1. DEVELOPMENT OF EPA AIRCRAFT PISTON ENGINE EMISSION STANDARDS

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INTRODUCTION

On July 17, 1973, after over 3 years of development effort, the Environmental Protection Agency promulgated emission regulations for aircraft piston engines. The regulations for aircraft piston engines are to become effective for engines manufactured after December 31, 1979. The standards specified in the regulations are based on modest emission control technology which is considered to be feasible to implement within the stated time.

AIRCRAFT EMISSIONS

Before discussing characteristic piston engine emission levels and EPA Standards it is necessary to define specifically what is being measured. At present, the EPA is primarily concerned with emissions in the vicinity of the airport, and the emission test cycle reflects this philosophy. Carbon monoxide, hydrocarbon, and oxides of nitrogen emission rates are measured with the engine operating at idle-taxi, takeoff, climbout, and approach power modes with no consideration to cruise emissions. These engine loading conditions are obtained with the engine operating on an engine dynamometer or test stand. The emission rates at each power setting are multiplied by a specified representative time for the mode, giving the mass emissions for the mode. The emissions for the modes are summed to give the mass emissions for the LTO cycle. To take engine size into consideration in establishing standards, it was assumed that the useful work performed by the aircraft is generally proportional to the engine power and one standard was <u>not</u> set for all sizes of engines as with passenger cars. Rather, the aircraft standards are based on total mass emissions per LTO cycle per rated horsepower for the engine. The cycle can be illustrated in figure 1-1. Here we have the power setting and time in mode for each operating condition of the test cycle. The EPA allows the manufacturer to specify the power settings for the taxi-idle and climbout modes with the provision that climbout is at least 75 percent power.

As part of the development of aircraft emission regulations, measurements were made on a total of 70 engines, representing approximately nine different basic models. The measurements were made by Teledyne Continental (ref. 1) and Scott Research Laboratories (ref. 2). Statistical processing of the data was performed by Cornell Aeronautical Laboratories (ref. 3). The majority of the data presented in this discussion was taken from this early work.

Figure 1-2 is a tabulation of some of the results of the testing. The EPA standards are also shown for reference. The boxed numbers indicate emission levels falling within the EPA standards. A comparison of the EPA standards and the baseline test results reveals that the aircraft piston engine standards are primarily a CO control with some reductions for HC and a substantial margin for increases in NO_x. In addition, by comparing the standards of the individual pollutants, it can be seen that the CO levels are grossly higher than the HC or NO_x levels.

Figure 1-3 further illustrates the emission characteristics of piston engine aircraft. Here we have plotted the fuel specific emission rate as a function of engine air-fuel mixture ratio. The different scales for CO to the left and HC and NO_x to the right should be noted. The baseline data used indicated that engines typically operated well on the fuel rich side of the stoichiometric mixture ratio. The data actually revealed engines operating richer than shown here. To put aircraft emissions in perspective, a significant point can be made from this CO curve. An engine operating at an air-fuel ratio of 10:1 is producing approximately 1300 pounds of CO pollutant for every 1000 pounds of fuel consumed. Leaning that engine to 13:1 (approximate best power mixture ratio) would reduce CO emissions by better than 50 percent.

INFLUENCE OF PISTON AIRCRAFT EMISSIONS ON AIR QUALITY

In the studies supporting the promulgation of the aircraft regulations (refs. 4 and 5) two airports were examined, Van Nuys and Tamiami. Based on these studies, it was determined that the CO emissions from piston engine aircraft has a significant influence on the carbon monoxide levels in the ambient air in and around the airport property to which workers and travelers in the airport vicinity would be exposed. In preparing this presentation it was decided to review these past studies and expand the analysis to investigate other airports as well. The expanded study included three additional airports to the Van Nuys and Tamiami airports. The selection was somewhat arbitrary, but it was, in general, intended to sample airports having significant general aviation piston engine traffic as compared to larger airports dominated by commercial traffic. Figure 1-4 presents the results of the latest analysis for the five airports considered. As can be expected, from the previous discussion, the carbon monoxide emissions are substantial compared to the hydrocarbon and oxides of nitrogen emissions.

Comparing these emissions with the total regional CO emissions will reveal that the aircraft airport contribution is of the order of 1 percent. Unfortunately, unlike the HC and NO_x oxidant problem where dispersion is involved, CO emissions are critical at points of heavy concentration, and this 1 percent concentrated in one location, such as an airport, is of concern. For example, in the vicinity of the Van Nuys airport, which is a known CO "hot spot," the piston aircraft contribution is approximately 10 percent of the total CO emission, affecting a population of 67 000 people. As you draw your reference area closer and closer to the airport the contribution of aircraft emissions of course increases.

Another example is the Fairbanks Airport which is also located in a CO troublespot. In all of North Alaska the estimated CO emissions, excluding aircraft, are 6000 tons per year for 1985 and the CO concentrations are still expected to be well above air quality limits. It is estimated that piston engine aircraft will contribute 1400 tons per year at the Fairbanks airport, or one-third of the total allowable CO for North Alaska. Granted, I may be accused of selecting only special cases to make a general argument, but, considering the modest level of control required, the fuel benefits associated with the controls and the disadvantages of other alternatives to reducing emissions, the standards were and still are considered warranted. The EPA had assumed that modest standards would be less detrimental to the industry than limitation on operation at all critical airports. If the Fairbanks problem were typical of a greater number of regions, the national regulation would, of course, be much more stringent. To conclude this air quality discussion I would like to quote from the preamble of the final aircraft rule making published on July 17, 1973. "In the development of the regulations it was concluded that emissions from aircraft and aircraft engines should be reduced to the extent practicable with present and developing technology." In the Proposed Rule Making of Dec. 12, 1972, it was stated that the piston engine standards are considered by EPA to be attainable with existing technology with some improvement in engine cooling concepts and improved fuel management. How the standards were actually established, assuming this emission control concept, is described in the following section.

SELECTION OF EMISSION STANDARDS

As already stated, the set of piston engine standards selected were based on a technologically feasible and economically reasonable control of carbon monoxide. The approach to selecting the standard can be illustrated by returning to figure 1-3. The baseline studies revealed that piston aircraft operate over a wide range of fuel-air ratios. The baseline testing found engines were operating in the range of fuel-air ratios of 0.08 to 0.14 during ground operations. After reviewing a variety of potential control systems it was concluded substantial CO reductions could be realized if this range of typical fuel air ratios could be narrowed. Thus, improvements in fuel management were determined as reasonable controls to impose on a source which has minimal impact on national air quality but clearly significant impacts on certain critical locations. The selection of the actual levels of the standards were based on figure 1-3. The fuel-air ratio of 0.077 to 0.083 was chosen as a reasonable mixture ratio for engine operation especially since some engines already performed in this range. Thus, using these values and other baseline engine characteristics, the EPA standards for CO, HC, and NO_x were calculated. Figure 1-5 illustrates the standard selection more directly than the previous figure. Here we have characteristic piston engine emissions in terms of the regulatory parameter and fuel-air ratio. As shown, the average mixture ratio to achieve the CO standard is about 0.082. This value is richer than both best power and best economy. The mixture ratio to achieve the HC standard is even richer, thus fuel management control to achieve the CO levels should easily control the HC emissions. Figure 1-6 further illustrates how these controls will influence engine performance. As shown, current engines operate over a wide range of fuel-air ratios in the LTO cycle. The emission standards narrow this range forcing more of the engines toward the best economy and best power operating points.

Recognizing that the aircraft piston engine has varying operational requirements, it is not reasonable to suggest that an engine should operate at the same fuel-air ratio over all operating conditions. To identify the modes which are critical from the standpoint of achieving the EPA standards, figure 1-7 was prepared. Again, this manipulation of data was based on the measurements of in-use engines. The major point to be made, is that the climbout, taxi-idle, and approach modes are the significant operating conditions, with respect to emissions. Thus, reasonable fuel cooling to suppress detonation can still be utilized for the full power takeoff mode as long as leaning is achieved in the other modes. Figure 1-8 is an outline of a sample calculation of CO emissions resulting from modal fuel management.

What is being suggested is a specific fuel-air mixture for each mode. Based on figure 1-9 taken from an aircraft engine maintenance manual, this is apparently not a new concept. It is presently utilized to achieve design goals other than emissions. At low power settings or low air flow, mixtures are maintained rich to produce smooth engine acceleration and possibly cooling. At midrange or cruise, mixtures are leaned for economy; and at high power modes, mixtures are enrichened again for detonation suppression.

The following series of figures 1-10 to 1-12 illustrate fuel flow schedules typical of in-use aircraft. Again, we are dealing with test results from the baseline measurements. The O-200 engine data on figure 1-10 supports the fuel flow schedule just described (i.e., rich idle, lean mid-range, and rich full power). In reviewing this summary of in-use engines, it should be recalled that the fuel-air ratio for best power is 0.076 fuel-air and best economy is 0.064.

It may be possible to utilize these same programming mechanisms for emission controls by improved calibration or modified scheduling. For instance, at the taxi-idle conditions where rich mixtures have been used to supplement cooling air and provide smooth low power operation, emissions should also be considered in the fuel management system design. Under approach conditions, mixtures are generally enriched to provide smooth engine operation which will assure response to sudden full-power needs. Methods other than rich mixtures such as acceleration pumps should be sought to satisfy these design requirements.

THE FUTURE OF THE STANDARDS

The standards in effect for engines produced after December 31, 1979, are based on technology which is considered feasible for the piston engine powered aircraft; namely, fuel management. The EPA will continue to monitor progress of the industry and supporting government agencies in their attempt to develop engines capable of complying to the EPA standards. As stated in the preamble of the final rule making, "If it should become evident that the standards as promulgated cannot be achieved at that time which are safe and in other respects air-worthy, additional rule making action will be considered to ensure that the best technology is reflected in the standards." This position on the part of the EPA should not be mistaken. We continue to feel the standards are achievable with reasonable control methods. It will take sound technical arguments with supporting data to modify this position. The fact that existing engines cannot be tuned to achieve these standards is not sufficient reason to consider new rule making. It is expected, at least in some engine models, that hardware changes will be required to achieve the standards.

If the EPA determined that a change may be justified, possibly stimulated by an industry petition, the rule making process would be initiated with a Notice of Proposed Rule Making (NPRM). At that time information would be solicited from interested parties which normally includes the affected manufacturers, their trade organizations, environmental groups and private citizens. After evaluating the pro and con arguments presented in response to the proposed action and performing indepent technical analysis a revised rule making package would be prepared. Forums such as we are engaged in here are not part of the rule making process but do perform a useful means for exchange of technical information.

As some of you may be aware, the EPA recently held public hearings concerning the aircraft turbine engine standards. As a result of that hearing, there is in process a thorough assessment of the need/justification for a NPRM for modifications of the aircraft turbine engine regulations. The changes presently under consideration relate to the turbine engines; however, there is one aspect of the piston standards which may be addressed in this NPRM. As is hopefully apparent, after hearing my earlier comments, the piston engine regulations are primarily directed to CO control. The HC and NO_x standards were set at levels anticipated as a result of the CO controls. At the time the standards were established, the general approach was to set controls for each of the regulated pollutants, primarily to prevent trade-offs that might unnecessarily increase one pollutant while reducing another. However, recently, when emission standards were developed for motorcycles, it was decided not to set a NO_x standard because the effort to control that pollutant from motorcycles could not be justified by the air quality impact analysis which had been made. This same argument can be considered relative to the piston aircraft regulations. CO is the pollutant of concern. Standards for HC and NO_x were set to establish "trade-off boundaries." Removing these standards altogether would allow greater flexilibity for the selection of emission control systems.

If this action were taken, it would avoid the discarding by designers, of good CO control systems, which may be marginal in compliance with the HC and NO_x standards. Also, during future compliance testing, the costs associated with the rejection of an engine failing the HC or NO_x limits would be difficult to justify when considering the benefits received from slight reduction in HC or NO_x emissions which may be realized.

Whether or not EPA as an organization will consider removing the existing limitations on HC and NO_x emissions from piston aircraft engines is something that I am not in a position to say. Rather, I am sharing with you candidly the considerations that I and my colleagues are wrestling with at the technical staff level at which we work. We will dig deeply into the potential air quality impact of any such change before even proposing it to the executive levels of the EPA, for we know as well as you that the removal of the HC and NO_x standards would be a complicated process involving inputs from many levels and organizations of the government.

CONCLUSIONS

Piston engine light aircraft are significant sources of carbon monoxide in the vicinity of high activity general aviation airports.

Substantial reductions in carbon monoxide can be achieved by fuel mixture leaning using improved fuel management systems.

The air quality impact of the hydrocarbon and oxides of nitrogen emissions from piston engine light aircraft appear to be insufficient to justify the design constraints being confronted in present control system developments.

REFERENCES

1. "Collection and Assessment of Aircraft Emissions." Prepared for the Environmental Protection Agency by Teledyne Continental Motors, October 1971, Contract 68-04-0035.

2. "A Study of Aircraft Powerplant Emissions." Prepared for the Environmental Protection Agency by Scott Research Laboratories Inc., January 1971, Contract No. 68-04-0037.

3. "Analysis of Aircraft Exhaust Emission Measurements." Prepared for the Environmental Protection Agency by Cornell Aeronautical Laboratory, Inc., November 1971, Contract No. 68-04-0040.

4. "The Potential Impact of Aircraft Emissions Upon Air Quality." Prepared for the Environmental Protection Agency by Northern Research and Engineering Corporation, December 1971, Contract No. 68-02-0085.

5. "Aircraft Emissions: Impact on Air Quality and Feasibility of Control." United States Environmental Protection Agency.

DISCUSSION

Q - B. Rezy: When you mentioned an average fuel-air ratio of 0.077 to 0.083, how was that average defined?
A - W. Houtman: It was not weighted as in the way TCM does their work. The data were plotted at a given power setting and fuel-air ratio but not on a modal basis.

Q - B. Rezy: You are assuming a constant fuel-air ratio for all modes?
A - W. Houtman: That would be an effective average, yes.

COMMENT - B. Rezy: The fuel-air ratio you've mentioned corresponds to an equivalence ratio of 1.23, and we will show later that none of the emissions were met at that equivalence ratio.

Q - K. Stuckas. You referred to carbon monoxide concentrations at the five airport sites. Were CO emissions actually measured at these sites? If so, how were you able to determine what proportions of the CO levels were due to piston engine aircraft?
A - W. Houtman: No, the CO levels were not measured for this study or analysis; they were based on FAA statistics for the traffic at the five airports. We looked at the types of aircraft flying, the distribution of air traffic, and the number of engines on each aircraft; we then broke these down by engine type, calculated the totals, and compared them to total regional CO emissions. There are some CO measuring sites near the Van Nuys Airport, which is one of the problem areas.

Q - K. Stuckas: Were you able to determine what portion of the CO levels was due to piston engine aircraft as opposed to passing traffic?
A - W. Houtman: We did make an analysis, but it was not based on measurments of CO. We could calculate the CO, but again a lot of assumptions would be involved. We can break it up to some extent, and that's what the 10 percent piston engine contribution refers to.

COMMENT - M. Steele: The GAMA environmental subcommittee has reviewed the available data for the pre-1973 time frame on which it is believed the standards for aircraft piston engines were made in 1973. The reviewer revealed to us that the decisions were made on very incomplete data and at a time when instrumentation and measurement techniques were far from fully established. Today there is a greatly expanded knowledge in the subject. It is hoped that the three agencies will give careful consideration not only to this expanded technical data base but also to the broader aspects of safety, schedules, costs, and facility and manpower limitations. The member companies of GAMA welcome the opportunity afforded at this meeting and hope that the information provided will assist in realistic decisions on the subject of such national concern. It is hoped that the proceedings will recognize the fact that general aviation is only a small part of the national transportation system amd that aircraft piston engine pollution levels should be placed in true perspective with respect to the rest of the transportation system and the respected emission improvements be derived therefrom.

Q - D. Powell: Was the 1 percent CO in the vicinity of the airports based on the calculated emissions from the aircraft and then divided by some area, and what was the area of the airport in square miles?
A - W. Houtman: The 1 percent value is based on the air quality region where the airport is located. For instance, the Van Nuys Airport is located in the Los Angeles air quality region and the CO emissions are of that order. These are estimated projected emissions for 1985. One EPA estimate of the CO emissions in 1985 for a given model is about 1 000 000 tons a year compared to less than 10 000 tons for Van Nuys alone. The concentration of CO is a local problem and not a regional problem. This is why the HC and NO_x are not considered to be critical.

Q - D. Powell: I was trying to get some idea of how large an area the CO was spread over.
A - W. Houtman. Possibly 100 square miles, I'm not sure what the Los Angeles region is. We didn't take all the general aviation traffic in the Los Angeles air quality control region, but just at one of the airports. There are other general aviation airports in that air quality region and if we summed these it would still be of the order of 1 to 3 percent.

Q - L. Duke: Were these projections for 1985 based on having aircraft controls or standard aircraft compared against automotive controls?
A - W. Houtman: Even by 1985 there will be very little impact of the aircraft standards because first they don't become effective until essentially 1980 and then 5 years of production compared to the total aircraft population would not be very much.

Q - R. Tucker: I'd like to make a general comment concerning the information you have on figure 2 on the CO level for the IO-520. You state that it is a lean climb and I assume that it is basically a baseline mode cycle with the climb mode leaned out.
A - W. Houtman: I don't recall actually but I suspect that's it. It's certainly a baseline engine.

Q - R. Tucker: Comparing these data to our IO-520 data, we have a value in the same units of 0.079 for baseline. If all the modes were leaned out to the point of imposing a safety problem the CO value would be 0.035 and the lean limit of our model spec gave us a CO level of 0.053. All three of those are considerably larger than the 0.028 that you quoted there.
A - W. Houtman: It's from the data taken at the time. It's either from the Cornell report or possibly from the Continental data.

Q - R. Tucker: I would like to know what the information in figure 3 is based on.

A - W. Houtman: This was taken from the Scott report in which all the data were plotted. You can see the CO data up in the upper left corner plots quite well. You might give some argument on the HC and NO_x, but there is another curve for carbureted engines and injected engines. If you overlay the injected on the carbureted engine curve you'll see that they all fall on each other. So the CO curve is pretty good. The data for the injected and carbureted engines plot quite well as a straight line.

TEST CYCLE POWER AND TIME IN MODE

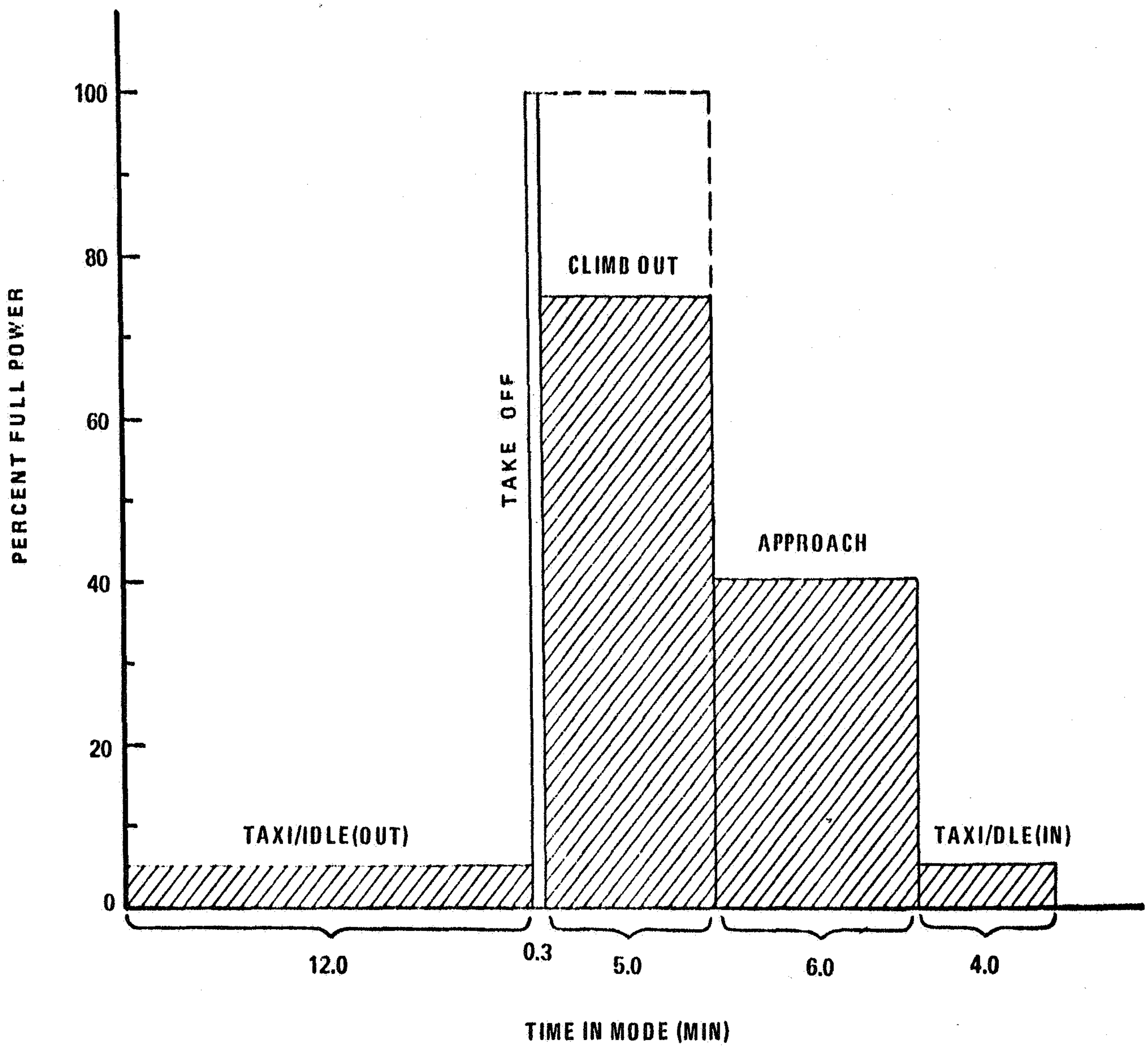


Figure 1-1

TYPICAL AIRCRAFT PISTON ENGINE EMISSIONS
(LBS/CYCLE/RATED POWER)

	CO	HC	NO_x
EPA STANDARD	.042	.0019	.0015
0-200	.091	.0015	.0003
0-320	.074	.0017	.0003
10-360	.065	.0042	.0003
0-470	.054	.0014	.0002
10-540	.082	.0035	.00006
0-540	.071	.0026	.0007
10-520 (LEAN CLIMB)	.028	.0029	.0013

Figure 1-2

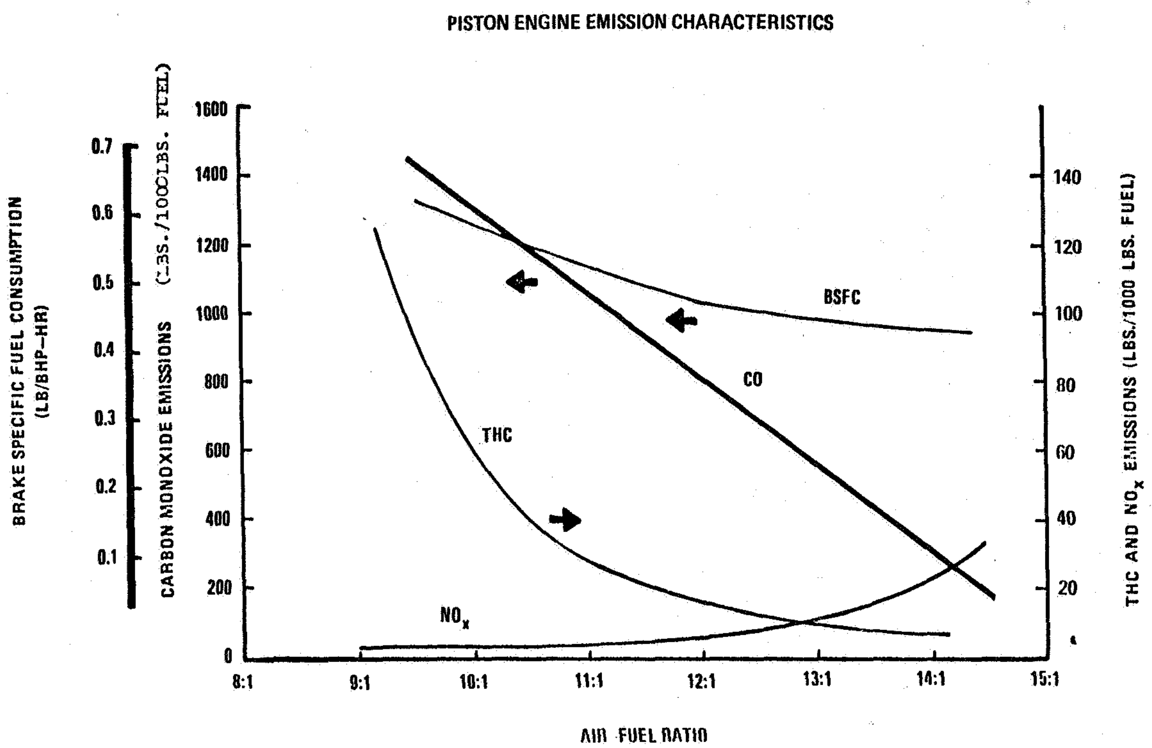

PISTON ENGINE EMISSION CHARACTERISTICS
BRAKE SPECIFIC FUEL CONSUMPTION (LB/BHP-HR)
CARBON MONOXIDE EMISSIONS (LBS./1000LBS. FUEL)
THC AND NOx EMISSIONS (LBS./1000 LBS. FUEL)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1600
1400
1200
1000
800
600
400
200
0
140
120
100
80
60
40
20
BSFC
CO
THC
NOx
8:1
9:1
10:1
11:1
12:1
13:1
14:1
15:1
AIR FUEL RATIO

Figure 1-3

Air Pollution Contribution of Piston Engine
Aircraft at Five Selected Airports

	Rank	Year	HC	Tons/Year CO	NOx
Van Nuys	3	1974	56	2500	10
		1980	74	3300	13
		1985	83	3700	15
Tamiami	31	1974	35	1600	6
		1980	55	2400	9
		1985	78	3500	13
San Jose (2 airports)	10,28	1974	64	2800	12
		1980	84	3800	15
		1985	94	4200	17
Phoenix	9	1974	31	1400	5
		1980	44	1900	8
		1985	50	2200	9
Fairbanks	133	1974	14	600	3
		1980	25	1100	4
		1985	31	1400	5

*Projections based on FAA terminal area forecast for 1976 through 1986

Figure 1-4

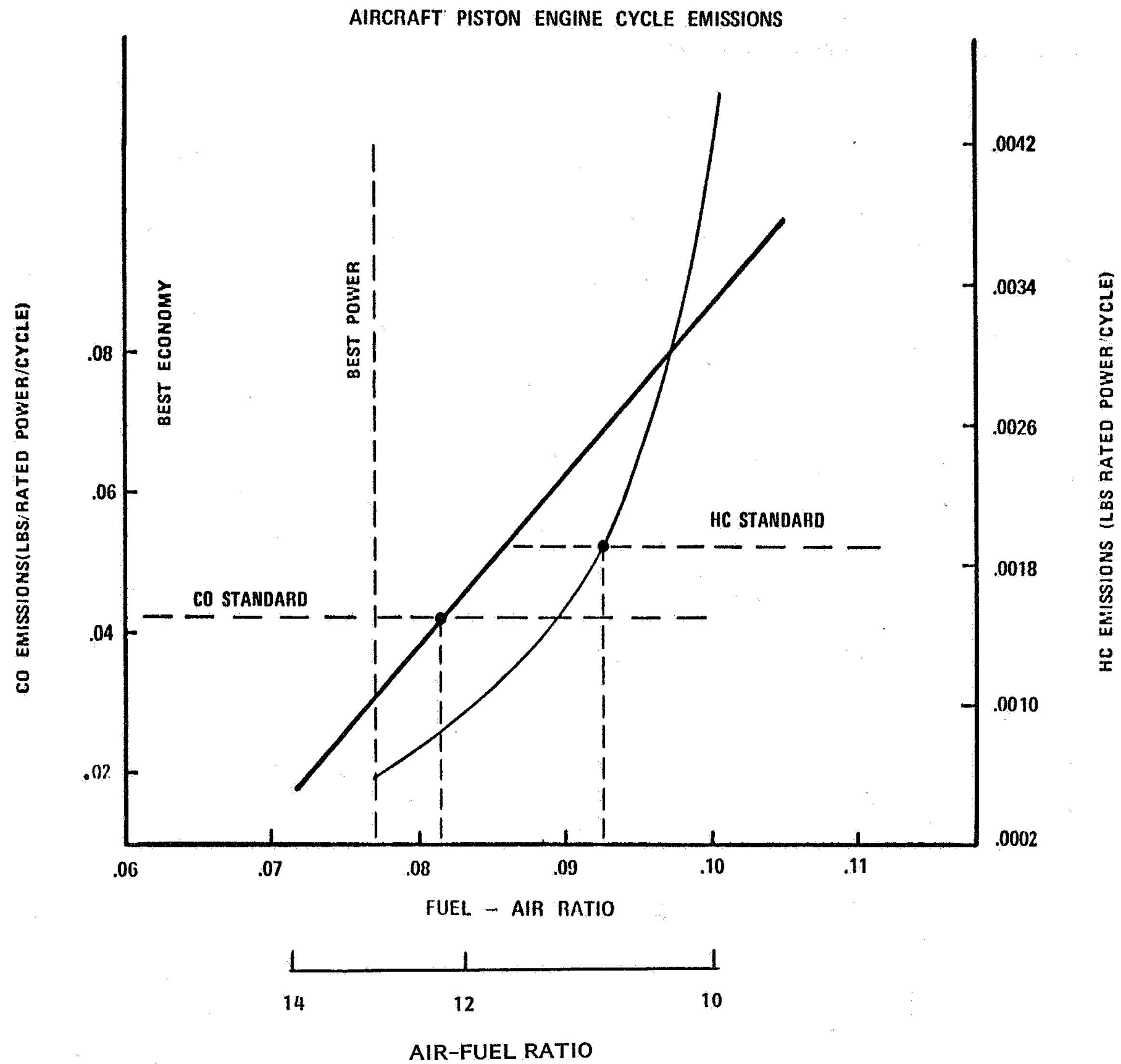

AIRCRAFT PISTON ENGINE CYCLE EMISSIONS
CO EMISSIONS(LBS/RATED POWER/CYCLE)
HC EMISSIONS (LBS RATED POWER/CYCLE)
BEST ECONOMY
BEST POWER
HC STANDARD
CO STANDARD
.08
.06
.04
.02
.0042
.0034
.0026
.0018
.0010
.0002
.06
.07
.08
.09
.10
.11
FUEL - AIR RATIO
14
12
10
AIR-FUEL RATIO

Figure 1-5

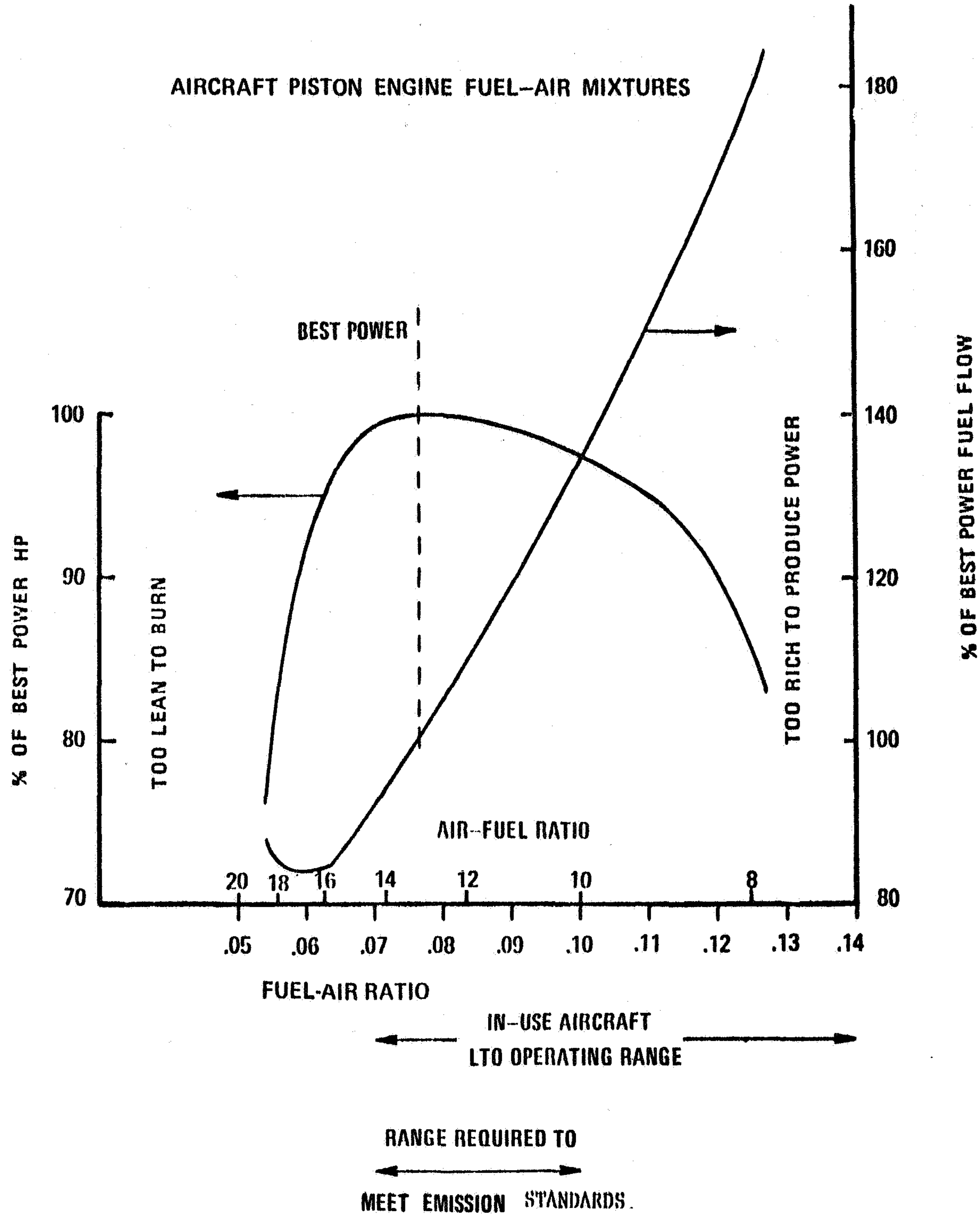

AIRCRAFT PISTON ENGINE FUEL–AIR MIXTURES
BEST POWER
% OF BEST POWER HP
100
90
80
70
TOO LEAN TO BURN
TOO RICH TO PRODUCE POWER
% OF BEST POWER FUEL FLOW
180
160
140
120
100
80
AIR–FUEL RATIO
20
18
16
14
12
10
8
.05
.06
.07
.08
.09
.10
.11
.12
.13
.14
FUEL-AIR RATIO
IN–USE AIRCRAFT
LTO OPERATING RANGE
RANGE REQUIRED TO
MEET EMISSION STANDARDS.

Figure 1-6

% CO EMISSIONS BY MODE

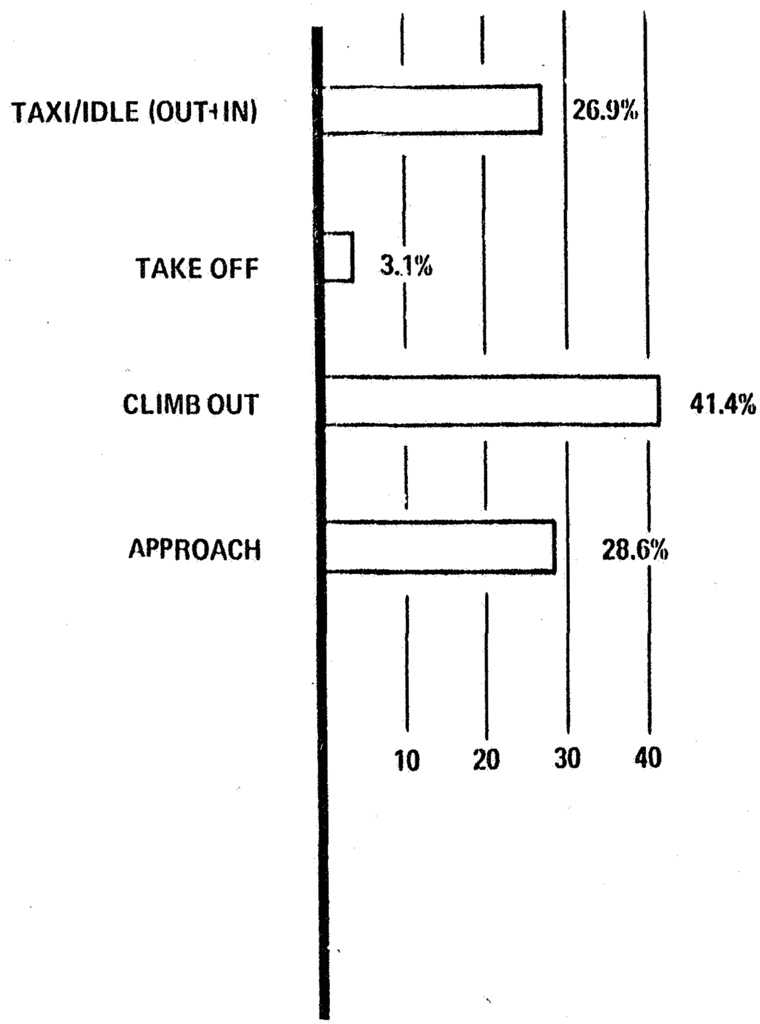


Figure 1-7

Sample Calculation
LTO Cycle Emissions

	A/F	$\dot{M}_{CO}/\dot{M}_f$	$\dot{M}_f/_{bhp\ hr}$	% bhp	TIM hr	
Taxi/idle	13:1	.530	.45	.05	.27	.003
Takeoff (detonation suppression)	10:1	1.300	.62	1.00	.005	.004
Climbout (best power)	12.6:1	.650	.46	.80	.083	.020
Approach	13:1	.530	.45	.40	.10	.010
						.037/.042

$$\sum_{Mode} \frac{\dot{M}_{CO}}{\dot{M}_f} \times \frac{\dot{M}_f}{\text{bhp-hr}} \times \frac{\text{bhp mode}}{\text{bhp rated}} \times \frac{\text{hr}}{\text{mode}} = \frac{\dot{M}_{CO/LTO}}{\text{rated bhp}}$$

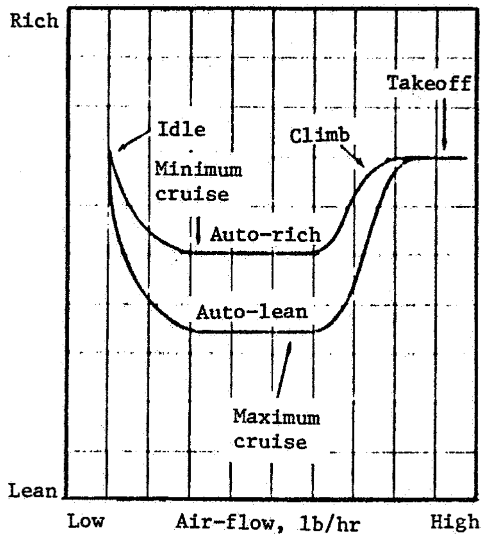
$\frac{\dot{M}_{CO}}{\dot{M}_f}$ = fuel specific emissions from Figure 3

$\frac{\dot{M}_f}{\text{bhp-hr}}$ = brake specific fuel consumption from Figure 3

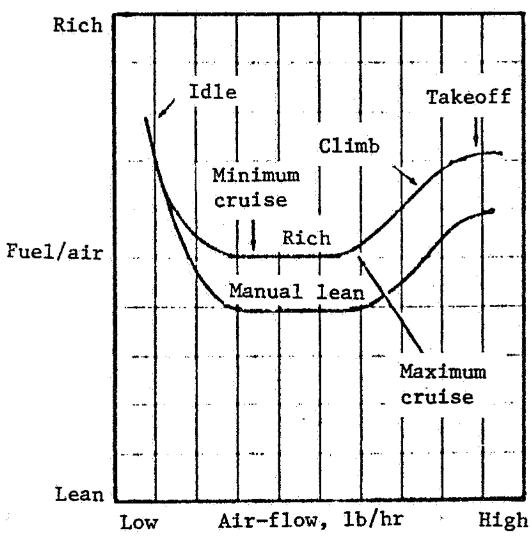
$\frac{\text{bhp mode}}{\text{bhp rated}}$ = specified mode power setting

TIM = specified time in mode

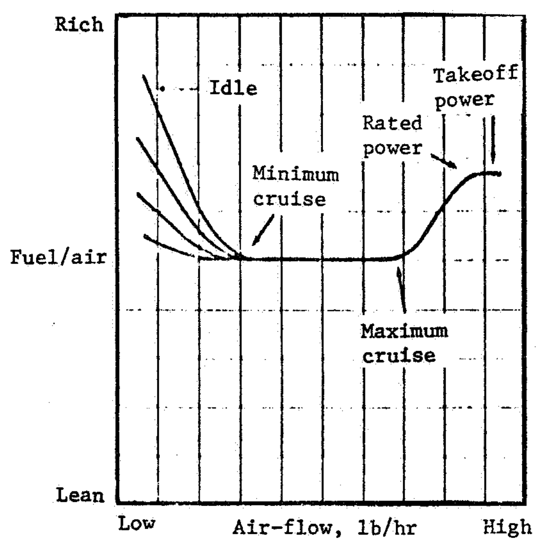
Figure 1-8



Typical fuel/air mixture curve for injection-type carburetor.

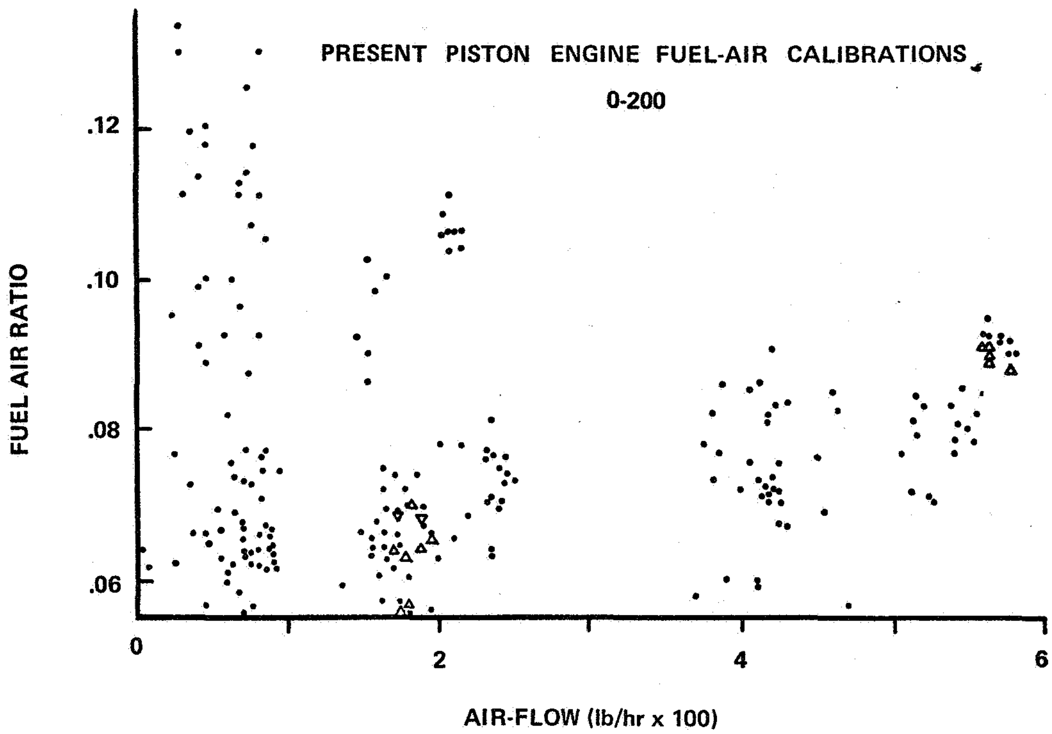


Typical fuel/air mixture curve for float-type carburetor.



Idle mixture curve

Figure 1-9


PRESENT PISTON ENGINE FUEL-AIR CALIBRATIONS
0-200
FUEL AIR RATIO
.12
.10
.08
.06
0
2
4
6
AIR-FLOW (lb/hr x 100)

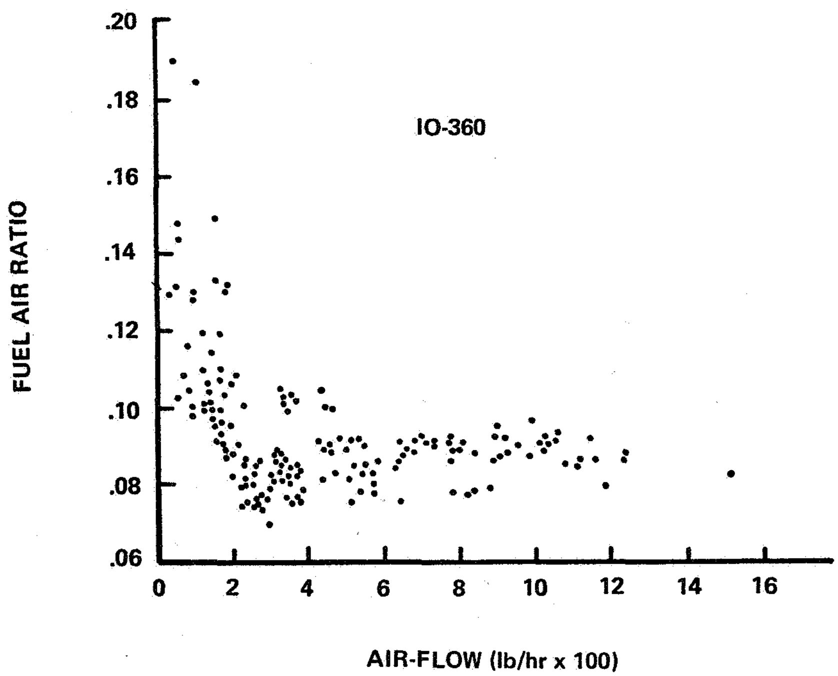
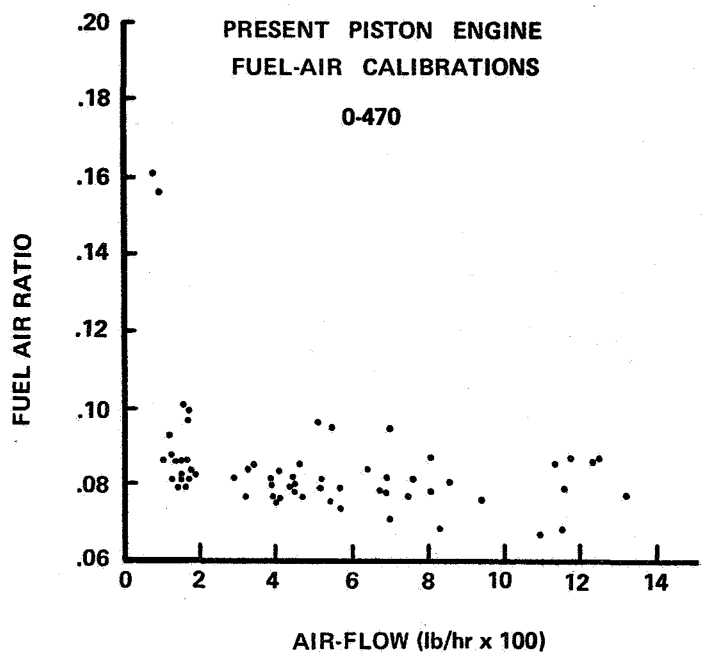

IO-360
FUEL AIR RATIO
.20
.18
.16
.14
.12
.10
.08
.06
0
2
4
6
8
10
12
14
16
AIR-FLOW (lb/hr x 100)

Figure 1-10


PRESENT PISTON ENGINE
FUEL-AIR CALIBRATIONS
0-470
FUEL AIR RATIO
.20
.18
.16
.14
.12
.10
.08
.06
0
2
4
6
8
10
12
14
AIR-FLOW (lb/hr x 100)

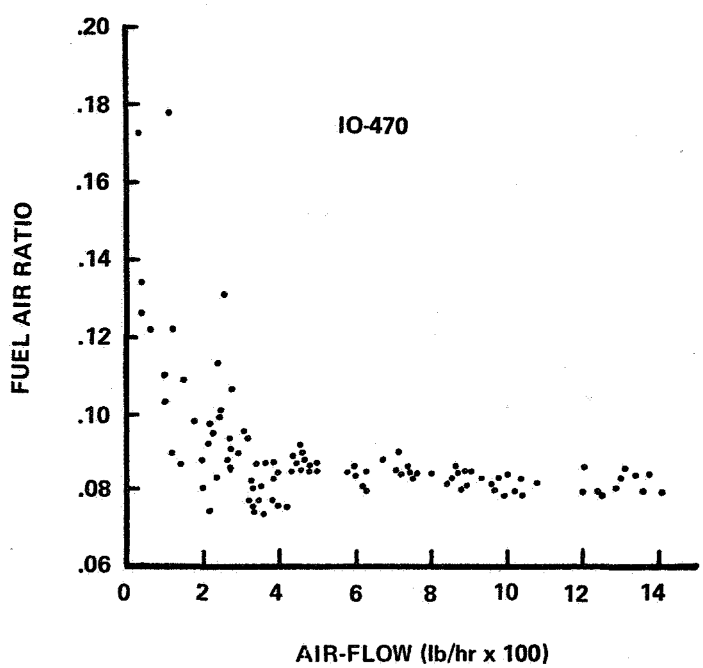
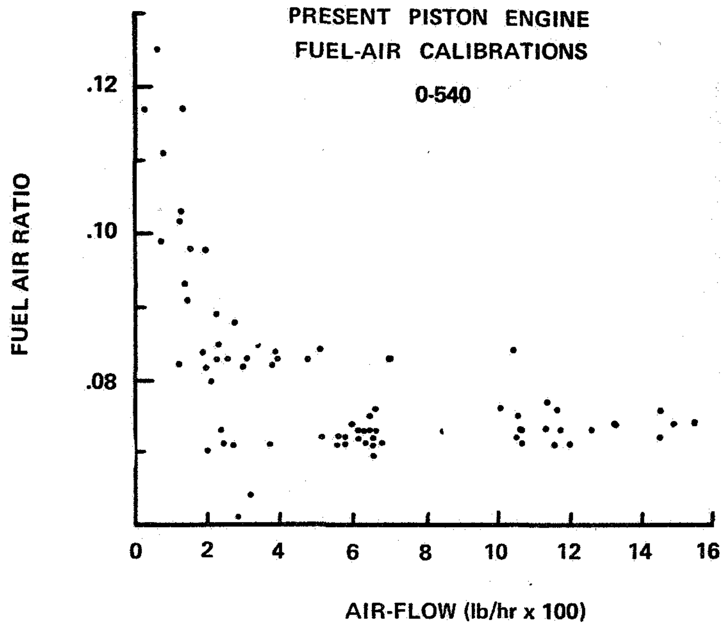

IO-470
FUEL AIR RATIO
.20
.18
.16
.14
.12
.10
.08
.06
0
2
4
6
8
10
12
14
AIR-FLOW (lb/hr x 100)

Figure 1-11


PRESENT PISTON ENGINE
FUEL-AIR CALIBRATIONS
0-540
FUEL AIR RATIO
.12
.10
.08
0
2
4
6
8
10
12
14
16
AIR-FLOW (lb/hr x 100)

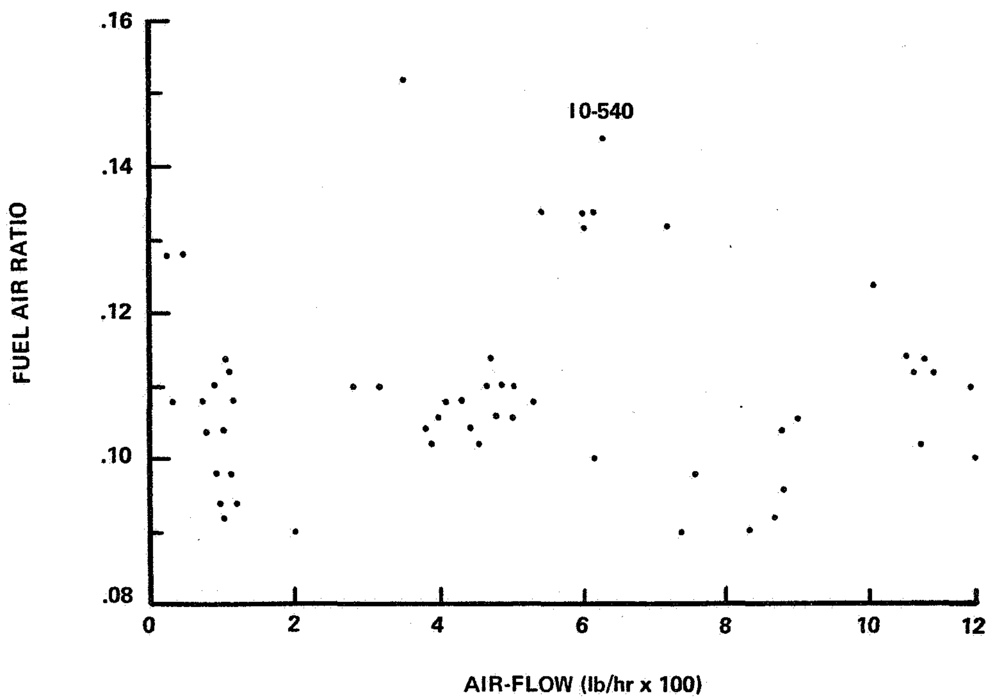

I0-540
FUEL AIR RATIO
.16
.14
.12
.10
.08
0
2
4
6
8
10
12
AIR-FLOW (lb/hr x 100)

Figure 1-12