6. EMISSIONS DATA BY CATEGORY OF ENGINES

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INTRODUCTION

Beginning in 1967, Congress enacted a series of laws which added environmental considerations to the civil aviation safety, control, and promotional functions of the FAA. This legislation was in response to the growing public concern over environmental degradation. Thus, the FAA is committed to the development, evaluation, and execution of programs designed to identify and minimize the undesirable environmental effects attributable to aviation.

In accordance with the Clean Air Act Amendments of 1970, the EPA established emission standards and outlined test procedures when it issued EPA Rule Part 87 in January 1973. The Secretary of Transportation and, therefore, the FAA was charged with the responsibility for issuing regulations to implement this rule and enforcing these standards.

Implementation is contingent on FAA's finding that safety is not derogated by whatever means is employed to achieve the standard. It is for this reason that FAA undertook a program, subsequent to the issuance of the EPA Emission Standards in July 1973, to determine the feasibility of implementation, to verify test procedures, and to validate test results. Based on this background, the FAA will be in a position to establish appropriate regulation and to enforce compliance with the regulation.

As many of you are aware, the FAA stated to the EPA prior to EPA's promulgation of standards that the exhaust emission levels dictated by these standards for new aircraft piston engines were beyond those which were likely to be feasible without considerable engine modification. Other comments by FAA are part of the rule docket. The point of my reference at this time to the history on the development of the standards is simply to point out the original concerns of FAA.

As you will note from the program results to be presented, FAA has examined the operation of one each of several engine types using "near-term" techniques of (1) lean mixture fuel scheduling and (2) variable ignition timing. Coordination with NASA on this program lead to the understanding that NASA would investigate the technological feasibility of more extensive engine modifications such as (1) variable valve timing, (2) improved combustion chamber design, (3) higher energy ignition systems, and (4) improved fuel dispersion and distribution.

With regard to the "near term," particularly the lean mixture fuel scheduling, FAA may, to a degree, quantify the potential effect on safety by identifying the effect of leaning on engine acceleration, detonation, cylinder head temperature, and hesitation. The effect on safety which has not been quantified and which may not be possible to quantify - but which must be considered - is whether or not the modifications which may be made to achieve reduced emissions will reduce a safety-factor margin which history has shown results in a particular engine failure rate, pilot error rate, or in overall terms on accident rate. We would prefer to improve these margins and cannot chance degrading them. In view of the testing to date, we are not in a position to present any agency conclusion as to the feasibility of fuel-mixture leaning on reducing aircraft safety.

The additional information which we will receive today on the results of flight test work by the airframe manufacturers is of particular interest to us, and further provides a basis for understanding the technological feasibility of the fuel-leaning technique.

The papers presented by NASA will give us insight into other techniques which may be feasible approaches to reducing engine emissions. The FAA will proceed to assess what further actions should be undertaken in order that the mandate of making aviation compatible with the environment is achieved.

When the FAA began the investigation of piston engine exhaust emissions in fiscal year 1973, there was concern that the actions indicated as necessary to comply with the EPA emission standards, such as operating engines at leaner mixtures, might compromise safety.

We, therefore, structured our efforts to first identify if such actions might result in hazardous operating conditions. Our contractors, Lycoming and Continental, selected engines that they considered typical of their production; tested them as normally produced to establish where the emissions were with respect to the EPA requirements; and then altered the fuel schedule and ignition timing to attempt to reach the EPA limits and retested them.

In the event that hazardous operating conditions were indicated by these tests, independent verification of data would be necessary. It was decided that duplication of the manufacturer's tests at NAFEC, the FAA facility near Atlantic City, New Jersey, would provide the needed verification.

Followup efforts were planned as part of this program; that is, if hazards were encountered in the first phase of our work, then corrective measures that might achieve compliance with the EPA values while maintaining safety would be investigated. It was agreed that any such corrective measures investigated by FAA would be the type that would involve minimal modification to the design of the engines. The more complex investigations, which rely on technology improvements, were to be the responsibility and goal of the parallel NASA efforts.

We have tested the eight engines listed in figure 6-1 as of this date. We are confident of the data on six engines; two of the engines, the O-200-A and the IO-320-D, have to be retested. The TIO-540-J and CTSIO-520-K have yet to be tested by FAA, although the manufacturers have completed their work. We had estimated completion of the first phase, or Baseline and Hazards Determination as it is referred to, in 18 months. The slippage in our schedule is attributed primarily to a number of problems associated with acquiring reliable data. In addition, the problem of correlating such data between three separate test facilities - where knowledge of principles, test techniques, and data analysis had to be developed as the work progressed - caused additional slippage.

It has been unfortunate that in this particular case, when information concerning safety is being gathered to form the basis for a regulatory posture and a fixed deadline for enforcement is being approached, valuable time had to be used in investigating and solving such test problems.

The paper that follows will describe the results of our testing and present the analyses of that which has been completed. While we are still in the first phase, we feel there is some evidence of certain trends.

As expected, we find the engines cannot now demonstrate compliance with the EPA limits in an as-produced condition. The rich mixtures cause, in most cases, the carbon monoxide limit to be exceeded by about 100 percent. In the case of the turbocharged engine, the hydrocarbon limit was also exceeded by about 100 percent. As expected, the engines produce sufficiently low levels of nitrogen oxides as to be acceptable.

Our test-stand investigations have shown the emission levels can be substantially reduced by leaning in only the approach and taxi modes. Extending the leaning operation such that climb is at "best power" gives results where 5 or 6 engines are below the limits and the 6th, the TSIO-360-C, is close. However, achieving these levels is not without problems. Instances of poor acceleration from the taxi power setting and from approach power were encountered. Problems of this sort could represent hazardous operating conditions. The use of possible corrective measures at the taxi condition, such as momentary fuel enrichment, appears to be within the present level of technology.

Also encountered was an instance where the maximum cylinder head temperatures of the TSIO-360-C would have been exceeded on a 100° F day. Increasing the test stand cooling flow from 3.5 inches of differential pressure (ΔP) to 5.5 inches ΔP held the limit. But, whether this is realistic or not relative to aircraft installations has not been determined.

These results must be considered in light of the following unknowns:

(1) Engine-to-engine variability has yet to be considered. In the papers to follow (both NAFEC and engine manufacturers), discussions of the effects of the rich and lean production limits of the fuel system will show a part of this variability. These, coupled with the other manufacturing tolerances of the engine, are important.

(2) Aircraft type installation-to-installation effects can govern how each engine must be adjusted. Furthermore, there are installation tolerances associated with aircraft of the same type. The industry papers that follow are expected to again point out that the impact of this variable cannot be ignored and has not yet been investigated.

(3) The requirement of continued compliance with the standards throughout the life of the engine further impacts what average level of emissions a manufacturer must strive for, and this is another area which at this time represents an unknown quantity.

(4) We do not know what maintenance will do to emission levels. Even minor maintenance such as changing plugs represents an unknown effect.

(5) None of the modifications which have shown promise under our tests have yet been reduced to actual production flight hardware. The step from test stand demonstration to flight demonstration of reliability is a large one, and its significance cannot be overstated.

(6) There has been no assessment to date by FAA as to how much time is necessary to incorporate whatever changes are needed to meet the EPA limits, verify their reliability, and approve them as flight worthy.

Although our knowledge of where we stand in piston engine emissions has been vastly increased and our knowledge of what is needed is growing, it is far too early to make definitive statements about whether general aviation engines, either as a type or a class, can or cannot comply with the EPA limits. We are expanding our program to include collection of information on four of the six items mentioned. The assessments of production hardware flight performance and time required to achieve compliance are important, but both rely on knowledge of the type of fix envisioned, and as such will have to be addressed later. We feel this expanded program will require the investigations to proceed well into 1979.

A discussion of the emission test data and of the analysis follows.

TYPES OF TESTS CONDUCTED

The FAA program obtained exhaust gas pollutant emissions data under test stand conditions for the following:

(1) Full-rich baseline test (7-mode cycle)

(2) Lean-out tests for each power mode

(3) Different spark settings

The test data were also used to create a theoretical 5-mode cycle (no idle) baseline. This paper will be primarily concerned with the analysis of the emissions data in the framework of the theoretical 5-mode cycle. It can be shown that there is no significant difference in the test results produced by data exhibited on the 7-mode cycle or 5-mode cycle (no idle). In most cases, it appears that the 5-mode cycle (no idle) is slightly more conservative for the carbon monoxide pollutant than the 7-mode cycle.

LEAN-OUT EFFECTS

General Comments

Based on an analysis of the factors affecting piston engine emissions, it can be shown that the mode conditions having the greatest influence on the gross magnitude of pollutant levels produced by the combustion process are taxi, approach, and climb as shown in figures 6-2 to 6-10. The 5-mode cycle baseline shows that approximately 99 percent of the total cycle time (27.3 min) is attributed to these three mode conditions. Furthermore, the taxi modes (both out and in) account for slightly less than 59 percent of the total cycle time. The remainder of the time is almost equally apportioned to the approach and climb modes (22 and 18 percent, respectively).

As a result of these time apportionments in the various tests modes, it was decided that an investigation and evaluation of the data should be undertaken to determine which mode(s) has the greatest influence on improving general aviation piston engine emissions. In the subsequent sections of this discussion it will be shown what improvements can be achieved as a result of making lean-out adjustments to the fuel metering device: (1) taxi mode only, (2) taxi and approach modes combined, and (3) leaning-out of the climb mode to "best power."

Effects on Carbon Monoxide (CO) Emissions

The test data obtained under FAA contracts have been evaluated on the basis of leaning-out the taxi, approach, and climb modes while continuing the operation of the test engine(s) at the production rich and lean limits in the takeoff mode. The results of leaning-out under this procedure are shown in bargraph form in figures 6-11 to 6-14.

When the taxi mode only was leaned-out from either the production rich or lean limits to a fuel-air ratio of 0.075 or lower, but not lower than stoichiometric (F/A = 0.067) (see fig. 6-12), CO emissions are reduced approximately 40 to 70 percent. However, adjustments to the taxi mode alone are not sufficient to bring the total 5-mode cycle CO emission level below the federal standard.

The combinations of leaning-out both the taxi and approach modes to a fuel-air ratio of 0.075 or lower will result in additional improvements to CO emissions. In the case of operating the engine at production rich limits for takeoff and climb while operating taxi and approach at F/A = 0.075 or lower, the total 5-mode cycle CO emission level will be reduced an additional 45 to 50 percent as shown in figure 6-13.

When the same lean-out adjustments are applied to the taxi and approach modes with takeoff and climb at the production lean limit of the fuel metering device setting, the CO emission level, for the 5-mode cycle, will vary from 50 percent above the Federal standard to 20 percent below the Federal standard as shown in figure 6-13.

Additional improvements in the total 5-mode cycle for CO emissions can be achieved as shown in figure 6-14 if all engines are adjusted to operate at "best power" fuel-air ratios in the climb mode.

Effects on Unburned Hydrocarbon Emissions

The test data show that all the engines can be leaned-out sufficiently in the taxi mode to bring the unburned hydrocarbon emissions below the federal standard (see figs. 6-15 and 6-16). Additional leaning-out in the approach and climb modes provides added improvements but is not required to produce HC emission levels below the Federal standard.

Effects on Oxides of Nitrogen (NO_x) Emissions

Oxides of nitrogen (NO_x) emissions are not improved as a result of applying lean-out adjustments to the fuel metering devices. In fact, the NO_x levels are at their lowest when the engines are operating full rich as shown in figure 6-17. Test results have shown if all the test modes (takeoff, climb, approach, and taxi) were leaned-out excessively the NO_x emission level would exceed the Federal standard. This latter negative effect was another reason why it was decided to evaluate and study the effects of adjusting/manipulating selected mode conditions rather than adopt the philosophy of adjusting all modes. Another reason for not adjusting the takeoff mode was that the test results showed that the emissions curves for each pollutant (particularly CO) were too flat to make the adjustment effort worthwhile.

Effects on Allowable Maximum Cylinder Head Temperature

One of the major problems that has resulted as an effect of leaning-out general aviation piston engines in order to improve emissions is the increase or rise in maximum cylinder head temperatures.

It has been reported that most general aviation aircraft are designed to operate with cooling air pressure differentials of 4.0 inches of water or less (see fig. 6-18).

Propeller test stand data obtained during this program have shown that some engines will require pressure differentials of from 5.5 to 7.0 inches of water across the engine when leaned-out to meet emission requirements and still remain within cylinder head temperature limits. The engines that have exhibited particular sensitivity in this area are TCM-IO-520-D, TCM TSIO-360-C, and TCM-O-200-A.

Summary of Results - Engines in Experimental Test Stand

Current production aircraft piston engines:

1. They do not meet the EPA carbon monoxide standard for 1979/80.

2. Most engines do not meet the EPA unburned hydrocarbon standard for 1979/80.

3. All unmodified engines meet the EPA oxides of nitrogen standard for 1979/80.

Adjusted (leaned-out) aircraft piston engines:

1. All engine fuel metering devices in the test program could be adjusted on the test stand to reduce their current carbon monoxide ex-

haust emission level, but not necessarily to levels required by EPA standards.

2. All the engines tested could be adjusted on the test stand to reduce their unburned hydrocarbon exhaust emission level below the EPA standard for 1979/80.

Maximum cylinder head temperatures (CHT):

1. Elimination of fuel metering device adjustments in the takeoff mode results in no changes to current maximum CHT limitations.

2. Adjusting the fuel metering device in the climb mode to constant best power operation will result in an increase in maximum CHT.

3. This latter change will also necessitate an increase in cooling air flow (or increase in cooling air pressure differential of approximately 1.0 in. H_2O).

4. No increases beyond the limits in maximum CHT's were measured as a result of leaning-out the approach and taxi modes.

Acceleration Problem: One engine (of six tested) demonstrated an acceleration problem during the NAFEC tests (TCM IO-520-D).

DISCUSSION

Q - L. Helms: Did you, at any time, run any tests in which airflow was coming from the rear of the engine or the side as opposed to the front?

A - E. Becker: No, all front.

Q - G. Kittredge to W. Westfield: What you reported on here today, and they are most impressive, are the results of your phase 1 contracts and internal efforts at NAFEC documenting the emissions behavior of these baseline engines. At one time I know there was a plan to go into a second phase in which you'd look at methods for reducing emissions below the levels that you could achieve by the simple kinds of changes you've just described. Is it still planned to continue with that phase 2 investigation?

A - W. Westfield: To date we do not have any active work with either of the two manufacturers primarily because we have not accepted the suggested changes they have offered to us but the door is still open. We do have underway with the University of Michigan an investigation of the Ethyl Corporation turbulent flow manifold system and we will be reporting on that as soon as we get the data.

Q - F. Monts: You mentioned that with all of the engines the mixture strength could be adjusted to make certain improvements. Was this adjustment done on a scheduled basis or was it done merely by pulling the mixture control back?

A - W. Westfield: There was a mixture adjustment. We reduced fuel flow by increments of 3 pounds of fuel per hour.

TELEDYNE CONTINENTAL MOTORS ENGINES IN THE PROGRAM

ENGINE	DESCRIPTION	START DATE	FINISH DATE
0-200-A	100 HP, CARBURETOR TYPE	01/24/75	03/05/75
10-520-D	300 HP, INJECTOR TYPE	06/27/75	08/01/75
TSI 0-360-C	220 HP, TURBO-INJECTOR TYPE	02/16/76	05/21/76
TIARA-6-285-B	285 HP, GEARED PROP. DRIVE, INJECTOR	07/01/76	08/31/76 (EST.)
GT S10-520-F	435 HP, GEARED TURBO-INJECTOR		

AVCO LYCOMING ENGINES IN THE PROGRAM

ENGINE	DESCRIPTION	START DATE	FINISH DATE
10-320-D	160 HP, INJECTOR TYPE	12/10/74	01/09/75
0-320-D	160 HP, CARBURETOR TYPE	01/14/75	01/15/75
10-360-B	180 HP, INJECTOR TYPE	04/21/75	05/27/75
10-360-A	200 HP, INJECTOR TYPE	09/04/75	12/05/75
0-320-D	160 HP, CARBURETOR TYPE	———	
10-320-D	160 HP, INJECTOR TYPE	———	
T10-540-J	350 HP, TURBO-INJECTOR	———	

Figure 6-1

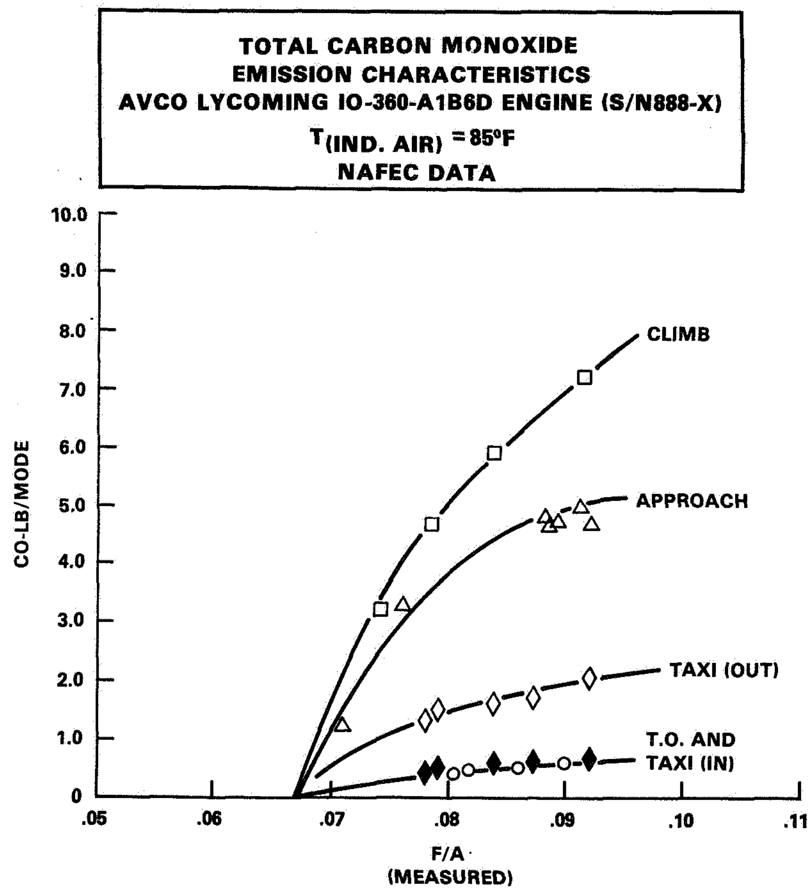


Figure 6-2

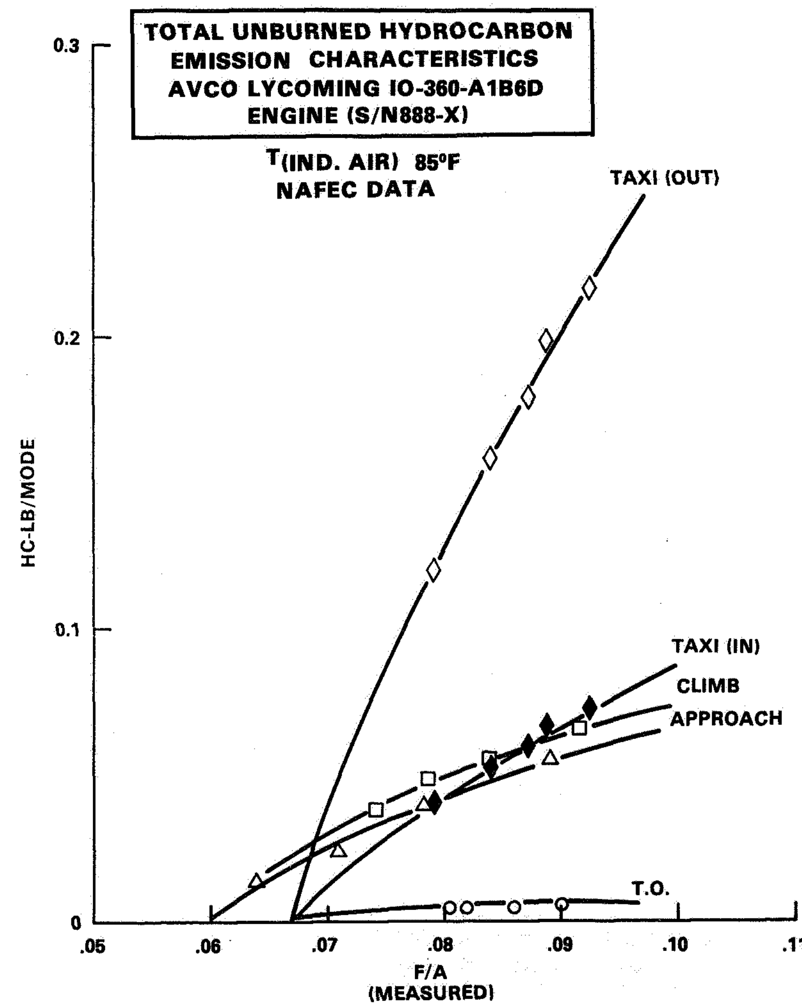


Figure 6-3

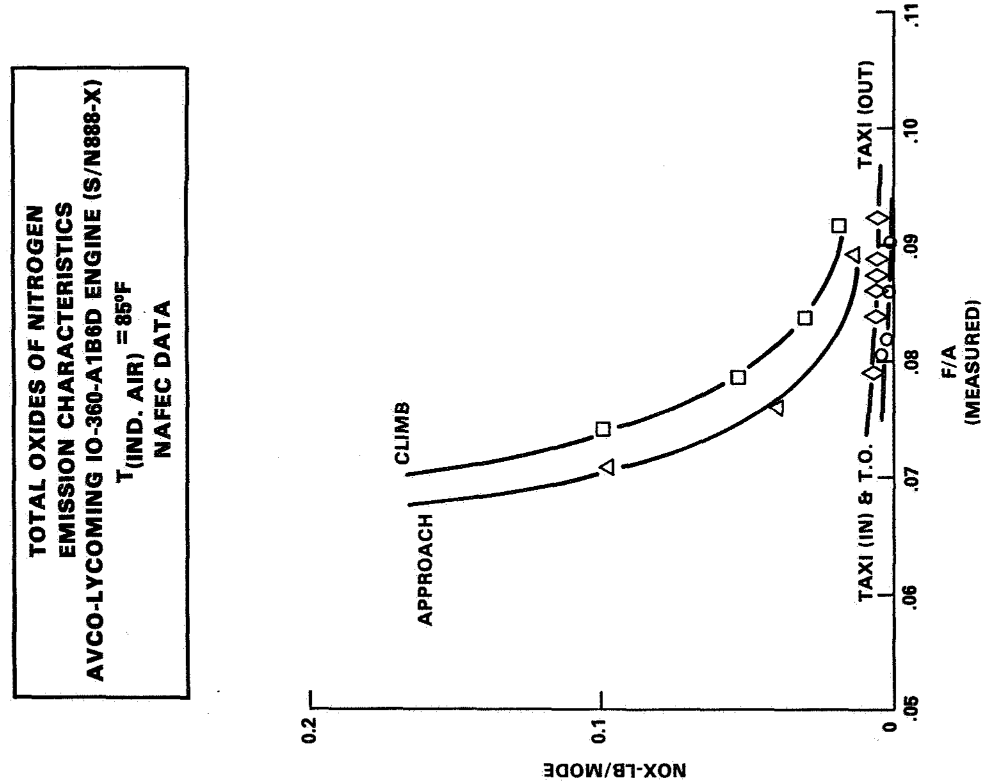


Figure 6-4

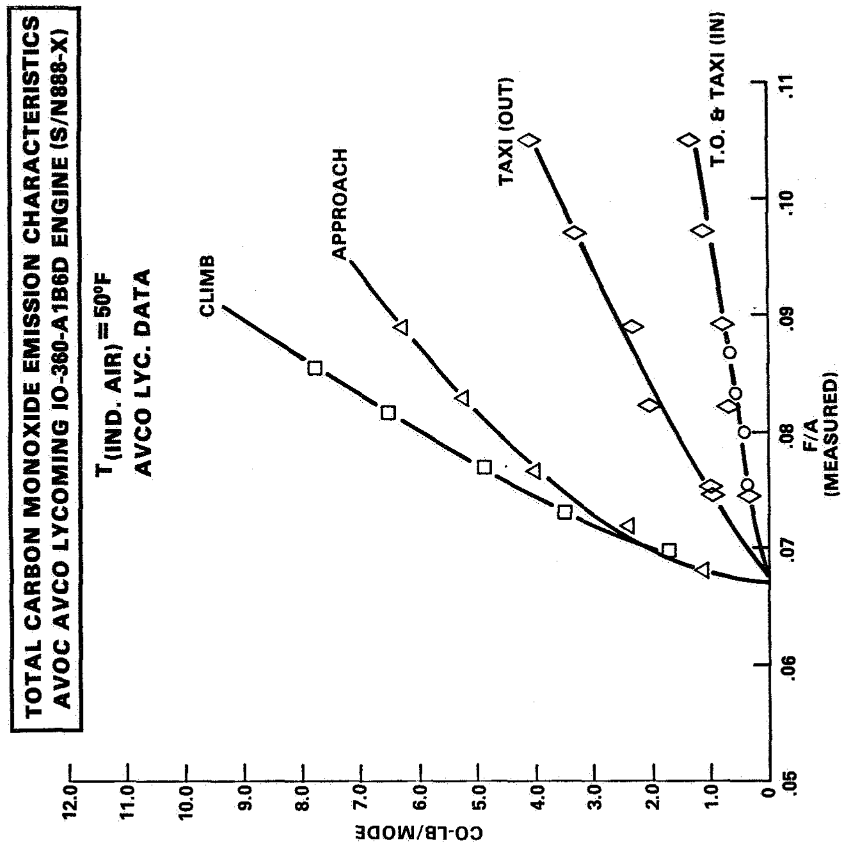


Figure 6-5

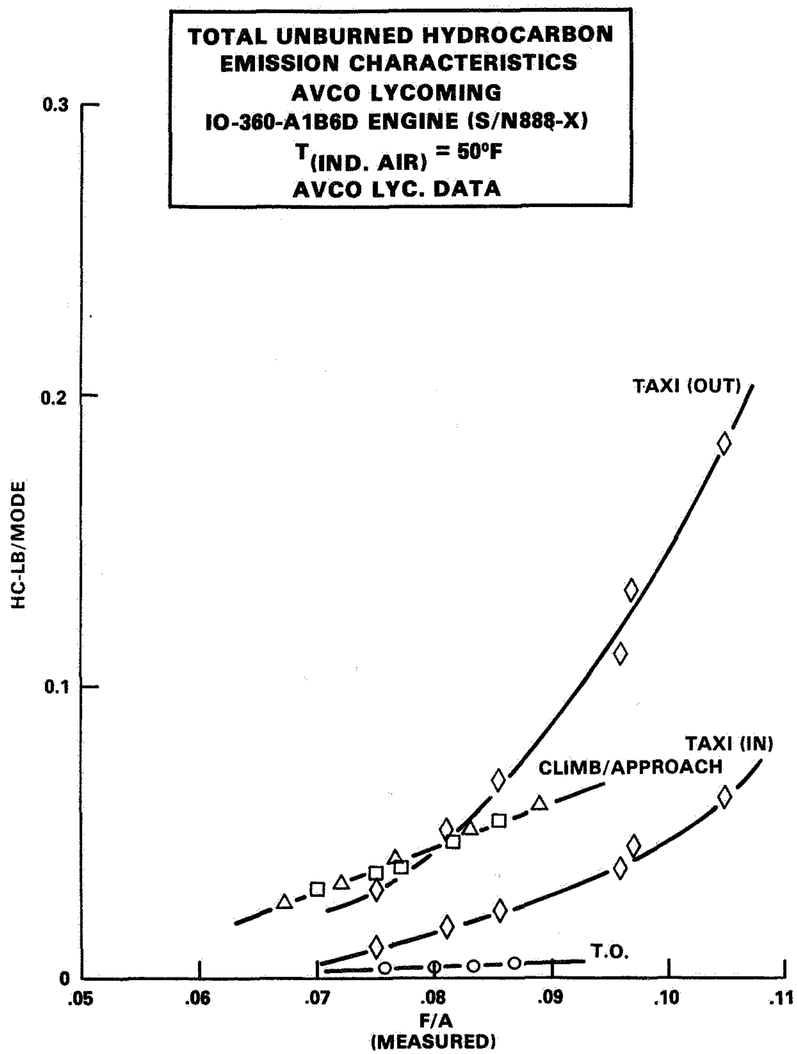


Figure 6-6

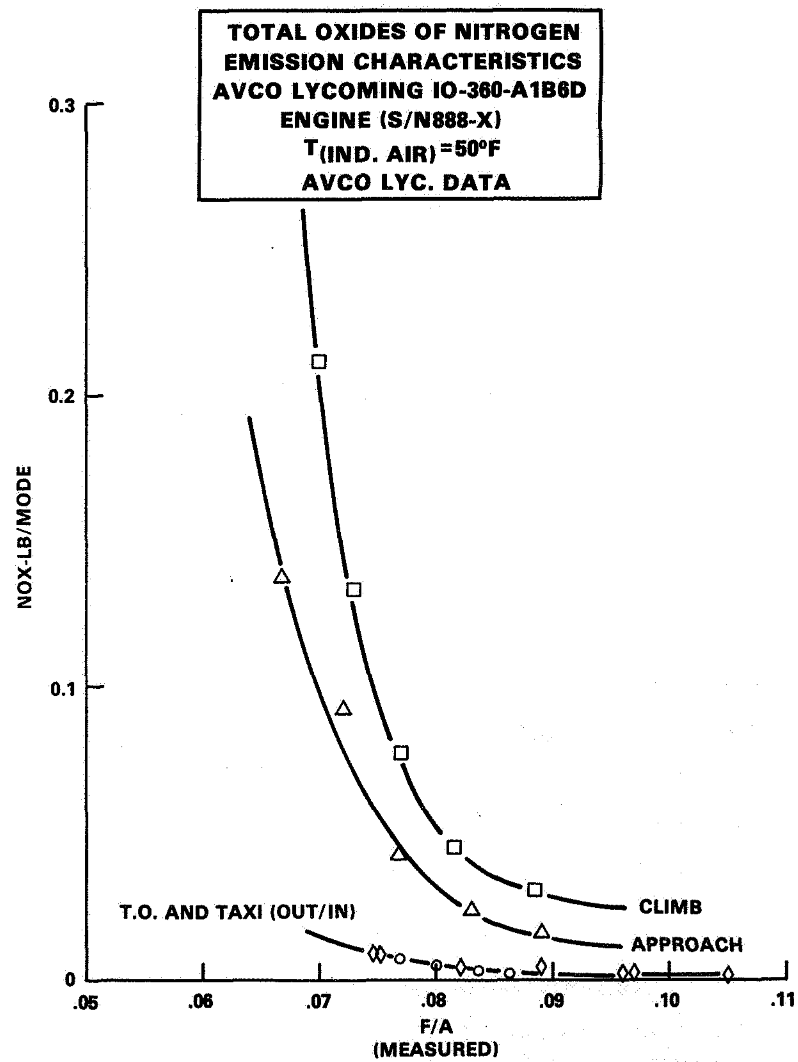


Figure 6-7

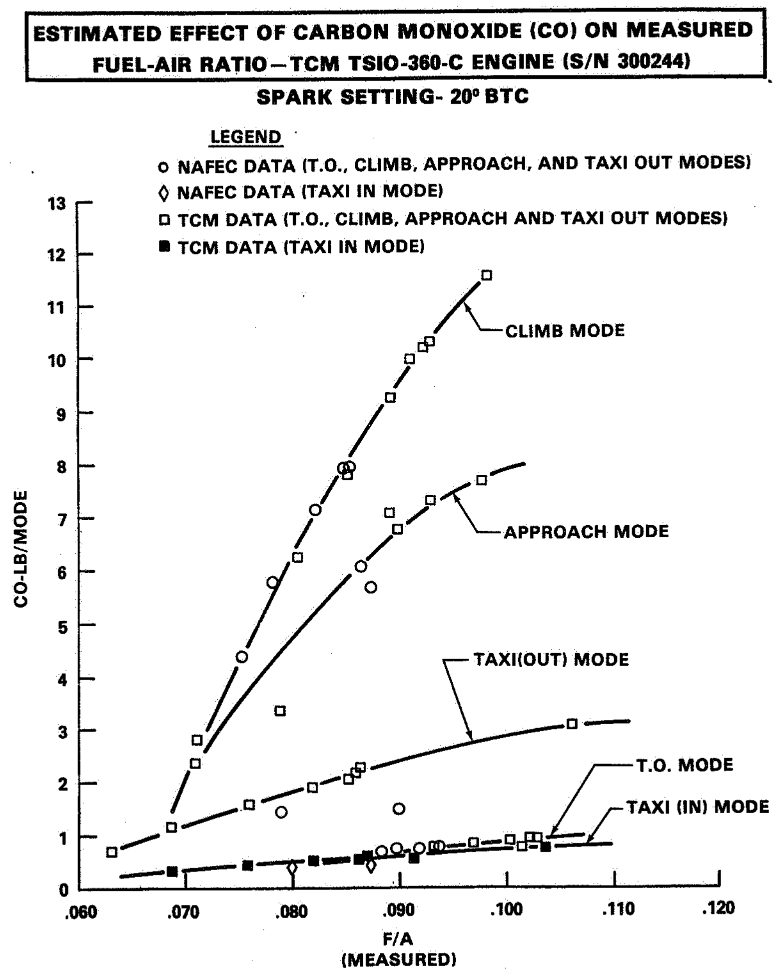


Figure 6-8

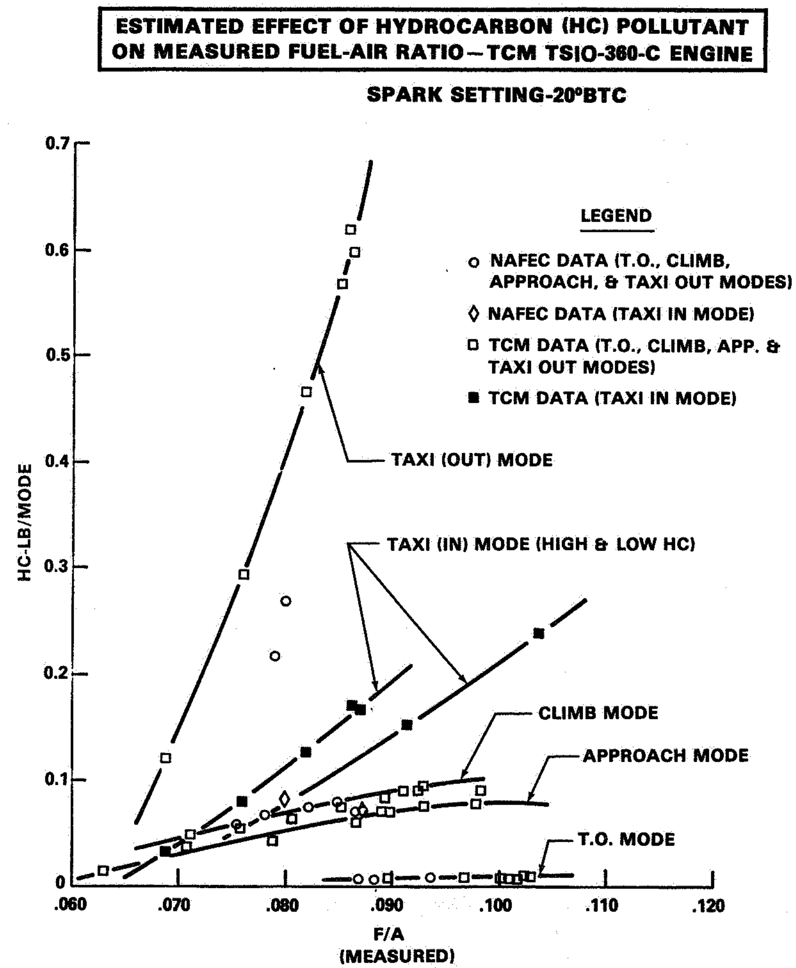
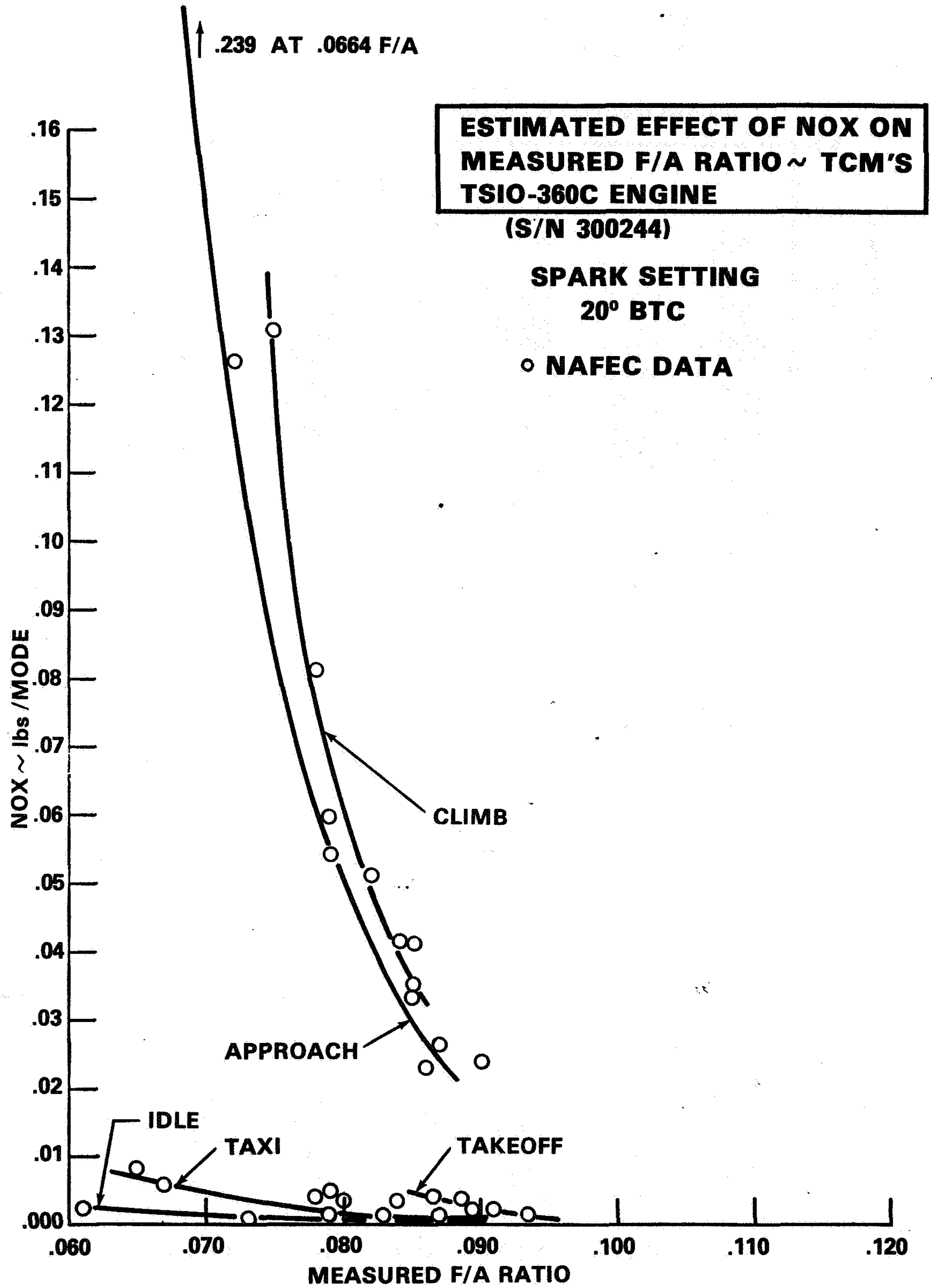


Figure 6-9



.239 AT .0664 F/A
ESTIMATED EFFECT OF NOX ON MEASURED F/A RATIO ~ TCM'S TSIO-360C ENGINE
(S/N 300244)
SPARK SETTING
20° BTC
NAFEC DATA
NOX ~ lbs /MODE
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.000
CLIMB
APPROACH
IDLE
TAXI
TAKEOFF
.060
.070
.080
.090
.100
.110
.120
MEASURED F/A RATIO

Figure 6-10

TOTAL CARBON MONOXIDE EMISSION CHARACTERISTICS PHASE I

Six (6) General Aviation Piston Engines

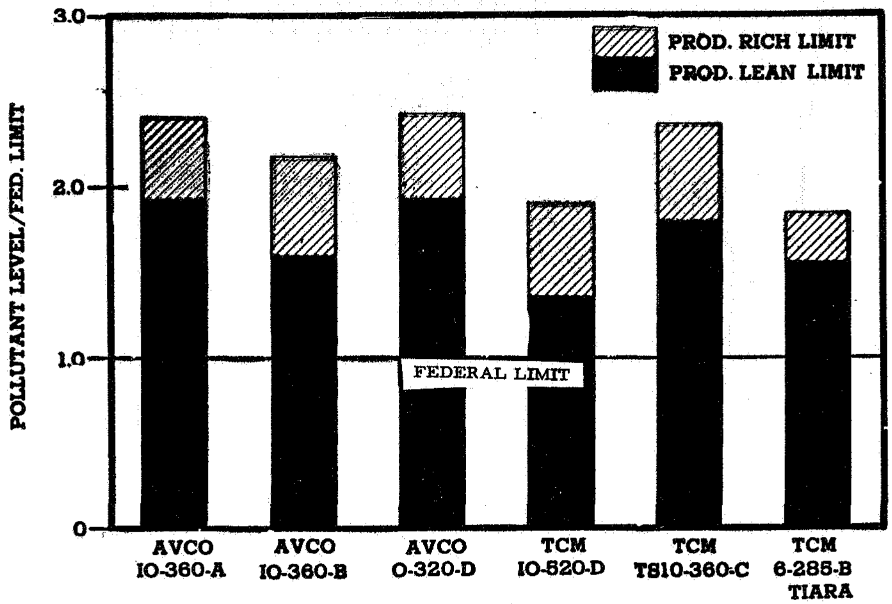


Figure 6-11

TOTAL CARBON MONOXIDE EMISSION CHARACTERISTICS PHASE I

Six (6) General Aviation Piston Engines

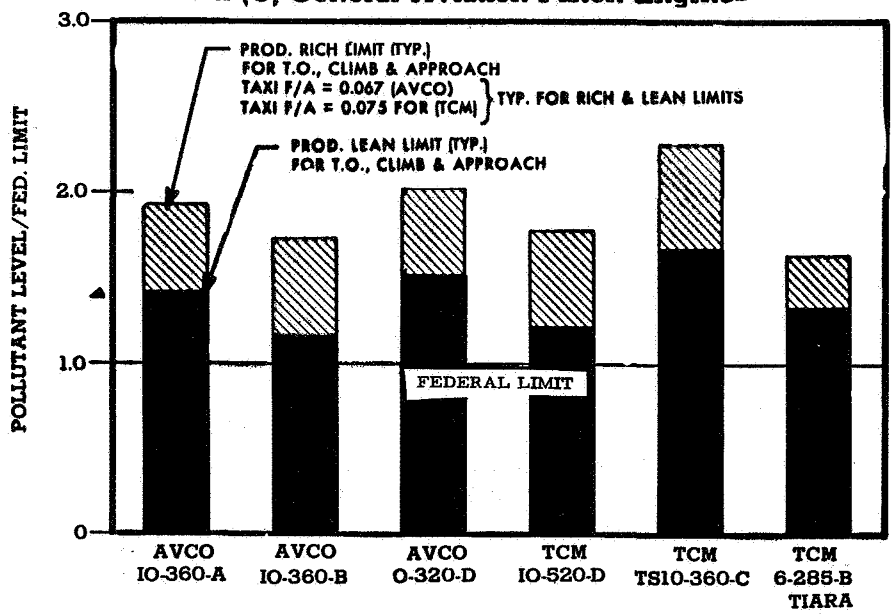


Figure 6-12

TOTAL CARBON MONOXIDE EMISSION CHARACTERISTICS
PHASE I
Six (6) General Aviation Piston Engines

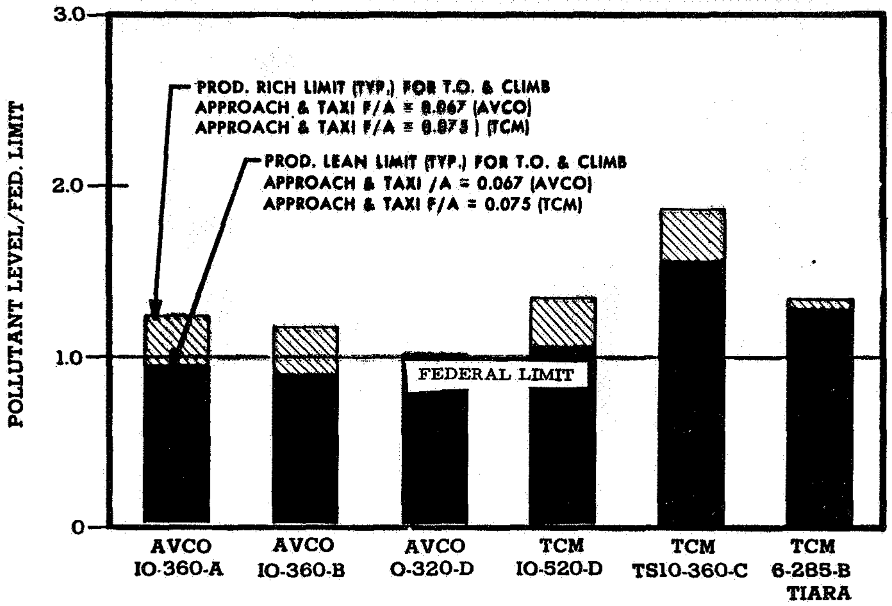


Figure 6-13

TOTAL CARBON MONOXIDE EMISSION CHARACTERISTICS
PHASE I
SIX (6) GENERAL AVIATION PISTON ENGINES

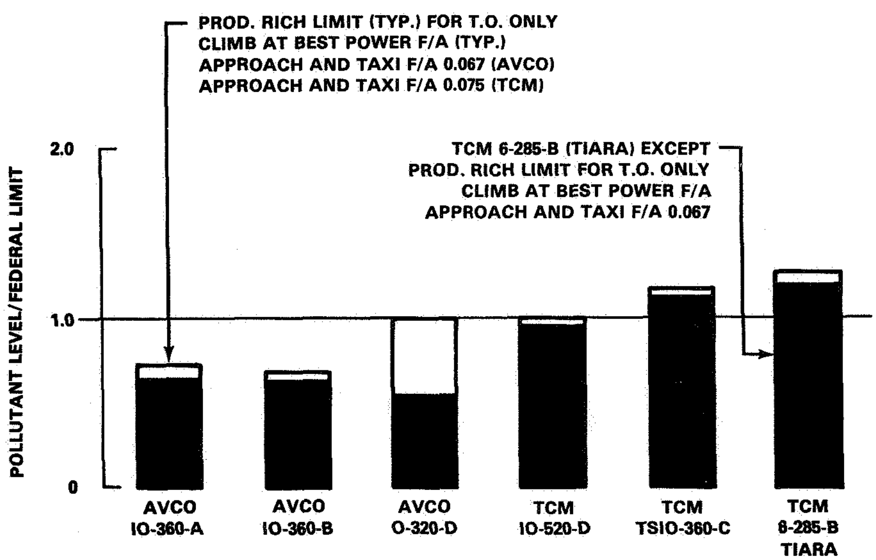


Figure 6-14

TOTAL UNBURNED HYDROCARBON EMISSION CHARACTERISTICS

PHASE I

Six (6) General Aviation Piston Engines

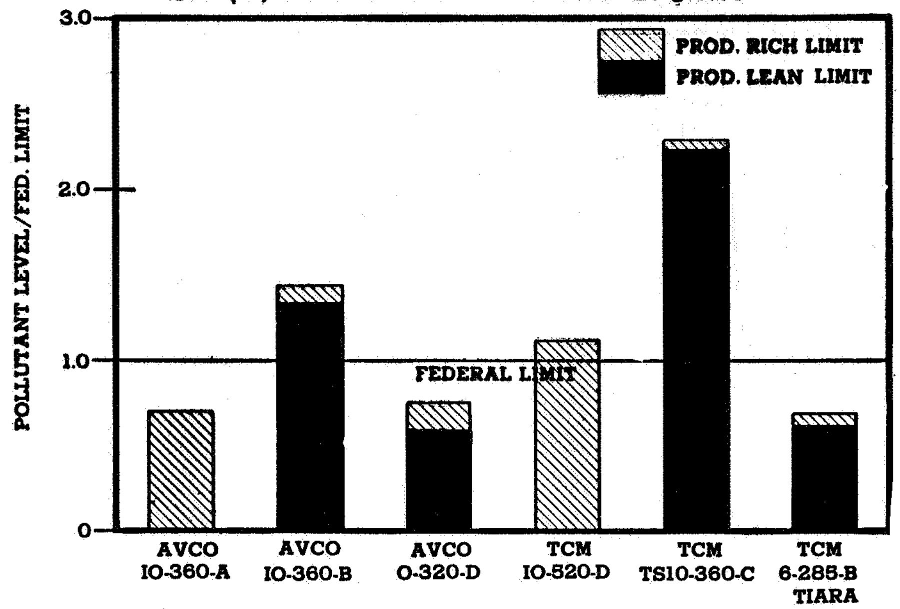


Figure 6-15

TOTAL UNBURNED HYDROCARBON EMISSION CHARACTERISTICS

PHASE I

Six (6) General Aviation Piston Engines

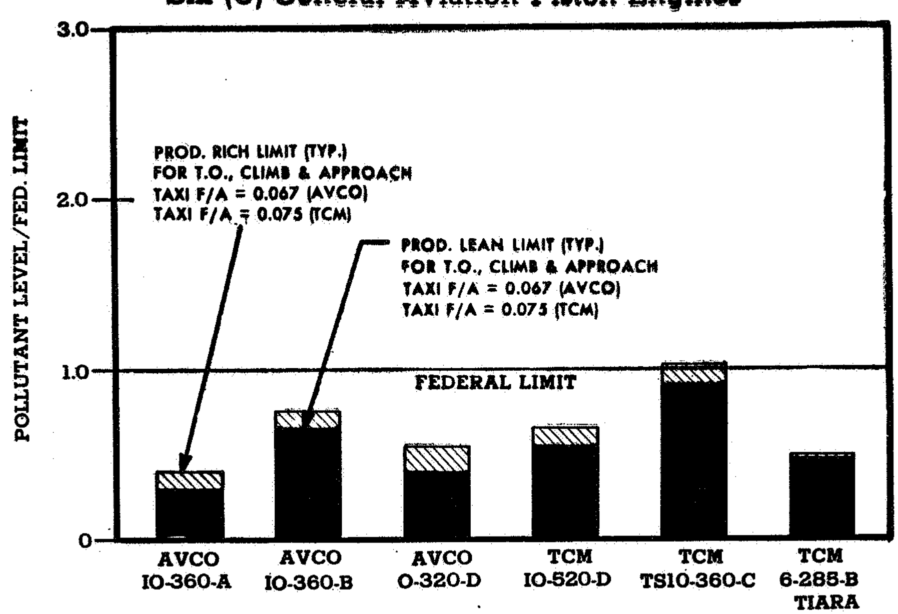


Figure 6-16

TOTAL OXIDES OF NITROGEN EMISSION CHARACTERISTICS

PHASE I

Six (6) General Aviation Piston Engines

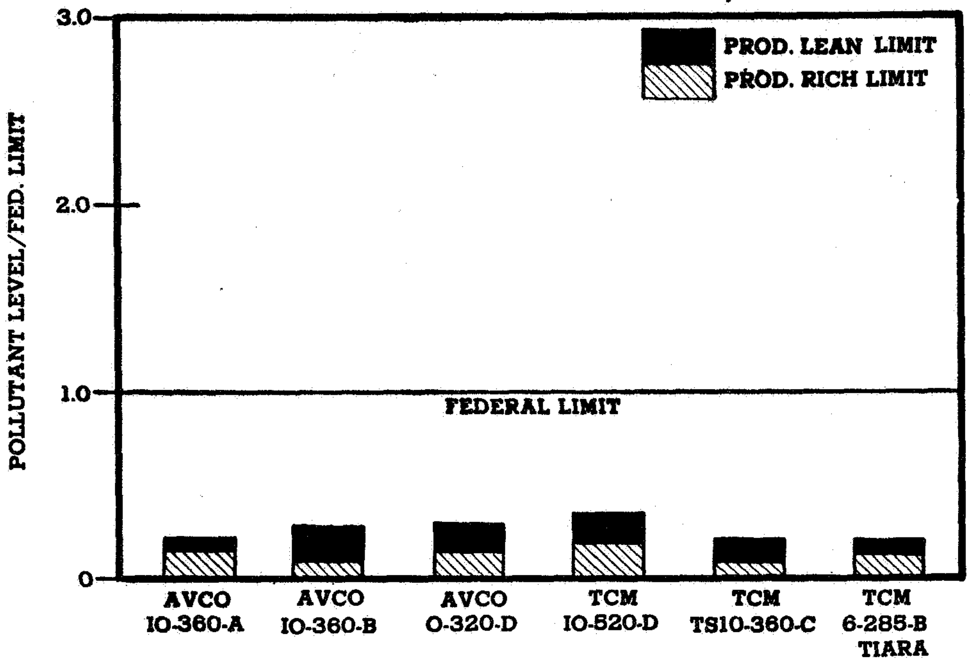


Figure 6-17

MAXIMUM CYLINDER HEAD TEMPERATURE AVCO LYCOMING IO-360-A ENGINE

TEST STAND		MODE	FLT. TEST MAX. CHT (CORR. TO 100° DAY) (°F)	CHT LIMIT	TEST STAND	
MAX. CHT (CORR. TO 100° DAY) (°F)	COOLING AIR $\Delta P = H_2O$				COOLING AIR FLOW (PPH)	COOLING AIR FLOW (CFM)
430	4.0	CLIMB	460	475	7390	1745
460	3.0	CLIMB	460	475	6550	1546

Figure 6-18