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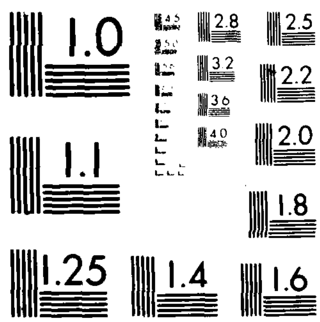

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A CRITICAL REVIEW

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ENVIRONMENTAL SCIENCES BRANCH

SEPTEMBER 1979

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This report is a comprehensive summary and analysis of proposed aircraft turbine engine air pollution regulations and their relevance to the USAF. Existing USAF aircraft turbine engine emission goals are critically reviewed, and revised goals are proposed. The original goals contained emission standards and compliance dates; the proposed goals contain neither. The authors believe that the goals should be set to provide an incentive for emission reduction and should not be numerical standards

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20. ABSTRACT (Concluded)

and dates, which may or may not be met. The proposed USAF goals cover the critical turbine engine emissions. Carbon monoxide and oxides of sulfur are not considered serious problems at today's emission levels, while smoke and hydrocarbon emissions appear to warrant the highest priority for reduction. Although cost effective oxides of nitrogen control (NO_x) is viewed with pessimism, it is concluded that NO_x reduction deserves continued USAF research.

EXECUTIVE SUMMARY

When the USAF set forth the aircraft exhaust emissions goals in 1975, they contained the statement, "Accordingly, the goals established by this memorandum should be periodically evaluated to insure support of national environmental objectives."

This report is the evaluation of the original goals study. The report is composed of three general segments:

(1) The need and rationale for evaluating USAF aircraft engine emission goals.

(2) The USAF aircraft engine emissions goals.

(3) The effect the USAF aircraft engine emission goals will have on the Air Force.

The first segment discusses the situation existing when the first goals were proposed and the changes that have occurred since that time. Major changes have occurred in several critical areas:

(1) Control technology concepts have advanced and new technologies have come into being.

(2) Air quality models have been applied to USAF bases.

(3) The Environmental Protection Agency (EPA) has proposed extensive revisions to the original gaseous pollutant regulations. In general the proposed regulations are less restrictive (both quantities and enforcement dates) than the previous regulations.

The USAF goals are extensively reviewed as written. The fact that the 1975 goals are not being met by today's USAF aircraft is pointed out.

The original goals contained emission standards and compliance dates. The proposed goals contain neither. The authors believe that the goals should be set to provide an incentive for emission reduction and should not be numerical standards and dates, which may, or may not, be met. In summary, the proposed USAF goals cover the critical turbine engine emissions:

(1) Carbon monoxide is not a serious problem at today's emission levels. Any further reduction should be incidental while reducing hydrocarbon emissions.

(2) Hydrocarbon emissions are a concern and considerable additional development is necessary before practical reductions may be achieved.

(3) Oxides of nitrogen are still being studied to determine the severity of the emission problem. The USAF should continue efforts to reduce NO_x emissions.

(4) Smoke is a serious problem and will probably become more of a problem if fuel changes occur. Invisible smoke emissions is the only acceptable goal.

(5) Oxides of sulfur are a potential problem if the level of sulfur in jet fuel increases dramatically from the current low levels.

The effect that the proposed USAF goals will have on the Air Force hopefully will not be a major change from present operations. They definitely will serve as a guide for all operations from research through acquisition. If they are adopted, the USAF will continue to again demonstrate its leadership role in environmental protection. Several factors are discussed that are of interest to the USAF:

(1) Costs and cost-effectiveness of emission controls are of critical concern. The cost of engine with emission controls will be more than the cost for an uncontrolled engine. USAF costs will parallel those of commercial aircraft.

(2) The control of emissions from USAF engines should in no way interfere with the USAF mission. Operational capability, reliability, and ease of maintenance are still the guiding criteria.

(3) The technology of emission minimization must be continually advanced. The funding for research and development should be considered as top priority.

(4) The USAF turbine engines in current use do not meet the proposed EPA rules. However, USAF aircraft are exempt from proposed EPA aircraft emission regulations.

(5) The USAF needs to continue extensive research on emission reduction but should not neglect other areas of investigation such as changing landing and takeoff cycles, etc.

(6) The USAF must continue basic research in areas of combustion, smoke formation, etc.

(7) Variability of emissions is an area where more research is necessary to evaluate the data being reported on emissions.

Recommendations for the future conclude this study. A continuing review of USAF goals is suggested. Cooperation with, and support of, other government agencies, industries, consultants, and universities is emphasized as a necessity.

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PREFACE

This report was prepared by HQ AFESC Engineering and Services Laboratory (ESL), Tyndall Air Force Base, Florida. This work was accomplished under Job Order Number 19007001; Dr Richard W. Boubel and Maj Joseph A. Martone were the project officers.

This report is a comprehensive summary and analysis of proposed aircraft turbine engine air pollution regulations and their relevance to the USAF. The report is intended to stand by itself bringing together pertinent information from many and often obscure sources. Special attention is given to the existing USAF aircraft emission goals and revised goals are proposed. The work was conducted within the framework of Air Force Regulation 19-1 which established the current USAF aircraft emission goals and mandated their periodic review. The report recommendations do not represent Air Force policy or philosophy but can be used by USAF policy makers to decide if, when, and how to modify existing USAF aircraft emission goals. The report is a valuable primer for USAF personnel who need thorough familiarization with USAF concern for aircraft turbine engine pollutant emissions.

The principal author, Dr Richard W. Boubel, performed this work as a temporary USAF employee while on sabbatical leave from Oregon State University. Dr Boubel is a noted air pollution control authority as evidenced by his position as President of the 7,000 member Air Pollution Control Association from June 1978 to June 1979. The USAF was very fortunate to have his wealth of experience brought to bear on a very important and difficult Air Force issue. Even though Dr Boubel was technically a USAF employee during preparation of this report, his viewpoints and findings are the result of independent thought by a leader in the field of air pollution control.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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SECTION I

PURPOSE OF THIS REPORT

The Air Force established turbine engine goals in a Memorandum, dated 11 June 1975, from the Secretary of the Air Force (Reference 1). These goals were based on information available to the Secretary at that time. In his cover letter, the Secretary stated,

> "In keeping with the intent of the Clean Air Act Amendments of 1970, goals for control of Air Force aircraft engine exhaust emissions are hereby established. Recognizing the existence of Environmental Protection Agency standards for commercial aircraft and the essentiality that emission controls applied to Air Force engines not infringe upon flight safety and combat effectiveness, the attached goals are established for turbofan, turbojet, and turboprop engines beginning development subsequent to the date of this memorandum.
>
> Engines currently in development and which will be in substantial production after January 1, 1979, will be modified/retrofitted if engineering/cost studies indicate such modification/retrofit is warranted. Piston engines and engines used for remotely piloted vehicles, auxiliary power units, and rotary wing aircraft are exempt from these standards; however, future procurements should take advantage of emission control advancements.
>
> Adherence to these goals is not only in keeping with the Clean Air Act Amendments of 1970, but will also demonstrate the Air Force's commitment to fully comply with the 'United States Air Force Pledge to Environmental Protection.' Accordingly, the goals established by this memorandum should be periodically evaluated to insure support of national environmental objectives."

Since the statement of these goals, many changes in control technology, models, regulations and environmental/energy considerations have occurred. This report is a critical review of the goals with reference to the changes which have taken place since the goals were established. It is meant to be inclusive and therefore, to stand alone. Thus, it contains a considerable amount of material, from other sources, which is important background material. This report addresses the emissions of carbon monoxide, hydrocarbons, oxides of nitrogen, and smoke covered by the original goals. It also addresses the emission of oxides of sulfur which may become a concern.

1.1 Need for Periodic Evaluation of Goals and Related Standards

The memorandum establishing the Air Force turbine engine goals (Reference 1) recognized that a review of the goals was necessary to assure that they were kept current. This report is the first review of the goals established in 1975. No time schedule was established for review or evaluation; however, four years does appear to be a reasonable interval.

Review and evaluation at this time seems particularly timely in view of the Environmental Protection Agency (EPA) Proposed Revisions to Gaseous Emissions Rules for Aircraft and Aircraft Engines (Reference 2) which are being studied for adoption. These rules would establish levels of emission of pollutants for commercial aircraft engines and could relate to turbine engines available to the Air Force.

1.2 Review of Improvements in Control Technology

Since the establishment of the original Air Force goals, several millions of dollars have been spent on research to reduce emissions from turbine engines. A significant percentage of this research has been funded by the Air Force. Many of these programs are covered in detail later in this report. Since the EPA proposed rules have been promulgated considering the latest control technology, it is equally important to consider the effect of this technology on the Air Force goals. In some cases, reduction in pollutants has not been so great as predicted from the research in progress four years ago. In these cases, it may be desirable to recognize, and re-evaluate, the actual level of pollutants emitted from today's production engines.

Not all emission reduction technology is applicable to military aircraft. The guideline which is considered of greatest importance to the Air Force is: "in no case shall pollutant controls be allowed to infringe on military engine design or operation in a manner which compromises system effectiveness." (Reference 3)

1.3 Review of Mathematical Models

In the four years since the establishment of the original Air Force goals tremendous progress has been made in modeling aircraft emissions and their concentrations in the receiving environment. On the other hand, some models of the atmosphere and atmospheric reactions have been discarded and entirely new models proposed during this four year period. In other cases, models that were assumed to be nearly operational are still being revised and may be farther from application than they were four years ago.

1. Airport Models

The original report by Blazowski and Henderson (Reference 3) which was the basis for the USAF goals stated,

> "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 quantify the effects of air base operations on air quality are critical."

In fact, at the time of the original goals promulgation, only a few models of the impact of aircraft on the airport environment had been reported (Reference 4).

During the four-year interval, since the original goals, several additional models have been developed including several specific for Air Force bases. These USAF models are still being evaluated and revised but they do document the general situation at military airports.

1.3.2 Atmospheric Models

Atmospheric dispersion modeling has been subject to active review over the last few years. Several recent conferences and discussions (Reference 5) have been held with special reference to the inconsistencies of the methods and their limitations in application to real flows which usually do not conform to the ideal form assumed.

Questions concerning the conversion of NO to NO_2 are still being studied. This is a complex atmospheric chemistry process depending upon many factors, not all of which can always be evaluated. It does appear at this time that the available models generally used to predict NO_x in the atmosphere overestimate the amount and that the NO is usually greatly dispersed and not oxidized to NO_2 (Reference 6).

1.3.3 Stratospheric Models

The primary concern with emissions to the stratosphere from aircraft is the amount of oxides of nitrogen. Modeling of the effects of NO_x emissions in the stratosphere are confused by lack of firm data concerning reactivity, oxidation, dispersion, and conversion. Rather than being closer to the answers today than we were four years ago, the opposite is the case. It is because of this lack of specificity that oxides of nitrogen emissions from turbine engines are still being evaluated today and no standards are being proposed to take effect until 1984.

1.4 Engine Developments Pointed Towards 1981 and 1984 Standards

When the original Air Force goals were proposed, it was assumed that the EPA would establish emission standards in 1979. The EPA has since proposed rules for compliance by January 1981 and January 1984. It is further apparent that engines manufactured in 1981 and 1984 will probably be the same engines currently being produced with only minor modifications. It is possible that by 1984 the Air Force may be using a completely new model of engine but even such a new model will probably be very similar, from the combustor standpoint, to today's engine.

Concepts being promoted to lower emissions of commercial aircraft engines, such as sector burning and changes in bleed air, will probably not be operational as far as the Air Force is concerned. If major changes are required in the core engines to meet the "1984 standards" it is probable that the "standards" will be re-evaluated as the 1984 date approaches and a more realistic date proposed. A change in the core engines to meet future commercial emission standards would probably result in the Air Force adopting these engines rather than developing a separate line of engines. This is based upon the requirement, however, that the Air Force will not compromise system effectiveness.

1.5 Need for Critical Evaluation

A critical evaluation should be based upon the knowledge and facts that exist at a point in time. Therefore, the facts and knowledge can be expected to change with time. It is important to establish the facts and state of knowledge in existence before establishing the goals which really are the end result.

1.5.1 Need for Control of Pollutants

By definition, "pollutants" are undesirable and hence should be "controlled". Whether this control should be elimination, minimization, or reduction to some acceptable level is debatable. The most realistic approach is to base the need for control on the level of the individual pollutant which is acceptable - or possibly that level which optimizes the benefits to mankind and the total environment. The EPA has established primary ambient air quality standards for several pollutants, based on health effects, and secondary ambient air quality standards, which are usually more restrictive and are based upon aesthetic effects.

Particulate Matter. Particulate matter is defined as either a liquid or solid at ambient conditions. It can be suspended in the atmosphere (an aerosol) or fall from the atmosphere due to gravity (dust fall). Particulate matter can be inorganic or organic, crystalline or amorphous, of any color or refractive index. Currently standards exist for Total Suspended Particulate (TSP) in the ambient air and the EPA is considering an additional standard for "fine particulate" which is currently defined as that less than 15 microns in diameter.

Smoke. Smoke is particulate matter generated by combustion processes. It is usually of small size (less than 1 micron) and highly visible because it is of the ideal size to absorb and scatter visible radiation. Smoke is usually determined to be of an acceptable level (or unacceptable level) based upon visual observation of the plume. If the plume is so dense that it will not transmit a certain percentage of incident visible radiation it is said to have too high an opacity value and is unacceptable.

Carbon Monoxide. Carbon Monoxide (CO) is a colorless, odorless gas which is considered a pollutant because it causes health effects in humans. At levels below the health effect threshold value, it cannot be considered as a pollutant. The need to control carbon monoxide only exists in cases where the level will exceed the ambient standard if it is not controlled. Carbon monoxide is very stable in the lower atmosphere and follows classical diffusion/dispersion patterns.

Hydrocarbons. Hydrocarbons are any organic chemical which may be emitted to the atmosphere. They may be designated as HC, UBHC (unburned hydrocarbons), or C_xH_y. None of these designations are technically proper because organic chemicals generally are composed of more than just atoms of carbon and hydrogen. For consistency, the designation HC will be used throughout this report. Hydrocarbons may be a problem because they can be partially oxidized tc form odorous or irritating compounds. They may also be a problem as they enter the photochemical cycle when some of them serve as precursors of ozone or free radicals. Hydrocarbons are generally considered as undesirable because they can react and exhibit their harmful effects away from the point of their release. They are an area problem and must be evaluated as such.

Oxides of Nitrogen. Oxides of nitrogen (NO_x) are generally considered as nitric oxide (NO) or nitrogen dioxide (NO_2) but other oxidation states exist. NO_2 is considered as a primary pollutant because of health effects at high concentrations. EPA is currently considering short term standards for NO_2 in ambient air to limit its concentration (Reference 7). NO_2 is also a secondary pollutant because it can be photoreduced by ultraviolet radiation to form NO and a free radical oxygen atom. The free radical oxygen atom can react with the oxygen molecule to form ozone or can react with some hydrocarbon molecules to form partially oxidized organics which may be irritating or odorous. NO is a problem because it can oxidize to NO_2 in the ambient air because of combination with molecular oxygen, ozone, or the free radical oxygen atom. Reduction in the emission of oxides of nitrogen results in a probable reduction of photochemically generated air pollution.

Oxides of Sulfur. Oxides of sulfur (SO_x) are classed together, regardless of their oxidation state, because they may be oxidized or reduced in the ambient air. Sulfur dioxide (SO_2) is a primary pollutant which can cause health effects if in sufficient concentration. SO_x can cause environmental damage as it is removed from the atmosphere by rain or snow. The SO_x can be converted to either sulfates or sulfuric acid depending upon the atmospheric chemistry occurring between the time of the SO_x release and the scavenging by precipitation. The end result is "acid rain" which can cause a critical pH shift in the receiving environment.

1.5.2 Air Pollution Caused by Gas Turbine Aircraft

The material in this section is covered thoroughly by Blazowski and Henderson in their 1974 report (Reference 3). Their material, with minor modifications and updating, is included because of its relevance toward understanding the Air Force goals.

To better understand the ways in which aircraft engines produce pollutant emissions, the following subsections discussing the fundamental chemical and thermodynamic processes are included. Separate consideration of main engine types of interest (non-afterburning and afterburning turbines) are given.

1.5.2.1 Non-afterburning Turbine Engines

The non-afterburning turbine engine has received by far the most attention in characterization of emissions. The non-afterburning 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 HC 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. The sulfur content of current JP-4 fuel is low (usually less than 0.05 percent by weight) and, therefore, SO_x emission is not now considered to be a serious problem. Emitted particulates are composed largely of carbon; the principal problem is one of defining, for specifica-

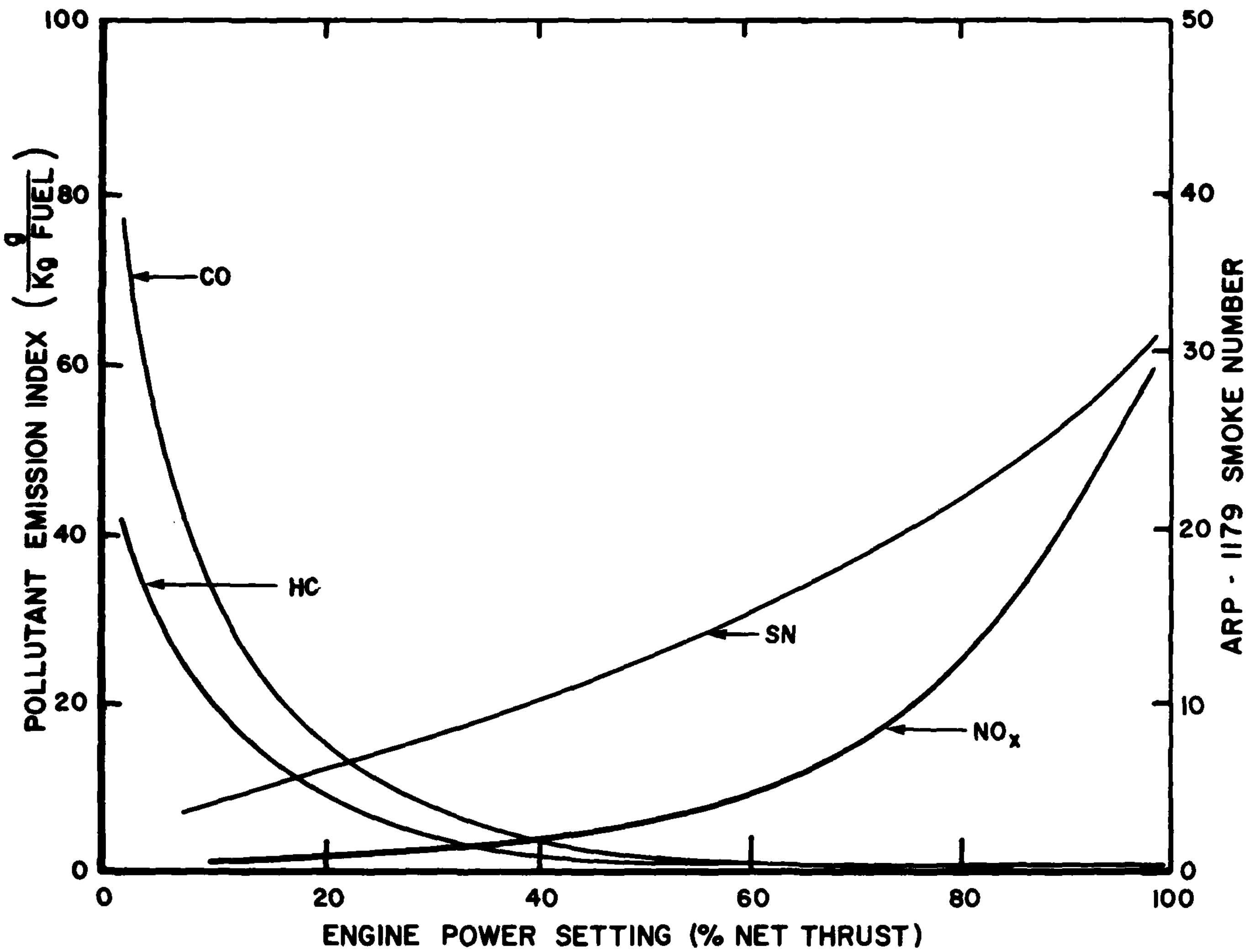

Figure 1. Typical Non-Afterburning Turbine Engine Emission Trends (Reference 3)

tion purposes, that point at which the carbonaceous particulates become visible.

Since the majority of the present and future 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.

Hydrocarbons and Carbon Monoxide. 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 HC. A relationship between combustion inefficiency and emission of these two pollutants is given by the following equation:

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

Where: η_b = combustion efficiency of main burner

$1 - \eta_b$ = inefficiency of main burner

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

$(Q_L)_i$ = constant pressure lower heating value for exhaust constituent i (BTU/lb_m or cal/g). 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/g), and that for JP-4 is 18,700 BTU/lb_m (10,000 cal/g). However, the composition of HC 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/g, 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, 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:

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

This relation is graphically shown in Figure 2.

Engine emission data at idle power conditions have been extracted from a report by Scott and Naugle (Reference 8). They are shown graphically on Figure 3 which includes the hydrocarbon to carbon monoxide ratio in addition to combustion inefficiency values. The scatter of data in Figure 3 indicates the wide variation of idle emissions from existing USAF engines. Expressed as combustion inefficiency, these data can be related to engine pressure ratio and/or combustor entrance temperature at idle as shown in Figure 4. 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.

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

A correlation of data from many engines has shown that NO_x emission is strongly related to the combustor inlet temperature (Reference 9). 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 10). Both the correlation and the subsequent analysis are based on data from engines which have no specific design modifications intended to control the formation of NO_x. Consequently, Figure 5 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 emissions 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 6.

An extremely important aspect of this correlation is that the emission characteristics are expressed as

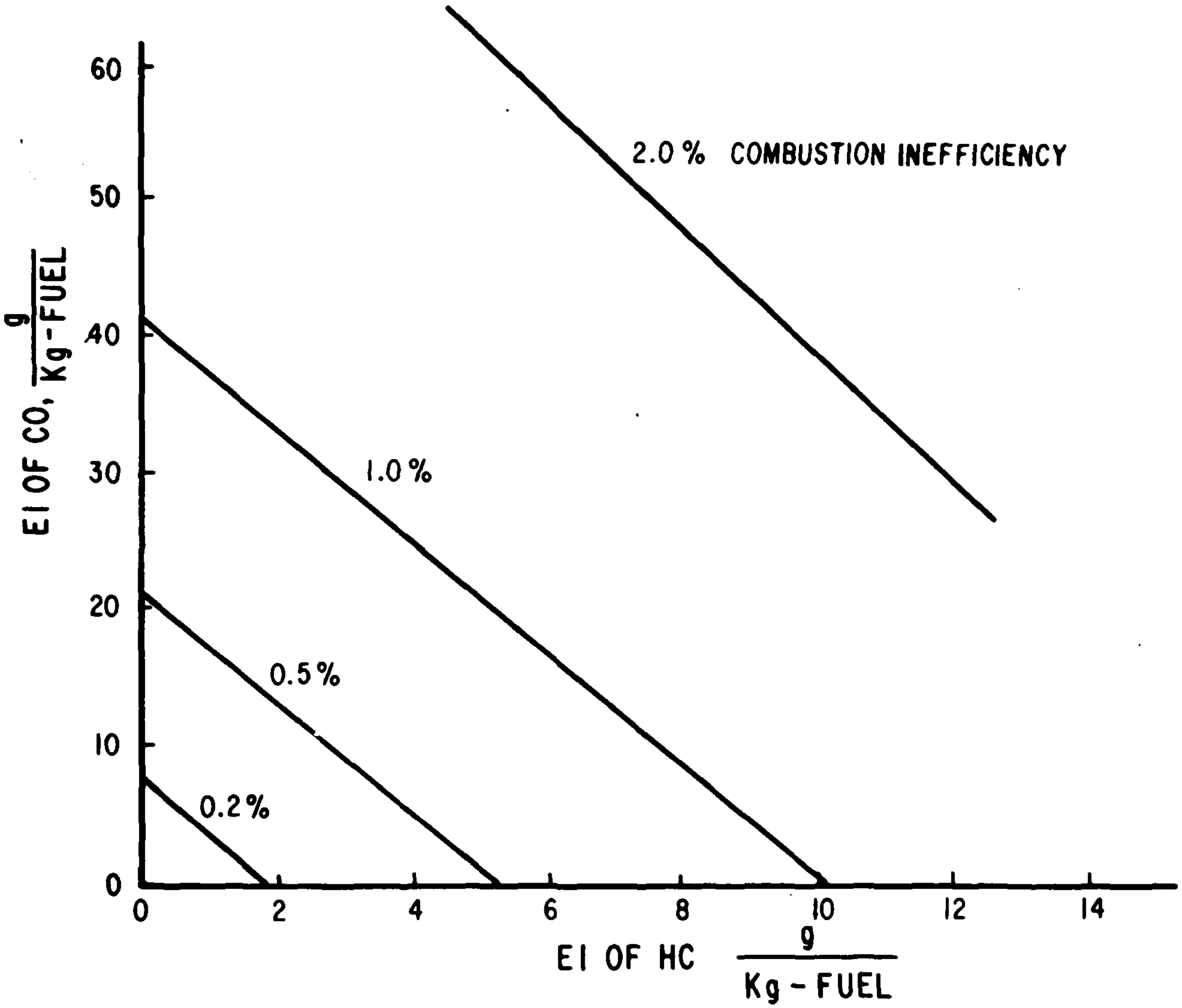

Figure 2. Relationship between Combustion Inefficiency and Pollutant Emissions (Reference 3)

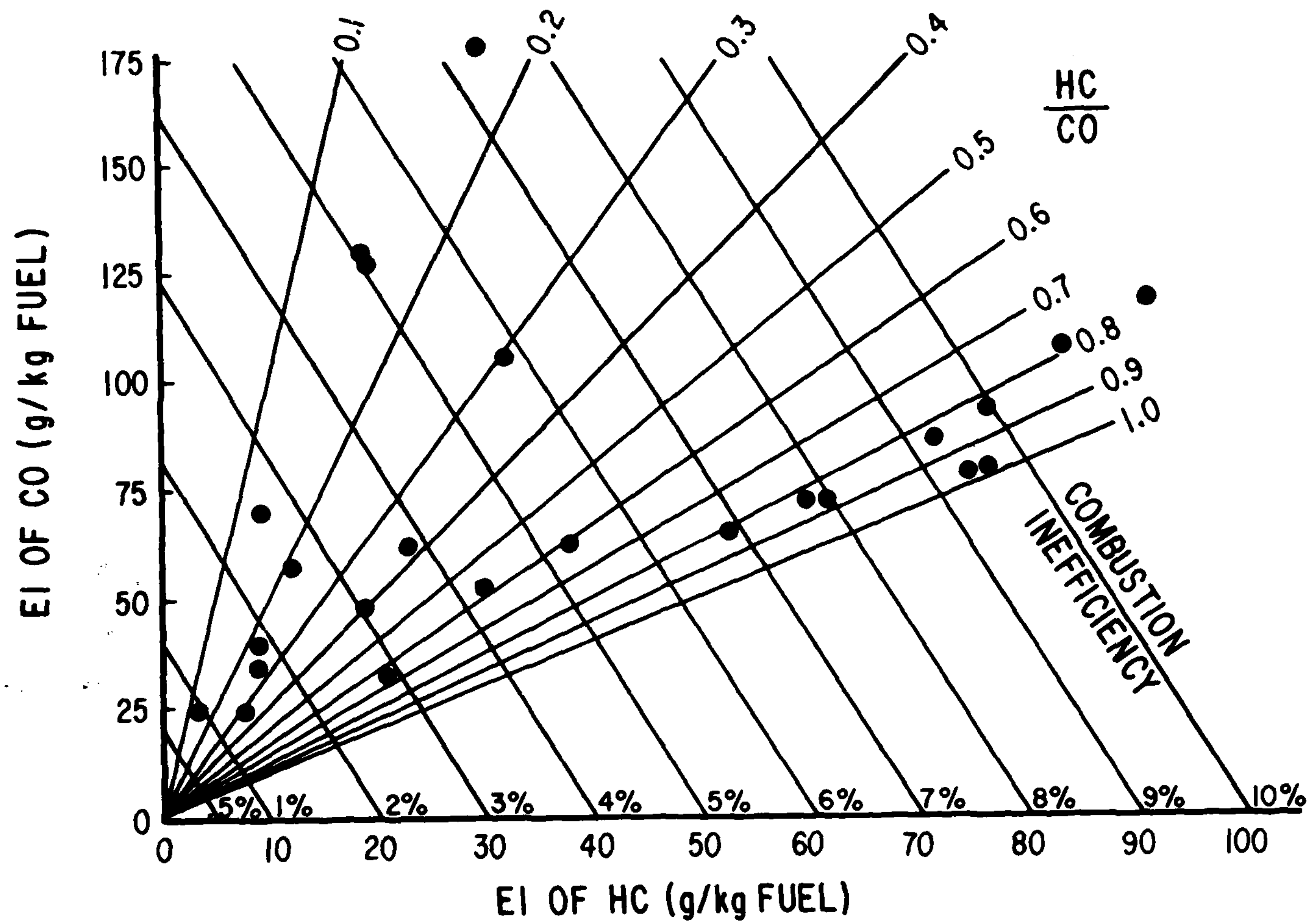

Figure 3. Idle Emissions from Existing USAF Gas Turbine Engines (Reference 8)

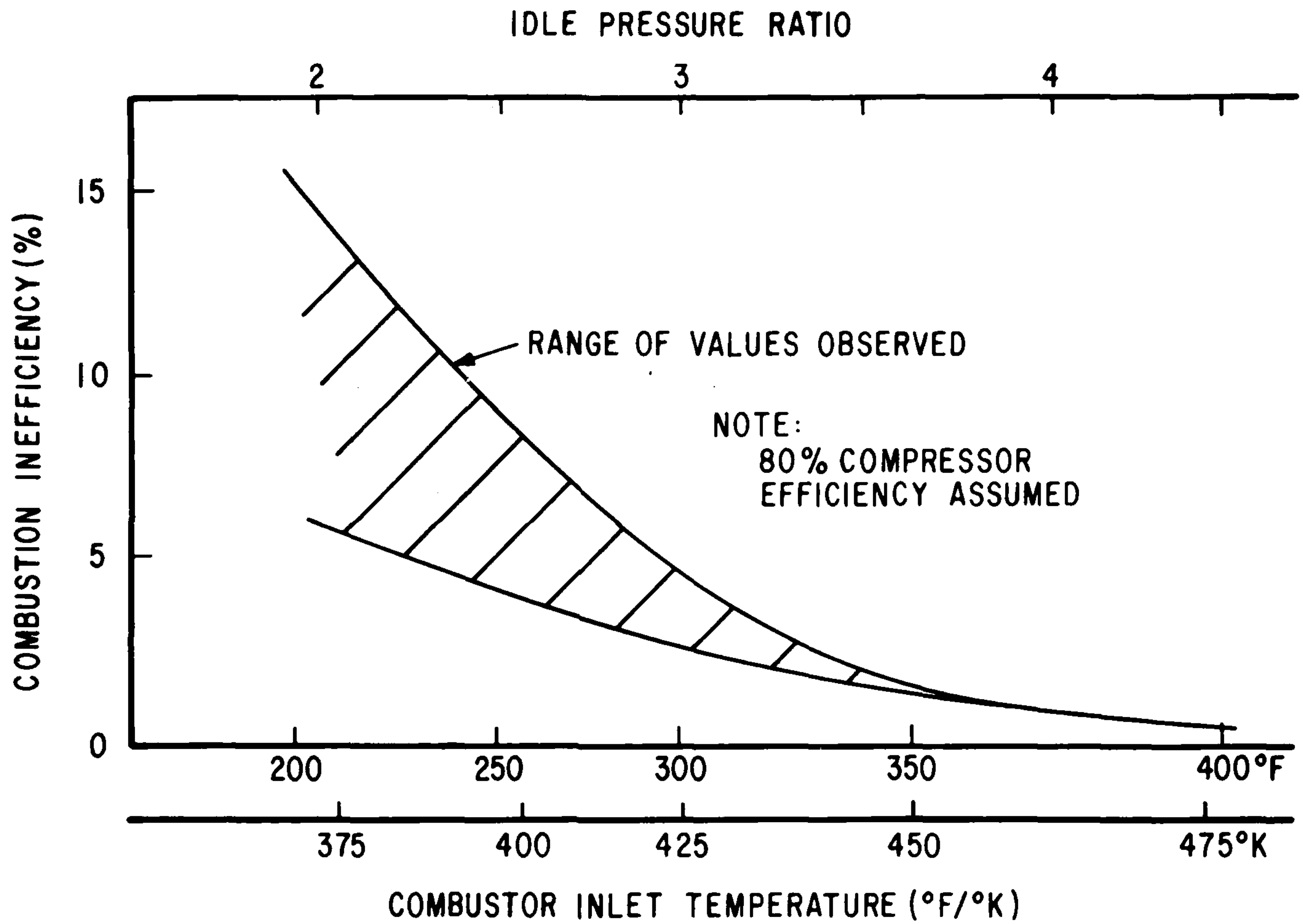

Figure 4. Effect of Combustor Entrance Conditions on Idle Combustion Inefficiency (Reference 3)

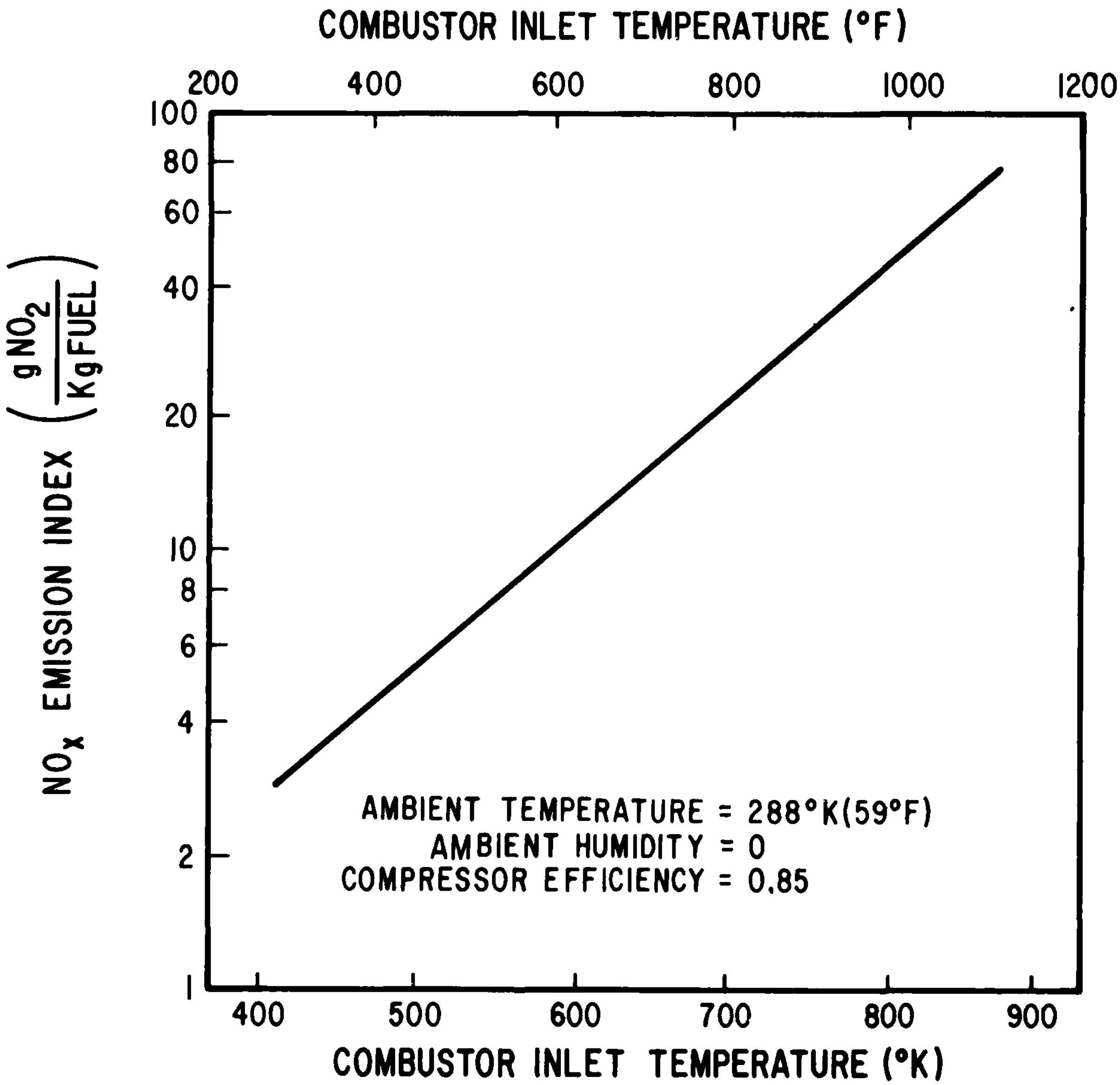

Figure 5. Combustor Inlet Temperature Effect on Oxides of Nitrogen; the Uncontrolled Correlation (Reference 10)

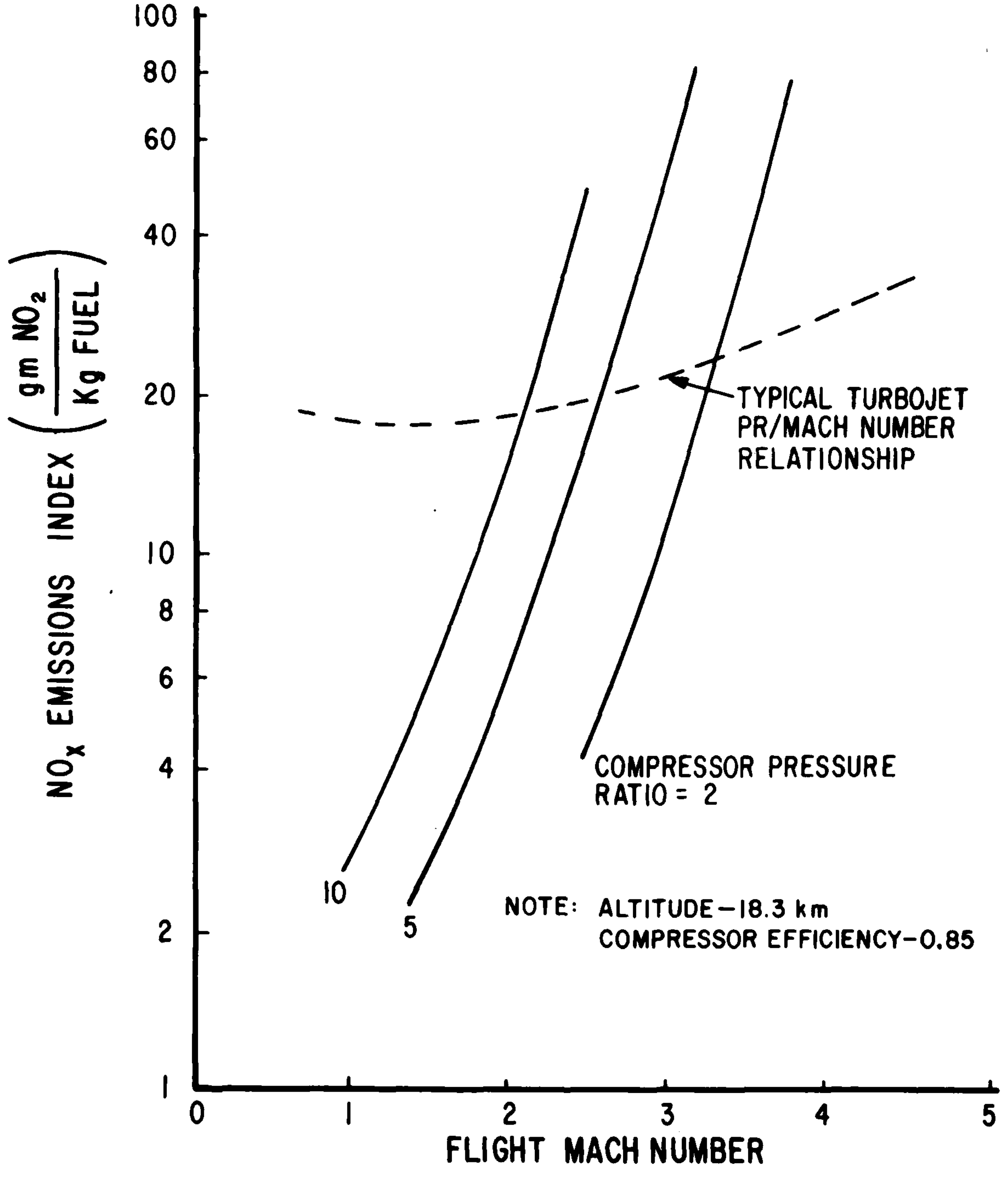

Figure 6. Oxides of Nitrogen Emission Characteristics During Stratospheric Flight (Reference 10)

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 5 confirms that EI versus combustor inlet temperature is one way to characterize NO_x emission. Further, this suggests the NO_x control techniques could be judged on the basis of reductions from uncontrolled emission levels, expressed as grams per kilogram of fuel.

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 suggest that the problem be elimintated.

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. These engineering advances may be nullified, however, by fuels with a high carbon to hydrogen ratio. Fuels with high aromatic percentages are in this category.

An important factor in smoke visiblity 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 11), the quantitative relationship between visibility from this position and a smoke measurement remains a very complicated, unsolved task.

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 12 was performed by Champagne (Reference 13).

1.5.2.2 Afterburning Turbine Engines

The afterburning turbine engine differs from the non-afterburning 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 fact that the afterburner is normally used during takeoff and climb-out accents the potential seriousness of emissions in this mode because only emissions below 3000 feet are considered in present EPA aircraft emissions standards (Reference 2).

Very little information is presently available for pollutant emissions from afterburning engines; however, general trends in available data (References 14, 15, 16, 17) indicate possible significant emissions of CO and HC, 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 plane are extremely reactive and at high temperature; consequently, much of the CO and HC present at the exhaust plane is reacted to CO_2 and H_2O further downstream. Assessment of these afterburner emissions involves determination after the reactions have been completed; i.e., placement of sampling probes downstream of the exhaust plane or using exhaust plane measurements coupled with a reactive plume analytical model.

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 HC 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, it is not possible to accurately assess the emissions characteristics of or to specify emissions limitations for afterburning engines.

1.5.3 Application of Best Available Control Technology (BACT) Concept

Best Available Control Technology (BACT) is a concept which states that pollutants from a source must be minimized. For example, if an engine is emitting visible smoke, it would not be enough to apply a technology which only reduced the smoke to the legal standard. The best available technology would have to be applied - that which would minimize the smoke without regards to cost, energy consumption, safety, etc.

In the consideration of EPA emission standards (Reference 2) it appears that the EPA has considered BACT in some instances but has chosen not to use BACT across the board. The final proposed standard eliminated some engines from the requirements to control emissions. This would indicate that other concerns, such as cost effectiveness, took precedence over BACT. The EPA has however applied BACT to NO_x levels proposed for existing engines -

> "It is proposed that the NO_x standards be changed from an EPA Parameter (EPAP) of 3.0 to 4.0 with the implementation date delayed three years after the effective date for the HC and CO standards to January 1, 1984. It is further proposed that a rated compressor pressure ratio adjustment be applied to NO_x emission measurement values for newly manufactured engines with pressure ratios greater than 25. This adjustment factor is proposed for the newly manufactured engine standards since existing engines have significantly different pressure ratios, and pressure ratio significantly affects NO_x emission levels. An adjustment factor is therefore necessary to insure that the best available technology is used on all existing engines. A standard which could be met by the existing higher pressure ratio engines would require only minimal reductions (or none at all) from the lower pressure ratio engines."

It would appear that because of the factors of cost, energy usage, safety, range, etc., that aircraft turbine engines should be regulated on the basis of emission levels rather than with BACT.

1.5.4 Cost Effectiveness of Control

The concept of examining various control measures to determine the relative cost of reducing a given unit of pollution is currently a popular justification for control (or lack of control). If it is estimated to cost $10,000 to reduce a ton of NO_x from a turbine engine but only $500 to reduce a ton of NO_x from a coal fired power plant, the EPA would probably concentrate their control measures on the coal fired power plant. In this regard it is advantageous to continually emphasize the high cost of aircraft gas turbines and combustor modification.

The EPA (Reference 2) expects lower costs of controls on new engines than on engines which require retrofit -

> "The cost of control for the newly certified engine standards is expected to be lower due to a broader distribution of development costs. These costs and cost-effectiveness values for HC and CO are in the same range as those of other pollution control strategies being implemented or considered for implementation by the Agency at this time. The NO_x value is higher than costs associated with other NO_x strategies being implemented (and may be even higher as more information on maintenance costs is obtained), but until a more comprehensive analysis can be performed based on more detailed comprehensive cost estimates, relative cost effectiveness alone cannot be a basis for rejecting aircraft NO_x control."

1.6 Application of Legislation and Regulations to Only Non-Military Aircraft

Previous studies (Reference 3) have cited the "exemption" from the EPA standards for military aircraft. Also, because the Clean Air Act, and the amendments, continually refer to aircraft as mobile sources, control of aircraft emissions is the prerogative of the EPA, not state or local government units.

Blazowski and Henderson (Reference 3) in their previous study recommended that the USAF not comply with EPA standards for non-military aircraft -

> "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 themselves, but rather follow the proposed goals outlined. 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."

The EPA, in discussion of the proposed rules for aircraft emissions (Reference 2), has proposed several definitions which further emphasize that they do not intend the rules for military aircraft -

> "Subpart A - General Provisions
>
> 87.1 Definitions.
>
> (a) As used in this part, all terms not defined herein shall have meaning given them in the Act: "Act" means the Clean Air Act, as amended (42 U.S.C. 7401 et seq). "Administrator" means the Administrator of the Environmental Protection Agency and any other officer or employee of the Environmental Protection Agency to whom the authority involved may be delegated. "Aircraft" means any airplane for which a US standard airworthiness certificate or equivalent foreign airworthiness certificate is issued. "Aircraft engine" means a propulsion engine which is installed in or which is manufactured for installation in an aircraft. "Aircraft gas turbine engine" means a turboprop, turbofan, or turbojet aircraft engine."

Since military aircraft are not issued a "US standard airworthiness certificate," the act does not apply to them.

The definition which was added to the proposed rules (Reference 2) between their original promulgation and the public hearing brought in the term, "Commercial aircraft engine". It was defined as -

> "Commercial aircraft engine" means any aircraft engine used by an air carrier, foreign air carrier, supplemental air carrier, or charter air carrier engaging in: (1) Interstate or overseas air transportation, (2) foreign air transportation, or (3) intrastate air transportation with large aircraft."

It is obvious from examination of this definition that the proposed rules do not apply to military aircraft.

SECTION II

INTRODUCTION AND BACKGROUND

With the advent of the gas turbine engine for aircraft propulsion systems in the 1950s came an instant citizen awareness of the environmental problems of the gas turbine. Most of the fuels used for gas turbine engines emit a typical petroleum odor which is detectable at low levels. Some persons find this odor to be objectionable. The engines also emit unburned hydrocarbons, at some operating conditions, which may exceed the odor threshold.

Probably the most noticeable environmental effect of the early gas turbine aircraft engines was that they emitted visible smoke. Black smoke plumes could be observed behind aircraft as they took off the runways and again when they were landing. It is not surprising that the visible smoke plumes were the subject of citizen complaints and the justification for studies by various air pollution control agencies.

The odorous and smokey emissions from gas turbine powered aircraft were also of concern to federal regulatory authorities, airport managers, engine and airframe manufacturers, fuel suppliers, the users of the aircraft (airlines and others), and the military which was involved in all phases of the problem.

2.1 History of Aircraft Emission Legislation and Regulation

This section covers the applicable portions of various public laws, federal regulations, executive orders, and military reports and directives concerning aircraft gas turbine engines in particular and the concern of the USAF for environmental quality in general. This section will not discuss the philosophy of the material presented.

2.1.1 Federal Acts and Laws

The Federal Government has initiated laws for the specific purpose of preventing further degradation of the atmosphere. Naugle (Reference 18) has summarized the Federal Aircraft Emission Control Legislation in Table 1. The Clean Air Act of 1963 is the first major legislation to be enacted for the purpose of investigating and controlling air pollution, mainly at the regional and local level. The Act gives the Federal Government authority to intervene in interstate problem areas.

The first mention of aircraft emissions as a possible source of air pollution in a Federal law came about in the Air Quality Act of 1967. Under section 2116 of the Emission Standards Act of 1967 is the following statement (Reference 19):

TABL_ 1. FEDERAL AIRCRAFT EMISSION CONTROL LEGISLATION (Reference 18)

DATE	LEGISLATION (Including Proposed Actions)	SUBSTATIVE ISSUES
Dec 17, 1963	P.L.* 88-206 - "Clean Air Act of 1963"	Original Federal Legislation
Oct 20, 1965	P.L. 89-272 - "Motor Vehicle Air Pollution Control Act"	Precidence for Federal Emission Standards for Automobile
Nov 21, 1967	P.L. 90-148 - "Air Quality Act of 1967" (Section 211b)	-First mention of aircraft in air pollution legislation. -Required study of feasibility of controlling aircraft emissions by national emission standards. -Required the secretary to provide this study and his recommendations to Congress within 1 year from this Act.
Dec 31, 1970	P.L. 91-604 - "Clean Air Amendments of 1970" (Section 102)	-Gave authority to EPA Administrator instead of Secretary of HEW.
	(Section 109)	-Required EPA to issue national primary and secondary ambient air quality standards.
	(Section 231)	-Directed EPA to set aircraft emission standards subject to requirements of public health and welfare and limited by safety considerations. -Subsequently used as authority for all later EPA rule making.
	(Section 232)	-Required DOT to enforce aircraft emission standards.
	(Section 233)	-Limited states from adopting or enforcing standards different than the national aircraft emission standards.
Dec 12, 1972	**37FR26488 - "Aircraft and Aircraft Engines: Proposed Standards for Control of Air Pollution"	-Proposed various aircraft engine emission standards and test procedures with deadlines ranging from 1/1/74 to 1/1/79.
Dec 12, 1972	3FR26502 - "Ground Operation of Aircraft to Control Emission: Advance Notice of Proposed Rulemaking"	-Considered rulemaking to reduce emissions by altering aircraft taxi procedures at large "Class A" commercial airports. This action solicited comments prior to an EPA judgement on the advisability of rulemaking.
Jul 17, 1973	***40CFR Part 87 (or 38FR19088) - "Control of Air Pollution from Aircraft Engines: Emission Standards & Test Procedures for Aircraft" (Sections 87,10-87,52)	-Promulgated standards for civil aircraft for: 1) Fuel venting from gas turbine engines. 2) HC, CO, NO_x and smoke from turbine engines. 3) HC, CO, NO_x from piston aircraft 4) HC, CO, NO_x from onboard auxiliary power units.

* P.L. = Public Law
** FR = Federal Register, Page Number.
*** CFR = Code of Federal Regulations, Part Number, Section Number.

TABLE 1. FEDERAL AIRCRAFT EMISSION CONTROL LEGISLATION (CONCLUDED) (Reference 18)

DATE	LEGISLATION (Including Proposed Actions)	SUBSTATIVE ISSUES
Jul 22, 1974	39FR26653 - "Proposed Regulations on Control of Air Pollution from Supersonic Aircraft"	-Proposed standards which allow for inherently high emissions of SST type aircraft engines. -HC, CO, NO_x and smoke controls are proposed for 1979 or 1981.
Mar 24, 1978	43FR12615 - "EPA Proposed Revisions to Gaseous Emissions Rules for Aircraft and Aircraft Engines	-Proposal to: 1) Withdrawl standards for general aviation aircraft. 2) Withdrawl standards for auxiliary power units. 3) Two to five year delay in implementing standards depending on specific engine and pollutant classification. 4) Relax NO_x standard and delete NO_x retrofit requirement. 5) Re-examine the need for NO_x standard, prior to implementation of this proposed standard.

> "The Secretary shall conduct a full and complete investigation and study of the feasibility and practicability of controlling emission from jet and piston aircraft engines and of establishing national emission standards with respect thereto..."

This statement concerning the establishment of national emission standards for aircraft engines is the primary reason that considerable public interest has been generated in the area of aircraft emission determination.

The National Environmental Policy Act (Reference 20) of 1970 established policy and the means of carrying out that policy. Pertinent sections of the NEPA are summarized:

(1) The purposes of this Act are: To declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare of man; to enrich the understanding of the ecological systems and natural resources important to the Nation; and to establish a Council on Environmental Quality.

(2) This Act is divided into two parts: Title I declares the environmental policy and Title II establishes the Council on Environmental Quality (CEQ). It is in Title I where we find the legislation which can significantly affect USAF operations. The Act, in Section 101 of Title I, declares that it is the responsibility of the Federal Government to use all practical means, consistent with other essential considerations of national policy, in carrying out the environmental policy and purpose of the act.

(3) Title II establishes the CEQ in the Executive Office of the President. Some of the functions of the council are:

(a) to assist and advise the President in the preparation of the yearly Environmental Quality Report to Congress which includes a review of the various programs, including deficiencies, of Federal agencies;

(b) to gather timely and authoritative information concerning the conditions and trends in the quality of the environment;

(c) to review and appraise the various programs and activities of the Federal Government in light of the policy set forth in Title I of NEPA;

(d) to document and define changes in the natural environment, and

(e) to establish guidelines for the preparation of Environmental Impact Statements.

The Clean Air Act of 1970 (Reference 21) which created the Environmental Protection Agency contains additional specific references to possible pollution being emitted from aircraft operations. The Clean Air Act contains in section 231.1 the following statement:

> "The Administrator shall commence a study and investigation of emissions of air pollutants from aircraft in order to determine:
>
> A. The extent to which such emissions affect air quality in air quality regions throughout the United States and,
>
> B. The technological feasibility of controlling such emission.."

Based on the information obtained from this study the administrator (EPA) was to issue proposed emission standards applicable to the emission of any air pollutant from any class or classes of aircraft or aircraft engines. The Clean Air Act of 1970 also contains a section (118) that directs all Federal facilities to:

> "....comply with Federal, State, Interstate and local requirements respecting control and abate ment of air pollution to the same extent that any person is subject to such requirements."

The next sentence in this section does allow the President to exempt any Federal emission source if he determines that it is in the best interest of the country to do so.

The Clean Air Act is divided into four titles which: provide for air pollution prevention and control; require emission standards for motor vehicles, fuel, and aircraft; establish administration and regulatory requirements of the Act, and create the Office of Noise Abatement and Control within the EPA and assign its functions.

(1) Title I covers the prevention and control of air pollution. The functions and responsibilities of the EPA are defined, including provisions for an administrator, staff and facilities. The Act required the establishment of national primary and secondary ambient air quality standards by the EPA

Administrator. The State has the primary responsibility for assuring that the air quality within its geographical boundaries does not exceed the primary and secondary ambient quality standards. Each State is required to submit a plan or plans for implementing, maintaining and enforcing the primary and secondary ambient air standards to the EPA Administrator for approval or disapproval. The Act provides the States or a political subdivision, such as a county, with exclusive rights to adopt and enforce air pollution standards and requirements for control and abatement of air pollution, except for provisions contained in the Act governing moving sources. Stationary sources are defined as any building, structure, or installation which emits or may emit any air pollutant.

(2) Title II of the Act is concerned with emissions standards for motor vehicles and aircraft, and the establishment of standards for fuel and fuel additives. The EPA Administrator is responsible for determining which of the emissions are harmful and for setting standards against them. As a result of his finding, an EPA Regulation was issued setting standards for carbon monoxide, oxides of nitrogen, unburned hydrocarbons and smoke from aircraft and aircraft engines. This regulation will be discussed later in this section. The Secretary of Transportation is required to enforce the standards on motor vehicles, aircraft, fuels and fuel additives and, in the aircraft case, to insure that safety of flight considerations are included in the formulation of emission standards.

(3) The two main points of Title III of the Act are the sections covering citizen suits and Federal procurement procedures. Section 304 permits citizen suits, that is, private actions by citizens acting in their own behalf. This section does not authorize the so called "class action" suits. Any person may commence a civil action against any person, including the United States Government, who is in violation of an emission standard, limitation, or order, or against the Administrator if he fails to perform an act or duty required by the Clean Air Act. This Title also prohibits Federal facilities from contracting with anyone convicted of violating a standard. The prohibition is to continue until the administrator certifies that the cause of the violation has been corrected.

(4) Title IV is concerned with noise pollution and requires the Administrator to establish an Office of Noise Abatement and Control, to conduct investigations of noise, and to report his findings to the President and Congress.

2.1.2 Federal Regulations

Federal regulations are prepared by the appropriate Federal Authority to comply with the intent of the Federal Acts and Laws passed by the Congress. The regulation applicable to gas turbine powered aircraft, and to the USAF, are cited:

EPA Regulations on Prior Notice of Citizen Suits Under The Clean Air Act

The publication of the regulation (Reference 22) satisfies the requirement of the Clean Air Act that the EPA prescribe procedures governing notices of civil actions for violations under the Act. A person can take action against the EPA Administrator for falure to perform duties defined in the Act; or against person(s) responsible for a facility which is or has violated a standard or limitation established by the EPA.

Council on Environmental Quality - Guidelines on Preparation of Environmental Impact Statements

(1) Guidelines for environmental impact statements (EIS) were issued by CEQ (Reference 23). These guidelines are intended to provide a consistent and common format for all Federal agencies. The guidelines require an initial assessment from which a draft environmental impact statement is made and circulated to the public and other pertinent Federal, State, and local agencies for comment. The responses are reviewed by the designated agency writing the EIS and are appropriately formulated, as necessary, in the final EIS. The initial assessment should be made concurrently with the technical and commercial studies. The preparation of the statement requires that the agency has gathered, taken or searched all data and information relevant to the issue. Studies should be directed to show good faith objectivity towards environmental considerations rather than subjective impartiality. In all cases, the assessment must be completed before the decision is made to submit the proposal for legislation.

(2) The guidelines require that an EIS contain:

(a) a description of the proposed action, a statement of the purpose of the action and description of the environment affected;

(b) the relationship of the proposed action to land use plans, policies, and controls for the affected areas;

(c) the probable impact of the proposal on the environment;

(d) alternatives to the proposed action, including those not within the existing athority of the responsible agency;

(e) any possible adverse environmental effects which cannot be avoided;

(f) the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity;

(g) any irreversible and irretrievible commitments of resources that would be involved in the proposed action should it be implemented; and

(h) an indication of what other interests and considerations of federal policy are thought to offset the adverse environmental effects of the proposed action.

EPA Regulations and Control of Air Pollution from Aircraft and Aircraft Engines

The proposed standards for aircraft and aircraft engines were published in the Federal Register (Reference 24) on Tuesday, December 12, 1972 at the same time proposed standards for ground operation of aircraft to control emissions were published (Reference 25). Three major reasons for proposing these standards are stated as follows:

"...(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,

...(2) that airports and aircraft are now, or are projected to be, significant sources of emissions of carbon monoxide, hydrcarbons 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;

...(3) that maintenance of the national ambient air quality standards and reduced impact of smoke emission requires that aircraft and aircraft engines be subjected to a program of control compatible with their significance as pollution sources."

The first of the proposed standards, "Control of Air Pollution From Aircraft and Aircraft Engines," (Reference 26) was promulgated on 17 July 1973. This regulation was adopted by the EPA on 21 December 1973 (Reference 27). Emission standards are set for total hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke. Standards apply to newly manufacturered engines and in some cases, in-use engines. Test procedures are also indicated. These standards, however, do not currently apply to military aircraft.

Standards were also proposed for the control of emissions from supersonic aircraft (Reference 28) on July 22, 1974.

The regulation also included test procedures for sampling and measuring exhaust emissions and procedures for calculating an emission index (EI). The EPA EI is a parameter used in characterizing the emission level of an engine for comparison purposes against the standard. The test procedures and systems specified in the regulations represent the state-of-the-art.

The Secretary of Transportation, through the Federal Aviation Administration (FAA), has promulgated Special Federal Aviation Regulation (SFAR) No. 27 (Reference 29) requiring compliance to the prohibition of fuel venting or dumping in all commercial aircraft and enactment of engine exhaust emissions standards when they become effective. February 1974 was set as the deadline for a smoke number of 30 applicable to the JT8D model engine class, only.

2.1.3 Executive Orders

Another vehicle that the Federal Government has used to express concern about pollution is that of the Executive Order. One of the earliest of these dealing with air pollution is Executive Order 10779 (Reference 30) (August, 1958) which directs Federal agencies to cooperate with state and local officials.

Prior to the passage of the Clean Air Act of 1970 (December 1970) the President issued Executive Order 11507 (Reference 31) (February 4, 1970), "Control of Air and Water Pollution." The following statement, made by the President upon signing Executive Order 11507 shows the intent of the executive order:

> "The order I am issuing today will require that all projects or installations owned by or leased to the federal government be designed, operated, and maintained so as to conform with air and water quality standards present and future--which are established under federal legislation."

The first section of the Executive Order, the policy statement, intends to broaden the responsibility of the Federal Government from maintaining its own facility to providing leadership to the nation in the areas of air and water pollution control and abatement.

One could assume from the intent of this Executive Order that the Air Force should take the lead in determining the extent of air pollution produced by military aircraft operations, and when once determined, should derive a plan to eliminate as much of the pollution as is practicably possible. This task should be met and accomplished irrespective of the speed of compliance in the civilian sectors. Also, this order requires the Federal facilities to comply with all present and, more importantly, future air and water quality standards.

Other Executive Orders were passed which apply to the USAF as far as gas turbine engine emissions are concerned. In some cases the legality of the application to the order may be questioned but the intent to comply with the order should be foremost.

Executive Order 11514 - Protection and Enhancement of Environmental Quality

This executive order (Reference 32) identifies specific executive and administrative responsibilities to implement the environmental policy of the EPA. It provides, in greater detail, the responsibilities of Federal agencies in carrying out the policies of the EPA. Some of the detailed responsibilites are to monitor, evaluate, and control the effects of their respective activities upon the environment and to develop procedures to ensure public understanding of the Federal activities' environmental plans. The CEQ will review and recommend Federal programs to enhance the environment and publish guidelines for preparation of environmental impact statements.

Executive Order 11738 - Providing for Administration of the Clean Air Act and the Federal Water Pollution Control Act with Respect to Federal Contracts, Grants and Loans

This executive order (Reference 33) prohibits Federal activities from procuring or contracting goods, services and materials from convicted violators under the appropriate section of Clean Air and Water Pollution Control Acts. Exemption can be granted in the paramount interest of the United States Government by the head of a Federal agency after consultation with the EPA administrator. The order directs that the Federal Procurement Regulations, Armed Services Procurement Regulations, and related procurement regulations be amended to provide for compliance with standards issued for carrying out the purposes of the Acts.

Executive Order 11752 - Prevention, Control and Abatement of Environmental Pollution at Federal Facilities

The purpose of this order (Reference 34) is to require all Federal facilities to conform to applicable local, interstate, State and Federal standards. The term "facility" as used in this order is all-inclusive and means any buildings, installations, structures, land, public works, equipment, aircraft, vessels, and other vehicles and property, owned by or constructed or manufactured for the purpose of leasing to, the Federal Government. The impact that local, interstate and State regulation authorities can have on Federal facilities is limited by the following excerpt: "In light of the principle of Federal supremacy embodied in the Constitution, this order is not intended, nor should it be interpreted, to require Federal facilities to comply with State or local administrative procedures with respect to pollution abatement and control." The preservation of the Federal supremacy doctrine does not relieve Federal agencies of the responsibility to cooperate with those air pollution agencies in the control and abatement of environmental pollution. Responsibilities of department heads for requesting funds for facility improvements, modification or new facilities with respect to air and water pollution are outlined. The order also establishes a relationship between the EPA administrator and heads of Federal facilities in that he shall: be consulted on applicable standards, mediate conflicts between Federal and various State and local air pollution governing agencies, provide liaison between the governing agencies, and offer technical advice and assistance.

The summary of the public laws and executive orders just presented clearly states that emissions from aircraft operations are a significant cause of pollution in some areas and can become more significant in the future. With this in mind, EPA has proposed standards that should be implemented to remedy the situation. Section 118 of the Clean Air Act of 1970 places responsibility on the Federal Government to comply with the Clean Air Act, but Executive Order 11507 (although signed before the Clean Air Act) places even greater responsibility on the Federal Government, in that the government should take the lead in controlling air pollution. Therefore, the Air Force must take the lead and do all that is possible to determine the significance of the aircraft pollution problem and then do as much as required to reduce the pollution from military aircraft operation.

2.1.4 USAF Technical Reports

The efforts of the USAF to provide leadership in meeting the intent of the many regulations and orders is well documented. A few of the most relevent reports are cited in this review:

AFAPL-TR-72-102

Blazowski and Henderson published their first comprehensive report, "Assessment of Pollutant Measurement and Control Technology and Development of Pollutant Reduction Goals for Military Aircraft Engines" in 1972 (Reference 35). This report summarizes the USAF position up to 1972 as indicated in the Abstract of the report:

> "ABSTRACT
>
> The problem of mass emissions from aircraft gas turbine engines is reviewed and the aspects of this problem which are unique to military aircraft operation are discussed. Pollutant measurement technology and the existing data base are presented and candidate control techniques are identified. Proposed Environmental Protection Agency regulations for aircraft engine emissions are examined in terms of their impact on and application to military engines. It is concluded that the special considerations, both performance and otherwise, which must be afforded to military aircraft prohibit direct application of the EPA regulations. Nevertheless, in recognition of the leadership role required of Federal agencies in protecting the environment, appropriate research and development efforts are underway and in planning to supplement emission-reducing advances made in the commercial sector. This report concerns Air Force mission limitation goals established in light of these Maximum allowable idle combustion inefficiency, oxide of nitrogen emission (ℓbm/1000 ℓbm fuel),

and smoke number are specified. The rationale behind using these parameters, and the means by which the numerical goals were derived are discussed."

AFWL-TR-73-199

Naugle and Delaney published a report in November 1973, "United States Air Force Aircraft Pollution Emissions" (Reference 36). This report was an extensive compilation of numbers of aircraft, times in various modes of operation and flight (later to be known as TIM for Times in Mode), and emission rates for the pollutants that had been measured to that time. The Abstract for this TR states:

"ABSTRACT

The interest in pollution emissions from aircraft has been enhanced the by the Environmental Protection Agency's recent determination that major civilian airports are significant contributors to localized air-quality degradation. This report summarizes the USAF aircraft and engines in common use, presents normalized engine pollution emission factors (emission indices), reviews deficiencies in present emission data, and recommends future efforts to better analyze aircraft emissions. Primary goals of the report are to provide aircraft emission data which can be used in environmental impact assessments at many locations and to stimulate comment on the direction of future USAF efforts concerning the recommended projects."

AFAPL-TR-74-64

Blazowski and Henderson published a second report, "Aircraft Exhaust Pollution and its Effect on the U.S. Air Force," in 1974 (Reference 3). This report covers the developments that had occurred since their first report of 1972 (Reference 35). During this period the EPA published their standards, Government-funded and industry-sponsored programs generated helpful information, and changes were suggested in previously proposed goals. The Abstract from this TR states:

"ABSTRACT

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.

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."

CEEDO-TR-78-33

"Aircraft Air Pollution Estimation Techniques-ACEE," by Scott and Naugle (Reference 8) gives USAF aircraft engine emission factors for current engines in various modes. Pollutant values are given for carbon monoxide, unburned hydrocarbons, oxides of nitrogen, total particulates, and oxides of sulfur. The Abstract for this TR states:

"ABSTRACT

A five-step analytical methodology is presented that can be adapted to nearly any aircraft related air quality assessment problem. The methodology is for use by base level environmental personnel to calculate (1) annual aircraft emissions and (2) downfield pollutant concentrations. The latest individual engine emission factors and other information required for the methodology are contained in this report."

CEEDO-TR-78-36

USAF research and development efforts to measure and model aircraft related air pollution problems is best summarized in "Measurement and Analysis of Airport Emissions" by Daley (Reference 79). The Abstract for this TR states:

"ABSTRACT

This paper is of interest to those involved in regulation and analysis of aircraft related air pollution problems. USAF efforts to measure and model airport pollution are summarized. Efforts include: (1) a joint EPA study at Williams AFB, AZ which involves both modeling and measurement, (2) photographic studies to track plume rise, (3) theoretical modeling studies to analyze airport pollution. The author concludes that the Williams study, soon to be completed, will greatly aid in determining the accuracy of air-port air pollution dispersion models, that air quality modeling studies have shown that state-of-the-art Air Force engines cannot be cost-effectively modified to reduce pollution except possibly in the hydrocarbon area and that, at present, unpredictable thermal plume rise of aircraft exhausts renders models ineffective at locations close (<1 km) to the source."

ESL-TR-79-33

The airbase air quality measurement and modeling study at Williams AFB referred to by Daley (Reference 79) is now complete and is described in "Williams Air Force Base Air Quality Monitoring Study", by Sneesley, Gordon, and Ehlert (Reference 80). The Abstract for this TR states:

"ABSTRACT

Air quality and meteorological data were collected continuously from a network of five ground monitoring stations located at Williams Air Force Base (WAFB) near Phoenix, Arizona, during the period from June 1976 through June 1977. Data reported here will serve as detailed input for defining the accuracy limits of the Air Quality Assessment Model, and these data have been analyzed in order to determine the air quality impact, if any, due to WAFB operations. Also reported are the preliminary results obtained from several related special studies designed to characterize horizontal and vertical dispersion of WAFB emissions. Based upon evaluation of a data set with approximately 70% recovery over the 13-month monitoring period, results reported indicate no measurement of significant air quality impact at WAFB due to aircraft/airbase operations. Results obtained from the special studies indicate that WAFB emissions may influence air quality levels outside the airbase, depending upon local meteorological phenomena."

2.1.5 Secretary of USAF Memo

The Secretary of the USAF issued a Memorandum of 11 June 1975 with an attachment stating the USAF Aircraft Exhaust Emission Goals (Reference 1). These goals have been in effect (unchanged) since this Memorandum. The Memorandum and Attachments follow:

DEPARTMENT OF THE AIR FORCE
WASHINGTON 20330

OFFICE OF THE SECRETARY

June 11, 1975

MEMORANDUM FOR ASSISTANT SECRETARY OF THE AIR FORCE (RESEARCH AND DEVELOPMENT)
ASSISTANT SECRETARY OF THE AIR FORCE (INSTALLATIONS AND LOGISTICS)
ASSISTANT SECRETARY OF THE AIR FORCE (FINANCIAL MANAGEMENT)
CHIEF OF STAFF, UNITED STATES AIR FORCE

SUBJECT: Aircraft Engine Emissions

In keeping with the intent of the Clean Air Act Amendments of 1970, goals for control of Air Force aircraft engine exhaust emissions are hereby established. Recognizing the existence of Environmental Protection Agency standards for commercial aircraft and the essentiality that emission controls applied to Air Force engines not infringe upon flight safety and combat effectiveness, the attached goals are established for turbofan, turbojet and turboprop engines beginning development subsequent to the date of this memorandum.

Engines currently in development and which will be in substantial production after January 1, 1979, will be modified/retrofitted if engineering/cost studies indicate feasibility and environmental impact studies indicate that such modification/retrofit is warranted. Piston engines and engines used for remotely piloted vehicles, auxiliary power units, and rotary wing aircraft are exempt from these standards; however, future procurements should take advantage of emission control advancements.

Adherence to these goals is not only in keeping with the Clean Air Act Amendments of 1970, but will also demonstrate the Air Force's commitment to fully comply with the "United

States Air Force Pledge to Environmental Protection." Accordingly, the goals established by this memorandum should be periodically evaluated to insure support of National environmental objectives.

Signed
J. W. Plummer
for John L. McLucas

1 Attachment
USAF Aircraft Exhaust Emission Goals

USAF AIRCRAFT EXHAUST EMISSION GOALS

These goals are applicable to turbopropulsion engines for fixed wing manned aircraft. Afterburning engines are required to meet these goals only during non-afterburning operation. For a detailed discussion refer to AFAPL-TR-74-64, "Aircraft Exhaust Pollution and Its Effect on the U.S. Air Force."

Carbon Monoxide (CO) and Hydrocarbons (HC)

For engines in substantial production after 1 January 1979, CO and hydrocarbon levels are to be below levels which result in an idle combustion efficiency of 99 percent for engines with an idle pressure-ratio above 3:1, and a combustion efficiency of 98 percent for engines with an idle pressure-ratio below or equal to 3:1.

For engines in substantial production after 1 January 1981, CO and hydrocarbon levels are to be below levels which result in an idle combustion efficiency of 99.5 percent for engines with an idle pressure-ratio above 3:1, and a combustion efficiency of 99 percent for engines with an idle pressure-ratio below or equal to 3:1.

Oxides of Nitrogen (NO_x)

For engines in substantial production after 1 January 1979, NO_x levels are to be less than 75 percent of the present or uncontrolled level, and after 1 January 1981, NO_x levels are to be less than 50 percent of the present or uncontrolled level. For engines using water injection, NO_x levels are to be less than 25 percent of the present or uncontrolled level for all engines produced in substantial quantity after 1 January 1979.

Figure 1 graphaically illustrates the 1979 and 1981 goals. It is emphasized that these reductions apply to takeoff (max-dry) and climbout modes of operation only. However, to simplify compliance procedures, the NO_x goal must be satisfied at the max-dry power condition. Idle and approach levels should be maintained at or below the level indicated as uncontrolled.

Smoke

For engines in substantial production after 1 January 1979, emission levels of smoke are to be below the invisibility threshold as defined by Figure 2. 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 exhaust diameters.

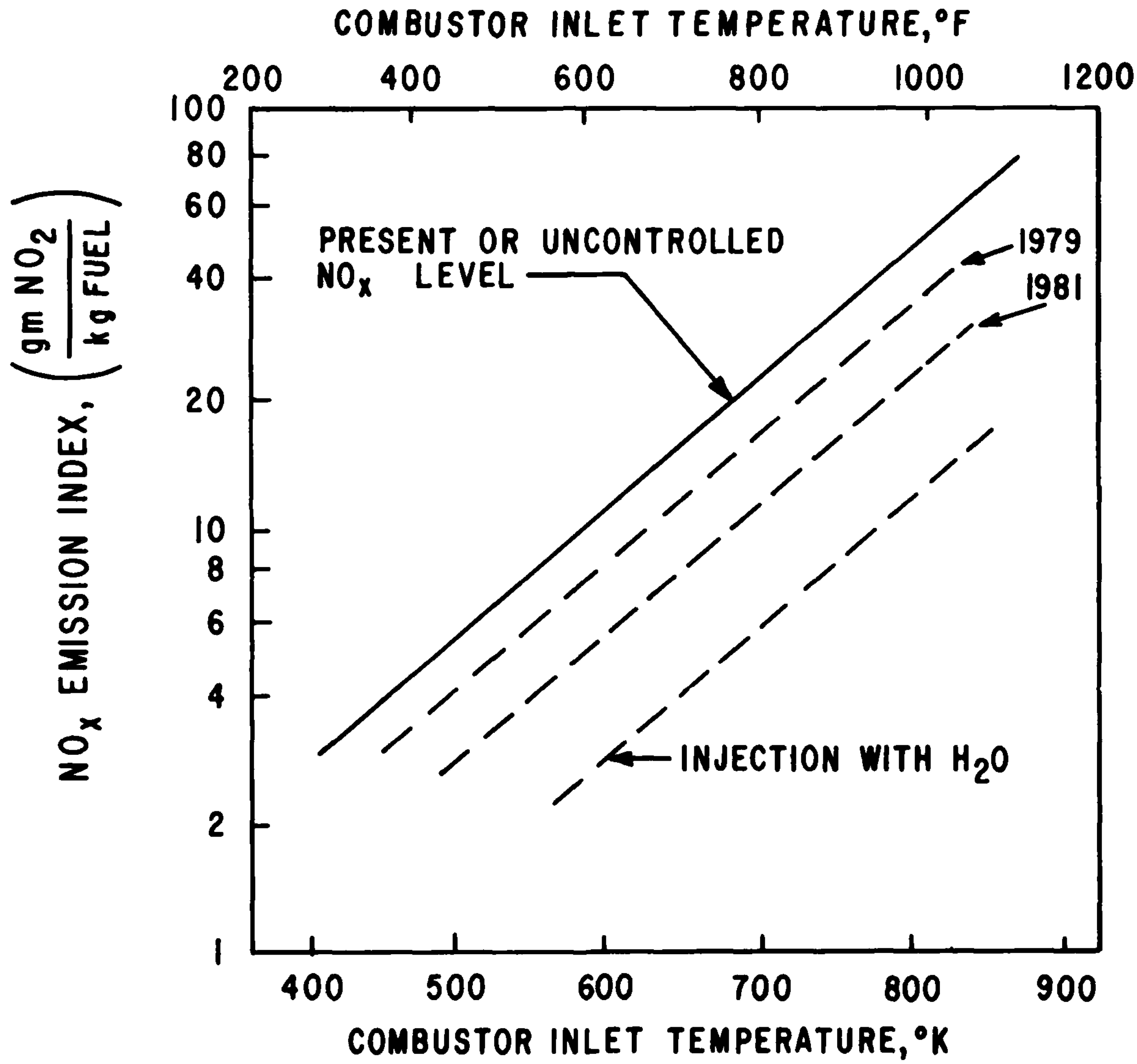

Figure 1. Air Force Oxides of Nitrogen Goals

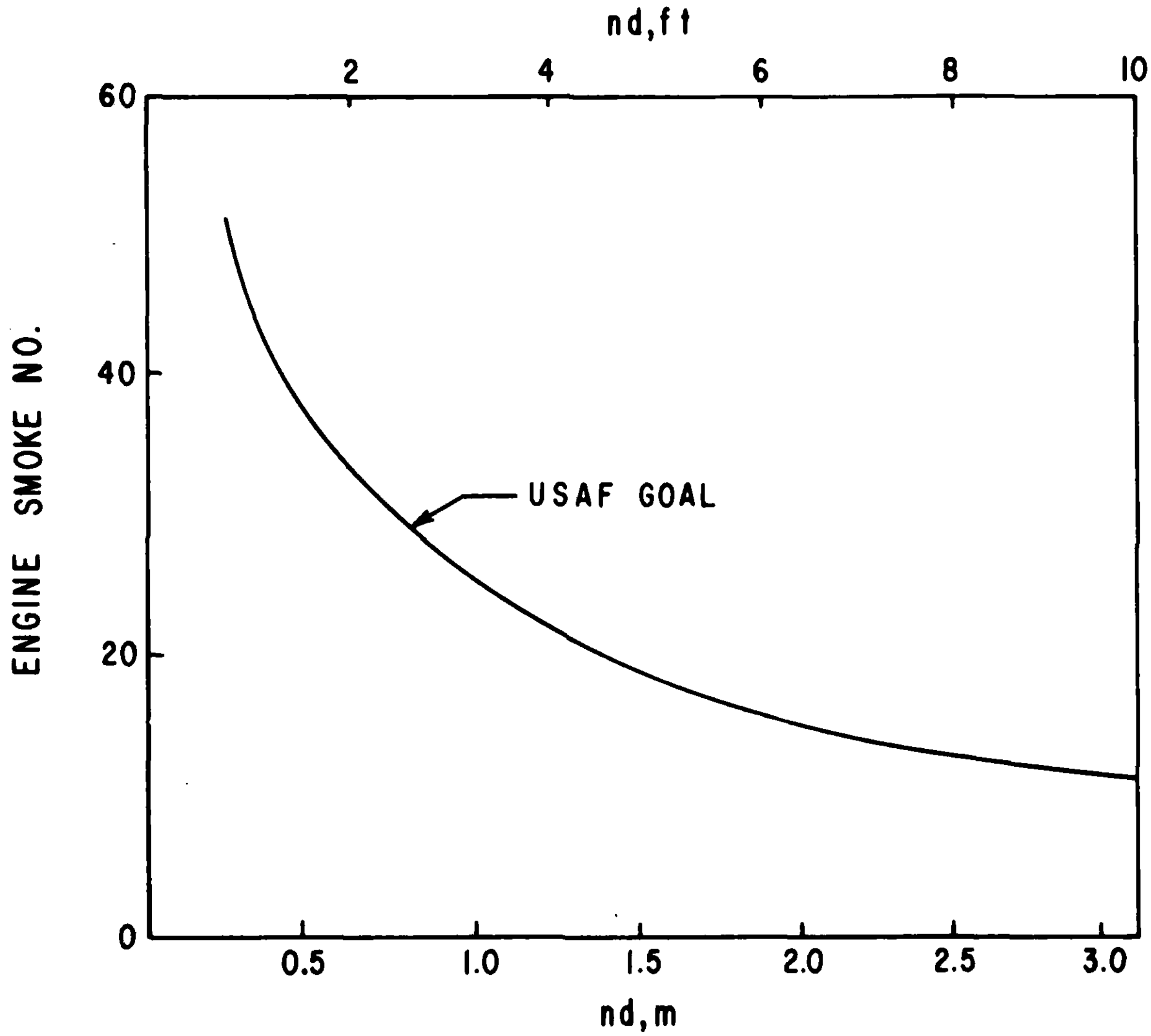

Figure 2. Air Force Smoke Goals

2.1.6 Naval Air Systems Command Policy

By letter of 8 September 1975 (Reference 37) the Commander, Naval Air Systems Command in a letter to the Chief of Naval Operations on the subject of Aircraft Exhaust Emissions stated, "The Naval Air Systems Command, therefore, recommends that the USAF Aircraft Exhaust Emission Goal, forwarded under enclosure (1) be adopted as the DOD 'Aircraft Engine Exhaust Emission Control Goals' for both fixed wing and rotary wing aircraft propulsion systems."

More recently, Bonafede and Klarman of the Naval Air Propulsion Center of Trenton, New Jersey, in an Interim Report, NAPC-LR-78-19, on NAVAIR Work Unit Assignment NAPC-OP7-438 (Reference 38) set forth two proposed recommendations which differ somewhat from the previous:

> "Recommendations.
>
> a. Hardware development for the control of gaseous emissions for Navy aircraft should not commence until the Navy establishes a policy requiring the control of emissions and a set of standards.
>
> b. The AF exhaust emission goals for hydrocarbons (HC), carbon monoxide (CO), and smoke should be adopted as Navy standards, contingent upon the establishment of a Navy gas turbine engine exhaust emission policy. No oxides of nitrogen (NO_x) standard should be established at this time."

2.1.7 Military Specifications

The general military specification for turbojet and turbofan aircraft engines, MIL-E-5007D (Reference 82), and its companion for turboshaft and turboprop aircraft engines, MIL-E-8593A (Reference 83), contain requirements to specify engine pollutant emission levels. Both specifications were published before the current USAF aircraft engine emission goals were adopted and; therefore, neither specification explicitly mentions the goals. The specifications require that the maximum allowable emission levels of smoke, hydrocarbon, carbon monoxide, and oxides of nitrogen be specified in the engine specification. The specifications also state that the engine shall not emit visible exhaust smoke at any power setting and that emission measurements shall be as specified by SAE ARP 1179 and 1256 (References 12 and 63). It is important to note that MIL-E-5007D and MIL-E-8593A (References 82 and 83) are approved for use by all departments and agencies of the Department of Defense.

2.1.8 USAF Regulation 19-1, 9 January 1978

This regulation entitled, "Environmental Protection - Pollution Abatement and Environmental Quality" (Reference 39) states:

> "This regulation sets up an environmental protection program. It states policies and assigns responsibilities for the development of an organized, integrated, multidisciplinary, environmental protection program to make sure that the Air Force, at all levels of command, conducts its activities in a manner that protects and enhances environmental quality. It implements DOD Directives 5030.41, 1 June 1977; 5100.50, 24 May 1973, and Changes 1 and 2, 6050.1, 19 March 1974; DOD Instructions 4120.14, 30 August 1977; 4170.6, 21 June 1965 and Change 1; and the National Pollution Discharge Elimination System. It applies to all Air Force installations and facilities, the Air Force Reserve, and contractor activities performed in Air Force-owned industrial facilities."

It further states that the USAF has the responsibility to: "(21) Comply with USAF Aircraft Exhaust Emission Goals." Under DCS/ Research and Development, two sections are pertinent to gas turbine engine emissions, the first states:

> "f. Determines that aircraft engines must be modified/retrofitted to comply with USAF aircraft exhaust emission goals when engineering/ cost studies indicate that such action is warranted."

and the second which is directed to "Specific Commands, ...AFSC" states:

> "(4) Considers environmental research for development of realistic standards and criteria for pollutants of special interest or peculiar to the Air Force.
>
> (5) Considers rearch and development on environmental pollution controls. Develops methods and techniques for detecting, controlling, and abating environmental pollution. Tests and evaluates instruments and equipment used, or proposed for use, in USAF pollution programs."

2.1.9 Proposed USAF Data Item Description for Turbine Engines Emissions Data Acquisitions

The USAF has proposed, by letter of 20 December 1978 to HQ AFSC/DEV a Data Item Desripcion which is intended to be included in procurement contracts for gas turbine engines. The proposed DID is included as Appendix A. The paragraph pertinent to this review is as follows:

> "Description/Purpose. The purpose of this Data Item Description is to assure that all turbine engine emission data procured under Air Force engine development contracts is provided in a form suitable for use in the environmental assessment process and useful for making comparisons between engines procured under different contracts."

The Sample Work Statement Requirment outlines what shall be covered:

> "Engines shall be tested for pollutant emissions in accordance with the methodology set forth in Title 40, Code of Federal Regulations, Part 87. (Exceptions to this methodology may be permitted if the nature of the engine or its application clearly indicates that the methodology is not suitable.) Testing shall be performed using fuels representative of operational fuel types. Augmentation mode testing shall be conducted in accordance with one of the methods proposed in AFAPL TR 75-52, October 1975. Equilibrium atmospheric emissions shall be either directly measured or computed as provided for in AFAPL-TR 75-52. Smoke number determinations are not required in the afterburner mode.

The history of the rules and regulations, along with the USAF's efforts to reduce atmospheric pollution from gas turbine engines, points to the complexity of the problem. Even though the laws, regulations, orders, reports, and directives are wordy, and at times confusing, the underlying goal of supporting national environmental objectives is foremost. The DOD is committed to this concept.

SECTION III

PURPOSE OF USAF AIRCRAFT ENGINE EMISSION GOALS

Blazowski and Henderson (Reference 3) submitted the material in their 1974 report "in response to an Air Force Air Staff request to provide information necessary in establishing a policy on this matter." It is not known whether this request was verbal or written but it does appear that the emission goals which were published in the memorandum from the Secretary of the Air Force on 11 June 1975 (Reference 1). This memorandum stated,

> "Adherence to these goals is not only in keeping with the Clean Air Act Amendments of 1970, but will also demonstrate the Air Force's commitment to fully comply with the 'United States Air Force Pledge to Environmental Protection'."

One of the charges in the USAF Pledge to Environmental Protection (Reference 40) states, "...each of us pledge to ...Evaluate honestly and conscientiously each proposed Air Force action for environmental consequence as an integral part of the decision process."

3.1 Demonstration of USAF Commitment to Environmental Quality

The EPA Rules (Reference 2), which have been proposed, clearly exempt USAF aircraft. This could be used by the Air Force as justification for future operation with complete disregard for atmospheric emissions from turbine powered aircraft. However, the various Executive Orders, Memos, and Regulations cited previously (Section II) indicate that it is the intent and commitment of the USAF to remain a leader in reducing turbine engine emissions. The Air Force continually will place environmental quality among its primary goals.

3.2 Minimizing Aircraft Engine Pollution at a Reasonable Cost to the Taxpayers

Control of CO and HC from turbine engines may lead to increases in fuel economy which could offset a portion of the cost of the control. However, since the maximum amounts of CO and HC are emitted at taxi and idle, where fuel usage is at a minimum, this offset may be considered negligible. All other control of pollutants, such as for NO_x, SO_x, and smoke and particulate, contributes no forseeable economic benefits. It is therefore safe to assume that control of pollutants from turbine engines will result in increased costs for development, procurement, operation, and maintenance of the engines. In the Air Force case these costs will be paid entirely by the taxpayers.

Because none of the costs of pollution control can be passed on by the Air Force it becomes important to focus on the incremental costs of control along with the incremental benefits that can be expected.

For example, if CO in the ambient atmosphere is below the primary standard (the only standard used because no aesthetic effects are due to CO) it is a disservice to the taxpayers to consider a further reduction in CO emission from aircraft engines operating in that area. It is pointless to consider that the cost of reducing CO is "X" dollars per ton of pollutant. The cost/benefit ratio to the taxpayer is infinity.

On the other hand, oxides of nitrogen and hydrocarbon emissions can enter into the photochemical smog reaction and cause air pollution damage even though the short term standards in the local ambient air are not exceeded. Since photochemical smog does "cost" the taxpayer some amount in damages, it is important to consider both cost per ton of pollutant released and cost/benefit ratios.

3.3 Motivating a Consideration of Emission Control Technology in Future Aircraft and Engine Procurement

It is important for the USAF to establish a position relative to aircraft/engine procurement. The Air Force must rely on the same core engines, from the same manufacturers, that the commercial carriers purchase. If lower emissions are required by law for the commercial carriers, it is important for the Air Force to have a parallel program. This is particularly true if the proposed EPA standards (Reference 2) are adopted which specify that all commercial engines must meet the standards. It would be against all National interests to consider that the Air Force would purchase the engines that could not meet the EPA standards because they were "exempt" from the regulations.

If the Air Force does have a solid policy regarding engine procurement based on emission control technology, it would serve as an incentive for the engine manufacturers to apply the appropriate control technology. The proposed USAF - Data Item Description, included as Appendix A, will provide the technical base to evaluate the effectiveness of USAF policy.

3.4 Encouraging Continued Research and Development Directed Toward Reduced Engine Emissions

The USAF, along with the Navy, NASA, EPA, FAA and other Federal agencies, is responsible for funding of research and development projects to reduce emissions from turbine engines. The vast majority of the money spent on such projects in the United States is from the Federal Treasury. The engine manufacturers, and other segments of the private sector, contribute a relatively small percentage of the funds spent on research and development for emission control technology.

This expenditure of funds and effort by the USAF to support research and development is also in line with the established USAF Aircraft Emission Goals (Reference 1) and the USAF Pledge to Environmental Protection (Reference 40).

3.4.1 Combustion Research

Blazowski, in a recent USAF publication (Reference 41) discusses the nature of combustion technology and the need for research and development to increase our understanding of the subject. He includes a diagram, shown as Figure 7, which shows the complexity of the problem and the many disciplines and research areas involved. Since many of these research areas are basic rather than applied, it is particularly appropriate that the USAF support them.

Blazowski further points out, "The sequence of events occurring during combustion of a practical hydrocarbon fuel is extremely complex and not understood in detail." He uses Figure 8 to illustrate his statement and show the many ways that the combustion reaction can proceed. In order to reduce the emissions from turbine engines a better understanding of hydrocarbon fuel combustion is necessary.

Henderson, in another chapter of the same book (Reference 42) analyzes the combustion problems in turbine engines from a more applied viewpoint. He states:

> "While the combustion system was the primary limitation in development of the first aircraft gas turbine in 1939, the complexity and hardware costs associated with current rotating engine components (compressor and turbine) now far exceed that of the combustion system. Recent developments, however, have once again caused significant shifts in development emphasis toward combustion technology."

Applied combustion research and development is equally as important as basic research if our goal is to minimize pollution from the turbine engine. Continued support by the USAF is vital.

3.4.2 Fuel Research

Henderson (Reference 42) discusses present and future turbine engine fuels as well as citing the need for continued research in the area of fuel technology:

> "If the general nature of future aircraft (size, weight, flight speed, etc.) is to remain similar

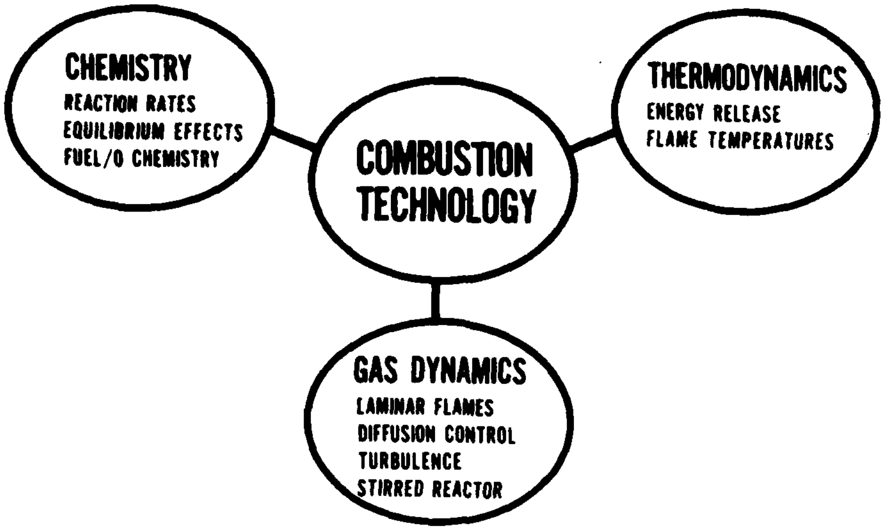

Figure 7. The Interdisciplinary Nature of Combustion Technology (Reference 41)

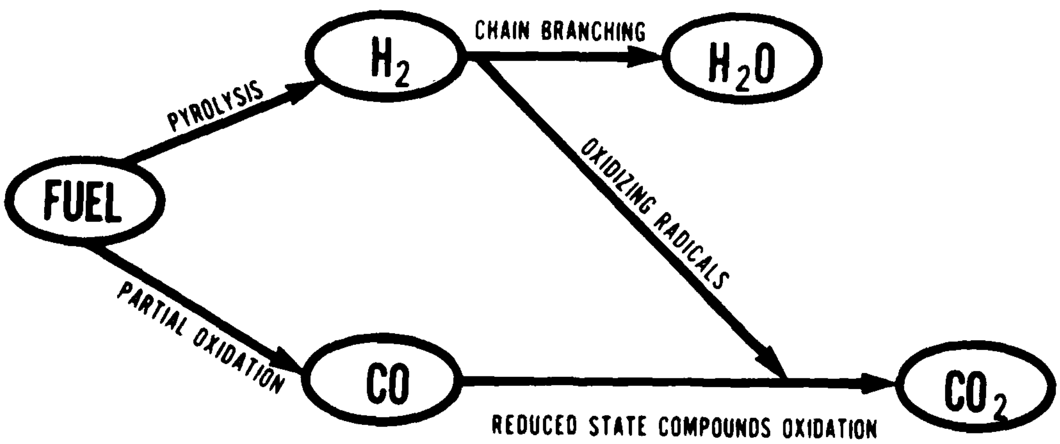

Figure 8. Hydrocarbon Combustion Chemistry Schematic (Reference 41)

to today's designs, liquid hydrocarbons can be expected to continue as the primary propulsion fuel. Liquified hydrogen and methane have been extensively studied as alternatives but seem to be practical only for very large aircraft. The basic non-petroleum resources from which future liquid hydrocarbon fuels might be produced are numerous. They range from the more familiar energy sources of coal, oil shale, and tar sands to possible future organic materials derived from energy farming. Some of the basic synthetic crudes, especially those produced from coal, will be appreciably different than petroleum crude. Reduced fuel hydrogen content would be anticipated in jet fuels produced from these alternate sources."

In a recent paper, "Shale Oil - The Answer to the Jet Fuel Availability Question" (Reference 43), Angello and others from AFAPL state:

"The specification for JP-4, the standard Air Force jet fuel, was defined at a time when this product was both inexpensive and plentiful. While there have been refinements to the fuel specification to keep pace with engine development, JP-4 has basically maintained the critical properties first specified to insure availability and to fulfill aircraft operational requirements. A clear understanding of the relationship between fuel characteristics and aircraft systems performance, engine durability, emissions, and survivability may result in dramatic cost reductions for a broadened specification fuel, but these reductions can only be realized with assurance that aircraft performance is not adversely affected."

Figure 9, showing the concept of the Air Force Fuel Technology Program, again illustrates the complexity of the research and development necessary. It is important that the USAF continue to direct this research effort, not only toward the availability of adequate fuel supply, but also to the minimization of atmospheric emissions of engines using these fuels.

3.4.3 Engine and Engine Component Research

Engine research is done both on full scale engines and on combustors. Engine component research and development is done primarily on combustors in "rig" tests. By mounting only the combustor in the "rig" test stand the combustion variables and combustor configurations may be studied without operating the

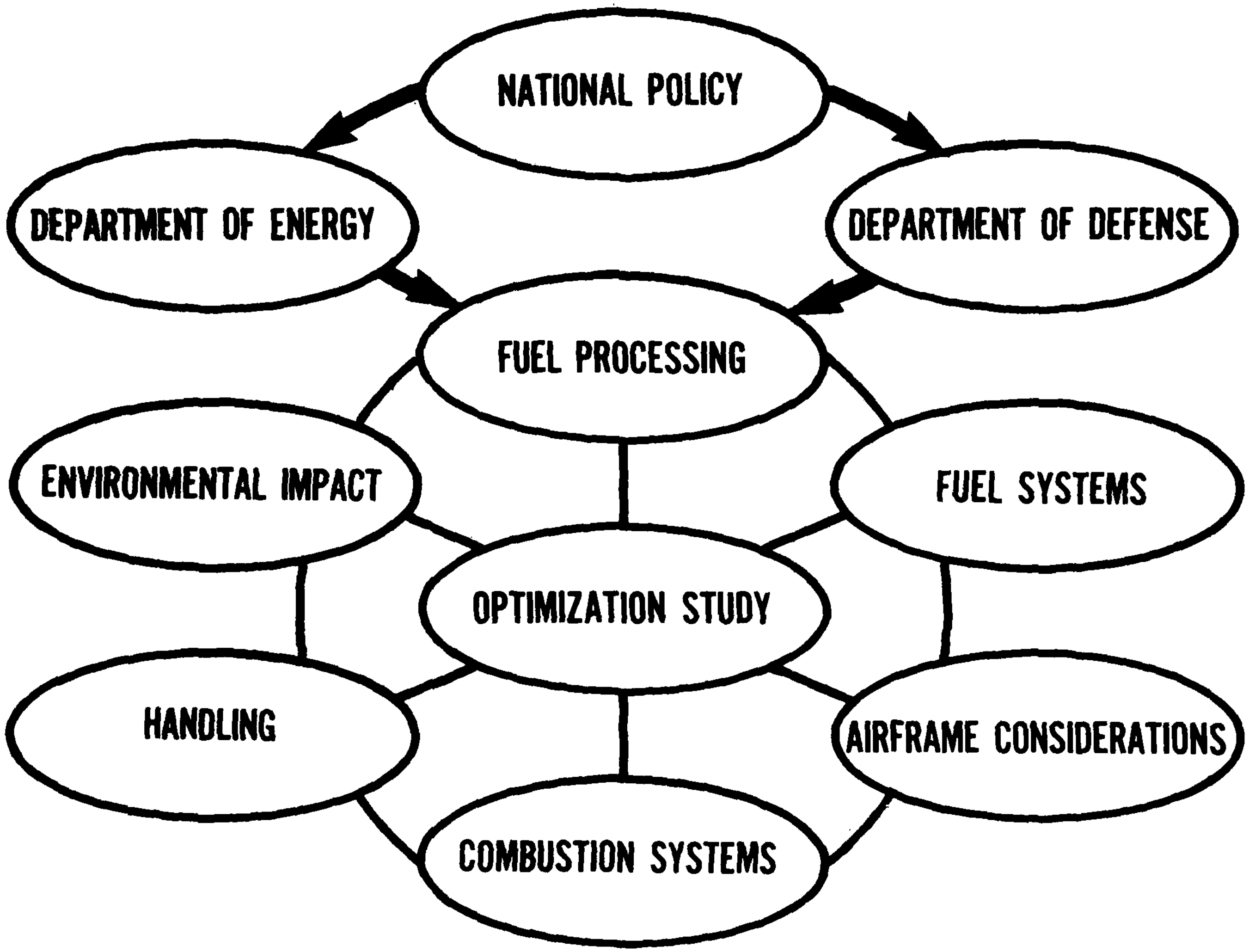

Figure 9. Air Force Aviation Turbine Fuel Technology Program (Reference 43)

entire engine. The USAF is resonsible for part of the engine and combustor research and development being conducted at this time. This frequently involves "rig" tests at major engine manufacturer's facilities, and possibly full scale engine testing at Arnold Engineering and Development Center or at NASA, Lewis Research Center. Table 2 summarizes most of the current research being conducted on gas turbine combustors to minimize pollutants.

Bahr and Gleason (Reference 44) have summarized the current state of combustor development in the "Conclusions" of their paper:

> "1. Significant progress has been made in the development of technology for the design of combustors with much reduced smoke emission levels. As a result of these efforts, combustors with virtually invisible smoke emission levels at all engine operating conditions and which meet the applicable EPA standards have been developed and placed into service. The peak SAE ARP 1179 Smoke Numbers of these advanced combustors are typically in the order of 20 or less. Smoke Numbers of this order correspond to very low concentrations of smoke particulates in engine exhausts, only about 2 parts per million parts (by weight) of the core engine exhaust gas.
>
> 2. Based on the results of investigations conducted to date, much reduced CO and HC emissions levels appear to be attainable through the use of combustor design modifications which provide improved fuel atomization at idle and higher primary combustion zone fuel-air ratios at idle. With the use of these approaches in advanced turbine engines, it appears that CO and HC emissions levels that approach the values needed to meet the applicable EPA standards, may be realizable.
>
> 3. Some potentially promising approaches for providing suppression of the NO_x emissions levels of combustors have also been identified in the development efforts. In particular, the use of advanced fuel injection and atomization methods has been found to be effective. Further, the use of precisely regulated lean primary combustion zone fuel-air ratios at the high engine power operating conditions, appears to offer considerable promise. However, extensive further development effort to permit the satisfactory use of this latter general design approach in advanced turbine engine combustors appears to be needed. Also the use of this lean primary zone approach is expected to result in the need for

TABLE 2. ASSESSMENT OF POLLUTION CONTROL TECHNIQUES FOR GAS TURBINE COMBUSTORS (Reference 43)

CONTROL TECHNIQUE	APPLICATION DIFFICULTY	REDUCTION POTENTIAL
Air-Assist Fuel Atomization	Minor Modification **(Low development risk)	Good for CO & HC; Negligible for NO_x
Air Blast Fuel Atomization	Moderate Modification (Low development risk)	Good for CO & HC; Small for NO_x
Fuel Scheduling	Moderate Modification (Moderate development risk)	Excellent for CO & HC; *No effect for NO_x
Leaner Fuel/ Mixtures	Moderate Modification (Moderate development risk)	Poor for CO & HC; Moderate for NO_x
Modular Combustor	Major Modification (Moderate development risk)	*Poor for CO & HC; Excellent for NO_x
Premixing Fuel and Air	Major Modification (High development risk)	Excellent for CO & HC; Excellent for NO_x
Catalytic Combustor	Major Modification (Very high development risk)	*Poor for CO & HC; Excellent for NO_x

* May be excellent if used in conjunction with other techniques.

** Development risk is defined as the ability to convert a demonstrated experimental technique into a workable engine combustor.

> significantly more advanced, sophisticated and complex combustor designs. At the present time, therefore, satisfactory attainment of the applicable EPA standards for this category of emissions in advanced turbine engines has yet to be demonstrated."

Active sponsorship by the USAF is necessary to assure that engine component research will continue and that the results of such research will be compatible with the USAF mission.

3.4.4 Engine Application Research

Concurrently with research and development of the engine components, application research is necessary to assure that the components are compatible with the entire system. Diehl (Reference 45) emphasizes this point in a recent paper:

> "In order to properly assess the applicability of the various low emission combustor concepts to in-service aircraft engines, one must certainly consider the impact on the overall engine operating characteristics. Other factors such as maintainability and safety must also be considered. Evaluation of these factors must be undertaken to properly assess whether or not trade-offs between emissions, performance and operational chracteristics are required.
>
> One important factor that must be considered in assessing the applicability of converting the low emissions concepts into production type engine combustors is the impact of the increased comlexity that some of these concepts have brought forth compared to the baseline combustors currently in use."

In all of the research and development efforts of the USAF toward reduced engine emissions, one factor should stand out above all others. This is the guideline stated by Blazowski and Henderson (Reference 3),

> "in no case shall pollutant controls be allowed to infringe on military engine design or operation in a manner which compromises system effectiveness."

The final test of the success of the research and development effort will be evaluated in the production engine in the production aircraft.

SECTION IV

ENVIRONMENTAL PROTECTION AGENCY - PROPOSED EMISSION RULES FOR AIRCRAFT ENGINES

The United States government first became involved with regulation of emissions from aircraft engines with the passage of the Clean Air Act Amendments of 1970 (Reference 21). This legislation required that the EPA assess the technological feasibility of controlling such emissions and establish aircraft emission standards if they were determined to be necessary.

The resulting EPA assessment (Reference 46) indicated the necessity to regulate aircraft emissions of carbon monoxide (CO), total hydrocarbons (HC), oxides of nitrogen (NO_x) and visible smoke. The following excerpt from EPA's discussion accompanying the final announcement of the aircraft emissions standards (Reference 26) 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 welare 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 consideration . . . but, instead, reflect EPA's judgment as to what reduced emission levels are or will be practicable to achieve for turbine and piston engines."

The 1973 announcement of aircraft emission standards proposed by the EPA was concerned with gaseous emission regulations for several classes of newly manufactured and newly certified aircraft engines.

In 1978 the EPA proposed revisions to the gaseous emissions rules for aircraft and aircraft engines (Reference 2). The summary for these proposed amendments stated:

"In 1973 EPA promulgated gaseous emission regulations for several classes of newly manufactured and newly certified aircraft engines (40 CFR Part 87). EPA also proposed standards for large in-use gas turbine engines; this standard has not yet been promulgated. This notice proposes changes to the existing rules and supersedes the earlier proposal. The most significant proposed changes to the existing standards are: The addition of the classification category 'commercial aircraft engines,' the revocation of emission standards for general aviation engines; modifications to the levels of the emission standards; and extensions to the effective dates for the standards. This proposal differs from the earlier proposal (38 FR 19050 July 17, 1973) requiring the retrofit of in-use engines in that it extends the applicability to all commercial aircraft engines of 12,000 pounds thrust or greater in place of the previously propsed applicability of 29,000 pounds thrust or greater, deletes the requirement for retrofit of oxides of nitrogen (NO_x) control technology (although this requirement may be reinstituted in the future), and extends the proposed effective date for the standards. In addition of the classification category 'commercial aircraft engines' facilitates an emission control strategy which requires controls of only those aircraft engines which have been determined to be the major cause of air pollution at high activity major air terminals. The proposed changes to the gaseous emission standards will require only engines of 6,000 pounds thrust (or equivalent power) or greater, used in commercial applicatons, to comply with gaseous emission standards. This action will withdraw emission control requirements from piston engines, small turboprop and small (6,000 pounds thrust) turbojet and turbofan engines, and auxiliary power units (APUs)."

A public hearing on the EPA proposed revisions to the rules was held November 1 and 2, 1978 at San Francisco, California (Reference 46). At the hearing, engine manufacturers, control officials, and airline and airframe representatives presented testimony. At this writing the EPA is still evaluating all of the information and is projecting that regulations will be published in late fall of 1979 or early in 1980.

Again it should be mentioned, referring to all the rules and regulations, the military aircraft of the United States are not subject to the standards.

4.1 Definition and Discussion of Terms

The EPA proposed rules contain many specific terms which relate to the intent and interpretation of the rules. These terms themselves contain words and phrases which require further definition to assure clarity of the intended rules. This section defines the terms, words, and phrases as stated in the latest EPA revisions (Reference 2). Some of the general definitions, which apply to understanding the rules, follow:

"Exhaust emissions" means substances emitted to the atmosphere from the exhaust discharge nozzle of an aircraft engine.

"In-use aircraft gas turbine engine" means an aircraft gas turbine engine which is in service.

"New aircraft turbine engine" means an aircraft gas turbine engine which has never been in service.

"Newly certified aircraft gas turbine engine" means an aircraft gas turbine engine which is originally type-certified on or after the effective date of the applicable emission standard.

"Oxides of nitrogen" means the sum of the amounts of the nitric oxide and nitrogen dioxide contained in a gas sample as if the nitric oxide were in the form of nitrogen dioxide.

"Power setting" means the power or thrust output of an engine in terms of newtons thrust for turbojet and turbofan engines and shaft power in terms of kilowatts for turboprop engines.

"Rated compressor discharge temperature (rT3)" means the combustor inlet total temperature achieved by an engine operating at rated output.

"Rated output (rO)" means the maximum power/thrust available for takeoff at standard day conditions as approved for the engine by the Federal Aviation Administration.

"Rated pressure ratio (rPR)" means the ratio between the combustor inlet pressure and the engine inlet pressure achieved by an engine operating at rated output.

"Shaft power" means only the measured shaft power output of a turboprop engine.

"Smoke" means the matter in exhaust emissions which obscures the transmission of light.

"Smoke number (SN)" means the dimensionless term quantifying smoke emissions.

"Taxi/idle (in)" means those aircraft operations involving taxi and idle between the time of landing roll out and final shutdown of all propulsion engines.

"Taxi/idle (out)" means those aircraft operations involving taxi and idle between the time of initial starting of the propulsion engine(s) used for the taxi and turn onto duty runway.

4.1.1 Engine Classes

The EPA has divided turbine engines into several "classes" for determination of appropirate standards. These are defined as follows:

"Class P2" means all aircraft turboprop engines.

"Class T1" means all aircraft turbofan or turbojet engines except engines of Class T5 of rated power less than 35,600 newtons thrust.

"Class T2" means all turbofan or turbojet aircraft engines except engines of Class T3, T4 and T5 of rated power of 35,600 newtons thrust or greater.

"Class T3" means all aircraft gas turbine engines of the JT3D model family.

"Class T4" meas all aircraft gas turbine engines of the JT8D model family.

"Class T5" means all aircraft gas turbine engines employed for propulsion of aircraft designed to operate at supersonic flight speeds.

The proposed standards vary with the class of engines. Some classes are even exempt from some of the proposed standards.

4.1.2 Time in Mode

The time in mode (TIM) is defined as the time, in minutes, when the aircraft is being operated in a particular ground situation or flight condition. The most commonly used modes are:

(1) Idle - Aircraft stationary, engine at minimum thrust or speed.

(2) Taxi - Aircraft moving on airport surface with engine thrust or speed necessary to maintain aircraft motion. Note: This mode may be combined with the idle mode to give a single "Taxi/Idle" mode.

(3) Takeoff - Aircraft moving from start of takeoff roll (at maximum engine power), thru aircraft liftoff, to point of power reduction at the start of climb configuration.

(4) Climbout - Aircraft climbing at power reduction from takeoff mode. Note: The climbout mode is terminated when the aircraft passes thru 0.914 km (3000 feet). This may be a 2 phase mode if noise abatement procedures are in effect.

(5) Descent - Aircraft descending at reduced power. Note: This mode only starts when aircraft is below 0.914 km (3000 feet). On some cycles, this mode may be eliminated so it is combined with the approach mode.

(6) Approach - Aircraft on approach from altitude to point of touchdown at landing. Power is partially reduced. Note: This mode only starts when aircraft is below 0.914 km (3000 feet).

The modes for all portions of a typical landing and takeoff (LTO) cycle (not touch and go cycle) are shown in Figure 10. Times in mode will vary for individual aircraft and airports but the EPA has normalized them for purposes of the gaseous emission rules application. Section 87.70 of the rules states,

"The times in mode (TIM) shall be as specified below:"

Aircraft Operating Mode	Engine Class T1, P2	T2, T3 or T4	T5
	Time in Mode (minutes)		
(1) Taxi/idle (out)	19.0	19.0	19.0
(2) Takeoff	.5	.7	1.2
(3) Climbout	2.5	2.2	2.0
(4) Descent	NA	NA	1.2
(5) Approach	4.5	4.0	2.3
(6) Taxi/idle (in)	7.0	7.0	7.0

The TIM's used by the EPA for the proposed rules are typical of those for "commercial aircraft" as reflected by the proposed regulations. Military operations vary considerably from the EPA defined cycle. USAF LTO cycles have been averaged for specific series of aircraft (fighter, bomber, cargo, etc.) and listed by actually measured TIM's for specific aircraft (F-101, B-52, C-141, etc.) in each series (Reference 47).

The Naval Air Systems Command has also measured, and averaged TIM's for aircraft operations at Naval Air Station (NAS), North Island (Reference 48). The abstract for the Navy report states,

"Military operations varied considerably from the EPA defined cycle so it was necessary to define another LTO cycle which is more representative for military aircraft."

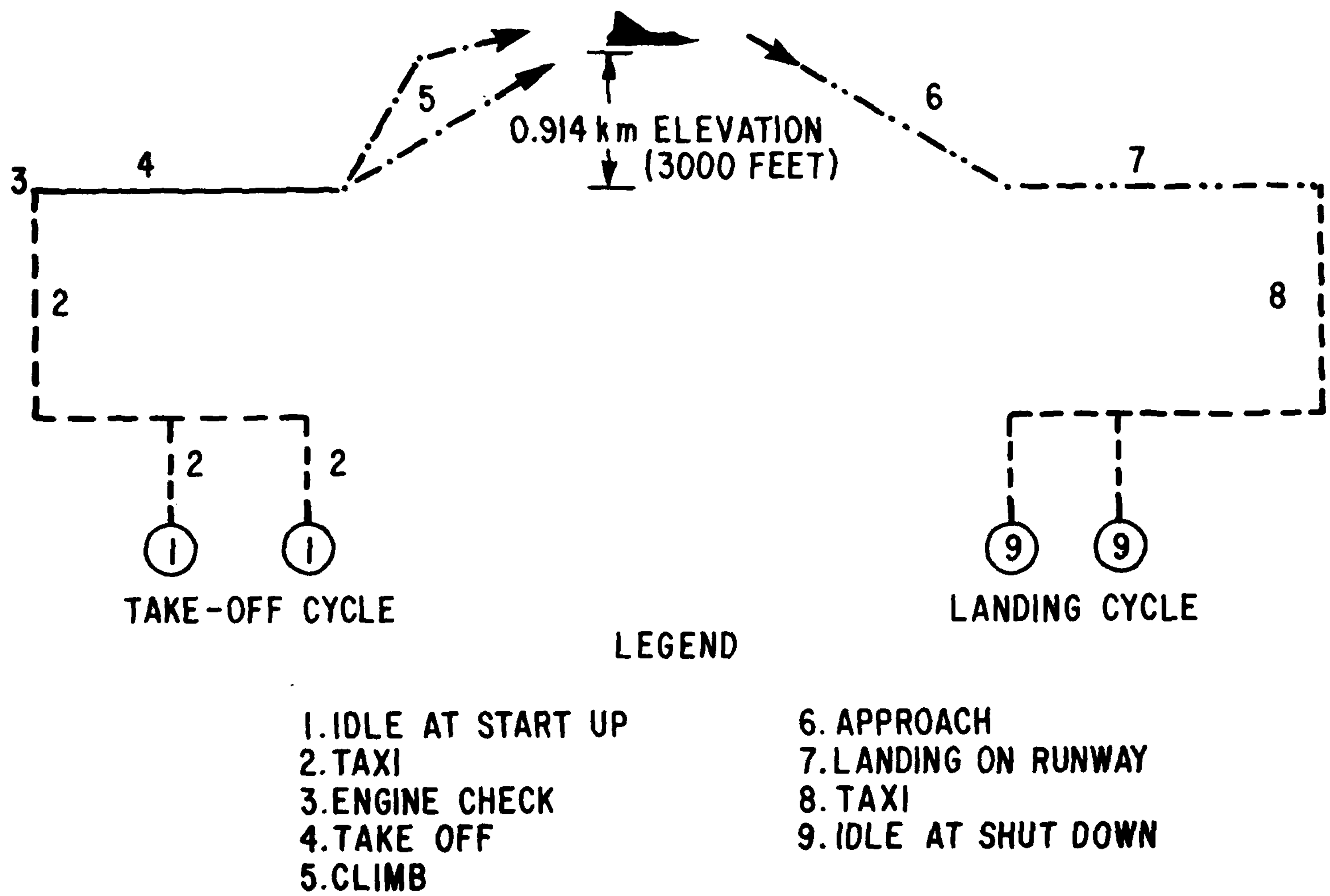

Figure 10. Landing and Takeoff Cycle

4.1.3 Emission Index

The emission index (EI) is the mass quantity of pollutant emitted per mass quantity of fuel consumed. The usual units are pounds of pollutant per thousand pounds of fuel consumed or grams of pollutant per kilogram of fuel consumed (Reference 8). Emission indices and fuel flows are tabulated for each engine mode for engines in use by the USAF (Reference 8). (The emission index may also be called an emission factor or emission rate.)

For example a J57-P-21B engine, used in a F-101 fighter, uses 0.134 kilograms of fuel per second at idle. The CO emission index at idle is 72.0 grams per kilogram of fuel. The idle emission of CO for each minute of engine operation at idle is therefore:

$$\frac{0.134 \text{ kg fuel}}{\text{sec-engine}} \times \frac{72 \text{ g CO}}{\text{kg fuel}} \times \frac{60 \text{ sec}}{\text{min}} = \frac{579 \text{ gram CO}}{\text{min-engine}} \qquad (3)$$

When using the EPA, LTO cycle, the total TIM for taxi/ idle is 26 minutes. Therefore, the F-101 fighter would emit for the idle portion of the LTO cycle:

$$\frac{579 \text{ gram CO}}{\text{min-engine}} \times 26 \text{ min} \times 2 \text{ engines} = 30{,}102 \text{ grams CO} \qquad (4)$$

It is obvious from observing the previous discussion, and equation (4) that the total quantity of pollutant emitted from an aircraft is dependent upon both the EI and the TIM. This is a direct relationship with each term.

4.1.4 EPA Parameters

The EPA, in their proposed rules, determines the emissions by using the Environmental Protection Agency Parameter (EPAP). This is simply a summation of emissions, for all TIM's. Using the previous F-101 fighter example, the $EPAP_{CO}$ could be calculated as:

$$EPAP_{CO} = \Sigma CO_{taxi/idle} + CO_{takeoff} + CO_{climbout} + CO_{approach} \qquad (5)$$

Substituting the calculated values in equation (5) yields:

$$EPAP_{CO} = \Sigma 30{,}102 + 1{,}528 + 672 + 2{,}374 = 34{,}676 \text{ grams CO/EPA-LTO cycle} \qquad (6)$$

The EPAP for this particular aircraft and engine combination would be listed as 34,676 grams CO. The allowable amount of carbon monoxide (for new engines after January 1, 1981) from the EPA proposed rules (Reference 2) is listed as:

$$\text{ALLOWABLE CO} = 169.47 \times 10^{(-0.007462 \times rO)} \ \frac{\text{grams}}{\text{kilonewton}} \qquad (7)$$

where: rO is rated output in kilonewtons (40 for each engine of the F-101 aircraft.

Substituting in equation (7) yields:

$$\text{ALLOWABLE CO} = [169.47 \times 10^{(-0.007462 \times 40)}] \times 40 \times 2 \qquad (8)$$

ALLOWABLE CO = 6,818 grams

The F-101 fighter aircraft is emitting approximately 5 times the allowable amount of CO, if it were operated on the EPA-LTO cycle with engines manufactured after 1981, according to the proposed EPA rules.

The EPAP is a factor of both the quantity of pollutant emitted and the time in which the engine is operated in a specific mode. A change in either emission rate or time in mode will effect the quantity of pollutant emitted. However, since the EPAP is based on a standard LTO cycle, with fixed times in each mode, only the quantity of pollutant emitted may be considered as a variable.

Figure 11 illustrates the relative contributions of pollutants to the EPAP if the F-101 fighter is used as an example.

4.2 EPA Considerations in Proposing the New Rules

Between the time the EPA gaseous emissions were promulgated in 1973 and the time the proposed revisions were issued in 1978 many significant changes were made. The 1978 proposed rules indicate these (Reference 2) as:

> "The most significant proposed changes to the existing standards are: The addition of the classification category "commercial aircraft engines;" the revocation of emission standards for general aviation engines; modifications to the levels of the emission standards; and extensions to the effective dates for the standards."

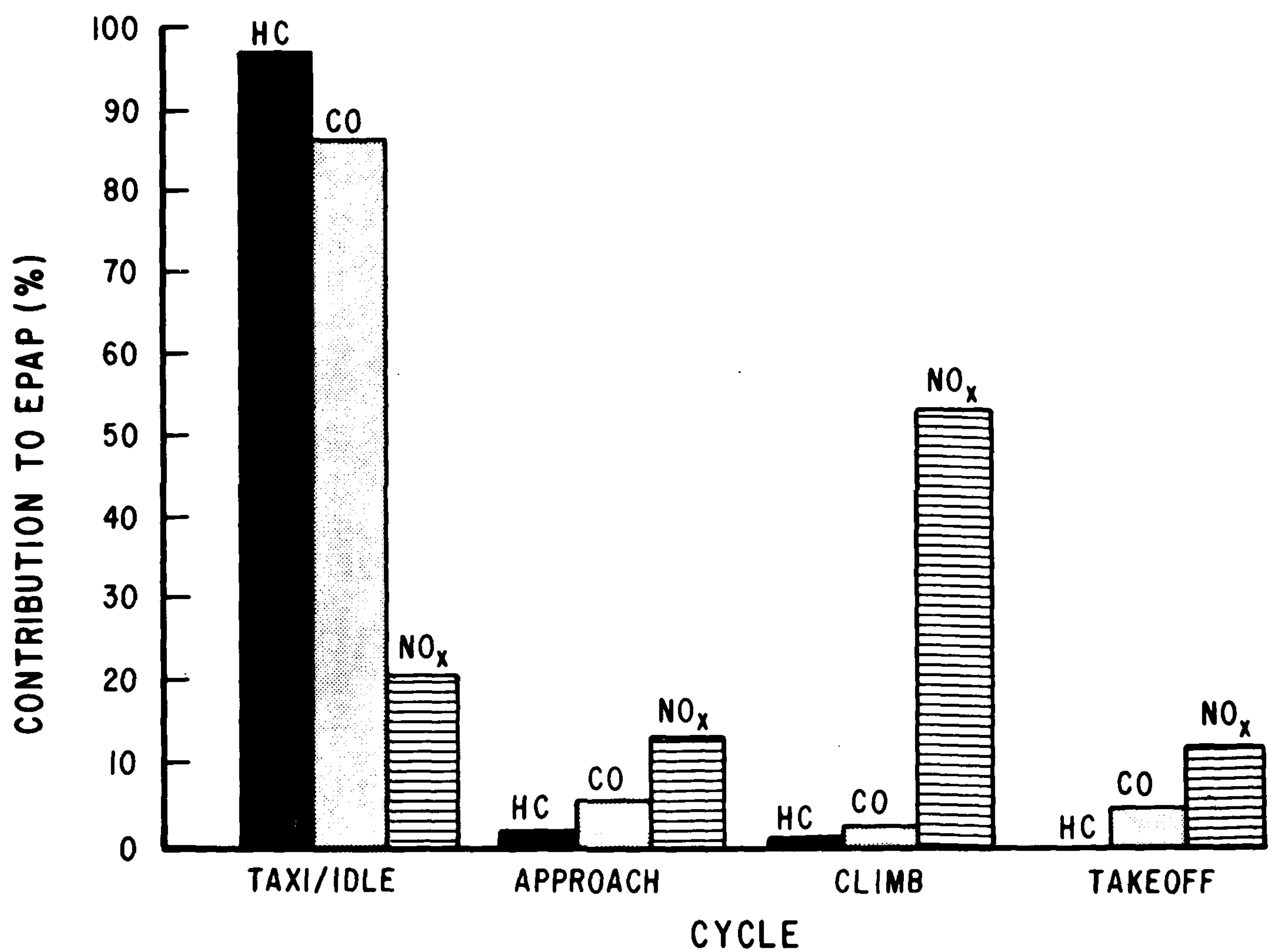

Figure 11. Percentage Contribution of Various Pollutants for F-101 Fighter for EPAP, LTO Based on Standard TIMs

4.2.1 Supplementary Information in the Proposed Revisions of 1978

The proposed rules contain material which is used to justify the proposed revisions to the previous regulations (Reference 2). The supplementary information is as follows:

"SUPPLEMENTARY INFORMATION: The APU standards are being withdrawn for several reasons. These are: (1) No NO_x control technology has been developed in spite of extensive good faith efforts; (2) only minimal CO control is obtainable, yet significant costs would be incurred by both industry and the government; and (3) the HC emissions are already below the standard in the uncontrolled engine.

The newly manufactured engine standards for hydrocarbon (HC) and carbon monoxide (CO) remain at the current levels for engines of 20,000 pounds thrust and above. For commercial aircraft engines with rated thrust between 6,000 pounds and 20,000 pounds, a continuous transition of the standards with thrust is proposed to better account for the technology limitations of existing engines in this thrust range. This results in a slight relaxation of the standards. The implementation date of these standards is proposed to be delayed from January 1 1979 to January 1, 1981.

It is proposed that the NO_x standards be changed from an EPA Parameter (EPAP) of 3.0 to 4.0, with the implementation date delayed three years after the effective date for the HC and CO standards to January 1, 1984. It is further proposed that a rated compressor pressure ratio adjustment be applied to NO_x emission measurement values for newly manufactured engines with pressure ratios greater than 25. This adjustment factor is proposed for the newly manufactured engine standards since existing engines have significantly different pressure ratios, and pressure ratio significantly affects NO_x emission levels. An adjustment factor is therefore necessary to insure that the best available technology is used on all existing engines. A standard which could be met by the existing higher pressure ratio engines would require only minimal reductions (or none at all) from the lower pressure ratio engines.

In addition, the justification for imposition of NO_x standards on newly manufactured aircraft engines will be re-examined after EPA has developed the necessary supporting information for responding to the August 1977 Clean Air Act Amendments relating to promulgation of a short term NO_2 ambient air quality standard. The EPA will take no action towards final promulgation of an NO_x emissions standard for newly manufactured aircraft gas turbine engines until completing the necessary actions relating to the short term NO_2 standard and until a joint FAA/EPA air quality study is completed and considered. Completion of the joint FAA/EPA study is expected in the summer of 1979.

Existing rules for smoke and fuel venting standards will remain in effect as promulgated, except for a proposed modification in the T3 compliance schedule. The proposed modification will change the present full T3 engine fleet compliance date from January 1, 1981 to a phased program with full compliance by January 1, 1985. The revised compliance schedule is identical to the noise retrofit schedule specified in 14 CFR Part 91, Subpart E--Operating Noise Limits. The purpose of the extension is to avoid requiring the airlines to implement double retrofit programs or to retrofit aircraft that are scheduled to be phased out of service.

The present levels of the HC and CO emission standards for newly certified engines are considered feasible and require no change with respect to this proposed action. Based on technological considerations it is proposed that the newly certified engine NO_x standards be relaxed to the same level as that for newly manufactured engines, but without a pressure ratio adjustment. The effective date of the newly certified engine standards is proposed to be delayed from January 1, 1981 to January 1, 1984.

These proposed changes to the aircraft standards result from the continuing technology assessment which has been undertaken since the promulgation of the standards on July 17, 1973.

This proposed action would also extend the applicability of the proposed standards to certain in-use aircraft engines. The proposal of

July 17, 1973 (38 FR 19050) applied only to T2 class engines of 29,000 pounds rated thrust or greater. The current proposal extends the applicability to include all commercial T2 engines of 12,000 pounds thrust or greater, and all commercial T4 engines. This results from a determination that the technology developed for HC and CO compliance with the newly manufactured engines is readily adaptable to in-use engines within a four year period, and the fact that engines in the 12,000 to 29,000 pound rate thrust category represent a substantial portion of the in-use fleet. It has also been determined that the NO_x technology that has thus far evolved is not readily adaptable for retrofit and, therefore, no requirement for retrofit of oxides of nitrogen control technology is being proposed. EPA will monitor the further development and refinement of the emerging NO_x control technology, and if in the future it appears this technology is reasonably capable of being retrofitted additional rulemaking will be considered. The applicability date is designed to correspond to the two year delay proposed for the newly manufactured engine standards. The proposed effective date for in-use engines thus is January 1, 1985.

In addition to the major proposed amendments summarized above, this action proposes that the units of measurement be converted to the Interntional System of Units, that a clarification of the idle power setting be adopted and that a minor modification to the EPA parameter be incorporated into the regulations."

4.2.2 Major Decision Issues

Between the time of promulgation of the EPA regulations in 1973 and the publication of the proposed revisions in 1978, several critical points and questions were raised. The 1978 proposed revisions lists the "Major Decision Issues" that were considered (Reference 2). The pertinent sentence from each "Major Decision Issue" follows along with a brief summary of the EPA justification where appropriate:

Should the Emissions Standards Applicable to General Aviation Aircraft be Retained?

It was concluded that the most cost effective control strategy for aircraft would be to control only those aircraft engines which cause the most significant pollution load, namely commercial aircraft engines.

Are the Levels of the Present Standards Applicable to Commercial Aircraft Appropriate?

The EPA technology assessment of newly manufactured engines concluded that the T2 class HC and CO standards were technically feasible for engines with rated thrust above 20,000 pounds. The smaller T2 engines and some T1 engines are subject to certain standards that are available with engine size, the smallest engines tending to have the highest emission rates. After consideration of the limited overall air quality impact of such engines, it was determined that control of engines less than 6,000 pounds rated thrust was not justifiable at this time.

The Agency intends to defer, until after promulgation of the short-term ambient NO_2 standard in August 1978 and after completion of the joint EPA/FAA airport air quality analysis discussed earlier, pr9ulgaton of the NO_x standard based on this proposal.

Are the Present Compliance Dates for the Standards Appropriate?

In view of the availability of adequate NO_x control in 1984 and in consideration of the span of time between this date and the date of initial HC and CO control, an implementation date of January 1, 1984 for newly certified engines is proposed.

Should Special Provisions be Made for Low Production or Old Engines?

All engines in this situation are produced for general aviation applications, the proposed rulemaking, which would impose no standards for these engines, will resolve this problem.

Is the Proposed In-Use Aircraft Engine Retrofit Program Appropriate?

It was generally agreed among the commenters that a period of four years will be required to incorporate the necessary changes in the commercial aircraft fleet. Therefore projecting that the control systems will be available for application in 1981, the compliance date for in-use aircraft engines is proposed for January 1, 1985.

Has a Margin for Variability Been Included in Setting the Standards?

The standards are to be considered upper limits with respect to compliance testing and manufacturers must set their design goals sufficiently below the standards to account for variability.

How Should the Idle Power Setting be Specified?

The "manufacturer's recommended idle" definition is expanded to explicitly state that the engine be tested at the minimum idle set point for each particular engine with simulation permitted of minimum accessory influences experienced by the engine when operated in the idle mode. This approach is equitable and eliminates much of the ambiguity problem.

Should NO_x Limits Be Corrected for Engine Pressure Ratio?

A standard which permits higher emissions for high pressure ratio engines will force all existing engines to apply the best advanced technology that has been identified in order to achieve the required emissions levels and yet will not unduly penalize those engines which obtain high efficiency through high pressure ratios.

Are the Compliance Test Fuel Specifications Properly Defined?

It has been brought to EPA's attention that the test fuel as now specified may change from time to time under the pressure of rising fuel costs and, in the future, synthetically derived alternative fuels. It is known that combustion pollutant levels in an engine are related to fuel properties and composition. This may cause difficulties with the continuous compliance requirement and with the establishment of technology capable of achieving the standards with fuels significantly different from those used to develop the technology. Comments on this matter are requested.

Should the EPA Limit the Applicability of the Standards to U.S. Aircraft Only and Look to ICAO* to Control International Aircraft?

These standards will apply to aircraft of foreign registry until such time as the ICAO* has promulgated regulations of at least equivalent stringency. At that time consideration can be given to applicability of ICAO standards to aircraft of foreign registry while the EPA standards would continue to apply to aircraft of United States registry.

*International Civil Aviation Organization"

4.2.3 Considerations Mentioned in EPA Support Documents

Several EPA support documents were prepared during the period between promulgation of the regular revisions in 1978. Many of these were summarized in the previous section, 4.2.2 Major Decision Issues. Others which bear more directly on the USAF mission, as well as the USAF goals, deserve a more complete analysis. Most of these studies were published by the EPA, Office of Mobile Source Air Pollution Control. Considerable data from the FAA, EPA, USAF, NASA, US Navy, engine and airframe manufacturers, and consultants were analyzed in preparation of these support documents.

Proposed Amendments to Emission Standards for Aircraft Engines

This document (Reference 49), issued by the Deputy Assistant Administrator in August of 1977, contains most of the input data to EPA, along with the EPA evaluation and decisions, at that point in time. The summary of this memo states:

"SUMMARY

This action is the issuance of a Notice of Proposed Rulemaking (NPRM) containing amendments to the Emission Standards for Aircraft Engines (40 CFR Part 87). The recommended amendments by engine class are:

P1 Class (Aircraft Piston Engines) - The gaseous emission standards should be withdrawn. The reduction in emissions that would be achieved by the existing standards would provide minimal improvements in air quality at high cost.

P2 Class (Aircraft Turboprop Engines) - The present gaseous standards should be withdrawn and replaced with standards for only large, newly certified engines to be used in commercial service. These large, newly certified engines could, and should, comply with standards significantly more stringent than the present standards for newly manufactured aircraft engines. (The current standards had to be sufficiently lenient so that the smaller engines of this class could comply). The present fleet of turboprop powered aircraft (predominantly general aviation) have a minimal impact on the aircraft pollution problem and will not become a problem unless a new engine is introduced which would be used in a significant portion of the commercial fleet.

APU Class (Auxiliary Power Units) - All requirements for emission controls on aircraft APU's should be withdrawn. This class of engine inherently has low HC emissions resulting in a negligible contribution to the oxidant problem. CO and NO_x emissions are somewhat higher; however, technology is not available to provide significant reductions. Also, the emissions contributions of CO and NO_x are relatively low as compared to the aircraft propulsion engines.

T1 Class (Turbofans and Turbojets under 8000 pounds thrust) - All T1 class engines under 6,000 pounds thrust should have their gaseous emissions (HC, CO and NO_x) standards withdrawn, as well as T1 engines over 6,000 pounds thrust used in general aviation applications. T1 engines above 6000 pounds thrust which are used in commercial application should comply with standards set for all commercial subsonic turbofan and turbojet engines. The air quality impact of this class of engines (excluding the larger commercial engines) is minimal and the cost of compliance would be high.

T2, T3 and T4 Classes (Turbofans and Turbojets above 8000 pounds thrust, JT3D and JT8D - The standards would apply to all commercial engines above 6000 pounds thrust. For those newly manufactured engines above 20,000 pounds thrust the HC and CO levels should remain as presently specified. Between 6000 and 20,000 pounds thrust the levels should have a thrust dependent transition between the levels at 20,000 pounds to a level slightly above the current T1 standards at the minimum thrust of 6000 pounds. It is further recommended that the HC and CO standards be delayed two years. Implementation of the NO_x standards should be delayed three years after the HC and CO standards, be applicable to only engines above 20,000 pounds thrust and be relaxed from an EPAP of 3.0 to 4.0 (with no pressure ratio adjustment). These standards should be delayed 3 years to 1984. These revisions are necessary because of technical constraints, and represent the most aggressive implementation schedule and levels of control technically feasible.

Standards for HC and CO should be adopted that require all large, in-use commercial engines (over 12,000 lbs thrust) to achieve levels equivalent to the newly manufactured engine standards. This would require the retrofit of the technology required to meet the newly manufactured standards into existing engines. Such a retrofit would require about 4 years to implement after the technology became available, thus resulting in a final compliance date of January 1, 1985.

While these recommended amendments in several cases represent a deletion of existing regulations and in other cases result in the relaxation of the levels of the standards and/or the implementation dates, the net result of this regulatory action will be to improve the effectiveness of the aircraft regulations for HC and CO control at the major commercial airports (aircraft air pollution problem areas), and to recognize that the full degree of NO_x control called for in the existing standards is not technically achievable in the foreseeable future."

Cost-Effectiveness Analysis of the Proposed Revisions - Industry Data

This report by Wilcox and Munt (Reference 50) considered industry submittals to determine the cost-effectiveness of the proposed regulations. This document, as other EPA Technical Support Reports, contains a notice that it does not necessarily represent the final EPA decision on regulatory issues. the Introduction to this report states:

"INTRODUCTION

This report contains a cost-effectiveness analysis of the proposed revisions in exhaust emission standards for new and in-use aircraft gas turbine engines using information supplied by engine manufacturers. The resulting cost-benefit ratios may be compared with those of other aircraft and non-aircraft pollution abatement control strategies in order to determine the most cost effective means of achieving the National Ambient Air Quality Standards (42 CFR 1420).

The control strategies analyzed are:

1. Control of newly manufactured gas turbine engines (NME) in 1981 for HC and CO only:

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

3. Control of newly manufactured gas turbine engines (NME) in 1984 for HC, CO, and NO_x.

The lack of detailed data available for study has made a rigorous analysis impossible. The cost information received thus far is incomplete and poorly documented; therefore, it is impossible to determine the validity of the data submitted. Furthermore, the very nature of the study necessitates using assumptions and projections in an attempt to ascertain future facts. No matter how carefully considered, these forecasts will be subject to error and interpretation.

Within the constraints described above, the cost-effectiveness figures generated by this analysis represent EPA's best estimate of the costs imposed by the control strategies under consideration based on industry submittals.

In this analysis, the JT8D is assumed to be out of production by 1984. However, shortly after finalization of the report, the EPA learned that production of this engine would continue and, in fact, a growth version of the engine was planned. This new information along with EPA's independent cost estimate of the proposed standards will be addressed in a subsequent report."

The conclusion of this report further outlines the problems of obtaining reliable cost data:

"CONCLUSIONS

The cost-effectiveness information generated in this report is based on a limited amount of data and lacked sufficient detail to allow a rigorous analysis. Within this constraint, the cost-effectiveness figures are considered to be a reasonable approximation of the control costs as a consequence of the standards under consideration based on industry submittals.

The costs of controlling HC and CO to the levels prescribed by the 1981 NME Standard are similar to other control strategies and in combination with the 1985 Retrofit Standard, they are more cost-effective. The price of NO_x control under the 1984 NME Standard is considered to be comparable to other proposed control strategies for mobile and stationary sources.

A fuel comsumption penalty is associated with the 1981 standard, although when combined with the 1985 retrofit an overall reduction in fuel usage is expected. A very substantial fuel savings is expected from engines in compliance with the 1984 standard."

Cost-Effectiveness Analysis of the Proposed Revisions - EPA Independent Estimates

Because of discrepancies between industry estimates and data from earlier EPA studies, the EPA felt it necessary to prepare an independent cost estimate. Wilcox and Munt (Reference 51) published this report about 3 months after their previous report using industry supplied data (Reference 50). The Conclusion of this report states;

"CONCLUSIONS

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

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

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

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

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

US Aircraft Fleet Projection and Engine Inventory to Year 2000

This report by Munt (Reference 52) in early 1978 projects the US fleet into the year 2000. It does not include the non-US fleet which would be effected by the proposed EPA rules if they were operated from airports within the U.S. Other shortcomings of the forecast are stated in the report:

"The shortcomings of this forecast for EPA use are fourfold. First, the forecast does not break down the categories (e.g., two-engine narrow-body) into specific aircraft types (e.g., DC-9). Second, the fleet is not presented in terms of categories defined by short, medium, or long haul. These limitations prevent a knowledge of the engine types in use in the fleet. Third, the forecast is in terms of the net only and there is no projection of the production and attrition which is necessary to separate the engines according to the standard complied with. Fourth, the data are presented in five year increments only, thus requiring interpolation."

The introductory statement of this report does recognize these shortcomings while stating the usefullness of the report:

"INTRODUCTION

This report provides a forecast of the number of aircraft gas turbine engines which must comply with the proposed revisions to the EPA emissions standards. In providing this, it also supplies an aircraft forecast (useful if engines are changed on a given airframe) and a general engine forecast (useful if other revisions are proposed). This information may be used directly to obtain estimates of the total impact of various standards and implementation dates and, more importantly, to obtain estimates of the total cost and cost effectiveness of the standards. In view of the diverse uncertainties in forecasting, the reader is cautioned to treat this forecast as only a representative scenario whose accuracy is limited by the quality of the assumptions and judgments made in its derivation."

Potential Impact of CO, HC, and NO_x Emissions on Air Quality

Lorang (Reference 53) in March of 1978 published this Technical Support Report which was a review of past studies. The Conclusions of this report outline the rationale behind the EPA revisions:

"CONCLUSIONS

The 1971 study by Northern Research and Engineering (Reference 54) was the most comprehensive of the airport air quality studies. Unfortunately it was also probably the least accurate, certainly the least demonstrably accurate. If the argument for emission controls on commercial aircraft depended only on the 1971 NREC study and the 1972 EPA report (Reference 55) it would be weak. However, more recent sutdies by both EPA and FAA have confirmed some of the NREC conclusions and added others. These have been summarized in the Discussion section of this report.

Very briefly, CO violations attributable to aircraft are occurring at at least a few terminal gate areas and at the ends of runways. The areas of high CO attributable to aircraft are not extensive, but can include areas where persons have regular access. HC emissions from commercial aircraft create regions of high HC concentrations that include the major commercial airports and the areas several miles downwind. NO_x emissions create smaller regions of high

NO_x concentrations, but ones that still extend beyond the airport boundaries.

The past air quality studies do not provide an answer to the question of whether NO_2 and oxidant violations can be attributed to aircraft. This is because they have not been able to consider the photochemical processes by which these criteria pollutants are formed from HC and NO_x. It seems reasonable that on an annual basis most of the aircraft NO_x disperses from the airport before it can oxidize to NO_2. On a short-term basis, only judgment is available at present and that suggests that the chances of short-term violations are much better than for annual violations.

Oxidant violations on the airport due to aircraft could only occur under stagnant conditions. With a wind, the area of violation would be well downwind of the airport. However, it is reasonable to assume that even in the relatively far future (at least to the year 2000) aircraft HC emissions will be in addition to those from other sources and that the total will cause widespread oxidant problems in most American cities. Aircraft HC controls are a cost-effective way of helping to reduce this oxidant problem. In particular, the HC/CO retrofit program is the only control strategy which reduces aircraft HC emissions in the near future.

The desirability of the modifications that would be forced into use by the HC standards is reasonably well demonstrated in the results of the past studies. Further study of HC will not contribute to the development of the amendments to the existing standards. There is still some uncertainty about the number of localized areas which are experiencing CO problems because of commercial aircraft. Monitoring of CO levels at a number of airport terminals would help resolve this uncertainy. There is a great amount of uncertainty and speculation about the need for aircraft NO_x controls, as this largely hinges on the contribution of aircraft to short-term NO_2 levels. Past studies have not considered this question in any depth.

The new air quality study should attempt to resolve the two areas of present uncertainty by concetrating on short-term, localized CO and NO_2 air quality. CO monitoring will be more

> definitive than CO modeling. Monitoring should also include both NO and NO_2 in order to help resolve the questions of how quickly aircraft NO oxidizes to NO_2. A study which is not designed to effectively address the CO and NO_2 questions will be a minimal contribution to the development of the aircraft amendments."

Re-Evaluation of the EPA Aircraft Engine Emission Standards - Need and Feasibility

This paper by Houtman and Munt (Reference 56) is a compilation of the information contained in the other Technical Support Reports. the recommendations are; therefore, a summary regarding, "Air Quality Considerations", "Cost Consideration", and "Technology Considerations". The entire paper is pertinent to this study and the proposed EPA revisions (Reference 2). It is relatively brief (19 pages) but still too lengthy to be included in its entirety in this report.

4.2.4 Material Presented at Public Hearing

A Public Hearing, regarding the Proposed Revisions was held at EPA Regional Headquarters in San Francisco, California, on 1 and 2 November 1978. This was done to comply with Section 231 of the Act (Reference 2):

> "Section 231 of the Act provides that the Administrator shall hold a public hearing with respect to proposed aircraft emission standards. A notice of time, date, and place for the hearing will be published in the FEDERAL REGISTER in the near future. This hearing is intended to provide an opportunity for interested persons to state their views or arguments, or provide information relative to the proposed amendments to the standards."

The Public Hearing resulted in a great deal of testimoney which has been reported (Reference 46). The summary conclusions for the hearings, as transcribed by Boubel, state:

> "Hydrocarbon emissions can be controlled with existing technology. There was general agreement that control is needed as hydrocarbon emissions contribute to the regional problem.
>
> Carbon monoxide emissions cannot be controlled consistently with existing technology. Control

of hydrocarbons does not accomplish a parallel control of carbon monoxide and the main efforts have recently been directed toward hydrocarbon emission control methods. The engine manufacturers were all in agreement that control of carbon monoxide was not necessary for air quality improvements.

Oxide of nitrogen emissions cannot be controlled with existing technology. Some level of control is possible with modified combustors but there are operational problems which make these combustors unacceptable to the industry. The 1984 date for enforcing NO_x emissions is not realistic according to the engine manufacturers as the technology (adequately tested) will not be available. The engine manufacturers all agreed that the need for NO_x to be controlled in order to meet national air quality standards has not been shown.

Smoke may again become a problem as some combustors, and engines are showing increasing smoke as HC, CO, and NO_x control technology is advanced. Smoke may also become a greater problem if fuel specifications or hydrocarbon ratios are changed.

Timing of the proposed regulations was questioned by all engine manufacturers. All wanted the original date changed from January 1, 1981 to January 1, 1982 for the HC and CO standards. They were also in agreement that the January, 1984 date for establishment of NO_x standards should be postponed until NO_x control technology can be demonstrated.

Variability of the engine emissions was of concern to all at the hearings. The engine manufacturers claimed that calling for maximum emissions standards, rather than average emission standards, would be difficult, if not impossible, to comply with because of engine variability. The hearing panel agreed that variability was a critical problem, but they claimed that none of the manufacturers had supplied enough data to clarify the situation.

Of particular concern to the USAF was a statement made by Mr. David Knight of the South Coast Air Quality District of California. He was generally critical of the EPA for not being more vigorous in their proposed standards."

Additional information regarding costs, variability, etc. was submitted to the EPA Hearing by several manufacturers after the hearing. No official transcript, or compilation of the additionally submitted information is available at this writing.

4.3 Proposed Aircraft Gas Turbine Engine Emission Rules

The proposed revisions to the gaseous emission rules (Reference 2) are dependent on the definition of the time of manufacture of the engine and when it was placed in service (see definitions in Section 4.1). The standards for HC, CO, and NO_x are called a "Proposed EPAP" and are upper limits. The standards for smoke emission (although smoke is not truely a "gas") are still referred to as maximum values of smoke number (SN).

Table 3 is a listing of the proposed limits for newly manufactured engines. Table 4 is a similar table for newly certified engines. Table 5 is for in-use engines, some of which must be retrofitted on a sliding scale.

AD-A090 282 AIR FORCE ENGINEERING AND SERVICES CENTER TYNDALL AF--ETC F/G 21/5
USAF AIRCRAFT ENGINE EMISSION GOALS: A CRITICAL REVIEW.(U)
SEP 79 R W BOUBEL, J A MARTONE
UNCLASSIFIED AFESC/ESL-TR-79-30 NL

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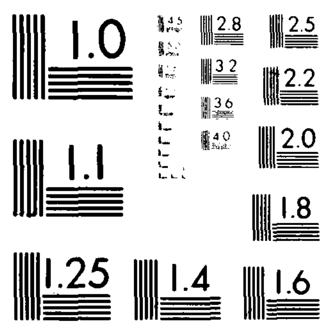

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS 1963-A

TABLE 3. EPA PROPOSED AIRCRAFT ENGINE EMISSIONS RULES FOR NEWLY MANUFACTURED ENGINES

ENGINE CLASS	PROPOSED COMPLIANCE DATE	PROPOSED EPAP=GRAMS/KILONEWTON (KILOWATTS)/CYCLE HC	CO	NO_x	SMOKE
T4	1/1/74	--	--	--	30
T2 Greater Than 129,000 Newtons	1/1/76	--	--	--	$79(r0)^{-0.265}$
T3	1/1/78	--	--		25
T1, T2, T3, T4 Greater than 27,000 Newtons but less than 90,000 Newtons	1/1/81	$26.51 \times 10^{-0.006637r0}$	$169.47 \times 10^{-0.007642r0}$		$79(r0)^{-0.265}$
	1/1/84	--	--	*	
T2, T3, T4 Equal to or greater than 90,000 Newtons	1/1/81	6.7	36.1		$79(r0)^{-0.265}$
	1/1/84	--	--	*	
T5	1/1/80	30.7	237.0	70.8	$79(r0)^{-0.265}$

NOTE: r0 = Rated output in kilonewtons, rT3 = Rated compressor discharge temperature in °K, rPR=Rated pressure ratio

* (a) 33.0 grams/kilonewton for rPR less than or equal to 25; or (b) 33.0 $(rPR/25)^{0.5}$ exp [rT3/288.15-2.774] grams/kilonewton for rPR greater than 25.

TABLE 4. EPA PROPOSED AIRCRAFT ENGINE EMISSIONS RULES FOR NEWLY CERTIFIED ENGINES

ENGINE CLASS	PROPOSED COMPLIANCE DATE	PROPOSED EPAP=GRAMS/KILONEWTON (KILOWATTS)/CYCLE HC	CO	NO_x	SMOKE
T1,T2, T3, T4 Equal to or greater than 27,000 Newtons	1/1/84	3.3	25.0	33.0	$79(r0)^{-0.265}$
T5	1/1/84	7.8	61.0	39.0	$79(r0)^{-0.265}$
P2 Equal to or greater than 2,000 Kilowatts	1/1/84	0.045	0.34	0.45	$277(r0)^{0.280}$

NOTE: r0 = RATED OUTPUT IN KILONEWTONS

TABLE 5. EPA PROPOSED AIRCRAFT ENGINE EMISSIONS RULES FOR IN-USE ENGINES

ENGINE CLASS	PROPOSED COMPLIANCE DATE	PROPOSED EPAP=GRAMS/KILONEWTON (KILOWATTS)/CYCLE HC	CO	NO_x	SMOKE
T4 Retrofit	1/1/74	--	--	--	30
T3 Retrofit	25% 1/1/81 50% 1/1/83 100% 1/1/85	--	--		25
T2 and T4 greater than 53,000 but less than 90,000 newtons	100% 1/1/85	$26.51 \times 10^{-0.006637 r0}$	$169.47 \times 10^{-0.007642 r0}$	--	$79(r0)^{-0.265}$
T2 and T4 equal to or greater than 90,000 Newtons	100% 1/1/85	6.7	36.1	--	$79(r0)^{-0.265}$
T2 equal to or greater than 129,000 Newtons	1/1/76	--	--	--	$79(r0)^{-0.265}$

NOTE: r0 = RATED OUTPUT IN KILONEWTONS

SECTION V

PROPOSED ICAO EMISSION STANDARDS

The International Civil Aviation Organization (ICAO) established a Committee on Aircraft Engine Emissions (CAEE) which first met in Montreal, Canada, June 12 to June 22, 1978. The report of the first meeting (Reference 57) is 189 pages in length and contains detailed reporting of all transactions. A report by the chairman of the U.S. delegation (Reference 58) is considerably shorter and contains most of the significant information presented by the U.S. at the meeting. The U.S. report lists the agenda items for the meeting as:

Agenda Item 1: The overall effects of aircraft engine emissions

Agenda Item 2: Developments in States in respect of regulatory actions.

Agenda Item 3: Development of details of certification schemes for future aircraft engines.

Agenda Item 4: Scientific need for international standards for aircraft engine emissions in the stratosphere

Agenda Item 5: Future Work

After considerable discussion the CAEE came up with suggested standards for turbine engine emissions. The standard for each pollutant was a function of the mass of emissions and the rated thrust of the engine. The following is a statement of the rationale behind the ICAO standards as stated in the report (Reference 57):

> "It was determined that the expression of the emissions limits should be accomplished by use of a parameter in which the mass of pollutant emitted during the reference cycle (D_p) is divided by the engine's rated thrust at sea level, static, ISA conditions (F_{oo}), expressed as a function of pressure ratio (π). This form of parameter, based on overall engine performance or thrust, is easily understood by the public since it relates the emissions limits to the useful capability of the polluting source. It makes comparison between different engines simple and shows up variations of emissions with all relevant engine design features, including thermodynamic cycle as well as combustor variables. By simply multiplying through by rated thrust, the impact of emissions from different engines

on the airport environment can readily be estimated. By including pressure ratio as a controlling variable, differences between engine emissions which arise from the basic influence of pressure ratio on fuel consumption and combustion performance are normalized, thus easing the burden on the design of an emission control system for an existing engine type whose pressure ratio is already fixed."

The proposed ICAO standard form smoke number is:

Maximum Permissible Smoke Number = 555 (F_{oo} or F^*_{oo} as applicable)$^{-0.274}$ or a value of 50, whichever is the lesser

Where:

F_{oo} Take-off thrust rating.

F^*_{oo} Reference pressure ratio.

The proposed ICAO standards (Reference 57) for gaseous emissions depend upon the date when the type certificate for the first variant was granted. If the type certificate was granted before 1 January 1981, but the engine was manufactured on or after the date, the applicable standards are as follows (for subsonic engines):

Hydrocarbons (HC) $\frac{D_p}{F_{oo}} = (0.92)\P_{oo} \times 10^{-4}$ or a value of 0.44×10^{-4} whichever is lower.

Carbon monoxide (CO) $\frac{D_p}{F_{oo}} = \frac{3.1}{\P^2_{oo}} \times 10^{-2}$ or a value of 0.031×10^{-2} whichever is lower.

Oxides of nitrogen (NO_x) $\frac{D_p}{F_{oo}} = (3.2 + 0.12\P_{oo})10^{-5}$ or a value of 7.0×10^{-5} whichever is lower.

Where:

D_p The mass of any gaseous pollutant emitted during the reference emissions landing and take-off cycle.

F_{oo} Take-off thrust rating.

π_{oo} Reference pressure ratio.

If the type certificate was granted after 1 January 1981, the applicable standards for subsonic engines are as follows:

Hydrocarbons (HC) $\frac{D_p}{F_{oo}} = 6.25\ (0.92)^{\pi_{oo}} \times 10^{-5}$ or a value of 2.75×10^{-5} whichever is lower.

Carbon monoxide (CO) $\frac{D_p}{F_{oo}} = \frac{2.7}{\pi_{oo}^{2}} \times 10^{-2}$ or a value of 0.027×10^{-2} whichever is lower.

Oxides of nitrogen (NO_x) $\frac{D_p}{F_{oo}} = (3.2 + 0.08\,\pi_{oo})10^{-5}$ or a value of 6.4×10^{-5} whichever is lower.

The ICAO also proposed a different set of numbers for the time in mode than the EPA. They further were more specific in their specification of thrust settings than the EPA. The rationale, and values, proposed by ICAO are as follows (Reference 57):

> "<u>Times in mode and thrust settings</u>
>
> For the purpose of estimating and expressing emissions data, time for a reference landing and take-off cycle were established which are representative of aircraft operations at busy international airports. These are the operations for which aircraft are predicted to have the most significant impact on pollution concentrations in the atmosphere in and around the airport. Engine thrust settings corresponding to the various phases of this standard LTO cycle and representative of typical values employed in these phases were then established. The times and thrusts in the various phases provided a reference operation for which the emissions could be calculated for any type of engine using data obtained at the reference thrust setting. Only operations conducted at altitudes below 900 metres were considered. This was because it was not thought that, on the average, pollutants emitted above this altitude could diffuse back to ground level through normal atmospheric mixing processes and contribute to the general air quality problem together with other sources. Accordingly, a landing/take-off cycle was chosen which consists of the

following operating phases each of which is associated with a time and thrust setting which is, on the average, representative for the operating phase:"

Operating phase	Time in mode minutes	Thrust setting-percentage of take-off thrust rating
Taxi and ground idle (in and out)	22.0	7%
Take-off	0.7	100%
Climb	2.2	85%
Approach	4.0	30%

The ICAO standards have been summarized and tabulated by D. W. Bahr of the General Electric Aircraft Engine Group (Reference 59). Table 6 is adopted from the material summarized by Bahr.

TABLE 6. PROPOSED ICAO EMISSIONS STANDARDS

APPLICABILITY	SUBSONIC TURBOJET/TURBOFAN ENGINES USED IN CIVIL AIRCRAFT
FORMAT	GRAMS EMISSIONS PER CYCLE PER KILONEWTON RATED THRUST
EFFECTIVE DATE	
EXISTING ENGINES	1/1/81
NEW ENGINES	1/1/84
LTO CYCLE	SAME AS EPA, EXCEPT FOR PRESCRIBED IDLE POWER SETTING OF 7% AND TIME DURATION AT IDLE OF 22 MINUTES
HC/CO STANDARDS	INVERSELY PROPORTIONAL TO CYCLE PR, GENERALLY LESS STRINGENT THAN EPA STANDARDS
NO_x STANDARDS	DIRECTLY PROPORTIONAL TO CYCLE PR, MUCH LESS STRINGENT THAN EPA
SMOKE STANDARD	SAME AS EPA STANDARD

5.1 ICAO Standards Versus Proposed EPA Standards

Table 7 and Table 8 were also prepared by Bahr (Reference 59) to show the proposed ICAO and EPA emission standards for two different model G. E. engines, the CF6-6D and CF6-50C.

Bahr (Reference 59) has also tabulated the values for a current G.E. production engine to show the actual emissions of the engine versus the EPA and ICAO proposed standards. Table 9 presents his results.

The EPA and ICAO are in agreement as to the definition of a "derivative engine". Table 10 lists these values as shown in the report by Bahr (Reference 59).

TABLE 7. COMPARISON - PROPOSED EPA AND ICAO EMISSIONS STANDARDS APPLICABLE TO G.E. CF6-6D ENGINE MODEL (Reference 59)

		EPA	ICAO
CO	(GRAMS PER CYCLE PER KILONEWTON RATED TAKEOFF THRUST)	36.1	51.4
HC		6.7	12.9
NO_x		39.4	61.5
SMOKE	(SMOKE NUMBER)	20.0	21.0

TABLE 8. COMPARISON - PROPOSED EPA AND ICAO EMISSIONS STANDARDS APPLICABLE TO G. E. CF6-50C ENGINE MODEL (Reference 59)

		EPA	ICAO
CO	(GRAMS PER CYCLE PER KILONEWTON RATED TAKEOFF THRUST)	36.1	35.7
HC		6.7	8.5
NO_x		39.4	67.6
SMOKE	(SMOKE NUMBER)	18.0	19.0

TABLE 9. CURRENT PRODUCTION G.E. CF6-50C ENGINE MODEL POLLUTANT EMISSIONS STATUS (Reference 59)

	RELATIVE TO EPA STANDARDS		RELATIVE TO IACO STANDARDS	
	STATUS	ALLOWABLE	STATUS	ALLOWABLE
HC	49.4	6.7	18.6	8.5
CO (GRAMS PER CYCLE PER KILO-	110.8	36.1	56.8	35.7
NO_x NEWTON RATED TAKEOFF THRUST)	61.6	39.4	64.2	67.6
SMOKE (SMOKE NUMBER)	13.0	18.0	13.0	19.0

TABLE 10. ICAO/EPA - GUIDELINES FOR DEFINITION OF DERIVATIVE ENGINE (Reference 59)

GUIDELINES TO BE MET BY DERIVATIVE ENGINE:

- THRUST IS WITHIN ±25% OF PARENT ENGINE
- CORE PRESSURE RATIO IS WITHIN ±20% OF PARENT ENGINE
- DIMENSIONS AND LOCATIONS OF CORE BEARINGS AND SHAFT ARE NOT SIGNIFICANTLY CHANGED FROM PARENT ENGINE
- OTHER FACTORS DEEMED IMPORTANT ARE NOT SIGNIFICANTLY CHANGED

It is obvious that there are areas of difference and similarity between the EPA and the ICAO. Both organizations, however, are proposing that standards be imposed on gas turbine aircraft engines.

SECTION VI

USAF AIRCRAFT EXHAUST EMISSION GOALS

The current USAF Aircraft Exhaust Emission Goals were established based on the understanding of the Clean Air Act, and the amendments to the act, at the time of their writing (References 21 and 27). Since the establishment of these original USAF goals, the EPA Proposed Revisions for commercial aircraft, dated March 24, 1978 have been published (Reference 2) and the required public hearing on the Proposed Revisions has been held (Reference 46). As previously stated in this report, many changes have been made in both the philosophy, and levels of the originally proposed EPA standards.

6.1 1975 USAF Goals

The 1975 goals were based on knowledge established by combustion emission research, atmospheric research, military requirements at the time, projections of future aircraft/engine systems, and objective judgements about possible federal or international rules. It is important to examine these original goals in light of the information available today.

6.1.1 Carbon Monoxide and Hydrocarbon

The 1975 goals state (Reference 1):

"Carbon Monoxide (CO) & Hydrocarbon

For engines in substantial production after 1 January 1979, CO and hydrocarbon levels are to be below levels which result in an idle combustion efficiency of 99 percent for engines with an idle pressure-ratio above 3:1, and a combustion efficiency of 98 percent for engines with an idle pressure-ratio below or equal to 3:1.

For engines in substantial production after 1 January 1981, CO and hydrocarbon levels are to be below levels which result in an idle combustion efficiency of 99.5 percent for engines with an idle pressure-ratio above 3:1, and a combustion efficiency of 99 percent for engines with an idle pressure-ratio below or equal to 3:1."

This goal contains actual numerical values for CO and HC emissions. It is important to point out that this is a goal not a standard to be met. Examination of Figure 3 illustrates the necessity of emphasizing this point. It shows that of all the engines currently being supplied to the USAF, only one, the Pratt & Whitney F100-P-100 engine, meets the 1 January 1979 goal of 99 percent idle combustion efficiency. The idle combustion efficiency for this engine is 99.1 percent (0.9 percent inefficiency). If this engine is still in "substantial production after 1 January 1981" its idle combustion efficiency must be 99.5 percent or greater in order to comply with the goals. It is doubtful if this will be achieved.

It should be pointed out that any numerical values in the goals study would be equally difficult to meet. Had an Emission Index (EI) or an Environmental Protection Agency Parameter (EPAP) been stated as a goal, it too would be exceeded by existing engines. Table 11 illustrates the problem for the F100-P-100 engine, the cleanest currently used by the Air Force.

TABLE 11. EMISSIONS OF CARBON MONOXIDE AND HYDROCARBONS FOR F100-P-100 ENGINE

Component	Emissions, Grams per LTO Cycle Per EPA Standards After 1-1-81	Emissions, Grams per LTO Cycle Per EPA Standards After 1-1-84	Measured EPAP
CO	3,593	1,668	8,327
HC	638	220	1,069

6.1.2 Oxides of Nitrogen

The 1975 goals state (Reference 1):

"Oxides of Nitrogen (NO_x)

For engines in substantial production after 1 January 1979, NO_x levels are to be less than 75 percent of the present or uncontrolled level, and after 1 January 1981, NO_x levels are to be less than 50 percent of the present or uncontrolled level. For engines using water injection, NO_x levels are to be less than 25 percent of the present or uncontrolled level for all engines produced in substantial quantity after 1 January 1979."

This statement refers to a percentage reduction which is translated into an absolute value, based on the combustor inlet temperature, by the next paragraph from the regulations, and the USAF Goals Figure 1, which follows it.

> "Figure 1 graphically illustrates the 1979 and 1981 goals. It is emphasized that these reductions apply to takeoff (max-dry) and climb-out modes of operation only. However, to simplify compliance procedures, the NO_x goal must be satisfied at the max-dry power condition. Idle and approach levels should be maintained at or below the level indicated as uncontrolled."

The extreme difficulty of meeting NO_x standards has been recognized by the EPA in their Proposed Rules (Reference 2). They have decided not to enforce NO_x emission standards until 1 January 1985.

In contrast, the USAF Goals study contains actual numbers which may not be met. For example, the F100-P-100 engine has a combustor static inlet temperature, at a sea-level takeoff power setting, of 800°K (Reference 3). This value, on the USAF Goals Figure 1, amounts to 50 grams of NO_x (measured as NO_2) per kilogram of fuel. The 50 percent reduction would amount to an emission of 25 grams of NO_x per kilogram of fuel "for engines in substantial production after 1 January 1981." The measured EI for this engine (Reference 8) is 27 grams of NO_x per kilogram of fuel which exceeds the value for engines in production after 1 January 1981.

The allowable emissions, if this were a "commercial aircraft" engine, based on EPA proposed standards (Reference 2) would be 2,201 grams per LTO cycle. The actual emissions for the EPAP, based on the EPA time in mode, has been calculated as 2,715 grams per LTO cycle. Again, this points out the problems of using another set of numbers, such as the EPA standards or EPAP, for a goals statement.

6.1.3 Smoke

The 1975 AF Goals were very specific that no visible smoke was the goal. The statement of the goal was:

> "Smoke
>
> For engines in substantial production after 1 Janaury 1979, emission levels of smoke are to be below the invisibility threshold as defined by Figure 2. 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

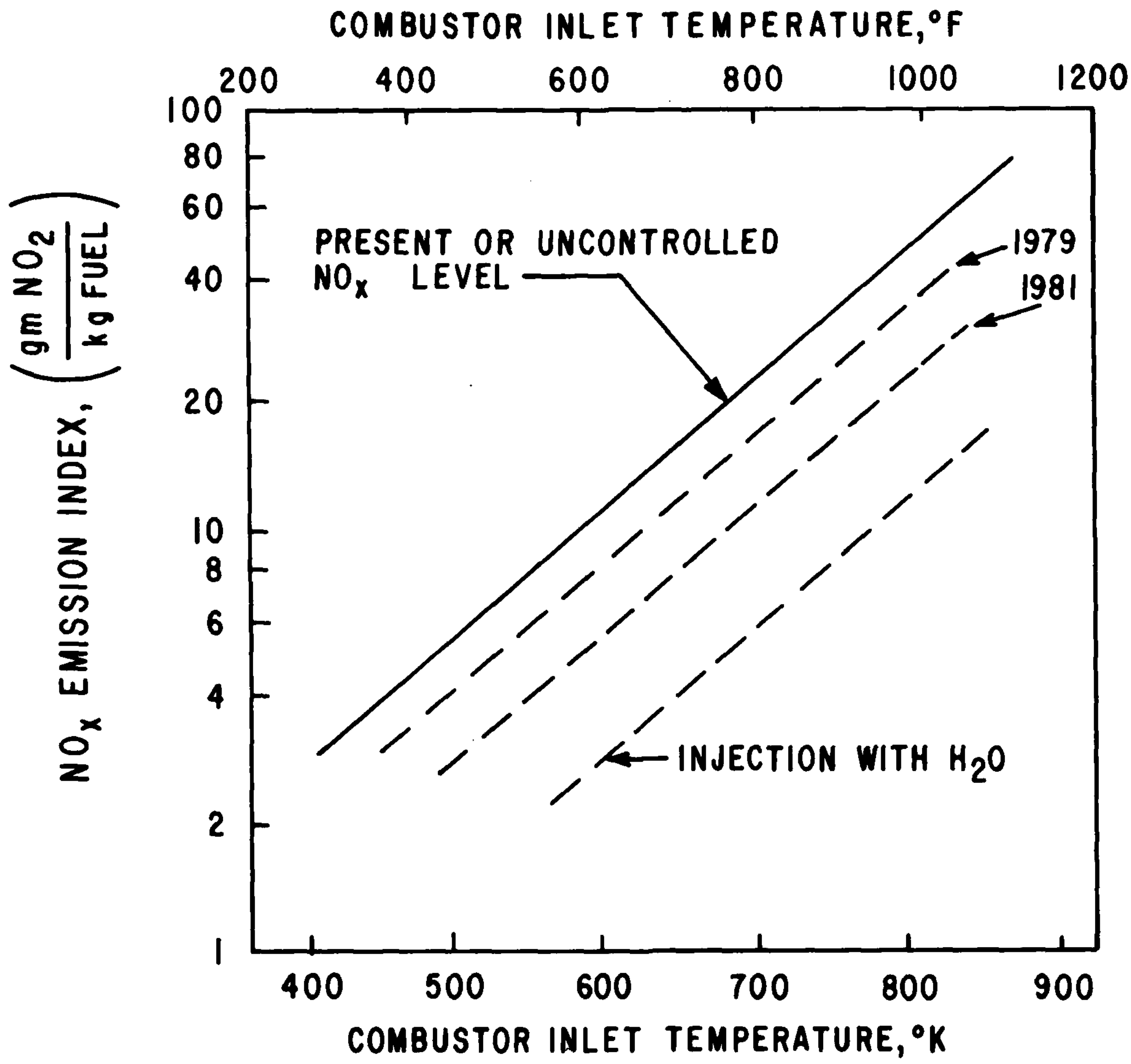

Figure 1. Air Force Oxides of Nitrogen Goals (Reference 1)

where two engines are closely coupled such that the appropriate light attentuation path length represents the exhaust diameters."

Figure 2 from the goals, and referred to in the preceeding paragraph, is shown on the following page. Generally, "invisible" smoke is meant to be below a smoke number of 25. The F100-P-100 engine emits smoke with a measured smoke number of 32.5 at takeoff power. This may certainly be classed as a "visible" plume indicating that this engine will not meet the goals. It will be in production after 1 January 1979. The value of the EPA acceptable smoke number from the 1979 proposed rules, for the F100-P-100 engine, is 26. Again, the F100-P-100 engine cannot meet the numerically established standards.

The situation regarding smoke is probably much more critical than when the goals were written in the early 70's. Fuel aromatic content has increased toward the maximum level allowed by the specifications. This has resulted in increasing smoke from USAF aircraft and some engines which were previously classed as having "invisible" exhaust plumes are now reported to be showing visible smoke. With the present supply of crude oil available to the U.S. refineries, and the subsequent supply of JP-4 to the USAF, smoke can probably be expected to increase, rather than decrease, in the future.

6.2 Considerations for Establishing New Goals

The secretarial memorandum (Reference 1) which established the current USAF aircraft emission goals stipulated that the goals support national environmental objectives. Even though military aircraft are exempt from EPA aircraft emissions regulations, the USAF must recognize the official positions and actions of the EPA as a reflection of the national environmental objectives which the USAF aircraft emission goals must support.

To some, the fact that military aircraft only contribute a small percentage of the overall burden on air quality (Reference 80) might be grounds to justify no emission goals for military aircraft. This position is contrary to EPA philosophy. The EPA acknowledges (Reference 56) that reductions in aircraft emissions alone may make no significant improvement in regional air quality; however, they justify pollution standards for commercial aircraft on the assumption that future air pollution problems will not be the result of any one source as it was in the case of the automobile in the assessments of the late 1960s. The EPA expects that future air quality improvements will require reductions from many different sources which individually would not account for a significant portion of the total air pollution problem. Having USAF aircraft emission goals supports the EPA national environmental objective to achieve National Ambient Air Quality Standards.

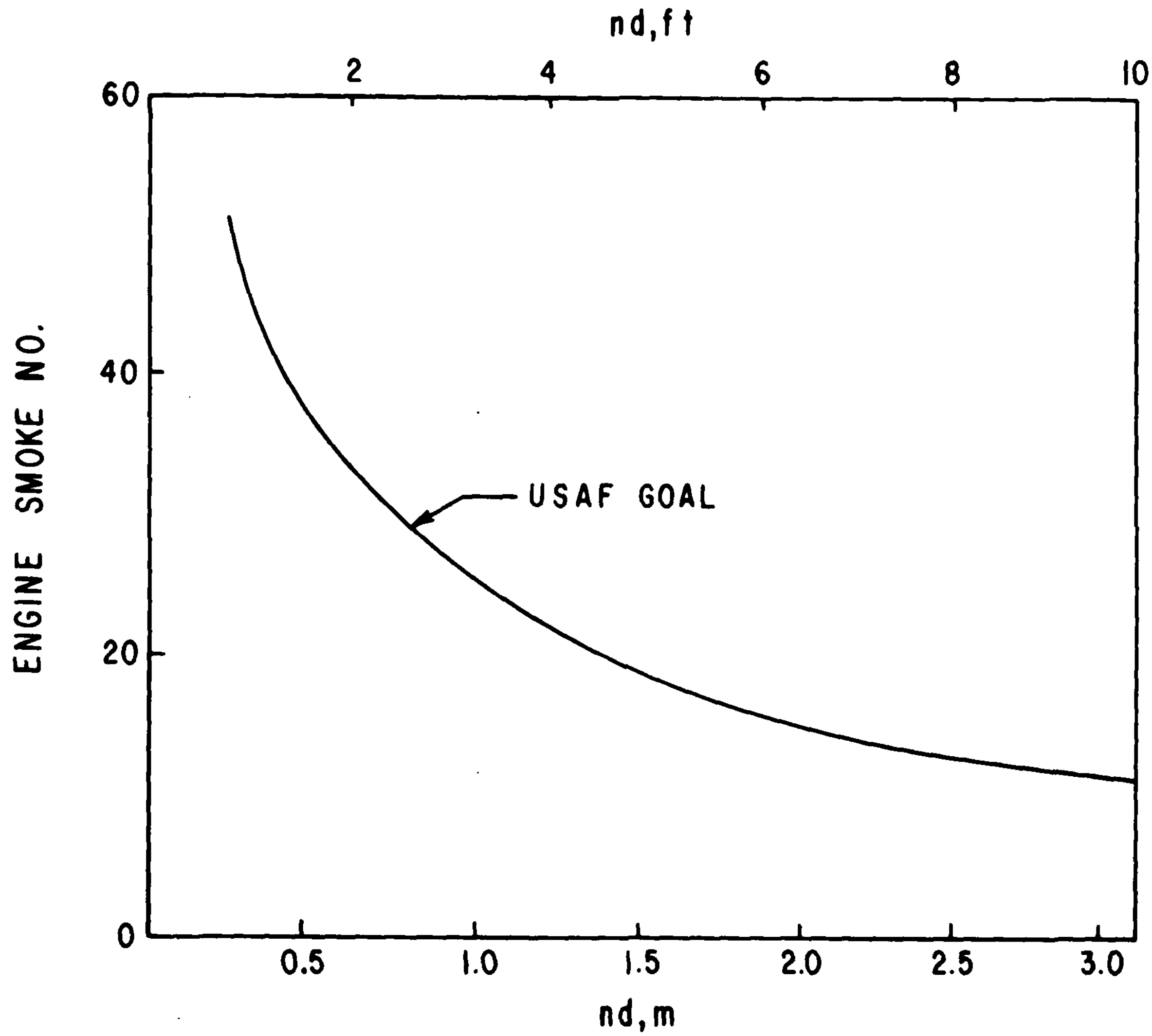

Figure 2. Air Force Smoke Goals (Reference 1)

In light of the tremendous amount of information which has been developed and presented regarding turbine engine emissions, it is important to look at the entire picture before establishing new USAF Goals. Both the EPA and ICAO have considered such items as cost-effectiveness, technology, variability, etc., in setting their suggested standards. The same considerations should be made when setting USAF Goals.

6.2.1 Possible Goals for Carbon Monoxide and Hydrocarbons

It appears to still be valid to consider the reduction of CO and HC concurrently even though such a reduction probably will not occur on a 1 to 1 basis. Generally, HC is easier to reduce through combustion chamber modification or fuel inlet modification than CO. The temperature at which HC may be oxidized to CO_2 and H_2O is lower than that at which CO is oxidized to CO_2. Even though the CO and HC are not reduced corresponding amounts by modifictions, it may still be stated that a change which reduces CO will reduce HC, and vice versa.

Another important consideration is that CO does not appear to be as critical an environmental concern as HC. The effect of CO is only in the immediate vicinity of the emitting source and then the only concern is with human health effects. If the CO concentration is below the ambient threshold value it can be said that there is no effect of CO on the environment.

Hydrocarbons, on the other hand, enter into the photochemical reaction system and; therefore, can cause an effect on the environment at some distance away from their point of release. Any amount of hydrocarbons emitted act additively with those already present in the atmosphere and no "threshold concept" can be applied. It is, therefore, desirable to establish hydrocarbon emissions at the lowest possible level considering technology, cost-effectiveness, etc.

Combustion Efficiency

Blazowski and Henderson (Reference 3) discuss the rationale in using combustion efficiency (or combustion inefficiency) as the limiting parameter for CO and HC. They state:

> "Establishment of CO and HC 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 (η_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, η_c does not separately address CO and HC as would be the case if idle emissions were specified. In a sense, this adds favorably to the argument that specification of η_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 HC and CO. Hence, η_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/HC 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 HC emission indices will increase.

As previously discussed, η_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."

One area which is mentioned by Blazowski and Henderson (Reference 3) concerns the ratio of CO to HC. Their specific sentence is, "As combustion efficiency is improved, the ratio of CO to HC emission indices will increase." this statement was undoubtedly made because of the generally accepted (and previously stated) theory that HC are more easily oxidized than CO. Figure 3 verifies this theory even though it uses "combustion inefficiency" and the HC/CO ratio as variables. The engines with the lowest combustion inefficiency (say less than 2 percent) are also the engines with the lowest HC/CO ratios (0.1 to 0.3). The older engines with combustion inefficiencies from 7 to 12 percent have HC/CO ratios of 0.8 to 1.0.

Some have suggested that HC/CO ratios should be specified as a part of the combustion efficiency parameters. In view of the previous discussion this would appear to be redundant.

Emission Index

The emission index for NO_x, for currently used USAF turbine engines, has been recently published by Scott and Naugle (Reference 8). These EI's are expressed as units of pollutant mass per 1000 mass units of fuel consumed, e.g., grams per kilogram. The emission factors and fuel flows are given for each engine mode.

From these EI values the emissions can be calculated for any engine mode. This is an advantage over the "combustion inefficiency" concept which is applied only at idle conditions. Also, the calculation of emissions for a particular cycle is a simple calculation using the EI, the fuel flow, the engine mode, the time in that mode, and the number of engines. CO and HC values can therefore be obtained for an entire LTO cycle rather than just for the idle portion of the cycle.

HC Emission Index values at idle conditions agree very well with the combustion inefficiency parameter for current USAF engines. Figure 12 shows the regression of combustion inefficiency on the Idle EI of HC. The correlation coefficient "r" is 0.97 which is highly significant.

The correlation of the Idle Emission Index for CO with the combustion inefficiency parameter is not nearly as good as that for the HC. Figure 13 shows the linear regression, with a correlation coefficient, "r", of 0.61. The regression of the idle EI for CO versus the combustion inefficiency shows a much greater scatter for the older engines which are the high CO emitters.

EPA Parameter

The EPA Parameter (EPAP) is based on a summation of EI's multiplied by the appropriate fuel flows, times in mode (TIM) and number of engines on the aircraft. For CO and HC the EI and TIM are both so high for "Taxi/Idle" that an approximation of the EPAP may be made by only performing the calculation for the "Taxi/Idle" mode rather than summing the emissions from all of the modes.

For calculation of the EPAP, the EI is fixed for each pollutant at each mode, the fuel flow is fixed for each mode, the TIM is fixed (by normallizing to the stated EPA standard TIM), and of course, the number of engines on the aircraft is fixed. If an engine modification were made and tested the EI and fuel flow could change, but not the TIM.

It would probably be desirable to use a different but similar, parameter to the EPAP for the USAF. If, for example, aircraft at a USAF base are able to cut their Taxi/Idle TIM to 1/2 of the EPA TIM, the calculated level of emissions of CO and HC, would be cut nearly in half. Naugle and Nelson (Reference 47) did this for several categories of USAF aircraft and reported individual, measured TIM's as well as the average TIM for each type of aircraft. Of course this procedure can be a detriment if the measured, or average TIM, for "Taxi/Idle" exceeds the normalized time used by the EPA. If such were the case, the emission of CO and HC would exceed that calculated and reported as the EPAP.

The Navy has reported on such a problem (Reference 60) in a paper discussing aircraft air pollution legislation and Naval aircraft operations. One of the conclusions in this paper states,

> "Actual naval aircraft flight cycles at the Miramar Naval Air Station (NAS) differ from those used by the EPA in establishing the Emission Indices of pollutants for aircraft. The difference is not in favor of naval aircraft because it consists primarily of increased idle operation time. Unburned hydrocarbons and carbon monoxide are produced in their greatest concentration in the exhaust gas at the idle operating condition."

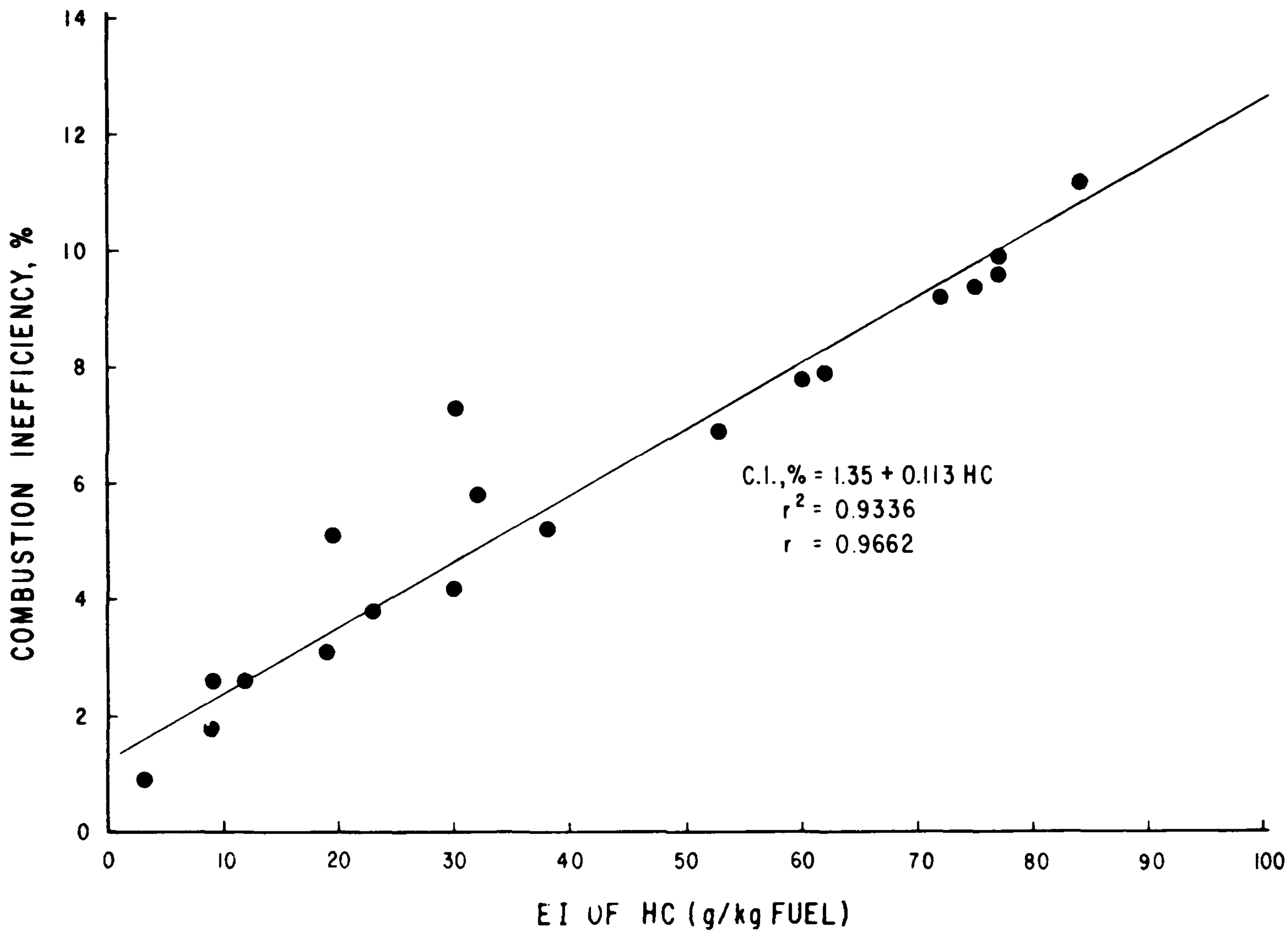

Figure 12. Regression of Combustion Inefficiency on Idle Emission Index of Hydrocarbon for Current USAF Engines

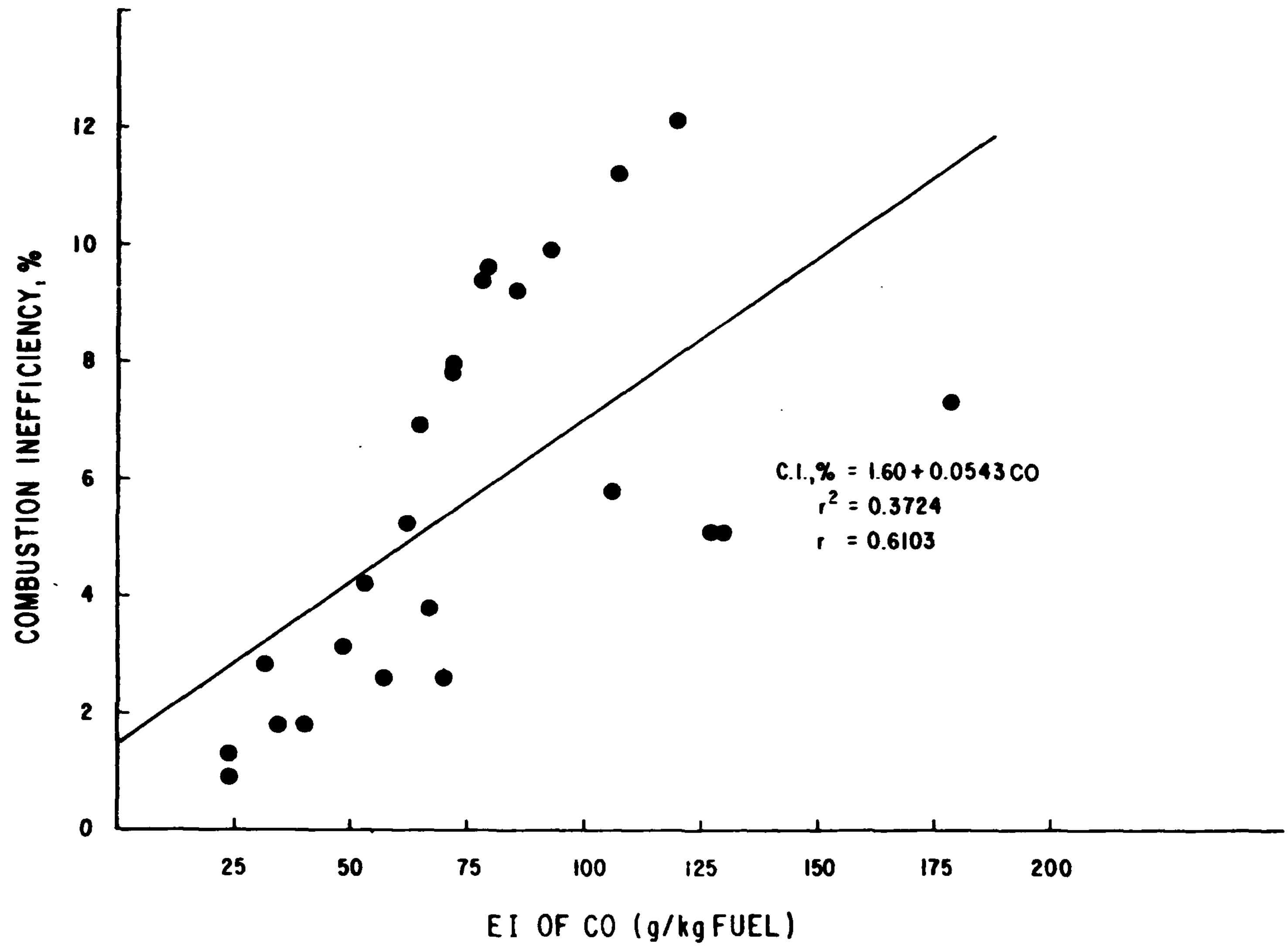

Figure 13. Regression of Combustion Inefficiency on Idle Emission Index of Carbon Monoxide for Current USAF Engines

The actual data reported by the Navy in this paper indicates the magnitude of the problem, as shown in Table 12. The TIM data in this table indicates that the TIM for the Taxi/Idle mode for the F-4J Aircraft was a total of 41.1 minutes compared to a TIM for the EPA standard cycle of 26.0 minutes. The CO and HC emissions would be approximately (41.1 divided by 26.0)100 = 158 percent, or half again as much as the EPAP calculated values for the F4-J Aircraft. The A-4E Aircraft also had measured emissions (based on TIM) of half again the EPAP calculated values.

TABLE 12. UNITED STATES NAVAL AIRCRAFT MEASURED TIME IN MODES (Reference 60)

Aircraft	Operating Mode	Time in Mode, (minutes)	
		Miramar Study	EPA Standard Cycle
F-4J	Taxi (Out)	24.5	19.0
	Take Off	0.3	1.2
	Climb Out	0.7	2.0
	Descent	-	2.3
	Approach	4.1	1.2
	Taxi (In)	16.6	7.0
A-4E	Taxi (Out)	25.0	19.0
	Take Off	0.2	0.5
	Climb Out	0.9	2.5
	Descent	-	-
	Approach	4.4	4.5
	Taxi (In)	14.2	7.0

6.2.2 Possible Goals for Oxides of Nitrogen

Questions concerning possible goals for NO_x are probably more numerous than answers. The EPA has recognized this in its proposed rules (Reference 2) by relaxing the date of implementation for the NO_x standard until 1984 for engines manufactured after 1981, and, 1985 for all engines.

Currently studies are being conducted to determine the actual degradation of the atmosphere due to NO_x emissions (Reference 6, 7). These studies are concerned with both short term contributions where local effects due to NO_2 may be a problem and the long range problems of NO_x in the atmosphere and stratosphere where it reacts in the photochemical cycle. Until these, and other, studies are completed and evaluated it appears that a valid determination of the effect of aircraft turbine generated NO_x on the quality of ambient air cannot be made. It does not appear that numerical goals for NO_x emissions should be established until the effects of such emissions are determined.

The cost-effectiveness of NO_x controls for aircraft also does not appear to be favorable. Other sources can reduce NO_x emissions at a lower cost per unit of reduction than that for turbine engines. The EPA recognized this in their proposed rules and cited cost-effectiveness as one of the reasons for their delay in implementation of NO_x standards.

Much of the needed research for NO_x control from turbine engines is still in the conceptual stage. This is in contrast to the control methods for CO and HC which have been thoroughly investigated and widely reported. A recent joint paper by EPA and Pratt & Whitney Aircraft (Reference 61) indicates the number of different concepts which are being considered as possible NO_x control, or reduction, methods. Table 13 lists the design concepts currently being considered for stationary gas turbine engines. Many of these concepts are also valid for NO_x reduction for aircraft gas turbine engines.

Percentage Reduction

Blazowski and Henderson (Reference 3) discuss the rationale of using a percentage reduction value for NO_x. They state:

> "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 percent 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."

The method of application of this rationale is as follows:

(1) Determine the combustor inlet temperature (a design value).

(2) Use the regression of NO_x emissions on combustor inlet temperature to determine the uncontrolled NO_x value.

TABLE 13. CANDIDATE DESIGN CONCEPTS (FOR OXIDES OF NITROGEN CONTROL)
(Reference 61)

Concept No.	Title
1	Low-Intensity Flame
2	Premixing Catalytic Burner
3	Superlean With Heat Recirculation
4	Superlean With Preburner
5	Heat Removal
6	Quench Reheat
7	Staged-Centertube Burner
8	Exhaust-Gas Recirculation
9	Hydrogen Enrichment
10	Surface Combustion
11	Distributed Flame
12	Ceramic Liner
13	External Combustion
14	Boost-Air Dilution
15	Artificial Excitation
16	Extended Injector
17	Pebble Bed
18	Coanda Flame
19	Electric Assist Nozzles
20	Virtual Staging
21	Engine Inlet Fuel Injection
22	Flameless Combustion
23	Air Staging
24	Fuel Staging
25	Vorbix (Vortex Burning and Mixing)
26	Fuel/Air Premixing

(3) Apply the desired percentage reduction to achieve the controlled NO_x emission value.

It may be seen that assumptions of accurately forcasting the combustor inlet temperature, and, of little error in application of the regression equation are necessary for this approach. This approach also assumes that there is no effect due to fuel-bound nitrogen, or fuel hydrogen to carbon ratio, which could both be future problems as fuel requirements change.

Emission Index

The emission index for NO_x, for currently used USAF turbine engines, has been recently published by Scott and Naugle (Referdnce 8). The same comments made earlier in this report about the EI's for HC and CO, regarding units and calculation of emissions for a particular cycle, apply to the EI for NO_x.

The emission index of NO_x is shown in Figure 1 of the attachments to the 1975 USAF Goals (Reference 1) to be a logarithmic function of the combustor inlet temperature. The wide variation in EI for NO_x reported by Scott and Naugle (Reference 8) can be related to the combustor inlet temperature of the particular engine. The newer engines have a higher pressure ratio, hence a higher combustor inlet temperature and an higher EI for NO_x. The converse is true for the older engines still in use by the USAF.

EPAP Parameter

The EPA Parameter (EPAP) based on the summation of the EI's, fuel flows, and TIM's may be calculated for NO_x just as it was for CO and HC. For NO_x, however, the EPAP is composed more equally of emissions from the various cycles. This is because the "Taxi/Idle" cycle, which contains the longest TIM, has the lowest EI and fuel flow. Table 14 illustrates this with a calculation for the F-16 aircraft with the F100-P-100 engine.

TABLE 14. OXIDES OF NITROGEN EMISSIONS AND EPAP FOR F100-P-100 ENGINES

Operation Mode	EI, g/kg Fuel	FUEL kg/sec	EPA-TIM, Minutes	NO_x Emission, g & (%)
Taxi/Idle	3.3	0.179	26.0	921 (30)
Take Off*	3.1	5.797	0.7	756 (24)
Climbout	9.8	0.643	2.2	832 (27)
Approach	6.7	0.378	4.0	608 (19)
				TOTAL = EPAP = 3,117 (100)

*Assumes afterburner used on takeoff.

As previously mentioned, in the discussion of the EPAP for CO and HC, a different but similar parameter could be advantageous for the USAF. For example, the EPAP calculated for the F-16 with the F100-P-100 engine, was 3,117 grams of NO_x per LTO cycle (Table 14). If the average USAF values for TIMs of fighters is used instead of the EPA, normalized TIMs, the value becomes 3,706 grams of NO_x per LTO cycle. This increase occurs because the average TIM for some cycles is longer for the USAF average. If, however, the actual TIMs of the F-16 aircraft are used, the NO_x emission value is 2,450 grams per LTO cycle. This is a considerable reduction compared to the EPAP of 3,117 grams.

6.2.3 Possible Goals for Smoke

The goals previously proposed for smoke were directed a obtaining an invisible plume. This is desirable from both aesthetic and combat viewpoints. There is another consideration that bears on the issue of smoke. Because of the difficulties in sampling particulate from turbine powered aircraft, the total particulate emitted is calculated from the smoke number (SN) rather than measured. This procedure is outlined by Shaffernocker and Stanforth in an SAE paper (Reference 62). It consists of converting the SNs to mass per unit volume values and then using those values, the engine operating characteristics, and the mass balance to calculate the total particulate emissions. The values so obtained are the EI of the total particulates.

Invisibility Threshold

The previous USAF goals (Reference 1) set smoke levels below the invisibility threshold as defined by a curve based on smoke number and path length. This approach recognized the problem which is inherent in some military aircraft where engines are located adjacent to each other. For example, the F-16 uses one F100-P-100 engine while the F-15 uses two of these same engines side by side. The visual path length for the F-15 exhaust, viewed from the side, is twice that of the F-16 exhaust so an exhaust plume classed as "invisible" for the F-16 could be classes as "visible" for the F-15 even though the smoke numbers were the same.

The problem is further complicated in aircraft such as F-15 and F-16 because they use a variable diameter exhaust for the engines. The exhaust diameters at maximum smoke condition must be stated along with the other variables.

If the invisibility is used as a goal, or "standard", it is desirable to have a smoke number at or slightly below the invisibility threshold. Reduction to lower levels can result in compromises to stability, ignition, and altitude relight characteristics without achieving "lower emissions" because of the definition of the goal or standard.

Smoke Number

Both the EPA and ICAO have adopted the smoke number, as determined by the Society of Automotive Engineers (SAE) (Reference 12), as the recommended method of measuring smoke emissions from turbine powered aircraft. Standards have been set at the maximum permissible SN for each engine which does not consider exhaust diameter or engine configuration as a variable.

The allowable SN for the F100-P-100 engine, used in the F-15 and F-16 aircraft, has been set by the EPA at 26 according to the formula proposed in the regulations. Because of the path length, viewed across the exhaust plume, this would probably be an invisible plume for the F-16 but a visible plume for the F-15.

6.2.4 Possible Goals for Oxides of Sulfur

Oxides of sulfur were not mentioned in the USAF Goals of 1975 (Reference 1). The reason for not mentioning SO_x is that it is strictly a function of the sulfur content of the fuel and therefore cannot be considered as an engine problem. The same reasoning applies to any consideration of USAF emission goals today. The only control the aircraft engine designer has over SO_x emission is through fuel specifications for the engine. Since turbine fuel sulfur content varies within specification (i.e., typical values are 0.01 to 0.08 wt percent) the SO_x emission, usually listed as "average sulfur emissions,"are taken as 1.0 g/kg fuel for turbine engines using JP-4 fuel (Reference 8). "Sulfur emissions" are measured as SO_2.

If the sulfur content of JP-4 is allowed to increase to the maximum current specification of 0.4 percent, (Reference 64) the SO_2 emissions will increase to 8 g/kg fuel. If increased refining of high sulfur crude oil is necessary to provide fuel, it is possible that the allowable sulfur specification could be raised even higher than the current 0.4 percent. Naugle (Reference 81) used air quality modeling to predict that JP-4 fuel sulfur levels up to 1.0 wt percent will not produce measurable ambient SO_x concentrations under typical meteorological conditions. Naugle (Reference 81) conculded that sulfur in jet fuels should be governed by engine durability and not by environmental considerations.

6.3 Present USAF Goals Versus EPA Proposed Regulations

It should not be surprising that the present USAF Turbine Engine Emission Goals (Reference 1) and the proposed EPA Rules (Reference 2) are different from both a qualitative and quantitative standpoint. The EPA has as its primary purpose the reduction of pollutant emissions to obtain acceptable air quality. The USAF has stated, "... in no case shall pollutant controls be allowed to infringe on military engine design or operation in a manner which compromises system effectiveness" (Reference 3). This publication further explains the USAF rationale,

> "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. 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"

The USAF cannot sacrifice mission design effectiveness (operational capability) in order to comply with a specific emission standard. This, however, does not mean that the USAF can ignore emission standards proposed by the U.S. government.

6.3.1 USAF Performance Requirements

Aircraft in the USAF fleet are as diverse a mix of types as can be found. They vary from single engine, light aircraft through multi engine, supersonic research aircraft. Of greatest concern, as far as compliance with any exhaust emission standards, are the aircraft designated as "combat" aircraft. These are the aircraft with critical performance requirements. They are also the aircraft with the largest differences if a comparison is made with the U.S. airline fleet (for which the proposed EPA rules are being developed). A listing, and discussion, of the requirements of "combat" aircraft is important in establishing or evaluating the USAF goals. It must also be pointed out that the specific military requirements are concurrent with many of the usual turbine engine requirements such as altitude relight,ease of ground starting, etc.

Specific Fuel Consumption

Combat aircraft are operated in maximum power output modes (such as "afterburner") an appreciable amount of time. Even older fighter aircraft, such as the F-101, which has been in servce since the 1950s, use afterburner for the takeoff mode. This requirement of high levels of power (or thrust) by the USAF results is high specific fuel consumption (SFC) for USAF engines. If an emission index (EI) value (grams of pollutant per kilogram of fuel) is multiplied by the SFC to obtain the quantity of the emitted pollutant, a greater value can be expected for the military aircraft with high SFC.

Power at Altitude

Commercial gas turbine powered aircraft are generally operated at cruise power at altitude. The emission of NO_x from these aircraft would be less than that from combat aircraft which are operated at higher power at altitude to meet performance requirements. This would not effect the EPAP values because they are only determined for emissions at altitudes less than 0.914 km (3000 feet). It would, however, be a serious consideration in studies of high altitude emissions and conversion rates.

USAF Times in Mode

The USAF Times in Mode (TIM) are considerably different from the EPA, TIMs. It is obvious that an F-15 aircraft will climb to the 0.914 km (3000 feet) altitude in only a fraction of the EPA "Climbout" TIM of 2.2 minutes. The EPA, TIMs are average values for turbine powered, airline aircraft and in no way represent the variety of TIMs found at various USAF bases for the many different components of the USAF fleet of aircraft. If serious comparisons of emissions are to be considered it would be absolutely necessary to use the Emission Index (EI) values for USAF aircraft along with actual USAF TIMs.

Smoke is an Operational Consideration

A smoking commercial airliner is only causing an aesthetic problem. The smoking combat aircraft has more than just an aesthetic problem. It becomes a much more visible target than a non-smoking aircraft. The USAF is therefore committed to reducing smoke as operational and an aesthetic problem. The goal of an invisible exhaust plume may receive more support than any other of the USAF goals.

Need for Test Aircraft

Commercial gas turbine engines may be evaluated by attaching them to an existing aircraft for testing purposes. Most combat aircraft (and engines) are tested by test pilots flying prototypes. The USAF does not have the advantage of evaluating new engines, or engine modifications, on flying test beds. Determination of the actual emissions from operating USAF aircraft becomes of matter of considerable extrapolation of data rather than actual measurement. The problem is often cited of the near impossibility of determining the emissions from a supersonic combat aircraft, at altitude, operating on full afterburner.

Power Reduction for Control

Commercial turbine powered airliners can consider varying the power settings as a means of obtaining maximum fuel economy, minimum emissions, minimum noise, etc. The military cannot consider varying power settings without compromising their mission in many cases. This is particularly true with combat aircraft which usually have extremely tight performance specifications.

The same can be said for other proposed methods of control of various emissions by changing operational methods or power settings (increased idle RPM is an example). The military pilot is trained to be combat ready and he therefore needs to be continually operating his aircraft as a weapon. He cannot maintain optimum efficiency if he is required to follow one pattern for training (say a pattern to minimize emissions) and another only when be expects an actual combat situation.

6.3.2 Determination of Compliance

The determination of compliance with standards is quite different for civil and military aircraft. If the EPA adopts the proposed emission regulations for commercial turbine powered aircraft, the Federal Aviation Administration (FAA) will be responsible for enforcement of the regulations. The EPA and

FAA have worked closely during the past several years in this matter but the situation still exists that two separate Federal agencies are involved. This can create problems with funding, reporting, etc.

The USAF, on the other hand, is responsible for all phases of turbine engine exhaust research, measurement, testing, evaluation, and control. These responsibilities extend to contractors and manufacturers. They apply to new engines, operational engines, overhauled engines and even engines which may be awaiting a retrofit.

The result of this complete responsibility by one agency, the USAF, is much more amenable to a systems approach than the EPA/FAA split approach. The operational capability, reliability and maintainability, implementation, cost, etc. are more readily and more reliably determined.

6.4 Proposed USAF Goals

The proposed USAF Goals are based upon the original goals of 1975 (Reference 1) modified through consideration of the information contained in this report. The proposed goals contain neither numbers or dates so that they can be applied in programs ranging from basic research through aircraft production and acquisition contracts. The burden will be on individual project officers, program managers, and systems program offices to formulate technical objectives, consistent with the stated goals, appropriate for the particular project/program under consideration.

The proposed goals are applicable to turbopropulsion engines for fixed wing manned aircraft. Afterburning engines would be required to meet these goals only during non-afterburning operation. The proposed revisions to the current USAF Aircraft Exhaust Emission Goals are as follows:

Carbon Monoxide (CO)

The Emission Index (EI) is the most desirable means of reporting CO emissions. It is recommended that the USAF adopt this as its standard reporting form with the units specified as grams of CO emission per kilogram of fuel burned, for each specific mode of engine operation. CO is only of consequence in the Taxi/Idle mode so this is the only critical mode to consider in design and procurement. CO has not been shown to be a serious problem at present emission levels. Therefore, it does not appear to be appropriate to spend additional time or money on systems to further reduce CO unless an unforseen problem surfaces.

Hydrocarbon (HC)

The Emission Index (EI) is the most desirable means of reporting HC emissions. It is recommended that the USAF adopt this as its standard reporting form with the units specified as grams of HC emission per kilogram of fuel burned, for each specific mode of engine operation.

A highly significant correlation exists between combustion efficiency (or inefficiency) and the EI for HC. For combustor design and experimentation, the concept of combustion efficiency may still be appli·d. For final engine testing and acceptance, the EI should be determined and reported.

HC is only of consequence in the Taxi/Idle mode so this is the only critical mode to consider in design and procurement. HC emissions are excessive at the present emission levels and continued efforts to lower them are necessary. The goal for USAF turbine engines should be compatible with levels specified by EPA for the equivalent engine used in "commercial service." No retrofit or modification of existing engines for HC control should be made unless the engineering and cost studies indicate that such retrofit/ modification is environmentally necessary and will not interfere with the USAF mission.

Oxides of Nitrogen (NO_x)

The Emission Index (EI) is the most desirable means of reporting NO_x emissions. It is recommended that the USAF adopt this as its standard reporting form with the units specified as grams of NO_x emissions per kilogram of fuel burned, for each specific mode of engine operation. NO_x is of consequence in all modes of operation except the Taxi/Idle mode. In the Taxi/Idle mode the EI and fuel flow are both low enough that the product of the two (to obtain the mass emission of NO_x) is negligible.

NO_x emission may be considered as critical at lower altitudes where high power is used for takeoff and climbout. NO_x emissions may also be critical pollutants during stratospheric missions. However, since the EPA has stated that additional studies and further information is necessary to accurately determine the effects of NO_x emission, it is recommended that the USAF not consider NO_x emission requirements at this time.

Smoke

The USAF goal for smoke emission levels shall be that the exhaust emissions are invisible at all modes of operation. For a particular engine/aircraft system the invisibility threshold is a function of the system and the smoke number (SN). Therefore, the SN should be specified to meet the goal for smoke. Smoke reduction is important to the USAF mission and continued effort toward such reduction is a vital part of this goal.

Oxides of Sulfur (SO_x)

The Emission Index (EI) is the most desirable means of reporting SO_x emissions. It is recommended that the USAF adopt this as its standard reporting form with the units specified as grams of SO_x emission per kilogram of fuel burned for each specific mode of engine operation. Although the emissions of SO_x are currently of only minor consequence at all modes, they will increase if the sulfur content of the fuel increases. The USAF goal, therefore, should be toward minimization of fuel sulfur with continued research directed toward this goal. This will become particularly important as changes in fuel specifications are considered and alternative fuels are investigated. The EPA has not considered standards for SO_x critical so the USAF should be aware of potential problems even though a specific goal is not recommended at this time.

These proposed USAF Goals are compatible with the proposed USAF, DID, shown as Appendix A.

6.5 Proposed USAF Goals Versus EPA Regulations

The proposed USAF Aircraft Engine Emission Goals are different than the proposed EPA rules (Reference 2). The EPA rules contain specific numerical emission values (expressed as EPAP and SN) while the USAF Goals do not. This is in contrast to the previous USAF Goals (Reference 1) which stated numerical values for emission limits. It is believed that the proposed USAF Goals are in philosophical agreement with the EPA rules as they were published in the Federal Register and later discussed at the Public Hearing in San Francisco (Reference 46). The support documents considered by the EPA in promulgating these rules (Reference 49-53) further bear out this concept of philosophical agreement.

The proposed USAF goals are meant to be a directive to all concerned stating the intent of the USAF to strive for environmental quality, as in the "USAF Pledge to Environmental Protection" (Reference 40). The EPA Proposed

Revisions to Gaseous Emission Rules are numerical standards with the appropriate dates, methods, etc. Within the structure of the proposed USAF Goals, numerical standards can be established if the USAF wishes. Dates and methods can also be established as standards within the Goals structure. It is important that the USAF Goals are continually used as a guiding principle in any setting of numerical standards, dates, methods, etc. as they might apply to USAF aircraft.

6.6 Implementation of USAF Goals

The implementation of the proposed USAF Aircraft Engine Emission Goals would be much more realistic than was the implementation of the previous goals (Reference 3). The proposed goals indicate the direction the USAF should proceed to achieve the stated purposes of the USAF "Pledge to Environmental Protection" (Reference 40). The previous goals indicated the direction, but then put in numerical values which could be interpreted as standards or limiting values.

The proposed USAF Goals are compatible with other USAF research efforts and directives (such as the proposed DID, Appendix A). If adopted, they can give guidance to those working on USAF turbine engine emissions programs without establishing the numerical limits for achievements from the programs.

The proposed USAF Goals are compatible with military specifications (Reference 82 and 83) that apply to all Departments and Agencies of the Department of Defense. Maximum allowable emission levels will be specified by engine program managers on a case-by-case basis within the framework of the USAF Goals.

The proposed goals recognize that there must be some flexibility in the programs of the USAF because the USAF does not have absolute control over all of the input variables. Examples are programs looking at changes in jet fuel specifications and alternate fuels, programs analyzing the variability of emissions and the effect of engine degradation on emissions.

The proposed USAF Goals should be compatible with the proposed EPA Rules because they are goals, not standards. The previous, 1975 Goals, listed numerical values which were continually compared to EPA emission standards or ICAO standards. It will be possible for an engine manufacturer to state that a certain model engine complies with both EPA standards for some exhaust pollutant and USAF Goals.

When future EPA/FAA studies and other studies concerning NO_x in the atmosphere, are completed, the proposed goals should be compatible with the findings. If NO_x controls need to be implemented, to prevent serious atmospheric degradation, requirements can be applied to existing and future engines.

The total implementation of the USAF Goals must be a matter of awareness of the Goals and a commitment from all concerned to comply with them. This certainly is within the letter and the spirit of the USAF mission. The remaining sections of this report are based on the assumption that the proposed USAF Aircraft Engine Emission Goals will be adopted.

SECTION VII

USAF ENGINE CONSIDERATIONS

Both the military and airlines are customers for large, gas turbine aircraft engines. If the proposed EPA rules (Reference 2), or some similar rules, are adopted the commercial aircraft will be under strict emission regulations. If the proposed USAF Goals are adopted, as outlined in the previous section, the USAF will be required to consider their application for engine research, procurement, operation, testing, etc. Many different factors enter the picture as far as USAF engine considerations are concerned. It is important to examine them in light of the proposed USAF Goals.

7.1 Gas Turbine Engine Pollution Control

With the exception of SO_x, which is a totally fuel related pollutant, the control of pollution from turbine engines is related to combustor design. Variations in combustor design may impact upon other engine components but pollution reduction research can be carried out using only the combustor section, along with the necessary accessory sections (fuel pump, ignition, etc.) The combustors will probably be tested in "rig tests" instead of full engine tests. Exhaust pollutants can then be measured at the rig outlet rather than at the tailpipe of the engine where stratification of by-pass air and combustion products may be a serious measurement problem.

Research may be conducted using only one burner can, if a can type system is being tested, or one segment of an annular combustor. This can greatly reduce the costs compared to modification and operation of the entire combustor section of an engine.

If a structural, or material failure, occurs during a rig test it is relatively inexpensive compared to what could occur during a full engine test where debris could enter the turbine section. This also would be a point in favor of safety considerations for rig tests versus full engine tests.

7.2 Costs

Any pollution controls which are added to an engine will increase the cost of that engine. No systems are used, or proposed, which will recover enough energy to pay even a small part of this additional cost. The USAF must anticipate any additional costs before their budget is submitted which means that long range financial planning is necessary. Also, the USAF does not have the ability that the commercial airlines have of increasing their income (raising ticket prices) if operating and maintenance costs increase.

Since all current research efforts on controlling emissions from gas turbine engines are concentrated on combustor design, research, and development, the combustor costs become of primary consideration in any cost study. Henderson and Blazowski (Reference 42) state,

> "...the cost of contemporary combustion systems including ignition and fuel injection assemblies remain at approximately 2-4 percent of the total engine cost."

Henderson and Blazowski (Reference 42) list the cost of "Contempory Combustors", in mid-1970 dollars as shown in Table 15.

TABLE 15. CONTEMPORAY COMBUSTOR COST (REFERENCE 42)

Engine	Combustor Type	Cost
TF39	Annular	$42,000
TF41	Cannular	$17,000
J79	Cannular	$11,300
JT9D	Annular	$80,000
T63	Cannular	$ 710

Blazowski and Henderson (Reference 3) do recognize that costs are highly variable and they state,

> "The cost of developing an emissions control technique is a function of its current state-of-development and its ultimate application. It is exceedingly difficult to forecast costs of implementing any control technique because of varying complexity, extent of procurement action, and inflationary factors.
>
> 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."

Table 16 lists cost data as presented by Blazowski and Henderson (Reference 3) in 1974 dollars. They go on to discuss their concept of "Mid-Term Technology,"

"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. 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 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."

They continue their discussion of "Advanced concepts,"

"Development of advanced ultra-low emissions technology requires an additional increment of cost beyond that described previously. Initial development of the 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."

TABLE 16. EXHAUST EMISSION COST SUMMARY, MILLIONS OF DOLLARS (1974) (Reference 3)

	Research	Expl Dev. Per Eng Mode	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.

They conclude with a discussion of the costs,

"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 costs, 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."

Naugle (reference 66) has summarized the data and information from two previous, extensive studies (Reference 51 and 65). He discusses the costs associated with compliance with the proposed EPA Rules. The following discussion and Tables 17 through 19 are from Naugle's paper [His references to "LMI" refers to the Logistic Management Report by Day and Bertrand (Reference 65) and his reference to "Wilcox" refers to the EPA report by Wilcox and Munt (Reference 50), NME means newly manufactured engines, IUE means in use engines]:

"Comparsions of the two studies are shown in Table 17. Considerable variation in the estimates is shown. Potential cost penalties due to uncertain testing and penalties account for the difference between LMI "Best" and "Worst" cases. EPA costs should more closely agree with the "Best" cases since these potential costs were not included. This is not the case for the engines manufactured after 1/1/81 (NME 81) and engines manufactured after 1/1/84 (NME 84) standards, however. Disagreements between study results are due to differences in aircraft fleet projections, controlled engine assumptions, reoccurring cost assignments, maintenance cost treatments, and discounting procedures. Itemization of these differences is obscured since EPA performed computations by engine type, LMI by aircraft type, and different conversions from one to the other were used in each study.

The greater economic rigor of the LMI study and improved fleet projections promote greater confidence in their results. Also, as LMI points out, all U.S. and foreign owned aircraft operating at U.S. airports must meet the emission standards. Although not explicitly stated, the

TABLE 17. COMPARISON OF PREVIOUS COST STUDIES (US Aircraft, Millions of Dollars) (Reference 66)

PROPOSED STANDARD	EPA (1)	LMI BEST CASE (2)	LMI WORST CASE (2)
NME 81 (Engines manufacutured after 1/1/81)	142	68	138
NME 84 (Engines manufactured after 1/1/84)	1179	448	1051
IUE 85 (All engines in use, after 1/1/85)	254	386	492

(1) Complied from WILCOX, pages 16 through 22. Expressed in 1979 dollars, zero discount rate.

(2) LMI, page A-28. Expressed in 1978 dollars, unspecified discount rate.
"Best Case" includes all known estimatable costs.
"Worst Case" includes possible penalties which may or may not occur due to unknown financial risks from inadequate engine testing and uncertain engine life penalties.

TABLE 18. ITEMIZATION OF COMPLIANCE COST (U.S. and Foreign Aircraft Operating at U.S. Airports)
(Reference 66)

	COMPLIANCE COSTS (1)					(MILLIONS OF DOLLARS)	
	HARDWARE	MAINTENANCE	FUEL PENALTY	SERVICE TESTING	COMBUSTOR LIFE	PREMATURE REMOVAL	TOTAL
BEST CASE							
NME 81	110.2	130.8	-105.2	-	-	-	$ 135.8
NME 84	676.0	201.2	-52.6	-	-	-	824.6
IUE 85	580	200.3	-207.7	-	-	-	572.7
							$1533.1
WORST CASE							
NME 81	110.2	130.8	-105.2	136.0	-	-	$ 271.8
NME 84	676.0	201.2	-52.6	493.5	569.2	-	1187.3
IUE 85	580.1	200.3	-207.7	144.8	-	6.7	724.2
							$2883.3

(1) Recategorized from LMI (pages A-24 to A-28). Represented in 1978 dollars.

TABLE 19. COST OF COMPLIANCE TO FEDERAL AIRCRAFT EMISSION STANDARDS (Reference 66)

	COST OF COMPLIANCE(1) (MILLION OF DOLLARS)			
	HC(2)	CO(2)	NO_x	TOTAL
BEST CASE				
NME 81	$ 68	$ 68	N/A	$ 136
NME 84	-	-	825(3)	825
IUE 85	286	286	N/A	572
TOTAL	$354	$354	$825	$1533
WORST CASE				
NME 81	$136	$136	N/A	$ 272
NME 84	-	-	1887(3)	1887
IUE 85	362	362	N/A	724
TOTAL	$498	$498	$1887	$2883

(1) LIM, Page A-28.

(2) Cost for HC and CO compliance are each 50 percent of the combined costs computed in previous table. This assumption is consistent with WILCOX, page 6,.

(3) Some unknown portion of this cost is attributable to HC and CO control.

EPA report appears to have considered only U.S. aircraft, based on the number of projected engines. Basic cost data from the LIM report are therefore used in the rest of this study.

COST OF COMPLIANCE

An itemization of control costs are presented in Table 18. They are based on unit costs per engine supplied by Pratt and Whitney Aircraft, General Electric Aircraft, Rolls-Royce Limited, and several airlines. All incremental costs were made by personnel within the industry and are difficult to substantiate. Overall costs to develop a new engine are in the order of one billion dollars. The values shown in Table 17 are incremental costs associated wth the three proposed standards. Hardware costs include both non-recurring costs of future development and testing, and incremental manufacturing costs. Maintenance costs are due to the increased complexity of the required systems. Fuel costs are negative if a savings results from improved combustion efficiency. As shown, fuel penalties due to greater weight in the NME 84 engines are more than compensated for by improved efficiency. This is true for the assumed mix of aircraft and engines but not true for every specific engine type.

Possible additional costs are included in the "Worst" case assessment. Service testing includes the financial risk of engine manufacturers by not having adequate service testing time prior to the start of the standards. Combustor life is uncertain with these high-technology, staged combustor, engines and is included as an associated cost. Premature removal costs are possible in the retrofit program of engines in use after 1/1/85 (IUE 85). This may occur when an engine has to be retrofitted with the low HC/CO combustor prior to the time when it would normally be overhauled. Total compliance costs between one and a half and nearly three billion dollars are shown.

A breakdown by pollutant type is shown in Table 19. NO_x control is not proposed for the NME 81 or IUE 85 standards. Since HC and CO costs were not separately compiled, an assumption is made that 50% of the costs are allotted to each species and is consistant with the EPA report (WILCOX, page 6). All NME 84 costs are attributed to NO_x control in the LMI study. This is not true in practice since the new staged combustor engines must also have low HC and CO emission levels. The alternative cost of controlling only HC and CO emissions should be considered for the fleet of NME 84 aircraft and engines. While the cost per engine for HC and CO controls will essentially be the same as the NME 81 increment, the aggregated costs will be much different than shown in Table 19 due to the time dependent mixture of aircraft and engines."

7.3 Cost-Effectiveness

It is a narrow viewpoint to only consider the cost of controls and not the reduction in pollutants that the controls will bring about. For instance if a control method costs one million dollars but eliminates one million tons in its lifetime the cost-effectiveness is one dollar per ton. If it only eliminates one ton of pollutant in its lifetime, its cost-effectiveness is one million dollars per ton. It is important, therefore, to consider the cost-effectiveness of control of pollutants from aircraft and compare this value with similar values for other sources which have been controlled or are being considered for control.

Naugle (Reference 66) has summarized cost-effectiveness data from two previous, extensive studies (Reference 51 and 65). The following discussion and tables are from Naugle's paper:

> "The cost estimates from Table 19 were divided by the corresponding pollution emission reductions to produce the cost-effectiveness ratios presented in Table 20. All projected U.S. and foreign aircraft operating out of the U.S. airports have been considered. Values are compared to the cost-effectiveness ratios computed in the EPA study (WILCOX, page 24). Agreement is surprisingly (perhaps coincidentally) close considering the detailed differences between the studies.
>
> ### Evaluation of HC Controls
>
> Nonmethane hydrocarbon emissions in the miscellaneous mobile source category (railroads, aircraft, and vessels) are expected to rise from 7.4 percent of the total in 1972 to 8.9 percent of the total in the year 2000. Both activity increases and approximate unit emission reductions have been considered. The ranking of cost-effectiveness for incremental controls of these sources range from a -$210 per ton where a savings results for degreasing operation controls to $700 per ton for gasoline handling improvements. The cost of $470/ton to control light duty vehicles from 0.9 to 0.41 grams per mile now required by EPA is comparable to that of aircraft as shown in Table 19. More importantly, the conclusion has been reached that control of all sources under consideration may not lower oxidant levels below the NAAQS values for many U.S. cities.

TABLE 20. COST-EFFECTIVENESS OF AIRCRAFT STANDARDS (Reference 66)

SOURCE		INCREMENTAL COST EFFECTIVENESS[1] ($/TON) HC	CO	NO_x
	BEST CASE			
THIS WORK	NME 81	430	169	-
	NME 84	-	-	1122[2]
	IUE 85	392	184	-
	WORST CASE			
	NME 81	861	337	-
	NME 84	-	-	2567[2]
	IUE 85	497	233	-
WILCOX (Page 24)	NME 81	560	220	-
	NME 84	560[3]	220[2]	11316
	IUE 85	390	170	-

(1) Computed from Table 18.

(2) May be artifically high since all costs have been lumped into NO_x category.

(3) Arbitrarily set equal to NME 81 since HC and CO costs were not separable from the aggregate NEM 84 costs lumped in the NO_x category.

TABLE 21. RANKING OF INCREMENTAL OXIDE OF NITROGEN CONTROL STRATEGIES (Reference 66)

CONTROL STRATEGY	INCREMENTAL CONTROL	EMISSION REDUCTION (10^6 TONS)	COST-EFFECTIVENESS ($/TON)
New Utility Boilers	25% to 50%	3.52	100
Industrial Boilers	25% to 75%	2.46	150
Exist Utility Boilers	25% to 50%	0.62	225
Sta IC Engines	25% to 75%	2.87	340
Other Mobile	1.0 gm/mile to 80%	2.90	450
Light Duty Vehicles (Cars)	2.0 to 1.0 gm/mile	1.91	450
Utility Boilers	50% to 90%	6.62	1200
Sta IC Engines	75% to 90%	0.86	1700
Commercial Aircraft	to best available control technology	0.74	1122-2567
Light Duty Vehicles (Cars)	1.0 to 0.4 gm/mile	1.15	2300

Evaluation of CO Controls

Cost-effectiveness data to compare to aircraft was not readily available. EPA has indicated that the aircraft ratios are in the range of those under consideration for controls (Reference 2). The real question, however, relates to the National Ambient Air Quality (NAAQS) constraint. Many cities are having difficulty in attaining CO, NAAQS levels.

Evaluation of NO_x Controls

NO_x emissions come from a variety of both stationary and mobile source categories. Attainment of NAAQS levels can probably be achieved without controlling all sources to the best available technology. The decision criteria is therefore to control the economically cost-effective sources. A ranking of possible strategies is shown in Table 21. Since the required overall tons of NO_x emission reduction is uncertain, EPA is systematically implementing incremental controls until the desired ambient concentrations can be reached. At least one study has concluded that a reduction of NO_x from 2.0 to 1.0 grams/mile in light duty vehicles at a cost of $450/ton is not as cost-effective as reductions in other strategies."

7.4 Operational Capability

The proposed USAF Goals must be considered from the standpoint of the operational capability of the USAF to perform its mission. While costs are extremely important, and were therefore extensively discussed in the previous section, they become a secondary consideration to the operational capability. For example, assume two equally effective methods of control are proposed for HC reduction. The first method is the least expensive but has shown problems of high altitude power loss, possible flame-out, and poor relight. The second method has none of these problems at altitude but is the most expensive, and therefore less cost-effective. The USAF would, of course, choose the second method.

The operational capability of the USAF is recognized throughout the proposed Goals. No numerical standards, which could be interpreted as operational limits, are listed. The proposed USAF Goals consistently refer to the USAF mission as the dominant consideration while making a dedicated effort toward control of pollutant emissions.

7.5 Reliability and Ease of Maintenance

The reliability and ease of maintenance are factors that must be considered whether the pollution control measure being considered are retrofit, modification, or included in the new engines being purchased. If a pollution control system did require extensive maintenance, or decrease in the time between overhauls, it could conceivably be necessary to add more aircraft to the fleet to cover the extensive amount of "down-time" necessary to maintain the system.

While reliability and maintenance are not mentioned specifically in the proposed USAF Goals, reference is made to the USAF mission which certainly would include these important engine considerations. A system that controlled emission of a pollutant, but which was not reliable or could not be maintained at its desired operational level, would not be beneficial to either the USAF or the atmospheric environment it was supposed to improve. The proposed USAF Goals would be compatible with USAF philosophy regarding reliability and maintenance.

7.6 Impact of Emission Controls

The impact of emission controls on the other engine systems, or engine operation overall, is a vital concern to the USAF. As more output is required from new gas turbine engines in order to meet performance criteria it is possible that pollutant emissions may increase - not decrease. A modern engine, with a high energy release but shorter combustor, can produce a tremendous amount of thrust. This same engine at idle may produce much more CO and HC than an older engine with a longer combustion chamber.

The problem may become even more complex for NO_x emissions. As advances are made in materials and design methods that allow greater energy release from combustors, the temperatures (and hence the NO_x) will also increase. If the reduction of NO_x is to be accomplished in parallel to developments increasing the engine output, it appears that a direct conflict situation exists.

The proposed USAF Goals recognize that these conflicts do exist and that reasonable methods are being examined to try to resolve them. The proposed USAF goals do not establish numerical values of emission, and dates for application of those values. To do so would be to say that the emission controls should be developed regardless of their impact on the other considerations such as costs, operational capability, reliability, maintenance, safety, etc.

The USAF must also consider the satisfactory operation of any emission control measures, or system, while the engines are being operated in any configuration that might classify them as "stationary sources." This occurs, for example, when turbine engines are being operated in a test cell following overhaul. In this configuration, the emissions may be subjected to control by local or state regulatory authorities. A system which might be satisfactory for in-flight operation may not comply with the regulations of the agency responsible for the "stationary source." It is even possible that engines that meet all of the EPA proposed rules will be in violation of some local and state standards when operated in test cells. The proposed USAF Goals appear to be compatible with any directives that may be issued regarding engines operated in test cells and the regulation of emissions from those engines.

7.7 USAF Lead Time Necessary

If the USAF should ever agree to establishment of specific emission limits for a new engine they must consider the lead time necessary for achieving those limits. It is impossible for the USAF to consider meeting the EPA, in use engine standards for 1985, for any aircraft engines under development now. The EPA has not yet adopted the rules, so, the time interval from eventual adoption to required compliance cannot be more than 4 years. This is not a satisfactory lead time to apply a new concept, test and evaluate it, and adopt it for USAF procurement of aircraft/engines.

The turbine engine manufacturers agree with this statement and said so at the EPA Public Hearings on the Revised Standards held at San Francisco, November 1978 (Reference 46). Rolls Royce, General Electric, and Pratt and Whitney all agreed that the time constraints of the proposed rules were too severe and that they would not allow adequate evaluation of new concepts to assure safety, costs, etc.

The proposed USAF Goals, again, are compatible with the recognition that the USAF, and engine manufacturers need realistic lead times. By not including dates, the proposed goals can suggest guidelines without time constraints.

7.8 USAF Programs for Engine R&D

The USAF continually works with manufacturers, other federal agencies, consultants, technical societies, and international organizations regarding engine and aircraft pollutant emission problems. The USAF commitment is in the form of money, time, and expertise toward engine R&D. These programs, and USAF future commitments, are certainly consistent with the proposed USAF Goals.

There are also internal programs, within the USAF, which are directed toward ongoing engine R&D. Some of these programs which would be used to develop emissions reduction hardware are:

Component Improvement Program (CIP). This program is involved with retrofit or redesign for existing engines. This would be of concern if a change were being considered in the combustors currently in use.

Advance Turbine Engine Gas Generator (ATEGG). This program is the way that manufacturers keep the USAF up to date on core engine research. The USAF would evaluate a new combustor, proposed by a manufacturer, under this program.

Aircraft Propulsion Subsystem Integration (APSI). This program is the way that manufacturers keep the USAF up to date on engine components and systems other than the core engine. This program would be used, for example, by a manufacturer to inform the USAF of an improvement in afterburner technology.

The proposed USAF Goals are compatible with current internal USAF programs, at all levels of R&D.

SECTION VIII

BEST AVAILABLE CONTROL TECHNOLOGY

Best Available Control Technology (BACT) is a broad term which is widely applied to controlling of pollutants to their minimum emission levels. Another term that is sometimes used is Best Practicable Control Technology (BPCT). This section will consider BACT as applied to USAF turbine engine emissions. Some methods will be discussed which will never be used in a production engine so BPCT is not truly applicable.

8.1 Legal Requirements for Military Aircraft/Engines

The EPA proposed Rules (Reference 2) exempt military aircraft from the emission standards. The Rules do not specifically state that military aircraft are "exempt" but rather that the rules apply only to "commercial aircraft engines" which is defined as an engine used by an air carrier with a U.S. standard airworthiness certificate. The USAF still is considering BACT as their approach to turbine engine emissions even though they are not legally bound to comply with EPA regulations.

There have been pressures by various groups to include all aircraft in the U.S. under EPA aircraft engine standards. Some of these pressures were expressed during the EPA Public Hearings on the Revised Standards held at San Francisco, November 1978 (Reference 46). They appeared to follow two lines of reasoning:

1. In many areas the USAF is operating from joint use airports. If the commercial aircraft are controlled the military should also be controlled.

2. If commercial aircraft are controlled under the EPA Rules they will be much less polluting than USAF aircraft. Therefore, if USAF with their uncontrolled aircraft were banned from urban areas it would permit many additional, controlled, commercial aircraft to use the airshed without degradation.

It certainly does appear that the USAF should be very obvious in the application of the proposed USAF Goals. They should also let it be widely known that they are actively supporting BACT R&D even though they are not legally bound to meet emission standards. By so doing they can help to make the USAF Pledge to Environmental Protection known. They can also assure that control of aircraft emissions stay with the EPA/FAA rather than being delegated to State or Local Control Agencies who might be overly restrictive.

8.2 Best Available Control Technology for Specific Pollutant Reduction

Over the past decade, the USAF has invested millions of research and development dollars toward turbine engine emission control. Currently the USAF has projects with consultants, universities, engine and system manufacturers, research institutes, and other government agencies. The following discussion of BACT applied to specific pollutants contains brief descriptions of these USAF sponsored projects and, also, descriptions of other reported projects which show promise even though they are not funded by the USAF.

8.2.1 Smoke Reduction

The goal for smoke from turbine engines is an invisible plume. Some of the engines used by USAF can meet this goal but as fuel composition changes they too may start showing visible smoke. Bahr (Reference 44) summarizes the situation and discusses the mechanisms of smoke formation and the problem of preventing visible smoke.

> "The smoke emissions contained in the exhausts of aircraft turbine engines are comprised of minute agglomerates of carbon, or soot, particles. The specific chemical mechanisms by which these carbon particles are produced in engine combustion systems are generally quite complex and only partially understood. In general, however, the formation of these carbon particles is known, from thermochemical considerations, to be associated with the combustion of fuel-air mixtures which have high fuel concentrations. In addition to the vapor-phase oxidation of rich fuel-air mixtures, other probable carbon producing mechanisms include the thermal cracking of liquid fuel droplets. The rates of these various formation mechanisms are highly dependent on the ambient pressure level, increasing rapidly as pressure is increased.
>
> The smoke standards defined by the EPA for commercial aircraft engines basically require that the smoke emissions of these engines be reduced to invisible levels. To meet this requirement, very low exhaust gas smoke concentrations - generally less than 2 parts per million parts (by weight) of core engine exhaust gas - are required. Exhaust gas smoke concentrations of this order are equivalent to a smoke emission index of about 0.1 gram per kilogram of fuel."

Current Technology for Existing Engines

The current technology for smoke control on existing engines involves combustor modification to achieve leaner fuel/air ratios and better mixing. Bahr (Reference 44) discusses the combustor modifications which have proven to be practical and are in use today.

> "Investigations have shown that the design of low smoke emission combustors involves providing both leaner fuel-air mixtures and more effective fuel-air mixing in the primary combustion zone, as compared to those of combustors with high smoke emission levels. These investigations have demonstrated that both of these provisions are needed to eliminate any fuel-rich mixtures within the primary combustion zone and, therefore, that both are of major importance. Providing the required leaner fuel-air mixtures and improved mixing in the primary zone has been found to involve significant changes in the overall design approaches used in the combustors of older technology engines. Also, combustor design features added to reduce smoke emission levels can, in some instances, result in losses in other aspects of combustor performance, especially ignition performance. Thus, the design and definition of low smoke emission combustors have generally been found to entail careful, iterative development efforts to provide the required low smoke emission characteristics, as well as to meet all the usual ignition, stability, combustion efficiency, exit temperature distribution, life and other performance requirements."

Future Technology for New Engines

Smoke control for future engines may rely on some of the current technology, or rely on future technology being suggested now. The future technology is concentrating on smoke reduction through investigation of fuels, fuel additives and emulsions, and combustor fuel tolerance (Reference 67).

Fuel technology studies are involved in investigating alternate sources of gas turbine fuels and the effects on the engines using those fuels. A recent SAE paper by personnel from the USAF Aero Propulsion Laboratory (Reference 68) states the problem,

> "At the present time, there is a great deal of emphasis by both the Department of Energy

(DOE) and industry to develop the technology to produce hydrocarbon liquids from sources such as coal and oil shale whch are available in huge quantities in this country. In addition, much research is being conducted to utilize heavy crudes (low pour point viscous oils) and residues (tar-like solids) which heretofore have been too costly to extract and process. Also, the North Slope crude, which is currently impacting the west coast refineries is more highly aromatic and heavier than conventional crudes and thus results in different refinery process economics for a conventional slate of products."

The fuel problems, as they tend to increase smoke levels, were further explained in a recent paper from NASA (Reference 69):

"Increases in aromatic content, or conversely decreases in hydrogen content of the fuel, have a pronounced effect on exhaust smoke levels. Current Jet-A fuel has an average aromatic concentration of about 17 percent (vol.). Jet fuel produced from certain heavy crudes may have aromatic concentrations as high as 25 percent (vol.). Exhaust smoke levels have been negatively correlated with fuel hydrogen content. Although the fuel aromatic content does not uniquely specify the fuel hydrogen content, increases in aromatic content generally reduce the hydrogen content of the fuel.

Combustor test evaluations of the effect of fuel blends with varying aromatic concentrations have been performed using a single JT8D combustor can. The results which were obtained at both simulated cruise and takeoff conditions for the JT8D engine (Compressor Pressure Ratio,16) show a significant increase in exhaust smoke as the hydrogen content of the fuel is decreased. Aircraft engines that have a marginally acceptable smoke number using current Jet-A fuel may be unable to meet the established standards for smoke number using fuels with increased aromatic content."

Fuel additives and fuel emulsions are being studied as means of reducing gas turbine engine smoke. The fuel additive studies also include tests of engine degradation. The study of fuel microemulsions for jet engine smoke reduction is a newer approach but it is currently under intensive USAF investigation. The statement of work for this project lists the objectives.

> "(1) The primary objective of this contractual effort is to synthesize water in aviation jet fuel and alcohol in aviation jet fuel microemulsions and to determine their capacity for reducing smoke emissions from an aviation gas turbine combustion system.
>
> (2) A secondary objective is to determine the effect of fuel microemulsions on other combustor pollutant emissions including total hydrocarbons, carbon monoxide and nitrogen oxides as well as on performance parameters such as combustion efficiency and combustor temperature rise.
>
> (3) Smoke suppressant fuel additives will be included in the test matrix to determine any significant synergistic effect with the fuel microemulsions."

It does appear that there is some hope for smoke reduction from the newer combustors being developed at this time. These combustors appear to have a wider fuel tolerance than the older combustors. This means that the higher aromatic fuels may be burned with less smoke in the newer combustors. NASA (Reference 69) refers to this in a report on combustor development,

> "Limited unpublished results have been obtained in Phase III for the NASA Experimental Clean Combustor Program that compare the smoke number for the Double/Annular Combustor using Jet-A and No. 2 Diesel Fuel at the takeoff conditions for the G.E. CF6-50 engine (PR = 30). These results indicate that this particular combustor's smoke number is relatively insensitive to the hydrogen content."

Recent USAF sponsored fuel character effects studies on the J79 and F101 engine combustion systems reported by Gleason and Martone (Reference 70) substantiate the NASA findings with regard to smoke. The J79 engine combustion system, a current rich burn cannular design, exhibited extreme smoke number sensitivity to fuel hydrogen content while the F101 engine combustion system, an advanced full annular design, produced smoke levels expected to be well below the visible threshold for any of the test fuels which had aromatic contents ranging from 12.2 to 63.4 percent by volume.

8.2.2 Carbon Monoxide and Hydrocarbon Reduction

Carbon monoxide (CO) and Hydrocarbon (HC) emissions are a problem in the Taxi/Idle Mode so reductions are concerned with the inefficient combustion during low power output. The problem is further complicated by the fact that reductions in HC from newer engines will nearly meet the EPA standard (Reference 2). The CO emissions, however, are still well above the levels necessary to satisfy the EPA. Neither the 1981 nor 1984 EPA standards for CO can be met. Bahr (Reference 44) gives a summary of the problem involved,

> "Both CO and HC emissions are, of course, products of inefficient combustion. These emissions are primarily produced at idle and other low power operating conditions. These emissions mainly occur at these operating conditions because the combustion efficiencies (degree to which the available chemical energy of the fuel is converted to heat energy) of most present day engines at these low engine power operating conditions are not optimum and are typically in the 90 to 96 percent range. At higher engine power settings, the combustion efficiency levels of most engines are generally well in excess of 99 percent and, therefore, virtually all of the fuel is converted to the ideal combustion products, carbon dioxide and water, at these operating conditions. The somewhat reduced combustion efficiency performance of most existing aircraft turbine engines at idle and other low engine power operating conditions is due to the adverse combustor operating conditions that normally prevail at these engine operating conditions. At the low engine power operating conditions, the combustor inlet air temperature and pressure levels are relatively low, the over all combustor fuel-air ratios are generally low and the quality of the fuel atomization and its distribution within the primary combustion zone is usually poor because of the low fuel and air flows. In any given engine, all of these adverse combustor operating conditions are rapidly eliminated as the engine power setting is increased above idle power levels and, accordingly, its combustion efficiency performance is quickly increased to near-optimum levels."

Current Technology for Existing Engines

Current technology may involve minor combustor redesign with higher fuel/air ratios and better mixing. It also may involve major combustor redesign incorporating techniques such as "airblast" and "swirling". Other possibilities for current technological application to existing engines are sector burning and increased compressor air bleed but these are not combustor related solutions. NASA (Reference 71) discusses these possibilities,

> "Many techniques to reduce low power emissions have been evaluated by NASA including the use of air-assist fuel nozzles, airblast fuel nozzles, and fuel scheduling in the primary zone. Air assist and airblast fuel nozzles use high pressure and high velocity air, respectively, to aid in atomizing the fuel and are very effective for reducing CO and HC at idle conditions. Fuel scheduling reduces the number of fuel nozzles that are supplied with fuel thus resulting in improved atomization for a constant fuel flow rate. The effectiveness of improving fuel atomization by using air-assist and airblast fuel nozzles is reasonably well documented."

Bahr (Reference 44) outlines some of the technology being applied to minimize current emissions of CO and HC,

> "Modest reductions were obtained by the use of fuel nozzles which were modified so that all of the fuel was delivered at idle through the primary orifices of these dual orifice nozzles. Another attractive means of improving fuel atomization at idle in combustors with dual orifice fuel nozzles is to use an air-assist approach. In this approach, the fuel is delivered at idle through the primary orifices and a very small amount of supercharged compressor air flow is introduced through the secondary fuel orifices of the nozzles. In investigations conducted by the NASA, this small quantity of air flow has been found to result in significantly improved fuel atomization quality and, thus in significantly reduced CO and HC emissions levels at idle. This approach was found in these investigations to result in CO and HC emissions level reductions of about 70 and 90 percent, respectively, with only about 0.25 per cent of the total combustor air flow introduced through the secondary orifices of the fuel nozzles."

Bahr (Reference 44) goes on to explain the other features of these systems,

> "With the airblast methods, the fuel is injected at low pressures and is atomized in swirl cup devices by a portion of the combustor air flow. Since the fuel atomization process is primarily dependent on the air kinetic energy,

rather than on fuel pressure, very effective fuel atomization and fuel-air mixing are attained with these airblast fuel atomization methods over wide ranges of engine operating conditions, including idle."

The possibilities of changing fuel/air ratios at idle have been thoroughly investigated by NASA and engine manufacturers. Bahr (Reference 44) reports on fuel/air ratio changes to reduce CO and HC,

> "Increases in the overall fuel-air ratio above the nominal engine design value at idle result in significant decreases in the CO and HC emissions levels, particularly in the case of the HC emissions. In most engines, the overall combustor fuel-air ratios at idle are low, generally less than 0.012. In many combustors, especially the more advanced designs in which relatively high primary combustion zone air flows are used to obtain low smoke emission levels, the resulting average primary zone fuel-air ratios at idle are, therefore, quite lean, generally less than 0.04. These average fuel-air ratios are equivalent to fuel-air equivalence ratios of 0.6 or less. Any CO contained in leaner-than-average portions of such primary zone mixtures will be consumed relatively slowly and, if further diluted, the CO consumption process will be largely quenched and terminated. Thus, at idle, somewhat higher average primary zone fuel-air equivalence ratios are generally needed in these advanced low smoke emission combustors to obtain reduced HC and CO emissions levels. These higher fuel-air ratios are especially important if significant CO emissions levels reductions are to be obtained. These higher primary zone equivalence ratios must, of course, be attained at idle without changing the primary zone equivalence ratios that already prevail at high engine power operating conditions. Thus, simply reducing the percentage of the total combustor air flow that is introduced into the primary zone is not an acceptable approach. An air flow split change of this latter kind would be expected to result in significant and unacceptable smoke emission level increases at the high engine power operating conditions."

Another method of approaching the CO, HC problem, at low power output, is to change the cycle rather than the combustor. Bahr (Reference 44) outlines the concepts of sector-burning and compressor air bleed as CO and HC reduction techniques,

> "Still another means of obtaining the required higher primary zone fuel-air ratios is to use fuel injection staging techniques at idle operating conditions. In this type of approach, fuel is valved to only selected fuel nozzles, or fuel injectors, instead of to the full complement of nozzles. This approach not only results in higher primary zone fuel-air ratios in the portions of the combustor annulus where the fuel is concentrated, but also results in improved fuel atomization since the same fuel flow is being delivered through fewer fuel nozzles and the fuel nozzle pressure drops are thereby increased. Various forms of such fuel injection staging can be considered, depending on the nature of the combustor design.
>
> One relatively simple means of obtaining beneficial higher primary zone fuel-air ratios at idle, without adversely affecting combustion performance characteristics at high power operating conditions, is to extract and dump overboard increased amounts of the compressor discharge air flow when operating at idle. This approach results in increased fuel-air ratios throughout the combustor. The use of increased bleed air extraction also results in small, but beneficial, increases in primary zone gas residence time, which are the result of the lower air mass flows through the combustor. Significant CO and HC emissions levels reductions were obtained in these investigations. Since many advanced engines have provisions for extracting large amounts of compressor discharge air flow, this concept appears to be an attractive one."

Future Technology for New Engines

Technology, which is several years down the line as far as application to production of USAF engines is concerned, consists of major combustor design concepts which will have to be evaluated as far as other USAF requirements are concerned. Two of these concepts are the double/annular combustor which uses parallel combustion chambers and the vorbix combustor which introduces the fuel at two points in the combustor to essentially yield a series combustion situation. Another type combustor which has been tested is a combination of the two systems and is referred to as the "Radial-Axial Low Emissions Combustor " (Reference 3). It is not within the scope of this report to evaluate the practicality of the various systems as they are throughly discussed in several research papers and reports. Tables 22 and 23 (Reference 69) list an assessment of these experimental combustors.

Another approach to the low power emission of CO and HC is to use a system of fuel prevaporization to promote better combustion. NASA (Reference 43) describes this system:

> "Gaseous Propane or atomized Jet-A is injected upstream of a perforated flame holder with sufficient distance to provide a completely prevaporized/ premixed fuel-air mixture to the primary zone (flame zone) test section."

Later NASA publications (Reference 69 and 71) indicate that this prevaporization work is still in the preliminary stage with most of the work still being done on flame tubes. Some studies have advanced to basic combustor tests in rigs but these are still being evaluated.

The concept of fuel/air premixing shows considerable promise for CO and HC reduction. NASA (Reference 71) reports that this concept appears to also be viable for NO_x reduction but not using the same technology or system for CO and HC reduction:

> "For the past five years, NASA has been evaluating several experimental combustors which incorporate a variety of the emission control techniques. The majority of the effort on the evaluation of low pollutant emission combustors conducted at the Lewis Research Center has been with the swirl-can-modular combustor. This combustor consists of a large number (80 to 120) of swirl can modules. (each acting as a small, separate fuel/air mixer) arranged into a full annular array. A fuel and air mixture passes through a swirler which, in conjunction with a flame stabilizer, forms a small stable flame zone. The combination of a small flame zone and the partially premixed fuel and air provides for short residence times and some degree of flame temperature control. Thirty to fifty percent reductions in NO_x emission index have been obtained with this concept over a range of combustor inlet temperatures typical of present day aircraft gas turbine engines. The greatest difficulty in the development of this combustor concept has been the inability to simultaneously reduce low power emissions of CO and HC and high power emissions of NO_x. Low values of CO and HC

TABLE 22. ASSESSMENT OF DOUBLE/ANNULAR COMBUSTOR DEVELOPMENT STATUS (Reference 69)

	No further development required	Additional development required	Extensive additional development required
Emission levels			
CO		X	
HC	X		
NO_x			X
Smoke		X	
Ground starting	X		
Altitude relight	X		
Main stage crossfiring	X		
Pressure loss	X		
Combustion efficiency	X		
Exit temperature profile/ pattern factor		X	
Metal temperature	X		
Acoustic resonance	X		
Carboning	X		
Fuel nozzle coking		X	

TABLE 23. ASESSMENT OF VORBIX COMBUSTOR DEVELOPMENT STATUS (Reference 69)

	No further development required	Additional development required	Extensive additional development required
Pressure loss	X		
Exit temperature pattern factor		X	
Exit temperature radial profile		X	
Idle stability (lean blowout)	X		
Sea-level starting			X
Main-stage ignition	X		
Altitude relight	--	(Not evaluated)	--
Transient acceleration		X	
Carbon:			
Liner deposits		X	
Fuel passage cooking			X
Liner durability (overheating)		X	

have been achieved by using specialized module designs and by employing fuel scheduling but these modifications were not successfully coupled with low NO_x designs to provide integrated combustor for low emissions at all operating conditions."

Recent advances in premixed prevaporized combustor technology are detailed in the proceedings of a conference devoted to this subject held at NASA Lewis in January 1979. (Reference 72).

Variable geometry combustors have been undergoing tests for several years. Blazowski and Henderson (Reference 3) explain the concept, at an early stage of development,

> "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 HC emission is minimized by increasing primary zone fuel-air ratios--reducing the proportion of air entering the primary zone."

Several studies at various Federal and industrial laboratories are now into the test and evaluation phase of variable geometry combustors. In the near future, results should be reported from these studies. If they are favorable, the variable geometry combustor can be considered as a viable method for CO and HC control of gas turbine engines of the future.

The Experimental Clean Combustor Program is a part of the Energy Efficient Engine (E^3) program being conducted by NASA. NASA (Reference 71) discusses the progress of this program,

> "The Experimental Clean Combustor Program (ECCP), was initiated in December 1972 with the objective to develop and demonstrate, in a full-scale engine, advanced technology combustors that are capable of reducing pollutant emissions in the large high bypass ratio engines (U.S. EPA Class T2, thrust over 8,000 lbs) that power the wide body jets. The original emission level goals were established from NASA studies and were subsequently adjusted to be consistent with the EPA Standards published in mid-1973. The two contractors that were selected, and are currently under contract, are Pratt & Whitney Aircraft (JT9D-7 engine) and the General Electric Company (CF6-50 engine).
>
> The two advanced technology CF6-50 engine combustor concepts that were evaluated utilize staged combustion for reducing pollutant emissions over the entire engine operating range.

The pilot stages of both the radial/axial staged and the double annular were optimized for high efficiency (low CO and HC emissions) at engine low power (idle) and the main stages are optimized for lean combustion (low NO_x) at full power (takeoff). Various combinations of combustion staging can be used for off-design operation such as approach power settings. The radial/axial staged configuration utilizes a premixed fuel and air technique in the main stage whereas the double annular configuration uses airblast fuel nozzles and airflow control in the main stage. The double annular concept has been chosen for the engine demonstration tests. All of the testing was performed in a full annular combustor test rig which closely duplicated the flow path of the CF6-50 engine. All engine inlet and exit operating conditions were simulated except for combustor inlet pressure which was limited to a maximum of 10 atmospheres.

The two advanced technology JT9D-7 engine combustor concepts that were evaluated used staged combustion as the principal approach to controlling overall pollutant emissions. The *hybrid concept* utilized a parallel (radial) staging approach which included a premix technique in the pilot stage and a variation of the swirl can concept in the main stage. This configuration was an attempt to mate the lowest CO and HC emission design (premix pilot stage) and the lowest NO_x emission design (swirl-can-module stage) that was tested. The vorbix configuration utilized a series-type (axial) fuel staging approach with standard pressure atomizing fuel nozzles in both the pilot and main stages. High intensity swirlers were located immediately downstream of the main stage fuel injection point to promote very intense, rapid mixing of the fuel and air in the flame zone. The combination of the intense mixing and hot gases exiting from the pilot stage allowed lean combustion in the main stage and also reduced residence time due to quick quenching of the hot gases."

8.2.3 Oxides of Nitrogen Reduction

Oxides of nitrogen (NO_x) are greatest in the high power operating mode of gas turbine engines. NO_x emissions must be considered from several standpoints. High performance engines operate at higher combustor inlet temperatures which result in high NO_x emissions. Proposed engines appear to have higher

NO_x emissions than current engines. NO to NO_2 conversion rates and mechanisms are not fully understood and are still being investigated. Short term NO_2 standards have not yet been promulgated. In spite of these problems the EPA (Reference 2) has proposed an NO_x standard for new engines, which will be enforced 1/1/84, and for all engines, which will be enforced 1/1/85. It is doubtful if these standards can be met with existing technology and no new technology, capable of meeting these standards, is apparent at this time. The major manufacturers have publically stated (Reference 46) that their engines cannot meet the proposed NO_x standards.

Even in this pessimistic environment, considerable research is being conducted toward reducing the NO_x problem. Several of the technologies being tried are showing promise of substantial NO_x reduction even though they may not meet the proposed EPA standards.

Bahr (Reference 44) gives a good summary of the mechanisms and problems involved in NO_x formation,

> "When gases containing oxygen and nitrogen are heated to elevated temperatures, generally above 1900°K, some oxidation of the nitrogen occurs and NO_x emissions are produced. Thus, NO_x emissions are generated, to some degree, in most combustion processes. In the main combustor of a turbine engine, these emissions are primarily formed within the primary combustion zone, and within the dilution zones immediately downsteam of the primary zone. These emissions consist mainly of nitric oxide, together with small amounts of nitrogen dioxide. The small amounts of nitrogen dioxide emissions result from the subsequent further oxidation of the nitric oxide that is formed in the primary combustion zone. Once discharged into the atmosphere, however, the nitric oxide is gradually converted to nitrogen dioxide. the thermo-chemical equilibrium quantities of nitric oxide that can be generated with a given mixture of fuel and air are strongly dependent on the flame temperature levels of the resulting combustion gases and on the availability of oxygen. Thus, these equilibrium quantities increase rapidly as the initial combustion air temperature is increased and as the primary combustion zone fuel-air equivalence ratios approach values on the order of 0.8.
>
> The quantities of nitric oxide that are formed in any given turbine engine combustor are usually far less than the thermochemical

equilibrium quantities, since the chemical kinetics of the nitric oxide formation process are relatively slow. The chemical kinetics of the nitric oxide formation process are reasonably well understood. The rates at which nitric oxide is formed are highly dependent on flame temperature level and increase very rapidly as the flame temperature is increased. Thus, with a given initial combustion air temperature, these rates are highest with fuel-air mixtures that have near-stoichiometric proportions. With a given fuel-air mixture, these rates increase very rapidly as the initial combustion air temperature is increased, because of the associated flame temperature increases. Further, these rates also increase as the pressure level of the combustion gases is increased, because of the direct effects of pressure on the chemical kinetics of the formation process. However, because these nitric oxide formation rates are generally far slower than the fuel combustion reactions, the quantities of NO_x emissions generated in turbine engines are limited by the short residence times of the hot combustion gases within the engine combustors. As a result, very high fuel combustion efficiencies can be attained without the generation of thermochemical equilibrium concentrations of nitric oxide."

Current Technology for Existing Engines

Most of the technology that has been investigated for possible application to current engines, with only minor modifications, has not been very promising. Large reductions in NO_x are desired but only relatively small reductions are being achieved. Still, the technology has reduced NO_x to some extent over the uncontrolled engines, even though not to the levels listed in the existing USAF Goals (Reference 1).

Bahr (Reference 44) describes the research being conducted by General Electric Company to reduce NO_x by minimizing combustor temperatures,

"Based on the chemical kinetics consideration associated with the formation of nitric oxide in combustors, the attainment of required NO_x emissions level reductions must involve precise control of the flame temperatures and combustion gas residence times within the primary zones of these combustors. Specifically, these flame temperatures and residence times must be minimized. At General Electric, investigations to identify and develop means of attaining this improved primary zone temperature and residence time control have been underway for the past several years. These investigations have been conducted in conjunction with the CO and HC emissions level reduction investigations. As in these latter investigations, the NO_x emissions level reduction development efforts have been primarily conducted with advanced turbofan engine combustors, with already developed low smoke emission characteristics. A major objective of these development investigations has, therefore, also been to retain those already developed low smoke emission characteristics. To date, some promising methods of obtaining significantly lower NO_x emissions levels by the use of advanced combustor design approaches have been identified. In general, however, these investigations have clearly shown that approaches that result in lower NO_x emission levels tend to result in higher CO and HC emissions levels, unless added design sophistication is introduced into the combustor.

Another general approach for reducing flame temperatures, and thereby, of minimizing the quantities of NO_x emissions formed in a given combustor is to minimize the quantities of combustion gas mixtures with near-stoichiometric fuel-air proportions. This type of approach offers a potential means of reducing NO_x emissions levels by combustor design features. Analytical and experimental studies to define and develop methods of this kind, which involve the difficult problems of precisely controlling the average and local fuel-air ratios within the primary combustion and dilution zones, have also been conducted at General Electric. Some potentially promising results have been obtained in these investigations. The use of advanced fuel injection methods involving airblast fuel atomization has been found, for example, to result in somewhat lower emissions levels as compared to those of combustor designs with more conventional pressurized fuel injection provisions - - at the same combustor operating conditions. NO_x emissions levels reductions in the order of 10 to 15 percent have been obtained in tests with these advanced airblast fuel injection techniques. These lower emissions levels appear to be the result of the very effective fuel-air-mixing obtained with fuel injection techniques of this kind. Tests have shown that this highly effective mixing process results in more uniform mixtures in the primary combustion and dilution zones than those obtainable with the more conventionally used fuel injection methods, thereby permitting the use of shorter gas residence times in these zones. As a result, more rapid elimination of any localized fuel-air mixtures with near-stoichiometric proportions and, thus, reduced NO_x emissions levels may be attained.

With any type of fuel injection method, a general approach for reducing NO_x emissions is to reduce the dwell time of the high temperature primary zone gas mixtures. An approach for reducing the residence times of these high temperature gases is to cool them as rapidly as possible using the available combustor dilution airflow as the coolant. Investigations of this latter approach have also been conducted as a part of the General Electric development efforts to develop combustors with NO_x emission levels. With approaches of this kind, NO_x emission level reductions in the order of 30 percent have been obtained. In general, the use of approaches of this kind has been found to be acceptable in combustors and to produce no adverse effects on the CO, HC and smoke emission characteristics of these combustors.

Other General Electric Investigations have shown that reductions in NO_x levels may be obtained by operating with either much richer or much leaner average primary combustion zone fuel-air ratios that those normally used in current combustor designs. The use of lean primary zone mixtures, in particular, results in significantly decreased NO_x emissions levels. These lean mixtures were obtained by increasing the percentage of the total combustor air flow that was introduced into the primary zone. In present day combustors, the direct use of such lean primary zone mixtures at the high engine power operating conditions would, of course, be expected to result in unsatisfactory ignitiion characteristics and much increased CO and HC emissions levels at idle because of the very lean primary zone mixtures that would prevail at these low engine power operating conditions.

Smaller NO_x emissions level reductions were obtained in these tests with higher primary zone fuel-air ratios. These findings suggest that the nitric oxide formation process was apparently shifted from the primary zone to the dilution zones immediately downstream, with little net change in the NO_x emissions levels. In any event, the use of higher primary zone fuel-air ratios would be expected to result in unacceptable smoke emission level increases at the high engine power operating conditions.

Based on these findings, it appears that the most promising approach for obtaining low NO_x emissions levels in advanced turbine engine combustors at the high engine power operating conditions is to provide lean and unfiorm fuel-air mixtures, preferably homogeneous mixtures, in the primary zones of these combustors. However, means of applying this general design approach are required that do not result in unacceptable losses in ignition performance and in unacceptable increases in CO and HC emissions levels at idle. Thus, means of obtaining the required lean and uniform primary zone mixtures at high engine power operating conditions and, also, of obtaining the relatively richer required primary zone mixtures at idle are needed. The attainment of these somewhat conflicting operating capabilities, in turn, necessitates consideration of combustors within which the combustion process can be staged in appropriate ways or of combustors in which variable geometry features are incorporated to modulate the quantities of the total combustor air flow that are introduced into their primary combustion zones. Accordingly, the preferred combustor design approach for satisfactorily attaining the applicable EPA standards for NO_x emissions appears to involve significant changes and advances in the combustors used in present-day engines."

NASA (Reference 71) reports on some of their research studies with combustor temperature reduction for NO_x control:

"Techniques to reduce high power emissions have concentrated on evaluating the efect of prevaporizing and premixing fuel and air prior to combustion using a 'flame tube rig' at the NASA, Lewis Research Center. Gaseous or atomized fuel is injected upstream of a perforated flame holder with sufficient distance to provide a completely prevaporized/premixed fuel/air mixture to the primary zone (flame zone) test section.

Extremely low levels of NO_x emissions (EI < 1 g/kg) were obtained at very lean equivalence ratios, (ratio of the fuel/air ratio to stoichiometric fuel/air ratio). These low NO_x EI values were obtained at reasonable residence time (about 2 milliseconds) and at combustion efficiencies in excess of 99.7 percent. This type of data is being used in an attempt to define minimum levels to which NO_x may be reduced by utilizing the lean prevaporized/premixed combustion technique. Therefore, the operating conditions for the experimental tests were very carefully controlled and do not necessarily duplicate conditions in an actual engine except for the levels of inlet pressure and temperature which simulate a supersonic cruise condition. At extremely lean equivalence ratios, combustion stability can be a problem because operation is near the lean flammability limit, thus limiting the NO_x emission reduction potential of the lean combustion technique."

Bahr (Reference 44) reports on General Electric Company research and development efforts in staged combustion,

"Advanced combustors with design features to provide both favorable primary combustion zone fuel-air ratios at idle, as well as lean and uniform primary zone mixtures at high engine power operating conditions, are currently being defined and developed in the NASA Experimental Clean Combustor Program. The primary objective of this important program is to develop technology for the advanced turbofan engine combustors which meet the EPA-defined 1979 standards for CO, HC, NO_x and smoke emissions - without the use of water injection methods for obtaining the objective low NO_x emissions levels. These advanced combustor configurations are being sized and designed to fit and operate in an existing General Electric CF6 engine. Several versions of each basic design concepts are being defined, evaluated and developed in this program.

The first of these basic concepts consists of a lean single annular dome approach, in which much increased percentages of the total combustor air flow are introduced into its dome, or primary combustion zone. Of the basic design concepts, this lean dome approach involves the least degree of design modification of the production combustor currently being used in this General

Electric CF6 engine. However, to obtain satisfactory operation at low engine power operating conditions with this lean dome design, variable geometry features to reduce the amounts of air flow introduced into its primary zone at idle would probably be needed.

The second of these basic conepts consists of a lean double annular dome design. As in the single annulus configuration, a key design feature is its high dome air flow percentage. In this way both primary combustion zones are operated with lean fuel-air mixtures at the high engine power operating conditions. However, the use of two domes, or primary combustion zones, permits the use of beneficial fuel staging methods at idle. Thus, with this approach, all of the fuel may be concentrated in one of the two primary zones at idle, thereby, providing much more favorable local fuel-air ratios and reduced CO and HC emissions levels.

The third of these basic concepts is another design in which beneficial fuel staging provisions are an important feature. In this staged combustion design approach, only the pilot (primary) stage is used at the low engine power operating conditions. By limiting the air flow percentage that is introduced into this stage, its fuel-air ratios at idle are quite favorable. At the higher engine power operating conditions the second stage is also fueled. In this latter stage, which handles a high percentage of the total combustor air flow, the fuel is premixed to some degree with its air flow and, therefore, the resulting fuel-air mixutes that flow into its combustion zone are lean and relatively uniform. The burning of these lean mixtures is stablized by the pilot stage of the combustor.

The fourth of these basic concepts consists of a modular dome design, which is based on the NASA Swirl-Can-Modular combustor concept. The dome is comprised of a multitude of individual combustor elements, each with its own fuel injector, fuel-air mixing device and flame stabilizer. As in the other three concepts, high dome air flow percentages are being used to obtain low NO_x emissions levels. Various fuel staging patterns may be used at idle by fueling only selected modules, to obtain reduced CO and HC emissions levels."

NASA (Reference 71) discusses some of the successes and failures in the current research to reduce NO_x emissions:

"The reduction in high power emissions that were obtained using the 'selected' advanced technology combustor concepts are the same ones used for the low power emission reduction evaluation. All values were either measured or extrapolated to engine operating conditions at takeoff power. Significant reductions in NO_x emission index levels, up to 50 percent, were achieved using the three staged concepts, i.e., double annular (CF6-50 engine) and the two vorbix designs (JT9D-7 and JT8D-17 engines.) An increase in the NO_x emission index was realized with the reverse flow concept (501-D22A engine) because the particular configuration selected was optimized for reducing CO and HC at low power conditions.

The principal reason for the 'short fall' in NO_x emission level reduction, compared to the goals, can be attributed to the inability to make maximum use of the lean burning approach to control NO_x in the advanced concepts. In all cases, lean burning and quick quencing techniques were employed in the main stages of the staged concepts but the effectiveness of lean burning is significantly reduced unless ther fuel is prevaporized and technology needed to design and evolve effective and practical prevaporized/ premixed concepts is still several years in the future. Therefore, the reductions in NO_x emission levels obtained are probably the "best" attainable with the level of advanced technology evaluated for the CF6-50,JT9D-7 and JT8D-7 engines. The term 'best' is used here to describe the level of the achievable reductions bearing in mind that variations about this level will likely occur with the application of these advanced technology combustor concepts to operational aircraft engines. Since the piloted-airblast and reverse flow concepts are primarily applicable for controlling low power emissions, the ability to achieve reduced levels of NO_x emissions using advanced technology in the TFE731-2 and 501-D22A engines will likely require different techniques.

In comparing the minimum levels of NO_x emissions achieved by the various advanced concepts, variations are certainly apparent. One factor that is paramount in the production of NO_x is combustion flame temperature. In a diffusion flame process (fuel droplet burning), the flame temperature is principally controlled by the inlet temperature and pressure of the air entering the combustion zone."

Another technology for NO_x reduction on existing engines is the injection of water (or water/alcohol mixes) into the engine at high power operation. Bahr (Reference 44) discusses water injection,

"One general approach for reducing flame temperatures within a combustor involves the addition of inert liquids or gases into its primary combustion zone. The introduction of water into the primary zone is an approach of this kind. Water injection in amounts of 1 to 2 percent (by weight) of the total combustor air flow was found to provide considerable reductions of NO_x. These investigations showed that, to achieve these reductions, the water must be injected directly into the primary combustion zone and must be uniformly distributed with the primary zone fuel-air mixtures. If effective atomization of the water and rapid mixing with the fuel-air mixtures are not obtained, greater quantities of water are needed for the same degree of NO_x emissions level suppression.

Based on results of this kind, water injection is a possible means of obtaining significant reductions in NO_x emissions levels during takeoff and climbout operations. The use of water injection at cruise operating conditions is, of course, unacceptable. However, the use of water injection in aircraft engines, even when limited to takeoff and climbout operations, does involve some weight penalties and does require the addition of water tankage, pumping valving and plumbing provisions to the engine. As such, the use of water injection has some significant drawbacks. Accordingly, means of reducing the levels of these emissions by combustor design modifications, rather than by the use of water injection, represent an important development need. Further if NO_x emissions level reductions at cruise operating conditions are identified as an important need, reductions by means of combustor design modifications will be essential."

Future Technology for New Engines

The future technology for reduction of NO_x is not very promising. Only two viable concepts exist. One method, the variable geometry combustor, looks best for high power output (such as takeoff) while the other method, the catalytic combustor, looks best for NO_x emissions at high altitude cruise.

Most of the information on the variable geometry combustor was presented in Section 8.2.3, Carbon Monoxide and Hydrocarbon Reduction, of this report. Blazowski and Henderson (Reference 3) explain the technology of the variable geometry combustor for NO_x reduction,

> "At high-power, NO_x is 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_x reduction, with good idle emission as well, has been achieved. 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 program is currently examining this technique."

In November 1978, the USAF and the Navy initiated a jointly funded two phase contractual variable geometry combustor development program. The objective is to identify, evaluate and demonstrate design techniques using variable combustor geometry for improvements in gaseous emissions, smoke, ground start, altitude relight and low power efficiency. Phase I, preliminary design and development, is in progress and as of this writing no conclusive results are available to report.

The catalytic combustor has been proposed as a method of control of NO_x at high-altitude cruise conditions. NASA (Reference 71) gives a summary of the rationale, and problems of the catalytic combustor:

> "The use of catalytic reactors to enhance the combustion process using extremely lean fuel/air mixtures is also being evaluated in fundamental studies.

Both in-house and contract work is underway and some of the preliminary results obtained have been reported. Extremely low values for all of the pollutant emissions are possible using the catalytic technique, however, they are limited to a very narrow fuel/air ratio operating range. Special emphasis is being placed on the capability to control NO_x emissions at simulated high altitude cruise conditions."

A recent NASA paper by Szaniszlo (Reference 73) lists the program goals and advantages of the current NASA/USAF catalytic combustor program:

"Program Goals

The overall goal is to substantially reduce cruise NO_x emissions using catalytic combustion techniques that inherently have the potential for widening combustion stability limits and increasing turbine blade life with minimum compromises, if any, in durability and maintainability. Smoke emissions are not of primary interest in this program; however, smoke levels should meet the EPA standards

Advantages

Present day combustors with high heat-release rates have peak flame temperatures greater than 1900 K. As a result, high levels of NO_x emissions are present. The lean, premixing-prevaporizing technique has a low adiabatic flame temperature which prevents the formation of high levels of NO_x emissions. However, at the required low fuel-air ratios, flame instability and combustion efficiency are potential problems. These problems are circumvented by using the technique of heterogeneously-catalyzed combustion.

The advanced catalytic combustor is now being recognized as a possible future replacement of conventional combustors. Several attractive and distinguishing features make the catalytic combustor a viable candidate. Ultra-low thermal NO_x emission indices - 0.06 g NO_2/kg fuel - are obtainable with high-release rates at relatively uniform temperatures ($\approx$1300 K) well below the lean flammability limit. Combustion stability is far superior to other combustor types not only because homogeneous thermal comnbustion occurs in parallel with heterogeneous thermal reactions at the catalyst surface, but also because of the increased combustion-zone thermal inertia which damps system thermal perturbations. Homogeneous combustion is a result of the heterogeneous combustion temperature monotonically increasing along the axis of the catalyst to a value high enough to initiate reactions off the catalyst surface within the homogeneous fuel-air mixture at a temperature (≈1300 K) substantially less than required for conventional combustion. At this lower temperature level, the homnogeneous gas-phase reactions control the energy release as the gas flows through the catalyst. Consequently, the exit section of the catalytic combustor need not have any catalyst. Exit gas temperature level is approximately the adiabatic flame temperature and is essentially uniform across the catalyst exit plane; hence, an improved pattern factor. A nearly uniform catalyst exit temperature permits higher average exit temperatures without damage to turbine blades and gives a reduced specific fuel consumption. Finally, the monolithic-substrate structures for the catalyst do not present a major combustor-pressure-drop problem."

The NASA paper by Szaniszlo (Reference 73) also lists the disadvantages of the current catalytic combustors,

"<u>Current Disadvantages</u>

Successful implementation of catalytic combustor systems into future aircraft will require further work for minimizing and/or eliminating the following present-day application constraints: (1) uniformity of inlet velocity, temperature, and fuel-air composition; (2) thermal durability and performance stability of the catalytic reactor over long time periods; and (3) autoignition and flashback.

A uniform inlet velocity profile to the catalytic reactor is highly desirable since the monolithic substrate will preserve the inlet velocity distortions to the catalyst exit plane. Temperature at the catalyst inlet plane should be practically uniform since combustion efficiency is dependent on the temperature level. Complete upstream fuel vaporization for uniform fuel-air composition is desirable, but may not be necessary. Good performance has been reported with 5 to 10 percent of the fuel not vaporized. The volumetric expansion of reacting gases within each catalyst tube during homogeneous combustion helps prevent unvaporized fuel droplets from impinging on the catalyst tube wall. Nevertheless, uniformity of the inlet fuel-air mixture is desired to avoid the possibility of causing local high temperature regions within the catalyst bed.

Thermal durability for continuous and cyclic operation without catalyst degradation is a cost-effective performance requirement. The maximum temperatures tolerated by present-day catalytic reactors is about 1650 K. A near term (2-3 year) projection raises this temperature limit to 1700 K. Far term (5-10 year) projection values exceed 1800 K assuming a major development effort. This catalytic-combustor technology program will use existing catalyst technology. Reactivity of the catalytic reactor must be acceptably stable at a high enough level for repeatable, reliable and rapid low-temperature ignition over a long-term operating period. More work needs to be done in this area.

Available autoignition data for pressures up to sixty atmospheres shows an autoignition delay time of about 4 milliseconds for hot, sea-level takeoff conditions. If the catalytic combustor is to be used during sea-level takeoff operation, the length of the fuel-air mixing section can be at most only 12 centimeters for a 30 m/sec. reference velocity. Clearly, the fuel injector must finely atomize the fuel for rapid vaporization and mixing without autoignition. Flashback has been observed in a catalyst system with increases in the fuel-air ratio after very high combustion efficiency was obtained. An active flame formed immediately upstream of the catalytic reactor with subsequent flame propagation upsteam to the fuel inlet. Flashback can be eliminated by designing for a higher velocity in the fuel-air inlet section."

NASA (Reference 73) reports the progress of the NASA/USAF catalytic combustor program, in Phase I (the Design Study):

"The objective of the concept analysis and evaluation portion of Phase I is to select the two most promising concepts from each set of six independently conceived by each of the two contractors. Each set of two concepts would then go into preliminary design. Due to an earlier contract award to General Electric Company, two of the six concepts have been identified and selected for preliminary design. Analysis and evaluation of the six concepts by Pratt & Whitney Aircraft Company is nearing completion. Brief descriptions of the two General Electric concepts and the Pratt & Whitney concepts under evaluation are presented below.

The two most promising General Electric concepts identified are the Basic Parallel Staged and the Cannular Reverse-Flow Parallel Staged. Maximum fuel flow to the catalytic reactor will be restricted to maintain reactor temperature below 1811 K. Combustor liners downstream of the catalyst will be cooled by backside convection and have a 0.5 mm thick thermal barrier coating on the inside wall. This permits a maximum allowable catalyst-to-total fuel flow split of 0.92 at normal cruise. Both concepts are mechanically promising. The can-annular, reverse-flow concept has the best catalyst accessibility. Catalyst accessibility for the basic, parallel-staged concept is viewed as being a possible problem during testing and development, but not after a final configuration has been achieved. The normal-cruise NO_x emission index predicted for each of the concepts is the low-level of two. Further reductions in the NO_x emission index possibly can be achieved by changing to a hot-liner wall for the pilot stage that will permit more airflow through the catalyst stage. As a result of the increased airflow, the fuel flow to the catalyst stage can be increased - maintaining a constant overall fuel-air ratio - with a corresponding decrease in fuel flow to the pilot stage. This decrease in fuel flow to the pilot stage with its relatively high NO_x-emission level helps reduce the overall NO_x-emission level from the combustor. Fuel to the catalyst stage for both concepts is introduced just below the approach power level (30 percent takeoff power) while the pilot stage fuel flow is decreased to maintain a constant increase in combustor fuel flow. Pilot stage fuel flow is finally decreased to a maintenance level by fueling only a fraction of the pilot stage injectors. This fuel flow is held constant until the catalytic-reactor maximum use temperature level is reached. At this point, the pilot fuel flow is then increased.

The six concepts of Pratt & Whitney Aircraft Company are presently undergoing analysis and evaluation; therefore, complete details are not given, but only the descriptive combustor-concept names which are the following: (1) basic, pure catalytic reactor; (2) rich, front-end hybrid; (3) basic radially-staged; (4) axial fuel staging with variable geometry; (5) radially-staged, can-annular with variable geometry; and (6) folded Vorbix with a radial inflow pilot and individual cruise catalytic combustor. The rich front-end hybrid and the radially-staged, can-annular with variable geometry appear to be the most promising concepts."

The need for considerably more research than accomplished to date is emphasized by NASA (Reference 71):

Results of fundamental combustion studies indicate that a new generation of jet aircraft engine combustor technology may be possible that would provide emission levels far below those currently possible with the advanced technology concepts developed in the Experimental Clean Combustor Program (ECCP) and Pollution Reduction Technology Program (PRTP). Considerable fundamental knowledge is still needed, however, before the techniques being studied can be translated into useful combustors. Successful development of these techniques into operational engine combustors would provide the level of NO_x emission reductions desired for both local air quality and high altitude cruise considerations."

SECTION IX

AREAS FOR CONTINUING USAF RESEARCH

This report has documented the need for the USAF to continue leadership in the reduction of emissions from turbine engine aircraft. This leadership role has been promoted by the USAF Pledge to Environmental Protection (Reference 40). It has been directed by the various Federal Acts, Laws, Regulation, and Executive Orders cited in Section II of this report. An important portion of this leadership role is the USAF participation in research in the several areas of pollution reduction from turbine engines. The past USAF research has been briefly mentioned in this report along with a few comments about the necessity of the research. This report also mentions several areas where additional research is needed. If the USAF is to remain a leader in this field, it must contine, or expand, its research effort.

9.1 Effort Toward USAF Meeting EPA Proposed Rules

A valid question arises when USAF aircraft are evaluated for their current emissions (Reference 8). If the EPA proposed rules were adopted would the USAF aircraft comply or would they not? Since the USAF is exempt from any enforcement action under the rules, the question is hypothetical. It certainly would be to the USAF advantage, however, if they could state that their aircraft (or even a substantial portion of their aircraft) met the EPA proposed rules.

The calculation methods of Scott and Naugle (Reference 8) were applied to current USAF aircraft to determine their emissions for the EPA-LTO cycle (Reference 2), a normalized USAF-LTO cycle for category of aircraft (Reference 47), and, the actually measured LTO cycle for the particular aircraft if it was available (Reference 47). Also, the allowable emissions were calculated according to the proposed EPA Rules (Reference 2). The results are shown on Table 24, USAF Current Engine/Aircraft Emissions, on the following several pages. It is obvious from examination of the results presented in Table 24 that USAF cannot meet proposed EPA standards. This is a powerful incentive for the USAF to continue its research effort.

9.2 Effort Toward Lowering Pollutant Emissions

While it is important that the USAF continue its research to reduce pollutant emissions from gas turbine engines, it is more important that the USAF priorities for pollution reduction are applied to research funding. For example, none of the studies by the USAF, EPA, or other State or Local pollution control agencies indicate that carbon monoxide (CO) is a serious problem in the ambient air around USAF airfields. It, therefore, does not appear to be in the USAF best interest to

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS

ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT OUTPUT, KW(2)	IDLE COMBUST. INEFF., % (100%-EFF)	RATIO HC/CO @ IDLE	CARBON MONOXIDE, GM/LTO CYCLE — EPA STANDARD (1): MFG AFTER 1/1/81	EPA STANDARD (1): MFG AFTER 1/1/84	EPA STANDARD (1): ALL 1/1/85 ①	EMISSIONS (3): EPA TIME IN MODE (1)	EMISSIONS (3): USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)
F100-P-100	F-15	T2	66.7	0.9	0.13	7,187	3,335	7,187	16,654	17,468 (13,000)
F100-P-100	F-16	T2	66.7	0.9	0.13	3,593	1,668	3,593	8,327	8,734 (6,500)
JT8D-17	C-9	T4	66.7	1.8	0.26	7,187	3,335	7,187	16,967	11,170 (9,090)
J33-A-35	T-33	T1	26.7	5.1	0.15	②	②	②	39,903	21,162 (22,659)
J57-P-19W	B-52 D/E	T2	42.3	9.6	0.97	27,726	8,460	③	137,513	229,995 (251,795)
J57-P-21B	F-100	T2	40.0	7.8	0.83	3,409	1,000	③	17,338	18,848 (20,981)
J57-P-21B	F-101	T2	40.0	7.8	0.83	6,818	2,000	③	34,676	37,696 (NA)
J57-P-21B	F-102	T2	40.0	7.8	0.83	3,409	1,000	③	17,338	18,848 (NA)
J57-P-43	KC-135A	T2	44.5	9.4	0.96	14,043	4,450	③	70,482	121,768 (117,499)
J57-P-43	B-52F/G	T2	44.5	9.4	0.96	28,086	8,900	③	140,964	243,536 (258,089)

① CANNOT EXCEED STD. WHEN ENGINE WAS NEW
② NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
③ NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
④ NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONTINUED)

						CARBON MONOXIDE, GM/LTO CYCLE				
						EPA STANDARD (1)			EMISSIONS (3)	
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT OUTPUT, KW(2)	IDLE COMBUST. INEFF., % (100%-EFF)	RATIO HC/CO @ IDLE	MFG AFTER 1/1/81	MFG AFTER 1/1/84	ALL 1/1/85 (1)	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)
J57-P-59W	KC-135-A	T2	44.5	6.9	0.81	14,043	4,450	(3)	78,937	133,862 (128,339)
J60-P-5B	T-39	T1	13.3	2.6	0.13	(2)	(2)	(2)	14,722	7,335 (6,499)
J69-P-25	T-37	T1	4.4	5.1	0.15	(2)	(2)	(2)	15,124	11,528 (10,785)
J75-P-17	F-106A	T2	71.2	9.2	0.84	3,550	1,780	3,550	29,535	32,476 (NA)
J75-P-19W	F-105	T2	80.1	5.2	0.61	3,428	2,002	3,428	25,761	27,354 (24,941)
J79-GE-15	F-4C/D	T2	53.4	2.6	0.21	7,231	2,670	7,231	29,518	31,865 (31,867)
J79-GE-17	F-4E	T2	53.4	1.8	0.22	7,231	2,670	7,231	25,891	25,810 (24,645)
J85-GE-5	F-5	T1	12.5	7.3	0.17	(2)	(2)	(2)	40,557	42,320 (NA)
J85-GE-5	T-38	T1	12.5	7.3	0.17	(2)	(2)	(2)	39,909	30,198 (30,361)

(1) CANNOT EXCEED STD. WHEN ENGINE WAS NEW
(2) NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
(3) NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
(4) NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONTINUED)

						CARBON MONOXIDE, GM/LTO CYCLE				
						EPA STANDARD (1)			EMISSIONS (3)	
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT OUTPUT,KW(2)	IDLE COMBUST. INEFF., % (100%-EFF)	RATIO HC/CO @ IDLE	MFG AFTER 1/1/81	MFG AFTER 1/1/84	ALL 1/1/85 (1)	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)
TF30-P-3	F-111 A/E	T2	46.7	7.9	0.86	7,095	2,335	(3)	27,114	29,644 (28,075)
TF30-P-7	FB-111A	T2	53.4	4.2	0.57	7,231	2,670	7,231	23,071	24,934 (23,530)
TF30-100	F-111F	T2	64.5	3.1	0.40	7,217	3,225	7,217	21,617	22,990 (21,735)
TF33-P-3	B-52H	T2	75.6	11.2	0.78	27,962	15,120	27,962	159,796	287,515 (306,679)
TF33-P-7	C-141	T2	82.3	9.9	0.83	13,565	8,230	13,565	82,982	53,447 (65,063)
TF34-GE-2	A-10	T1	33.4	5.8	0.30	6,377	1,670	(3)	17,153	19,289 (NA)
TF39-GE-1	C-5A	T2	182.4	3.8	0.34	26,339	26,339	26,339	67,598	46,017 (57,333)
TF41-A-1	A-7D	T2	62.3	12.1	0.77	3,620	1,558	3,620	25,149	28,204 (NA)
T56-A-7	C-130A-F	P2	2567	2.8	0.66	NONE	3,491	-	20,865	14,215 (12,377)
T76-G-10	OV-10	P2	1200	1.3	0.31	(4)	(4)	(4)	3,006	2,136 (NA)

(1) CANNOT EXCEED STD. WHEN ENGINE WAS NEW
(2) NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
(3) NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
(4) NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONTINUED)

						UNBURNED HYDROCARBONS, GM/LTO CYCLE				
						EPA STANDARD (1)			EMISSIONS (3)	
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT OUTPUT, KW(2)	IDLE COMBUST. INEFF., % (100%-EFF)	RATIO HC/CO @ IDLE	MFG AFTER 1/1/81	MFG AFTER 1/1/84	ALL 1/1/85 ①	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)
F100-P-100	F-15	T2	66.7	0.9	0.13	1,276	440	1,276	2,138	2,362 (1,600)
F100-P-100	F-16	T2	66.7	0.9	0.13	638	220	638	1,069	1,181 (800)
JT8D-17	C-9	T4	66.7	1.8	0.26	1,276	440	1,276	4,080	2,550 (2,228)
J33-A-35	T-33	T1	26.7	5.1	0.15	②	②	②	5,115	2,453 (2,709)
J57-P-19W	B-52 D/E	T2	42.3	9.6	0.97	4,700	1,117	③	116,482	212,871 (228,158)
J57-P-21B	F-100	T2	40.0	7.8	0.83	575	132	③	12,904	14,677 (16,301)
J57-P-21B	F-101	T2	40.0	7.8	0.83	1,150	264	③	25,808	29,354 (NA)
J57-P-21B	F-102	T2	40.0	7.8	0.83	575	132	③	12,904	14,677 (NA)
J57-P-43	KC-135A	T2	44.5	9.4	0.96	2,390	587	③	59,502	108,290 (104,960)
J57-P-43	B-52F/G	T2	44.5	9.4	0.96	4,780	1,174	③	119,004	216,580 (232,309)

① CANNOT EXCEED STD. WHEN ENGINE WAS NEW
② NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
③ NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
④ NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONTINUED)

						UNBURNED HYDROCARBON, GM/LTO CYCLE				
						EPA STANDARD (1)			EMISSIONS (3)	
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT OUTPUT, KW(2)	IDLE COMBUST. INEFF., % (100%-EFF)	RATIO HC/CO @ IDLE	MFG AFTER 1/1/81	MFG AFTER 1/1/84	ALL 1/1/85 (1)	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)
J57-P-59W	KC-135-A	T2	44.5	6.9	0.81	2,390	587	(3)	56,089	100,405 (96,655)
J60-P-5B	T-39	T1	13.3	2.6	0.13	(2)	(2)	(2)	1,880	912 (826)
J69-P-25	T-37	T1	4.4	5.1	0.15	(2)	(2)	(2)	1,961	1,495 (1,452)
J75-P-17	F-106A	T2	71.2	9.2	0.84	636	235	636	22,551	25,679 (NA)
J75-P-19W	F-105	T2	80.1	5.2	0.61	624	264	624	15,137	16,425 (14,877)
J79-GE-15	F-4C/D	T2	53.4	2.6	0.21	1,252	352	1,252	5,638	6,356 (6,445)
J79-GE-17	F-4E	T2	53.4	1.8	0.22	1,252	352	1,252	5,471	5,603 (5,390)
J85-GE-5	F-5	T1	12.5	7.3	0.17	(2)	(2)	(2)	5,915	6,538 (NA)
J85-GE-5	T-38	T1	12.5	7.3	0.17	(2)	(2)	(2)	5,836	4,373 (4,573)

(1) CANNOT EXCEED STD. WHEN ENGINE WAS NEW
(2) NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
(3) NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
(4) NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONTINUED)

						UNBURNED HYDROCARBON, GM/LTO CYCLE				
						EPA STANDARD (1)			EMISSIONS (3)	
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT OUTPUT,KW(2)	IDLE COMBUST. INEFF., % (100%-EFF)	RATIO HC/CO @ IDLE	MFG AFTER 1/1/81	MFG AFTER 1/1/84	ALL 1/1/85 (1)	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)
TF30-P-3	F-111 A/E	T2	46.7	7.9	0.86	1,213	308	(3)	21,024	24,009 (22,832)
TF30-P-7	FB-111A	T2	53.4	4.2	0.57	1,252	352	1,252	11,621	13,179 (12,484)
TF30-100	F-111F	T2	64.5	3.1	0.40	1,276	426	1,276	7,456	8,431 (7,971)
TF33-P-3	B-52H	T2	75.6	11.2	0.78	5,050	1,996	5,050	122,163	222,033 (237,763)
TF33-P-7	C-141	T2	82.3	9.9	0.83	2,481	1,086	2,481	65,831	40,978 (51,702)
TF34-GE-2	A-10	T1	33.4	5.8	0.30	1,063	220	(3)	4,980	5,685 (NA)
TF39-GE-1	C-5A	T2	182.4	3.8	0.34	4,888	4,888	4,888	23,150	15,735 (19,643)
TF41-A-1	A-7D	T2	62.3	12.1	0.77	637	206	637	18,538	21,149 (NA)
T56-A-7	C-130A-F	P2	2567	2.8	0.66	NONE	462	-	13,274	8,932 (7,772)
T76-G-10	OV-10	P2	1200	1.3	0.31	(4)	(4)	(4)	737	472 (NA)

(1) CANNOT EXCEED STD. WHEN ENGINE WAS NEW
(2) NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
(3) NO "IN USE, 1985 STDS" FOR LESS THAN 53 KILONEWTONS THRUST
(4) NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONTINUED)

				OXIDES OF NITROGEN, GM/LTO CYCLE				
				EPA STANDARD (1)		EMISSIONS (3)		
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT KW OUTPUT (2)	MFG AFT. 1/1/81 BUT NOT EFF 1/1/84	ALL 1/1/85 (1)	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)	EPA STD SMOKE NUMBER SN (1)
F100-P-100	F-15	T2	66.7	4,402	-	6,234	7,412 (4,900)	26
F100-P-100	F-16	T2	66.7	2,201	-	3,117	3,706 (2,450)	26
JT8D-17	C-9	T4	66.7	4,402	-	8,964	5,903 (4,498)	30
J33-A-35	T-33	T1	26.7	(2)	(2)	788	478 (497)	33
J57-P-19W	B-52/DE	T2	42.3	11,167	(3)	17,643	19,563 (18,222)	29
J57-P-21B	F-100	T2	40.0	1,320	(3)	2,262	1,583 (1,845)	30
J57-P-21B	F-101	T2	40.0	2,640	(3)	4,524	3,166 (NA)	30
J57-P-21B	F-102	T2	40.0	1,320	(3)	2,262	1,583 (NA)	30
J57-P-43	KC-135A	T2	44.5	5,874	(3)	8,760	9,580 (7,428)	29
J57-P-43	B-52F/G	T2	44.5	11,748	(3)	17,520	19,160 (18,083)	29

(1) CANNOT EXCEED STD. WHEN ENGINE WAS NEW
(2) NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
(3) NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
(4) NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONTINUED)

				OXIDES OF NITROGEN, GM/LTO CYCLE				
				EPA STANDARD (1)		EMISSIONS (3)		
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT KW OUTPUT (2)	MFG AFT. 1/1/81 BUT NOT EFF 1/1/84	ALL 1/1/85 (1)	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)	EPA STD SMOKE NUMBER SN (1)
J57-P-59W	KC-135A	T2	44.5	5,874	(3)	5,365	7,128 (6,851)	29
J60-P-5B	T-39	T1	13.3	(2)	(2)	639	379 (324)	40
J69-T-25	T-37	T1	4.4	(2)	(2)	273	202 (171)	53
J75-P-17	F-106A	T2	71.2	2,350	-	4,630	2,653 (NA)	26
J75-P-19W	F-105	T2	80.1	2,643	-	3,566	2,246 (2,254)	25
J79-GE-15	F-4C/D	T2	53.4	3,524	-	4,176	3,121 (2,725)	28
J79-GE-17	F-4E	T2	53.4	3,524	-	4,786	3,452 (2,995)	28
J85-GE-5	F-5	T1	12.5	(2)	(2)	633	507 (NA)	47
J85-GE-5	T-38	T1	12.5	(2)	(2)	730	577 (455)	47

(1) CANNOT EXCEED STD. WHEN ENGINE WAS NEW
(2) NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
(3) NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
(4) NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

TABLE 24. USAF CURRENT ENGINE/AIRCRAFT EMISSIONS (CONCLUDED)

				OXIDES OF NITROGEN, GM/LTO CYCLE				
				EPA STANDARD (1)		EMISSIONS (3)		
ENGINE	AIRCRAFT	EPA ENGINE CLASS (1)	MAX THRUST, KN OR SHAFT KW OUTPUT (2)	MFG AFT. 1/1/81 BUT NOT EFF 1/1/84	ALL 1/1/85 ①	EPA TIME IN MODE (1)	USAF AVERAGE TIME IN MODE (4) (MEAS. TIM)	EPA STD SMOKE NUMBER SN (1)
TF30-P-3	F-111A/E	T2	46.7	3,082	③	4,201	2,718 (2,468)	29
TF30-P-7	FB-111A	T2	53.4	3,524	-	5,798	3,629 (3,274)	28
TF30-100	F-111F	T2	64.5	4,257	-	8,445	4,710 (4,254)	26
TF33-P-3	B-52H	T2	75.6	19,958	-	18,057	18,099 (18,261)	25
TF33-P-7	C-141	T2	82.3	10,864	-	9,388	5,683 (4,746)	25
TF34-GE-2	A-10	T1	33.4	2,204	③	1,388	1,030 (NA)	31
TF39-GE-1	C-5A	T2	182.4	24,077	-	33,324	19,062 (17,427)	20
TF41-A-1	A-7D	T2	62.3	2,056	-	3,117	1,927 (NA)	26
T56-A-7	C-130A-F	P2	2,567	4,621	-	4,159	2,742 (2,628)	NONE
T76-G-10	OV-10	P2	1,200	④	④	1,300	926 (NA)	④

① CANNOT EXCEED STD. WHEN ENGINE WAS NEW
② NO EPA STANDARDS FOR ENGINE LESS THAN 27 KILONEWTONS THRUST
③ NO "IN USE, 1985 STDS." FOR LESS THAN 53 KILONEWTONS THRUST
④ NO EPA STDS. FOR ENGINES LESS THAN 2000 KW OUTPUT
"NA"-MILITARY TIME IN MODE NOT MEASURED FOR THIS A/C

REFERENCES FOR TABLE 24

USAF CURRENT ENGINE/AIRCRAFT EMISSIONS

(1) EPA Proposed Revisions to Gaseous Emissions Rules for Aircraft and Aircraft Engines", 43 FR 12615, March 1978.

(2) Sousa, A. F. and P.S. Daley, "USAF Turbine Engine Emission Survey", CEEDO-TR-78-34, September 1978.

(3) Scott, H. A. Jr. and D. F. Naugle, "Aircraft, Air Pollution Emissions Estimation Techniques - ACEE", CEEDO-TR-78-33, September 1978.

(4) Naugle, D. F. and S. R. Nelson, "USAF Aircraft Pollution Emission Factors and Landing and Takeoff (LTO) Cycles", AFWL-TR-74-303, February 1975.

expend large amounts of time and money on research studies to lower CO from turbine engines.

The USAF must also consider that lowering one pollutant may increase the output of another. If lowering NO_x for example, increases hydrocarbon emissions it becomes necessary to evaluate the possible consequences to determine which is more critical to the USAF, the emission of NO_x or HC.

At this time, it would appear that the priority of reduction, (with a brief statement of the rationale involved) for pollutant emissions from gas turbine engines used by the USAF, is as follows:

(1) Smoke - The pollutant which first directed public attention to gas turbine powered aircraft was smoke. Combustor retrofit and modification reduced smoke to acceptable levels but all indications are that smoke numbers are now increasing and will continue to increase. The USAF is continuing its use of several older model engines which are prone to smoke. The aromatic content of JP-4 is increasing so smoke will increase. Alternate fuels being investigated may cause increased smoke. All of these factors are important, but two critical facts are foremost; smoke is causing short-term problems in jet engine test cells, some of which have been cited by local authorities for opacity violations, and, smoke is a current and long-term operational problem for combat and support aircraft operating in wartime conditions.

(2) Hydrocarbons - HC is emitted in quantities greatly in excess of the desired amounts. It is emitted primarily at ground level and can enter into the photochemical air pollutant cycle to cause substandard ambient air. The mechanisms of HC conversion in the photochemical reaction is well documented as is the dispersion of the HC at airports. Research into low-power combustion emissions should be continued with the major effort directed toward HC reduction.

(3) Oxides of Nitrogen - NO_x reduction deserves continued USAF research. This research should be directed to not only methods of reducing NO_x formation but also to possible effects of NO_x on the environment. If short term NO_2 standards are developed by EPA it will be important to address this issue. The same can be said if the NO_x emissions at altitude are found to be harmful.

(4) Carbon Monoxide - CO reduction will occur if HC reductions are implemented. It does not appear that CO reduction research should be carried out as a separate program because CO is currently below threshold levels, most of the time, around most airports.

(5) Oxides of Sulfur - SO_x emissions are strictly fuel related and any research studies on them should be fuel related. SO_x emissions are probably not a serious problem at this time and other than the fuel research studies, no other research is recommended.

9.3 Research on Fuel Related Problems

Fuel related problems can be two general types. The first type occurs when fuels change within the specification for that fuel. An example of this type of change would be an increase in the percent aromatics to approach the maximum level specified of 20 percent for Jet A and B, or the maximum of 25 percent for JP-4, JP-5 and JP-8. Currently, the aromatic content of JP-4 is just over 12 percent (Reference 74). The second type of fuel related problem can occur when alternate fuels are being studied. The fuel bound nitrogen of raw shale oil could be as high as 2 percent (Reference 68), for example.

9.3.1 Carbon Monoxide and Hydrocarbon

CO and HC are combustion variables which are related to combustor design. They are only slightly changed by changes in fuel variables. Research on alternative fuels should consider that HCs are critical engine emissions and should not be caused to increase because of changes in fuel variables.

9.3.2 Oxides of Nitrogen

NO_x emissions are a function of combustor operating conditions and fuel-bound nitrogen. Fuel-bound nitrogen is converted from 20 percent to 75 percent to NO_x within the engine (Reference 68). For this reason they should be minimized in gas turbine fuel. Fortunately, nitrogen compounds are known hydrotreating catalyst poisons so jet fuels are treated to remove them. Also, because many organic nitrogen compounds are detrimental to required thermal stability levels of jet fuel, extensive efforts are already being used to minimize them, as noted by Angello (Reference 68).

> "Therefore, it is unlikely that shale oil derived fuels will ever have high levels of nitrogen. However, other portions of the overall Air Force program should provide guidance to this aspect."

It does appear that the USAF should have an active program to assure that fuel-bound nitrogen is minimized. Further, it should be noted that environmental protection is only one of the justifications for such a program.

9.3.3 Smoke

Smoke has been found to be so positively correlated with fuel hydrogen/carbon ratios and aromatic content that fuel related research should be considered at least on the same level as combustor research to reduce smoke. It is known that the more readily available sources of crude oil are showing higher aromatics all the time. It is to the USAF advantage to establish, and continue, research programs looking at the smoke producing potential of current and future gas turbine engine fuels. Increased hydrogen/carbon ratio fuels can be produced but they would be produced at signficant cost increases and increased energy consumption.

9.3.4 Oxides of Sulfur

Organic sulfur compunds, and free sulfur, are converted to SO_x in a jet engine with nearly 100 percent conversion efficiency. The only viable method for reducing SO_x emissions therefore, is to reduce the sulfur content of the fuel supplied to the engine. The USAF should be working toward maintaining low levels of sulfur in jet fuel as one of its research goals. It should also be stated that sulfur reduction mechanisms are available, but at the expense of increased fuel processing costs and energy use.

9.4 Revision of Landing and Takeoff Cycles

As long as the EPA intends to base their emission standards on a normalized LTO cycle, a change in the LTO cycle may be considered as a means for control of emissions to the atmosphere. If, for example, the Taxi/Idle time can be halved, the emissions of CO and HC can be nearly halved. It would, therefore, appear that the USAF could do considerable research on revising LTO cycles to obtain more favorable Times in Mode (TIM). This research might be more cost-effective than combustor research.

9.4.1 Revised LTO Cycles for Individual Aircraft

Multi-engine aircraft can use one engine (one twin engine aircraft) or less than all engines (on aircraft such as the B-52) for a considerable portion of the taxi mode. This increases the power output on the operating engine(s) which in turn reduce CO and HC emissions to the atmosphere. This is currently a standard operating procedure at many USAF bases as a combination emission - energy saving procedure.

Another example of modification of an LTO cycle would be using an auxillary power supply while checking the electronic gear on a B-52 before takeoff. Naugle and Nelson (Reference 47) report a Taxi/Idle TIM of 30 minutes, from engine start up to the start of the takeoff roll. Any method that would cut this time in half would greatly reduce the emissions for the LTO cycle. Note that Table 24 lists HC emissions for the B-52H as

122,163 grams per LTO cycle for the EPA cycle, 222,033 for the USAF average TIM-LTO cycle, and 237,763 for the USAF measured TIM-LTO cycle. The allowable emission of HC for this aircraft, under the proposed EPA Rules, is 5,050 grams per LTO cycle for engines manufactured after 1/1/81 and 1,996 per LTO cycle for engines manufactured after 1/1/84.

9.4.2 Revised LTO Cycles for Individual Bases

Individual USAF bases may have some options available to change LTO cycles. For example, a base with many touch and go operations may consider setting pattern altitude at one kilometer which is equal to 3,300 feet. This would place the aircraft above the 3000 foot (.914 km) level specified in the EPA-LTO cycle. The emissions above 3000 feet would not be charged to the cycle.

Another option which might be considered would be to use high-speed turn-offs from the active runway to the ramp. This would cut down on the amount of time in the Taxi/Idle TIM.

Other systems such as scheduling aircraft start-up and taxi to eliminate cueing at the end of the active runway are realistic approaches to the problem. They surely would be less expensive than major engine retrofit or modification to reduce emissions.

9.4.3 Split Taxi and Idle Times

Some control can be exercised over the amount of thrust used for taxi. This is in contrast to the idle mode when the engine is carrying its minimum load. By combining the taxi and idle modes, as EPA has done (Reference 2), a higher than actual CO and HC emission for the LTO cycle is calculated. This is because the calculation is based on the Emission Index (EI) for the idle mode which is the higher of the two.

If the two modes were used, and the TIM for each calculated, the CO and HC emissions would not only be lower for the LTO cycle, but the LTO cycle would be closer to the actual cycle being used.

9.5 Revise the Current LTO Cycle to a Real Time Cycle

The current LTO cycle is an average, derived from commercial aircraft operating at large civilian airports. It is, therefore, a good basis for calculations concerning emissions at such faciliteis. It is much easier to use averages for modeling input rather than measure each individual aircraft TIM.

The USAF should not be expected to consider using the EPA-LTO cycle because they are not operating "commercial" aircraft, and, in most cases, are not operating from civilian airports. Section 9.4 suggested some areas that the USAF might consider to obtain more realistic TIMs for their operations.

Another system that could be used by the USAF (probably for research purposes at this time) would be to install equipment to record the actual TIMs for specific aircraft at specific bases. This equipment would record the real time engine output which could then be used as a computer input for that aircraft. The emission data could also be entered into the computer in the form of continuous data (curves) rather than the discrete data input now used. With this system the computer could calculate the actual emissions of pollutants over an actual cycle.

The only equipment necessary on the aircraft would be a sensor to pick up the engine output and an electronic recording system. The sensor could even be one which was already in place on the engine/aircraft for another purpose. Examples of sensors (transducers) which could be used could be:

(1) Load cells to pick up the thrust of the engine. The electronic system would have to consider this input with inputs from the airspeed and altitude recording systems.

(2) A system based on engine speed. The RPM would be the primary input but again airspeed and altitude data should also be used as inputs.

(3) Flow meters on the fuel system could be used for engine output data through correlation equations in the electronic system.

(4) Temperature measurements at the turbine outlet and afterburner outlet could be used as the inputs to the electronic system to obtain continuous mode data.

9.6 Continuation of Research and Development Studies

The USAF has been a leader in basic research studies related to gas turbine engines. Many of these studies have led to important applied research areas. It is vitally important to the USAF to continue an active program of research in the critical areas which relate to engine emissions. A listing of these areas would include:

(1) Photochemistry, reaction rates, products, etc.

(2) Combustion, initiation, propogation, inhibition, etc.

(3) Smoke, formation, mechanisms and control.

9.7 Studies of Emission Variability

It has only been recently that the subject of emission variability from gas turbine engines has received attention even though it has been questioned for several years. The variability was considered in establishing the acceptance levels mentioned in the EPA Proposed Rules (Reference 2),

> "Has a Margin for Variability Been Included in Setting the Standards?"
>
> "Thus, the standards are to be considered upper limits with respect to compliance testing and manufacturers must set their design goals sufficiently below the standards to account for variability."

This issue of variability, limits, and standards was discussed at the EPA Public Hearings (Reference 46) in San Francisco. The various engine manufacturers expressed concern with the EPA Proposed Rules and wanted to use some other system of acceptance/rejection.

Rolls-Royce stated their objections in a paper presented at a recent APCA meeting (Reference 75),

> "Over the past few years it has become clearly recognised that the emissions observed from nominally similar aero-gas turbines exhibit appreciable variability and that any regulatory scheme must take this into account. As a consequence of variability and of the small number of engines available for testing, it will not be practicable to devise a regulatory scheme which can be met with 100 percent compliance.
>
> The Certification Authority has to accept a small risk that it may occasionally award a certificate to an engine type which produces slightly more pollution than defined by the legislative standards while the manufacturer may sometimes be refused a certificate for a satisfactory engine type and may have to test a further one or two engines to demonstrate compliance.
>
> In all certification procedures, there is a margin between the level which is technically achievable by the average engine and the published Regulatory Limit. The size of this margin depends on the variability, the way in which the regulations are to be interpreted and the risks accepted by the manufacturer and the Certification Authority. To make these risks small the margins have to be large, leading to a wide disparity between the average level of emissions and the Regulatory Limit and dissociating the Limit from the environmental consequences of the regulations."

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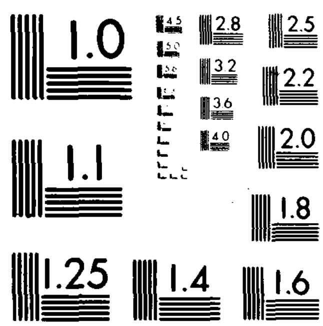

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Rolls-Royce (Reference 75) presents an excellent set of conclusions to their paper. These conclusions point to some of the research areas that the USAF might consider to clarify the many issues involved concerning variability:

"1. Gaseous emissions from aircraft gas turbines exhibit great variability, especially in the case of hydrocarbons.

2. For carbon monoxide, hardware differences and measurement factors contribute equally to total variability .

3. The majority of the variability in hydrocarbon emissions is attributable to measurement factors, although the fundamental variability is still substantially more than carbon monoxide.

4. Emissions certification schemes must recognize that this variability, combined with the very small number of engines available, demands the provision of margins between the Regulatory Limits and the achievable technology levels.

5. The size of these margins depends on the degree of risk acceptable to the certifying authorities and manufacturers.

6. The margin is greatly reduced by adopting universal values of variability and basing compliance demonstration on the control of the population mean."

9.8 Studies of Sampling Methods and Systems

Sampling methods and systems for accurately obtaining representative samples from jet engine exhausts are also subject to the variability mentioned in the previous section (9.7). The Rolls-Royce paper (Reference 75) refers to the variability due to sampling,

"Measurement Variability

(a) Instrumentation scatter refers to variations that may occur in the actual analysis of identical samples.

(b) Sampling variations arise because the distribution of the pollutant species is neither uniform across the jet pipe sampling plane nor constant from engine-to-engine."

Standard methods of sampling gas turbine emissions have been established (Reference 76) and in general have been adopted by the EPA as part of the EPA Proposed Rules (Reference 2). The USAF has actively participated on the committees that have established these sampling and analytical methods. Continued support of these committees through research and participation should be an important USAF function.

An earlier paper by Dieck and Elwood of Pratt & Whitney Aircraft (Reference 77) addressed the problems of accuracy of emission data. A more recent paper by Dieck (Reference 78) summarizes the several years work by Pratt & Whitney. The conclusion of this paper states:

> "1. Over seven years of documented evaluations there have been no trends in the precision of CO_2, CO, HC, or NO_x instruments in use during tests on gas turbine engines.
>
> 2. Significant variation in instrument precision exists even for six month averages thus requiring continuous instrument precision assessment for proper error analysis.
>
> 3. EPA recommended analysis instrumentation for CO_2, CO, HC and NO_x, utilizing present technology, will not, in general, achieve the precision required by the EPA regulations.
>
> 4. Instrumentation calibration curve determination may be used to uncover calibration gas analysis errors.
>
> 5. Properly fit calibration curves will have residual errors roughly equivalent to those of the calibration gases.
>
> 6. Smoke filter papers can exhibit batch-to-batch errors of two smoke numbers.
>
> 7. A standard set of smoke filters should be established for all facilities who often must change filter paper batches.
>
> 8. Side-to-side filter paper bias error may be as much as 3.4 smoke numbers so only one side should be used in all gas turbine smoke testing."

There clearly exist many areas where research is needed in order to determine how representative the values reported for emissions really are and what errors are involved.

9.9 Continued Studies of Cost of Control Technology

Many different studies have been conducted to determine the cost of control of pollutant emissions. Some also include cost-effectiveness data. These papers are not in total agreement and additional USAF investigation in this area is warranted to assure that the USAF has the best information available.

The EPA has presented their own cost studies (Reference 50 and 51) and have contracted another study (Reference 66). Naugle (Reference 67) reports on the similarities, and differences, in these studies. Blazowski and Henderson (Reference 3) reported the USAF research on the subject but this data is probably out of date for today's situation, and the changed EPA Proposed Rules.

9.10 Continued Studies of Models

The ability of existing air quality models to predict the effects of turbine engine emissions on the environment is limited at best, due in part to the reliability of the input data and also to the representativeness of the models themselves. Thus, it is important that the USAF continue its research to develop the most accurate, least biased models possible. The models necessary for understanding the effect of turbine engine emissions on the environment generally break down to (1) airport and ambient air, (2) atmospheric, and (3) stratospheric.

9.10.1 Airport Models

Airport models calculate the affect of the pollutants on ambient air. The pollutants of concern affect the area in the immediate vicinity of the airport. Models should concentrate on the dispersion and diffusion of CO, SO_x and NO_x (short term).

9.10.2 Atmospheric Models

Pollutants which become entrained in large scale air masses can cause harmful effects after traveling long distances from their point of release. Also, because of photochemical and other reactions, secondary pollutants can form which may be more harmful than the original engine emissions. Pollutants of concern in atmospheric models are HC, NO_x and SO_x.

9.10.3 Stratospheric Models

Stratospheric models are of concern because they are the least defined of the three models. So much conversion of NO-NO_2, O_2-O_3, HC-oxidants, etc. is involved that reliable values are difficult to predict. This, along with the stratospheric circulation variables and the extreme difficulties of stratospheric sampling, points out the great need for the USAF to continue research on stratospheric models.

SECTION X

RECOMMENDATIONS FOR THE FUTURE

The USAF must stay in a leadership role in the eyes of the world. This will entail a continued expenditure of time, money, and effort to accomplish the goals stated. The results may not always be readily apparent to an untrained observer. The results may not bear fruit for several years. The push toward continued leadership may not even be a popular stand. These recommendations are made realizing that such pitfalls do exist.

10.1 Continuing Review and Application of USAF Goals

It is not enough just to set down the USAF goals periodically and then sit back and not evaluate them until some later point in time. A USAF Directorate should be charged with continual review of the goals and their application to new programs as technology is advanced. Military specifications (References 82 and 83) should be updated to explicitly incorporate USAF goals. USAF scientists and engineers should be informed that they are expected to continually be aware of the USAF goals and direct their research and other projects accordingly. Application to new programs would be accomplished through Directorate review of USAF Program Management Directives (PMDs) and insertion of the goals into them.

Some point in time should be slected as the target at which time the USAF goals will be again critically reviewed, and possibly rewritten. This time should not be more than five years into the future (1984). This would be compatible with several other studies which should be completed about the same time.

10.2 Cooperation with EPA, ICAO, and FAA

The USAF cannot tell the EPA, ICAO, and FAA what rules and standards they should adopt. The USAF can, however, continually consult and cooperate with these agencies in every way possible. It may be possible that the USAF will not have direct representation to ICAO. In that case the USAF should cooperate with the FAA, which is represented, and use the FAA as its voice to ICAO. The USAF does coordinate in a yearly meeting with personnel from the regulatory, standard setting agencies (such as FAA and EPA) and other U.S. Governmental agencies working on control of gas turbine emissions. The 1979 meeting, the "Eleventh Annual Coordination Meeting of Government Representatives Dealing with Research Efforts in Aircraft Pollution", was hosted by the Air Force Engineering and Services Center, Tyndall AFB FL. This is the type of cooperation which should be encouraged. Any input the USAF can develop into the setting of rules and standards will be a direct benefit.

10.3 Liaison with the Army and Navy

The USAF works jointly with, and consults with, Army and Navy organizations actively involved in turbine engine pollutant reduction, atmospheric modeling, atmospheric research, etc. This cooperation must be continued and encouraged to maintain a coordinated effort within the Department of Defense. These organizations were in attendance at the "Annual Coordination Meeting" mentioned in Section 10.2.

10.4 Liaison with Universities, Consultants, Engine Manufacturers, Etc.

Many private and public groups currently work with the USAF on a cooperative basis. This takes many forms such as university professors on summer appointment at USAF facilities and USAF Systems Command cooperative education programs which allow qualified students to work cooperatively with the USAF. The USAF personnel will confer with consultants, suppliers, and major engine manufacturers to attempt to develop mutually beneficial projects. All of these programs, and other similar programs, should be encouraged and expanded.

10.5 Participation in Technical Societies

The USAF and USAF personnel are an important resource to technical societies concerned with gas turbine engine emissions. A look at the list of references for this report will show several such societies. The USAF, military and civilian personnel, are active on the committees and councils of these societies. Such activities are to be encouraged and promoted, even though they require an expenditure of USAF funds and a time commitment from the personnel involved. It is also recommended that the USAF continue a policy of sending qualified personnel to local, regional, national, and even international meetings dealing with their special areas of expertise. The USAF should gain as much from such a meeting as it gives.

10.6 Support of Research Grants and Contracts

Currently the USAF supports all areas of research and development on turbine engines in the amount of several million dollars each year. This support must be continued, and perhaps even expanded in areas necessary to assure that the USAF will always be in an environmentally sound position. The military is currently exempt from the EPA rules governing turbine engine emissions. One reason for this exemption is that the military is known to be at the forefront of the research on these engines. This reputation is worth keeping and a major reduction in research funding would be detrimental to this reputation, and to the USAF.

10.7 Maintain a High Level of Interest in USAF Goals

The USAF should constantly be aware of the turbine engine emission goals. USAF personnel should realize how critical the "exemption" is to the capability of the USAF to conduct its mission. Every effort must be made, from initial research considerations through aircraft operations, to minimize turbine engine emissions. If the USAF Pledge to Environmental Quality is upheld in spirit as well as literally, the USAF will have no trouble meeting the goals presented in this report.

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APPENDIX A

USAF Proposed Data Item Description for Aircraft Turbine Engine Pollutant Emissions Measurement

DATA ITEM DESCRIPTION	2. IDENTIFICATION NO(S)	
	AGENCY	NUMBER
1. TITLE Aircraft Propulsion Turbine Engine Air Pollution Emissions Data		UDI-E-3935(ASD)
3. DESCRIPTION/PURPOSE The purpose of this Data Item Description is to report turbine engine emission data procured under Air Force engine development contracts in a form suitable for use in the environmental assessment process, including making comparisons between engines procured under different contracts.	4. APPROVAL DATE 5. OFFICE OF PRIMARY RESPONSIBILITY 6. DDC REQUIRED 8. APPROVAL LIMITATION	
7. APPLICATION/INTERRELATIONSHIP This data item applies to all Air Force turbojet, turbofan, and turboprop aircraft engine development and procurement programs which include emissions measurement tasks. Because these data are needed for early evaluation of air pollution emissions in the environmental assessment/statement process, it should be considered for use on prototype engine programs.	9. REFERENCES (Mandatory as cited in block 10) a. Title 40, Code of Federal Regulations, Protection of Environment, Part 87. b. "Development of Emissions Measurement Techniques for Afterburning Engines," AFAPL TR 75-52, WPAFB, OH Oct 75. c. AFR 19-1. MCSL NUMBER(S)	

10. PREPARATION INSTRUCTIONS

a. Report emission measurements in accordance with the requirements set forth in the current issue of Title 40, Code of Federal Regulations, Part 87. Report data from augmented engine measurements IAW the requirements of AFAPL-TR-75-52.

b. Report data for each type of fuel tested in the engine.

c. Data presentation and units. Present results in SI (Systems International) metric units except where traditional English nomenclature refers to nominal sizes and not exact dimensions, e.g., 1/4 inch tubing. Show English units parenthetically if desired Report data for conditions representative of idle, taxi, takeoff, cruise, and approach modes. Express emission rates of CO, NO_x, SO_x, and hydrocarbons for each engine operational mode in grams pollutant emitted per kilogram of fuel consumed. Present results in tabular as well as graphical format. For graphical presentation, plot emissions for each pollutant measured as a function of engine fuel flow. Also, indicate the percent engine power on the abscissa. Display engine smoke number as a function of both fuel flow and engine power setting. Emissions per 1000 pound-thrust hours are not required. For comparison with AF goals (AFR 19-1), specify (a) ground idle pressure ratio (b) combustor inlet temperature at condition of maximum NOx emissions and (c) exhaust nozzle diameter at maximum smoke unaugmented condition.

d. Stratospheric Emissions. Present the emission rates of CO, CO_2, HC, H_2O, and NOx as a function of fuel flow for altitudes of 10 and 20 km. These data may be estimated and are required only for aircraft that will operate in the stratosphere.

e. Augmentation Mode. Report equilibrium atmospheric emissions measurements or estimates, as well as exhaust plane measurements in the same format used in item 3.c.

DD FORM 1 JUN 68 1664

CONTRACTOR DATA REQUIREMENT SUBSTANTIATION

I. PROCUREMENT IDENTIFICATION

CONTRACT / PR, END ITEM, ETC

II. DD FORM 1423 ENTRIES *(OPRs complete all items using AFSCR 310-1 as guide, inserting own symbol in item 6. Other respondents complete as applicable.)*

1. SEQUENCE NUMBER:

2. TITLE OR DESCRIPTION OF DATA: Aircraft Propulsion Turbine Engines

3. SUBTITLE: Air Pollution Emissions Data

4. AUTHORITY *(Data Item Number)*:

5. CONTRACT REFERENCE *(Identify Related Task)*:

6. TECHNICAL OFFICE: HQ AFESC/RDV

7. DD 250 REQ:

8. APP CODE:

9. INPUT TO IAC:

10. FREQUENCY: As Req

11. AS OF DATE:

12. DATE OF 1ST SUBMISSION:

13. DATE OF SUBSEQUENT SUBM/EVENT ID:

14. DISTRIBUTION AND ADDRESSES *(Addressee-Regular / Repro Copies)*

HQ AFESC/RDV	1/0
HQ AFSC/DEV	0/1
AFAPL/TBC	0/1
AFAPL/SFF	0/1
ASD/YZ	0/1
ASD/AWZ	0/1
15. TOTAL	1/5

16. REMARKS

This data item applies to all Air Force turbojet, turbofan, and turboprop aircraft engine development and procurement programs which includes emissions measurement tasks. It applies to prototype engines as well as production versions because of need for early evaluation of air pollution emissions in the environmental assessment/statement process.

17. REQUESTER IDENTIFICATION

NAME: Capt Joseph A. Martone

ORGANIZATION: HQ AFESC/RDVC

PHONE: AUTOVON 970-4234

DATE: 6 March 79

III. DD FORM 1423 ENTRY RATIONALE/CHECKLIST *(Complete all items and adjust Part II as appropriate)*

18. FORMAT REQUIREMENTS ARE CRITICAL [X] OR ALTERNATE CONTRACTOR FORMAT MAY SUFFICE [ ] *(Explain)*

Data must be provided in a format useful for making comparisons between engines procured under different contracts. Standard format is essential.

19. ENTIRE DID REQUIRED [X] OR CAN BE REDUCED IN SCOPE [ ] *(Explain in item 16)*

20. CONTRACT TASK WHICH SUPPORTS / GENERATES THE DATA

Data required for all USAF aircraft turbine engine development and procurement programs which includes emissions measurements tasks.

21. IDENTIFICATION OF REQUIREMENT DETAILS *(Scope, Content, Quantities, Due Dates)* CAN BE DEFERRED [ ] YES [ ] NO *(Comment)*

22. LIST OTHER DIDS THIS MIGHT DUPLICATE / BE COMBINED WITH IF ORDERED

23. DELIVERY ESSENTIAL [ ] OR ON-SITE REVIEW SUFFICIENT [ ] *(Explain)*

24. DATA COULD BE AVAILABLE FROM AFPRO/DCAS [ ] YES [ ] NO *(Comment)*

It is possible that the AFPRO/DCAS office could prepare a suitable report if they were given the reduced emissions data by the contractor.

25. FOR RECURRING REPORTS, EXPLAIN FREQUENCY REQUIREMENT, STATE IF IT CAN BE REDUCED

Report will be required for each aircraft turbine engine development and procurement program. This frequency cannot be reduced.

26. ACCEPTABLE COST RANGE: $10K-20K per program

27. SEPARATELY FUNDED [ ] *(Identify Agency)*

28. HAS ITEM 8 APPROVAL BEEN EXPLAINED IN ITEM 16 [ ] YES [ ] NO

29. RELATED MCSL MGT SYS NO. *(If applicable)*

30. DATA REQUIREMENTS REVIEW BOARD ACTION

[ ] APPROVED [ ] DISAPPROVED [ ] OTHER DATE

REMARKS

PROGRAM DMO

APPROVAL AUTHORITY

AFSC FORM MAY 71 40

AFSC—Andrews AFB Md

CONTRACTOR DATA REQUIREMENT SUBSTANTIATION *(CONTINUATION)*

31. IDENTIFICATION *("U" DID PROCESSING ONLY)*

TITLE Aircraft Propulsion Turbine Engine Air Pollution Emission Data

NUMBER

SUBMITTING ACTIVITY HQ AFESC/RDV

IV. JUSTIFICATION

32. STATE WHAT DICTATES REQUIREMENT The AFSC Environmental Protection Committee has recognized the need for inclusion of engine air pollutant emissions data as part of the Data Management Program. Collection of emission data prior to beddown of new aircraft of relocation of older aircraft is mandatory in order to prepare environmental statements and assessments. The incorporation of emission data into the Data Management Program is also consistent with AFR 19-2 which states that environmental effects are to be identified by the unit responsible for the action and included at the earliest possible moment in the planning process.

33. State Use of Data

Data will be used to prepare environmental assessments and/or statements prior to beddown of new aircraft or relocation of older aircraft.

34. IDENTIFY SPECIFICALLY WHO WILL USE DATA

The unit responsible for the beddown or relocation of aircraft.

35. DESCRIBE IMPACT IF NOT OBTAINED If these data are not part of the manufacturer's data package, they must be collected under separate contract or measurement programs. Such programs are costly and often cannot be completed within the necessary time limits. Since engine manufacturers have emissions measurement capability, they should be able to complete the measurement programs in a timely manner at minimum cost.

36. STATE WHY STANDARD DID WILL NOT SATISFY *("U" DID PROCESSING ONLY)*

There are no standard DIDs which address aircraft turbine engine air pollution emission data.

V. SUPPORTING "U" DID INFORMATION *("U" DID PROCESSING ONLY)*

37. COORDINATION	38. BURDEN *(Cost Range and Frequency)*
DMO	$10-$20K per report for each aircraft engine development and procurement program.
FUNCTIONAL STAFF	
MGT SYS CONTROL	
REMARKS	**39. RECOMMENDED APPLICATION LIMITATION** General use by all - include in ADL

VI. DISPOSITION

IDMO	CDMO
☐ APPROVED ☐ DISAPPROVED ☐ FOR ADL ☐ OTHER *(Explain)*	☐ APPROVED ☐ DISAPPROVED ☐ FOR ADL ☐ OTHER *(Explain)*
DATE	DATE

INITIAL DISTRIBUTION

HQ TAC/SGPA	1
HQ SAC/SGPA	1
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HQ PACAF/SGPE	1
HQ MAC/SGPE	1
HQ AAC/SGB	1
HQ AFLC/SGB	1
Federal Aviation Admin	1
HQ TAC/DEEV	1
HQ SAC/DEPV	1
HQ USAFE/DEPV	1
HQ MAC/DEEE	1
HQ ATC/DEPV	1
AMRL/CC	1
USAFSAM/CC	1
ASD/CC	1
AFOSR/CC	1
AEDC/CC	1
USAFCRE/WR	1
USAFCRE/CR	1
USAFCRE/ER	1
DTIC/DDA	2
HQ AFSC/SGB	1
NEPSS	1
AEDC/DOTR	1
HQ USAF/LEEVP	1
OASD/(I&L)EES	1
AFATL/DLODL	1
EPA/ORD	1
AFWAL/POSF	1
AFWAL/POTC	1
ASD/DES	1
HQ AFESC/RDVC	10
HQ AFSC/DLW	1
AVCO-Lycoming	1
Pratt & Whitney Acft Group	1
Airesearch Manufacturing Group	1
NAFEC/ANA-420	1
Detroit Diesel Allison Div	1
AESO/CODE 64270	1
AMD/RD	1
NASA Lewis Research Center	1
AEDC/DDTR	1
EPA/SDSB	1
EPA	1
AVRADCOM/DAVDL-ATL-ATP	1
Oregon State University	3
General Electric Aircraft Engine Group	1
Pratt & Whitney Acft Corp	1
ANGSC/DEV	1
ASD/YZEQ	1
HQ AFESC/DEV	1
HQ PACAF/DEMU	1
Naval Air Propulsion Center	1
HQ USAF/LEEV	3
HQ USAF/SGPA	1
OSAF/MIQ	1
OSAF/OI	1
AFIT/LGSM	1
AFIT/Library	1
AFIT/DE	1
USN Chief, R&D/EQ	1
OEHL/CC	2
HQ AFESC/DEV	1
USAFSAM/EDE	2
HQ AFISC	2
AUL/LSE 71-249	1
HQ USAFA/Library	1
HQ AFESC/TST	1
OL-AD; USAF OEHL	1
USAF Hospital, Wiesbaden	1
HQ AAC/DEV	1
HQ AFLC/DEPV	1
HQ USAF/SGES	1
EPA/ORD	1
HQ AFSC/SGPA	1

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