambers, and previous EPA reports and contract efforts; and 3) preparing new cost estimates with the data elements acquired from the above sources.

In spite of the efforts made to gather accurate cost data and because of uncertainties in forecasting future airline aircraft requirements, the values derived in this analysis should be interpreted as being representative and not absolute indicators of cost effectiveness.

Methodology

The procedure used in this analysis consisted of determining the annual costs and exhaust emission reductions for the fleet-weighted average engine under each control scenario or strategy, as appropriate. A portion of the total annual cost was allocated to the reduction of each pollutant by using either of two methodologies. The methodologies differ in the way the cost is distributed among the pollutants.

The first method divides the control costs equally between the pollutants being regulated by each particular standard. The second method allocates the compliance costs by specifying a maximum allowable cost-effectiveness value for one or more of the pollutants. The remaining unaccounted for portion of the total cost is then burdened to the pollutants for which no cost-effectiveness values were specified. Regardless of the cost methodology which was used, the resulting HC, CO, and NOx cost-effectiveness factors are defined in terms of dollars spent per ton of pollutant reduced ($/t). The costs of pollution control are expressed in 1978 dollars throughout this analysis.

The relative cost effectiveness of the aircraft engine standards was evaluated by comparing their costs and benefits with those for non-aircraft control strategies which are either presently in effect, or may be implemented in the future.

Results

The 1982 Newly-Manufactured Engine (NME) and 1986 In-Use Engine (IUE) Standards were found to be as cost effective as other non-aricraft control strategies under every scenario evaluated. However, no scenario containing the 1986 NME low-NOx standard was found to be as cost effective at this time. The higher cost-effectiveness values for NOx control are principally caused by a large maintenance increase which appears to be associated with low-NOx stage-combustion systems.

The effect on cost-effectiveness values of excluding sunk investment costs was investigated since money which has already been spent is not relevant to the present issue of deciding whether or not to proceed with implementing the aircraft standards. It was found that by using only the costs which have yet to be spent, the cost-effectiveness values of the 1982 NME and 1986 IUE Standards were reduced up to about 45 percent from the figures derived by using the total cost (past and present) of the standards. The cost-effectiveness values for the 1986 NME low-NOx standard were not significantly affected. None of the cost-effectiveness values for any of the standards were sensitive to reasonable changes in the projection of new engine production.

The cost-effectiveness values for aircraft exhaust emission standards are summarized below. They were calculated by excluding sunk costs and by using the most appropriate cost allocation methodology. Under these constraints, the figures represent the maximum cost-effectiveness values (i.e., the highest cost per ton of pollutant reduced), for the scenarios and strategies considered in the analysis.

Scenario/Strategy 1/	Maximum Value Cost Effectiveness ($/t) (Sunk Costs Excluded)		
	HC	CO	NOX
1982 NME only	160	120	N/A
1982 NME and 1986 IUE only	200	160	N/A
1982 NME in conjunction with 1986 NME	260	150	N/A
1982 NME and 1986 IUE in conjunction with 1986 NME	420	150	N/A
1986 NME only	1,781	150	3,400
1986 NME in conjunction with 1982 standards	N/A	N/A	9,700
1986 IUE strategy only (analyzed as an increment to 1982 NME)	925	150	N/A

1/ See Table 1 for a complete explaination of the scenarios.
N/A - Not Applicable.

The analysis identified some consistent patterns of economic and energy impacts. The average engine produced in compliance with the 1982 NME Standard, or the 1982 NME Standard and the 1986 IUE Standard when evaluated as a single control strategy, will experience penalties in fuel consumption during taxi-idle ($+230 to $+1300/yr), and in hot section maintenance ($+530 to $+630/yr). The increased fuel consumption results from the use of sector-burning control technology in many engines. When the 1986 IUE Standard was considered as a separate control strategy from the 1982 NME Standard, the retrofit would result in a small decrease in taxi-idle fuel consumption ($-500/yr), but this cost was offset by a small maintenance increase ($+460/yr).

For engines complying with the 1986 NME Standard, which reduces NOx in addition to HC and CO, both a benefit and penalty in fuel consumption were calculated. The benefit occurs during taxi-idle because of increased combustion efficiency ($-1100 to $-2200/yr). The penalty occurs during cruise flight and is the consequence of an increase in aerodynamic drag resulting from the additional weight of the low-emissions combustor ($+1130/yr). The overall change in fuel consumption ranges from about zero to a small decrease in fuel use ($0 to $-1100/yr). A very significant maintenance penalty may occur for the average engine produced under the 1986 NME Standard ($+42,500/yr). Because of the magnitude of this penalty and the speculative nature of the assumptions upon which it is based, EPA will continue to evaluate the potential maintenance increments of low-NOx staged combustors during the final rulemaking on aircraft engine emission standards.

As described in the preceding paragraph, the proposed standards could result in fuel consumption increments ranging from an increase of up to about $1300/yr, to a decrease of about $1100/yr for the fleet-weighted average engine. The increase of $1300/yr is associated with the average engine produced in compliance with the 1982 NME Standard when the 1986 NME Standard is also promulgated (this fuel penalty lasts for the 4-year life of the 1982 standard). The decrease of $1100/yr is associated with the average engine produced in compliance with the 1986 NME Standard. The figures are equal to or less than about 0.2 percent of the total fuel consumed by the average aircraft engine in one year. Expressed differently, the change in annual fuel consumption for all of the aircraft engines in the U.S. fleet would equal the annual heating requirements of about 20,000-25,000 homes in Detroit, Michigan.

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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 strategies is compared and the most effective are implemented. This report contains the final cost-effectiveness analysis of alternative aircraft emission control strategies. It was prepared in support of the current rulemaking action on aircraft engine gaseous exhaust emission standards (43 FR 12615).

Several alternative scenarios which incorporate three basic control strategies are evaluated. The three strategies are:

1. Control newly-manufactured commercial gas turbojet or turbofan engines in 1982 for HC and CO (1982 NME);

2. Retrofit in-use commercial gas turbojet or turbofan engines by 1986 for HC and CO (1986 IUE); and

3. Control newly-manufactured commercial gas turbojet or turbofan engines in 1986 for HC, CO, and NOx (1986 NME).

This final report is the result of an extensive effort to assemble and document uniform cost data from the aircraft engine manufacturers and the domestic air carriers. The effort yielded more specific and complete cost information than was available at the time the two previous cost-effectiveness analyses were prepared (Wilcox and Munt, 1977 and 1978). In addition to the information gathered by EPA's active solicitation of data from the industry, all comments received regarding the March 24, 1978 Notice of Proposed Rulemaking (NPRM) were considered in the preparation of this report.

Every major cost element has been accounted for in the analysis. The cost figures in this report are based on data gathered from a variety of sources: engine manufacturers, original equipment vendors, major airlines, and previously documented information. EPA critically reviewed all of this data. Special attention was given to the information supplied by the engine manufacturers, since they have historically overestimated the economic impact of aircraft pollution control requirements. The Agency supplemented and attempted to verify the industry figures with data from other sources whenever possible. In some cases, industry data was tempered by EPA's best judgment when large inconsistencies between industry submittals were evident. If the necessary cost data were completely lacking or if the economic claims were clearly unjustifiable, substitutions were made based on previously documented information.

The added effort which was required to quantify some of the minor cost elements could not be justified since it is doubtful that their inclusion would significantly affect the concluding cost-effectiveness values. Also, because of the conservative nature of the industry submitted cost estimates, i.e., many appear to be excessive, it is assumed that the smaller undocumented costs are accounted for in the industry figures which were used in the analysis; therefore, their specific inclusion would be repetitive.

The complexity of the subject matter necessitates the use of simplifying assumptions and projections in an attempt to ascertain future facts. No matter how carefully considered, these forecasts will be subject to error and individual interpretation. Within these constraints, the cost-effectiveness ratios derived in this analysis represent EPA's best estimate of the costs and benefits which will accrue by implementing any of the alternative control scenarios. Furthermore, these values should be interpreted as being representative and not absolute cost-effectiveness indicators.

The Discussion section of this analysis is divided into three parts. Part I documents the various cost parameters and fully explains the derivation of the overall cost-effectiveness values for the various aircraft engine control scenarios. Part II applies a variety of assumptions to the basic data elements from Part I to more completely document alternative cost-effectiveness values. Part III compares the cost effectiveness of aircraft engine emission controls to values for other control strategies which either have been implemented or are being considered.

METHODOLOGY

The procedure used in this analysis consisted of determining the annual costs and exhaust emission reductions for the fleet-weighted average engine under each control scenario. A portion of the total annual 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 costs of pollution control are expressed in 1978 dollars throughout this analysis.

A brief description of each part of the methodology is presented in the following sections.

Cost Derivation

The incremental cost of each control scenario was separated into three major components: non-recurring production, recurring production, and operating. The amounts of each cost component were derived with data acquired from aircraft engine manufacturers, major airlines, original equipment vendors, independent manufacturers of engine combustion chambers, and information from previous EPA contract efforts. The most recent unpublished cost information is presented in Appendices B and C.

Non-Recurring Production

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.

Recurring Production

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.

The non-recurring and recurring costs associated with each of the proposed standards are presented in greater detail in Appendix D.

Operating

Operating cost is defined as the increment in fuel consumption and maintenance between regulated and non-regulated engines. Differences in fuel use will occur at ground idle for each control strategy, and during cruise flight conditions for the 1986 low-NOx standard. The use of low-emission technology is also expected to increase engine hot section maintenance costs. No performance penalties (such as a loss of thrust) are associated with the standards. The incremental costs for idle fuel consumption and maintenance are derived in Appendices F and G, respectively.

The above major components were used to determine the total annual cost of aircraft engine pollution control. This cost is made up of (1) the annualized engine selling price increase (first cost), and (2) the increment in annual operating expenses.

Annual Costs and Emission Reductions

First Cost Increase

The non-recurring and recurring production expenses are incurred in different years. Because of the time value of money, these costs are not comparable to one another. To account for this aspect of future capital expenditures, their present value was calculated by using a discount factor of 10% per annum. All values were discounted to the effective date of the standard being analyzed in each scenario, i.e., 1982 or 1986.

The present value of the first cost increase was derived by assuming that the annual production costs are incurred on January 1 of the year in which the expenditure is made, and that the revenue from that year's engine sales are received on January 1 of the following year. Furthermore, it was assumed that the discounted costs (which includes profit) are equivalent to the discounted revenues as shown in the following equation:

$$\text{(Discount Factor)(Revenues)} = \text{(Discount Factor)(Costs)} \qquad (1)$$

If the revenue received from the average engine price increase (ΔP) is equal to the number of engines sold multiplied by ΔP as shown below:

$$\text{Revenue} = (\Delta P)\text{(Engine Sales)} \qquad (2)$$

Then by substituting Equation 2 into Equation 1 and rearranging, the first cost increase is found by the following equation:

$$\Delta P = \frac{\text{(Discount Factor)(Cost)}}{\text{(Discount Factor)(Engine Sales)}} \qquad (3)$$

The increase in engine selling price was then annualized based on the useful life of the fleet-weighted average engine.

The average first cost increase is derived in Appendix E.

Operating Costs

The incremental costs of fuel and maintenance for each engine type were calculated as constant recurring annual expenditures; therefore, no discounting was necessary.

Emission Reductions

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

The following formulae were used to determine the number of LTO cycles for specific engines based on their representative aircraft type. The data inputs came from CAB statistics published in CAB (1978) and AWST (1978 and 1979).

$$\text{LTOs/yr} = \frac{(\bar{x}\ \text{Stage Length})\ (\text{Total Annual Revenue Airborne Hours})}{(\bar{x}\ \text{Airborne Speed})\ (\bar{x}\ \text{Number of Aircraft in Service})} \qquad (4)$$

or

$$\text{LTOs/yr} = \frac{\text{Total Annual Revenue Hours}}{(\bar{x}\ \text{Airborne Speed})\ (\bar{x}\ \text{Number of Aircraft in Service})} \qquad (5)$$

or

$$\text{LTOs/yr} = \frac{(\text{Total Annual Revenue Hours})(\text{Annual Revenue Departures})}{(\text{Daily Aircraft Utilization})(365\ \text{Days/Year})} \qquad (6)$$

A complete discussion and table of the emission performances for the engines affected by the proposed regulations are presented in Appendix H.

Fleet Projection

In order to define the average engine costs and emission reductions for each control scenario, the appropriate figures for each engine model were weighted by their population in the overall aircraft fleet. There are three basic fleets of interest: (1) the fleet of pre-1982 aircraft which is subject to the 1986 IUE

Standard; (2) the 1982 through 1985 aircraft fleet which is subject to the 1982 NME Standard; and the 1986 and beyond fleet of new aircraft which is subject to the 1986 NME Standard. The projection used to obtain each fleet mix was based on an EPA technical report by Munt (1978), which relied primarily on an earlier FAA fleet projection (FAA, 1977). The number of foreign aircraft that would be affected by the proposed standards are included in this analysis, and were estimated from information contained in Day and Bertrand (1978).

Cost Effectiveness

Two methodologies were used to determine the cost-effectiveness values in this analysis: method A and method B. Both methods assign compliance costs to the same pollutants, but differ in the way the cost is distributed among the pollutants. Each method is described in the following sections.

Cost Apportionment

Method A

This costing methodology is consistent with that used for automobile emission control strategies (DOT, 1976). For the 1982 NME and 1986 IUE Standards which control only HC and CO, no quantitative approach to cost application exists which is based on technological costs, since the same technology controls both species. For this reason, the cost of control is divided equally between the two pollutants.

The 1986 NME Standard which regulates NOx, also regulates HC and CO to the same levels that are allowed by the 1982 NME Standard. Therefore, in the control scenarios where both standards are implemented, the incremental burden of NOx control is qualified by determining the costs accrued beyond those encountered by controlling HC and CO in 1986 with 1982 control technology. This incremental cost burden is attributed to NOx emission controls.

In scenarios which evaluate the 1986 NME Standard as the only standard in effect, i.e., no preceding 1982 standard, the cost of control is divided equally between the three pollutants.

Method B

As previously mentioned, methods A and B differ only with respect to the way costs are distributed among the various pollutants being controlled. Method B allocates the compliance costs by specifying a maximum allowable cost-effectiveness value for one or more of the pollutants. The portion of the total cost which is accounted for by these specified pollutants is then calculated by multiplying the emission reduction for each pollutant by its respective cost-effectiveness value. The remaining unaccounted for portion of the total cost is then burdened to the pollutants for which no cost-effectiveness values were specified.

Cost-Effectiveness Calculations

The cost effectiveness for each control scenario was calculated by determining the total annual cost for the fleet-weighted average engine, and then using method A or B to complete the calculation. The total annual cost is found by the following equation:

$$\text{Total Annual Cost} = \text{Annualized First Cost Increase} + \text{Annual Fuel Consumption Increment} + \text{Annual Maintenance Increment} \quad (7)$$

Method A

By using this method to evaluate the 1982 NME and 1986 IUE Standards, 50 percent of the total annual cost is allocated to the annual reduction in each pollutant (HC and CO) for the average engine. This yields the final cost-effectiveness ratio:

$$\text{Cost Effectiveness for Pollutant A} = \frac{50\ \%\ \text{of Equation 5}}{\text{Annual Reduction in Pollutant A}} \quad (8)$$

When the 1986 NME standard is considered as the only requirement, 33 percent of the total annual cost is applied to the annual reduction in each of the three pollutants being controlled (HC, CO, and NOx).

$$\text{Cost Effectiveness for Pollutant A} = \frac{33\%\ \text{of Equation 5}}{\text{Annual Reduction in Pollutant A}} \quad (9)$$

When the 1986 NME Standard is required in conjunction with the earlier 1982 NME Standard, the cost-effectiveness ratio for HC and CO is the same as that found by Equation 6 for the preceding standards. The total annual cost of NOx control is defined by Equation 5 where:

1) The first cost increase (ΔP) includes the non-recurring manufacturing expenses incurred as a result of developing and implementing 1986 control technology, no 1982 technology non-recurring costs are included;

2) The first cost increase also includes the difference

between the 1986 NME and 1982 NME recurring average engine manufacturing costs; and

3) The fuel consumption and maintenance costs are the differences between the increments calculated for the in-service engines when utilizing either 1986 NME or 1982 NME control hardware.

The cost effectiveness of NOx control is found by the following equation:

Cost Effectiveness for NOx = (10)

$$\frac{\text{Equation 5}}{\text{Annual Reduction in NOx}}$$

The cost effectiveness of the retrofit control strategy (1986 IUE Standard) was calculated as an increment, since the 1986 retrofit would not be implemented unless the 1982 NME Standard was also promulgated. Therefore, the total annual incremental cost of the 1986 IUE Standard is defined by Equation 5, where the annualized first cost increase is based only on the recurring costs of production. The non-recurring costs for this technology are assumed to have been paid by the preceding 1982 NME Standard.

The 1986 IUE Standard's cost effectiveness is found by the following equation:

Incremental Retrofit Cost Effectiveness for Pollutant A = (11)

$$\frac{\text{50\% of Eq. 5 (recurring costs only)}}{\text{Annual Reduction in Pollutant A}}$$

Method B

This method is used only when method A proves to be unsatisfactory. If, by using method A, the cost-effectiveness values for one or two pollutants is unacceptably high, method B is employed to determine if reweighting the costs would lead to acceptable values for all pollutants. Therefore, method B distributes the costs of compliance unequally between the pollutants. The costs, however, are defined in the same way by both methodologies.

The method can be used with any number of pollutant species, but will be illustrated for standards which control two pollutants simultaneously, e.g., the 1982 NME or 1986 IUE Standards. By specifying a maximum acceptable cost-effectiveness value for Pollutant A, the cost effectiveness of controlling Pollutant B is determined by the following equations:

Cost Allocated to Pollutant A = (12)

(\$/ton for Pollutant A) (Annual Reduction in Pollutant A)

Cost Allocated to Pollutant B = (13)

Total Annual Cost - Equation 10

Cost Effectiveness for Pollutant B = (14)

$$\frac{\text{Equation 11}}{\text{Annual Reduction in Pollutant B}}$$

DISCUSSION

Part I

In order to comply with the aircraft emission standards, manufacturers will have to make changes to the turbine engine's hot section (e.g., combustor). For a more complete understanding of the major issues involved in the cost-effectiveness analysis, brief descriptions of these changes are presented in this part of the discussion. If desired, the reader may refer to Munt (1979) for a more rigorous description of the requisite control technology.

The discussion of control techniques is followed by a description of several control scenarios which are used to evaluate the cost effectiveness of promulgating alternative emission standards. The major elements of the cost-effectiveness analysis are then derived (i.e., fleet projection, engine costs, operating costs, and emission reductions), and the final cost-effectiveness values for the fleet-weighted average engine in each control scenario are calculated.

Control Methods

Four basic types of technology will be used singly or in combination to produce a low-emission combustion system. Fuel sectoring, minor combustor redesign, and air blast concepts will be used to control HC and CO as required by the 1982 Newly-Manufactured Engine (1982 NME) Standard and the 1986 In-Use Engine (1986 IUE) Standard. To comply with the 1986 Newly-Manufactured Engine Standard (1986 NME) which controls NOx in addition to HC and CO, fuel staging will be required.

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 to 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 to CO_2 reaction.

Minor Combustor Redesign

This method may consist of enrichening the primary combustion zone or delaying the introduction of dilution air into the combustor. 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 to CO_2 conversion when O_2 becomes available in the secondary combustion zone, 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. Mediating excessive smoke emissions may require complicated air flow patterns and dilution zones in the secondary.

The delayed dilution concept consists of postponing the introduction of dilution air, thereby producing a longer combustion zone at intermediate temperatures. This allows the CO to CO_2 conversion to approach equilibrium and unburnt hydrocarbons are consumed by increasing the residence time of the reactants. 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 spray 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.

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 to 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 and may have additional cooling and temperature profile problems.

Control Method by Manufacturer

Pratt and Whitney Aircraft (PWA)

The air blast control concept will be used in each engine model to control HC and CO to the levels required by the 1982 NME and 1986 IUE Standards. This will require modifications to the fuel nozzles, nozzle supports, combustion liners, combustion dome, and in some cases the transition and diffuser case must be reworked.

To meet the 1986 NME Standard, PWA will use a vortex-mixing fuel-staged combustor called the Vorbix. This combustor is considered the most complex configuration which is required to reduce NOx emissions. Along with the staged combustion systems of the other manufacturers, the Vorbix incorporates changes to the liner, dome, fuel nozzle, nozzle supports, fuel manifold, swirlers, and fuel logic control system.

General Electric (GE)

The control methods used by this manufacturer to meet the 1982 NME and 1986 IUE Standards are sector burning and air blast. At the present, the following engine models are scheduled to be introduced with sectoring hardware: CF6-6, CF6-32, CF6-50, CF6-45, and CFM-56. The hardware modifications include: fuel nozzle orifice diameter changes, nozzle support check valves in the primary fuel delivery of the unfueled sector, fuel manifold, and logic control. No changes are required to the dome or combustion liner. The newest GE derivative engine, the CF6-80, is expected to use the air blast control method in lieu of sector burning. Air blast affects the design of the fuel nozzles and supports, dome, and lines. Because the air blast concept enjoys greater customer acceptance than does the sector burning concept, GE has recently indicated it may change to air blast in their other CF6 engine models if possible. If GE actually decides to make this switch, the air blast hardware would not be available to the airlines until sometime after the compliance date of the 1982 NME Standard. Therefore, it is expected that GE will certify and produce some engine models with sectoring controls regardless of whether or not air blast will eventually predominate in the fleet.

To control NOx emissions in 1986, GE engines will use the fuel staging control method. Their combustor configuration, however, differs from PWA's and is called the Double Annular. This combustor incorporates the same design changes from conventional hardware as was described for the Vorbix.

Rolls Royce (RR)

This manufacturer will use the same control technology as GE to meet the 1982 NME, 1986 IUE, and 1986 NME Standards. Rolls Royce, however, does not appear to have the option of using the airblast concept. Controlling HC and CO to the required levels with air blast modifications appears to be impossible because of certain engine design constraints. Therefore, all RR engines will be produced with sector burning hardware in order to comply with the 1982 NME and 1986 IUE Standards.

Control Scenarios

Several control scenarios are evaluated to determine the cost effectiveness of promulgating alternative emission standards. These control scenarios are presented in Table 1, along with a brief explanation of each. As shown in this table, Scenarios 7 and 8 evaluate the potential effect of General Electric's change from sector burning to combustor modifications in order to meet the 1982 NME and 1986 IUE Standards. The analysis of these CF6 alternative scenarios necessitated the use of several important assumptions.

As previously stated, the CF6-80 will be produced with combustor modifications and could precipitate a change to similar control Hardware in the other CF6 models. If the conversion does take place, it would be accomplished sometime after the scheduled introduction of the CF6-80 in 1982.

A significant amount of time and money will be required to incorporate the CF6-80 control hardware into other engine models, and to allow for an adequate service evaluation. The EPA does not expect any production change from sector burning to combustor modifications until the 1985 to 1986 time frame if any HC and CO standards are promulgated.

The assumptions that were used to complete the CF6 alternative scenarios are presented below. These assumptions were necessary to limit the analysis to manageable proportions.

1. Combustor modifications are incorporated into CF6-6, CF6-32, CF6-50, and CF6-45 production engines beginning on January 1, 1986. By choosing this date, the CF6 alternative will not exist prior to 1986; therefore, the alternative affects only the 1982 NME Standard when it is effective beyond that date, i.e., when it is promulgated without the 1986 NME Standard.

2. The increments in maintenance and emission reductions are considered to be equivalent for sector burning and combustion modifications. The assumption concerning incremental maintenance is based on information contained in the section entitled, "Operating Costs." This information shows that the added costs of maintaining modified PWA combustors, which are very similar to GE's alternative combustor design, are nearly identical to the incremen-

tal maintenance costs for GE's sector burning hardware. Since the PWA and GE modified combustors are very similar, it is assumed that the costs would also be about the same. The emission reductions are assumed to be equivalent because both technologies must meet the same standards.

3. For newly-manufactured engines, the differences in the average engine selling price for sector burning and modified combustor engines is ignored. The number of sector burning engines produced prior to 1986 is small in relation to the number of engines produced with combustor modifications after that date. For this reason, the increments are of minor consequence to the overall results of the study. A difference in price of only about 8 percent would occur if the engines produced with sector burning were accounted for. This is well within the experimental uncertainty of the analysis.

4. No significant penalty is associated with concurrently maintaining retrofitted engines which utilize sector burning hardware and newly-manufactured engines incorporating combustor modifications within the fleet. EPA is aware that the possibility of logistics problems exists in operating and maintaining two different types of control hardware for the same engine model, but that the problems are manageable and are not economically significant in a study of this kind. Furthermore, the magnitude of any potential problems is not expected to be great enough to force the airlines to voluntary retrofit combustor modification hardware into engines already equipped with sector burning hardware.

5. For retrofitted and newly-manufactured engines the differences in fuel consumption during ground idle operations for engines equipped with either sector burning or combustor modifications are ignored. All engines are assumed to have idle fuel usage increments equivalent to the vast majority of engines in the fleets of interest. Since the GE alternative is relevant only when the 1982 NME Standard is promulgated without the 1986 NME Standard, the vast majority of engines will be equipped with combustor modification hardware. This assumption simplifies the analysis and maintains compatibility with the way in which annual fuel increments are calculated in the other scenarios. On the basis of total engine years for each fleet, newly manufactured engines with sector burning control make up only 6 percent or less of the total, and retrofitted engines with these controls make up only 1 percent of the total. These small percentage differences will not have a significant effect on the results of this study.

One of the major constraints of incorporating modified combustors into CF6 engines is in attaining the CO standard. Therefore, if EPA promulgated a standard that controlled only HC emissions, GE might be able to produce engines which utilize this technology prior to 1986. The effect of producing a smaller number of sector-burning engines would be two fold. First, it would reduce the fuel penalty which is associated with those engines. Second, the average engine selling price would be reduced slightly, since sector-burning is more expensive to manufacture than combustor modifications. However, these small potential benefits may be offset by a larger cost penalty if a smaller fleet of engines with sector-burning controls was regarded by the airlines as a strong incentive to voluntarily retrofit modified combustors to maintain commonality within the fleet. These possibilities are purely speculative of this time, and are not considered to be within the scope of this analysis.

Average Engine

The cost effectiveness of each control scenario is based on a representative fleet-weighted average engine. This hypothetical engine is defined by weighting the costs and emission reductions for each affected engine model by 1) its fractional population within the aircraft fleet of interest, and 2) its useful life. Therefore the average engine is directly determined by the aircraft engine fleet projections which vary according to the standards being reviewed.

Fleet Projection

The fleet projections used in this analysis are based on an EPA technical report entitled, "U.S. Aircraft Fleet Projection and Engine Inventory to the Year 2000" (Munt, 1978). The fleet figures from the above report have been updated to reflect the most recent information concerning future aircraft demand, and to include an estimate of the foreign aircraft which would be affected by the proposed standards. The foreign aircraft fleet was estimated from information contained in Day and Bertrand (1978).

To derive the average engine statistics for each control scenario, three different aircraft fleet projections are used. These fleets, singly or in combination, correspond directly to the standard being analyzed. For the 1982 NME and 1986 NME Standards, the estimates of new aircraft production include airplanes built for both the domestic and foreign markets. New foreign air carrier aircraft are included because engine manufacturers are not expected to produce engines in both controlled and uncontrolled configurations. The additional cost of maintaining two production facilities simply could not be justified. For the 1986 IUE Standard, the estimate of retrofitted aircraft reflects the inventory of the domestic airlines in addition to foreign air carrier airplanes that may operate within the U.S.

Each aircraft fleet forms the basis for determining the number of in-service and spare part engines that will be produced or retrofitted. The number of spare engines is assumed to be 20% of the in-service engine population. The engine projections are presented in Table 2.

The fleet projections are based on an assumed aircraft attrition rate. In EPA's fleet projections, the selection of this rate is the main determinant of the number of new aircraft entering the fleet and, hence, the number of new aircraft engines being produced each year. In previous cost-effectiveness analyses (Wilcox and Munt, 1978) , EPA used an attrition rate of 15 years. This rate was an approximation of the corporate accounting lifetime. None of the comments which were received in response to the March 24, 1978 Notice of Proposed Rulemaking were directly critical of this selection. Actually, some reinforcement for this useful life was received when Pratt and Whitney Aircraft Group used the same figure in some of its comments (United Technologies, 1978). Also, a very similar figure (16 years) was used by Douglas Aircraft Company (1976) in an economic analysis of energy consumpton by commercial air transport. Therefore, because no comments were received that suggested the figure was incorrect,a useful life of 15 year is used again in this study. Previous EPA fleet projections were criticized in general, however, by the Air Transport Association (1978). In response to this criticism, this report incorporates a sensitivity analysis of each control scenario based on $\pm$10 percent of the projected engine inventory. In this way, a "best" and "worst" case is estimated. The sensitivity analysis is applied to EPA's "best estimate" in the discussion section entitled, "Cost-Effectiveness Calculations."

Weighting Factors

The weighting factors for each engine model are divided into two principle types: population and useful life. The population factors are based the ratio of each model's population to the total engine population within the fleet. The useful life factors are necessary to account for the varying life expectancies in scenarios which evaluate the 1986 IUE Standard. If an engine has an expected life which is less than the maximum, it receives proportionately less weight in the derivation of the average engine parameters with regard to annual increments in maintenance, fuel consumption, and gaseous emissions.

Population Factors

Three fleet projections are used either singly or in combination to derive the four groups of population weighting factors which are required to define the particular average engine for the scenario being reviewed. These groups of weighting factors, and the corresponding control scenarios in which they are used, are shown in Table 3.

Useful Life Factors

Only one group of useful life weighting factors is used in the scenarios which evaluate the 1986 retrofit standard. These factors are based on the overall aircraft attrition rate which is used in the fleet projections.

Newly-manufactured engines are considered to have a useful life of 15 years. The fleet projection forecasts that all retrofitted engines except the CF6-50, CFM56, and JT8D-209 will have an average useful life of 7 years remaining. The CF6-50 was introduced on later airplane models and would have expended less of its useful life; therefore, this engine has 10 of its original 15 year lifetime remaining. The CFM56 and JT8D-209 would be retrofitted on older aircraft (e.g., B707), but because of the high cost of reengining these airplanes they are expected to remain in service beyond the end of their normal service lives. Therefore, these engines are considered to have a useful life of 15 years, and are treated as newly-manufactured engines. The useful life weighting factors are presented in Table 4.

Engine Costs

EPA undertook an extensive program to define the costs of controlling gaseous exhaust emissions from gas turbine aircraft engines. The program resulted in quantifying all of the major cost increments which are associated with the proposed standards: engine selling price; idle fuel consumption; cruise fuel consumption; and maintenance. The costs for each of these major categories are based on data gathered from the engine manufacturers, major airlines, EPA independent investigations, and other published and unpublished information. Each major category is discussed in detail below.

Engine Selling Price Increment

Specific Engine Costs - - The categories of cost for each engine model 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 and the costs of incorporating control hardware into in-use aircraft engines. The main elements within each component are shown in Table 5.

Recent studies which have attempted to define the engine-specific costs of aircraft emission controls have referred to the difficulties of acquiring complete and verifiable information. This study attempted to mediate these difficulties by developing a standardized format for gathering relevant cost information (Appendix A). A request for information was then sent to the three engine manufacturers, a fuel nozzle vendor, and several major airlines. The standardized format was necessary to reduce the variability of all the responses into a manageable form. The requests for information were detailed enough to allow an objective evaluation of the economic claims made by the industry, and at the same time, attempted to avoid sensitive or proprietary subject matter. Independent EPA sponsored investigations were also used to document the costs of producing low-NOx staged combustion liners (Appendix C).

The complexity of controlling emissions from large turbine engines places the affected industry in a superior position to accurately assess the associated costs. Therefore, this study began with industry supplied data whenever possible. However, after carefully reviewing manufacturers' cost information it was often necessary to make substitutions or to adjust manufacturers' cost estimates. Sometimes it was preferable to use costs from EPA's independent estimates. These deviations were required for a variety of reasons:

1) Manufacturers did not always report cost data in EPA's recommended format. In some cases, the manufacturers claimed the data was proprietary, while in others, no reason was given.

2) Manufacturers' submittals were sometimes incomplete or vague. For some categories, no cost data was reported.

3) Some cost estimates were grossly inconsistent when figures reported in the same format were compared. Some figures that were not directly comparable, but which should have varied in a normally expected way, were also grossly inconsistent.

4) Manufacturers claimed the information was not needed for various reasons. They also claimed the costs of specific items could not be estimated even though their previous statements may have attempted to quantify those same costs.

If, after reviewing an engine manufacturer's cost information, it was not used in the analysis for any of the above reasons, an attempt was generally made to be consistent with any other related information supplied by that manufacturer or other manufacturers if these costs were judged to be reasonable. Therefore, the cost data which were used to generate the specific engine costs in this study, are often based on manufacturers' estimates, although they will not necessarily agree with the estimates submitted by the manufacturers in every instance. The estimates can be considered somewhat conservative, i.e., overestimate the actual costs of control, because of the vested interests of the industry. This is probably most true of the costs associated with the 1986 NOx standard.

Tables 6 and 7 contain the specific engine costs for the various control strategies. Additional information concerning the actual deviation of these figures is presented in Appendix D. Footnotes to the tables have been provided, however, to indicate the basis and source of the cost figures. The reader should consult the appendix for a more complete description of the estimates.

Some of the engines in Tables 6 and 7 are derivatives of others. These derivative engines and their so-called "parent" engines are shown in Table 8. The engines in this table are so closely related that most of the non-recurring costs cannot be ascribed to any single engine model. Because they utilize the same basic engine parts or design, the new new engine increment is the same. It should be pointed out, that although the RB211-524 is not generally considered to be derivative of the RB211-22B, they do utilize the same combustor. Therefore, the RB211-524 is treated as a derivative of the RB211-22B in this analysis.

As in the case of new engines, derivatives do not require a service evaluation of emission control hardware. These evalutions are necessary only to define the durability of design changes in relation to the prior service characteristics of an existing engine. For new engines such as CFM56, no prior service record exists for comparison, so no evaluation is required. Derivative engines do not require a service evaluation because it is assumed that the information gathered for the parent engine is also useful for characterizing the derivative.

Certification is the only non-recurring cost category where derivatives incur some costs independently of their parent engines. For the HC and CO emission standards which begin in 1982, the derivative engines may have some unknown incremental certification costs due to emission controls. These engines are expected to be type certified while incorporating emission control hardware, however, so any cost increment will be insignificant in relation to the total expense. Additionally, the certification costs for the parent engines have some associated uncertainties and some the costs appear to be inflated. For these reasons, no allowance is made for HC and CO emission control certification testing in these derivatives (Table 8).

The retrofit prices in Table 6 are based on the costs of purchasing and installing the requisite control hardware. No allowance which reflects the cost of prematurely scrapping life-limited parts has been included. Conversely, no allowance has been included which reflects the possibility that some low-time, life-limited parts or non-life limited parts that are displaced by the retrofit, could be sold to foreign airlines not requiring emission control hardware (This possibility exists primarily for JT8D engines). The salvage value of non-life limited parts has also been excluded. These potential costs and revenues are assumed to cancel out each other.

The engine-specific costs are different from those shown in

Table 6 for scenarios which evaluate the change from sector burning to combustor modifications by all CF6 engines except the CF6-80. The costs to develop, certify, service, evaluate, and initially produce the CF6 alternative for the derivatives and parent engines (Table 9) are additional expenses to the non-recurring costs that have already been incurred to introduce sector burning. The new engine increment is reduced since combustor modifications are less expensive to produce and install. The retrofit price is unchanged because the alternative is not introduced until after the end of 1986 when the retrofit is complete.

The JT10D and Spey engines represent a special case in the analysis. Recent information indicates that the JT10D presently has no companion airframe, nor does it appear likely to have one in the near future. The only potential use for the JT10D appears to be on the B757 airframe, although it is not expected to capture this market because airlines preceive an inherent risk in using a totally new engine, and because suitable derivative engines exist such as CF6-32 and RB211-535. For these reasons EPA's engine inventories for the 1982 NME and 1986 NME Standards do not include the production of any JT10D's. However, the manufacturer has claimed an expenditure of development funds for the controlling HC and CO emissions from this engine. These costs are accounted for in Table 6 since the engine is ready to be certified, and the money has already been spent. It is assumed that because no market exists, the company will not develop the requisite NOx control hardware to meet the 1986 standard. For this reason, no development costs are shown in Table 7. The Spey is an older engine that cannot possibly meet the standards. It is not included in this analysis because it is assumed to be out of production by the time the 1982 standard is implemented. Several possibilities exist which explain why the Spey will not be produced:

1. If it does not meet the standard, it will not be made;

2. No market exists; and

3. If a market does develop in the future, it is likely the Spey will be replaced with the RB432. (EPA lacks emission control information on the RB432.)

The manufacturer of the Spey claimed an expenditure for development funds for reducing HC and CO emissions, although none are accounted for in Table 6 for three principle reasons. First, the engine cannot meet the standard and is not ready to be certified with low-emission hardware as was the case for the JT10D. Therefore, only a portion of the claimed development funds have actually been expended. Second, EPA does not have data with which to quantify the expenditures made by Rolls Royce to reduce HC and CO emissions from the Spey. Third, it is assumed that the manufacturer has not continued to expend funds without an identifiable market for the engine.

Annualized Average Engine Selling Price

The average engine selling price increment is based on the non-recurring and recurring costs of control as defined in the above section. Computing the selling price in this manner is considered to be more accurate than relying on manufacturers' estimates of this price increment. Manufacturers use various strategies to determine the selling price of their engines. Generally, however, the costs incurred by one engine model are not recovered solely in the sales price of that engine. Instead, the non-recurring costs from all engine models are pooled. These costs are then amortized across the product line of the company as the anticipated market and other variables permit. Therefore, the selling price increment is somewhat independent of the money spent on any one individual engine model. This also explains why a manufacturer's estimate of the increment in selling price for a particular engine model may vary from time to time.

Basing the average selling price increment on the actual costs which are incurred by the manufacturers and airlines, is also a more realistic expression of the true cost to society. The computation insures that all costs are recovered, i.e., no company loses money and no company will make excess profits. These types of profits are not a societal cost but are simply transfer payments.

The costs of emission controls actually occur as a series of variable annual disbursements by either the engine manufacturers or the airlines. To make these disbursements comparable, they must be converted into equivalent uniform annual payments. To determine the annual cost for the average engine in each scenario, the present value of the selling price increment for the average engine must be calculated from the non-recurring and recurring costs. This present value engine price increase is then multiplied by a suitable capital recovery factor to obtain the uniform equivalent annual cost.

To derive the average engine price increase (ΔP), certain assumptions were made. First, the revenue which is received from the engine price increase is exactly equal to the total engine costs including profit. In this manner, no excess profits or losses are experienced. Second, the revenue received from the average price increase is equal to the annual sales multiplied by ΔP. Third, the revenues for a particular year's sales are received on January 1 of the following year, and the total annual costs are charged on January 1 of the year in which they are incurred. A discount rate of 10 percent per annum is used to calculate the present value of the costs and revenues at the first date a standard is implemented in a scenario, i.e., 1982 or 1986. The average engine price increase (ΔP), therefore, is equivalent to the total discounted annual costs, divided by the total discounted annual engine sales.

Before the discounted selling price increment can actually be calculated, however, a time series of expenditures for the non-recurring costs must be estimated, and an average recurring cost increment has to be determined. The cash flow was estimated by assuming that the most substantial disbursements would occur near the implementation date of each standard when certification, service evaluation, and initial production were taking place simultaneously. The earliest expenditures would be predominately for development. The estimated annual disbursements are shown in Figures 1 and 2.

The average recurring cost increment is different for each year because the sales mix of engines does not remain constant. Rather than laboriously sales weighting the recurring engine prices for every year under each scenario, the cost increment was sales weighted by the fleet mix which occurred over the life of each standard. This greatly simplified the computations without compromising the final results of the analysis.

A computer program was devised to compute the average engine selling price increment for each scenario. The results for each scenarios are shown in Table 10. The derivation of these figures is presented in Appendix E.

Now that the discounted selling price increase for the average engine has been determined, it must be annualized with the use of a suitable capital recovery factor. The discount rate for this factor is the same as that used to determine the present value of the engine costs and revenues, i.e., 10 percent per annum. The useful life of the average engine in each scenario is found by sales weighting each engine model's respective useful life as previously discussed under "Fleet Projection." The average useful lives and the appropriate capital recovery factors are shown in Table 10, along with the annual engine costs for each scenario.

Operating Costs

Three types of operating costs have been identified as a consequence of emission control schemes. These costs are the differences in ground idle fuel consumption, in-flight cruise fuel consumption, and hot section maintenance between non-regulated and regulated engines. They are calculated on an equivalent annual basis for the average engine in each scenario. Therefore, it is not necessary to derive uniform payments as it was for the engine selling price increment.

Fuel Consumption Increments - Idle

To meet the proposed standards, manufacturers will improve the combustion efficiency of their engines. This improvement will result in a specific fuel consumption (SFC) reduction during ground idle operations. Most engines will experience a 3 percent reduction in idle SFC with the exception of the JT8D. The JT8D's smokeless combustor is already more efficient than average; it will experience about a 1 percent improvement.

The General Electric and Rolls Royce engines which are produced in compliance with the 1982 NME and 1986 IUE Standards may experience a net increase in fuel consumption in spite of the improvement in combustion efficiency. The use of sector burning by these engines causes an 8 percent decrease in component efficiency, which coupled with the 3 percent benefit in combustion efficiency, yields a 5 percent overall penalty in idle SFC.

Furthermore, the CFM56 apparently can only meet the 1982 CO emission standards by increasing its idle thrust from about 4 percent up to 6 percent of rated output. The EPA estimates 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 (idle only) are summarized in Table 11. These changes are the differences in usage from a baseline engine to the controlled engine under the various standards. For the 1982 standards (which includes the retrofit standard) and the 1986 standard with no pre-existing 1982 standards, the baseline engine for each model is its uncontrolled counterpart. For the 1986 standard, which is implemented in addition to a prior standard, the already-controlled engine is used as a baseline. As shown (Table 11), the use of sector burning has two interesting effects. First, the majority of engines in compliance with the 1982 standards will experience an increase in idle SFC unless GE produces the alternative combustor modifications. Second, when sector burning is replaced by staged combustors in 1986, a substantial fuel benefit occurs. This is most apparent for the CFM56 where a portion of the benefit is due to a reduction in idle thrust since the staged combustor is more effective than sector burning in reducing CO emissions.

The derivation of incremental idle fuel costs is presented in Appendix F and is summarized in Table 12 for each scenario.

Fuel Consumption Increments - Cruise

The staged combustion systems that have been configured by the engine manufacturers to comply with the 1986 NOx standard are not only more complex than current systems, but also weigh more. The manufacturers have estimated this increase at between 200 and 300 pounds per engine. This additional weight increases the aerodynamic drag of the aircraft during the flight regime. This penalty is most significant during cruising flight, and manifests itself as an increase in fuel consumption. The value of this increment was estimated by Logistics Management Institute (Day and Bertrand, 1978) for various aircraft categories from industry-supplied data. The LMI document, however, did not specify cost penalties for the medium-and regular-bodied aircraft that are represented in EPA's fleet projection. The costs for these aircraft were arbitrarily estimated by EPA and are included in Table 13.

The fuel penalty costs are assigned to each engine model on the basis of its predominate usage on a particular aircraft type. As shown in Table 14, these figures are weighted on the basis of the engine's useful life and market share to determine the cost for the fleet average engine.

Maintenance Increments

Historically, even minor combustor changes have often resulted in an increase in maintenance costs. Therefore, some increase is anticipated when emission control hardware is implemented. Two types of maintenance penalties could occur. The first type is the result of introducing immature or unproven hardware. As stated by the engine manufacturers in submittals to EPA (United Technologies, 1977) and testimony at the aircraft public hearings (EPA, 1978a), the standards as originally proposed would not have allowed enough time to adequately service evaluate the requisite hardware. The penalty of introducing these immature combustors would last until an adequate amount of data could be collected and production configurations were modified accordingly. In the case of the proposed 1984 NME Standard (NOx control), this penalty would last about 3 years as estimated by PWA (United Technologies, 1977) at a cost of about $493.5 million to the industry worldwide (Day and Bertrand, 1978). The penalty for the proposed 1981 NME and 1985 IUE Standards was somewhat less. In considering the significance of the penalties, EPA concluded that the benefits do not justify the added costs. For this reason, it is very likely that the implementation schedule for HC and CO control will be delayed from the proposed 1981 date to 1982 for newly-manufactured engines, and from 1985 to 1986 for retrofitted engines. The proposed 1984 standard which controls NOx in addition to HC and CO, will likely be delayed to 1986, if implemented. EPA has determined that these dates would allow the industry to perform adequate service evaluations which will avoid the penalty associated with introducing immature combustors.

The second potential maintenance cost is associated with a reduction in combustor durability throughout the life of the engine, higher replacement costs for life limited parts, or is the result of maintaining all new engine parts. Durability can be impacted because emission control generally entails "fine tuning" the combustor system. A common design requirement involves altering the airflow distibution of the combustor. This can adversely affect liner temperatures and turbine inlet temperature profiles. Higher replacement costs are not necessarily caused by an increase in manufacturing costs, as was demonstrated in EPA-sponsored investigations of staged-combustion designs (Appendix C), but occur through the amortization of low-emissions research and development expenses over the expected production volume. In addition, some low emissions configurations will be produced with hardware that has no existing counterpart. The maintenance of this hardware, such as the sectoring control valve used by General Electric and Rolls Royce, is totally charged to the costs of emission control.

Some maintenance increases which have been described may be partially offset by the use of staged combustors to reduce NOx emissions. The aromatic content of jet fuel has been escalating in recent years and the use of high-aromatic shale and coal-derived fuels in the future is almost certain. Conventional technology combustors cannot cope with these fuels: combustion becomes smokey and increases in flame luminosity cause combustor cooling problems. Staged combustors avoid these problems since they are lean burning and, therefore, operate at cooler temperatures. Moreover, higher aromatic fuels are expected to be lower in price. This potential benefit has not been accounted for in this analysis.

Since no experience with in-service, gaseous emission control hardware has occurred, the quantification of potential maintenance penalties is difficult to determine and is, of course, speculative. This has been amply exemplified in Pratt and Whitney Aircraft submittals to EPA with regard to this subject. When EPA conducted its economic analysis of the proposed standards, PWA (United Technologies, 1977) estimated a maintenance cost increase for engines in compliance with the 1982 NME and 1986 IUE Standards. In its most recent submittal to EPA (United Technologies, 1979), PWA concluded that no maintenance increment is expected from the use of low-emission hardware in these engines.

Overall, the evidence suggests that a penalty is associated with the use of low-emission technology in all engines which are produced in compliance with any of the standards. For 1982 technology, this penalty is expected to be small. For 1986 technology, industry representatives have stated that the penalty will probably be significant, although no real evidence has been presented to substantiate this claim.

EPA independently estimated the increase in maintenance costs based primarily on data acquired from engine manufacturers (Appendix B), major air carriers (Appendix B), the LMI document (Day and Bertrand, 1978), and independent manufacturers of engine combustion chambers (Appendix C). The incremental maintenance costs for the 1986 NME Standard are based on a "worst case" situation. EPA remains skeptical of industry estimates concerning the incremental maintenance costs for low-NOx staged combustors, and will continue to evaluate these potential penalties in the future. The fleet-weighted annual costs of the expected maintenance increment for each engine are shown in Table 15. The costs are determined for parent engines only. All derivative engines are assumed to have basically the same maintenance characteristics and, hence, the same costs as their respective parent engines. No penalty is estimated for the CFM 56 because it is a completely new engine without any prior maintenance history. Therefore, controlling this engine has no increment associated with it. The cost per engine hour and the fleet-weighted annual cost for each scenario are derived in Appendix G.

Emission Reductions

Reductions in gaseous exhaust emissions for each engine model were calculated from data contained in an EPA report entitled, "Review of Emissions Control Technology for Aircraft Gas Turbine Engines" (Munt, 1979). The emission reductions for the average engine in each control scenario are derived in Appendix H.

The engine specific reductions were computed by assuming an average landing and takeoff cycle (LTO) time for all airports in the nation. Previous cost-effectiveness reports (Wilcox and Munt, 1977 and 1978) used the EPA defined LTO time of 26 minutes. This cycle was originally developed to reflect peak traffic times at the nation's busiest air terminals. The use of that figure was criticized by industry representatives as being unrealistically long to characterize the national average. EPA concurs with this criticism, but at the time of the previous reports the Agency had no data upon which to base a more realistic average LTO time. It should also be clarified that only HC and CO are significantly affected by the choice of an average figure. All but an extremely small portion of these emissions are generated during the taxi-idle modes of the LTO. There are two principle reasons for this: (1) emissions of HC and CO are related to the poor combustion environment that occurs during low-power operations and (2) the taxi-idle time-in-mode makes up the majority of the LTO cycle.

The production of NOx emissions is associated with the hot temperatures that occur during high-power operations; consequently, very little NOx is generated during the taxi-idle mode. The time spent in the higher power operations of the cycle does not change significantly between airports, although the taxi-idle times do. Therefore, the average airport NOx emissions are adequately characterized by EPA's LTO cycle, but HC and CO emissions are not.

In the preparation of this report, airport specific taxi-idle times were determined for EPA by ORI (Bauchspies, 1979), and were based on data contained in FAA (1977) and Bauchspies et al. (1978). This information is displayed in Table 16. The figures in this table are block-to-block times and, therefore, do not include the time incurred while idling at the gate, or, as described by CAB

(1978), the time the aircraft is being towed by the ground-service tractor. Additionally, the control strategies being analyzed are most effective in future years when air traffic is expected to become more congested. For this reason, some period of time greater than the national average is more realistic when projecting airport emissions. The simple average of the figures contained in Table 16 is about 16 minutes. To account for the above mentioned shortcomings of this taxi-idle time, 19 minutes is used to calculate the HC and CO emission reductions from all types of aircraft engines.

The gaseous emission reductions for the average engine in each scenario are presented in Table 17.

Baseline Cost Effectiveness Values

The cost effectiveness values for each of the scenarios are derived in Table 18. Scenarios 1, 2, 6, and 7 are the most cost effective and can be considered to have the same level of cost effectiveness because of uncertainties in the analysis. Each of these scenarios control HC and CO emissions beginning in 1982 without any follow-on 1986 NOx standard.

As shown in Table 18, the introduction of the CF6 alternative in Scenarios 6 and 7 makes very little difference in the new engine selling price increment when compared to Scenarios 1 and 2. Even though the alternative is much less expensive to manufacturer (Table 6), that savings is equally offset in the price calculations by the increased non-recurring costs which are incurred in developing the alternative combustion system. Therefore, the slightly lower cost-effectiveness values for Scenarios 6 and 7 are due almost exclusively to the reduction in idle fuel consumption when sector burning engines cease production.

The effect of the 1986 retrofit in conjunction with other standards (i.e., Scenarios 2, 4 and 7) is to decrease the cost-effectiveness of the strategy, although the result is of minor consequence. Nevertheless, the effect is caused by two principle factors. First, the annualized average engine cost is higher. This occurs because the retrofit kit costs more than the new engine increment (Table 6), and the remaining useful life of the average engine is less. Second, JT8Ds account for as much as 35 percent of the controlled engines in these scenarios. Since the JT8D "smokeless combustor" is already cleaner than many larger engines at present, the preponderance of JT8Ds causes a reduction in the pollution abated from the average engine. However, the large number of these engines also offsets some of the decrease in cost effectiveness by lowering the average costs for maintenance and idle fuel consumption. This is accomplished by reducing the fraction of high-cost engines in the fleet (e.g., the CFM 56 sector burning fuel penalty is greatly reduced in Scenario 4).

The next higher group of cost-effectiveness values comes about in Scenarios 3 and 4 when the 1986 NOx standard is added to the 1982 standards. The primary cause for higher values is that the non-recurring expenses for controlling HC and CO only, must be amortized over fewer engines; consequently, each engine produced costs more.

The 1986 NOx standard scenarios are the least cost effective (Scenarios 5, 8, and 9). Within the group, however, the cost effectiveness is best when the 1986 standard is promulgated without a prior 1982 standard. The cost per ton of pollutant reduced is still much larger than if any 1982 strategy were promulgated alone (including the retrofit). As shown in Table 18, Scenario 8, a substantial benefit in idle fuel consumption results when staged, low-NOx combustors replace sector burning hardware in GE and RR engines. Comparing Scenarios 8 and 9 reveals that there is very little change in the NOx cost-effectiveness figure regardless of whether or not GE sector burns.

DISCUSSION

Part II

In this part of the discussion, a variety of assumptions are applied to more completely document alternative cost-effectiveness values. This part includes a sensitivity analysis which investigates the effect that variations in the production of new engines would have on the final cost-effectiveness values. Alternative cost-effectiveness values are also determined for each of the control scenarios by assuming that the cost-effectiveness computations should be restricted to include only those costs that have yet to be spent. Finally, the incremental cost effectiveness of the 1986 IUE Standard (retrofit) is determined.

Sensitivity Analysis

The fleet projection used in this analysis is an attempt to ascertain future facts by using reasoned assumptions. As time passes and updated information becomes available, the projection will become less accurate. Also, no matter how carefully considered, the assumptions which were necessary to complete the projection may be incorrect. The sensitivity analysis is an attempt to account for these inaccuracies by parametrically evaluating the effect of different production volumes on the average engine selling price and the final cost effectiveness of the various scenarios.

The number of newly-manufactured engines produced under each scenario is varied by ± 10 percent. To ensure that the production volume is the only parameter being evaluated, it is assumed that the variations are the result of fluctuations in air traffic demand; therefore, the expected useful life of each engine is unchanged. Also, it is assumed that each engine model experiences the same relative change in production volume. In this way, the costs for the other major cost categories remain unchanged. The sensitivity analysis excludes variations in the number of retrofitted engines since the number of these engines is not expected to change significantly.

Table 19 shows the sensitivity of the costs to changes in new engine production volumes. By manipulating the projected production figures by ± 10 percent, the engine selling price increments vary from about 3 to 9 percent. The final cost-effectiveness values vary from 2 to 7 percent depending on the scenario. These small differences do not seriously affect the accuracy or comparability of the baseline cost-effectiveness figures. Therefore, the overall analysis shows very little effect from reasonable changes in the projection of new engine production.

Sunk Investments Excluded

The aircraft standards were originally promulgated in 1973. Since that time, the industry has been working toward achieving those standards. Currently, the standards have undergone revisions in reponse to more recent information concerning the costs of control, technological limitations, and air quality impacts of aircraft and aircraft engines. Because the standards are being reevaluated on the basis of whether or not to proceed from this time forward, it is also reasonable to review the cost effectiveness of the standards on the basis of what must be spent from this point onward to achieve the requisite controls. Therefore, previous expenditures are treated as unrecoverable sunk costs, and judgments as to the cost effectiveness of the standards are made entirely on the future costs and benefits which will accure.

EPA's estimate of the annual disbursements which are necessary for the engine manufacturers to begin the production of the engines in compliance with the various standards was previously presented in Figure 1 and 2. These figures are based on a division of the total non-recurring expenses into two categories: funds that have already been expended and funds that remain to be expended. EPA estimated that at the time this analysis was prepared (mid-1979), manufacturers had spent about 75 percent of their development funds to meet the 1982 standards, or about 60 percent of the total non-recurring costs. For the 1986 standard, it was estimated that manufacturers had spent about 10 percent of the development costs or about 6 percent of the total non-recurring costs.

As previously stated, the average engine selling price increment was calculated by assuming that all annual costs are incurred at the beginning of each year. Therefore, to compute the average engine selling price, all sunk costs prior to January 1, 1980 were excluded. Table 20 presents the alternative cost-effectiveness values, along with the previously determined baseline (total cost) values for comparison. As might be expected, the cost-effectiveness values for the 1982 standards (NME and IUE), are affected the most since a large share of the non-recurring funds will already be expended by 1980.

Retrofit Cost Effectiveness

The 1986 IUE Standard was not separately evaluated in Part I of the Discussion because it is not, strictly speaking, a complete control strategy by itself. The retrofit would not be considered without an accompanying newly-manufactured engine standard. It is relevant, however, to be concerned with the incremental cost effectiveness of the retrofit as an addition to the 1982 NME Standard.

Since the 1986 retrofit standard is optional, only the costs and benefits which would accrue exclusively because of the retrofit are considered. Specifically, any costs which were previously incurred to develop the requisite control hardware are excluded from the cost-effectiveness computations. All other costs and benefits are calculated in the same manner as described in the Methodology. Table 21 shows the cost-effectiveness derivation for the retrofit. In comparison to the 1982 NME Standard (Table 18), the incremental cost effectiveness of the 1986 IUE Standard is significantly more expensive.

The higher cost figures result primarily from 1) a high annual engine price increment, and 2) the relatively low emission reductions for the average engine. For the average retrofit engine, the selling price increment is up to $3,000 higher than the increment which is associated with a newly manufactured engine (Tables 18 and 21). This higher cost results because installing pollution control hardware in an in-service engine is more expensive than installing the same hardware in its newly produced counterpart. Also, the useful life of the average retrofitted engine is only 7 years, compared to 15 years for a new engine. This causes the annual cost of the retrofit to be relatively more expensive because the selling price increment is amortized over a much shorter time period.

The relatively low emission reductions from the average retrofitted engine also contribute to the high cost-effective values. For the average in-service engine, the mass of emissions abated are only about 50 percent of those achieved by controlling the average 1982 newly-manufactured engine (Tables 18 and 21). The preponderance of JT8D engines in the retrofit fleet is the primary cause of this lower emission reduction. JT8Ds have a relatively clean baseline combustor (because of the previous retrofit for smoke control), so when these engines are controlled, the mass of pollutants which are reduced is less than for many other engines. The above factors, acting in concert, overwhelm the retrofits small fuel savings, and result in a higher cost per ton of pollutant reduced in comparison to the 1982 newly-manufactured engine standard.

DISCUSSION

Part III

Aircraft Cost Effectiveness Compared to Other Strategies

In this part, the cost effectiveness of aircraft engine emission controls are evaluated on the basis of their relative cost effectiveness. Before this evaluation is presented, however, several of the basic tenants of cost-effectiveness analysis are briefly discussed.

First, the point at which a control strategy is not considered to be cost effective has never been precisely defined. For this reason, the cost-effectiveness values of other implemented or seriously considered strategies are used as a general benchmark for determining cost efficiency. Second, when future control strategies are being evaluated, it is important to remember that as the most efficient controls are implemented, each succeeding control increment will have a higher marginal cost. Because of this expected price increase, it is not necessarily correct to make decisions with regard to a potential control strategy by limiting its cost effectiveness to that of other past or presently considered programs. Third, because of uncertainties and different methodologies, differences between analyses of up to a few hundred dollars per ton for HC, less than a few hundred dollars per ton for CO (e.g., perhaps $100 per ton), and several hundred dollars per ton for NOx should generally be regarded as insignificant.

As previously presented, the aircraft cost-effectiveness values which will be compared with values for other strategies are the figures which characterize "post-1979 costs" and the incremental cost of the 1986 retrofit standard. These values are summarized in Table 22. In the cost effectiveness comparisons, the values that reflect the exclusion of pre-1980 costs are appropriate since the decision of whether or not to proceed must be based only on the future investment which will be required to attain the goal of aircraft engine pollution control. Previously expended funds are not relevant to this issue. The cost effectiveness values for the other strategies are presented in Table 23. The values for these strategies range up to about $1,000 per ton of HC, $50 per ton of CO, and $3,000 per ton of NOx. Emission control strategies for aircraft engines will be considered cost effective if they are reasonably close to these values for each respective pollutant.

As shown in Tables 22 and 23, all scenarios which included the 1986 NME Standard (low NOx) either singly, or in combination with a previous standard, are not considered to be as cost effective as other non-aircraft control strategies at this time (Scenarios 5, 8, and 9). Controlling HC and NOx emissions in Scenario 5 for about $1,000 and $3,400, respectively, are reasonably close to the upper values of about $1,000 and $3,000, respectively, for other non-aircraft related strategies. The cost effectiveness of $900 for CO control, however, is much higher than the cost of about $50 per ton for other non-aircraft strategies. In cases such as these, it is important to remember that one of the main determinants of cost effectiveness is the cost allocation methodology. Therefore, when one or more of the pollutants being controlled is significantly more costly than with other techniques, an alternate method may be used to ascertain if reweighting the costs would lead to more reasonable cost-effectiveness values for all pollutants. In this instance, $150 per ton of CO and $3,400 per ton of NOx will be specified as cost-effectiveness values. The portion of total costs which are represented by these two pollutants are then recalculated with their respective total emission reductions, and the remaining costs are burdened to HC control. By following this methodology, the cost effectiveness for HC is $1,781 per ton. This is still greater than the $1,000 per ton for non-aircraft strategies as shown in Table 23.

Scenarios 8 and 9 are not reasonably close to the $3,000 per ton of NOx allotted for non-aircraft strategies (Table 22). Therefore, no 1986 NME Standard scenario is as cost effective as other alternative methods of controlling NOx when a 1982 NME Standard is also promulgated.

Control scenarios which evaluate the 1982 NME Standard and 1986 IUE Standard remain to be discussed. The cost-effectiveness values for Scenarios 1, 2, 6, and 7 are either less than, or reasonably close to, the values for other non-aircraft strategies. Controlling HC emissions with the 1982 NME Standard singly, or in conjunction with the 1986 IUE Standard, ranges from $110 to $200 per ton. This is significantly more cost effective than the highest value for other non-aircraft strategies, i.e., $1,000 per ton. The reduction in CO emissions at $90 to $160 per ton is reasonably close to the $50 per ton for other strategies, and is also considered to be equally as cost effective.

The cost-effectiveness values for Scenario 3 are $230 per ton of HC and $180 per ton of CO reduced. This scenario evaluates the 1982 NME Standard when the 1986 NME Standard is also promulgated. Scenario 4 evaluates the 1982 NME and 1986 IUE Standards as a single control strategy when the 1986 NME Standard is also promulgated. The cost-effectiveness of controlling HC and CO in this scenario is $310 per ton and $230 per ton, respectively. The alternate methodology of cost allocation will be applied to Scenario 3 and 4. The CO cost effectiveness values will be specified at $150 and $50 per ton. The costs of controlling HC when CO is specified at $150 per ton are $260 per ton for Scenario 3 and $420 per ton for Scenario 4. When CO is specified at $50 per ton, the costs of controlling HC increase to $400 and $560 per ton for Scenario 3 and 4, respectively. It is clear that values below $50 per ton of CO could be specified and the cost-effectiveness of controlling HC emissions from aircraft engine would remain less costly per ton than the maximum which is already being spent by non-aircraft strategies.

As a control strategy, the retrofit has an incremental or marginal cost effectiveness of $590 for HC and $360 for CO. Since CO control at this value is much greater than for other strategies, but the HC value is lower, the alternate cost methodology will be used to ascertain the effect of reallocating the costs of pollution control. If the CO control is specified at $150 per ton, the HC cost-effectiveness value would be $925. The CO could also be specified as low as $50/ton, the maximum currently being spent (Table 23), with a resulting HC cost effectiveness of about $1,100. Even at this level for HC, the retrofit is reasonably close to the $1,000 per ton which has been calculated for non-aircraft strategies. Therefore, the retrofit is as cost effective as the non-aircraft control strategies.

Table 24 summarizes the cost-effectiveness comparisons of the various control scenarios and the 1986 retrofit strategy.

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Table 1

Description of the Aircraft Emission Control Scenarios

Scenario Number	Scenario Title	Description
1.	1982 NME only.	Evaluates HC and CO control in 1982 for newly-manufactured engines only.
2.	1982 NME and 1986 IUE only.	Evaluates HC and CO control in 1982 for newly-manufactured engines and a retrofit of the same hardware for in-use engines by 1986.
3.	1982 NME in conjunction with 1986 NME.	Evaluates four years of HC and CO control in 1982 newly-manufactured engines prior to the control of NOx in addition to HC and CO in 1986 newly-manufactured engines.
4.	1982 NME and 1986 IUE in conjuntion with 1986 NME.	Evaluates four years of HC and CO control in 1982 newly-manufactured and 1986 in-use engines prior to the control of NOx in addition to HC and CO in 1986 newly-manufactured engines.
5.	1986 NME only.	Evaluates HC, CO, and NOx control in 1986 newly-manufactured engines only.
6.	1982 NME only with CF6 alterntive.	Evaluates HC and CO control in 1982 newly-manufactured only with GE using combustor change on all CF6 engine models instead of sector burning. RR continues with sector burning.
7.	1982 NME and 1986 IUE with CF6 alternative.	Evaluates HC and CO control in 1982 newly-manufactured and 1986 in-use engines with GE using combustor change on CF6 engine models.
8.	1986 NME in conjunction with 1982 standards.	Evaluates HC, CO, and NOx control in 1986 newly-manufactured engines as an increment to previously implemented 1982 standards.
9.	1986 NME in conjunction with 1982 standards and the CF6 alternative.	Evaluates HC, CO, and NOx control in 1986 newly-manufactured engines as an increment to previously implemented 1982 standards in which only RR ssector burns, i.e., with the CF6 alternative.

Table 2

Estimated Engines Affected by Each Standard

	1986 IUE			1982 NME w/1986 NME			1986 NME		
	In-Service	Spares	Total	In-Service	Spares	Total	In-Service	Spares	Total
JT8D-17	3,349	670	4,019	0	0	0	0	0	0
JT8D-200	0	0	0	764	153	917	816	163	979
JT8D-7	1,250	250	1,500	302	60	362	1,869	374	2,243
JT9D-7R	0	0	0	93	19	112	286	57	343
JT9D-70	0	0	0	307	61	368	1,869	374	2,243
CF6-6	587	117	704	235	47	282	1,267	253	1,520
CF6-32	0	0	0	180	36	216	1,084	217	1,301
CF6-50	144	29	173	503	101	604	3,225	645	3,870
CF6-45	0	0	0	187	37	224	573	115	688
CF6-80	0	0	0	91	18	109	286	57	343
RB211-22B	583	116	699	235	47	282	1,267	253	1,520
RB211-535	0	0	0	174	35	209	1,088	218	1,306
RB211-524	0	0	0	235	47	282	1,267	253	1,520
CFM56	0	0	0	404	81	485	818	164	982
	5,913		7,095	3,710		4,452	15,715		18,858

Table 3

Population Weighting Factors by Scenario

	Group 1 Scenarios #1, 2, 6, 7 1982 NME (w/o 1986 NME)	Group 2 Scenarios #3, 4 1982 NME (w/1986 NME)	Group 3 Scenarios #2, 4, 7 1986 IUE 1/ (w/1982 NME)	Group 4 Scenarios #5, 8, 9 1986 NME
	Weighting Factors	Weighting Factors	Weighting Factors	Weighting Factors
JT8D-17	0	0	0.57	
JT8D-200	0.08	0.22	0	0.05
JT9D-7	0.11	0.08	0.21	0.12
JT9D-7R	0.02	0.03	0	0.02
JT9D-70	0.11	0.08	0	0.12
CF6-6	0.08	0.06	0.10	0.08
CF6-32	0.07	0.05	0	0.07
CF6-50	0.19	0.14	0.02	0.21
CF6-45	0.04	0.05	0	0.04
CF6-80	0.02	0.02	0	0.02
RB211-22B	0.08	0.06	0.10	0.08
RB211-535	0.06	0.05	0	0.07
RB211-524	0.08	0.06	0	0.08
CFM-56	0.06	0.11	0	0.05

1/ These population weighting factors represent only the retrofitted portion of the fleet. Therefore, they are used in conjunction with the population factors for newly manufactured engines to describe the total fleet in Scenarios #2, 4, and 7.

Table 4

Useful Life Weighting Factors

	Retrofit Useful Life (yr)	Scenarios #2, 4, 7 1986 IUE (W/1982 NME) Weighting Factor
JT8D-17	7	0.47
JT8D-200	NA	NA
JT9D-7	7	0.47
JT9D-7R	NA	NA
JT9D-70	NA	NA
CF6-6	7	0.47
CF6-32	NA	NA
CF6-45	NA	NA
CF6-50	10	0.67
CF6-80	NA	NA
RB211-22B	7	0.47
RB211-535	NA	NA
RB211-524	NA	NA
CFM56	NA	NA

Table 5

Cost Components and Their Elements

Component	Element
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 Labor

Table 6

Engine Costs Associated with the 1982 Standards
(Thousands of 1978 dollars)

	Development	Certification	Service Evaluation	Initial Production	Non-recurring Total	New Engine Increment	Retrofit
JT8D-17	19,725	6,575	1,200	300	27,800	2.7	23.5
JT8D-200						2.7	
JT9D-7	14,063	4,688	600	800	20,151	6	55
JT9D-7R						6	
JT9D-70	14,063	4,688	600	500	19,851	6	47
CF6-6	5,130	600	276	165	6,171	25	43
CF6-32						25	
CF6-50	7,370	600	284	165	8,419	25	50
CF6-45							
CF6-80	7,370				7,370	6	
RB211-22B	44,608	4,565	1,500	850	51,523	25	73
RB211-535	5,763				5,763	25	
RB211-524		4,565			4,565	25	73
CFM56	3,860	150	NA	35	4,045	5	NA
JT10D	5,850	NA	NA	NA	5,850	NA	NA
Spey	NA	NA	NA	NA	NA	NA	NA

Table 7

Engine Costs Associated with the 1986 Low-NOx Standard
(Thousands of 1978 dollars)

	Development	Certification	Service Evaluation	Initial Production	Non-recurring Total	New Engine Increment
JT8D-200	18,000		4,200	1,800	24,000	21
JT9D-7	35,300	17,200	5,300	3,800	61,600	33
JT9D-7R		4,000			4,000	
JT9D-70	35,300	17,200	5,340	3,800	61,000	33
CF6-6	16,000	7,700	5,400	3,400	32,500	25
CF6-32		3,400			3,400	25
CF6-50	16,000	7,700	5,400	3,400	32,500	25
CF6-45		3,900			3,900	25
CF6-80		3,900			3,900	25
RB211-22B	30,000	4,565	4,300	3,400	42,300	25
RB211-535		4,565			4,600	25
RB211-524		4,565			4,600	25
CFM56	13,000	5,000	3,300	2,600	23,900	17
JT10D	NA	NA	NA	NA	NA	NA
Spey	NA	NA	NA	NA	NA	NA

Table 8

Parent Engines and Their Derivatives

Parent	Derivative	Characteristics
JT8D-17 (-7, -9, -15)	JT8D-200	Higher thrust--basically same core
JT9D-7	JT9D-7R	Higher thrust--same core
JT9D-70	NA	
CF6-6	CF6-32	Clipped fan--same core
CF6-50	CF6-45	Derated--same core
	CF6-80	Lower thrust--smaller in size--basically same core
RB211-22	RB211-535	Clipped fan--same core
	RB211-524	Higher thrust--same core
CFM-56	NA	
JT10D	NA	

Table 9

Engine Costs Associated with the CF6 Alternative Combustor 1/
(Thousands of 1978 dollars)

	Development	Certification	Service Evaluation	Initial Production	Non-recurring Total	New Engine Increment
CF6-6	7,000	4,600	600	500	12,700	8
CF6-32	2/	4,600	2/	2/	4,600	8
CF6-80	NA	NA	NA	NA	NA	NA
CF6-50	3/	4,600	3/	3/	4,600	6
CF6-45	3/	4,600	3/	3/	4,600	6

1/ Based on the latest manufacturer or vendor submittals to EPA (Appendicies B and C).

2/ Requirements for the CF6-32 already have been fulfilled by the CF6-6 parent engine; therefore, no additional cost is incurred.

3/ Requirements for the CF6-50 and CF6-45 already have been fulfilled by the closely related CF6-80; therefore, no additional cost is incurred.

Table 10

Annual Engine Expenses

Scenario #	Average Engine Increase	Average Useful Life	Capital Recovery Factor	Annual Engine Cost
1	40,800	15	.1315	5,360
2	41,200	13	.1408	5,800
3	78,800	15	.1315	10,360
4	56,000	10	.1628	9,120
5	72,600	15	.1315	9,550
6	35,500	15	.1315	4,670
7	39,100	13	.1408	5,500
8	57,200	15	.1315	7,520
9	57,200	15	.1315	7,520

Table 11

Approximate Percentage Idle Fuel Increment by Engine Model

	1982 1/	1982 w/ GE Alternative	1986 w/ 1982	1986 w/1982 Alternative	1986 w/o 1982
JT8D-17	+1	+1	0	0	+1
JT8D-200	+1	+1	0	0	+1
JT9D-7	+3	+3	0	0	+3
JT9D-7R	+3	+3	0	0	+3
JT9D-70	+3	+3	0	0	+3
CF6-6	-5	+3	+8	0	+3
CF6-32	-5	+3	+8	0	+3
CF6-50	-5	+3	+8	0	+3
CF6-45	-5	+3	+8	0	+3
CF6-80	+3	+3	0	0	+3
RB211-22B	-5	-5	+8	+8	+3
RB211-535	-5	-5	+8	+8	+3
RB211-524	-5	-5	+8	+8	+3
CFM56	-22	-22	+20	+20	+3

1/ Since the 1985 retrofit standard begins in 1982, it is termed a 1982 standard.

Table 12

Annual Idle Fuel Consumption Increment for the Average Engine

Scenario	Gallons	Dollars 1/
1	+2,855	+1,142
2	+2,630	+1,052
3	+3,306	+1,322
4	+1,569	+ 628
5	-2,632	-1,053
6	+ 674	+ 270
7	+ 566	+ 226
8	-5,425	-2,170
9	-3,023	-1,209

1/ At a nominal value of $.40 per gallon.

Table 13

Cruise Flight Fuel Penalty

	4EWB	3EWB	2EWB	2EMB	3ERB	2ERB
Engine Weight Increase (lbm)	300	200	200	200	200	200
Cost per Pound per Year ($)	8	5	4	4	4	2.5
Cost per Engine per Year ($)	2400	1000	800	800	800	500

Table 14

Annual Cruise Fuel Consumption Increment for the Average Engine Brought About by NOx Control (Scenarios 5, 8, and 9 only) (1978 dollars)

	Weighted Useful Life	Weighted Sales	Annual Cruise Penalty (Dollars)	Weighted Annual Cruise Penalty (Dollars)
JT8D-200	1	.05	500	25
JT9D-7	1	.12	2,400	288
JT9D-7R	1	.02	2,400	48
JT9D-70	1	.12	1,000	120
CF6-6	1	.08	1,000	80
CF6-32	1	.07	800	56
CF6-50	1	.21	1,000	210
CF6-45	1	.04	1,000	40
CF6-80	1	.02	1,000	20
RB211-22B	1	.08	1,000	80
RB211-535	1	.07	800	56
RB211-524	1	.08	1,000	80
CFM56	1	.05	500	25
				1,128

Table 15

Annual Maintenance Costs for the Average Engine (1978 dollars)

Scenario	Dollars
1	632
2	604
3	541
4	526
5	42,500
6	632
7	604
8	42,500
9	42,500

Table 16

Average Airport-Specific Taxi-Idle Times

Airport		Jumbo Jet Idle Out	Jumbo Jet Idle In	Long-Range Jet Idle Out	Long-Range Jet Idle In	Medium-Range Jet (3 engines) Idle Out	Medium-Range Jet (3 engines) Idle In	Medium-Range Jet (2 engines) Idle Out	Medium-Range Jet (2 engines) Idle In
Atlanta Hartsfield	ATL	11.8	8.0	10.3	7.0	10.3	7.0	9.9	6.7
Boston Logan	BOS	9.6	5.7	8.3	5.0	8.3	5.0	7.9	4.8
Cleveland Hopkins	CLE	6.1	5.7	5.3	5.0	5.3	5.0	5.1	4.8
Washington National	DCA	8.4	5.7	7.3	5.0	7.3	5.0	7.0	4.8
Denver Stapleton	DEN	7.3	8.0	6.3	7.0	6.3	7.0	6.0	6.7
Dallas-Forth Worth	DFW	7.3	6.8	6.3	6.0	6.3	6.0	6.0	5.8
Detroit Metropolitan	DTW	6.1	6.8	5.3	6.0	5.3	6.0	5.1	5.7
Newark	EWR	10.7	9.1	9.3	8.0	9.3	8.0	8.9	7.7
Honolulu	HNL	18.6	13.0	16.2	11.4	16.2	11.4	16.5	10.9
Houston	IAH	10.2	9.3	8.9	8.2	8.9	8.2	8.5	7.9
John F. Kennedy	JFK	19.8	12.5	17.3	11.0	17.3	11.0	16.6	10.6
McCarran	LAS	11.8	8.2	10.3	7.2	10.3	7.2	9.9	6.9
Los Angeles	LAX	10.7	9.1	9.3	8.0	9.3	8.0	8.9	7.7
La Guardia	LGA	15.3	9.1	13.3	8.0	13.3	8.0	12.7	7.7
Kansas City	MCI	9.6	9.3	8.3	8.2	8.3	8.2	7.9	7.9
Memphis	MEM	7.6	7.4	6.6	6.5	6.6	6.5	6.3	6.2
Miami	MIA	8.4	6.8	7.3	6.0	7.3	6.0	7.0	5.8
Minneapolis-St. Paul	MSP	8.4	5.7	7.3	5.0	7.3	5.0	7.0	4.8
Chicago O'Hare	ORD	15.3	10.3	13.3	9.0	13.3	9.0	12.7	8.6
Philadelphia	PHL	9.6	8.0	8.3	7.0	8.3	7.0	7.9	6.7
Phoenix Sky Harbor	PHX	10.7	8.8	9.3	7.7	9.3	7.7	8.9	7.4
Greater Pittsburgh	PIT	5.0	5.7	4.3	5.0	4.3	5.0	4.1	4.8
Seattle Tacoma	SEA	7.3	5.7	6.3	5.0	6.3	5.0	6.0	4.8
San Francisco	SFO	10.7	6.8	9.3	6.0	9.3	6.0	8.9	5.8
Lambert St. Louis	STL	7.3	5.7	6.3	5.0	6.3	5.0	6.0	4.8
Tampa	TPA	10.4	8.0	9.0	7.8	9.0	7.8	8.6	7.5

Table 17

Annual Pollution Reductions for the Average Engine

Scenario	Annual Pollution Reduction (tons) HC	CO	NOx
1	16.4	20.8	NA
2	15.4	19.8	NA
3	14.5	19.1	NA
4	12.2	16.9	NA
5	17.7	19.2	5.0
6	16.4	20.8	NA
7	15.4	19.8	NA
8	NA	NA	5.0
9	NA	NA	5.0

Table 18

Cost Effectiveness Computation (1978 Dollars)

ontrol cenario	Engine Cost Increment ($)	$\overline{x}$ Engine Life (years)	Capital Recovery Factor	Annual Idle Fuel Increment ($)	Annual Cruise Fuel Increment ($)	Annual Maintenance ($)	Average Engine Pollution Reduction			Cost Effectiveness ($/t)		
							HC	CO	NOx	HC	CO	NOx
1	40,800	15	0.1315	+1142	0	+632	16.4	20.8	0	220	170	NA
2	41,200	13	0.1408	+1052	0	+604	15.4	19.8	0	240	190	NA
3	78,800	15	0.1315	+1322	0	+541	14.5	19.1	0	420	320	NA
4	56,000	10	0.1628	+ 628	0	+526	12.2	16.9	0	420	300	NA
5	72,600	15	0.1315	-1053	+1128	+42,500	17.7	19.2	5.0	980	900	3500
6	35,300	15	0.1315	+ 270	0	+632	16.4	20.8	0	170	130	NA
7	39,100	13	0.1408	+ 226	0	+604	15.4	19.8	0	210	160	NA
8	57,200	15	0.1315	-2170	+1128	+42,500	0	0	5.0	NA	NA	9800
9	57,200	15	0.1315	-1209	+1128	+42,500	0	0	5.0	NA	NA	10,000

Table 19

Effect of Variations in Fleet Projections (1978 Dollars)

Scenario	Selling Frice Increment ($) -10%	Baseline	+10%	Cost Effectiveness ($/t) -10 Percent HC	CO	NOx	Baseline HC	CO	NOx	+10 Percent HC	CO	NOx
1	43,300	40,800	38,800	230	180	NA	220	170	NA	210	160	NA
2	42,700	41,200	39,800	250	190	NA	240	190	NA	240	180	NA
3	85,900	78,800	73,100	450	340	NA	420	320	NA	400	300	NA
4	57,600	56,000	54,500	430	310	NA	420	300	NA	410	300	NA
5	77,400	72,600	68,700	990	920	3,500	980	900	3,500	970	900	3,400
6	37,800	35,500	33,300	180	140	NA	170	130	NA	160	130	NA
7	40,800	39,100	37,500	210	170	NA	210	160	NA	400	310	NA
8	62,000	57,200	53,300	NA	NA	9,900	NA	NA	9,800	NA	NA	9,700
9	62,000	57,200	53,300	NA	NA	10,000	NA	NA	10,000	NA	NA	9,900

Table 20

Effect of Excluding Sunk Cost (1978 Dollars)

Scenario	Selling Price Increase ($)		Cost Effectiveness ($/t)					
			Post 1979			Baseline		
	Post 1979	Baseline	HC	CO	NOx	HC	CO	NOx
1	26,100	40,800	160	120	NA	220	170	NA
2	31,800	41,200	200	160	NA	240	190	NA
3	36,700	78,800	230	180	NA	420	320	NA
4	39,800	56,000	310	230	NA	420	300	NA
5	68,700	72,600	970	900	3,400	980	900	3,500
6	20,600	35,500	110	90	NA	170	130	NA
7	29,600	39,100	160	130	NA	210	160	NA
8	53,300	57,200	NA	NA	9,700	NA	NA	9,800
9	53,300	57,200	NA	NA	9,900	NA	NA	10,000

Table 21

Incremental Cost Effectiveness of the 1986 IUE Standard (1978 Dollars)

Engine Cost Increment ($)	$\overline{x}$ Engine Life (years)	Annual Capital Recovery Factor	Idle Fuel Increment ($)	Annual Maintenance ($)	Average Engine Pollution Reduction (t) HC	CO	Cost Effectiveness ($/t) HC	CO
41,798 1/	7	0.2054	-497 2/	460 3/	7.3 4/	12.0 4/	590	360

1/ Derived in Appendix D.
2/ Derived in Appendix C.
3/ Derived in Appendix B.
4/ Derived in Appendix H.

Table 22

Selected Cost-Effectiveness Values for Aircraft Emission Control (1978 Dollars)

Scenario/Strategy		Cost Effectiveness ($/t) (Post 1979 costs only)		
Scenario Number	Description	HC	CO	NOx
1.	1982 NME only.	160	120	NA
2.	1982 NME and 1986 IUE only.	200	160	NA
3.	1982 NME in conjunction with 1986 NME.	230	180	NA
4.	1982 NME and 1986 IUE in conjunction with 1986 NME.	310	230	NA
5.	1986 NME only.	970	900	3,400
6.	1982 NME only with CF6 alternative.	110	90	NA
7.	1982 NME and 1986 IUE with CF6 alternative.	160	130	NA
8.	1986 NME in conjunction with 1982 standards.	NA	NA	9,700
9.	1986 NME in conjunction with 1982 standards and the CF6 alternative.	NA	NA	9,900
	1986 IUE (retrofit) only.	590	360	NA

Table 23

Cost Effectiveness for Non-Aircraft Control Strategies (1978 Dollars)

Control Strategy	Cost Effectiveness ($/t) HC	CO	NOx
Degreasing 0-48%	-230 1/		
Gravure 0-98%	-60 1/		
Gas Terminal 0-67%	0 1/		
Miscellaneous Chemicals 0-35%	0 1/		
Dry Cleaning 0-80%	10 1/		
GHDV Evap. 5.8-0.5 g/mi.	20 1/2/		
Degreasing 41-90%	100 1/		
Industrial Finishing 76-97%	110 1/		
Gasoline Handling 16-50%	110 1/		
Miscellaneous Chemicals 35-53%	220 1/		
Gasoline Distributions 67-99%	300 1/		
Coke Ovens 0-80%	490 1/		
LDV Exhaust 0.9-0.41 g/mi	530 1/		
Gas Handling 51-91%	780 1/3/		
GHDV 90% of Baseline	300 4/	8 4/	
DHDV 90% of Baseline	162 4/		
LDV I/M	955 5/	49 5/	2,763 6/
LDT 1.7-0.8 g/mi	139-201 7/		
Motorcycles 9 to 8-22.5 g/mi	420 8/		
Motorcycles 34.67-27.4 g/mi		neg.8/	
LDV 15-3.4		48 1/	
LDV 3.1-0.4			2,700 1/
Stationary Engines 0-75%			400 1/
Utility Boilers 0-90%			1,400 1/

1/ U. S. DOT (1976)

2/ A more recent EPA analysis, which supports a regulation yet to be published as a proposal, yields numbers in the range of $70 to $250 per ton (yet to be released).

3/ Agrees reasonably well with a more recent EPA analysis (yet to be released).

4/ U.S. EPA (1978b).

5/ O'Rourke (1979).

6/ Vector Research (1978).

7/ U.S. EPA (1979).

8/ U.S. EPA (1976).

Table 24

Summary Results of Aircraft Emission Control Cost Effectiveness Evaluation

Scenario/Strategy

Scenario Number	Description	Relative Cost Effectiveness Compared to Other Strategies
1.	1982 NME only.	Better
2.	1982 NME and 1986 IUE only.	Better
3.	1982 NME in conjunction with 1986 NME.	Better
4.	1982 NME and 1986 IUE in conjunction with 1986 NME.	Better
5.	1986 NME only.	Worse
6.	1982 NME only with CF6 alternative.	Better
7.	1982 NME and 1986 IUE with CF6 alternative.	Better
8.	1986 NME in conjunction with 1982 standards.	Worse
9.	1986 NME in conjunction with 1982 standards and the CF6 alternative.	Worse
	1986 IUE (retrofit) only.	Equivalent

1/ Relative cost effectiveness is determined on the basis of the maximum cost for other strategies, taking into account that those figures also have an associated range of costs because of uncertanties which are found in all cost-effectiveness analyses.

Figure 1

Time Expenditure of Non-Recurring Funds for the 1982 NME and 1986 IUE Standards.

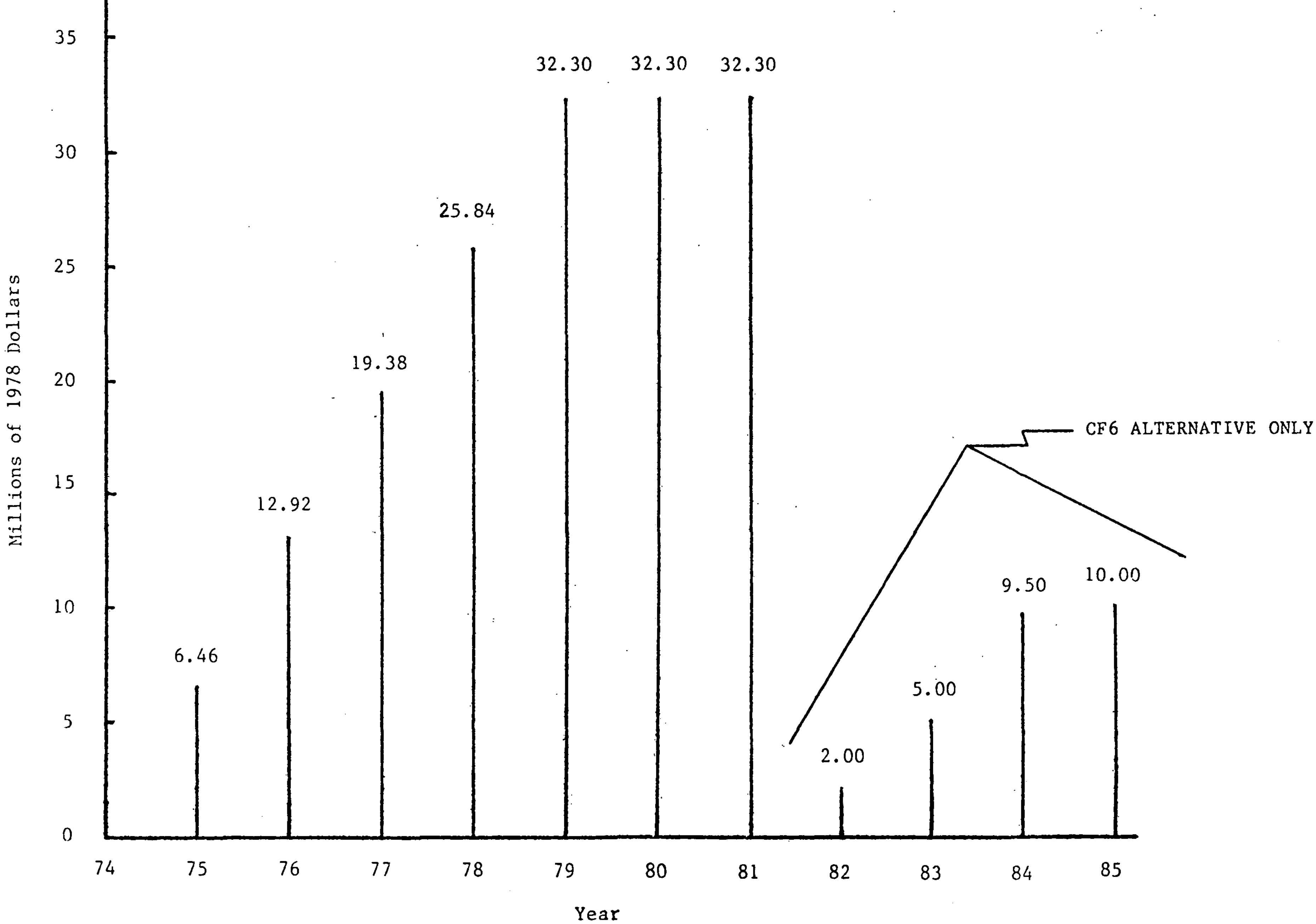
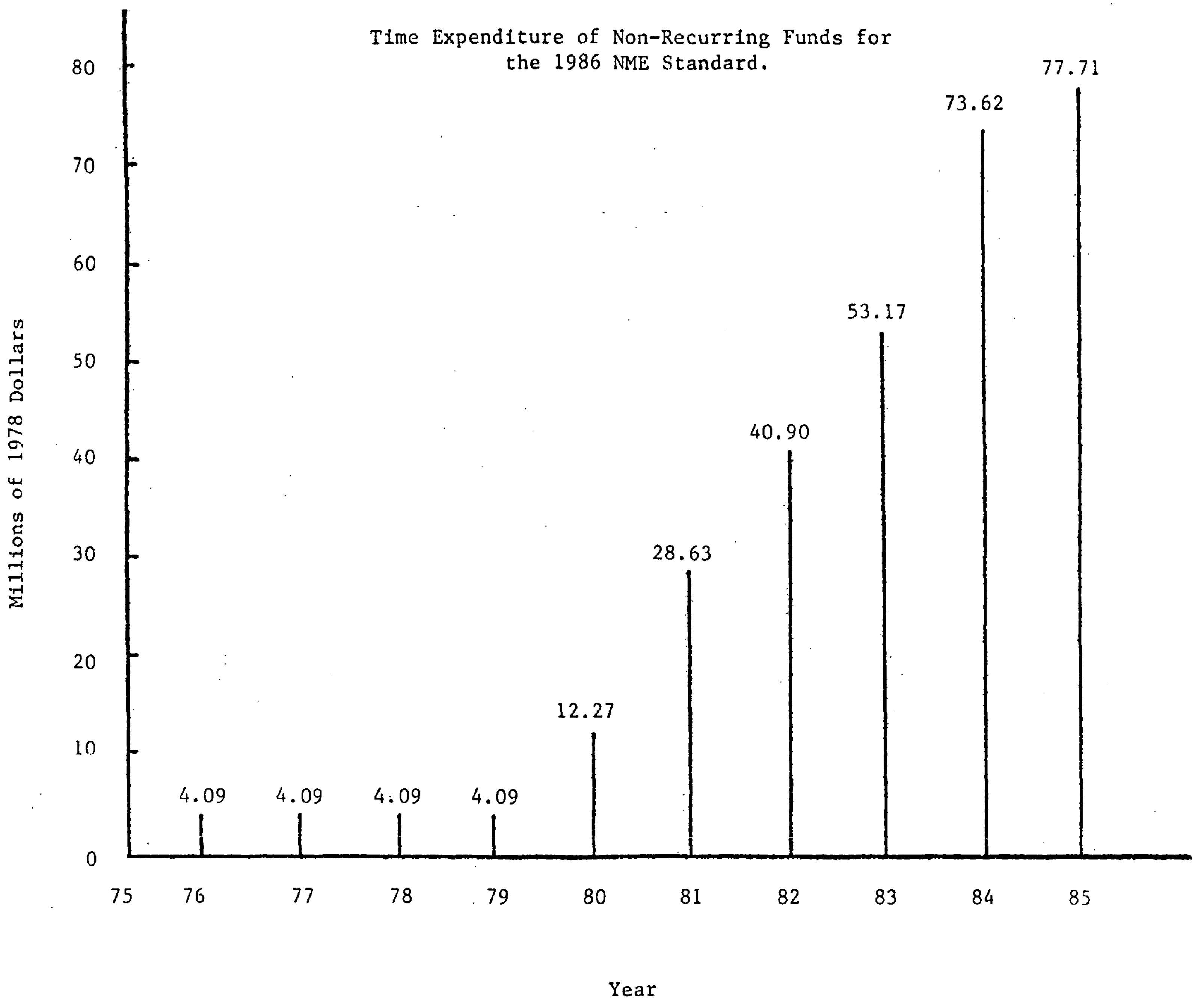


Figure 2

Time Expenditure of Non-Recurring Funds for the 1986 NME Standard.



Appendix A

EPA Cost Questionaire

QUESTIONNAIRE TO MAJOR AIRLINES

Enclosure I

Retrofit Cost Information

To be most cost effective, airlines are expected to rework existing engine components into low-emission configurations during routine maintenance to the greatest extent possible. Therefore, the economic impact of the 1985 Retrofit Standard will be defined as the increment between the cost of incorporating low-emission hardware and the cost of routinely repairing existing components. We expect that your company will be able to supply only the routine repair costs. The costs associated with the low-emission hardware will be supplied by the engine manufacturers.

The baseline routine repair cost estimates should be specific for each generic engine family, unless otherwise indicated. Exclude engine disassembly and assembly unless components are involved that are not normally accessible during hot section or related maintenance. Costs for repairing (or replacing as appropriate) the following items are of interest at this time:

Combustion liners and dome

Fuel nozzle tip and support

Fuel manifold

Fuel sectoring control hardware (CF6 generic families)

Transition duct (JT8D-1, -7, and -9 generic family)

Transition duct guides (JT8D-1, -7, and -9 and JT8D -15 and -17 generic families)

The answers may be reported as an average with an associated range of uncertainty, if necessary. Additional baseline information may be included if, in your opinion, more detail or other items should be considered. All expenses should be reported in 1978 dollars.

If premature engine removals appear necessary to complete the retrofit within the scheduled time, they will be accounted for in a more general manner using data from Enclosure II and other information from the comments on this and prior rulemaking actions.

Enclosure II

Maintenance Cost Information

Possible maintenance increments associated with the low-emission control hardware will be evaluated with the following data elements. These elements represent the absolute minimum amount of information from the airlines that is essential to complete the analysis. Additional comments are invited if, in your opinion, other information should also be considered.

The estimates should be specific for each generic engine family.

1. What is the mean of the times between overhaul?

2. What is the mean of calendar intervals between overhaul?

3. What is the mean shop cost for engine maintenance in 1978 dollars?

4. What is the mean number of man-hours necessary to remove and reinstall an engine on the aircraft?

QUESTIONNAIR TO PARKER HANNIFIN CORPORTION

Enclosure I

Manufacturer's Cost and Price Information

The following information will be used to develop EPA's third and final cost-effectiveness analysis of the proposed standards. The format of this report will closely resemble TSR AC78-01 which is enclosed. Specific responses are needed to assure a more accurate and complete economic assessment than has been possible in the past. If some cost categories require modification to be more representative, please retain the degree of detail. Specific figures based on your records for each generic engine family are preferred; however, when these are unavailable, please include an estimate, based on your best judgment, of the anticipated cost. In these non-specific cases, insert the word "typical" under the engine model heading along with any additional qualifying information. The expenses may be presented as an average with an associated range of uncertainty where necessary. Only the costs incurred as a consequence of the gaseous emission standards should be included in the cost estimates; items relating to normal product improvement should be excluded. All prices should be reported in 1978 dollars.

When low-emission hardware involves a design change to existing hardware, or the addition of a new part, and it is not obvious why it is necessary, please include a brief explanation of the modification including how it relates to the control strategy.

Your submittal should include, but not be limited to, information on the following items:

1981 NME and 1985 Retrofit HC and CO Control Hardware

General Electric	Pratt and Whitney Aircraft
nozzle tip	dual-aerating nozzle
nozzle support	single-aerating nozzle
check valves	
swirler	

1984 NME HC, CO, and NOx Staged Combustion Hardware

General Electric	Pratt and Whitney Aircraft
nozzle assembly	nozzle assemblies
swirlers	

During EPA's initial investigation of the PWA aerating nozzle design, several pieces of information were acquired. This information may be used as a basis for your cost estimates of fuel systems not produced by Parker Hannifin.

ENCLOSURE II

If the low-emission fuel nozzles will require special overhaul tools and dies, please estimate the retail value per set and the number of sets typically required by an airline maintenance shop.

NEW ENGINE PRICE INCREMENT[1]

Generic Engine Model	Price Increment

[1] Do not include amortization on non-recurring costs.

INITIAL PRODUCTION

Engine Model	Part Name	Tool Design	Tool Procurement	Increment in Manufacturing Cost Based on Current Part[1]	Economic Production Volume

[1] Increment should account for increase or decrease in material, labor, machining, and corporate profit. No amortization of development, certification, or other non-recurring expenses should be included. If no conventional counterpart exists, the increment will be the full manufacturing cost of the part.

Enclosure II

Retrofit Cost Information

The following information is needed for our evaluation of the economic impact of the 1985 Retrofit Standard. Please make your responses as specific as possible for each generic engine family. Some of the answers may be reported as an average with an associated range of uncertainty where necessary.

1. To be most cost effective, airlines will rework existing engine components into low-emission configurations to the greatest extent possible. Therefore, it seems plausible that in most cases, items such as all new combustion liners or cans will not be purchased, but instead a kit containing modified parts will be available to rework existing hardware. Please detail the minimum number of parts per engine that airlines are likely to use for in-house low-emission modifications along with an estimate of their retail price.

2. As described in question one, the retrofit of low-emission hardware is expected to be accomplished during routine maintenance activities. The following simplified format was developed to provide the necessary information while providing a clearer understanding of how the final results were derived. The basic elements of the format may also be useful in analyzing other portions of the economic impact.

   The estimates should be specified for each hardware item (e.g., combustion liner, fuel nozzle tip, and transition duct), and exclude engine disassembly and assembly unless the modification would involve items not normally accessible during hot section or related maintenance. (This possibility exists in parts c and d below.) In all cases, a general description of the changes should be included along with the reason why the modification is necessary. Please specify the cost per manhour used in the analysis.

   a. When low-emission modifications are incorporated into the repair of existing hardware, certain materials and labor that would have normally been expended should be deducted from the cost of the modification.

   Response format: ($ Mod. hardware + $ Mod. labor) - ($ Routine material + $ Routine labor) = $ Increment

   b. When new low-emission hardware totally replaces hardware that would normally be reworked or repaired, the cost of the repair (material and labor) should be deducted from the purchase price of the new part.

Response format: \$ New component - (\$ Routine material + \$ Routine labor) = \$ Increment

c. In parts which have no existing counterpart, both the cost of the part (available from question one), and the average number of manhours for its installation should be reported.

Response format: \$ New component + \$ Installation labor = \$ Increment

d. For parts which must be reworked to accept the low-emission modification (e.g., JT9D-7 diffuser case), the cost should include disassembly and assembly if it involves items not normally accessible during typical hot section or related maintenance.

Response format: \$ New parts + \$ Mod. labor + \$ Installation labor = \$ Increment.

3. Estimate the one-time cost of new rework fixtures or other tools which will be needed (per set), and the number of sets necessary to equip the average repair facility.

4. What are the range and mean of times between overhaul experienced by different models? We realize that much maintenance is done "on condition", but as part of the statistical history, the mean TBO's are available.

Enclosure III

Maintenance Cost Information

Part I

In some instances, maintenance increments may be associated with the use of low-emission control hardware due to durability degradation and added complexity. Estimate what increases may be experienced by engines in compliance with the 1981 NME and 1984 NME Standards. These changes may be reported as a "best" and "worst" case if desired. Be sure to include the quantitative basis for the estimate.

Completion of this part should not be substituted for Part II.

Part II

In addition to the above, possible maintenance increments will be evaluated with the following data elements. These elements represent the absolute minimum amount of baseline information that is essential to complete EPA's analysis. Additional comments are invited if in your opinion other information should also be considered.

The estimates should be specific for each generic engine family.

1. What is the mean time between overhauls? (See Enclosure II question 4).

2. What is the mean calendar interval between overhauls?

3. What is the mean shop cost for engine maintenance?

4. What is the mean number of man-hours necessary to remove and reinstall an engine on the aircraft?

5. For a mature low NOx staged combustor (1984 NME), what is the increase in labor (man-hours) for a typical repair beyond that incurred by a conventional combustor. This additional effort should reflect the increase in complexity only.

6. What is the mean incremental cost per shop visit that may be expected because of sector burn control hardware?

ADDITIONAL ENCLOSURES TO PRATT AND WHITNEY QUESTIONNAIRE

ENCLOSURE V

I. As referenced below, the following questions pertain to Pratt & Whitney Aircraft's December 15, 1978 submittal to Mr. Cornelius Day of Logistics Management Institute (hereafter called the LMI submittal), and the letter of August 25, 1978 from Mr. G. N. Frazier, Vice President, Engineering, Pratt & Whitney Aircraft, to Charles L. Gray, Director, Emissions Control Technology Division, EPA.

1. LMI Submittal.
Are the costs for the JT8D-209 the same as those for the JT8D-9?

2. LMI Submittal, Table I and II, pages 3-1 and 3-2, and Pratt & Whitney Aircraft's August 25, 1978 letter by Mr. G. N. Frazier to EPA.
In Mr. Frazier's letter, the 1981 NME total development costs appear to be the sum of the Table I column entitled Total Through 1977 for each specific engine model, and the total cost for each specific engine model as listed in Table II of the LMI submittal. Does this mean that none of the other previous development costs are attributable to the proposed 1981 NME gaseous exhaust emission rules as shown in Table I?

3. LMI Submittal, Table I and II, pages 3-1 and 3-2.
What portion of these costs is attributable only to gaseous emissions control? Presumably some funds were expended for smoke control and these should be excluded since the existing standard is not significantly affected by the proposed smoke standard.

4. LMI Submittal, Table II, page 3-2.
Some of the categories in this table are the same as those used in EPA Report No. AC78-01 (e.g., service evaluation), while others are not. We assume that certification is included and initial production (e.g., tooling) is excluded; however, neither is directly stated nor implied in the text. Is this correct? If these categories are not accounted for in Table II, what are the costs associated with them?

5. LMI Submittal, Table II, page 3-2.
Why is the future development cost of the 1984 NME JT10D so high? It would seem that vorbix experience gained from the JT9D and the fact that the JT10D is not in production would both reduce the total development for this engine as well as the new selling price increment shown in Table III, page 4-1.

6. LMI Submittal, Table III, page 4-1 and Pratt & Whitney Aircraft's August 25, 1978 letter by Mr. G. N. Frazier to EPA.
As the text of your LMI submittal indicates, the production

price increments for 1981 NME includes a portion of the development costs which will be recovered. In Mr. Frazier's letter, the increments do not account for the recovery of specific development costs, yet these figures are nearly identical to those in Table III (LMI). Please clarify this apparent discrepancy.

7. LMI Submittal, Table IV, page 5-2.
For the column entitled Retrofit in Conjunction With Other Hot Section Maintenance, is the Shop Labor (Manhours) the difference between normal maintenance on the affected parts and the installation of the retrofit kit consisting of new parts, or just the time it takes to install the retrofit kit? In other words, some manpower would have normally been expended maintaining the affected parts and EPA wants to be sure that fact is accounted for so the true incremental cost is reported. The same is true for material costs.

8. LMI Submittal, Table VI, page 6-1.
For the worst case, estimated increases in maintenance costs included a value for HP turbine degradation in the 1984 NME configuration. Please specify the degree of turbine maintenance assumed (rework or replace blades) and the typical charge for this work.

9. Pratt & Whitney Aircraft's August 25, 1978 letter by Mr. G. N. Frazier to EPA.
How is the aggregate 1981 NME price increment without specific development costs determined? The prices quoted seem very high for a new engine where some changes may be as simple as rearranging the location of dilution and cooling holes in the combustor.

II. The following questions are general in nature.

1. It is our understanding that the dual aerating nozzle will be used by the JT8D and JT9D to meet the 1981 NME and 1985 Retrofit Standards until the less expensive single aerating nozzle is perfected. What is the anticipated introduction date and price difference of the single aerating nozzle compared to the dual aerating nozzle, and what will be the impact on the new engine price increment?

2. Will Pratt & Whitney Aircraft produce low emission configurations for the domestic airline fleet and uncontrolled configurations for foreign air carriers not operating in the U.S.? Or will only low emission configurations be produced?

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ADDITIONAL ENCLOSURES TO PRATT AND WHITNEY QUESTIONNAIRE

Enclosure IV

The 15 December 1978 Pratt and Whitney submittal to Logistics Management Institute has been reviewed. Please include information on the JT8D-209 in your submittal to this request.

ADVANCED DEVELOPMENT, CERTIFICATION, AND SERVICE EVALUATION COSTS[1]
(in $1000)

Development				Certification		Service Evaluation	
Generic Engine Model	Design and General Laboratory Effort	General Engineering Support	Testing Hardware	Certification Tests	Miscellaneous Tests	Engine Hardware	Total Cost

[1]Development should not include product improvement.

Enclosure I

Manufacturer's Cost and Price Information

The following information will be used to develop EPA's third and final planned cost-effectiveness analysis of the proposed standards. The format of this report will closely resemble TSR AC78-01 which is enclosed. Specific responses are needed to assure a more accurate and complete economic assessment than has been possible in the past. If some cost categories require modification to be more representative, please retain the degree of detail. The expenses may be presented as an average with an associated range of uncertainty where necessary. Only the costs incurred as a consequence of the gaseous emission standards should be included in the cost estimates; items relating to normal product improvement should be excluded.

ADVANCED DEVELOPMENT COSTS[1]
(in $1000)

Generic Engine Model	Design and General Laboratory Effort	General[2] Engine Hardware	Specific Modification Hardware	Rig[3] Tests	Engine[3] Tests	Emission Testing	Special Tests	General Engineering Support	Total Cost

[1] Development should not include product improvement.

[2] If applicable, include number of engines dedicated.

[3] Breakdown into general tasks, e.g., cold and hot starting test, coking and temperature distribution test, and low cycle fatigue test, as appropriate.

CERTIFICATION COSTS
(in $1000)

Generic Engine Model	Engine Hardware	Specific Modification Hardware	Endurance Test	150 Hour Certification Test	Hot and Cold Starting Test	Overtemperature Test and L.P. Turbine Overspeed Test	LCF Test	Foreign Object Ingestion	Emission Testing	Engineering Support	Flight Test	Total Cost

INITIAL PRODUCTION

Generic Engine Model	Part Name	Tool Design	Tool Procurement	Increment in Manufacturing Cost Based on Current Part[1]

[1] Increment should account for increase or decrease in material, labor, machining, and corporate profit. No[redacted]rti[redacted]on[redacted]dev[redacted]me[redacted]cer[redacted]ca[redacted], o[redacted]her[redacted]-re[redacted]ring[redacted]xpen[redacted] sh[redacted] be[redacted]lu[redacted]

SERVICE EVALUATION[1]

Generic Engine Model	Total Cost	Total Time Required

[1] Include a description of typical service evaluation, i.e., what responsibilities or cost categories are incurred separately by the engine manufacturer and the air carrier?

NEW ENGINE PRICE INCREMENT

Generic Engine Model	Price Increment[1]

[1] Do not include amortization of non-recurring costs.

Appendix B

Cost Information
Submitted in Response to
EPA Questionnaire

PRATT & WHITNEY AIRCRAFT GROUP
Commercial Products Division

East Hartford, Connecticut 06108

December 21, 1978

Mr. Charles L. Gray, Jr.
Director
Emission Control Technology Division
United States Environmental Protection Agency
Ann Arbor, Michigan 48105

Dear Mr. Gray:

This letter is in reply to your letter of December 8 in which you request additional information relative to the proposed aircraft engine exhaust emission standards.

Enclosed are attachments answering the inquiries of your Enclosures IV and V. We are working on answers to enclosures I, II and III. Considerable effort is involved. We will forward the requested information as soon as it is available.

Very truly yours,

Gordon A. Titcomb
Executive Vice President

cc: Mr. George Kittredge
Senior Technical Advisor
Office of Mobile Source Air Pollution Control
Environmental Protection Agency
Waterside Mall, Washington, D.C. 20460

Re: Docket #OMSAPC-78-1
Control of Air Pollution from Aircraft and Aircraft Engines

Enclosures

UNITED

Enclosure IV - All production JT8D-209 engines will incorporate the best available reduced emission combustion systems. Therefore, there should be no requirement to retrofit in use JT8D-209 engines. If a current production type combustion system were incorporated in this engine, the engine price would be lower by an amount equal to the price increment listed for the JT8D-9 in Table III of P&WA's report to LMI.

Enclosure V -

I.1. See above (Enclosure IV discussion).

I.2. The other costs listed in Table I, Technology Contracts, Proposals and Emissions R&D, relate to technology development efforts for control of all emitted pollutants of concern (HC, CO, NO_x and smoke). A precise breakdown of these costs to reflect the specific effort directed toward the proposed 1981 NME Rules is not possible.

I.3. All costs listed in Tables I and II are attributable to gaseous emissions control. Efforts related to reduction of smoke emissions have been undertaken only to the extent made necessary by increases in smoke above the proposed level induced by the control strategies adopted for gaseous emissions. The proposed regulations require simultaneous control of gaseous and smoke emissions.

I.4. True.

I.5. The JT10D development cost estimates are predicated upon a more difficult development effort induced by operation at higher pressure ratios and by constraints placed upon combustion section volume and geometry. The competitive pressure of the market place for specific fuel consumption and shorter lighter engines have brought about this situation.

I.6. The figures in Mr. Frazier's letter are averages for each engine model of the specific increments presented in Table III. These increments and their averages although not including the specific development cost write-offs for each engine model, do include allowances for recovery of development costs. Development costs have been "pooled" and then allocated across the entire P&WA commercial engine production base in a manner analogous to the way other necessary development costs are recovered.

I.7. The Shop Labor (manhours) represents the added work over the work that would normally be performed at a hot section inspection (HSI). It includes the manhours required to rework parts and the effort required for more extensive disassembly into the engine than would normally be required in a normal HSI.

I.8. The worst case burner repair estimates are predicated on the basis that JT9D engines manurfactured from January 1984 to the end of 1986 (NME) will have immature burners with up to a 50% reduction in life relative to a mature 1984 rule vorbix burner. This analysis indicates that these engines will require two extra shop visits for burner and turbine repair during an engine's lifetime. Our best engineering judgements indicate that a 50% reduction in burner life will cause a 25% reduction in high pressure turbine (HPT) life and a 12% reduction in low pressure turbine (LPT) life. This HPT and LPT degradation is fundamentally blade, vane and seal replacement due to loss of life or increased frequency of scrappage. The labor value reflects the increased frequency of repairing the HPT and LPT modules.

I.9. The price increments are based upon the modifications required to incorporate the new reduced emission combustors. These modifications include new fuel injector supports, new fuel injectors, and changes to the combustor itself to accommodate the new fuel injectors and the new combustor and cooling airflow distributions. In at least one instance, modifications are required to engine cases to accommodate the new combustors are also included. The increased prices are a result of the estimated increase in costs for the new and modified parts.

II.1. P&WA has no current plan to develop a new single aerating nozzle for the JT9D or JT8D engines. Based upon our current state of knowledge, if such a nozzle could be developed, utilization in JT8D and JT9D engines would require completely new fuel systems, modified fuel controls and new fuel pumps. The net result of these changes would probably be more costly than the current dual aerating nozzle approach being pursued.

II.2. No decision has been made in this regard. The regulations finally promulgated by EPA, the actions of ICAO, inputs from our customers, and the pressures of competition will all play a role in deciding whether to produce both controlled and uncontrolled engines.

EASTERN AIR LINES INCORPORATED / INTERNATIONAL AIRPORT / MIAMI, FLORIDA 33148 / 305 - 873 - 6733

Sr. VICE PRESIDENT / OPERATIONS SERVICES

June 26, 1978

Mr. Charles L. Gray, Acting Director
Emission Control Technology Division
United States Environmental Protection Agency
Ann Arbor, Michigan 48105

Subject: Economic Impact of Proposed Jet Engine Emission Standards.

Reference: 1) Letter from C. L. Gray to F. Borman dated May 31, 1978.
2) Our File No. 2PP 511/72-00-17

Dear Mr. Gray:

Attached is the information requested in your referenced letter.

The EAL engine maintenance program is an "on condition" program which keys engine restoration action to actual engine condition and performance, rather than to fixed intervals of calendar time or operating hours. The term "time between overhaul" is not applicable to a program of this type. Hence the information in Tables I and II is presented in terms of mean time between combustion section repair.

We will be happy to supply any additional information you require.

Sincerely,

P. M. Johnstone

P. M. Johnstone

JMS/JEW/mf

Encl.

TABLE I -- COST OF REPAIR OF COMBUSTION SECTION COMPONENTS.
(Mean Time Between Repair Shown in Table II)

COMBUSTION SECTION COMPONENT	JT8D ENGINE	RB211 ENGINE
Combustion Liners & Dome	$1,700/Eng.	$7,300/Eng.
Fuel Nozzle Tips & Support	$1,000/Eng.	$ 280/Eng.
Fuel Manifold	$ 140/Eng.	$ 280/Eng.
Fuel Sectoring Control Hardware	Not Applicable	Not Applicable
Transition Duct	$ 650/Eng.	Not Applicable
Transition Duct Guides	$ 100/Eng.	Not Applicable

TABLE II -- MAINTENANCE COST INFORMATION.

ITEM	JT8D ENGINE	RB211 ENGINE
Mean Time Between Combustion Section Repair (Hrs.)	Approximately 4800 Flt. Hrs.	Approximately 1400 Flt. Hrs.
Mean Time Between Combustion Section Repair (Mos.)	Approximately 18 Mos.	Approximately 6 Mos.
Maintenance Costs (1978 $'s)	$28/Flt. Hr.	$80/Flt. Hr.
Man-Hours Required For Engine Change	727 = 30 Man-Hrs. DC9 = 23 Man-Hrs.	64 Man-Hours

DELTA AIR LINES, INC.

GENERAL OFFICES/HARTSFIELD ATLANTA INTERNATIONAL AIRPORT/ATLANTA, GEORGIA 30320 U.

July 5, 1978

Mr. Charles L. Gray
Acting Director
Emission Control Technology Division
U.S. Environment Protection Agency
Ann Arbor, Michigan 48105

Dear Mr. Gray,

Thank you for your letter of May 31, 1978 to our Mr. W.T. Beebe concerning EPA's continuing effort to accurately define the economic impact of proposed revisions in the aircraft jet engine exhaust emission standards. Attachment's I and II contain the information you requested relative to Delta's recent jet engine maintenance experience.

This data, together with data from other operators and the engine manufacturers should assist you in your attempt to define the impact on maintenance costs, which, incidentally, we noted were not included in the analyses covered by your report No's AC 77-02 & AC 78-01. Inasmuch as maintenance costs are a significant portion of our total operating expenses, we strongly feel that any meaningful impact analysis must include maintenance cost considerations, both installation and repair costs as well as - and probably more significantly - lost revenue due to schedule disruptions.

If there is any other information we can provide that will assist you in this effort, please advise.

Sincerely,

D.C. Garrett, Jr.
President

DCG/mn

ATTACHMENT I
July 5, 1978

ENCLOSURE I INFORMATION

Total cost to repair the following items in 1978 dollars include parts and labor for all engines in our operation.

1. Combustion liners and dome

   a. JT8D-7 =$3,774.00 average per engine
   b. JT8D-15 =$3,906.00 average per engine
   c. JT3D =$5,244.00 average per engine
   d. RB211 =$7,295.00 average per engine

2. Fuel Nozzle and Support

   a. JT8D-7 =$1,125.00 average per engine
   b. JT8D-15 =$1,097.00 average per engine
   c. JT3D =$1,175.00 average per engine
   d. RB211 =$490.00 average per engine

3. Fuel Manifold

   a. JT8D-7 =$350.00 average per engine
   b. JT8D-15 =$300.00 average per engine
   c. JT3D =$916.00 average per engine
   d. RB211 =$740.00 average per engine

4. Transition Duct

   a. JT8D-7 =$795.00 average per engine
   b. JT8D-15 =$522.00 average per engine
   c. JT3D =$1,126.00 average per engine
   d. N/A

5. Transition Duct Guides

   a. JT8D-7 =$208.00 average per engine
   b. JT8D-15 =$208.00 average per engine
   c. JT3D - N/A
   d. RB211 - N/A

ATTACHMENT II
July 5, 1978

ENCLOSURE II INFORMATION

1. What is the mean times between overhaul?

We do not have a hard time overhaul. All engines are scheduled off at specific intervals for inspection and maintenance except the RB211 which is on an on condition/condition monitoring program. The present scheduled intervals are:

JT8D-7	- 4200 hours
JT8D-15	- 6200 hours
JT3D	- 6000 hours

2. What is the mean of calendar intervals between overhaul?

The mean of calendar time between scheduled shop visits are:

JT8D-7	- 20 months
JT8D-15	- 25 months
JT3D	- 32 months
RB211	- N/A

3. What is the mean shop cost for engine maintenance in 1978 dollars?

JT8D-7 and -15	- $16.38 per engine hour
JT3D	- $29.01 per engine hour
RB211	- $69.64 per engine hour

4. What is the mean number of man hours necessary to remove and reinstall an engine on an aircraft?

JT8D-7	= 20 man hours
JT8D-15	= 20 man hours
JT3D	= 47 man hours
RB211	= #1 and 3 positions = 51 manhours
	#2 position - 70 manhours

AmericanAirlines

July 20, 1978

United States Environmental Protection Agency
Office of Air and Waste Management
Ann Arbor, MI 48105

Attention: Mr. Charles L. Gray, Acting Director
Emission Control Technology Division

Reference: Your Letter to Mr. A. V. Casey dated May 31, 1978

Dear Mr. Gray:

In response to your letter, we are attaching the specific information regarding engine maintenance. We have provided this in tabular form as Enclosures I and II, as outlined in your request. The information is for the JT8, CF6 and JT9 family of engines and the question numbers and individual items directly reflect those contained in your letter.

American Airlines operates the JT8D-1,-7,-9, CF6-6D and JT9D-3A,-7AH models of engines, and the data are the actual experience for the first five months of 1978. We also operate the JT3D model, but no information is provided for it as its operation will not extend into 1985 and will, therefore, not be affected by the new exhaust emission standards.

We appreciate your efforts to accurately define the economic impact of the proposed revisions to exhaust emission standards. We are concerned, however, about those costs which cannot be determined at this stage, but will have adverse effect on future airline operations. We refer to the long-range aspects of operating revised designs and the increased costs to the airlines of coping with added operating problems. The JT8 reduced smoke burner conversion is an excellent example. The problems of off-idle stall and the 1500-2000 hour loss in engine hot section life were not forecast, but related costs continue to impact us. In addition, the actual material costs for that conversion were 25% higher than estimated and we believe the manufacturer who provided the estimate, and not the airlines, should absorb that difference. We trust your economic impact study will include some factor for optimistic estimates.

If you feel you require further information, please contact us.

Very truly yours,

D. J. Lloyd-Jones
Senior Vice President
Operations

File: 10-9/J6

ENCLOSURE I

Retrofit Cost Information Note 1

	JT8	CF6	JT9
Combustion Liner & Dome	$1917	$11410	$9740 Note 2
Fuel Nozzle & Support	$1031	$1576	$3700
Fuel Manifold	$ 53	$ 638	-0-
Fuel Sectoring Control Hardware (CF6)	X	Note 3	X
Transition Duct (JT8)	$ 742	X	X
Transition Duct Guides (JT8)	$ 31	X	X

NOTES

1 - Costs are actual direct maintenance cost per engine for first five months of 1978. Repair cost includes labor, material, and outside service. New material cost for replacement is also included in total.

2 - American Airlines has no repair experience on TN combustion liner for JT9. Cost provided represents best estimate of production and staff personnel.

3 - American Airlines has no meaningful basis on which to estimate routine maintenance costs for the components required in what General Electric refers to as "sector burning". It is a concept being developed for the CF6 to meet the proposed standards for CO and HC. Testing to date has used laboratory components and the results, along with schematic line drawings, have been discussed with various airline engineers. Production components have yet to be designed and cost estimates at this stage could be wrong by several orders of magnitude.

File: 10-9/J6

ENCLOSURE II

Maintenance Cost Information

Question	JT8	CF6	JT9
1	3645 Hours	2726 Hours	1856 Hours
2	16.7 Months	10.9 Months	8.25 Months
3	$80389	$201526	$271200
4	35 M/Hrs.	50 M/Hrs.	50 M/Hrs.

All figures represent actual experience of cost and utilization for the first five months of 1978.

TWA TRANS WORLD AIRLINES, Inc.
P. O. BOX 20126
KANSAS CITY INTERNATIONAL AIRPORT
KANSAS CITY, MISSOURI, U.S.A. 64195

July 31, 1978

Mr. Charles L. Gray
Acting Director-
Emission Control Technology Division
United States Environmental Protection Agency
Ann Arbor, Michigan 48105

Subj: Aircraft Engine Exhaust Emission Control

Ref: Letter, Charles L. Gray to Charles C. Tillinghast, dated May 31, 1978

Dear Mr. Gray:

Attached, in accordance with your request, is data relative to the maintenance of the various aircraft engine types operated by TWA.

I hope this data satisfies your requirements. Please let me know if I can be of further assistance.

Sincerely yours,

R. D. Pearson
Vice President-
Technical Services

Attachments

TWA ENGINE MAINTENANCE DATA FOR EPA EXHAUST EMISSION CONTROL ANALYSES

Reference: Letter, Charles L. Gray to Charles C. Tillinghast, dated May 31, 1978

The attached Table 1 contains the repair costs for specific components of TWA engines as requested by Enclosure I of the reference EPA request. The costs in Table 1 are based on direct labor, at the current mechanic rate of $10.28 per hour, and direct material. It was assumed that direct costs would be of most value to the EPA in their analyses. The other labor rates commonly used by TWA for various purposes are $18.30 per hour (direct labor plus employee fringe benefits) used for purposes such as make or buy studies, and $25.10 per hour (all costs including overhead) used for evaluating capital projects.

The descriptions of the items provided in Enclosure I of the EPA request were general without reference to the specific parts that were to be included in the cost calculations. Therefore, the nomenclature of the parts that were included in the TWA cost calculations for Table 1 are listed in Table 2.

Table 3 answers the questions contained in Enclosure II of the EPA request. The mean shop costs for engine repairs are direct costs only. TWA does not routinely "overhaul" any of its engine types so the mean time between repairs is provided in answer to question number one of Enclosure II.

Care should be exercised when comparing or consolidating TWA cost data with that submitted by other airlines or engine manufacturers. Cost accounting procedures and engineering, quality control, and shop practices may vary significantly from company to company. Cost estimates, therefore, may vary accordingly in the absence of a common basis for computation. In particular, it may be misleading to compute incremental repair costs for incorporating low emission hardware by comparing pre-modification repair costs provided by the airlines with post-modification costs provided by the engine manufacturers.

O. W. Johnson
Maintenance Systems Planning
July 19, 1978

Item 2/		Average Cost Per Repaired Engine 1/			
		JT3D-3B	JT8D-7 & -9	JT9D-7AH	RB211-22B
Combustion Liners and Dome	Labor	$ 565.40	$ 408.12	$ 175.30	$178.89
	Material	170.25	236.54	5,511.40	276.43
	Total	$ 735.65	$ 644.66	$5,686.70	$455.30
Fuel Nozzle Tip and Support	Labor	$ 123.36	$ 277.56	$ 515.03	$ 99.72
	Material	-	12.35	1,365.20	-
	Total	$ 123.36	$ 289.91	$1,880.23	$ 99.72
Fuel Manifold	Labor	$ 419.42	$ 313.54	$ 318.68	$182.98
	Material	1,135.08	-	-	154.53
	Total	$1,554.16	$ 313.54	$ 318.68	$337.51
Transition Duct/Guides	Labor	$ -	$1,245.93	$ -	$ -
	Material	-	469.03	-	-
	Total	$ -	$1,714.96	$ -	$ -

1/ Includes direct labor (at rate of $10.23 per hour) and material.

2/ See Table 2 for breakdown of components included in the calculation of the costs to repair these items.

Table 1.

Item as Listed in Enclosure I of EPA Letter	Components by Nomenclature Included in Item to Arrive at Repair Costs Given in Table 1.			
	JT3D-3B	JT8D-7 & -9	JT9D-7AH	RB211-22B
Combustion liners and dome	Combustion chamber assemblies. Clamp.	Burner cans. Burner can guides.	Outer burner can. Inner burner can. Guide plates. Guide assembly.	Front combustion liner. Rear inner combustion liner. Rear outer combustion liner.
Fuel nozzle tip and support	Fuel nozzle.	Fuel nozzle and support assembly. Fuel nozzle assembly.	Fuel nozzle and support assembly.	Fuel spray nozzles.
Fuel manifold	Fuel manifold.	Fuel manifolds(left). Fuel manifolds (right). Fuel inlet manifolds (left) Fuel inlet manifolds (right).	Fuel manifolds. Fuel tubes.	Fuel manifold(left). Fuel manifold(right). Fuel manifold.
Transition duct/guides.	-	Transition ducts. Transition duct guides.	-	-

Table 2.

	JT3D-3B	JT8D-7 (DC-9 Aircraft)	JT8D-7 (727-100 Aircraft)	JT8D-9	JT9D-7AH	RB211-22B
Mean time 1/ between repairs (flying hours)	3,685	1,479	2,729	2,444	1,438	1,115
Mean calendar interval between repairs (days)	409	247	390	306	120	112
Mean shop 2/ repair cost	$86,462	———	$64,737	———	$133.667	$105,581 4/
Mean number 3/ of manhours to remove and install engine	48	30	36	36	75	51

1/ This is the mean time between shop visits for scheduled or unscheduled repairs. None of TWA's engines are routinely "overhauled".

2/ Includes direct labor and material and outside repair costs.

3/ Includes approximately five manhours inspection time on JT3D and JT8D engines. and ten manhours inspection time on JT9D and RB211 engines.

4/ Includes $25,366 per repair recovered from manufacturer while engine under warranty.

Table 3.

PRATT & WHITNEY AIRCRAFT GROUP
Commercial Products Division

East Hartford, Connecticut 06108

February 28, 1979

Mr. Charles L. Gray, Jr.
Director
Emission Control Technology Division
United States Environmental Protection Agency
Ann Arbor, Michigan 48105

Dear Mr. Gray,

This letter transmits the completion of our reply to your letter of December 8, 1978 in which you requested additional information relative to the proposed aircraft engine exhaust emission standards. Our initial response on December 21, 1978 answered the inquiries of your Enclosures IV and V. Enclosed with this letter are responses for Enclosures I, II and III. The information presented represents our best estimates of costs in accordance with your requested breakdown. These estimates assume our reduced emission combustor programs will be successfully completed without major problems and that the proposed regulations will be modified before final promulgation to accommodate these combustors.

You stated in your letter that the data solicited "......is necessary for the preparation of a complete and meaningful cost effectiveness analysis." In furtherance of that purpose, we enclose for your consideration, and by copy submit for the docket, EPA's report on "Control Techniques for Carbon Monoxide Emissions", dated December, 1978. As shown in Table 2-4, the CO emissions estimated by EPA from commercial aircraft in 1977 totalled less than 2/10 of 1% of CO emissions from all transportation sources. We conclude that control of the commercial aircraft source is not cost effective.

We have not generated any new estimates related to the proposed 1984 NO_x and the newly certified engine requirements nor do we expect to generate such estimates. As stated in my July 11, 1978 letter to Mr. George Kittredge and in our comments both verbal and written to the NPRM, neither the need nor the technology exists for the proposed 1984 regulations. It is therefore not possible to estimate the costs associated with these proposals.

Very truly yours,

Gordon A. Titcomb
Executive Vice President

cc: Mr. George Kittredge
Senior Technical Advisor
Office of Mobile Source Air Pollution Control
Environmental Protection Agency
Waterside Mall, Washington, D.C. 20460

Re: Docket #OMSAPC-78-1
Control of Air Pollution from Aircraft and Aircraft Engines

Enclosures

ENCLOSURE I

MANUFACTURER'S COST AND PRICE INFORMATION

The cost and price estimates for Enclosure I are based on the following assumptions:

- Only costs incurred as a consequence of the proposed gaseous emission standards are included in the cost estimates.
- Development program estimated costs include both development and certification costs but exclude service evaluation costs which are provided separately.
- Contract and non-specific engine related technology research and development work is excluded.
- Our reduced emissions combustor programs will be successfully completed without major problems and that the proposed regulations will be modified before final promulgation to accommodate these combustors.

ADVANCED DEVELOPMENT COSTS
1978 DOLLARS (in $1000)
Estimate of Costs to Address Proposed 1981 EPA Emissions Regulation

	Design & Analysis	General[1] Engine Hardware	Specific[2] Modification Hardware	Rig Tests	General[3] Engine Tests	Engine[4] Emission Tests	Flight Test	General[5] Engineering Support	Total
JT8D	$1,200	$2,700	$2,500	$2,700	$3,100	$6,800	$1,700	$5,600	$26,300
JT9D	3,900	2,400	6,100	800	7,000	7,300	1,700	8,300	37,500
JT10D	2,000	1,100	500	800		700	1,600	1,100	7,800

NOTES:

(1) Costs of engine hardware required to support engine test programs except burner or controls related hardware which affects emissions.
(2) Costs of all burner or controls related engine hardware which affects emissions whether utilized in engines or rigs.
(3) Costs of all engine endurance tests specific to emissions.
(4) Costs of all emissions and performance testing.
(5) All costs not included in other categories.

CERTIFICATION COSTS
(in $1000)

Generic Engine Model	Engine Hardware	Specific Modification Hardware	Endurance Test	150 Hour Certification Test	Hot and Cold Starting Test	Overtemperature Test and L.P. Turbine Overspeed Test	LCF Test	Foreign Object Ingestion	Emission Testing	Engineering Support	Flight Test	Total Cost

- o These costs are included in Advanced Development Cost estimates. A precise breakout is not possible. However, we expect that certification costs will be not more than 25 percent of total estimated development costs.

INITIAL PRODUCTION

Generic Engine Model	Part Name	Tool Design	Tool Procurement	Increment in Manufacturing Cost Based on Current Part[1]

THIS INFORMATION IS PROPRIETARY

[1]Increment should account for increase or decrease in material, labor, machining, and corporate profit. No amortization of development, certification, or other non-recurring expenses should be included.

SERVICE EVALUATION
ESTIMATE OF COSTS TO ADDRESS PROPOSED 1981 EMISSIONS REGULATIONS
1978 dollars (in $1000)

Generic Engine Model	P&WA* Cost	Estimated Airline Operator Cost	Total Cost	Total Time Required
JT8D	1,100	100	1,200	2 Years
JT9D	2,100	100	2,200	2 Years

*During the service evaluation program time period, burner development continues. The costs associated with this development have been included in the table of Advanced Development Costs.

NEW ENGINE PRICE INCREMENT
ESTIMATE OF COSTS TO ADDRESS PROPOSED 1981 EMISSIONS REGULATIONS
1978 dollars (in $1000)

Generic Engine Model	Price Increment

THIS INFORMATION IS PROPRIETARY

SERVICE EVALUATION

I. Description of Hardware Changes and Programs

A. <u>JT9D Engine Family</u>

1. For the 1981 Emissions Combustor in the JT9D-7 series engine, current plans call for six (6) combustor/fuel nozzle sets to be supplied to six (6) different operators. In addition to one new inner combustor liner, one new outer combustor liner, and twenty (20) new fuel nozzles and support assemblies per engine, a reoperation to the D-7 series diffuser case is required as follows: a) the fuel nozzle mount pad will require a cutback to allow installation of the increased length fuel nozzle supports; b) the inner wall of the diffuser case will require installation of seven (7) grommets to locate mount pins and ensure proper combustor positioning; c) two (2) borescope bosses will require modification to become igniter bosses for the new configuration.

2. For the 1981 Emissions Combustor in the JT9D-59A/-70A series engine, current plans call for six (6) sets of combustors and fuel nozzles and supports to be supplied to three (3) operators. One inner combustor liner and one outer combustor liner and the twenty (20) fuel nozzle and support assemblies per engine will be a direct replacement of the current configuration with no required modification.

B. <u>JT8D Engine Family</u>

1. For the reduced HC and CO combustor in the JT8D-1, 7, 9, series engine, current plans call for ten (10) sets of JT8D-9 reduced emissions combustors, ten (10) sets of louver cooled outer transition ducts, ten (10) sets of split combustor rear support guides and ten (10) sets of fuel nozzles and supports.

2. For the reduced HC and CO combustors in the JT8D-15, 17 series engine, the planned program is the same as that for the JT8D-1, 7, 9 series engine except JT8D-15, 17 combustors will be used and no change of outer transition ducts is required.

II. Expected Schedule of Events

Item 1

Airline operators considered for participation will be selected.

Item 2

An Engineering Change (EC) which authorizes the use of evaluation parts and describes any reoperation requirements will be prepared. Based upon the information contained in the EC, a Special Instruction document for use by the operators will be prepared.

Item 3

Pratt & Whitney Aircraft will offer the operators the opportunity to participate in the Service Evaluation Program by letter. The Special Instruction will be attached to the letter.

Item 4

The participating airline operators will transform the Pratt & Whitney Aircraft supplied Special Instruction into an instruction sheet suitable for use in their overhaul shop.

Item 5

Upon receipt of agreement to participate, Pratt & Whitney Aircraft will deliver the Service Evaluation parts to the airline operator.

Item 6

After the Service Evaluation parts are received, the airline operator will dissemble the selected candidate engine, make the necessary reoperations, install the service evaluation parts, and reassemble the engine.

Item 7

The assembled engine will then be tested and if acceptable, installed in the next available aircraft position. At this time, the airline operator will document the total engine time and cycles and report this information to PWA.

Item 8

During the evaluation period, the operator will provide Pratt & Whitney Aircraft with the results of borescope and/or isotope inspection of the evaluation parts. Inspections will be a combination of scheduled and special request inspections.

Item 9

Periodically, Pratt & Whitney Aircraft will publish the results of the evaluation to date. This will include the engine serial number (S/N), the time and cycles accumulated on the combustor and the results of inspections for each airline operator.

Item 10

When an engine with a high time set of hardware is removed for any cause, a Pratt & Whitney Aircraft specialist will travel to the operator to review the condition of the combustors and fuel nozzles and resultant HPT/LPT condition.

Item 11

After conclusion of the service evaluation program, whenever the combustors and fuel nozzles are removed during normally scheduled engine refurbishment periods, the parts will be returned to Pratt & Whitney Aircraft for final review and analysis. Subsequently, the parts will either be scrapped or returned to the participating operator.

Item 12

Pratt & Whitney Aircraft will provide each airline operator with a letter report summarizing the evaluation program results.

ENCLOSURE II

ESTIMATED JT8D/JT9D RETROFIT COST INFORMATION

1. Summary

To meet the proposed in-use engine requirements, all JT8D and JT9D engines delivered prior to 1982, pursuant to our recommended time schedule, will have to be retrofitted with new aerated fuel nozzles and revised combustion chambers.

Engine Model	Minimum Qty. of Parts/Engine	Estimated Kit Price per Engine (1978 Dollars)
JT8D-7/9	33	$40,000
JT8D-15/17	27	$37,000
JT9D-3A/7	46	$102,000
JT9D-59A/70	45	$102,000

2. Retrofit Estimates

The following are JT8D/JT9D retrofit estimates for each hardware item together with a general description of the change and the reason for each modification. All estimates assume that retrofits would be performed during routine maintenance when the engine hot section is exposed. All estimated labor costs are based on a labor rate of $18.50/man-hour.

JT8D Engine

To reduce JT8D engine emissions, significant modifications to the current production combustion system are required. The fuel nozzle and support assemblies in all JT8D engines delivered prior to 1982 will require replacement with aerated fuel nozzles which incorporate pressure atomizing primary and aerated secondary supply passages. All JT8D models will also be retrofitted with combustion chambers which incorporate a modified dome, revised cooling air distribution, and modified combustion and dilution hole patterns in the combustor liners. The combustion chamber liner dilution hole patterns for the JT8D-15 and JT8D-17 engines, which have air cooled stages in their high pressure turbine, will be different from those for the JT8D-9. In addition, the JT8D-9 will require replacement of the outer transition duct and rework of the transition duct guides, whereas the JT8D-15 and -17 engines will require only rework of the transition duct guides.

Table 2.1 provides a detailed breakdown of the estimated average retrofit costs per engine.

TABLE 2.1

JT8D ESTIMATED RETROFIT COST INFORMATION
(1978 Dollars)

JT8D-7/9

Estimated Retrofit Kit Cost	$40,000
Estimated Modification and Installation Labor	+3,400
Normal Repair Labor and Material	-4,100
Cost Increment	$39,300

JT8D-15/17

Estimated Retrofit Kit Cost	$37,000
Estimated Modification and Installation Labor	+ 100
Normal Repair Labor and Material	-4,100
Cost Increment	$33,000

JT9D Engine

To reduce JT9D engine emissions also requires significant modifications to the current production combustion systems.

The JT9D-7 fuel nozzle will be replaced with a dual-pipe welded aerated nozzle similar to those discussed for the JT8D engines. Clearance relief cuts in the diffuser case fuel nozzle insertion holes will be required for each assembly. A major change will be required in the combustor front end. A new bulkhead front end combustion liner will be substituted for the current combustion liner, which consists of twenty short cone front ends. The bulkhead combustion liner will require increased length fuel nozzle supports and will incorporate a new hood, revised mount pin arrangement, and new ignitor locations. To accommodate these changes in the JT9D-7 engine, the diffuser case will have to be removed and reworked as follows:

a) The fuel nozzle mount pad will require a cutback to allow installation of the increased length fuel nozzle;

b) The inner wall of the diffuser case will require installation of seven (7) grommets to locate mount pins and ensure proper burner positioning; and

c) Two (2) borescope bosses will require modification to become igniter bosses for the new configuration.

For the JT9D-59/70 engine, the major modification will be to replace the present fuel nozzles with new aerated fuel nozzle and support assemblies, since the engine already incorporates a bulkhead combustion liner. Other modifications will include redistribution of the combustion and dilution air, revisions to the liner cooling air schedule, and the addition of support pins to maintain the louver tip spacing to maintain combustor durability. The JT9D-59/70 engine will not require reoperation of the diffuser case.

Table 2.2 provides a detailed breakdown of the estimated average retrofit costs per engine.

TABLE 2.2

JT9D ESTIMATED RETROFIT COST INFORMATION
(1978 Dollars)

JT9D-3A/7

Estimated Retrofit Kit Cost	$102,000
Estimated Modification and Installation Labor	+ 3,600
Normal Repair Labor and Material	-16,700
Cost Increment	$ 88,900

JT9D-59A/70

Estimated Retrofit Kit Cost	$102,000
Estimated Modification and Installation Labor	+100
Normal Repair Labor and Material	-20,900
Cost Increment	$ 81,200

3. Estimated Tool Costs

The following are the estimated JT8D/JT9D one-time cost in 1978 dollars for rework fixtures or other tools that will be required in the retrofit program.

Engine	Cost Per Set	Average No. of Sets per Repair Facility
JT8D	$5,000	One set per Maintenance Facility
JT9D	None	None

4. Mean Time Between Overhaul

In general JT8D/JT9D maintenance is performed based on engine condition and the intervals for scheduled engine refurbishment reflects a particular airline's operation (average flight length, derating, engine modification status, etc.).

ENCLOSURE III

MAINTENANCE COST INFORMATION

We assume that production incorporation will not begin until January 1, 1982 as recommended by Pratt & Whitney Aircraft and that the results of the service evaluation program will allow engines produced after 1982 to have maintenance characteristics comparable to current engines.

PRATT & WHITNEY AIRCRAFT GROUP
Commercial Products Division

East Hartford, Connecticut 06108

August 25, 1978

Mr. Charles L. Gray
Acting Director
Emissions Control Technology Division
Environmental Protection Agency
Ann Arbor, Michigan 48105

Dear Mr. Gray:

In your letter of July 14, 1978, you indicated that the Pratt & Whitney Aircraft submittal of 26 February 1976 from D. D. Pascal to Eric O. Stork followed the EPA recommended format by reporting the increment in engine selling price and development costs separately. You requested that we provide updated cost information in this same manner which you stated has proven to be both appropriate and worthwhile.

In response to your request, the attachment to this letter provides our latest estimates of the production engine price increases resulting from incorporation of the new combustors currently being developed for reduced HC and CO emissions, kit prices for retrofitting these same combustors into in use engines and total combustor development program costs associated with each specific engine family exclusive of costs for technology development. It should be noted that the JT8D prices are believed to be representative of combustors which have substantial reductions in CO but which fall short of meeting the proposed CO emissions standard.

No cost information relative to NOx is included because EPA has not proposed a NOx standard based on air quality/public health needs or on available technology.

We trust this information will be useful in your study.

Sincerely,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Commercial Products Division

G. N. Frazier
Vice President-Engineering

UNITED TECHNOLOGIES

Low Emission Burner Pricing Estimates

The pricing information given below represents estimates for incorporation of reduced HC and CO combustors currently under development into production engines. Because development is not complete, this pricing information can only be considered as "rough order of magnitude" estimates and is in no way to be construed as forming any commitment on the part of Pratt & Whitney Aircraft for use as a basis for the establishment or negotiation of actual prices. It should be noted that the JT8D prices are believed to be representative of combustors which have substantial reductions in CO but which fall short of meeting the proposed CO emissions standard.

	1978 Dollars	
	JT8D	JT9D
Production price increment for modified low emissions burners w/o specific development (average)	$ 11,300	$ 48,300
Retrofit kit price w/o specific development (average)	$ 34,200	$166,300
	Then Year Dollars	
Total Development Cost	$15,156,000	$35,827,000

GENERAL ELECTRIC

AIRCRAFT ENGINE GROUP

GENERAL ELECTRIC COMPANY . . . . CINCINNATI, OHIO 45215
Phone (513) 243-2000
Mail Drop H-52 243-3537

February 19, 1979

Mr. Charles L. Gray, Acting Director
Emission Control Technology Division
U. S. Environmental Protection Agency
2565 Plymouth Road
Ann Arbor, Michigan 48105

Dear Mr. Gray:

In response to your letter request, we have assembled the attached information concerning the estimated costs of compliance by our various commercial aircraft turbine engines with the proposed gaseous emission standards.

The attached information is presented in the format requested in your letter. To the extent possible, we have attempted to answer the various questions asked in your reporting format and to provide the detailed cost breakouts included in the various cost element forms of this reporting format.

The attached information only includes the cost impacts associated with the proposed carbon monoxide (CO) and hydrocarbons (HC) standards, which are presently proposed to become effective on January 1, 1981. No information is included concerning the cost impacts associated with the proposed nitrogen oxides (NO_x) standard, which is presently proposed to become effective on January 1, 1984. In our view, the feasibility and practicality of attaining satisfactory compliance with this latter standard, while still meeting all the other performance and durability requirements of commercial aircraft engines, have not yet been fully demonstrated. As such, we believe that any cost estimates we might attempt to provide at this time concerning the design and development of an arbitrary combustor concept, not yet known to be capable of meeting the mandatory requirements of commercial aircraft engines, would be meaningless and possibly misleading.

The attached cost data consist of actual costs incurred during the period of 1974 through 1978 and estimates of the remaining costs associated with attaining compliance with the proposed CO and HC standards. Only the actual and projected costs directly associated with the development,

Continued on Page 2

GENERAL ELECTRIC

Mr. Charles L. Gray
February 19, 1979
Page 2

demonstration and production of CO and HC abatement features for use in the specific engine families noted in the attachments are shown. Thus, the costs associated with various generalized emission control technology programs we have conducted during the past several years are not included in the attached cost tabulations.

As is indicated in Enclosure I of the attached material, a new CF6 family, the CF6-80, has been recently added to our series of CF6 engines. Efforts are currently underway to define and develop suitable features for use in this new engine family to permit compliance with the proposed CO and HC standards. For this new engine family, CO and HC abatement features different from those evolved to date for the CF6-6 and CF6-50 engine families are being developed. The intent of these CF6-80 engine development efforts is to evolve a combination of CO and HC abatement features which do not include the use of sector burning at idle. Thus, this latest CF6 engine emission abatement program is expected to involve a significant effort and an additional total development cost similar in magnitude to that associated with the CF6-50 engine family--as is noted in Page 1 of Enclosure I.

I trust the attached information will be useful to you in the studies you are conducting to assess the economic impacts of the proposed gaseous emission standards applicable to commercial aircraft turbine engines. If you have any questions or comments on this information, please do not hesitate to contact me.

Very truly yours,

D. W. Bahr

D. W. Bahr, Manager
Combustion and
Emission Control

DWB/cr
Attachments

ENCLOSURE I - PAGE 1

ADVANCED DEVELOPMENT COSTS[1]

(In 1978 Dollars)

To Meet Proposed 1981 Standards For CO & HC Emissions

Generic Engine Model	Design and General Laboratory Effort	General[2] Engine Hardware	Specific Modification Hardware	Rig[3] Tests	Engine[3] Tests (See Note A)	Emission Testing	Special Tests (See Note B)	General Engineering Support	Total Cost (See Note C)
CF6-6 / CF6-32	$1,750 K	$110 K	$ 470 K	$ 790 K	$1,680 K	$220 K	$110 K	-	$5,130 K
CF6-50 / CF6-45	1,660 K	220 K	1,210 K	1,280 K	2,240 K	670 K	90 K	-	7,370 K
CF6-80	(Detailed Cost Estimates Not Available At This Time - Total Cost Is Expected To Be Approximately The Same As Total Cost Associated With CF6-50/CF6-45 Engine Family)								
CFM56	1,110 K	670 K	450 K	620 K	560 K	450 K	-	-	3,860 K
CF34	(Detailed Cost Estimates Not Available At This Time)								

NOTES:

(A) Includes extensive cyclic endurance testing to verify acceptability of using sector burning at idle.
(B) Includes special flight tests of engines to determine altitude starting performance capabilities.
(C) Includes actual costs incurred during 1974 through 1978 and projected costs for 1979 and 1980.

[1] Development should not include product improvement.

[2] If applicable, include number of engines dedicated.

[3] Breakdown into general tasks, e.g., cold and hot starting test, coking and temperature distribution test, and low cycle fatigue test, as appropriate.

ESTIMATED CERTIFICATION COSTS
(In 1978 Dollars)
To Meet Proposed 1981 Standards For CO & HC Emissions

Generic Engine Model	Engine Hardware	Specific Modification Hardware	Endurance Test	150 Hour Certification Test	Hot and Cold Starting Test	Overtemperature Test and L.P. Turbine Overspeed Test	LCP Test	Foreign Object Ingestion	Emission Testing	Engineering Support	Flight Test	Total Cost (See Note A)
CF6-6, CF6-32	————————→											$600 K (See Note B)
CF6-50, CF6-45	————————→											$600 K (See Note B)
CF6-80	————————→											$150 K (See Note C)
CFM56	————————→											$150 K (See Note C)
CF34	————————→											$150 K (See Note C)

NOTES:

A) Because the details of the certification testing required to demonstrate compliance with gaseous emission standards have not yet been specified, detailed cost estimates cannot be provided.

B) Approximate estimate of total cost of special engine tests conducted to demonstrate compliance with proposed CO and HC standards--assuming testing of only a single engine is required for this purpose.

C) Approximate estimate of total cost of special engine tests conducted to demonstrate compliance with proposed CO and HC standards--assuming testing is conducted in conjunction with the initial type-certification testing of these engines. The target schedules for the completion of these initial type-certification tests are:

CF6-80	1981
CFM56	1980
CF34	1981

ESTIMATED INITIAL PRODUCTION COSTS
(In 1978 Dollars)
To Meet Proposed 1981 Standards For CO & HC Emissions

Generic Engine Model	Part Name	Tool Design	Tool Procurement	Increment in Manufacturing Cost Based on Current Part[1]
CF6-6 / CF6-32	• Fuel Splitter Valve	← $150 K (See Note A)		(Not Applicable)
	• Misc. Piping/ Valving	← $ 15 K →		(Not Applicable)
CF6-50 / CF6-45	• Fuel Splitter Valve	← $150 K (See Note B)		(Not Applicable)
	• Misc. Piping/ Valving	← $ 15 K →		(Not Applicable)
CF6-80	← (To Be Determined) →			
CFM56	Combustor Dome	$10K	$25 K	$5 K
CF34	← (To Be Determined) →			

NOTES:

(A) 50% Cost Sharing With CF6-50/CF6-45 Program.
(B) 50% Cost Sharing With CF6-6/CF6-32 Program.

[1] Increment should account for increase or decrease in material, labor, machining, and corporate profit. No amortization of development, certification, or other non-recurring expenses should be included.

ENCLOSURE I - PAGE 4

ESTIMATED SERVICE EVALUATION[1] COSTS
(In 1978 Dollars)
To Meet Proposed 1981 Standards For CO & HC Emissions

Generic Engine Model	Total Cost	Total Time Required
CF6-6 (See Note A)	$276.0 K	12 Months
CF6-50 (See Note A)	$284.0 K	12 Months
CF6-32, CF6-45, CF6-80, CFM56, CF34	(Not Applicable)	

NOTES:

(A) Program involves service evaluation testing of 5 engines. The above cost total includes the procurement/fabrication of six engines sets of emission abatement hardware, with one set intended as a spare. All costs associated with engine removal from the aircraft, modification/rework, ground checkout, reinstallation on the aircraft and inspection are borne by General Electric. However, some of these latter operations are performed by the air carriers which operate the 5 engines.

---

[1] Include a description of typical service evaluation, i.e., what responsibilities or [illegible]

ENCLOSURE I - PAGE 5

ESTIMATED NEW ENGINE PRICE INCREMENT
(In 1978 Dollars)
To Meet Proposed 1981 Standards For CO & HC Emissions

Generic Engine Model	Price Increment[1]
CF6-6 CF6-32	$24.0 K
CF6-50 CF6-45	$25.5 K
CF6-80	(To Be Determined)
CFM56	$ 5.0 K
CF34	(To Be Determined)

[1] Do not include amortization of non-recurring costs.

ENCLOSURE II - PAGE 1

ESTIMATED RETROFIT COST INFORMATION
(In 1978 Dollars)
To Meet Proposed 1981 Standards For CO & HC Emissions

Cost (To Air Carrier)	Engine Family CF6-6/ CF6-32	Engine Family CF6-50/ CF6-45
• Added Hardware (See Note A)	$27.6 K	$52.6 K
• Engine Fuel Nozzle Rework (16 Out of Each Engine Set of 30)	6.1 K	-
• Engine Main Fuel Control Rework	3.5 K	3.5 K
• Engine Modification/Assembly With New Hardware & Reworked Control--If Performed As A Part Of Routine Engine Maintenance Operations.	2.0 K	2.0 K
• Average Depreciated Cost of Fuel Nozzle Hardware That Must Be Replaced, Less Salvage Value of Hardware.	2.8 K	9.0 K
TOTAL COST PER ENGINE	$52.0 K	$67.1 K

NOTES: (See Page 2)

ENCLOSURE II - PAGE 2

ESTIMATED RETROFIT COST INFORMATION

NOTES:

A) For the most part, the selected CF6 engine emission abatement features require that replacement of existing fuel nozzle hardware and the addition of new hardware. The costs of these required hardware items are:

Hardware Item	Quantity Required
1) Replacement Hardware	
- Fuel Nozzles	30 (CF6-50)
- Fuel Nozzles	14 (CF6-6)
2) New Hardware	
Fuel Nozzle Check Valves	15
Splitter Valve	1
Enrichment Valve	1
Starter Valve	1
Electric Cable	1
Pylon Fireseal	1
Tubes & Manifold Assembly	1 Set
Misc. Plumbing Hardware	1 Set
Misc. Brackets	1 Set

B) The following comments are in response to the question on the mean time between overhaul (TBO) of the CF6 engine models:

As maintenance work is done "on condition" and as the engine shop work is done on modules, "mean TBO" is not a meaningful parameter. Shop visit rate (number of shop visits per 1000 flight hours based on a three-month rolling average) is a much more useful and meaningful measurement. The shop visit rate of the CF6 engine models was running at 0.36 during mid-1978. The range was 0.24 to 0.59. This average shop visit rate of 0.36 equates to a mean of 2780 flight hours between removals resulting in shop maintenance.

ENCLOSURE III - PAGE 1

MAINTENANCE COST INFORMATION

Pertinent To Meeting Proposed 1981 Standards for CO & HC Emissions

Part I

The impacts of the selected CO/HC emission abatement features (sector burning at idle and fuel nozzle modifications) on the maintenance costs of the CF6 engine models cannot be estimated at this time - as the effects on engine life of the differential heating and cooling associated with the use of sector burning cannot be fully evaluated at present. The planned service evaluation tests are expected to provide the information needed for such assessments. In any case, overhaul of the required additional fuel control hardware will be a maintenance cost adder. Specifically, the flow splitter valve will require a test bench that has been quoted at $300,000 by a proposed supplier. However, airline operators may be able to adapt existing facilities (at some expense) to provide the necessary test bench if they desire to overhaul the valve.

Part II

1. Main Time Between Overhauls: See Note B of Enclosure II.

2. Mean Calendar Interval Between Overahuls: The average CF6 engine is currently operated 9.9 hours per day. Therefore, the mean time between shop visits is approximately 280 days (based upon the mean of 2750 flight hours between removals resulting in shop maintenance).

3. Mean Shop Cost For Engine Maintenance: The average cost is approximately $224,000 (labor, material and outside services) per shop visit.

4. Mean Number Of Man-hours Necessary To Remove And Reinstall A CF6 Engine On The Aircraft: 35-40 man-hours for wing-tail engines, respectively.

5. Increase In Repair Labor Required For Low NO_x Staged Combustor, Compared To Conventional Combustor: Cannot be estimated at this time.

6. Mean Incremental Cost Per Shop Visit That May Be Expected Because Of Sector Burning Control Hardware: Cannot be estimated at this time.

FILE COPY

ROLLS-ROYCE LIMITED

AERO DIVISION

P.O. Box 31, DERBY DE2 8BJ
Telegrams: 'Roycar, Derby' Telex: 37645
Telephone: Derby (0332) 42424 Ext. 1406

ABW 3/KN

31 January 1979

Dr R Munt
Environmental Protection Agency
Office of Air and Waste Management
2565 Plymouth Road
Ann Arbor
Michigan 48105
USA

Dear Dick

It was good to talk to you on the telephone on 23 January and to know that you had received both the cost data which was dispatched from Derby while I was on vacation and the material which we presented to George Kittredge on 6 December last.

I can confirm that while the average level of RB211-524 and RB211-22B emissions will, on the basis of our present data, lie below the proposed EPA standards of 36.1 g/kN for CO and 6.7 g/kN for HC (without sector burning at 7% idle thrust), this cannot be achieved by the RB211-535. The -535 values are still about twice the proposed standard demonstrating the very significant influence of rated pressure ratio on the operating conditions at idle (all other parameters like combustor volume remaining unchanged). You will, of course, appreciate that "on average" implies that there are no margins available for variability so that our considered opinion would be that the standards as currently proposed represent the base technology level now available for the high pressure ratio large fan engines. They do not, therefore, take account of lower pressure ratio derivatives nor do they take account of the known engine emissions variability (since EPA has never had sufficient data of this type on which to base any rational judgements).

In addition, the impact of the size of the sample of engines available for emissions certification of a new engine type on the safety margins, that must be allowed for both the engine manufacturers and the certification authority, has never been assessed.

Thus, Rolls-Royce would recommend that the base technology levels as represented by the present CO and HC standards be made a function of engine rated pressure ratio (refer to charts CVG 3715, CVG 3716 from the 6 December, 1978 presentation - attached here for convenience) and should further be raised to take account of the known variability and the need for certification margins.

You asked whether Rolls-Royce could suggest what values might be adopted for the standards. I, therefore, instructed some further work aimed at identifying a possible regulatory position (bearing in mind the ICAO position which is also currently under review as you know) which is summarised for CO and HC on the attached charts CVG 6117, CVG 6118.

The charts show the current EPA standard set at a pressure ratio of 27.5 (approximate average of the three large fan engines) through which a curve is drawn based on the ICAO emissions output/pressure ratio relationships. This then purports to represent the available level of technology. You will note that the RB211 data points (a 7% idle has been assumed) suggest that a true technology relationship would be steeper than that proposed so that lower pressure ratio engines are still slightly penalised. In both cases, an absolute maximum would be specified regardless of pressure ratio (no consideration has been given to these maxima so no values are recommended here).

In the following analysis it has been assumed that the objective of the regulations is to ensure that there will be 90% confidence that the mean of the population of all engines will lie below the standard. This objective has to be reached in two stages:-

(a) The manufacturer has to meet a certification value which is set assuming that he will have a 90% chance of passing based on the average of three engine tests and

(b) The regulation limit is set to achieve the desired compliance confidence assuming that the manufacturer will, in fact, only use one engine.

Thus two further curves are defined, as shown on the charts. The use of a certification value above the achievable technology level takes account of the known variability, but forces the manufacturer to produce a population whose mean is unlikely to exceed the available technology curve. This curve also represents the expected level of emission output and would normally be used to calculate the average impact.

On the other hand, if upper bound predictions of aircraft emissions were required, it would be appropriate to use the regulation limit (ie. 90% confidence) as the basis for impact calculations.

The Rolls-Royce recommendation would therefore be to specify the standards as defined by the curves labelled "Regulation Limit" for CO and HC emissions as shown on CVG 6117/6118 respectively, but expect the certificating authority to administer the legislation on the basis of the certification value curve. It would, of course, be possible to construct a certification value curve depending on the number of engines sampled, based on the fixed regulation limit defined above, but this is a refinement which needs to be discussed only if EPA adopts the above philosophy. It must once again be emphasised that the above recommendations assume a 7% idle thrust (to achieve equitability throughout the industry) and the choice of any other idle thrust definition would necessitate an upward revision of the [illegible] recommended standard

I have reviewed the cost data I supplied in my letter of 21 December 1978 and have had the advanced development costs for the RB211-22 and RB211-524 split down to identify the separate expenditure on the "1981" technology (CO and HC) and the "1984" technology (CO, HC and NOx). I hope you will find this satisfactory.

It has not, however, been possible to find an uncomplicated way in which to present the increase in the new production hardware price to conform with your requirements. I can confirm that the prices quoted do include a contribution associated with the non-recurring costs of both the engineering programme and tooling since this is the way in which we quote prices in the market place - and is consistent with the way in which we supply data to our customers (eg. via ATA response to the 24 March 1978 NPRM).

Since in arriving at a price, different manufacturers will use different judgements, it is our considered opinion that you will obtain a more accurate economic impact of the regulations by using the price differentials as we have quoted them and we should be loathe to alter our position and accounting practices.

Yours sincerely

Tony

A B Wassell
Chief Research Engineer
(High Temperature Components)

Att:

c: G Kittredge - EPA

Date 29 Jan 79
Chart No. CVG 7069

ADVANCED DEVELOPMENT COSTS ($ 1000) (1972 - 1984)

ENGINE	DESIGN & GENERAL ENGINE SUPPORT	ENGINE PARTS	RIG TESTS	ENGINE TESTS	SPECIAL TESTS	TOTAL
RB 211-22 & -524						
1981	8,982	15,149	12,146	7,971	360	44,608
1984	2,410	5,302	3,663	2,780	40	14,195
RB 211-535	2,607	768	1,806	382	200	5,763
SPEY	2,020	5,552	1,245	3,521	3,080	15,418
TOTALS	16,019	26,771	18,860	14,654	3,680	79,984

ALL IN 1978 TERMS, CONVERTED AT $2 TO £1

B-50

B-51

ROLLS-ROYCE LIMITED
AERO DIVISION

FILE COPY

P.O. Box 31, DERBY DE2 8BJ
Telegrams: 'Roycar, Derby' Telex: 37645
Telephone: Derby (0332) 42424 Ext. 1406

ABW 8/KN

21 December 1978

Mr Charles L Gray
Acting Director, Emission Control Technology Division
United States Environmental Protection Agency
Office of Air and Waste Management
Ann Arbor
Michigan 48105
USA

Dear Charles,

In response to your letter to Sir Kenneth Keith dated 31 May 1978 and to the commitments made to EPA by Mr Pepper in his acknowledgement of 23 June 1978 and by myself at the Public Hearings held in San Francisco recently, Rolls-Royce has been collating the cost data you requested. This has proved to need a very extensive investigation and has only just been completed.

It has not been possible to break down our engineering costs into the precise format that you requested, but we have endeavoured to identify equivalent categories of work. Nor are we able to supply you with our internal production costs since these represent proprietary information, but the price increases associated with the new low emission hardware have been identified. We have also attempted to quantify the costs associated with service evaluation, supply of retrofit kits and resulting increases in maintenance costs as well as the supplementary data requested in your letter.

Should you have any queries relating to these costs, please do not hesitate to write to me. You will, of course, appreciate that all the costs or prices we are supplying are only indications since, as we have already pointed out, the severity of the regulations themselves has yet to be defined and the combustor modifications which we have been developing may still need further changes that could affect both the engineering costs and the combustor configuration (and hence production costs).

Yours sincerely

Tony

A B Wassell
Chief Research Engineer (High Temperature Components)

Att:

c: Mr G D Kittredge - EPA Washington for Docket OMSAPC-78-1
Mr D J Pepper - Buckingham Gate
Mr D R Blundell } Rolls-Royce Inc
Mr A G Gray }

ADVANCED DEVELOPMENT COSTS ($1000)

(1972 - 1984)

Date 1 DEC 78

Chart No. CVG 7061

ENGINE	DESIGN & GENERAL ENGINE SUPPORT.	ENGINE PARTS	RIG TESTS	ENGINE TESTS	SPECIAL TESTS.	TOTAL.
RB211-22 & -524	11,392	20,451	15,809	10,751	400	58,803 1981 - 44,608 1984 - 14,195
RB211-535	2,607	768	1,806	382	200	5,763
SPEY	2,020	5,552	1,245	3,521	3,080	15,418
TOTALS.	16,019	26,771	18,860	14,654	3,680	79,984

ALL IN 1978 TERMS, CONVERTED AT \$2 TO £1.

JLM. 30.11.78

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CERTIFICATION COSTS ($1,000)

1 DEC 78
Chart No.
CVG 7062

ENGINE	ENGINEERING SUPPORT	HARDWARE	CERTIFICATION TESTING.	TOTAL.
RB211-22B LOW EMISSIONS (UHC.CO) COMBUSTOR + SECTOR BURNING.	1980	1,595	990	4,565
RB 211-524 LOW EMISSIONS COMBUSTOR + SECTOR BURNING.	1980	1,595	990	4,565
RB211-535 LOW EMISSIONS COMBUSTOR + SECTOR BURNING.	1,980	1,595	990	4,565
RB 211-22B. LOW NO_x COMBUSTOR	1,980	1,595	990	4,565
RB211-524 LOW NO_x COMBUSTOR	1,980	1,595	990	4,565
RB211-535 LOW NO_x COMBUSTOR	1980	1,595	990	4,565
SPEY SMOKELESS COMBUSTOR	1,111	638	469	2,218
SPEY LOW EMISSIONS COMBUSTOR	1,111	638	469	2,218
SPEY SECTOR BURNING.	1,111	638	469	2,218
TOTAL.	15,213	11,484	7,347	34,044

ALL IN 1978 TERMS CONVERTED AT $2 TO £1

VLM 30.11.78

CERTIFICATION COSTS ($1,000)

Date: 1 DEC 78
Chart No. CVG 7062

ENGINE	ENGINEERING SUPPORT	HARDWARE	CERTIFICATION TESTING.	TOTAL.
RB211-22B LOW EMISSIONS (UHC.CO) COMBUSTOR + SECTOR BURNING.	1,980	1,595	990	4,565
RB 211-524 LOW EMISSIONS COMBUSTOR + SECTOR BURNING.	1,980	1,595	990	4,565
RB211-535 LOW EMISSIONS COMBUSTOR + SECTOR BURNING.	1,980	1,595	990	4,565
RB 211-22B. LOW NO_x COMBUSTOR	1,980	1,595	990	4,565
RB211 - 524 LOW NO_x COMBUSTOR	1,980	1,595	990	4,565
RB211 - 535 LOW NO_x COMBUSTOR	1,980	1,595	990	4,565
SPEY SMOKELESS COMBUSTOR	1,111	638	469	2,218
SPEY LOW EMISSIONS COMBUSTOR	1,111	638	469	2,218
SPEY SECTOR BURNING.	1,111	638	469	2,218
TOTAL.	15,213	11,484	7,347	34,044

ALL IN 1978 TERMS CONVERTED AT $2 TO £1

VLM 30.11.78

B-54

Date	1. DEC 78
Chart No.	CVG 7065

SERVICE EVALUATION ($1000)

ENGINE	TOTAL COST	TIME REQUIRED
RB 211. Low Emissions (CO HC) Combustor	3,900	2 Years.
RB 211 Low Emissions + Sector Burning.	7,220	2 Years
RB 211 Low NO_x Combustor	12,780	2 Years.
SPEY	540	4 Years

ROLLS ROYCE

NEW ENGINE PRICE INCREMENT.

Date: 1 DEC 78

Chart No. CVG 7064

ENGINE	INCREMENT
RB 211-22, -524 LOW EMISSIONS (CO. HC)	$50,000
RB 211-22, -524 SECTOR BURN CONTROLS	$27,000
RB 211-535 LOW EMISSIONS + SECTOR BURNING	$77,000
RB 211-22, -524, -535 LOW NO_x	$186,000
SPEY SMOKELESS	$8,500
SPEY LOW EMISSIONS	$56,000
SPEY SECTOR BURN CONTROLS	$46,000

B-56

RETROFIT COST INFORMATION

RB211 ONLY

4 DEC 78
Chart No. CVG 7066

1. MINIMUM NUMBER OF PARTS:-

   (a) COMBUSTOR — RETAIL PRICE $ 95,000

   (b) SECTOR BURNING — RETAIL PRICE $ 45,000

2. (a) NOT APPLICABLE

   (b) COMBUSTOR $ 72,300.

   (c) SECTOR BURNING $ 45,000 + 100 MAN HOURS.

   (d) NOT APPLICABLE

3. REWORK TOOLS RETAIL PRICE $60,000 per set.

   EACH REPAIR FACILITY REQUIRE 2 SETS.

4. TIME BETWEEN OVERHAULS (HOURS)

	MEAN	RANGE
- 22B	2,400	1,500 - 5,500
- 524	4,500	3,000 - 7,000

MAINTENANCE COSTS (PART 1)	Date DEC 78
	Chart No. CVG 7067

THE INCREASE IN MAINTENANCE COST ASSOCIATED WITH COMPLIANCE WITH 1981 NME STANDARDS IS ESTIMATED TO BE IN THE REGION OF 40 c/hr, FOR THE RB211-22 AND 20 c/hr FOR THE RB 211-524 (THESE REPRESENT A REASSESSMENT OF COSTS PREVIOUSLY QUOTED TO A.T.A. REF. ABW 2/JC 1 JUNE 1978)

SINCE WE HAVE NOT RUN AN ENGINE TO THE 1984 STANDARD WE ARE UNABLE TO GIVE ESTIMATES OF THE INCREASE IN MAINTENANCE COSTS BUT IT IS ANTICIPATED THAT THEY WILL BE SUPSTANTIALLY MORE THAN THOSE INCURRED IN COMPLIANCE WITH 1981 NME STANDARD.

ROLLS ROYCE

MAINTENANCE COST INFORMATION (PART II)

Date: DEC 78
Chart No.: CVG 7068

	RB211 - 22	RB211 - 524	SPEY
MEAN TIME BETWEEN OVERHAULS (HOURS)	2,400	4,500	2,500
CALENDER INTERVALS BETWEEN OVERHAULS (MONTHS)	10	19	48
MEAN SHOP COST FOR ENGINE OVERHAUL (LABOUR & PARTS)	$ 85,000	$ 85,000	$ 85,000
TIME TO REMOVE & RE-INSTALL ENGINE (MAN HOURS)	30	30	24
INCREMENTAL SHOP COST ASSOCIATED WITH SECTOR BURN CONTROLS	$ 1,000	$ 1,000	–

COMMUNICATION RECORD

Originator of Record (Name - Organization): R.S. Wilcox

Communication With (Name - Organization): Tony Wassel - R^2

Date: 2/15/78

Subject of Communication: Engine Cost Submittal.

Communication Summary

1. Under Development Costs, why is the cost for 1984, RB211 so small? That cost figure reflects only expenditures made up to 1984 and does not reflect the cost of meeting the std. R^2 feels the std can not be achieved.

2. Why is there added development costs for the RB211-535 when this engine is nearly the same as the RB211-22B? Development the -535 was not done concurrently with the -22B so many things had to be done over. Therefore, some of the benefits of concurrent development were lost.

Action Required

Distribution

COMMUNICATION RECORD

Originator of Record (Name - Organization) R.S. Wilcox + R. Munt - SDSB

Communication With (Name - Organization) Mr. Wassell - Rolls Royce

Date 1/23/78

Subject of Communication Emissions Control

Communication Summary

The following questions and answers are in regard to the R^2 cost submittal of 21 December 1978.

1. What parts compose the "low emissions combustor"? Presently only the liner. There is some possibility that the nozzles and injector may be modified.
2. Does the total cost of sector burning include the cost quoted separately for a "low emissions combustor"? Yes. Both the cost of the "low emission combustor" and "sector burning controls" make up the total cost of sector burning.
3. Does the price for the new engine increment or retrofit parts include any recovery of non-recurring costs? If not, why is the cost so high? No. An answer to the second part will be supplied at a later date.
4. The Rolls Royce submittal did not separate the development costs of 1981 and 1984 control technology, will you do this? Yes. An answer will be supplied at a later date.
5. The Rolls Royce submittal did not include a cost of increased maintenance for low NO_x combustors, what is it? Not enough experience has been gained upon which to base an estimate.
6. Would the RB211 family be able to comply with the proposed levels with their present low emissions combustor (Stage II) and no sector burning if the idle point were defined as 7%? Possibly for the -22B and -524

Distribution

-- but likely not for the -535) <u>if</u> the standard were based upon the average, not the worst case (100% compliance) as urged by R^2 in the hearing.

7. What then would be the situation if there were no CO standard? No real change as the RB211 is an HC as well as CO problem.

8. Does the -535 exhibit a pressure ratio dependence for HC as well as for CO? Yes

Parker Aerospace

November 9, 1978

U.S. Environmental Protection Agency
Ann Arbor, Michigan 48105

Parker Hannifin Corporation
Gas Turbine Fuel Systems Division
17325 Euclid Avenue
Cleveland, OH 44112 USA
Phone (216) 531-3000
Telex 98-0636

Attention: Mr. Richard S. Wilcox

Dear Mr. Wilcox,

Attached is your completed questionaire for fuel nozzle costs in lower emission gas turbine engines. These estimates are based on projected designs now being qualified for production engines.

We appreciate this opportunity to be of service.

Regards,

PARKER HANNIFIN CORPORATION
Gas Turbine Fuel Systems Division

W.R. Haney
Division Sales Manager

Attachment

Letter Reference #78-1108

:ba

ADVANCED DEVELOPMENT, CERTIFICATION, AND SERVICE EVALUATION COSTS[1]
(in $1000)

	Development			Certification		Service Evaluation	
Generic Engine Model	Design and General Laboratory Effort	General Engineering Support	Testing Hardware	Certification Tests	Miscellaneous Tests	Engine Hardware	Total Cost
1981 CF6-50	100k	150k	90k	100k	30k	180k	[illegible]k
CF6-6	100k	150k	90k	100k	50k	180k	670k
* CFM56	250k	200k	300k	100k	60k	300k	1210k

1984
costs about same as CFM56

[1]Development should not include product improvement.

* CFM56 is more difficult since everything had to be redesigned from scratch.

INITIAL PRODUCTION

Engine Model	Part Name	Tool Design	Tool Procurement	Increment in Manufacturing Cost Based on Current Part[1]	Economic Production Volume
CF6-50	sector nozzle*	80K		400.00 ea *	6000/yr.
	staged (NO_x) "	80K		450.00 ea.	"
	aerating "***	80K		150.00 ea	8000/yr.
CF6-6	staged (NO_x)"	80K		275.00 ea	3000/yr.
CF6-(All)	H_2O injection (NO_x)"	80K		175.00 ea	6000/yr.
CFM56	Sector "*	80K		500.00 ea.*	1000/yr.

[1]Increment should account for increase or decrease in material, labor, machining, and corporate profit. No amortization of development, certification, or other non-recurring expenses should be included. If no conventional counterpart exists, the increment will be the full manufacturing cost of the part.

* for sector burning, ½ will require check valving. Other nozzles have different tips (flow numbers) and their cost is same as production for all practical purposes. (CFM56 - 20 nozzles, CF6 - 30 nozzles).

** sectoring fuel control will be about $20K for unit excluding electrical (e.g., landing gear switch and cockpit indicators).

*** R^2 & GE are keeping aerating warm for possible use in 1981.

NEW ENGINE PRICE INCREMENT[1]

FUEL NOZZLES ONLY @ COST *

Generic Engine Model	Price Increment
CF6-50	$6000.
CF6-6	8000.
CFM56	5000.

[1] Do not include amortization on non-recurring costs.

* Cost to manufacturer.

ENCLOSURE II

If the low-emission fuel nozzles will require special overhaul tools and dies, please estimate the retail value per set and the number of sets typically required by an airline maintenance shop.

AIRLINE REQUIRES ONE (1) SET OF OVERHAUL TOOLS. $35K/SET.

References for Appendix B

Bahr, D.W., General Electric Company, Aircraft Engine Group. 1979. Letter of February 19, 1979, C.L. Gray, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

Frazier, G.N., United Technologies Corporation, Pratt and Whitney Aircraft Group. 1978. Letter of August 25, 1978 to C.L. Gray, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

Garrett, D.C., Delta Airlines, Inc. 1978. Letter of July 5, 1978 to C.L. Gray, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI

General Electric Company, Aircraft Engine Group. Approximate distribution design/development/qualification/ initial production costs (double annular combustor). Cincinnati, OH. Undated 1978 submittal to Logistics Management Institute, Washington, D.C.

Haney, W.R., Parker Hannifin Corporation, Gas Turbine Fuel Systems Division. 1978. Letter of November 9, 1978, to R.S. Wilcox, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

______________. 1978. Personal communication of November 14, 1978 with R.S. Wilcox, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

Johnstone, P.M., Eastern Airlines, Inc., Operations Services. 1978. Letter of June 26, 1978 to C.L. Gray, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

Lloyd-Jones, D.J., American Airlines, Operations. 1978. Letter of July 20, 1978 to C.L. Gray, Emission Control Technology Division, Office of Mobile source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

Pearson, R.D., Trans World Airlines, Inc., Technical Serives. 1978. Leter of July 31, 1978 to C.L. Gray, Emission Control Technology Division, Office of Mobile Source air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

Titcomb, G.A., United Technologies Corporation, Pratt and Whitney Aircraft Group. 1979. Letter of February 28, 1979 to C.L. Gray, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

United Technologies Corporation, Pratt and Whitney Aircraft Group. 1977. Estimated economic impact of proposed EPA emissions regulations for aircraft, East Hartford, CT. Prepared for Logistics Management Institute, Washington, D.C.

Wassell, A.D., Rolls-Royce Limited, Aero Division. 1978. Letter of December 21, 1978 to C.L. Gray, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

_______________. 1978. Personal communication of January 23, 1978 with R.W. Munt and R.S. Wilcox, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

_______________. 1979. Letter of January 31, 1979 to R.W. Munt, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

_______________. 1978. Personal communication of February 15, 1978 with R.S. Wilcox, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, U.S. Environmental Protection Agency, Ann Arbor, MI.

Appendix C

Summaries of
EPA Combustion Assembly Price
Estimates - Double Annular and Vorbix Designs

3000 TAFT STREET, HOLLYWOOD, FLORIDA 33021

Jet Avion

DIVISION OF HEINICKE INSTRUMENTS CO.
(305) 987-6101 TELEX 512-610

July 7, 1978

U. S. Environmental
Protection Agency
2565 Plymouth Road
Ann Arbor, Michigan 48105

Attn: Mr. Richard Wilcox
Project Officer, SDSB
Ref: Order No. CD-8-02-0280-A

Gentlemen:

In accordance with your purchase order we hereby submit a selling price estimate of the JT8D Vorbix Combustion Can. The estimate is based on information gleaned from the Pratt and Whitney drawings L105810 and L105372, memo dated April 28, 1978, photographs supplied, and verbal information supplied by telephone and your visit with us on June 13, 1978.

PART	QTY	MAT	LABOR	TOOL DESIGN	TOOL MFG.
L105810-1	1	2.70	4.92	750.00	1035.00
L105810-2	1	5.14	9.10	1250.00	2485.00
L105810-3	1	6.44	10.66	2500.00	4065.00
L105810-5	1	12.00	26.60	2250.00	3180.00
L105810-6	1	8.76	14.00	800.00	1350.00
L105810-7	1	12.00	21.96	250.00	975.00
L105810-8	1	1.86	8.98	-0-	-0-
L105810-9	2	4.68ea	2.32ea	-0-	-0-
L105810-10	1	2.52	14.20	600.00	900.00
L105810-11	1	.44	4.90	1200.00	2325.00
L105810Assy	1	-0-	69.66	2500.00	3225.00
L105372-14	1	3.86	8.82	1800.00	2715.00
L105372-15	1	6.42	9.12	1600.00	2715.00
L105372-16	1	8.34	7.75	1400.00	2015.00
L105372-20	1	8.10	9.92	1600.00	2950.00
L105372-21	1	7.70	9.00	800.00	1465.00
L105372-22	1	7.20	9.00	800.00	1465.00
L105372-23	1	27.50	38.66	400.00	975.00
L105372-24	1	4.86	4.10	450.00	900.00
L105372-27	1	6.84	6.76	1500.00	2895.00

JULY 7, 1978

PART	QTY	MAT	LABOR	TOOL DESIGN	TOOL MFG.
L105372-28	1	3.38	6.30	2000.00	4615.00
L105372-29	1	2.44	3.84	700.00	1165.00
L105372-30	1	20.80	36.66	2000.00	4525.00
L105372-52	3	30.00ea	5.06ea	200.00	375.00
L105372-53	6	2.46ea	2.56ea	75.00	75.00
L105372-54	3	30.00ea	5.06ea	200.00	375.00
L105372-58	1	10.96	16.80	2200.00	5775.00
Fuel Inj. Tube	1	4.68	5.48	-0-	-0-
Assy 5	1	-0-	56.88	1000.00	2250.00
Assy 8	1	-0-	126.68	1000.00	2100.00
Final Assy	1	-0-	39.00	1000.00	2250.00
TOTAL		$379.06	$630.12	$32,825.00	$61,140.00

This amounts to a unit price of $1009.18. Our selling price for a JT8D,-1,-7,-9, part No. JA731562 (with igniter plug) is $911.00. This is an increase in selling price of 10.77%. Pratt & Whitney sells this combustion chamber for $1300.00. If we can assume proportionality then Pratt & Whitney's selling price for the Vortex can would be about $1440.00

The estimates are based on a total production quantity of 6,000 cans with deliveries at the rate of 400 cans per year over a period of 15 years. Should this quantity be increased to 9,000 cans with deliveries of 600 cans per year (to include sales to the foreign market), the reduction in estimated unit price would be about .5%.

The method of estimating is as outlined in our letter of June 2, 1978, except that packing and shipping costs have been omitted.

Very truly yours,

Harold Holden
Manager of Engineering

HH:PR

A COMPARISON OF THE FABRICATION COST AND SELLING PRICE OF THE PROPOSED LOW EMISSION COMBUSTION CHAMBERS WITH CURRENT COMPONENTS

SEPTEMBER 1978

Prepared for
The Environmental Protection Agency
Under EPA Order No. CD-8-1312-A

ELECTRO-METHODS INC.
Governors Highway
South Windsor
Connecticut

INTRODUCTION

The Environmental Protection Agency has been seeking to determine the cost impact of its proposed gaseous emission regulations for commercial aircraft engines. The studies that have been performed to date (Ref. 1-3) have been dependent upon the engine manufacturers estimates of fabrication cost analysis and an incremental cost estimate based upon current flight hardware.

The results presented herein are the products of work performed by Electro-Methods for EPA under Order Number CD-3-1312-A.

SUMMARY

A detailed fabrication cost analysis was performed on both the proposed Pratt & Whitney Aircraft Vorbix Combustion Chamber and the proposed General Electric Double Annular Combustion Chamber. It was determined that the proposed P&WA design would result in a minor cost increase while the proposed G. E. design would increase the cost of the combustion section by over 200%.

The cost increase in the G. E. design can be reduced to be competitive to the P&WA design if improved fabrication tecnniques are assumed for production quantities.

DISCUSSION

General Procedure

The drawing sets provided by the Environmental Protection Agency were analyzed and the major assemblies of each of the combustion sections were reduced to their basic components and listed on Electro-Methods cost analysis sheets. These sheets are provided as Appendix I (P&WA) and Appendix II (G.E.) respectively.

Each component was then studied to determine the method of fabrication, tooling design and procurement costs, material costs and labor hours to fabricate. In general, where Electro-Methods normally would sub-contract a specialized procedure such as resistance welding it was assumed that the equipment was in-house therefore, the labor content was estimated. It was assumed that the acquisition of such equipment would have a negligible effect upon quoting rates.

Electro-Methods normal suppliers were solicited for quotations on material charges and fabrication charges for the specialized components. These quotations are presented in Appendix III for P&WA's Vorbix Combustion Chamber and Appendix IV for General Electric's Double Annular Combustion Chamber. The results of these quotations formed the basis for the resulting material costs for each configuration.

Electro-Methods own rate structure was evaluated from a direct cost and absorption cost basis. This was done to eliminate all "design engineering" charges so that the resulting selling price would be based upon a true fabrication cost and, therefore, more indicative of an aftermarket replacement cost.

It should be remembered that Electro-Methods rates do not have to include the "write-off" of the original design costs nor the costs inherent with a continuing product improvement effort.

Direct costing is a form of cost analysis that divides all costs into two areas: 1) those costs that are dependent upon production volume, ie, material costs and production labor, and 2) costs that are time dependent, ie, rent, salaries, etc. It is a form of cost analysis that is an extremely useful management tool. Absorption costing is more commonly utilized by accountants. It is based upon the philosophy that each production hour worked must bear its share of all costs incurred.

The two costing methods resulted in a minimal difference therefore the current quoting rate of $34/hour was used. The rates utilized for both the Pratt & Whitney and General Electric analysis were assumed. Electro-Methods is constantly in a competitive position with both manufacturers, therefore, we feel that the $53 and $43 hourly rate is quite accurate for this type of fabrication.

The selling price was computed by marking up the tooling and material cost by 15% and adding it to the cost of the labor. The tooling charges were distributed over the full production run (Table I). The selling price of both the JT9D and CF6 components were obtained from each manufacturer's customers. The labor and material content of the JT9D and CF6 was estimated from Electro-Methods experience in fabricating similar interchangeable components.

Pratt & Whitney Aircraft Vorbix Combustion Chamber

The P&WA Vorbix Combustion Chamber is a modification of the existing JT9D combustion chamber. The chamber has been extended and the geometry has been modified. These changes do not greatly affect the fabrication cost or selling price (Table II). The material (Hastelloy X) remains unchanged. The additional labor is required to fabricate the additional sections. The result of these changes is to create a 15% increase in the selling price. The massive cost increase shown in Ref. 1 is either ultraconservative or based upon information beyond the scope of this study.

General Electric Double Annular Combustion Chamber

General Electric's design is a radical departure from the CF6 in both design and required fabrication techniques. The double row of nozzles require a centerbody (Part No. 4013182-608G01) which in itself is expensive: approximately $6,000. In addition, the construction methodology has departed from the conventional developed sheet metal to machined forgings. The increase in the selling price exceeds 200% as shown in Table III. It is our opinion that this configuration may be greatly simplified to make it more cost effective without sacrificing its performance.

It is our estimate that if General Electric were to redesign to utilize developed sheet metal fabrication techniques, the cost of the double annular combustor would approximate Vorbix Combustion Chamber.

TABLE I

ASSUMED PRODUCTION QUANTITIES

Year	1200 Units	1800 Units
1	80	120
2	80	120
3	80	120
4	80	120
5	80	120
6	80	120
7	80	120
8	80	120
9	80	120
10	80	120
11	80	120
12	80	120
13	80	120
14	80	120
15	80	120

Table II

P&WA Vorbix Combustion Chamber

	Electro Methods	P&WA Vorbix	P&WA JT9-D	Δ
<u>Tooling</u> (x10^{-3})				
Design	$ 160	$ 294		
Procurement	$ 780	$ 1,435		
Total	$ 940	$ 1,729		
<u>Fabrication (Unit)</u>				
Labor Hours	775	775	700	+75
Labor Rate	$ 34	$ 53	$ 53	
Labor Cost	$26,350	$41,075	$37,100	$+ 3,975
Material Cost	$ 4,630	$ 4,630	$ 4,000	$+ 630
<u>Unit Selling Price</u>				
1200 Units	$37,000	$48,000	$41,400	$+ 6,600
1300 Units	$36,000	$47,500	$41,400	$+ 6,100

TABLE III

G.E. Double Annular Combustion Chamber

	Electro Methods	G.E. Annular	G.E. CF6	G.E. Δ
Tooling ($x10^{-3}$)				
Design	$ 222	$ 407		
Procurement	$ 944	$ 1,738		
Total	$ 1,166	$ 2,145		
Fabrication (Unit)				
Labor Hours	1,600	1,600	650	+950
Labor Rate	$ 34	$ 43	$ 43	
Labor Cost	$54,400	$ 68,800	$27,950	$ +40,850
Material Cost	$17,000	$ 17,000	$ 5,000	$ +12,000
Unit Selling Price				
1200 Units	$75,000	$125,000	$53,500	$ 71,500
1800 Units	$74,700	$124,500	$53,500	$ 71,000

CONCLUSIONS

1. The JT9-D Combustor can be modified to the Vorbix configuration with an approximate 15% cost increase in the combustor section.

2. The CF6 Combustor can be modified to the proposed double annular configuration with a 200% cost increase. It is likely that the proposed fabrication methods will be modified to maintain a competitive position.

3. In the case of such a simplification, the cost incurred for the double annular configuration should be comparable to Vorbix configuration.

References

1. The Economic Impact of Revised Gaseous Emission Regulations for Commercial Aircraft Engines prepared by Logistics Management Institute
4701 Sangamore Road
Washington, D. C. 20016

2. 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 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
No. AC78-01

3. Cost-Effectiveness Analysis of the Proposed Revision in the Exhaust Emission Standards for New and In-Use Gas Turbine Aircraft Engines based on Industry Submittals by 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
No. AC77-02

References for Appendix C

Holden, H. 1978. Selling price estimate of the JT8D Vorbix Combustor. Jet Avion, Hollywood, FL. EPA Order No. CD-8-02-0280-A.

Electro-Methods Inc. 1978. A comparison of the fabrication cost and selling price of the proposed low-emission combustion chambers with current components. South Windsor, CT. EPA Order No. CD-8-1312-A.

Appendix D

Derivation of Non-Recurring and Recurring Engine Costs

Appendix D

Derivation of Non-Recurring and Recurring Engine Costs

For each of the proposed standards, engine costs are separated into broad categories: non-recurring and recurring. These categories reflect the costs for manufacturing and installing emission control hardware as well as corporate profit.

The cost figures which are documented in this appendix originate longly with manufacturers' or vendors' estimates. EPA revised the manufacturers' figures or made independent estimates (1) when industry submittals were incomplete, (2) when large unexplainable descrepancies existed between different manufacturers' estimates, or (3) when manufacturers' estimates appeared to be inappropriate based on additional information acquired by EPA.

The expenditures for specific cost categories are shown in Tables D-1A through D-3A. Each of these tables have an accompanying table, when required, which more completely explains the basis of each cost figure (Tables D-1B and D-3B).

TABLE D-1A

Engine Costs Associated with the 1982 Standards
(Thousands of 1978 dollars)

	NON-RECURRING					RECURRING	
	Development	Certification 9/	Service Evaluation	Initial Production	Total	New Engine Increment	Retrofit Installed
JT8D-17 1/	19,725 16/	6,575 16/	1,200 16/	300 17/	27,800	2.7 16/	23.5 16/
JT8D-200 1/						2.7 16/	
JT9D-7	14,063 10/16/	4,688 10/16/	600 10/16/	800 17/	20,151	6 16/	55 16/
JT9D-7R 2/						6 16/	
JT9D-70	14,063 10/16/	4,688 10/16/	600 10/16/	500 17/	19,851	6 16/	47 16/
CF6-6	5,130 16/	600 16/	276 16/	165 11/16/	6,171	25 16/	43 16/
CF6-32 3/						25 16/	
CF6-50	7,370 16/	600 16/	284 16/	165 16/	8,419	25 16/	50 16/
CF6-45 4/							
CF6-80 5/	7,370 16/				7,370	6 12/16/	
RB211-22B	44,608 13/16/	4,565 16/	1,500 14/	850 13/17/	51,523	25 16/	73 16/
RB211-535 6/	5,763 15/16/				5,763	25 16/	
RB211-524		4,565 16/			4,565	25 16/	73 16/
CFM56	3,860 16/	150 16/	NA	35 16/	4,045	5 16/	NA
JT10D 7/	5,850 16/	NA	NA	NA	5,850	NA	NA
Sepy 8/	NA	NA	NA	NA	NA	NA	NA

Table D-1B

Explanation of Footnotes in Table D-1A

1/ Cost for all JT8D models or average cost where appropriate.

2/ JT9D-7R is a rerated JT9D-7, same combustor as JT9D-7, no extra development, no certification differential because it is assumed the engine will be certified with 1982 type technology, or crossover from "parent" engine will fulfill certification requirements of combustor, it is a new engine so no service evaluation, no added tooling, and new engine increment is the same as "parent" engine.

3/ CF6-32 is a rerated CF6-6, same combustor as CF6-6, same cost considerations as 2/ above.

4/ CF6-45 is a derated CF6-50, same cost considerations as 2/ above.

5/ CF6-80 is a derivative of the CF6-50, redesign needed because of different control system. Therefore, added development costs and a different new engine increment. Because engine is new and must go through certification and initial production regardless of emission control requirements, no cost is allowed for these categories.

6/ RB211-535 is a derated RB211-22B, essentially the same core as RB211-22B, assumed to use phase II combustor as other RB211's, same considerations as in 2/ above for other cost categories.

7/ JT10D has no market at present and its prospects are not bright. Manufacturer is expected to certify with 1982 type technology so no added certification costs are allowed. Added development costs are allowed. Because EPA fleet projection shows no engines produced, there is no initial production, no new engine increment and no retrofit. No service evaluation will be performed since it is a new engine.

8/ The Spey is an engine of older design that can not possibly meet the proposed standards. EPA assumes the engine is out of production either because (1) it would not meet the standard, and hence, would not be made, (2) there is no market, or (3) it is replaced by the RB432 for which EPA has no information.

9/ For all derivative engines, some certification cost for emission control may be expected. In relation to other costs of certification, when incurred (e.g., CF6-80), these costs well be insignificant. Additionally, the "parent" engine certification costs have a fairly large degree of uncertainity and in some instances appear to be inflated. Also the "parent" engine certification can often be used in the certification of the derivative's combustor. Therefore, no allowance is made for emission certification testing in derivative engines.

10/ Fifty percent cost sharing between JT9D-7 and JT9D-70 families.

11/ Fifty percent cost sharing between CF6-6 and CF6-50 families.

12/ CF6-80 will be produced with aerating nozzles instead of sector burning.

13/ Fifty percent cost sharing between RB211-22B and RB211-524. EPA is unable to explain this high cost in relation to the task involved.

14/ Service evaluation cost as reported by Rolls Royce ($7.22 million) disallowed because they were completely inconsistent with information from the other engine manufacturers. EPA estimated this cost based on data contained in Wilcox and Munt (1978). EPA's figure may still be somewhat liberal in comparison to the cost reported for sector burning hardware by General Electric.

15/ Additional cost claimed by the manufacturer for the RB211-535 because development was not done in conjunction with other RB211's. Also, extra expense may be do, in part, to an evaluation of a phase III combustor in this engine.

16/ Based on the latest manufacturer or vendor submittal to EPA (see Appendices B and C).

17/ From Wilcox and Munt (1978) with costs updated to 1978 dollars by using a 6 percent annual inflation rate for industrial prices.

TABLE D-2A

Engine Costs Associated with the CF6 Alternative Combustor 1/
(Thousands of 1978 dollars)

	Development	Certification	Service Evaluation	Initial Production	Non-recurring Total	New Engine Increment
CF6-6	7,000	4,600	600	500	12,700	8
CF6-32	2/	4,600	2/	2/	4,600	8
CF6-80	NA	NA	NA	NA	NA	NA
CF6-50	3/	4,600	3/	3/	4,600	6
CF6-45	3/	4,600	3/	3/	4,600	6

1/ Based on the latest manufacturer or vendor submittals to EPA (Appendices B and C).

2/ Requirements for the CF6-32 already have been fulfilled by the CF6-6 parent engine; therefore, no additional cost is incurred.

3/ Requirements for the CF6-50 and CF6-45 already have been fulfilled by the closely related CF6-80; therefore, no additional cost is incurred.

TABLE D-3A

Engine Costs Associated with the 1986 Low-NOx Standard
(Thousands of 1978 dollars)

	Development	Certification 10/	Service Evaluation	Initial Production	Non-recurring Total	New Engine Increment
JT8D-200 1/	18,000 12/		4,200 12/	1,800 13/	24,000	21 12/
JT9D-7	35,300 11/14/19/	17,200 11/14/19/	5,300 11/14/	3,800 13/	61,600	33 13/
JT9D-7R 2/		4,000 15/			4,000	33 13/
JT9D-70	35,300 11/14/19/	17,200 11/14/19/	5,340 11/14/	3,800 13/	61,000	33 13/
CF6-6	16,000 18/19/	7,700 18/19/	5,400 14/	3,400 13/	32,500	25 13/
CF6 32 3/		3,400 15/			3,400	25 13/
CF6-50	16,000 18/19/	7,700 18/19/	5,400 14/	3,400 13/	32,500	25 13/
CF6-45 4/		3,900 15/			3,900	25 13/
CF6-80 5/		3,900 15/			3,900	25 13/
RB211-22B 6/	30,000 12/	4,565 16/	4,300 17/20/	3,400 13/	42,300	25 13/
RB211-535 7/		4,565 16/			4,600	25 13/
RB211-524		4,565 16/			4,600	25 13/
CFM56	13,000 13/	5,000 12/	3,300 12/	2,600 13/	23,900	17 12/
JT10D 8/	NA	NA	NA	NA	NA	NA
Spey 9/	NA	NA	NA	NA	NA	NA

Table D-3B

Explaination of Footnotes in Table D-3A

1/ Costs for all JT8D models are average costs where appropriate.

2/ JT9D-7R is a rerated JT9D-7, same combustor as JT9D-7, no extra development, no added initial production, and the new engine increment is the same as the "parent" engine. Additional certification costs are allowed for derivatives using low-NOx combustors because of the possibility that the complexity of the hardware may require some separate certification testing (e.g., flight tests) to verify the airworthiness of the hardware even though essentially the same hardware was certified in "parent" engines. No separate service evaluation is required because data acquired from the "parent" engine is expected to apply.

3/ CF6-32 is a rerated CF6-6. same cost considerations as 2/above.

4/ CF6-45 is a derated CF6-50. Same cost considerations as 2/ above.

5/ CF6-80 is a derivative of CF6-50. Same cost considerations as 2/ above.

6/ Development of the Rolls Royce (RR) double annular combustor is higher than for General Electric's comparable combustor design because RR does not have crossover from other engine families to reduce costs. Also, they have not benefited from U.S. Government IR&D and NASA funding as domestic manufacturers have.

7/ RB211-535 is a derated RB211-22B. Same cost conisderations as 2/ above.

8/ JT10D is forecast to have no market and, therefore, will not be redesigned to comply with the 1986 low-NOx standard.

9/ The Spey is assumed to be out of production by 1986.

10/ Some certification cost for emission control may be expectd for all derivative engines. For the 1986 low-NOx standard, these costs are accounted for in the overall cost of certification which is listed for each engine.

11/ Fifty percent cost sharing between JT9D-7 and JT9D-70 families.

12/ From Wilcox and Munt (1978) with costs updated to 1978 dollars by using a 6 percent annual inflation rate for industrial prices.

13/ New estimate based on Wilcox and Munt (1978), latest manufacturer or vendor submittal to EPA (Appendix B), and EPA combustor price estimates (Appendix C).

14/ From United Technologies Corporation (1977).

15/ New estimate based on data contained in Wilcox and Munt (1978).

16/ Based on the latest manufacturer or vendor submittals to EPA (Appendices B and C).

17/ EPA revised figure based on manufacturers latest submittals to EPA (Appendix B).

18/ From General Electric Company (1977) updated to 1978 dollars.

19/ General Electric and Rolls Royce reported development and certification costs which did not fully correspond to the EPA cost accounting format. The manufacturers expenses were reapportioned by using weighting factors for the two categories which were based on data contained in Wilcox and Munt (1978). This method produced cost figures which are comparable between manufacturers. The overall cost as reported for the two categories was not changed, however.

20/ Service evaluation costs as reported by Rolls Royce ($12.78 million) were disallowed because they were completely inconsistent with information submitted by other manufacturers. EPA reduced the cost to 33 percent of that claimed, to reflect service evaluation for one "parent" engine within the RB211 family.

References for Appendix D

Wilcox, R.S. and R.W. Munt. 1978. 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. TSR AC 78-01. Emission Control Technology Division, Office of Mobile Source Air Pollution Control, Environmental Protection Agency, Ann Arbor, MI.

United Technologies Corporation, Pratt and Whitney Aircraft Group. 1977. Estimated economic impact of proposed EPA emissions regulations for aircraft. East Hartford, CT., Prepared for Logistics Management Institute, Washington, D.C.

General Electric Company, Aircraft Engine Group. 1977. Approximate distribution-design/development/qualification/ initial production costs (double annular combustor). Cincinnati, OH. Undated submittal to Logistics Management Institute, Washington, D.C.

Appendix E

Derivation of the Average Engine Selling Price Increment

Table E-1

SCENARIO #2: 1982 NME AND 1986 IUE STANDARDS ONLY - EXPECTED SALES.

YEAR	NEW ENG SOLD	OLD ENG RTRO	FIXD COST	NME HARD WARE	IUE HARD WARE	TOT COST	TOT# ENG CONT	DISC FACT	PRES VALU COST
1975.	0.	0.	6460000.	0.	0.	6460000.	0.	1.94871	12588667.
1976.	0.	0.	12920000.	0.	0.	12920000.	0.	1.77156	22888497.
1977.	0.	0.	19380000.	0.	0.	19380000.	0.	1.61051	31211603.
1978.	0.	0.	25840000.	0.	0.	25840000.	0.	1.46410	37832265.
1979.	0.	0.	32300000.	0.	0.	32300000.	0.	1.33100	42991233.
1980.	0.	0.	32300000.	0.	0.	32300000.	0.	1.21000	39082959.
1981.	240.	0.	32300000.	17000.	0.	36380000.	240.	1.10000	40017979.
1982.	902.	1773.	0.	17000.	38000.	82708000.	2675.	1.00000	82708000.
1983.	910.	1774.	0.	17000.	38000.	82882000.	2684.	0.90909	75347312.
1984.	1224.	1774.	0.	17000.	38000.	88220000.	2998.	0.82645	72909167.
1985.	1129.	1774.	0.	17000.	38000.	86605000.	2903.	0.75132	65067720.
1986.	1266.	0.	0.	17000.	0.	21522000.	1266.	0.68301	14699846.
1987.	1418.	0.	0.	17000.	0.	24106000.	1418.	0.62092	14967968.
1988.	1498.	0.	0.	17000.	0.	25466000.	1498.	0.56448	14374938.
1989.	1552.	0.	0.	17000.	0.	26384000.	1552.	0.51316	13539213.
1990.	1092.	0.	0.	17000.	0.	18564000.	1092.	0.46651	8660279.
1991.	1108.	0.	0.	17000.	0.	18836000.	1108.	0.42410	7988340.
1992.	782.	0.	0.	17000.	0.	13294000.	782.	0.38555	5125439.
1993.	836.	0.	0.	17000.	0.	14212000.	836.	0.35050	4981248.
1994.	1135.	0.	0.	17000.	0.	19295000.	1135.	0.31863	6148020.
1995.	1230.	0.	0.	17000.	0.	20910000.	1230.	0.28967	6056923.
1996.	1174.	0.	0.	17000.	0.	19958000.	1174.	0.26333	5255603.
1997.	1335.	0.	0.	17000.	0.	22695000.	1335.	0.23939	5433045.
1998.	1372.	0.	0.	17000.	0.	23324000.	1372.	0.21763	5076024.
1999.	1608.	0.	0.	17000.	0.	27336000.	1608.	0.19785	5408330.
2000.	1415.	0.	0.	17000.	0.	24055000.	1415.	0.17986	4326544.
2001.	0.	0.	0.	0.	0.	0.	0.	0.16351	0.
UTOT	23226.	7095.	161500000.	340000.	152000.	825952000.	30321.	19.80082	644687162.
DTOT	11032.	6185.	222125205.	175125.	132500.	644687162.	17217.		

THE FIRST PRICE INCREASE IS COMPUTED USING THE PRESENT VALUE OF ALL COSTS AND THE TOTAL NUMBER OF ENGINES AFFECTED, DISCOUNTED TO THE SAME YEAR AS THE COSTS. THIS COST ANALYSIS ASSUMES THAT ALL COSTS ARE INCURRED AT THE BEGINNING OF THE YEAR, AND ALL REVENUES ARE RECEIVED AT THE END OF THE YEAR, THUS FORCING DISCOUNTING ONE ADDITIONAL YEAR. THEREFORE, THE FIRST PRICE INCREASE IS THE PRESENT VALUE OF ALL COSTS DIVIDED BY THE DISCOUNTED TOTAL ENGINES AFFECTED AND MULTIPLIED BY 1.10.

FIRST PRICE INCREASE = $ (644687162.07 / 17216.69) * 1.10 = $ 41190.01

Appendix F

Derivation of Idle Fuel Consumption Increments

In order to meet the standards under consideration, manufacturers will improve the combustion efficiency of their engines at idle power settings. For all engines except the JT8D, this improvement will reduce idle specific fuel consumption (SFC) by about 3 percent. The JT8D smokeless combustor is already more efficient than average and will experience a 1 percent reduction in idle SFC.

The sector-burning control concept which may be used to comply with ther 1982 NME and 1986 IUE Standards has net fuel consumption penalty associated with it. Sectoring at idle causes an 8 percent decrease in turbine component efficiency. This decrease, in conjunction with the combustion efficiency improvement of 3 percent, yields a 5 percent over all penalty in idle SFC. The CFM 56 has the greatest fuel penalty of any controlled engine. To achieve the CO standard, the idle thrust must be increased from about 4 percent to 6 percent. This change along results in 19.6 percent fuel consumption increase. When this penalty is combined with the 8 percent increase brought about by the use of sector burning and the 3 percent combustion efficiency benefit, the result is an overall 20 percent increase in the engine's uncontrolled baseline idle SFC.

Low-NOx staged combustors (1986 technology) are also about 3 percent more efficient at idle than are their uncontrolled counterparts. In control scenarios where a preexisting standard is assumed, no increment in idle SFC occurs unless a staged combustor replaces an emission control scheme that had a fuel penalty associated with it, i.e., sector burning. Therefore, the fuel penalty of a previous standard provides an additional fuel savings when 1986 technology is introduced into the fleet. In scenarios with no preexisting standard, the introduction of a staged combustion system produces a benefit in every engine because of better combustion efficiency. .

The fuel consumption increment in gallons per year for the average engine in each control scenario is calculated by using the following equation:

Idle fuel increment=

$$\frac{L_t\ U_l\ S_f\ M_f\ T_i\ F_c/F_w}{\Sigma\ U_l\ S_f} \qquad (1)$$

Where:

L_t = landing and take-off cycles per year for each engine model.

U_l = useful life weighting factor for each engine model.

S_f = sales weighting factor for each engine model.

$\dot{M}_f$ = baseline idle fuel flow in pounds mass per hour.

T_i = average time spent in idle mode (19/60)

F_c = fractional fuel consumption increment.

F_w = weight of jet fuel in pounds per gallon (6.7).

The dollar value of the fuel increment is found by:

$$(\text{Equation 1})\ (\$\ 0.40) \qquad (2)$$

Where: $0.40 per gallon, including tax, represents a nominal value for jet fuel in 1978.

Table F-1 illustrates the derivation of the idle fuel consumption increments for each control scenario.

Table F-1

Annual Idle Fuel Increment Scenario 2
(1982 NME and IUE Only)

Engine	A Fraction Useful Life	B Fractional Sales	$\frac{A \times B}{\Sigma A \times B}$ Sales Weighted Useful Life	LTOs/ Year	Parent Thrust Correction Factor	Baseline M_f Idle (uncontrolled)	Controlled Increment M_f Idle	Weighted Controlled Increment M_f Idle	lbm Weighted Annual Fuel Increment	Annual Gallons (6.7 lb/ gal)	Annual Costs ($0.40/ gal)
JT8D-17	1	0		2,000	0	1,150	0	0	0		
Retro	0.47	0.13	0.07	2,600		1,150	-12	-0.8	-659		
JT8D-200	1	0.06	0.07	2,600		1,090	-11	-0.8	-659		
JT9D-7	1	0.09	0.10	900		1,850	-56	-5.6	-1,596		
Retro	0.47	0.05	0.03	900		1,850	-56	-1.7	-484		
JT9D-7R	1	0.01	0.01	2,600	1.04	1,925	-58	-0.6	-494		
JT9D-70	1	0.09	0.10	900		1,800	-54	-5.4	-1,539		
CF6-6	1	0.06	0.07	1,300		1,060	+53	+3.7	+1,523		
Retro	0.47	0.02	0.01	1,300		1,060	+53	+0.5	+206		
CF6-32	1	0.05	0.06	1,300	0.82	870	+44	+2.6	+1,070		
CF6-50	1	0.15	0.17	1,300		1,210	+60	+10.2	+4,199		
Retro	0.67	0.01	0.01	1,300		1,210	+60	+0.6	+247		
CF6-45	1	0.03	0.03	2,600	0.93	1,125	+56	+1.7	+1,400		
CF6-80	1	0.01	0.01	2,600	0.96	1,160	-35	-0.4	-329		
RB211-22B	1	0.06	0.07	1,300		1,475	+74	+5.2	+2,141		
Retro	0.47	0.02	0.01	1,300		1,475	+74	+0.7	+288		
RB211-535	1	0.05	0.06	2,600	0.76	1,120	+56	+3.4	,2,799		
RB211-524	1	0.06	0.06	1,300		1,500	+75	+4.5	+1,852		
CFM56	1	0.05	0.06	2,600		715	+155	+9.3	+7,657		
Total									+17,622	+2,630	+1,052

Appendix G

Derivation of Maintenance Increments

Emission control has the potential of increasing maintenance costs by reducing combustor durability throughout the life of the engine, increasing replacement costs for life-limited parts, or necessitating the maintenance of all new engine parts (e.g., sectoring control). No maintenance increment is associated with the introduction of immature engine hardware for the standards analyzed in this study. The implementation date for each proposed standard has been selected to provide an adequate service evaluation by the engine manufacturers which will eliminate any potential service penalty.

The incremental maintenance cost estimates are based upon manufacturers' estimates, supplemental data from major airlines, information from EPA's contractor report entitled, "The Economic Impact of Revised Gaseous Emission Regulations for Commerical Aircraft Engines" (Day and Bertrand 1978), and EPA's independent estimates of increased maintenance requirements.

EPA recognizes the possibility that significant maintenance penalties may be associated with the staged-combustion systems which are required to comply with the proposed 1986 NME Standard. However, industry proponents of these potential penalties have not presented evidence which substantiates their claim. Therefore, any discussion of this issue remains conjecture.

The "worst case" maintenance cost for staged combustors is evaluated in this analysis. The estimate is predicated on the assumption that 500 additional person-hours of repair work are required to overhaul a large engine with a Vorbix combustor and 400 added person-hours are required for Double Annular combustors. Also, it is assumed that mature staged-combustors could experience up to a 25 percent reduction in the average number of engine hours between hot section overhauls and that some turbine blade degradation will occur.

The annual maintenance increment for each engine is calculated by using the following equation:

$$\text{Annual Maintenance cost} = \frac{12\, H_o\, C_h}{M_o}$$

Where: 12 = Number of calendar months in a year.
H_o = Mean engine hours before combustor overhaul.
C_h = Dollar cost per engine hour for incremental maintenance.
M_o = Mean calendar months between combustor overhaul.

The annual increment for each engine (Table G-1) is then weighted by the appropriate sales- and useful-life factors to derive the average engine maintenance increment in each control scenario. Table G-2 illustrates this latter computation for Scenario 2.

Table G-1

Incremental Maintenance Costs per Engine

	$\bar{x}$ Hot Section Overhaul Intervals 1/ (Months)	$\bar{x}$ Overhaul per Year 1/	Engine Hours Between Overhaul 2/	1982 Standards 3/ Dollar/Hour (HC and CO)	1986 Standards 4/ Dollar/Hour (HC, CO and NOx)	1982 Standards Dollar Annual Costs	1986 Standards Dollar Annual Costs
JT8D-17	20	0.6	4,700	0.10	6.65	280	18,700
JT8D-200	20	0.6	4,700	0.10	6.65	280	18,700
JT9D-7	9 5/	1.3	2,700	0.20	13.25	700	46,500
JT9D-70	9 5/	1.3	2,700	0.20	13.25	700	46,500
CF6-6	9	1.3	2,780	0.20	12.50	725	45,200
CF6-50	9	1.3	2,780	0.20	12.50	725	45,200
RB211-22	10	1.2	2,400	0.20	13.00	575	37,450
RB211-524	19	0.63	4,500	0.20	11.50	900	32,600

1/ Based on the latest engine manufacturer and airline submittals (Appendix B), and Day and Bertrand (1978).
2/ Based on the latest engine manufacturer and airline submittals (Appendix B).
3/ Based on the latest engine manufacturer submittals (Appendix B), United Technologies Corporation (1977), and EPA's estimate of maintenance requirements.
4/ Based primarily on United Technolgies Corporation (1977), and EPA's estimate of maintenance requirements .
5/ Insufficient data. Based on CF6.

Table G-2

Annual Maintenance Increment for Scenario 2
(1982 NME and 1986 IUE Only)

Engine	A Fractional Useful Life	B Fractional Sales	$\frac{A \times B}{\Sigma A \times B}$ Sales Weighted Useful Life	$ Annual Maintenance	$ Weighted Annual Maintenance
JT8D-17	1				
Retro	0.47	0.13	0.07	280	20
JT8D-200	1	0.06	0.07	280	20
JT9D-7	1	0.09	0.10	700	70
Retro	0.47	0.05	0.03	700	21
JT9D-7R	1	0.01	0.01	700	7
JT9D-70	1	0.09	0.10	700	70
CF6-6	1	0.06	0.07	725	51
Retro	0.47	0.02	0.01	725	7
CF6-32	1	0.05	0.06	725	44
CF6-50	1	0.15	0.17	725	123
Retro	0.67	0.01	0.01	725	7
CF6-45	1	0.03	0.03	725	22
CF6-80	1	0.01	0.01	725	7
RB211-22B	1	0.06	0.07	575	40
Retro	0.47	0.02	0.01	575	6
RB211-535	1	0.05	0.06	575	35
RB211-524	1	0.06	0.06	900	54
CFM56	1	0.05	0.06	0	0
Total					604

References for Appendix G

Day, C. F. and H. E. Bertrand. 1978. The economic impact of revised gaseous emission regulations for commercial aircraft engines. Logistics Management Institute, Washington, D.C. EPA Contract No. 68-01-4647 (Task EP701).

United Technologies Corporation, Pratt and Whitney Engine Group. 1977. Estimated economic impact of proposed EPA emissions regulations for aircraft. East Hartford, CT. Prepared for Logistics Management Institute, Washington, D.C.

APPENDIX H

Derivation of Emission Reductions

The regulated EPAP values used to derive the exhaust emission reductions per engine reflect the actual levels achievable based on current test results (Munt 1979). By using these values instead of the more conservative approach of limiting the EPAP's to the maximum allowable levels permitted by the regulation, a more realistic simulation of the actual decrease in air pollutants at major air carrier terminals is accomplished.

In a few instances where the demonstrated EPAP's were above the maximum permissible levels, they were adjusted to meet the standard. This is consistent with the fact that all engines must comply with the regulation or they will not be certified. Where no data were available and no reasonable basis for estimating the engine's emissions existed, EPAP values which conformed to the standard were assigned.

Except for CO, the levels of the standards are as proposed by EPA in the March 24, 1978 Notice of Proposed Rulemaking (43 FR 12615). Based on the comments which were received in response to the NPRM, EPA has tentatively concluded that the proposed CO standard may be technically unattainable by most turbine engines and that some relaxation may be necessary. For the purposes of this analysis, it is assumed that the standard is 40 percent less stringent than the proposed value. This results in a total reduction from uncontrolled CO emissions of about 60 percent instead of about 70 percent.

The tons of pollutant reduced per engine each year is computed by using the following equation:

Annual reduction of pollutant A =

$$[EPAP(A)_{unregulated} - EPAP(A)_{regulated}]\ R_t\ L_y/(2{,}000\ lbm/t) \quad (1)$$

Where: R_t = pounds of rated thrust.
L_y = annual landing-takeoff cycles (LTOs).

The EPA values used in Equation 1 are based on the EPA-defined LTO cycle. This cycle is representative of maximum times-in-mode for aircraft at major metropolitan air terminals. It is not useful to characterize modal times at average airports in future years, however. The pollutant species HC and CO are sensitive to the time-in-mode differences between major and average air terminals, because they are mainly the products of low-power operations, i.e., taxi-idle. Emissions of NOx do not change significantly between airports since it is produced during high-power modes of the flight regime which do not vary substantially from airport-to-airport.

EPA assumes that the average taxi-idle time-in-mode for turbine-powered aircraft at airports throughout the nation is about 19 minutes (see Discussion -- Part I). This contrasts with the 26 minutes of the EPA LTO cycle upon which the EPAP's are based. To account for the difference in ground times, the annual HC and CO emission reductions derived in Equation 1 are adjusted to represent the average airport time-in-mode in the following way:

Adjusted annual reduction in HC or CO =

(Equation 1)(0.73) (2)

Where: 0.73 is the ratio of the average and major air terminal taxi-idle times (19/26).

The annual emission reductions for the average engine in each control scenario is determined by weighting the annual reductions for each engine model (Tables H-1 through H-3) by useful life and sales projection data.

This computation is illustrated in Table H-4 for the average engine in Scenario 2.

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Emission Reductions per Engine Resulting from the 1982 NME and 1985 IUE Standards

Engine	lbm Thrust (000)	LTOs/Yr	Standard LTO Unregulated EPAP (uncorrected) HC	Standard LTO Unregulated EPAP (uncorrected) CO	Standard LTO Regulated EPAP (uncorrected) HC	Standard LTO Regulated EPAP (uncorrected) CO	Standard LTO Net EPAP Reduction (uncorrected) HC	Standard LTO Net EPAP Reduction (uncorrected) CO	Taxi-idle Correction Factor (HC-CO only)	Tons Annual Reduction (corrected) HC	Tons Annual Reduction (corrected) CO
JT8D-17	16.0	2,600	0.37	1.1	0.075	0.48	0.30	0.62	0.73	4.6	9.4
JT8D-200 1/	18.5	2,600	0.37	1.1	0.075	0.48	0.30	0.62	0.73	5.3	10.9
JT9D-7	46.2	900	0.45	0.97	0.056	0.24	0.39	0.73	0.73	5.9	11.1
JT9D-7R	48.0	2,600	0.47 2/	1.0 2/	0.66 3/	0.50 4/	0.40	0.5	0.73	18.2	22.8
JT9D-70	51.2	900	0.20	0.86	0.037	0.20	0.16	0.66	0.73	2.7	11.1
CF6-6	38.9	1,300	0.42	0.95	0.016	0.28	0.40	0.67	0.73	7.4	12.4
CF6-32	32.6	1,300	0.47	1.0	0.020	0.29	0.45	0.71	0.73	7.0	11.0
CF6-50	49.9	1,300	0.62	1.2	0.010	0.36	0.61	0.84	0.73	14.4	19.9
CF6-45	46.5	2,600	0.58 2/	1.1 2/	0.066 3/	0.50 4/	0.51	0.60	0.73	22.5	26.5
CF6-80	48.0	2,600	0.60 2/	1.2 2/	0.066 3/	0.50 4/	0.53	0.70	0.73	24.1	31.9
RB211-22B	42.0	1,300	1.3	1.7	0.041	0.28	1.26	1.42	0.73	25.1	28.3
RB211-535	32.0	2,600	3.0 5/	3.1 5/	0.025	0.50 4/	2.98	2.60	0.73	90.5	79.0
RB211-524	50.0	1,300	1.1	1.4	0.030	0.22	1.07	1.18	0.73	25.4	28.0
CFM56	22.2	2,600	0.12 6/	0.78 6/	0.009	0.41	0.11	0.37	0.73	2.3	7.8

1/ No data. Based on JT8D-17.
2/ Based on the thrust ratio of the parent engine and the derivative.
3/ No data. Assumed to meet the standard.
4/ Assumed to meet the standard with a 40% increase; compliance not yet demonstrated.
5/ Based on the thrust ratio of the parent and the derivative, multiplied by the EPAP's of the RB211-22B with a Phase II combustor. Also accounts for the RB211-535's reduced idle speed.
6/ Based on the Mod. PFRT combustor.

Table H-2

Emission Reductions per Engine When 1986 NME is implemented subsequent to the 1982 NME Standard

	lbm Thrust (000)	LTOs/Yr	Std. LTO Unregulated EPAP (uncorrected) NOx	Std LTO Regulated EPAP (uncorrected) NOx	Net EPAP Reduction (uncorrected) NOx	Tons Annual Reduction (corrected) NOx
JT8D-17	16.0	2,600	NA	NA	NA	NA
JT8D-200	18.5	2,600	0.67	0.32 2/	0.35	6.1
JT9D-7	46.2	900	0.46	0.26	0.20	3.0
JT9D-7R	48.0	2,600	0.48 3/	0.32 4/	0.16	7.3
JT9D-70	51.2	900	0.48	0.35	0.13	2.2
CF6-6	38.9	1,300	0.64	0.32 2/	0.32	5.9
CF6-32	32.6	1,300	0.63	0.32 2/	0.31	4.8
CF6-50	49.9	1,300	0.60	0.38 2/	0.22	5.2
CF6-45	46.5	2,600	0.56 3/	0.34 4/	0.22	9.7
CF6-80	48.0	2,600	0.58	0.36 4/	0.22	10.0
RB211-22B	42.0	1,300	0.63	0.32 4/	0.31	6.2
RB211-535	32.0	2,600	0.30	NA 5/	NA	NA
RB211-524	50.0	1,300	0.69	0.34 4/	0.35	8.3
CFM56	22.2	2,600	0.43	0.32 4/	0.11	2.3

1/ Baseline is 1982 NME emissions.
2/ Assumed to meet standard; compliance not yet demonstrated.
3/ No data. Baseline emissions estimated on the basis of the parent engine.
4/ No data. Assumed to meet the standard.
5/ 1982 NME meets the NOx standard.

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Emission Reductions per Engine Resulting from the 1986 NME Standards 1/

Engine	lbm Thrust (000)	LTOs/Yr	Std. LTO Unregulated EPAP (uncorrected) HC	CO	NOx	Std LTO Regulated EPAP (uncorrected) HC	CO	NOx	Net EPAP Reduction (uncorrected) HC	CO	NOx	Std. LTO Taxi-idle Correction Factor (HC-CO only)	Tons Annual Reduction (corrected) HC	CO	NOx
JT8D-200 2/	18.5	2,600	0.37	1.1	0.67	0.016	0.50 3/	0.324/	0.35	0.6	0.35	10.5	6.1	10.5	6.1
JT9D-7	46.2	900	0.45	0.97	0.46	0.021	0.30	0.26	0.43	0.67	0.20	0.73	6.5	10.2	3.0
JT9D-7R	48.0	2,600	0.47	1.0	0.48 5/	0.066 6/	0.50 7/	0.32 6/	0.40	0.5	0.16	0.73	18.2	22.8	7.3
JT9D-70	51.2	900	0.20	0.86	0.48	0.020	0.26	0.35	0.18	0.60	0.13	0.73	3.0	10.1	2.2
CF6-6	38.9	1,300	0.42	0.95	0.64	0.027	0.50 3/	0.32 4/	0.39	0.45	0.32	0.73	7.2	8.3	5.9
CF6-32	32.6	1,300	0.47	1.0	0.63	0.031	0.50 3/	0.32 4/	0.44	0.5	0.31	0.73	6.8	7.7	4.8
CF6-50	49.9	1,300	0.62	1.2	0.60	0.024	0.49	0.38 4/	0.60	0.71	0.22	0.73	14.2	16.8	5.2
CF6-45	46.5	2,600	0.58	1.1	0.56 5/	0.066 6/	0.50 7/	0.34 6/	0.51	0.60	0.22	0.73	22.5	26.5	9.7
CF6-80	48.0	2,600	0.60	1.2	0.58	0.066 6/	0.50 7/	0.36 6/	0.53	0.70	0.22	0.73	24.1	31.9	10.0
RB211-22B	42.0	1,300	1.3	1.7	0.63	0.066 6/	0.50 7/	0.32	1.23	1.2	0.31	0.73	24.5	23.9	6.2
RB211-535	32.0	2,600	3.0	3.1	0.30	0.066 6/8/	0.50 7/8/	NA 9/	2.93	2.6	0	0.73	89.0	79.0	0
RB211-524	50.0	1,300	1.1	1.4	0.69	0.066 6/	0.50 7/	0.34 6/	1.03	0.90	0.35	0.73	24.4	21.4	8.3
CFM56	22.2	2,600	0.12	0.78	0.43	0.066 6/	0.50 7/	0.326	0.05	0.28	0.11	0.73	1.1	5.9	2.3

1/ The HC and CO values presented in this table are used in scenarios where no previous 1982 standard exists.
2/ No data. Based on JT8D-17.
3/ Assumed to meet the standard with a 40% increase; compliance not yet demonstrated.
4/ Assumed to meet the standard; compliance not yet demonstrated.
5/ Based on thrust ratio of parent and derivative.
6/ No data. Assumed to meet the standard with a 40% increase.
7/ No data. Assumed to meet the standard.
8/ The RB211-535 may not require a staged combustor, but to simplify the analysis, a staged combustor is assumed in scenarios which evaluate a 1986 low-NOx standard with no previous 1982 standard.
9/ Not applicable. The uncontrolled RB211-535 meets the standard.

Table H-4

Annual Reduction in Pollutants for Scenario 2
(1982 NMF and 1986 IUE Only)

Engine	A Fractional Useful Life	B Fractional Sales	$\frac{A \times B}{\Sigma A \times B}$ Sales Weighted Useful Life	Tons Pollutant/Year HC	Tons Pollutant/Year CO	Weighted Annual Tons HC	Weighted Annual Tons CO
JT8D-17	1	0	0	4.6	9.4	0	0
Retro	0.47	0.13	0.07	4.6	9.4	0.3	0.7
JT8D-200	1	0.06	0.07	5.3	10.9	0.4	0.8
JT9D-7	1	0.09	0.10	5.9	11.1	0.6	1.1
Retro	0.47	0.05	0.03	5.9	11.1	0.2	0.3
JT9D-7R	1	0.01	0.01	18.2	22.8	0.2	0.2
JT9D-70	1	0.09	0.10	2.7	11.1	0.3	1.1
CF6-6	1	0.06	0.07	7.4	12.4	0.5	0.9
Retro	0.47	0.02	0.01	7.4	12.4	0.1	0.1
CF6-32	1	0.05	0.06	7.0	11.0	0.4	0.7
CF6-50	1	0.15	0.17	14.4	19.9	2.4	3.4
Retro	0.67	0.01	0.01	14.4	19.9	0.1	0.2
CF6-45	1	0.03	0.03	22.5	26.5	0.7	0.8
CF6-80	1	0.01	0.01	24.1	31.9	0.2	0.3
RB211-22B	1	0.06	0.07	25.1	28.3	1.8	2.0
Retro	0.47	0.02	0.01	25.1	28.3	0.2	0.3
RB211-535	1	0.05	0.06	90.5	79.0	5.4	4.7
RB211-524	1	0.06	0.06	25.4	28.0	1.5	1.7
CFM56	1	0.05	0.06	2.3	7.8	0.1	0.5
Total						15.4	19.8

References for Appendix H

Munt, R. W. 1979. Review of emissions control technology for aircraft gas turbine engines. Emission Control Technology Division, Office of Mobile Source Air Pollution Control, Environmental Protection Agency, Ann Arbor, MI.