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LEVEL II

AIR QUALITY ANALYSIS OF POSSIBLE F-15 AND A-10 AIRCRAFT ENGINE MODIFICATIONS TO REDUCE POLLUTION

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JUNE 1978

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CIVIL AND ENVIRONMENTAL ENGINEERING DEVELOPMENT OFFICE

(AIR FORCE SYSTEMS COMMAND)

TYNDALL AIR FORCE BASE

FLORIDA 32403

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A-10	Carbon Monoxide	
F-15	Total Hydrocarbons	
F-100-PW-100	Oxides of Nitrogen	
Air Pollution	Particulate	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Air Force has established goals for the control of aircraft engine exhaust emissions. Neither the F-15 nor A-10 aircraft engines completely meet these goals even though they are much less polluting than the F-4E and A-7 aircraft they often replace. This study compares air quality impacts of all four aircraft and shows the relative improvements possible with a modification/retrofit program for the F-15 and A-10 aircraft. Significant improvement is obtainable only for the A-10 hydrocarbon emissions. A five step analytical

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methodology is presented and can be adapted to nearly any aircraft related air quality assessment problem.

PREFACE

This study was accomplished at the request of the Environmental Planning Division, Engineering and Services Directorate, Headquarters USAF to determine what environmental benefits could be obtained by modifying state-of-the-art turbine engines to bring them in compliance with recently developed turbine engine emission goals. The study was accomplished using the Air Quality Assessment Model, developed by the Air Force for the specific purpose of predicting air pollutant concentrations in the vicinities of airports. The results and recommendations do not represent Air Force policy but will be considered in the evaluation of possible engine modification programs to reduce emissions.

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

This report is approved for publication.

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SECTION I

INTRODUCTION

Goals for the control of Air Force aircraft engine exhaust emissions were established by the Secretary of the Air Force on 11 June 1975 (Reference 1) and are now officially sanctioned in Air Force Regulation 19-1. They are in keeping with the intent of the Clean Air Act Amendments of 1970 and with the fact that EPA has promulgated standards for commercial aircraft. The Air Force goals apply to all turbofan, turbojet, and turboprop engines beginning development after 11 June 1975. The goals will be applied to engines in development as of that date and in substantial production after 1 January 1979 through modification/retrofit programs if cost-benefit studies indicate retrofit is warranted (Reference 1). In this report the environmental benefits of modifying or retrofitting the engines used to power F-15 and A-10 aircraft will be analyzed.

A second report function is to present a five step procedure applicable to nearly any aircraft operation air quality assessment. This methodology can be applied with a desk calculator, the "Aircraft Emissions Estimator" (ACEE) report (Reference 2), and the "Compilation of Emission Factors" report (Reference 3). It may be used with the Air Quality Assessment Model (AQAM, Reference 4) when numerous sources must be considered or when greater accuracy is required.

Throughout this study, all measured source emissions of total hydrocarbons (THC), oxides of nitrogen (NO_x), oxides of sulfur (SO_x) and particulate matter (PM) are assumed to yield reactive hydrocarbons (RHC), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and total suspended particulate matter (TSP) pollutants, respectively, when dispersed in the ambient air.

SECTION II

BACKGROUND

The assessment of environmental impact of complex emission sources on surrounding air quality has never been an easy or straightforward task. Air quality assessments of environmental pollution should be made at those locations generally accessible to the public. However, since pollution levels are caused by the collective actions of many and sometimes distant emission sources, determination of a clear cause and effect relationship is difficult. The five phase procedure presented in this study permits the problem to be evaluated from several viewpoints. These varying prospectives make cause and effect relationships more apparent. The phases and their merits are listed in Table 1. Since each phase has both advantages and disadvantages, final conclusions must be based on all the data available. Phases I and II provide preliminary procedures. This study includes all five phases, but many assessments can end with the second phase if these two "screening" techniques indicate there is no significant environmental impact.

TABLE 1. FIVE PHASE ANALYSIS PROCEDURE

PHASE	ADVANTAGE	DISADVANTAGE
1. Compute Emissions Per Unit Operation	- Obtained from documented sources (References 2 and 3) - Easiest and most accurate of 5 phases	- Little meaning without Phase 2
2. Compute Emission Changes	- Easy to interpret (Results have an intuitive meaning)	- Not a measure of "impact"
3. Compute Hourly Air Quality Concentrations	- Can be related to some air quality standards ("Worst case" hourly meteorological conditions used to correspond to peak hourly standards)	- Difficult interpretation of results
4. Compute Pollutant Standards Indices	- Best measure of "impact" results most meaningful to laymen.	- New technique, not fully accepted
5. Analyze Cost Effectiveness of Control	- Used for control feasibility determination	- "Cost of control" difficult to estimate

SECTION III

USAF AIRCRAFT EXHAUST EMISSION GOALS

Aircraft exhaust emission goals were developed in 1974 for carbon monoxide, hydrocarbons, oxides of nitrogen and smoke (Reference 5). Oxides of sulfur (SO_x) goals were not developed since they are a function of fuel specification, not engine design, and sulfur emissions are generally considered insignificant from aircraft sources. The numerical values of these goals were established by evaluating what was then considered the best available technology (Reference 5). Separate goals were established for engines in substantial production after 1979 and after 1981. For simplicity, this study considered only the more stringent 1981 goals. A reprint of the USAF goals is included in Appendix A.

Tables 2 and 3 summarize the current A-10 and F-15 aircraft emissions as calculated from measurements taken at the exit plane of the engine exhaust (Reference 2). The exhaust emission levels required to meet the 1981 emission goals are also shown.

Complete computations are presented in Appendices B and C. The A-10 aircraft considerably exceeds the goals for CO and THC. CO from Air Force aircraft is of little consequence, however, as shown in previous work (Reference 6). The F-15 aircraft slightly exceeds the goals for NO_x and smoke.

TABLE 2. A-10 AIRCRAFT ENGINE EMISSIONS: CURRENT AND WITH 1981 GOALS

Power Setting	Fuel Flow (kg/s/eng)	Emission Index* (g Pollutant/kg Fuel) THC	NO_x	PM	CO
1. Current A-10 Emissions**					
Idle	0.049	32.0	2.0	0.04	106.0
Approach	0.157	0.6	5.8	0.02	8.3
Military	0.323	0.1	10.0	0.05	2.3
2. A-10 Emissions After 1981 Goals (Shown only when lower than current emissions)					
Idle	--	3.0***	--	--	30.0***

* SO_x Emissions = 1.0 g per kg JP-4 for all modes.

** Reference 2.

*** Based on a 99% Combustion Efficiency Goal (Reference Appendix B).

TABLE 3. F-15 AIRCRAFT ENGINE EMISSIONS: CURRENT AND WITH 1981 GOALS

Power Setting	Fuel Flow (kg/s/eng)	Emission Index* (g/kg Fuel) THC	NO_x	PM	CO
1. Current F-15 Emissions** (Smoke Number, SN, also shown)					
Idle	0.179	3.2	3.3	0.12 (SN = 5.7)	24.0
Approach	0.378	1.9	6.7	0.271 (SN = 28)	5.8
Military	1.301	0.1	27.0	0.34 (SN = 31)	0.5
Afterburner	5.797	0.01	3.1	0.15	4.0
2. F-15 Emissions After 1981 Goals (Shown only when lower than current emissions. Smoke Number, SN also shown)					
Approach	--	--	--		--
Military	--	--	21***	.18 (SN = 21)	--

* SO_x Emissions = 1.0 g per kg JP-4 for all modes.
** Reference 2
*** Reference Appendix C.

SECTION IV

ANALYSIS OF RESULTS

Phase I. Emissions per Unit Operation. Computing the pollutant emissions per operational cycle is the first task in any aircraft air quality assessment. To compute these emissions for this screening procedure measured emission factors, Tables 2 and 3, were combined with corresponding fuel flows and aircraft operational data to determine the emissions for a single LTO (landing and takeoff cycle). Operational parameters, such as time in taxi, etc. were treated specifically for each aircraft type but for only one typical taxi-runway arrangement. The input data was then processed with the Air Quality Assessment Model (AQAM) for virtually every aircraft used by the Air Force. The compliation of results is called the Aircraft Emissions Estimator (ACEE) and is described elsewhere (Reference 2). All emission and dispersion analyses for this report were done with ACEE and a desk calculator without additional AQAM runs on a large computer. If ACEE is not considered sufficiently accurate for a specific study, emissions for other landing and takeoff cycles may be computed at little cost.

Emissions per landing and takeoff (LTO) cycle taken from the ACEE report are shown in Figure 1. Present A-10 and F-15 aircraft are compared with ones they might typically replace, the A-7 and F-4E aircraft. The newer aircraft have lower emissions for all pollutants. While lower emissions are expected for CO, THC, and particulate matter (PM), the lower value of NO_x emissions from newer aircraft is not expected because newer engines are known for their high NO_x emissions. The NO_x emissions per LTO are lower for newer aircraft in spite of higher emissions per unit of fuel because of the much better aircraft performance. New aircraft spend much less time on the runway than older ones and this more than compensates for the higher emission factors. This conclusion serves to emphasize the need to make a complete emissions analysis and not stop at a preliminary step such as comparing only emissions per unit of fuel.

The effects of engine exhaust emission goals on aircraft emissions are also shown in Figure 1. They were computed by modifying the emissions of each applicable aircraft operating mode in the LTO cycle by the 1981 goals summarized in Table 3.

Phase II. Emission Changes. Annual emissions of a typical F-4E and A-7 aircraft wing were computed by multiplying the emissions per LTO by an assumed 15,000 LTO's per year. Results are presented in Figure 2 as the "Baseline" condition. The percent changes resulting from replacing one F-4E with one F-15 aircraft and one A-7 with one A-10 aircraft are also shown. The third condition in Figure 2, the percent change due

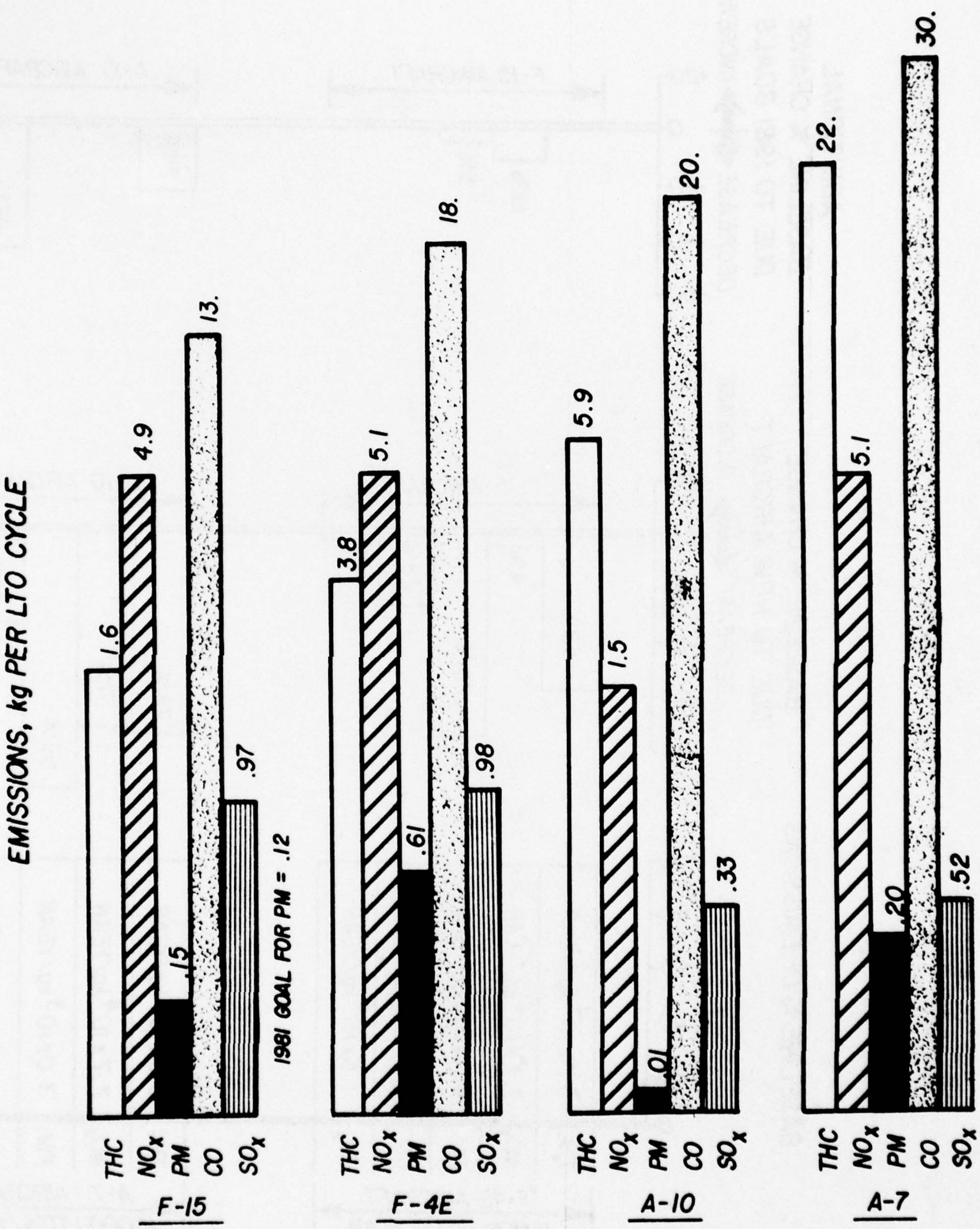

Figure 1. Aircraft Emissions per Landing and Takeoff (LTO) Cycle

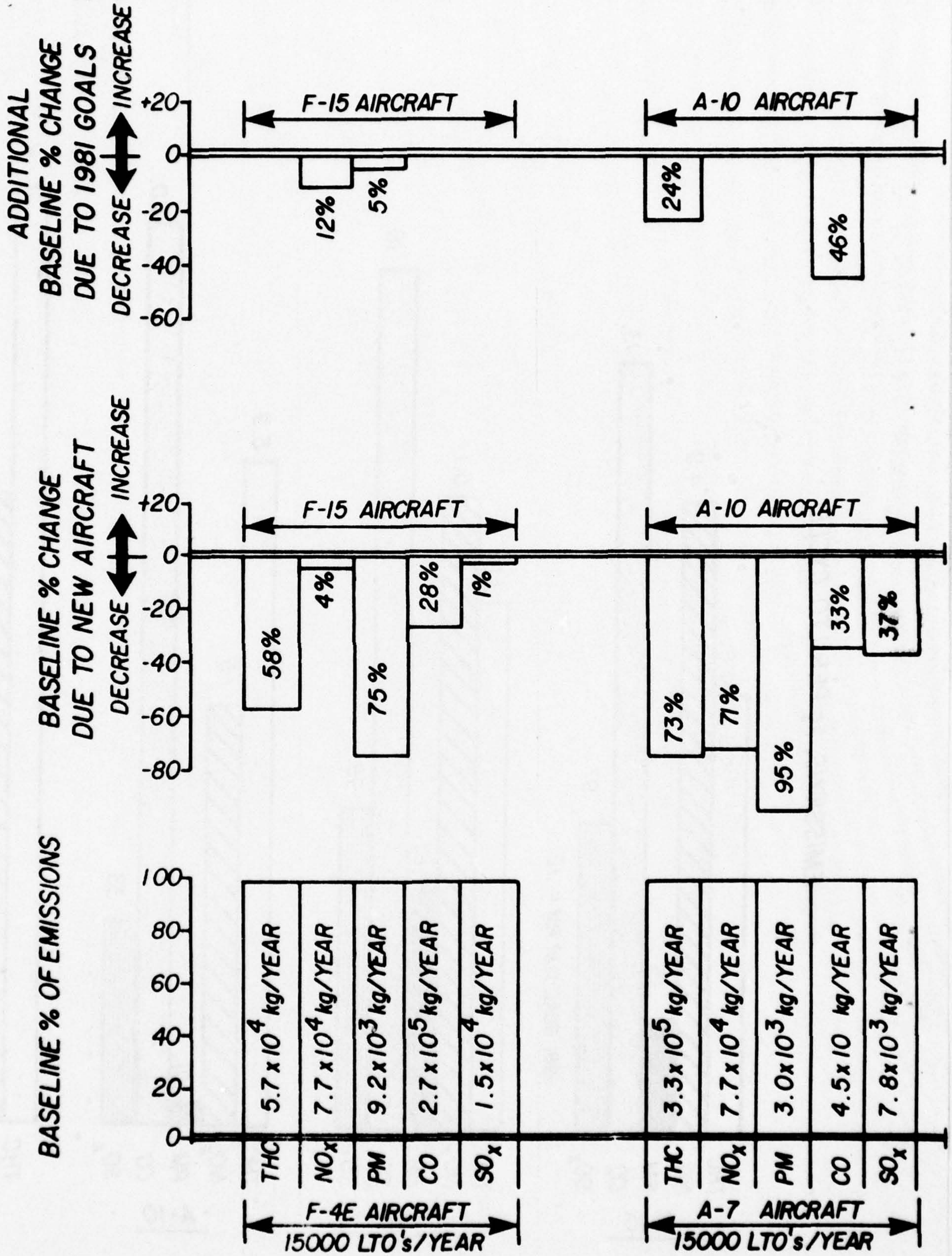

Figure 2. Emission Decreases with New Aircraft and 1981 Goals

to 1981 goals, was computed using the data in Figure 1. Additional emission decreases from the current engine to a modified/retrofitted engine are shown relative to the baseline condition. The net total reduction is the sum of both percent changes (e.g. switching from an A-7 aircraft to an A-10 aircraft which meets 1981 goals will reduce the hydrocarbon emissions by 97 percent). Figure 2 indicates substantially greater improvements due to switching to the newer A-10 and F-15 aircraft than from a modification/retrofit program required to meet the 1981 goals.

Phase III. Hourly Air Quality Concentrations. Hourly average ambient air quality concentrations were estimated using normalized data from the ACEE report (Reference 2). Results are in Table 4. "Worst case" meteorological conditions were used rather than more typical conditions since the ambient air quality standards are generally designed to prevent even rare occurrences of high concentrations. A high activity rate of 15 takeoffs and 15 landings per hour was assumed. This higher than normal activity rate offsets the fact that other aircraft types are assumed not to fly within the hour. Concentrations closer than 5 km from aircraft takeoff cannot be estimated using the ACEE technique because of its generalized runway, taxiway and parking area geometries. Higher resolution models, such as AQAM would be needed for this purpose.

Phase IV. Pollutant Standards Index (PSI). The US Environmental Protection Agency developed the PSI technique to provide a readily understandable way to relate air quality concentrations to possible health and welfare effects (Reference 7). The index has been adapted to aircraft environmental impact analysis to facilitate comparison of different pollutants (Reference 6). The annual NO_x standard of 100 $\mu g/m^3$ was set equal to a PSI level of 50 units since there are currently no short-term NO_x ambient standards. While this technique is very new and not yet accepted, it is better suited to compare various pollutants and for a simple measure of "impact" than any other available technique.

The conversion of hourly ambient concentrations to the PSI scale is shown in Figure 3. A PSI level of 100 is an estimate of the air quality threshold above which there is greater risk of health damage. RHC and NO_x are the only pollutants of significance. TSP, CO and SO_2 levels are less than one percent of values which are judged to cause "impact", (i.e., below a PSI of one). Even under restrictive meteorological conditions, RHC and NO_x levels from the A-10 and F-15 aircraft are of marginal concern. Figure 3 shows that 1981 goals would not appreciably lower the NO_x levels. The benefit from applying the hydrocarbon goals to the A-10 aircraft is weakly supported by data in this study. A reduction of PSI levels from 12 to 1.2 is a large percentage decrease but will only have significant environmental benefits in areas where decreasing hydrocarbon emissions will correspondingly decrease high oxidant levels. A major aircraft modification/retrofit action does not appear warranted unless confirmed by more detailed, site specific studies including all emission sources within the air quality regions of concern.

TABLE 4. AIR QUALITY CONCENTRATIONS*
(15 LTO Cycles per hour, $\mu g/m^3$)

	RHC	NO_2	TSP	CO	SO_2
A-10 @ 5 km	23 (2.3)**	6.6	<.08	77(25)	1.4
A-10 @ 10 km	21(2.1)	4.1	<.08	70(22)	0.9
F-15 @ 5 km	9.6	28(25)	1.1(.8)	68	6.6
F-15 @ 10 km	7.4	17(15)	0.6(.5)	54	4.2

*Assumes "worst case" meteorology of 1m/s winds," F "Stability, and 115m mixing depth

**( ) = After exhaust emission goals

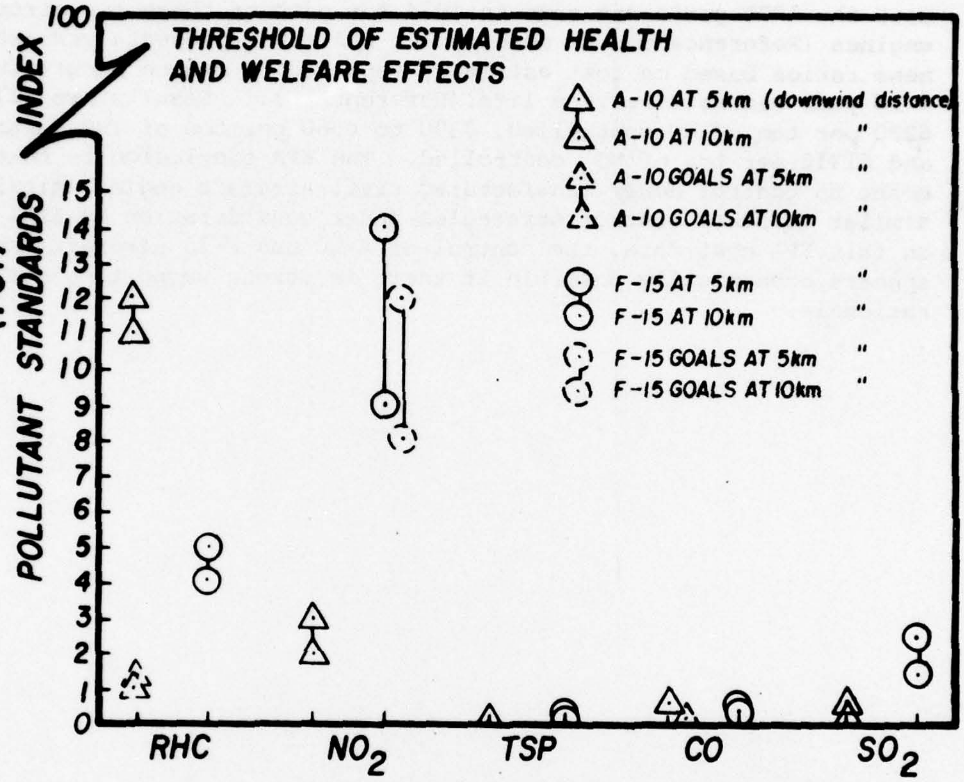

Figure 3. PSI Levels from 15 LTO's per Hour

Phase V. Cost Effectiveness of Control. The costs of controlling the engines in the A-10 and F-15 aircraft to levels sufficient to meet the 1981 goals are not well defined. A rough estimate of $10 million to meet the 1979 goals was made in 1974 for each of these two aircraft engines (Reference 5). A more recent EPA study presents cost-effectiveness ratios based on cost estimates supplied by engine manufacturers and a 15 year aircraft service life. (Reference 8). Results are $170 to $220 per ton of CO controlled, $390 to $560 per ton of THC controlled, and $1316 per ton of NO_x controlled. The EPA conclusion is that the costs to control newly manufactured civil aircraft engine emissions are similar to other control strategies under consideration by EPA. Based on this EPA cost data, the control of A-10 and F-15 aircraft engines appears economically possible if there is strong supporting environmental rationale.

SECTION V

CONCLUSIONS

The current A-10 aircraft engine exceeds the carbon monoxide and hydrocarbon exhaust emission goals by a large margin (Table 2).

The current F-15 aircraft engine exceeds the oxide of nitrogen and smoke emission goals by a small margin (Table 3).

Both the F-15 and A-10 aircraft are significantly less polluting than the F-4E and A-7 aircraft that they typically replace (Figure 1).

Replacement of older aircraft with newer aircraft has greater environmental benefits than the modification/retrofit of newer aircraft to meet the 1981 goals (Figure 2).

Air Quality relationships indicate that concentrations five kilometers and more from the aircraft takeoff roll are well below levels of likely air quality impact (Figure 3).

Modification/retrofit of A-10 aircraft engine to meet the hydrocarbon goal is the most environmentally beneficial action of those analyzed.

A modification/retrofit program for the A-10 and F-15 aircraft engines does not appear justified from data and analyses in this study. While such a program would be possible, it would cause a very slight improvement to local air quality.

APPENDIX A

USAF AIRCRAFT EXHAUST EMISSION GOALS

DEPARTMENT OF THE AIR FORCE
WASHINGTON 20330

OFFICE OF THE SECRETARY

11 June 1975

MEMORANDUM FOR ASSISTANT SECRETARY OF THE AIR FOFCE (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) & 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.

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 graphically 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.

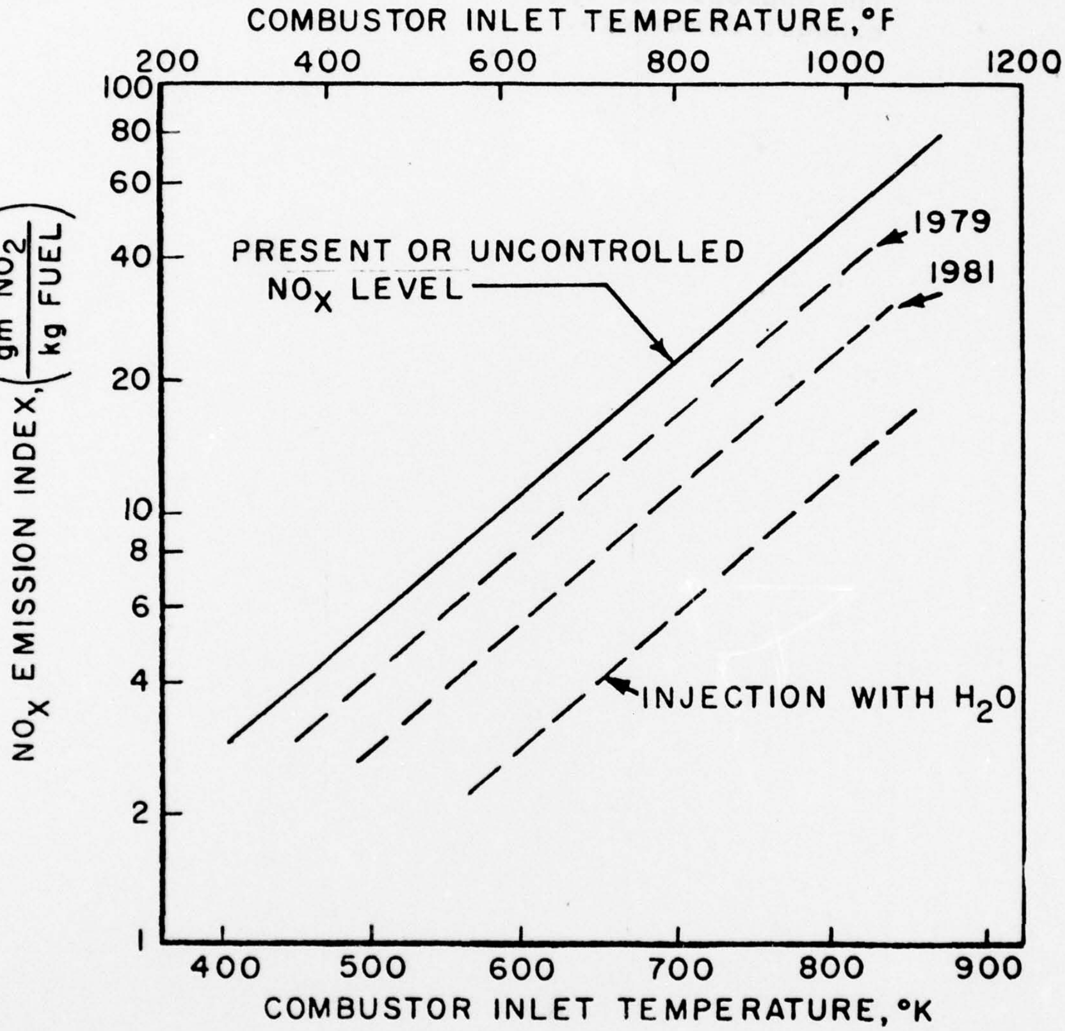

Figure 1. Air Force No_x Goals.

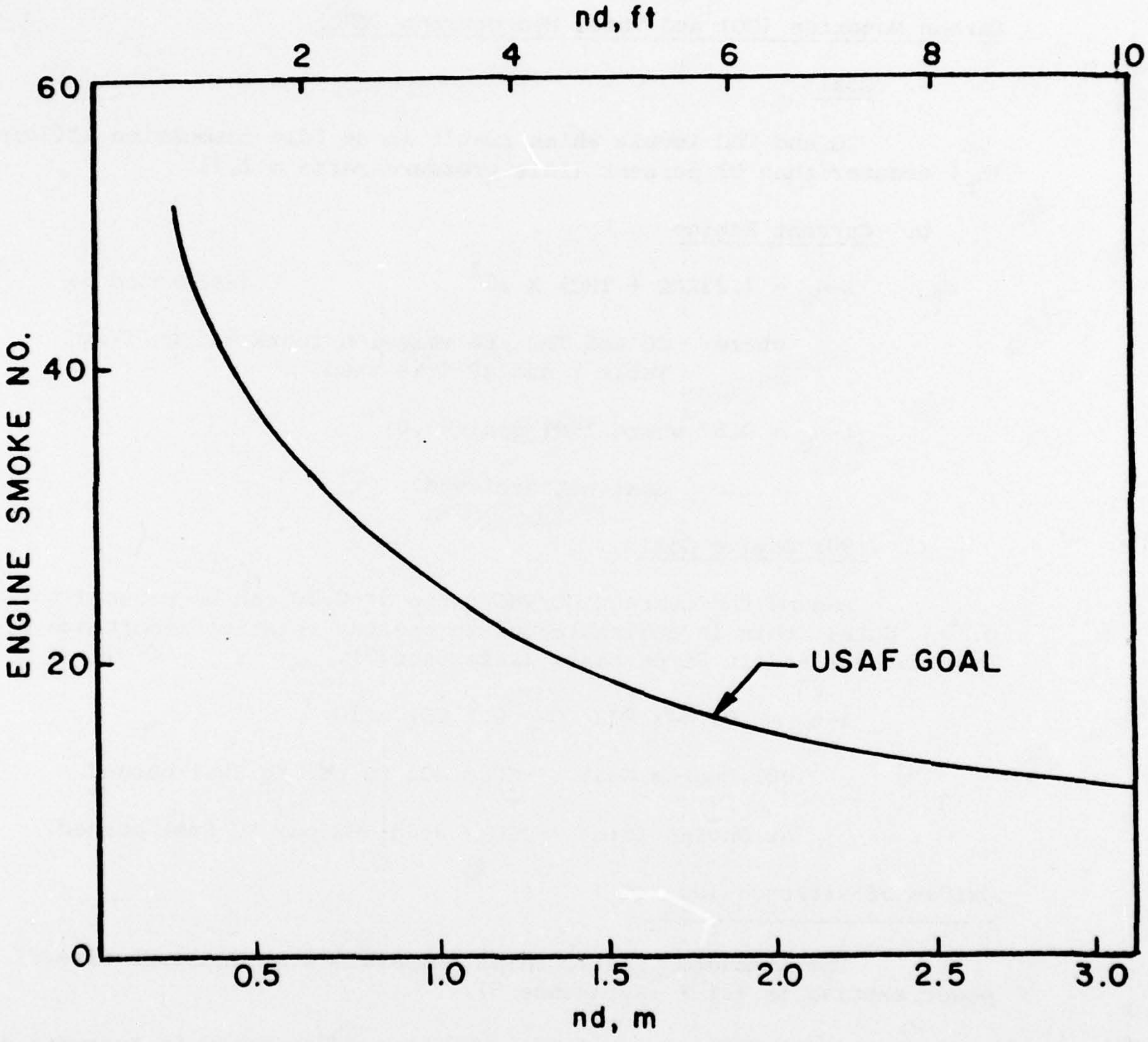

Figure 2. Air Force Smoke Goals.

APPENDIX B

CALCULATION OF A-10 AIRCRAFT ENGINE GOALS FOR 1981

Engines Used

Two TF-34-GE-100 engines

Carbon Monoxide (CO) and Total Hydrocarbon (THC)

a. Goal

CO and THC levels which result in an idle combustion efficiency (η_b) greater than 99 percent (idle pressure ratio = 2.7).

b. Current Engine

$$1-\eta_b = (.232CO + THC) \times 10^{3} \qquad \text{(Reference 5)}$$

where: CO and THC are emission index values from Table 1 and JP-4 is used.

$1-\eta_b = 0.57$ where 1981 goal = .01

Goal not achieved.

c. 1981 Engine Goal

Assume the current CO/THC ratio of 0.30 can be reduced to 0.10. Note: this is desirable due to greater relative importance of hydrocarbons at Air Force bases (Reference 7).

$$1-\eta_b = .01 = (.232\ CO + 0.1\ CO) \times 10^{-3}$$

1981 Engine Goal CO = 30g CO per Kg Fuel burned.

at Engine Idle THC = 3.0g THC per KG Fuel burned.

Oxides of Nitrogen (NO_x)

The combustor static inlet temperature at sealevel takeoff power setting is 721°K (Reference 5).

The 1981 NO_x goal is currently met as shown in Appendix A, Figure 4.

Smoke

The engine exhaust diameter is 0.43 meters (Reference 9). SAE smoke numbers of 7.8, 2.4, and 3.6 have been measured in the military, approach, and idle power settings respectively (Reference 11).

The 1981 smoke goal is currently met as shown in Appendix A, Figure 5.

APPENDIX C

CALCULATION OF F-15 AIRCRAFT ENGINE GOALS FOR 1981

Engines Used

Two F-100 engines (Pratt and Whitney Aircraft).

Carbon Monoxide (CO) and Total Hydrocarbon (THC)

a. Goals

CO and THC levels which result in an idle combustion efficiency (η_b) greater than 99.5 percent (idle pressure ratio = 4.4).

b. Current Engine

$1-\eta_b = (.232\ CO + THC) \times 10^{-3}$ (Reference 5)

where: CO and THC are emission index values from Table 2 and JP-4 is used.

$1-\eta_b = .0038$ where the goal = .005

1981 goal is met with current engine.

Oxides of Nitrogen (NO_x)

The combustor static inlet temperature at a sea-level takeoff power setting is 800°K (Reference 5).

The 1981 goal is 21g NO_x per Kg Fuel and is not met by the current engine as shown in Appendix A, Figure A-1.

Smoke

The engine exhaust diameter is 0.635 meters (Reference 5). SAE smoke numbers of 31, and 5.7 have been measured in the military, and idle power settings, respectively (Reference 10). A smoke number of 17 is estimated for the approach mode.

Smoke levels from the current engine are above the 1981 goals of 21 as shown in Figure A-2.

A mass emission rate of 0.18 grams per kg fuel corresponds to a smoke number of 21 using the conversion procedure described in Reference 2.

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US Army Aviation Research and Development Command	1
Environmental Protection Agency (Mobile Sources)	1