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# AIRCRAFT EXHAUST POLLUTION AND ITS EFFECT ON THE U.S. AIR FORCE

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August 1974

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This report presents information thought to be necessary in establishing an Air Force Policy on aircraft engine pollution. The reasons that different pollutants are emitted is discussed. Relevance of this problem to the Air Force is also investigated. Actions which may be taken to reduce pollutants are presented in terms of technology level: current, mid-term, and advanced technology. Operation, reliability and maintainability, implementation and cost impacts are evaluated for each of the technology levels. The EPA standards and possible use by the Air Force are discussed.

134

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Air Force goals, which differ from the EPA standards in method of specification, are developed. These goals will permit control technology application without influencing basic engine design parameters or performance. The cost to meet these goals is established for current AF systems.

## FOREWORD

In November of 1972, an AFAPL report (AFAPL-TR-72-102) was written to offer an evaluation of the possibility of controlling emissions from military aircraft engines. Since that time, many important developments have made that report outdated. Among these events was the publication of Environmental Protection Agency Standards (July 1973) for commercial aircraft. In addition, many Government-funded and industry-sponsored programs have generated information very helpful in assessing emissions reductions which can be reasonably attained.

This report expands upon and revises the information included in the previous report. Because of the new information now available, the present assessment indicates some necessary changes to the previously proposed goals.

In addition, the contents of this report are being submitted in response to an Air Force Air Staff request to provide information necessary in establishing a policy on this matter. As such, some information from the original AFAPL report is repeated in a manner which allows the present report to stand alone.

Finally, the authors wish to acknowledge the assistance of Lt A. Roth of ASD/ENJEA and Mr. Bruce Richter of AFLC/MMEA for their reviewing of the report.

TABLE OF CONTENTS


| SECTION | | PAGE |
|---|---|---|
| I. | INTRODUCTION | 1 |
| II. | POLLUTANT FORMATION | 6 |
| | 1. Nonafterburning Engines | 6 |
| | a. Hydrocarbons and Carbon Monoxide | 8 |
| | b. Oxides of Nitrogen | 12 |
| | c. Visible Particulates (Smoke) | 17 |
| | 2. Afterburning Turbine Engines | 18 |
| III. | MILIT^RY RELEVANCY | 23 |
| IV. | EMISSIONS CONTROL TECHNOLOGY | 29 |
| | 1. Current Technology | 29 |
| | a. Minor Combustor Redesign | 29 |
| | b. Major Combustor Redesign | 30 |
| | c. Controlled Fuel Injection | 30 |
| | d. Compressor Air Bleed | 32 |
| | e. Water Injection | 32 |
| | f. Engine Cycle Modification | 33 |
| | 2. Mid-Term Technology | 35 |
| | a. Staged Fuel Injection | 37 |
| | b. Fuel Prevaporization/Premixing | 41 |
| | c. Variable Geometry | 41 |
| | 3. Advanced Concepts | 43 |


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| SECTION | | PAGE |
|---|---|---|
| V. | CONTROL TECHNOLOGY IMPACT | 49 |
| | 1. Operational Capability | 50 |
| | a. Current Technology | 50 |
| | b. Mid-Term Technology | 51 |
| | c. Advanced Concepts | 52 |
| | 2. Reliability and Maintainability (R&M) | 53 |
| | a. Current Technology | 53 |
| | b. Mid-Term Technology | 54 |
| | c. Advanced Concepts | 56 |
| | 3. Implementation | 56 |
| | a. Current Technology | 57 |
| | b. Mid-Term Technology | 58 |
| | c. Advanced Concepts | 61 |
| | d. Discussion | 61 |
| | 4. Cost | 61 |
| | a. Current Technology | 62 |
| | b. Mid-Term Technology | 66 |
| | c. Advanced Concepts | 69 |
| | d. Discussion | 69 |
| VI. | EPA STANDARDS AND POSSIBLE USAF IMPACT | 71 |
| | 1. EPA Standards for Turbopropulsion Engines | 71 |
| | 2. Discussion | 74 |
| | 3. Other Standards | 80 |

| SECTION | | PAGE |
|---|---|---|
| | 4. USAF Compliance with EPA Standards | 81 |
| VII. | USAF EMISSIONS GOALS | 84 |
| | 1. Selection of USAF Emission Goal Paramters | 85 |
| | a. Low Power Emissions | 85 |
| | b. $NO_x$ Emission | 87 |
| | c. Smoke Emission | |
| | 2. 1979 Goals | 88 |
| | a. Combustion Efficiency | 88 |
| | b. Oxides of Nitrogen | 90 |
| | c. Smoke | 92 |
| | 3. 1981 Goals | 94 |
| | a. Combustion Efficiency | 94 |
| | b. Oxides of Nitrogen | 94 |
| | c. Smoke | 97 |
| | 4. Advanced Technology Policy | 97 |
| | 5. Comparison of AFAPL Goals and EPA Standards | 97 |
| | 6. Implementation of Proposed Goals | 100 |
| VIII. | USAF COST BREAKDOWN | 102 |
| IX. | SUMMARY AND CONCLUSIONS | 109 |
| | REFERENCES | 120 |

## LIST OF ILLUSTRATIONS


| FIGURE | | PAGE |
|---|---|---|
| 1. | Typical Non-Afterburning Turbine Engine Exhaust Emission Trends | 7 |
| 2. | Relationship Between Combustion Inefficiency and Pollutant Emissions | 10 |
| 3. | Effect of Combustor Entrance Conditions on Idle Combustion Inefficiency | 13 |
| 4. | Combustor Inlet Temperature Effect on $NO_x$ Emission; the Uncontrolled Correlation | 15 |
| 5. | $NO_x$ Emission Characteristics During Stratospheric Flight | 16 |
| 6. | Exhaust Smoke Visibility Correlation | 19 |
| 7. | F101 Carbureting Combustor Design | 31 |
| 8. | Ideal Effectiveness of Water Injection for $NO_x$ Control | 34 |
| 9. | Staged-Premix Low Emissions Combustor (NASA/P&W ECCP) | 39 |
| 10. | Radial-Axial Low Emissions Combustor (NASA/GE ECCP) | 40 |
| 11. | Premix/Vaporizing Low Emissions Combustor | 42 |
| 12. | Variable-Geometry Low Emissions Combustor | 44 |
| 13. | Implementation - Current Technology | 59 |
| 14. | Implementation - Mid-Term Technology | 60 |
| 15. | Implementation - Advanced Technology | 60 |
| 16. | Idle Emissions Goal for 1979 | 89 |
| 17. | $NO_x$ Goals for 1979 | 91 |
| 18. | Smoke Goals for 1979 | 93 |
| 19. | Combustion Efficiency Goal for 1981 | 95 |
| 20. | $NO_x$ Goals for 1981 | 96 |

LIST OF TABLES


| TABLE | | PAGE |
|---|---|---|
| 1. | Combustion Inefficiency at Idle for Several Contemporary Aircraft Gas Turbine Engines | 11 |
| 2. | Summary of Annual Airfield Emissions | 25 |
| 3. | Some Military-Commercial Engine Conversions | 28 |
| 4. | Emission Reduction Potential Using Current Technology | 36 |
| 5. | Emission Reduction Potential Using Mid-Term Technology | 45 |
| 6. | Emission Reduction Potential Using Advanced Technology | 47 |
| 7. | Exhaust Emissions Cost Summary | 63 |
| 8. | J79 and JT8D Smoke Retrofit Cost Summary | 65 |
| 9. | Exploratory Development Cost Summary | 68 |
| 10. | EPA Duty Cycle -- Time in Mode (TIM) and Power Setting (PS) | 75 |
| 11. | EPA Standards | 76 |
| 12. | EPA Standards Impact to JT3D and JT9D Engines | 79 |
| 13. | Comparison of EPA and AFAPL Emission Limitations | 99 |
| 14. | USAF Engines Affected by Proposed Goals | 103 |
| 15. | Smoke Retrofit Cost Summary | 107 |
| 16. | Overall Cost Summary | 108 |

## SECTION I

## INTRODUCTION

In recent years, increased citizen concern over environmental issues coupled with the obvious visible smoke emissions from jet aircraft has brought substantial public attention to aircraft-contributed pollution. Although smoke by itself may not be harmful, it has focused attention on jet engines as a source of additional gaseous pollutant emissions (carbon monoxide, hydrocarbons, and oxides of nitrogen). As airport traffic increased, it became evident that at least the possibility existed that these individual mass emissions, when concentrated in the local airport environment, could result in ambient levels which exceed allowable levels.

Concern within the United States culminated in the inclusion of exhaust mass emissions from aircraft engines in the considerations of the Clean Air Act Amendments of 1970. This legislation requires that the Environmental Protection Agency (EPA) assess the extent to which aircraft emissions affect air quality, determine the technological feasibility of controlling such emissions and establish aircraft emission standards, if necessary.

The resulting EPA assessment[Reference 1] has indicated the necessity to regulate aircraft emissions of carbon monoxide (CO), total hydrocarbons ($C_xH_y$), oxides of nitrogen ($NO_x$)* and visible smoke. Currently, the EPA standards apply to commercial and general

* It should be noted that $NO_x$ as used herein represents the summation of emissions NO and $NO_2$

aviation but not military aircraft. The following excerpt from EPA's discussion accompanying the final announcement of the aircraft emissions standards[Reference 2] summarizes this policy:

> In judging the need for the regulations, the Administrator has determined (1) that the public health and welfare is endangered in several air quality control regions by violation of one or more of the national ambient air quality standards for carbon monoxide, hydrocarbons, nitrogen oxides, and photochemical oxidants, and that the public welfare is likely to be endangered by smoke emissions; (2) that airports and aircraft are now, or are projected to be significant sources of emissions of carbon monoxide, hydrocarbons, and nitrogen oxides in some of the air quality control regions in which the national ambient air quality standards are being violated, as well as being significant sources of smoke; and therefore (3) that maintenance of the national ambient air quality standards and reduced impact of smoke emissions requires that aircraft and aircraft engines be subject to a program of control compatible with their significance as pollution sources. Accordingly, the Administrator has determined that emissions from aircraft and aircraft engines should be reduced to the extent practicable with present and developing technology. The standards proposed herein are not quantitatively derived from the air quality considerations . . . but, instead, reflect EPA's judgment as to what reduced emission levels are or will be practicable to achieve for turbine and piston engines.

Although carbon monoxide, hydrocarbons, oxides of nitrogen and smoke are the most often mentioned jet engine pollutants, a more detailed description of undesirable constituents could be considered: (a) total hydrocarbons can be further organized into unreactive hydrocarbons and reactive hydrocarbons, or even finer subgroups; (b) besides the considerations of visible smoke, the problem of total particulates may be addressed; (c) sulfur oxides, although not a significant problem because of the low levels present in aviation fuels, can be considered as one of the pollutants; and (d) emissions responsible for odor, although part of the total hydrocarbon class, could be addressed as a separate entity. The present scope of understanding, however, does not allow the more detailed problems associated with each of these categories to be discussed here. Consequently, the four principal pollutant categories mentioned above (CO, $C_xH_y$, $NO_x$ and Smoke) are employed as the main format for discussion of pollutants in this report. Occasional reference, however, is made to the various more detailed aspects of the problem.

Current EPA regulations[Reference 2] are based on reducing aircraft engine emissions during their operation below 3000 feet. However, an additional environmental problem has been associated with aircraft--the potential problem of high altitude emissions. There are many mechanisms by which this might arise: (1) emission of water vapor and carbon dioxide into the stratosphere may cause a "greenhouse effect", (2) hydrocarbons might react with nitrogen oxides both emitted into and naturally present in the stratosphere to form a smog-type condition at high altitude and (3) increased concentrations of water vapor and $NO_x$ due to emissions into the stratosphere might deplete the ozone layer and allow increased penetration of solar ultraviolet radiation. Much more investigation is needed, however, before these potential stratospheric problems can be suitably defined.

In response to the concerns described above, a number of Government agencies have begun efforts to better assess the problem and to develop measurement techniques as well as control technology. An idea of the magnitude of the effort can be gained by examining the approximate FY74 expenditures of the various participating agencies. These are: NASA, $5.5 million; Department of Transportation, $5.7 million; Air Force, $1.5 million; Federal Aviation Administration, $1.1 million; Navy, $0.7 million; Environmental Protection Agency, $0.5 million; Army, $0.15 million. Total yearly expenditure is about $15 million. Further significant support is recognized under industry and IR&D programs*, but cannot be accurately tabulated.

The purpose of this report is to provide the necessary background information on aircraft exhaust emissions as related to military systems so that a reasonable Air Force policy may be established on this matter. This report expands upon and revises the information previously included in Reference 3. Significant developments and additional information in this field warrant the writing of a new report. In addition, two other thorough assessments are available and have been considered in this report. NASA has recently undertaken a study oriented towards the capability of reducing high-altitude commercial aircraft emissions.[Reference 4] The present report, which has the principal intent of minimizing ground-level emissions, draws conclusions which agree well with the NASA findings. The other thorough evaluation of emission control technology is Reference 5. This NREC report, however, does not consider the all important development of the last three years.

Main sections of this report address the following major questions: (a) factors influencing pollutant formation; (b) relevance of the

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* Independent Research and Development programs where efforts are sponsored jointly by industry and Government.

problem to the military; (c) control technology; (d) impact on operational capability, reliability and maintainability, implementation, and cost; (e) EPA standards and possible use by the USAF; (f) USAF emission goals; and (g) USAF cost breakdown.

## SECTION II

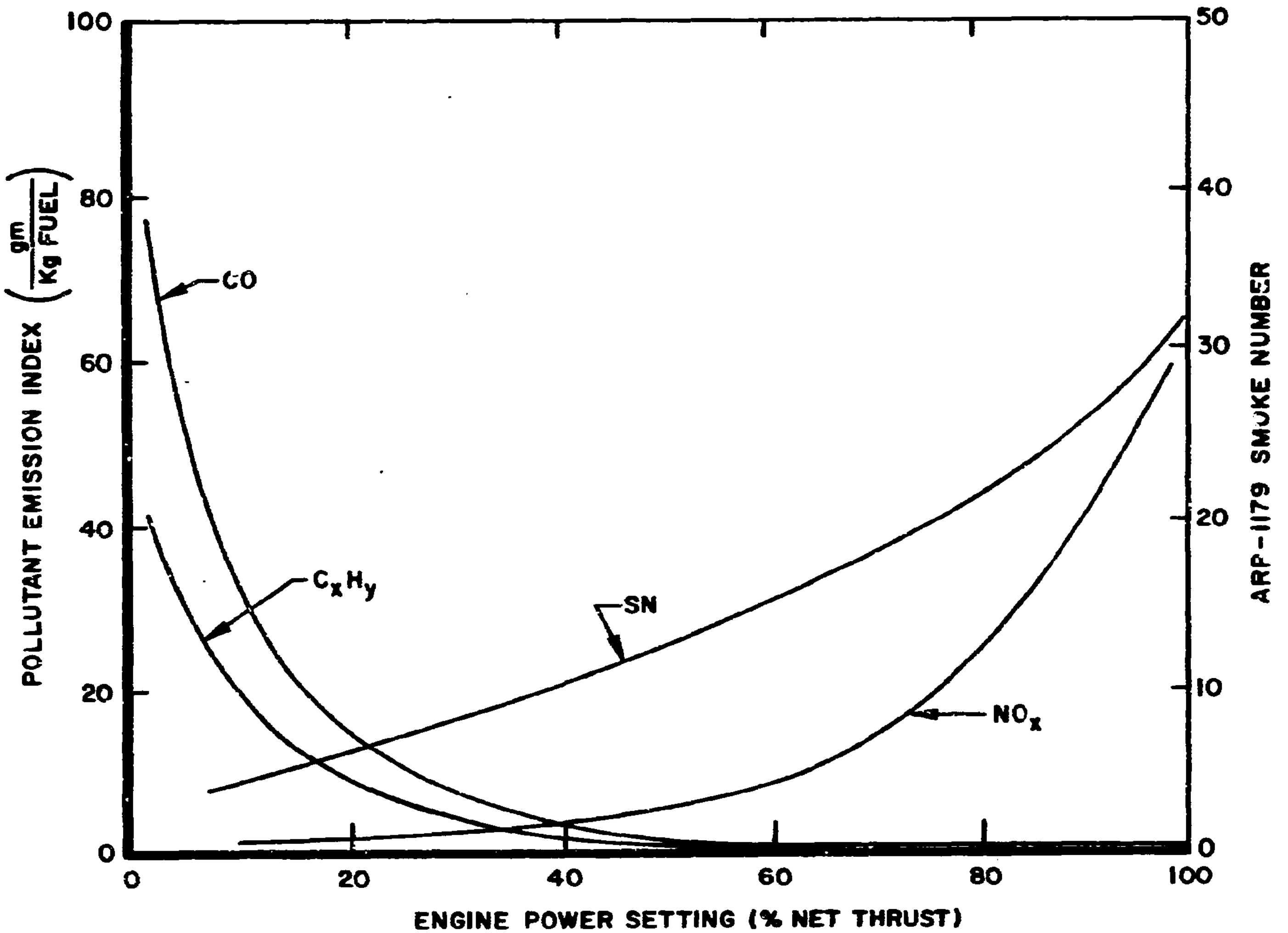
## POLLUTANT FORMATION

To better understand the ways in which aircraft engines produce harmful emisisons, the following subsections discussing the fundamental chemical and thermodynamic processes have been included. Separate consideration of main engine types of interest (nonafterburning and afterburning turbines) are given below. It is later concluded that Air Force goals for piston engines are not appropriate. Consequently, pollutant formation characteristics from this engine class are not considered herein.

### 1. Nonafterburning Turbine Engines

The nonafterburning turbine engine has received by far the most attention in characterization of emissions. The nonafterburning turbine class includes turbojets, turboshafts, and turbofans. Pollutant formation characteristics of all of these engines are similar due to the fact that each type uses the same basic core--a compressor, a combustor and a turbine.

There have been many attempts to correlate and explain emission trends for these engines. Basically, it is well known that emissions of CO and $C_xH_y$ are a significant problem at idle power conditions while smoke and $NO_x$ emissions tend to be a greater problem at the higher power settings. These trends are illustrated in Figure 1. Sulfur content of the fuel is low (usually less than 0.05% by weight) and, therefore, $SO_x$ emission is not considered to be a serious problem.




**<u>Figure 1:</u>** Typical Non-Afterburning Turbine Engine Emission Trends

Emitted particulates are composed largely of carbon; the principal problem is one of defining, for specification purposes, that point at which the carbonaceous particulates become visible.

Since the majority of the present and future U. S. Air Force (USAF) aircraft fleet will be powered by turbine engines, the impact and means of pollutant control for these engines must be considered. As a basis for later consideration of control techniques, the following discussion addresses the means by which each of the general pollutants from gas turbine engines is generated.

a. <u>Hydrocarbons and Carbon Monoxide</u>

Aircraft turbine engine combustors are designed for peak efficiency at cruise and higher power settings. Combustor conditions during idle and taxi operations are appreciably different from the cruise setting and, consequently, the engine operates inefficiently at these points. The major effect of inefficient operation is the emission of species which represent unused chemical energy--CO and $C_xH_y$. A relationship between combustion inefficiency and emission of these two pollutants is given by the following equation:

$$1 - \eta_b = \frac{(EI)_{CO}\,(Q_L)_{CO} + (EI)_{C_xH_y}\,(Q_L)_{C_xH_y}}{(Q_L)_{fuel} \times 10^3} \quad (1)$$

Where: $\eta_b$ = combustion efficiency of main burner

$1 - \eta_b$ = inefficiency of main burner

$(EI)_i$ = emission index in lb/1000 lb fuel or gm/Kg fuel for exhaust constituent i

$(Q_L)_i$ = constant pressure lower heating value for exhaust constituent i (BTU/$lb_m$ or cal/gm). Although chemical energies should be used in the above equation, the error incurred in using $Q_L$ values is only slight

The value of $Q_L$ for carbon monoxide is known to be 4343 BTU/$lb_m$ (2410 cal/gm), and that for JP-4 is 18,700 BTU/$lb_m$ (10,000 cal/gm). However, the composition of $C_xH_y$ emitted from an aircraft gas turbine engine is not known and, consequently, its value of $Q_L$ is unknown. Measurement of hydrocarbons is usually made with a flame ionization detector which actually senses total carbon atoms, and the reduced data are represented as grams of hydrocarbons per kilogram of fuel. Most hydrocarbons have $Q_L$ values between 8,900 and 11,600 cal/gm, but those that would be emitted from the engine (as unburned fuel or as other organic species) would generally have a hydrogen-carbon ratio similar to that of the original fuel. Consequently, the value of $Q_L$ for Equation 1 has been taken as the same as for JP-4.

By inserting the $Q_L$ values into Equation 1, the following relationship is obtained:

$$1 - \eta_b = [0.232 \, (EI)_{CO} + (EI)_{C_xH_y}] \, 10^{-3} \qquad (2)$$

This relation is graphically shown in Figure 2. This equation has been used to reduce some engine emission data to combustion inefficiency values for various engines, the results of which are given in Table 1.

Engine emission data at idle power conditions have been extracted from many sources, the majority taken from the EPA survey of engine emission factors.[Reference 6]

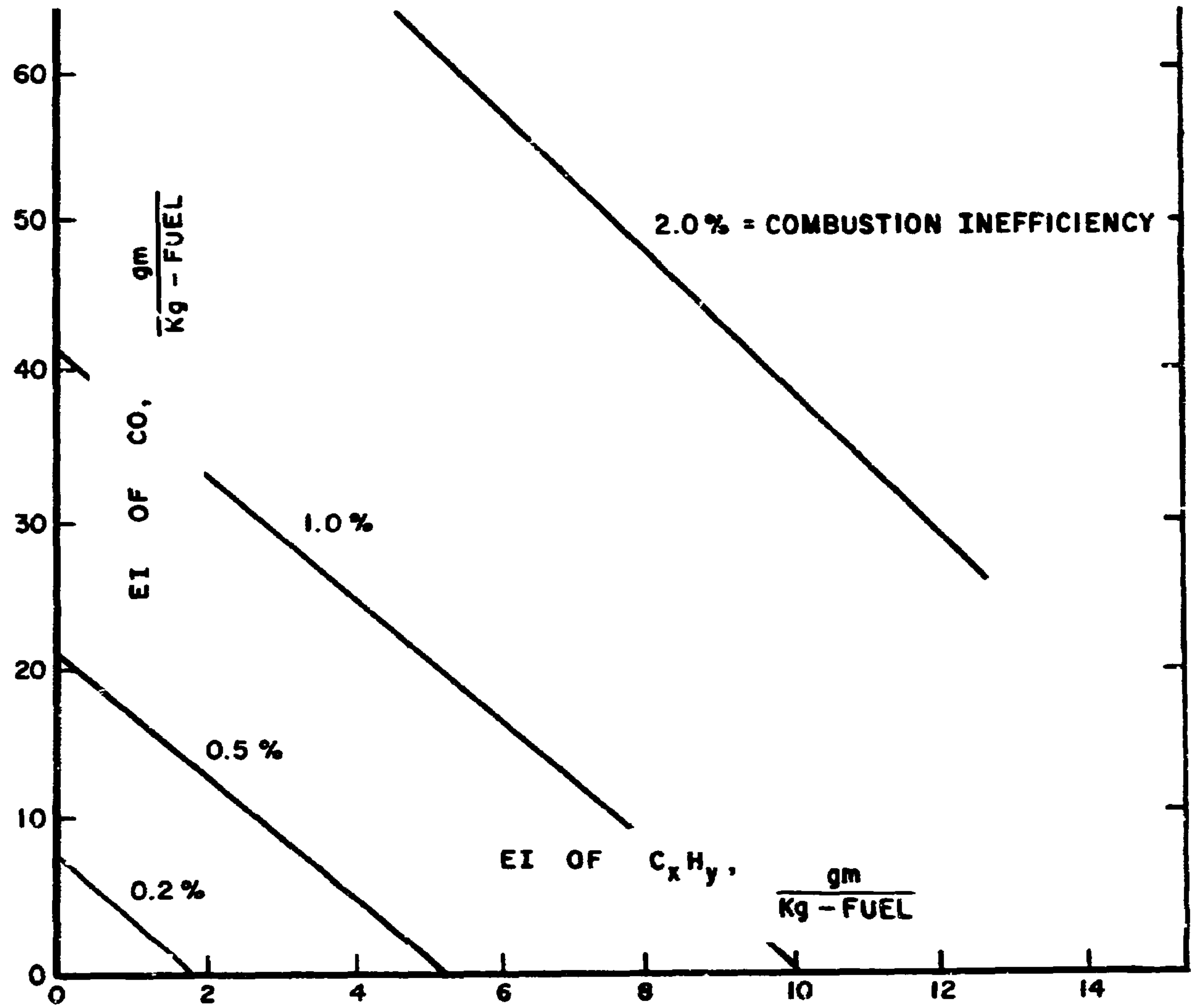



Figure 2: Relationship Between Combustion Inefficiency and Pollutant Emissions

## TABLE 1

### COMBUSTION INEFFICIENCY VALUES AT IDLE FOR SEVERAL CONTEMPORARY AIRCRAFT GAS TURBINE ENGINES

| | Engine Type* | Idle Pressure-Ratio | Idle Combustion Inefficiency, % |
|---|---|---|---|
| MILITARY SYSTEMS | | | |
| J85 | TJ | 1.49 | 7.7 |
| J79 | TJ | 2.55 | 3.3 |
| J57 | TJ | 2.60 | 5.5 |
| J52 | TJ | 2.80 | 4.2 |
| T63 | TS | 3.03 | 3.7 |
| TF39 | TF | 3.05 | [illegible] |
| T56 | TP | 3.50 | 1.9 |
| TF30 | TF | 3.56 | 3.3 |
| COMMERCIAL SYSTEMS | | | |
| JT3D | TF | 1.95 | 14.4 |
| CJ805 | TJ | 2.14 | 4.2 |
| JT3C | TJ | 2.60 | 9.7 |
| JT8D | TF | 2.66 | 2.0 |
| CF6 | TF | 3.38 | 3.3 |
| JT9D | TF | 3.43 | 2.9 |

* TJ-Turbojet; TF-Turbofan; TP-Turboprop; TS-Turboshaft

Expressed as combustion inefficieny, these data can be related to engine pressure ratio and/or combustor entrance temperature at idle as shown in Figure 3. A reasonable correlation is obtained indicating that higher inlet temperatures and pressures at idle result in improved combustion efficiency. Consequently, it is important to note that larger high pressure ratio engines are less prone to low power emissions problems than those of the low pressure ratio design.

Variation in hydrocarbon specie participation in smog-forming reactions is very significant and, therefore, specification of total hydrocarbons is not fully acceptable. The true environmental impact is dependent on the types as well as the total amount of hydrocarbons emitted. Only limited detailed studies of aircraft hydrocarbon emissions have been performed to date. Some experimental work has begun in a cooperative effort between the AFAPL, the Aerospace Research Laboratory, and the Air Force School of Aerospace Medicine. In this investigation, hydrocarbon emissions from a combustor rig are cryogenically trapped, grab sampled, or absorbed into a suitable material for subsequent gas chromatographic analysis. Based on these results, the effects of combustor operating conditions and fuel type are being assessed.

b. Oxides of Nitrogen

Although highest at full power, the emissions of $NO_x$ in the exhausts of aircraft turbine engines predominate during takeoff, climbout, and landing approach. The problem stems from the molecular oxygen and nitrogen in air being exposed to the extremely high

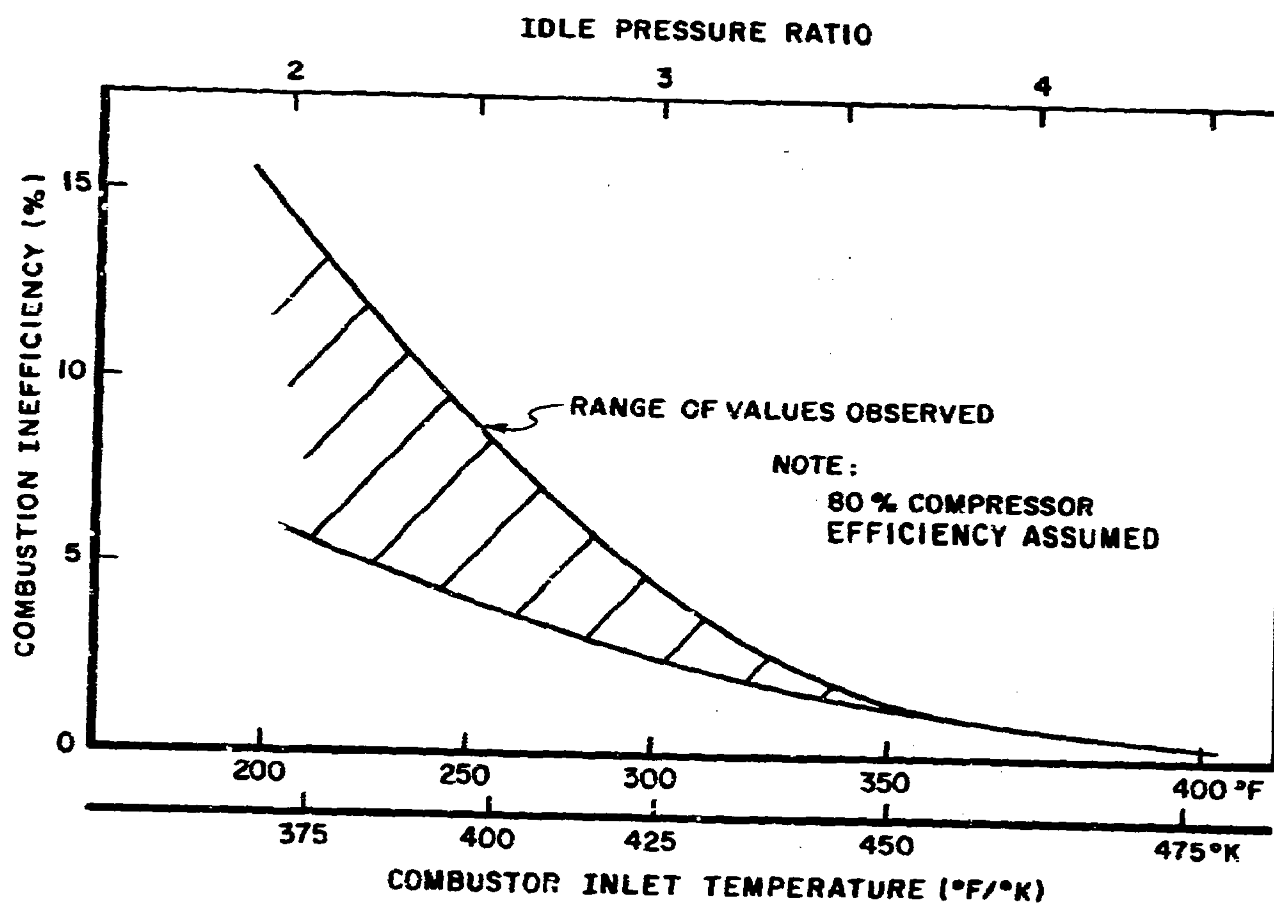



Figure 3: Effect of Combustor Entrance Conditions on Idle Combustion Efficiency

temperatures of the combustor primary zone where, for stability considerations, fuel-air mixtures have been designed to be approximately stoichiometric.

A reported correlation of data from many engines has shown that $NO_x$ emission is strongly related to the combustor inlet temperature.[Reference 7] A subsequent analysis of the $NO_x$ formation process has been used to explain this correlation and provides the basis for extrapolation to combustor conditions beyond those of present systems.[Reference 8] Both the correlation and the subsequent analysis are based on data from engines which nave no specific design modifications intended to control the formation of $NO_x$. Consequently, Figure 4 is referred to herein as the "uncontrolled engine correlation." It is further apparent that economic considerations for stratospheric flight require engine cycles with a high combustor inlet temperature and this leads to increased stratospheric ingestion of $NO_x$. The relationship between the important parameters for stratospheric flight (Mach number and engine pressure ratio) and $NO_x$ emission is shown in Figure 5.

An extremely important aspect of this correlation is that the emission characteristics are expressed as grams of pollutant per kilogram of fuel--the Emission Index (EI). In non-afterburning engines, considerations such as specific fuel consumption and total thrust depend on the engine type and cycle parameter, but the emission index of $NO_x$ is dependent only on the conditions of combustion. The successful correlation of Figure 4 confirms that EI versus combustor

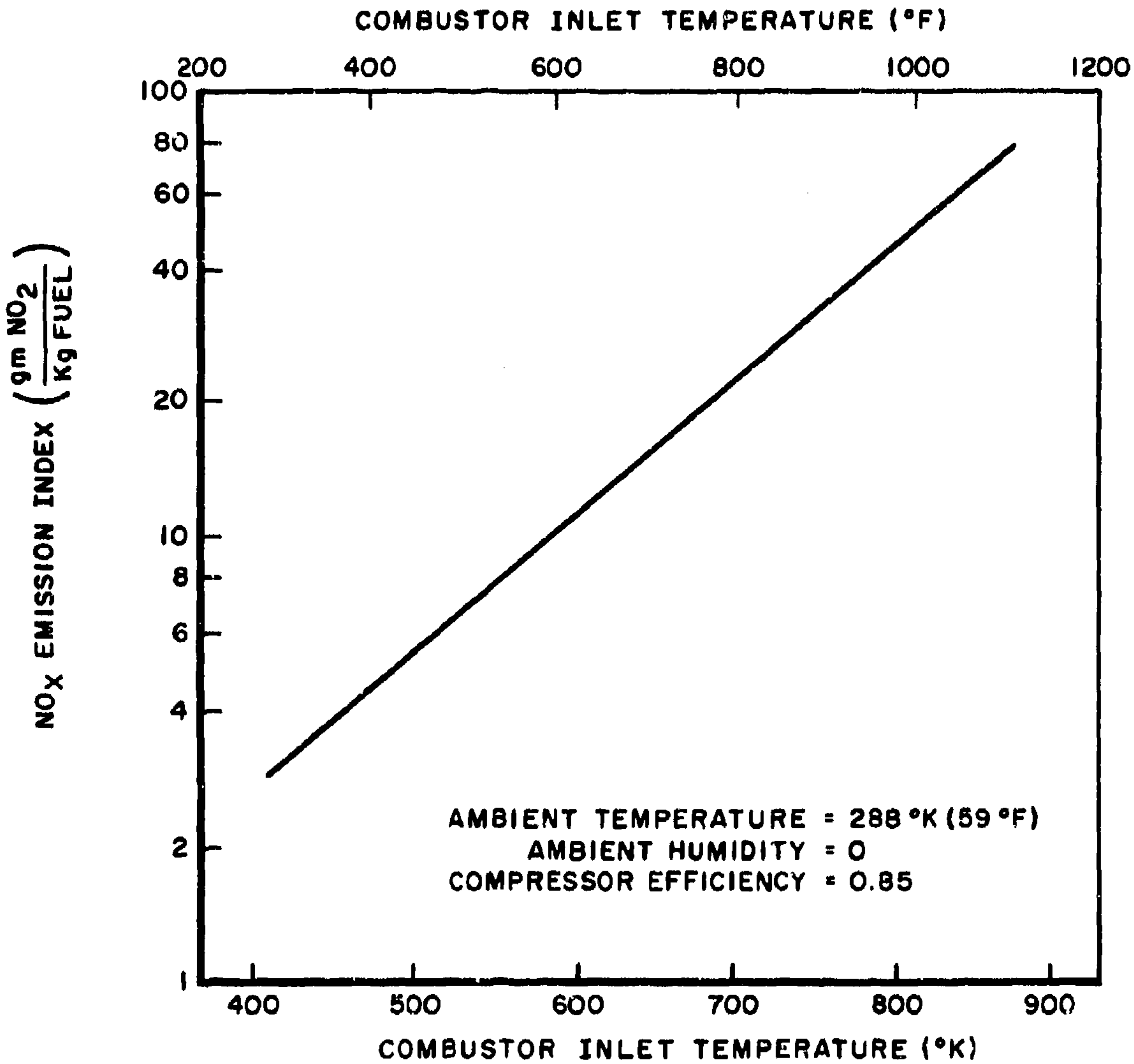



Figure 4: Combustor Inlet Temperature Effect on $NO_x$ Emission; the Uncontrolled Correlation[Reference 8]

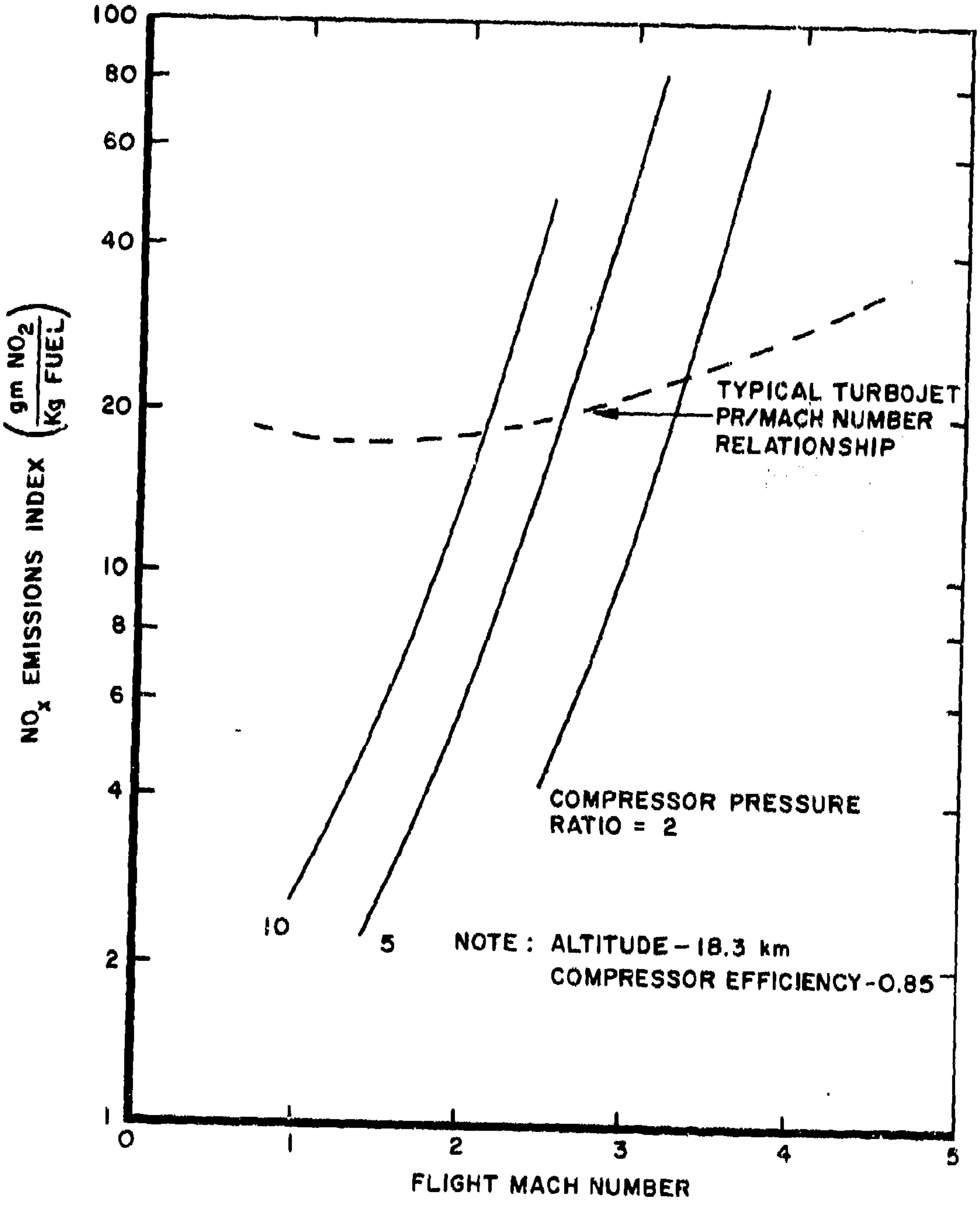



Figure 5: $NO_x$ Emission Characteristics During Stratospheric Flight[Reference 8]

inlet temperature is the proper means to characterize $NO_x$ emission. Further, this strongly suggests that $NO_x$ control techniques should be judged on the basis of reductions from uncontrolled emission levels expressed as grams per kilogram of fuel. Outright comparison with a single emission index value is not appropriate.

c. Visible Particulates (Smoke)

Visible smoke emitted from aircraft turbine engines is principally composed of carbon. It is generated in systems which operate unusually fuel-rich in local zones of the combustor. It has been established that the presence of exhaust smoke has little effect on the overall operation and performance of the engine system--any combustion inefficiency associated with this emission is negligible. Nevertheless, the aesthetic nuisance and tactical vulnerability arising from smoke emissions require that the problem be eliminated.

Efforts to abate visible smoke from aircraft gas turbine engines date back nearly a decade. The engineering know-how to design smokeless combustors for new engines without sacrificing any desirable engine characteristics is now in hand. The purpose of this brief section is to describe the background upon which smoke emissions may be quantified.

An important factor in smoke visibility is the relative position of the observer to the exhaust plume--the worst possible case is observation of the exhaust plume just slightly skewed from the centerline of the engine. Although attempts have been made to account for plume dispersion and turbulent mixing behind the aircraft,[Reference 9] the quantitative relationship between visibility from this position and a smoke measurement remains a very complicated, unsolved task. The Air Force Aero Propulsion Laboratory (AFAPL) has awarded a contract [Reference 10] to develop a method for predicting plume visibility from exhaust plane smoke concentration data using an analytical plume dispersion model.

Investigation of the perpendicularly-viewed case has yielded some useful quantitative information. Analytical correlation of exhaust plume visibility as viewed perpendicularly and smoke number as measured by the techniques described in Reference 11 was performed by Champagne.[Reference 12] This important relationship between smoke number and path length for noticeable visible light attenuation is graphically shown in Figure 6. A reasonable agreement between data and theory is apparent and the lower boundary of Figure 6 is presently being used to specify smoke number requirements for future USAF engine procurements.[Reference 13]

Very little has been done regarding an assessment of total particulate environmental impact and, as previously mentioned, this is considered to be a problem which eventually may be regulated. Efforts under the direction of the Coordinating Research Council have indicated serious problems with measurement and interpretation of data.[Reference 14] EPA is currently sponsoring a program to define improved measurement techniques.[Reference 15]

2. <u>Afterburning Turbine Engines</u>

The afterburning turbine engine differs from the non-afterburning

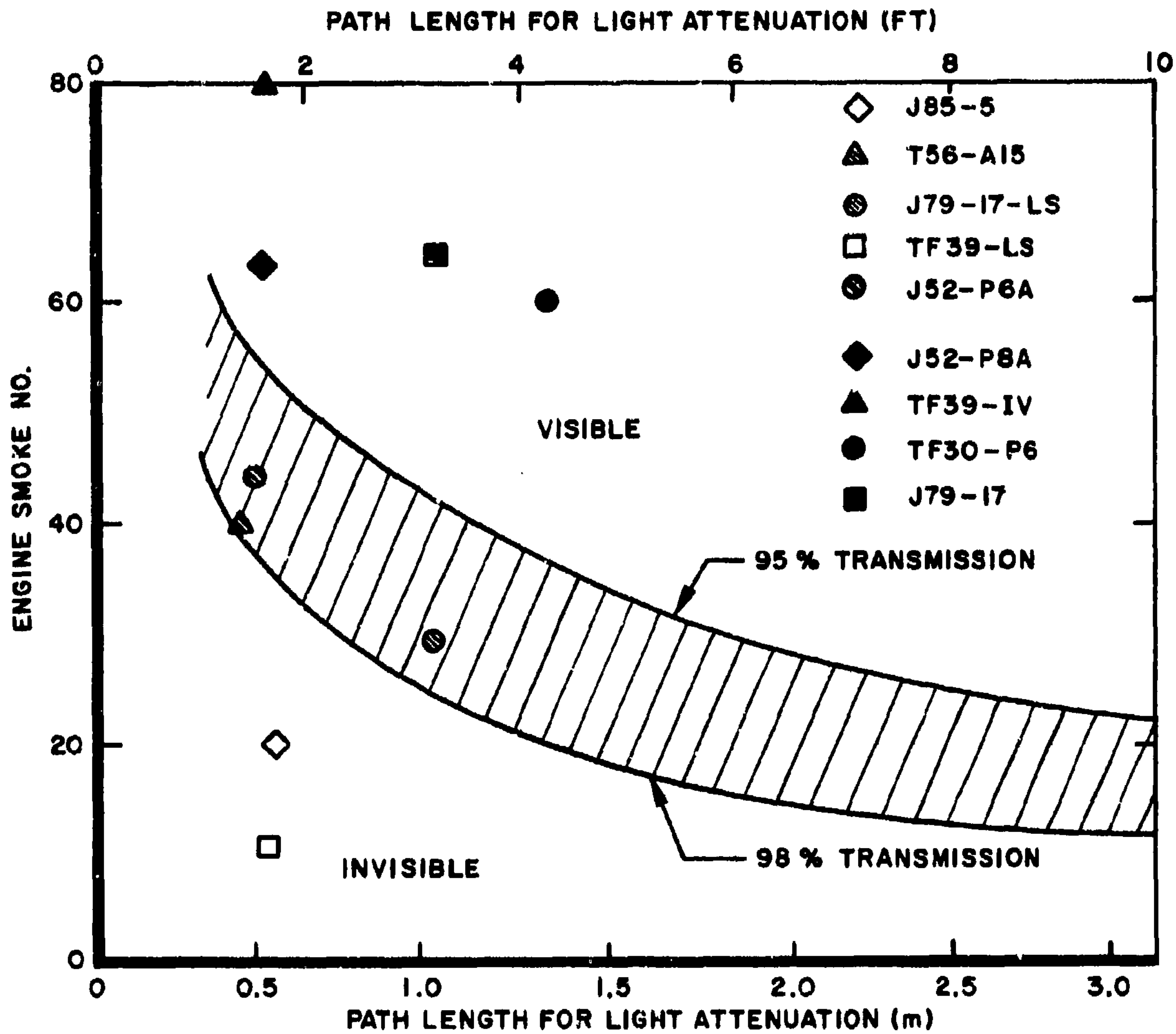



Figure 6: Exhaust Smoke Visibility Correlation [Reference 12]

(Shaded data points indicate engine smoke observed; clear points indicate no smoke observed; partially shaded points indicate faint smoke trail observed.)

type only by the addition of a secondary burning device to provide additional thrust during critical points of an aircraft mission. Thrust augmentation by afterburning involves combustion of fuel injected into the exhaust gases exiting the turbine section of the engine. The temperature rise in the afterburner which is normally used during takeoff and climbout, accents the potential seriousness of emissions in this mode--as stated earlier, only emissions below 3000 feet are considered in present EPA aircraft emissions standards. [Reference 1]

Very little information is presently available for pollutant emissions from afterburning engines; however, general trends in available data[References 16 - 20] indicate possible significant emissions of CO and $C_xH_y$, especially at the lower afterburner power settings. On the other hand, $NO_x$ emissions during afterburner operation, when expressed on an EI basis, appear to be lower than during non-afterburning high-power operation. These results, however, are presently described only as trends because truly quantitative data are difficult to obtain. Combustion product gases at the exhaust plan are extremely reactive and at high temperature; consequently, much of the CO and $C_xH_y$ present at the exhaust plane is reacted to $CO_2$ and $H_2O$ further downstream. Accurate measurement of these afterburner emissions involves determination after the reactions have been completed; i.e., placement of sampling probes downstream of the exhaust plane is necessary. Presently, no well-defined method exists to do this.

In April of 1973, the AFAPL began a program with the General Electric Company to develop a measurement technique for afterburning turbine engines.[Reference 21] This effort is sponsored by the Air Force Control of Noxious Effluents Program (CONE) administered through the Air Force Weapons Laboratory, Kirtland AFB, New Mexico. The reactive afterburner plume is being analytically modeled and exhaust plume survey tests on J85, J79 and F101 engines are being conducted. A procedure for sea level static emission measurement will be established. It will involve either downstream measurement or exhaust-plane emissions determination with subseuqent use of the analytical model to predict final emission levels. The analytical model will also allow test cell exhaust plane data to be used for the evaluation of final exhaust pollutant levels.

The fact that reactions in the plume are important indicates that the conditions of the ambient air could also significantly influence the resulting emissions. Cooler ambient temperatures would tend to cool the plume more quickly and thus quench the plume reactions which are responsible for converting CO and $C_xH_y$ to $CO_2$ and $H_2O$. Further the ambient pressure could also be expected to influence emission via an effect on the rate of chemical reaction and data obtained at sea level are not applicable to altitude operation where both pressure and temperature differences may significantly affect the extent of plume reaction.

Considering the problems cited above, it is not possible at this time to assess the emissions characteristics of or to specify emissions limitations for afterburning engines. Consequently, this should be an area of concerted research over the next several years.

## SECTION III

## MILITARY RELEVANCY

Current EPA aircraft emission standards apply to civil aircraft only. As previously discussed, the need for these regulations was documented by ambient air studies at commercial airfields. No conclusive air quality assessments of Air Force Bases are available. An urgent need to control Air Force aircraft emissions has not yet been established as no evidence of Air Base air quality violations has been uncovered. However, Air Force Weapons Laboratory efforts to quantify the affects of air base operations should be emphasized. Military relevancy considerations beyond the question of basic air quality violations are addressed below and introduce additional complexities requiring consideration.

It is recommended that the legal requirements, or lack thereof, for military aircraft be formally established. It should be noted that the present EPA policy of not requiring military aircraft compliance has been strongly influenced by continued military activity in the environmental area. Furthermore, a leadership role is expected of U.S. Federal Agencies in protecting the environment[References 22, 23] and appropriate Air Force response in reducing the input of aircraft operations is required.

Some general idea of the extent of military operation is available. Worldwide military aircraft operations are responsible for approximately half of all aviation fuels consumed by U.S. users.[Reference 24]

Within the continental U.S., the Air Force consumes approximately 30% of all jet fuel, making the Air Force by far the world's largest airline. This, however, is not a valid indication of the military contribution to the environmental problem. In general, military air bases are much more widely dispersed than commercial airports where air quality violations have been observed. Furthermore, the traffic patterns at most military air bases are much less active than those at commercial airports such as Los Angeles International, Kennedy and Washington National.

On other hand, some military bases may present a more significant problem than the typical commercial installation. A more specific examination of several individual air bases has been provided by the Air Force Weapons Laboratory. Table 2 compares the annual airfield emissions of Williams AFB, Luke AFB, and Wright-Patterson AFB to the most active commercial airfields--O'Hare, Van Nuys, JFK and Washington National. A medium-sized airfield, Dayton, has also been included. The table illustrates that some bases are very active and do have fairly high levels of annual emissions. In contrast to the military case, commercial traffic consists of several aircraft types emitting varying degrees of exhaust pollutants. Consequently, should an Air Force base's operations constitute predominately one aircraft type having a consistently high level of exhaust pollution, the local environmental impact of that particular base could be substantial. This, in fact, appears to be the case for Williams AFB--predominately afterburning T-38 aircraft operations. [24]

TABLE 2

SUMMARY OF ANNUAL AIRFIELD EMISSIONS [25]

| | | TONS/YEAR | | | |
|---|---|---|---|---|---|
| | CYCLES/YEAR* | CO | $C_xH_y$ | $NO_x$ | $SO_x$ |
| O'Hare [1] | 339,900 | 14,740 | 7,580 | 3760 | 562 |
| Van Nuys[1] | 281,600 | 1,650 | 100 | 12 | .033 |
| LAX[1] | 272,000 | 16,030 | 12,570 | 3060 | 431 |
| Williams AFB (ATC Base) | 250,448 | 7,828 | 1,851 | 483 | 41 |
| JFK[1] | 219,200 | 12,590 | 9,490 | 2580 | 418 |
| Washington National[1] | 166,700 | 2,410 | 610 | 820 | 105 |
| Luke AFB (TAC Base) | 84,220 | 2,916 | 355 | 413 | 29 |
| W-PAFB (SAC Base + Significant Transient Activity) | 47,739 | 1,426 | 536 | 425 | 23 |
| Dayton[2] | 34,138 | 2,370 | 394 | 1090 | -- |

* Includes Touch-and-Go Operations

[1] From Reference 2

[2] From Reference 26

Data from Table 2 should be used with caution. Serious air pollution problems occur with relative infrequency. Consequently, the maximum hourly or daily emissions levels would be of more direct use in the discussion above.

In consideration of USAF aircraft operations, it must also be recognized that some pollution problems are particularly unique to the military. For example, the U.S. Armed Services presently account for nearly all afterburning engines within the U.S., and operate most helicopters. Air Force aircraft ground operations are often considerably different from commercial activities. In some cases, long ground operation times are necessary due to extensive system checks and equipment warmup. Furthermore, military training often requires a significant number of touch-and-go operations which also impact the local air base environment.[Reference 27]

Other unique military aircraft considerations are:

(a) Unknown emission levels and lack of control techniques, if required, for afterburning turbine engines.

(b) High performance aircraft of the future will require engines operating at overall combustor fuel-air ratios approaching stoichiometric--a factor which will make emission control of $NO_x$ more difficult.

(c) Supersonic cruise aircraft missions require low pressure ratio engine cycles with consequent high idle CO and $C_xH_y$ emission levels.

(d) Some military aircraft operations occur within the stratosphere.

Emission from the presently anticipated SST aircraft fleet, however, is expected to be many orders of magnitude more significant; a specific study has been performed for the case of the B-1 aircraft.[Reference 28] The total impact of anticipated commercial operations is currently under study as part of the Climatic Impact Assessment Program sponsored by the Department of Transportation.

(e) Not all emission control techniques will be applicable to military engines because of inherent weight and volume penalties. This may be particularly true of the high performance combat aircraft.

(f) Multi-mission capability of many military systems complicates application of control technology as well as method of emission limit specification.

It is evident that the needs, requirements, and operational use of military aircraft are entirely different from those of the commercial fleet, Nevertheless, as in the past, the military's role in future commercial aviation developments will be significant. The present extent of military/commercial engine conversion is illustrated in Table 3. As one will note, these conversions have been extensive; hence, the omission of appropriate emissions control technology from military systems could result in substantial engine design differences, increased costs and perhaps very limited/commercial technology transition potential in the future.

TABLE 3

SOME MILITARY-COMMERCIAL ENGINE CONVERSIONS

| Military Engine Designation | Commercial Engine Designation | Engine Manufacturer | Commercial Aircraft Application |
|---|---|---|---|
| J57 | JT3C | Pratt & Whitney Aircraft | Boeing 707, 720<br>Douglas DC-8 |
| TF33 | JT3D | Pratt & Whitney Aircraft | Boeing 707, 720<br>Douglas DC-8 |
| J75 | JT4 | Pratt & Whitney Aircraft | Boeing 707<br>Douglas DC-8 |
| J52 | JT8D* | Pratt & Whitney Aircraft | Boeing 727, 737<br>Douglas DC-9 |
| J60 | JT12A | Pratt & Whitney Aircraft | North American Sabreliner<br>Lockheed Jetstar |
| J79 | CJ805 | General Electric Company | Convair 880, 990<br>Lear Jet |
| J85 | CJ610 | General Electric Company | Douglas DC-10 |
| TF39 | CF6 | General Electric Company | A300 Airbus |
| T56 | [illegible] | Detroit Diesel Allison | Lockheed Electra<br>Convair Turboprop Conversions |

*Basic J52 core plus fan

## SECTION IV

## EMISSIONS CONTROL TECHNOLOGY

As stated in the previous section, the main emphasis in aircraft engine pollution reduction has centered around turbine engine main combustors. This section will survey proposed methods of control for the main burner only. It is now clear that techniques can be organized into a number of groups depending on the time required before implementation. The discussion below is organized into subsections concerning current technology, mid-term technology, and advanced concepts.

### 1. Current Technology

Many control techniques have been developed to the point where they may now be applied to new engine designs or used in existing system combustor redesigns. Application to specific engine combustors can result in production of low emissions engines in 1979. These techniques are discussed below.

#### a. Minor Combustor Redesign

This consists of a minor modification to the combustor liner hole patterns and/or fuel nozzles not involving a change in the basic design concept. Design changes such as these will affect, but may not substantially decrease, the four principal exhaust pollutants (CO, $C_xH_y$, $NO_x$, and smoke). It is expected that emissions affected predominantly by small deviations in primary and secondary zone fuel-air ratios (smoke and idle efficiency) will be the only pollutants affected. Two such redesign programs have been conducted--the smoke retrofit development programs for the J79 and the JT8D engines. A statistical analysis of resulting emissions data show that the smoke reduction modifications have substantially reduced idle CO and $C_xH_y$ levels while $NO_x$ emissions remained nearly constant.[References 29, 30]

b. Major Combustor Redesign

These techniques consist of major design changes to the combustor liners and/or fuel system perhaps introducing an improved fuel injection concept, i.e., airblast atomizers. A major combustor liner change could entail conversion from a can-annular to an annular configuration, thus changing many combustor operating characteristics--fuel vaporization, fuel distribution, turbulence levels, reference velocities, and residence times. All emissions can be affected by such a change because combustor temperature, specie concentration and residence time patterns under all operational modes can be optimized. The F101 engine combustor shown in Figure 7 is an example wherein fuel is "carburated" with an airblast technique and all emissions are reduced.[Reference 31] The most difficult emission to reduce is $NO_x$; 25% reductions from the uncontrolled values can be expected.

c. Controlled Fuel Injection

This consists of modification to the fuel supply system to allow a fraction of the fuel nozzles to be shut-off during low-power or idle operation. A localized fuel-flow increase to the operating nozzles permits a higher local fuel-air ratio in the combustion regi resulting in more efficient combustion with attendant lower CO and $C_xH_y$ levels. It has been found, however, that fuel injection to alternate

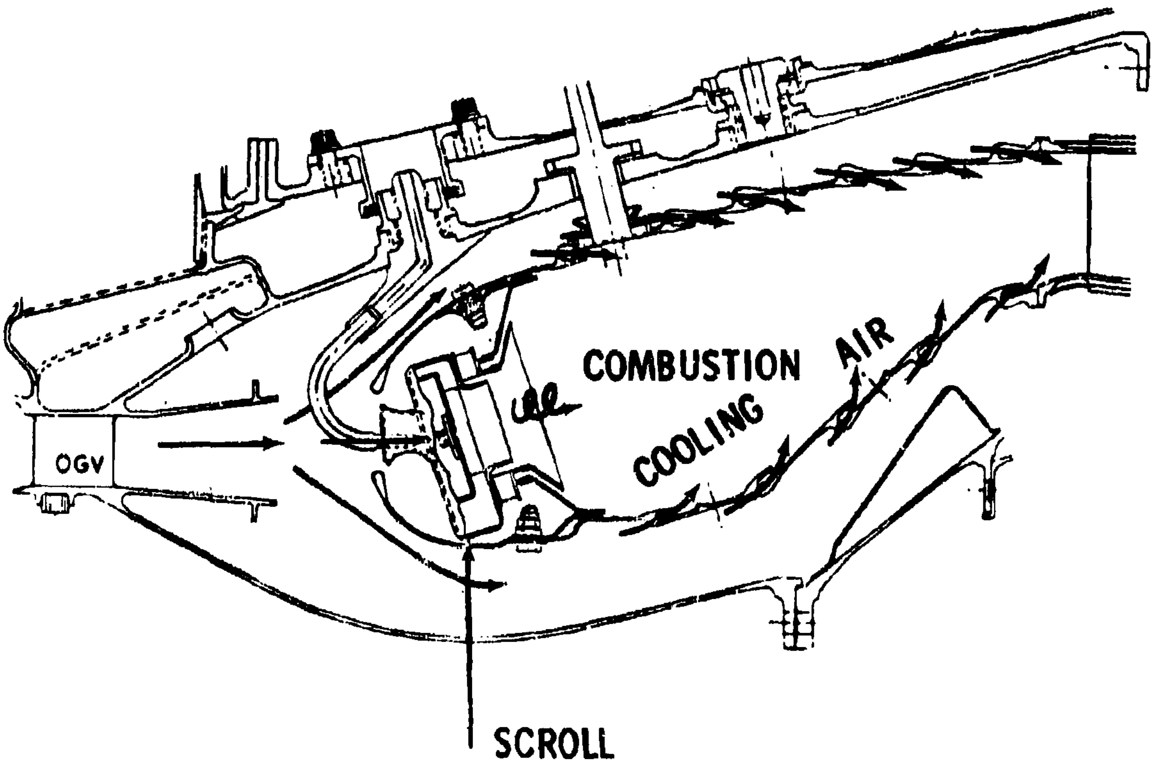



Figure 7: F101 Carbureting Combustor Design[Reference 31]

nozzles does not reduce, and many even increase, emissions.[Reference 32] However, operating with alternate quadrants (sector burning) of the combustion system has been found to significantly reduce emissions. Because of the low idle fuel-air ratios of most engines, even a doubling of the local fuel flows does not cause turbine inlet temperature problems.

d. Compressor Air Bleed

Another method of increasing idle fuel-air ratios involves decreasing combustor air flow while maintaining constant or slightly increased fuel flow. This can be accomplished by increasing compressor bleed air flow. Substantial CO and $C_xH_y$ reductions have been shown[References 33, 34], even when no significant engine modification was necessary to provide for the increased bleed. An additional advantage of this technique is that engine speed may be increased (with no increase in idle thrust) to give higher values of combustion inlet temperature which will also help to reduce CO and $C_xH_y$ emissions. In some cases, however, provisions for increased diameter bleed pipes, better control systems, and increased overboard dump capability will be necessary. A combination of fuel injection control and compressor bleed extraction provides an excellent means of idle emissions reduction with minor engine modification.

e. Water Injection

This entails introducing water to the primary zone where NO formation occurs and, hence, is principally a controlling technique for $NO_x$. Because of increased combustion product specific heat and the water vaporization effect, local flame temperature and, hence NO formation rate decreases. The effect of water on $NO_x$ emission control is predictable and well documented (see Figure 8). The technique would only be used during takeoff and climbout modes of operation. Nevertheless, because required water flow rates would be approximately equal to that of the fuel, substantial quantities of water would be required. The water must be demineralized to prevent deposition in the engine hot section. Moreover, water injection techniques must be carefully designed to insure against severe combustor and turbine thermal stresses which would arise from poor water distribution. Previous experiences with water injection for thrust augmentation indicated increased smoke emission. This is not the case for primary zone injection which involves smaller water flow rates and minimal reductions of secondary zone smoke consumption reaction rates.

f. Engine Cycle Modification

The strong dependence of idle emission on combustor inlet temperature also leads to examination of engine idle cycle changes for newly designed engines. Possible approaches are:

1. The intentional design of a compressor to be inefficient at idle resulting in higher combustor fuel-air ratios to meet increased turbine work requirements and higher combustor inlet temperatures.

2. Offset in compressor variable blade positioning to cause poor compressor efficiency in an existing engine design. These techniques would be especially applicable to lower pressure ratio engines

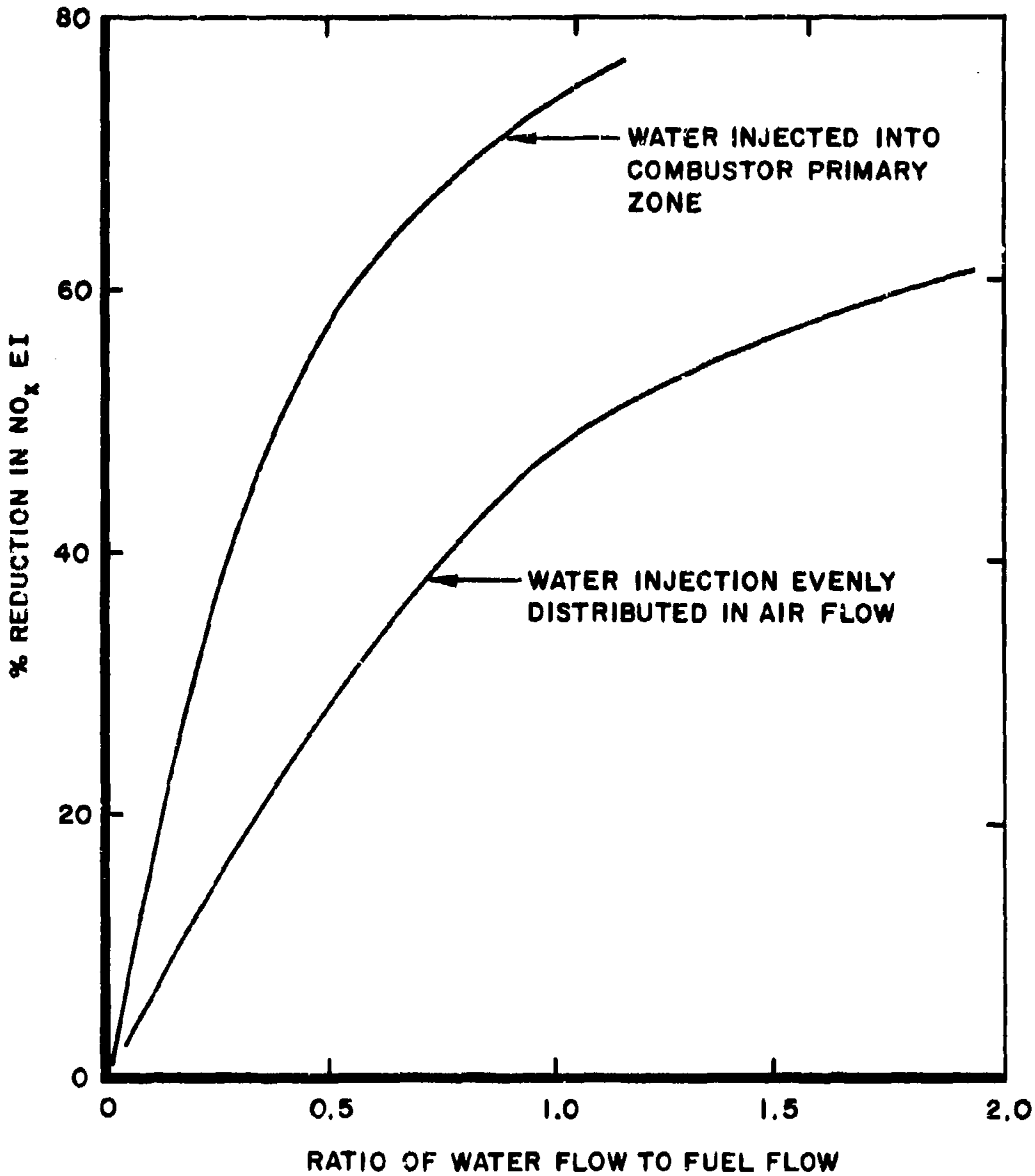



Figure 8: Ideal Effectiveness of Water-Injection for $NO_x$ Control

for which unfavorable idle combustor inlet conditions prevail. Unfortunately, little data on these concepts are presently available. However, an AFAPL in-house engine test program is to investigate some of these ideas.

In summary, current technology control techniques can reduce all emissions. Methods 1, 2, 3, 4 and 6 reduce CO and $C_xH_y$, methods 2 and 5 address $NO_x$, and methods 1 and 2 affect smoke emissions. It is apparent that significant CO and $C_xH_y$ reductions are possible, 25% $NO_x$ reduction can be anticipated and smoke emission can be reduced below the visibility threshold. These results are summarized in Table 4.

2. Mid-Term Technology

At the present time, three important Government-sponsored programs are developing technology applicable to engines produced in the early 1980's--mid-term technology. These are the following:

a. The NASA Experimental Clean Combustor Program (ECCP)[Reference 35] is an exploratory development effort to examine full-scale low-emissions combustors. Designs are aimed at production engines of the two contractors involved: the JT9D in the case of Pratt and Whitney Aircraft, and the CF6 in the case of the General Electric Aircraft Engine Group. Plans include choosing the most favorable techniques for subsequent engine demonstration.

b. The AFAPL Low-Power Emissions Program[Reference 36] has provided advanced designs and techniques in premixing and prevaporizing

TABLE 4

EMISSION REDUCTION POTENTIAL USING CURRENT TECHNOLOGY

| | Current Values | | | Reduced Values | | |
|---|---|---|---|---|---|---|
| TYPE ENGINE | COMBUSTION EFFICIENCY-% | $NO_xEI$ (gm-$NO_2$ / Kg-fuel) | SAE SMOKE NUMBER | COMBUSTION EFFICIENCY-% | $NO_xEI$ (gm-$NO_2$ / Kg-fuel) | SAE SMOKE NUMBER* |
| High Pressure Ratio Cycles | 95 | 40 | 25 | 99 | 30 | 15 |
| Low Pressure Ratio Cycles | 92 | 16 | 35 | 98 | 12 | 20 |

* Technology to reduce smoke number has advanced to the point where these numbers are thought to correspond to exhaust plume invisibility.

the fuel-air mixture to improve idle combustion efficiency. Uniformity of fuel-air distribution and absence of fuel droplets in the combustion zone are responsible for the more optimal combustion. Substantial reduction in the CO and $C_xH_y$ emissions were achieved. In addition, an analytical model of the combustion process which aids in the design of low emissions burners was developed. Pratt and Whitney Aircraft was the contractor for this project.

c. The Army T-63 Emissions Investigation[Reference 37] at Detroit Diesel Allison Division (DDA) evaluated a large number of candidate emissions reduction schemes and was able to determine a number of techniques which substantially reduce emissions. In particular, variable combustor geometry and premixing/prevaporizing techniques were found to significantly and simultaneously reduce emissions.

All of these programs examined many of the same control techniques. Overall descriptions of the principal mid-term technology approaches are given below.

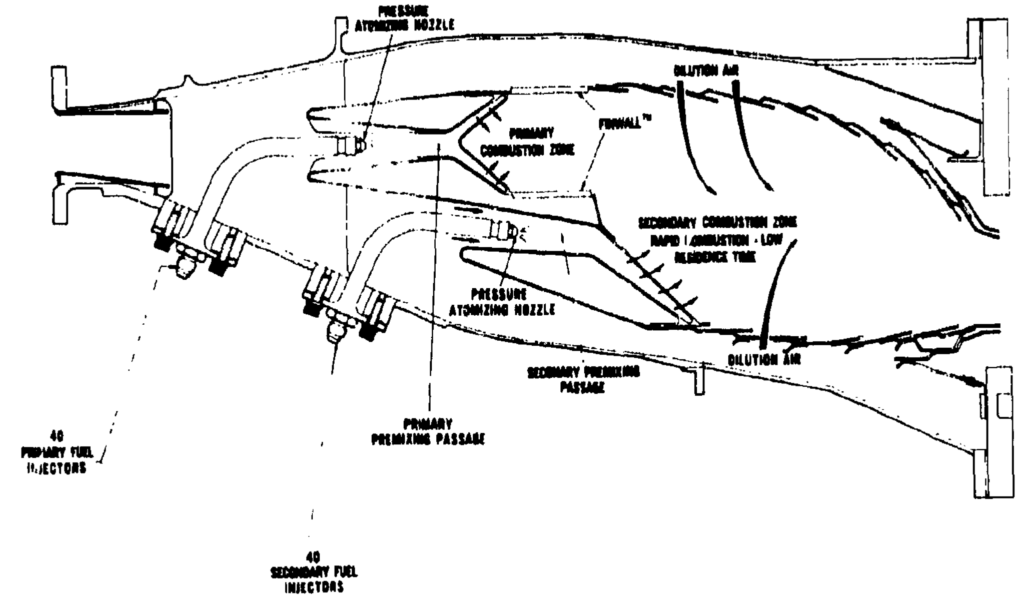
a. Staged Fuel Injection

In this control concept, combustion occurs in discrete zones of the combustor. In general, the combustor will employ either a radial or axial staged fuel injection technique. The first stage accounts for a small portion of the total air and fuel flow. It is designed such that at engine idle only this portion of the combustor is in operation and combustion conditions are optimized for low emissions. The second stage provides for combustion of the major portion of fuel flow at high power operation. High combustor inlet temperature at these conditions aids in fuel prevaporization.

Combustion zone fuel-air ratios are designed to be below those where appreciable $NO_x$ formation results. Smoke formation is extremely low because of the low fuel-air ratios used. A conventional combustor designed with a primary zone fuel-air ratio equal to that of the second stage of a staged fuel system may not provide stable combustion over the entire operating range. However, the staged combustor is stabilized by the piloting effect of the first stage which operates at conditions optimal for stability event though at a low fuel flow rate.

This technique is also attractive from a practical point of view. Although a more complicated fuel introduction and control system is required, moving combustor parts are not involved. No performance penalties are anticipated, and hardware departure from present day combustion systems is not severe.

Because of these factors, each of the contractors on the NASA ECCP is studying one of these techniques. Pratt and Whitney's version is called the staged-premix combustor and GE's is called the radial axial combustor. These combustors are shown in Figures 9 and 10. Both have been extremely successful in attaining good emissions characteristics at nearly all modes of operation. The exception is that combustion efficiency at full power operation is not at an acceptable level. Because of the ECCP $NO_x$ goal of 10g/kg-fuel [Reference 35] secondary zone fuel-air ratios are not permitting complete combustion




<u>Figure 9</u>: Staged-Premix Low Emissions Combustor (NASA/P&W ECCP) [Reference 38]

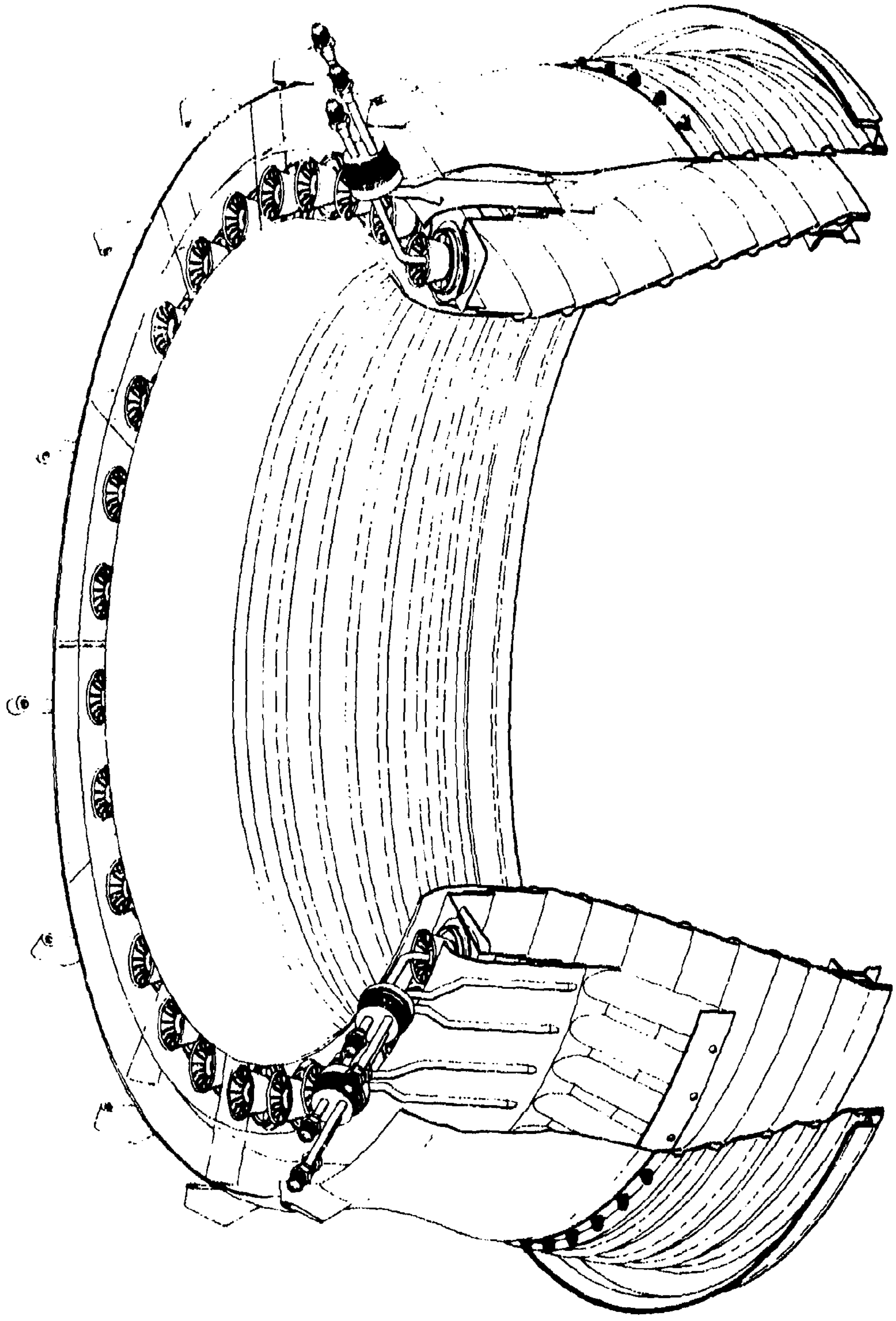


Figure 10: Radial-Axial Low Emissions Combustor (NASA/GE ECCP)[Reference 39]

within the volume available. However, if the goal were adjusted to 20g/kg-fuel (50 rather than 75% reduction), it is expected that secondary zone combustion would then provide acceptable efficiency.

b. Fuel Prevaporization/Premixing

Providing a uniform, fully vaporized fuel-air mixture is important in a number of respects. Fuel droplets which might otherwise not fully vaporize and have time to burn are absent. The combustion zone burning rates are optimized since turbulent mixing and/or diffusion processes to force-mix fuel and air are not required--relatively fast molecular collision and reaction processes occur within the gaseous mixture. These factors improve combustion efficiency and consequently reduce CO and $C_xH_y$ emissions.

Beyond this, improved combustion rates allow the range of fuel-air ratios for acceptable combustion efficiency to be extended. Consequently, operation at lower fuel-air ratio allows a means of reducing NO emissions as well. Prevaporizing systems, therefore, may also achieve low $NO_x$ emissions without fuel staging. Figure 11 shows the Pratt and Whitney premix/prevaporizing combustor developed under the Low-Power Emissions Program.[Reference 32]

c. Variable-Geometry

This combustor design concept achieves emission control at all operating modes by modulating air flow through combustor geometry alterations. During low-power operation, CO and $C_xH_y$ emission is minimized by increasing primary zone fuel-air ratios--reducing the proportion of air entering the primary zone. At high-power, $NO_x$ is

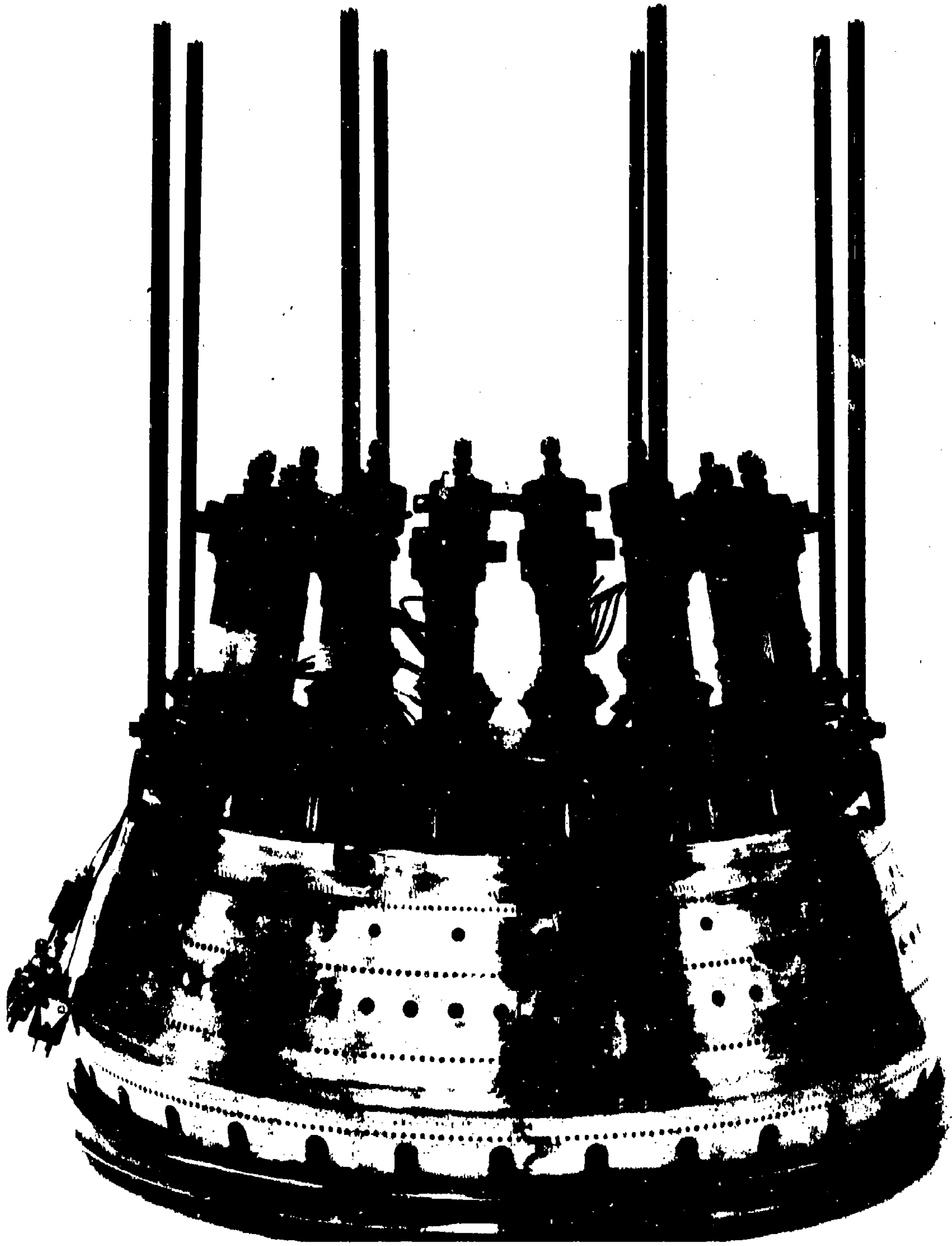


Figure 11: Premix/Prevaporizing Low-Emissions Combustor[Reference 32]

minimized by increasing primary zone air flow to maintain fuel-air ratio well below stoichiometric levels where $NO_x$ formation rates are highest. Substantial NO reduction, with good idle emission as well, was achieved in the T63 program.[Reference 40] Furthermore, no pilot zone was used to stabilize combustion at high-power when reduced fuel-air ratios exist. Although perhaps not to the same degree, the problem of reduced high-power combustion efficiency is likely to occur with variable geometry in the same manner as experienced in the staged combustor. Further, because of the attendant increased mechanical complexity and the known development problems associated with its application to large combustion systems, neither contractor in the NASA ECCP is currently examining this technique. The variable-geometry combustor used in the DDA program is shown in Figure 12.

In summary, mid-term technology control techniques can significantly reduce all emissions. $NO_x$ emission reductions below 50% of uncontrolled values, however, have been found to cause sacrifices to high power combustion efficiency. Table 5 presents reduction levels thought to be achievable without significant impact on other desirable combustor characteristics.

3. Advanced Concepts

A number of studies into combustor design for ultra-low emission levels (predominantly NO) have been proposed. Primary motivation for these studies involves minimizing NO emission during stratospheric cruise. These methods also involve fuel-air premixing and

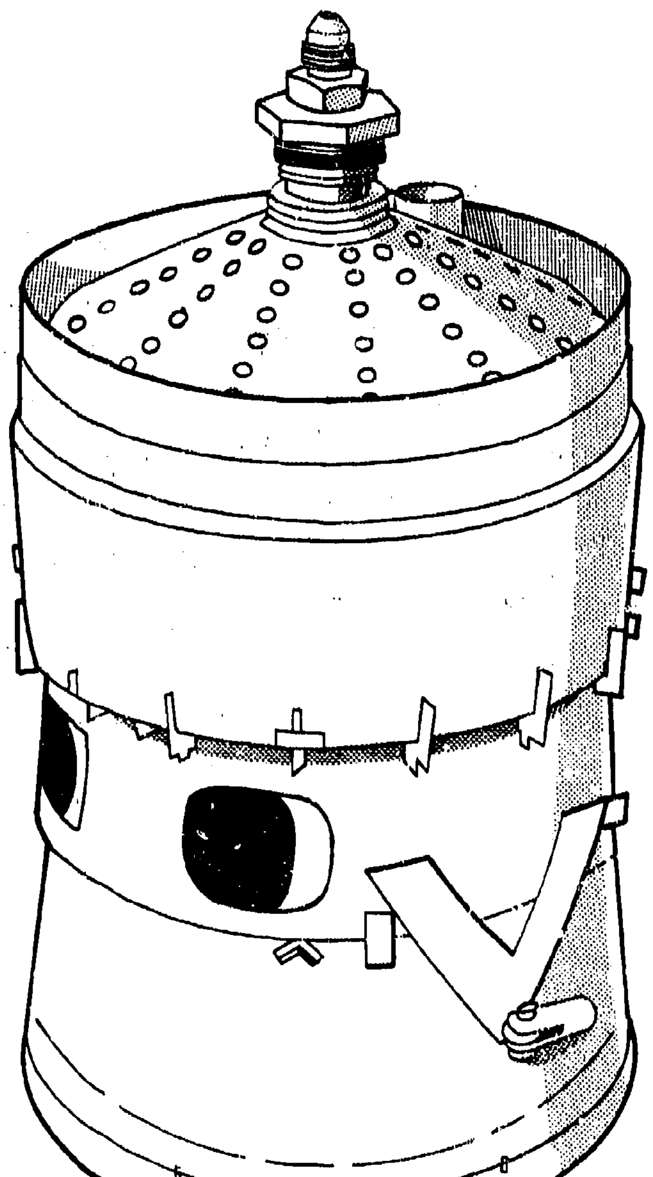


Figure 12: Variable-Geometry Low Emissions Combustor [Reference 37]

TABLE 5

EMISSION REDUCTION POTENTIAL USING MID-TERM TECHNOLOGY

| | Current Values | | | Reduced Values | | |
|---|---|---|---|---|---|---|
| TYPE ENGINE | COMBUSTION EFFICIENCY-% | $NO_x$EI ($\frac{gm\text{-}NO_2}{Kg\text{-}fuel}$) | SAE SMOKE NUMBER | COMBUSTION EFFICIENCY-% | $NO_x$EI ($\frac{gm\text{-}NO_2}{Kg\text{-}fuel}$) | SAE SMOKE NUMBER |
| High Pressure Ratio Cycles | 96 | 40 | 25 | 99.5 | 20 | 15 |
| Low Pressure Ratio Cycles | 92 | 16 | 35 | 99.0 | 8 | 20 |

prevaporization but burning occurs at appreciably lower equivalence ratios with consequent very low $NO_x$ emissions levels. These investigations are discussed below and projected emission reductions are shown in Table 6.

Detroit Diesel Allison Division of General Motors[Reference 41] and Professor Ferri of New York University,[Reference 42] have conducted experiments which show that $NO_x$ emissions can be reduced to less than 1 gm/kg fuel. In these techniques combustion takes place in the gas phase. Mr. Verkamp (DDA) has made some important comments with regard to this work. He points out that inlet temperature is the dominant factor in determining the combustion stability/efficiency tradeoff. For example, at high inlet temperatures, where the potential for high $NO_x$ emission exists, combustors with good stability characteristics can be achieved with much lower equivalence ratio operation. However, because peak flame temperatures are so much lower, chemical kinetic considerations almost certainly will force designs toward much larger combustors to gain good combustion efficiency. These advanced concepts and their attendant stability characteristics, ignition performance and emissions at other operating modes have not been fully examined.

An additional approach to ultra-low $NO_x$ levels has recently been investigated by both the USAF and NASA--the catalytic combustor.[References 43, 44] In this technique, solid catalytic beds are placed in the reaction zone to provide stability at low equivalence

TABLE 6

EMISSION REDUCTION POTENTIAL USING ADVANCED TECHNOLOGY

| | Current Values | | | Reduced Values | | |
|---|---|---|---|---|---|---|
| TYPE ENGINE | COMBUSTION EFFICIENCY-% | $NO_xEI$ $\left(\frac{gm\text{-}NO_2}{Kg\text{-}fuel}\right)$ | SAE SMOKE NUMBER | COMBUSTION EFFICIENCY-% | $NO_xEI$ $\left(\frac{gm\text{-}NO_2}{Kg\text{-}fuel}\right)$ | SAE SMOKE NUMBER |
| High Pressure Ratio Cycles | 96 | 40 | 25 | 99.7 | 1.0 | 15 |
| Low Pressure Ratio Cycles | 92 | 16 | 35 | 99.5 | 1.0 | 20 |

ratios through catalytic action as well as thermal inertia due to the presence of the bed. $NO_x$ emissions have been demonstrated to be well below the 1 gm/kg fuel, and relatively good pressure drop, combustion efficiency and heat release rates are apparent at high inlet temperature conditions. Studies are continuing to develop methods for producing low emissions at low inlet temperatures (idle operation) as well. Possible advanced hybrid techniques such as gas-phase/catalytic combustion are also attractive and should be pursued.

## SECTION V

## CONTROL TECHNOLOGY IMPACT

The purpose of this section is to present, in a general manner, the impact and potential problems one might encounter when applying the control technology described above to both current and future Air Force propulsion systems. Before any new device, design change, or operating procedure can be considered for either a new or existing propulsion system to improve performance, reduce weight, lower exhaust emission levels, etc., a thorough assessment of at least the following impact items must be accomplished:

(1) Operational Capability

(2) Reliability and Maintainability (R&M)

(3) Implementation

(4) Cost

Furthermore, the type of aircraft system which will utilize the modified engine must be considered. High performance "combat" aircraft are generally weight and/or volume limited, and performance is optimized for a specific mission. Therefore, propulsion system changes which could result in reduced capability cannot be tolerated. On the other hand, the "non-combat" transport-type aircraft are often more tolerable to such changes, the operational impact of which should be comparable to that of commercial aircraft systems. A brief discussion of each of the above impact items as they relate to emissions control technology application follows.

1. Operational Capability

a. Current Technology

All techniques within this category, except water injection, should have minimal impact on the aircraft/propulsion system's operational capability. Combustion system pressure drops and efficiencies will not be detrimentally affected. In fact, no change in the combustion system's thermodynamic function is expected. Consequently, engine thrust level will remain the same. Furthermore, little or no increased mechanical complexity should result through incorporation of current technology emissions control; hence, little increase in system weight would be expected.

Although cruise and full power SFC will remain unchanged, some increased ground fuel usage is a penalty of current technology approaches which depend on increasing the compressor discharge temperature for more favorable combustion conditions. The overall impact of this change would be small--25% increase in idle fuel flow would decrease range about 0.5% for a mission of two hours duration (a 26-minute ground idle time was assumed in this analysis). It should further be noted that use of many of these techniques can easily be eliminated during periods when performance/range compromises cannot be tolerated; i.e., national emergencies.

Two other possible drawbacks may be anticipated in applying some current technology controls. A minor combustor redesign may result in some altitude relight compromise because of the necessity to reduce primary zone fuel-air ratios for smoke abatement. Many of the engines which have the worst smoke problem have extraordinarily good relight characteristics because of very high primary zone fuel-air ratios. The second drawback involves the use of water injection for $NO_x$ control where large quantities of water are required. For example, large (40,000 pound thrust) turbofan engines require as much as 400 pounds of water per engine, all of which is expended during takeoff and climbout. The eventual result of this increased weight is a decrease in system range.

b. Mid-Term Technology

Control techniques within this category are expected to have little or no impact on the propulsion system's operational capability. If properly designed, combustion system performance (efficiency and pressure loss) should remain unchanged; hence, engine fuel consumption and gross thrust should remain constant. It should be noted, however, that if designs are oriented towards very low $NO_x$ emission (greater than 50% reduced), full power combustion efficiency will decrease and cause fuel consumption to increase.

Application of some mid-term control techniques may cause combustor weight to increase slightly. However, if the combustor design can be accommodated within the existing engine envelope, propulsion system weight changes will be minimal. Combustor length changes beyond existing limits could have a significant impact on propulsion system weight--increased shaft length and diameter, additional bearing supports, etc. Combustor designs in the NASA

Experimental Clean Combustor Program do employ mid-term emissions control techniques but the hardware is to be constrained by both length and volume limitations to fit within the CF6-50 or the JT9D-7 engine envelope.[Reference 35]

It should be noted that application of so-called mid-term technology for emissions control also offers improved performance advantages --particularly the staged-premix system. The low emissions staged-premix design offers the following high performance characteristics: (a) the first-stage pilot provides broad ignition/altitude start capability; (b) the pilot also provides a wide stability margin with excellent blow-out characteristics; (c) the pre-mixed fuel of the second stage permits a high volumetric heat release with increased reaction rates; and (d) the inherent lower fuel-air ratios significantly reduce flame luminosity with reduced thermal loading and heat transfer to the combustor liners. It should also be noted that future uncertainties in fuel availability as well as moves to implement higher flash-point fuels[Reference 46] provide further motivation for combustor design and performance improvement. Although it is known that use of hydrogen as a fuel[Reference 47] has emission benefits, it does not seem that hydrogen-fueled aircraft will be developed before the year 2000, if at all.[Reference 48]

c. Advanced Concepts

Data which might be used to determine the advanced technology combustor's effect on performance and operational capability are not available. It does appear, however, that operation at fuel-air ratios close to the combustion limits may compromise required altitude stability and ignition characteristics. Furthermore, increased combustor size is likely because of the reduced chemical reaction rates attendant with lower primary zone temperatures. This could aggravate the problem of increased engine shaft and bearing size previously mentioned.

It is anticipated that some of these problems, however, might be overcome by the use of catalytic techniques which inherently provide accelerated chemical reaction rates and thermal inertia. Nevertheless, initial problems will be encountered relative to catalytic material and substrate integrity causing performance deterioration with time.

2. Reliability and Maintainability (R&M)

Any combustor design change incorporated for emissions control must exhibit good relability and maintainability characteristics. The change must be easily accommodated by the engine overhaul centers relative to repair and/or replacement. Furthermore, it must meet safety-of-flight criteria relative to installation and operational reliability of the part/unit during system operation.

a. Current Technology

In general, techniques within this category have already been judged to have minimum R&M penalties. However, some specific comments should be made.

Compressor bleed extraction, fuel distribution modification, and changes to the engine idle thermodynamic cycle must be implemented with due care to minimize the influences on other engine components. In particular, changes to combustor exit temperature patterns on the turbine, possible changes to compressor performance, and minimization of fuel control complexity should be considered. Effects on combustor life have not been fully investigated but are thought to be small--changes are made predominantly at the idle power setting where conditions are not severe.

Water injection requires special attention because of previous experiences with JT9D power-assist water injection. Thermal fatigue due to both time and spatial temperature variations in that design initially affected engine durability characteristics.[Reference 45] Subsequent design improvements to the water injectors have since minimized these thermal problems. Furthermore, demineralized water to minimize suspended mineral deposits will be necessary, adding further to the required logistical support.

Because these current technology approaches do not involve significant departures from present designs, minimal impact to the overhaul/rework facilities is anticipated.

b. Mid-Term Technology

Due to the very limited developement experience with these techniques, R&M is difficult to assess. Only the following general conclusions can be offered.

The greatest R&M drawback of the staged-fuel designs is the increased complexity of the fuel distribution and injection system. Maintenance of the many fuel-injector lines and metering systems during repair, replacement, and overhaul must be considered. It is quite probable that additional supporting equipment and special installation fixtures will be necessary to provide proper maintenance and inspection of the injection system. Reliability problems attendant with the staged-premix system relate to individual fuel nozzle reliability--flow metering, clogging, and fuel flow uniformity. The increased number of fuel nozzles alone presents a reliability problem. Relative to the overall propulsion system employing a staged-premix combustor, problems should be minimized if this design approach is accommodated in the early stages of the engine development program. This would, in turn, minimize the impact to overall engine R&M.

Increased mechanical complexity inherent with any variable-geometry unit, be it compressor, turbine, or burner, becomes immediately obvious. Hence, development of such a variable-geometry combustor must consider R&M. It is anticipated that the reliability of a variable-geometry system will be significantly lower than conventional systems. The increased probabilities of failures of control systems or of actuating parts and linkage mechanisms make variable-geometry a technique to be avoided, if at all possible. It is expected the engine overhaul centers will require special installation and linkage calibration fixtures for proper actuator alignment and travel.

Furthermore, because the actuation arms may pass through the high pressure combustor case, special sealing techniques will be required, adding further to the R&M problems. In addition, the engine control system requirements increase because the variable-geometry actuation system of the burner must be integrated with all other operational aspects of the engine.

In summary, some mid-term technology techniques (staged combustion and prevaporization) can be applied with relatively small R&M impact. Designs involving the variable-geometry concept, however, should be avoided.

c. Advanced Concepts

Advanced gas-phase combustors have undefined reliability and maintainability because of the lack of available information. It is noted, however, that stability and light-off problems will no doubt compromise reliability. Maintainability may also suffer due to the larger combustor lengths that may be anticipated. Catalytic combustors will require significant work at the applied research level before R&M assessment is possible.

3. Implementation

Depending upon the state-of-the-art of existing technology, the period required for emissions control implementation may range from as little as five years to more than twelve years. Under this subsection, the timing impact for implementing the three basic technology categories--current technology, mid-term technology and advanced technology--is considered.

a. Current Technology

Emissions control techniques which can utilize existing control technology will require a minimal development period. Modifications to the combustor hardware would normally begin with combustor rig testing (not involving the actual engine). In the case of current USAF engines, these tests would involve a component improvement program (CIP) for the particular engine model. Any planned engine developments would consider an advanced development program (ADP) to address the emissions control development phase. USAF programs like ATEGG (Advanced Turbine Engine Gas Generator) and APSI (Airframe Propulsion System Integrator) comprise ADP efforts not oriented towards a specific engine. Although the time required is dependent on complexity and degree of risk, a period of about 2-3 years is normally required. Other techniques not involving combustor hardware modifications (i.e., compressor bleed or fuel distribution control) would not require this long development and demonstration period, a six-month to one-year period of investigation would be suitable.

The results are then incorporated into an engine for ground testing where performance, endurance, and other problems are analyzed. Approximately one year is necessary for this technology certification. Subsequent to this is an extensive flight test phase which normally requires an additional year. Flight suitability and propulsion system performance impact and compatability will then have been thoroughly investigated.

Implementation into the aircraft fleet may be delayed yet an additional year for acquisition of special tooling and establishment of the production routine. Figure 13 illustrates these phases and indicates a total time to production of current technology emissions control hardware to be approximately five years.

b. Mid-Term Technology

Emissions control techniques defined under the mid-term category will require considerably more development than those state-of-the-art techniques discussed above. Mid-term technology control measures will normally begin with an exploratory research and development effort (like the present phase of the NASA Clean Combustor Program) to firmly establish component capabilities and limitations. This initial R&D program may require two-to-three years to complete appropriate experimental substantiation testing and development of a proposed control technique.

Once the technology has been firmly established through exploratory development, subsequent steps similar to those described for current technology may be undertaken. Existing systems, for which this technology might be considered would follow the component improvement, technology certification, flight test and tooling phases. New systems would make use of advanced development, technology certification, flight test and tooling phases.

Figure 14 illustrates these phases and indicates a total time to production of mid-term technology emissions control hardware to be approximately eight years.

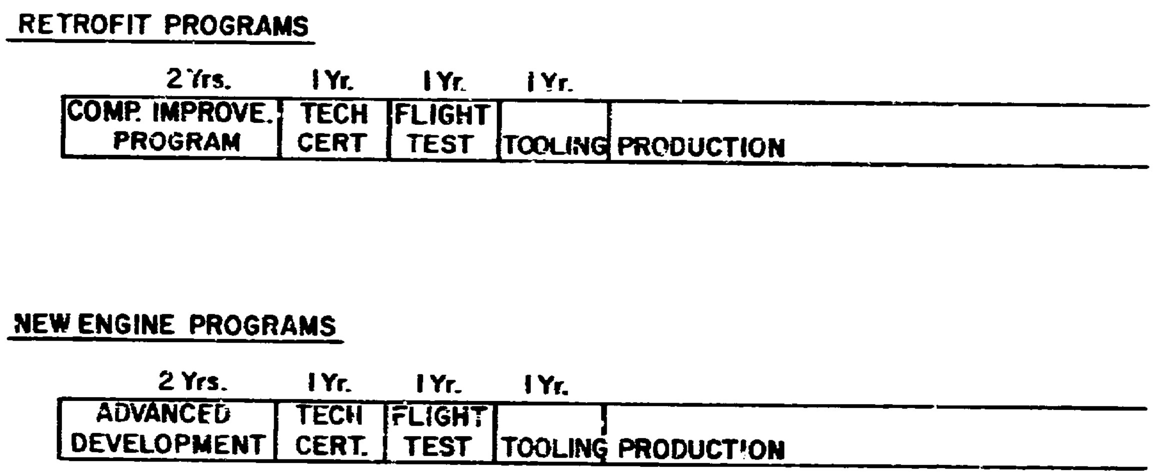



Figure 13: Implementation - Current Technology

FIGURE 14

IMPLEMENTATION — MID-TERM TECHNOLOGY

| 3 YR. | 2 YR. | 1 YR. | 1 YR. | 1 YR. | |
|---|---|---|---|---|---|
| EXPLORATORY DEVELOPMENT | ADANCED DEVELOPMENT | TECH CERT. | FLIGHT TEST | TOOLING | PRODUCTION |

FIGURE 15

IMPLEMENTATION — ADVANCED TECHNOLOGY

| 4 YR. | 3 YR. | 2 YR. | 1 YR. | 1 YR. | 1 YR. | |
|---|---|---|---|---|---|---|
| RESEARCH | EXPLORATORY DEVELOPMENT | ADVANCED DEVELOPMENT | TECH CERT | FLIGHT TEST | TOOLING | PRODUCTION |

c. Advanced Concepts

Advanced control techniques for ultra-low combustor emissions will require even longer technology development periods. The timing illustrated in Figure 15 presents an optimistic estimate of twelve (12) years--representing what one might expect for the full development of an advanced concept like catalytic combustion. The advanced technology candidates will require a period of about 4 years of basic and/or fundamental concept research. Once a sound understanding has been established relative to how this new emissions control concept functions, an exploratory R&D program may be established to further develop and apply this new technology. Progress beyond the R&D stage would then be similar to the schedule described for mid-term technology.

d. Discussion

The above planning criteria for implementing new emissions control technology illustrates the importance one must give to the timing required for various development functions. Current state-of-the-art technology can generally be applied with a minimum of development effort; whereas, the newest, most advanced concepts require an extensive research, development and demonstration program. Consequently, if exhaust pollution limitations are established, an implementation schedule consistent with the technology level required must be a prime consideration.

4. Cost

The cost of developing an emissions control technique is a function of its current state-of-development and its ultimate application. This subsection attempts to identify approximate financial outlays which one could expect in order to develop an effective emissions control technique for engine application. It is exceedingly difficult to forecast costs of implementing any control technique because of varying complexity, extent of procurement action, and inflationary factors. An attempt to overcome some of these uncertainties is made by offering a range of costs to be expected. As in the previous sections, the general technology categories of current, mid-term and advanced techniques will be considered. Table 7 provides a cost summary of each major development phase as discussed below.

a. Current Technology

Although the technology development and demonstration period may be of relatively short duration when incorporating state-of-the-art control technology, the development costs may still be quite large. In addition, a significant differential can exist between the cost for retrofit kit development (existing engine application) and development of a new low emissions combustor for a new engine.

The cost information presented herein is based largely on exploratory R&D costs incurred under current Government-sponsored emission control programs and on costs incurred by the F4-J79 CIP and Pratt and Whitney JT8D low smoke programs. Both the F4-J79 and JT8D low smoke combustor development programs utilized technology just developing at the time. Furthermore, both programs were to result in retrofit

TABLE 7

EXHAUST EMISSION COST SUMMARY

| | Research | Expl. Dev. Per Eng. Model | Adv. Dev. Per Eng. Model | Tech. Certif. Per Eng. Model | Flight Test Per Eng. Model | Tooling Cost Per Eng. Model | Combustor Production Cost Increase % |
|---|---|---|---|---|---|---|---|
| CURRENT TECHNOLOGY | | | | | | | |
| Retrofit | - | - | 4.0-8.0 | 0.5 | 0.5 | 1.0-3.0 | 0-25% |
| New Dev. | - | - | A | A | A | A | 0-25% |
| MID-TERM TECHNOLOGY | | | | | | | |
| New Dev. | - | 1.0-2.0 | 4.0-8.0 | A | A | A | 50% |
| ADVANCED CONCEPTS | | | | | | | |
| New Dev. | .5 | 1.0-2.0 | B | A | A | B | B |

A - Cost included in the initial development procurement package.

B - Cost cannot be forecasted at this time.

units which could still meet essentially all baseline engine performance and envelope requirements; hence, a significant Component Improvement Program was required. Demonstrated smoke-free performance required considerable component development (nearly five years) for each engine type. Table 8 summarizes the approximate costs of these two development efforts.

Table 8 indicates the cost impact one might encounter if required to develop an emissions control technology technique for an existing engine ultimately resulting in a retrofit unit. It must be recognized that this cost is a direct function of the state-of-development, degree of sophistication and extent of hardware modification required to accommodate a particular control scheme. The J79 combustor redesign involved extensive dome modifications resulting in a substantially greater development cost than that for the JT8D retrofit program. In addition, some of the development costs for the JT8D were shared by the Navy J52 smoke reduction program.

Although the end item production cost for a low emissions combustor may increase, the life-cycle costs of the unit may be improved because of greater combustor life. This is particularly true for smoke retrofits as a result of reduced flame radiation loads. However, current technology controls to reduce other emissions may not have the same benefit. Consequently, in Table 7 it has been estimated that production costs may increase from 0-25% depending upon the complexity of the control technique employed; i.e., increased compressor

TABLE 8

J79 AND JT8D SMOKE RETROFIT COST SUMMARY
(Millions of Dollars)

J79-17 Smokeless Combustor

(a) Component Development - $6.0

(b) Flight Demonstration and Certification - $1.0

(c) Production Tooling - $2.7[1]

(d) Total Development Cost - $9.7

JT8D Smokeless Combustor (45)

(a) Component Development - $6.0[2]

(b) Flight Demonstration and Certification - $0.585[3]

(c) Production Tooling - $0.175

(d) Total Development Cost - $6.7

---

[1] J79 tooling cost high due to introduction of major burner dome redesign for both low smoke and increased durability/life.

[2] Includes some preliminary demonstration flight testing.

[3] Flight demonstration conducted under Commercial Airline Service Evaluation; hence, costs cannot be completely estimated since included with normal scheduled flight operations.

bleed as opposed to a major combustor redesign.

Implementation costs of current technology emission control measures for new engine systems should result in a minimal cost impact. As stated earlier, if emissions controls can be incorporated during baseline engine development, the development cost beyond the ADP becomes a part of the overall combustion system cost. Consequently, a low emissions combustor can be developed in the most cost-effective manner as an integral part of the engine development effort. Since no new engine system has yet been developed with emissions control requirements, other than smoke, no information on additional development costs is available at this time. It is not likely, however, that combustion system design and development costs, as part of a major engine development effort, will increase substantially over current costs. Consequently, Table 7 indicates new engine development costs for emissions control to be a part of the basic engine development package.

b. Mid-Term Technology

The development costs associated with low emissions combustors employing mid-term technology will include a cost increment involving initial exploratory research and development. As in the case of current technology, this is followed by advanced development and technology certification to define component hardware/engine integration capabilities. This provides the necessary design and performance confidence for technology transition to an existing and/or new propulsion system.

Typical costs associated with the exploratory R&D phase of mid-term technology range from $1-3 million. The cost of a particular program is a function of the design sophistication required to demonstrate emission goals, the number of candidate combustor designs to be considered during the R&D program and the scope of demonstration required to permit subsequent transition to an advanced development effort.

Examples of a few exploratory R&D programs directed specifically toward advanced emissions control technology are given in Table 9. Funding for these programs is approximately $1,000,000 for each engine type addressed. As stated above, once the exploratory R&D work has been completed, the new technology is then ready for transition to an advanced development program. Subsequent costs are likely to be approximately the same as those mentioned in the current technology section.

As one would observe from the above preliminary estimates for the initial development of mid-term low emissions technology, the approximate cost could range from 5 to 10 million dollars for the combined exploratory and advanced developments of mid-term technology. This brings the technology level to the point of implementation into either a new or existing propulsion system requiring the emissions control. The cost of production and implementation is dependent primarily upon the quantity of systems required and the degree of design modification/sophistication employed.

TABLE 9

EXPLORATORY DEVELOPMENT COST SUMMARY

| Sponsoring Agency | Program Title | Contractor | Approximate Funding |
| --- | --- | --- | --- |
| USAF, Aero Propulsion Laboratory | Low-Power Turbopropulsion Combustor Exhaust Emissions (36) | P&W | $1,200,000 |
| NASA-Lewis Research Center | Experimental Clean Combustor Program (ECCP) (35) | General Electric | $1,100,000 |
| NASA-Lewis Research Center | Experimental Clean Combustor Program (ECCP) (35) | P&W | $ 900,000 |
| US Army, AMRL* | Investigation of Aircraft Gas Turbine Combustor Having Low Mass Emissions (37) | Detroit Diesel Allison | $ 97,000 |

*Program costs are low because small-size combustors were investigated and control techniques were not pursued beyond the concept demonstration phase.

c. Advanced Concepts

Development of advanced ultra-low emissions technology requires an additional increment of cost beyond that described above. Initial development of this technology will require some amount of basic research to establish a fundamental understanding of information necessary to apply the technique. Although the duration of basic research required is estimated at 4 years, the associated cost is very uncertain. However, a number of research programs costing from $25,000 to $100,000 might be started. As one can see, this has a relatively insignificant impact on the overall cost which would ultimately be associated with the full development of this concept.

Development and implementation costs cannot be established because of the unforeseen complication of the advanced concepts. However, an estimate of $100 million for total development of these concepts has been made.[Reference 50]

d. Discussion

In conclusion, the cost impact of applying emissions control technology is greatly dependent upon the state-of-technology development, the associated propulsion system constraints, and the time required for technology application. Again, the discussion within this section considers only those developments leading to the point of production. Production costs could differ by an order of magnitude, depending upon the number of units required. A detailed discussion of these costs is beyond the scope of this technical report. However, since the combustor expense is typically 3 percent of the total engine cost,[Reference 51] the overall propulsion system cost impact is minor. Moreover, as has been previously noted, increased combustor performance requirements will in themselves dictate designs similar to those associated with low emissions.

## SECTION VI

## EPA STANDARDS AND POSSIBLE USAF IMPACT

The purpose of this section is to describe the commercial engine standards recently established by EPA and their implications with respect to various types of military aircraft. Standards for non-afterburning turbine engines will be discussed in the following subsection. No standards applicable to afterburning turbines have yet been established because of the previously mentioned problems in afterburner emission measurement and assessment. Furthermore, there are no standards being considered at this time to limit aircraft emissions in the stratosphere or emissions from rotary wing aircraft.

### 1. EPA Standards for Turbopropulsion Engines

The basic purpose of the EPA standards is to reduce emissions of aircraft so that air quality standards are not violated. This requires limitation of emissions at the passenger loading areas, during taxi-out to the main runways, during take-off and climbout, during approach and landing, during taxi-in to the passenger loading area and during final idle and shutdown. Emission during each of these modes contributes differently to the ambient pollutant levels at the various airport locations which have been found to have concentrations in excess of air quality standards. Analytical models which might be expected to assign a degree of importance to emissions at each mode are far too underdeveloped at this time. Consequently, EPA considers it reasonable to place limitations on the total pollutants which are emitted into the immediate environment of the airport below 3000 feet.

The parameter which is used to express total pollutants from aircraft turbine engines is critical. For example, it is possible to specify a commercial aircraft limitation in terms of pounds of pollutant per passenger seat per landing take-off cycle. This would be the most fundamental approach, requiring limitation of pollutant emissions by engine improvements, airframe considerations, considerations of choosing the proper type and number of engines for a particular airframe design and even by optimized seating arrangements. It is also possible to specify emission limitations based on pounds per thousand pounds of fuel or pounds per thousand pounds of thrust, EI or EIT respectively. These units are related in the following way:

$$EI \times SFC = EIT \qquad (3)$$

Where: SFC = thrust specific fuel consumption, lbm fuel/hr/lbf thrust

$$EIT = \frac{\text{lbm pollutant/hour}}{\text{1000 lbf thrust}}$$

When on a per-pound-of-fuel basis, the emissions of CO and $C_xH_y$ can be translated back to the considerations of idle combustion inefficiency discussed earlier. Also, as previously mentioned, the $NO_x$ emissions based on a pound per thousand pounds of fuel basis are known to be closely tied to the combustor inlet temperature, or pressure ratio.

Since SFC is an indication of total engine efficiency and EI indicates how well the combustor was designed from the exhaust pollution standpoint, the use of EIT would imply then that pollution emission criteria should be included in the selection of basic engine cycle parameters (pressure ratio and turbine inlet temperature). This, however, may adversely affect optimization of system performance.

The approach which EPA has adopted for their proposed regulations for gaseous emissions is intermediate between specification of emission per passenger seat and specification of EI and EIT. It involves the use of a parameter based on the emission per thrust-hour summed over a typical landing take-off (LTO) cycle. The EPA parameter has the dimension:

$$\frac{\text{lbm pollutant}}{\text{lbf thrust-hour cycle}}$$

Data-reduction details to obtain this parameter are presented in Reference 2. EPA considers this to be the most practical parameter from the commercial aircraft engine standpoint since it:

a. Gives a number which is physically recognizable as the total emission of the engine into the airport environment per unit of power output.

b. Ties p[illegible]tant emission to an engine, not an engine/airframe combination.

c. Represents the effect of total engine cycle pollutant reductions.

The EPA exhaust smoke limitation is a specified smoke number determined by the engine-rated gross thrust.

Since the EPA parameter, EPAP, makes use of a landing-take off cycle, the cycle must be defined. Duty cycles, shown in Table 10, have been specified for the following classes of turbine engines produced after 1 January 1979.

| | |
|---|---|
| Class T1 | Turbojet and turbofan engines with thrust less than 3000 $lb_f$ |
| Class T2 | Turbojet and turbofan engines with thrust greater than 3000 $lb_f$ |
| Class T5 | Turbine engines intended for supersonic application |
| Class P2 | Turboshaft engines used for fixed wing propulsion |

Table 11 lists the EPA standards for the T1, T2 and P2 classes; standards have not yet been published for the T5 class.

2. Discussion

The EPA parameter (EPAP) is not simply related to EI or EIT because it represents a summation over a specified duty cycle. However, some significant simplifications are possible in the case of CO and $C_xH_y$. As previously mentioned, emissions of these species are only significant during the idle/taxi power setting. The following list shows the average emissions for each operating mode for a JT9D engine. [Reference 6]

| Mode | CO Emissions (lbm) | $C_xH_y$ Emissions (lbm) |
|---|---|---|
| Taxi/Idle (Out) | 32.25 | 8.65 |
| Take Off | 0.10 | 0.03 |
| Climbout | 0.43 | 0.10 |
| Approach | 2.17 | 0.20 |
| Taxi/Idle (In) | 11.88 | 3.19 |

TABLE 10

EPA DUTY CYCLE - TIME IN MODE (T.I.M.) AND POWER SETTING (P.S.)

| | Classes T1 or P2 | | Class T2 | |
|---|---|---|---|---|
| | T.I.M. | P.S. | T.I.M. | P.S. |
| Taxi/Idle (Out) | 19 Min. | * | 19 Min. | * |
| Takeoff | .5 | 100%** | .7 | 100%** |
| Climb-out | 2.5 | 90. | 2.2 | 85. |
| Approach | 4.5 | 30. | 4.0 | 30. |
| Taxi/Idle (In) | 7.0 | * | 7.0 | * |

* That specified by engine manufacturer

** The Percent of maximum rated thrust

TABLE 11

EPA STANDARDS

| | Hydrocarbon EPAP | Carbon Monoxide EPAP | Nitrogen Oxide EPAP | Approximate SN Required |
|---|---|---|---|---|
| **Engines Produced After 1 Jan 1979** | | | | |
| Class T1 | 1.6 | 9.4 | 3.7 | 30 |
| Class T2 | .8 | 4.3 | 3.0 | 20 |
| Class P2 | 4.9 | 26.8 | 12.9 | 30 |
| **Engines Certified After 1 Jan 1981** | | | | |
| Class T2 | .4 | 3.0 | 3.0 | 20 |
| Class T1 & P2 | ---- Remain same as 1979 ---- | | | |

Note that 94.3% of the CO emissions and 97.3% of the $C_xH_y$ emissions are from the idle power setting. Therefore, the EPAP for total CO and $C_xH_y$ over the LTO cycle can be well approximated by the taxi/idle emissions contribution. Further, the parameter relating EPAP to EI or combustion inefficiency is idle SFC, a term of little fundamental importance to engine performance.

$NO_x$ emission from today's uncontrolled engines cannot be attributed to one mode. The following list shows the contribution of various modes for a JT9D engine over the LTO cycle.[Reference 6]

| Mode | $NO_x$ Emissions (lbm) |
|---|---|
| Taxi/Idle (Out) | 1.92 |
| Take Off | 8.40 |
| Climbout | 16.81 |
| Approach | 3.61 |
| Taxi/Idle (In) | 0.71 |

Only the taxi/idle power settings are low in the case of $NO_x$ emissions.

It might be thought that by virtue of the fact that the thrust dependency is included in the denominator, the EPAP favors engines with a low SFC. This is true for the emission of CO and $C_xH_y$ because the idle emission characteristics are related to an engine's pressure ratio. Further, it is true that if two engines have the same $NO_x$ EI, the one with the lower SFC will have a lower EPAP value. Although an engine's SFC value is dependent on its pressure ratio, the dependence of $NO_x$ emission on combustor primary zone temperature is dominant;

hence, increased $NO_x$ EPAP results from increased pressure ratio. This fact is extremely important. Engine design motivation for commercial subsonic aircraft has always been toward minimum SFC. EPA proposes techniques such as water injection and advanced combustor design concepts to solve the $NO_x$ problem for commercial aircraft without compromising SFC.

The technology implied by the EPA standards may be evaluated by determining the emission levels required of different engines. Two specific cases will be discussed. The JT3D, representing a low-pressure ratio design, and the JT9D, representing a high pressure ratio design, are engines which at present have no emissions control technology other than smoke. Table 12 compares current emission indices of these engines with the 1979 EPA requirements. A forecasted level of emissions reduction, from Table 4, has been used to estimate the emissions to be expected using current technology as discussed in Section IV. Finally, approximate emission levels based on mid-term technology have also been defined.

It is important to note that the JT3D has much less of a change to meet the EPA standards. Two specific engine parameters are at fault: (a) engine idle pressure ratio is much lower than a JT9D and (b) idle SFC is high, thus requiring lower values of EI to satisfy the EPA limits.

In summary, it is seen that the EPA method of specifying emissions (especially the $NO_x$ limitation) involves complicated tradeoffs which

TABLE 12

EPA STANDARDS IMPACT ON JT3D AND JT9D ENGINES

| | Pollutant | EPA Standard* | Present[1] Level | Reduction[2] Factor | Current Technology Estimate (Table 5) | Mid-Term Technology Estimate Table 5) |
|---|---|---|---|---|---|---|
| JT3D | CO | 4.3 | 30.2 | 7.0 | 8.0 | 6.0 |
| | $C_xH_y$ | 0.8 | 25.9 | 31.0 | 2.0 | .7 |
| | $NO_x$ | 3.0 | 4.34 | 1.45 | 1.3[3] | 2.5[4] |
| JT9D | CO | 4.3 | 11.3 | 2.6 | 4.3 | 3.0 |
| | $C_xH_y$ | 0.8 | 2.95 | 3.7 | .8 | .3 |
| | $NO_x$ | 3.0 | 7.6 | 2.5 | 2.5[3] | 3.5[4] |

* Reference 2, Class T2 or T3

1 Reference 6, Section IV, lb-pollutant/$10^3$ lb-thrust-hr-cycle

2 Reduction Factor = Present Level/EPA Standard

3 With $H_2O$ Injection

4 Assumes $H_2O$ Injection not used

affect basic engine design. Moreover, the characteristics of engine usage are involved in a manner which is only meaningful in applications where scheduling and procedures cause regularity of operations. The EPA standards applied to large subsonic commercial engines are in reasonable agreement with the forecasts for control technology effectiveness made in Section IV. However, engines with idle operating conditions like the JT3D cannot be expected to meet the standards.

3. Other Standards

In addition to the standards for new turbopropulsion engines mentioned above, regulations to limit smoke emissions from in-use engines have been promulgated. EPA has established engine class T3 for the JT3D family and T4 for the JT8D family. All T3 engines must have smoke numbers below 25 by 1 January 1978 and all T4 engines must have smoke numbers below 30 by 1 January 1974. The JT8D retrofit program was begun in 1965 long before regulatory measures were required by law. Pratt and Whitney is currently developing smoke reduction design changes for the JT3D combustor. T3 and T4 EPA duty cycles as well as gaseous emission limitations for engines produced after 1979 are identical to those for class T2 described earlier. Further limitations involve non-radial piston engines, auxiliary power units and engine fuel venting.

Standards for non-radial piston engines take effect on 31 December 1979. The limitations are expressed in units of pounds of pollutant per rated horsepower per cycle. Basically, these will require a 50% reduction in CO and $C_xH_y$ from present typical values. An oxide of nitrogen limitation has been included to prevent substantial $NO_x$ increases due to applied control techniques. The $NO_x$ limitation is calculated to represent the $NO_x$ emission from a piston engine operating at the increased air-fuel ratio necessary to attain the 50% CO and $C_xH_y$ reduction discussed above.

Fuel venting standards which prohibit any discharges to the atmosphere will take effect on 1 January 1974 for all Class T1 and P2 aircraft and has already gone into effect (1 January 1974) for Class T2, T3 and T4 engines. Previous to this rule, fuel remaining in lines during shutdown was collected in a sump and dumped on subsequent take-off.

APU standards are expressed in $lb_m$ pollutant per 1000 hp-hr of power output. Emissions are examined at one operating point only--maximum load. These standards, which take effect on 1 January 1979, will require all APU engines produced to have emission characteristics better than today's cleanest engine.

4. USAF Compliance with EPA Standards

The possibility of Air Force aircraft complying with existing Environmental Protection Agency Standards for turbopropulsion engines has been evaluated. The most important guideline considered in the evaluation was: in no case shall pollutant controls be allowed to infringe on military engine design or operation in a manner which would compromise system effectiveness. Additional considerations were: (a) pollution control technology for aircraft gas turbine engines developed in commercial as well as in military programs should be utilized and

(b) military engines should approach the related EPA commercial regulations to the greatest extent possible.

Three basic factors make direct application of standards to Air Force aircraft systems impractical.

a. The EPA method of specifying emissions involves complicated trades which can affect basic engine design, thus violating the guideline described above. In particular, the high pressure ratio systems have difficulty meeting $NO_x$ limitations while the low pressure ratio systems have difficulty meeting the low power (CO, $C_xH_y$) limitations.

b. The characteristics of engine usage are involved in the EPA specification in a manner meaningful only in commercial considerations where scheduling and specified operating procedures lend regularity to idle, taxi and other modes of operation. It is not possible to characterize military aircraft operation modes in the same manner EPA has done for commercial activities. Further, this reasoning applies to the aircraft system design philosophy as well. Where commercial aircraft optimization involves the single purpose of efficient economic transport between two locations of a given typical range, military aircraft, in contrast, generally have many legs to their mission involving different engine requirements. Exhaust pollution considerations in the cycle optimization process are more likely to significantly impact aircraft system effectiveness in the military case.

c. Recent results of ongoing technology programs indicate that all EPA limitations will not be achieved without some compromise to propulsion system effectiveness. For example, a $NO_x$ reduction can be achieved with current technology (that which is anticipated to be available by 1979) without employing water injection. Recall that water injection has inherent drawbacks. Furthermore, engines with low idle pressure ratios will have considerable difficulty meeting the CO and $C_xH_y$ limitations.

Based on these observations it is recommended that the Air Force not elect to comply with the present EPA standards, but rather follow the proposed goals outlined in the following section.

## SECTION VII

## USAF EMISSIONS GOALS

Proposed Air Force goals outlined below parallel EPA standards as much as is considered feasible. Goals for turbopropulsion engines produced in significant quantity after 1979 and for those qualified after 1981 are proposed. No differentiation between turbojet, turbofan and turboprop engines is made, and afterburning engines are to meet goals during non-afterburning operation.

Turbopropulsion engines used in drones and remotely-piloted vehicles are not included in the above goal recommendation. Hourly use of these systems is extremely limited and emissions reduction is not cost effective.

Current Air Force procurement of non-radial piston engines (the only type for which EPA regulations have been developed) is extremely low. Consequently, support of control technique development would not be cost effective. However, emissions reductions made possible through general aviation development should be incorporated into the limited Air Force procurement.

Air Force auxiliary power units, while relatively substantial in number, are used with much less frequency than those in the commercial sector for which EPA standards have been established. Again, it is not cost effective to support control technique development, but commercial technology should be applied to new equipment procurements.

Because of their impact in commercial aviation, helicopter emissions have not been regulated. Rotary wing aircraft within the Air Force are also relatively few in number. Moreover, the U.S. Army has prime responsibility for developments in this area. Consequently, it is not logical to impose limits on these systems.

Fuel venting restrictions also fall into the category of not being cost effective. Air Force aircraft operational use is appoximately an order of magnitude less than that of commercial aircraft and, although modification costs would be similar, benefits of each individual modification would be much less.

The remainder of this section is divided into a discussion of the parameters chosen, 1979 goals, the 1981 goals, a proposed policy on advanced concepts, and implementation.

1. Selection of USAF Emission Goal Parameters

The most apparent differences between the proposed AFAPL goals and the current EPA standards involve the method of specification. In the case of the AFAPL goals, parameters have been chosen which allow emission reduction without requiring design trades. These are discussed below.

a. Low Power Emissions

Establishment of CO and $C_xH_y$ emission limits basically involves idle operation as discussed earlier. The basic parameter which may be used to evaluate reductions in low power emissions is idle combustion efficiency ($\eta_c$). This parameter is an excellent means of comparing the quality of technology or success of a low emissions design. Complicating factors like idle SFC and time-in-idle-mode are avoided by using this parameter for specifying idle emission limits. Furthermore, $\eta_c$ does not separately address CO and $C_xH_y$ as would be the case if idle emission indices were specified. In a sense, this adds favorably to the argument that specification of $\eta_c$ is most realistic. All control techniques known to reduce one idle pollutant reduce the other as well and combustor designers have difficulty in controlling the trade between $C_xH_y$ and CO. Hence, $\eta_c$ provides an excellent indication of the overall quality of the combustor design from the idle emissions point of view. However, combustor-to-combustor similarities do allow some preliminary assessment of future $CO/C_xH_y$ trends. Basically, it may be expected that the hydrocarbons will be reduced at a much faster rate than the CO. As combustion efficiency is improved, the ratio of CO to $C_xH_y$ emission indices will increase.

As previously discussed, $\eta_c$ is strongly dependent on the conditions for combustion. This may support the conclusion that those engines with less favorable combustion conditions (low idle pressure ratios) should be allowed lower efficiency levels than others. The problem is mainly with engines of the following two categories:

(a) High Mach aircraft, for which pressure ratios must be limited in order to maintain acceptable combustor inlet temperatures during high Mach flight, will inherently have lower idle pressure ratio.

(b) Small low cost engines must employ less complicated, smaller compressors with low pressure ratios at all operating points.

To a limited extent, all engines may be operated in a manner which will permit higher combustion efficiency. One corrective measure would be to operate at higher idle thrust levels, aircraft-system permitting. In addition, variable compressor systems could be set to give low compressor efficiency at idle; hence, maintenance of the required engine idle pressure-ratio would cause higher combustor inlet temperatures. Both approaches would result in higher idle combustion efficiencies. Nevertheless, it is considered justifiable to allow the lower pressure ratio engines some margin from that specified for others--the low pressure ratio machine will have a baseline emission level significantly greater than that of the high pressure-ratio system.

b. $NO_x$ Emission

$NO_x$ emission characteristics of current engines are very predictable. Strong ties with combustor inlet temperatures are apparent from previous discussions. Means of limiting $NO_x$ emission must, therefore, consider this trend.

The most realistic means of specifying $NO_x$ limitations is to compare the reduced level with that expected from an uncontrolled system. Depending on the assessment of control technology potential, 25, 50, or 75% reductions from the uncontrolled level would be specified. Consequently, all engines would have $NO_x$ emission goals specified as a percentage reduction below their respective uncontrolled level.

c. Smoke Emission

Military interest in reducing smoke emission goes beyond the need to reduce esthetic nuisance. The more stringent requirement of invisibility from approach angles to reduce tactical vulnerability dictates the smoke limit to be set. Unfortunately, the smoke numbers which will insure invisibility for a propulsion system are not accurately predictable at the present time. Studies are currently underway to correct this situation. For the present, we must use the knowledge developed from the perpendicular sighting case previously mentioned (see Figure 6).

2. 1979 Goals

Proposed goals for turbopropulsion engines produced in significant quantity after 1979 have been written to be consistent in both implementation time and emission level with current technology expectations. Individual goals are outlined below:

a. Combustion Efficiency

CO and hydrocarbon levels are to be below levels which result in an idle combustion efficiency of 99% in the case of engines with an idle pressure ratio above 3:1, and a combustion efficiency of 98% in the case of engines with an idle pressure ratio below or equal to 3:1. Figure 16 shows this goal as it relates to the current idle inefficiency correlation. This specification provides some allowance for difficulties which are expected at the lower idle pressure ratios. Note that this is a specific addition to the Air Force goals originally proposed by AFAPL in 1972.[Reference 3]

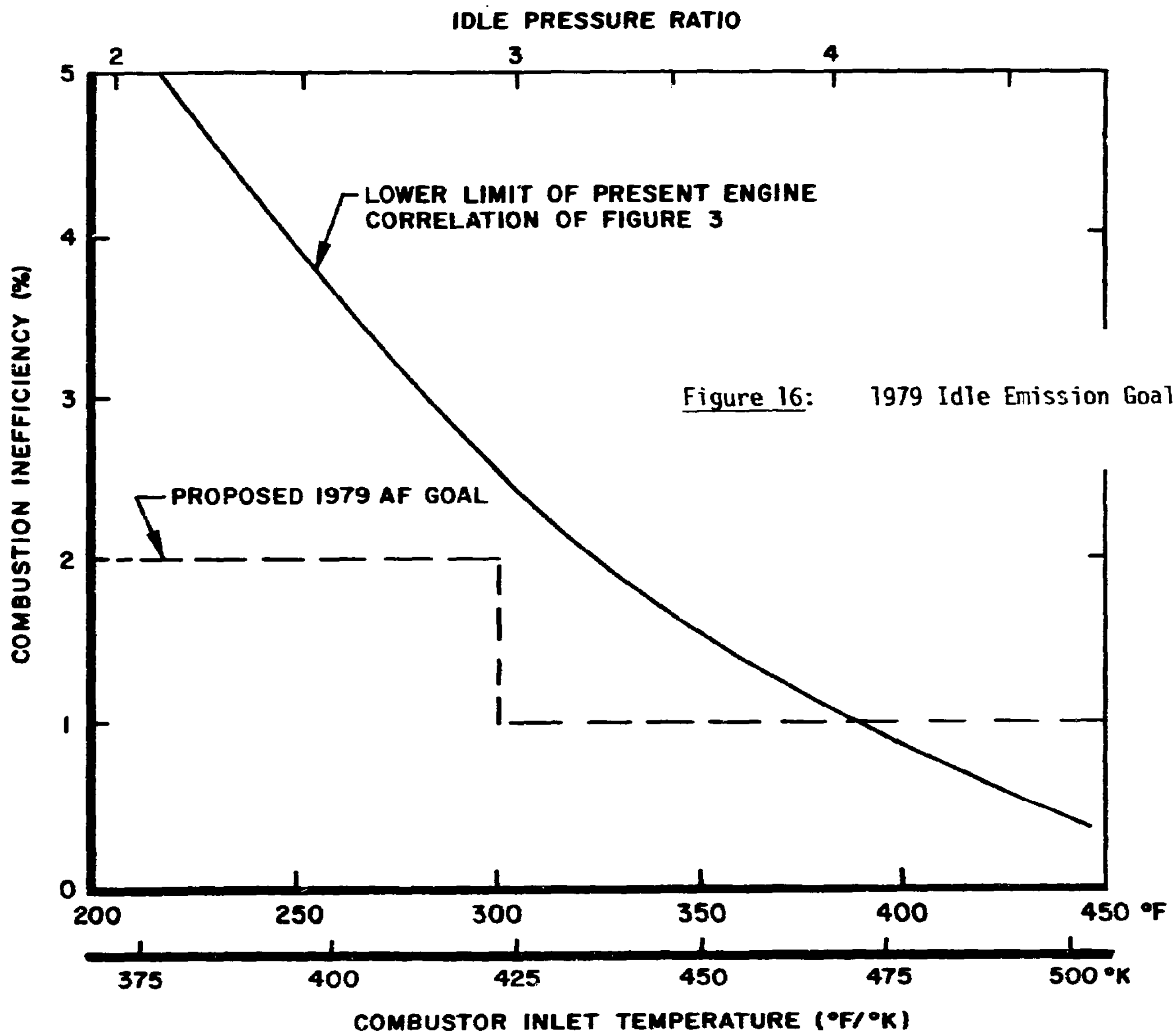



Figure 16: 1979 Idle Emission Goal

b. Oxides of Nitrogen

Goals for oxides of nitrogen limitations are all based on a percentage reduction from an uncontrolled baseline level--the idealized or upper level defined as a function of engine cycle parameters, in particular, pressure ratio and combustor inlet temperature. Combustor water injection can be employed in certain aircraft systems to achieve 75% reductions from the uncontrolled $NO_x$ levels shown in Figure 4. Transport type aircraft are the most likely to use water injection and EPA may very well require use of this level in their standards. Consequently, it is recommended that for each new aircraft system having a transport mission, a review be made of the feasibility of the water injection method. Should this technique be applied, a 75% reduction from the uncontrolled $NO_x$ level should be the goal.

It is not expected that other current technology hardware modifications can reduce $NO_x$ emission more than 25% from the uncontrolled level. This 25% reduction is based mainly on assessments of the attributes of airblast and/or carbureting technology. Hence, the proposed goal for engines not employing water injection is a 25% reduction from the uncontrolled level. Note that this is a change to the previously proposed AFAPL goal,[Reference 3] which called for a 50% reduction.

Figure 17 graphically illustrates the proposed 1979 $NO_x$ goal. It is emphasized that these reductions apply to takeoff (max-dry) and climbout modes of operation only. However, to simplify compliance

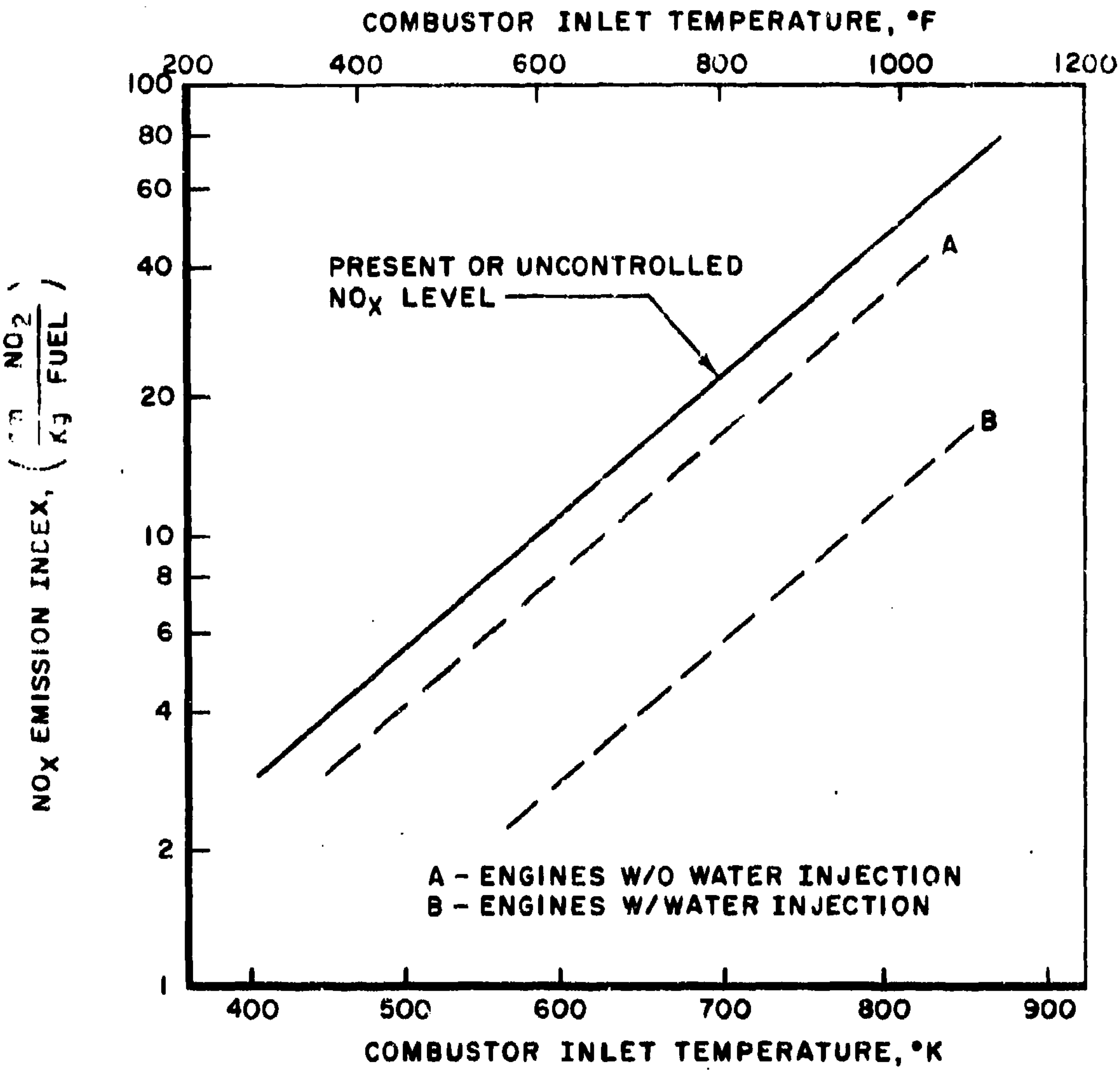



Figure 17: $NO_x$ Goals for 1979

procedures, the $NO_x$ goal must be satisfied at the max-dry power condition. Significant variability in climbout operation prevents specification of a climbout power setting. Idle and approach levels should be maintained at or below the level indicated as uncontrolled.

c. Smoke

Emission levels of smoke can be reduced to levels well below the visibility threshold. However, reductions to extremely low levels can result in undue compromises to stability, ignition, and altitude relight characteristics. Consequently, it is necessary to set the smoke limit at or slightly below the visibility threshold.

Unfortunately, the ability to accurately establish the value of smoke number corresponding to invisibility does not exist. At the present time, the best that can be done is to use the smoke number/visibility correlation of Figure 6. Specifically, the lower limit of the uncertainty band has been defined and is shown in Figure 18. Rather than use the abscissa term "path length for light attenuation," the parameter nd has been employed, where d is the exhaust diameter of the engine and n is the maximum number of engine exhaust streams through which an observer could possibly sight. For example, the value of n is 2 for the case where two engines are closely coupled such that the appropriate light attenuation path length represents the exhaust diameters. Figure 18 also shows the EPA smoke standards for the T1 and T2 classes. Note that these are plotted for a single engine configuration (n = 1). In a case where n = 2, the proposed Air Force

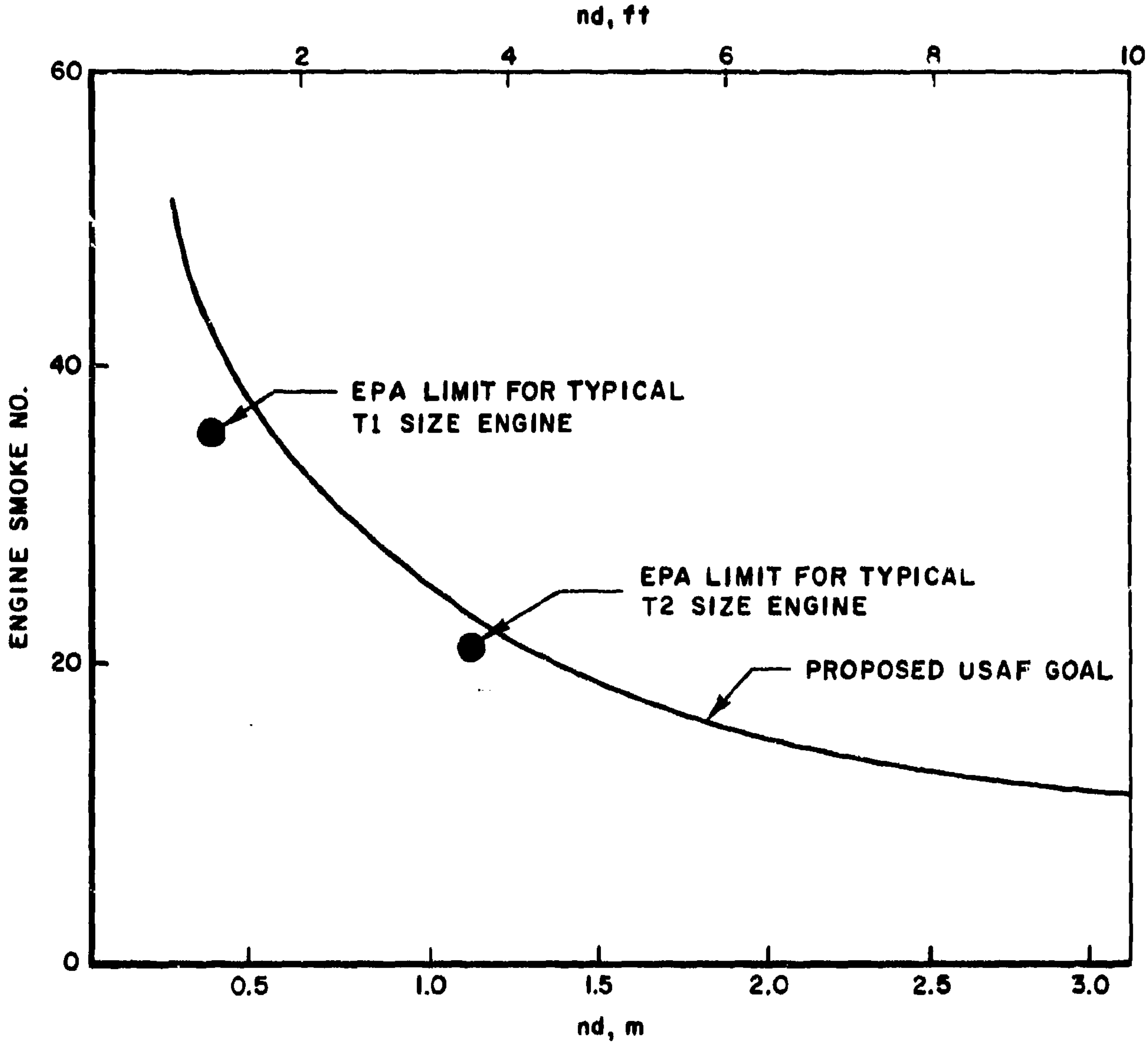



Figure 18: Proposed Air Force Smoke Goals Illustrating Correlation with EPA Limitations

goal is more stringent.

As more accurate correlations become available, appropriate substitutions will be made.

3. 1981 Goals

Proposed goals for engines qualified after 1981 and produced in significant quantities for the inventory have been written to be consistent in both time and emission level with mid-term technology expectations. These had not been proposed in the previous AFAPL publication.[Reference 3] Individual goals are outlined below:

a. Combustion Efficiency

CO and hydrocarbon levels are to be below levels which result in an idle combustion efficiency of 99.5% for engines with an idle pressure-ratio above 3:1, and a combustion efficiency of 99% for those engines with an idle pressure ratio below or equal to 3:1. Figure 19 illustrates the 1981 combustion efficiency goal.

b. Oxides of Nitrogen

Engines in systems for which combustor water injection has been determined to be feasible should again have as a goal the 75% reduction from the uncontrolled $NO_x$ emission level. For these which must depend on other hardware control techniques, the 50% reduction identified under the discussion of mid-term control technology can be expected. Therefore, the 1981 goal for $NO_x$ is a 50% reduction from the uncontrolled level. These are indicated in Figure 20.

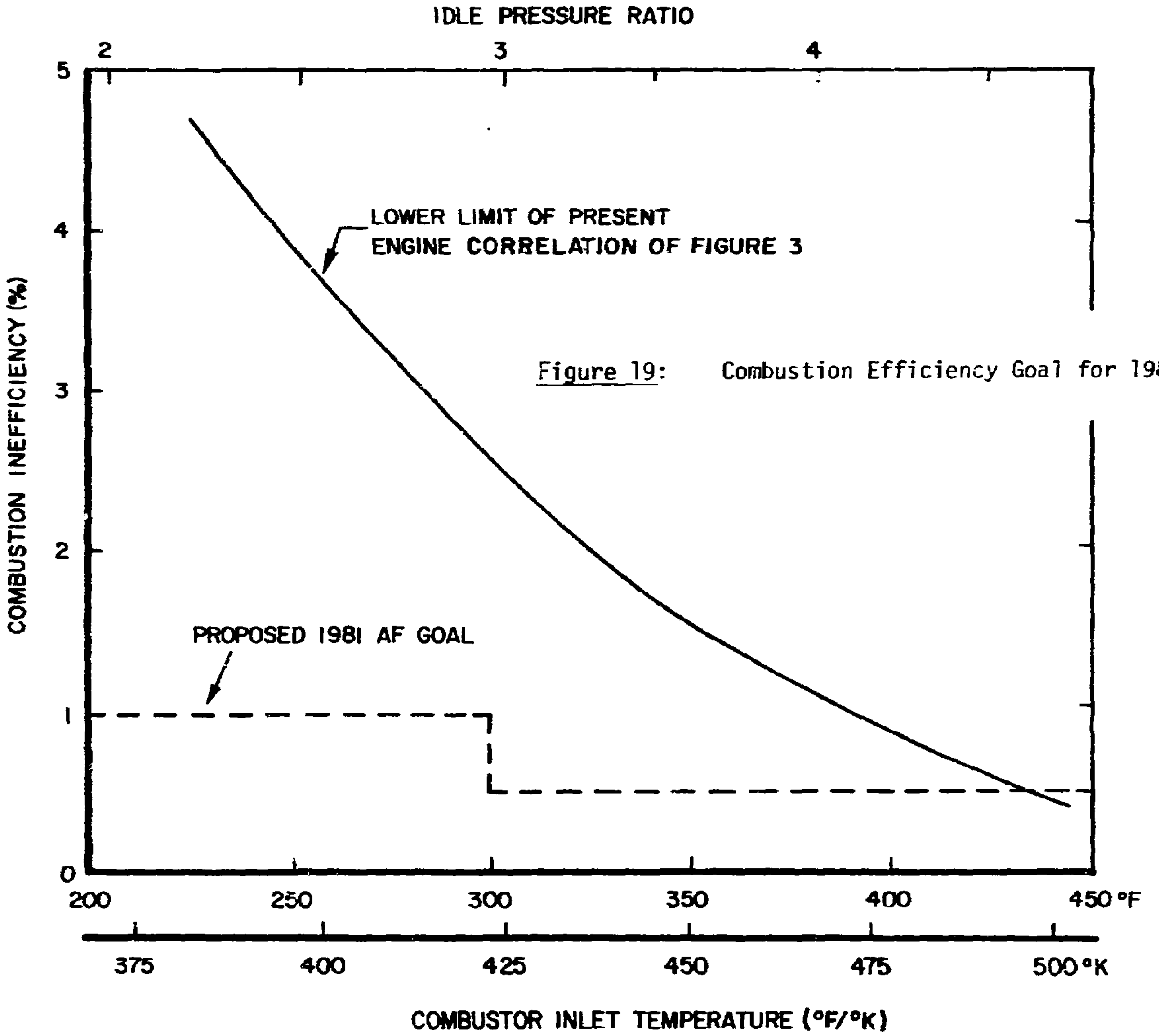



Figure 19: Combustion Efficiency Goal for 1981

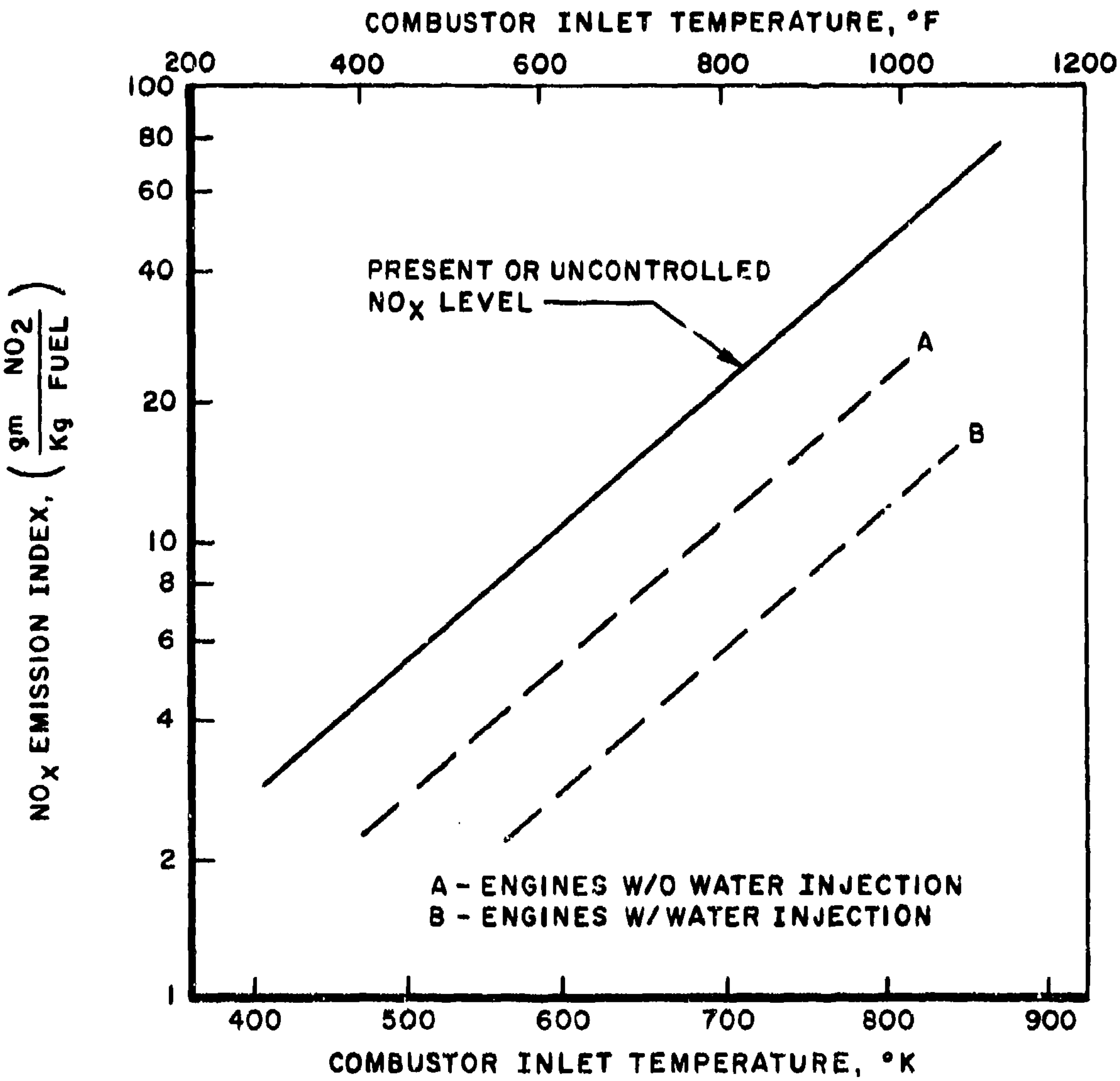



Figure 20: $NO_X$ Goals for 1981

c. Smoke

As the 1979 goal will achieve the basic objective of an invisible exhaust plume, the 1981 goal is identical to that of 1979 shown in Figure 18.

4. Advanced Technology Policy

The primary motivation for this work is the very substantial reduction of stratospheric $NO_x$ emissions--current EPA standards do not themselves require this technology to be developed. The proposed policy is that goals based on advanced technology not be established at this time because of the uncertainties in both feasibility of the advanced control techniques identified and extent of the stratospheric problem. However, research programs currently underway should be continued for possible transition to subsequent development programs should the need be identified.

5. Comparison of AFAPL Goals and EPA Standards

It is difficult to compare AFAPL and EPA emission limits because of the different methods used to express the goals and standards. The discussion below illustrates differences by selecting engines representati.e of EPA classes and translating the EPA standards into the AFAPL goal parameters. Engines used in the comparison have been chosen to illustrate a modern design and an older model. The engines are:

| EPA Class | Engine | Rated Power |
|---|---|---|
| T1 | J85<br>TFE-731 | 2,500 $lb_f$<br>2,800 $lb_f$ |

| | | |
|---|---|---|
| T2 | JT3D | 18,000 $lb_f$ |
| | JT9D | 45,000 $lb_f$ |
| P2 | TPE-331 | 590 H.P. |
| | T56 | 3,755 H.P. |

Table 13 illustrates the comparison.

In each case, some similarity in the combustion efficiency re-requirements are seen. However, the EPA required levels do not provide for the more difficult reduction problem associated with the lower pressure ratio designs, in particular the J85 and JT3D in the case of Table 13. This discrepancy may be justified in the commercial case by arguing that the intent of the EPA standards is to force lower emissions through engine design as well as low emissions combustor design.

$NO_x$ emissions reductions are seen to vary more widely. It is apparent from previous discussions that engines requiring more than a 25% reduction will not meet the standards unless water injection is applied. HT9D and JT3D engines (if still produced beyond 1979) must make use of the water injection technique to meet 1979 EPA $NO_x$ standards. On the other hand, it is apparent that the full extent of available technology will not be applied to other engines. In the case of turboprops, this may be justified from EPA's standpoint in that these engines will be in competition with piston engines; emissions limitations requiring any modification would slow transition from piston engines to cleaner, but more expensive, turboprop designs.

Smoke limits in both the EPA standards and AFAPL goals are intended to insure invisibility. Although different methods are used to establish the smoke limit corresponding to invisibility, comparison

TABLE 13

COMPARISON OF EPA AND AFAPL EMISSION LIMITATIONS

| EPA Engine Class | Engine and Manufacturer | IDLE COMBUSTION INEFFICIENCY, % | | APPROXIMATE REQUIRED $NO_xEI$ AT TAKEOFF | |
|---|---|---|---|---|---|
| | | 1979 EPA Req'd[1] | 1979 AFAPL Goal | 1979 EPA Required[1] | 1979 AFAPL Goal |
| T1 | J85 (General Electric) | 0.4 | 2.0 | 7.0 | 6.0 |
| | TFE-731 (AiResearch) | 1.12 | 1.0 | 10.0 | 10. |
| T2 | JT3D (Pratt & Whitney) | 0.8 | 2.0 | 7.0 | 10.5/3.5[2] |
| | JT9D (Pratt & Whitney) | 1.0 | 1.0 | 10.5 | 31.5/10.5[2] |
| P2 | TPE 331 (AiResearch) | 0.8 | 1.0 | 7.0 | 7.5 |
| | T56 (Allison) | 1.6 | 1.0 | 20.5 | 10.0 |

[1] EPAP (lb Pollutant/$10^3$ $lb_f$-hr-cycle) for CO and $C_xH_y$ have been converted to equivalent combustion inefficiency or $NO_xEI$

[2] If water injection can be applied, a 75% reduction is anticipated.

would show that AFAPL goals require more control of smoke because of the necessity to address the problem of sighting military aircraft at a distance (see Figure 18 for the case where n = 2).

6. Implementation of Proposed Goals

All the goals discussed above have resulted from a general assessment of technology as compared to average emission levels of current engines. Consequently, the goals are applicable to the average emission level of the engine being considered. This view is desirable from the enforcement standpoint because, once the engine has satisfied requirements, routine emission measurements of all production engines will not be required. However, details of the statistical proof to be required of the contractor in his claim that goals have been met cannot now be established. These should be set when better knowledge of 1979 measurement accuracy and cost, reliability of correction methods, and engine-to-engine variations are available.

Levels discussed above are intended to apply to emissions under standard-day conditions. In the case of $NO_x$ emissions, the uncontrolled levels have been established to be consistent with this detail--data obtained under this condition can be corrected to the proper level. Vatiations of idle emissions with ambient conditions are not well documented and correction factors for data obtained under other conditions are not available. Current Government-sponsored programs are investigating this problem. Smoke emissions are not especially sensitive to ambient conditions and, therefore, corrections are not thought to be necessary.

An answer to the question of ensuring continuing compliance must also be postponed because of present uncertainty in the extent of emission degradation with time. Current Government-sponsored programs are attempting to establish this factor. Should continual periodic monitoring be necessary, a significant logistic and cost effect would result.

Finally, it should be noted that emission standards/goals discussed herein are based on the use of standard JP-4 fuel. Since there is the possibility that significant changes in fuel composition may result from current oil shortages, a future reassessment of pollution limitations may be required. For example, if future jet fuel is refined from oil shale, aromatic content may increase beyond 50% (below 20% in today's JP-4 jet fuel).[Reference 52] Hence, significant changes in emission characteristics may arise.

## SECTION VIII

## USAF COST BREAKDOWN

This section is intended to review the USAF systems affected and to summarize the cost impact to each system. Basically, four engines currently in engineering development or production are expected to be produced in significant quantity in the post-1979 time period. These will, therefore, be affected by the 1979 goals mentioned in the previous section. These are:

1. F101-GE-100
2. F100-PW-100
3. J85-GE-21
4. TF34-GE-100

Possible additions to this list are an advanced turbofan engine of the 20,000 $lb_f$ thrust class (ATE), a lightweight-fighter propulsion system and a large turbofan engine of the 50,000 $lb_f$ thrust class (F103).

A summary of the emission characteristics of the four existing engines is given in Table 13. The F101 engine is seen to already meet the goals proposed for engines produced after 1979. Recall that the improved levels of the F101 engine served as the basis for establishing some of the 1979 limits. However, the F100, J85 and TF34 will require modification.

If the proposed goals are adopted, the F100, J85 and TF34 engines

## TABLE 14

## STATUS OF ENGINES AFFECTED BY PROPOSED GOALS

| Engine | Idle Pressure Ratio | SLTO[1] Combustor Static Inlet Temp. (°K) | Engine Exhaust Diameter (m) | Number of Engines, n | Idle Combustion Efficiency (%) | | SLTO[1] $NO_x$ Emission Index | | SLTO[1] Smoke Number SN | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Goal | Current Status | Goal | Current Status | Goal | Current Status |
| F101 | 4.0 | 818. | 0.8 | 2. | 99 | 99.5 | 40.0 | 23.9 | 18. | 22. |
| F100[2] | 4.4 | 800 | 0.635 | 2. | 99 | 99.3 | 36.5 | 44.0 | 22 | 36. |
| TF34* -100 | 2.7 | 721. | 0.73 | 2. | 98 | 95.9 | 20.5 | 19.5 | 20. | 12 |
| J85[3] -21 | 1.56 | 555 | 0.33 | 2. | 98 | 92.3 | 6.5 | 6.5 | 33. | 20 |

*Emissions levels based on corrected data from Reference 55 for TF34-2.

[1] Sea-level take-off power setting.

[2] Emissions levels based on corrected data from Reference 53 and on Reference 54.

[3] Emissions data based on corrected data from Reference 16 for J85-5.

will require some combustor redesign starting with a component improvement program (see Figure 14). Recalling the cost figures previously mentioned (Table 7), this indicates an average total cost to develop low emissions techniques per system of approximately 10 million dollars. It should be noted, however, that not all systems will require the same extent of modification. For example, the TF34 may satisfy the requirements with a fuel distribution modification in addition to increased compressor bleed. On the other hand, the J85 may require substantial modification exceeding the $10 million estimate.

Two of the engines mentioned previously, the lightweight fighter and large turbofan (F103) system, have already been developed to the point where a redesign or component improvement effort would be necessary. Consequently, if production beyond 1979 seems likely, combustor development programs should be implemented. This raises the possibility of two additional $10 million program. However, in the case of the F103 system, combustor development programs addressing the EPA standards (the commercial version of this engine is the CF-50) will provide the necessary hardware.

Engines which have not yet begun development (the ATE) will not require the funding discussed above. Any additional cost would be accounted for in the basic engine development program. Further, this will be the case for engines which are conceived in the next few years and certified before 1981.

The 1981 goals address engines certified after that date. It is further noted that only engines produced in significant quantity should be required to provide the further phase of emission reduction. Basically, this will affect engines for which development begins after 1977. By this time, exploratory development programs will have yielded the mid-term control technology required to meet these goals. It should be noted that if these exploratory programs are not begun by FY75, mid-term technology will not be available. Current Government-supported programs are underway or planned for most of the engine types which must be addressed. A significant exception, however, involves low pressure ratio engines intended mainly for supersonic applications. The AFAPL has formerly identified the need for such a program; however, funding has not yet been made available. Subject to the extent of design sophistication required, this R&D program could cost as much as $2 million, consistent with costs reflected under Table 7. The above conclusions summarize costs expected from application of the proposed AF goals.

It is difficult to evaluate increased combustor production costs for the 1979 and the 1981 goals because of uncertainties of the design to be used. An approximation of a 0-25% production cost increase for current technology and a 0-50% cost increase for mid-term technology was previously projected. Further, recall that combustor costs have a relatively minor effect on propulsion system expense and that future systems will most likely employ designs similar to low emissions configurations. Consequently, on a qualitative basis the production cost impact is minor.

Research to develop advanced concepts is underway. A number of Government-supported programs are pursuing different methods of achieving ultra-low emissions. Although this work should continue, no additional Air Force support is required.

The final issue to be discussed in this section involves low-smoke combustor retrofits of current systems to reduce tactical vulnerability with commensurate reduction in esthetic nuisance. This will involve systems no longer in production which are not affected by the goals discussed herein. Engines for which smoke retrofits may be considered are listed in Table 15. Current technology implementation costs discussed in Section VI of $10 million for development and $10 thousand per engine can be forecasted for each engine system indicated. It should be noted, however, that a production cost far less than $10,000 per engine is possible if the combustor modification required results in a simple hardware change. This was the case for the JT8D smoke retrofit. Upper estimates of total costs for a fleet-retrofit of each engine system are summarized in Table 15. Retrofit of the higher-usage engines listed would cost approximately $265 million.

All costs discussed in this section are summarized in Table 16.

TABLE 15

SMOKE RETROFIT COST SUMMARY

| Engine | Inventory | Year Introduced Into Inventory | Total Cost ($ Million) |
|---|---|---|---|
| J57 | 10,475 | 1956 | 115. |
| J79 | 4,709 | 1961 | 48. |
| T56 | 3,533 | 1958 | 45. |
| TF30 | 2,672 | 1965 | 37. |
| TF33 | 1,831 | 1961 | 20. |
| | | TOTAL PROJECTED RETROFIT COST: | $265 MILLION |

TABLE 16

OVERALL COST SUMMARY

| Program | Cost ($ Millions) |
|---|---|
| Research for Ultra-Low Emissions (Advanced Concepts) | Continued Current Effort |
| Exploratory Development for Low Pressure Ratio Engine Combustors (Mid-Term Technology) | 2.0 |
| Exploratory Development for Other Engine Designs (Mid-Term Technology) | Continued Current Effort |
| Control Technology Development to Meet Proposed 1979 Goals (Current Technology) | |
| F100 | 10.0 |
| TF34 | 10.0 |
| J85 | 10.0 |
| ATE | 0.0 |
| Advanced Lightweight Fighter | ? |
| F103 | ? |
| Smoke Retrofit Program (Current Technology) | 265.0 |

## SECTION IX

## SUMMARY AND CONCLUSIONS

This report presents information thought to be necessary in establishing an Air Force policy on aircraft engine pollution. Before considering specific issues, however, the following general remarks are appropriate.

a. EPA standards do not currently address military engines. It is recommended that the legal requirements or lack thereof bearing on military compliance be formally established.

b. No conclusive air quality assessments of Air Force Bases are available. An urgent need to control emissions has not yet been uncovered. Air Force Weapons Laboratory efforts to qualify the effects of air base operations on air quality are critical.

c. Military relevancy beyond the question of basic air quality violations are addressed introducing additional complexities requiring consideration. For example, the strong history of military engine conversion to commercial use could be affected if the Air Force elects not to require any emissions limitation policy.

d. EPA standards for future supersonic commercial aircraft which use afterburners are being considered. Military aircraft today account for practically all afterburning engine usage. However, because of the uncertainties in both the extent of pollutant emissions and the resulting impact of afterburner emissions, goals have not been developed for this mode of operation. The goals described in this report apply to non-afterburning turbopropulsion engines and afterburning turbopropulsion engines operating in the non-afterburning mode.

e. Programs to develop low smoke combustors for engines already in use (retrofit program) should be considered primarily from the point of view of reducing tactical vulnerability. Appropriate cost-performance tradeoff analyses should be conducted on a system-by-system basis. An estimated expense of up to $265 million to retrofit the Air Force engine fleet cannot be justified on the basis of reduction of esthetic nuisance.

f. Piston engines should not be formally regulated because emissions by military engines of this type are relatively insignificant. Although future procurements should make use of emission controls developed in the commercial sector, no Air Force expenditures in this area are justified.

g. Elimination of engine fuel venting for in-use systems or development of APU/drone/RPV emission controls is not considered cost effective (costs are not commersurate with environmental benefit) and should not be undertaken for military aircraft engines.

The following discussions address six specific questions or impact subjects.

a. USAF Compliance with EPA Standards

The possibility of Air Force aircraft complying with existing Environmental Protection Agency standards for turbopropulsion engines has been evaluated. The following guideline was considered in the evaluation: in no case shall pollutant controls be allowed to infringe on military engine design or operation in a manner which compromises system effectiveness.

It is recommended that the Air Force not elect to comply with the EPA standards thenselves, but rather follow the proposed goals outlined in paragraph b., below. This recommendation is based on the following: (1) the EPA method of specifying emissions involves complicated trades which can affect basic engine design, thus violating the guideline mentioned above; (2) the characteristics of engine usage are involved in the EPA specification in a manner meaningful only in commercial considerations where scheduling and specified operating procedures lend regularity to idle, taxi, and other modes of operation; and (3) in light of recent emission control technology programs, it now seems doubtful that all EPA limitations will be achieved without some compromise in propulsion system effectiveness.

b. Compliance with Proposed AFAPL Goals

Air Force compliance with the AFAPL goals outlined below is recommended. A revision to the military turbine engine specification (MIL-E-5007D) is suggested as a means to effect this recommendation. This will provide the Air Force with goals which require application of emissions reduction technology paralleling that required of the commercial sector to the extent possible. The most apparent differences between the two sets of limitations involve method of specification. Parameters have been chosen which allow emission reduction without requiring basic engine design trades. The proposed goals are in terms of idle combustion inefficiency, oxides of nitrogen emission index (gm $NO_x$/kg fuel) and SAE smoke number. Allowable idle combustion inefficiency and oxides of nitrogen emissions are a function of the engine thermodynamic operating cycle. Maximum allowable smoke number is specified as a function of exhaust nozzle diameter.

In addition to the use of other methods of specifying emission limits, the proposed AFAPL goals differ from the EPA standards in the actual levels of reduction required. This is due to the more recent AFAPL technology assessment conducted in response to an Air Force Staff inquiry. Goals previously specified in AFAPL-TR-72-102 have been adjusted accordingly.

Goals have been established by considering three levels of technology. Emission goals for 1979 have been developed which will require existing control techniques (current technology) to be applied. Goals intended for engines qualified after 1981 have also been developed, constituting best estimates of technology now in the exploratory development phase (mid-term technology). It is recommended that emission goals for techniques presently in the research stage (advanced concepts) not be established at this time. The dates chosen for effecting the goals have been from a careful assessment of current control development programs and the engine development process.

EPA standards and AFAPL goals are compared in this technical report. In summary, carbon monoxide and hydrocarbon limits are in approximate agreement where future commercial engines are considered.

However, lower pressure ratio engine designs are not likely to comply with the EPA standards, while the AFAPL goals afford allowances for the difficulties to be encountered by such designs. EPA and AFAPL $NO_x$ emission limits differ appreciably as a result of the more recent AFAPL technology assessment and the apparent EPA acceptance of water injection as a control technique. In both cases, limitations on smoke emissions are oriented toward specification of emission levels which ensure invisibility; AFAPL smoke limits are based on reasoning which gives increased confidence over the EPA method.

c. Compliance for Specific Engines

Four engines currently in engineering development or production are expected to be produced in significant quantity in the post-1979 time period. These will, therefore, be affected by the proposed 1979 AFAPL goals. The engines affected are the F101-GE-100, F100-PW-100, TF34-GE-100 and the J85-GE-21. Possible additions to this list are an advanced turbofan engine of the 20,000 $lb_f$ thrust class (ATE), a lightweight-fighter propulsion system and a large turbofan engine of the 50,000 $lb_f$ thrust class (F103). All engines, however, will not require the same degree of emissions control to meet the proposed goals. In fact, the YF101 (PFRT) already meets the goals while the J85 will require substantial improvement. Furthermore, if the ATE development were approved, emissions limitations could be a part of the initial development procurement package.

Emission goals for 1981 address engines qualified after that date.

This will involve engines for which development begins on or after 1977. Control technology development programs are underway for most of the engine types, the exception being the low pressure ratio engines intended for extended supersonic applications. Development beyond the exploratory phase would be part of the initial development procurement package.

d. Funding Requirements

An estimate of the total aircraft engine emissions reduction cost to the Air Force can be itemized into the following categories: (1) current technology applied to systems already designed and/or operational; (2) current technology applied to new system developments; (3) mid-term technology applied to new system developments; and (4) advanced concepts applied to new system developments.

Category (1)

The F100, TF34 and J85 engines described in the previous section would require a component improvement program process. Cost variation from engine to engine will be significant because of the wide scope of control technique complexity anticipated. Nevertheless, it is estimated that a program approximating the following will be necessary in each case. The costs represent an average for the systems involved.

| Program | Duration (Yrs) | Yearly Cost ($M) |
|---|---|---|
| Advanced Development | 2.0 | 3.5 |
| Hardware Certification | 1.0 | 0.5 |

| | | |
|---|---|---|
| Flight Test | 1.0 | 0.5 |
| Production Tooling | 1.0 | 2.0 |

Category (2)

Engines in a situation similar to the ATE will have the above costs borne in the engine development program itself. In addition to program costs, supplemental production costs of current technology control techniques may be involved. These have been estimated to range from 0-25% of the original combustor cost.

Category (3)

Mid-term technology is required for engines qualified and produced in significant quantity after 1981. In all cases, the engine development program should provide the resources for all development phases beyond exploratory development. Current Government-sponsored programs will provide technology for all engine types except the case of the low pressure-ratio designs intended for supersonic application. The latter technology development program is estimated to cost $2 million. Supplemental production costs for these new designs are difficult to assess because of the current uncertainty in complexity. Nevertheless, a general assessment indicates increased combustor costs of approximately 50%. It should be noted that combustor concepts being examined for low emissions also bear significant similiarities to those advanced concepts being designed for optimized performance in future systems. Further, it is recalled that combustor cost is approximately 3% of the propulsion system production cost; consequently, even large fractional changes in combustor development and production costs do not seriously affect engine costs.

Category (4)

Just as goals for advanced concepts are not possible to formulate at this time, the attendant cost impact of these system changes cannot be projected. Much further concept feasibility demonstration will be required before either goals or costs can be estimated.

The table given below summarizes approximate RDT&E costs expected from application of the proposed AFAPL goals. Certain costs for specific engines (systems definitely considered) plus the necessary exploratory development amount to $32 million.

- Development Programs to Reduce Engine Emissions for 1979 Goals

| | |
|---|---|
| F100 | $10. M |
| TF34 | 10. |
| J85 | 10. |
| Other Engines | ? |

- Exploratory Development Programs Oriented Toward 1981 Goals

| | |
|---|---|
| Low Pressure Ratio (Supersonic Application) | $2.0 M |
| Other Engine Types | No Additional Support Required |

| | |
|---|---|
| • Research on Advanced Concepts | No Additional Support Required |

Finally, programs currently underway throughout the Air Force to better characterize the problem, to develop better measurement and control methods and to conduct other fundamental studies should be continued at current levels. Many of these programs have been mentioned in this technical report.

e. Operational Capability Impact

Both 1979 and 1981 goals have been developed with the thought of not affecting operational capability. The fundamental methods of specification have been chosen so as not to influence selection of engine thermodynamic cycle parameters. Further, levels are consistent with control technology thought to have no significant effect on performance parameters.

Current technology techniques do not involve exotic designs but rather involve the most modern combustor design philosophy (i.e. the F101 combustor design). In some cases, the techniques involve even fewer alterations like fuel sectoring or increased compressor bleed at idle power settings.

Mid-term technology currently under development offers further emissions reduction, but with some increase in design complexity. Proposed techniques have been evaluated and goals are consistent with expected emission levels for designs where performance impact is not significant.

Advanced concepts cannot yet be evaluated from the operational capability standpoint.

f. Maintenance and Logistics Requirements

Any combustor design change incorporated for emission control must exhibit good maintenance and logistics characteristics. The change must be easily accommodated by the engine overhaul centers relative to repair and/or replacement, must not require significantly increased resource expenditure or logistic ground support and must meet safety-of-flight criteria.

In general, current technology control techniques have already been judged to have minimal impact on maintenance factors. Mid-term technology impact is difficult to assess because detailed designs and/or operational experience is not yet available. Nevertheless, it is certain the increased complexity will have some impact. The 1981 goals have been developed to minimize use of the more complicated techniques, like variable geometry, which might be expected to have significant impact. Advanced concepts cannot be evaluated because of the lack of available information.

Increased fuel costs for both current and mid-term technology will be minimal. Cruise and full power SFC will not be influenced through changes in basic engine cycle, combustion efficiency considerations or other influences on combustion system performance. Idle SFC will increase slightly for those current technology approaches which depend on increasing the compressor discharge temperature for more favorable combustion conditions (increased compressor bleed, increased engine idle power setting, and changes in engine idle cycle characteristics are in this category). The overall impact of these changes on

SFC would be minor--25% increase in idle fuel flow would decrease range by about 0.5% for a mission of two hours duration. It should further be noted that use of these techniques can easily be eliminated during periods when performance/range compromises cannot be tolerated; i.e., national emergencies. Mid-term technology methods employ techniques which are expected to have little or no fuel consumption penalty.

One technique to reduce oxides of nitrogen emissions through water injection during takeoff and climbout does have significant logistics support impact. Special tankage, plumbing and valve control systems will be required with their inherent weight penalties. Because required water flow rates would be approximately equal to that of the fuel, substantial quantities of water would be required. The water must be demineralized to prevent deposition in the engine hot section. Moreover, water injection techniques must be carefully designed to insure against severe combustor and turbine thermal stresses which would arise from poor water distribution. Consequently, these problems have resulted in this technique being listed only as an optional means for emissions control--at the discretion of the responsible SPO and the using command.

It is recognized that the current energy crisis may have a dramatic impact on many emission control techniques presently being considered. Therefore, in that significant changes in fuel composition may result from current oil shortages, a future reassessment of pollution limitations may be required.

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