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AIRCRAFT PISTON ENGINE EXHAUST EMISSIONS SYMPOSIUM

Lewis Research Center
Cleveland, Ohio 44135
September 14-15, 1976

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

A 2-day symposium on the reduction of exhaust emissions from aircraft piston engines was held on September 14 and 15, 1976, at the Lewis Research Center in Cleveland, Ohio. Papers were presented by both government organizations and the general aviation industry on the status of government contracts, emission measurement problems, data reduction procedures, flight testing, and emission reduction techniques. The proceedings contains all the papers that were presented as well as the discussion following each presentation. A list of attendees is also included.

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FOREWORD

The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the Environmental Protection Agency (EPA), and the general-aviation industry are actively involved in programs directed toward reducing exhaust emissions from aircraft piston engines. A two-day symposium was held at the NASA Lewis Research Center, Cleveland, Ohio, to provide those actively interested an opportunity to review and comment on information recently obtained on the nature of these emissions and efforts to reduce them.

This compilation contains all papers presented at that symposium. Two papers on the review of measurement problems were not presented at the symposium but are included here for the record. After each oral presentation, a question-and-answer period was allowed. These discussions and the presentations were recorded on tape and then edited for publication.

Attending the symposium were 77 people representing 20 organizations. A list of the attendees is included at the end of this compilation.

Gordon Banerian
NASA Headquarters
Chairman

Erwin E. Kempke, Jr.
NASA Lewis Research Center
Cochairman

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1. DEVELOPMENT OF EPA AIRCRAFT PISTON
ENGINE EMISSION STANDARDS

William Houtman

Office of Mobile Source Air Pollution Control
U.S. Environmental Protection Agency

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 not 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 nar-

rowed. 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 Environ-
   mental 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 Labora-
   tory, Inc., November 1971, Contract No. 68-04-0040.

4. "The Potential Impact of Aircraft Emissions Upon Air Quality." Pre-
   pared 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 Con-
   trol." 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 dis-
   tribution of air traffic, and the number of engines on each air-
   craft; 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 mea-
   surments 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 re-
viewer 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 man-
power 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
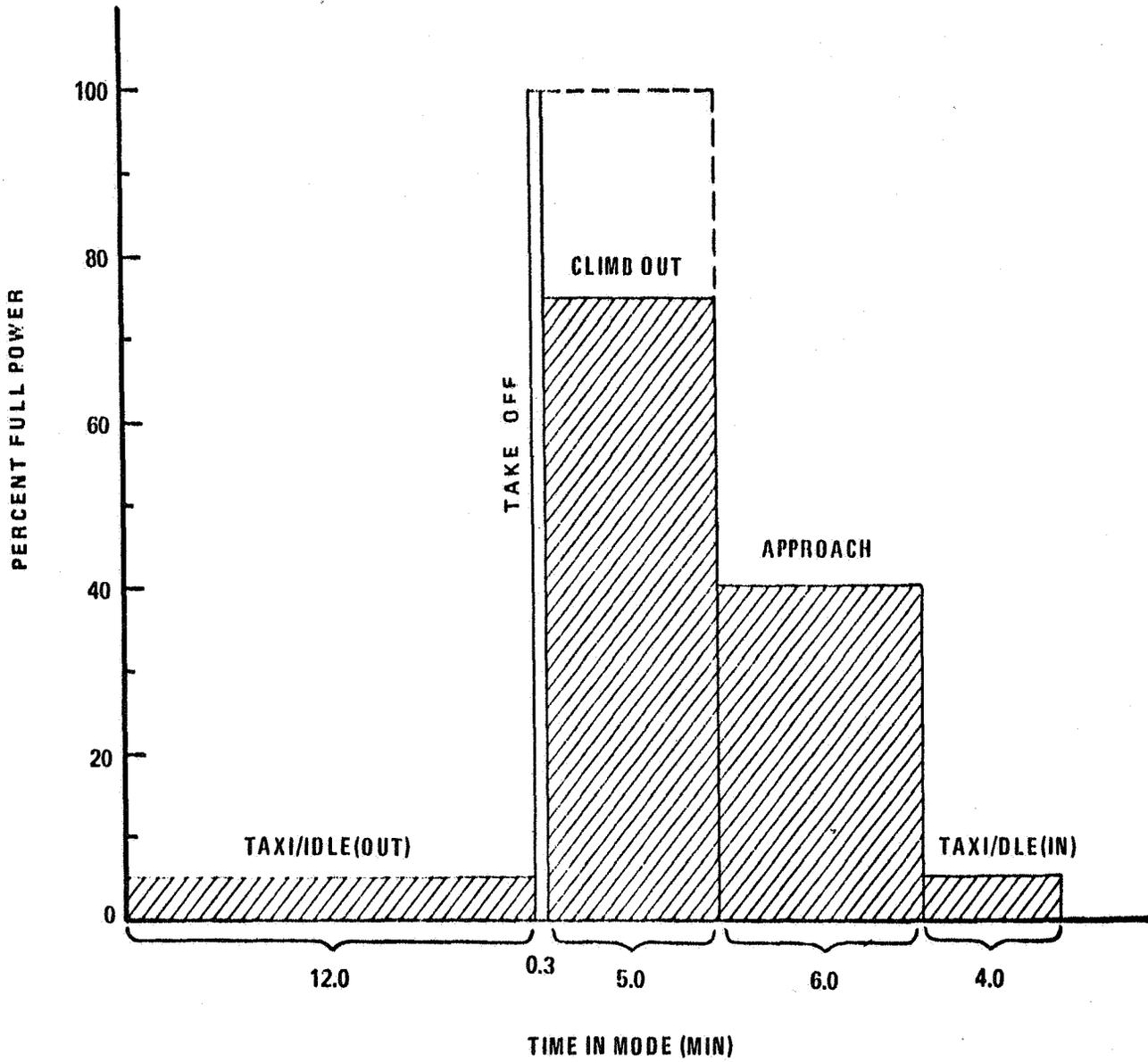
Figure 1-1

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

13

PISTON ENGINE EMISSION CHARACTERISTICS
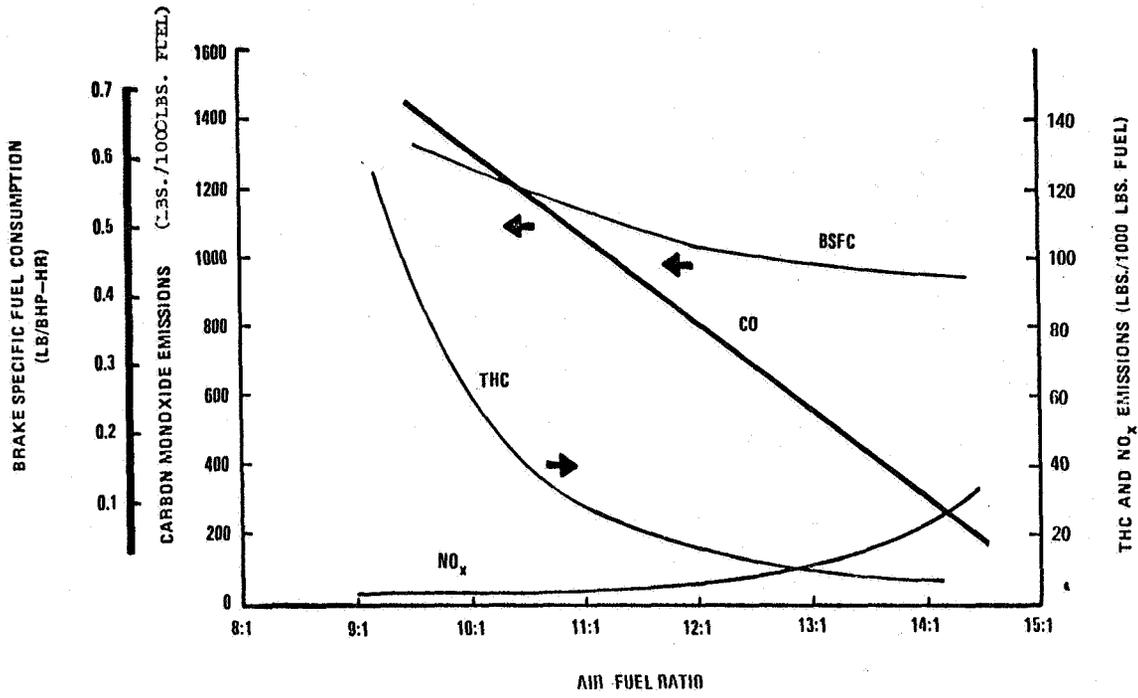
Figure 1-3

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
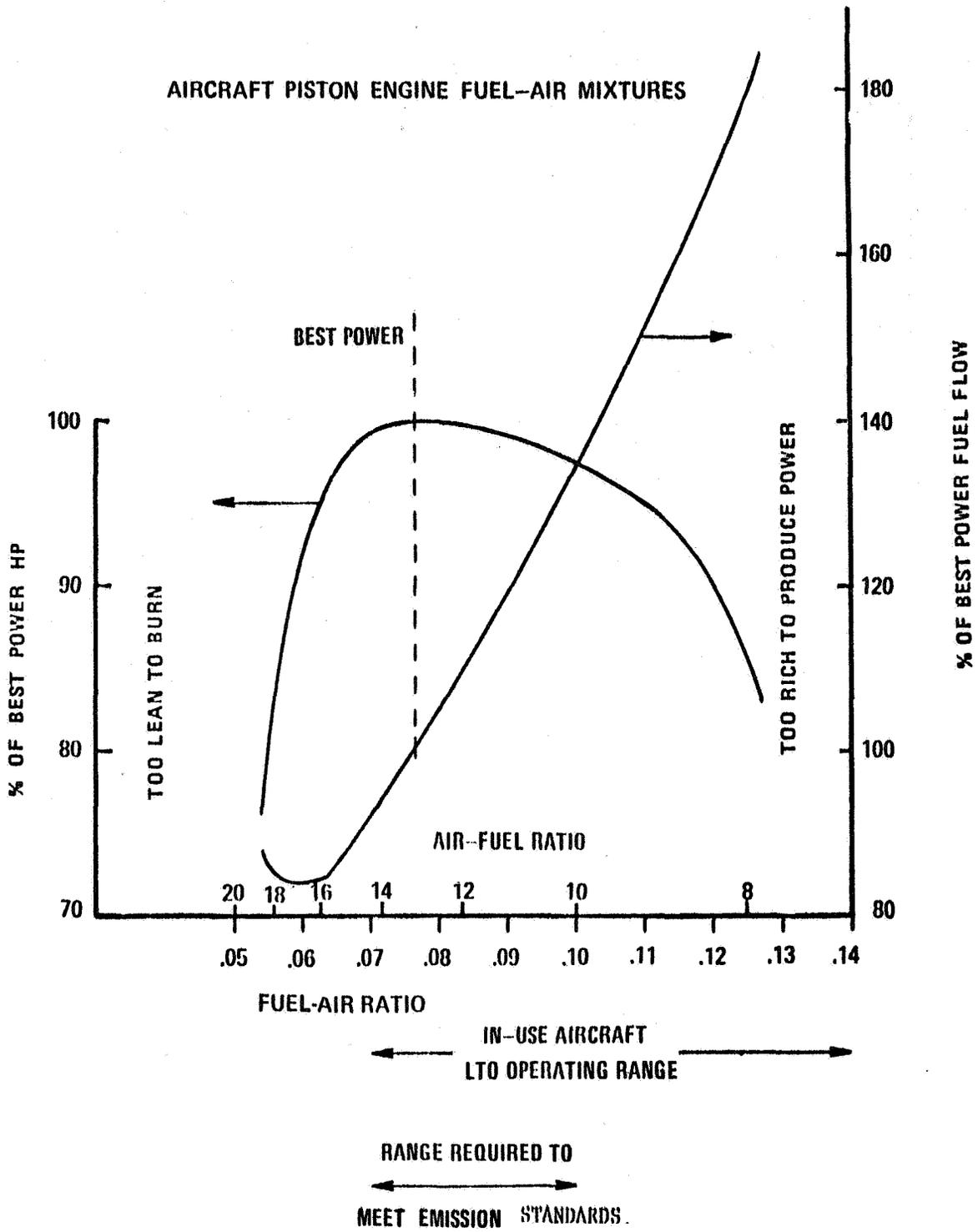
Figure 1-5

Figure 1-6

% CO EMISSIONS BY MODE
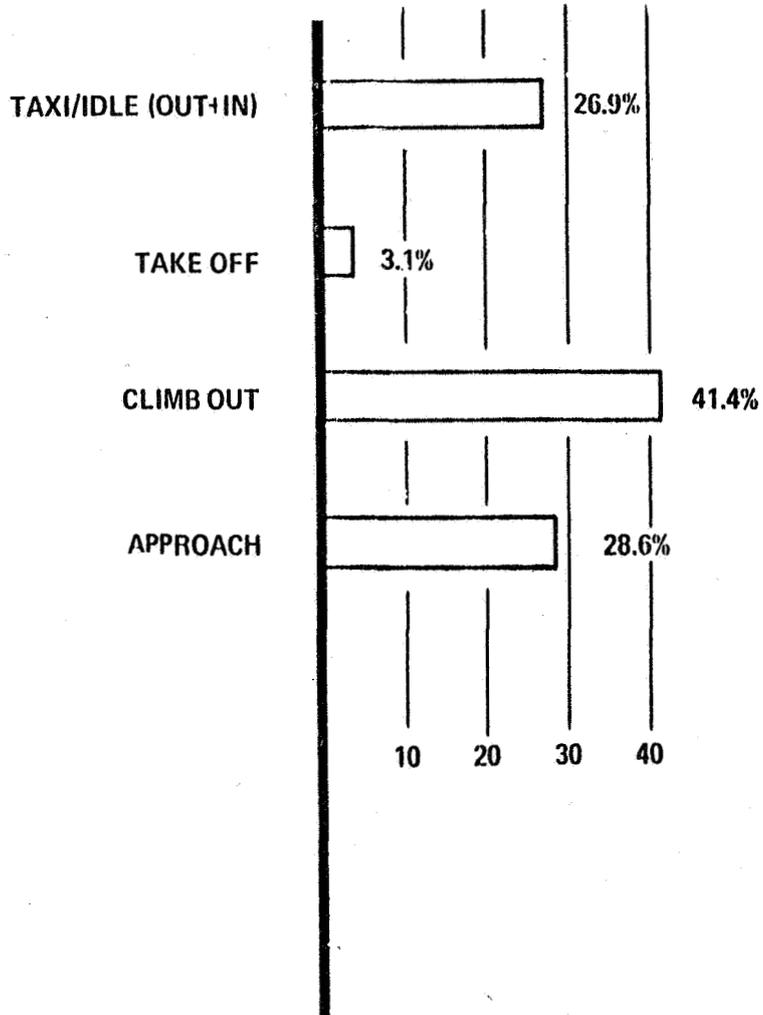
Figure 1-7

Sample Calculation
LTO Cycle Emissions

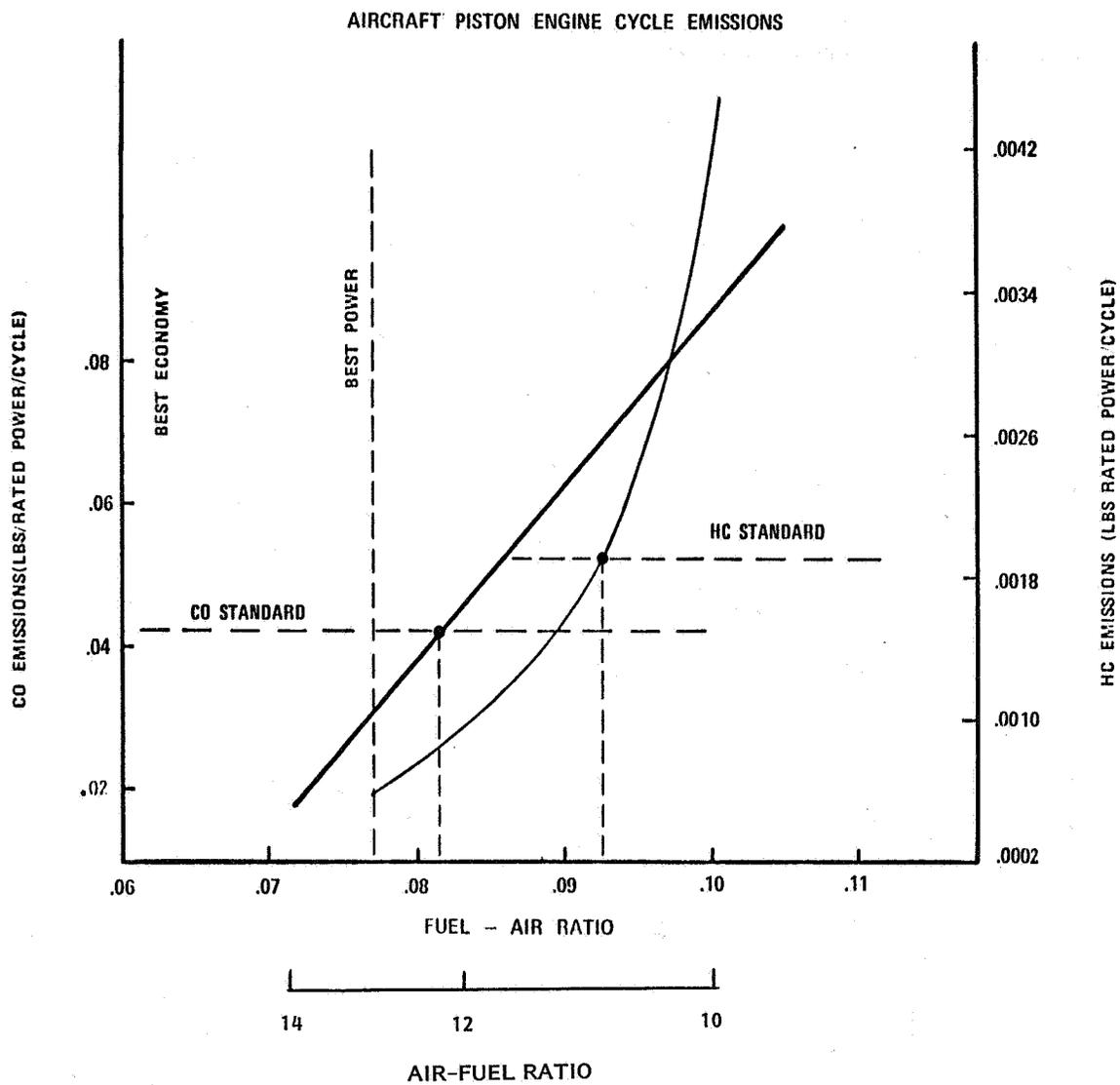|	A/F	$\dot{M}_{CO}/\dot{M}_f$	$\dot{M}_f/$bhp hr	% bhp	TIM hr	
Taxi/idle	13:1	.530	.45	.05	.27	.003
Takeoff (detonation suppression)	10:1	1.300	.62	1.00	.005	.004
Climbout (best power)	12.6:1	.650	.46	.80	.083	.020
Approach	13:1	.530	.45	.40	.10	.010

.037/.042

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

$\dfrac{\overset{\circ}{M}_{CO}}{\overset{\circ}{M}_f}$ = fuel specific emissions from Figure 3

$\dfrac{\overset{\circ}{M}_f}{\text{bhp-hr}}$ = brake specific fuel consumption from Figure 3

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

TIM = specified time in mode

Figure 1-8
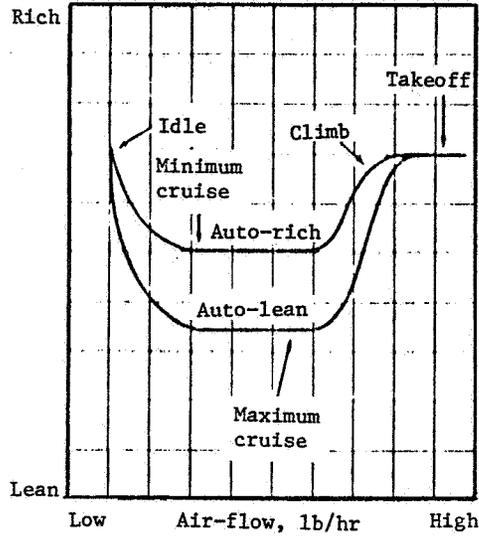
Typical fuel/air mixture curve
for injection-type carburetor.
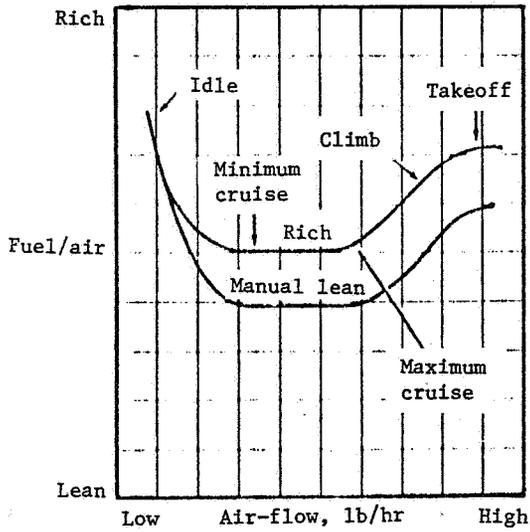
Typical fuel/air mixture curve
for float-type carburetor.

Idle mixture curve

Figure 1-9

PRESENT PISTON ENGINE FUEL-AIR CALIBRATIONS

0-200

FUEL AIR RATIO

AIR-FLOW (lb/hr x 100)

IO-360

FUEL AIR RATIO

AIR-FLOW (lb/hr x 100)

Figure 1-10

PRESENT PISTON ENGINE
FUEL-AIR CALIBRATIONS

0-470

IO-470

Figure 1-11

Figure 1-12
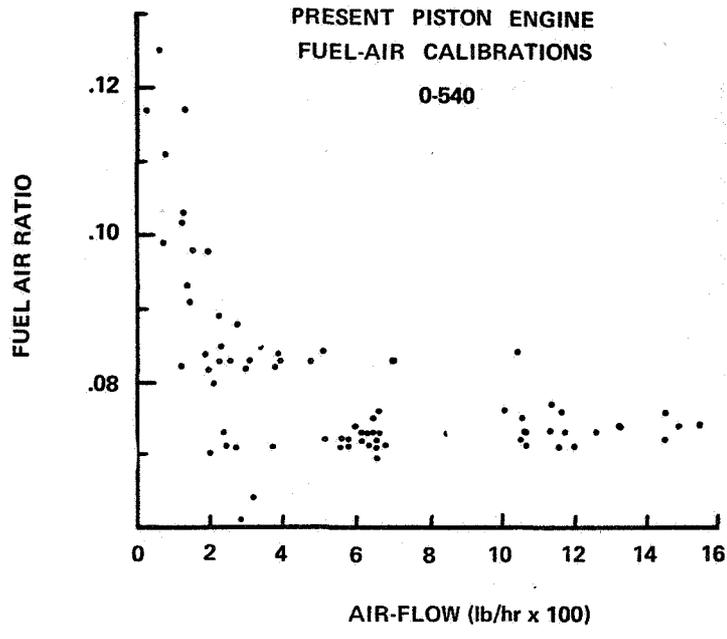
2. APPLICATION OF AUTOMOBILE EMISSION CONTROL TECHNOLOGY

TO LIGHT PISTON AIRCRAFT ENGINES

David Tripp and George Kittredge

Office of Mobile Source Air Pollution Control
U.S. Environmental Protection Agency

INTRODUCTION

The interest of the Federal Government in the subject of pollutant emissions from aircraft powerplants was stimulated by the Air Quality Act of 1967, which required the (then) National Air Pollution Control Administration of the Department of Health, Education, and Welfare to carry out a study and prepare a report describing the environmental effects of emissions from aircraft and suggesting methods for reducing aircraft emissions.

In this study (ref. 1), some attention was given to horizontally opposed piston engines powering light aircraft, although there were no experimental data available to support this discussion. Consequently, it was simply estimated that the rich air-fuel mixtures which are characteristic of all known light aircraft powerp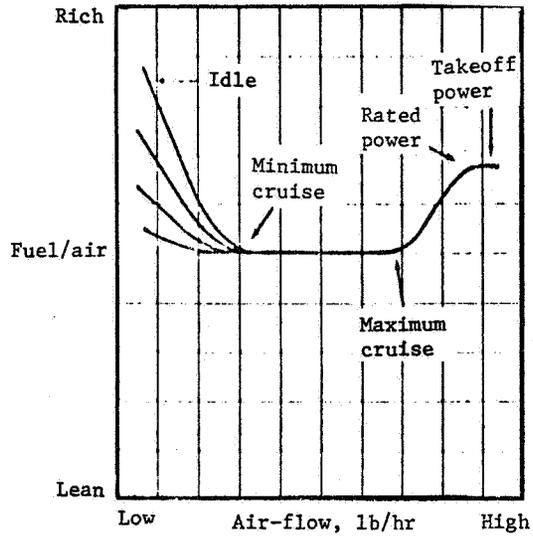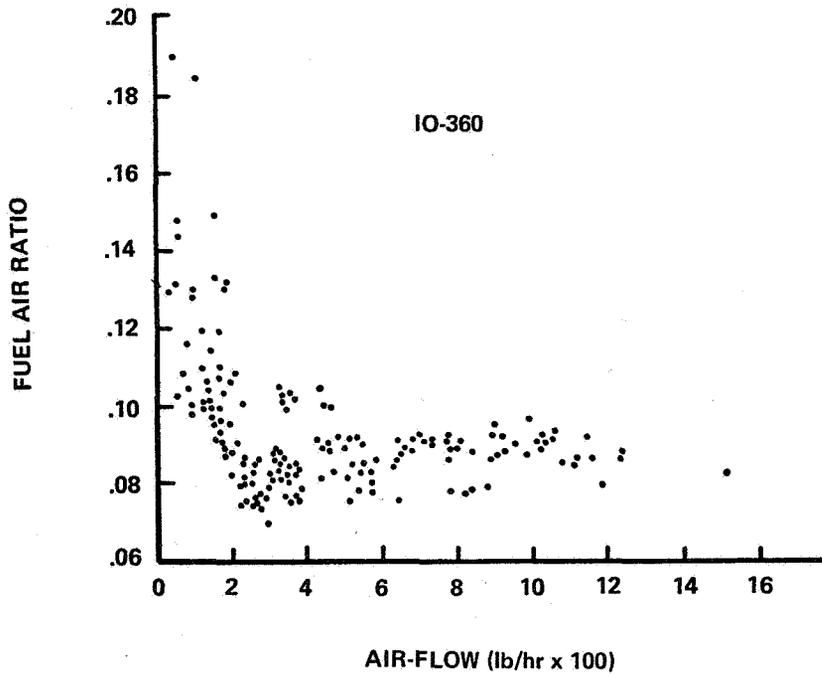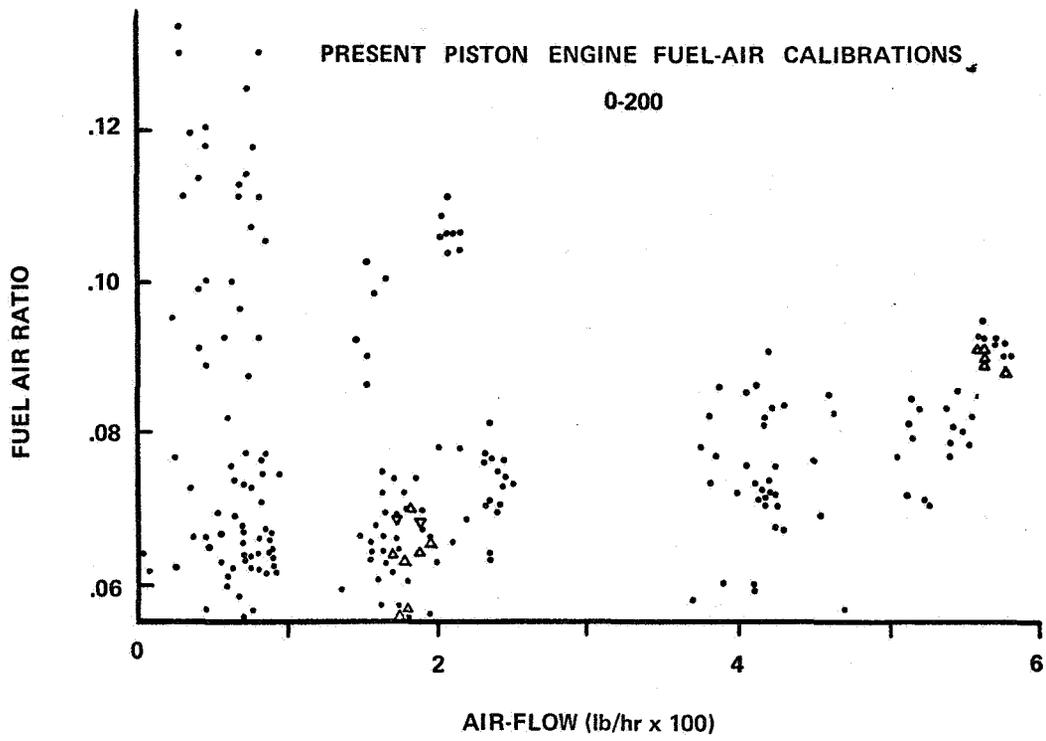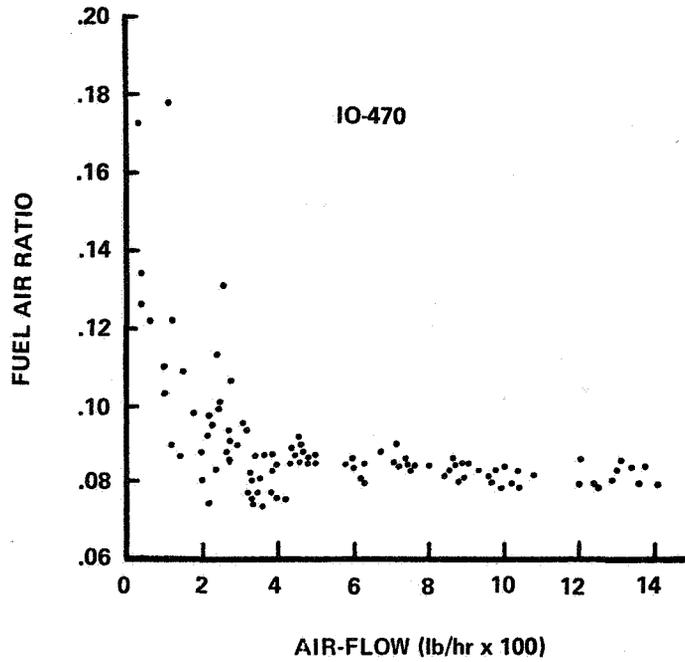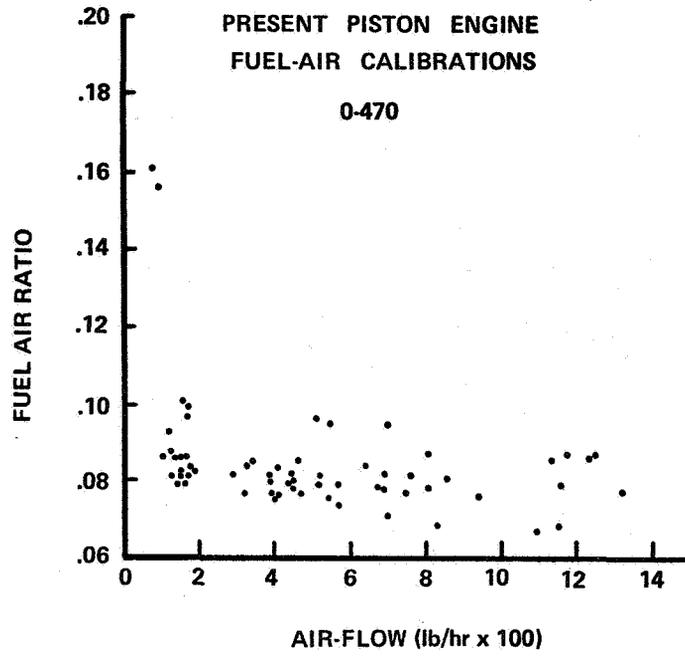lants would cause them to have relatively high carbon monoxide and hydrocarbon emissions, but low nitrogen oxide emissions, compared to automobiles of that period (1968). In this report, it was assumed that to reduce these emissions it would be necessary to employ exhaust system reactors of some type, because the basic design and operating characteristics of the engines could not safely be altered.

To respond to the need for emissions data on this type of power-plant, a flight test program was initiated in 1969 through a contract to Scott Research Laboratories of Plumsteadville, Pennsylvania. In this project, nine light aircraft representing various configurations and powerplant types were operated through a standard landing/takeoff cycle during which samples were taken from the exhaust stream for pollutant analysis. The report describing this work (ref. 2) verified that the carbon monoxide emissions over the LTO cycle were quite high compared to automobiles, hydrocarbon emissions were about the same and nitrogen oxide emissions were very low. In considering potential control technology, some attention was paid to the potential of "leaning" the engine air-fuel

ratio at nonpeak power engine operating modes, particularly at idle
and taxi, but most attention was paid to the possibilities offered by
exhaust system reactors of either catalytic or thermal types.

During the study carried out in 1971 in response to the varied
aircraft requirements of the Clean Air Act of 1970, further attention
was given to documenting both the basic emissions characteristics of
existing light aircraft power plants (described in another paper) and
to methods for their reduction upon which emissions standards could be
based. At the same time, a project was initiated under contract to
Bendix Research Laboratories, Southfield, Michigan, to investigate ex-
perimentally the levels of emissions achievable by modifying light air-
craft engines to permit the installation of emissions control devices
such as air pumps and thermal and catalytic reactors. The influence on
emissions of variations in engine adjustments such as air-fuel ratio and
ignition timing was also studied. The results of this work showed
(ref. 3) that various combinations of air-fuel ratio settings and operat-
ing modes existed with the two engines tested which successfully reduced
the emissions to values at or below the levels subsequently promulgated
as federal standards. The exhaust treatment approaches also were suc-
cessful in reducing emissions, to varying degrees, but not with suffi-
ciently greater effectiveness to offset their added expense, weight,
and bulk. The study concluded that "further investigation of piston en-
gine emissions should initially emphasize fuel and air management over
exhaust treatment as the most promising approach to the control of emis-
sions from light piston engine aircraft." It was pointed out that if
engine overheating or other considerations interferred with satisfactory
lean mixture operations, additional measures short of "add-on" exhaust
treatment devices would be to "improve air-fuel preparation and distribu-
tion for more precise control of the mixture in individual cylinders.
This would allow increased average leanness with minimum increases in in-
dividual cylinder and exhaust port temperatures."

Therefore, the approaches considered by EPA as potentially useful
for reducing emissions from light aircraft powerplants ranged from an
early emphasis on exhaust treatment only to an ultimate preference for
mixture enleanment coupled with whatever ancillary improvements in air-
fuel mixture preparation, distribution, and engine cooling as were needed
to permit such enleanment. The control of hydrocarbon emissions through
retarded ignition timing, in contrast, has never been of particular in-
terest to the EPA as applied to aircraft engines, because of its predicted
ineffectiveness with the very rich mixtures characteristic of aircraft
engines and because of the need to minimize degradation of engine power
and fuel consumption performance.

Since the time of publication of these earlier reports, intensive
engineering studies have been carried out by all of the auto makers to
develop technology capable of achieving the extremely low emissions re-
quirements for such vehicles required by the Clean Air Act. From the
perspective of having studied and evaluated the approaches being taken

by the automakers, it is now possible to take another look at the particular problems posed by reduction of emissions from light aircraft powerplants.

CHARACTERISTICS OF AIRCRAFT ENGINES WHICH INFLUENCE THE

DESIGN OF EMISSIONS CONTROLS

This section will review some of the basic considerations which strongly influence the types of emissions control approaches which can be considered for light aircraft piston engines.

The first of these is that aircraft engines, in contrast to their automobile counterparts, must be designed to operate at maximum power conditions part of the time during every single flight, while there are probably automobile engines in service which never experience maximum power operation. To ensure safe and reliable operation under these conditions, rich air-fuel ratios are employed to help maintain safe cylinder temperatures and to prevent detonation, keeping in mind that all modern aircraft piston engines employ air cooling. These rich mixtures cause high carbon monoxide and hydrocarbon emissions. The potential for reduced emissions through operation at leaner mixtures at maximum power conditions, is limited by the extent to which cylinder cooling can be improved by other measures. (In contrast, there is much more latitude for controlling these two pollutants by employing leaner mixtures at all other power conditions, where cooling is not so critical a problem.)

To maximize the power available to meet takeoff requirements, valve timing is usually optimized for highest specific output at high performance conditions, which leads to high carbon monoxide and hydrocarbon levels (but low nitrogen oxide levels) at low power conditions. A compromise in valve timing to improve emissions would require sacrifices in peak power performance which are probably unacceptable.

Minimization of powerplant weight and bulk is a key constraint in all aeronautical propulsion applications; this constraint limits the use of emissions control devices which represent new additions to the basic engine (as opposed to redesign of existing engine components). Examples of such emissions control devices include thermal reactors, catalysts, and air injection systems. While such devices should not be absolutely excluded from consideration, they should be carefully screened for their ability to do the job with the least adverse impact on weight and space.

The wide range of environmental conditions which may be encountered by aircraft powerplants must be considered when developing the emissions control system. Even though it need only function at altitudes under 3000 feet, it must be compatible in all respects with the total aircraft operating environment.

On the plus side, there are certain characteristics of light air-
craft powerplants which tend to work in favor of achieving and main-
taining low emissions, which do not exist with automobile powerplants.
These include the following:

(1) Carefully controlled preventative maintenance programs are
required of all aircraft components for safety and reliability. This
should help to ensure that any initial level of emissions control
achieved with new engines will be maintained in service to a much
greater degree than is characteristic, unfortunately, of automobiles.

(2) The normal practice of utilizing dual, independent ignition
systems with two spark plugs per cylinder also should contribute to
maintenance of low emissions levels in service, as well as helping to
minimize a quenching of hydrocarbon oxidation reactions in the combus-
tion chamber.

(3) The lesser degree of engine operation under transient speed/
load conditions compared to automobiles should minimize some of the
problems in the area of "driveability" or engine responsiveness which
have required much attention in the engineering of integrated emissions
control systems for automobiles. In terms of the EPA Standards, the
absence of a requirement to minimize emissions from light aircraft en-
gines under cold start conditions eliminates one major and difficult
requirement which the auto makers have had to respond to.

DISCUSSION OF POTENTIALLY APPLICABLE EMISSION CONTROL TECHNOLOGY

This section will address the alternative emission control ap-
proaches available for light piston aircraft usage.

Air-Fuel Ratio Enleanment

Air-fuel enleanment will be the first emission control approach
to be discussed. This is appropriate because air-fuel ratio enlean-
ment is both an important control technique by itself and is intimately
related to other control approaches. The general relationships between
air-fuel ratio and the important parameters of brake specific emissions
and fuel economy are shown in figure 2-1 (ref. 3).

The technique of running the engine with less excess fuel has other
benefits besides just emission control. Figure 2-1 shows the same trend
that is well known for most conventional engines - leaner operation
toward stoichiometric from the rich side improves fuel economy. The
fuel consumption benefits obtainable from leaner engine operation may
warrant consideration for implementation from a fuel conservation stand-

point alone, even if there were no concern for emission control.

During the Landing Take-Off (LTO) cycle, current light piston air-craft (LPA) generally operate with air-fuel ratios in the range of 10:1 to 12:1 (ref. 4). Based on this knowledge and the previous figure, one draws the immediate conclusion that air-fuel ratio enleanment is a fertile area of potential control. While this fact appears to be ac-knowledged by all, controversy exists regarding the degree to which enleanment can be safely and effectively utilized. To comprehend this rather complex situation, one must first have a good understanding of why current LPA operate at such a rich air-fuel ratio during the LTO. The answer to this is that enrichment is a cheap and effective means of overcoming fuel metering and overheating problems.

Fuel metering problems. - The principal fuel metering problems as-sociated with carbureted LPA are poor distribution and transport lag. Both arise from the fact that carburetors are not totally effective in vaporizing fuel and as a result the carburetor delivers to the intake manifolding a nonhomogeneous mixture of air along with fuel in the va-por, liquid and droplet forms. For efficient engine performance, the manifolding must deliver under both steady-state and transient condi-tions an accurate, equal portion of this mixture to each cylinder. Un-fortunately, this nonhomogeneous mixture does not behave well in terms of flowing over the long distances typical of LPA intake manifolds and adjusting to transient operation and differing flow rates. The in-take manifold runners of LPA engines are significantly longer than auto-motive type runners as a consequence of the basic engine configuration. Automotive engines are generally of an in-line or Vee construction with the intake manifold on the side in the case of the in-line or nestled between the cylinder banks of the Vee. In contrast modern LPA engines are exclusively of the opposed cylinder design. Feeding the cylinders of an opposed engine with a single carburetor requires that the intake manifold passages span the distance from the centerline of the crackshaft to the cylinder heads, in addition to the full lengthwise dimension of the engine. Automotive manifolds generally only have to cover the lengthwise dimension. The result is unequal cylinder to cylinder air-fuel ratio distribution and poor transient performance (e.g., momentary enleanment under rapid throttle opening).

To offset these problems, LPA engine manufacturers have calibrated their carbureted engines with very rich mixtures so that even under the worst combination of the conditions LPA engines would not suffer from poor responsiveness under the fluctuating throttle requirements of landing and takeoff operations. Fuel injected engines for LPA probably do not suffer as much from the maldistribution and transport lag of carbureted engines. They do, however, have problems associated with conditions of low fuel flow. To effectively atomize the fuel, the fuel injector nozzle must emit the fuel in a fine spray. Unfortunately, cur-rent systems at low flow conditions frequently emit the fuel as a weak

stream or dribble. Curing this problem is considered to be a straight-forward matter of improving nozzle design and injection pressure ratios (ref. 5).

Another factor that comes into play in LPA fuel metering is the effects of varying air and fuel density. LPA engine manufacturers must provide enough margin of richness to overcome all the combined conditions of high and low altitude, warm and cold air, and warm and cold fuel. This problem is greatly reduced by automatic mixture control, which automatically compensates for changes in barometric pressure and fuel temperature. This concept can be applied to both fuel injection and carburetion systems.

If it is presumed that the LPA industry and their normal suppliers can solve the temperature and pressure compensation and fuel injection dribble problems, then the remaining problems related to LPA engine responsiveness under enleaned conditions are fuel maldistribution and transport lag problems.

Techniques to help solve these problems can be extracted from automotive technology. These techniques fit into the general categories of (1) improved fuel metering and (2) improved fuel air mixture management and distribution.

(1) Improved fuel metering: As previously discussed, fuel injection has important inherent advantages over carburetion in LPA applications. Thus one logical approach to improve LPA fuel metering would be to expand the usage of fuel injection systems. If LPA manufacturers elect to retain carburetion, attention should be devoted to improvement in the areas of acceleration enrichment and power enrichment.

To understand the need for and role of acceleration enrichment one must first understand that the air-fuel mixture moves through the intake manifolding as a combination of vapor, liquid, and droplets. Due to the dynamics of the situation, the liquids and droplets travel at a slower rate than the air. As the throttle is opened to provide increased power the manifold absolute pressure increases. This causes some of the vapor and droplets to condense and merge into the film that is moving along the manifold walls. Since this film is traveling much slower than the air, there occurs a fuel transport lag. This occurs in automotive installations in a similar manner and it is counteracted by acceleration enrichment. Generally taking the form of an accelerator pump, acceleration enrichment meters into the intake air stream a spray of fuel proportionate to the rate of throttle opening. This spray of fuel helps make up for the fuel that condensed into the wall film.

Power enrichment is intended to tailor the air-fuel mixture to the power demands of the engine. At low power, the air-fuel ratio can be in a relatively lean regime; when the operator demands full power, the fuel metering system can be designed to automatically enrichen the mixture. This is usually accomplished by having an enrichment circuit activated by large throttle openings.

Fuel injected engines also need power enrichment and it is understood that some LPA fuel injection systems have this feature at present. It would appear to be desirable for all LPA fuel injection systems to have this feature.

A recent inovation in fuel metering is a carburetor that makes use of a standing sonic wave in the carburetor throat to improve fuel atomization. Figure 2-2 shows the operating principle behind a sonic carburetor developed by Dresser Industries.

The Dresser concept is to achieve fine fuel atomization over a wide range of operating conditions by maintaining a choked flow condition in the carburetor throat and metering fuel upstream of the throat. The fuel must pass through the shock wave that occurs when the flow goes subsonic in the diffuser which is located downstream of the throat. The extremely fine droplet sizes reportedly created by the Dresserator (10-μ diam) allow uniform air-fuel ratios to be achieved during warmup and transient conditions that cause variability problems with conventional carburetors.

Another recent development in fuel metering is a hybrid between carburetion and fuel injection. Commonly known as single point injection, it utilizes fuel injection techniques for determining the fuel flow rate and it uses a pressurized nozzle for introducing fuel into the air stream. It departs from fuel injection, however, by injecting the fuel at a central location in the intake manifold. An example of this type system is illustrated in figure 2-3.

(2) Improved fuel mixture management and distribution: The opposed cylinder layout of LPA engines makes rather long intake manifold runners unavoidable. As explained before, these runners contribute to maldistribution and transport lag problems. Fuel injection helps to circumvent the problem since it injects the fuel at the intake port. The problems can be minimized with carbureted systems by mounting the carburetor centrally over the engine. This will allow the manifold runners to be made as equivalent in length as possible. Manifold heating would also assist in improving vaporization and reducing the wall film effect.

Another approach to correct the vaporization and distribution problems is to improve the mixing of the air-fuel mixture in the in-

take manifold and thereby produce a better atomized, more homogeneous
mixture. Ethyl Corporation has developed a turbulent flow system (TFS)
to accomplish this. Shown in figures 2-4 and 2-5 are the essential fea-
tures of the TFS: the long mixing tube below the primary venturi, the
change of flow direction in the mixing box, and the secondary venturi
bypass. The long mixing tube allows the air-fuel mixture downstream of
the throttle to become more uniform. Changing the flow direction in-
creases turbulence which improves the mixture quality and causes large
fuel droplets to fall onto the mixing box floor where they are vaporized
before reentering the stream. The secondary flow bypasses the mixing
box to minimize pumping losses, thus minimizing losses in volumetric ef-
ficiency.

Overheating problems. - As stated earlier, LPA engines utilize rich
air-fuel ratios to overcome overheating problems in addition to fuel
metering problems.

It is well known that richer mixtures burn at lower temperatures.
The explanation for this is that the surplus fuel consumes thermal en-
ergy during its vaporization and heating in the combustion chamber.
LPA engine installations have traditionally used enrichment to overcome
the high cooling requirements of the takeoff and climbout modes. Enlean-
ment to reduce emissions will increase the cooling requirements and in
some installations overtemperature conditions may be experienced. A so-
lution to this problem would be to improve the engine's ability to cool
itself and/or to improve the engines tolerance to high temperatures.
One approach to improving the engine's ability to cool itself would be
to better optimize the cooling fin configurations. Improvements may be
possible in this area. Avco has recently developed a "low drag head"
version of their 541 series engine which features increased spacing be-
tween the cooling fins. Similarly, Teledyne's new Tiara series engine
has increased fin spacing. The theory behind these new fin designs is
that the greater fin spacing will present less resistance to the cooling
air flow and will thereby increase the flow and improve cooling. A fun-
damental limiting condition in the ability of LPA engines to cool satis-
factorily is their sole reliance upon ram air flow from the propeller.
A very significant improvement in cooling would result from the adoption
of an engine powered cooling fan. This change may result in weight,
cost, and reliability penalties but these might be more than offset by
the improved cooling and resultant improved power and fuel economy dur-
ing LTO operations. Cooling fans are presently used in helicopters
powered by LPA engines.

Another approach to improving cooling would be to improve the heat
transfer from the cylinder barrel. Currently all cylinder barrels ex-
cept those on the Teledyne Continental Motors Tiara engines are of a
one piece steel construction. Steel has the needed wear resistance but
is a relatively poor heat conductor. A better arrangement might be the
approach used by Porsche on their air-cooled Carrera engines. Porsche
uses an aluminum cylinder barrel which has excellent heat-transfer char-

acteristics and applies a hard nickel alloy coating to the surfaces
exposed to wear. While it is recognized that the most critical over-
heating problems are experienced in the cylinder head area, not in the
cylinder barrel, the aluminum cylinder barrel could help alleviate the
situation by conducting heat away from the head area. A significant
cost reduction might result from the changeover from the very expensive
process of machining the steel cylinders from solid stock to casting
them in aluminum.

Another approach is one that has been adopted by the U.S. Army on
their air-cooled diesel tank engines. The technique is to cast a
hemispherically shaped alloy steel cap into the combustion chamber.
This cap is welded to the steel cylinder liner and is temperature and
wear resistant. It is called the Unisteel Cylinder and is manufactured
by Teledyne Continental Motors.

Another technique which will lower the cooling requirements of the
critically important exhaust port area is the use of exhaust port liners.
Figure 2-6 shows a relatively simple example of one. Exhaust port liners
can be double walled with an air gap or they may use an insulative ma-
terial such as Kaowool. Conceived originally as a means of conserving
exhaust gas heat to promote after reaction of pollutants, exhaust port
liners effectively reduce the heat transfer to the exhaust passage area.
Of course, a concurrent benefit of exhaust port liners is that by con-
serving the exhaust gas heat the effectiveness of afterreaction tech-
niques for HC and CO reduction can be dramatically improved. This is
further discussed in the following section.

Air Injection

Secondary air injection has been used as an effective HC and CO
control device since the late 1960's. The fundamental technique is the
introduction of air into the exhaust stream in the vicinity of the ex-
haust port. This serves to promote the afterreaction of HC and CO.
The air is supplied by an engine driven pump. This technique appears to
particularly appropriate to LPA because of their very rich operation and
resultant lack of oxygen in the exhaust.

When operated at the rich air-fuel ratios typical of current LPA
engines during LTO cycles, the exhaust gas temperatures may be too low
during low power modes to achieve significant afterreaction. This may
be counteracted, in part at least, by enleanment which will raise the ex-
haust gas temperature. Another means of raising exhaust gas tempera-
ture is through the use of exhaust port liners.

Discussed in the previous section as means of alleviating overheat-
ing problems, exhaust port liners have demonstrated the capability to
increase exhaust gas temperatures by as much as 100° F (ref. 6). To

maximize the effectiveness of air injection and exhaust port liners, they can be integrated into a combined unit as shown in figure 2-7 (ref. 7).

A further optimization of air injection and heat conservation will result if the exhaust piping between the exhaust ports and the mufflers are made of a double wall construction. One automobile maker (Subaru) uses this technique and insulates the area between the inner and outer pipes with Kaowool.

Some installation difficulties may need to be overcome to accommodate an air injection system in LPA's. One of these is the installation and drive system for the air pump. Current aircraft commonly have differing combinations of engine driven accessories. These include alternators, hydraulic pumps, air conditioning compressors, and vacuum pumps for deicing equipment. It appears reasonable to consider that an air pump could also be accommodated.

The power absorbed by the air pump is proportional to the air flow rate. The optimum flow rate appears to be that amount that will bring exhaust up to stoichiometry (ref. 3). Thus, whatever is done in the way of enleanment will reduce the air flow requirement.

Horsepower consumption data for automotive air pumps is rather sparse, but figure 2-8 provides data for a typical installation (ref. 8). Automotive pumps are positive-displacement, carbon vane units. The flow output is proportional to pump speed and the pressure is only the few psi necessary to overcome the exhaust overpressure.

An alternative means of introducing air into the exhaust makes use of the negative pressure pulsations at the exhaust port to aspirate air into the exhaust stream. Used by General Motors (ref. 9) and Subaru, the system has the advantage of requiring no air pump. GM calls their system Pulsair and Subaru uses the term air suction valve. Figure 2-9 shows the Subaru installation (ref. 10). There are many variations of this type of system including arrangements that have a separate aspirator valve for each cylinder. Successful application of aspirator systems requires a certain amount of tuning of the aspirator piping. In addition, the air flow capacity is believed to be more limited than with an air pump system.

A potential problem associated with air injection systems is the increased temperature of the exhaust piping. As previously discussed, this can be alleviated by adopting double wall piping. Another means of resolving this would be to modify the cooling air shrouding to direct more air over the exhaust piping.

Valve Timing

An important contributing factor in LPA HC emissions is the large amount of valve overlap customarily used. Large overlap is employed to maximize horsepower output within the constraint of maximum allowable engine speed. A more conventional approach for increasing an engine's specific power is to increase its speed. LPA manufacturers, however, apparently to some degree work under the self-imposed limitation of restricting the maximum engine rpm to a speed that will not cause a directly coupled two bladed propeller to exceed Mach 1 at the tip. This typically works out to be in the neighborhood of 2700 to 2900 rpm. To obtain high specific power outputs at this rather low maximum speed, LPA engines employ a large amount of valve overlap. Automotive experience tells us that as overlap increases, HC emissions tend to increase as well. This results from short circuiting of the intake charge to the exhaust and misfire caused by dilution of the intake charge by the exhaust. One way to circumvent this maximum speed limitation is to use speed reduction gearing between the engines and the propeller. This is currently used on some installations. Another approach which should be explored is the use of three or four bladed propellers having smaller tip diameters. This would allow increased maximum engine speed. Increased allowable speed will make possible a reduction in valve overlap. This increased speed can also be utilized to make up in power output for any losses resulting from emission control related changes.

Thermal Reactors and Catalytic Converters

Thermal reactors and catalytic converters have demonstrated good capability for reducing LPA emissions. Effective techniques for the utilization of these approaches on LPA are contained in the previously referenced report prepared by Bendix Corp. (ref. 3).

This paper gives a thorough accounting of the merits and demerits of these approaches and it would be repetitious to present the material in this report. Moreover, the appropriateness or need for these techniques is questionable in light of the reduction levels called for in the LPA emission standards.

Integrating Available Emission Control Technology with LPA Requirements

Before discussing the effectual bringing together of available technology, it should be pointed out that several important elements of proven emission control technology have not been discussed. Among these are exhaust gas recirculation (EGR), high energy ignition (HEI), and spark advance tailoring. EGR is effective at controlling NO_x and has the added benefit of suppressing detonation.

Figure 2-10 illustrates the relative effectiveness and the approximate degree of improvement obtainable using several of the control measures discussed in this paper. The heavy duty engine in this testing was a 350 cubic inch Chevrolet. The emission figures were calculated using test results from the heavy duty Federal Test Procedure. Given the variety of control approaches available, the question appears to be - How can these approaches be best integrated or combined to achieve the desired emission reductions with the minimum adverse effects upon aircraft cost, complexity, performance and safety?

While every engine installation has its own peculiarities and emission reduction needs, it appears that a good general guideline to follow is to take advantage of the synergistic relationships between the different control approaches. For example, enleanment reduces HC and CO directly, but it also raises the exhaust temperature which increases the effectiveness of after treatment techniques, such as air injection. Likewise, exhaust port liners alleviate the engine temperature problems due to enleanment by insulating the exhaust port area and at the same time conserve the exhaust gas heat, thereby further improving the effectiveness of afterreaction techniques. Thus, it can be seen that used wisely, different emission control measures can combine synergistically to reinforce their effectiveness while at the same time diminishing their adverse effects.

It also appears that the relative need to reduce HC and CO emissions at the expense of a rise in NO_x emissions must be taken into account in the selection of the approaches to be used.

CONCLUSIONS

There are excellent possibility for achieving the EPA Standards for HC and CO emissions through the use of air-fuel ratio enleanment at selected power modes combined with improved air-fuel mixture preparation, and in some cases improved cooling.

Air injection is also an effective approach for the reduction of HC and CO, particularly when combined with exhaust heat conservation techniques such as exhaust port liners.

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DISCUSSION

Q - B. Rezy: That was a very interesting talk you gave on the different
concepts. Most of our comments to this section will be incorporated
tomorrow in our presentation of the different concepts that we've
studied under the NASA program. Under this program we evaluated the
concepts you presented not only as to their feasibility to reduce
emissions but their impact on 14 other design criteria such as per-
formance, cooling, cost, reliability, etc.

A - D. Tripp: EPA realizes that the industry has looked at these tech-
niques. We were asked to prepare a paper, and I think it has value
because it gives you in printed form what we feel are the most val-
uable techniques. I would comment that exhaust port liners are
pretty exciting because they have the combined benefits of not only
reducing the cooling load but also improving the after reaction. In
previous meetings there wasn't much discussion of the exhaust port
liners.

Q - S. Jedrziewski: You stated that most of the engines now produced
are injected rather than carbureted. This isn't quite true. Ap-
proximately half of the Lycoming engines are carbureted.

A - D. Tripp: I believe 80 percent of the Teledyne's engines are fuel
injected. When I said most, I was thinking of both manufacturers.

Figure 2-1

Sonic Fuel Metering
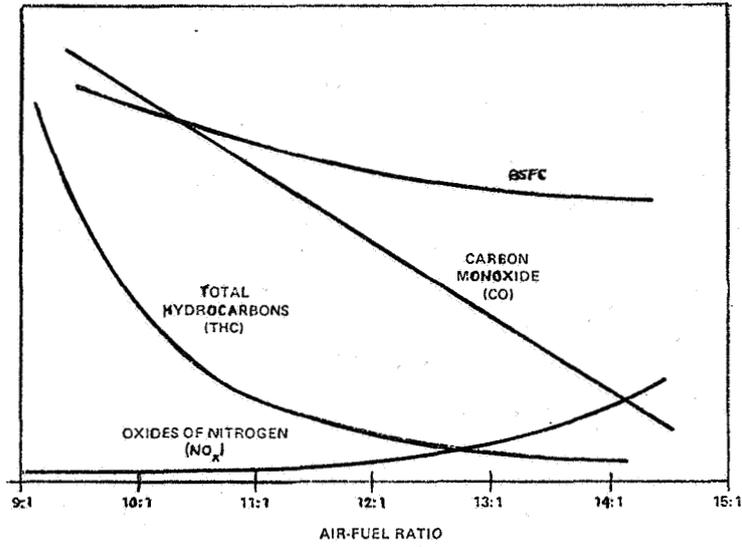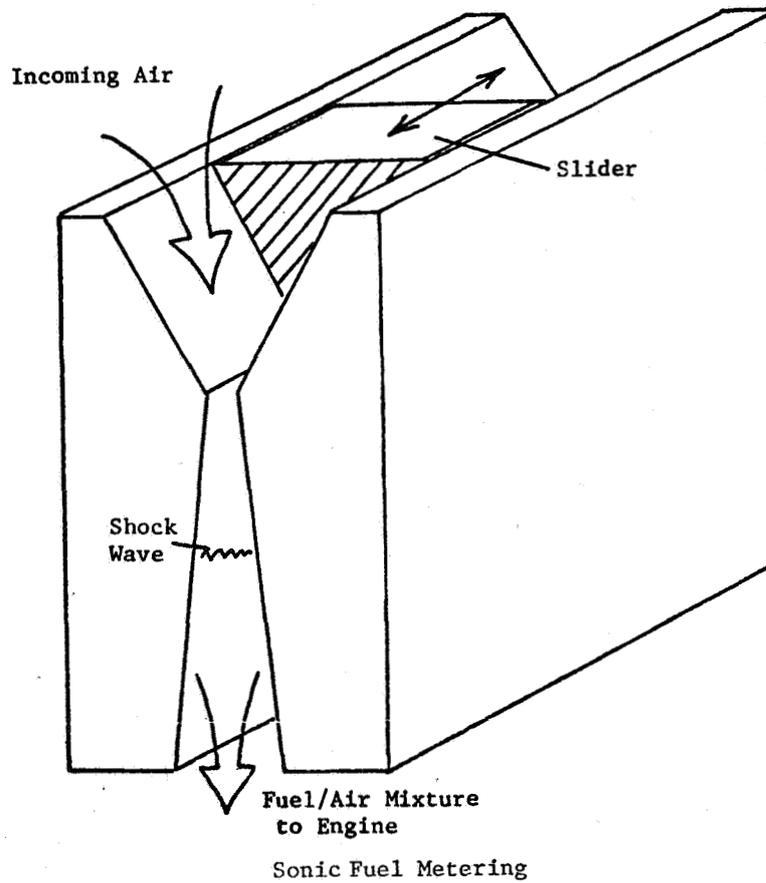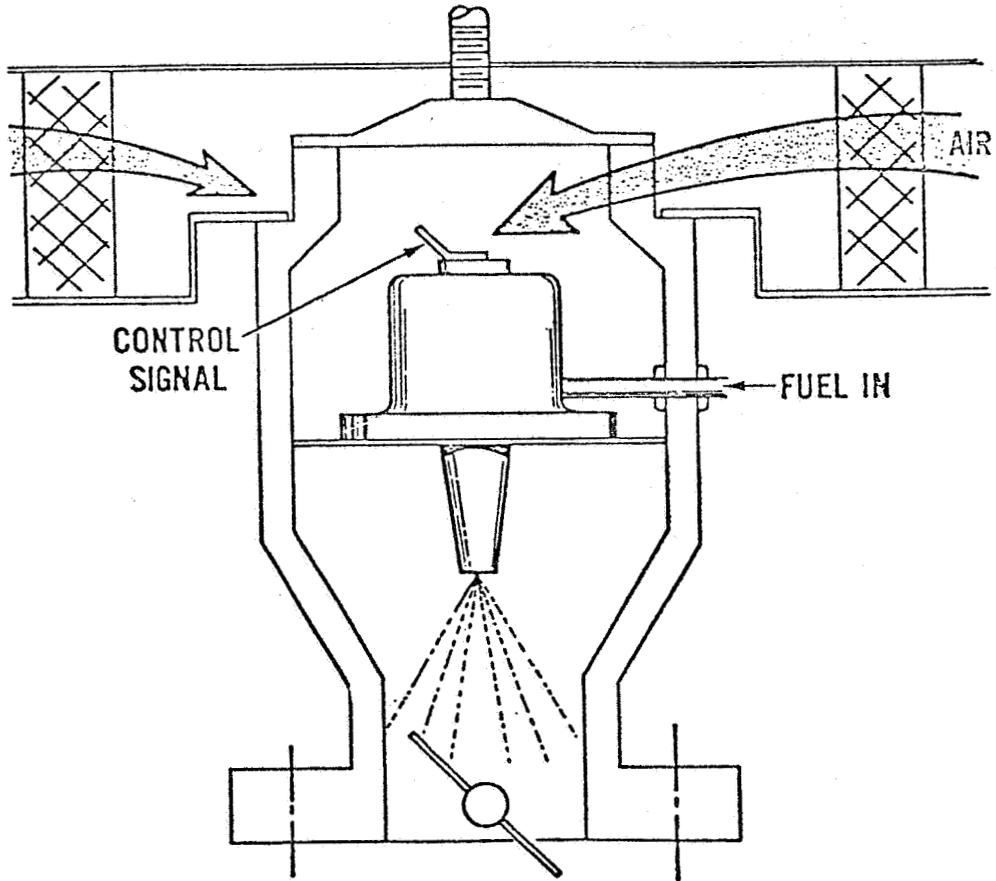
Figure 2-2

Single Point Injection

Figure 2-3

**Primary Metering
System**

**Manifold
Runners**

Mixing Tube

Heating Media

**Conditioning
Chamber**

**Chamber
Exit**
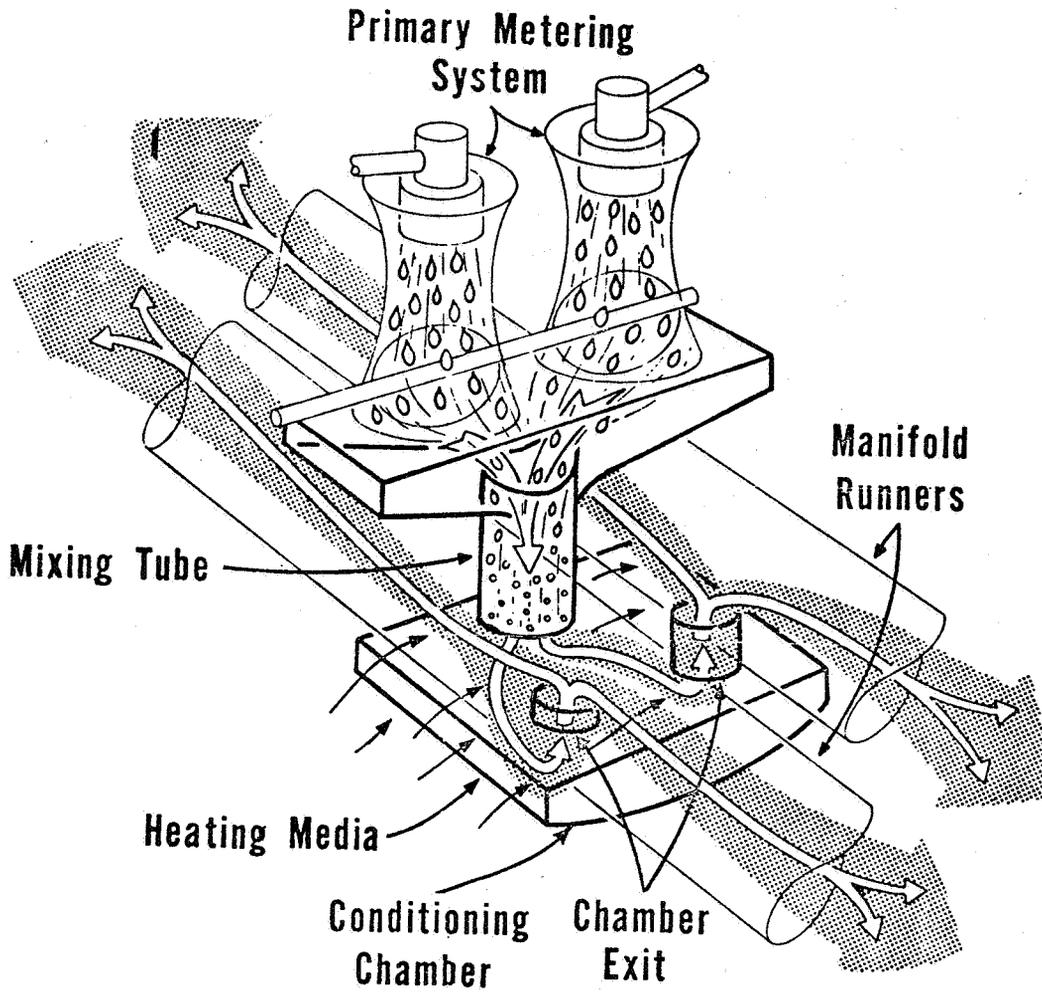
Turbulent Flow System (TFS)

Figure 2-4

Secondary
Venturi

Primary Venturi

Air-Fuel Mixture

Coolant
Jacket

Standard Manifold

Primary
Venturi

Secondary Venturi

Adapter
Plate

Mixing Box Exit

Primary
Mixing
Tube

Coolant Jacket

Conditioning Chamber
Cover

Conditioning
Chamber

Coolant Jacket Cover

Turbulent Flow Manifold
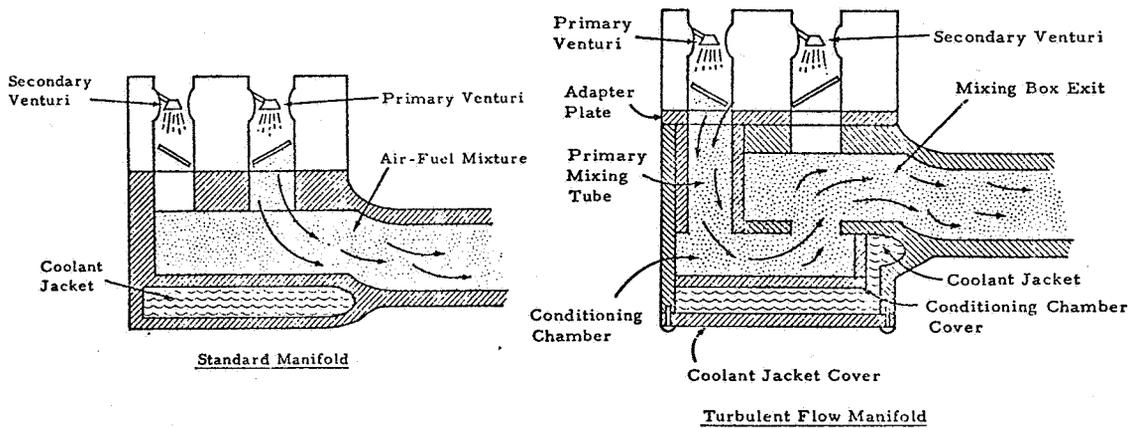
Comparison of TFS with standard manifold

Figure 2-5

Exhaust Port Liner

Figure 2-6
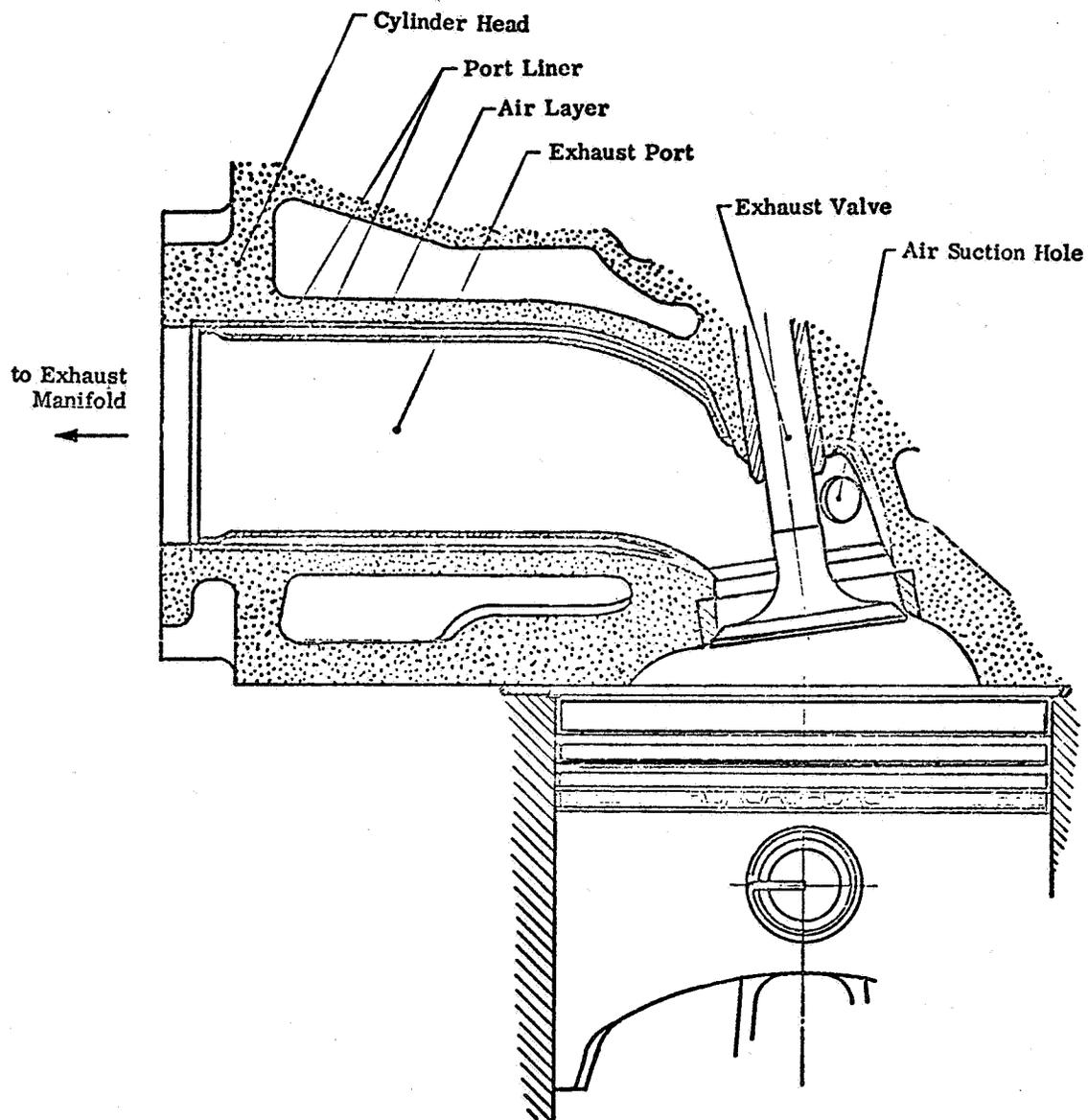
Exhaust Port Liner

Figure 2-7
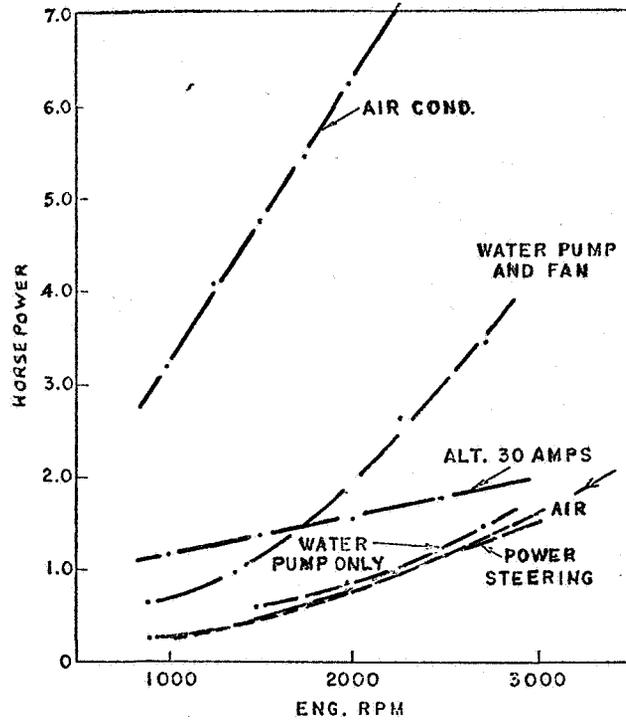
Air Pump Power

Figure 2-8
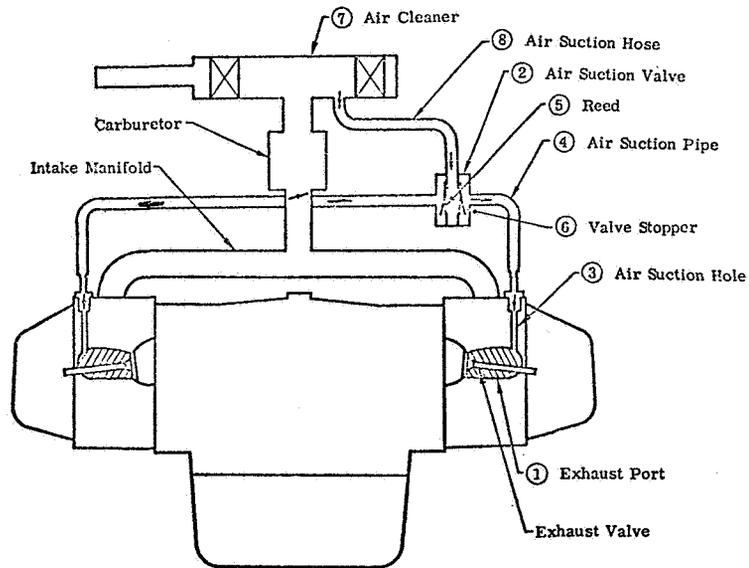
Air Injection Aspirator System

Figure 2-9

Emissions Performance on Light Piston Aircraft
Landing Takeoff Cycle
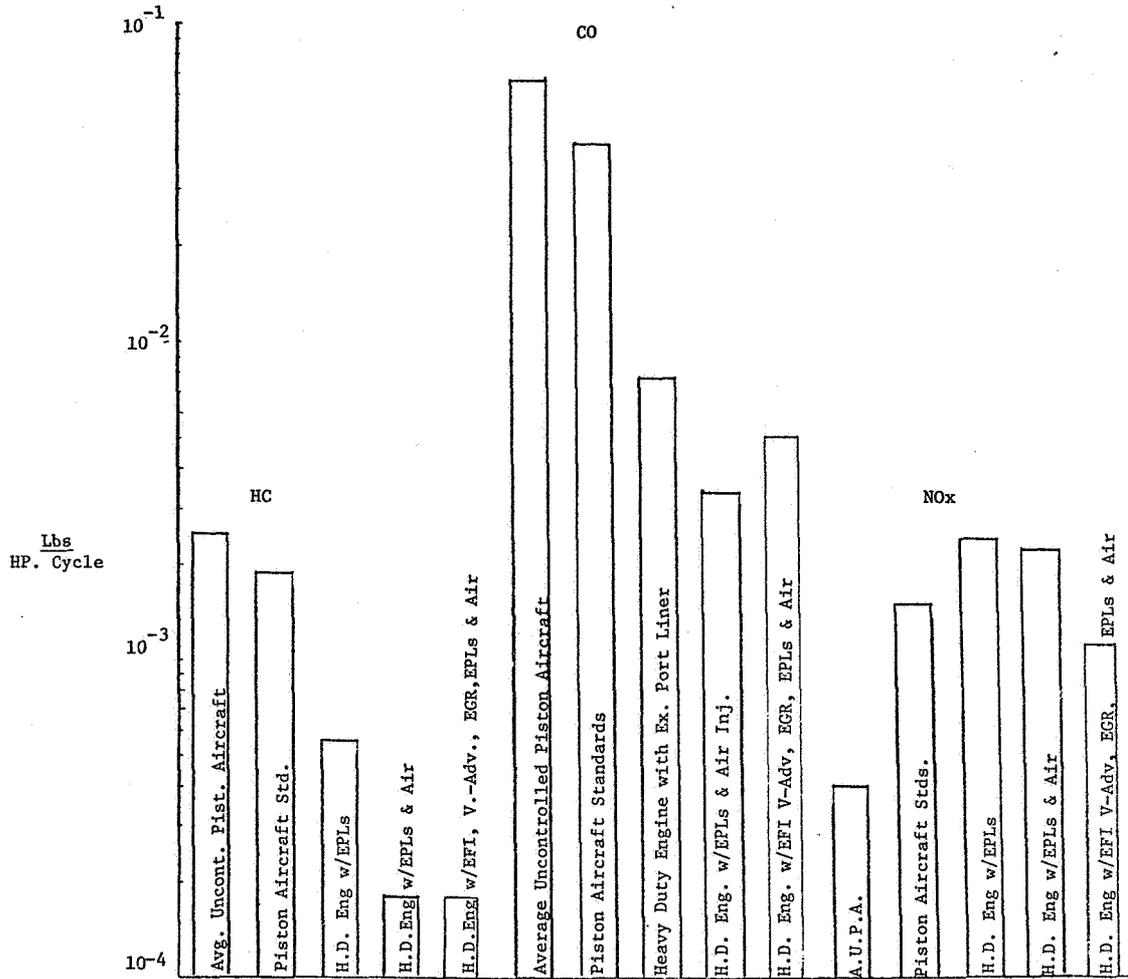
Figure 2-10

3. MEASUREMENT AND TESTING PROBLEMS EXPERIENCED DURING FAA'S EMISSIONS TESTING OF GENERAL AVIATION PISTON ENGINES

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INTRODUCTION

One of the objectives of the FAA program was to establish an accurate, reliable method of determining exhaust emissions from piston engines. The words accurate and reliable are inexact and should be defined. The EPA has touched upon this requirement. In writing the standards, the EPA requires that the exhaust pollutants be measured with sufficient precision so that a carbon balance can be determined within an accuracy of ±5 percent. Thus, there are two areas of investigation which require precision to meet this standard. The engine performance or input side of the equation and the emission measurements or output side of the equation. This paper will emphasize the importance of measuring accurate air and fuel flows as well as the importance of obtaining accurate exhaust pollutant measurements. During the past 2 years of testing general aviation piston engines at NAFEC and at Avco Lycoming, Teledyne Continental Motors, and the University of Michigan, numerous problems have been identified in the emissions measuring equipment. This paper will identify some of the problems and the corrective actions taken to incorporate fixes and/or modifications.
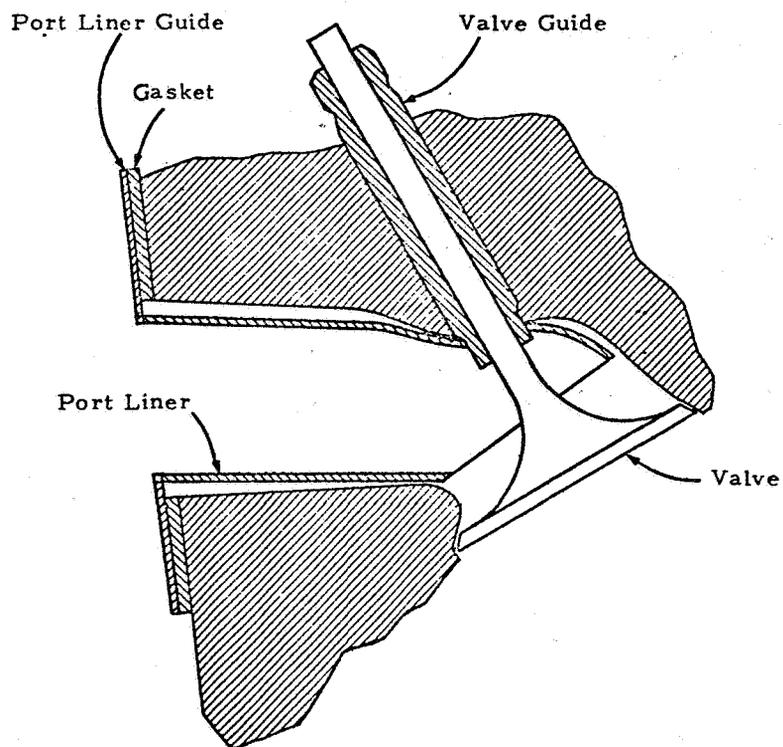
DESCRIPTION OF NAFEC'S AIR AND FUEL FLOW MEASURING SYSTEMS

Air Flow

The first area to be discussed is the airflow measuring method(s). There is a great deal of information available on airflow measuring techniques. These techniques go back many years and the precision of the methods can be reliably estimated. The major points to be discussed are: (1) type of instrumentation, (2) sizing, (3) calibration and accuracy, and (4) redundancy.

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Type of instrumentation. - In assessing the requirements of the program, it was determined to use two types of instruments to measure the airflow, sharp-edged orifices, and flow transducers. There are advantages to be realized in using either of these devices. The orifice is reliable and not subject to wear and deterioration. A permanent record of a test is assured by a photographic record of the manometry to which the instrumentation is connected. The flow transducer is very convenient since it can display information digitally and data handling can be expedited by connecting instrument input to a computer. Each measurement method operates independently of the other and therefore can be used as either a primary or a backup measuring system. Figure 3-1 is a schematic of the NAFEC airflow measuring system.

Sizing. - It is very important that the range of airflows to be measured is in the upper half of the maximum range of the measuring device. For instance, the piston engines have an idle airflow as low as 40 pounds per hour and a takeoff airflow as high as 2000 (or more) pounds per hour. This is a range of 50 to 1. If only one size device is used across this range, the error at the low end can be very large as shown in figure 3-2. To illustrate this point with both an orifice and a flow transducer, the following example is shown:

Orifice	Power	P in, in. H_2O	Air flow (std day)
3.792 in. in 8 in. pipe	Takeoff	4.00	1775 pph
3.792 in. in 8 in. pipe	Idle	.10	115 pph

If it is assumed that the ΔP observed can be read accurately to within ±0.05 inch of H_2O, the error at takeoff is ±10 pph or ±0.5 percent. At idle, however, an error of 0.05 inch is ±45 pph and results in an airflow tolerance of ±39 percent. The same problem arises using flow transducers. This particular point is most graphically demonstrated when referring to an Autoronics 750S transducer calibrated by the manufacturer. This device has an upper flow limit of 600 CFM. Seven calibration points were made from 100 to 600 CFM. In addition, seven calibration points were made from 0 to 100 CFM (the low end of the instruments range). A calibration curve from 0 to 600 CFM was drawn by the factory and all the points fell very close to the straight line calibration. However, when reading the tabulated calibration data (fig. 3-3) for the low end of the instrument range, it shows the following:

CPS	Measured, CFM	Calibrated curve, CFM	Percent difference
20	10	15	+50
25	25	25	0
57	40	44	+10

The previous discussion indicates the necessity of proper sizing for the airflow measuring system. This is true whether using orifices, laminar flow meters, or flow transducers.

Calibration. – The two types of instruments used at NAFEC for airflow measurements were orifices and flow transducers. The orifices were fabricated at NAFEC in accordance with ASME standards. No calibrations were made of this equipment until about 6 months after it was in use. This sounds very imprecise; however, there was such an abundance of information on flow coefficients, sizing, pressure measurement location, and accuracies that it was not critical. In addition, it was possible, with the airflow system used, for a cross-check of the flow to be made by comparing orifice results with a calibrated flow transducer, and small orifices operating simultaneously. Thus, confidence in the system was high. Later, an orifice and attendant hardware were built, used at NAFEC, and then shipped to each of the other facilities to compare results and to develop a correlation between the various air measuring systems in the program. Conservatively, it is estimated that airflow at the takeoff, climb, and approach powers is measured accurately to within ±2 percent. At taxi and idle, the accuracy is within ±3 percent. The flow transducers were calibrated at the time of procurement and recalibrated 1 year later. The large transducer (750S) showed a shift in calibration of approximately 7 percent; the low flow unit showed no change. The shift in the large unit did not effect the program data because at the time of the shift (it appeared to be a step change) it was detected from data taken with the orifice. Inspection of the orifice showed no damage and the large transducer was removed and sent out for calibration. Inspection at the factory showed that the bearing lubricant had changed due to cycling from hot to cold and this temperature cycling had affected the calibration. The lubricant temperature sensitivity is no longer a problem with this equipment.

Redundancy. – In the earlier paragraphs it has been implied several times that there is a redundancy to the airflow measuring system used at NAFEC. It was planned to have this redundancy in the system to obtain a continuing check on the information obtained during the tests. It is much easier to detect bad data and run again while the engine is available than to come back months later, reinstall an engine and rerun the tests. A reference to the airflow schematic shows the redundancy

(and, incidentally, the instrument sizing technique) which was employed
from the beginning in the NAFEC tests. The value of redundancy is the
saving in time and money obtained by pinpointing the moment when in-
strument errors arise. All the engine performance data collected at
NAFEC have been manually recorded. Due to human error mistakes are in
evitable, but in almost all cases, they can be overcome by comparison
of the various systems used during a test and referring to the photo-
graphed manometry data used at NAFEC as a backup and a double check of
the manual readings. It is felt that the use of independent systems
for measuring airflow has been of great value to NAFEC in all its
tests.

The emphasis placed on airflow measurement accuracy at NAFEC might
be considered to be overdone, but there is no question that an effort
of this type must be made if satisfactory results are to be obtained
from the tests.

Engine Cooling Air

The cooling air system used in all tests in the laboratory con-
sisted of a high volume blower, ducting, airflow measuring station,
and engine cooling hood. The quantity of cooling air supplied to the
engine during the three power runs (takeoff, climb, and approach) was
usually set by measuring a nominal pressure drop across the engine of
3 inches of water. At idle and taxi, no cooling air was supplied to
the engine. It was felt that the quantity of engine cooling air would
be of considerable importance to the program when determining the ef-
fect of fuel leanout mixture on emissions and the possible introduction
of engine overtemperature problems. For this reason, a series of tests
were run with each engine wherein the ΔP across the engine was
related to the quantity of cooling air for that condition. Detailed
information on the cooling air quantity was obtained for each engine by
holding a constant power and varying the cooling air ΔP from 1.5 to
7 inches of water. There is a unique relationship between ΔP and
pounds per hour of cooling air for each engine tested in the laboratory.
This information could prove useful in relating the aircraft installa-
tion cooling airflows to those obtained on the test stand. The test
stand cooling hood is not identical to the aircraft installation, but
a relationship might be developed between the two.

Fuel Flow

The second major parameter to be measured on the input side of
the equation is fuel flow. This, too, has a long history of techniques
and methods. The measurement of fuel flow in some ways is easier than
measuring airflow. For one thing, it can be physically weighed quite
readily. This characteristic lends itself to easier calibrations of the

measuring instrument. As in airflow measurement, the major points to be covered are (1) type of instrumentation, (2) calibration and accuracy, and (3) redundancy.

Type of instrumentation. - It was decided at the outset of the program to use two types of instruments. A schematic of the full flow system is shown in figure 3-4. In measuring idle and taxi fuel flow, it was determined that some sort of dead weight or known volume technique would have to be used. This resulted from the nonsteadiness of engine operation found in the low power region. At NAFEC all idle and taxi fuel flows were measured with the use of a 250 ML burette and a timer. The amount of fuel, by volume, consumed during a fixed time period was found to be the most accurate and consistent method available. By making the time period of sufficient length, a good average value of fuel flow at low powers was obtained. In the same fuel line were low flow turbine meters and rotameters. But due to the manner in which fuel is brought into the engine, there were very large fluctuations in fuel flow readings at the idle power settings which would result in extremely large errors in fuel measurement if an insufficient time period for averaging the readings is not used.

Calibration. - At the start of the tests all the flowmeters were calibrated using AVGAS as the medium. The rotameter was not calibrated since it was felt that very little could go wrong with it and it would have delayed the start of the program. This was a poor assumption since later in the program discrepancies in fuel measurement developed and when the rotameter was calibrated it was found to be reading high by about 6 percent. All the data previously obtained from the rotameter were then corrected for this error. Since that time there has not appeared to be any problem associated with either the rotameters or the turbine meters.

Redundancy. - As in the case of airflow measurement, the fuel flow system had redundant instrumentation for both taxi-idle and high power tests. The taxi-idle redundance was ineffective at idle in most cases. But at taxi where the engine operated more consistently, the agreement between the burette measurement and the turbine flowmeter was usually very good. The schematic of the overall fuel system is helpful in understanding the sizing and redundancy incorporated in the system.

The accuracy for fuel flow measurement which was obtained in the NAFEC tests is ±1.0 percent at high powers and ±2 percent at taxi and idle.

AIR AND FUEL FLOW MEASUREMENT RECOMMENDATIONS

As a result of the experience at NAFEC, the recommendations are as follows:

(1) Air and fuel flow measurements should be made with instrumentation which considers the factors of instrument accuracy, proper sizing, and redundance of measurements during all tests.

(2) The target accuracies should be at least ±1 percent at high powers, ±2 percent at idle and taxi for fuel flows, and ±2 percent and ±3 percent for airflow at high powers and taxi/idle, respectively.

(3) A relationship between actual cooling airflow and pressure drop across the engine for all engine test stand configurations should be developed. This would be useful in relating aircraft installed cooling to test stand cooling.

DESCRIPTION OF NAFEC'S EMISSIONS MEASURING SYSTEM

Emission Analyzers

The instrumentation used to monitor the exhaust emissions from general aviation piston engines was basically the same as that recommended by EPA but with a number of modifications and additions to enhance the reliability and accuracy of the system. A schematic of the emissions measurement system is shown in figure 3-5. The basic analysis instrumentation utilized for this system, which is summarized in figure 3-6, is as follows:

Carbon dioxide. - The carbon dioxide subsystem is constructed around a Beckman Model 864-23-2-4 Nondispersive infrared analyzer (NDIR). This analyzer has a specified repeatability of ±1 percent of full scale for each operating range. The calibration ranges on this particular unit are as follows: range 1, 0 to 20 percent; range 3, 0 to 5 percent. Stated accuracy for each range is therefore ±0.2 percent CO_2 and ±0.05 percent CO_2, respectively.

Carbon monoxide. - The subsystem used to measure carbon monoxide is constructed around a Beckman Model 865-x-4-4-4 NDIR. This analyzer has a specified repeatability of ±1 percent of full scale for ranges 1 and 2 and ±2 percent of full scale for range 3.

Range 1 has been calibrated for 0 to 20 percent by volume, range 2 for 0 to 1000 ppm and range 3 for 0 to 100 ppm. The wide range capability of this analyzer is made possible by using stacked sample cells which in effect give this analyzer six usable ranges when completely calibrated.

Effects of interferring gases, such as CO_2 and water vapor, were determined and reported by the factory. Interferences from 10 percent CO_2 were determined to be 12 ppm equivalent CO and interferences from 4 percent water vapor were determined to be 6 ppm CO equivalent. Even though the inteference from water vapor is negligible, a condenser is

used in the CO/CO_2 subsystem to eliminate condensed water in the lines, analyzers, and flowmeters. This condensation would have decreased analyzer sensitivity and necessitated more frequent maintenance if it had not been eliminated.

Total hydrocarbons. - The system that is used to measure total hydrocarbons is a modified Beckman Model 402 heated flame ionization detector. This analyzer has a full-scale sensitivity that is adjustable to 150 000 ppm carbon with intermediate range multipliers of 0.5, 0.1, 0.05, 0.01, 0.005, and 0.001 times full scale.

Repeatability for this analyzer is specified to be ±1 percent of full scale for each range. In addition, this modified analyzer is linear to the full-scale limit of 150 000 ppm carbon when properly adjusted. The two major modifications to this analyzer were the installation of a very fine metering valve in the sample capillary tube and the installation of an accurate pressure transducer and digital readout to monitor sample pressure. Both of these modifications are necessary because this analyzer is extremely pressure sensitive as shown in figures 3-7, 3-8, and 3-9. Correct instrument response depends on the amount of sample passing through a capillary tube. If there is too high a sample flow the analyzer response becomes nonlinear when a high concentration gas is encountered. Sample flow may be controlled by varying the pressure on this capillary or increasing the length of the capillary. On this particular analyzer, linearity to 50 000 ppm carbon was obtained by reducing the sample pressure to 1.5 psig. However, the need for linearity to 120 000 ppm carbon was anticipated. Further reduction of the sample pressure increased the noise level of the analyzer to an unacceptable level. In order to reduce the flow through the capillary without using a lower pressure, either the length or the resistance of the capillary had to be increased. The standard modification for this analyzer to limit flow is the installation of an additional length of capillary tubing. This procedure requires trial and error determination of proper capillary length and is a permanent modification that limits sensitivity at low hydrocarbon levels. By installing a metering valve in the capillary, flow could be selectively set at either low flow for linearity at high concentrations or high flow for greater sensitivity at low concentrations. Installation time was reduced by eliminating the cut-and-try procedure for determining capillary length.

The addition of a sensitive pressure transducer and digital readout to monitor sample pressure was needed since the pressure regulator and gage supplied with the analyzer would not maintain the pressure setting accurately at low pressures. Using the digital pressure readout, the sample pressure could be monitored and easily maintained to within 0.05 in. H_2O.

Oxides of nitrogen. - Oxides of nitrogen are measured by a modified Beckman Model 951H atmospheric pressure, heated, chemiluminescent ana-

lyzer (CL). This analyzer has a full-scale range of 10 000 ppm with
six intermediate ranges. Nominal minimum sensitivity is 0.1 ppm on the
10 ppm full-scale range.

The atmospheric pressure analyzer was chosen because of its sim-
plicity, ease of maintenance, and compactness. Anticipated water vapor
problems in the atmospheric pressure unit were to be handled by the
heating of the internal sample train. Interference from carbon dioxide
quenching, common in the atmospheric pressure type CL analyzers, was
checked and found to be nonexistent.

A series of major modifications were performed by the manufacturer
on this analyzer to insure compliance with specifications. One such
modification was installed in order to maintain the temperature of the
sample stream above the dew point of the sample gas. Originally this
analyzer was specified to maintain a temperature of 140° F at all points
in contact with the sample. After a survey of the 951H analyzers in
use on FAA projects it was determined that this temperature was not
being achieved because the method used to heat the components was in-
adequate. A recommendation was made to the manufacturer to install a
positive method of heating the sample tube compartment and reaction
chamber that would be thermostatically controlled. In time the modi-
fication was made and this problem was eliminated. Increasing the tem-
perature of the internal sample components eliminated the condensed wa-
ter problem; however, the elevated temperature caused an instability in
the photomultiplier tube output. Another recommendation was made to
thermostatically control the temperature of this tube. This was ac-
complished by installating an electronic cooling jacket designed to
maintain the photomultiplier tube at a constant temperature below the
internal case temperature.

A further modification required on this analyzer was the addition
of a flow control valve to adjust and balance the flow rate through
the NO and NO_x legs. This valve replaced a restrictor clamp that was
used by the manufacturer to set the NO to NO_x flow balance. The prob-
lem that was encountered with this clamp was that it was not a positive
method of adjusting the restriction on the capillary. The clamp com-
pression was affected by the flexible material on which the clamp was
mounted and the variable flexibility of the teflon capillary as it was
heated. This caused the restriction on the capillary to change with
time after it was set and caused permanent deformation of the capillary
allowing only adjustment that would increase the restriction.

Oxygen measurement. - Oxygen is being measured by a Beckman Model
OM-11 oxygen analyzer. This analyzer uses a polagraphic type sensor
unit to measure oxygen concentration. An advanced sensor and amplifica-
tion system combine to give this analyzer an extremely fast response
and high accuracy. Specified response for 90 percent of final reading
is less than 200 ms with an accuracy of less than ±0.1 percent O_2.
Ranging on this unit is a fixed 0 to 100 percent O_2 concentration.

Description of Sample Handling System

Exhaust samples are transported to the analysis instrumentation under pressure through a 35-foot-long, 3/8-inch o.d., heated, stainless steel sample line. The gas is first filtered and then pumped through this line by a heated Metal Bellows Model MB-158 high temperature stainless steel sample pump. The pump, filter, and line are maintained at a temperature of $300°\pm4°$ F to prevent condensation of water vapor and hydrocarbons. At the instrumentation console, the sample is split to feed the hydrocarbon, oxides of nitrogen, and $CO/CO_2/O_2$ subsystems which require different temperature conditioning. The sample gas to the total hydrocarbon subsystem is maintained at $300°$ F while the temperature of remaining sample gas to the NO_x and $CO/CO_2/O_2$ system is allowed to drop to $150°$ F. Gas routed to the oxides of nitrogen subsystem is then maintained at $150°$ F, while the gas to the $CO/CO_2/O_2$ subsystem is passed through a $32°$ F condenser to remove any water vapor present in the sample. Flow rates to each analyzer are controlled by a fine metering valve and are maintained at predetermined values to minimize sample transport and system response time. Flow is monitored at the exhaust of each analyzer by three 15-centimeter rotameters. Two system bypasses are incorporated into the system to keep sample transport time through the lines and condenser to a minimum without causing adverse pressure effects in the analyzers.

Filtration

Particulates are removed from the sample stream at three locations in the system (fig. 3-5). Upstream of the main sample pump is a heated clamshell-type stainless steel filter body fitted with a Whatman GF/C Glass Fibre paper filter element capable of retaining particles in the 0.1 micron range. A similar filter is located in the total hydrocarbon analyzer upstream of the sample capillary. An MSA Type H Ultra Filter capable of retaining 0.3 micron particles is located at the inlet to the oxides of nitrogen and $CO/CO_2/O_2$ subsystems. Filters located at these three locations allow the entire sample transport and analysis system to be free of particulate contamination, thereby minimizing downtime due to contaminated sample lines and analyzers.

IDENTIFICATION OF PROBLEM AREAS

Gas Analyzers

The analysis instrumentation that is available from the manufacturer for most gases will perform reliably once this equipment is properly assembled and checked out. However, the majority of instrumentation purchased by the FAA and its contractors for exhaust gas

analysis was not in operating condition when received from the factory. In most instances, the problems that were encountered with the analysis instrumentation were due to the lack of adequate quality control and inspection on the part of the individual instrument suppliers. For example:

(1) Amplifier board missing on the Model 402 Total Hydrocarbon analyzer.

(2) Malfunctioning temperature control board on the Model 864 CO_2 analyzer.

(3) Damaged sample capillary, NO_2 to NO converter temperature set 200° too low, and photomultiplier tube voltage set too low on the Model 951H NO_x analyzer.

(4) Jammed interrupter blade and loose power supply assembly in the Model 315B CO analyzer.

All of these problems were corrected by the manufacturer's field service technician at no cost. However, all of these problems resulted in delays in the FAA test program.

Other problems with the basic instruments, not related to quality control, were encountered and to varying degrees corrected in the course of emissions research and testing at NAFEC. Use of the high temperature version of the hydrocarbon analyzer as recommended by the EPA led to a problem of linearity at high hydrocarbon levels. This high temperature flame ionization detector was originally intended to measure heavy molecular weight hydrocarbons which could possibly condense in an unheated sample system. Generally, internal combustion engines which emit these heavier hydrocarbon exhaust products do so at concentrations less than 10 000 ppm carbon (or ppmc). The burner characteristics of this heated analyzer as supplied from the manufacturer prevent linear operation above 10 000 ppmc using the sample pressures and flows specified in the operating instructions. Aircraft piston engines at certain power modes emit hydrocarbons above this 10 000 ppmc linear cutoff point. The response of the flame ionization detector above 10 000 ppmc is such that operation in this range through the use of a calibration curve would be extremely insensitive. The modification made to the Beckman flame ionization detector used at NAFEC was described in the section on that instrument. The Scott Model 215 total hydrocarbon analyzer used by one FAA contractor was also modified to produce more linear results at high concentrations. Flows were reduced in this analyzer by inserting a fine wire into the sample capillary tube thereby increasing the restriction imposed by the capillary and in turn lowering the sample flow rate to the burner. Both modified analyzers now produce linear results to approximately 125 000 ppmc.

The use of the Chemiluminescent (CL) analyzer to monitor oxides of nitrogen emission is specified by the EPA. This type of instrumentation has just recently been recommended for the measurement of turbine engine exhaust where the concentration of known interferring gases are low. The vacuum chemiluminescent analyzer was well able to handle water condensation problems in the low water environment of turbine engine exhaust. Also, interference of other gases, such as hydrocarbons and carbon monoxide, in thermal NO_2 to NO converter operation did not present a problem because of their relatively low concentrations. Water vapor contamination in the atmospheric pressure CL analyzer during turbine testing was handled satisfactorily by line heating although frequent cleaning of the reaction chamber assembly was required.

Many major problems were encountered when attempting to adopt this turbine instrumentation to the more severe environment encountered in direct exhaust sampling from piston engines.

At NAFEC, instrumentation that was used to measure emissions from turbine engines was adapted and modified for use in piston engine measurements. The original unheated CL analyzer was unable to function properly in the presence of high exhaust water vapor. Initially, a permeable membrane-type dryer was used to precondition the exhaust sample before entering the CL analyzer. Generally, the use of dryers in the oxides of nitrogen system is not recommended. However, the use of a membrane dryer avoided the possible loss of the sample usually found when using conventional water traps, condensers, or desiccants and therefore was considered satisfactory. Preliminary tests of this dryer indicate that there is little or no loss of NO or NO_2 gas in the sample after being dried in this manner. To eliminate a continued need for a drying system, a heated chemiluminescent analyzer was purchased. This analyzer was designed to maintain the temperature of the incoming sample gas above the dew point of the sample gas. All internal components that came in contact with the sample were enclosed in a heated chamber which was heated by the NO_x thermal converter boot. This method of heating proved totally unsatisfactory. After undergoing the major modifications described earlier, this instrument now satisfactorily analyzes wet exhaust samples.

Another problem encountered in other CL analyzers which was not encountered in the Beckman unit used at NAFEC was the inability of the NO_2 to NO thermal converter to operate efficiently in the low oxygen, high carbon monoxide environment of piston engine exhaust. Early in the program, the heated stainless steel tube type converter exhibited a tendency to eliminate any NO in the sample when passed through the converter in the presence of high concentrations of CO and low concentrations of O_2. This deficiency in the early stainless steel converter was never eliminated; however, other types of converters, particularly the molybdenum alloy type have been used with varying degrees of success. To date the proprietary material used in the Beckman converter seems to pose little or no problems in the measurement of oxides of nitrogen.

Sampling System

The majority of problems affecting the analysis instrumentation were found to be in the sample handling systems. Systems that were purchased assembled from the vendor were found to have many tubing connections loose and leaking. A leak in the sample system may affect the performance of the system in one of two ways. If a large leak was located downstream of a sample pump, it would cause a loss of sample pressure to the analyzers, affecting response and instrument performance. If the leak was located upstream of a sample pump, it would tend to dilute the sample and give erroneous emissions readings. The result of even a small leak upstream of a pump could possibly go undetected for some time and cause incorrect data to be collected. Once again, many of the problems of sample leakage could have been prevented during system assembly had adequate quality control procedures been in effect.

Assuming that the system had been carefully assembled, small leaks may still develop during continuous operation of the equipment. Installation of a large capacity sample pump as near the sample probe as possible would prevent any leakage from diluting the sample.

To avoid problems of water vapor condensation, sample lines upstream of the water trap should be heated. The recommended sampling system as outlined by the EPA specifies that all lines upstream of the water trap should be heated to 300° F. This requirement has caused problems with the ability of the water trap to remove water vapor in the $CO/CO_2/O_2$ subsystems. At the flow rates required to keep sample transport time below 2 seconds, gas at a temperature of 300° F is unable to be cooled sufficiently in the condenser to remove enough water; consequently, the remainder of the water vapor will condense out in the CO or CO_2 analyzers or flowmeters. It has been found that maintaining a sample line temperature of 150° F in the section of sample line between the total hydrocarbon analyzer and the oxides of nitrogen analyzer and the water trap gives the sample gas enough time to chill while passing through the water trap, and yet maintain the sample gas above its dew point ahead of the oxides of nitrogen analyzer. Care must be taken to insure that any flowmeters that are in a heated leg of the system are either heated or well insulated. Unheated flowmeters on the exhaust ports of both the total hydrocarbon and oxides of nitrogen analyzers will cause erroneous readings due to back pressure on the analyzers from the condensed water.

Calibration Gases

The most troublesome problem encountered in the use of emissions measurement equipment is finding calibration gas standards reliable enough to accurately calibrate the instrumentation. This problem is

especially evident when dealing with low concentrations of unstable gases such as oxides of nitrogen and carbon monoxide. These gases, when used in concentrations below 1000 ppm, have a tendency to be very sensitive to changes in cylinder pressure and ambient temperature, and, when stored over a period of time, they tend to change concentration unpredictably (fig. 3-10). The effect of cylinder type on stability of NO_2 is shown in figure 3-11. However, the impact of this stability problem on piston engine emissions measurements is limited to the analysis of oxides of nitrogen since concentrations of carbon monoxide which are used in these measurements are much above the unstable 1000 ppm level. Instability and mixing problems associated with the other gases (CO, CO_2, O_2, and C_3H_8) do not present a problem in the higher concentrations used in calibrating for piston engine tests. Problems in these gases arise because of poor quality control while analyzing these gas mixtures at the supplier's laboratory. Therefore, accuracy levels claimed on the analysis certificates should be used with caution.

An in-house calibration gas acceptance program should be instituted to insure repeatability of data throughout a test series. This program would insure that no major shifts in instrument calibration occur because of improperly certified calibration gases. By using in-stock calibration gases to verify new gases as they are purchased, a new gas which deviates from the certified concentration by more than the manufacturers tolerance would be discovered and then should be returned to the supplier for reanalysis. A gas that is within the manufacturer's tolerance should be labeled as to the exact in-house analyzed concentration and used as that concentration from the on. This method insures that data from one system always will be repeatable. However, this method does not insure that the data will be consistent between laboratories.

One method of insuring consistency among laboratories is to participate in a calibration cross reference service. This service statistically compares the results of each laboratory's analysis of a referee gas. To be of real value, this service should coincide with the required monthly instrumentation calibration and should provide for immediate feedback as to the accuracy of each laboratory's analysis.

Accuracy of Emission Systems

Accuracy of emissions data depends on many parameters, least of all published instrument accuracy. When surveying the published instrument specifications, it is clearly evident that most instrumentation designed to be used for exhaust emission measurements meets the requirements set forth by EPA. However, whether or not this instrumentation lives up to its design specifications during actual field use is more a function of calibration accuracy and system reliability. Assuming that the gases used to calibrate the analysis instrumentation have all been verified

and the instrumentation is functioning properly, the method used to obtain the analyzer calibration curves is critical. Analyzer specifications claim repeatability of ±1 percent of full scale. This repeatability can be translated to instrument accuracy only at the exact points of calibration. At any other point within the range of the analyzer, the reading is only an estimate based on a best fit curve drawn through these calibration points. This, therefore, means that the accuracy of the data is dependent on how well this best fit curve follows the actual behavior of the analyzer.

Determining the proper calibration curve for each analyzer requires that the basic shape of the curve be known. The total hydrocarbon analyzer (FID), oxides of nitrogen (CL) analyzer, and oxygen analyzer are known to be linear up to a predetermined limit. Therefore, a best fit curve based on a linear regression should be used to determine the calibration curve for these analyzers. A minimum of three verified calibration gas standards must be used to determine these curves. The infrared analyzers used to measure carbon monoxide and carbon dioxide are known to be nonlinear. By using a third degree polynomial regression, a best fit curve for these two analyzers may be found that very closely approximates the behavior of these analyzers. A minimum of five verified calibration gas standards should be used to determine these curves.

Both regression methods generate calibration curves which fall within the ±1 percent accuracy levels of the analyzers.

EMISSIONS MEASUREMENT SUMMARY

Emission measurement instrumentation commercially available will reliably and accurately measure exhaust from piston engines provided the instruments are functioning according to design specifications, are properly calibrated, and used on a regular basis. Care must be taken when purchasing this equipment to specify exactly the operating conditions under which the instrumentation is to be used and the performance expected of the system. Each system or component should be checked thoroughly for compliance with specifications prior to being accepted from the vendor. Calibration gas standards should be verified prior to being used to calibrate the instrument. A sufficient number of calibration points must be used to insure that the calibration curves determined for each analyzer accurately predict the behavior of each analyzer. Also, a periodic interlaboratory calibration cross reference check should be made to insure that data collected are compatible from laboratory to laboratory. Reliability and accuracy of analysis instrumentation is greatly enhanced if the instrument is calibrated and operated on a regular basis. A preventative maintenance and calibration schedule could be established if the instrument is used in this manner. The possibility of further simplifying the analysis system and determining the cause of variability in piston engine emis-

sion measurements should be investigated. The cumulative effect of individual measurement uncertainties on final emissions data accumulated should also be determined.

TEST PROCEDURES

To understand the tests it is necessary to describe the EPA cycle. In the cycle, EPA specifies an idle-taxi operation of 12 minutes duration at startup, a 0.3-minute operation at takeoff power, a 5-minute climb, a 6-minute approach, and a 4-minute idle/taxi operation coming in. At the outset of the program, it was decided to run at both idle and taxi in order to develop information at both powers. The idle power was selected at 600 rpm and taxi at 1200 rpm with the time in modes at 1 and 11 minutes, respectively, when going out and a 3-minute taxi and 1-minute idle coming in.

The 7-mode baseline shown in figure 3-12 is conducted in sequence, but the time in mode for computing emissions is a calculated value. The actual test time in mode for any run is about 5 minutes. This is because it takes about that long to set the power conditions, stabilize the engine, and record the values of engine performance and emissions. In conducting the 7-mode tests it has been observed that idle and taxi going out are not necessarily identical with taxi and idle in. This is attributed to the fact that at start up the preconditioning of the engine consists only of starting and running the engine until the oil is heated up to a specified temperature. During this warmup period, some buildup of carbon, oil past the rings, etc., will occur and this will be reflected in the emissions measured. After the idle run, the taxi condition is set with no clear-out of the engine and this too will have an impact on the measured emissions. However, at taxi in, which follows a sequence of high power runs which have cleared the engine out, the emissions usually are lower than those measured at taxi out. The same is usually true for idle in.

The previous observations indicate that the level of emissions can be changed by varying the procedure used during the testing. It also should be recognized that the impact of the idle-taxi modes in the 7-mode baseline is quite significant. The total time for the cycle is 27.3 minutes. Admittedly, the rate of emission production is low at idle and taxi, but the time in mode is sufficiently long to have a considerable impact on the overall emissions level.

In the course of the tests it became apparent that the yardstick for determining whether data were acceptable or unacceptable was rather broad at the three high powers. The data at takeoff, climb, and approach were usually consistent for all the engines tested and agreement between measured and calculated fuel-air ratio was high (i.e., probably 90 percent or more of these tests produced acceptable data). At idle

and taxi, the degree of acceptability was considerably lower with idle power providing the lowest percentage of acceptable data. This can be attributed to a variety of causes: (1) the engine is not running in a true steady-state condition at idle power where rpm fluctuations are rather wide while data are being collected, (2) the combustion process is not consistent and wide fluctuations in emissions are recorded during a test, and (3) the effect of cylinder-to-cylinder variations is more pronounced and these variations are reflected in the wide band of emissions recorded. The same comments which are made for idle power can be cited for taxi, but on a reduced level. The acceptability of data at taxi is much higher than that at idle, probably there are only 50 percent as many unacceptable test points run at taxi as at idle.

Recognizing these limitations of the 7-mode cycles, it has been suggested by the various participants in the program that a 5-mode cycle be used as the basic measuring medium for pollution tests. What is being suggested is the use of a 5-mode cycle (fig. 3-13) which eliminates idle tests at the beginning and end and adds 1 minute to both taxi modes. The results obtained from this type of test are slightly more conservative (i.e., the emissions are slightly higher) than those obtained when computed from a 7-mode cycle. However, the degree of accuracy of data obtained, the repeatability of the data, and the capability of setting the conditions at taxi are considerably greater. A comparison of a typical 7-mode and 5-mode cycle (fig. 3-14) using the same data results in agreement between the two types of cycles within 5 percent. With all the problems which occur in attempting to measure emissions accurately at idle, it would seem that this effort offers only a very slight increase in information about emissions. This is true especially when it is realized that the degree of accuracy suffers a sharp decline when going from taxi to idle power. This modification to the basic cycle emission calculation should be considered in the light of the previous comments. At any rate, all the tests at NAFEC are being run with the 7-mode cycle and can readily be modified to a 5-mode cycle in the computation procedure.

The tests conducted at NAFEC and at the engine manufacturers have all been of two types, 7-mode baselines and lean-out runs at all powers. The lean-out runs are conducted by setting the power at full rich and taking a reading of emissions. The next test is set at an incrementally reduced fuel flow. Usually a series of four tests is made at each power (i.e., from full-rich to 12 or 15 lb lean). The information gained from these tests is quite useful in that acceptable data produce smooth curves when they are plotted with F/A ratio versus pollutant in pounds per hour. Unacceptable data become very apparent when plotted in this way. In addition, when such tests are run under different ambient conditions, the curves produced can be useful in determining the impact of temperature and humidity on the emissions. For purposes of correlating data from different facilities, the use of lean-out runs is a necessity. A 7-mode baseline yields information which is

unique to the conditions under which it was run.

It is difficult to compare baseline bargraphs with any degree of accuracy unless identical ambient conditions prevail for the tests under comparison. The use of lean-out tests, however, provides a more convenient mechanism for comparison or analysis of the data. Tests at different ambient conditions can generate lines of pollutant against F/A ratio which can serve as guidelines for interpolation or extrapolation to other ambient conditions. In this way data can be compared and evaluated.

Lean-out tests can be used to generate 7-mode or 5-mode baselines and bargraph presentations can be made from these curves. The use of lean-out testing in this way can yield more consistent information on the cycle emissions, since the curves themselves eliminate the randomness which occurs in any individual test point. The accumulated tolerances of the emission measurements instrumentation and the fuel and air measurements alone could render all data unacceptable. On a statistical basis, however, this result does not occur. However, some of this randomness of data can be eliminated by the use of lean-out tests in developing total cycle emission values.

The lean-out curves are also useful in constructing hypothetical flight profiles for an engine. Thus, at takeoff, climb, approach, and taxi, specific F/A ratios can be selected, and the emissions from this cycle can be determined without actually trying to set the engine conditions on the stand. Application of this principle is also very useful in comparing data from facility to facility. Assuming that the data on the engine are taken over a range of ambient conditions, which can be used for interpolation or extrapolation, a direct comparison of cycle emissions can be developed for purposes of comparison. The lean-out tests therefore can be extremely useful and should also prove to be quite valuable in assessing emissions when corrected to an agreed upon standard. It is felt, therefore, that a very significant contribution to accurate and usable data on emissions can be obtained by the use of lean-out tests at the various powers.

DISCUSSION

Q - G. Kittredge: Your arguments and recommendation for deletion of the idle power setting were very persuasive and certainly the data seem to be unharmed by such a change. We do owe you a response to that recommendation. Is there someone here today with aircraft design orientation that can comment on Bob's recommendation and say whether the idle power setting is a realistic power setting in the context of the way such aircraft are really operated?

A - L. Helms: The 1 minute of time allocated to idle is not particularly significant one way or the other. There is the more far reaching impact, however, of eliminating that 1 minute of idle per se and trying to build an automatic mixture control system to take into account all of those conditions. We'll see later the possibility of taking perhaps the worst, which might be climb or maybe takeoff, and scheduling a mixture control approach to reduce all of the pollutants and certainly CO. Our problem would be dramatically easier if we would eliminate just one mode, which in this case is the idle with only 1 minute. I would certainly encourage it - particularly in view of the fact that I noticed on your chart you could tell no difference between the 5 and 7 modes. From our viewpoint it could only help us significantly and certainly would reduce the magnitude of the complexity of the problem.

Q - M. Steele to S. Imbrogno: I was very impressed with the magnitude of the errors that you could get from the Beckman instruments. Since most of us use these same instruments, at what point were the improvements made in the Beckman instruments? In particular, if you go back to the pre-1973 era, are we dealing with instruments that were grossly inaccurate or did I misunderstand some of the comments that were made?

A - S. Imbrogno: You are speaking of which analyzer in particular? The errors in the CO and CO_2 are very small. The modifications we made in the hydrocarbon analyzer really only affected the very high emission levels. At the lower emission levels, such as approach and possibly takeoff and climbout, the modifications we made didn't affect the measurements at all.

Q - M. Steele: What about the variations in NO_x measurements?

A - S. Imbrogno: The problem with the analyzer was more of an operational problem. The operation of the analyzer would degrade and we'd have to stop testing and repair the analyzer. It didn't particularly affect the data once the analyzer was operating properly.

Q - B. Westfield to S. Imbrogno: In the automotive field they use a bag collection system. Do you feel that there would be any benefit for aircraft systems to go to that same type of a system; and, secondly, could the manufacturers give me their comments on the same point?

A - S. Imbrogno: Using the constant volume sample with the bags would be adding another piece of instrumentation; however, it would

eliminate problems with high concentrations that are measured for piston engines. You'd be bringing the concentrations down in the ppm range and would be eliminating the problem of nonlinearity in the hydrocarbon measurements at the high end. Also, it would possibly be eliminating the water problem in the chemiluminescence analyzer.

COMMENT - T. Cackette: One problem with the CVS system is that you don't get a heated hydrocarbon measurement. It's going to be difficult to heat a flow to 300° F that's diluted with 300 CFM of dilution air - which is what happens in an automotive system.

COMMENT - L. Duke: Initially we are against a bag collection system because we trade one problem for another. We do have high hydrocarbon concentrations and water problems with exhaust emissions in the NO_x detector. When we look at the magnitude of these problems as far as we have refined the instrumentation today, we have reduced them so that those problems are not a factor in trying to pass the Federal Standards. If we go to the bag system then we have a new set of problems. Instead of looking at high concentrations we are now looking at low concentrations as we stated in the ppm range with a new set of problems to define. What you are saying is let's throw out all the work we've done to date and start fresh. We aren't in the position to do that and my first response would be to say no for that reason and also for increased complexity in the test cycle and test procedures which we'd have to start working with now.

COMMENT - K. Stuckas: First of all, I'd have to concur with Steven Imbrogno's remarks about the equipment, and second, at this time we feel we have the equipment in shape and are on top of the situation to the point of where we feel we can produce accurate results within the constraints of the exhaust emission standards as written in the Federal register. I don't feel there is any benefit or value in going to a bag system at this time, although we have tried it with very little success.

Q - H. Nay: This question is directed to those who have done emissions testing relative to fuels composition. There is a fairly broad range of content of aviation gasoline. For instance, the 100 octane low lead fuel contains a high content of aromatics relative to the regular 100 octane leaded fuel. Has there been any experience in regard to emissions measurements, analysis results, or that type of thing relative to the actual composition of the fuel? And is the a standard test fuel used in conjunction with emission measurements?

A - P. Kempke: NASA-Lewis has used the standard aviation reference fuel throughout our program. Although we have not made any experimental comparative tests, as a general comment in comparing our data to that generated by the industry for similar engines, there does not seem to be any difference that I would attribute to fuel differences. I believe the industry did not use the reference fuel but instead used the commercially available aviation fuel.

COMMENT - L. Duke: We did not use a standard reference fuel. We buy a commercially available fuel and each time analyze it for aromatic content, olefin lead content, and other things that would influence the hydrocarbon ratio in the calculation procedure. We did not use different fuels to try to characterize the effects on emissions.

COMMENT - W. Mirsky: If you look at the effect of hydrocarbons on the enviroment, you get into a very difficult situation when looking at the reactivity of the hydrocarbon exhaust. You measure total quantity of hydrocarbons but the type of hydrocarbons has a large effect on how they each affect the atmosphere. This requires a very elaborate analysis. A lot of this work has been done and supported by EPA. Dick Hurn of Bartlesville, Oklahoma, has done a lot of work and it was found that there may be as many as 200 different types of hydrocarbons in the exhaust as was shown in some of their early work. Methane and the single bond hydrocarbons are not very reactive and do not affect the atmosphere. The olefinic type of double bond hydrocarbons are reactive so you get into a complex situation if you start to analyze the affect of individual hydrocarbons. I think the major problem with aircraft engines is not so much the hydrocarbons as the CO and that's a much simpler problem.

INDUCTION AIR SCHEMATIC FOR 10-360B TESTS AT NAFEC

NOTE: (1) VALVE IS OPEN FOR TAKE-OFF, CLIMB AND APPROACH POWER
(2) VALVE IS CLOSED FOR TAXI AND IDLE POWER
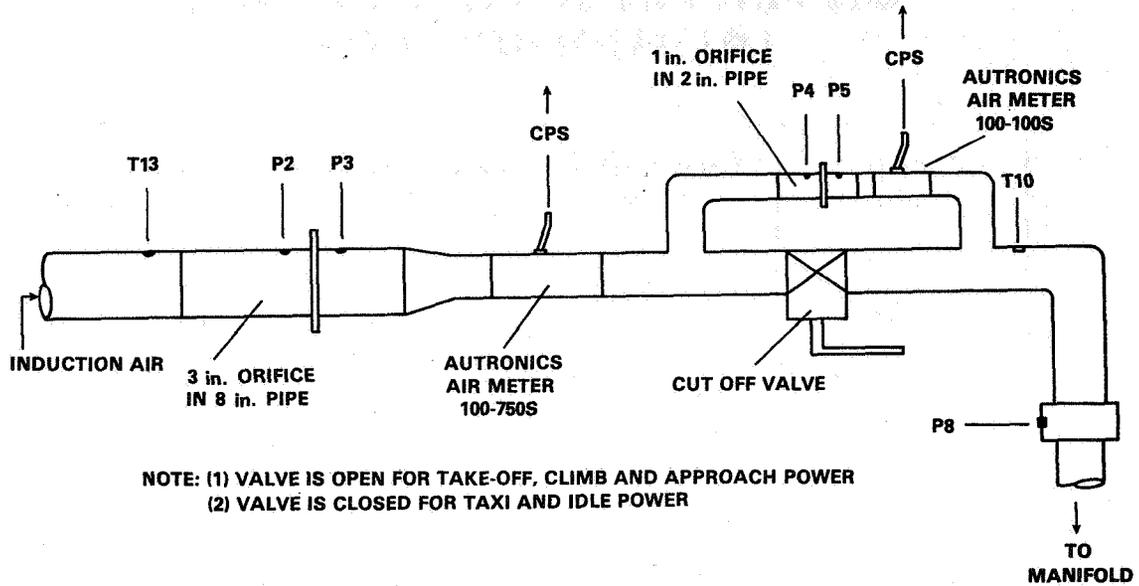
Figure 3-1

SIZING EFFECTS
ON 3.8 in. ORIFICE IN 8 in. PIPE

POWER SETTING	ΔP (in. H_2O)	AIR FLOW (lb/hr)	ΔP TOLER. (in. H^2O)	AIR FLOW TOLER. (lb/hr)	ACCURACY (%)
TAKEOFF	4.0	1775	±0.05	±10	±0.5
IDLE	0.1	115	±0.05	±45	±39.1

INSTRUMENT RANGE: 0-2000 lb/hr WITH + 3 in. H_2O BLOWER PRESSURE

Figure 3-2

SIZING EFFECTS
ON AIR FLOW TRANSDUCER
(AUTRONICS 750S)

CPS	MEASURED CFM	CALIBRATION CURVE CFM	PERCENT DIFFERENCE
20	10	15	+ 50
57	40	44	+ 10
661	500	503	+ .6

INSTRUMENT RANGE: 0-600 CFM

Figure 3-3

FUEL FLOW SYSTEM
PRIOR TO TIARA 6-285-B
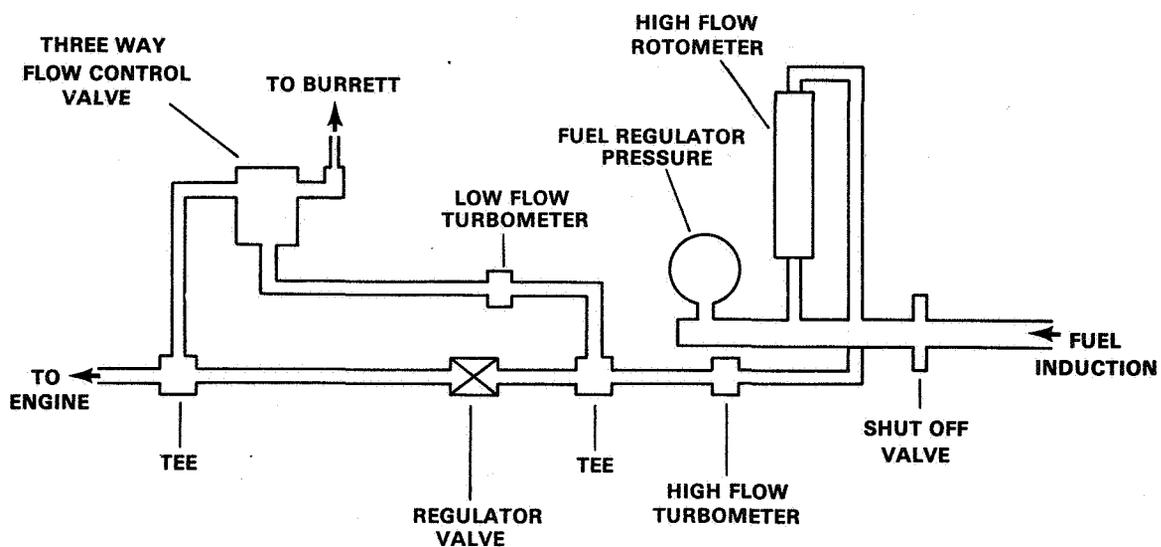
Figure 3-4

SCHEMATIC OF EMISSIONS MEASUREMENT SYSTEM
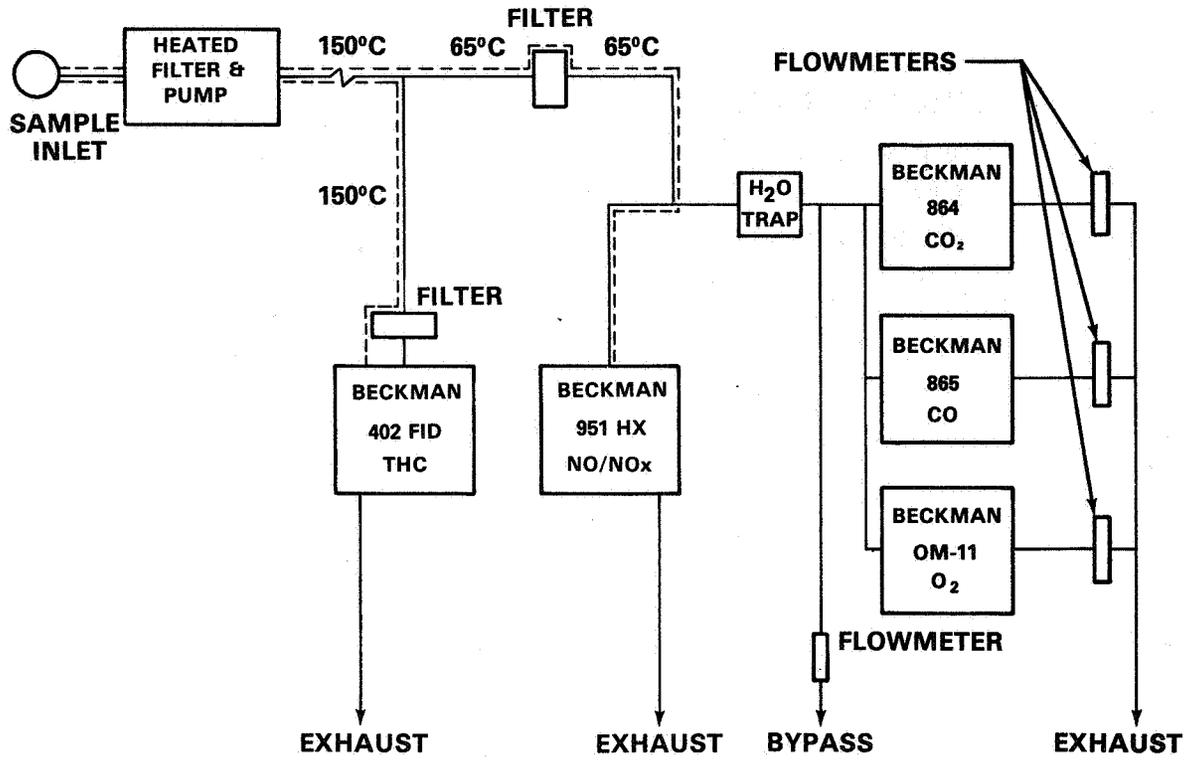
Figure 3-5

NAFEC
EMISSION MEASUREMENT SYSTEM

- **CARBON DIOXIDE—CO_2**
  - NONDISPERSIVE INFRARED (NDIR)
  - RANGE   0-20%
  - REPEATABILITY $\pm$ 0.2% CO_2

- **CARBON MONOXIDE—CO**
  - NDIR
  - RANGE   0-20%
  - REPEATABILITY $\pm$ 0.2% CO

- **TOTAL HYDROCARBONS—THC**
  - FLAME IONIZATION DETECTOR (FID)
  - RANGE   0-150,000 ppm_c
  - MINIMUM SENSITIVITY   1.5 ppm_c
  - LINEAR TO   150,000 ppm_c

- **OXIDES OF NITROGEN—NO_X**

  - CHEMILUMINESCENT (CL)
  - RANGE   0-10,000 ppm
  - MINIMUM SENSITIVITY   0.1 ppm

- **OXYGEN—O_2**

  - POLARAGRAPHIC
  - RANGE   0-100%
  - REPEATABILITY   0.1% O_2
  - RESPONSE   200 ms

Figure 3-6

**BECKMAN MODEL 402
THC ANALYZER**

PPM CARBON X 10^{-3}

1.5 PSI (UNMODIFIED)

INSTRUMENT RESPONSE ∼ % FULL SCALE

Figure 3-7

**BECKMAN MODEL 402
THC ANALYZER**

PPM CARBON X 10^{-3}

1.5 PSI (MODIFIED)

INSTRUMENT RESPONSE ∼ % FULL SCALE

Figure 3-8

**BECKMAN MODEL 402
THC ANALYZER**

3 PSI (UNMODIFIED)
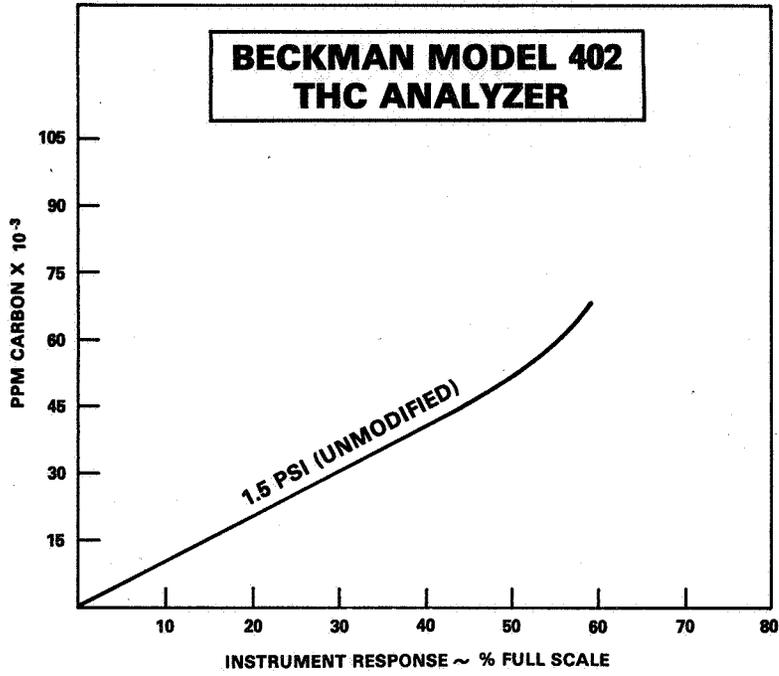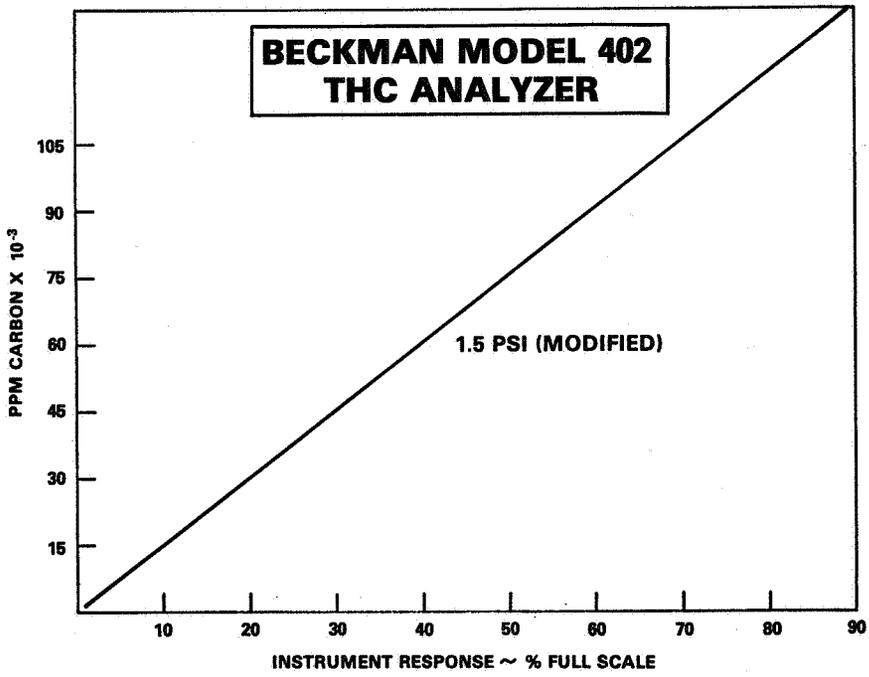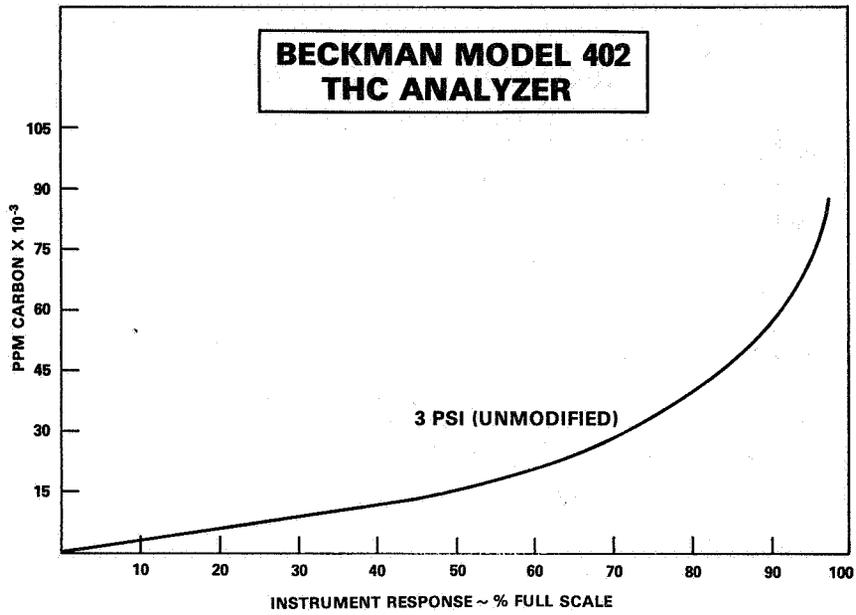
Figure 3-9

STABILITY OF NITRIC OXIDE MIXTURES
(SOURCE-NBS)
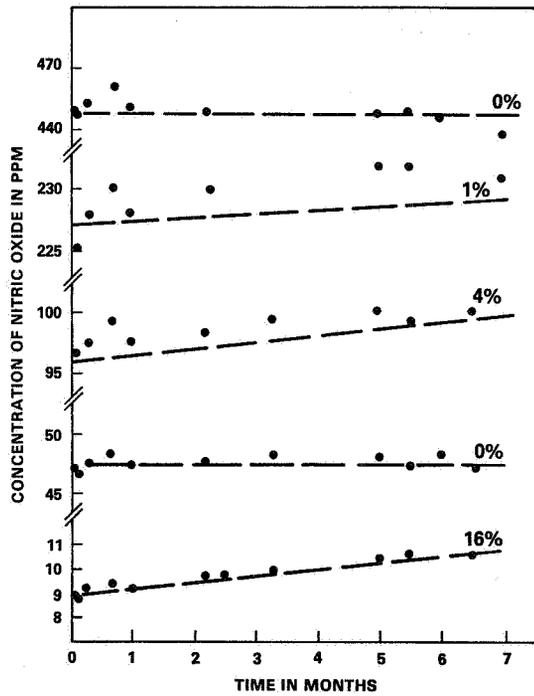
Figure 3-10

EFFECT OF CYLINDER TYPE
ON STABILITY OF NO_2

CYLINDER TYPE	ANALYSIS 2 MONTHS	ANALYSIS 2 YEARS
WAX LINED	135 ppm	1 ppm
STEEL (Cr-Mo)	179 ppm	151 ppm
TREATED ALUMINUM	197 ppm	200 ppm

FILLED TO BE 200 PPM NO_2 IN N_2
(SOURCE—AIRCO INDUSTRIAL GASES)

Figure 3-11

DESCRIPTION OF 7 MODE
BASELINE TEST FOR EMISSIONS

TIME IN MODE	RPM	POWER
1 MINUTE	600	IDLE OUT
11 MINUTES	1200	TAXI OUT
.3 MINUTE	2700*	TAKEOFF
5 MINUTES	2430*	CLIMB
6 MINUTES	2350*	APPROACH
3 MINUTES	1200	TAXI IN
1 MINUTE	600	IDLE IN

*NOMINAL RPM'S FOR MOST ENGINES TESTED

Figure 3-12

DESCRIPTION OF 5 MODE
BASELINE TEST FOR EMISSIONS

TIME IN MODE	RPM	POWER
12 MINUTES	1200	TAXI OUT
.3 MINUTE	2700*	TAKEOFF
5 MINUTES	2430*	CLIMB
6 MINUTES	2350*	APPROACH
4 MINUTES	1200	TAXI IN

*NOMINAL RPM'S FOR MOST ENGINES TESTED

Figure 3-13

EFFECT OF DELETION OF THE IDLE MODE
ON CYCLE EMISSION CALCULATION

Figure 3-14

4. DATA REDUCTION AND EVALUATION PROCEDURES

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Work at the University of Michigan has primarily been concerned with the computational procedures that are involved in exhaust emissions data reduction and the use of these computational procedures for determining the quality of the data that is obtained from exhaust measurements. We focused on four problem areas. The first was the various methods for performing the carbon balance. As has already been mentioned, Federal regulations specify that a ± 5-percent tolerance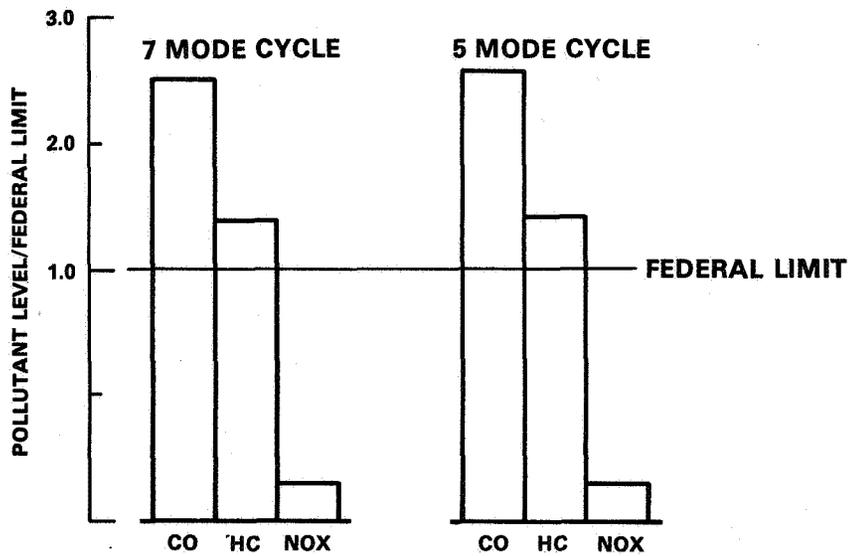 on the carbon balance should be met. There are at least four techniques that can be used to perform this carbon balance. Each technique gives a different error for the carbon balance. The second problem area was the method for calculating water correction factors. In the various exhaust measurement instruments that are used, some of the water is condensed from the exhaust sample and the concentration must be converted to either a totally wet or totally dry measurement. Because of the involvement of the water correction factor in the data reduction computations, part of our effort was to examine the methods used for determining this water correction factor. The third problem area was how to calculate the exhaust molecular weight. The fourth problem area was assessing the quality of the data. Is there a way of determining the quality of the data immediately from an analysis of the results or does one make comparisons with trends established over a series of runs?

Our accomplishments are as follows:

1. Review of the literature for methods of performing the carbon balance

    (a) Spindt (Gulf Research) (ref. 1)

    (b) Stivender (General Motors Research) (ref. 2)

    (c) Eltinge (Ethyl Research and Development Laboratories) (ref. 3)

2. Fundamental approach to performing the carbon balance

    (a) Find X equations for the X unknowns

    (b) Methods:

        1.1 Spindt (K), 4 equations in 4 unknowns

        1.2 Expanded Spindt (K), 15 equations in 15 unknowns

        2.1 XTC, 15 equations in 15 unknowns

        3.1 K and XTC, 16 equations in 16 unknowns

        3.2 Modified Stivender, 12 equations in 12 unknowns

    (c) Features of the University of Michigan methods:

        (1) Model the combustion process more accurately

        (2) Clearly identify assumptions and simplifications

        (3) Eliminate need for water correction

        (4) Give concentrations of 10 (11) major exhaust components

        (5) Compute exhaust molecular weight

        (6) Provide means for data assessment

        (7) Agree well with Eltinge's method

First, we reviewed the literature dealing with the methods for performing the carbon balance. We found three important works in this area. One method by Spindt at Gulf Research (ref. 1) seems to be very commonly used not only in the automotive industry but in many combustion studies. The second method was developed by Stivender at General Motors Research (ref. 2), and the third is a graphical method developed by Eltinge at the Ethyl Research and Development Laboratories (ref. 3).

In examining these computational procedures we found that the carbon balance could be performed in a more fundamental manner. This fundamental method consists of finding a sufficient number of equations to be able to solve for the unknowns that appear in the combustion equation model. By following this approach we were able to use an expanded and more accurate combustion equation that gave us more accurate information about the combustion model and about the emissions measurements. Based on this fundamental approach, we developed the following five methods: The first method (1.1) is equivalent to the Spindt method in that four equations are used for four unknowns. It is a fairly simple model. The

combustion equation is expanded by using a more accurate air composition that includes argon, water vapor, and variable carbon dioxide (CO_2) levels in the intake air and by taking into consideration 10 or 11 products in the exhaust (method 1.2). Methods 1.1 and 1.2 both use the equilibrium constant equation for the water gas reaction as one of the equations. Method 2.1 substitutes an equation that involves the sum of the mole factions in place of the equilibrium constant equation. Method 3.2 involves both the equilibrium constant and the sum of the more factions. Method 3.2 involves a modified Stivender system, which does not require an oxygen measurement. Note that we have gone from four equations involving four unknowns to 16 equations and 16 unknowns.

This approach gives us a computational method with the following features: first, we have a more accurate combustion equation involving more of the stable combustion products. Second, the assumptions and simplifications are clearly identified. Third, we eliminate the need for a water correction factor since there is no separate computation that involves the water correction factor. Measurements in either the dry, dried, or wet states can be used. If no water is condensed out of the sample, the measurement is wet. If water is condensed in the water trap, the measurement is somewhat dried but there is still some water vapor present. The sample must be passed through a drier to eliminate all the water. These are the three different types of measurements that can be handled in our computational procedure. These methods give the concentrations of 10 or 11 major exhaust components as well as the fuel-air ratio, whereas a procedure such as the Spindt method gives only the fuel-air ratio. From the concentrations of the 10 or 11 major exhaust components, we can then compute the exhaust molecular weight. This value is more reliable than one based on equilibrium computations as is commonly done.

Our method has also been of value in assessing the quality of the data. The method for assessing data quality was as follows: We started with a run that showed agreement for all the four computational methods. We then performed, on the computer, a calculation whereby we incremented the concentration of an exhaust species such as CO_2 while holding all other measurements constant. The effect would be similar to making an error in the CO_2 measurement. The results show the fuel-air ratio error obtained for each of the four computational methods. As shown in figure 4-1(a), if method 2.1 gives a +5-percent error, method 3.2 would give a +2-percent error, method 1.2 would give a -1-percent error, and method 3.1 would give approximately a -5-percent error. This illustrates the fact that the percentage of error in the carbon balance is a function of the method being used. A useful factor that comes out of this is the sensitivity factor that we call specific error. For example, the CO_2 specific error is the increase in fuel-air ratio error due to a 1-percent increase in CO_2. Each computational method shows a different specific error. Our analysis shows that the specific error varies with the concentration as shown in figure 4-1(b). Similar studies were made using

many other variables, such as carbon monoxide (CO), hydrocarbons (HC), oxygen (O_2), and ambient humidity. This information can be applied in assessing the exhaust emissions data in the following manner: An error in the CO_2 measurement such that the CO_2 measured is higher than the true CO_2 concentration would cause, depending on the concentration, an increase or decrease of the error as is shown in table 4-1. The magnitudes and signs of the errors from the four different methods show which measurement is primarily responsible for the difference between the measured and the calculated fuel-air ratios.

Tables 4-2 and 4-3 are two examples in which errors in the calculated fuel-air ratio based on four different calculation procedures are compared with measured test results. Table 4-2 (example 1) shows that all four methods gave fuel-air ratio errors of about 6 percent. On the basis of the +5-percent carbon balance criterion, this run would not be considered an acceptable run. Normally, all four methods would not give essentially the same result. The chances of having compensating errors so as to end up with the same results are very small, and one would have to presume that the calculated results are good. On the basis of these results, we would conclude either that there is an error in the fuel measurement value or the air measurement value or that there was an air leak in the system. In fact, in this particular case an air leak was discovered in the induction system.

In table 4-3 (example 2), the +5-percent error was not exceeded. The expanded Spindt method (method 1.2) gave an error of about 3 percent. Normally, this would be considered to be a good run. However, when the data were reduced by the three other methods, we got errors of 24, -10, and 10 percent. What we do now is to find out which of the measurements is the most probable cause for this error. Examining the fuel-air ratio errors shows that a correction of +10 percent is required for method 3.1, while method 3.2 would require a -10-percent correction. The specific errors for CO_2 of -1.4 and +0.5 percent for methods 3.1 and 3.2 in table 4-4 shows that these changes will not result from corrections in the CO_2 concentrations. However, it appears that CO might be in error here because the two CO specific errors of -0.9 and +0.8 percent are about equal and of opposite signs, indicating that the two fuel-air ratio errors of methods 3.1 and 3.2 could be reduced to approximately zero by a change in CO concentration. This would not be accomplished by an O_2 correction or by a hydrocarbon correction. This analysis therefore points to CO as the measurement causing the bad data point.

Next, we determine the necessary correction of CO, by using specific sensitivities, required to reduce all four fuel-air ratio errors to zero. Method 1.2 would require a -15-percent change in CO (table 4-4). Method 2.1 would require a -12-percent change. When the CO concentration was reduced by 11.8 percent, a value arrived at after two tries, the fuel-air ratio errors for all four methods were reduced to less than 1 percent, as shown. This procedure allows us to assess the quality of data from a single run and to pinpoint the source of error when the error is due pri-

marily to one bad measurement. The analysis becomes more complicated when more than one measurement is in error. Also note that a Spindt error which is less than 5 percent does not necessarily mean a good data run. The other computational methods are as acceptable as the Spindt method and often show much higher fuel-air errors as illustrated in example 2.

Our analysis has been applied to over 500 runs and has proved to be a reliable means for quickly assessing emissions data. This study is being continued to further refine the procedure for assessing data quality.

REFERENCES

1. Spindt, R. S.: Air-Fuel Ratios from Exhaust Gas Analysis. SAE Paper No. 650507, 1965.

2. Stivender, D. L.: Development of a Fuel-Based Mass Emission Measurement Procedure. SAE Paper No. 710604, 1971.

3. Eltinge, L.: Fuel-Air Ratio and Distribution from Exhaust Gas Composition. Ethyl Corporation Report 68-1, Jan. 1968.

TABLE 4-1. - SPECIFIC ERROR SUMMARY

	Method			
	1.2	2.1	3.1	3.2
CO_2	↑↓	↑	↓	↑
CO	↑	↑	↓	↑
O_2	↓	↑	↓	—
HCC	↑	↑	↑	↑

TABLE 4-2. - COMPARISON OF ERRORS IN THE CALCULATED

FUEL-AIR RATIO BASED ON FOUR DIFFERENT

CALCULATION PROCEDURES - EXAMPLE 1

Method	XTC	FACAL	FAM	F/A percent error
1.2	1.005	0.07565	0.07140	5.96
2.1	-----	.07576	↓	6.11
3.1	-----	.07557		5.84
3.2	-----	.07569	↓	6.01

Spindt error >5 percent.
Other methods give same result.
Found air leak from induction system.

TABLE 4-3. - COMPARISON OF ERRORS IN THE CALCULATED

FUEL-AIR RATIO BASED ON FOUR DIFFERENT

CALCULATION PROCEDURES - EXAMPLE 2

Method	XTC	FACAL	FAM	F/A percent error
1.2	1.0578	0.10752	0.10436	3.030
2.1	------	.13017		24.733
3.1	------	.09386		-10.053
3.2	------	.11529		10.477

Spindt error <5 percent.
Other methods give high errors.
Implies measurement error(s).

TABLE 4-4. - ERROR ANALYSIS - SPECIFIC

ERRORS OF EXAMPLE 2

Method	CO_2 (67022)	CO (129820)	O_2 (4310)	HCC (15688)
1.2	0.0	+0.2	-0.05	+0.13
2.1	+1.1	+2.0	+0.05	+0.18
3.1	-1.4	-0.9	-0.10	+0.07
3.2	+0.5	+0.8	0.0	+0.15

From: Specific error $= \dfrac{\text{Required change F/A error}}{\text{Percent increase in concentration}}$

Get: Percent increase concentration $= \dfrac{\text{Required change F/A error}}{\text{Specific error}}$

Method	
1.2	-3.03/+0.2 = -15.15 percent change CO
2.1	-24.73/+2.0 = -12.37
3.1	+10.05/-0.9 = -11.17
3.2	-10.48/+0.8 = -13.10

After -11.8 percent change in CO, result is

Method	XTC	FACAL	FAM	F/A percent error
1.2	1.001	0.10502	0.10436	0.632
2.1	-----	.10525	↓	.850
3.1	-----	.10486		.483
3.2	-----	.10511	↑	.717

DISCUSSION

COMMENT - W. Westfield: I'd like to add one thing that Dr. Mirsky didn't add. We supplied him with approximately 400 data points, many of which we knew were questionable. In the analysis of the work that he did for us he came up with a grouping of data points that appeared to be outside acceptable ranges. In going back and looking at the unacceptable data points I think the vast majority of those points were "idle mode" data points. We feel this is further support for getting rid of the procedure and computational process that really drives us up a tree when we try to come up with a cycle factor.

Q - T. Souza: Aren't there two ways of calculating emissions? One is based on exhaust volume where the concentrations in the exhaust are measured. The exhaust volume is then calculated and the pollutants are based on the ratio of the concentrations of the different gases. The second way is to simply assume that all the carbon in the fuel coming into the engine appears as carbon in some constituents in the exhaust.

A - W. Mirsky: Yes, there are two methods. What you're doing in performing the carbon balance is accounting for the carbon; but you also have to account for all the other atoms that come in with the fuel and air based on measurements in the exhaust. In the simple combustion equation you don't take into account all of the moles of the products so that the value that you substitute in the mathematical model is not quite the right value. What the four methods start out with are unknown quantities of air and fuel and you have to solve these. You first set a carbon balance and an oxygen balance. Then you introduce another unknown. In the Spindt method it turns out to be hydrogen and water so you have to have two more equations; that's how you get four equations and four unknowns in a modified Spindt method. The combustion model is not complete since the argon and some of the other species in the exhaust have been ignored. What you are trying to do is decide whether or not the value that you calculate does, in fact, agree with what you measure. If you have an error in CO_2 then you get different errors between the measured and calculated value depending on what method you use. The sensitivity curve shows that for a 1-percent change in CO_2 there can be four different answers for the errors between the calculated and the measured fuel-air ratio. This whole approach was to look at the problem comprehensively and understand what really went into the Spindt method, the Stivender method, and the Eltinge method. One of the problems is to decide whether the measured fuel-air ratio and calculated fuel-air ratio agree. The second problem is to come up with a computation for the molecular weight of the exhaust. Many people use the equilibrium concentrations in order to come up with the molecular weight of the exhaust. In our calculations we find that at a particular fuel-air ratio you can get a variety of molecular weights depending on how complete the combustion process is. If the combustion process is complete, you tend to approach the molecular weight as given by the equili-

brium calculations. If the combustion process is not complete, as you would get from a very poor quality mixture, the molecular weight is then considerably lower.

Q - R. Tucker: In example 2 with the expanded Spindt method you show the sum of the exhaust products mole fraction to be approximately 1.06. We've encountered the same problem of the sum of the mole fractions exceeding 1. Do you have any explanation for this?

A - W. Mirsky: The reason the sum of the mole fractions exceeds 1.0 or is less than 1.0 is that the measurements are not good. With a consistent set of measurements that satisfy the four different methods XTC will approach a value of 1.0, thereby providing a very nice parameter by which you can tell whether or not the measurements are good. In the first example, the XTC value is very close to 1.0. As a result, all of the calculated values come out to be the same. When your measurements are self-consistent, your XTC becomes equal to 1.0. If your measurements are not self-consistent, in other words, if they don't satisfy these equations properly, then the deviate from 1.0 and you can get either higher or lower values than 1.0.

Q - G. Kittredge: I'd like to ask Dr. Mirsky about his investigation of exhaust analyses and ways of complying with the carbon balance of our standards. I just reread that part of our standards in which we talk about carbon balance. It is an extremely tersely worded sentence. Are you making a recommendation that we make a change in the standards to be more compatible with the analysis that you have made?

A - W. Mirsky: My comment would be that you have to be more specific when you say that ±5 percent of tolerance on carbon balance will have to be met. Depending on which method I use, I can be outside that tolerance or within the tolerance. What I'm saying is that the method of computation will have to be specified. With our extensive work, we've examined this question very thoroughly and have written a report for the FAA that should be published soon. I would say at this time that the XTC value, or the sum of the mole fractions, is a more important parameter to meet than the fuel-air ratio. It tells you whether or not your instruments are self-consistent. We tend to recommend, although this has to be looked into further, a ±5 percent tolerance on the expanded Spindt method plus a ±5 percent tolerance on the XTC. We examined well over 500 runs and plotted the XTC and fuel-air ratio error. When you have good runs the points tend to congregate around the origin of those axes. For the high power runs, the group of points tends to go around the origin. In the taxi modes, there is a departure from the origin and a good percentage of the points start to fall outside the acceptable limits. In the idle mode, almost all of the runs tend to be outside the acceptable ranges. I would say that you have to specify the method of computation.

COMMENT - B. Rezy: We've heard a lot of comments on test procedures and different methods of calculation. I would like to propose that we finalize this and come up with one method so that everyone uses the same standard system. There are three ways of going about this: we could have the government set up the procedure; we could have a committee set up to determine these standards; or we could have GAMA set the standards. I would like to propose that we have a committee get together and determine what standards we should be going by.

Q - G. Kittredge: I thought the ground work was laid after an earlier meeting to ask the SAE aircraft exhaust emissions measurement committee E31 to evaluate and make recommendations concerning the light aircraft powerplant measurement procedures. I don't know whether that's actually been implemented. Does anybody else know?

A - W. Westfield: Since I am vice chairman of the committee, I'd have to say no. Nobody has started the work yet.

COMMENT - E. Kempke: Dr. Mirsky's techniques are interesting and I agree with Bernie Rezy of TCM that there does need to be further discussion and exploration of which techniques should be used. I feel that probably that's about the extent of what can be accomplished in this meeting. The subject is a very specialized one and it does need, as a minimum, a special meeting of those that are most intimately involved to discuss and try to get some more clarification of what's been proposed. I know in talking with others that there may exist some different ideas about what should be explored as well. We agree that the Spindt technique may have some deficiencies at the lower power conditions and, therefore, other alternatives should be looked at.

COMMENT - L. Helms: Speaking for the technical policy committee, I was not familiar with the effort of SAE that George Kittredge mentioned. However, we cannot stand the luxury of another 6 months or a year's delay. We are literally running out of lead time. I would like to reinforce the recommendation that a joint committee be formed between our GAMA people and the ones here and get on with it. I don't know how long the SAE panel has been debating or been delaying but we cannot stand additional delays.
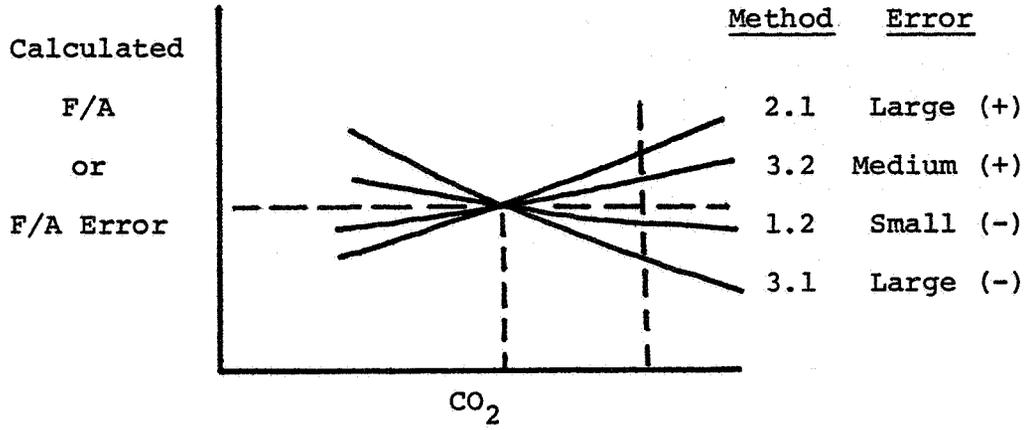
SPECIFIC ERROR = SLOPE = $\dfrac{\text{CHANGE IN \% ERROR}}{1\% \text{ INCREASE}}$

a)   SENSITIVITY PLOT, SPECIFIC ERROR
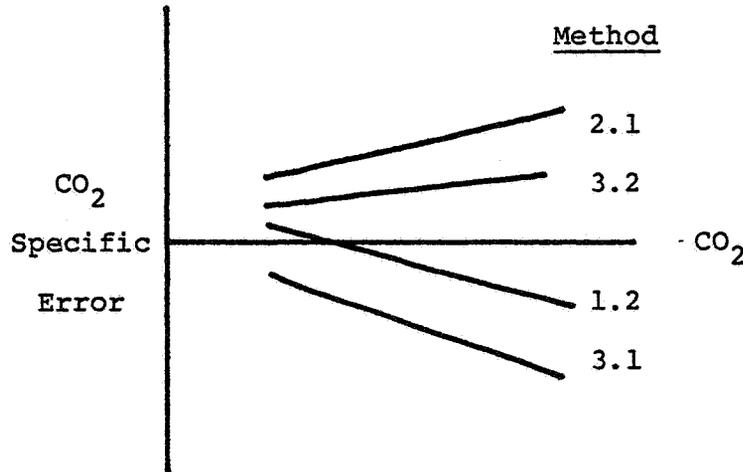
b)   SPECIFIC ERROR CURVES

Figure 4-1

5. SUMMARY REPORT ON EFFECTS AT TEMPERATURE, HUMIDITY,

AND FUEL-AIR RATIO ON TWO AIR-COOLED

LIGHT AIRCRAFT ENGINES

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INTRODUCTION

NASA is involved in a research and technology program related to general aviation engines. The overall objective of the program is to establish and demonstrate the technology which will safely reduce general aviation piston-engine exhaust emissions to the levels required by the EPA 1979 emissions standards.

One element of the R&T program is a joint FAA/NASA general aviation piston engine emissions reduction effort. Funded studies are now under way by the two primary engine firms building general aviation piston engines, Avco Lycoming and Teledyne Continental Motors. In phase I of their three-phase programs, each contractor is testing five different engine models to experimentally characterize emissions and to determine the effects of variation in fuel-air ratio and spark timing on emissions levels and other operating characteristics such as cooling, misfiring, roughness, power acceleration, etc. The FAA is using its NAFEC facility to perform independent checks on each of the engines the contractors are testing in phase I. It was recognized early in the program that the phase I tests would be conducted under essentially uncontrolled induction air conditions at widely different geographical locations and that a better understanding of temperature and humidity effects would certainly enhance the ability to make a correlation and better comparison of these data. Therefore, NASA Lewis Research Center has undertaken a series of aircraft engine tests to develop such a correlation. Two engines, identical to ones in the FAA/NASA program, were selected for testing. The engines were from two manufacturers; the first was the Avco Lycoming O-320-DIAD, four-cylinder, naturally aspirated engine, and the second was the Teledyne Continental TSIO-360, six-cylinder, turbocharged, fuel-injected engine.

This paper presents a brief summary of the results given in two NASA reports (refs. 1 and 2) covering the Avco Lycoming O-320-D engine testing and the recently obtained results on the Teledyne Continental TSIO-360-C engine.

APPARATUS AND PROCEDURE

Test Facility and Engines

The aircraft engine is shown photographically on the test stand in figure 5-1. The engine was coupled to a 300-horsepower dynamometer through a fluid coupling in the drive shaft which was located under a safety shield. Engine cooling and induction air were supplied by a laboratory air distribution system. The cooling and induction air system can be controlled to deliver air to the engine over a temperature range of 50° to 120° F and over a range of relative humidity from 0 to 80 percent. The cooling air was always at the same conditions as the induction air and directed down over the engine by an air distribution hood. This hood was the same as that which was used by the engine manufacturer in their engine testing. The engine cooling air was removed from the test cell by a high capacity, facility altitude exhaust system which had the inlet located beneath the engine. An additional cell exhaust fan was used to maintain a slightly negative pressure in the test cell. This was done to vent any combustible or toxic gases which may have been present in the test cell during engine operation.

The Avco Lycoming O-320-D engine exhaust was manifolded together in a standard configuration with the emission sample probe located about 4 feet downstream of the manifold. The exhaust was then ducted out the cell through the roof. Care was taken to insure that the exhaust system was leakproof. A leakproof system was necessary to prevent air dilution of the gas sample which would result in erroneous emission measurements. Bellows were installed over the slip joints of the TSIO-360-C engine exhaust system so as to eliminate air entering the system at the low power conditions.

Instrumentation

A complete description of the instrumentation used in the engine testing is contained in reference 1. All 100 channels of instrumentation were connected to the CADDE (Central Automatic Digital Data Encoder) central data acquisition system and the data were processed on a 360/67 timing-sharing computer.

Numerous modifications were made early in the project to the emissions analyzer instrumentation. In fact, an examination of facility problems disclosed that in the early stages of the project a very large

percentage was related to the emissions analyzer. The widespread problem in NO_x measurement at high levels of CO was revealed and solved by modifying the chemiluminescent NO analyzer (ref. 3). However, it is significant to also mention that in the last 9 months there have been very few analyzer problems. The initial concerted effort appears to have resulted in modifying the analyzer into a reliable and accurate instrument.

DISCUSSION OF O-320-D AIR TEMPERATURE AND HUMIDITY EFFECTS

FOR SEVEN-MODE CYCLE TEST

Test Procedure

The engine testing procedure was conducted as specified by the Environmental Protection Agency in the Federal Register, vol. 38, no. 136, dated Tuesday, July 17, 1973 (ref. 4) except for the separation of the idle and taxi time in and out modes as shown in the following table:

Mode	Mode description	Power level, percent	Speed, rpm	Time in mode, min
1	Idle out	--	600	1.0
2	Taxi out	--	1200	11.0
3	Takeoff	Full power	2700	.3
4	Climb	80	2430	5.0
5	Approach	40	2350	6.0
6	Taxi in	--	1200	3.0
7	Idle in	--	600	1.0

Prior to the start of a 7-mode cycle (LTO) test, the engine was warmed at 2000 rpm for approximately 10 minutes until all parts were temperature stabilized and all cylinder head temperatures were at least 300° F.

The 7-mode emission cycle data tests were conducted over a range of air temperatures and relative humidities. The induction air and cooling air temperatures were the same and were held at nominal values of 50°, 59°, 70°, 80°, 90°, and 100° F at relative humidities of 0, 30, 60, and 80 percent. For each test condition three LTO 7-mode cycles were run at the full rich fuel-air ratio. This procedure resulted in approximately 450 different engine test conditions.

Seven-Mode Cycle Test Results

Figures 5-2 and 5-3 summarize the CO, NO_x, and HC emissions gener-

ated over the 7-mode cycle for each of the four values of relative humidity as a function of air temperature and expressed as a percent of the EPA standards.

In general, the data show that the quantity of emissions produced is strongly affected by the relative humidity, and that this effect increases with increasing induction air temperature. The HC and CO emissions increase considerably at the higher values of air temperature and relative humdity, while at the same conditions the NO_x emissions show a significant decrease. A comparison of the temperature and humidity test results at 100° F and 80 percent humidity to those at 50° F and 0 percent humidity show that, with the increased temperature and humidity, the CO increases by a factor of 1.6, the HC increases by a factor 2.2, and the NO_x decreases by a factor 3.5.

Present-day aircraft engines do not use a temperature-density compensated fuel system. The change in the exhaust emission is primarily the result of richer fuel-air ratios which occur at the higher air temperatures and relative humidities. This is due to the decrease in air density with increased temperatures and the volume of air that is displaced by water vapor in the fuel-air mixtures.

DISCUSSION OF O-320-D AND TSIO-360-C AIR TEMPERATURE AND HUMIDITY

EFFECTS AT VARIOUS FUEL-AIR RATIOS ON A PER MODE BASIS

In the preceding section it was stated that the major factor affecting the level of emissions was the fuel-air ratio which occurs at the particular ambient condition. It is also known that an ambient condition can affect the induction vaporization and basic combustion process, thereby influencing the HC and NO_x emissions. Therefore, a series of tests was performed to establish the effect of air temperature and relative humidity at various fuel-air ratios on a per mode basis (idle, taxi, takeoff, climb, and approach). The test conditions include varying the fuel-air ratio for each of the five emissions test modes over the following range of ambient conditions: air temperature (°F), 50, 59, 80, and 100; relative humidity (percent), 0, 30, 60, and 80. Combinations of these parameters with the modes over a range of fuel-air ratios resulted in over 800 different test conditions. These data can be used to provide a variety of fuel schedules for the individual modes over a range of ambient conditions which can be used to correlate ambient conditions and emissions. The data can also be used to construct optimum baseline cycles based on leaner fuel schedules; the data thereby provide a quick and simple method for assessing the benefit of tailored fuel schedules.

The results of the per mode tests indicate that for a fixed fuel-air ratio the effect of temperature and humidity on the HC and NO_x exhaust emissions at the higher temperature and relative humidities was significant, whereas the CO exhaust emissions are essentially inde-

pendent of ambient conditions. At a fixed fuel-air ratio with higher air temperatures and relative humidities, the HC emissions increased and the NO_x emissions decreased in certain modes.

Figures 5-4 to 5-18 summarize for the Avco Lycoming 0-320-D engine the CO, NO_x, and HC modal emissions generated over a range of fuel-air ratios for the ambient conditions (50° F and 0 percent humidity, and 100° F and 80 percent relative humidity). The HC emissions (shown in figs. 5-5, 5-8, 5-11, 5-14, and 5-17) were higher especially for the climb, taxi, and idle modes at the high temperature and relative humidity condition. The NO_x emissions (shown in figs. 5-6, 5-9, 5-12, 5-15, and 5-18) decrease for the takeoff, climb, and approach modes at the higher temperature and relative humidity conditions. This decrease was more pronounced at the leaner fuel-air ratios. The CO emissions (shown in figs. 5-4, 5-7, 5-10, 5-13, and 5-16) are independent of ambient conditions with the exception of the climb mode, which indicates a very slight effect.

The previously mentioned trends of increasing HC and decreasing NO_x exhaust emissions at the higher temperature and humidity conditions are attributed to the volume of moisture in the induction air, which can affect the combustion process and the vaporization characteristics of the fuel.

A comparison of the previously discussed 7-mode cycle results with a similar constructed seven-mode cycle using the individual modes lean-out data showed reasonably good agreement.

Shown in figures 5-19 to 5-27 for the takeoff, climb, and approach modes are comparisons of the TCM TSIO-360-C engine and the Avco Lycoming 0-320-D engine temperature-humidity lean-out tests for the two extreme ambient test conditions of 50° F and 0 percent relative humidity, and 100° F and 80 percent relative humidity.

In general, the results of testing a naturally aspirated carbureted engine and a fuel-injected turbocharged engine show similar emission trends with changing temperature and humidity as the fuel-air ratio is changed. One exception occurred at the takeoff mode in which very little humidity effect on NO_x formation was observed for the TSIO-360 engine, whereas a significant effect was seen for the 0-320-D engine.

CONCLUDING REMARKS

The results reported herein are based on tests conducted on one carbureted naturally aspirated engine (testing completed) and one turbocharged fuel-injected engine (testing still in progress). A great deal of additional analysis of the data is required to develop a correlation that would relate emissions to the temperature-humidity condi-

tions. Although the results thus far are encouraging that such a correlation can be derived, it is not certain that one "universal" correlation based on only two engine types can be developed to cover the broad spectrum of engine models or classes produced today.

The following remarks are on what is viewed as hopefully a more direct and practical solution to the problem. NASA's test results to date have shown that temperature and humidity effects must be considered by those involved in setting regulations designed to insure the compliance with the emissions standards. Standard day conditions need to be specified and required for compliance testing. Although NASA does not at this time have a strong recommendation, it would seem that a temperature of 59° F would be a logical selection inasmuch as this is a standard value used in engine performance correction calculations. A pressure of 29.92 inches of mercury and a relative humidity of 0 to 10 percent might be acceptable for the same reasons. NASA's results as previously discussed have shown that the humidity effects at a temperature such as 59° F are insignificant; therefore, the humidity value selected should not be critical. Once the standard day conditions are specified, it is likely that modifications would have to be made to the emissions test stands so that one could conduct any further testing at these conditions.

REFERENCES

1. Meng, Phillip R.; Skorobatckyi, Michael; Cosgrove, Donald V.; and Kempke, Erwin E.: Emissions of an Avco Lycoming O-320-DIAD Air-Cooled Light Aircraft Engine as a Function of Fuel-air Ratio, Timing, and Air Temperature and Humidity. NASA TM X-73500, 1976.

2. Skorobatckyi, Michael; Cosgrove, Donald V.; Meng, Phillip R.; and Kempke, Erwin E.: Effect of Air Temperature and Relative Humidity at Various Fuel-Air Ratios on Exhaust Emissions on a Per-Mode Basis of an Avco Lycoming O-320-DIAD Light Aircraft Engine. NASA TM X-73507, 1976.

3. Summers, Robert: NO_x Destruction by CO in NO_x to NO Converters of Chemiluminescence NO Analyzers. NASA TM X-73480, 1976.

4. Control of Air Pollution From Aircraft and Aircraft Engines. Fed. Register, vol. 38, no. 136, pt. II, July 1973, pp. 19088-19103.

DISCUSSION

Q - W. Westfield: Was the cooling airflow supplied to the engine held constant or did it vary with the induction air temperature?

A - E. Kempke: The induction and cooling airflow were at the same temperature-humidity conditions.

COMMENT - E. Becker: We were privy to the O-320 engine data from NASA. As a result, I ran some comparison plots using our IO-360 engine NAFEC data to determine if this data lined up with NASA's data. For the CO pollutant, I got very similar trend curves. At selected temperature and humidity conditions the curves closely matched NASA's. They exhibited the same type of split characteristics as the NASA curves. Also, I noticed that apparently there is some characterization required because if one just relies on the low powered engines to define the shape of the curve one may end up getting slightly erronous results at higher power levels. Both the NASA TSIO-360 data and the NAFEC IO-360 data indicate that the higher powered engines do shift the characteristic shape of the curve a little higher. So I think some additional assessment is required to come up with an optimization type correction factor that takes all of these engine characteristics into consideration.

Q - E. Kempke: Is that conclusion based on making the comparison on a pound per mode basis.

A - E. Becker: Yes.

COMMENT - E. Kempke: Certainly we must look at other parameters in developing a correlation. The pound per mode parameter was originally selected because it is used by everyone when generating cycle data from leanout data. However, there is some preliminary evidence which shows better parameters may exist. NASA does plan to explore this further.

Q - B. Rezy: Have you taken this leanout data and applied it to a cycle in the two extremes just to see how bad the final answer is according to the EPA standards?

A - E. Kempke: A comparison of using leanout data to generate cycle data with the actual cycle data shows fairly good agreement.

Q - B. Rezy: Were those points taken at the same fuel-air ratios?

A - E. Kempke: Yes. In other words, we looked at the per cycle data, and, using the same measured fuel-air ratio values, we went to the leanout curves to find the pound per mode value. Finally, the pound per mode values for all seven modes were summed to generate the cycle.

Q - W. Westfield: Are you saying you really plugged in the effect of taxi/idle out versus taxi/idle in?

A - E. Kempke: We used the taxi-out fuel-air ratio and the taxi-in fuel-air ratio with the appropriate mode time.

Q — F. Monts: Were the leanout runs done on a fixed throttle basis or were they done on a fixed power basis?

A — E. Kempke: The tests conducted at Lewis were with a dynamometer and therefore were run at a constant power condition for each mode with one exception. The exception occurred during the O-320 engine testing, where the takeoff power fell off at the 100° F and 80 percent relative humidity condition.

Q — F. Monts: In that case, the data would be of interest for reasons other than emissions such as for power and humidity corrections. Did you try to maintain constant head temperature or did you maintain a constant cooling air flow?

A — E. Kempke: A constant delta pressure was maintained across the engine. Plots that show the variation in the cylinder head temperature and the exhaust gas temperature as fuel-air ratio is varied are available for the TSIO-360-C engine tests.

Q — F. Monts: Did you make any attempt to measure the cooling air mass flow?

A — E. Kempke: Yes, we do measure the cooling airflow.

Q — G. Kittredge: We have responded to one of NASA's recommendations concerning the specifying of a standard reference day. A package of technical amendments, which included a reference day specification, went to the Federal Register the middle of last week. The conditions are temperature of 59° F, relative humidity of 60 percent, and pressure of 29.92 inches of mercury. One of NASA's recommendations concerns correcting data to a standard day and another concerns conducting the testing at standard day conditions. These are two different ways at going at the same thing. Which approach does NASA prefer at this point?

A — E. Kempke: I think the most direct approach is to run the test at standard day conditions; then, no correction factor is needed.

Q — G. Kittredge: This is going to involve fairly expensive laboratory modifications in some areas is it not?

A — E. Kempke: I don't think so, but I must defer to the engine manufacturers to comment on the cost.

A — S. Jedrziewski: Speaking for AVCO Lycoming on the temperature correction factors, I see no need to duplicate elaborate test equipment if a good correction factor can be established. So, Lycoming prefers to do it on a correction factor basis after we have them for all engines we produce.

Q — E. Kempke: Are you saying you'll do that and in your compliance testing use those particular calibration curves for each engine to correct the compliance data?

A — S. Jedrziewski: We are not saying that AVCO Lycoming specifically will do it, we are just saying that probably with the aid of NASA or some other agency those correction factors could be established.

COMMENT - L. Helms: I think what you're saying is that we have no choice - that's the only way to do it.

COMMENT - B. Rezy: With the relative humidity variation that we know we have now in Mobile we honestly feel we cannot come up with a correction factor. Based on what Pete Kempke has presented today, there would be an enormous amount of testing required to find out for all these engines what kind of corrections factors we're really talking about. I don't see that we really have a choice but to try to control relative humidity and temperature.

COMMENT - K. Stuckas: Just as an addendum to what Bernie Rezy said. We are currently looking into purchasing equipment that will do that. We think we found a suitable unit which is produced by Environmental Techtonics and costs $34,000. It controls humidity, temperature, and pressure, and it is a self-contained unit having the capability right now of handling 300 horsepower engines. It can be boosted to handle engines of higher horsepower and the equipment is available right now.

Q - W. Westfield: We're in the R&D end and I'd like to hear from somebody else about whether the engine manufacturers do have the capability of setting actual temperature and humidity. Would this be carried through in a certification process for the airframe itself? What would you do when you tested the airplane outside?

A - B. Rezy: We will be discussing this later today. One of the things that we found very detrimental to leaning out these engines was the acceleration problem in taxi, idle, and approach. One of the advantages we see with having this humidity equipment is the ability to hold temperature and humidity and being able to change it whenever we want to find exactly what fuel-air ratios our fuel injection systems can hold. In the long run this is going to save a lot of flight testing problems.

Q - D. Powell: Were the cycle results of CO and HC emissions versus air temperature and relative humidity based on operating the engine at a constant fuel-air ratio or did the fuel-air ratio vary with the particular condition?

A - E. Kempke: Although the mixture control was set in the fuel rich condition, the actual fuel-air ratio varied with ambient conditions; this is the primary reason for the change in emissions.

Q - D. Powell: Do you have information in your TM X-73500 report on how the fuel-air ratio varied?

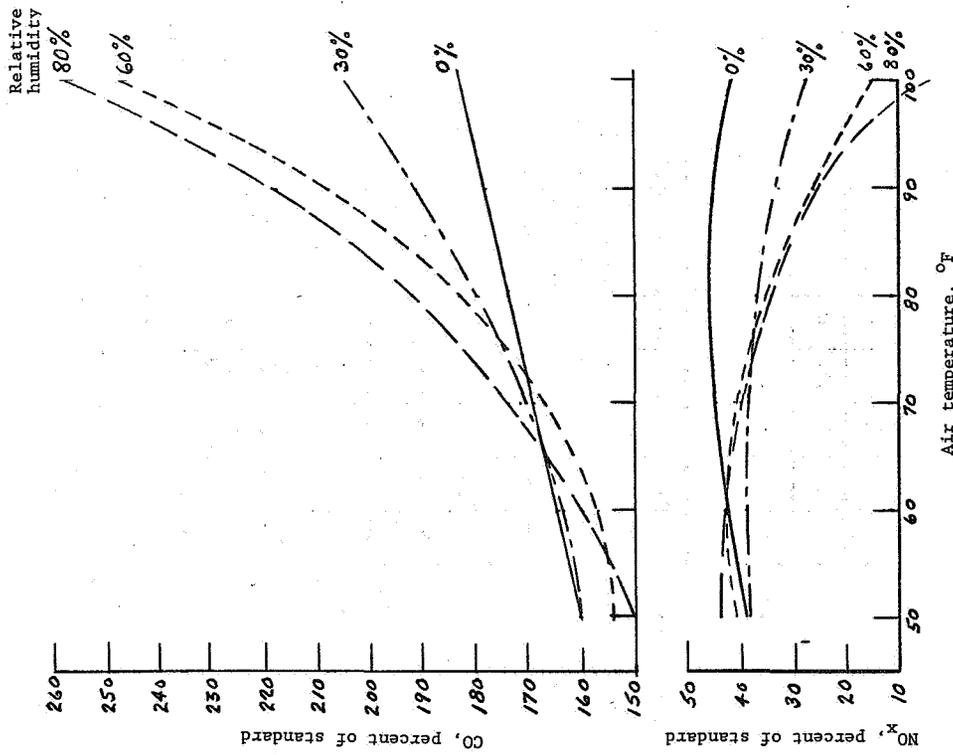A - E. Kempke. Yes. In that report are computer printouts which show the measured fuel-air ratio values for each test run.
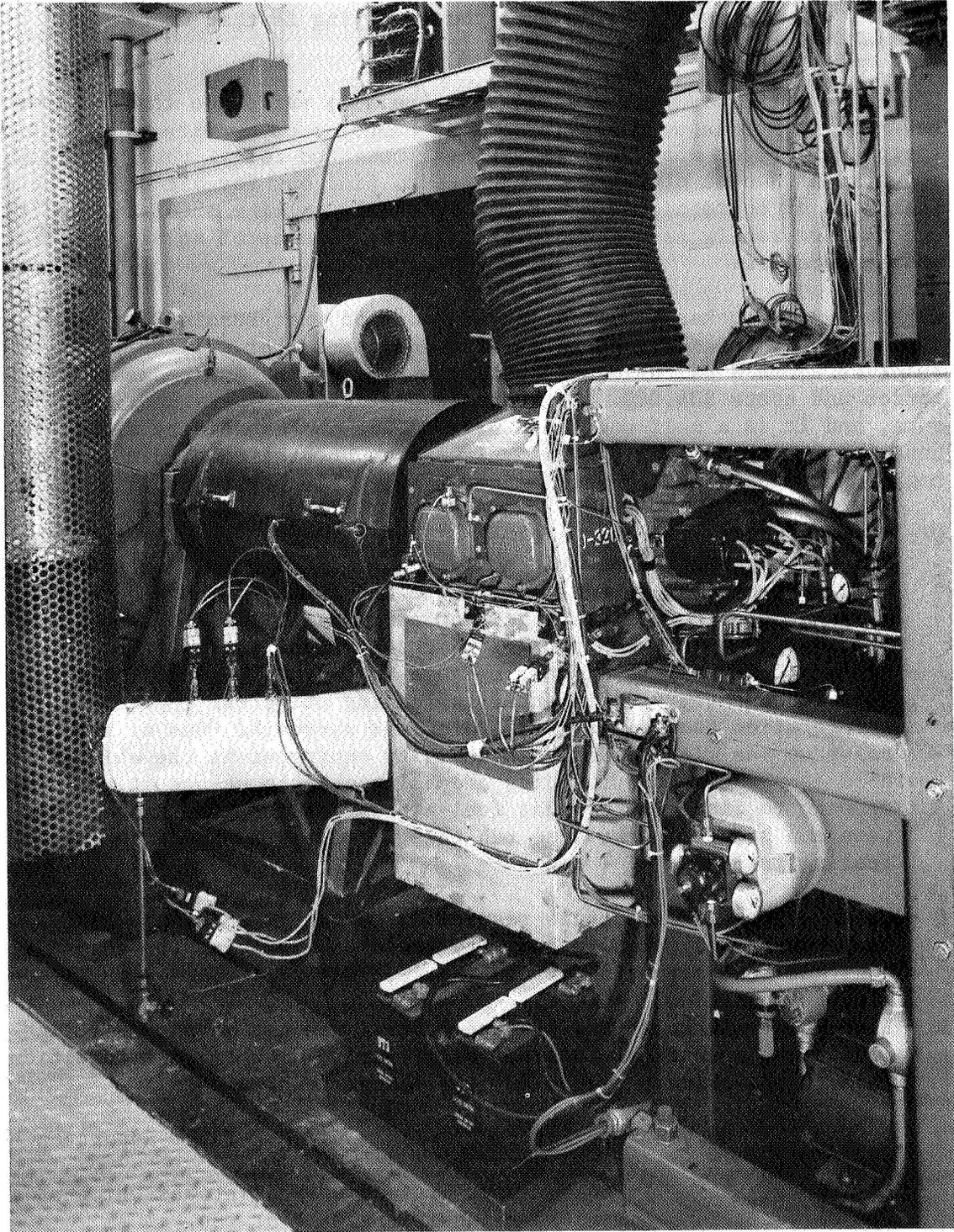
Engine test stand

Figure 5-1

95

Summary plot of hydrocarbon emissions with air temperature and relative humidity.

Figure 5-3

Summary plot of carbon monoxide and oxides of nitrogen with air temperature and relative humidity.

Figure 5-2

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%

TEMP. 100°F REL. HUM. 80%

TAKE OFF EMISSIONS Ø-32Ø-DIAD

TEMP. DEG.F	REL.HUMIDITY			
	Ø	3Ø	6Ø	8Ø
5Ø	Ø	◇	⬓	+
59	1	☉	▼	X
8Ø	2	△	◆	Y
1ØØ	3	✳	●	Z
OUT OF RANGE	━			

Figure 5-4

R00.2431
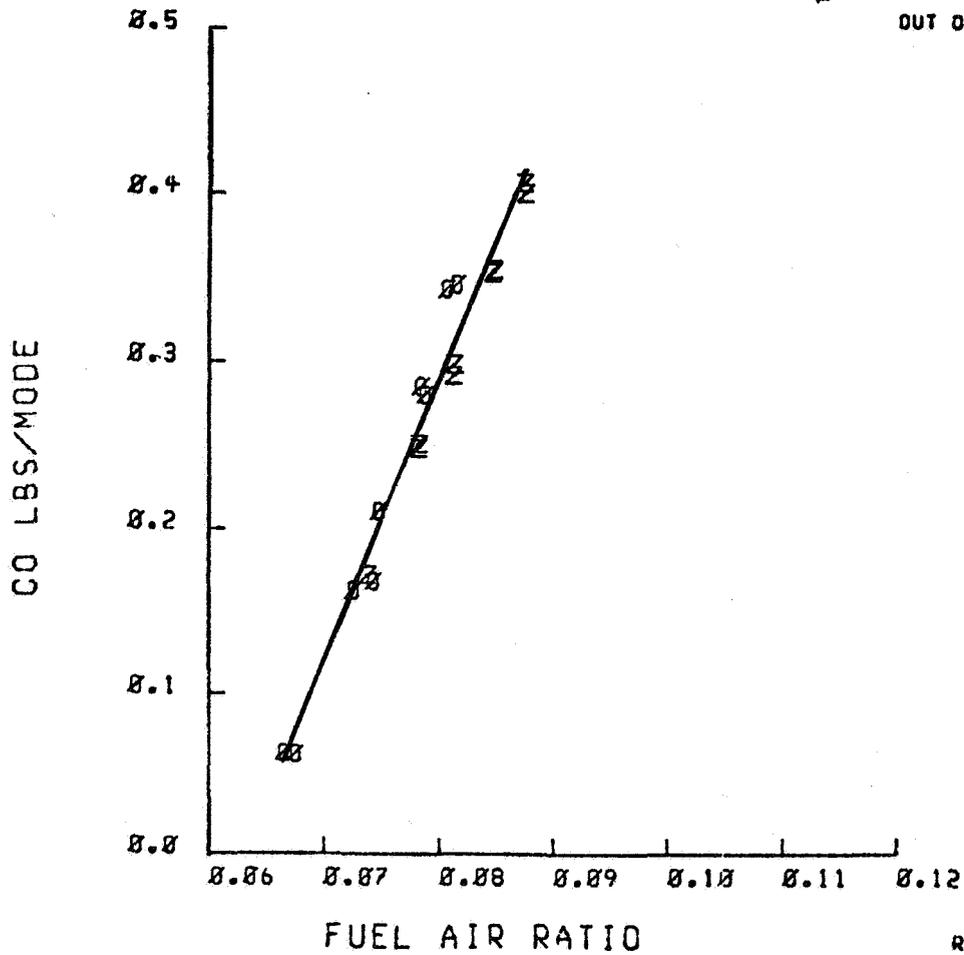
NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%
TEMP. 100°F REL. HUM. 80%

TAKE OFF EMISSIONS Ø-32Ø-DIAD

Figure 5-5

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%

TEMP. 100°F REL. HUM. 80%

TAKE OFF EMISSIONS   0-320-DIAD

Figure 5-6

Figure 5-7

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%

TEMP. 100°F REL. HUM. 80%
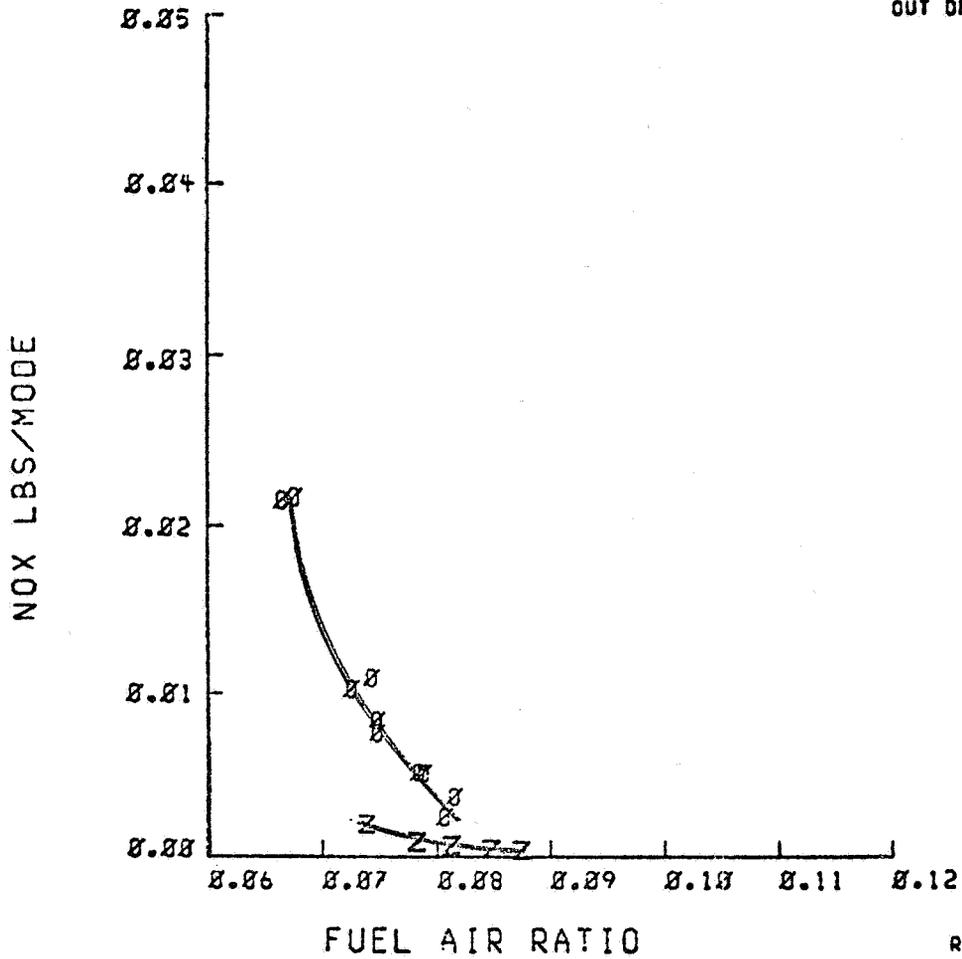
CLIMB EMISSIONS 0-320-DIAD

Figure 5-8

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%
TEMP. 100°F REL. HUM. 80%
CLIMB EMISSIONS Ø-32Ø-DIAD
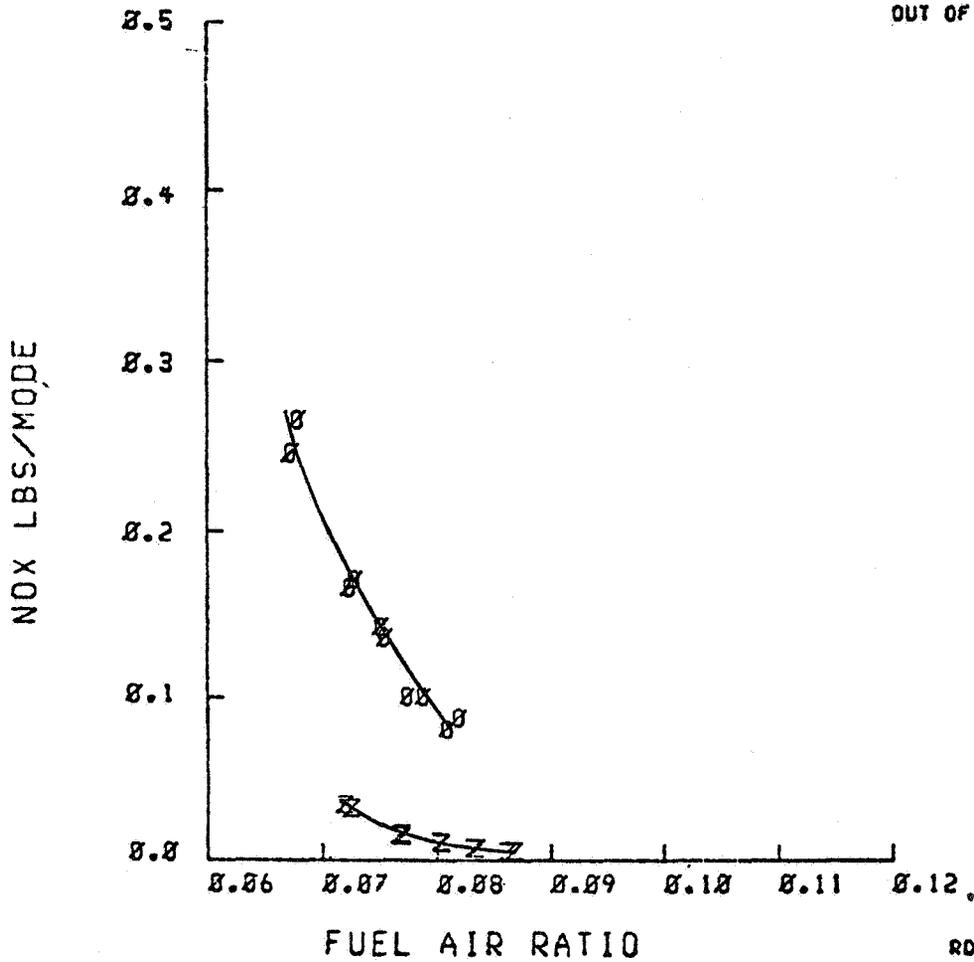
Figure 5-9

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%
TEMP. 100°F REL. HUM. 80%

APPROACH EMISSIONS   0-320-DIAD
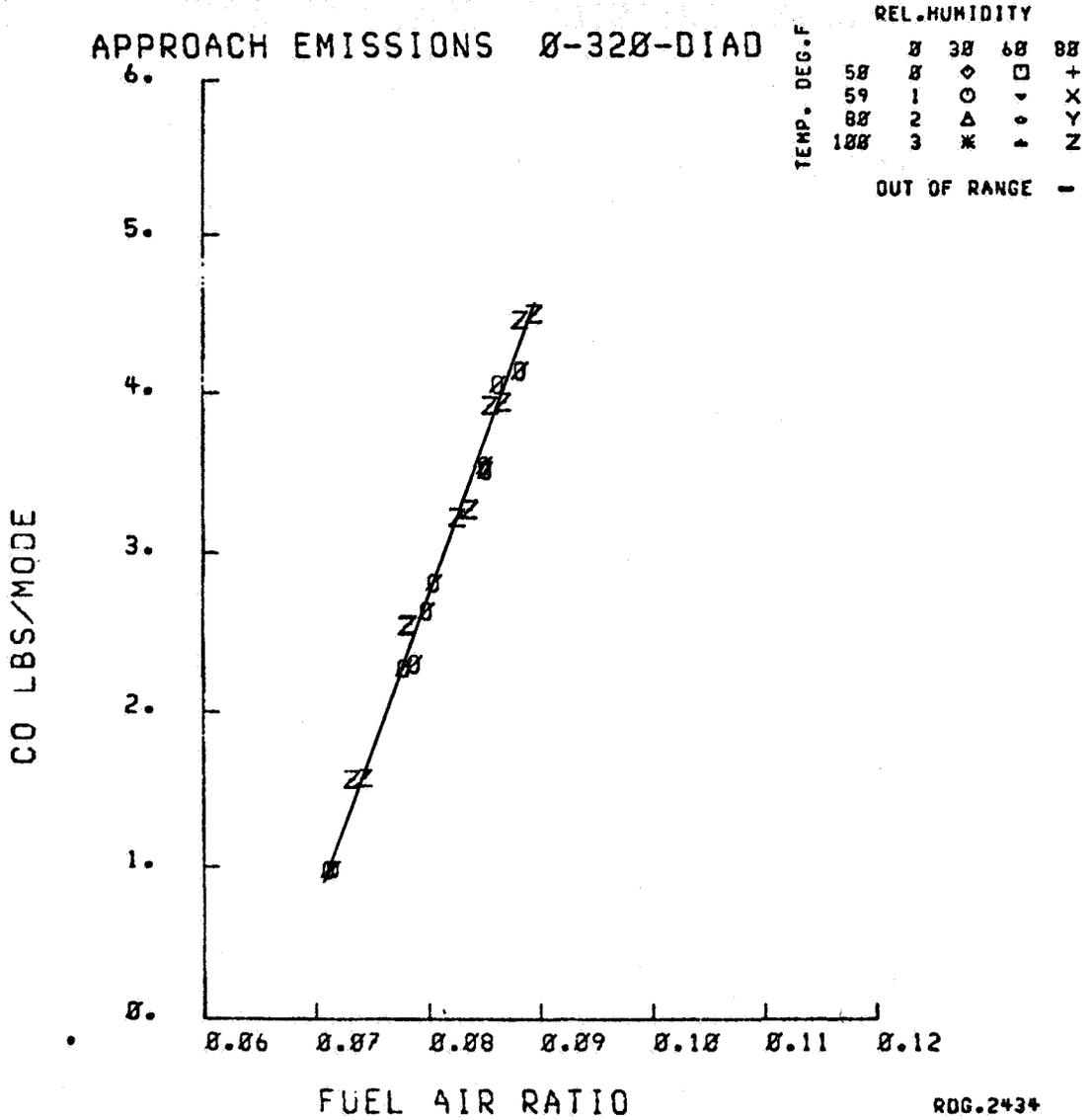
Figure 5-10

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%
TEMP. 100°F REL. HUM. 80%

APPROACH EMISSIONS Ø-32Ø-DIAD
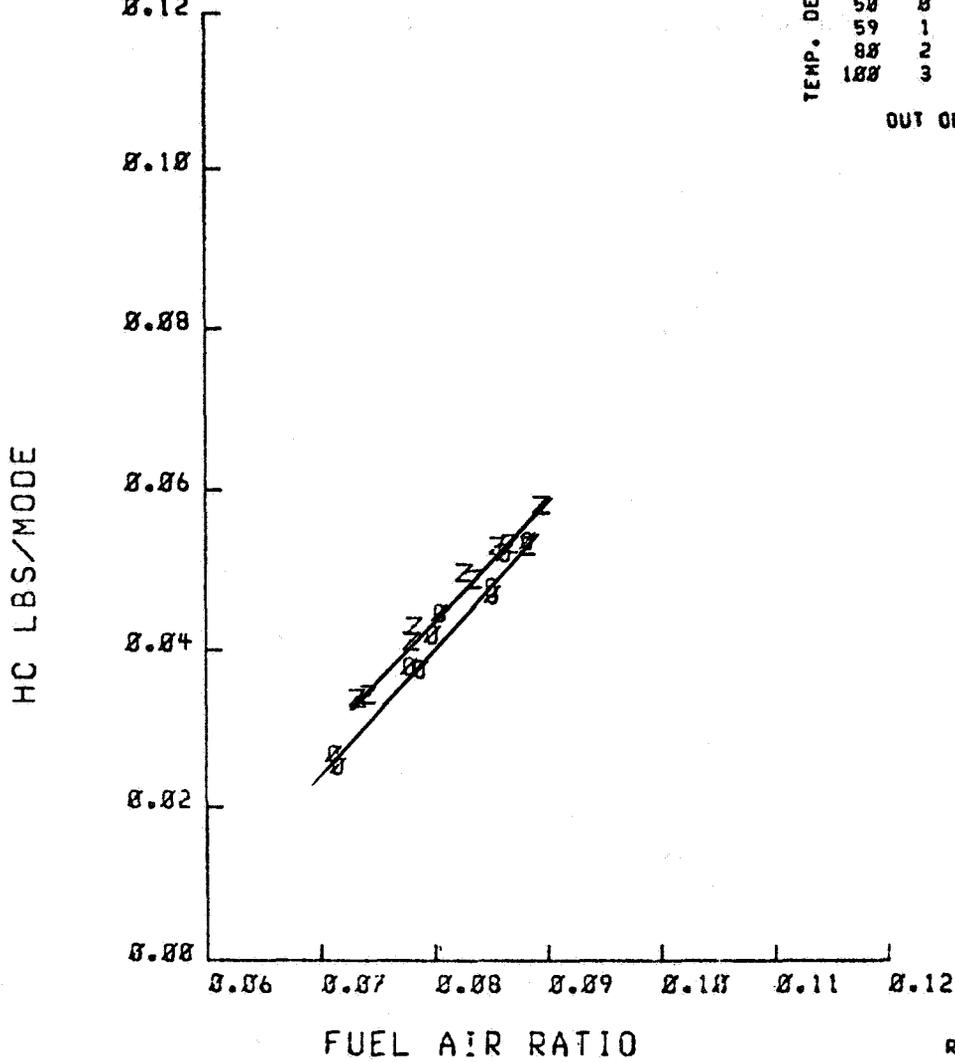
Figure 5-11

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%

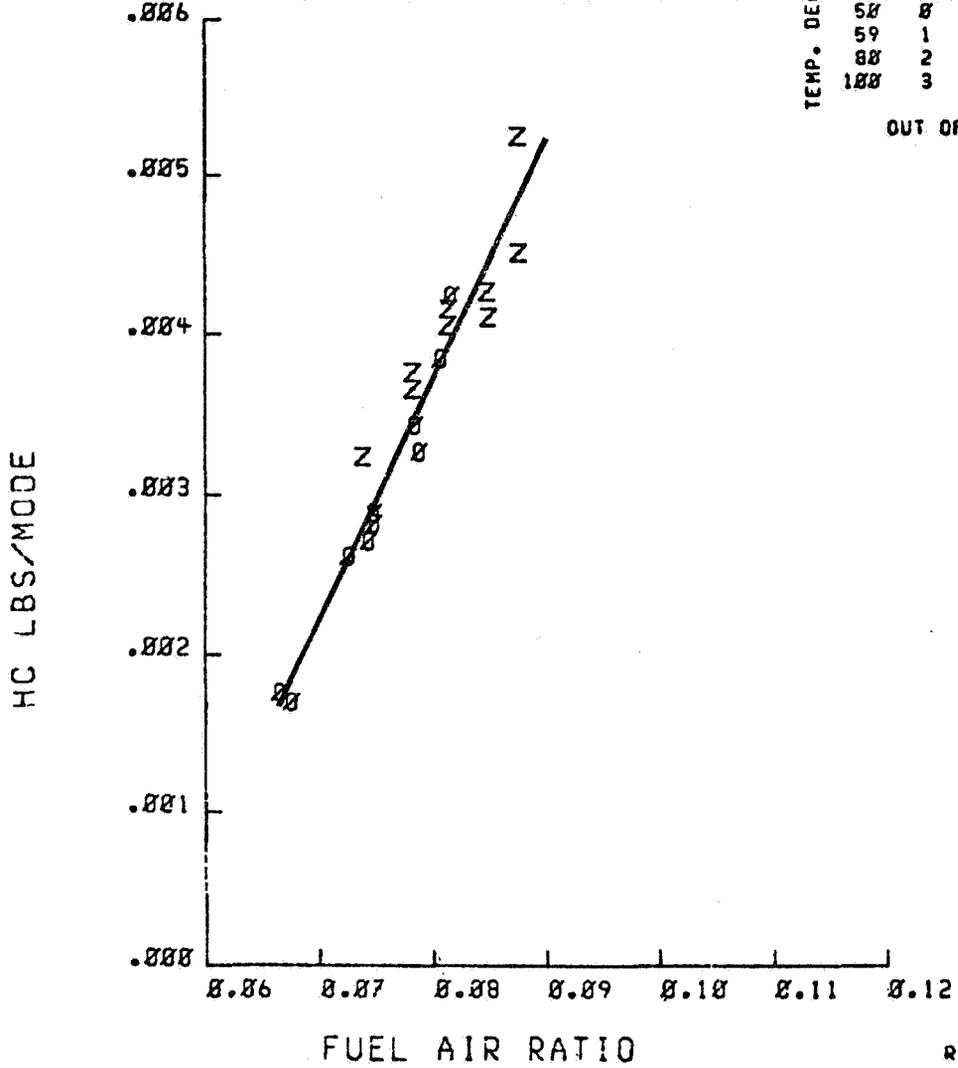TEMP. 100°F REL. HUM. 80%

APPROACH EMISSIONS   Ø-32Ø-DIAD
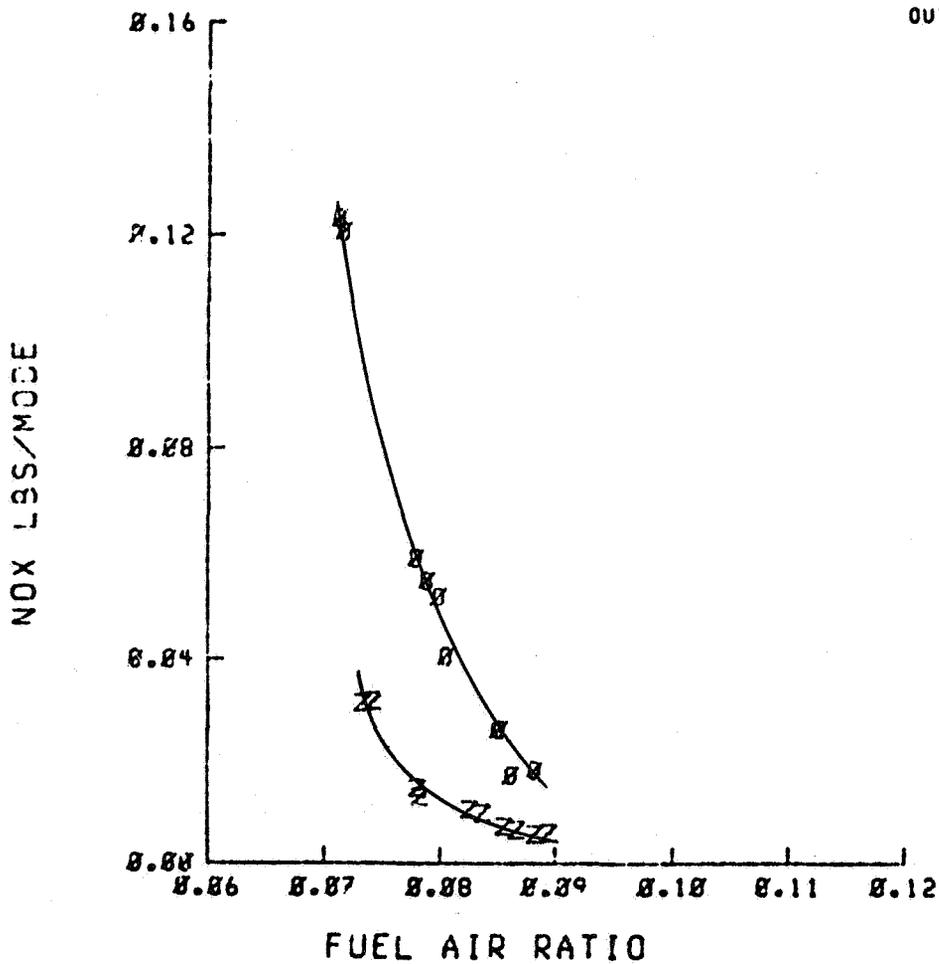
Figure 5-12

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%

TEMP. 100°F REL. HUM. 80%

TAXI EMISSIONS 0-320-DIAD

TEMP. DEG.F	REL.HUMIDITY			
	0	30	60	80
50	0	◇	▢	+
59	1	⊙	▾	X
80	2	△	◈	Y
100	3	✳	▲	Z
	OUT OF RANGE	▬		

RDG.2403

Figure 5-13

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%

TEMP. 100°F REL. HUM. 80%

TAXI EMISSIONS 0-320-DIAD

REL. HUMIDITY				
TEMP. DEG.F	0	30	60	80
50	0	◇	▢	+
59	1	◉	♥	X
80	2	△	◆	Y
100	3	✳	●	Z

OUT OF RANGE ━

HC LBS/MODE

0.50

0.40

0.30

0.20

0.10

0.00

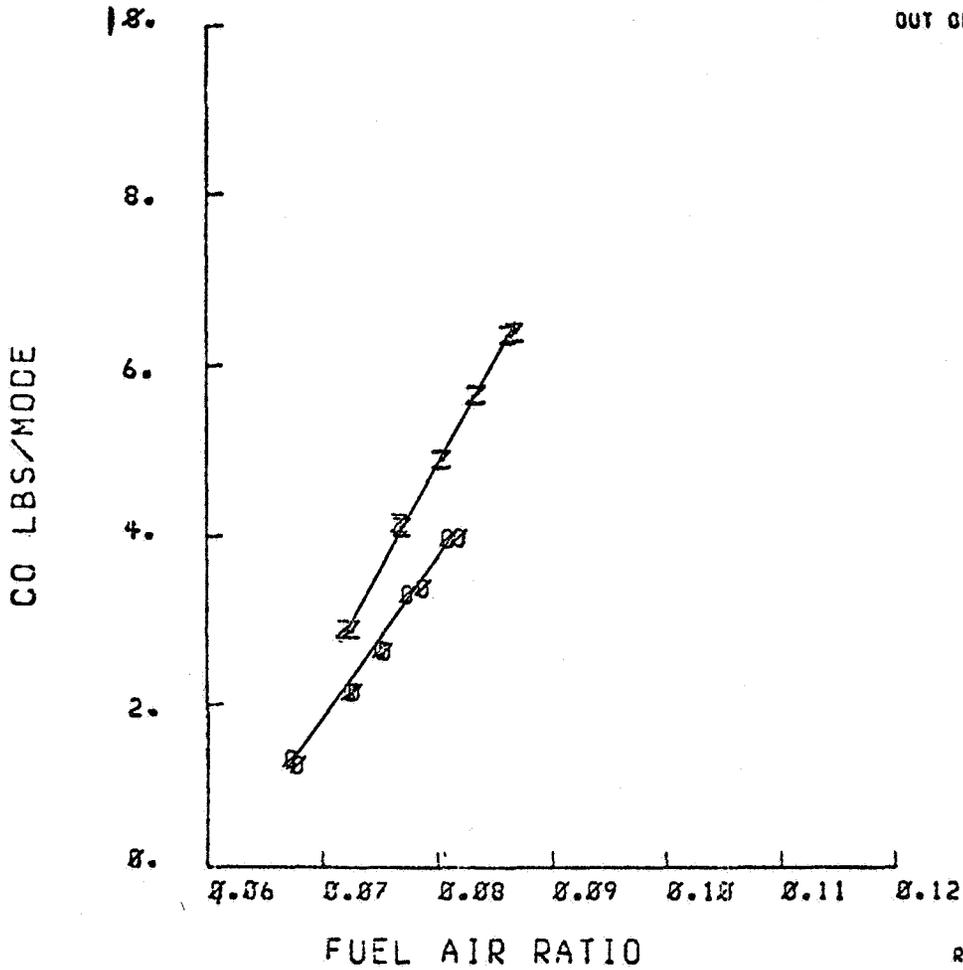0.06 0.07 0.08 0.09 0.10 0.11 0.12

FUEL AIR RATIO

ROG.2403

Figure 5-14

NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0%

TEMP. 100°F REL. HUM. 80%

TAXI EMISSIONS Ø-32Ø-DIAD

TEMP. DEG.F	REL. HUMIDITY			
	Ø	3Ø	6Ø	8Ø
5Ø	Ø	◇	▯	+
59	1	☉	♥	X
8Ø	2	△	◇	Y
1ØØ	3	✳	♠	Z
OUT OF RANGE	━			

Figure 5-15

RDG.24Ø3

Figure 5-16

Figure 5-17

Figure 5-18

Figure 5-19

Figure 5-20

Figure 5-21
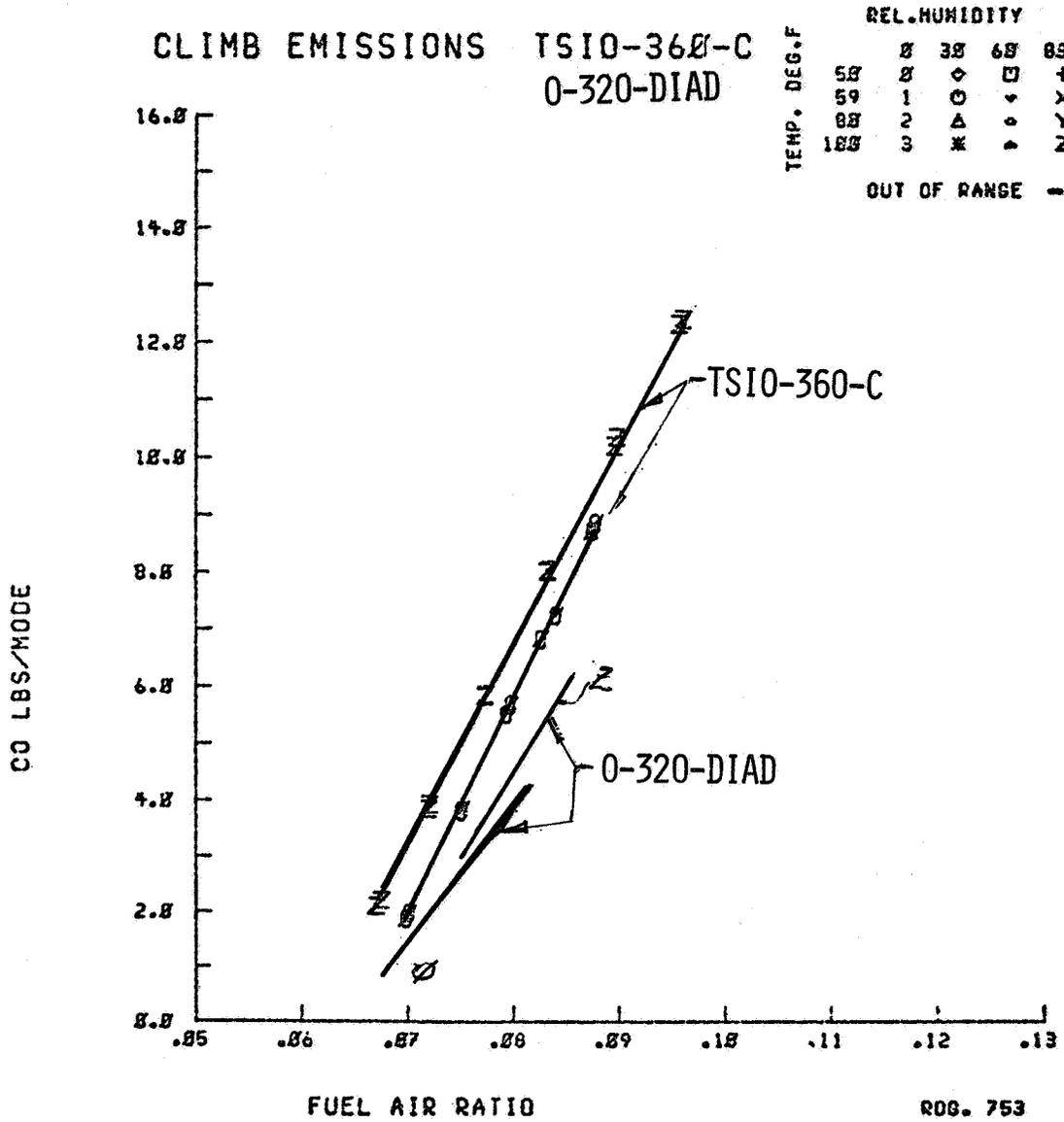
Figure 5-22
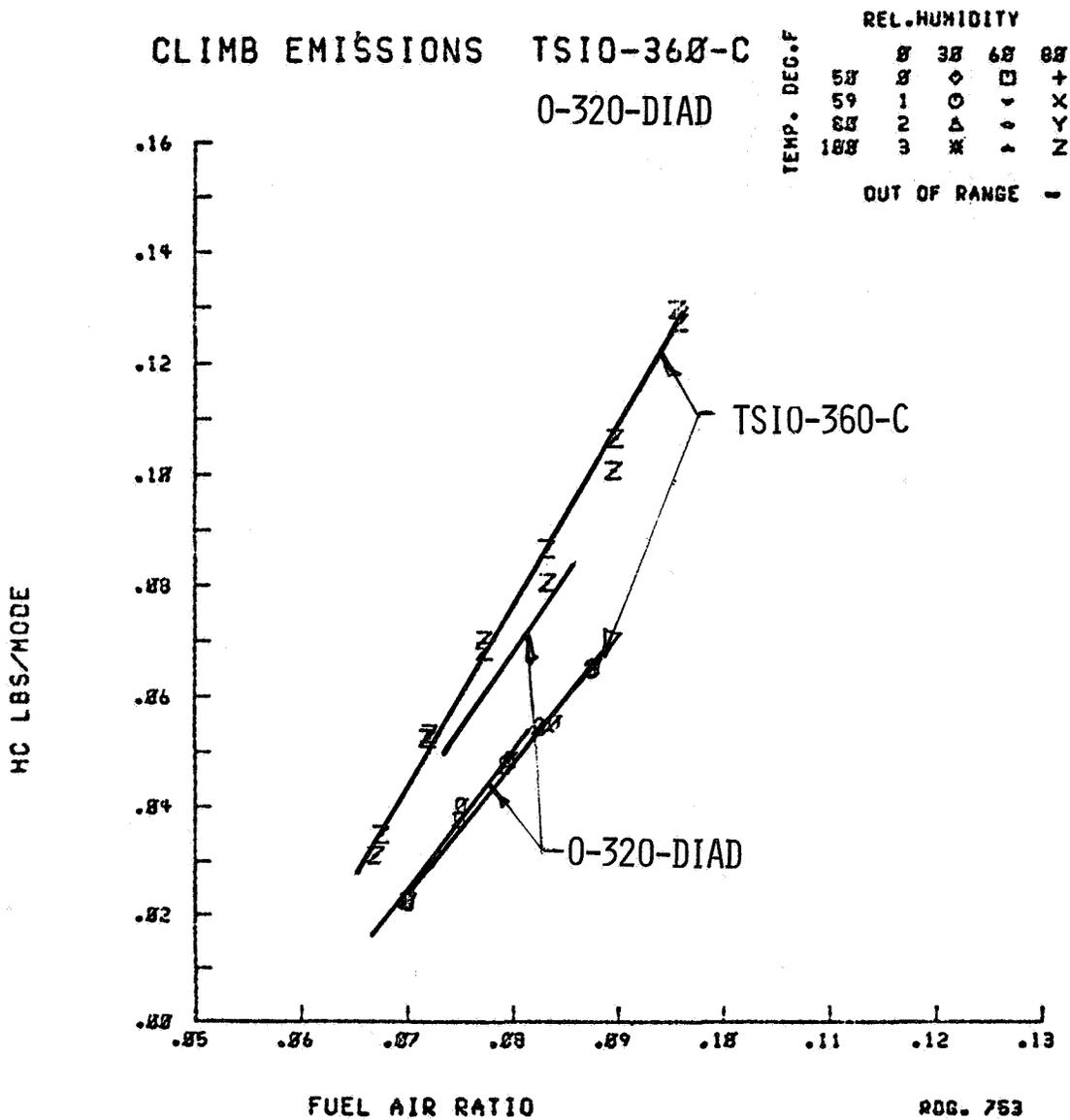
Figure 5-23
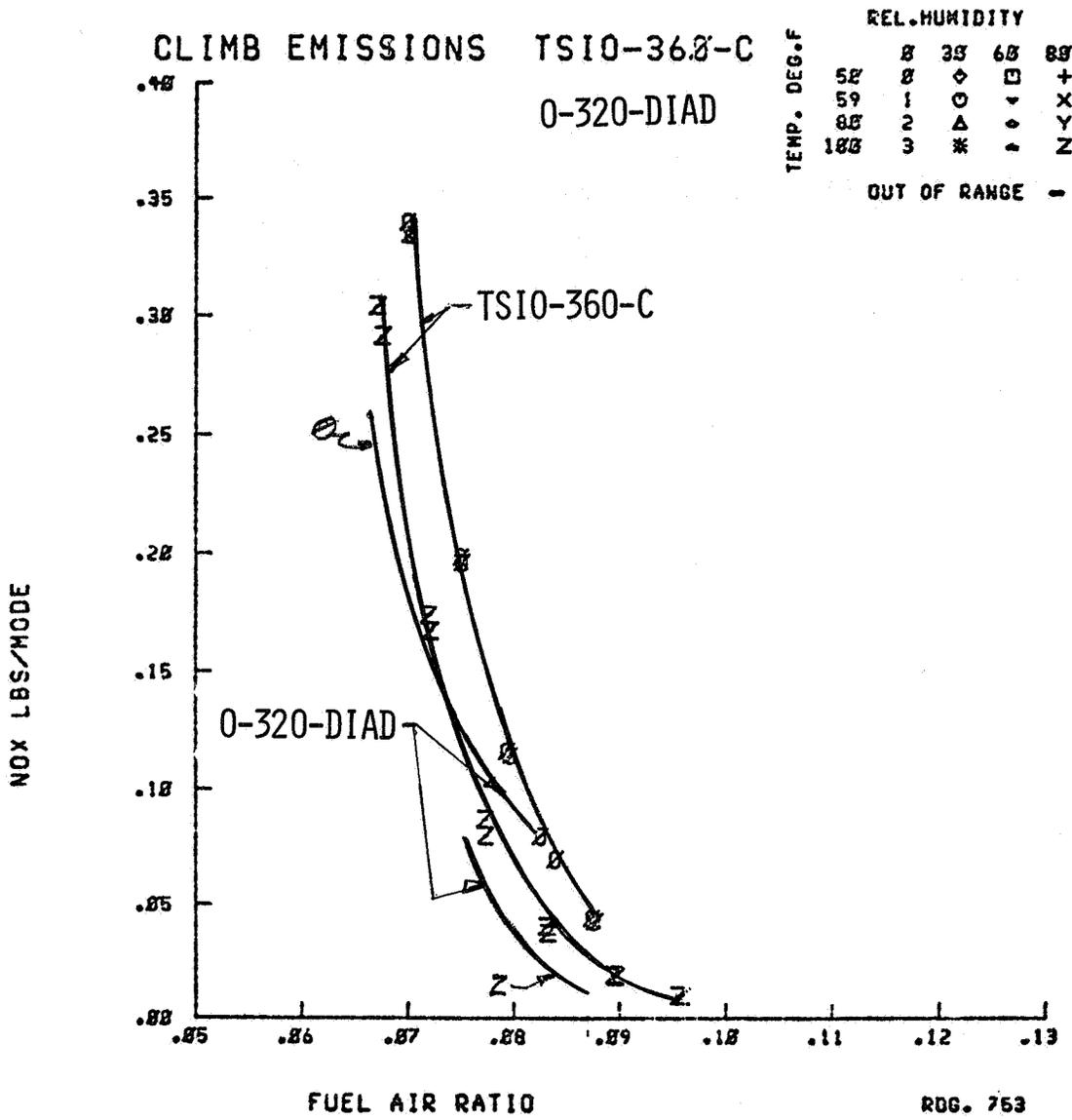
Figure 5-24
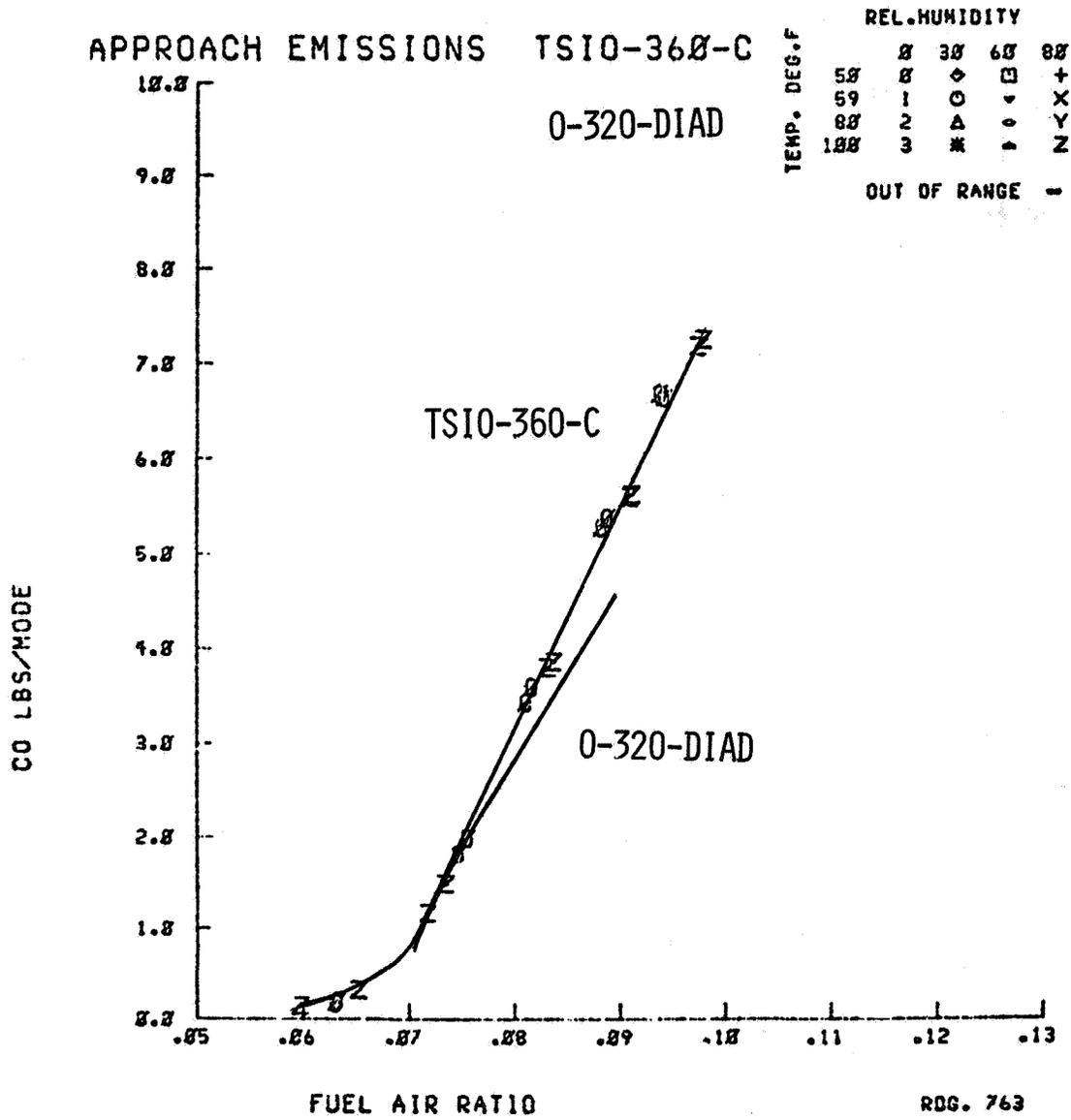
Figure 5-25
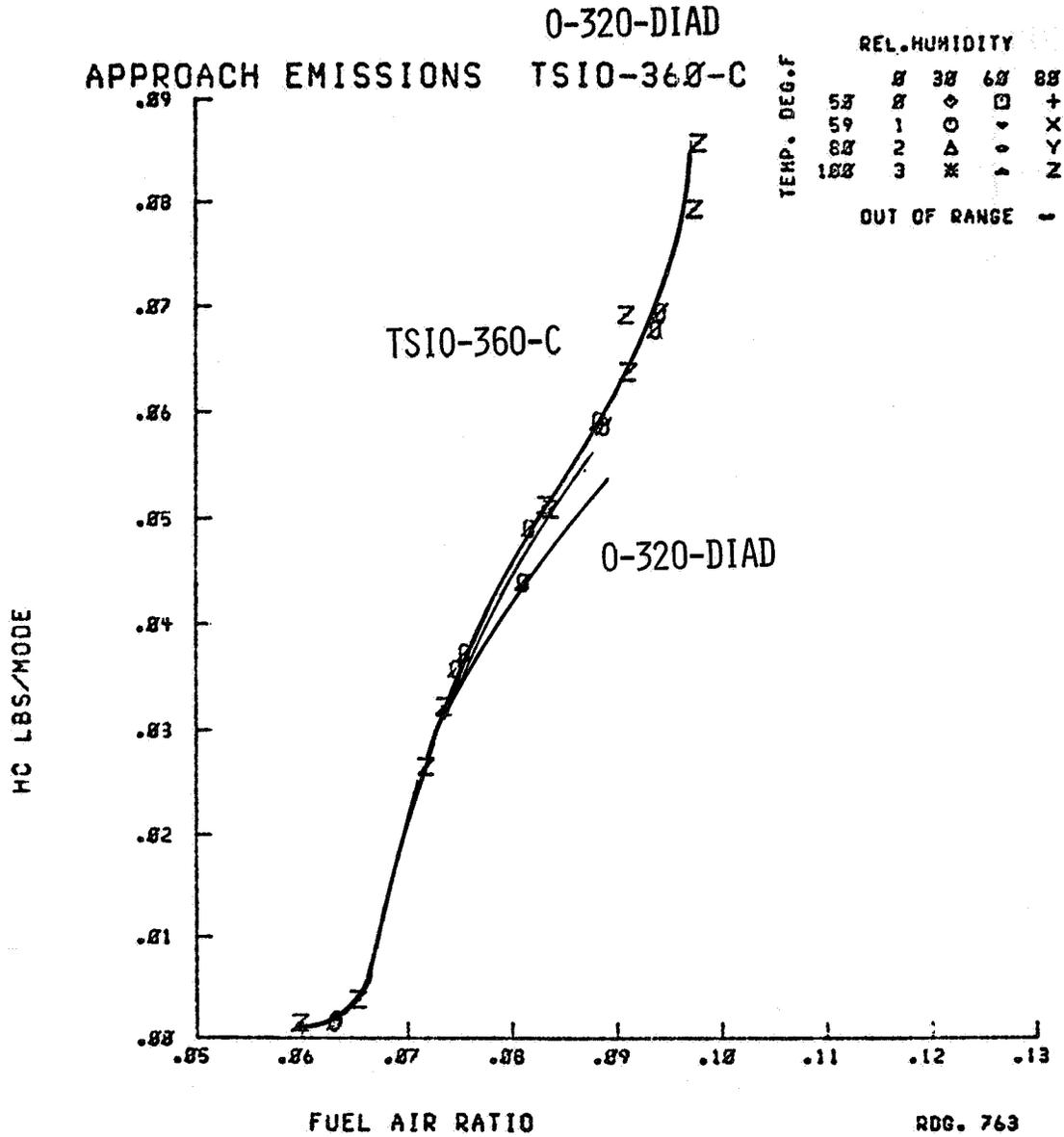
Figure 5-26
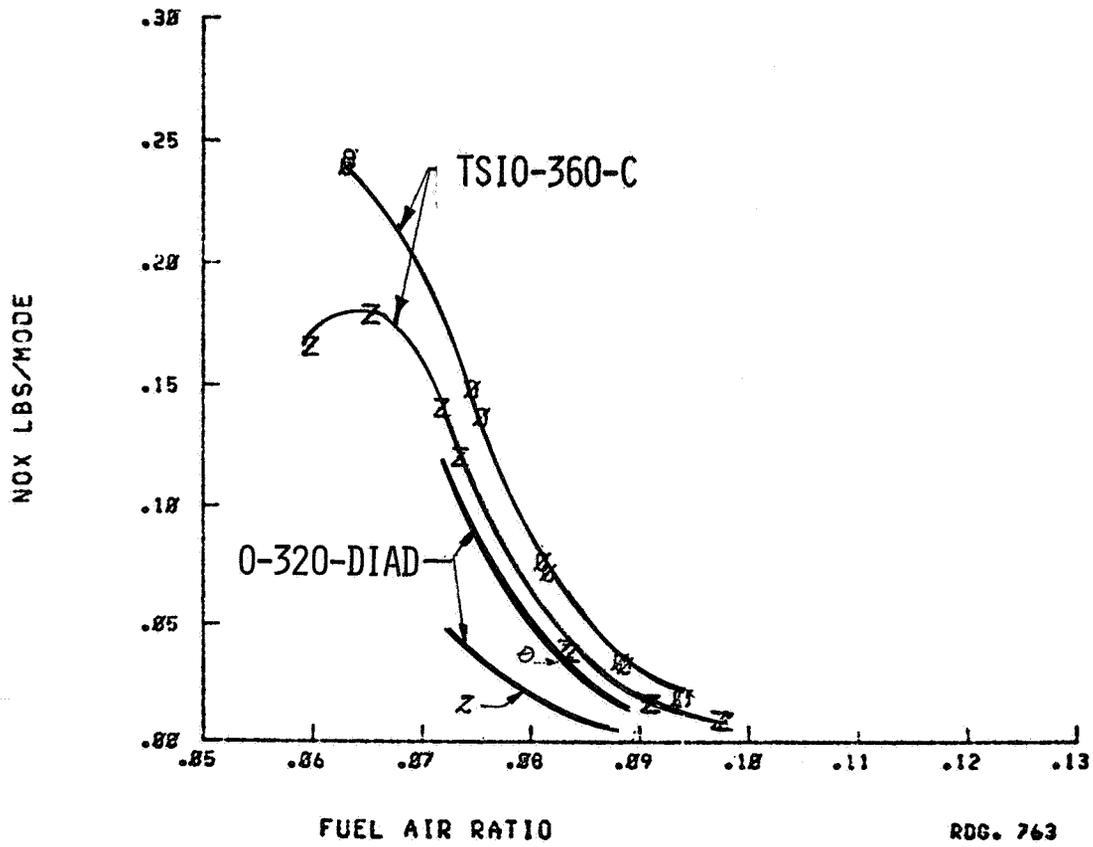
Figure 5-27

6. EMISSIONS DATA BY CATEGORY OF ENGINES

Joan Barriage, William Westfield, and Eric E. Becker

Federal Aviation Administration
Department of Transportation
Washington, D.C.

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 con-
tinue 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 inves-
tigation 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

TOTAL UNBURNED HYDROCARBON
EMISSION CHARACTERISTICS
AVCO LYCOMING IO-360-A1B6D
ENGINE (S/N888-X)

T(IND. AIR) 85°F
NAFEC DATA

TAXI (OUT)

TAXI (IN)
CLIMB
APPROACH

T.O.

HC-LB/MODE

0.3

0.2

0.1

0

.05   .06   .07   .08   .09   .10   .11

F/A
(MEASURED)

Figure 6-3

TOTAL CARBON MONOXIDE
EMISSION CHARACTERISTICS
AVCO LYCOMING IO-360-A1B6D ENGINE (S/N888-X)

T(IND. AIR) =85°F
NAFEC DATA

CLIMB

APPROACH

TAXI (OUT)

T.O. AND
TAXI (IN)

CO-LB/MODE

10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0

.05   .06   .07   .08   .09   .10   .11

F/A
(MEASURED)

Figure 6-2

TOTAL CARBON MONOXIDE EMISSION CHARACTERISTICS
AVOC AVCO LYCOMING IO-360-A1B6D ENGINE (S/N888-X)

$T_{(IND.\ AIR)} = 50°F$
AVCO LYC. DATA

Figure 6-5

TOTAL OXIDES OF NITROGEN
EMISSION CHARACTERISTICS
AVCO-LYCOMING IO-360-A1B6D ENGINE (S/N888-X)

$T_{(IND.\ AIR)} = 85°F$
NAFEC DATA

Figure 6-4

TOTAL OXIDES OF NITROGEN
EMISSION CHARACTERISTICS
AVCO LYCOMING IO-360-A1B6D
ENGINE (S/N888-X)
T(IND. AIR)=50°F
AVCO LYC. DATA

Figure 6-7

TOTAL UNBURNED HYDROCARBON
EMISSION CHARACTERISTICS
AVCO LYCOMING
IO-360-A1B6D ENGINE (S/N888-X)
T(IND. AIR) = 50°F
AVCO LYC. DATA

Figure 6-6

134
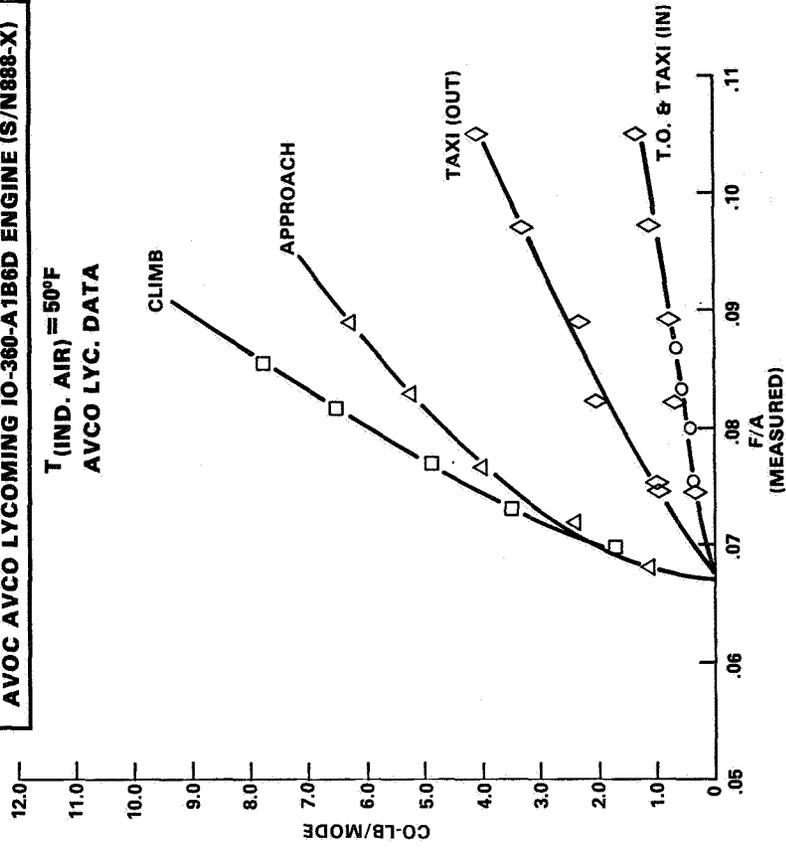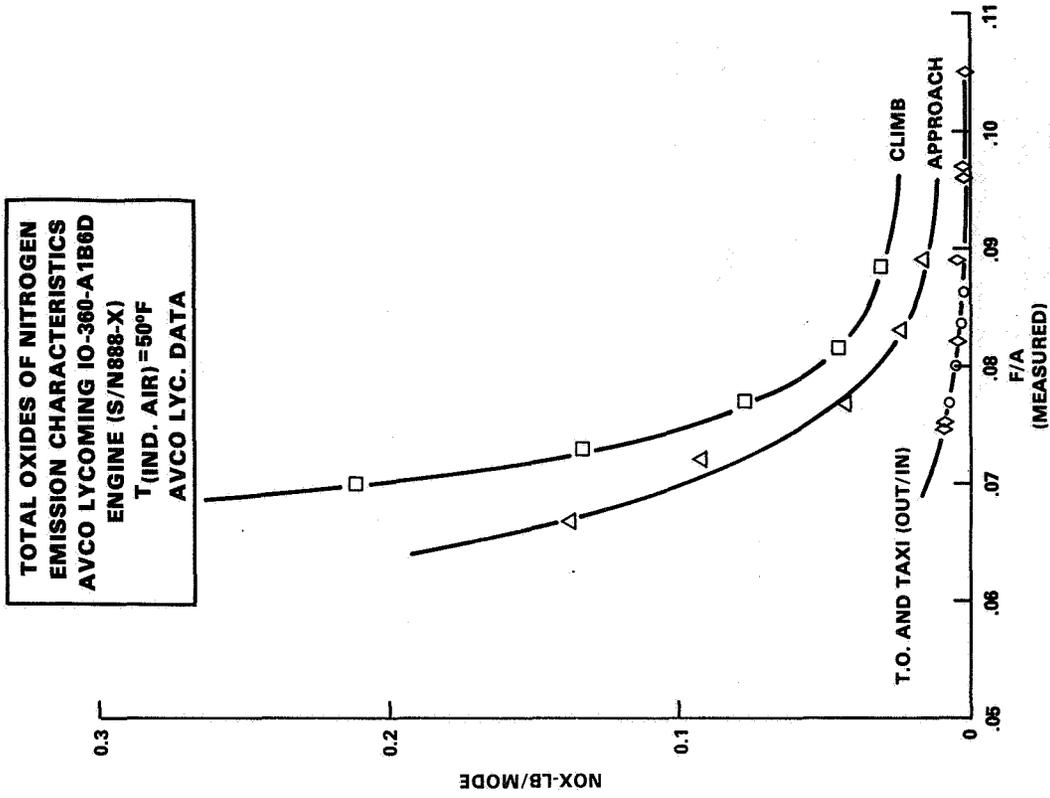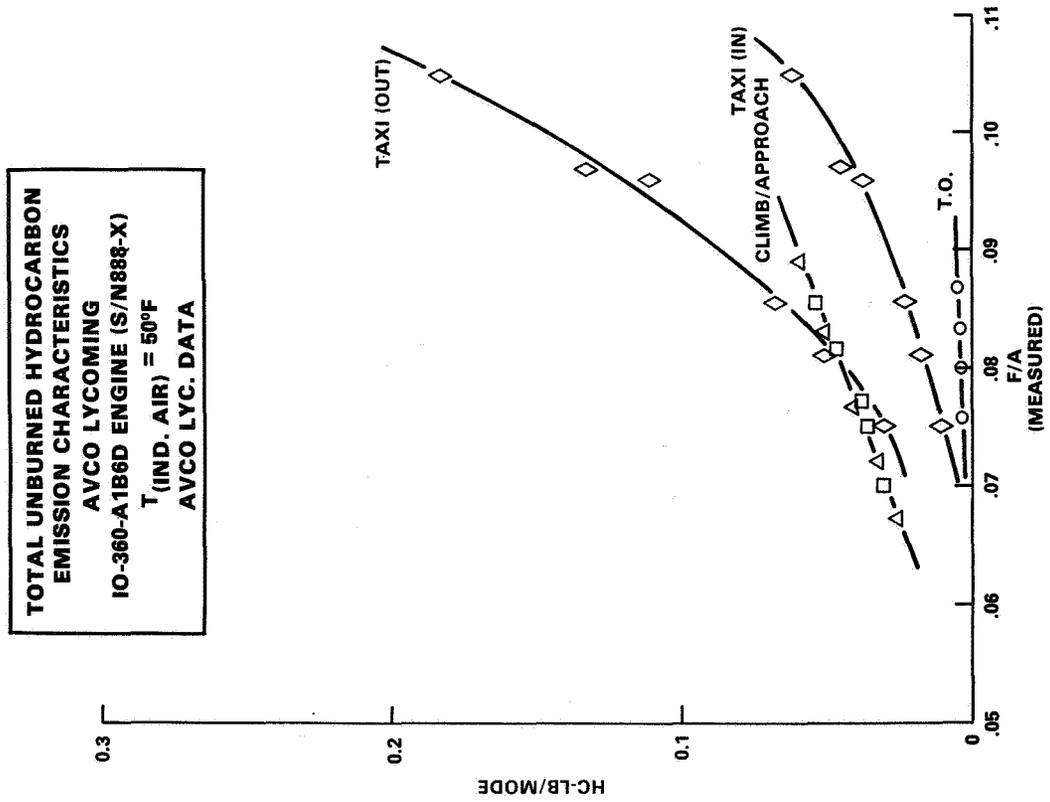
ESTIMATED EFFECT OF HYDROCARBON (HC) POLLUTANT ON MEASURED FUEL-AIR RATIO—TCM TSIO-360-C ENGINE

SPARK SETTING-20°BTC

LEGEND

o NAFEC DATA (T.O., CLIMB, APPROACH, & TAXI OUT MODES)
◇ NAFEC DATA (TAXI IN MODE)
□ TCM DATA (T.O., CLIMB, APP. & TAXI OUT MODES)
■ TCM DATA (TAXI IN MODE)
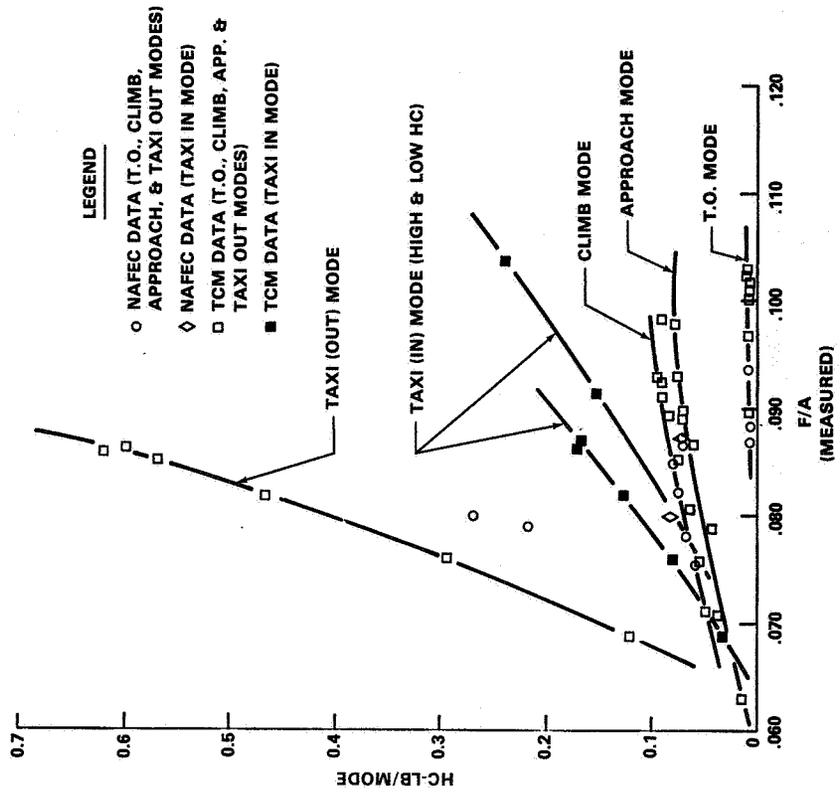
Figure 6-9

ESTIMATED EFFECT OF CARBON MONOXIDE (CO) ON MEASURED FUEL-AIR RATIO—TCM TSIO-360-C ENGINE (S/N 300244)

SPARK SETTING- 20° BTC

LEGEND

o NAFEC DATA (T.O., CLIMB, APPROACH, AND TAXI OUT MODES)
◇ NAFEC DATA (TAXI IN MODE)
□ TCM DATA (T.O., CLIMB, APPROACH AND TAXI OUT MODES)
■ TCM DATA (TAXI IN MODE)

Figure 6-8

.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

CLIMB

APPROACH

IDLE

TAXI

TAKEOFF

NOX ~ lbs/MODE

MEASURED F/A RATIO
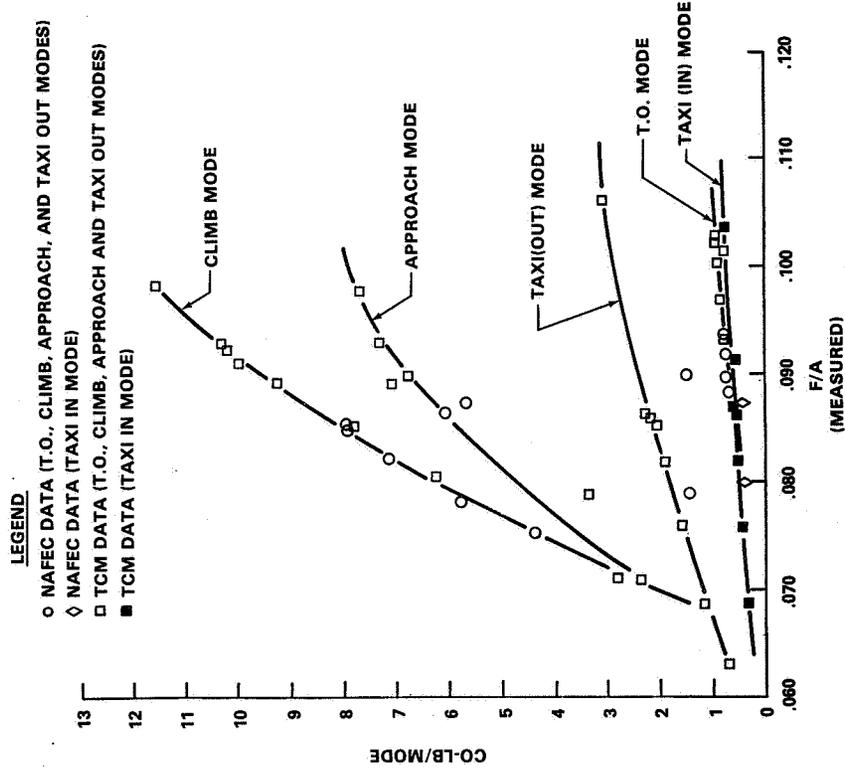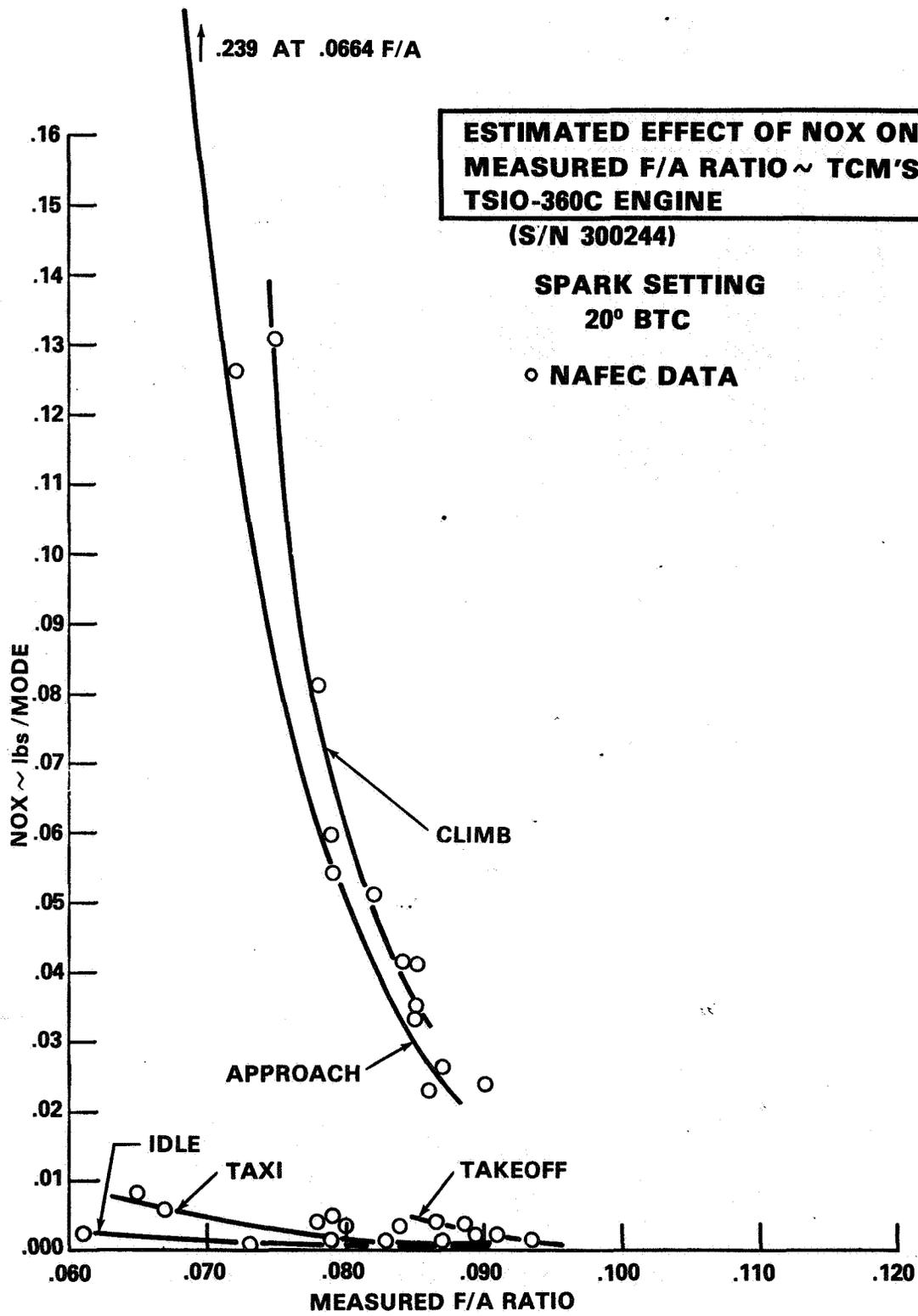
Figure 6-10

TOTAL CARBON MONOXIDE
EMISSION CHARACTERISTICS
PHASE I
Six (6) General Aviation Piston Engines
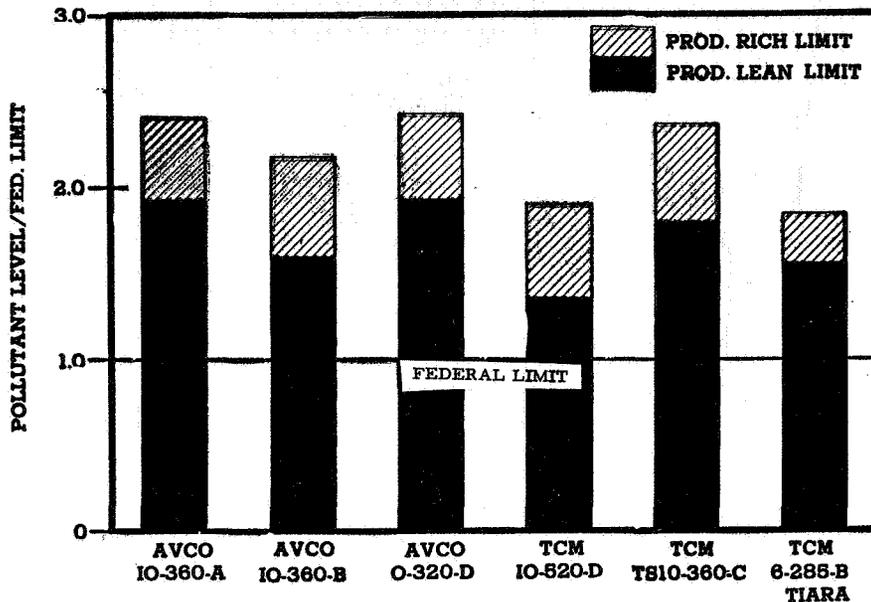
Figure 6-11

TOTAL CARBON MONOXIDE
EMISSION CHARACTERISTICS
PHASE I
Six (6) General Aviation Piston Engines
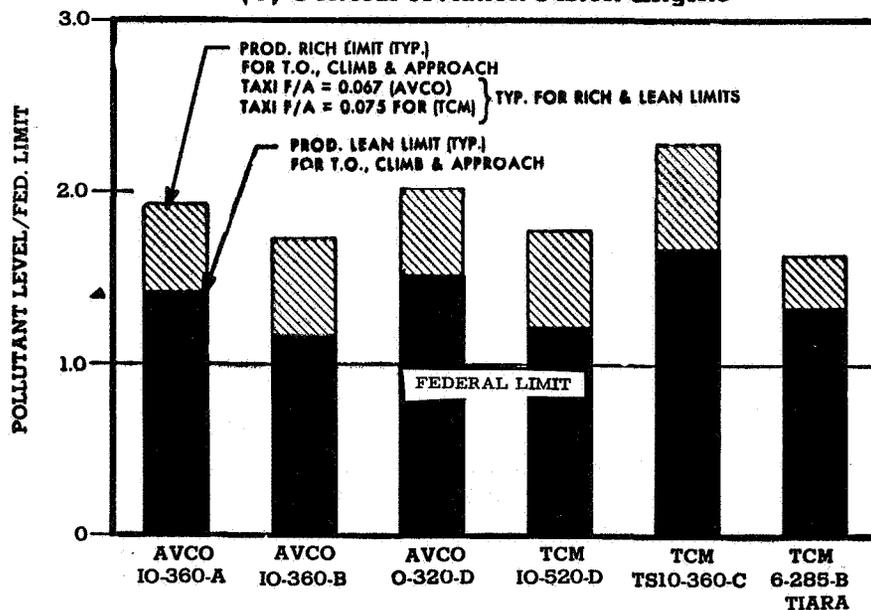
Figure 6-12

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

PROD. RICH LIMIT (TYP.) FOR T.O. & CLIMB
APPROACH & TAXI F/A = 8.067 (AVCO)
APPROACH & TAXI F/A = 8.873) (TCM)

PROD. LEAN LIMIT (TYP.) FOR T.O. & CLIMB
APPROACH & TAXI /A = 0.067 (AVCO)
APPROACH & TAXI F/A = 0.075 (TCM)

POLLUTANT LEVEL/FED. LIMIT

FEDERAL LIMIT

3.0

2.0

1.0

0

| AVCO IO-360-A | AVCO IO-360-B | AVCO O-320-D | TCM IO-520-D | TCM TS10-360-C | TCM 6-285-B TIARA |
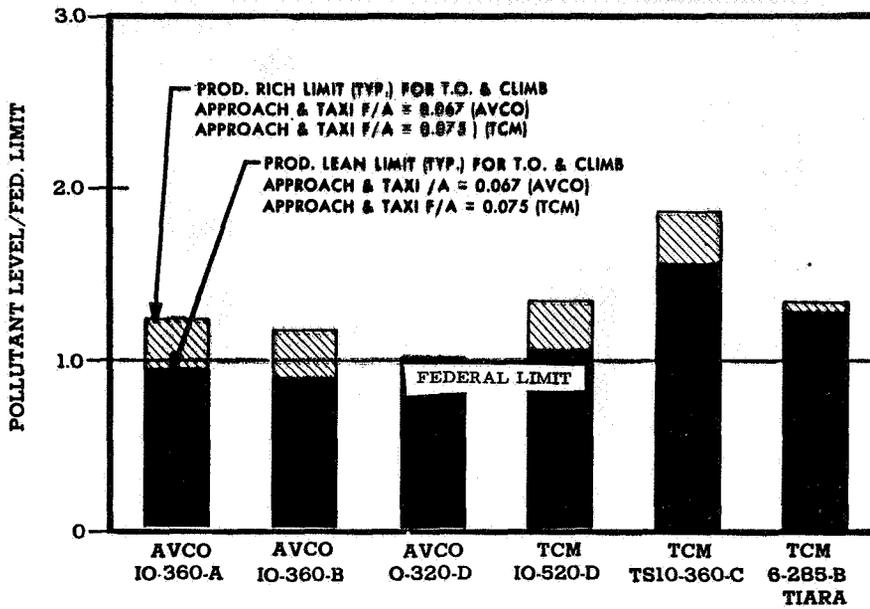
Figure 6-13

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

PROD. RICH LIMIT (TYP.) FOR T.O. ONLY
CLIMB AT BEST POWER F/A (TYP.)
APPROACH AND TAXI F/A 0.067 (AVCO)
APPROACH AND TAXI F/A 0.075 (TCM)

TCM 6-285-B (TIARA) EXCEPT
PROD. RICH LIMIT FOR T.O. ONLY
CLIMB AT BEST POWER F/A
APPROACH AND TAXI F/A 0.067

POLLUTANT LEVEL/FEDERAL LIMIT

2.0

1.0

0

| AVCO IO-360-A | AVCO IO-360-B | AVCO O-320-D | TCM IO-520-D | TCM TSIO-360-C | TCM 6-285-B TIARA |
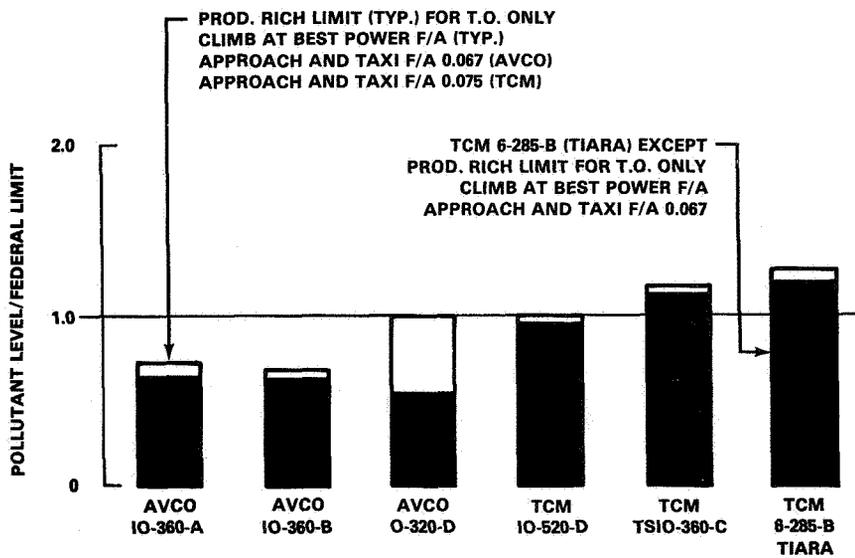
Figure 6-14

TOTAL UNBURNED HYDROCARBON EMISSION CHARACTERISTICS
PHASE I
Six (6) General Aviation Piston Engines
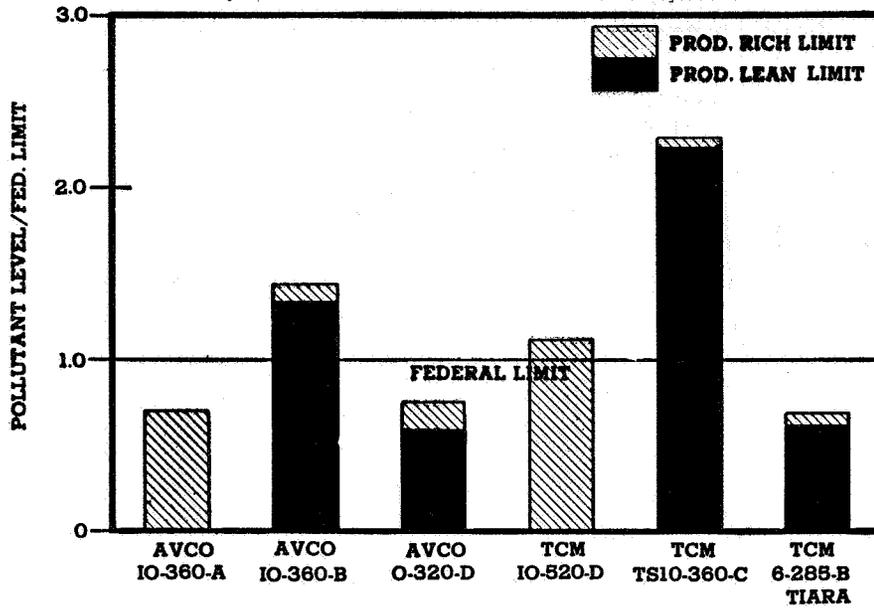
Figure 6-15

TOTAL UNBURNED HYDROCARBON EMISSION CHARACTERISTICS
PHASE I
Six (6) General Aviation Piston Engines
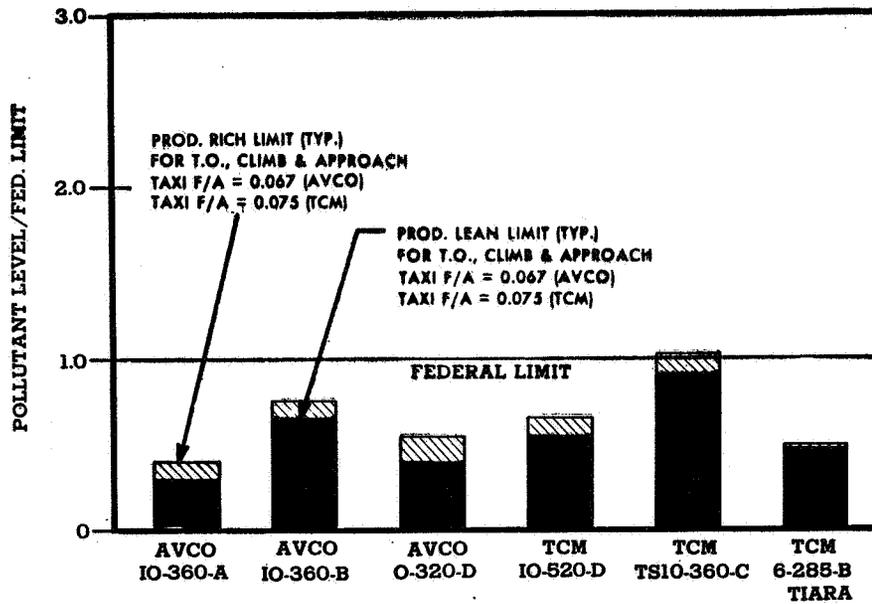
Figure 6-16

TOTAL OXIDES OF NITROGEN
EMISSION CHARACTERISTICS
PHASE I
Six (6) General Aviation Piston Engines
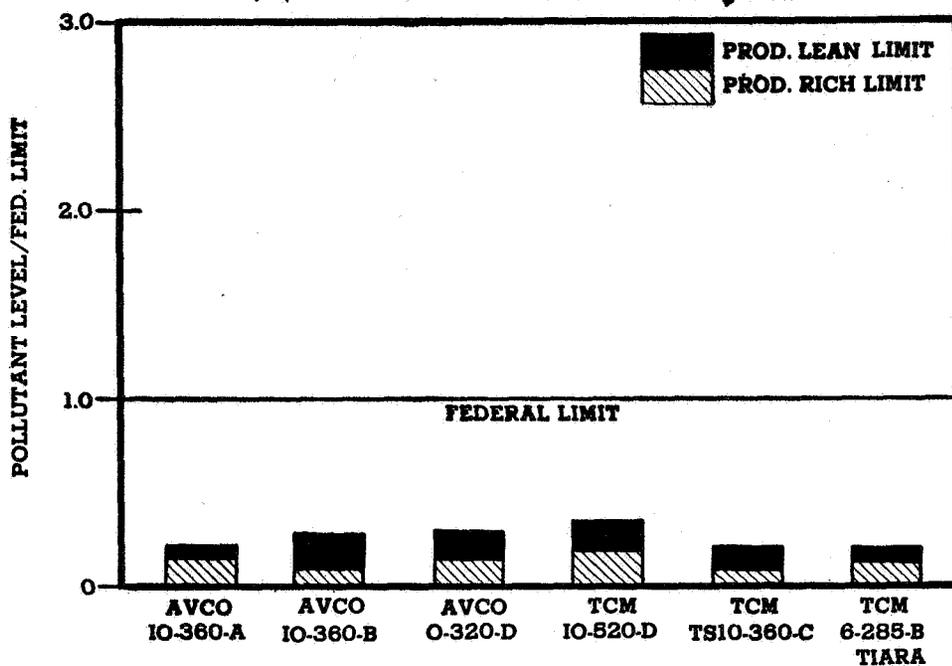
Figure 6-17

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

TEST STAND		MODE	FLT. TEST	CHT LIMIT	TEST STAND	
MAX. CHT (CORR. TO 100° DAY) (°F)	COOLING AIR $\Delta P = H_2O$		MAX. CHT (CORR. TO 100° DAY) (°F)		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

7. AVCO LYCOMING EMISSION AND FLIGHT TEST RESULTS*

Larry C. Duke

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EMISSION PROGRAM RESULTS

The Federal limits for piston aircraft engines, as stated by the EPA, Part 87, are defined as pollutant (CO, HC, NO_x) mass totals per rated horsepower obtained from engine operation through a prescribed LTO cycle, with modes specified by power and length of time. Table 7-1 shows a comparison between the 5-mode test cycle, as outlined by the EPA in Part 87, and the expanded 7-mode cycle currently being used by Avco Lycoming, with specific requirements for modes, mode times, engine speeds, and power settings not clearly defined in the specifications.

From the initiation of emissions testing, Avco Lycoming has felt that an important aid to the standard baseline cycle is the "leanout run" or mixture distribution run for each mode (fig. 7-1). As experience has increased with regard to data analysis and presentation, Avco Lycoming has found that, for development test work, the value of accurate pollutant trend data with respect to variable mixture strength exceeds that of individual baseline results. Whereas the baseline cyclic results are true only for the ambient conditions and fuel schedules for that baseline, leanout curves can be used to formulate cyclic results for a variety of fuel schedules (and/or production tolerances) over a range of ambient conditions.

Table 7-2 shows a comparison between the average of seven baseline cycles and the projected baseline cycle from the leanout curves for the IO-320-D engine. The results are typical of what Avco Lycoming has found in emissions testing to date; that is, sufficiently accurate baseline cycles can be constructed from pollutant trends of leanout data.

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*The data contained in this report are partially sponsored by FAA-NAFEC and have not been approved by them at this time. Therefore, the conclusions presented are solely those of Avco Lycoming and may not necessarily reflect those derived by the FAA.

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Table 7-3 shows a summary of the Avco Lycoming emissions program including those engines tested under the FAA-NAFEC contract. One advantage in formulating the cyclic results from leanout curves is that the pollutant totals for both the rich and lean production fuel schedules can be projected, as shown by figure 7-2. None of the 14 engines models tested to date by Avco Lycoming with their current production fuel schedules comply with the Federal standards. The variation in pollutant results, as shown between the IO-320 and O-320, is primarily due to the difference in production fuel schedules, not between fuel injector and carburetor.

Due to variations in the mode times and exhaust volume flow rates throughout the cycle, there are substantial differences in the contributions by mode to the cyclic total. As shown by figure 7-3, which gives a breakdown of pollutant contribution by mode for the IO-360-A, it can be seen that the taxi, climb, and approach modes produce approximately 9, 52, and 34 percent, respectively, of the CO cyclic totals.

In order to establish what possible improvements can be obtained by revised fuel schedules, it is important to assess the contribution from each mode separately. To show the effect of leaner fuel schedules for individual or combinations of modes on the cyclic pollutant totals, Avco Lycoming has developed the emission profile. The emission profile is constructed from the pollutant leanout curve trends, usually for those pollutants exceeding the Federal limits.

The emissions profile provides a fast, simple means of constructing various fuel schedules and determining the cyclic pollutant totals. For instance, figure 7-4 shows the emission profile for the IO-360-A engine with both the rich and lean limit production fuel schedules shown. Reconstructing the development of the lean limit fuel schedule is as follows:

(1) Select idle mode fuel-air (F/A) ratio (0.092) on upper left quadrant axis.

(2) Proceed vertically upward to intersect F/A ratio line for takeoff mode (0.085).

(3) Proceed horizontally to the right to intersect the F/A ratio line for the taxi mode (0.092).

(4) Extend line vertically down to intersect with climb F/A ratio line (0.085).

(5) Proceed horizontally to the left to intersect approach F/A ratio line.

(6) Proceed vertically upward to intersect with lower left quadrant axis and read cyclic total for CO.

Figure 7-5 shows the lean fuel schedule limits which Avco Lycoming predicted with respect to detonation and accelerations prior to flight test. These estimates were made based on a fuel system uncompensated for density for use with 0° to 100° F ambient temperatures. Avco Lycoming developed the profile to accommodate the concept of specifically tailored fuel schedules providing varying degrees of mixture leaning for individual modes and to permit quick and simple assessment of the benefits in cyclic pollutant totals. However, since test stand data were used in the development of the profiles, no limitations regarding cooling have been projected onto the profiles.

When reviewing emissions trends displayed on leanout curves or emissions profiles, limitations as to cylinder cooling, detonation, and acceleration must be identified, Avco Lycoming has found that based on the leanout emissions trends generated on the test stand and without regard to the limited quantity of cooling air available in the airframe installation, fuel schedules can be chosen whereby cyclic emissions comply with Federal regulations for all engine models tested to date. However, if sufficient tolerance is added to the fuel schedule to produce acceptable aircraft operation over the ambient temperature range from 0° to 100° F along with current production fuel system tolerances, projected cyclic emissions are outside Federal Limits for all engines tested. Therefore, Avco Lycoming does not presently stipulate "test stand" limitations since at best these limits would be artifical and unrepresentative of the aircraft installation. Limits as shown on the emissions profile are based on actual past flight test experience, inflight detonation surveys, and true realistic appraisal of aircraft constraints. Avco Lycoming has accumulated valuable cooling data in its recent flight test program. A review of these data has shown a positive indication that with some corrections, test stand cooling data can be projected to the actual installation. Additional data will be required to provide sufficient data sample for complete analysis. Acquisition of this data is in progress.

The effect that manufacturing tolerances have on the absolute pollutant levels for a given engine model and fuel schedule is important. Avco Lycoming is currently sampling representative engines from several engine models to define engine-to-engine emission variation. Figures 7-6 and 7-7 show leanout curves for the takeoff and approach modes, respectively, with data from three IO-360-A engines. Leanout data for the takeoff and climb modes for two model TIO-540-J engines are shown by figures 7-8 and 7-9. Accumulated test data on additional engines should provide a representative sample to sufficiently determine the extent of variation.

FLIGHT TEST RESULTS

The Avco Lycoming flight test program for reduced emissions was

conducted to determine and document the lean fuel schedule limits for current production aircraft based on flight safety. Based on analysis of the emissions profile, Avco Lycoming proposed to evaluate the effect of leaner schedules in the idle/taxi, climb, and approach modes. These modes were selected as areas where it was felt that possible improvements could be made with the greatest improvement in cyclic emissions reduction. Leaning in the takeoff mode, which would produce negligible cyclic pollutant reduction but require aircraft recertification, was not evaluated. The fuel systems to produce these leaner stepped fuel schedules were tailored specifically for the flight test and are not currently production items.

The flight test consisted of three phases:

(1) Cold weather testing to evaluate the effect of leaner mixtures in the idle/taxi and approach modes on safe engine acceleration.

(2) Hot weather ground testing to insure adequate ground cooling margin.

(3) Hot weather flight tests to study the possibility of leaning in the 80 percent climb mode.

Table 7-4 shows a brief description of the five aircraft flight tested in the Avco Lycoming program. To study the effect of installation variation on fuel schedule limitation, four aircraft with the 200 hp IO-360 engine were tested: Piper Arrow 200, Cessna Cardinal (tested under NAFEC contract), Rockwell Commander 112, and Beech Sierra. In addition, the Piper Pressurized Navajo was tested to evaluate possible emissions reductions on Avco Lycoming's highest power output current production engine, the TIGO-541.

The revised fuel schedule employed for the cold weather acceleration testing is shown by figure 7-10. A special lean idle plate was tailored to produce leaner fuel schedules in the idle/taxi modes. The fuel injector, a Bendix RSA-5AB1, incorporated a two-hole main metering valve which maintained a 0.067 F/A ratio from approximately 25 to 50 percent power (approach mode) and then enrichened with increased throttle angle to current production rich limits. An AMC unit to compensate for changes in ambient temperatures and air density was included to insure that the schedule would be maintained. The lean idle plate provided a nominal F/A ratio of 0.086 and 0.072 for idle (600 rpm) and taxi (1200 rpm), respectively.

For the acceleration testing, the throttle angle, engine speed, and manifold pressure were recorded for approximately 30 accels with the standard fuel injector set at manufacturer's recommended idle mixture setting and 30 accels with the revised injector with leaner fuel schedules. A similar flight test for both injector systems was de-

veloped which included 90 mph, 125 mph, and ILS approaches initiating
at 4000 feet with accelerations at 1000-foot intervals during descent.
Acceleration rates varied from 0.2 to 30 seconds from idle or part
throttle to full throttle. The idle mixture was set immediately prior
to each flight to insure consistent lean mixture settings with varying
ambient conditions. Table 7-5 shows the flight program outline de-
veloped for Avco Lycoming's flight test program.

Figures 7-11 to 7-14 show comparisons of engine response for rapid
throttle movements with the standard and revised injector systems for
each of the aircraft tested. The accelerations are at various alti-
tudes and flight conditions. Due to a limited time to procure the re-
vised fuel injector system, the idle to full throttle plate travel was
80° instead of the 70° travel for the standard injector. The accelera-
tion characteristics of each aircraft were similar, and the recorded
transients showed a very slight hesitation with rapid acceleration of
the revised injector system; however, none of the test pilots reported
a noticeable hesitation during the flight test. Figures 7-15 and 7-16
show slow accels made on the Rockwell 112 and Piper Arrow. A flat spot
in engine response is clearly evident from these curves corresponding
to the leaner than best power fuel schedule in the 25 to 50 percent
power range. All aircraft exhibited identical responses, and pilot re-
ports noted engine roughness in this area. In addition, magneto checks,
usually performed in this range, showed abnormally high single ignition
rpm drop resulting from the lean mixture.

Throughout the emissions program Avco Lycoming has noted that ac-
curate fuel and air flow measurements at idle and taxi are extremely im-
portant. Due to the low quantities of flows at these conditions, minor
errors in flow measurements can yield serious problems. For example,
at idle an error of as little as 0.2 pound per hour in fuel flow can
mean a 5 percent error in the measured F/A ratio – the maximum allow-
able, as indicated by the EPA, Part 87, for exhaust emission testing.
These same tight tolerances would apply to the allowable fuel system
variations in the idle/taxi modes.

A similar injector system with larger capacity was ground tested
on the Piper Pressurized Navajo. The leaner fuel schedule in the idle-
taxi range appeared acceptable for the limited ground acceleration test-
ing completed. No transient recording of engine parameters was taken.
However, a definite problem area was identified in the transition range
between the idle plate and main metering system of the injector. Severe
stumble and hesitation resulted during all accels in this area. At-
tempts at correcting this problem failed and it was decided that devel-
opment work of that nature was better performed on the flow bench and
test stand. It was noted during testing that in the 30 to 60 percent
power range, turbine inlet temperature was at the red line at full rich
mixture operation and was not acceptable.

Ground cooling evaluation of the leaner fuel schedules in the idle-taxi modes showed absolutely no cooling problem for any aircraft.

Cooling climbs to evaluate leaner fuel schedules in the 80 percent power range (Arrow, Cardinal, Sierra, and RC112) were made at 85 KIAS with best power fuel flow maintaining constant 80 percent power through critical altitude. Figure 7-17 shows a comparison of the 80 percent constant power climb versus the standard full throttle climb and the subsequent power loss with altitude for both standard conditions and corrected to 100° F. Avco Lycoming does not propose leaning beyond best power fuel flow in the climb mode.

A summary of the 80 percent power cooling climb results is shown by figure 7-18. Two cooling climbs were made with each aircraft from approximately a 500-foot altitude with stabilized conditions through critical altitude and peak temperatures. The summary shows the following:

(1) Three of the aircraft maintained engine CHT's within the 475° F maximum allowable through the 80 percent constant power climb at best power F/A ratio. The fourth aircraft had maximum corrected CHT's of 476° and 480° F, respectively, for the two climbs - or just over the limit.

(2) Two of the aircraft maintained the oil temperature within the 245° F maximum allowable.

After completion of the flight test program for five aircraft with fuel system modified for emissions reduction, Avco Lycoming has outlined the following problem areas and conclusions:

(1) The Bendix fuel injector (without density compensating unit) meters fuel by sensing induction air flow volume. Colder inlet air temperatures result in leaner mixtures supplied to the engine. Figure 7-19 shows the approximate relation between metered F/A ratio and induction air temperature. Note that the line indicating best power at 0° F shows that the resulting fuel schedule would yield a F/A ratio of approximately 0.084 at 60° F. The lean limit for the IO-360-A engine is 0.085 F/A measured between 60° to 80° F air temperature. Since the aircraft/engine combination must perform safely over wide temperature ranges, an AMC unit will be required to make any significant changes from current production fuel schedules. No assessment has been made by Avco Lycoming as to production tolerances of this unit.

(2) Leaner fuel schedules can be tolerated in the idle-taxi range of the IO-360 engine without affecting the acceleration of the engine. However, when considering even extremely tight production tolerances for the fuel injector in the idle range, there is negligible benefit when projecting the fuel schedule to 60° to 80° F induction air temperature.

To make any reasonable improvement in this area, a density compensating unit for the idle-taxi range must be incorporated into the injector unit. What the resultant production tolerance of such a system would be, or whether it would nullify any benefit to reduced emissions, is not known by Avco Lycoming at this time.

(3) The leaner fuel schedules in the idle, taxi, and approach modes, as evaluated in the cold weather test phase, revealed several major problem areas. Engine roughness, flat spots in engine response, and excessive engine speed drops during single ignition magneto operation would require solutions before any thought of production effectivity. At this time Avco Lycoming recommends a lean limit fuel schedule for these modes at best power fuel flow, which could eliminate these problem areas. With additional development work, it may be feasible at some time to revise the approach mode flow schedule towards stoichiometric as tested in the flight test program.

(4) The results of the 80 percent cooling climb test show that all of the aircraft (Arrow, Cardinal, Sierra, and RC112) could safely tolerate somewhat leaner fuel schedules in the 80 percent climb mode with regard to cylinder head limitations. However, modifications would be required to maintain acceptable engine oil cooling.

(5) Figure 7-20 shows the ultimate proposed fuel schedule pending solution of the problem areas considered in item (3). The fuel system to produce this schedule is not currently in production and would require new body castings and extensive development work. Four to six years of development are required before units would be available to Avco Lycoming for in-service test evaluation.

(6) The results of this test program are applicable to really only one engine model. They are not necessarily true of the other 350 models in production by Avco Lycoming; fuel injected, carbureted, turbocharged, and geared supercharged engines. Avco Lycoming is proceeding with a test program for carbureted engines and possible emissions reductions. A program for evaluating improvements to turbocharged engines is being formulated.

(7) The Avco Lycoming flight test program has shown that leaner fuel schedules can be safely tolerated. Figure 7-21 shows the emission profile for the IO-360 engine based on the flight test results. The solid line shows possible emissions reductions for a fuel system without density compensation. The dotted line shows the possibilities with a compensated system. There has been no effort to assign production tolerances to these results. Even with density compensation the profile shows that the projected cyclic total would be approximately 98 percent of the Federal limit for CO. Any production tolerance would exceed this limit.

(8) Avco Lycoming has conducted emissions surveys on six turbocharged engines of five different engine models on the flight test stand. A limited flight test of one turbocharged model, the TIGO-541, revealed unique problem areas dissimilar to those encountered with normally aspirated engines. The majority of turbocharged engine models are employed in twin engine aircraft, which have far more severe cooling climb requirements than single engine installations. Therefore, Avco Lycoming expects that the possible revisions to current fuel schedules for these engines will be extremely limited and will demand comprehensive testing. The turbocharged engine family may require a separate and more lenient set of Federal emissions limits.

With emissions reduction as a goal, time for fuel system development and implementation is the major factor. Evaluation of all current fuel systems and engine configurations with respect to possible improvements cannot be accomplished in the time remaining when factors such as flight safety, system integrity, and total cost impact must be considered.

DISCUSSION

Q — D. Powell: If you take your most complicated fuel schedule with the
couple bends in it, I see the 0.067 fuel-air ratio in the approach
mode, and if I then go to the circle graph, it shows about 0.077 in
the approach mode. Then, if you move that back to the 0.067 (like
the previous chart), it shows that you are about 25 percent under
the standards. Did I misread that?

A — L. Duke: No, you read it correctly. What we're trying to do is to
identify the problem with this slow acceleration where we saw the
engine go flat. One way of alleviating the problem and getting
something into production would be to run at best power, 0.077 in
the approach mode. We feel this will get us through that condition
without a big service problem, and right now, our remedy is to just
enrich it. That just gets us to the limit, but then we don't have
any tolerance for production. If we go to the 0.067 stoichiometric,
then we've again got the problem. That may be a development prob-
lem that can be worked out in the injector itself, but at this
moment that's a problem to us.

Q — G. Kittredge: That's a nice systematic piece of work which I found
very interesting. I understand from angry letters that have been
flowing across my desk that there is a trend away from 80/87 grade
low lead gasoline towards standardization on a higher grade, a new
version of the 100/130 octane. Won't that give you some additional
margin on detonation limits that would work in the direction of
compensating for that particular problem?

A — L. Duke: This engine happened to be certified on 100/130 octane
fuel. This is at the limit for that gasoline right now, so for
this engine there would be no benefit. Older engines certified on
the older gasoline may have some advantage.

Q — G. Kittredge: I didn't quite understand the introductory remarks
in your presentation or in Eric Becker's. You indicated some reser-
vations with the lean-out approach to establishing the emissions be-
havior of engines because it did not adequately correspond to the
way the engine was operated in service. That would have a bearing
on how we should respond to the earlier recommendation that you
heard.

A — L. Duke: If you're doing research work, you shouldn't be basing
all your work on running just baseline approaches. It is necessary
to know exactly what the engine is doing at each mode or over a
range of operating conditions. Certainly for future compliance
testing where specifications would be well-defined and engine test
conditions such as standard day and exact power are spelled out,
baseline cycles would be fine. For now, since we don't have a lot
of detailed specifications, we were suggesting that those involved
look mainly at manual lean-out runs to collect that data. It gives
you a background from which, if you must correct, you have some-
thing to correct from. Baseline runs should not be used to char-
acterize the engine.

COMMENT — G. Kittredge: I was very encouraged by your data showing that, although it took a lot of work, you did get very close to the CO standard, perhaps as much as 25 percent below if you can get rid of your flat spot. The earlier FAA data showing that these engines, relatively unmodified, can be brought below the standards is quite reassuring. We realize that it has taken a lot longer than anybody expected and we understand some of the reasons for this.

Q — F. Monts: I'd like to quote from an article by Peter Drucker. In comment to the fact that we have now identified the problem he says, "I hope we're over our belief that if you define a problem you don't have any more work to do. Now that you've identified the problem, you've only showed how much work there yet is to be done." My question is, did you run the climb cooling at an in-route climb speed or at best rate of climb speed for takeoff power?

A — L. Duke: We ran them all at the same conditions — best rate of climb speed as recommended by the manufacturers.

Q — F. Monts: There actually is no certification procedure for the single engine and 80 percent climb is there?

A — L. Duke: No.

Q — C. Gonzalez: Did you make any attempt to evaluate the startup and warmup characteristics of this revised full schedule?

A — L. Duke: We did qualitatively. I didn't report anything because we didn't really have it instrumented for that situation. We only took what the test pilot related to us, and his general opinion was that the engine started okay. However, at idle when he wanted to pull away from the chocks he had to wait a longer period of time before he could actually advance the throttle and move away. So essentially he had a longer wait for the engine to warm up before he could move away from the chocks.

Q — C. Gonzales: Did you run most of these tests in the winter season?

A — L. Duke: The acceleration tests were run essentially in the winter season. The temperature was in the neighborhood of 30° to 40°, but not the coldest it could have been run at.

Q — C. Gonzales: Were the fuel-air ratio adjustments made prior to the flights for the day carried out after the engine was warmed up or before the engine was warmed up?

A — L. Duke: After the engine was warmed up.

Q — W. Houtman: What investigations or analyses did you do to determine the cause of the slow acceleration or the flat spot on the speed curve?

A — L. Duke: We examined the power the engine should have been putting out at the condition of the flat spot in relation to what the injector was set for for the leaned-out approach condition. Those two appear to be in that 25 to 50 percent power range, and we estimated that the transition was between the idle circuit and the main metering circuit.

Q - W. Houtman: Do you think this might be strictly a hardware problem or is it a fundamental problem with operation at that point?

A - L. Duke: I think it's a little of both. It starts out appearing to be a definite hardware problem, but I think it carried over into actual installation problems too. It is certainly apparent in the turbocharged engine where we tried to do the same thing and saw all kinds of problems when the engine turbine appeared to be getting up to speed. In some instances it may be a straightforward developmental hardware problem, but that can't be carried over to all situations.

Q - W. Houtman: What would you consider the critical elements to be in the development period of 4 to 6 years?

A - L. Duke: Right now you can buy certain injectors with AMC units installed on it. The unit we tested is not a production injector. It was a cobbled up job. Also, the AMC unit is functional from approximately 25 percent power to 100 percent power. It was previously stated that taxi mode is a major source of pollution. It should be noted that the taxi mode was outside the compensated area of the AMC unit. That's the major area, getting that compensation to work for idle and taxi.

Q - P. Kempke: What work has been done on AMC units for carbureted engine?

A - L. Duke: We've essentially done no work for carbureted engines. We have programs underway to do that. There is no AMC unit for a carburetor like there is an injector AMC unit.

COMMENT - D. Tripp: On that slow acceleration, it looks like a classical carburetor fuel metering situation in which you have a constant manifold vacuum and a slowly opening throttle position. It would seem that by some hardware changes of a better optimized enrichment you could get over that condition.

A - L. Duke: The engine is not on the enrichment section when it encounters the problem. On the fast acceleration the engine goes right into the enrichment section, but when going very slowly, it is not getting into that enrichment section.

Q - E. Becker: Was any effort made to go back and check whether that stagger exists with the normal schedule as existed with the leaned condition?

A - L. Duke: Yes, an effort was made, and it does not exist.

Q - L. Helms: Your comment that you could have a bad mag drop is certainly applicable, but that's not our major concern. With due deference to the engine manufacturers and Bendix, the real problem we have is that that's the precise engine rpm where all pilots are taught to make their approach and landing. If there's any time he needs a rapid response, that's it, because of the danger of undershoot. So our major concern in the installation of the engine is

that that's the one point where we don't want any hangup of any kind. The second part is that it seems to me that the data you presented seem to underscore that the fuel schedules were set manually by a mechanic after the engine was warmed up. The greater the number of the individual modes that we can eliminate, the greater is the possibility of being able to come up with an AMC system in either a shorter period of time or with greater degree of vernier control. The earlier data we saw this morning indicated that most of the actual ppm pollution occurs in climb and approach. If the requirements for scheduling were reduced to just those two and eliminate the others, we have eliminated the major portion of the pollution. But the problem for fuel scheduling would be drastically simplified, am I correct?

A – L. Duke: That's a good observation.

Q – W. Mirsky: What are the possibilities of further reduction in CO due to better fuel-air distribution from cylinder to cylinder and also better mixture quality? In some cases at a given equivalence ratio, I find that you have high CO with high oxygen present with the CO levels higher than what you normally see for automotive practice. So, isn't there some potential for CO reduction by improved distribution and improved mixture quality?

A – L. Duke: There certainly is. Those items are covered under a different section concerned with future development and NASA contract work and don't fit under the NAFEC project. However, they are under investigation. This is especially true in carbureted engines, where there are various degrees of cylinder to cylinder distribution.

Q – F. Monts: Isn't the mixture distribution on this engine that you're talking about one of the better ones?

A – L. Duke: Yes, on this engine the distribution is good especially at the power modes. At idle and taxi it degrades a little. An injected engine normally has very good cylinder to cylinder distribution. This engine is an injected engine. It does have good distribution from cylinder to cylinder. The comment is really directed toward carbureted engines.

Q – N. Krull: Larry, this slow accel you found with a slow throttle advance is quite evident in the data. Was there any attempt when you got into this situation to rapidly advance the throttle and see whether the engine would actually pick up or would continue to hang in this condition?

A – R. Moffett: Yes, we tested extensively on the ground to try and determine if there is a hangup. The only think I can say is when you use a rapid accel you accelerate right through the flat spot. We never did see a hestitation.

TABLE 7-1

EMISSIONS TEST CYCLE

TEST CYCLE SPECIFIED IN FEDERAL REGISTER

MODE	% RATED SPEED	% RATED POWER	TUNE IN MODE (MIN.)
IDLE/TAXI			12
T.O.	100%	100%	.3
CLIMB		75-100%	5
APPROACH		40%	6
IDLE/TAXI			4
			27.3

EXPANDED TEST CYCLE

MODE	% RATED SPEED	% RATED POWER	TUNE IN MODE (MIN.)
IDLE	600 (Manufacturer's Recomm.)	——	1
TAXI	1200 (Manufacturer's Est.)	——	11
T.O.	100%	100%	.3
CLIMB	90%	80%	5
APPROACH	87%	40%	6
TAXI	1200	——	3
IDLE	600	——	1
			27.3

TABLE 7-2

COMPARISON OF BASELINE CYCLE AVERAGE
WITH PROJECTED CYCLIC TOTALS FROM LEAN OUT CURVES

IO-320-D ENGINE
AVCO LYCOMING TEST RESULTS

	CO LBS/HP-CYCLE	HC LBS/HP-CYCLE	NOX LBS/HP-CYCLE
AVERAGE 7 BASELINE CYCLES	.066	.00116	.000286
PROJECTED CYCLIC TOTALS BASED ON LEAN OUT DATA TRENDS	.065	.00112	.000273

TABLE 7-3

AVCO LYCOMING EMISSIONS TEST SUMMARY

NO. TESTED	ENGINE	RATED POWER	CARB.	FUEL INJ.	TURBO	GEARED
2	O-320-D	160	X			
2	IO-320-D	160		X		
1	IO-360-B	180		X		
3	IO-360-A	200		X		
2	TIO-540-J	350		X	X	
1	TO-360	210	X		X	
3	TIGO-541-D,E,G	450		X	X	X

TOTAL 14

755

TABLE 7-4

AIRCRAFT SUMMARY – AVCO LYCOMING FLIGHT TEST

	AIRCRAFT #1	AIRCRAFT #2	AIRCRAFT #3	AIRCRAFT #4	AIRCRAFT #5
ENGINE(S)	IO-360-C1C	IO-360-A1B6D	IO-360-A1B	IO-360-C1D6	TIGO-541-E1A
RATED POWER	200 BHP	200 BHP	200BHP	200 BHP	425 BHP
GROSS WEIGHT	2650 Lb	2800 Lb	2750 Lb	2650 Lb	7800 Lb
EMPTY WEIGHT	1522 Lb	1680 Lb	1711 Lb	1688 Lb	4900 Lb
RANGE 55% POWER	780 NM	1015 NM	721 NM	867 NM	1340 NM
MPG 55% CRUISE	16.3 MPG	16.9 MPG	13.9 MPG	12.8 MPG	5.7 MPG
75% CRUISE SPEED	143 KTS	148 KTS	131 KTS	140 KTS	231 KTS
MPG 75% CRUISE	13.6 MPG	13.8 MPG	12.8 MPG	11.2 MPG	4.3 MPG
SERVICE CEILING	15,000 FT	17,100 FT	14,342 FT	13,900 FT	29,000 FT
CLIMB RATE	900 FPM	925 FPM	893 FPM	1020 FPM	1600 FPM
COWL FLAPS		X		X	X
VAR. PITCH PROP	X	X	X	X	X
RETRC. GEAR	X	X	X	X	X

X = YES

REFERENCE: 1975 AIRCRAFT DIRECTORY FLYING ANNUAL

TABLE 7-5

TAXI

R. A. START
R. B. MOVE FROM SPOT
R. C. TAXI TO RUNWAY
R. D. RUN-UP
R. E. MOVE TO T.O. POSITION
   F. IDLE AGAINST STOP

A. NORMAL 90 IAS APPROACH

R. 1. TAKE OFF
   2. 4000 AGL 2400 RPM 25" 3 MIN.
R. 3. SNAP IDLE - SLOW TO 90 - GR. F.
R. 4. FAST ACCEL 5 SNAP IDLE 90 IAS
R. 5. 3000' 1 SEC ACCEL. 5 SNAP IDLE
R. 6. 2000' 1 SEC ACCEL. 5 SNAP IDLE
R. 7. 1000' RAPID ACCEL 3 DECEL
R. 8. FLARE PANIC ACCEL GO AROUND

B. HIGH SPEED 125 IAS APPROACH

R. 9. 4000 AGL 2400 RPM 25" 3 MIN
R. 10. SNAP IDLE 125 IAS GR-FL
R. 11. 3000' RAPID ACCEL 3 DECEL
R. 12. 2000' RAPID ACCEL " "
R. 13. 1000' RAPID ACCEL " "
R. 14. FLARE PANIC ACCEL GO 'ROUND

C. SHALLOW ANGLE ILS APPROACH

R. 15. 4000' AGL
   16. 2350 RPM 16.5" Hg   40%
   17. GEAR DWN FLAPS AR
R. 18. 3000' SLOW ACCEL 3 DECEL
R. 19. 2000' FAST ACCEL 3 DECEL
R. 20. PROP CONTROL TO HI RPM
R. 21. 1000' FAST ACCEL
R. 22. CHOP THROTTLE FLARE
R. 23. SNAP ACCEL
R. 24. CHOP THROTTLE LAND

D. NORMAL 90 IAS APPROACH

   25. 3000'
R. 26. CLOSE THROTTLE 90 IAS
   27. GEAR FLAPS
R. 28. 2000' SLOW ACCEL 3 DECEL
R. 29. 1000' SLOW ACCEL 3 DECEL
R. 30. FLARE, LAND, ROLL OUT, TURN OFF
R. 31. TAXI TO HANGAR - SHUT DOWN

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Figure 7-1

AVCO LYCOMING ENGINE EMISSIONS SUMMARY

Figure 7-2

PERCENTAGE OF POLLUTANT CONTRIBUTED BY MODE (% MODE-EPA CYCLE)
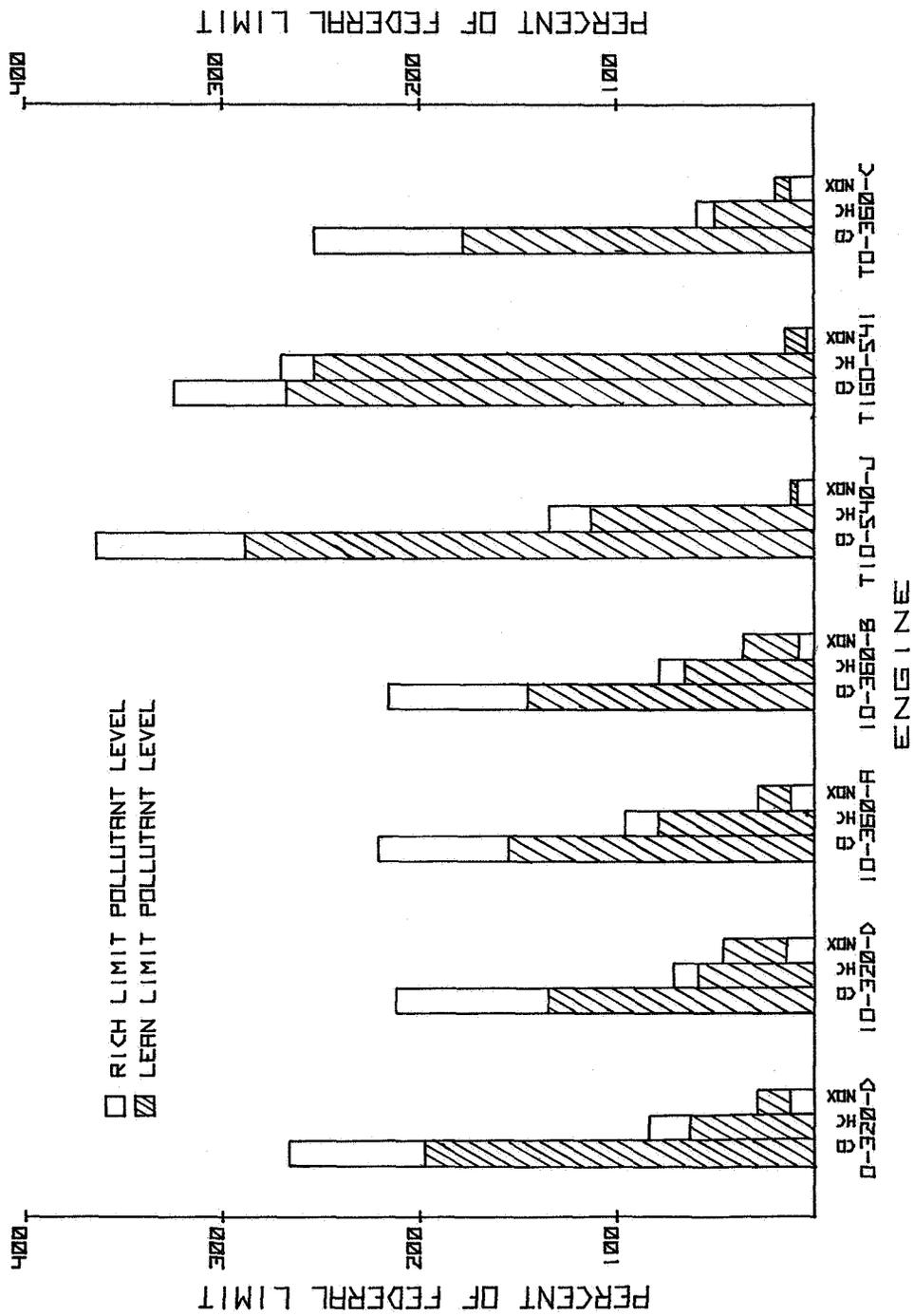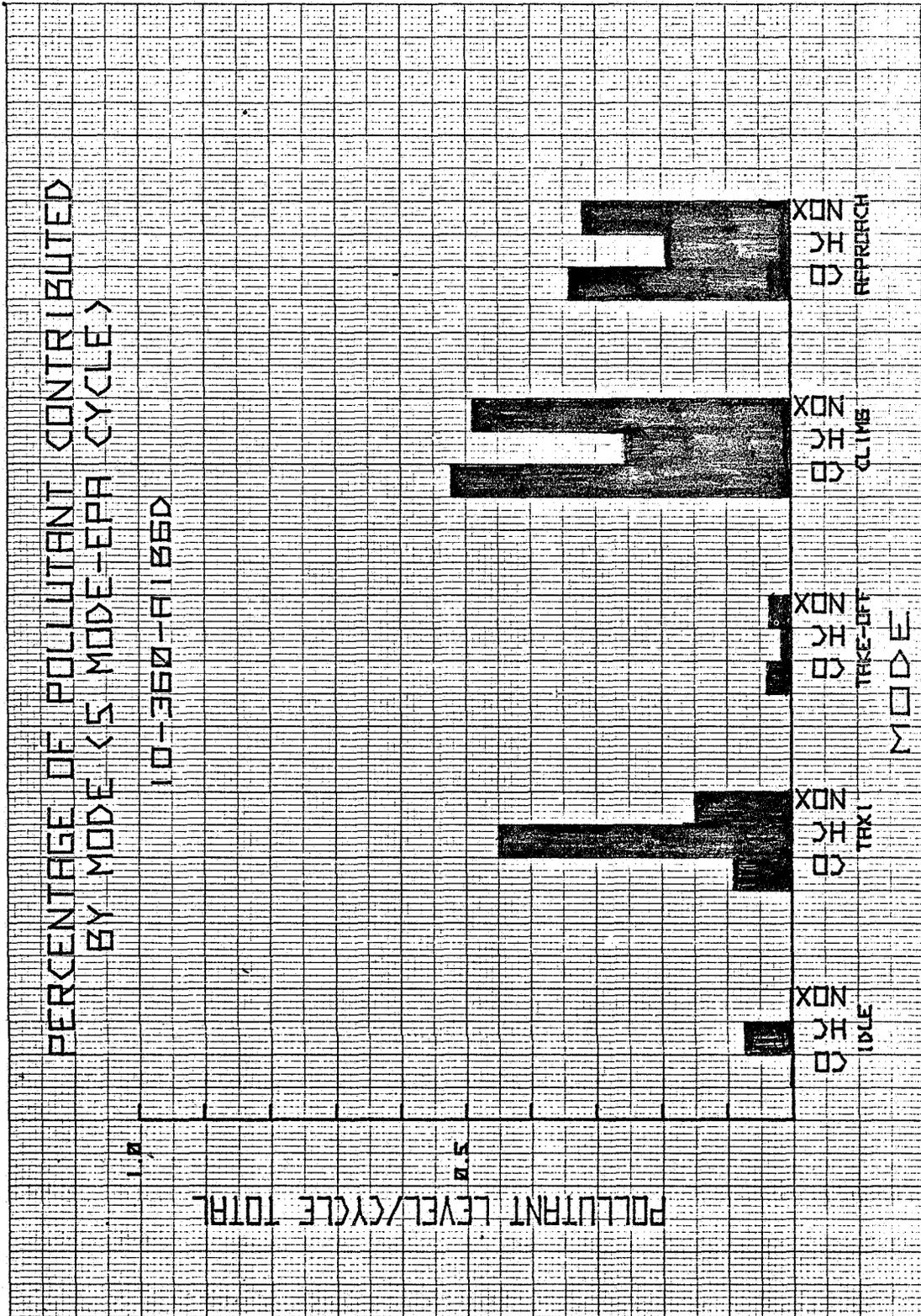
IO-360-A1B6D
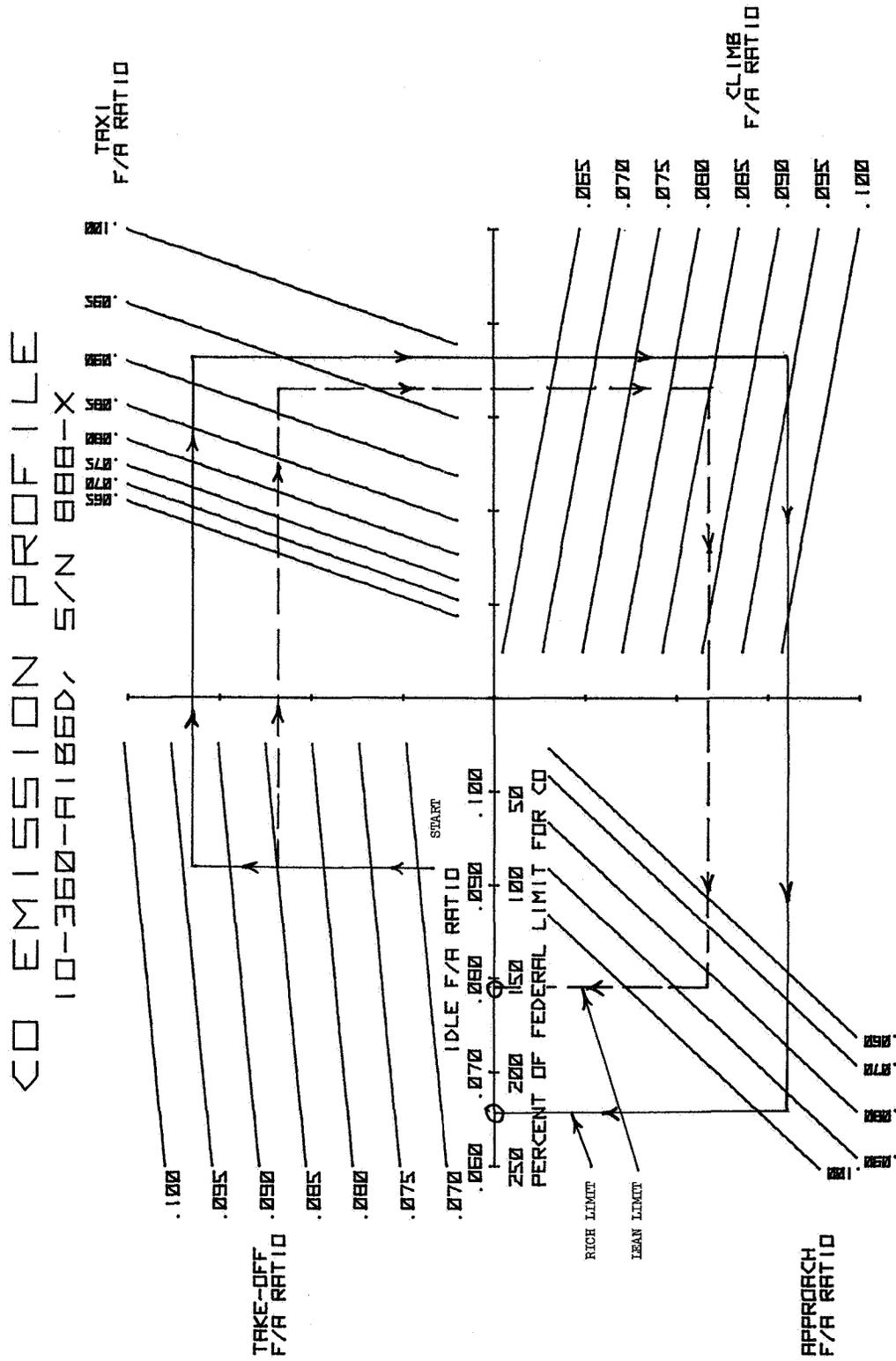
Figure 7-3

Figure 7-4

CO EMISSION PROFILE
10-360-A1B6D, S/N 888-X
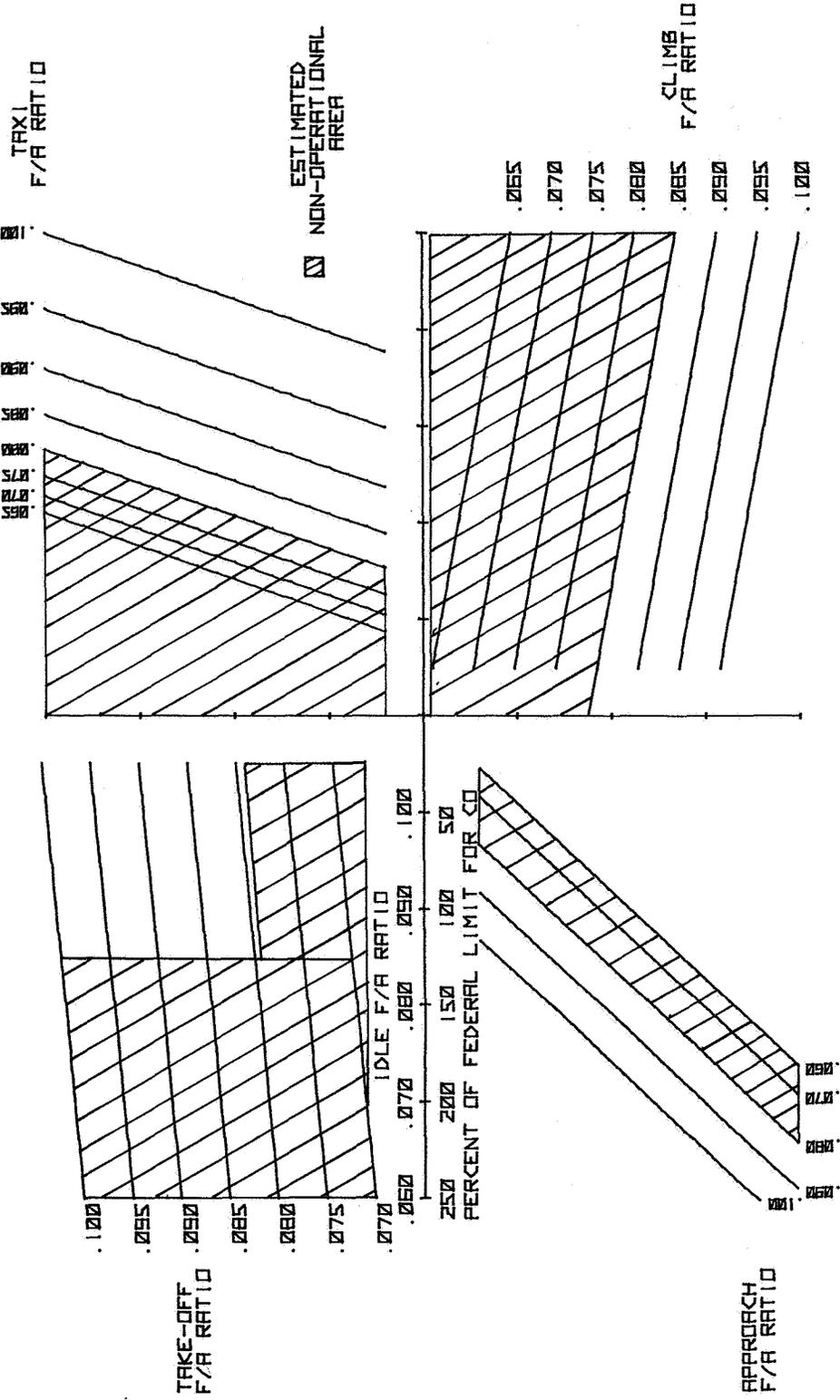
Figure 7-5
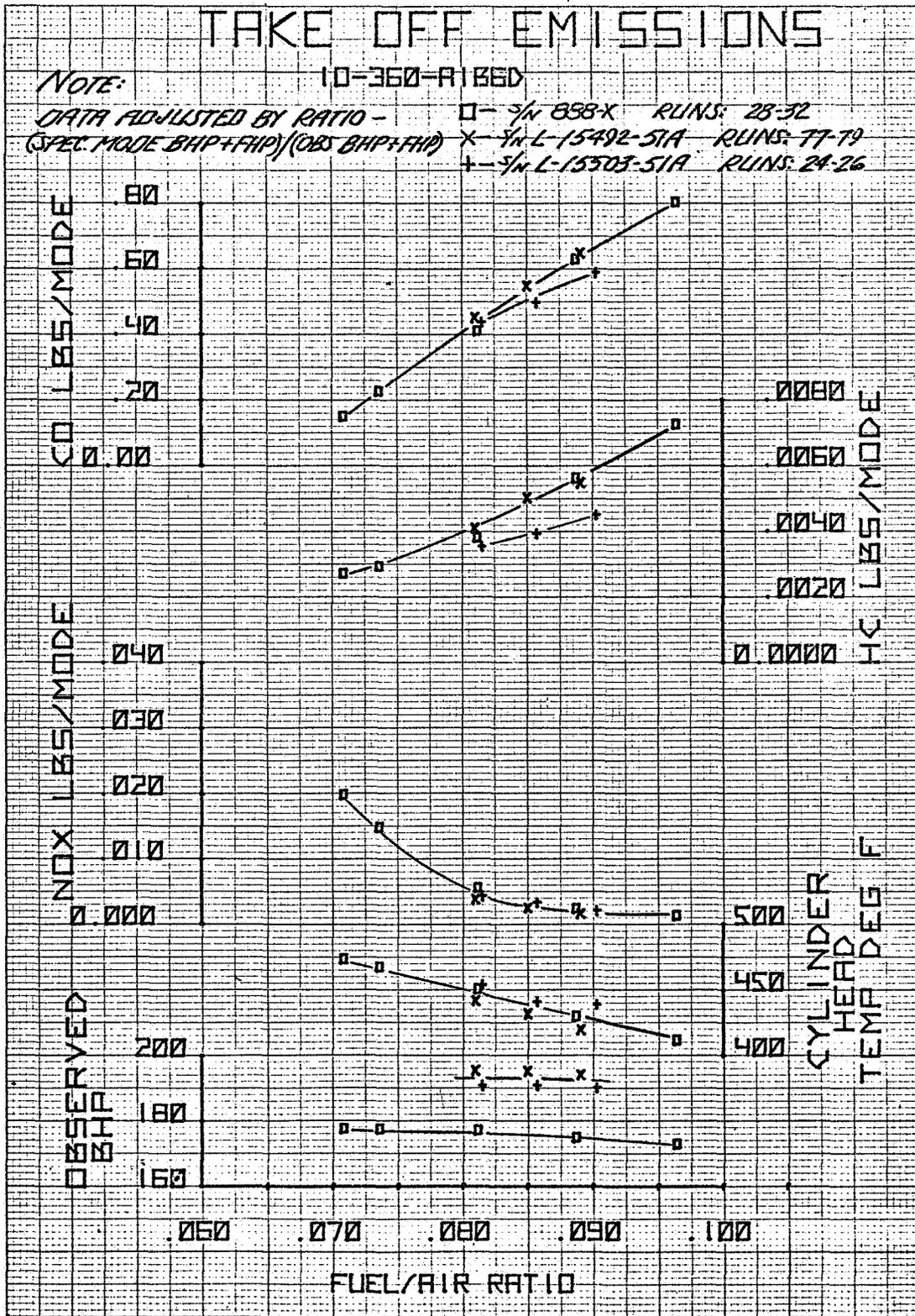
Figure 7-6

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Figure 7-7

TAKE OFF EMISSIONS
TIO-540-J

NOTE:

DATA ADJUSTED BY RATIO —
(SPEC. MODE BHP+FHP)/(OBS.BHP+FHP)

□ — S/N 890-X
RUNS: 254-259

X — S/N L-4277-61A
RUNS: 23-29

Figure 7-8

CLIMB EMISSIONS
T10-540-J

NOTE:
DATA ADJUSTED BY RATIO —
(SPEC. MODE BHP+FHP)/(OBS BHP+FHP)

□ — S/N 890-X
RUNS: 343-349

X — S/N L-4277-61A
RUNS: 30-39

Figure 7-9

REVISED FUEL SCHEDULE-RSA-SAB(FUEL INJECTOR WITH AMC UNIT

TAKEOFF
NO CHANGE
IN F/A RATIO

CLIMB MODE
80% POWER

2ND MAIN METERING
HOLE OPENING
THROTTLE ANGLE ENRICHMENT

APPROACH MODE
40% POWER
.067 F/A RATIO

IDLE/TAXI FUEL SCHEDULE
OPTIMIZED ON AIRCRAFT

FUEL/AIR RATIO

PERCENT POWER
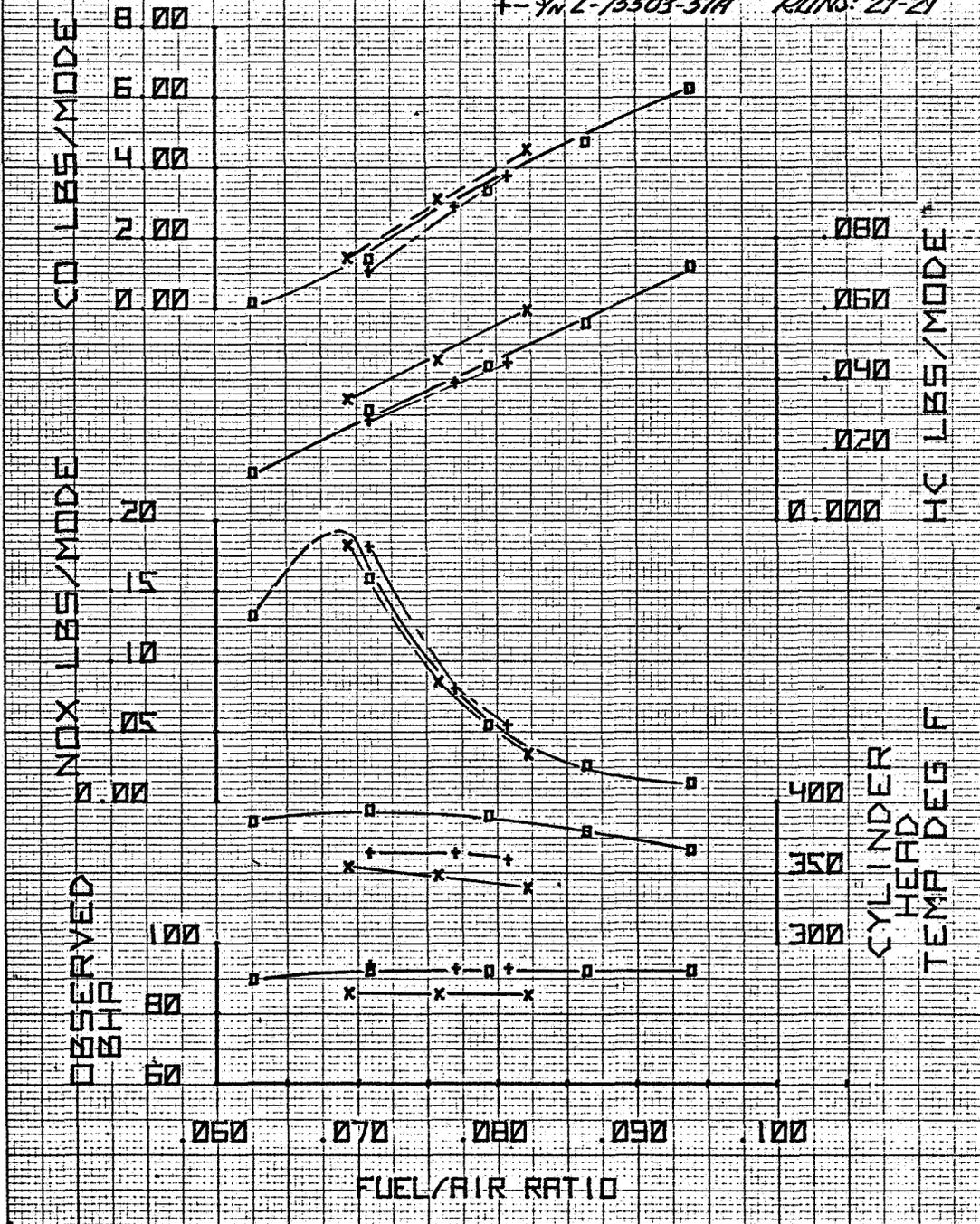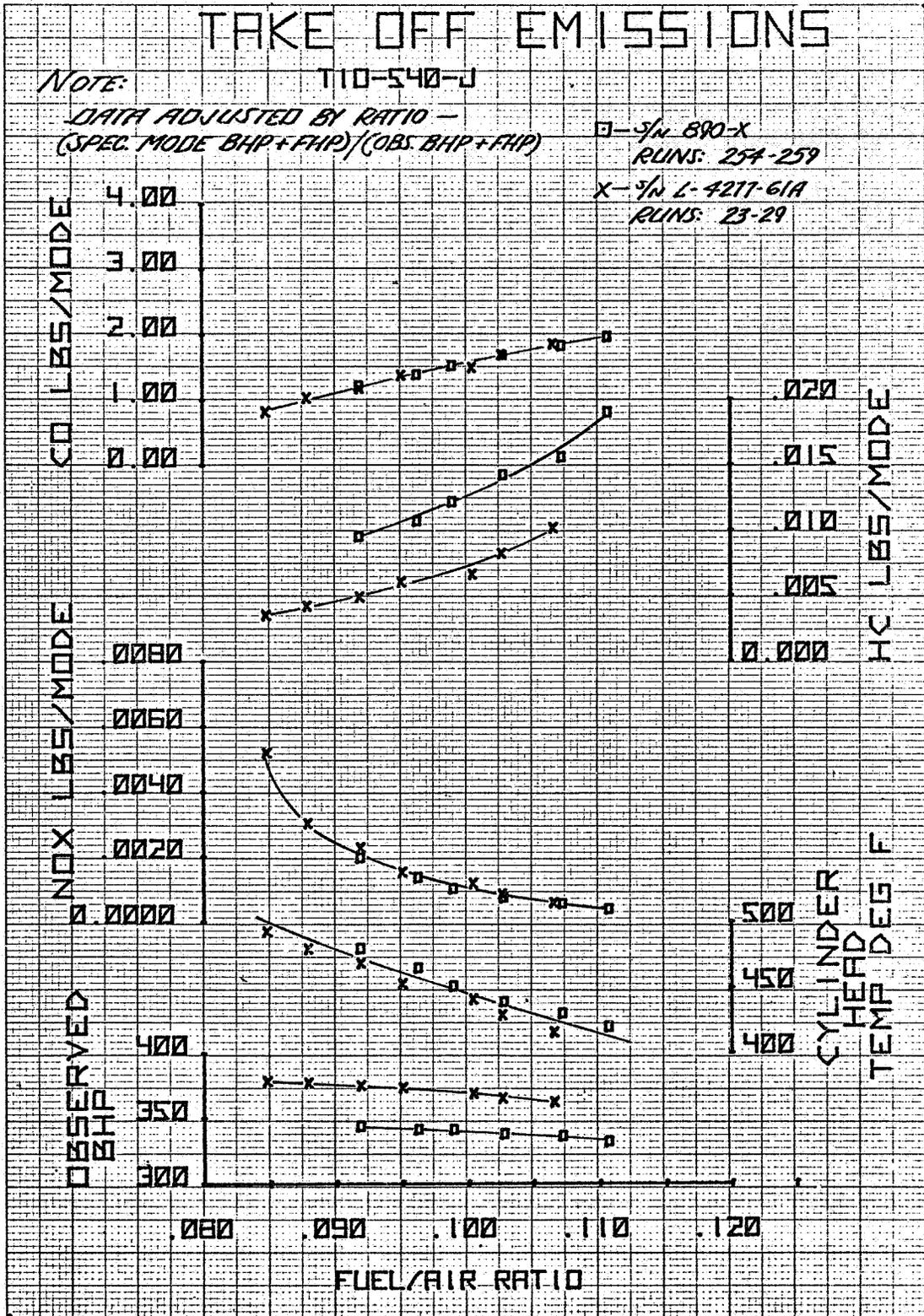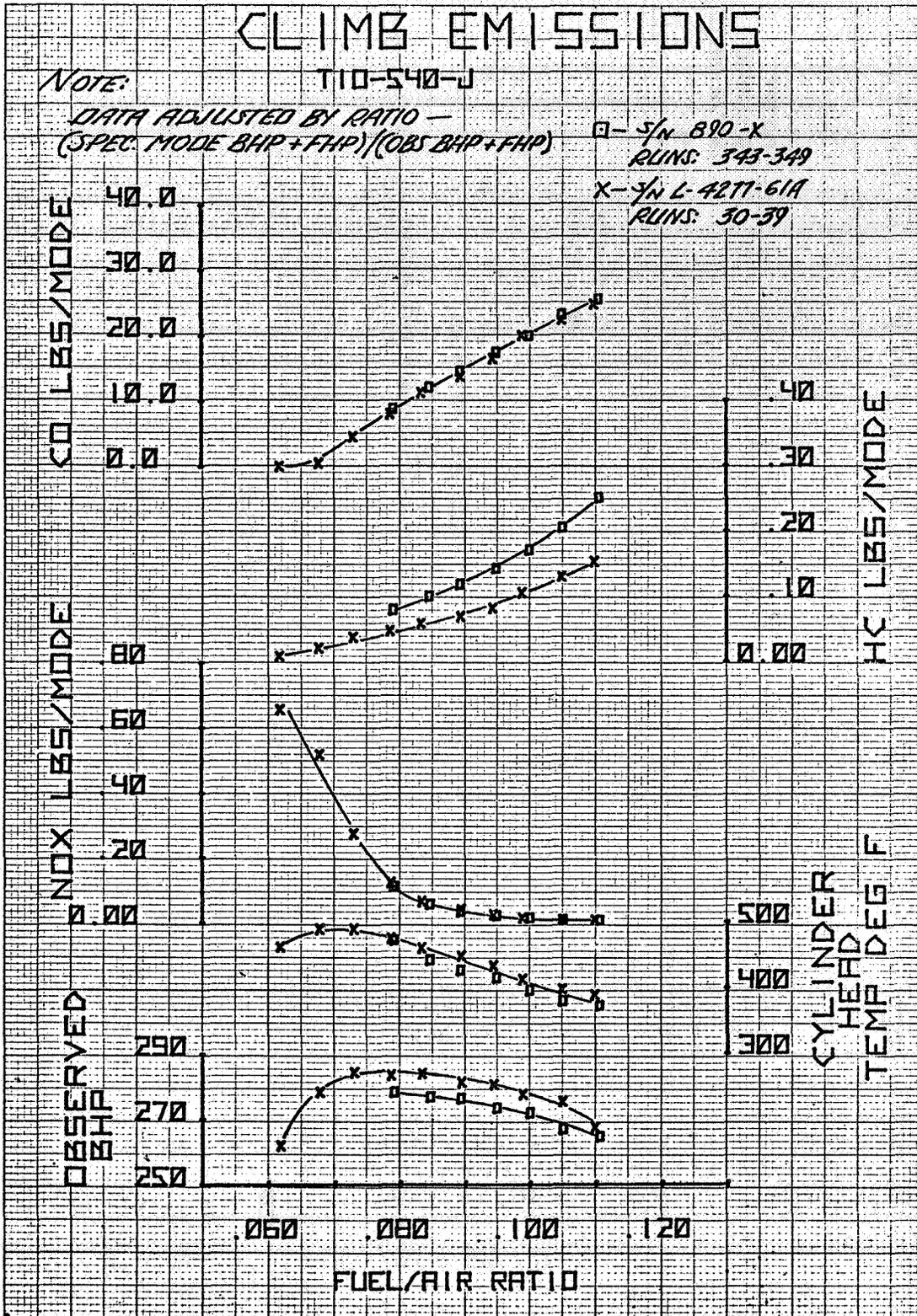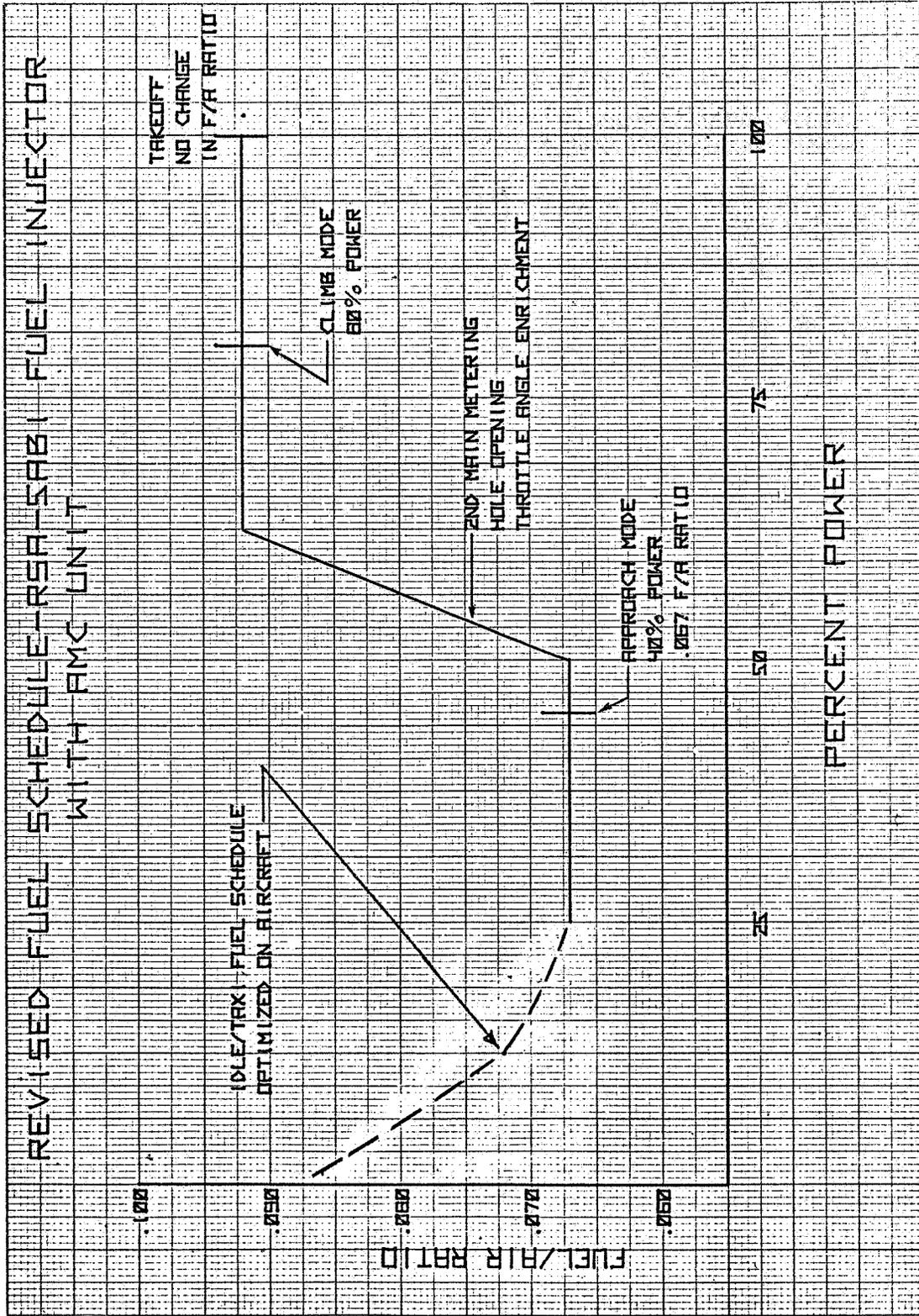
Figure 7-10

AVCO-LYCOMING COLD WEATHER FLIGHT TEST

CESSNA CARDINAL
4000 FT ALT
90 MPH IAS
FAST ACCEL
——STANDARD INJECTOR
---REVISED INJECTOR
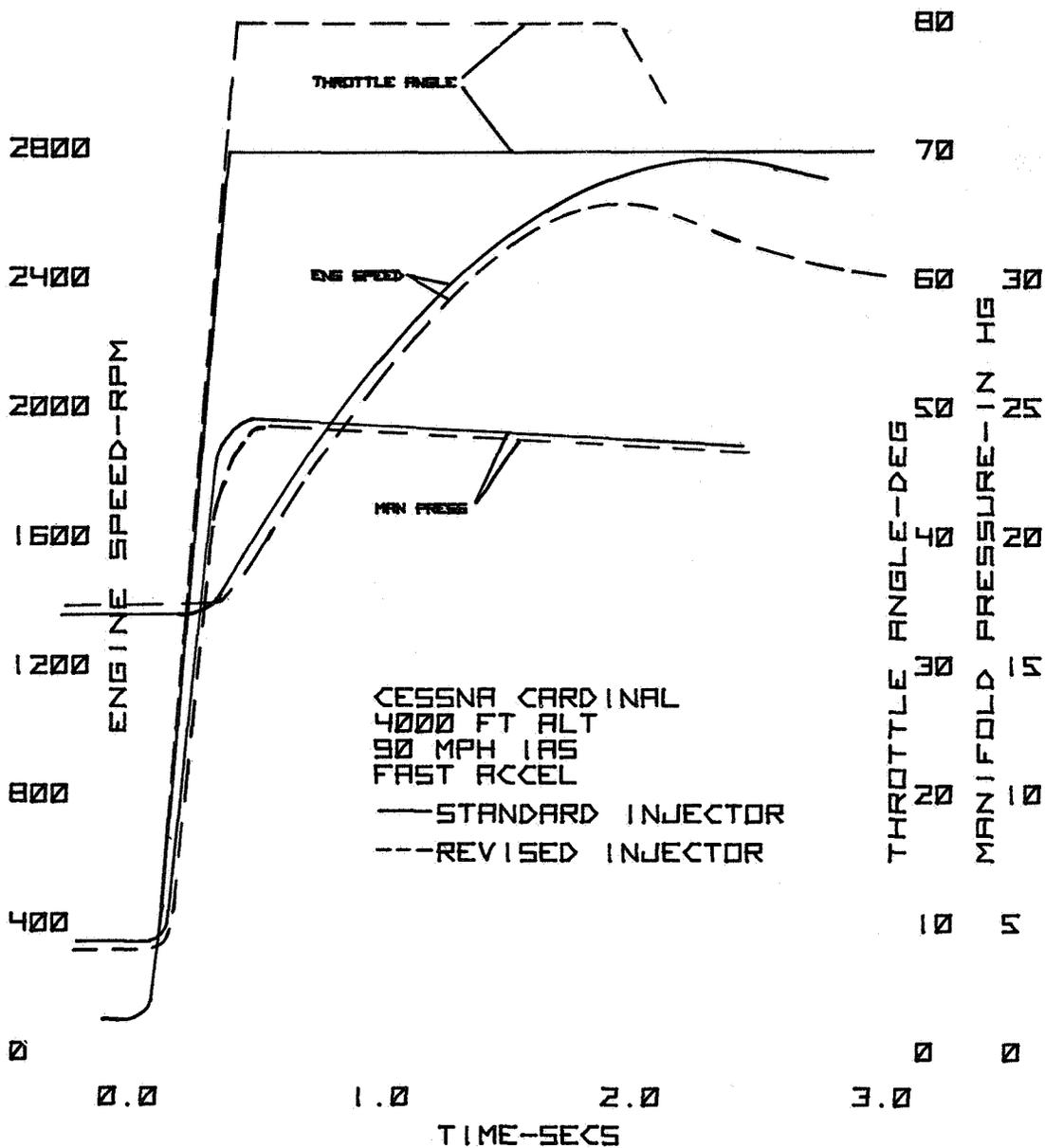
Figure 7-11

AVCO-LYCOMING COLD WEATHER FLIGHT TEST

ROCKWELL COMMANDER 112A
2000 FT ALT
125 MPH IAS
FAST ACCEL
— STANDARD INJECTOR
--- REVISED INJECTOR
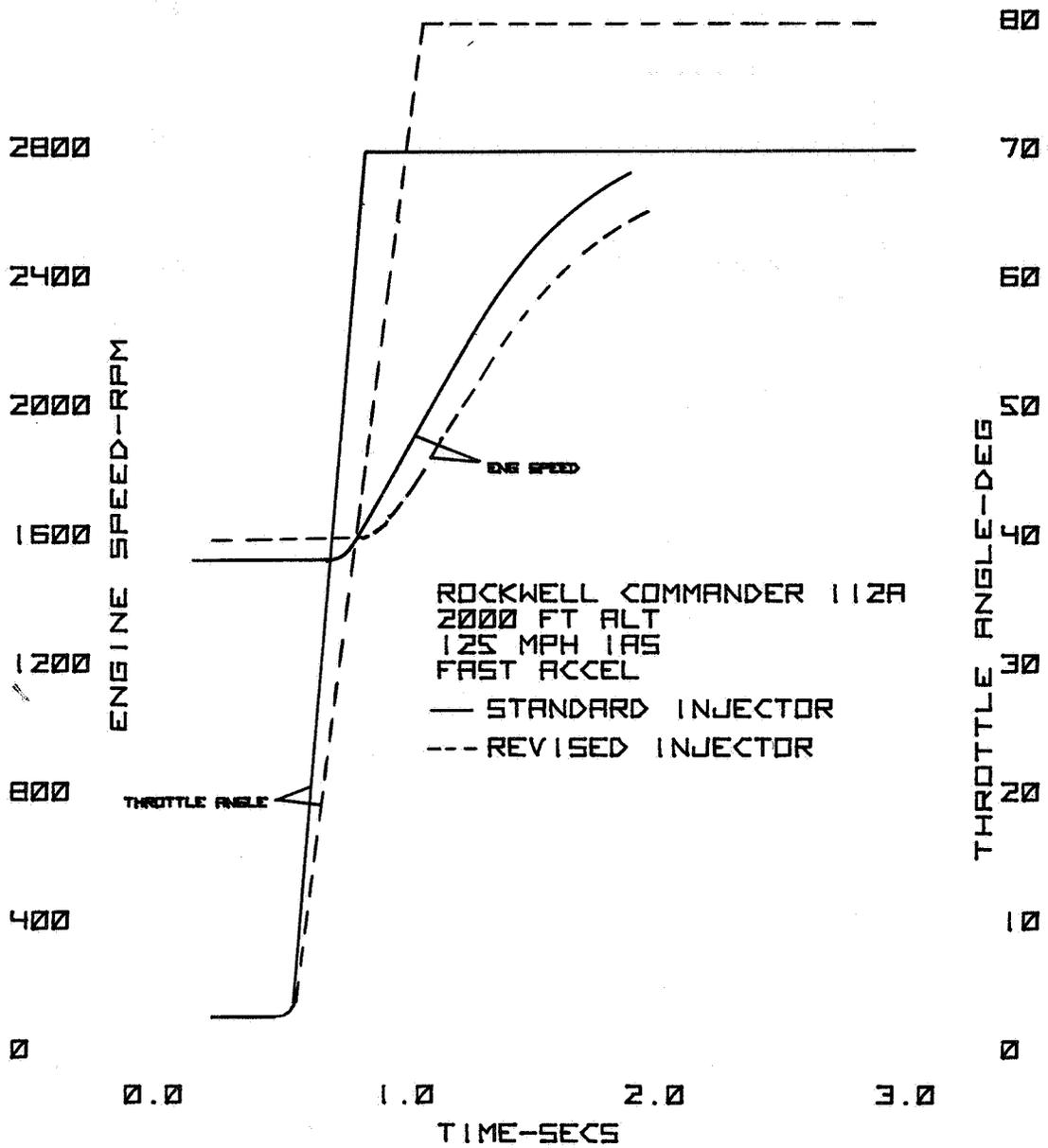
Figure 7-12

AVCO-LYCOMING COLD WEATHER FLIGHT TEST
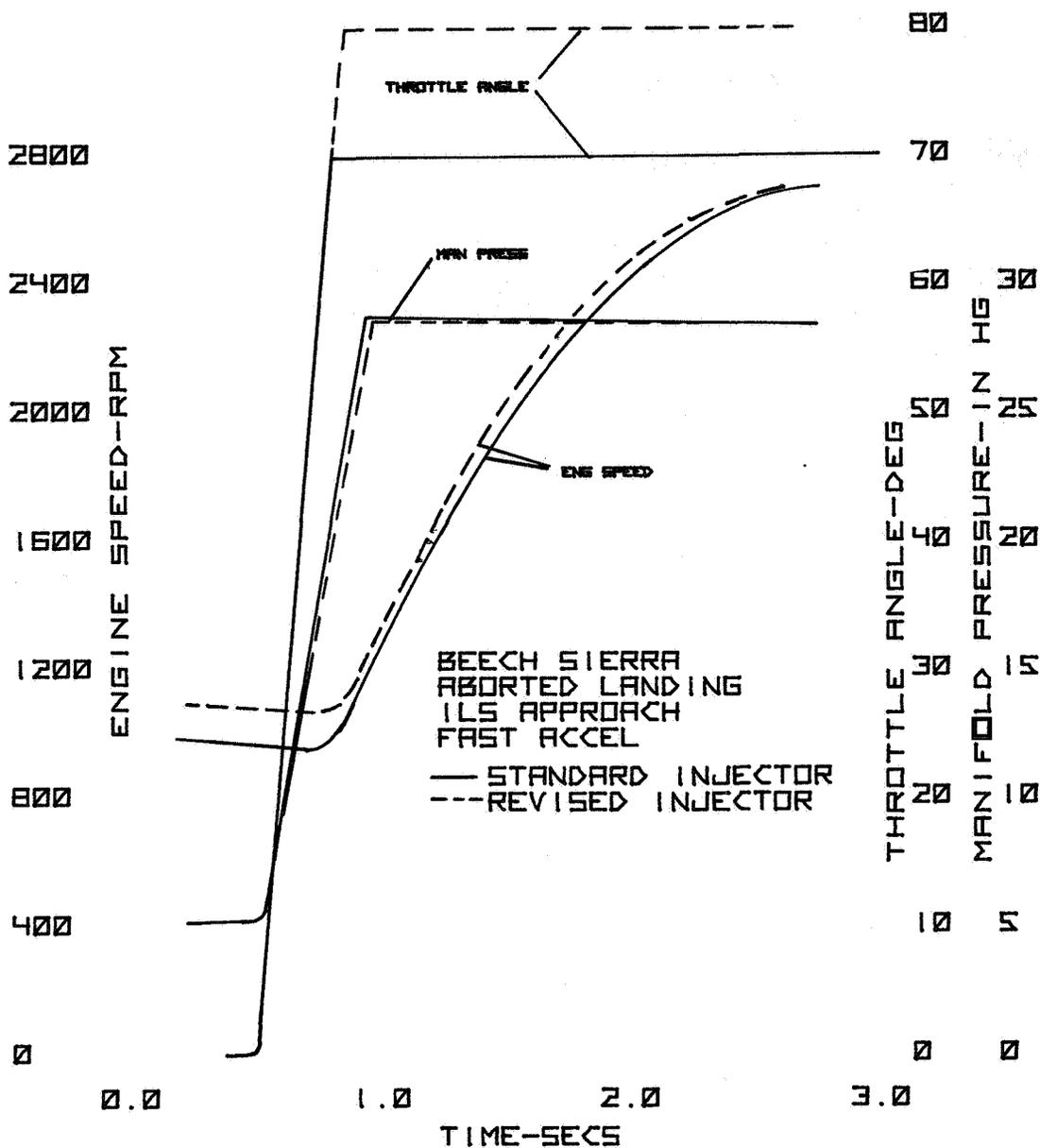
Figure 7-13

AVCO-LYCOMING COLD WEATHER FLIGHT TEST
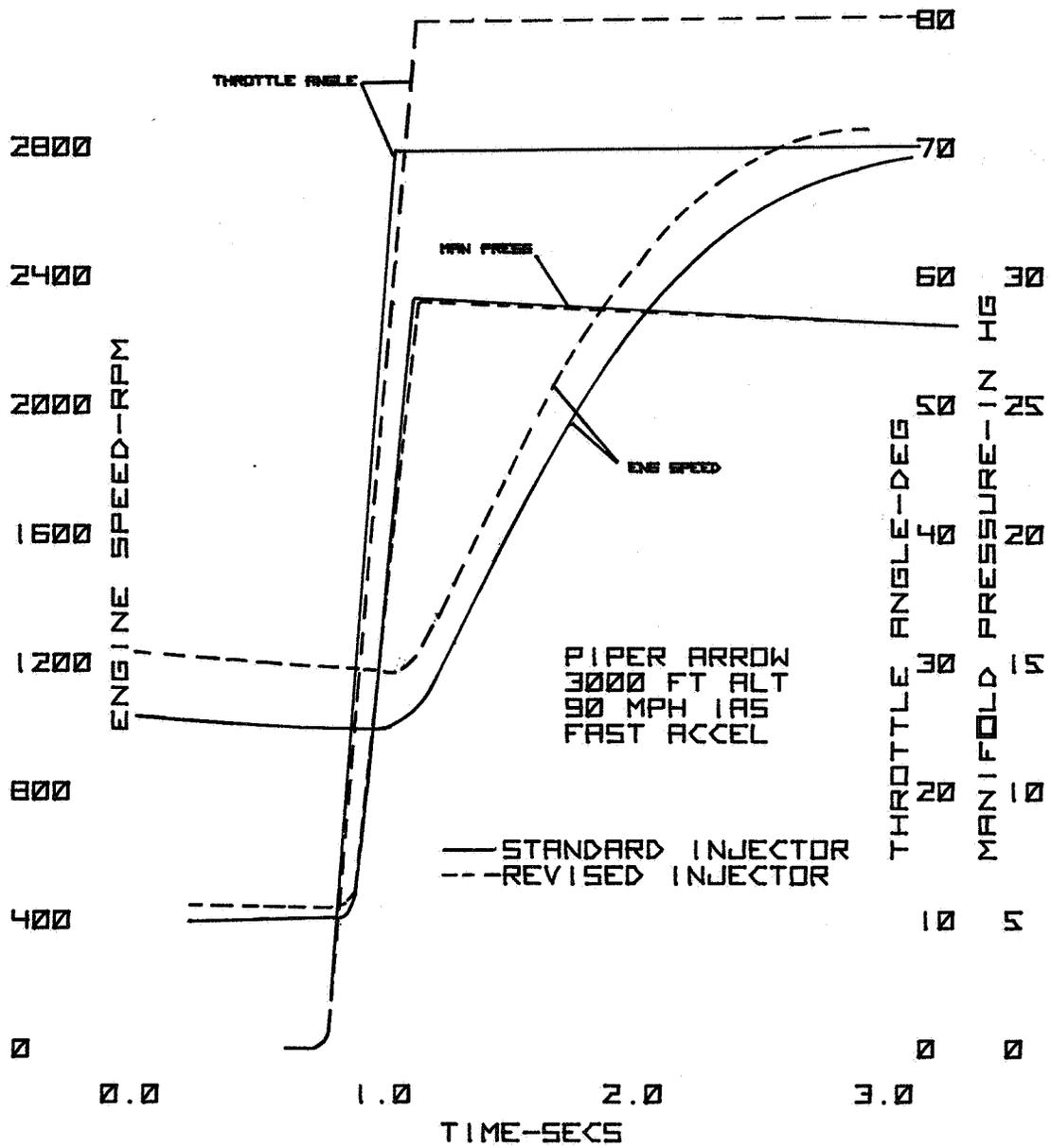
Figure 7-14

AVCO-LYCOMING COLD WEATHER FLIGHT TEST

ROCKWELL COMMANDER 112A
1000 FT ALT
90 MPH IAS
SLOW ACCEL

REVISED INJECTOR
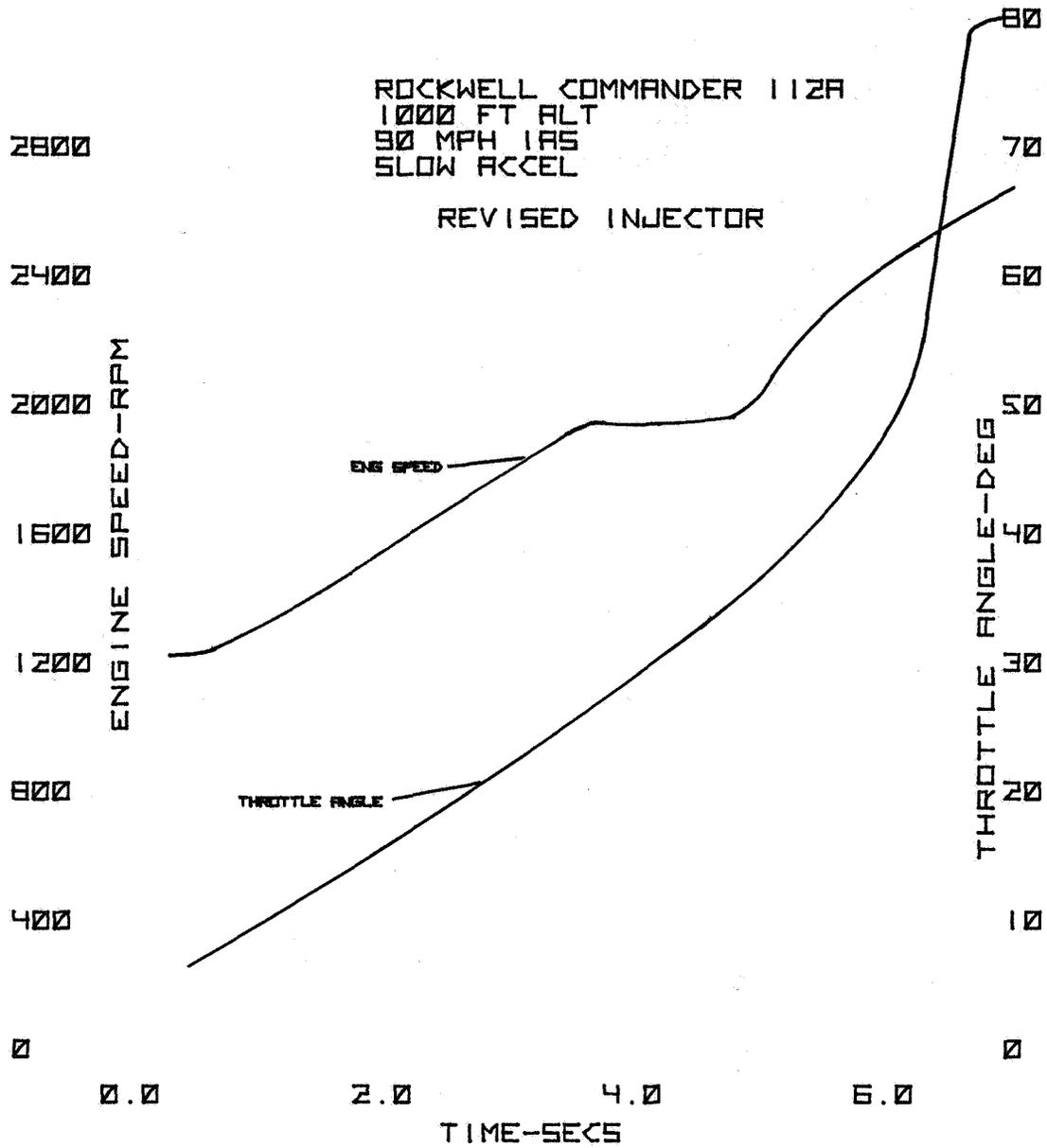
Figure 7-15

AVCO-LYCOMING COLD WEATHER
FLIGHT TEST

PIPER ARROW
STATIC GROUND
SLOW ACCEL

REVISED INJECTOR

ENG SPEED

THROTTLE ANGLE

ENGINE SPEED-RPM

THROTTLE ANGLE-DEG

TIME-SECS

Figure 7-16

ENGINE PERFORMANCE VS ALTITUDE
FULL THROTTLE VS 80 PERCENT CONSTANT POWER

IO-360-A/C

STANDARD CONDITIONS/SEA LEVEL

CORRECTED TO 100° F
AT SEA LEVEL

80% CONSTANT POWER

PERCENT RATED POWER

100
90
80
70

PRESSURE ALTITUDE—FT

0   1000   2000   3000   4000   5000   6000   7000   8000

Figure 7-17

80 PERCENT CONSTANT POWER COOLING CLIMB SUMMARY
AVCO LYCOMING FLIGHT TEST

Figure 7-18

INJECTOR METERING CHANGES
VS AMBIENT TEMPERATURE

INDUCTION AIR TEMP DEG F

INJECTOR METERING CHANGES (F/A RATIO)

BEST POWER
AT 0 DEG F

STOICHIOMETRIC
AT 0 DEG F

Figure 7-19

REVISED FUEL SCHEDULE-RSA-SAB FUEL INJECTOR WITH AMC UNIT

Figure 7-20

Figure 7-21

8. TELEDYNE CONTINENTAL MOTORS EMISSIONS DATA AND ANALYSIS

AND FLIGHT TEST RESULTS

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Teledyne Continental Motors
Mobile, Alabama

This presentation covers the results of a National Aviation Facilities Experimental Center (NAFEC) emissions contract. The emissions data are currently being reviewed by NAFEC and therefore this presentation cannot be approved by NAFEC at this time. The conclusions presented are those of Teledyne Continental Motors (TCM).

EMISSIONS DATA AND ANALYSIS

Under NAFEC contract DOT FA74NA-1091, Teledyne Continental Motors has tested five different engine models covering combinations of all engine categories in current production in the range from 100 to 435 brake horsepower. Engines are divided into five major types: carbureted, fuel injected, direct drive, geared, and turbocharged. Table 8-1 illustrates the combinations of engine categories tested. Engine displacements of 200, 360, 406, and 520 cubic inches were selected to cover the current production range. The five engine models tested were O-200A, IO-520D, TSIO-360C, Tiara 6-285B, and GTSIO-520K. Each engine was tested at seven steady-state modes of operation defined to simulate airport activity. The engine conditions in each mode are given in table 8-2.

Emissions data were categorized by three separate fuel system schedules: baseline, case 1, and case 2. Baseline is defined as the average fuel flow rate established by the fuel system's production tolerance band when operated with the mixture control at the full-rich position. Case 1 is defined as the minimum allowable fuel flow rate established by the engine certification. Case 1 for most modal conditions is approximately the best power. Case 2 is defined as the fuel flow rate corresponding to the leanest fuel-air ratio obtainable before a safety limit occurred with the engine operating on a propeller test stand. Safety limits that developed during testing were cylinder-head overheating or inadequate acceleration from a given mode of operation.

Figures 8-1 to 8-5 represent the mixture-strength fuel schedules for the five engine models tested. Each figure shows the fuel-air equivalence

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ratio for the three fuel system schedules (baseline, case 1, and case 2) as a function of power. Also shown for reference are the modal power points on the auxiliary abscissa scale. All the fuel-injected engines tested (figs. 8-2 to 8-5) exhibited the same general trend in mixture strength, that is, richer at low power, leaner at the midpower range, and richer at maximum power. This trend may be rationalized by considering the present fuel-injection system design. Rich mixtures are required at the low-power idle/taxi regime to provide adequate fuel distribution to all cylinders and to ensure adequate engine transient response (acceleration). Since the present fuel system is not temperature compensating, the fuel flow required for the idle/taxi modes depends on the fuel-air ratio required for cold-day operation. As the induction air temperature increases, the resultant fuel-air mixture is enriched. Leaner mixtures are acceptable and desirable in the midpower range where fuel distribution is good and cylinder-head temperatures are well within the limits. Richer mixtures are required at high-power points for cylinder-head cooling and detonation suppression. The Federal Aviation Administration (FAA) requires that the minimum fuel flow rate certified be at least 10 percent above the fuel flow rate at which detonation occurs.

The mixture-strength schedules of the engines tested also exhibit the same trend with respect to baseline, case 1, and case 2 fuel schedules. A wider equivalence ratio band exists between each fuel schedule at low power, and this band decreases to a minimum at maximum power. This is due to the larger tolerance band associated with controlling low fuel flow rates. In figure 8-1, the carbureted 0-200A engine's fuel schedule for baseline and case 1 follows the delivery characteristics of a typical commercial single-venturi carburetor. Case 2 illustrates the narrowing margin available between an uninstalled safety limit and the minimum allowable fuel flow (case 1) as power increases. Cylinder-head overheating was the safety limit encountered for the climb and takeoff modes, while inadequate acceleration was the safety limit encountered for the idle, taxi, and approach modes. Figure 8-2 illustrates the mixture-strength schedules for the IO-520D, a fuel-injected, 520-cubic-inch-displacement engine. Again the margin available between an uninstalled safety limit and the minimum allowable fuel flow decreases as power increases. The fuel-injected engines exhibited the same safety limits as the carbureted engine, that is, cylinder-head overheating during climb and takeoff modes and inadequate acceleration for the idle, taxi, and approach modes. Figure 8-3 shows the mixture-strength schedules for the Tiara 6-285B, a geared, fuel-injected, 406-cubic-inch-displacement engine. These curves indicate a much narrower band between baseline, case 1, and case 2. This is attributed to the high-speed engine design, allowing a higher percentage of the maximum fuel flow at low-speed conditions. Figure 8-4 illustrates the mixture-strength schedules for a turbocharged, fuel-injected, 360-cubic-inch-displacement TSIO-360C engine. Figure 8-5 shows the mixture-strength schedules for a geared, turbocharged, fuel-injected, 520-cubic-inch-displacement GTSIO-520K engine.

It is important to note that the five different engine mixture-strength schedules thus far discussed are for the specific engines tested.

The combined production tolerance effect of both fuel flow and induction airflow has not been determined to date. Also, the effects of engine cumulative operational time on mixture-strength schedules, and therefore on emissions, has not been determined.

Figures 8-6 to 8-10 are plots of the emission levels for the five engine models tested. The figures present the emission levels in percent of the EPA standard as a function of time-weighted, fuel-air equivalence ratio. Emission levels above 100 percent are over the standard; levels below 100 percent are within the standard. The time-weighted, fuel-air equivalence ratio ϕ_{tw} is defined as the summation of the product of the modal time and the modal equivalence ratio divided by the total cycle time. In equation form

$$\phi_{tw} = \frac{\sum_{i=1}^{7} T_i \phi_i}{27.3}$$

where

T_i time in mode i

ϕ_i equivalence ratio in mode i

The time-weighted equivalence ratio provides a means of establishing baseline, case 1, and case 2 emissions levels as a function of a common reference for each pollutant. The results of "leaning" can therefore be quickly recognized. As expected, leaning the engines decreased carbon monoxide (CO) and hydrocarbons (HC) but increased oxides of nitrogen (NO_x).

In figure 8-6, the O-200A engine baseline mixture-strength schedule results in a ϕ_{tw} of 1.43 with CO above the standard, HC slightly over the standard, and NO_x below the standard. Leaning to case 1 results in a ϕ_{tw} of 1.19 with corresponding reductions from baseline of 27 percent for CO and 43 percent for HC. However, NO_x increased by 221 percent, resulting in a level well over the standard. Additional leaning to case 2 resulted in a ϕ_{tw} slightly less than stoichiometric, 0.99, with decreases from case 1 of 39 percent for CO and 37 percent for HC. The NO_x emissions continued to increase, resulting in a 69-percent increase over case 1. Leaning the O-200A engine did not reduce all three pollutants (CO, HC, and NO_x) below the EPA limits.

Figure 8-7 shows the emissions levels for the IO-520D engine. The baseline mixture-strength schedule resulted in a ϕ_{tw} of 1.43, with CO and HC above the standard and NO_x well below the limit. Decreases of 34 percent for CO and 19 percent for HC were observed when the engine was leaned to a ϕ_{tw} of 1.23 (case 1); NO_x increased 118 percent but remained considerably below the limit. Case 2, ϕ_{tw} of 1.12, resulted in

levels for all three pollutants below the EPA standards, with decreases from case 1 of 34 percent for CO and 37 percent for HC; NO_x increased by 83 percent. From figure 8-7 an estimated band of time-weighted, fuel-air equivalence ratios that meet all EPA standards can be determined. This total band ranges from a ϕ_{tw} of 1.02 to 1.16. However, when case 2 is considered (uninstalled safety limits), this band is reduced to a ϕ_{tw} range of 1.12 to 1.16, which results in a ±1.75 percent tolerance band on fuel-air ratio for the complete seven-mode cycle.

Tiara 6-285B emission levels are presented in figure 8-8. Tiara differs considerably from the previous engines discussed (O-200A and IO-520D) in that the HC limit never exceeded the EPA standards. The primary reason for this is the higher engine speeds associated with a geared engine. Increasing the idle and taxi engine speeds provides better engine breathing with less short circuiting of the incoming charge and thus lower hydrocarbon emissions. The baseline mixture schedule resulted in a ϕ_{tw} of 1.24, with CO the only pollutant over the standard. Leaning to case 1 resulted in a ϕ_{tw} of 1.13, with corresponding reductions from baseline of 33 percent for CO and 26 percent for HC; NO_x increased by 105 percent. Additional leaning to case 2 resulted in a ϕ_{tw} of 1.10, with decreases from case 1 of 20 percent for CO and 7 percent for HC; NO_x increased by 45 percent. A narrow band of ϕ_{tw} (1.04 to 1.10) existed where all pollutants were below the EPA standard. However, this band was leaner than the uninstalled safety limits.

Figure 8-9 represents the emission levels for the TSIO-360C engine. This engine was the only engine tested that exhibited HC levels higher than the CO levels, as defined by the EPA standard. Fuel-air, cylinder-to-cylinder distribution is the predominant factor in the high hydrocarbon levels. A "runner" type of induction system coupled with short connecting tubes to the respective cylinder ports promotes variations in air distribution. Fuel distribution can also be affected by the oscillating flow within the short connecting tubes. Cylinder-head temperature variations tend to support this theory. Low-power, cylinder-head temperature variations are significantly larger for this engine than for the "spider" type of manifolds of the Tiara or GTSIO-520K engines. The baseline mixture schedule resulted in a ϕ_{tw} of 1.34, with both CO and HC well over the standards. The NO_x values were the lowest recorded of the five engines tested. Decreases of 51 percent for CO and 27 percent for HC were observed when the engine was leaned to a ϕ_{tw} of 1.19 (case 1); NO_x increased 630 percent but was still below the standard. Leaning to case 2, ϕ_{tw} of 1.10, resulted in a decrease from case 1 of 27 percent for CO and 31 percent for HC. But the NO_x emissions increased by 72 percent, resulting in a level exceeding the EPA standard. Leaning the TSIO-360C engine could not reduce all three pollutants below the EPA limits.

Figure 8-10 illustrates the emission levels associated with the GTSIO-520K engine. As in the case of the other geared engine (Tiara) the HC and NO_x levels were below the EPA standard for the three mixture

schedules tested. Carbon monoxide, however, could not be reduced below the limit while the engine was operating within the uninstalled safety limit. The baseline mixture schedule resulted in a ϕ_{tw} of 1.38, with CO the only pollutant over the EPA standard. Leaning to case 1 resulted in a ϕ_{tw} of 1.24, with corresponding reductions from baseline of 24 percent for CO and 14 percent for HC; NO_x increased by 219 percent. Additional leaning to case 2 resulted in a ϕ_{tw} of 1.08, with decreases from case 1 of 28 percent for CO and 24 percent for HC; NO_x increased by 57 percent. A narrow band of ϕ_{tw} (0.98 to 1.03) can be estimated where all pollutants are below the EPA standard; however, this band is leaner than the uninstalled safety limits.

With the stipulation that neither production tolerances nor the effect of engine cumulative operation time have as yet been established, the exhaust emissions levels presented thus far represent the pollutant levels associated with the three mixture-strength fuel schedules (baseline, case 1, and case 2).

Figures 8-11 to 8-15 represent the effect of modal equivalence ratio on CO, HC, and NO_x levels for each of the engines tested. Each figure illustrates the pollutant as a percent of the EPA standard as a function of modal equivalence ratio decrease from case 1. The curves clearly show the effects of each mode on the total cycle emission level as the modes are leaned beyond the lean limit of the engine model specifications. Case 1 was chosen as the starting point from which the leaning was referenced since leaning beyond case 1 has already been demonstrated as mandatory in order to reduce CO and HC to values below the EPA standard. Each modal curve has been identified with symbols that also locate two important points of reference, case 2 (flagged symbols) and the stoichiometric fuel-air ratio (closed symbols). The closed symbols represent the reduction in modal equivalence ratio required to provide a stoichiometric mixture and the corresponding emission level for the cycle. The flagged symbols represent the reduction in modal equivalence ratio required to lean to the uninstalled modal safety limit. Dashed lines are extrapolations of available data.

A significant amount of intelligent and useful information can be derived from these curves. From figure 8-11(a) the effect of modal leaning on CO for the O-200A engine can be determined. For example, if only the climb mode was leaned to case 2 ($\Delta\phi = 0.03$ decrease from case 1), the CO percent of the EPA standard would drop from 154 to 140 percent, or a change in reduction of 14 percent. Any combination of modal leaning can be predicted as illustrated in table 8-3, in which the taxi, climb, and approach modes are leaned to case 2. Note that the resultant CO emission level for this example is approximately equal to the case 2 value for the overall cycle (fig. 8-6). This can be rationalized by the relative effect that each mode has on the overall cycle results. Climb, approach, and taxi are the significant modes for CO reduction, while idle and takeoff have virtually no effect. Although climb and approach have the greatest effect on CO, taxi becomes the most promising mode for lean-

ing when consideration is given to the case 2 uninstalled safety limits. This conclusion is further supported when modal leaning effects on HC are analyzed (fig. 8-11(b)). However, figure 8-11(c) shows that a penalty must be accepted when consideration is given to the resulting NO_x levels.

Figure 8-12 represents the modal leanout effects for the IO-520D engine. The predominant modes for CO reduction were again climb and then approach. The taxi mode had little effect, as opposed to the O-200 results. Leaning the climb mode alone will bring the IO-520D engine within the CO limits if the modal installed safety limit can be leaned below the present uninstalled safety limit. This fact will be pursued later during the analysis of our flight test results.

Figure 8-13 illustrates the effect of modal leaning for the Tiara 6-285B engine. Since the hydrocarbons were below the standard for all fuel schedules tested, the modal leanout trade-off affects only CO and NO_x. In case 2, the only practical mode for leanout adjustments is climb, which comes very close to meeting the standard. Some additional reduction can be attained by leaning the approach mode.

The TSIO-360C modal leanout curves are presented in figure 8-14. Again, the climb mode is the most promising mode for CO reduction; however, taxi is the only mode for consideration for HC reduction. Leaning both climb and taxi to case 2 will significantly reduce CO and HC; however, HC and NO_x will still be over the EPA standard.

From figure 8-15 the GTSIO-520K engine resembles the results of the other geared engine, Tiara, in that HC and NO_x are within the limits and climb is the predominant mode affecting CO reduction.

FLIGHT TEST RESULTS

The modal leanout curves present a detailed picture of what is possible in modal leaning below the present engine fuel flow specifications (case 1). To determine what reductions are possible, the difference between uninstalled and installed safety limits must be understood. To accomplish this, TCM modified fuel systems to simulate the mixture strength schedules of case 1 and case 2. Leaned systems were delivered to Cessna for the O-200A to be flight tested in the Cessna 150 and for the TSIO-360C to be flight tested in the Cessna T337. Rockwell International received leaned systems for the GTSIO-520K to be flight tested in the Aero Commander 685. Under the NAFEC contract, TCM conducted flight testing on the IO-520 engine installed in a Cessna 210.

Separate reports by Cessna will cover the results of the O-200A and TSIO-360C flight tests. For completeness of this report, however, a brief summary of the results is given in table 8-4. To date, flight tests have not been conducted on the GTSIO-520K engine.

Teledyne Continental flight tested the IO-520D engine on the base-
line and case 2 mixture-strength schedules as defined in figure 8-2. The
case 1 mixture schedule would be tested only if flight test results indi-
cated problems with case 2. Determining the effect of climatic con-
straints, 0° to 100° F ambient temperature, was considered mandatory dur-
ing the flight tests. Cold weather testing was conducted at Fargo, North
Dakota; hot weather testing was conducted at Del Rio and Laredo, Texas.
Instrumentation consisted of an oscillograph that recorded manifold pres-
sure, fuel flow, engine speed, and throttle position. A temperature
strip-chart recorder monitored the six cylinder heads as well as the ex-
haust gas, inlet and exit cooling air, induction air, ambient air, fuel,
and oil temperatures. Additional data logged manually consisted of
cooling-air differential pressure, pressure altitude, indicated and ver-
tical airspeed, oil pressure, fuel pump pressure, fuel metered pressure,
cowl flap position, wing flap position, and mixture control position.

As discussed previously, cylinder-head overheating was the unin-
stalled safety limit encountered for the climb and takeoff modes; inade-
quate acceleration defined the uninstalled safety limit for the idle,
taxi, and approach modes. Figure 8-16 depicts a cold weather (30° F)
acceleration test for the baseline fuel schedule. The curves represent
manifold absolute pressure, engine rpm, and fuel flow as a function of
time. The acceleration test was an instantaneous throttle burst from
idle. Note that engine speed immediately responded from zero time; and
after 3.4 seconds had elapsed, the engine had attained full speed and
fuel flow. Figure 8-17 illustrates a cold weather (30° F) throttle burst
from idle for the case 2 fuel schedule. As in the preceding example,
manifold pressure peaked in less than a second; however, engine speed
and fuel flow began to rise but then decreased. The engine would con-
tinue to run at this low speed until the throttle was brought back to
idle and then slowly moved to the full-throttle position.

At 30° F ambient temperatures, no acceleration problems occurred for
the taxi or approach modes. Further testing at 0° F was therefore manda-
tory as colder inlet conditions will produce leaner fuel-air ratios since
the present fuel-injection system is not temperature compensating. Suit-
able environmental conditions could not be found, and as a result TCM
funded rental time at the Eglin Air Force Base climatic hangar. The
Eglin climatic hangar has the capability of maintaining 0° F and a wind
velocity simulating the approach mode. Results at 0° F for the baseline
fuel schedule were acceptable; however, case 2 acceleration from taxi and
idle was impossible as the engine would not operate at those fuel flows.
Acceleration from the simulated approach mode was acceptable for the
case 2 fuel system. As expected, no cylinder-head overheating occurred
during any of the cold ambient testing. Hot weather testing was con-
ducted near Del Rio and Laredo, Texas, in order to provide the required
100° F ambient conditions. With the less-dense induction air (richer
mixture), no acceleration problems occurred for baseline or case 2 fuel
schedules at idle, taxi, or approach.

Figure 8-18 depicts the case 2 fuel schedule results for the cooling climb tests at both cold- and hot-day conditions. The maximum and minimum cylinder-head temperatures, as well as the outside air temperatures, are plotted as a function of pressure altitude. A maximum cylinder-head temperature of 395° F occurred during the hot-day testing, well within the model specification limit. The case 2 fuel schedule at takeoff and climb was therefore acceptable.

The uninstalled safety limits are compared with the actual flight tests in table 8-5. Case 2, as defined earlier, is the fuel flow rate corresponding to the leanest fuel-air ratio obtainable before a safety limit occurred with the engine operating on a propeller test stand. Fuel flow rate was the parameter defining case 2 since the present fuel systems do not meter as a function of fuel-air mass ratio. The carbureted system meters fuel by sensing induction-air pressure drop across the venturi and ambient pressure (float bowl). The present, continuous-flow, fuel-injection system controls fuel flow in response to changes in throttle plate angle and engine speed. Compressor discharge pressure is also referenced on turbocharged engines. Temperature, and therefore air density, is not a controlling factor. It is not surprising therefore that the flight test results differ from the uninstalled-safety-limit (case 2) results.

Using the IO-520 data in table 8-5 as an example, all modes exhibiting an acceleration safety limit, except approach, became more of a hazard as temperature decreased, indicating leaner fuel-air ratios than case 2. The simulated approach made at 0° F temperature did not exhibit an acceleration problem. This was probably due to the windmilling effect of the high-velocity air across the propeller blades, which aids the engine in accelerating during a closed-throttle approach. As predicted, cylinder-head overheating did not occur in the takeoff and climb modes for the IO-520 installation. However, this was not true for the TSIO-360C installation. Reliable projections of uninstalled cooling data to actual installations will require a detailed understanding of the cooling air distribution for each installation. However, since climb operation may be conducted at speeds higher than the best-rate-of-climb speed, it is feasible to predict a mixture strength at climb leaned to case 2. The takeoff mode, as discussed previously, has little or no effect on the emission levels and therefore should be set at baseline. Case 2 can therefore be defined as the installed safety limits for the IO-520/Cessna 210 and TSIO-360C/Cessna T337 installations, provided the present fuel-injection system is modified to schedule fuel-air ratio and provided the airframe manufacturer can accept (if necessary) a performance penalty during climb.

Analysis of the flight tests and emission data led to the following conclusions:

(1) Baseline fuel schedules for the engines tested do not meet the EPA exhaust emission standards.

(2) Case 1 fuel schedules for the engines tested do not meet the EPA exhaust emission standards.

(3) Case 2 fuel schedules for the IO-520D and Tiara 6-285B engines met the EPA exhaust emission standards.

(4) Case 2 fuel schedules for the O-200A, TSIO-360C, and GTSIO-520K engines do not meet the EPA exhaust emission standards.

(5) Individual modal leaning should be restricted to the climb, approach, and taxi modes.

(6) Carbon monoxide contribution occurs principally during the climb mode.

(7) Hydrocarbon contribution occurs principally during the taxi mode.

(8) Approach mode is the second largest contributor to carbon monoxide and hydrocarbon emissions.

(9) Uninstalled engine safety limits (case 2) differ from installed engine safety limits.

POSSIBLE EMISSION REDUCTIONS

The flight test results presented the problems associated with leaning the present fuel systems to the case 2 fuel schedule. Some modes could be leaned to the case 2 fuel schedule; others could be leaned between case 1 and case 2. Using the IO-520 engine as an example, each mode can be analyzed for possible emissions reductions. In the idle and taxi modes the mixture-strength ratio is limited to that which permits safe transient response. The leanest fuel-air ratio will occur on a cold day. Leaning below case 1 was impossible for the idle mode. However, leaning below case 1 was possible in the taxi mode, resulting in a $\Delta\phi$ of 0.07, approximately halfway between case 1 and case 2. Takeoff has an insignificant effect on emissions and therefore will not be leaned out. Climb and approach could be leaned to the case 2 fuel schedule.

A total reduction from case 1 of 31 percent for CO and 19 percent for HC can be predicted (fig. 8-12). Oxides of nitrogen will increase by 81 percent but remain well below the limit. In terms of the EPA limits, CO, HC, and NO_x will be 86, 78, and 54 percent of the standard. Applying the production tolerance band, resulting from the baseline - case 1 fuel schedules (fig. 8-2), to the minimum installed fuel schedule reveals the nominal emission levels that can be expected:

Fuel schedule	Emission level, percent of EPA standard		
	CO	HC	NO_x
Minimum	86	78	54
Nominal	150	115	24
Baseline	189	119	14

These projections do not consider any engine-to-engine production toler-ances or the effect of engine cumulative time. The differences between the nominal and baseline levels represent the reductions possible by modal leaning within the installed safety limits for the IO-520D/Cessna 210 installation. A similar analysis can be made for the TSIO-360C engine. Approach could be leaned to case 2. Climb, although not veri-fied as yet, will be leaned to case 2 for the purpose of this analysis by increasing the aircraft's rate-of-climb speed.

From figure 8-14 a total reduction from case 1 of 21 percent for CO and 2 percent for HC can be expected. Oxides of nitrogen will increase by 71 percent, resulting in absolute percent of EPA standards of 91 for CO, 177 for HC, and 109 for NO_x. Applying the baseline - case 1 fuel schedule tolerance band (fig. 8-4) results in the following emission levels:

Fuel schedule	Emission level, percent of EPA standard		
	CO	HC	NO_x
Minimum	91	177	109
Nominal	207	240	12
Baseline	234	246	9

Again, engine-to-engine production tolerances and the effect of engine cumulative time were not considered. Nominal and baseline differences represent the reduction possible by modal leaning within the projected installed safety limits for the TSIO-360C/Cessna T337 installation.

Based on these examples, it does not appear practical to pursue individual modal leaning for each engine presently in production. The time involved to flight test, modify, and recertify all production engines will delay development of more significant emissions reduction concepts.

DISCUSSION

Q - G. Kittredge: The main thing that struck me with your presentation, compared to the preceding two by AVCO and NAFEC, is that the engines you are talking about include several which would be drastically affected if EPA were to go ahead with the tentative plans to eliminate the NO_x and HC standards. You did have several engines where they were the limiting pollutants?

A - B. Rezy: Yes, that is right.

Q - W. Westfield: George, I have to direct this to you and also to Bernie. Are you referring to Bernie's statement about 630 percent increase in NO_x for one case?

A - G. Kittredge: Yes.

Q - W. Westfield: Is a percentage term the right term to use in this case or should we be talking absolute numbers?

A - B. Rezy: I think he's talking absolute numbers. We've indicated that we went over the limits as we leaned out.

Q - W. Westfield: I realize that, but you're 630 percent over baseline which was well under. So you're talking 630 percent of a very small number.

A - L. Helms: The initial curves that you presented showed baseline, case 1 and case 2, where case 2 was identified as the uninstalled safety limit. There were several cases there where it appeared the uninstalled safety limit was equivalent to the lean production. Is that right?

A - B. Rezy: It was very close to the lean production limit.

Q - L. Helms: On your cold weather tests, could you tell me how you did those? Specifically, did you start the engine, warm it up, then make the adjustments and make the test runs?

A - B. Rezy: Yes, that is correct.

Q - L. Helms: At any time did you try to start the engine with the modified fuel metering system?

A - B. Rezy: Yes, we did try and it would not start. We had to heat the engine to get it to start. Once we could get it started, we then conducted our tests. That's at 0°.

Q - G. Kittredge: In your cold weather testing, you identified several conditions where you had acceleration problems. How fundamental do you feel these problems are? Are they solvable with a reasonable amount of developmental effort or are they basic to the fixed design of the engine?

A - B. Rezy: We feel that if you can hold fuel-air ratio, which these present fuel injection systems cannot in the idle/taxi modes, you then could run at those conditions. That does not include any production tolerances. We don't know what the true emission level would be if

we had a fuel injection system that could control the fuel-air ratio in the idle/taxi modes.

Q - G. Kittredge: With the experience that you now have, do you feel you are getting good data using the emission test procedures that have gradually evolved over the 3 years of experience that you have?
A - B. Rezy: Yes.

COMMENT - W. Westfield: On the first chart of your conclusions you said that none of the engines could meet the limit at case 1, but then the next thing you said was two engines could meet the limit at case 2.

A - B. Rezy: That's true, case 2 is leaner than case 1.

TABLE 8-1

ENGINE MODEL	O-200 A	TSIO-360 C	TIARA 6-285 B	IO-520 D	GTSIO-520 K
RATED BHP	100	225	285	300	435
DISPLACEMENT CU. IN.	201	360	406	520	520
PROPELLER RPM	2700	2800	2000	2850	2267
CARBURETED	●				
FUEL INJECTED		●	●	●	●
DIRECT DRIVE	●	●		●	
GEARED			●		●
TURBOCHARGED		●			●

TABLE 8-2

MODE NO.	MODE NAME	WEIGHTED TIME IN EACH MODE (Minutes)	ENGINE CONDITIONS Percent Power	Propeller Speed
1	Idle Out	1.0	-	600 RPM
2	Taxi Out	11.0	-	1200 RPM
3	Take-Off	0.3	100%	100% of Max. RPM
4	Climb	5.0	80%	90% of Max. RPM
5	Approach	6.0	40%	87% of Max. RPM
6	Taxi In	3.0	-	1200 RPM
7	Idle In	1.0	-	600 RPM
TOTAL		27.3		

TABLE 8-3

MODE	EMISSION LEVEL AT CASE 2 (Percent of EPA Standard)	DELTA REDUCTION IN EMISSION LEVEL FROM CASE 1 (Percent of EPA Standard)
Taxi	118.	36.
Climb	140.	14.
Approach	145.	9.
	$\sum$DELTAS =	59.

$$\begin{bmatrix} \text{Resultant Percent} \\ \text{of EPA Standard} \end{bmatrix} = \begin{bmatrix} \text{Percent of} \\ \text{EPA Standard} \\ \text{at Case 1} \end{bmatrix} - \sum\text{DELTAS}$$

$$= 154\% - 59\% = 95\%$$

TABLE 8-4

ENGINE	FUEL SCHEDULE	COMMENTS	
0-200A	Case 1	Acceptable for all conditions. Minor backfiring during throttle closure	
	Case 2	Unacceptable, engine would not operate below 1700 rpm and cylinder overheating occurred. Unsafe for flight tests	
TSIO-360C	Case 1 The fuel schedule for Case 1 was slightly leaner than the desired schedule	Idle-Taxi	- exhibited some roughness, acceleration marginally acceptable
		Take-Off	- cylinder overheating
		80% Climb	- cylinder head temperature would be over limit if corrected to a 100°F day
		40% Approach	- acceleration acceptable
		Closed Throttle Approach	marginally acceptable, minor engine - stumble on simulated go-arounds
TSIO-360C	Case 2	Idle-Taxi	- engine rough, acceleration was poor
		Take-Off	- not evaluated since Case 1 already exhibited cylinder overheating
	Case 2	80% Climb	- exceeded cylinder head temperature limit without 100°F ambient day correction.
		40% Approach	- acceleration acceptable
		Closed Throttle Approach	- unacceptable acceleration, engine died on occasion

TABLE 8-5

Engine/Aircraft Mode	Case 2 Mixture Schedule Uninstalled Safety Hazard	Case 2 Mixture Schedule Installed Safety Results
0-200A/Cessna 150		Unacceptable engine operation, unsafe for flight tests
Idle	Acceleration Limit	
Taxi	Acceleration Limit	
Take-Off	Cylinder Head Limit	
Climb	Cylinder Head Limit	
Approach	Acceleration Limit	
TSIO-360C/Cessna T337		
Idle	Acceleration Limit	Engine rough, poor acceleration
Taxi	Acceleration Limit	Engine rough, poor acceleration
Take-Off	Cylinder Head Limit	Not evaluated since Case 1 at cylinder head limit
Climb	Cylinder Head Limit	Exceeded cylinder head temperature
40% Approach	Acceleration Limit	Acceleration acceptable
Closed Throttle Approach	Acceleration Limit	Unacceptable acceleration, engine died on occasion
IO-520/Cessna 210		Engine would not accelerate at 30° F
Idle	Acceleration Limit	Engine would not operate to Case 2 idle fuel flows at 0° F
Taxi	Acceleration Limit	Engine would not operate to Case 2 taxi fuel flows at 0° F
Take-Off	Cylinder Head Limit	Cylinder head temperature within limits
Climb	Cylinder Head Limit	Cylinder head temperature within limits
40% Approach	Acceleration Limit	Simulated approach at 0° F was acceptable
Closed Throttle Approach	Acceleration Limit	Simulated approach at 0° F was acceptable
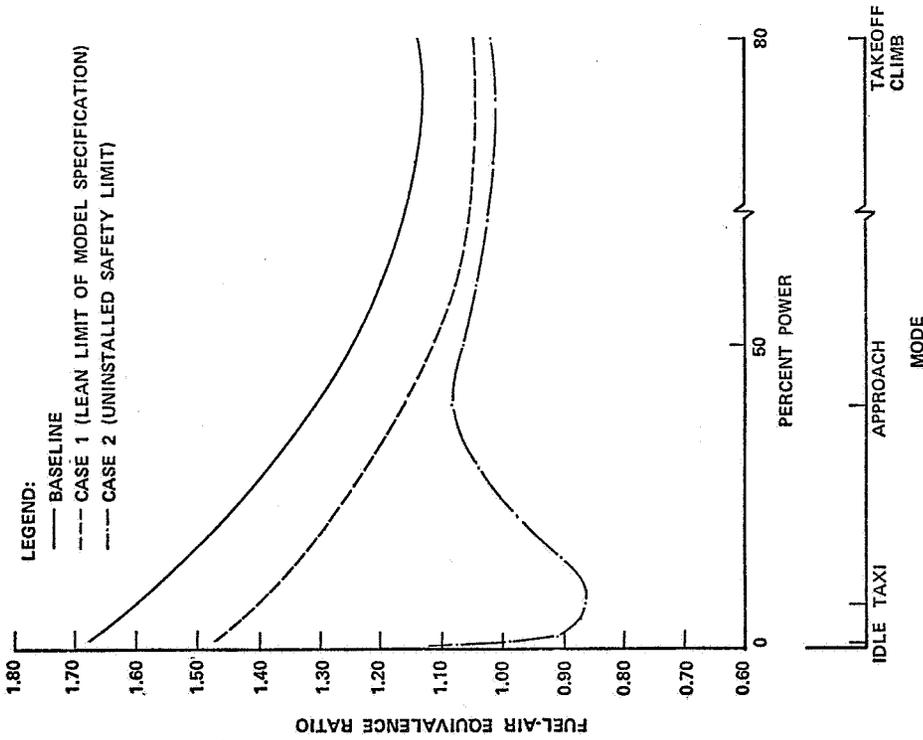
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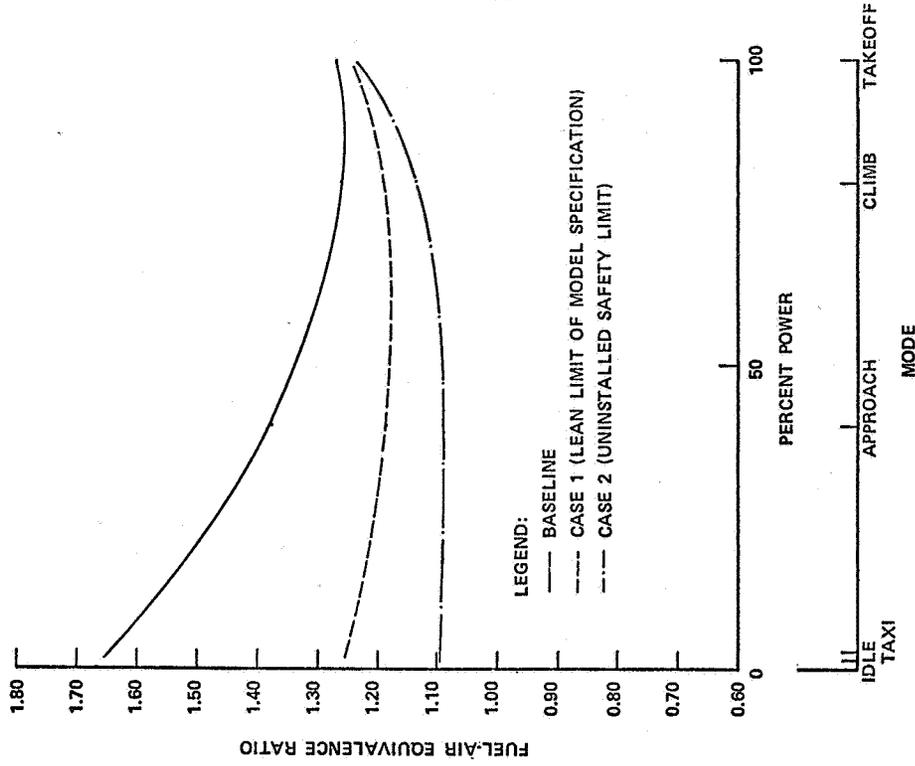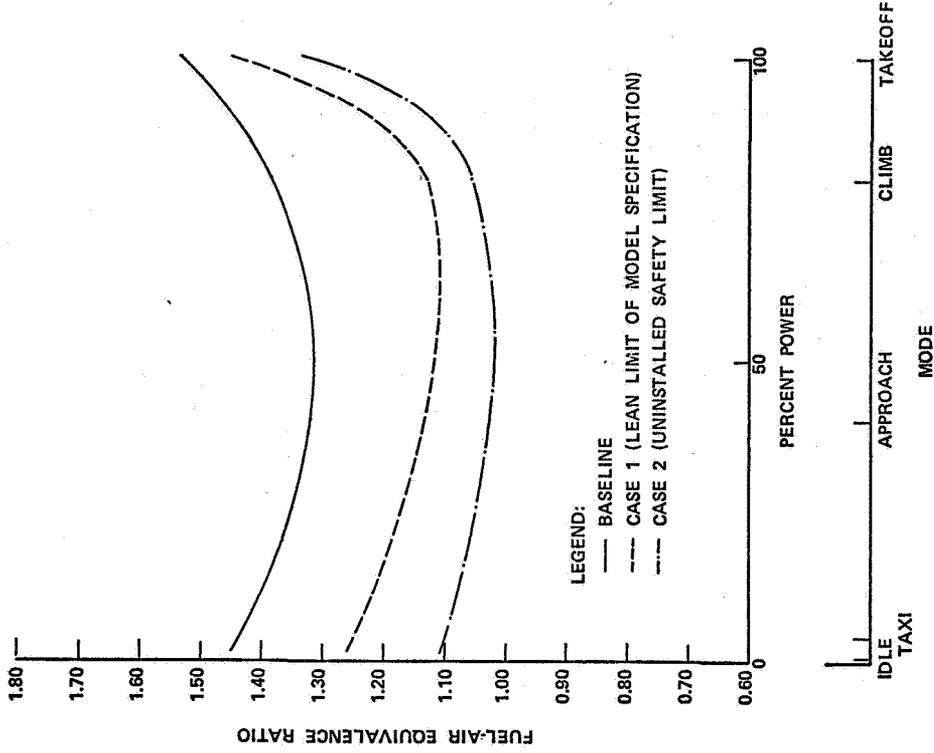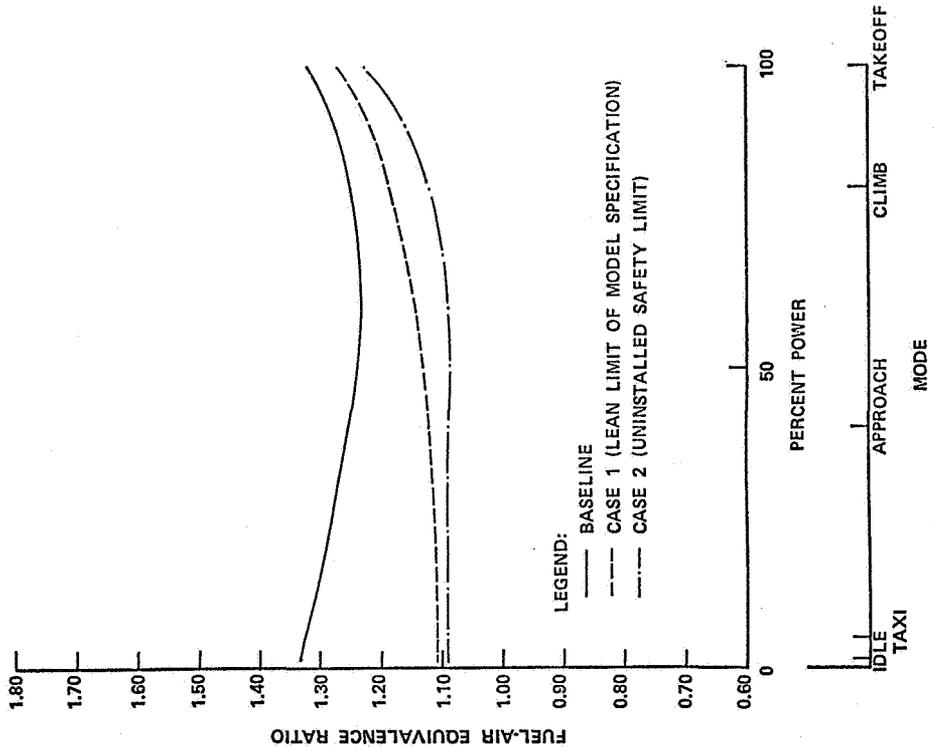
Figure 8-1

Figure 8-4

Figure 8-3
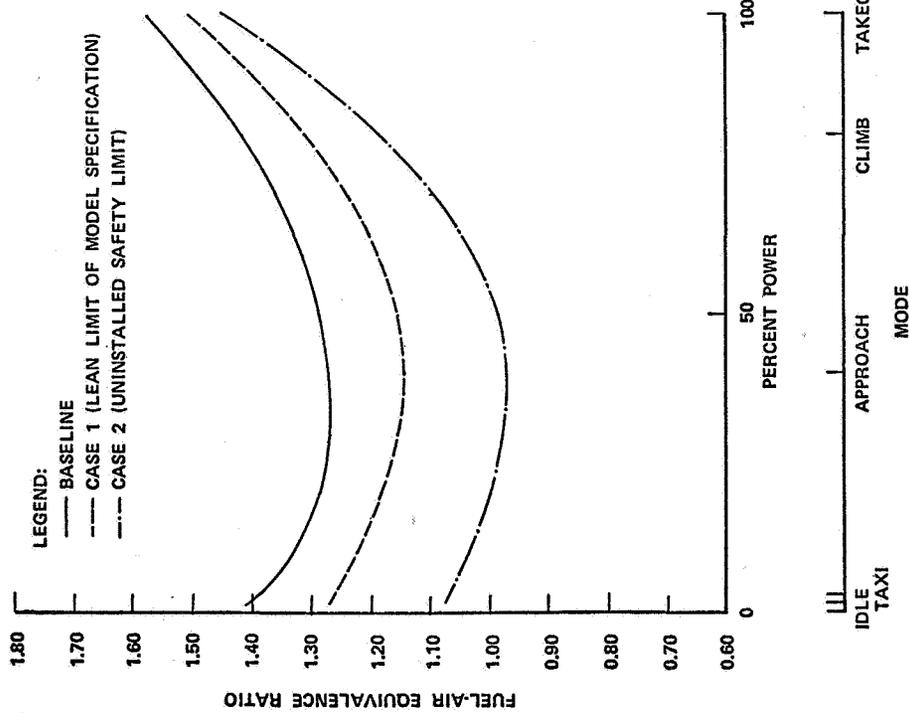
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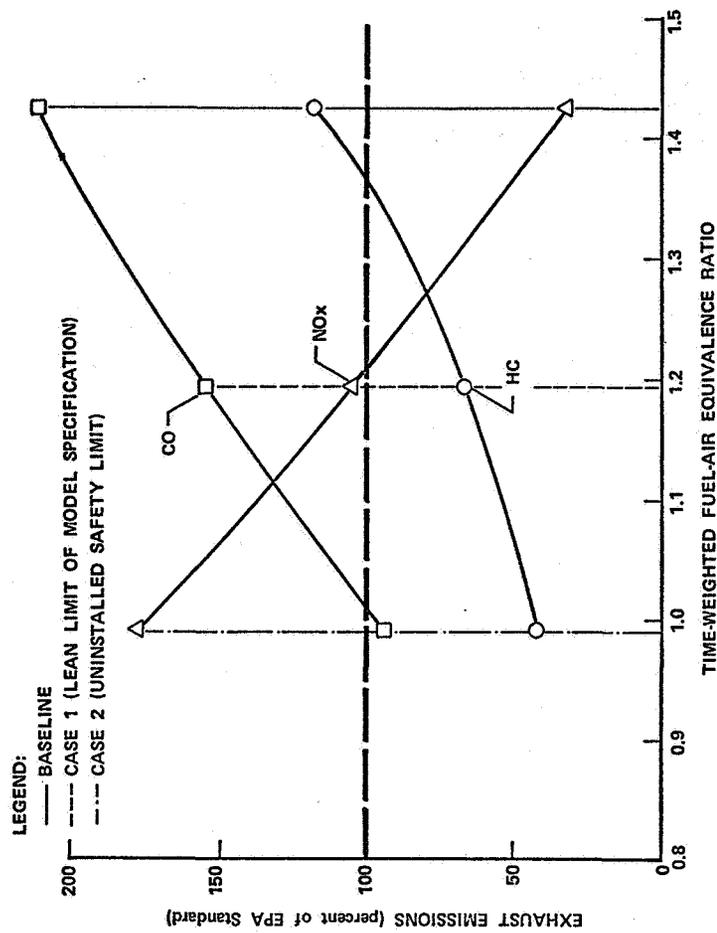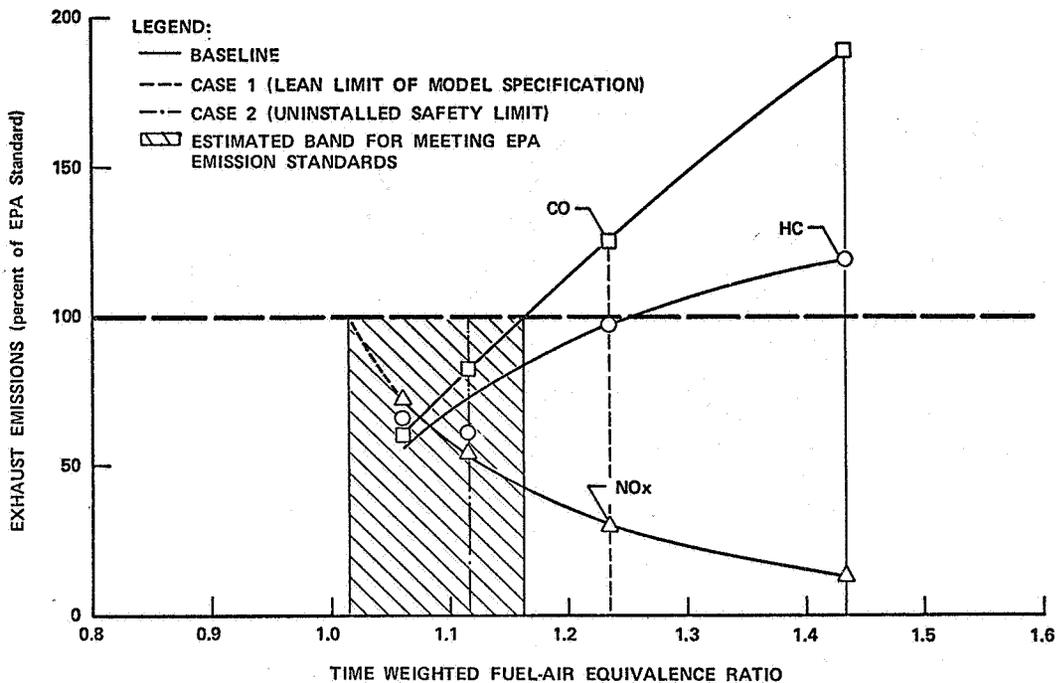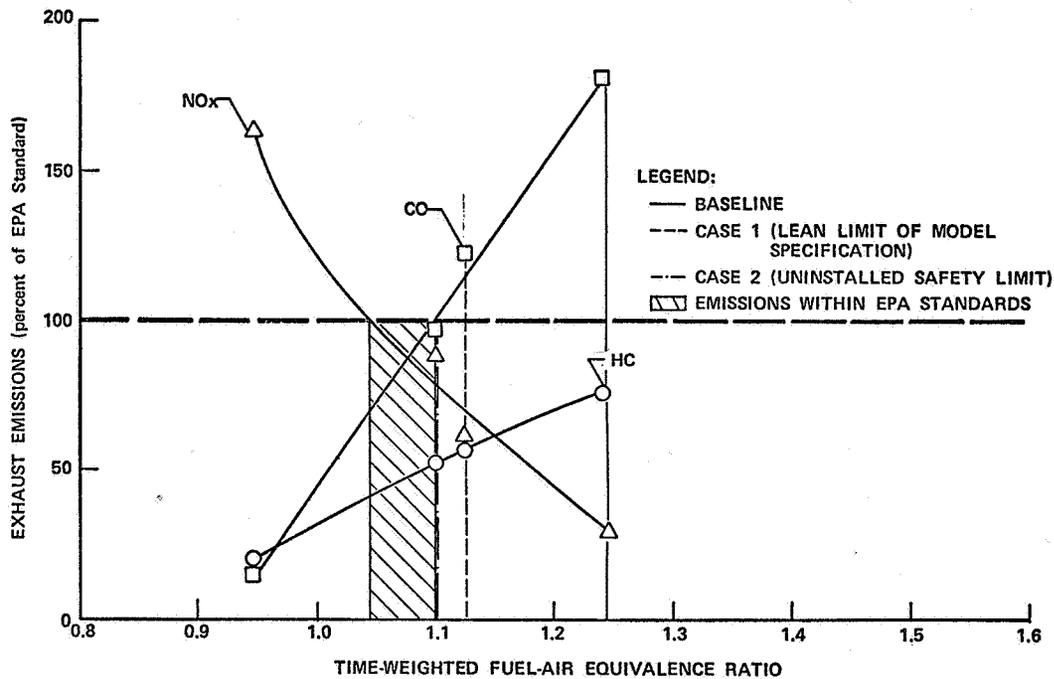
Figure 8-5

Figure 8-7

Figure 8-8
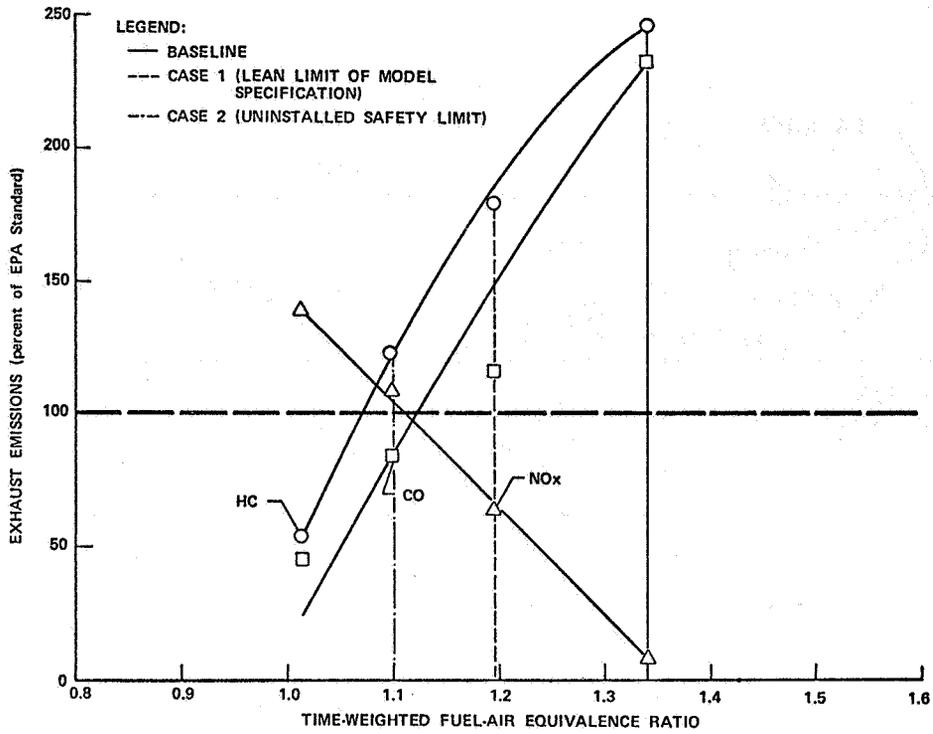
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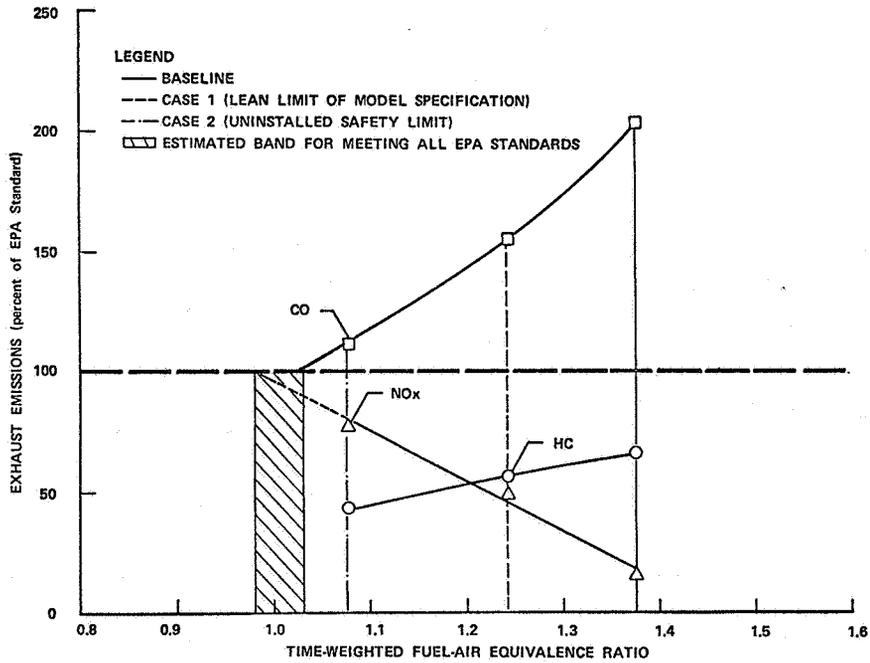
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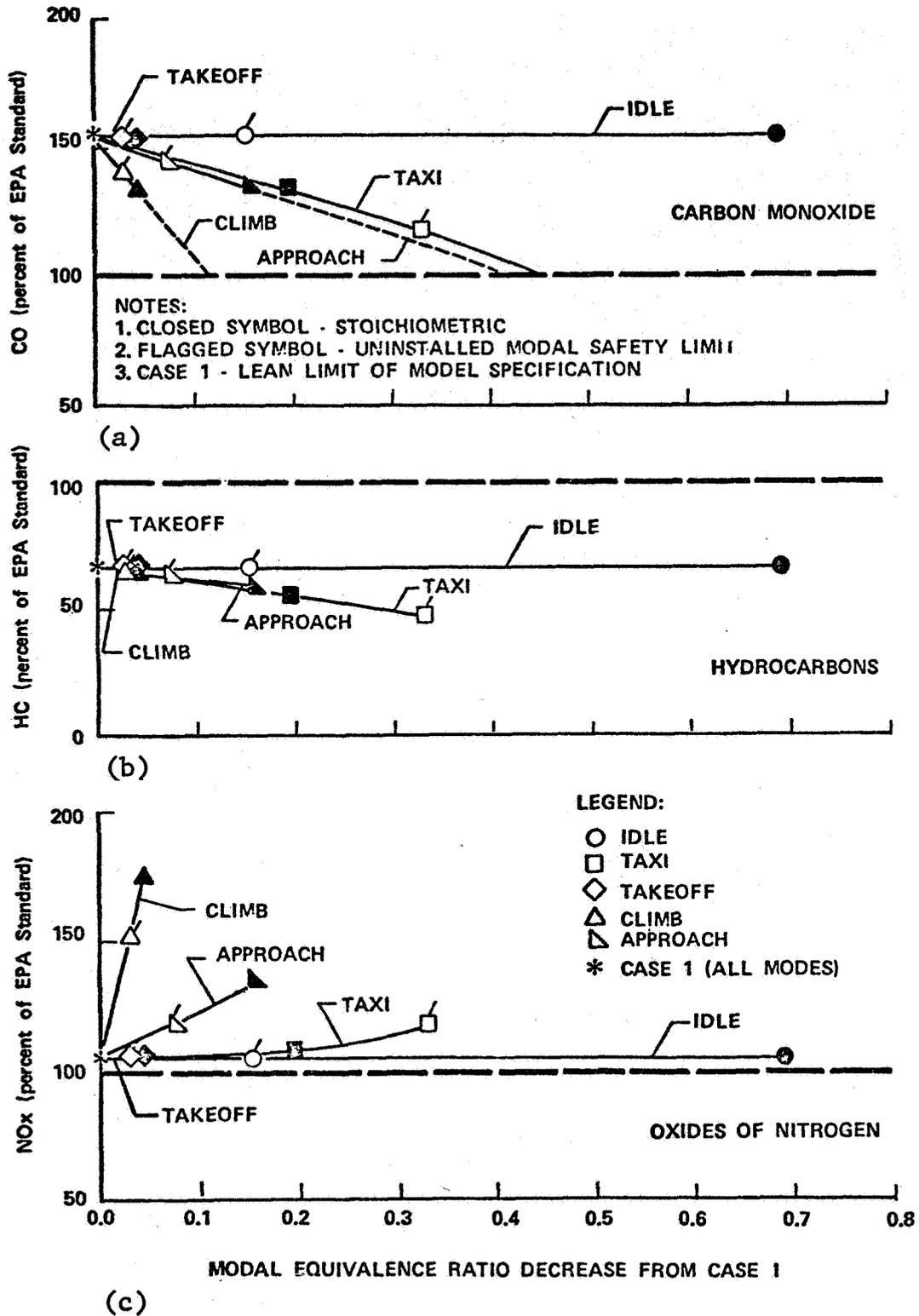
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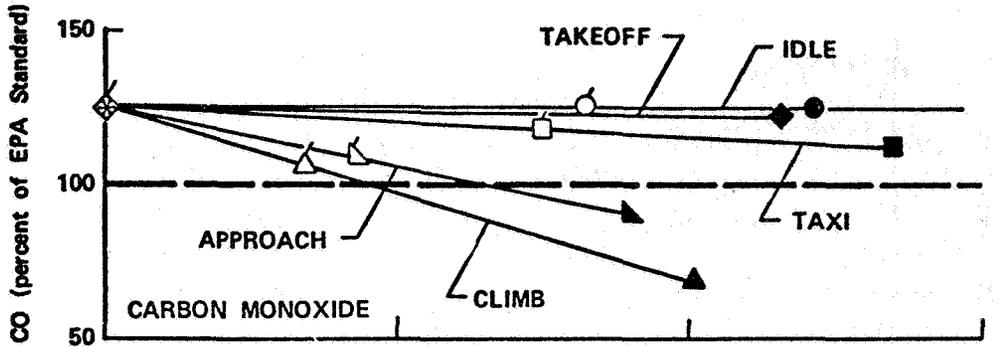
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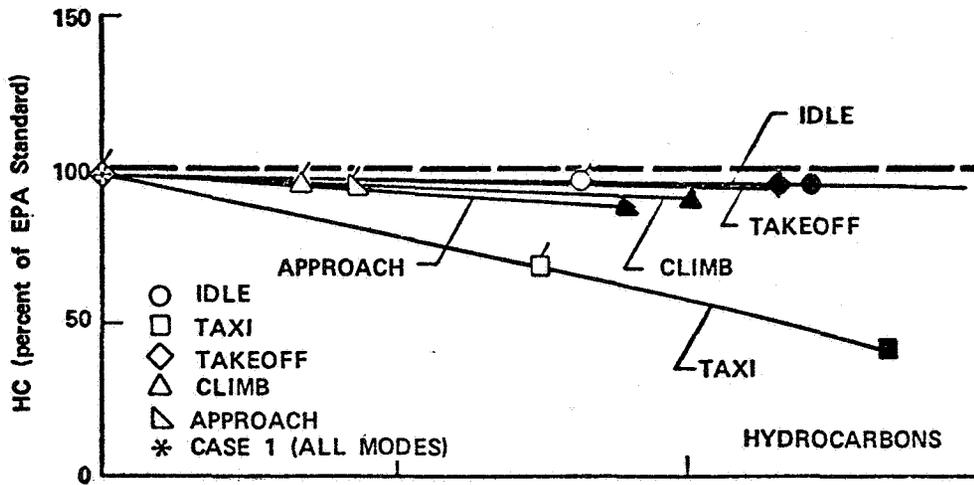
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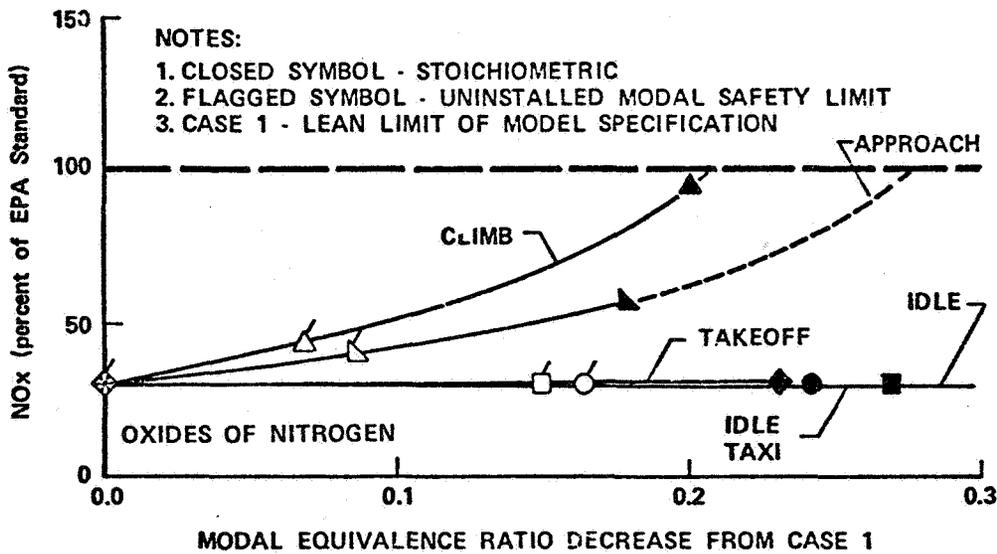
(c)

Figure 8-12

(a)

NOTES:
1. CLOSED SYMBOL - STOICHIOMETRIC
2. FLAGGED SYMBOL - UNINSTALLED MODAL SAFETY LIMIT
3. CASE 1 - LEAN LIMIT OF MODEL SPECIFICATION

(b)

LEGEND:
○ IDLE
□ TAXI
◇ TAKEOFF
△ CLIMB
◁ APPROACH
✳ CASE 1 (ALL MODES)

(c)

Figure 8-13

(a)

(b)
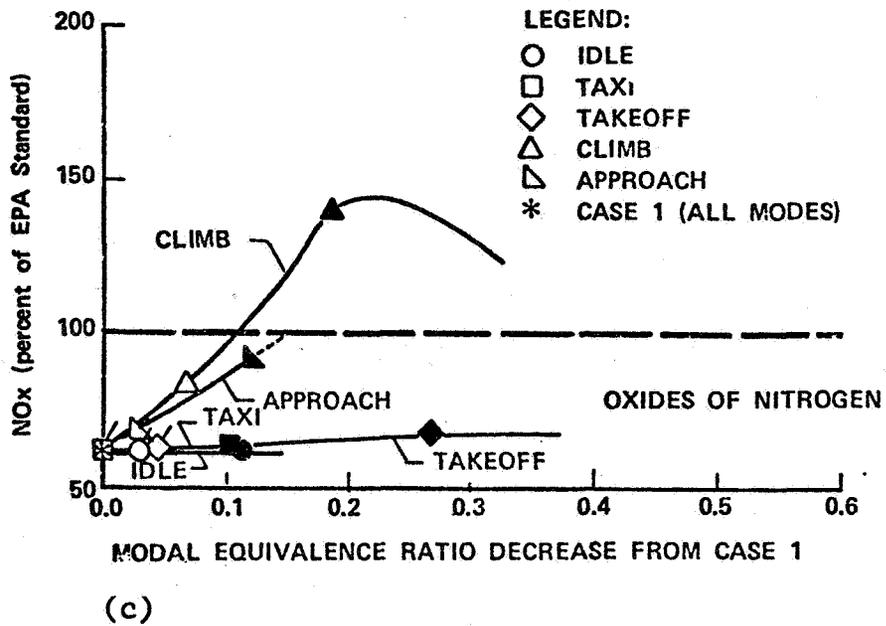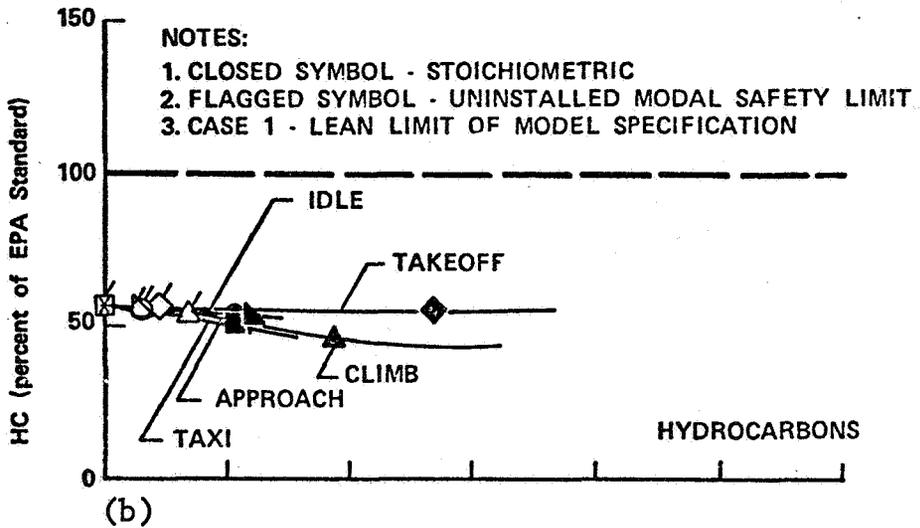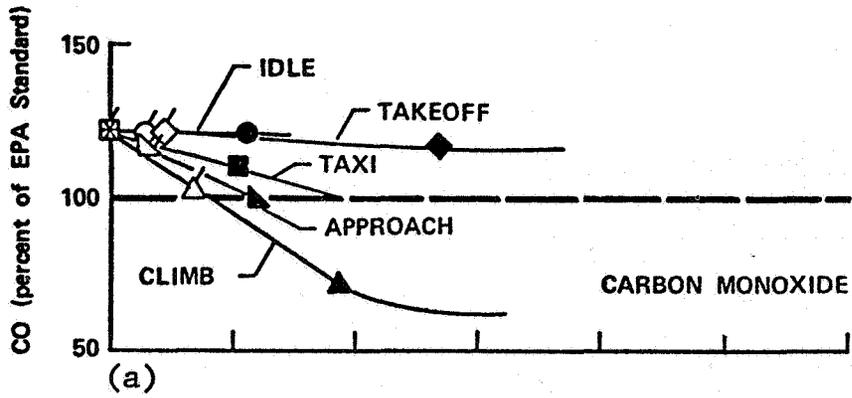
NOTES:
1. CLOSED SYMBOL - STOICHIOMETRIC
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3. CASE 1 - LEAN LIMIT OF MODEL SPECIFICATION

LEGEND:
○ IDLE
□ TAXI
◇ TAKEOFF
△ CLIMB
◺ APPROACH
✳ CASE 1 (ALL MODES)

(c)
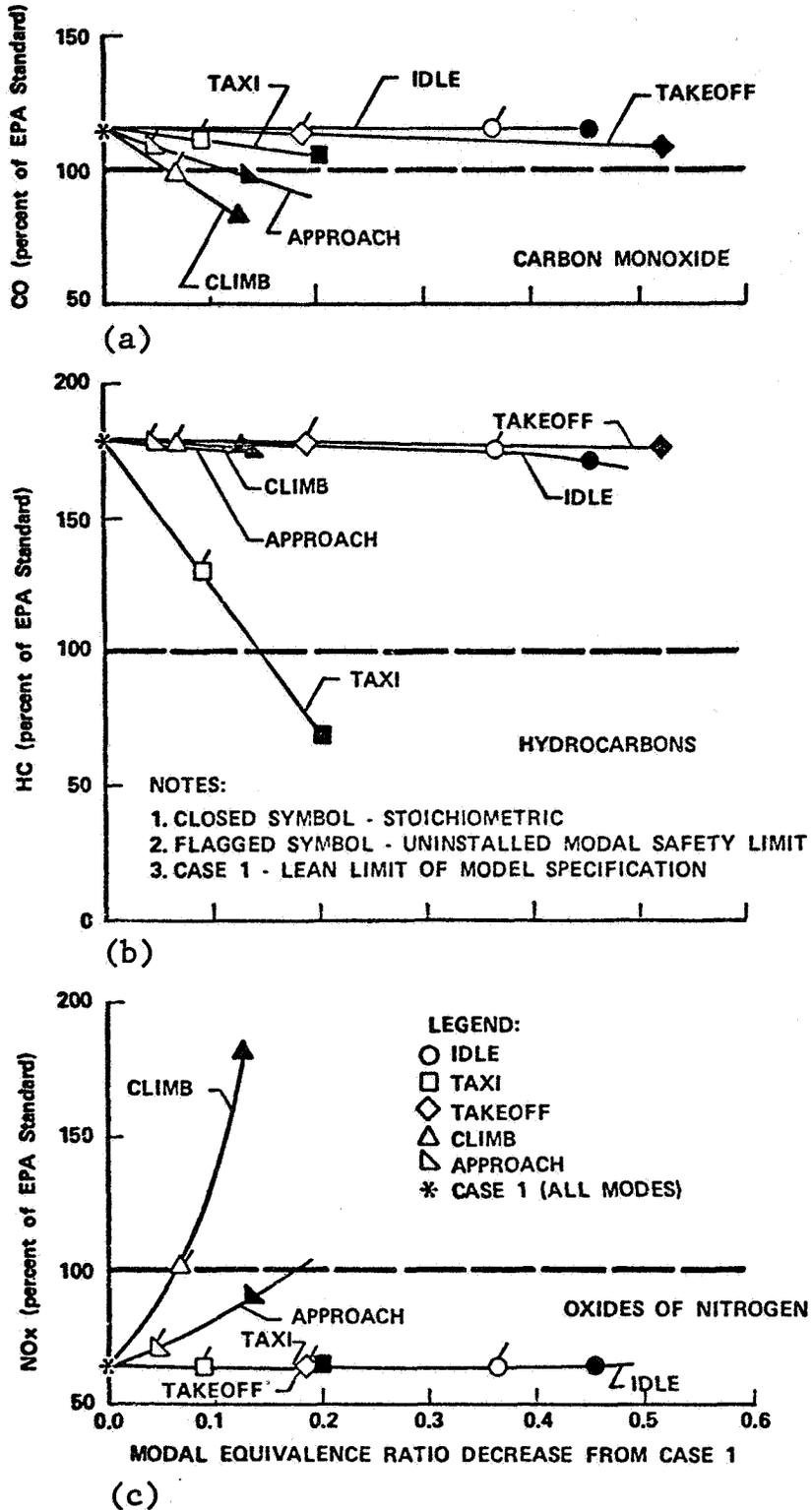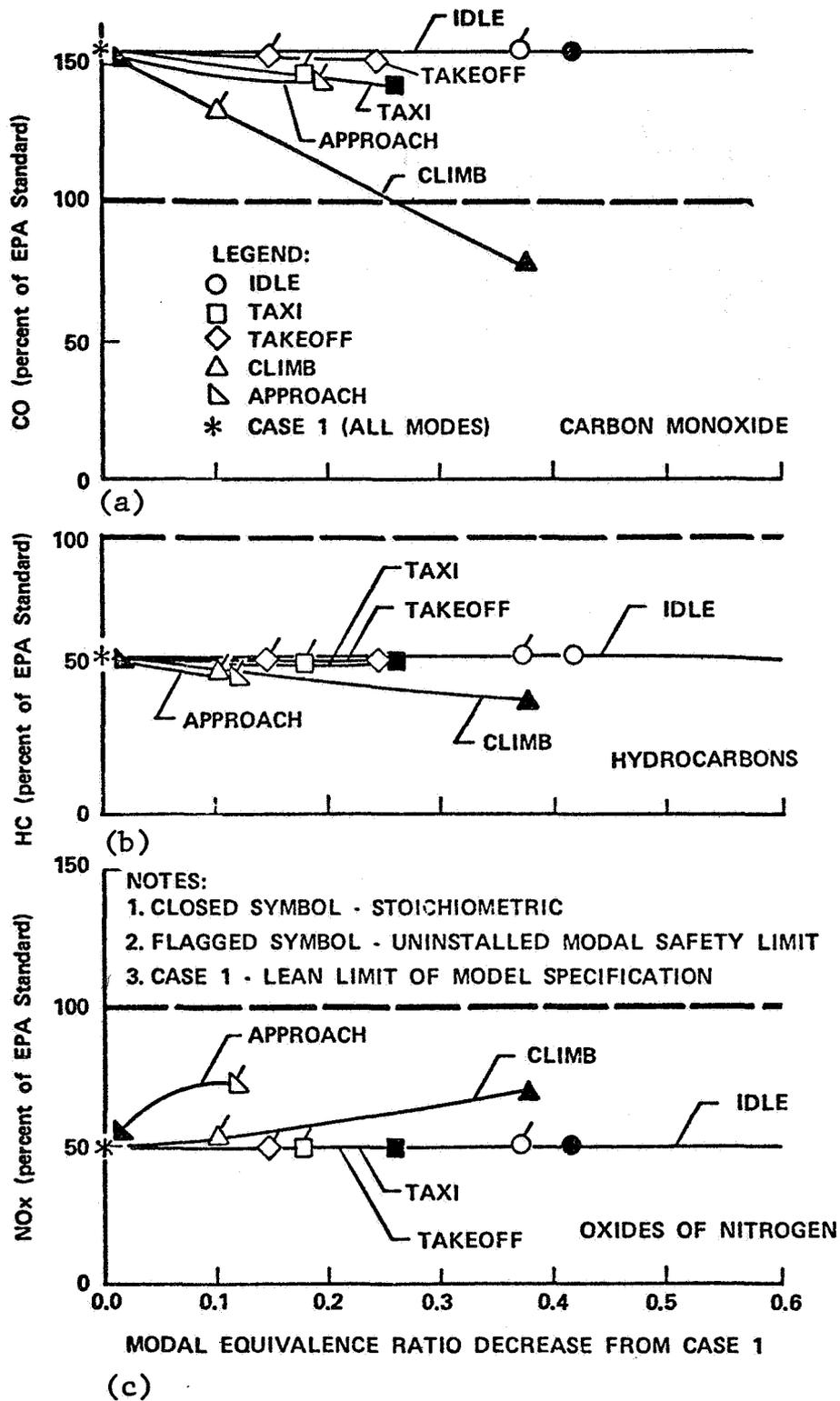
Figure 8-14

Figure 8-15
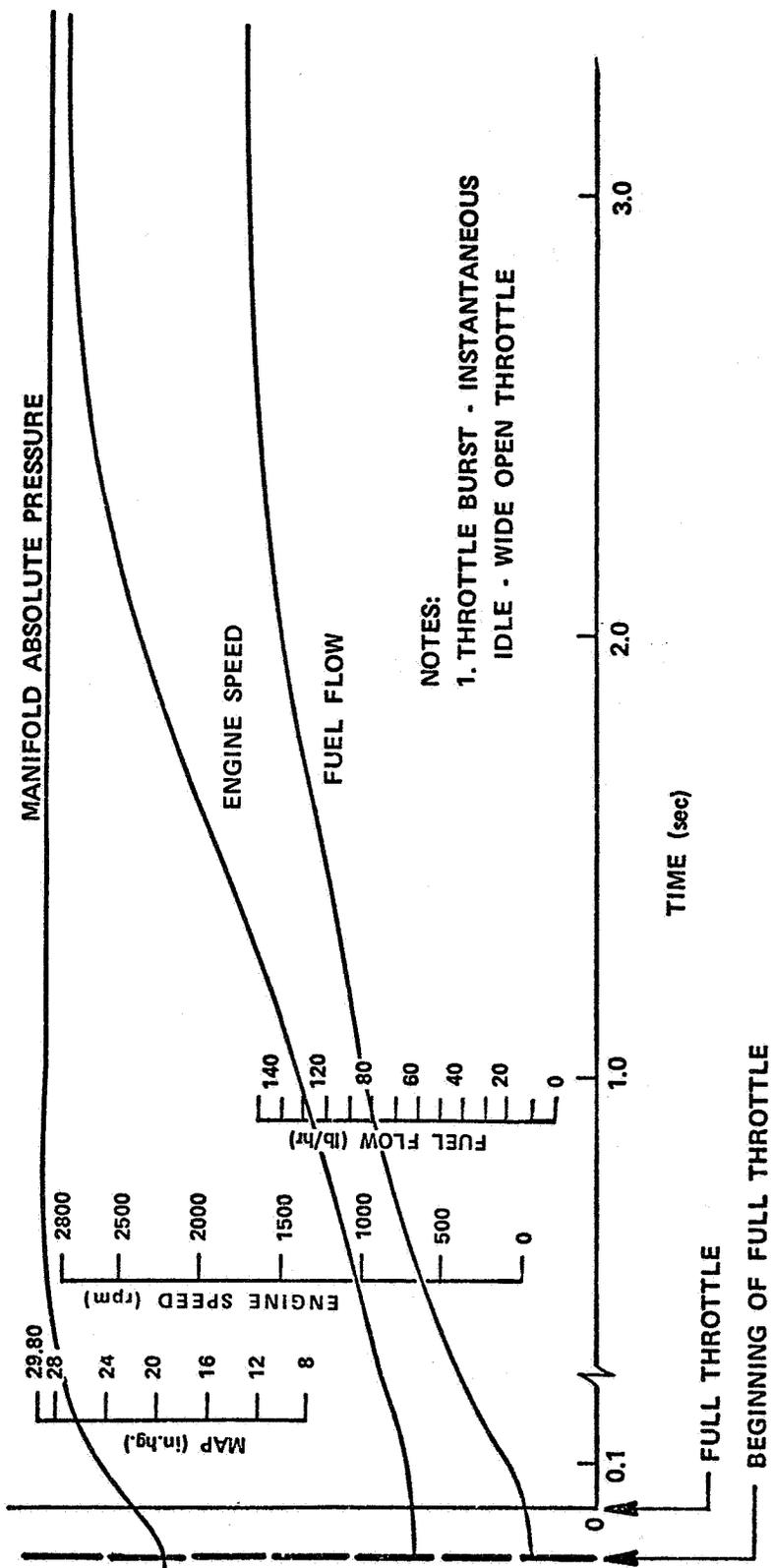
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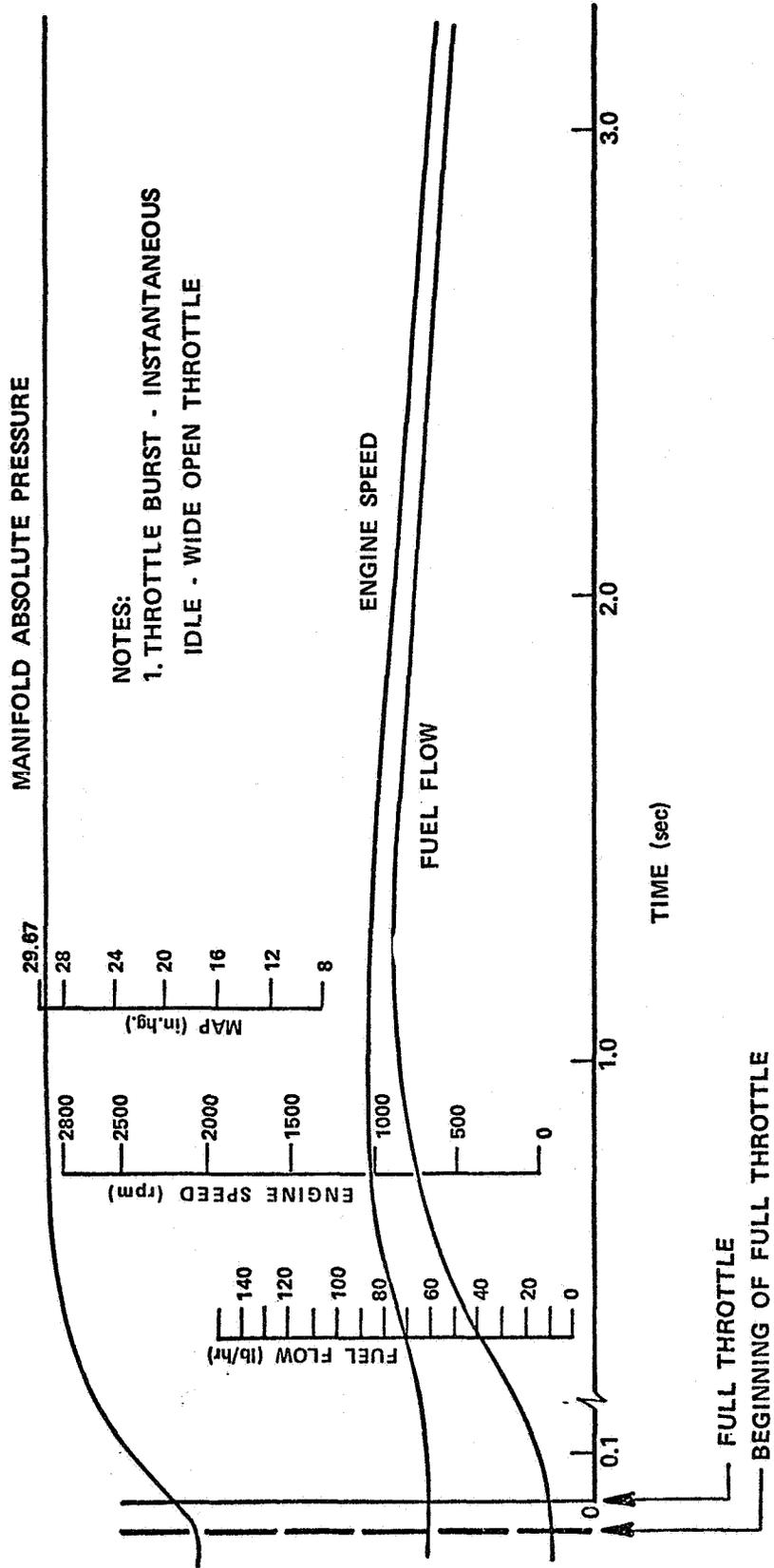
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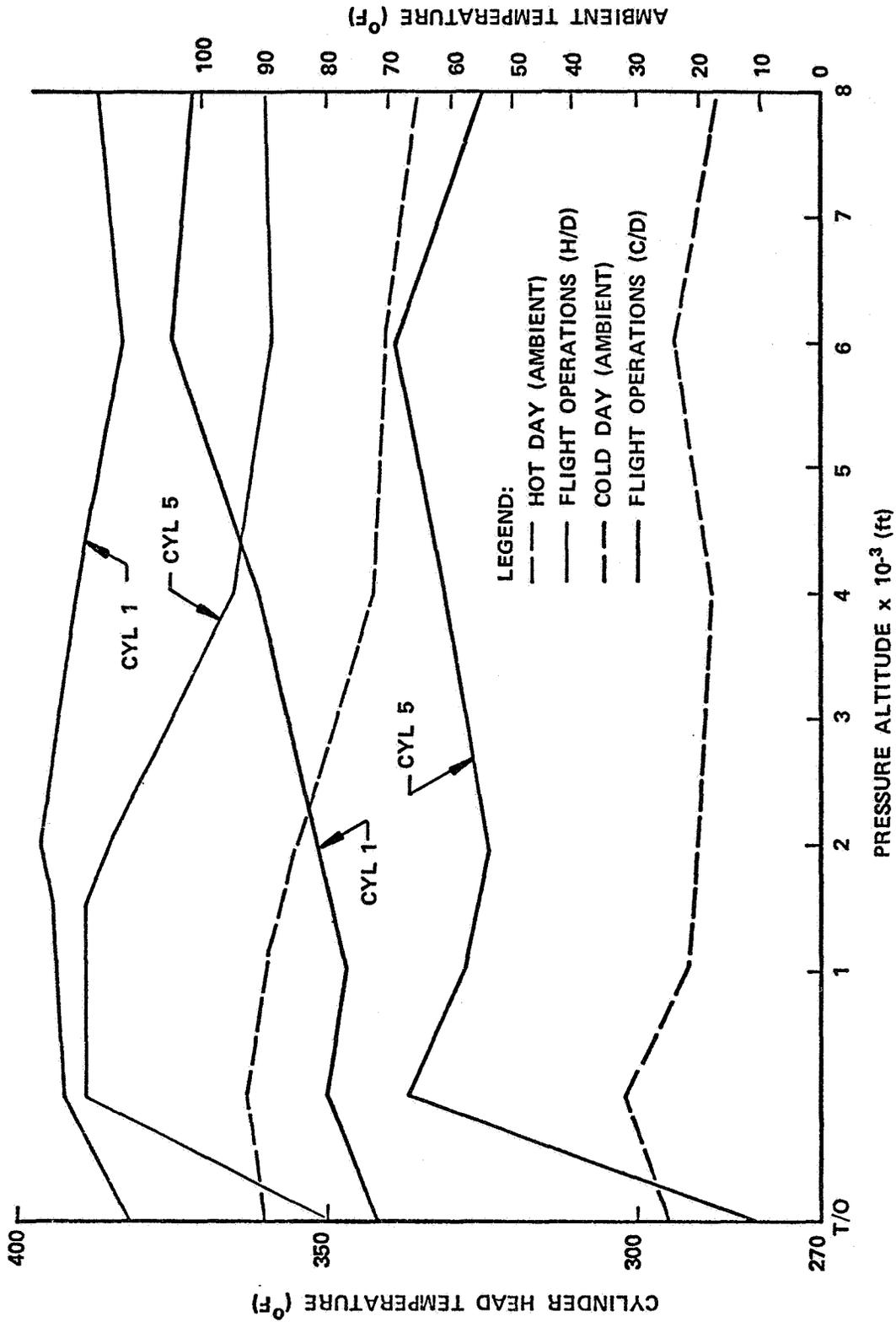
Figure 8-18

9. FLIGHT TEST SUMMARY OF MODIFIED FUEL SYSTEMS

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INTRODUCTION

During the spring and summer of 1976, Cessna Aircraft Company, in cooperation with Teledyne Continental Motors, flight evaluated two different aircraft designs, each with two modified fuel control systems. Each aircraft was evaluated in a given series of defined ground and flight conditions while quantitative and qualitative observations were made. During this program, some ten flights were completed, and a total of about 13 hours of engine run time was accumulated by the two airplanes. This report will briefly summarize the results of these evaluations with emphasis on the operational and safety aspects.

DISCUSSION

The first aircraft involved was the Cessna Model 150 (fig. 9-1). This is a single-engine training aircraft powered by the TCM O-200-A normally aspirated, carbureted engine. Instrumentation was supplied in the test aircraft to read engine rpm, manifold pressure, and various operating temperatures, as well as the important atmospheric parameters. In addition, the pilot monitored the general functional behavior of the engine.

The test profile is summarized in figure 9-2. The idle and taxi conditions simulate typical ground operations with this class airplane. The takeoff condition, as defined here, is analogous to the condition for engine cooling called out in the Federal airworthiness requirements. The climb condition, though not necessarily completely representative of the operation of a low power airplane, was included, originally, to allow evaluation of the effect of leaner mixtures at lower power settings on engine operating temperatures. The descent phase was investigated, both with partial power applied and with power completely off, followed by simulated go-arounds to evaluate engine response characteristics. Finally, the landing phase was used to evaluate the typical touch-and-go operations so prevalent to the training class airplane.

The two fuel systems evaluated in this airplane resulted from engine test stand data developed by TCM. The case I system simply results from use of today's lean limit production carburetors. The leaner case II system represented the ground test "safety limit" mixture strength found by TCM in their test cell runs. This safety limit was defined by engine temperatures at the higher powers and by acceleration characteristics of the engine in the lower power range.

The results of the testing on the Model 150 indicated that the case I system pretty well defined the leanest system acceptable. With the case I carburetor, all flight conditions were found acceptable. The case II carburetor, however, was another story. In the airplane, engine operation could not be sustained below approximately 1700 rpm. At this rpm, the engine began overheating rapidly during ground operation. The airplane was not considered at all airworthy in this configuration, and no flights were made with the case II carburetor.

The second aircraft involved was the Cessna T337 (fig. 9-3). This twin-engine airplane is powered by two TCM TSIO-360-C turbocharged, fuel injected engines. The engines are in tandem at either end of the fuselage. The front engine was used here to evaluate the modified fuel systems, while the rear engine was left in the standard configuration. Instrumentation was supplied to read front engine power parameters and operating temperatures, to record throttle position and manifold pressure, and to read appropriate atmospheric variables. In addition, the pilot monitored the behavior of the front engine from purely a functional standpoint.

The test profile is summarized in figure 9-4 for this airplane. Again, the idle and taxi conditions represent typical ground operations. The emergency, or single engine, climb condition represents the most severe condition with respect to FAA engine cooling requirements for this airplane. The normal climb represents a typical cruise climb used in this airplane conducted at a speed in excess of that for best climb performance. The descent phase was investigated in a way to stimulate typical instrument approach conditions, as well as with the power back to idle. In addition, two speed ranges were evaluated and, as with the smaller airplane, go-arounds were simulated following all descents. Finally, the landing phase included touch-and-go operations to observe engine response characteristics.

The case I fuel system was intended to represent the leanest fuel system using today's components which might result from using a full rich mixture for all operations with no supplement with an auxiliary fuel pump. However, the system actually tested was somewhat leaner than intended at maximum continuous power. The case II system represented the "safety limit" fuel mixtures established by TCM during their ground test stand runs, as described previously for the Model 150 tests.

The approximate relationship of the case I and case II fuel flows with those actually used in the present production airplane is shown in figure 9-5 for the various test conditions. As can be seen, the fuel flows actually specified for operation of the airplane in the form of operating limitations and instructions are consistently richer than either of the modified systems.

The results of the case I (as flown) and case II testing indicated both fuel systems to be unacceptable in several areas. In the idle and taxi ranges, some subtle engine roughness was evident with both fuel systems. With the tested case I system, response characteristics were probably marginally acceptable. The case II system, however, was noticeably slower to accelerate. In addition, while no specific measurements were made, the pilot's opinion was that engine starts, particularly with the case II system, were slightly more difficult.

The emergency climb condition was unacceptable as flown with the case I system because of engine overheating due to the lower than planned fuel flow. This is illustrated in figure 9-6 where the tested case I system produced engine temperatures near the limit immediately after the test was started. The case II system being leaner still was not evaluated in this condition. Cruise climbs at a comfortable airspeed higher than the maximum performance speed and with power set to 80 percent of maximum continuous were somewhat better, but even here, with the tested case I system, engine temperatures would be expected to exceed their limits in ISA + 40° F ambient temperatures due to the significantly lower fuel flows as compared to production (fig. 9-5). With the case II system, observed engine temperatures rapidly exceeded allowable limits. In addition, some subtle engine roughness was evident in this condition with the case II system.

The approach conditions evaluated revealed the tested case I system characteristics to be generally marginally acceptable, with the exception of some minor engine stumble on some simulated go-arounds. However, the case II system exhibited unacceptably slow "spool up" of power, as illustrated in figure 9-7, where, on a missed approach, almost twice as much time was necessary to obtain full power as is needed with the present production airplane. In addition, very rapid throttle advancement (throttle snaps) tended to cause the engine to die almost every time. Stumble or hesitation was always evident on the case II system on simulated go-arounds.

The operational acceptability of an airplane, with respect to the subject under question, falls into two major areas - safety and function.

Of prime importance, of course, are the safety aspects. Any system must be tolerant of mishandling to some degree as long as real

people are operating the system. A broad range of pilot knowledge and
skill must be accommodated. Such things as "jamming" in of a throttle
should not kill the engine. Engine power must always be available
rapidly to salvage a bad approach or in the event an intruder on a run-
way necessitates an aborted landing. The engine installation must pro-
vide adequate margins with respect to its temperature limitations to
accommodate all potential use of the airplane. Finally, the engine in-
stallation, with all of its supporting systems, must be as reliable and
foolproof as possible.

Functionally, the engine package must tolerate widely varying
atmospheric conditions. Wintertime operations, with the resulting
leaner mixtures, must be contrasted against summer operations, with the
resulting higher operating engine temperatures. Engine roughness or
hesitation will not be tolerated, and rightly so, by the majority of
pilots, no matter how subdued, due to the three-dimensional nature of
flight.

These comments, then, and others similar, can form a basis for judg-
ing the acceptability of the various fuel systems flown in this early
evaluation. It was found that with the present Cessna Model 150 the
case I fuel system represents, essentially, the leanest acceptable fuel
system. The case II system, being unairworthy in this airplane, was
completely unacceptable from either safety or functional standpoints.

For the Cessna Model T337, neither the case I (as flown) nor the
case II systems were acceptable. However, an analysis does indicate
that the case I fuel system with the slightly richer mixtures origi-
nally intended might be expected to be marginally acceptable. It is
possible that some further leaning could be tolerated for the power ap-
proach case and, with an attendant penalty in climb performance, for
the cruise climb case, if a higher airspeed can be accepted. However,
it should be noted that many pilots will be uncomfortable if any ten-
dency toward roughness is evident in this case, even if airworthiness
is not compromised. In the T337, the case II fuel system was found
unacceptable from both functional and safety viewpoints.

CONCLUSIONS

While some improvements in exhaust emissions control can be
achieved through mixture control on some airplanes, the tests on these
two airplanes indicated several important points:

1. Ground tests of the engine alone were not able to predict ac-
ceptable limiting lean mixture settings for the flight envelopes of
the Cessna Models 150 and T337.

2. The lean limits established today for the Cessna Models 150 and T337 approximately represent the leanest mixtures tolerable from safety and/or functional viewpoints.

3. Further leaning, beyond today's lean limits, for the Cessna Models 150 and T337 for the purpose of emissions control, must be accompanied by potentially extensive development and recertification flight testing to eliminate the safety and/or functional limitations found in this test series.

4. Each airplane design/engine combination must be evaluated in an individual effort to develop acceptable lean limiting mixtures and identify the areas where gains in emissions area are feasible for that airplane.

DISCUSSION

Q - D. Tripp: Does figure 9-7 show the response under approach conditions?

A - B. Barrett: This was the response as recorded during one of our aborted landing approaches. That is correct.

Q - D. Tripp: I'm not a pilot, but do you normally have the throttle all the way closed during approach?

A - B. Barrett: This particular one was a power off landing approach.

Q - D. Tripp: Is that the normal condition?

A - B. Barrett: Yes. It is a normal condition. It may not be completely normal for this particular airplane. This was the extreme case we saw as far as the power response goes. And I might add, I mentioned earlier that no matter how fast or how slow you brought the throttle in, it always stumbles to some degree or other with this particular fuel system.

COMMENT - L. Helms: I've heard that this is the normal condition in the student training film.

A - B. Barrett: Yes, in the case of the Cessna 150 it would be completely normal.

Q - D. Tripp: It was shown that under idle conditions, the condition when the throttle was shoved forward all the way, the engine stumbled, fell off in rpm, and did not respond as it did for the normal carbureted fuel-air ratio condition. Is that a safety problem? What condition would that represent as a safety problem when you are at idle and you shove the throttle forward very rapidly and it stumbled? I can't conceive why that would be a safety problem.

A - C. Price: There was an air worthiness directive, about 2 years ago, directed toward 0-320 engines, I believe in the Cherokee, for that very same reason. Power off approach and aborted landing or for some reason power would be applied and the engine would hang. Sometimes it would come out of it, but it's not very instinctive for a pilot to pull his power back off and try to clear an engine and then try to put power back on. So if he jams it forward and it hangs, he's in trouble.

Q - D. Tripp: Is that a safety problem?

A - L. Helms: Yes. Take the specific example at idle when the throttle is moved forward and the engine coughs and sputters. Consider the environment, a twin engine airplane under a freezing rain or very close to that temperature. The pilot does not know whether he has ice in the carburetor or whether he has ice in the induction system. Therefore, the FAA has properly said, and we agree with them 100 percent, no coughs and no sputters because that's the only way the pilot can be sure he has an absolutely clean carburetor. I'd like to make

another comment on the example he used on rate of climb. If we had looked at it it would have said, "Is the rate of climb of the aircraft good enough to where it would not have created the danger problem?" We talked about the horsepower rating and the rate of climb so now if we reduce the rate of climb slightly so there is no danger problem, we have now put ourselves back over onto the other side of the EPA problem where noise limitations are a function of rate of climb. Therefore, by reducing the rate of climb we got ourselves out of a problem on emissions and put ourselves in a problem on noise. The 84 PNdB allowed on climb is a direct function of the rate of climb. So we can't automatically make these adjustments and get out of our emissions because we can no longer meet the noise requirements.

Q - G. Kittredge: You made the comment that each engine/aircraft combination really has to be considered as a special case and you investigated two examples very thoroughly. Could you estimate for your company how many different combinations of aircraft and engines you would have to deal with?

A - B. Barrett: In my division of my company it's on the order of 25 separate and distinct engine and airframe combinations. In the other division across town it must be approximately a dozen.

COMMENT - L. Helms: For GAMA, there are 64 different aircraft and 407 different engines. Potentially, this gives you an order of magnitude of the problem.

Q - D. Page: You indicated that you were going over limits on your cooling efficiency. Was this a single engine climb condition, and what recovery efficiency are you getting on your particular installation in the 337?

A - B. Barrett: Yes, it was single engine climb, and I think we're running somewhere on the order of 3 to 3 1/2 inches ΔP on cooling air, but I'm not positive on that.

Q - D. Page: What is the percentage of recovery? - I'm trying to establish whether this is the most available at that air speed.

A - F. Monts: I think normally we'll see a dynamic recovery of about 0.75 to 0.8 for the single engine climb speed of just over 100 miles an hour. That's a little over 5 inches of water. You can put the cowl flap open and gain a bit more which for this particular installation is about as good as our industry does at the moment. We have to show single engine climb all the way to approximately 20 000 feet.

Q - B. Houtman: Would you specifically describe what the hardware changes were made in going from the baseline to case 1 and then again to case 2 to achieve the configuration you used?

A - B. Rezy: What we did on the engine was to take a standard fuel injection system and set up the fuel metering system with a particular pump and throttle body. We cut a throttle plate cam, such that we

could control the cases 1 and 2 to those conditions. We also had a modified fuel pump pressure to hold it there. It took our fuel lab well over a month to develop each one just to be able to hold it there. When we finally got it in the airplane it wasn't really what it should have been on case 1.

Q - E. Kempke: It's been said that the case 1 that was flown missed the target slightly on the fuel-air ratio. But in listening to the presentation there was a strong impression left that if the case 1 had made the fuel-air ratio it was extremely marginal. Is that the impression that one should come away with?

A - B. Barrett: Yes.

Q - E. Kempke: Is the case 1 not the lean limit of a production fuel injection system?

A - B. Barrett: The case 1 as flown is, in fact, the engine manufacturer's lean limit, the bottom line of the engine spec. On this particular airplane we have, in effect, established a lean limit for the installation that is richer than the lean limit demanded by the engine manufacturer.

Q - D. Tripp: I still have a question on that approach at closed throttle, and maybe someone from EPA could comment on this, too. Since the EPA LTO cycle specifies 40 percent power on approach, somehow there seems to be an anomaly here in that we're saying for the test procedure use 40 percent power. However, you're saying the way these planes are frequently flown is with a closed throttle. What's the explanation for it?

A - B. Barrett: The 40 percent power is reasonable, if you want to assign a reasonable specification for conducting your emissions testing. It is probably a reasonable simulation of an approach in many of the larger airplanes. But there's nothing that says the pilot is going to fly every approach that way. It's difficult particularly in the final stages of approach to be much lower in power than the 40 percent.

COMMENT - H. Nay: The approach is 6 minutes. In the traffic pattern in the approach to the airport, in that 6 minutes, 40 percent is not an unrepresentative power condition. The point is that in the final stages of approach, and this goes for high performance airplanes to some extent as well as low performance airplanes, you go to completely closed throttle. From that point when the cow walks out in the grass strip, a jet taxis out in front of you, or you have a foulup of some sort, you've got to have immediate power from closed throttle to 40 percent power or higher. That's an absolutely essential safety requirement as the FAA people pointed out.

COMMENT - F. Monts: I think the facts are being confused about the 40 percent approach power used in the EPA cycle. Whatever metering system is devised to meet the emissions limit, it must also work from a cold

throttle position. The complete flight envelope of the airplane and not just the EPA LTO emission cycle must be considered.

Q - D. Tripp: I was just wondering how 40 percent was arrived at?
A - B. Barrett: It's a good average.

COMMENT - G. Banerian: I realize that the controls being used are designed to be a minimum fixed and simple type. It seems to be that in both the Avco-Lycoming and TCM controllers a simple override feature could be incorporated such that in a transient mode it would automatically go to a rich condition. The other flight tests reported earlier did not have a cylinder head heating problem but Cesana's tests did indicate a cooling problem.

COMMENT - B. Barrett: That's an indication, too, of the individuality of each and every installation.

COMMENT - B. Rezy: TCM will discuss tomorrow possible ways of improving engine transient response between steady-state leaned conditions. One example of items which will be evaluated is the use of an accelerator pump.

Q - G. Banerian: Maybe I didn't notice it, but 1 was anxious to see a comparison of NAFEC data with the data taken at the contractors facilities and also the O-320 work done at Lewis. Are there some baseline emission data we can compare? I didn't see that comparison today.
A - E. Becker: The plots I had up were for the TSIO-360 tests at both NAFEC. The data lined up, there were no significant differences.

COMMENT - L. Helms: We haven't found any differences.

Q - G. Banerian: Have the differences that have been reported been in the idle mode?
A - E. Becker: Most of it is due to large scatter in fuel-air ratios. As NASA-Lewis pointed out earlier, the significance of temperature and humidity effects on hydrocarbons are also quite pronounced in the idle/taxi modes.

COMMENT - G. Banerian: We can then conclude that the measuring methods, even though they are different, at the various sites are sufficiently similar in results.

Q - T. Cackette: Both Avco and TCM data show that there is a fairly large difference in CO, due to the lean and rich production limits, which implies that there is a large fuel-air ratio difference on the production items. Could TCM or Bendix comment on what the causes of the large production tolerances are and possibly if they are anticipating taking any action to reduce those as a method of controlling emissions?

A - B. Rezy: You have to understand that both engine companies ran these tests differently. Lycoming ran full production rich limits and lean limits. TCM ran as baseline, the average fuel flow between the rich and the lean limit. That's why you see those differences.

COMMENT - S. Jedrziewski: Speaking for AVCO, our production limits are of the order of 7 percent of fuel flow right now. These limits are based on just manufacturing tolerances, reproducibility, airflow sensing, etc. We are engaged in programs trying to reduce these limits. At the present time we don't know how much they can be reduced.
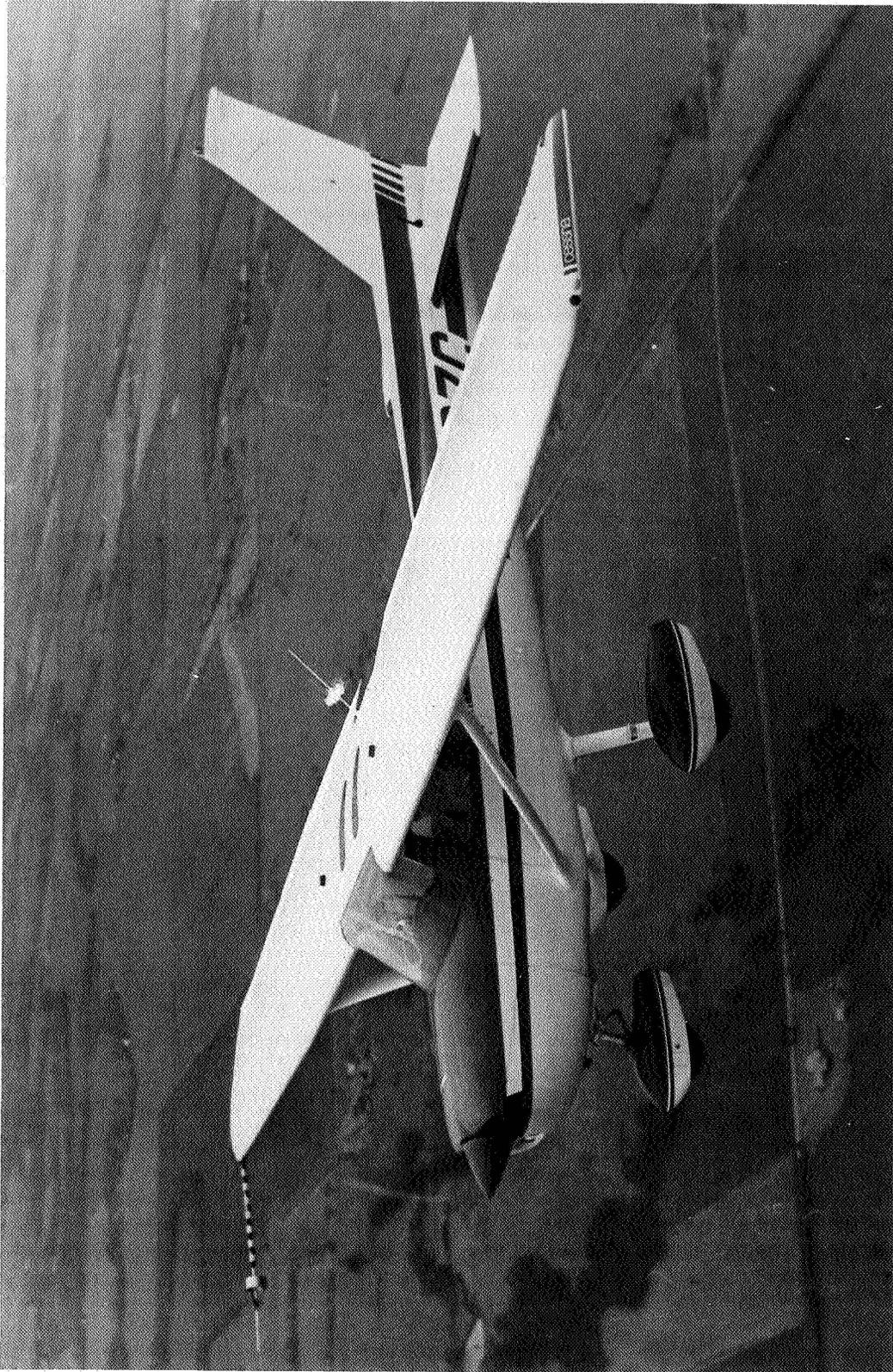
Figure 9-1

FLIGHT TEST PROFILE
CESSNA MODEL 150

FLIGHT CONDITION

	Idle (600 rpm)	Taxi (1200 rpm)	Takeoff (Full Throttle, Best Rate of Climb Speed)	Climb (80% Power, Best Rate of Climb Speed)	Descent	Landing (Power Off)
Fuel Flow: % Leaner Than Production Lean Limit						
Case I	0%	0%	0%	0%	0%	0%
Case II (Test Stand "Safety Limit")	5%	19%	3%	3%	8.5%	5%
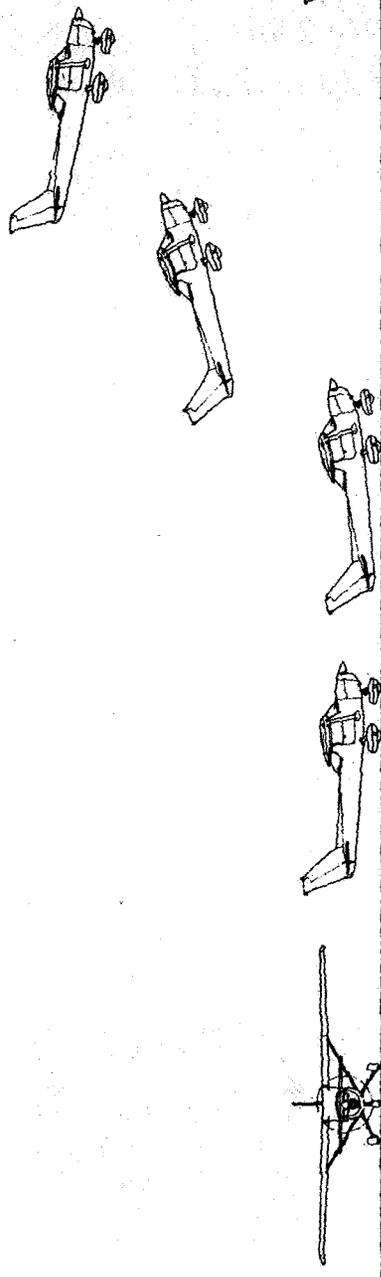
Figure 9-2
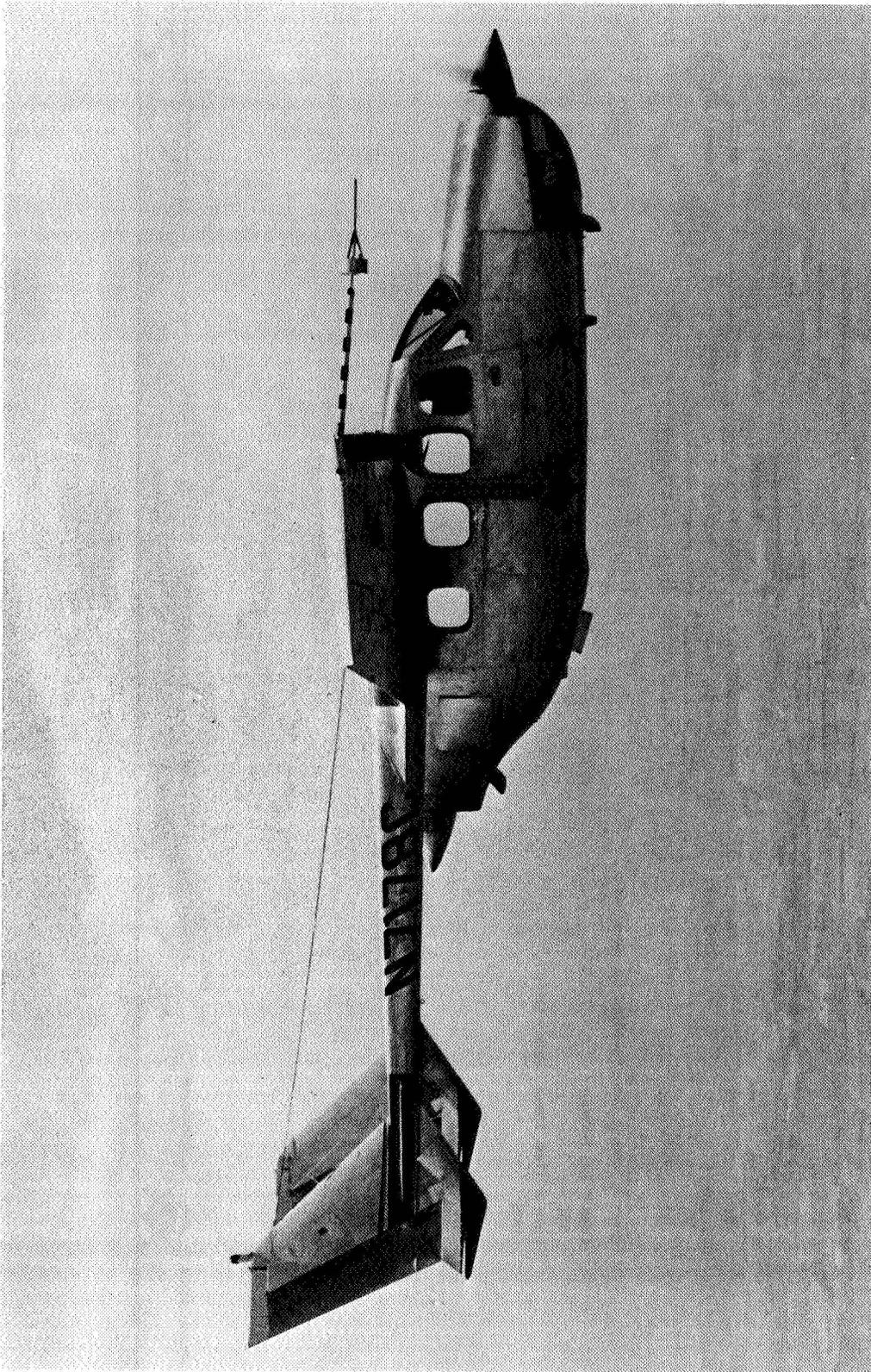
Figure 9-3

**FLIGHT TEST PROFILE
CESSNA MODEL T337**

FLIGHT CONDITION

| Idle
(600 rpm) | Taxi
(1200 rpm) | Emergency Climb
(Single Engine, Max.
Power, Best Single
Engine Rate of Climb
Speed) | Normal Climb
(Twin Engine,
80% Power, Rec.
Cruise Climb Speed) | Descent
(40% Power) | Landing
(Power Off) |

Fuel Flow: % Leaner Than Specified for Pilot Today.

Case I (As Flown)

| 0% | 6% | 7% | 9% | 6% | 0% |

Case II (Test Stand "Safety Limit")

| 14% | 21% | 14% | 19% | 20% | 14% |
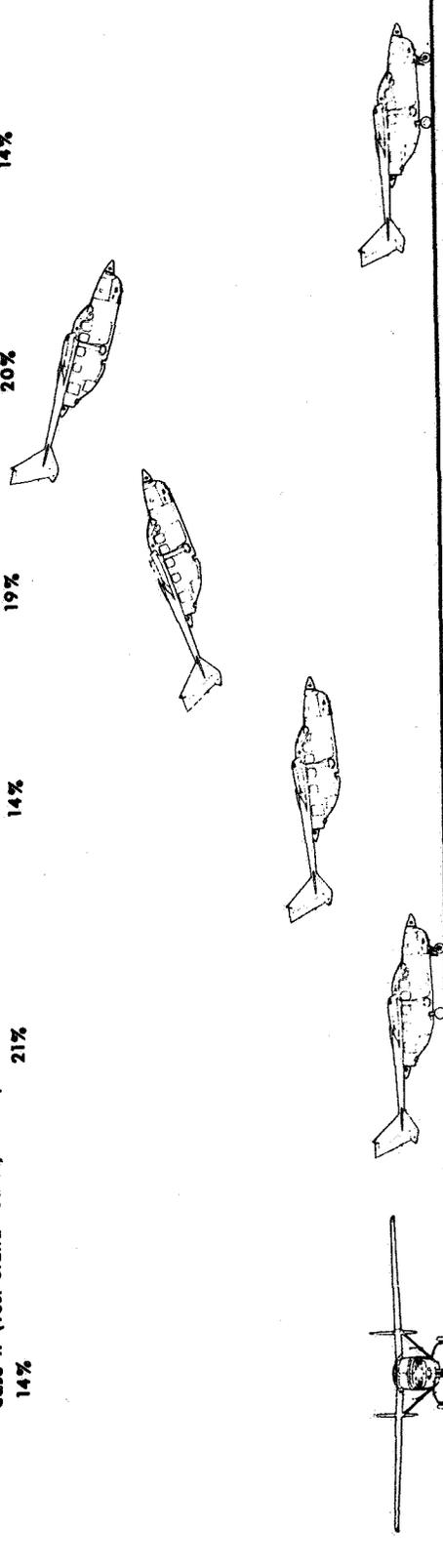
Figure 9-4

FUEL FLOW SUMMARY
Model T337G   N7178C
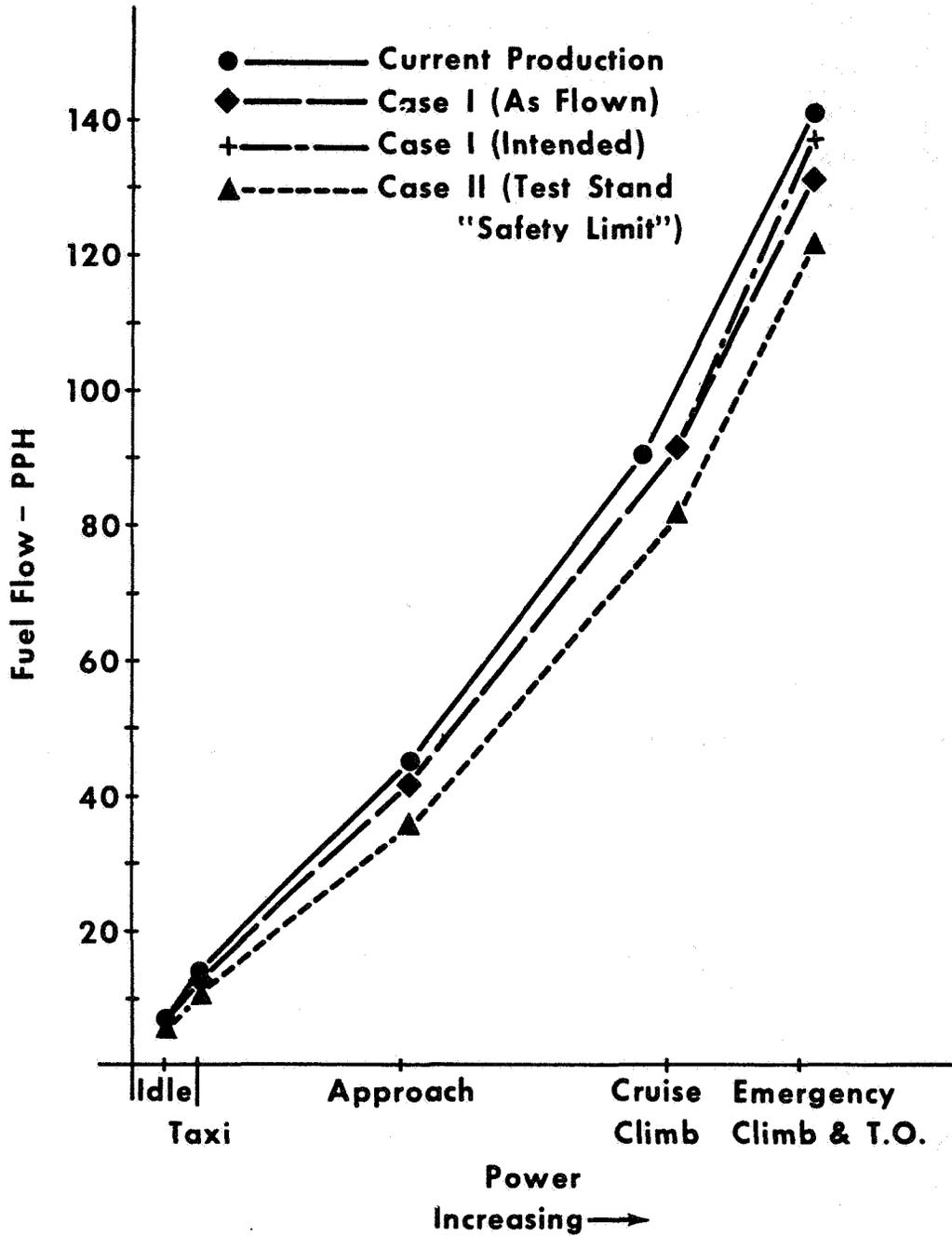
Figure 9-5

COOLING SUMMARY

Model T337G   N7178C

Single Engine Climb

Case I Fuel Flow (as Tested) - 130 PPH

Limiting CHT

Production Fuel Flow - 140 PPH

Cylinder Head Temperature - °F

Altitude - FT x 10³

Figure 9-6

Manifold Pressure - In. Hg.

Approx. Std. Fuel System

ENGINE RESPONSE

Case II Fuel System

Missed Approach

Throttle Position

100%

50%

Time - Sec.
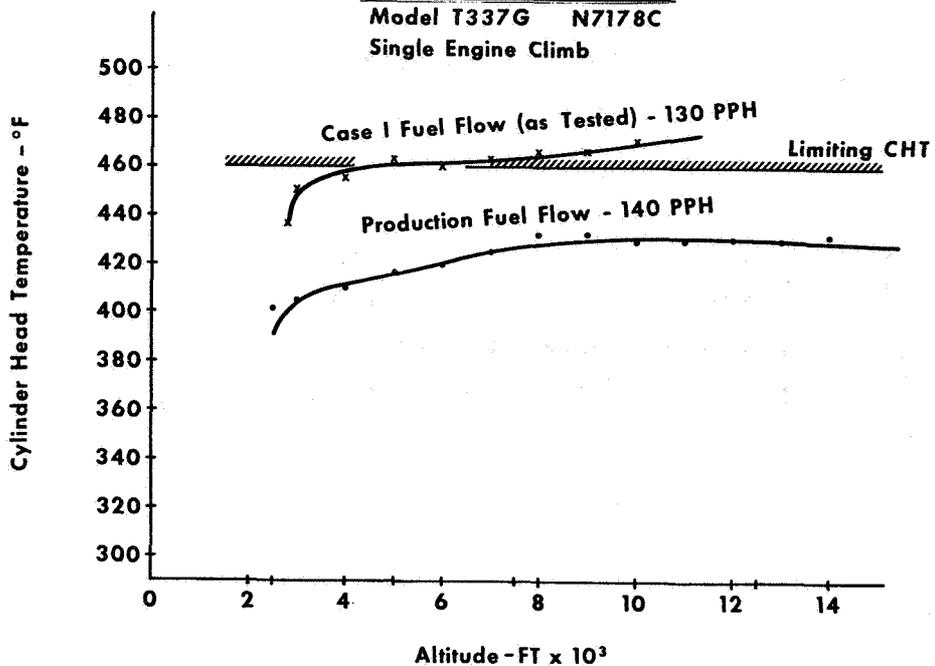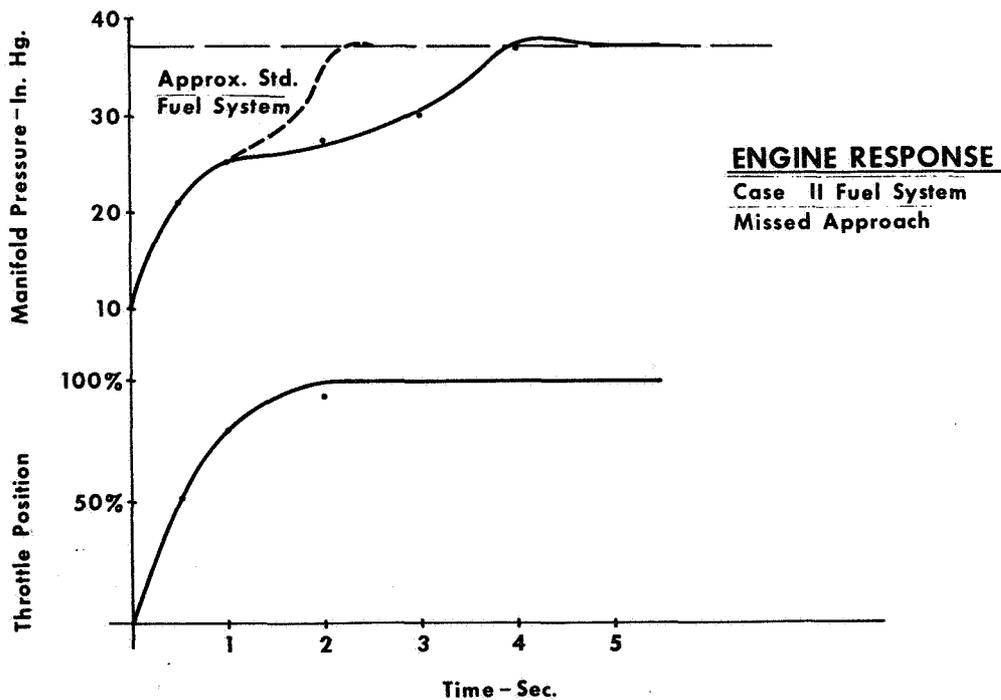
Figure 9-7

10. INTRODUCTION TO NASA CONTRACTS

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The division of activities that was agreed upon between the FAA and NASA is described in paper 6. When NASA agreed to participate with the FAA in the joint program previously described, NASA also decided to investigate more advanced technology concepts for exhaust emissions reduction. As a first step, the NASA Lewis Research Center issued Requests for Proposal (RFP) to Avco Lycoming and Teledyne Continental Motors (TCM) for a contractual effort to establish and demonstrate engine modifications to reduce exhaust emissions safely with minimum adverse effects on cost, weight, and fuel economy. In addition, although the emphasis of the effort is on emissions reduction as a primary thrust, it has at the same time, the secondary objective of reducing fuel consumption. NASA structured the program such that, according to the RFP, an initial task would be to screen and assess 10 concepts with emissions reduction potential. A preliminary list of candidate concepts contained in the RFP is shown in figure 10-1. The three most promising concepts would be designed, fabricated, and installed on an experimental engine or engines. Verification testing would then be performed by the contractor at his facilities. One other RFP requirement was that one of the three concepts require a major engine design modification and the other two concepts require relatively minor engine modification.

Cost-shared contracts to TCM and Avco Lycoming were let October 10, 1975. Each contract has a total estimated cost of $1.2 million, with the contractors share being 20 percent. The period of performance for each contract is approximately 3 years. One difference from what was previously stated is that Avco Lycoming elected, prior to the award of contract, to perform the screening and assessment task using their own funds. Accordingly, at the start of the contract, it was mutually agreed as to which three concepts Avco Lycoming would pursue. These are discussed in more detail in paper 12.

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CANDIDATE EMISSION REDUCTION TECHNIQUES

1. ENGINE GEOMETRY MODIFICATIONS
   A. COMBUSTION CHAMBER CONFIGURATION
   B. COMPRESSION RATIO
   C. INTAKE MANIFOLD
   D. VALVE TIMING, INCLUDING VARIABLE CAMSHAFT
   E. IGNITION TIMING
   F. IMPROVED COOLING

2. FUEL DISTRIBUTION AND IGNITION SYSTEM
   A. ULTRASONIC FUEL VAPORIZATION
   B. THERMAL FUEL VAPORIZATION
   C. CRACKING CARBURETOR
   D. IMPROVED FUEL INJECTION SYSTEM
   E. HIGH ENERGY-MULTIPLE SPARK IGNITION

3. EMISSION CONTROL ADD-ON
   A. AIR INJECTION
   B. WATER/ALCOHOL INJECTION
   C. THERMAL REACTOR
   D. CATALYTIC REACTOR

4. FUEL ADDITIVES
   A. HYDROGEN INJECTION
   B. METHANOL

Figure 10-1

11. TCM AIRCRAFT PISTON ENGINE EMISSION REDUCTION PROGRAM[*]

Bernard Rezy

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INTRODUCTION

Teledyne Continental Motors is currently under contract with the National Aeronautics and Space Administration to establish and demonstrate the technology necessary to safely reduce general aviation piston engine exhaust emissions to meet the EPA 1980 Emission Standards with minimum adverse effects on cost, weight, fuel economy, and performance. The contract is intended to (1) provide a screening and assessment of promising emission reduction concepts, and (2) provide for the preliminary design and development of those concepts mutually agreed upon. These concepts will then go through final design, fabrication, and integration with a prototype engine(s). Verification testing will then be performed at our facility.

Teledyne Continental Motors has completed the first portion (task II) of the NASA contract (NAS3-19755): "Screening and Assessment Analysis and Selection of Three Emission Reduction Concepts." A technical report is being prepared and is expected to be published during the last quarter of 1976 (ref. CR-135074).

A systems analysis study and a decision making procedure were used by TCM to evaluate, trade off, and rank the candidate concepts from a list of 14 alternatives. Cost, emissions, and 13 other design criteria considerations were defined and traded off against each candidate concept to establish its merit and emission reduction usefulness. A computer program documented in NASA TN X-53992 was used to aid the evaluators in making the final choice of three concepts.

The following is a summary of the Task II study.

APPROACH

The objectives of Task II were to conduct a screening analysis on a

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[*]NASA Contract NAS3-19755.

minimum of ten promising concepts and select three for further development. The approach used to fulfill the objectives was fivefold:

(1) Select a preliminary list of concepts

(2) Conduct a detailed literature search

(3) Contact firms for additional data

(4) Define criteria and method of evaluation

(5) Rank concepts based on a consistent set of weighted cost-effectiveness criteria

The first three steps of the approach resulted in a list of fourteen concepts which were investigated during the remainder of Task II. The promising concepts are listed in order of general category:

Stratified charge combustion chambers:
    Honda compound vortex controlled combustion
    Texaco controlled combustion system
    Ford programmed combustion
Improved cooling combustion chamber
Diesel combustion chambers:
    4-stroke, open chamber
    2-stroke, McCulloch
Variable camshaft timing
Improved fuel injection system
Ultrasonic fuel atomization – Autotronics
Thermal fuel vaporization – Ethyl TFS
Ignition systems:
    Multiple spark discharge
    Variable timing
Hydrogen enrichment
Air injection

Step four of the approach was accomplished by selecting and defining the decision factors (criteria). The criteria chosen in the evaluation of the concepts were as follows:

Cost	Integration
Reliability	Producibility
Safety	Fuel economy
Technology	Weight and size
Performance	Maintainability and maintenance
Cooling	Emissions
Adaptability	Operational characteristics
Materials	

Each decision factor was further defined by listing specific questions which were used in evaluating each concept.

The ranking of the concepts, step (5), was accomplished with a computer program that helps a decision maker to make consistent decisions under conditions of both certainty and uncertainty. The model aids in obtaining consistent rankings of the decision criteria and of the concepts relative to each of the criteria. The emphasis coefficients assigned to each criteria, the merit scores assigned to each concept relative to each criteria, and the associated uncertainties determined the overall merit coefficient for each concept. These merit coefficients defined the concept ranking which was used as a guide in the final selection of three concepts.

EMISSION RESULTS

Through the detailed literature search and contact with firms considered expert in their respective field, raw emissions data at the specific aircraft modal conditions were acquired for many of the concepts. These raw emissions data were input to the TCM aircraft cycle emissions deck. Where adequate raw emissions data were not available, concepts were evaluated by analyzing their impact on emissions as applied to the IO-520-D engine. The IO-520-D engine operating at the lean fuel flow limit of the model specification (case 1) was chosen as representative of a high volume production engine.

Figure 11-1 represents the emission levels for the concepts evaluated using raw emissions data. Shown for reference are the emission levels for the IO-520-D engine and two automotive engines, a conventional high production Chevrolet 350 CID V-8 engine and a high performance BMW 123 CID I-4 engine. The Chevrolet engine was a 1975 model without a catalytic converter, exhaust gas recirculation, or secondary air injection. The BMW engine was a 1973 model lacking the same pollution control devices. Neither engine met the EPA aircraft emission standard. While CO and HC were within the limits, the oxides of nitrogen were well over the allowable emissions as compared to 30 percent of the allowable emissions for the IO-520-D engine.

Graphical representation of engine emissions versus time-weighted fuel-air equivalence ratio from figure 11-1 and four current production TCM engines resulted in the generalized curves presented in figure 11-2. Data from the four TCM engines, IO-520-D, GTSIO-520-K, O-200-A, and Tiara 6-285-B, operating at three mixture strength schedules were utilized in developing the rich end of the curves. Emissions from all open-chamber-4-stroke Otto cycle engines evaluated adhered very closely to these trends. Note that only a narrow band of 7-mode time-weighted equivalence ratios, 1.03 to 1.13, exists where all three regulated pollutants are at or below the EPA limits.

The specific emission reduction conclusions for each concept are now presented.

Honda Compound Vortex Controlled Combustion (CVCC)

Raw emission data, received for the Honda CVCC, were based on oper-
ation with the standard exhaust system. The exhaust manifold was de-
signed with an inner liner to increase exhaust gas residence time and
provide an intake manifold "hot spot." Some benefits of HC and CO oxida-
tion and thermal fuel vaporization are therefore inherent in the data.
Honda CVCC met all EPA emission standards and was the best stratified
charge concept evaluated on overall emission reduction (see table 11-1).

Ford Programmed Combustion (PROCO)

Ford PROCO emission data indicated high oxides of nitrogen emissions
(32 percent over EPA limit) at a relatively lean 0.5 time-weighted equiv-
alence ratio. Hydrocarbons and carbon monoxide, at less than 10 percent
of the EPA standard, were typical of lean operation (fig. 11-1).

Texaco Controlled Combustion Systems (TCCS)

Three sets of raw emission data were evaluated on the TCM aircraft
cycle emissions deck. Almost all resulting time-weighted equivalence
ratios were the same. In two cases the engines were operated on gasoline
while the third case used diesel fuel. Oxides of nitrogen emissions were
comparable for all three cases and exceeded EPA limits up to 38 percent.
Carbon monoxide emissions were below the standard but not as consistent
as NO_x or CO, varying from 12 to 58 percent of the EPA limit (fig. 11-1).

Improved Cooling Combustion Chambers

No raw emissions data were available for evaluating an improved
cooling combustion chamber. Exhaust emission levels were projected by
realizing that improved cooling during climb and takeoff will permit
leaner fuel-air ratios while maintaining engine power. Application of
this theory to IO-520-D data resulted in emission levels of 106, 95, and
44 percent of the EPA standard for CO, HC, and NO_x, respectively. These
levels reflect a 16 percent CO decrease and a 47 percent NO_x increase.
Hydrocarbons were not significantly reduced since climb and takeoff con-
tribute only a small amount of the total HC emissions for the overall
cycle.

McCulloch Two-Stroke Diesel

Raw emissions data for this concept were evaluated on the TCM air-
craft cycle emissions deck. The resulting emission levels were 10, 140,
and 54 percent of the EPA standard for CO, HC, and NO_x, respectively.
These HC and NO_x levels compare to 47 and 163 percent of the EPA standard,
respectively, for a conventional four-stroke open chamber diesel

(table 11-1). The low NO_x level results from the unique combustion chamber and piston design and the fuel-air mixture burning/quenching process. This quenching process may also account for the high hydrocarbons. It should be noted that the HC level is conservative since full power data were not available and the rated power was reduced accordingly. Hydrocarbons should decrease for the higher speed/load conditions.

Four-Stroke Open Chamber Diesel

Raw data from three four-stroke open chamber diesels were evaluated on the TCM aircraft cycle emission deck. Data from one engine, a Datsun, is suspect due to the extremely low NO_x emissions (fig. 11-1). Oxides of nitrogen for the other two cases exceeded EPA limits by up to 90 percent. This level resulted from the high peak temperatures normally associated with diesel engines. Carbon monoxide and HC were below EPA standards for all cases.

Variable Camshaft Timing

Emission predictions for variable camshaft timing were based on Tiara 6-285-B engine data for idle, taxi, and approach modes, and on IO-520-D case 1 data for climb and takeoff modes. Tiara data were considered representative of HC emissions that could be expected on the IO-520-D for low valve overlap in low speed modes. This is due to higher engine speeds of a geared engine in these modes and because of the comparatively low Tiara valve overlap. The Tiara emission data was taken at IO-520-D fuel-air ratios for the respective modes and corrected for flow rate differences. No exhaust emission reduction benefits from exhaust gas recirculation were assumed for the IO-520-D because the design point for valve overlap is at high engine speed; that is, large valve overlap already exists on the IO-520-D and no increase in internal exhaust gas recirculation would be expected from variable camshaft timing Consistent with the literature, the CO remained essentially unchanged, exceeding the EPA limit by 27 percent. Hydrocarbons were reduced by 49 percent of the EPA standard (from 97 to 48 percent) relative to the IO-520-D engine. Oxides of nitrogen emissions remained essentially unchanged at 33 percent of the EPA standard.

Improved Fuel Injection System

Projected emission levels for an improved fuel injection system were determined by evaluating a system which would alleviate the attendant operational problems associated with carbureted or conventional aircraft fuel injection systems. That is, the system must provide a better homogeneous fuel-air mixture and decrease cylinder to cylinder fuel-air ratio variations. It was further required that the system would be compensated

to maintain lean fuel-air ratios within a reasonable band regardless of the air density. The actual range of fuel-air ratios that could be maintained was defined as a time-weighted equivalence ratio range of 1.03 to 1.13. Exhaust emission reductions were based on the IO-520-D engine (fig. 11-3), resulting in absolute emission levels of 55, 90, and 58 percent of the EPA standard for HC, CO, and NO_x, respectively.

Ultrasonic Fuel Atomization

No raw emission data were obtained for this concept. It was assumed to have the same emission reduction potential as the thermal fuel vaporization concept. This approach was taken because both concepts have essentially the same end result, homogeneous fuel-air mixture with decreased cylinder to cylinder fuel-air ratio variation.

Thermal Fuel Vaporization - Ethyl TFS

Raw emissions data from two engines, an American 350 CID V-8 and a European four cylinder I-4 were obtained and evaluated on the TCM aircraft emissions cycle deck. The results were inconsistent for the two engines (fig. 11-1). Results for the American V-8 seemed more reasonable because of the predictable insignificant effect on NO_x, whereas for the European engine the NO_x was reduced by almost 60 percent. The results of the American V-8 data analysis were used. Hydrocarbons were reduced 39 percent (with the addition of the turbulent flow system) with insignificant effects on CO and NO_x.

Variable Timing Ignition System

Variable timing ignition will not significantly reduce exhaust emissions for the aircraft emission cycle. However, the ability to provide variable ignition at idle, taxi, and the approach modes will decrease the acceleration problem associated with leaning these modes. Projected emission reductions of 11 percent for HC, 8 percent for CO, and an increase of 17 percent for NO_x based on IO-520-D data resulted in absolute CO, HC, and NO_x emission levels of 116, 86, and 35 percent of EPA standards, respectively. These levels were predicated on variable timing ignition improving transient operation at idle, taxi, and approach modes. The quantity of improvement was defined as that required to alleviate acceleration problems at the richest fuel-air ratio at which transient problems were encountered during lean-out testing on an uninstalled engine. This method resulted in fuel-air ratios richer than existing safety limits but leaner than best power fuel-air ratios (case 1) for the previous modes. Best power fuel-air ratios were used for climb and takeoff modes. The resulting exhaust emissions are considered conservative because at the fuel-air ratios chosen only transient hesitation was noted rather than complete response failure. Variable timing ignition should easily provide at least the minimum improvement required for satisfactory

transient operation at the previous conditions.

Multiple Spark Discharge Ignition System

Multiple spark discharge ignition systems provide a leaner misfire limit than do the conventional ignition systems. No emission reduction capability was demonstrated in the literature over a sizable range of fuel-air ratios except for hydrocarbons which differed beyond the point of incipient misfire. For the purpose of ranking a multiple spark discharge ignition, based on emission reduction potential, this theory was adhered to, that is, emissions would not be affected for a given fuel-air ratio above the lean limit of a conventional system. The IO-520-D engine case 1 emission levels were assumed to be the standard (table 11-1).

Hydrogen Enrichment System

No raw data were available for determining the exhaust emission reduction potential for an aircraft piston engine using the hydrogen enrichment method. The Jet Propulsion Laboratory predicted emission characteristics on an opposed aircraft engine using hydrogen enrichment. The predictions were based on the assumption that the correlations of indicated specific emission production with equivalence ratio are valid. The data base used in generating these representations at richer equivalence ratios (≥ 1.1) was for a TCM IO-520-D engine. Data for ultra-lean operation were obtained by JPL for a 350 CID V-8 engine operating with both straight gasoline and mixtures of gasoline and hydrogen-rich gases from a hydrogen generator. Reasonable coalescence occurred where the data sets joined.

Idle, taxi, and approach modal indicated specific emission rates (lbm pollutant/indicated horsepower hr) were defined at 0.6 equivalence ratio. The corresponding values of indicated horsepower were calculated from known brake horsepower and friction horsepower characteristics for the IO-520-D engine. Hydrogen enrichment was assumed nonoperational during takeoff and climb so that engine power could be maintained. Emission levels for takeoff and climb were taken directly from IO-520-D data for case 1. Applying hydrogen enrichment to the IO-520-D resulted in CO, HC, and NO_x levels of 68, 43, and 30 percent of the EPA standards, respectively (table 11-1).

Air Injection

The exhaust emission reduction potential of secondary air injection was evaluated using data from a TCM 0-200 engine. The results of that analysis were converted into terms that express the change in each pollutant per quantity of air injected as a function of equivalence ratio. These effects were applied to an IO-520-D engine, case 1 emission data

with the appropriate time-weighted equivalence ratio, assuming an air
injection flow rate equal to 20 percent of the engine inlet air flow
rate. Twenty percent was selected on the basis of minimum air injection
flow rate necessary to meet EPA emission standards for all three pollut-
ants at reasonable pump size and power requirements.

Expected reductions of 33 percent for HC, 23 percent for CO, and an
increase of 13 percent for NO_x were projected resulting in absolute
levels for HC, CO, and NO_x of 65, 97, and 34 percent of the EPA stand-
ards, respectively.

CRITERIA DEVELOPMENT AND METHOD OF EVALUATION

The selection of cost and design emission reduction criteria was
made after extensive documentation review and internal discussion. Fur-
thermore, the criteria (defined as "decision factors") are traceable to
the NASA Request for Proposal (LeRC RFP No. 3-499786Q). A list of solu-
tion attributes (indicating a further breakdown of policy, monetary, and
technical issues pertinent to the criteria) was generated and used for
evaluating the merit and usefulness of emission reduction concepts. A
solution attribute is defined as a subset of knowledge, considerations,
and thoughts (sometimes intangible or ill-defined) that identifies, par-
ticularizes, or supplements the meaning of the criteria. Solution attri-
butes actually drive the definition of criteria elements. Sample list-
ings of the attributes for cost and safety are shown in figures 11-4
and 11-5.

Four evaluators were asked to make critical value judgments concern-
ing the relative importance of the criteria as they would be used to
assign merit to the emission reduction alternative concepts. A combined
total of 42 years of industrial experience in combustion analysis, equip-
ment design, reciprocating and turbine engine development, and systems
engineering is noted for the evaluation team.

Each evaluator reviewed the criteria and the associated attributes.
He was then asked to choose between criteria elements as to their rela-
tive importance. For example, given any pairwise combination of criteria
elements, which one is preferred? Are the cost criteria more important
than the emissions criteria? Figure 11-6 shows the process used by each
evaluator. The criteria choices were denoted by rows and columns. Cri-
teria comparison choices were numerically recorded in each cell for the
attending row and column. By distributing a value (whose interval lies
between [0,1]) among criteria i^{th}, criteria j^{th}, and the associated un-
certainty ij^{th}, the evaluator logically orders the criteria to emphasize
its importance to him. Thus, the following equation below illustrates a
formal statement of the value assignment procedure between any pair of
properties and the associated uncertainty:

$$\begin{bmatrix} \text{Relative} \\ \text{importance} \\ \text{of property } j \end{bmatrix} = 1 - \begin{bmatrix} \text{Relative} \\ \text{importance} \\ \text{of property } i \end{bmatrix} - \begin{bmatrix} \text{Associated} \\ \text{uncertainty} \\ \text{of property } ij \end{bmatrix}$$

Property i^{th} value assignment is recorded in the upper left portion of the matrix cell, property j^{th} value assignment is calculated as the compliment of the matrix cell, and the associated uncertainty between the properties is recorded in the lower right portion of the cell as shown in figure 11-6. Hence, by substituting arbitrary values for cost, reliability, and the associated uncertainty, it follows that

$$\begin{aligned}
\text{Reliability } (j) &= 1 - \text{Cost } (i) - \text{Uncertainty } (ij) \\
&= 1 - 0.6 - 0.1 \\
&= 1 - 0.7 \\
&= 0.3
\end{aligned}$$

were the specific values assigned according to figure 11-6. A total of 105 pairwise choices was made. A simple logic check, based on the theory of transitivity, was made on the evaluator's choices to ensure consistent pairwise value judgments. Once the evaluator's value judgments were assigned and consistency established, a second computer program was used to rank his multidimensional complex criteria set. The criteria ranking emphasis coefficient is based on the theory of combinations as used to normalize the relative importance and uncertainty scores. An emphasis coefficient is associated with each criteria element and it is defined as the sum of the importance scores for that element normalized by the total number of pairwise comparisons made.

A similar analysis was conducted for evaluating each concept relative to each criteria element. Figure 11-7 shows the process used by each evaluator. That is, given the choice among alternative concepts, when traded off against the criteria, which ones are preferred? Is the improved cooling combustion chamber concept preferred over the air injection concept when considering emission benefits, advantages, and disadvantages? These are the fundamental questions answered by each evaluator. The choice among pairwise solution alternatives were depicted numerically. By distributing a value among alternative i^{th}, alternative j^{th}, and the associated uncertainty ij^{th}, the evaluator logically ordered the concepts to emphasize the importance to him. A total of 1365 pairwise choices (91 decisions for each of the 15 criteria elements) were made by each evaluator. Again, a consistency check was made to ensure a logical ordering of the evaluator's preferences. A second program that calculates the evaluator's merit scores (associated with his comparison of concepts and criteria elements) was enabled after consistency was established. The procedure for ranking the alternative concepts is similar to that of the criteria, as explained previously. The calculation of the merit coefficient for each concept is simply a summation of the product of criteria emphasis coefficients and the concept merit scores. The merit coefficient yields the resultant ranking. An example of a concept comparison trade-off evaluation for one of the evaluators is shown in figure 11-8.

CONCEPT RANKING AND SELECTION OF THREE CONCEPTS

After each evaluator established his individual criteria set and design concept preference ranking (and associated merit scores), he was directed to meet with his colleagues and select an optimized criteria and concept data set that reflects the consensus of the group. This was accomplished by arguing in favor of a generalized or explicit interpretation of the attributes/criteria elements, amalgamating ideas, compromising individual differences, and forming an opinion that was tolerated by the evaluation group. The optimized criteria data set was selected first and then the group assembled an optimized concept data set. The data flow process is schematically shown in figure 11-9.

The optimized emission reduction criteria ranking is shown in figure 11-10. Inspection of figure 11-10 shows that emissions, performance, and fuel economy rank within the top 40 percentile of 15 criteria elements. Emissions is ranked first; performance, third; and fuel economy, sixth. The previous criteria elements are considered congruent with respect to the decision criterion since they are explicitly stated in the primary and secondary objectives as the needs to be satisfied. Safety (ranked second), cooling (fourth), and weight and size (fifth) are important criteria design considerations that are also included in the upper 40 percentile. The first seven criteria elements are considered the dominant requirements that have the greatest influence on the selection of solution alternatives.

Table 11-1 depicts a final listing of the ordering for the fourteen concepts evaluated on the basis of emission usefulness. Table 11-2 presents a correlation matrix that depicts the results of the concept versus criteria tradeoff rank and merit scores as the result of the evaluators combined value judgments. The concepts are listed in order of their final ranking for the optimized preference analysis. The numbers shown at each intersection point represent the order of concept ranking based on the merit scores when compared with the criteria element. The improved cooling combustion chamber design concept is ranked first because it scored well among the dominant criteria elements - that is, first for safety, cooling, and weight and size, and moderately well among the remaining four dominant criteria. The improved cooling combustion chamber ranked ninth with the emissions criteria, but the influence of the remaining dominant criteria elements forced this design concept to be the top ranked candidate.

The improved fuel injection systems and air injection design concepts are ranked second and third, respectively. Inspection of dominant criteria (see table 11-2) shows a relative high rank scoring for these two candidates when compared against the remainder of design concepts. It becomes apparent that the further one proceeds down the list of design concepts the corresponding numerical ranking values increase in magnitude for the criteria elements, thus indicating lower utility.

Based on the results of the concept-criteria trade-off analysis, the following three concepts have been approved by NASA/Lewis Research Center for further development:

Improved fuel injection system

Improved cooling combustion chamber

Air injection

DISCUSSION

Q - W. Houtman: What would your selection have been if the hydrocarbon
and NO_x requirements were removed?

A - B. Rezy: If CO was the only pollutant being considered, the emis-
sions ranking would change significantly. The diesel concept has
the lowest CO emissions; however, the influence of the remaining cri-
teria has been shown to have a great effect on the overall ranking.
As stated earlier, the hydrogen enrichment concept best satisfied the
emission criteria; however, it ranked eighth in the overall prefer-
ence analysis. Therefore, I cannot make a statement as to how the
overall preference analysis would change if only CO was considered.
We will, however, report these findings[1] as part of the proceedings
from this symposium.

Q - G. Kittredge: Could you tell me whether the PROCO and TCCS strati-
fied charge engines that you showed were versions that employed
catalysts and exhaust gas recirculation?

A - B. Rezy: They did not.

Q - H. Gold: When you say improved fuel injection system, what kind of
improvements do you have in mind?

A - B. Rezy: An improved fuel injection system will consist of a timed,
airflow sensitive system capable of supplying fuel at moderate pres-
sure to the injectors. A timed, moderate fuel pressure system is
required to ensure a fuel mist with adequate cylinder distribution
as opposed to the present continuous flow, low pressure system. An
airflow (or speed-density) sensitive system is required to maintain
the desired fuel-air ratio, which will control the emission levels,
and, togehter with proper cylinder distribution, will provide better
engine transient response. We are currently evaluating a servo-
mechanical controlled system and an electronically controlled system.

---

[1]Comment on findings by B. Rezy following the Symposium: Table
11-3 presents the emission ranking for each concept based on the EPA
standards for CO only. Referring to table 11-1 reveals the significant
differences in the two rankings. The overall preference analysis based
on changing only the emission criteria is shown in table 11-4. Due to
the strong effect of the remaining criteria the four top tanking concepts
did not significantly change. Air injection did decrease from third to
fourth position since the emission ranking for this concept changed con-
siderably when only CO was considered. However, the three concepts
selected for further evaluation would not change if only CO was consid-
ered as the emission criteria.

CONCEPT RANKING FOR EMISSIONS

RANK	CONCEPT	PERCENT EPA STANDARDS		
		CO	HC	NOx
1	HYDROGEN ENRICHMENT, JPL	68.	43.	30.
2	HONDA CVCC	36.	22.	76.
3	IMPROVED FUEL INJECTION SYSTEMS	90.	55.	58.
4	AIR INJECTION	97.	65.	34.
5	TEXACO CCS	8.	58.	128.
6	FORD PROCO	4.	7.	132.
7	2-STROKE DIESEL, McCULLOCH	10.	140.	54.
8	4-STROKE DIESEL, OPEN CHAMBER	3.	47.	163.
9	IMPROVED COOLING COMBUSTION CHAMBER	106.	95.	44.
10	VARIABLE CAMSHAFT TIMING	127.	48.	33.
11	THERMAL FUEL VAPORIZATION, ETHYL	126.	59.	30.
12	ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	126.	59.	30.
13	VARIABLE TIMING SYSTEM	116.	86.	35.
14	MULTIPLE SPARK DISCHARGE SYSTEM	126.	97.	30.
**************				
REF.	IO-520-D, CASE 1	126.	97.	30.

TABLE 11-2

CONCEPT RANK ORDERING VERSUS CRITERIA IMPORTANCE

CONCEPT	CRITERIA														
	DOMINANT							SECONDARY				MINOR			
	EMISSIONS	SAFETY	PERFORMANCE	COOLING	WEIGHT AND SIZE	FUEL ECONOMY	COST	RELIABILITY	TECHNOLOGY	OPERATIONAL CHARACTERISTICS	MAINTAINABILITY AND MAINTENANCE	INTEGRATION	MATERIALS	PRODUCIBILITY	ADAPTABILITY
IMPROVED COOLING COMBUSTION CHAMBER	9	1	6	1	1	6	6	3	2	1	1	6	3	2	4
IMPROVED FUEL INJECTION SYSTEMS	3	2	1	14	2	5	7	4	1	6	2	4	2	7	6
AIR INJECTION	4	5	8	9	6	14	1	5	3	3	5	2	6	1	1
MULTIPLE SPARK DISCHARGE SYSTEM	14	3	5	7	3	12	2	6	4	2	3	1	1	5	2
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	12	4	9	11	5	10	4	1	5	5	4	10	4	4	7
VARIABLE TIMING IGNITION SYSTEM	13	6	3	8	4	11	5	7	7	9	6	3	5	6	3
THERMAL FUEL VAPORIZATION, ETHYL	11	7	10	13	7	9	3	2	6	4	7	9	7	3	5
HYDROGEN ENRICHMENT, JPL	1	14	7	4	8	1	12	8	9	12	8	7	14	8	8
TEXACO CCS	5	8	12	2	10	2	10	12	13	10	13	11	13	11	11
2-STROKE DIESEL, McCULLOCH	7	11	2	6	13	4	13	9	11	13	9	13	12	13	14
FORD PROCO	6	9	13	3	11	3	9	11	14	11	14	12	9	12	12
VARIABLE CAMSHAFT TIMING	10	13	4	10	9	13	8	14	8	8	10	5	8	9	9
HONDA CVCC	2	12	11	12	12	8	11	13	10	7	11	8	10	10	10
4-STROKE DIESEL, OPEN CHAMBER	8	10	14	5	14	7	14	10	12	14	12	14	11	14	13

TABLE 11-3

EMISSIONS RANKING BASED ON EPA STANDARDS FOR CO ONLY

CONCEPT	RANK
4-STROKE DIESEL, OPEN CHAMBER	1
FORD PROCO	2
TEXACO CCS	3
2-STROKE DIESEL, MC CULLOCH	4
HONDA CVCC	5
HYDROGEN ENRICHMENT, JPL	6
IMPROVED FUEL INJECTION SYSTEMS	7
AIR INJECTION	8
IMPROVED COOLING COMBUSTION CHAMBER	9
VARIABLE IGNITION TIMING	10
THERMAL FUEL VAPORIZATION, ETHYL	11
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	12
MULTIPLE SPARK DISCHARGE SYSTEM	13
VARIABLE CAMSHAFT TIMING	14

TABLE 11-4

CONCEPT PREFERENCE ANALYSIS
BASED ON EPA STANDARDS FOR CO ONLY

CONCEPT	RANK
IMPROVED COOLING COMBUSTION CHAMBER	1
IMPROVED FUEL INJECTION SYSTEMS	2
MULTIPLE SPARK DISCHARGE SYSTEM	3
AIR INJECTION	4
VARIABLE IGNITION TIMING	5
ULTRASONIC FUEL ATOMIZATION, AUTOTRONIC	6
THERMAL FUEL VAPORIZATION, ETHYL	7
HYDROGEN ENRICHMENT, JPL	8
2-STROKE DIESEL, MC CULLOCH	9
TEXACO CCS	10
FORD PROCO	11
HONDA CVCC	12
VARIABLE CAMSHAFT TIMING	13
4-STROKE DIESEL, OPEN CHAMBER	14
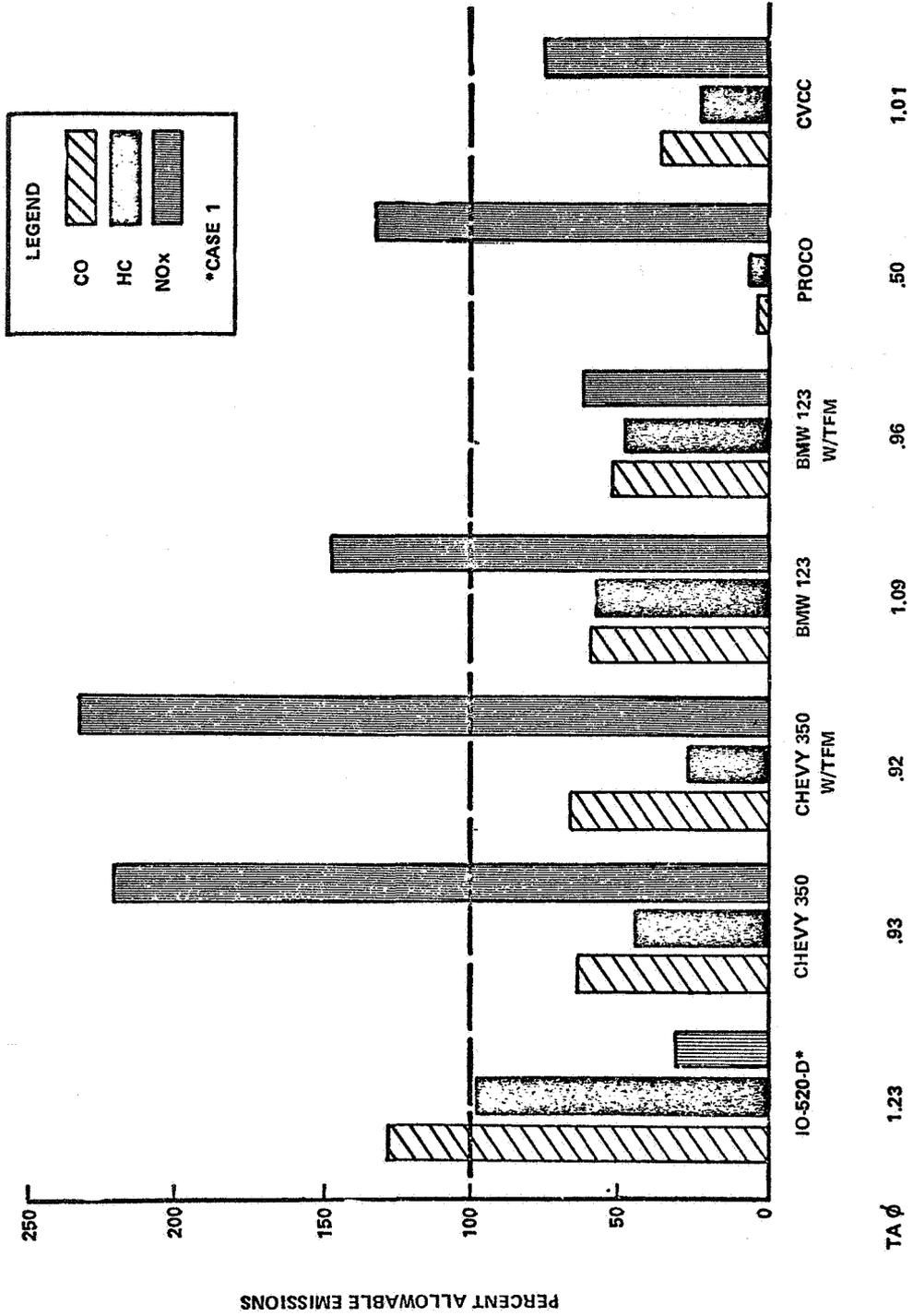
PERCENT ALLOWABLE EMISSIONS FOR CONCEPTS EVALUATED ON
A 7-MODE AIRCRAFT EMISSION CYCLE
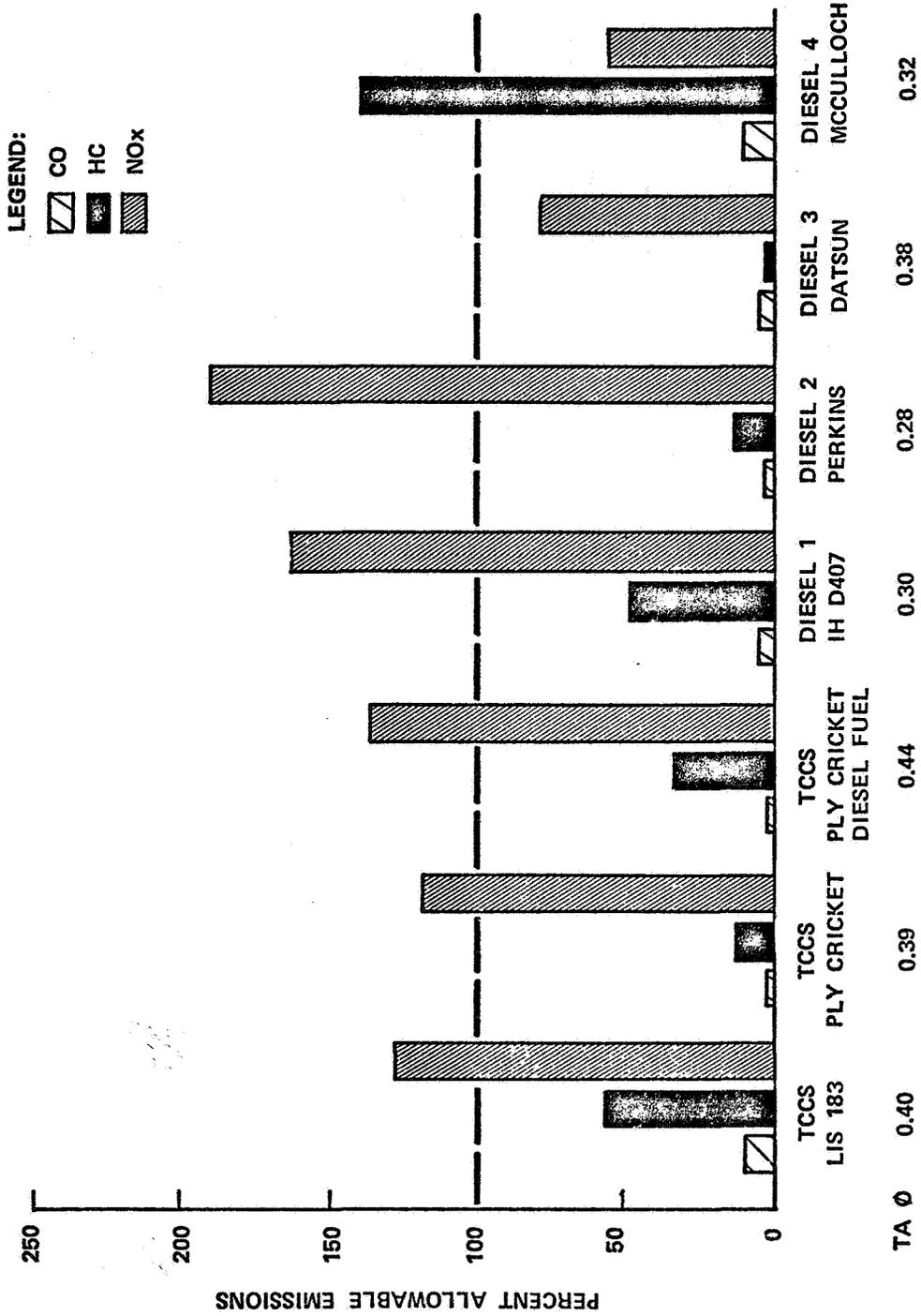
Figure 11-1

Figure 11-1. – Concluded.

PERCENT ALLOWABLE EMISSIONS FOR CONCEPTS EVALUATED ON
A 7-MODE AIRCRAFT EMISSION CYCLE
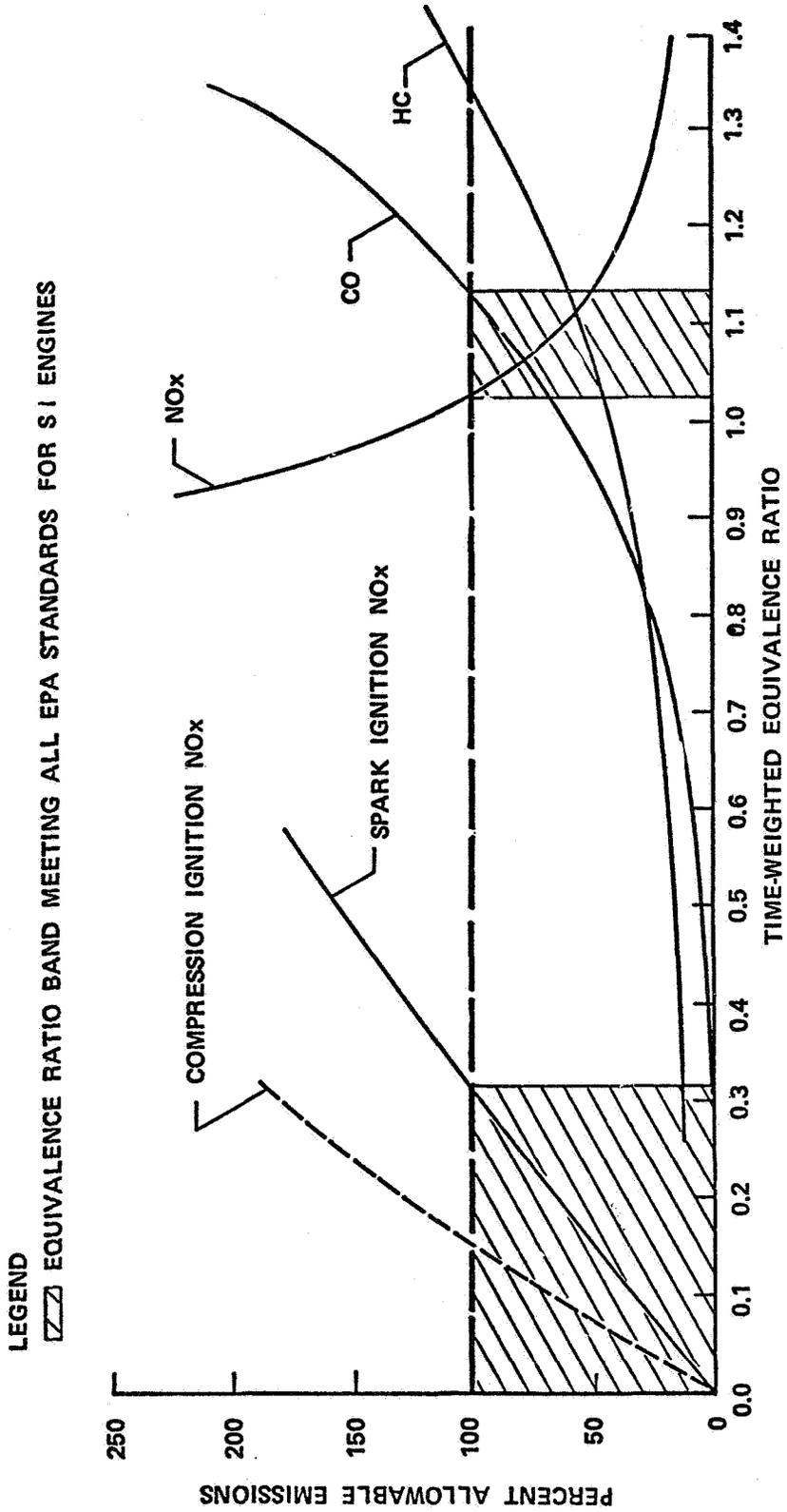
PERCENT ALLOWABLE EMISSIONS VERSUS TIME-WEIGHTED
EQUIVALENCE RATIO FOR ENGINES EVALUATED ON A
7-MODE AIRCRAFT EMISSION CYCLE

Figure 11-2
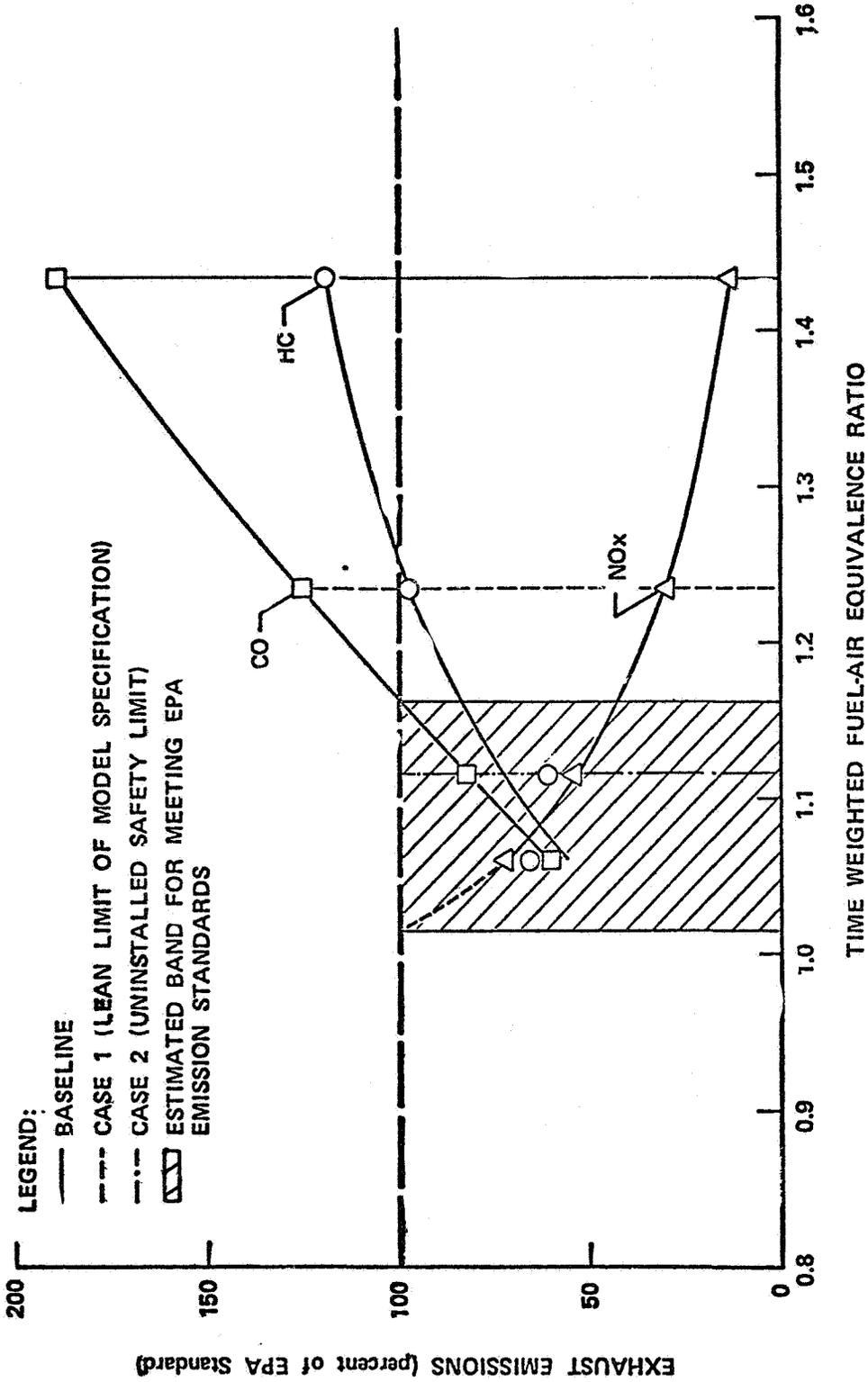
Figure 11-3

IO-520-D, EXHAUST EMISSION LEVELS FOR VARIOUS MIXTURE STRENGTH SCHEDULES

COST CRITERIA ELEMENT WITH A PARTIAL LISTING OF SOLUTION ATTRIBUTES

Sheet: 1 of 7

Criteria: COST

Definition:
Cost is the dollars paid by an organization for an end item or service. Cost is the expected expenditure of money for planning, engineering, manufacturing, and supportive services to realize an effective E3R design solution approach.

Value	
Attributes	Assignment
1. Will the expected cost, to produce the design approach, be high (H), moderate (M), or low (L)?	a. Give a ROM cost estimate range per concept unit:
Arbitrary Cost Scale	b. If ROM cost estimates cannot be made per concept. If ROM cost estimates L, M, H per concept that has low then indicate the concept and (0) to moderate Score (1) to cost indication or high.

Arbitrary Cost Scale

SCALE	RANGE ($)
Low	0 to 99
Moderate	100 to 999
High	1,000 to 9,999

2. Will the concept require engineering analysis and evaluation ability?

Figure 11-4

EFFECTIVENESS CRITERIA ELEMENT WITH A PARTIAL
LISTING OF SOLUTION ATTRIBUTES

Criteria: FUEL ECONOMY

Criteria: EMISSIONS   Sheet: ___ of ___

Criteria: RELIABILITY   Sheet: ___ of ___

Criteria: SAFETY   Sheet: ___ of ___

Definition: SAFETY   Sheet: __1_ of __5_

Definition: Freedom from those conditions that can cause injury or death to personnel, damage to
equipment or property. Safety also implies crashworthiness, freedom
or loss of equipment, and fire prevention.
from hazards,

Attributes	Value	Assignment
1. Are "fail-safe" principles incorporated into the design approach where failures would cause a catastrophe to personnel. or disable the system to personnel? catastrophe to equipment. or inadvertent damage of critical equipment protected operation of critical approach protected		3. If yes, score (1), if no score (0), better Score (1), to the concept features. "fail-safe" design that has minim (0) for concept that has minim safety features a. If yes
2. Is the E³R design approach against "backfire"?		
3. Does the design a minimize		

Figure 11-5

PROCEDURE FOR EVALUATING THE RELATIVE IMPORTANCE OF CRITERIA

- REVIEWS CRITERIA AND SOLUTION ATTRIBUTES

- COMPLETES DECISION ANALYSIS WORKSHEET TO:

  ◄ MAKE VALUE JUDGMENTS BETWEEN PAIRS OF CRITERIA

  ◄ ACCOUNT FOR UNCERTAINTY

ENGINEER NO. 4

ENGINEER NO. 3

ENGINEER NO. 2

ENGINEER NO. 1

EMISSIONS

RELIABILITY

COST

- DEFINITION
- ATTRIBUTES

15 CRITERIA

	CRITERIA	1	2	3	4	5
1	COST	.6/.1	.7/.1	.3/.1	.3/.5	.6/.1
2	RELIABILITY		.3/.5	.4/.4	.4/.4	.4/.3
3	SAFETY			.4/.4	.5/.2	
4	TECHNOLOGY				...	
5						

DECISIONS

Figure 11-6

PROCEDURE FOR EVALUATING THE RELATIVE IMPORTANCE OF CONCEPTS

ENGINEER NO. 4
ENGINEER NO. 3
ENGINEER NO. 2
ENGINEER NO. 1

OTHERS

CONCEPT NO. 2

CONCEPT NO. 1
- DESCRIPTION
- DATA

14 CONCEPTS

DECISIONS

EMISSIONS

CONCEPTS		1	2	3	n
1	HONDA CVCC		0.2/0.1	0.9/0.1	0.4/0.1
2	2-STROKE DIESEL			0.2/0	0.3/0.1
3	FUEL INJECTION				0.4/0
n	VARIABLE TIMING				

- REVIEWS DESCRIPTION OF CANDIDATE DESIGN CONCEPTS

- ASSESSES KNOWLEDGE WEAKNESSES AND EXPERTISE STRENGTHS

- COMPLETES DECISION ANALYSIS WORKSHEETS TO:

  - MAKE VALUE JUDGEMENTS BETWEEN PAIRS OF CONCEPTS WHEN TRADED OFF AGAINST THE CRITERIA AND CONSIDER:

    -- ADVANTAGES
    -- DISADVANTAGES
    -- RISKS
    -- CONSEQUENCES

  - ACCOUNT FOR UNCERTAINTY

Figure 11-7

EXAMPLE OF CONCEPT PREFERENCE RANKING

ENGINEER NO. 1
ENGINEER NO. 4
ENGINEER NO. 3

CONCEPT PREFERENCE RANK FOR ENGINEER NO. 2

CONCEPT	RANK	MERIT COEFFICIENT	UNCERTAINTY
Improved Cooling Combustion Chamber	1	0.06195	0.02917
Air Injection	2	0.05478	0.02845
Improved Fuel Injection Systems	3	0.05416	0.02544
Thermal Fuel Vaporization, Ethyl	4	0.05300	0.02726
Hydrogen Enrichment, JPL	5	0.04922	0.02226
Ultrasonic Fuel Atomization, Autotronic	6	0.04915	0.02525
Multiple Spark Discharge System	7	0.04779	
Texaco CCS			

SELECT
AND/OR
MODIFY INPUT
CONCEPT VERSUS CRITERIA
DATA SETS

INPUT

OPTIMIZED CONCEPT MERIT
COEFFICIENT AND RANKING
DATA SET

Figure 11-8

DATA FLOW PROCESS TO ACQUIRE CONCEPT RANKING
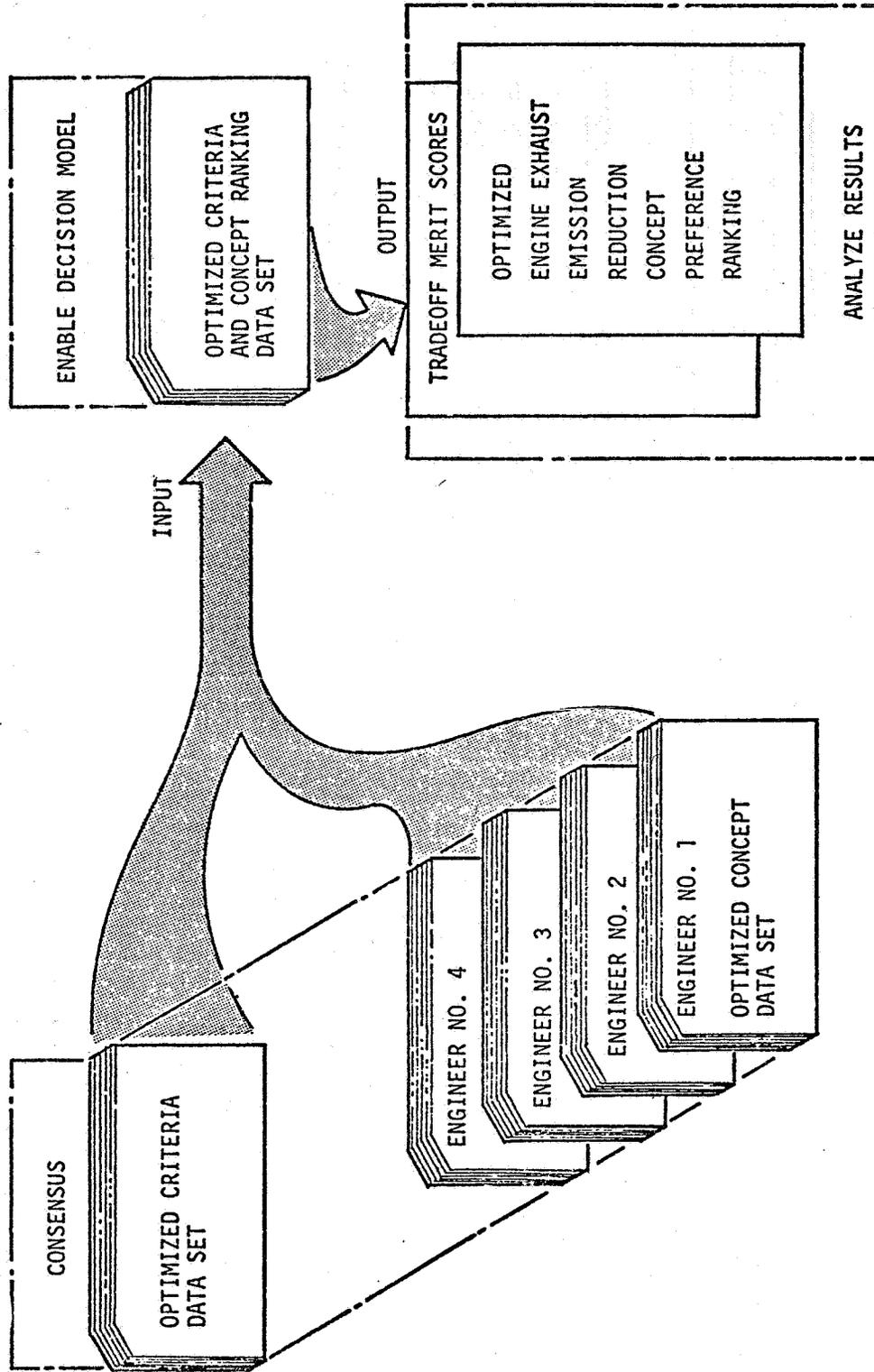
Figure 11-9

ENGINE EXHAUST EMISSION REDUCTION CRITERIA
EMPHASIS COEFFICIENTS AND RANKING - OPTIMIZED

CRITERIA	EMPHASIS COEFFICIENT	UNCERTAINTY
EMISSIONS	0.10952	0.00138
SAFETY	0.09676	0.00750
PERFORMANCE	0.08714	0.00701
COOLING	0.07695	0.00707
WEIGHT AND SIZE	0.07238	0.01159
FUEL ECONOMY	0.06990	0.01020
COST	0.06771	0.01192
RELIABILITY	0.05933	0.00903
TECHNOLOGY	0.05548	0.00658
OPERATIONAL CHARACTERISTICS	0.04200	0.01059
MAINTAINABILITY AND MAINTENANCE	0.04029	0.00924
INTEGRATION	0.03324	0.00295
MATERIALS	0.03029	0.00305
PRODUCIBILITY	0.02933	0.00210
ADAPTABILITY	0.02781	0.00267

Figure 11-10

12. AVCO LYCOMING/NASA CONTRACT STATUS

Larry C. Duke

Avco Lycoming
Williamsport, Pennsylvania

Avco Lycoming and Teledyne Continental are cooperating with the NASA Lewis Research Center in a study of ways to reduce emissions from aircraft piston engines. This study is based on the standards promulgated by the Environmental Protection Agency (EPA) for carbon monoxide (CO), unburned hydrocarbon (HC), and oxides-of-nitrogen (NO_x) emissions. We drew on many concepts that have been used in the automotive industry and also on practical experience. For example, 1973 and 1974 cars experience acceleration problems, particularly in accelerating from stoplights. Simple leaning procedures and spark advance changes were ruled out as suitable emission reduction methods. Our past experience showed that these methods can cause hesitation problems. And when tried by the automotive industry, leaning procedures degraded fuel economy to a certain extent. These factors, plus concern for diminishing fuel reserves, emphasize the importance of the objectives set forth in the NASA Request for Proposal (RFP).

The contract called for design and testing of aircraft piston engines to determine the effects of hardware changes on exhaust emissions, fuel consumption, safety, weight, performance, maintainability, and so forth. Specifically, the investigation was designed to document pollutant yields, namely unburned hydrocarbons, CO, and NO_x, from aircraft piston test engines. These engines would be modified to include a major redesign of the engine as well as two relatively minor changes. The RFP was a little broader than that; it allowed more than two minor changes to be made to the engines. We have combined two minor concepts into one to make a viable system in itself. Also, we wanted to document the effects of these changes on fuel consumption and to look at safety, cost, weight, and the other significant factors. Finally, we wanted to establish some operational limits in which these concepts may be used safely and in good engineering practice.

An in-house study reduced our original 10 concepts to three that we considered worthy of further testing and investigation. The first concept, a major one, was variable valve timing. High-power, high-speed engines such as TIGO-541, which is rated at 450 horsepower and 3200 rpm, have high valve overlap. Bringing that engine back to idle

or off-speed conditions from that rated power setting causes too much valve overlap and short circuiting of the intake charge. The raw fuel coming into the engine thus goes directly into the exhaust. As mentioned in an earlier paper, the higher power turbocharged engines were over the EPA hydrocarbon limits. A breakdown of the emissions contributed by each mode shows that most of the hydrocarbons come from the taxi mode, which is essentially a low-power mode where the effect of high valve overlap is very pronounced. A variable valve timing system allows the timing to be optimized at each power condition. At idle/taxi conditions the timing can be optimized for emissions control. At cruise conditions, which are also considered in component development, the timing can be optimized to produce fuel-lean conditions without the need to compromise as much for the power condition.

Two minor concepts were also considered. One was ultrasonic fuel atomization. This concept is directed uniquely to carbureted engines. Some carbureted engines have cylinder-to-cylinder distribution problems at part throttle. The cylinder-to-cylinder distribution of air actually makes the engine run in conditions that are not ideal for it. One cylinder may be running lean, and another one rich. Therefore, in cruise conditions, when the pilot is "leaning out" to obtain fuel economy, he will essentially be limited by the leanest cylinder in the engine, that is, the one that starts to get rough first. That cylinder will limit how much he can lean out and thus limit fuel economy. In the ultrasonic atomization concept, better breakup of the fuel should distribute fuel droplets more evenly, or minimize the quantity of large fuel droplets, and actually direct them or allow them to flow with the airstream to each cylinder.

The second minor change we considered was to the ignition system, where several changes were combined into one concept. A high energy, multiple-spark discharge system, basically a modified magneto, was combined with spark plug tip penetration tests. At low power, ignition of the intake charge is not always as good as desired. Better ignition will not only lower both CO and hydrocarbon emissions but also improve fuel economy.

VARIABLE VALVE TIMING SYSTEM

Each concept has gone through its initial design stage. Figure 12-1 shows a product of the initial design stage of the variable valve timing system. This is the camshaft of the engine, which is essentially the heart of the valve timing system. Basically, the camshaft is made of two concentric shafts. There are two disks with several holes in them at the right end of the shaft. One disk is connected to the inner shaft and one is connected to the outer shaft through a sequence of holes. The positions of these two shafts can actually be changed with respect to one another. One shaft has pinned to it all the intake

lobes of the camshaft. The outer shaft has pinned to it all the exhaust lobes of the camshaft. So essentially we have two concentric shafts: one controlling exhaust lobes, one controlling intake lobes. The intake-to-exhaust-valve overlap can be varied by turning the shafts relative to one another. In a standard engine, camshafts produce valve overlaps of about 35 to 50 shaft degrees. The variable design allows the overlap to be varied from essentially no overlap, to a degree or so of overlap, to about half again as much as the standard overlap. This is a fair range (approx 70 crankshaft degrees), and by a simple cutting or remachining process that range can be extended a little further.

At the left end of the camshaft (fig. 12-1) is another set of disks. These disks are also connected to two concentric shafts: one directly to the drive gear, the other to the camshaft proper. The gear in the accessory housing of the engine is the actual driving gear for the camshaft. Changing the position of one of these disks changes the timing of the opening of the intake valve. Both the intake and exhaust valve openings can be shifted relative to the engine timing. The first set of disks regulates the occurrence of the valve action; the second set regulates the relative action of one valve to the other.

This variable valve timing system is now being incorporated into an engine. This engine will initially be tested on a dynamometer. Since it is a new type of engine, some work must be done on it prior to emissions and performance testing. Essentially, we have to run through a torsional survey to ensure the integrity of the dynamic rotating system.

Variable valve timing is a major redesign of the engine, and as is evident from the type of fabrication, it is not an automatically controlled system. Because of the slip disks (the ones with the pins in them), the engine must be physically stopped, changed to the next condition, and then started again to get several data points. The variable overlap disk actually protrudes from the front of the engine, while the variable timing disk is in the accessory housing at the rear of the engine. Further development programs in this NASA-funded effort will examine ways of automating this system once the optimum conditions and timing are defined.

ULTRASONIC FUEL ATOMIZATION

The second concept that we are studying is ultrasonic fuel atomization. The atomizer has been adapted to a vertical-draft engine. It bolts to the oil sump and intake arrangement. The intake distribution system is contained within the oil sump. Figure 12-2 shows this adaption on an Autotronics Control Corporation engine. The atomizer fits between the carburetor and the sump in this development stage and is controlled

by a separate drive power unit that is mounted elsewhere on the test stand. The atomizer is about 4 inches long and is visible in figure 12-2 as the circular tube protruding toward the glass window. A power drive unit mounted on the side opposite the window vibrates the tube at ultrasonic frequencies. Fuel coming from the carburetor is directed onto the tube by two venturi-type wedges that are mounted inside the ultrasonic atomizer. Any large fuel droplets should hit this tube, be atomized by the ultrasonic action of the tube, and then continue into the sump in a normal manner and out to each intake pipe. In further development work, if the concept seems beneficial, this engine-atomizer combination will be applied to a current aircraft design. That is, the sump will be modified so that the ultrasonic atomizer can fit into it. Then the carburetor can be returned to its standard location so that the overall physical size of the engine will remain the same.

Of course, this is still far in the future. So far, we have tested this engine-atomizer combination on a dynamometer. Although there has been no detailed analysis yet, the venturi wedges seem to be limiting the full-throttle manifold pressure, causing a penalty in power output on the order of 3 percent. We expected a penalty but wanted to make sure of its magnitude. As examination of brake specific fuel consumption on the dynamometer test showed that the fuel consumption characteristics have remained unchanged. However, there were some indications of improved cylinder-to-cylinder distribution. No final conclusions on this will be made until after emissions testing has been performed. Fine tuning cylinder-to-cylinder distribution should show up in emissions testing but may not be reflected either in fuel consumption or power measurements. Thus, the ultrasonic fuel atomization concept is halfway through its development stage.

IGNITION SYSTEM CHANGES

The final concept is ignition system changes. Figure 12-3 shows a standard spark plug used in aircraft piston engines. The design philosophy that was used is apparent. The spark plug is actually in a small cove adjacent to the combustion chamber but protected from the combustion chamber itself. This design criterion was developed in detonation and high-power running tests, where it was found that projecting the spark plug tip too far into the chamber could cause detonation. The spark plug location is also dictated by the physical space available to install it. However, it may be that, by projecting the nose core forward into the chamber, detonation can be used to provide both lower emissions and greater fuel economy. Certainly, at low-power conditions where the combustion chamber pressures are not high and there is appreciable exhaust gas dilution, a spark plug that does not protrude sufficiently into the combustion chamber cannot provide an effective spark to the gases in the chamber.

Figure 12-4 shows the nose core extended so that it begins to project into the combustion chamber proper. Figure 12-5 shows the nose core extending further into the combustion chamber. This is a prototype system on which substantial work will be required. Detonation problems have been identified in the past, and we are reexamining them to see where detonation and emissions reduction can be traded off. The ignition system is to the point where the engine is built and ready to run as soon as a test stand is available.

CONCLUDING REMARKS

When will these innovations be available commercially? They are all "down the road" items. They are fairly radical systems, different from standard practice, and require much in-service testing to fully assess them. Figure 12-6 is a schedule showing roughly when each of these systems might come into use. The program has been divided into two parts: the major concept, variable valve timing; and the two minor concepts together, ultrasonic fuel atomization and ignition system changes. The NASA contract is structured as a 3-year program. The program started in October 1975 and will continue to August or September 1978. In that period, component development tests will have brought these concepts to a point where they are applicable to aircraft. Certainly, a major amount of engine development will be required after the NASA contract is completed, especially on the major concept. This concept will need to be endurance tested, so that it can be certified as viable for use in an aircraft. About $2\frac{1}{2}$ years of additional in-house work will be needed to make sure that every parameter is covered and that the system compensates for the variable valve timing automatically. This will require an engine certification program including an automatic control system. Difficult problems will have to be studied and solved. For the minor concepts, a fairly short period of about an additional 1/2 year will be needed for engine certification. Next, these concepts will be service tested and then certified in manufacturers' airframes. The major concept will require a new aircraft design, especially in the cowling area. The last step will be production release, production tooling, and actual marketing of the product.

In conclusion, for the minor concepts, it will be perhaps 1982 or 1983 before either is on the market. For the variable valve timing system, which is a radical change, it will be 1986 or 1987 before it will be available commerically. Of course, this is merely a rough estimate of the time needed to develop these concepts.

DISCUSSION

COMMENT - E. Kempke: NASA is extremely pleased with the wide variety of concepts that are being pursued in these two contracts. Each of the concepts we feel exhibits good potential benefits. They're challenging kinds of work with no assurances of success but the potential benefits are there and we feel that the wide variety of concepts should give us a good assessment of where the technology stands with regard to making impacts on the reduction of emissions in the future.

Q - H. Nay: The implementation development schedule you showed had quite a number of engines. If one of these concepts, either the major concept or one of the minor ones, appears to be attractive and you want to implement it, are the saying you can recertify all of your engines in that period of time?

A - L. Duke: No, that's a good point which I failed to bring out. As you can see, these concepts are really designed toward a specific engine - either a carbureted type or a unique engine. I've tried to carry the theme implying that all of these implementations are going to be designed along those same lines as if for one specific engine. This is especially true for the variable valve timing system where we feel that each system will have to be developed on its own for each particular engine or engine model. After you get the first engine out you can start shrinking these implementation schedules, but essentially this is one engine class type.

Q - H. Nay: How many basic types of engines from a seperate development standpoint are you looking at? I know you have some 384 models in production but those break down into specific configurations as affected by emissions, types, changes, etc. How many different classes relative to that criterion?

A - L. Duke: We have approximately 29 Type Certifications (TC's), which would cover engines from carbureted up to turbocharged geared. If you want to divide them into four or five classes, you could say of the order of five or six engines may be covered by one type of concept.

Q - H. Nay: Am I correct in concluding that there would be 29 separate certification programs required and varying amounts of development leading up to the establishment of the configuration that you're going to certificate under those 29 TC's?

A - L. Duke: That's right.

COMMENT - N. Nay: I just might expand right here and talk about the airframe/aircraft certification. The bar that you show represents an aircraft. There are, as far as the industry is concerned, about 64 separate and distinct aircraft involved.

Q - H. Nay: Mr. Helms made the point about the capacity of handling developments on a time schedule basis. Let's talk about your 29 TC aircraft engines. How many engines would you estimate you could recertificate a year if you had all the basic technology in hand and had it developed and proven for one of these major concepts on an engine?

A - S. Jedrziewski: I would say a maximum of 2, and that would really be pushing it.

Q - H. Nay: In other words, if this was the only thing in-house, so to speak, you could do about 2 a year?

A - L. Duke: Right.

COMMENT - H. Nay: That ties in pretty well with the airframe part of the thing. I've had conversations with Mr. Helms and Mr. Rembleski and we looked at this in the past in some detail. In each of the major aircraft divisions we figured that we could do about 2 to maybe a maximum of 3 TC's with some considerable expansion of facilities and capabilities. We are talking basically about a 10-year cycle for the industry to get up to date on a major change of this type.

Q - W. Westfield: On ultrasonic fuel vaporization, you said that you had seen some improvement in cylinder to cylinder distribution. Is this on an actual engine or on a flow-type rig?

A - L. Duke: This was on the actual engine on the dynamometer. It was not emissions data, but it was based on exhaust temperature data. It showed less of a spread indicating some better improvement in cylinder to cylinder distribution. Before we make the final assessment, we'll have to test it on an emissions stand where we are planning to do cylinder to cylinder distribution studies.

Q - W. Westfield: Could you describe how you do cylinder to cylinder studies other than by the temperature patterns?

A - L. Duke: Generally when we talk about cylinder to cylinder distribution in aircraft work we're talking about cylinder head temperatures and where the maximum temperatures of each cylinder occur with respect to fuel-air ratio. That is an indication of what the cylinder to cylinder distribution is if you want a macroscopic view. When we go to the test stand, we're talking about looking at cylinder to cylinder distributions with exhaust analysis equipment. These are microscopic analyses. We are taking measurements both ways and our intent is to correlate the two.

Q - D. Page: I understand the variable valve project is directed primarily toward the turbo supercharged engine in order to reduce hydrocarbons. This approach is addressing only a part of the problem on a certain class of engine. This concept will have to be integrated into the entire family of engines, which in turn must be integrated into the entire family of airplanes. It's going to involve a large amount of cooperation within the entire industry. Have you any comments on what you expect to do and where you expect to come out?

A - L. Duke: You've made a point that these concepts are not intended
to satisfy emission limits. They are aimed at getting to those lim-
its but the concept by itself will not satisfy the limit. Improving
cylinder to cylinder distribution alone without leaning will not
make a carbureted engine meet the EPA standards. I think the NASA
contribution to general aviation is their sponsorship as a whole,
so that anything that we do in this program will essentially be ap-
plicable to anyone who wants to use it, within limits.

COMMENT - L. Helms: He raises an excellent subject. To some extent
it's evident that a certain amount of sterility of subject has occurred
throughout the last 2 days because this subject is, and properly should
be, emissions. We've given little or no consideration in our discus-
sions to other items which are classed with equal priority by other
equally insistent governmental offices. Sometimes I'm often struck by
the various offices that cloister themselves in their own environment.
We in industry are being continually pressed very hard for fuel con-
servation efficiency, which is in tune with leaning. There are some
individuals who imply that we can aerodynamically cool the engine. How-
ever, you have to consider that more cooling air means a larger cowling,
which means more drag in cruise, and thus poor fuel economy. I men-
tioned yesterday that increase in drag also reduces our rate of climb
and puts us down to the point where we can't make the 84 dB curve for
noise. Now we're back to the same position with EPA on noise. We say
that we can increase engine rpm and help the cooling flow, but that in-
creases the tip Mach number of the propeller. So now we have the same
noise problem We in industry would prefer to decrease that rpm to get
the noise down. Outside of the technical areas, we have the National
Transportation Safety Board (NTSB), pressing us for systems for ex-
panded safety. We obviously feel, as we know most of you do, that
safety should be paramount. All of those discussions exclude the re-
quirements of the International Civil Aviation Organization (ICAO),
agreements which are handled by other segments of the government and
to which we must respond. The Commerce and State Department are pushing
us for more export sales because general aviation is a real gold mine
for them. We have about a $2 hundred million a year favorable balance
of trade. I continually get comments from the Commerce Department and
State Department on what can you fellows do to do better. A key item
is that our resources are not limitless and, as such, some of them are
very foolishly expended because of the various government agency re-
quirements. The best example I can think of is our new Lakeland plant
where we did an industrial engineering survey which resulted in the in-
stallation of red lights at eye level to warn our employees of a poten-
tial of fire. A group from OSHA came in and said that people may not
be looking and wanted bells, very large bells, mounted on the wall
with an automatic alarming sensoring system. We took out the lights and
put the bells on the walls. It took us 6 months and cost us some $15 to
$20 thousand. Another group came in and said the environment was too
noisy even though we had the small ear plugs. They wanted the large
ones so we furnished those. A third group came in and said those people
with ear muffs couldn't hear those bells. Now the result of this was a

study in which they came with the solution of getting rid of the bells and putting eye level lights on the plant. My remarks are not capricious and they're not casual. The isolation of one segment of the government yet interacting on another is something which we have to live with day to day. A very good point was raised about the total problem rather than just one engine, one aircraft, and one certification effort.

Q - C. Rembleske: Will the requirements for the installation of engines incorporating your concepts be changed in such a way that existing airframes will not adapt to that concept?

A - L. Duke: No. As far as the existing airframe goes, I'm sure that it will adapt to products like this if we could change cowling or mount configuration. Personally, I think that it is a good opportunity for the airframe manufacturers to incorporate new ideas on their own as far as aerodynamics or whatever since there is a re-certification required here. You may not be in agreement with that, but that does present itself as an opportunity.

COMMENT - C. Rembleske: Many times we utilize the same type of engine or the same engine with minor modifications in several of our aircraft. Each and every one of those aircraft is an individual aircraft and as such must be treated throughout the certification program as a separate and distinct problem. While we may utilize the same engine, we very often find that there are radical differences between installation in different aircraft models within our own plant. Turbine powered aircraft do not have that problem. Once a configuration has been established that will work for one turbine engine we have found that it's a relatively simple task to transform that installation to another aircraft. This has not proven to be the case in the reciprocating type installations. There we have found that only minor variations or changes in the final airplane characteristics have established complete new programs and have changed requirements from one aircraft model to the other. It's not a simple problem taking one engine and putting it into a similar aircraft. We do have major problems in those development areas.

COMMENT - W. Mirsky: In reference to your ultrasonic carburetor, I did quite a bit of work on ultrasonics. Before I did the work my hearing was good. Some years later my hearing was bad and I don't know if the ultrasonics was responsible for this decrease in hearing. I think it might be worth your while to get in touch with some medical people who may have expertise in this area to see what the potential health hazard would be when you are exposed to the ultrasonics. Because you cannot hear it, you don't know how much energy is involved and you don't know what potential damage may be occurring to your hearing.

COMMENT - L. Duke: When we were running the tests I kept wondering if I was losing my hearing or not.

Q - G. Kittredge: I have a question about your variable valve timing
project which touches on some of the comments that Mr. Helms just
made. It seems to me that this is a basic, complex, and presumably
more costly engine change than the other two engine concepts you're
looking at. It looks as though it might have to have more arguments
going for it to sell that kind of a change than just meeting the emis-
sions, particularly the CO, standard. It would seem reasonable that
variable valve time would also realize some benefits in terms of
part throttle fuel consumption. Have you looked at this in your
analysis or will I have to wait for experimental data?

A - L. Duke: As part of the analysis in NASA's program, we have looked
at the EPA cycle and the various power levels as to what fuel econ-
omies you can have, primarily for level cruise conditions. Our first
goal is emissions, but we put an equal emphasis on fuel consumption
as to what we're trying to reduce or improve.

Q - G. Kittredge: Do you think that variable valve timing might have
some payoff for you in that area?

A - L. Duke: Yes, we do.

Q - F. Monts: You mentioned that the variable valve timing concept would
require new installation requirements and perhaps different installa-
tion concepts. What has variable valve timing to do with our present
constraints in installation?

A - L. Duke: As I see it, the controlling factor is the actuating mech-
anism. If we're talking about something that's automatically con-
trolled and can be contained within the engine that's one thing. If
we're talking about an electronic control that has to be separated
or divorced from the engine, that's quite something else. The prob-
lems may not be metal bending but could be new problems of installing
that control unit in an aircraft, regardless of whether it's electronic
or hydraulic.

Q - F. Monts: Will the ultrasonic concept to make carburetors vaporize
fuel better work with a horizontal type of carburetor as well as an
updraft carburetor?

A - L. Duke: Yes, from all indications we have from Autotronics it will
although it may require a little modification to their design.

Q - H. Nay: Is one installation effect of the variable valve timing a
significant weight increase?

A - L. Duke: Yes. In this design we're talking about a cam shaft that
has doubled in weight. This is an early design so we are talking
about a heavier installation right now.

Q - H. Nay: In your presentation yesterday on IO-360 work you showed it
as being basically high idealized, under laboratory conditions, with
the fuel control adjusted after the engine was warmed up. Under those
conditions, the EPA standards levels of emissions could be met. I
didn't see any allowance for the real world production tolerances.
Could you give us an estimate of what those production tolerances

would be? Also, the reduction in CO with that approach is totally
dependent on a yet to be developed automatic mixture control device
to use in the low power range as well as the application of existing
technology in automatic mixture control devices applicable to the
higher power range. . I'd also like you to comment specifically on the
production tolerances expected with the automatic mixture control
devices.

A - L. Duke: We did show an idealized case fully compensated that came
to 98 percent of the CO limit. There were no production tolerances,
no real world situations. Taking off the compensating hardware,
which was the other case shown on that graph, caused the CO to go up
to 140 percent of the limit. With no compensation at all, you were
up to some 40 percent over the limit. Adding on the production tol-
erances of the injectors that are being produced now, that 140 per-
cent would be the minimum obtainable. An engineering estimate of
the CO with a rich limit system would be 160 or 170 percent of the
limit. The production band spread that we saw in the normally as-
pirated engine tested showed a 20 to 30 percent variation in the
emissions at the same mode. Essentially, we're talking about the CO
being anywhere from 100 to 200 percent of the limit. There could be
as much as a 100-percent spread if you took away all of these nicities
that were shown. Some tolerance band still exists on installing the
automatic mixture control because it's not a perfect item and will
have variations. I would guess those variations have on the order of
2 to 3 percent variation on fuel-air ratio. I can't come up with a
number as to what the overall reflected emissions would be, but it
could be some 20 percent.

Q - L. Helms: The ultrasonic fuel vaporization device was shown mounted
externally down below the oil sump. It was stated that the device
would be buried inside the oil sump in a final configuration. Yes-
terday's discussion showed the oil temperature rising in three cases
to an unacceptable level, which was very surprising to me. Would
the displacement within the sump of even that amount of oil require
a larger sump? Secondly, is it possible that we're creating a new
problem which entails a major oil cooler development?

A - L. Duke: I don't know the answer because of the difference in engines
we're talking about. Before we were talking about an IO-360, 200
horsepower engine; here we're talking about carbureted engines, pre-
sumably of the lower hp range. We could definitely have a problem
there. But that's something that's so far down the road we have not
even started to consider it yet.

Q - C. Rembleske: In this ultrasonic fuel vaporization system for car-
bureted engines, what effect will that have on the ice forming char-
acteristics on the various types of carbureation-type systems we
have today?

A - L. Duke: It is a potential problem, but it is far down the develop-
ment stage and it is something that is in the service and engine
certification testing area. It is something that we cannot really
answer on a test stand; it has to come from in-flight testing.

Q - C. Rembleske: Do you know of any work that has been actually done in that area relative to this type of carburetion system?

A - L. Duke: I do not.

Q - C. Gonzalez: Have you considered coupling the variable valve timing with the ignition timing changes since they both involve an accessory or gear case shifting device on the back of the engine?

A - L. Duke: We are approaching the program as if there are separate and individual concepts to be studied. At the end of the program there may be an opportunity to combine high energy spark with variable valve timing or even changing the timing of the ignition. If Continental can show progress in variable ignition timing, perhaps that, in conjunction with our improved spark, would be a good overall system.

Q - C. Gonzalez: In the event of a malfunction on the valve timing system, will it fail in such a way that the system will develop full power?

A - L. Duke: It would have to fail in full power since safety is one of our criteria.

Q - C. Gonzalez: If you go to a vaporization system, obviously you need an electrical source. Are you considering one? What would be the consequences of this electrical source becoming inactive and resulting in the ultrasonic device becoming inoperative? Are you considering an automatic enrichment under those conditons?

A - L. Duke: We've not gone as far as running lean or as running so lean that we saw we were in trouble if we turned the ultrasonic vaporizer off. We have conducted tests on the dynamometer where we ran with the vaporizer on and off and did not see any measurable power difference. My first impression is that the vaporizer does not affect a gross term such as horsepower as it does the minuscule term of emissions. There is no power penalty to pay.

Q - D. Page: It looks like we're attacking this problem piece meal. I ultimately foresee an engine with both the variable cam timing and the ultrasonic carburetor. It could be possible that you'd wish to have an idle range carburetor and run the engine under power conditions with a fuel injection system. The FAA, of course, is going to look at it with an extremely jaundiced eye. If it were my region I would probably give the manufacturer a real physical fitness program. There's something about the development schedule shown that rangles me. I'm saying maybe we'll get down to the year 1982 or 1984 and then we'll discover we can't fire what we've got in the cylinder. This is like a jigsaw puzzle. You don't know what the girl looks like till you get the last piece in the puzzle and it scares me to start out on a program like this without knowing that all pieces of the puzzle are in the box. Do you have any comments as to what you conceive might be out there that you haven't even through of yet?

A — L. Duke: Those kinds of questions are certainly well put when you
have a definite program like we've all experienced in piston aircraft
engines. If I want to certify an engine that was certified at 350 hp
to one certified at 380 hp, I know my beginning, I know my end, and
I know what goes in between because I've done it all before. I can
tell you in 3 days exactly what it's going to require. But these
programs are different. They are basically research programs. There
is no one answer to all the questions. We can only project and as-
sume that if everything goes right, this is what we think will
happen.

COMMENT — G. Banerian: I think that there's a bit of confusion as to what
the real motivation of NASA research is. Most of you know that NASA re-
search, like military research, is directed to long range solutions. We
want to provide a good data bank for decision making for future systems.
Unfortunately, from yesterday's virtually tweaking of the engine, to to-
day's radical changes, there is confusion that seems to imply that our
main motivation is to help industry to comply with the 1979 standards.
That's not our main reason to be in business. Now, it's true that we are
doing things that may be adaptable; for instance, ultrasonic fuel vapor-
ization may be adopted in time. But that's not the main motivation
behind our research. We want to essentially tell you about the technology
which is downstream and the dates of implementation. The dates of satis-
factory completion are contingement on the success of the technical pro-
gram and the amount of funds that are put into it. We'll uncover problems
and eventually we will have systems that are totally integrated, this in-
cludes the ignition and the carburetion systems. Even though some ele-
ments may be heavier than the cam shaft, ultimately they should lead to
a higher efficiency system with the pollution aspects taken care of con-
currently. Our program is essentially a long range one and not meant
necessarily to help you comply with the 1979 standards.

VARIABLE VALVE TIMING

C-76-3966

Figure 12-1

ULTRASONIC FUEL VAPORIZATION

C-76-3965
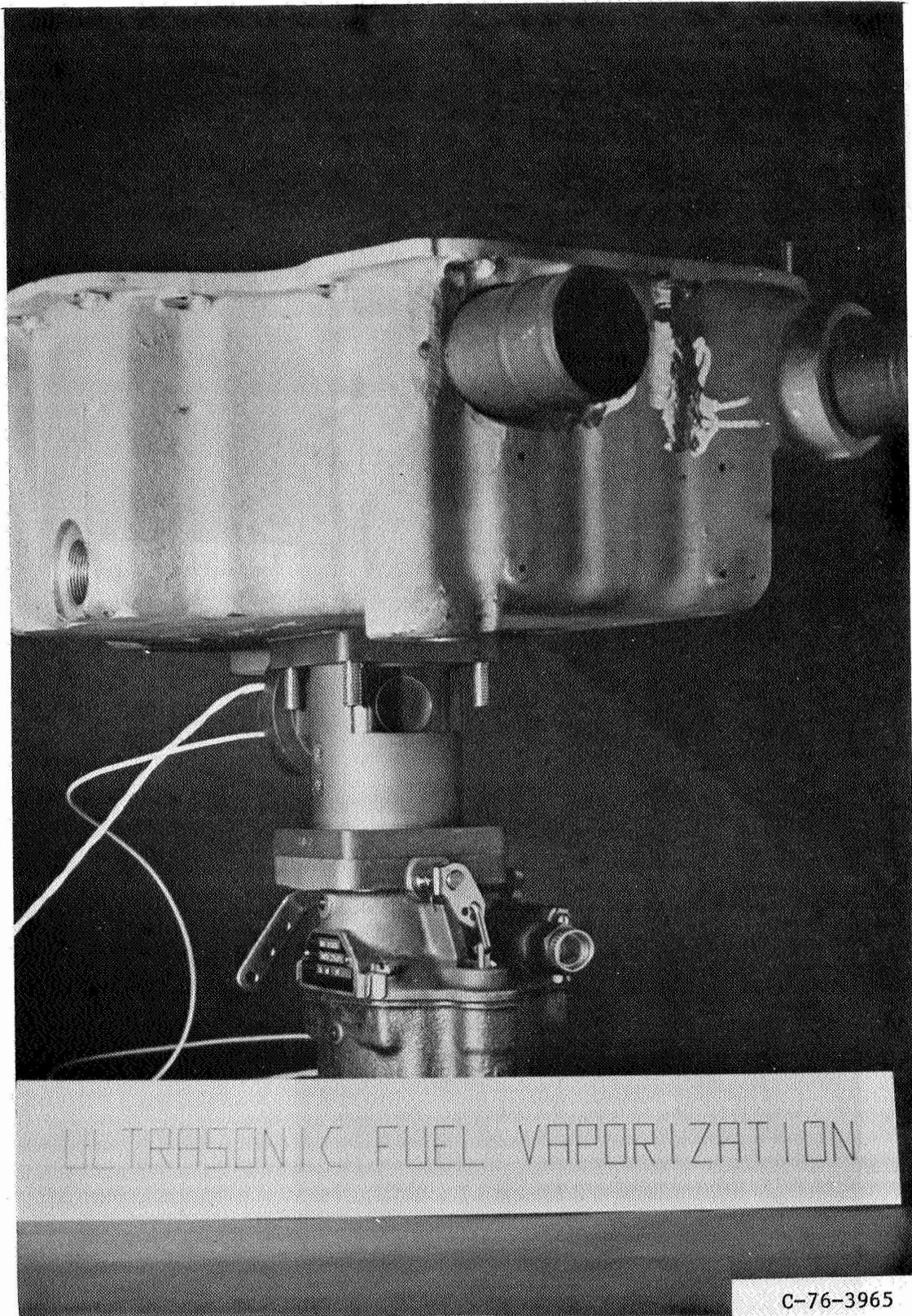
Figure 12-2
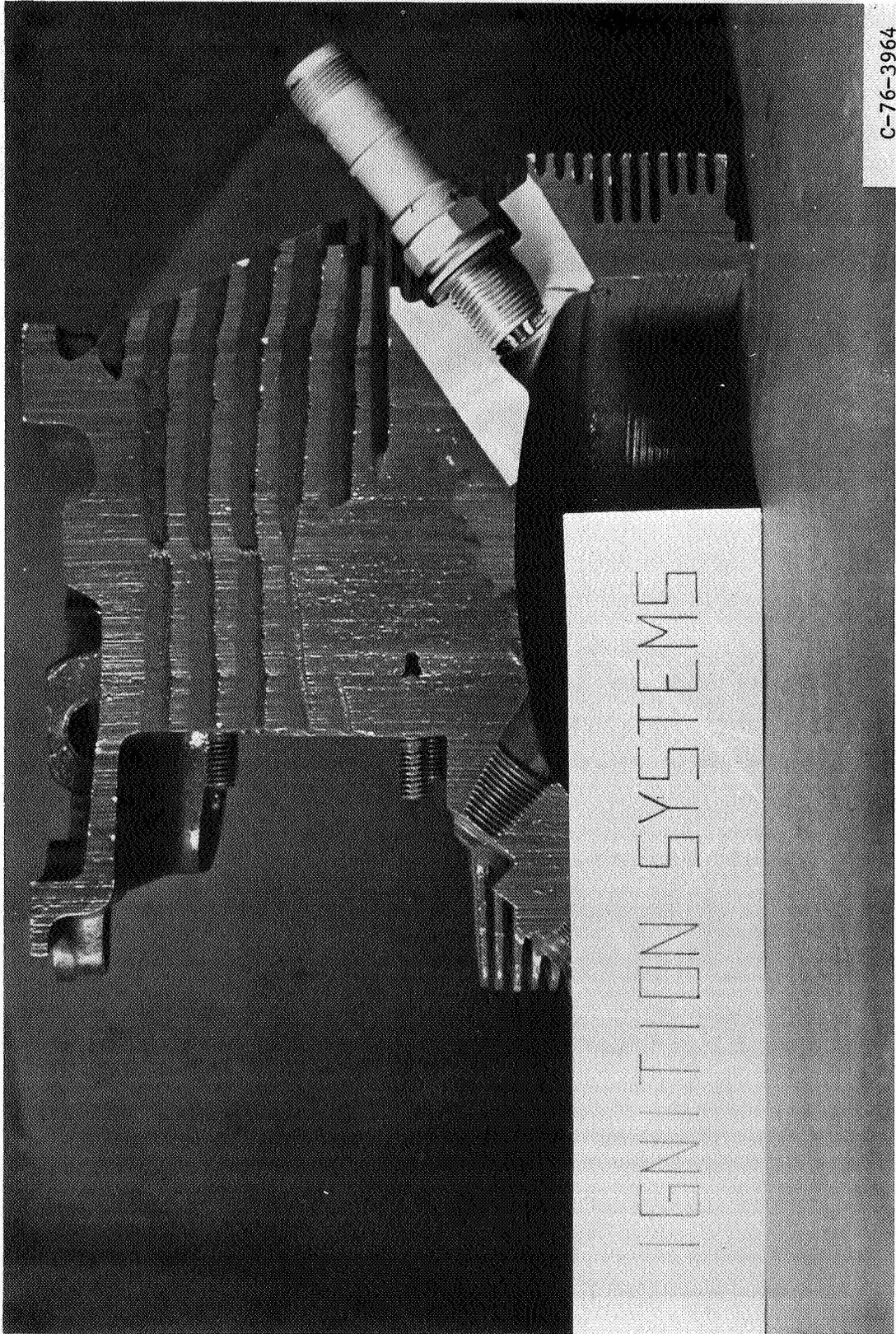
IGNITION SYSTEMS

C-76-3964
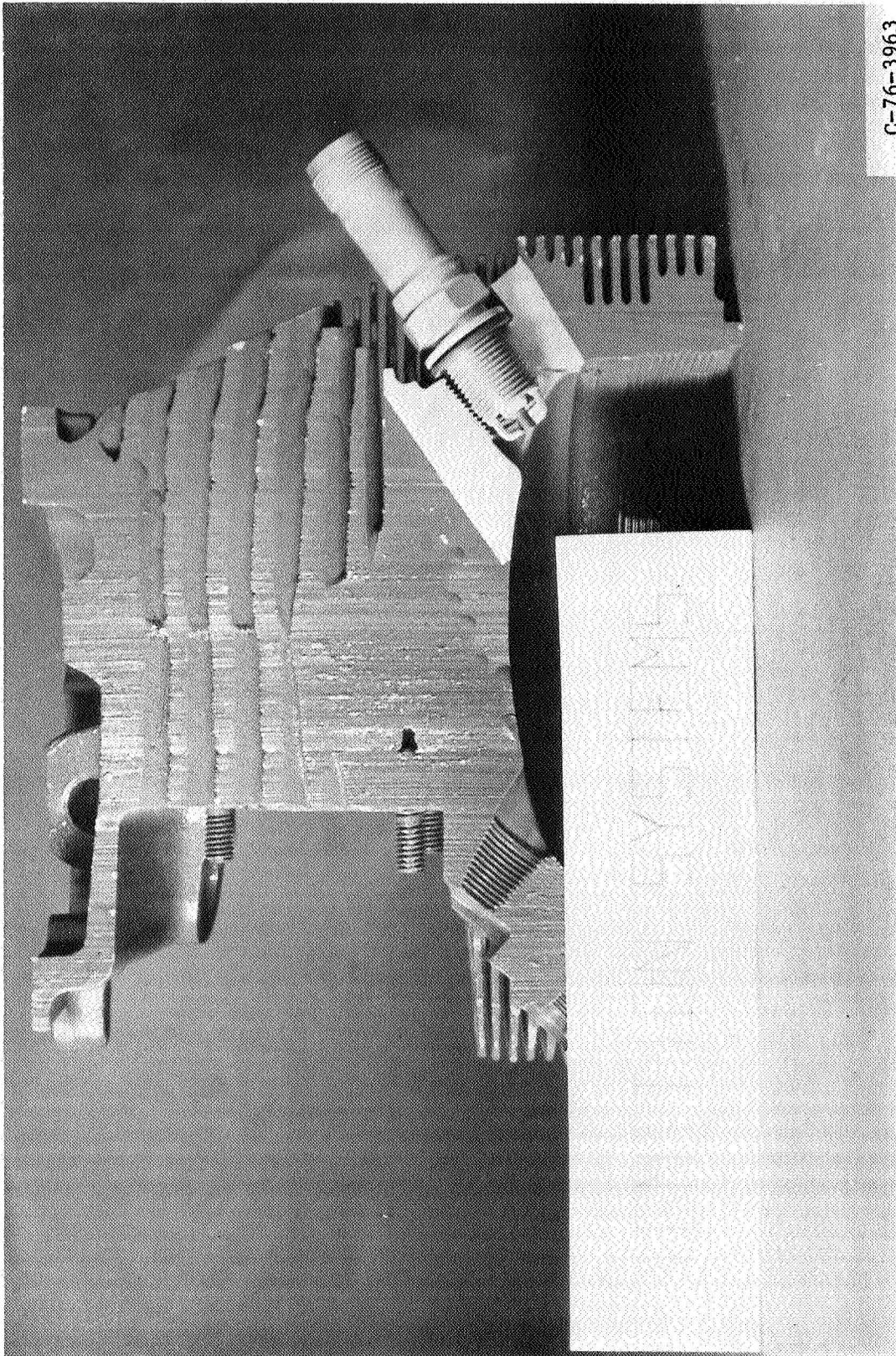
Figure 12-3

Figure 12-4
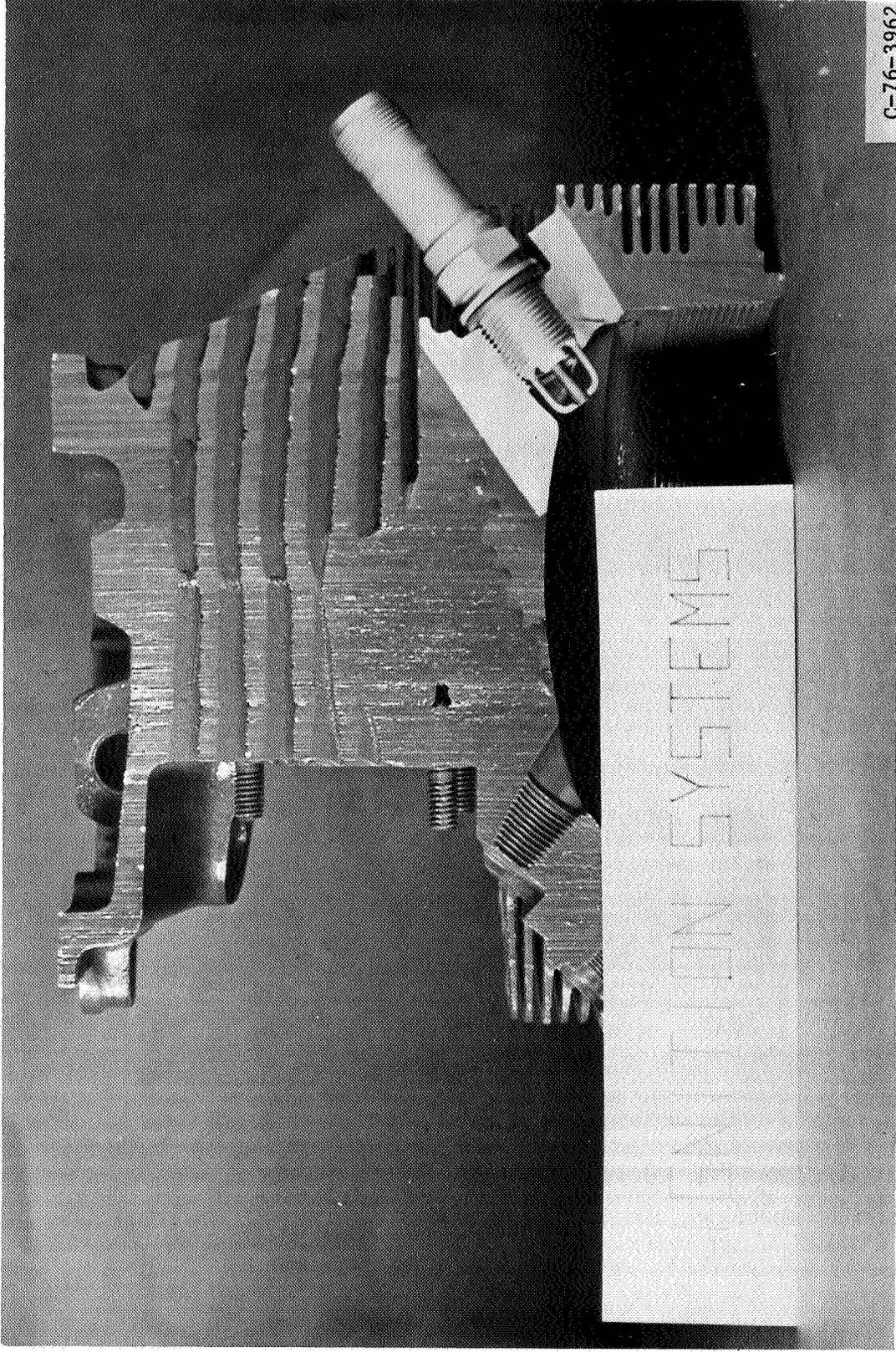
Figure 12-5

PROJECTED TIME SCHEDULE FOR
PRODUCTION AVAILABILITY OF
EMISSION REDUCTION CONCEPTS

MAJOR CONCEPT:
VARIABLE VALVE
TIMING

MINOR CONCEPTS:
ULTRASONIC FUEL VAPOR-
IZATION OR IGNITION SYSTEM

COMPONENT
DEVELOPMENT

ENGINE
CERTIFICATION

IN-SERVICE
TESTING

AIRCRAFT
CERTIFICATION

PRODUCTION
RELEASE

NASA
CONTRACT
NAS3 - 19754

COMPONENT
DEVELOPMENT

ENG.
CERT.

IN-SERVICE
TESTS

A/C
CERT.

PROD.
RELEASE

76   78   ,80   82   84   86   88

YEAR
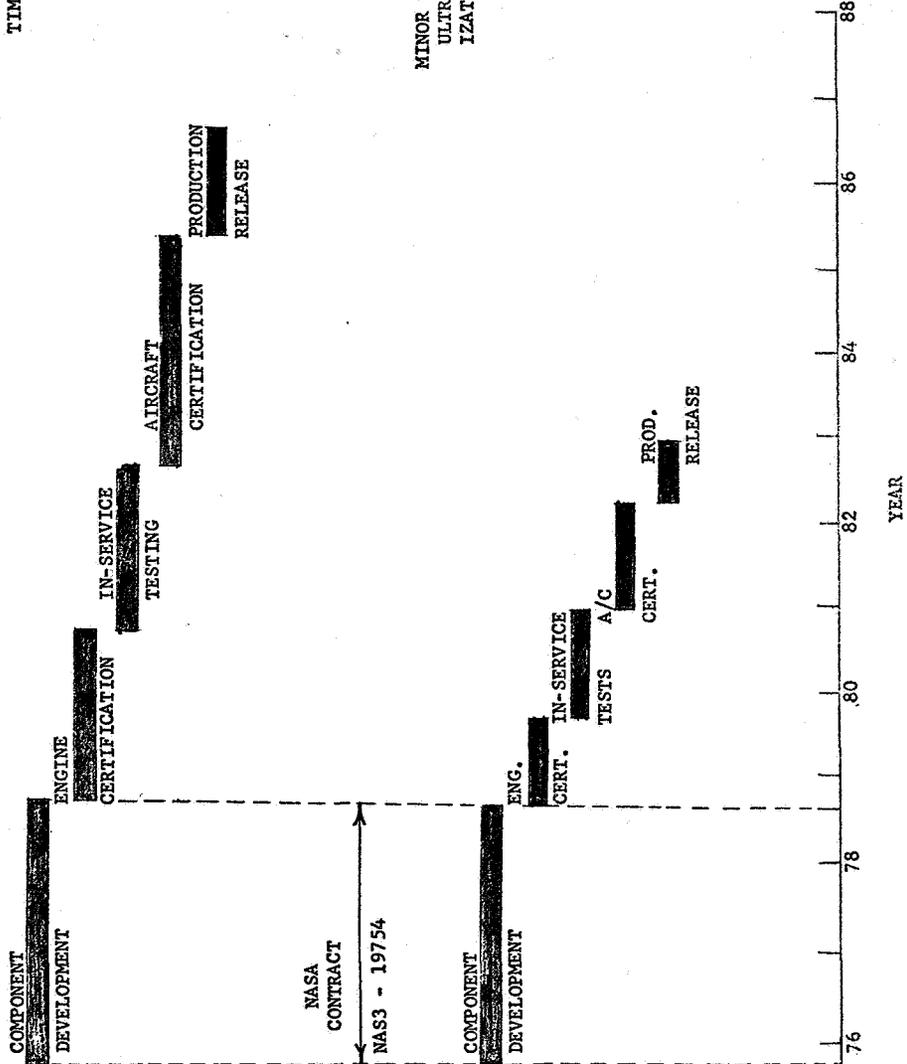
Figure 12-6

13. FUTURE DEVELOPMENT PROGRAMS

Les Waters

Teledyne Continental Motors
Mobile, Alabama

The programs conducted to date by TCM have provided useful information on aircraft engine emissions characteristics and on the potential for reductions obtainable by leaning of current fuel systems. The work completed to date allows us to draw important conclusions at this time, the most significant being that none of the engines tested in the program, which covers a significant group of our basic engine types, could meet Part 87 of EPA regulations on a production basis and within safety of flight limits. As stated in an earlier TCM presentation, some reductions are possible but they are small compared to baseline emissions of current engines.

In considering our present knowledge of exhaust emissions at TCM and the work that lies ahead of us to achieve the substantial emission reductions needed to meet Part 87, we have planned a company program which has a main drive to develop those emission reduction concepts that have the promise of earliest success. These programs will, in general, attempt to enhance existing engine systems, exploiting their potential for emission reduction as far as is compatible with retaining the well established features in them that are well understood and in current production. This approach will minimize development times and retain much of existing know-how that is always vital in ensuring technical performance in production engines.

This program of direct development of emission reduction requires complementing by an additional very substantial effort to provide a wide spectrum of information to fully circumscribe the problems of ultimately producing aircraft engines that meet Part 87.

The intended programs identified to date in the area of new concepts are

(1) Upgrading the TCM fuel system. Temperature and altitude compensation capability will be developed for the system. The potential benefit of better fuel-air ratio control over a temperature range would be, for instance, in reducing idle/taxi mode fuel-air ratio which presently is set for operation at the coldest day and is richer than necessary for engine operation at higher temperatures.

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(2) Evaluation of accelerator pump. We have seen that a limitation in leaning the idle and taxi modes is the inability to accelerate from those conditions. Temporary augmentation of fuel flow by acceleration pumps may have the potential to provide safe operation in the transient condition between steady-state leaned conditions.

(3) Reduced cooling requirement. Cylinder head overheating also imposes limitations on leaning. We are therefore investigating the potential for improved cooling using two approaches. These are means for reducing thermal loading of the cylinder assembly and secondly improved heat dissipation. Hardware evaluation will follow if present studies show promise.

(4) Variable spark timing. The lean misfire limits can be extended by varying the ignition timing. Although misfiring has not yet imposed a limitation on leaning, we believe it is possible that this limit will be met as we attempt further leaning. An automatically controlled variable spark timing could be beneficial, probably in transient conditions. No such systems are presently available for aircraft, and a considerable development program would be involved in attaining production status of this idea.

The following programs are intended to provide the information we believe is needed for a full definition of the emission reduction task in TCM engines.

(1) Survey of baseline emissions of TCM engine range. The baseline must be determined; case 1 and case 2 emission levels for the basic engine models have not been tested to date.

(2) Determine effect of production tolerances. We have seen in the difference between baseline and case 1 emissions that the effect of fuel flow tolerance is very significant. It is probable that other effects are significant also, one possibility being varying hydrocarbon emissions having as a source the lubricating oil which passes into the combustion chamber. The consistent control of lubricating oil in the first few hours of engine life is notoriously difficult especially in air cooled engines. An investigation of the effect and understanding of tolerances is clearly vital.

(3) Effects of cumulative operational time. Several areas of deterioration may be expected to affect emissions as an engine wears or loses initial calibration. Fuel calibration, piston sealing, and lubricating oil consumption are obvious possibilities that could affect emission characteristics.

(4) Flight testing. The flight testing conducted to date has been effective in demonstrating operational limits on leaning. Further testing in cooperation with airframe manufacturers is needed to provide in-

formation on the performance penalties incurred by improved cooling. Also, further data are required to enable us to project uninstalled engine results for the actual aircraft installation. Flight service testing will also be required to assess the effect on engine TBO and reliability.

(5) Effect of inlet manifold tuning. Aircraft engines extensively utilize tuning of inlet manifolds to improve volumetric efficiency. This arrangement can, however, produce inconsistency of fuel-air ratio between cylinders during low speed operation. This effect needs studying for its impact on emissions.

(6) Facilities. We intend to upgrade our emission test facility by the addition of equipment to control the temperature and humidity of engine induction air. This control will improve repeatability of emission determinations and allow us to study effects of temperature and humidity.

We have shown that small improvements in emissions in two TCM engine types are possible by leaning in two modes. Those two engines cover only a fraction of our total production, and further work would be involved to production release even these gains. Development of production hardware, service tests, and engine and airframe certification work would be necessary.

We believe that implementing these small improvements would be a Pyrrhic achievement. The effort could be better expended in the programs mentioned previously, which have the promise of more worthwhile gains.

It is abundantly clear that several years of work and large expenditures are required before the emission levels prescribed in Part 87 can be achieved. Although it is not possible to plan the detailed program required to achieve regulated emission levels, we have attempted a conservative estimate of the cost impact of doing so.

If we apply presently known technology and project progress typical of our industry, we would anticipate a cost increase per engine of 15 to 20 percent based on amortization of engineering development, production facilities, and the unit cost increase. This increase arises only from engine changes. It can reasonably be expected that engineering development and certification costs arising from airframe changes to accommodate the emission conforming engine will be similar to the increase in engine price. Since the cost of engine(s) in an aircraft is approximately 20 percent of the selling price, the increase in cost of the airplane will be approximately 6 to 8 percent.

After the time that engine development to EPA requirements would be achieved, we estimate that an additional 3 years would be needed to re-identify all engine models in their emission reduced versions.

Test facilities would require extending to achieve this, and we estimate that one-time expenditures of $800,000 would need to be made. These facilities would be surplus to our needs at the completion of work.

This discussion of costs is based on TCM projections.

Sales of piston powered general aviation aircraft is soon expected to be 1 billion dollars; thus, we are facing an annual expenditure of 60 to 80 million dollars to meet prescribed emission levels. It is a large sum for our industry and we seriously question the cost benefit to the community. We recognize that we have an obligation to the country to act responsibly toward upgrading and preserving the quality of life in all that this implies. But we believe that this end would better be served by expenditure of our technical effort in the direction of improving the fuel economy and reliability of aircraft.

DISCUSSION

Q - C. Rembleske: You mentioned something to the effect that it would
    take approximately 3 years to recertify the engines you now have in
    production. Is that all 60 models or 30 models?
A - L. Waters: It's 30 OEM models.

Q - C. Rembleske: One of the problems that concerns us in the airframe
    industry is the fact that you today still build engines for aircraft
    which have long been out of production. The way we interpret the
    rules today, and I feel they're rather clear, is that all newly
    manufactured engines are going to have to meet these specifications.
    How are we going to handle the engines for the aircraft which are
    no longer being produced but which are covered by the rules? There
    are a significant number of engines models, as you said 30 of your
    own, which fall into this classification. That means there are
    probably double that number of airplanes in the field, models of
    airplanes, that will have to be considered. We do not expect these
    people to junk these airplanes, and I'm sure that will not be done.
A - L. Waters: That is a very important point. There are another 30
    models. Moreover, the technology we would develop during the work
    to be done for our OEM models wouldn't apply co the older ones.
    Many of the older engines are quite different. It would be a messy
    problem. I would hope that there would be relief from certifying
    the older engines made for airplanes no longer in production. This
    obviously would be a massive, unrewarding task.

COMMENT - C. Rembleske: That was the purpose of my bringing it out.
It needs to be concerned when the EPA and FAA consider this matter.
Also, we need to seriously think about what we are going to do about
those aircraft which are still flying and must be re-engined periodi-
cally with new engines.

Q - G. Kittredge: I don't think I'm in a position to give you a
    really satisying response to this point. Certainly, as the rules
    are laid out now, newly produced engines for installation in any
    . sort of aircraft would be required to comply. Although we have
    talked about this problem within the government, we have not re-
    solved it yet. I think that what we need to dig into is the reason
    why is it not possible to install an emission control equipped en-
    gine in such older aircraft. It would be quite useful to the EPA
    if TCM could break the 15 to 20 percent estimated cost increase
    into the various components that went into it - that is, the spe-
    cific new emission control system devices, whatever they are, the
    projected market for the engines, etc.
A - L. Waters: I can't break the numbers down in that detail, but I
    certainly can tell you the elements that we took into account and
    I can tell you why I use the word conservative. The elements that
    we had used in this study are the engineering development cost,
    people, materials, and facilities covering the programs I have men-
    tioned. Bernie Rezy said we may have to go to a more sophisticated

timed injected fuel system. Our own fuel system is not timed. So
we are covering the programs I have mentioned plus the possibility
of an element of a new timed FIE system and the development of
new cooling cylinder heads. Remember we have six different basic
engines. In production facilities more test cells will be needed
and these cells will have to be more fully equipped for emission
regulation. On the unit cost side, the cost of the new fuel injec-
tion system, the cost of the improved new cylinder heads, and the
extra "break in time" of the engines were included. Presently, we
run engines for about 3 to 3 1/2 hours. It's common over the next
10 hours or even more for the lubricating oil consumption to fall
further. For all the emission testing that we have done on our
engines, we have run at least 10 hours to stabilize the lubricating
oil consumption because of its effect on hydrocarbons. If the con-
trol of hydrocarbons stays in the EPA standard, there's little doubt
that the engines will have to be run longer during the break-in
period. The conservatism is that we did not include inflation over
these years for the cost of the engineering or materials, and, sec-
ondly, we did not include any unknowns. Inevitably other programs
will arise that we will have to look into. We did not include any
of these in our estimate.

Q - C. Rembleske: I think one of the big things we have to recognize
is that even though the engine manufacturer comes up with an engine
that might meet certain emission requirements, that is by far a
long way from getting the FAA to approve that installation in a spe-
cific airplane. They may have a perfectly good and suitable engine.
However, to demonstrate the capability of meeting the right federal
regulations with that engine installed in an aircraft is going to
mean going out into the field, getting one of these old airplanes,
some of which may be 15 years old, and trying to get that airplane
recertified. Could the FAA comment on whether they have another
way?

A - N. Krull: We happen to be in the office of policy development
rather than flight standards. They're much more involved with the
individual certification. We're very much aware of the problems
that are going to come up with these emission standards and the
problems in certifying not only new engines but overhauled engines
as well as engines with various modifications. We will be contin-
uing to work with the EPA on developing these requirements to a
point where they can be applied within the industry. Earlier there
was a discussion concerning the time lapse for certification. In
our role of promoting aviation, we will certainly be working to
minimize the requirements in terms of certification of additional
engine models and to cut that time span as much as we possibly can
within the limitations of safety. Would somebody from Flight
Standards like to comment on the recertification of old aircraft?

A - C. Price: As the rules presently require, if there is a model change,
or any substantial change at all, it would require a recertification
of the aircraft as well as the engine. The current rules are Part 33

for the engine and probably Part 23 for the aircraft. When you change the fuel schedule you change power, and you change cooling requirements - all of this has to be recertified on the aircraft. The ridiculous example I used for an illustration was an A-65 engine and a J-3 Cub. It is conceivable that we would have to recertify a J-3 Cub under the present situation.

COMMENT - L. Waters: I would like to make one point. There seems to be no doubt to us at TCM that our final developed engine, our final emission new old model engine, will most certainly need full recertification. The design changes will be profound.

COMMENT - L. Helms: I can't help but pick up the example he used and pose the question to the group - who do we expect to pick up the costs of engineering to recertify the J-3 Cub? The J-3 Cub, incidentally, has been out of production for about 25 years.

Q - C. Price: An A-65 engine could conceivably come off in 1980 from his remanufactured or rebuilt engine line. And we would now have to do something with that engine?
A - L. Waters: Under present rules, that's right.

COMMENT - L. Helms: Even if there were changes and even if FAA eliminated the STC, there would have to be engineering to install that engine. And who wants to do engineering on an airplane that's 25 years old?

COMMENT - D. Page: The owner pays for everything that does into any product. If he has a J-3 Cub, it is on the market new as a $4000 to $5000 airplane. If he had to pay a $25,000 certification for it, he'd have a $30,000 airplane. He could put it in the barn, give it to a museum, or pay the money.

COMMENT - C. Price: Under the current rule, a Supplemental Type Certification (STC) would have to be issued to any model engine change and to the aircraft change for each individual aircraft that comes under this sort of thing. Now, of course, you could get blanket STC's, which could cover a number of aircraft under a specific model change. People are modifying aircraft engines constantly. They have a perfect right, under the rules, to do so provided they stay within the flight standard rules.

COMMENT - L. Waters: Quite clearly, the work involved in reducing emission for the 30 engines in our case that belong to the after market and the re-engineering of these engines into the airplane recertification is an astronomical task. Hopefully, this will be removed.

Q - H. Nay: Les, a point of clarification on your cost estimates. You refer to them as conservative. Does that mean these are upper limits or not?

A - L. Waters: There are lower limits. The element of conservatism was that we did not put in inflation for the years of escalation. We used 1976 dollars and we did not include any new programs with unknown problems that we might run into. The figures are low.

COMMENT - L. Helms: I might comment on that because it might help the other people in the audience. What we did was to ask Continental and Lycoming to select, on their own, two different approaches and come up with their own ideas. Obviously, in the GAMA technical policy committee, we considered this for some time. The industry people said, "Well, we don't know how to do that. It's not defined. We don't know what the requirements are going to be." But we did press on, on the basis of if we can't do it, certainly we can't expect the government to do it. So now that you've heard Les outline what Teledyne did, you might be interested in knowing the Lycoming side. Lycoming made their estimates and came up with a cost of approximately $1000 per engine. Since some were as low as $700 to $800 and others were as high as $1400 or $1500, they averaged it out at $1000 an engine. After you take that $1000 an engine to the airframe manufacturer, we then get into other things. The Truth in Pricing Act requires us to price certain things which can be explainable to the Treasury Department. The Treasury Department requires us to break this down for tax purposes, and we have to segragate the costs for tax purposes on every part when it comes in, so that we can meet the SEC regulations in truth and disclosure. We take that $1000 and we must allocate some to that, a portion of what we call material handling or material burden. It could be as low as 6 percent or as high as 12 percent. Each of the aircraft manufacturers must then install the engine, they must build it up, and/or put accessories on it. They must put their own baffles on it and that adds labor. Then to meet the SEC requirement of complete disclosure, you have to allocate the factory burden to it; the burden of the individual plant can be anywhere from 80 to 200 percent to that $1000. Then to meet the further requirements of the accounting profession of our respective auditors, we have to add G&A. What I'm saying is that the $1000 engine becomes somewhere around a $2000 engine when it goes out of the airframe manufacturer's plant and to the consumer. It could be as low as $1500 or could be as high as $3000. Let's say it's a $2000 engine. This year we'll built a little more than 15,000 airplanes. Next year we're forecasting an increase, of which approximately one-third would be twin engine airplanes. If we take 5000 of those, we've added 5000 more engines and we're up to 20 000 engines. If we export 3000 to 4000 engines a year, we're up to 23 000 or 24 000. Now we've got 2000 to 3000 or 4000 of after market engines or spares. I'm going to round this off to about 25 000 engines a year that go out. If you take that 25 000 engines a year and multiply them by the added cost, you come up to about $50 million or $60 million. So he went on the basis of 20 percent. We looked at it and said it is about 6 to 8 percent of the final sales price and came up with about 60 to 80 million. Lycoming came up with about $50 or $60 million. We can't make it any closer than that, but it does tend to give you an idea of the approach we took to get our arms around the subject some way. We're looking at somewhere between $50 and $100 million a year of added costs.

14. FUTURE DEVELOPMENT PROGRAMS

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From the programs, such as have been discussed previously (i.e., both government sponsored and in-house), the exhaust emission data from piston aircraft engines point to the need for not only more detailed data but also for a greater quantity of data as well. That is to say that although the exhaust emission trends are adequately defined by those data currently in hand additional data need to be collected in order to fully assess the piston aircraft engine as an emission source. For example, the effect of changing fuel-air ratio or spark advance on the emission levels of engines has been well defined for the engines tested. However, based on a limited amount of data, Avco Lycoming has shown that basic engine production tolerances have an effect on emission levels. If production tolerances are reflected as pollutant yields, then it is expected that, in addition, the emissions would also be influenced by the amount and type of accessories installed on each basic engine. These data have not been accumulated.

Therefore, while future industrial development programs are obviously aimed at utilizing the data on hand to reduce emission levels, an equal amount of time must be expended for simply defining, in greater detail, where individual problems lie within standard engine models and to what extent they can be, or need to be, accommodated. In essence, Avco Lycoming is taking a two pronged attack on the emissions program. And while the individual concepts proposed are intended to accomplish the overall goal of reduced pollutant levels, each technique essentially has its direction aimed toward (1) completely defining the emission problem or source points or (2) developing new materials, hardware, or operational procedures to exercise the trends defined by the data collected.

A review of the programs at Avco Lycoming to reduce the emission output of aircraft powerplants is listed below. The concepts listed here are not necessarily all those projects under study, but instead are provided to indicate the direction being pursued most vigorously. Also, it should be noted that programs not originally intended as an emission reduction item may indirectly reduce exhaust emissions through more efficient fuel utilization or less stringent operational limits, as in the cases of detonation restrictions or cylinder temperature maximums.

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At Avco Lycoming the following programs are being investigated as company funded projects:

(1) Continued establishment of baseline emissions for various engine models. It has been previously noted that different models (or a total of 14 engines) including variations of the Avco Lycoming piston aircraft engines have been tested under recent testing, both in-house and government funded. However, when compared to the more than 350 different models currently being produced, it is obvious that a major effort remains (fig. 14-1).

(2) Continued characterization of effect of production tolerances on emissions. From the limited data available (fig. 14-2), it is apparent that exhaust emissions are influenced by inputs other than fuel-air ratio. These influences, while not completely defined, may be incorporated into the broad term of production tolerances. These tolerances will then necessarily be added to the overall emission characteristics of engines to provide a safety factor for future exhaust emission verification.

(3) Carbureted engine development and flight tests. Following much the same trends as were used in the previous flight test of injected engines, Avco Lycoming is currently establishing a program to evaluate leaner carburetor settings. This program will be aimed at leaner settings for all modes (fig. 14-3) except takeoff; therefore, the certification of the aircraft will not be affected.

(4) Cylinder cooling/fin design programs. Avco Lycoming has developed an improved cooling cylinder head assembly. However, it has been questioned as to whether the design used is the optimum or if a better design is possible. Avco Lycoming is investigating both the theoretical and experimental aspects of this question.

(5) Revised combustion chamber configuration. The combustion chamber used on piston aircraft engines is basically the hemispherical dome configuration. Avco Lycoming has under development a new configuration combustion chamber to determine its effect on engine emissions.

(6) Revised fuel metering systems. Data accumulated under the flight test program have provided an impetus for developing new fuel systems for piston aircraft engines. Based on the fuel schedules, Avco Lycoming is evaluating the benefits obtainable from minor redesigns of current fuel metering systems to a complete new concept in fuel metering for piston aircraft engines.

In addition to these programs that are aimed at the engine itself, the interaction of the airframe and the engine is also being studied. In such a program a joint effort is being made by NASA and Mississippi State University to determine the various influence of aircraft cowl design on engine cooling. Avco Lycoming has supported this effort by pro-

viding equipment and supervisory input. This systematic approach at engine cooling may provide an important side benefit to allow reductions in emissions through improved airframe design.

Avco Lycoming is currently involved in these programs in an effort to reduce the pollutant emissions from piston aircraft engines. While each program possesses potential benefits, no unique technique has been perfected to yield a viable approach to meeting the proposed standards by 1980. Test stand and flight test data accumulated to date indicate that the current emission levels as specified in Part 87 of the EPA Regulations are too stringent for compliance with present state-of-the-art of piston engine aircraft technology. Avco Lycoming is not in a position at the present time to recommend a revised emission level. To reach this position we believe two things need to be done.

First, a unified and well-defined test procedure needs to be developed. As has been shown, there are some rather basic questions that need to be resolved.

Second, a broader base of data needs to be developed. We have tested some engines but we have not tested a sufficient variety of engines or enough engines of the same kind to come up with a data base that will allow us to predict with a degree of accuracy the type of emissions we can expect from existing engines.

To illustrate the magnitude of the affected installations, the following engine production schedule for July 1976 was tabulated to show the intermix of engines:

SCHEDULED ENGINE PRODUCTION - JULY 1976:

Number of Engines: 1010

   Normally aspirated:

   Carbureted models   30
   Carburetor settings   20
   Injected models   36
   Injector settings   24

   Turbocharged:

   Carbureted models   3
   Carburetor settings   2
   Injected models   15
   Injector settings   6

Based on the previous schedule, 52 different fuel metering systems would be required for flight and field testing before production implementation on presently certified installations.

Finally, some have proposed that we go to leaning the engines as an interim step in an attempt to reduce exhaust emissions. This approach may seem simple and straightforward, but an underlying network of complexity restricts Avco Lycoming from taking such action until all facets of the concept are considered. Not only inputs such as development and certification time, unit cost, and availability of production hardware, but engine aircraft performance acceptability and customer acceptance programs must be evaluated through flight and field service tests. The great variety of engines shipped in July illustrates the additional complexity of the job.

Therefore, we believe that the program which answers our two questions and our own in-house programs of the six steps we are taking will give us the necessary information that will allow us to state the emission level currently attained, potential steps to be taken to reduce emissions, and the related cost benefit ratio. Until then we cannot truthfully address ourselves to the questions.

If a fuel metering device were developed that would reduce emissions, we would estimate its costs and the associated costs of implementing an emission control as follows. Based on current knowledge and making an assumption that not only do we know what to do but that technically we can do what's required, our best estimate of the cost to our customer would be of the order of $1000 per engine or $12 million per year. Naturally, the cost to the ultimate customer would be higher than this.

DISCUSSION

Q - G. Kittredge: You stated that your company was not in a position to say that they would be able to comply with the standards laid out in Part 87. Was this in terms of the 1979 implementation date? In other words, if the date itself were conceivably to be adjusted backwards, would that change your prognosis?

A - S. Jedrziewski: Right. We are not in a position, right now, to say that we can or cannot meet the 1979 standards as they are written. We have data indicating that we cannot, but we don't have enough data on all of our engines to say that every one of our engines cannot meet it. We can't even recommend to you now whether we need 2, 3, or 4 years.

Q - G. Kittredge: Based on the fairly promising information that was presented yesterday, would you agree that some of your engines can meet it?

A - S. Jedrziewski: I don't think we indicated that yesterday. I think that the information presented yesterday indicated there was a trend. We could obtain the emission level by hand tailoring the fuel metering devices or leaning beyond the practical production limits. We don't know how we can arrive at that point with a production piece of hardware.

Q - G. Kittredge: If the standards were to be modified in the manner suggested in Mr. Houtman's paper and if you only had to comply with a CO standard, how would this affect your prognosis?

A - S. Jedrziewski: Without knowing what all our engines are doing, I don't believe we're in a position now to say whether we can meet the emissions. We could do it with certain models. We can't do it with all our engine line.

Q - W. Houtman: Up to now I understood that our test procedures problems had pretty well gone away and yet you indicated that procedures were critical items to be resolved.

A - S. Jedrziewski: Yes, they're not clearly defined. They're not spelled out. There have been some suggestions made during the last day and a half here.

Q - W. Houtman: You're referring stricly to the calculation procedure?

A - S. Jedrziewski: Calculations plus maybe some response times, length of the line, heated lines, and so forth. There is some question on what particular instrumentation is completely acceptable and what isn't. There are also questions on the sampling standard gases. We didn't bring all the fine details out during the last day and a half, but there are still some items that need resolving. We're not in a position now to recommend to you what they should be or how carefully they would have to be examined.

Q - W. Houtman: It might be difficult to resolve them unless we get some idea where the problems are.

A - S. Jedrziewski: Right, and as I indicated we're not in a position to
     go to you yet with these recommendations.

Q - F. Monts: Does Lycoming or anyone else understand what is required to
     show compliance in a production basis with the EPA standards?
A - S. Jedrziewski: We have read them, and it means that every engine
     must be tested. If you're referring to the cost, we pulled that out
     of the air. We're testing a sampling plan and not every engine. If
     we would have to test every engine for emissions before it went out
     the door, it would probably increase the cost another $500 per engine.

Q - F. Monts: Is there now in the federal regulations an established
     procedure for compliance testing?
A - S. Jedrziewski: Yes. Part 87 spells that out.

COMMENT - W. Houtman: The regulations state that every engine must meet
the standards. It does not state that every engine must be tested.
Again, compliance is an area of FAA responsibility. So you might ask the
FAA people on that.

COMMENT - S. Jedrziewski: That's why we need clarification on whether
every engine has to be tested or whether it can be done on a sampling
plan.

Q - C. Rembleski: Have you considered how much of a margin you're going
     to have to have so that you don't have to test each production engine
     assuming you have a sampling plan?
A - S. Jedrziewski: We're now sampling engines from production. We have
     to squeeze these in between other engines and production items, so
     that it's taking a very long time. We're trying to establish the so-
     called tolerance band. We need more input before we can clearly de-
     fine what we need or what the engines are actually doing.

COMMENT - N. Krull: The EPA did raise the point that the enforcement of
Part 87 is up to the FAA. In our presentation we pointed out that we had
done some testing on an experimental test stand with some six of ten en-
gines in a program. We recognized that we need a great deal more infor-
mation on engine to engine variation, installation to installation var-
iation, before we can come up with an enforcement policy. This policy,
including what the test requirements will be, is something that has to
be agreed on between the EPA and the FAA. We have started discussions on
that already. It does require more data before we can come to a conclu-
sion.

COMMENT - L. Helms: It seems to me that we in industry should at least
try to be a little more responsive to Mr. Kittredge's earlier point.
What I'm about to say is not a statement of policy, because it's obvious
that I have not had a chance to think it out nor meet with my colleagues.
I don't really know the answer to his question regarding where we would
stand on CO if the hydrocarbons and NO_x were eliminated. I think we

might be able to sit down and work out this type of thing. We might be able to look at the data from Lycoming and TCM on the basis of where the major pollutant contributions were. If it was during takeoff and climb, which is where it appears to be by the ppm count, perhaps the fuel scheduling modal analysis could be reduced to two modes. Based on this, and concentrating on CO, we might be able to come up with some type of automatic fuel control system on a more rapid basis. If this system is applied by a phased program on unsupercharged four cylinder engines first, we might be able to make the standards next year. Next, we might go to six cylinder or carbureted engines, and finally to the turbocharged engines. It's a proposal that we just haven't had a chance to think out. But I can envision the possibility that we could, in fact, come up with some type of program outline. I can't be any more definitive, but I think we owed you a positive response to your question.

COMMENT - E. Becker: I think we're losing sight of one thing. The elimination of two of the pollutants does not change the order of magnitude of the effort of reducing the CO problem.

COMMENT - L. Duke: Taking away the hydrocarbon and NO_x limits is not directing ourselves to the real problem. On the engines we've seen to date, and we've made the point we're not done yet, the major problem is the CO, especially the four cylinder naturally aspirated engines where there's not a problem with NO_x or hydrocarbons.

COMMENT - W. Houtman: Just to clarify the recommendation I made, it was not the intent to completely relax the standards and it wasn't an agrument for relaxation. When making the recommendation to drop the HC and NO_x, based on the analysis, there was no need to control these pollutants. There seemed to be some confusion that some very good CO control systems were being ignored because of high NO_x. We don't expect a difference on HC and NO_x as a result of removing HC and NO_x. The HC and NO_x standards were set at levels we would expect to see as a result of the CO controls.

COMMENT - P. Kempke: I agree with what's been said with regard to CO being the problem. If the hydrocarbon and NO_x standards were dropped, some of the development work would be simplified in the sense that the measurements of those two pollutants would not be a problem. It would minimize the amount of temperature-humiduty correction factors that have to be applied to the testing. However, I certainly agree that it does not change the overall problems facing the engines today. The CO is the big problem.

Q - G. Hicks: Regarding your sampling techniques, you indicate you have some type of sampling technique that you applied in the testing of the engines and not all engines were tested. Would you feel it would be a help to you if you had greater clarification in the regulation to indicate the type of tolerance bands that would be required in your sampling technique and the establishment of confidence intervals in your statistical analysis?

A - S. Jedrziewski: In our determination of costs, we have based that
cost on sampling selected engines. Only 1 out of 10 or maybe 1 out
of 20 engines off the production line would be run through the
emission level test to see whether or not it complies. Whether the
sampling plan has to be on production or whether it has to be done
only on certification, we're not in a position to know or make a
recommendation at this time. EPA has spelled out that every engine
that leaves the line has to meet the emission level. FAA and EPA,
as I indicated, are getting together to work out a sampling plan or
whatever is acceptable.

AVCO LYCOMING
PISTON AIRCRAFT ENGINE FAMILY

NATURALLY ASPIRATED

TURBOCHARGED

SUPERCHARGED

CARBURETTED

235* 340
290 360
320 435
540

GEARED

435
480

FUEL INJECTED

320
360
540
720

GEARED

480
540

CARBURETTED

360
435

FUEL INJECTED

360
540 & 541

GEARED

480
541

CARBURETTED

GEARED

480

FUEL INJECTED

GEARED

480
540
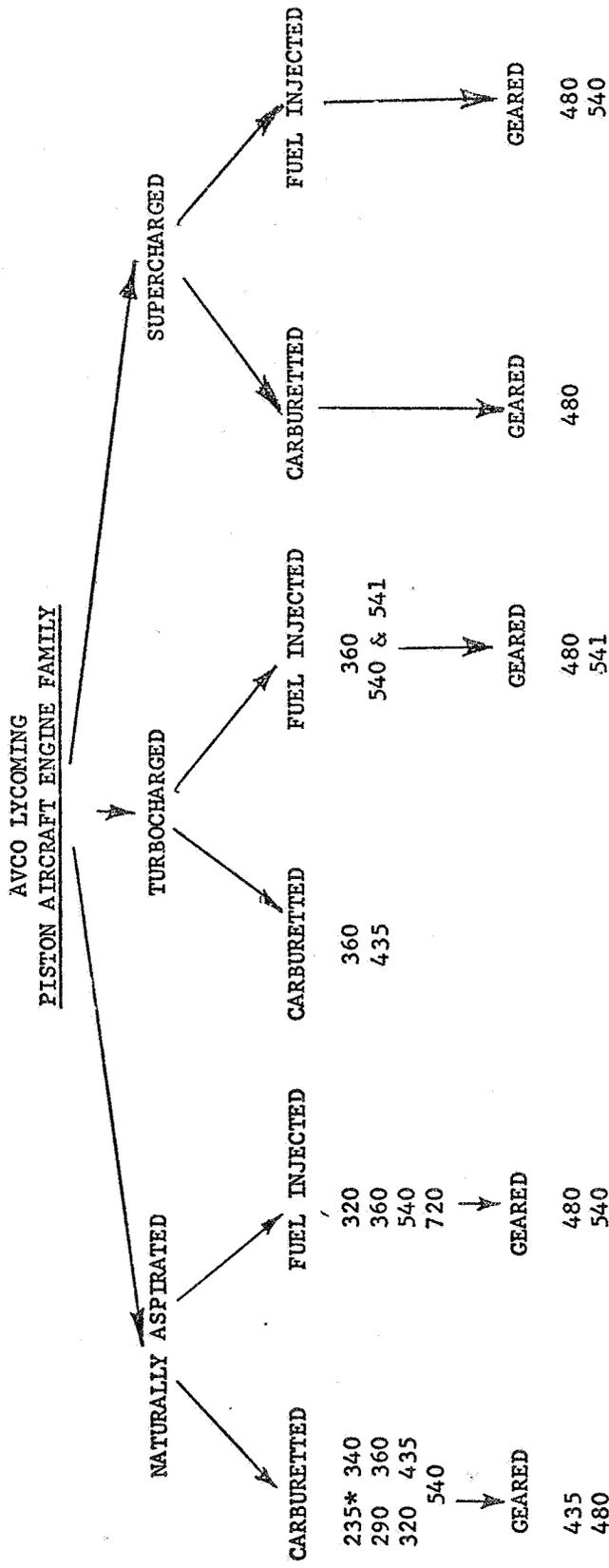
* Denotes Engine Displacement

ALL CLASSES OF ENGINES ACCOUNT FOR OVER 350 MODELS.

Figure 14-1

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Figure 14-2

PROPOSED REVISED FUEL SCHEDULE—CARBURETED ENGINES

TAKEOFF
NO CHANGE
IN F/A RATIO

CLIMB MODE
80 % POWER

APPROACH MODE
40 % POWER
.070 F/A RATIO

IDLE/TAXI FUEL SCHEDULE

FUEL/AIR RATIO

.100
.090
.080
.070
.060

PERCENT POWER

25   50   75   100
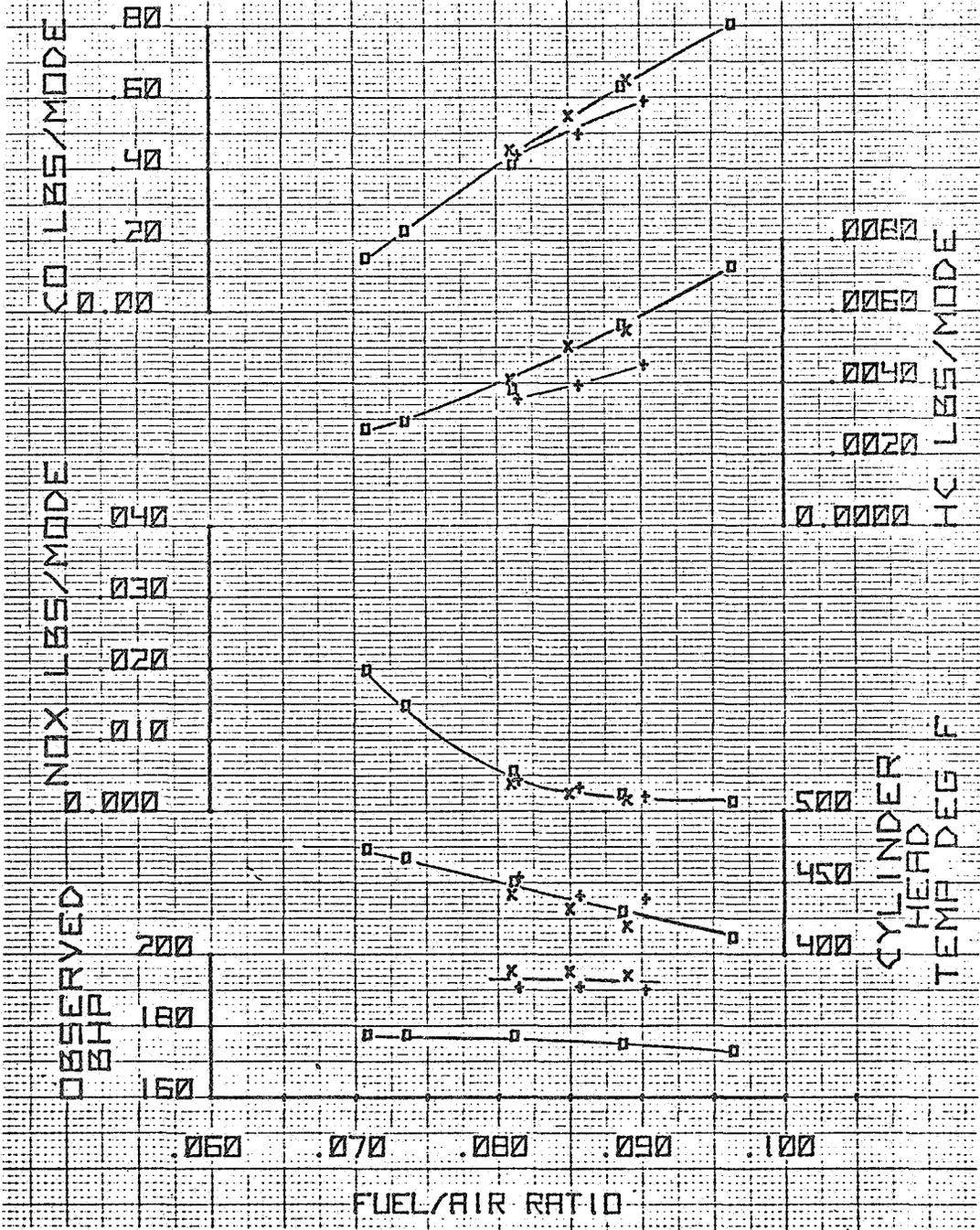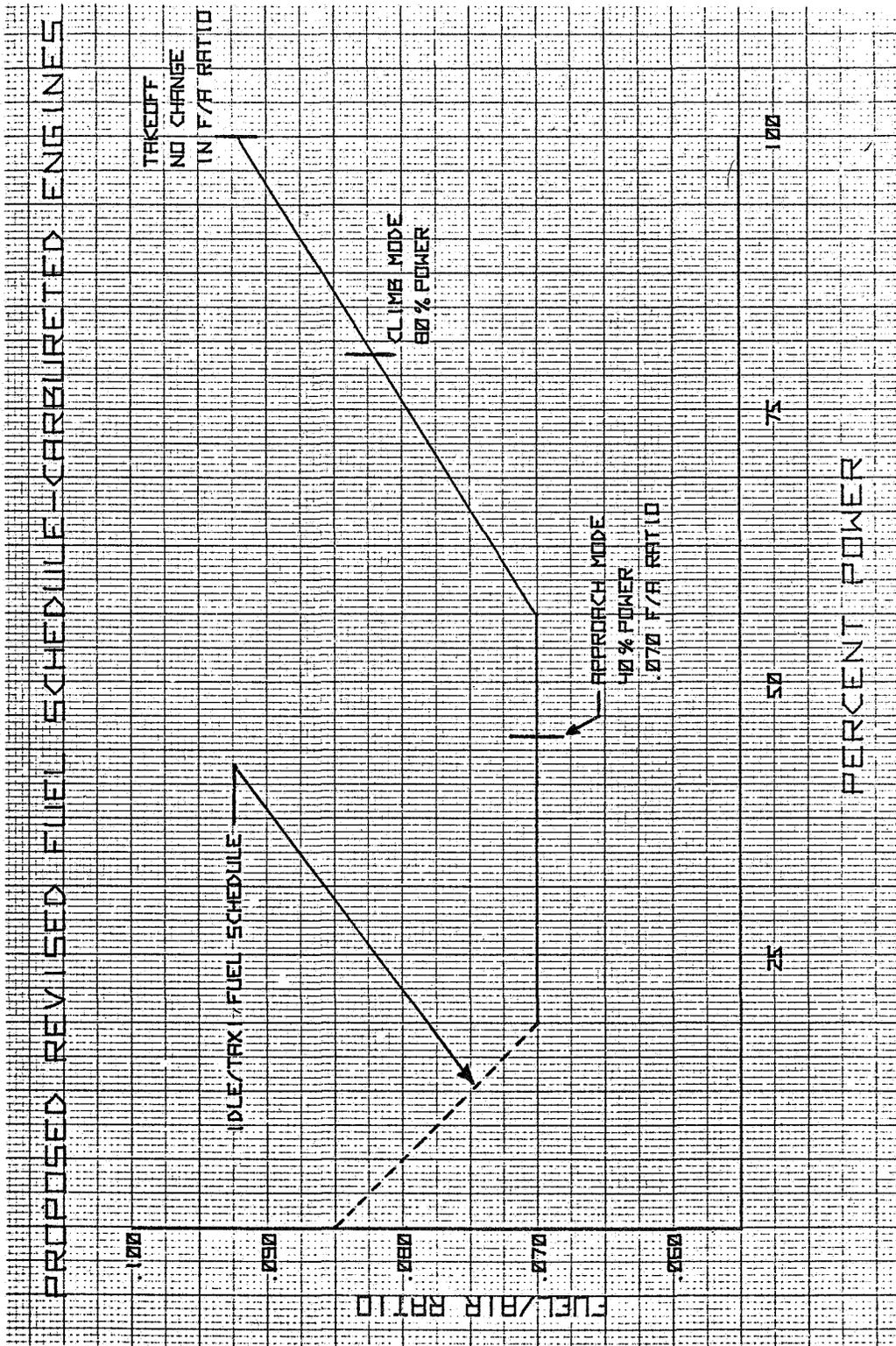
Figure 14-3

15. EMISSIONS AND NEW TECHNOLOGY PROGRAMS FOR

CONVENTIONAL SPARK-IGNITION AIRCRAFT ENGINES

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After the Environmental Protection Agency (EPA) issued exhaust emissions standards for general-aviation engines in 1973, NASA embarked on a number of programs to develop and demonstrate technology and to aid industry in developing and demonstrating exhaust pollution reduction techniques for those engines. The program has since been expanded to include improved performance and other areas of new technology for general-aviation internal combustion engines that are not necessarily being pursued by industry. A long-range technology plan in support of general-aviation engines has been formulated and is being implemented at the Lewis Research Center. For completeness, this paper briefly describes the overall program and presents in detail that part of the program that represents the in-house effort at Lewis.

LEWIS OVERALL INTERNAL COMBUSTION ENGINE PROGRAM

Three areas of government and industry effort involving conventional general-aviation piston engines are part of a coordinated overall plan:

(1) FAA/NASA Joint Program

(2) NASA Contract Exhaust Emissions Pollution Reduction Program

(3) NASA In-House Emissions Reduction and New Technology Program

FAA/NASA Joint Program

The objectives of this program are to establish emissions levels of current general-aviation piston engines and to investigate minor engine modifications to safely reduce emissions to the EPA 1979 standards. Co-funded studies by the Federal Aviation Administration (FAA) and NASA are now underway with the two primary engine firms building general-aviation piston engines, Avco Lycoming and Teledyne Continental Motors ,

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(1) To experimentally characterize the emissions from 10 representative aircraft piston engines, and

(2) To assess the feasibility of "leaning out" and spark timing changes for emissions reduction and to demonstrate the most satisfactory approaches to compliance for presently manufactured aircraft engines based on minimum engine changes that could quickly be adapted to and introduced on production models.

NASA Contract Exhaust Emissions Pollution Reduction Program

The overall objectives of this program are to establish and demonstrate by 1979, at the two engine manufacturers, technology that will safely reduce general-aviation intermittent combustion engine exhaust emissions to the EPA 1979 standards or better. Adverse effects on performance, cost, weight, and reliability must be held to a minimum. The two engine manufacturers each are investigating and demonstrating one major and two minor engine modifications that have the potential of significantly reducing exhaust emissions. The modifications are based on current state-of-the-art technology and will require a longer time to progress from experimental to preprototype engines than those in the FAA/NASA program.

NASA In-House Emissions Reduction and New Technology Program

The objectives of this program are to identify and demonstrate technology to safely reduce exhaust emissions and improve performance and to pursue other areas of new technology that are not necessarily being worked on by the industry. The benefits could be any one or a combination of reduced emissions, improved performance, improved reliability, reduced specific fuel consumption, reduced maintenance, and lower cost. In contrast to the work under contract with the engine manufacturers, the work at Lewis is concentrated on longer term solutions requiring additional or new analytical and/or experimental technology. Specific programs that are presently active are

(1) Temperature-humidity correlations

(2) Improved fuel injection

(3) Otto-cycle analytical simulation

(4) Improved engine cooling

Areas of work that have been identified for future study are

(1) High-energy ignition systems

(2) Automated engine controls

(3) Assessment of alternative fuels and engine modifications needed to use alternative fuels

(4) Improved induction and carburetion systems

The active programs are described in some detail, and the future work is described briefly.

Active programs. - The following programs are presently active.

Temperature-humidity correlations: The objective of this program is to develop a correlation and correction factor for the effects of ambient-air temperature and humidity on engine exhaust emissions levels and performance. Test results to date have shown that ambient-air temperature and humidity significantly affect data and may make comparisons between different test sites difficult on a modal or per-cycle basis. The general program involves an experimental effort being conducted on two aircraft engines (Lycoming O-320D and Continental TSIO-360C) on a dynamometer test stand. The two engines are being tested over their entire operating range. In particular, the tests are being conducted in the modes of the EPA emissions cycle at fixed, controlled temperature and humidity conditions over a range of fuel-air ratios. Correlation of emissions will first be attempted for each of the modes on the basis of fuel-air ratios and pounds per mode. An overall correlation of the raw emissions and modes will then be attempted, and finally comparisons will be made between the two engines. Based on these results, we are hoping to develop some generalized correction factors so that engine test results obtained under any ambient conditions can be corrected back to some standard reference conditions such as 59° F and zero percent relative humidity. The normalized test results of identical engines tested at different test sites and ambient conditions could then be directly compared.

Improved fuel injection: The primary objective of this program is to determine and demonstrate the potential of a pulsed fuel-injection system to reduce exhaust emissions and specific fuel consumption and to improve performance. A more precise fuel control would reduce variations in cylinder-to-cylinder and cycle-to-cycle fuel-air ratios, thereby allowing leaner engine operation than the present continuous-flow systems. A secondary objective of this program is to determine the effects of the various injection-controlling parameters (droplet size, spray pattern, fuel flow, fuel pressure, nozzle geometry, and injection timing) and just how much these parameters could vary and still yield both acceptable performance and emissions reduction.

Gasoline fuel-injection systems have been around since the Wright brothers, and various systems specifically for aircraft engines were worked on as early as the 1920's. They were pursued very sporadically and separately from engine development until the advent of World War II. Under military sponsorship in the 1940's and in conjunction with Wright and Pratt & Whitney, production fuel-injection systems for radial engines

were developed and manufactured. These systems fed fuel to each cylinder
individually from a mechanical plunger-type pump. After World War II,
these systems were adapted to horizontally opposed engines. In the late
1950's and early 1960's, continuous-injection systems, which were much
simpler, more reliable, and less costly, were introduced. These are
essentially the same systems used today.

Present automotive fuel-injection systems are more sophisticated and
at a higher state of development than those for aircraft. Some of these
systems could possibly be adapted to aircraft engine use. The Lewis pro-
gram is not directed toward adapting existing systems but is involved
with fundamentals of sprays and fuel timing and their effects on emissions
and performance.

A literature search on fuel-injection work has been performed, and
the information is being summarized. There is a lack of consistent in-
formation that is applicable to aircraft and other engines. Most basic
work either has not been reported completely or has not been reported at
all and may be proprietary. Sporadic work was done by NACA up to and
during World War II. Some limited work was performed by NACA on single-
cylinder engines, and also some basic work was done on nozzles primarily
furnished by the companies developing the injectors. No work was done
toward a complete fuel-injection system, and much of what was done is
apparently not translatable into today's applications. Some generaliza-
tions can be taken from the early work and will serve as a guide to our
program.

After experimental visualization techniques were established, bench
testing of existing injectors under ambient conditions was begun. All
previous visualization work reported in the literature was done with
liquids other than gasoline for safety reasons. The commonly used sub-
stitute for gasoline for injector and nozzle calibration and testing is
Stoddard solvent, a commercially available dry cleaning fluid. It has
viscosity, surface tension, and density properties similar to those of
gasoline. We visually compared water, Stoddard solvent, and gasoline
under identical conditions through a number of different injectors. Per-
formance with water was drastically different, giving poor atomization
relative to that with Stoddard solvent and gasoline. Visually, the pat-
terns with Stoddard solvent and gasoline looked similar under certain
conditions. Under other conditions, however, the Stoddard solvent showed
a much better and more atomized spray pattern. This, coupled with the
fact that our safety personnel consider Stoddard solvent to be just as
hazardous in our facilities as gasoline, dictated the choice of gasoline
for the visualization work.

We are in the process of testing a number of injectors under their
design operating conditions. For aircraft engine injectors, we have de-
fined seven operating modes that cover normal engine operation. The five
modes from the EPA emissions mode cycle are taxi/idle (out), takeoff,
climb, approach, and taxi/idle (in). However, since the engine operates

in the cruise mode 95 percent of the time, we chose cruise performance and cruise economy as being equally important and representative of most normal operation. We have just completed bench testing an injector for a Continental TSIO-360 engine that is now running on our dynamometer test stand. The testing was conducted by spraying fuel into air at the same flow rates and the same shroud air pressure differentials ΔP's. Figure 15-1 shows the operating modes. The main factor affecting injector performance was shroud-to-manifold ΔP. Where there was some ΔP, the injector fuel flow was maximized to some extent. Figure 15-1(a), idle and taxi (which were visually similar) and figure 15-1(d), cruise economy, did have shroud ΔP's and therefore fuel atomization. Figure 15-1(b), takeoff, and figure 15-1(c), climbout, approach, and cruise performance (which were visually similar), had no shroud ΔP's. The fuel came out as an almost solid stream of large droplets.

Work is underway to set up an injector flow test facility in order to control test conditions for visualization of flow patterns under simu- lated service conditions. A number of injectors will be fabricated and visually tested to observe various injector flow patterns. The visual flow patterns will be correlated with the relative performance and emis- sions from tests of these injectors in a single cylinder or an aircraft engine. The fuel injector/inlet manifold configuration will be as sim- ilar as possible to that of a standard aircraft engine. It is expected that these tests will, on a first-order basis, indicate the range and performance sensitivity of the injection variables, which will have to be verified later in a multicylinder aircraft engine.

To evaluate the complete injector system, the intake and exhaust manifolds of one cylinder of a water-cooled multicylinder engine will be isolated and fitted with a simulated aircraft engine intake configuration including an injector. This configuration is being used since the unmod- ified cylinders will maintain engine speed over a much wider range of conditions, in the isolated cylinder, than could be obtained by testing with a single-cylinder engine. Use of a water-cooled engine reduces cost and risk of damage to the engine. A research electronic control system will be used to vary the fuel-injection pulse timing and flow. The com- plete breadboard injection system will be functionally demonstrated over a wide range of test conditions. The breadboard system will then be adapted to an actual aircraft engine, and improvements in performance and emissions will be evaluated relative to those obtained with the standard injection system.

Otto-cycle program: Lewis has been trying for some time to develop an analytical computer program simulating the Otto cycle in a spark- ignition internal combustion engine. The objective of this program is to produce a generalized analytical model that can be used to predict emis- sions levels and engine performance for a broad range of design and oper- ating conditions. Limited experimental data could then be used to more finely tune the computer program for a specific engine and make possible a rapidly calculated engine performance map.

The program is composed of the various combustion, gas dynamic, and heat transport processes that have to be accurately described throughout the thermodynamic cycle in order to handle variations set up by different engine geometries and operating modes. The program computes a series of individual state points, more than 1000 over one cycle, which includes intake and exhaust blowdown and mixing. Figure 15-2 is a representative sketch of the pressure/volume diagram over which the individual calculations are made. At present, the program includes very limited ability to predict emissions levels and performance, including effects of residual-gas mass fraction, exhaust-gas recirculation mass fractions, and supercharging. The program is now being verified by comparing emissions and performance of an automotive V-8 engine. Eventually, performance and emissions of a number of actual engines of different sizes, geometries, and operating ranges will be compared with those predicted by the computer program.

The basis for the computer program is Lewis' activities in thermodynamics and combustion and in particular the Lewis chemical equilibrium and chemical kinetics programs. Since the combustion process is the most difficult to model, this then becomes the heart of the program.

To date, oxides-of-nitrogen (NO_x) emissions have been fairly accurately predicted when the combustion interval was accurately known. Because chemical equilibrium was used during combustion, carbon monoxide (CO) predictions were very low or almost zero. For the same reason, no hydrocarbons (HC) were formed in the model since all of the carbon goes to carbon dioxide (CO_2). Considerable work has recently been done on the program to be able to predict CO and HC. A new numerical integration technique for very rapid reactions has been incorporated in the program and is being checked out. This will now allow chemical kinetics to be used during the combustion process, as well as during the expansion process. No results have yet been obtained with the new technique.

The computer program can calculate relative differences in engine performance, but agreement with actual engine performance is poor at most conditions. The reason is that the Otto-cycle model does not yet include valve timing, variation in intake fuel-air charge, and prediction of the charge when the inlet valve closes. These will be included in the computer program at a later date after the new integration technique is working.

A program to supply experimental engine data to support development of the analytical model is in progress. In addition to supplying engine emissions and performance data, these tests will also supply data on such important factors in determining model accuracy as heat loss, inlet flow characteristics, combustion products, and combustion intervals. To aid in this experimental work, instrumentation has been designed and built and is being tested to determine on a per-cycle, per-cylinder basis the combustion interval and the indicated mean effective pressure. These formerly were manually calculated from photographs of the combustion

chamber pressure after testing. The mass fraction burned as an interim step is now determined on line in real time. A sample of oscilloscope traces of three successive cycles of the combustion chamber pressure and the mass fraction burned at a lean medium-power condition are shown in figure 15-3. Both the combustion chamber pressure and the on-line-determined mass fraction burned as a percentage of the maximum value are shown as functions of crank angle degrees. Two traces represent normal combustion and the third represents increased ignition lag and slow burning due to a very lean mixture. The combustion interval of about 80° can be measured from the curve of mass fraction burned. We have defined the combustion interval as the time that it takes to go from 10 to 90 percent of the mass fraction burned.

The on-line determination of the mass fraction burned of the charge was compared, at good combustion conditions, with that obtained with a digital planimeter connected to a minicomputer. Figure 15-4 is a computer plot of the rate of change of combustion chamber pressure and the mass fraction burned as functions of crank angle degrees using the planimeter method. Superimposed on the mass-fraction-burned curve is a series of dots representing values that were taken from an oscilloscope trace of the on-line measurement of mass fraction burned at the same test conditions. The agreement is very good. It is planned to very shortly have a direct digital output reading of combustion interval and apparent flame speed. The apparent flame speed is an average velocity of the flame in the combustion chamber. The distance used is that from the spark plug to the furthermost point in the combustion chamber at 90-percent mass fraction burned. The time interval is that required to go from 10 to 90 percent of the mass fraction burned.

Engine-indicated mean effective pressure (imep) in real time is continuously calculated by another prototype instrument currently under test. The work done on a per-cycle basis is measured directly. Using the combustion chamber pressure, a running integral of the change in pressure and volume as a function of crank angle is continuously summed over the 720° of one cycle to give one value. One-hundred consecutive cycles of imep are calculated, stored, and averaged to also give one mean value. In addition, the standard deviation is also calculated. The 100 cycles are displayed on an oscilloscope in a bar-graph output. The mean value of imep and its standard deviation are digitally displayed. Also, any of the individual imep values can be selectively read out. Figure 15-5 shows six sets of imep bargraphs for different operating conditions taken on an automotive V-8 engine that is being used for both instrument research purposes and in support of the Otto-cycle program. The six conditions are engine startup, idle at 1000 rpm, and engine operation at 2000 rpm and identical power at three equivalence ratios, stoichiometric ($\phi = 1.0$) and lean ($\phi = 0.81$ and 0.77). Also, engine operation at 2000 rpm and the lean limit is shown. It is a rather dramatic presentation of both slow combustion and misfires.

Improved engine cooling: The objective of this program is to gen-

erate, for analysis and design purposes, information on engine cylinder cooling consisting of both analytical and experimental data. This would include data and correlations for analysis, design, and optimization of finned cylinder heads, cooling airflow, and pressure drop. Work will be performed both in-house at Lewis and on contract.

A great amount of research was done in the early NACA days on cooling fin analysis and optimization. The major thrust of this work was toward overall minimum weight, airflow pressure drop, and highest heat transfer. Research has also been done for automotive air-cooled engines. General conclusions have been that the cooling fins should be as thin as possible and that there should be as many as practical, with spacing being a function of flow and pressure drop with fin flow length being as short as possible. During this same time period, research was done by NACA on baffling for radial engines, some of this technology can be applied to in-line engines. Cylinder baffling design is very important and depends on the specific cylinder-head finned configuration. It properly needs to be an integral part of the overall specific cooling design and the engine itself. Small variations in spacing or excessive clearance between the baffles and fins can cause a short circuit in the cooling flow and a substantial reduction in its effectiveness.

An initial analytical effort is now underway to define and analyze fin thickness, spacing, heat transfer, and flow and their effects on cylinder wall temperature. A computer program of a two-dimensional model of a single flow channel has been written and is being used to calculate cylinder wall temperatures at the end of the airflow path. Fin cooling is analyzed by looking at it as a system consisting of a heat exchanger with all of its interrelationships of fin, channel configurations, flows, and temperature differentials ΔT's. With the long, narrow, heat flow path from the front to the back of today's cylinders, it is possible to have a few hundred degrees temperature difference between the inlet and outlet air temperature, which is almost directly related to cylinder wall temperature differences at the corresponding air-fin locations. This initial computer work does not consider fin weight as an optimizing factor. The effect of weight sensitivity on finned configurations at this point is academic until a generalized cylinder-head configuration is modeled and the main heat paths and overall heat transfer are considered. Finned samples will be tested and the results correlated with this initial analytical work. Cylinder heads instrumented with thermocouples will be tested by the engine manufacturers. This information will be used to help determine major heat flow paths and to aid in analytically modeling these heat flow paths as possible parts of an overall cylinder-head analytical model.

In addition to the cooling fin analysis, and as a separate effort, such concepts for improving cooling as local forced-air cooling and shaft fans will be evaluated for their potential contribution to cooling.

Future programs. - As part of a long-range planning effort, new research that may reduce emissions and improve technology has been identi-

fied. The benefits could be any one or a combination of reduced emissions, reduced specific fuel consumption (sfc), reduced maintenance, lower cost, increased performance, and greater reliability. Specific areas of research that could be pursued as our resources allow are as follows:

High-energy ignition systems: Ignition systems with increased ignition energy and/or duration may have the potential to significantly reduce emissions, improve performance, and allow leaner engine operation. A unique ignition system that can provide significant amounts of increased ignition energy over any specified length of time to the spark plugs has been designed and an experimental model built. A system that can provide multiple sparks and the sustained arc system would also be adapted to and installed on an aircraft engine for testing. The relative effects of increased ignition energy from each system on engine performance and emissions compared with the standard ignition system would be evaluated. Based on this evaluation, an advanced ignition system might be designed and tested (perhaps as part of an automated engine control system) on an aircraft engine.

Automated engine controls: The objective of this program would be to determine and demonstrate the potential of an automated engine control (preprogrammed single-lever type) to operate an engine at preset conditions for various power levels, exhaust emissions within the EPA standards, minimum fuel consumption and yet provide the required safety margin for response and performance. Included in this control would be throttle/propeller pitch, fuel-air ratio, spark advance, and turbocharging.

System requirements would be defined along with the controlling and controllable parameters. Available experimental data on the sensitivity of input parameters would be used in a systems analysis to assist in the selection of control parameters and a system concept. A research breadboard system would be assembled and tested on an aircraft engine.

Technology from other areas of the general-aviation program (fuel injection, ignition, systems cooling) could be inputs to this specific program. It might also be necessary to evaluate the state of the art of control sensors and controls.

Assessment of engine modifications for and use of alternative fuels: The objective of this program would be to evaluate other available gasolines or synthetic fuels derived from either coal or organic materials as alternatives to existing aviation fuel. Alternative fuels would be evaluated for unmodified engines. Also to a limited extent, engine modifications needed to use these fuels would be explored.

An assessment would be made of what engine changes and modifications would be necessary and practical to be able to use other available fuels with lower octane ratings and/or volatility characteristics and a wider

tolerance on fuel specifications. Automotive no-lead gasoline or a derivative thereof would be a primary candidate because of its availability. Synthetic aviation fuel would be obtained for testing with current engines. Tests would be made to check for any emissions and/or performance differences. An endurance test could be proposed to determine if there might be any long-term effects on the engine and its performance or maintainability.

Improved induction and carburetion systems: The objective of this program would be to evaluate the potential of improved engine induction and carburetion systems to significantly improve engine operating conditions and performance. Present-day carbureted aircraft engines consistently run at leaner fuel-air ratios in the rear cylinders because the throttle plate deflects the fuel droplets toward the front cylinder. This maldistribution detrimentally affects both engine emissions and individual cylinder-head temperatures. This program would also complement and interface with the programs for engine modifications required to use alternative fuels and automated engine controls. Varying fuel-air ratios as a function of power demand (throttle position) may be required in order to help meet the EPA emission standards.

SUMMARY

In summary, the Lewis in-house program is pursuing new and/or improved technology for internal combustion engines that could be of long-term benefit to the industry. Specific areas of interest have been identified, a long-range program has been planned, and a number of efforts are underway.

1. Engine testing on a Lycoming 0-320 engine for baseline performance and temperature-humidity correlations has been completed. A preliminary data report on the baseline testing has been published, and a preliminary data report on temperature-humidity effects on emissions is being reviewed. Engine performance and emissions testing on a Continental TSIO-360 has just been started. Preliminary data analysis shows a definite trend and strong effect of ambient temperature and humidity on emissions.

2. Initial bench testing of existing aircraft injectors is in progress and shows that there is room for improvement.

3. An Otto-cycle computer program is under development. Chemical kinetics has just been incorporated in the combustion process, which should allow the prediction of hydrocarbons and carbon monoxide, which heretofore has not been possible. On-line engine indicated mean effective pressure and flame speed instrumentation, which has wide general applicability, is being developed and show good results in the experimental testing supporting the analytical effort.

4. A two-dimensional, fin-channel, cooling-airflow computer program has been written to study configuration effects on cylinder wall temperature. Results to date show that the change in wall temperature along a fin flow passage is almost exactly equal to the adjacent cooling-air temperature rise. One cylinder head has been thermocoupled, and another will be, for testing by the engine manufacturers. Main heat flow paths will be determined to aid in analytical modeling.

5. Other promising technology areas have been identified for possible future work. These are high-energy ignition systems, automated engine controls, alternative fuels and required engine modification, and improved induction and carburetion.

DISCUSSION

Q - C. Rembleske: NASA is to be congratulated on going back into this
     area. What are your projections for the completion of your research
     into reciprocating engines?

A - W. Wintucky: Our goal is to complete the temperature-humidity cor-
     relations within a year. The fuel-injection research will take sev-
     eral years and to get this on an aircraft engine will take a little
     longer. The cooling program effort is probably the longest program.
     It is an evolutionary program in that it is somewhat dependent on
     what we find out as we go along. The program is adjusted accord-
     ingly. This is also what we are doing with the Otto-cycle program.
     In that program, it will probably be 3 years before we have a model
     that could be used to generalize and predict emissions and per-
     formance.

COMMENT - M. Krasner: I would like to clarify what Bill has said. Ob-
viously, the final fruits of these sorts of research programs may take
some time to be realized. But we are fortunate, in this case, in deal-
ing with the limited number of people involved in the industry. It is
easy for us, since we are already in contact with them, to quickly and
directly relay information we have developed. And we intend to do so
even ahead of our regular reporting times.

Q - W. Wiseman: In your future programs you listed the investigation of
     alternative fuels, and you mentioned the problem that now exists
     with the use of 100 low lead fuel as a substitute for 80/87. Be-
     cause of that problem, there is a rapidly growing interest in using
     automotive gasoline for aircraft. Do you plan to investigate the
     possibility of using automotive gasoline for aircraft?

A - W. Wintucky: To go from 100/130 octane to automotive fuel requires
     a drastic modification to an aircraft engine. We would be looking
     at what engine changes would be necessary and whether it is feasible,
     in the first place, to take that drastic a step and go back to using
     lower octane fuel with the broad range of specifications in which
     this fuel is produced.

COMMENT - W. Wiseman: Of course, the trend is toward unleaded automo-
tive gasoline and, at the moment, octane is not a problem for the auto-
mobile.

Q - E. Becker: About 12 years ago the Army issued Military Specifica-
     tion 46005 with regard to reducing the logistics problem of ground
     vehicles and aircraft operating on different fuels. Is there any
     current interest in pursuing that particular effort or in branching
     out from it to develop a more common base fuel for both ground vehi-
     cles and aircraft.

A - W. Wintucky: I don't know.

COMMENT - G. Kittredge: We in the EPA are extremely pleased to see the rebirth of NASA's independent efforts in this very important area. I have a comment that deals with water injection as applied to diesel NO_x control. That has been looked at by the automotive industry and the diesel engine manufacturers as a NO_x suppression measure, and it has always been found wanting because of the additional fluid needed to be carried along. This would be an even more serious constraint in an aeronautical application. The automotive industry has gone to exhaust gas recirculation instead because that uses fluid already aboard the vehicle and carries no particular penalty.

Q - L. Waters: Several needs motivate the investigation of these areas of technology. In my view the most urgent one, by far, is fuel conservation. I might say that GAMA enthusiastically supports these investigations, and we certainly wish to be involved and give our input. We believe the programs described are in the right organization, that is, in NASA. They are not programs for the engine companies. Lastly, on behalf of my people, I would certainly like to register my vote of confidence in NASA for the type of programs they have devised and their pertinence to industry needs. The bar graphs you showed indicate the great cycle-to-cycle variation that occurs upon leaning. The richer condition showed a much more suitable cycle-to-cycle maximum pressure. We cannot determine anything but the gross effects of the cycle-to-cycle dispersions presently by just studying the exhaust gas. Do you believe that with your program it will be possible to say whether or not low-pressure cycles are worse emitters than high-pressure cycles and perhaps point the way to combustion development in that sense?

A - W. Wintucky: In our Otto-cycle experimental effort we will try to determine the combustion species on a per-cycle basis as they are produced and correlate them with the combustion process itself. This is a very difficult thing to do, and we may not be able to do it.

Q - D. Powell: You mentioned a single lever to control the fuel-air ratio. Are you contemplating the control of rpm with that single level also?

A - W. Wintucky: A single-lever system would probably be a power demand or certain type of performance condition control. The pilot would set it and the controller or controls would automatically set a number of things including rpm for best power, performance, emissions, or economy - whatever the compromise was at that particular condition.

Q - F. Riddell: When you started work on the fuel injector, did anybody contact both Porsche and Bosch?

A - W. Wintucky: Bosch only.

COMMENT - F. Riddell: It is my recollection that the original work on the Porsche 911 car was with the Bosch L jetronic, an electronic timed injector, and their original statements were that this was the only way

that they could meet the EPA limits on emission. About a year later, they took the timed injector off and went to the continuous flow, K jetronic mechanical system. They said they had found no difference in emissions on their engines. They have been using the Bosch K jetronic injectors ever since. We are talking about going in the opposite direction from what Porsche did. There is no doubt that the timed injector is much more expensive.

COMMENT - W. Wintucky: Porsche had electronic reliability problems with the L jetronic system and switched to the K jetronic mechanical system because it was proven and in production. The decision was not based on basic pulsed versus continuous flow system performance.

(a) Idle and taxi.
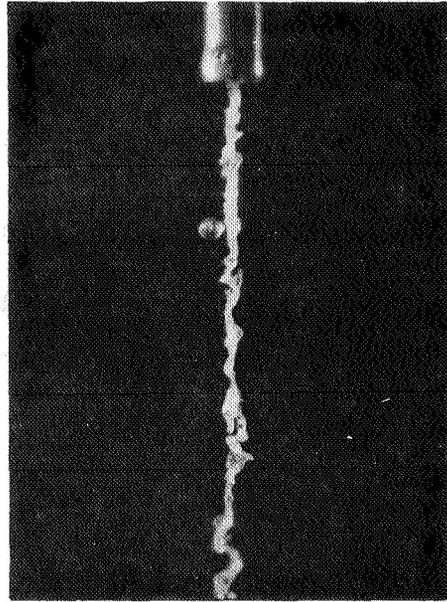
(b) Takeoff.
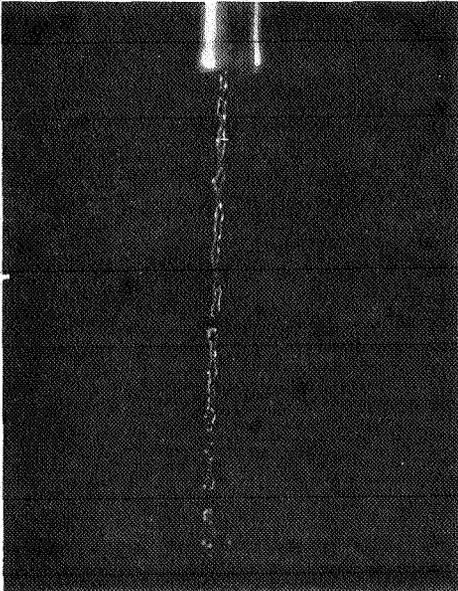
(c) Climb, approach, and cruise
performance.
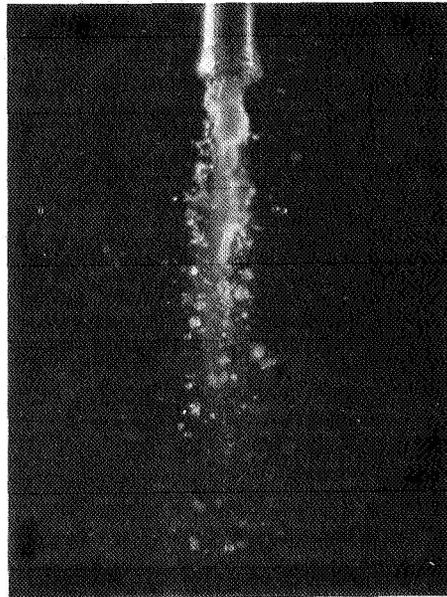
(d) Takeoff.

Figure 15-1
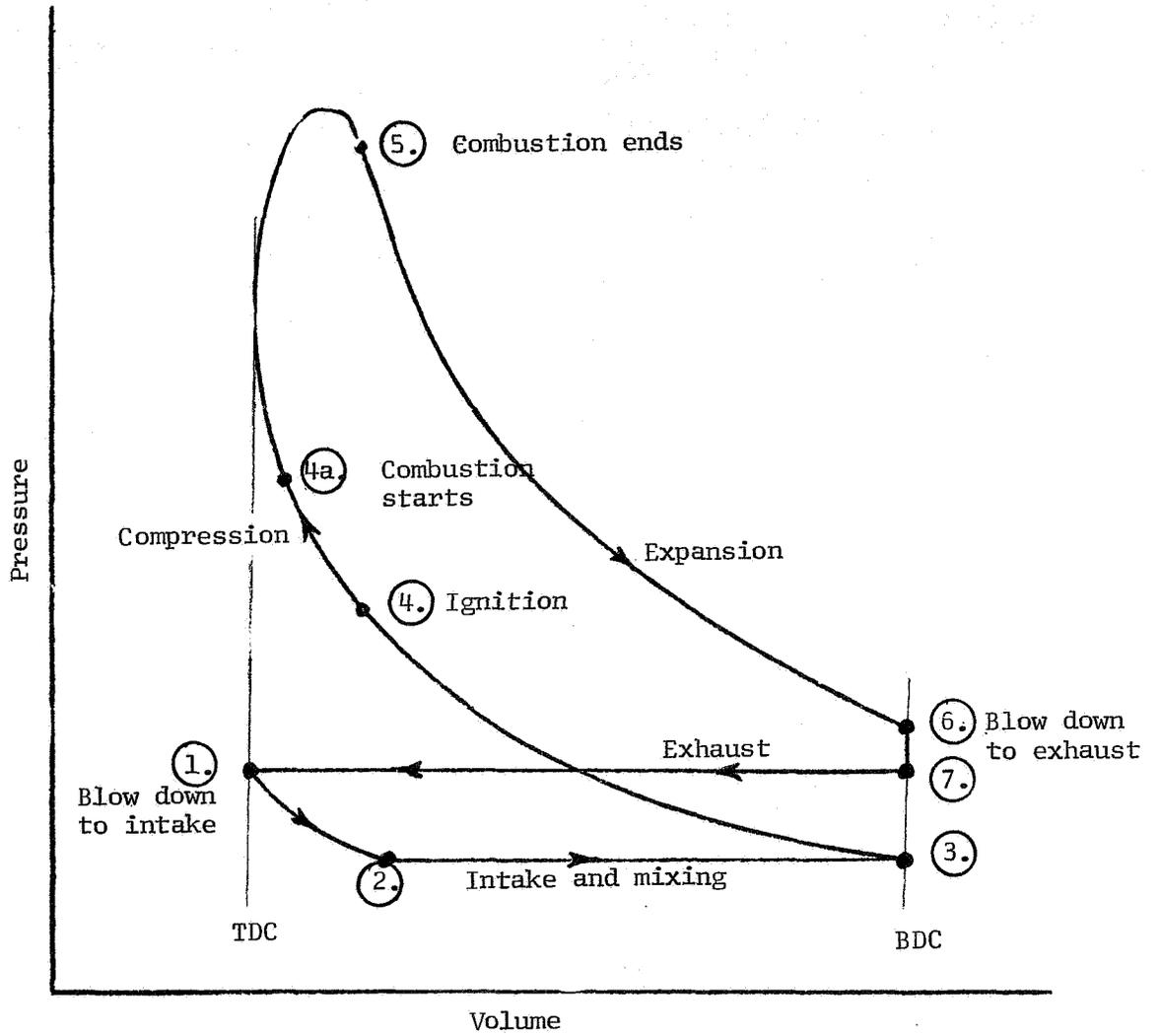
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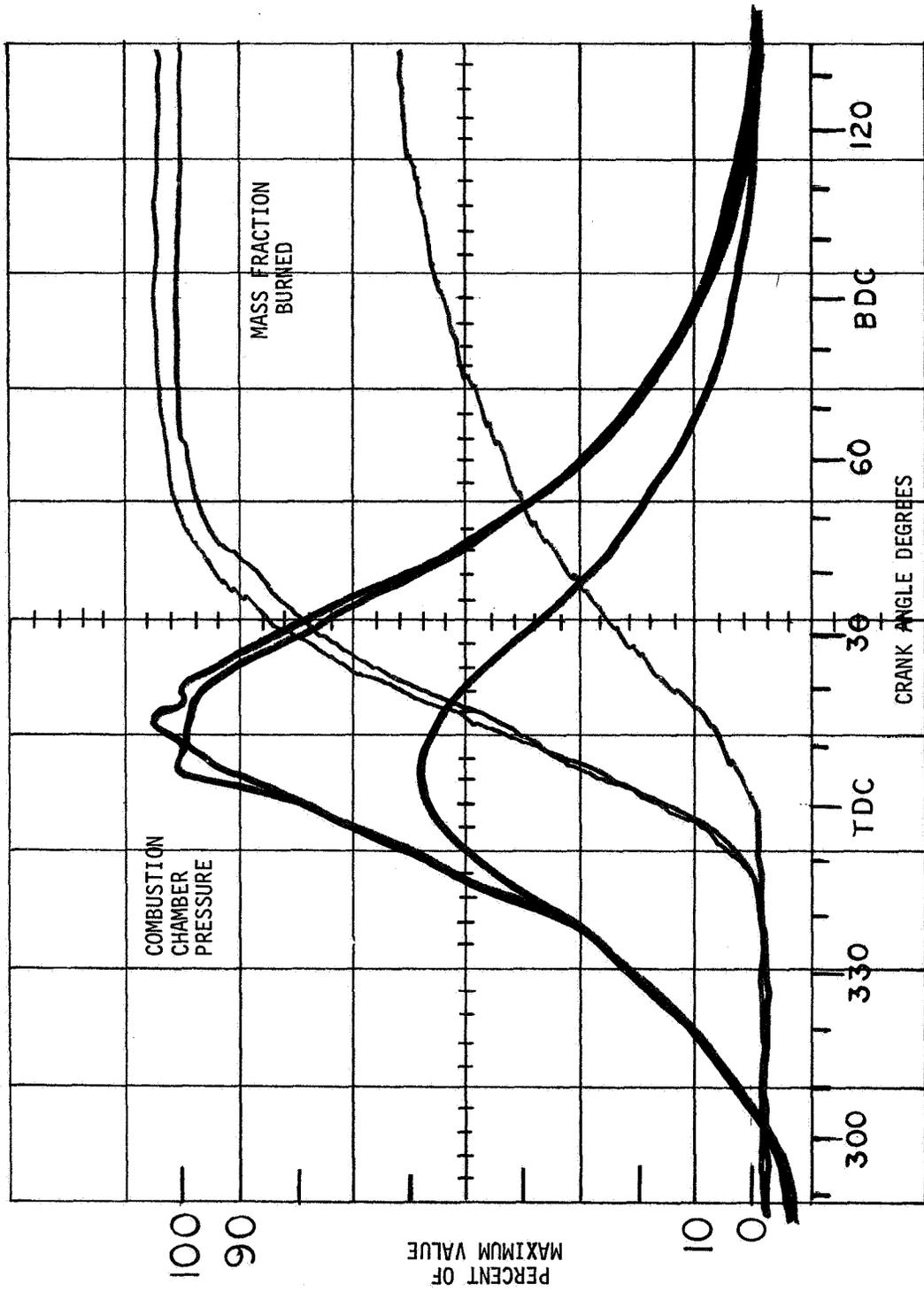
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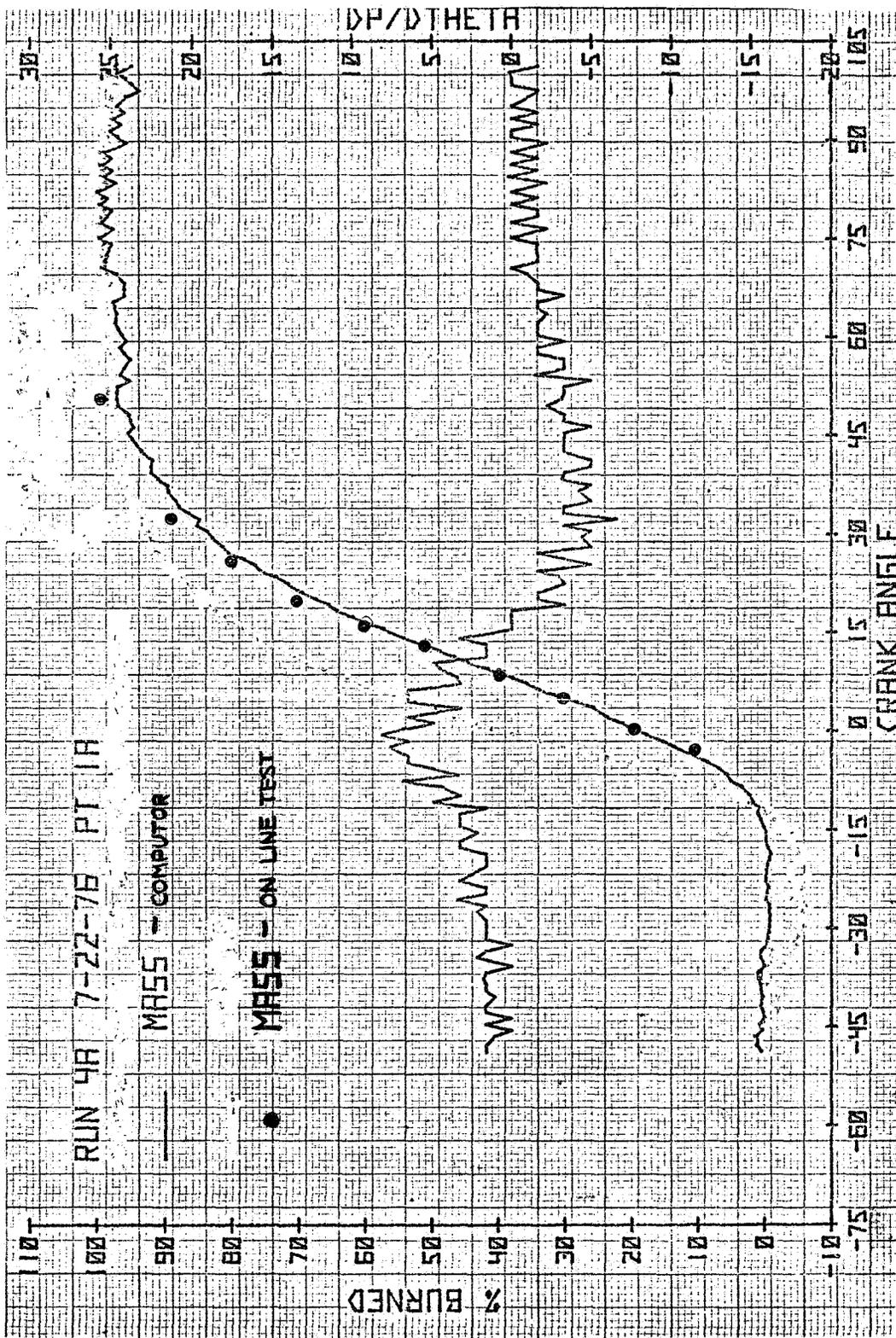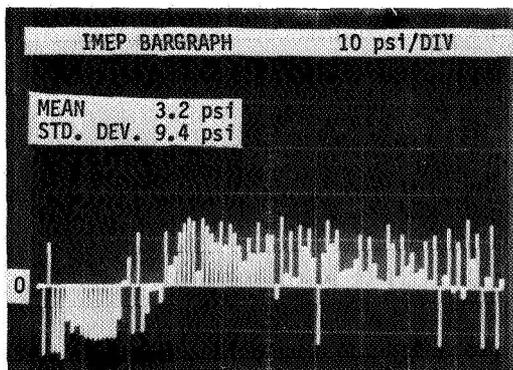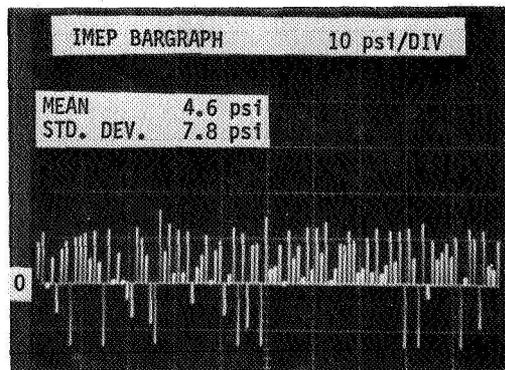
312

Figure 15-4

IMEP BARGRAPH   10 psi/DIV

MEAN   3.2 psi
STD. DEV.   9.4 psi

0

ENGINE STARTUP

IMEP BARGRAPH   10 psi/DIV

MEAN   4.6 psi
STD. DEV.   7.8 psi

0

1000 RPM IDLE

IMEP BARGRAPH   10 psi/DIV

0

MEAN   41.0 psi
STD. DEV.   0.7 psi

rpm = 2140 , T = 88 ft. lb. , ϕ = 1.0

IMEP BARGRAPH   10 psi/DIV

MEAN = 41.5 psi

STD. DEV. = 7.6 psi

rpm = 2140 , T = 88 ft. lb. ϕ = 0.81

IMEP BARGRAPH   10 psi/DIV

0

MEAN   40.9 psi
STD. DEV.   8.9 psi

rpm = 2140 , T = 88 ft. lb. ϕ = 0.77

MEAN = 25.4 psi

STD. DEV. = 9.77 psi
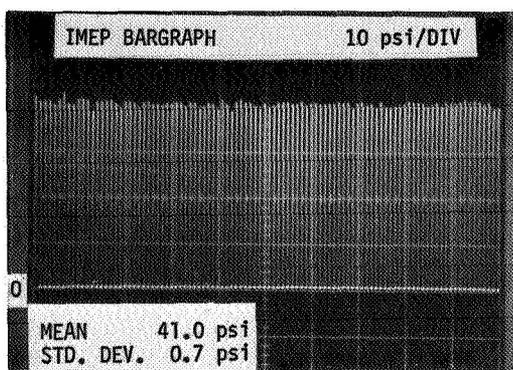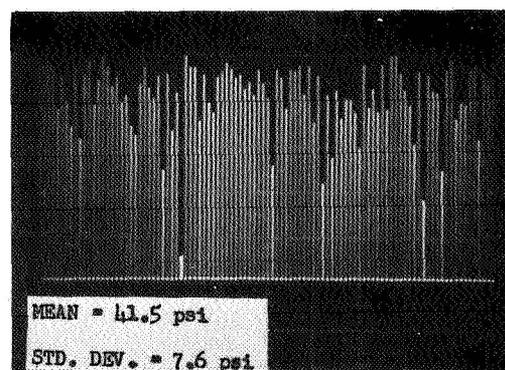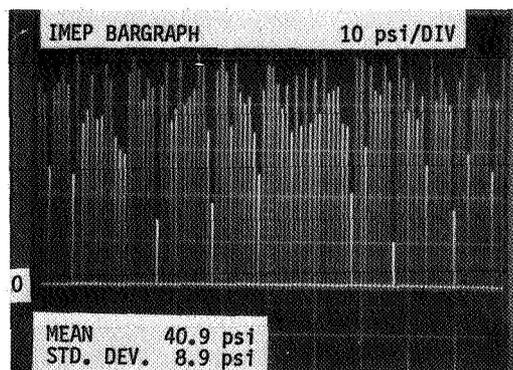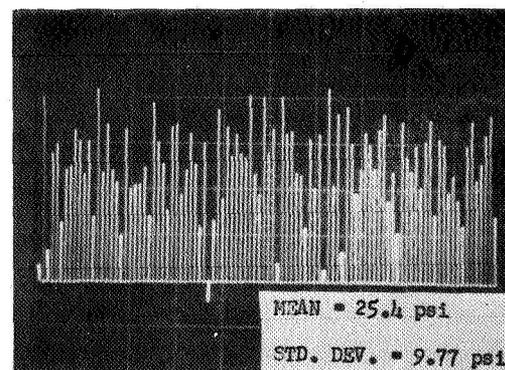
LEAN LIMIT ϕ = 0.66

Figure 15-5

16. ALTERNATIVE GENERAL-AIRCRAFT ENGINES

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National Aeronautics and Space Administration
Cleveland, Ohio

The objective of this effort is to define the most promising alternative engine (or engines) for application to general aircraft in the post-1985 time period and to advance the level of technology to the point where confident development of a new engine can begin early in the 1980's. A unified evaluation study and parametric analysis is needed of advanced propulsion concepts - alternatives to air-cooled, Otto-cycle engines - that will meet changing environmental requirements and have multifuel capability and lower fuel consumption. However, the data base necessary to accomplish the overall assessments of these engine concepts is incomplete. NASA's involvement will provide the focus (1) to obtain sufficient information to assess the many trade-offs, (2) to carry out a unified study to evaluate the suitability of alternative engines for aircraft applications and to select the most promising engine, (3) to define and carry out the most productive research and technology program for the selected engine, and (4) to assemble the pertinent technology into an experimental engine that will permit work on system technology and verify readiness for development by the aircraft engine industry. Much of this work will be done on contract.

The work will be focused on the objectives of low emissions, multifuel capability, and fuel economy. Six alternative propulsion concepts are considered to be viable candidates for future general-aircraft application: the advanced spark-ignition piston, rotary combustion, two- and four-stroke diesel, Stirling, and gas turbine engines. The first phase of the effort will be concerned with assembling an information base by means of analytical studies and experimental evaluation. This work will be done largely on contract in order to take advantage of specialized experience and capabilities. Sufficient information on each engine must be generated to allow evaluation for general-aircraft application. Design and operational characteristics - such as brake specific fuel consumption, emissions, specific weight, and so forth - must be sufficiently well defined to allow incorporation in conceptual aircraft designs for analytical evaluation of performance and other factors influencing suitability. Information derived from the NASA QCGAT program and other Lewis gas turbine technology will be used to define suitable general-aircraft turbine engine characteristics for

use in the unified aircraft systems studies. Insofar as possible, estimates will be made of the costs pertinent to each engine's development, manufacture, and operation.

Following assembly of the necessary engine characteristics data, total aircraft systems studies will be made to define the suitability of the alternative engines for general-aircraft application. It is expected that this work will be done both in-house and on contract. The results of these studies will be used to select a prime candidate engine for possible future application. Following this selection, a preliminary design of the selected alternative engine will be made in sufficient detail to characterize the engine design features and to define technology problem areas. In addition, this design will allow a better estimate of the costs involved in bringing the engine to the market. It is expected that this work will be done on contract. This contract will also include a definition of the research and technology program required to achieve the specified engine design characteristics and performance.

After selection of the most promising alternative engine, specific problems pertinent to that engine will be attacked in a comprehensive program to be carried out both in-house and on contract. The work to be done will include basic component technology - heat exchangers, seals, and so forth - component configuration, materials, manufacturing techniques, and system-related problems. This research and technology work will continue as necessary into the experimental phase. Pending the selection of that engine, a Lewis in-house, low-level, exploratory research and technology effort has begun on two contenders, the diesel and Stirling engines, about which probably the least is understood for modern aircraft use.

The research and technology effort will make possible the definition of an experimental version of the selected alternative engine. An experimental engine embodying the basic design characteristics required for aircraft application, but not to the level of refinement of a development or production engine, will be designed, built, and tested as a contractual effort extending over approximately 3 years. The design will be based on a preliminary design and on the engine research and technology done over the preceding several years. Testing will be carried out both on contract and at Lewis, with most of the latter effort coming after completion of the contractual effort. The results of this program should provide the basis for confident development of an alternative engine for general-aircraft application.

ENGINE CHARACTERIZATION PROJECTS

A good part of our effort is now directed to obtaining characteristic data for the engines of interest. The first of these is the spark-ignition piston engine.

The proposed effort can be described as follows:

(1) Objective: To obtain characteristics data for an advanced
    spark-ignition piston aircraft engine for use in a unified
    aircraft systems study

(2) Approach:

    (a) Complete conceptual design of a spark-ignition piston
    engine incorporating existing technology not used in
    present engines and near-term (5 yr), low-risk tech-
    nology

    (b) Project performance, physical characteristics, and in-
    formation pertinent to scaling

(3) Effort: To be done on contract

(4) Status: Statement of work in preparation

It may seem odd to list the spark-ignition engine as an alternative engine.
However, our intent here is to use a "clean sheet" approach by designing a
new engine that recognizes the existing or upcoming problems in emissions,
fuel economy, and fuel availability. Furthermore, to make a fair evalua-
tion of the potential of new alternative engine concepts, the current en-
gine must be suitably updated in terms of technology.

A very different engine is the Stirling engine. Some of the reasons
for our interest in the Stirling engine as a potential alternative air-
craft engine are low emissions, low engine vibrations, fuel flexibility,
and low engine noise. Emissions can be made very low, well below any pro-
jected standards, because of the continuous nature of the combustion. The
nature of the engine is such that very low vibrations are experienced and
the torque variation through the cycle is quite low. This should allow
for significant structural weight savings and provide fatigue life margin
for the propeller. The Stirling should be able to use essentially any
liquid fuel with some adjustments to the combustor and fuel delivery sys-
tem. In fact, any source of energy that can keep the engine hot and at
operating temperature will drive a Stirling engine. The engine is also
intrinsically very quiet in operation and requires no muffling.

However, the Stirling engine has a number of problems that must be
solved before it can be considered for aircraft use. The most serious
is probably the high specific weight (lb/hp). Substantial gains have
been made in the Ford-Philips Torino engine, but substantial improvement
is still required. Since the Stirling rejects about twice as much heat
through its cooling system as the internal combustion engine, it requires
a larger cooling system. Power control is more complicated because of
the need to change the effective inventory of the working fluid to
change power levels. Provision will have to be made for pressurized
combustion at altitude to maintain operation. Hydrogen is the

best working fluid for performance and power output but offers significant problems in sealing and containment.

Our approach to obtaining the characteristic data for the Stirling engine is similar to that for the spark-ignition engine and is as follows:

(1) Objective: To obtain characteristics data for a lightweight Stirling engine suitable for general-aircraft application for use in a unified aircraft systems study

(2) Approach:

    (a) Complete conceptual design of a lightweight Stirling engine using near-term (5 yrs), low-risk technology

    (b) Project performance, physical characteristics, and information pertinent to scaling

(3) Effort: To be done on contract

(4) Status: Agreement with contractor has not yet been reached; we hope to reach an agreement in fiscal 1977.

However, the ability to develop these data is unique. Understanding of the modern Stirling engine lies today principally with Philips of The Netherlands. They have been engaged in developing the Stirling engine from a concept to a workable engine for nearly 40 years. The Ford Motor Company, which is interested in Stirling for automotive application, has contracted with Philips for an exclusive worldwide license pertinent to automotive applications. We believe, therefore, that the best source of the information for an advanced, lightweight Stirling would be Ford-Philips. A contractual agreement with them has not yet been reached, however.

The rotary engine is a relatively new concept that offers promise for aircraft application. The key characteristic of interest for the rotary engine is its low weight. Although it appears that liquid cooling is necessary, its specific weight is low even when a cooling system is included. The superior cooling potential of this liquid system, moreover, may allow leaner operation without overheating problems. This should allow reduced emissions and improved fuel utilization. The rotary engine we are examining is, in contrast to most of the other alternative engines, which are largely conceptual, a full-scale operable experimental aircraft engine. Some of the engine characteristics are water cooling (experimental), 285 horsepower, 6000 rpm, a specific weight including the radiator of 1.26 lb/hp, and a brake specific fuel consumption of 0.48 lb/bhp-hr. Our approach to the rotary engine characterization effort is as follows:

(1) Objective: To obtain characteristics data for a two-rotor, rotary combustion aircraft engine for use in a unified aircraft systems study

(2) Approach:

    (a) Test engine to obtain complete performance and emissions data for an existing configuration

    (b) Obtain physical description of engine – drawings, weight data, operational limitations, and so forth

    (c) Obtain information that will allow analytical scaling of the engine from one-half to twice its present power

(3) Effort: Contract with Curtiss-Wright Corporation; estimated cost, $64,647.00; estimated period of performance, 6 months

(4) Status: Contract awarded May 6, 1976; basic dynamometer test facility/equipment completed; engine run-in completed; emission equipment calibration and basic engine calibrations in progress; sizing parameters and engine layouts showing dimensions, configurations, accessories, and so forth, in preparation

The approach differs from that for the other engines in that actual full-scale performance and emissions data will be obtained to form the basis for all the required characteristics data. A contract is now in force with Curtiss-Wright. The engine run-in has been completed, the emissions equipment and engine calibrations are in progress, and we hope to complete the emissions and performance data within the next few months. The analytical and layout effort pertinent to engine scaling is also under way.

Diesel engines offer several attractive features for aircraft use: multifuel capability, high reliability (no mixture control, no icing problems, and no ignition problems), reduced fire and explosion hazards, and easy maintenance. The diesel has some multifuel capability, which is attractive in light of potential problems with aviation gas availability. Moreover, the lower volatility of diesel fuel would greatly reduce fire and explosion hazards. Of course, the diesel engine has proven high reliability and low maintenance in truck application. Carburetor icing and ignition problems would not exist. However, diesel engines do have some disadvantages for aircraft application: high specific weight, large volume, and negative environmental factors (noise, smell, smoke, and high hydrocarbon emissions with two-stroke machines). The most obvious disadvantage of diesels is their high specific weight. Two promising approaches to reduced weight and higher output are the turbocharged two-stroke engine and the low-compression, turbocharged four-stroke engine. Other disadvantages are less serious and can probably be alleviated through design and development effort.

We have a contract with the University of Michigan to obtain characteristics data for a low-compression, highly turbocharged four-stroke diesel engine. A primary concern with such engines is the problem of starting and low-speed operation. Their concept involves preheating the inlet air at start to allow ignition even with low compression. Their initial projections are that the specific weight of this concept will be equal to or less than a conventional spark-ignition engine. The program includes experimental and analytical effort to define the characteristics of a lightweight, low-compression diesel engine and is outlined as follows:

(1) Objective: To obtain characteristics data for a lightweight, low-compression, turbocharged diesel engine for use in a unified aircraft systems study

(2) Approach:

    (a) Obtain test data on single-cylinder research engine with dieselized cylinder from standard aircraft engine

    (b) Project characteristics of a complete aircraft diesel engine

    (c) Design "hot-port" cylinder

(3) Effort: Contract with University of Michigan

(4) Status: Contract awarded June 30, 1976; single-cylinder engine being prepared

The experimental work will be done with a single-cylinder engine modified to incorporate a Teledyne Continental Motors GTSIO-520 cylinder converted to diesel operation. Tests will be made to define the optimum combination of compression ratio, inlet air temperature, and pressure. Performance will be determined for the optimum combination, and full-scale engine characteristics will be derived analytically from those data.

The two-stroke diesel engine intrinsically has a potential for high power output. Preliminary data on the McCulloch engine, which has a unique patented combustion chamber, indicate high specific output, high efficiency, and smooth operation. The engine has not yet been tested to full power. Our intent is to do so and to fully characterize the engine for input to our overall alternative engine comparison study. The planned approach is as follows:

(1) Objective: To obtain characteristics data for a two-stroke diesel engine for use in a unified aircraft systems study

(2) Approach:

    (a) Test McCulloch engine to obtain complete performance and emissions data for existing configuration

    (b) Obtain physical description of engine - drawings, weights, operational limitations, etc.

    (c) Obtain information to allow analytical scaling of the engine from one-half to twice its present power

(3) Effort: To be performed on contract

(4) Status: Agreement with contractor has not yet been reached; we hope to arrange for engine testing in fiscal 1977.

Some characteristics of the McCulloch engine are its experimental two-stroke design, 180-cubic-inch displacement, 180 horsepower, 2850 rpm, and high supercharging. It has been tested to 64-percent power, is equivalent to a naturally aspirated GTSIO-520 engine, and has a high-turbulence combustion chamber design.

Gas turbine engines for application to general aircraft will be examined in both turbofan and turboprop versions:

(1) Objective: To obtain characteristics data for a turboprop and turbofan engine suitable for general-aircraft application in a unified aircraft systems study

The approach is as follows:

(2) Approach: To use data from the QCGAT program and other Lewis Research Center gas turbine technology to define performance and physical characteristics

(3) Effort: To be performed in house

(4) Status: In planning stage

Data for characterization of small gas turbine engines for general aircraft will be obtained largely from the QCGAT program and other Lewis programs related to gas turbine technology. The specific conceptual designs and their characteristics will be developed at Lewis.

All the engine characteristics data obtained in these engine studies will be applied to an aircraft systems study. The project is as follows:

(1) Objective: To examine the candidate alternative engines to define the most promising engine (or engines) for general-aircraft application in the post-1985 period

(2) Approach:

    (a) Correlate the material obtained from the six engine characterization studies

    (b) Use engine data in analytical aircraft design and evaluation program to define best engine candidate for future application

(3) Effort: Both in-house and on contract

(4) Status: In planning stage for fiscal 1977

Performance specifications for a typical single-engine unpressurized airplane and a twin-engine pressurized airplane will be used as the base to develop conceptual aircraft designs to match each of the candidate powerplants. Appropriate missions will be examined analytically and the significant performance differences determined. Cost, both initial and continuing, will also be examined as a significant factor in comparing the engines. It is intended that this work will be done both in-house and on contract. This work in combination with the engine characteristics studies should provide the basic information that will allow us to make the appropriate comparisons and trade-offs and to select the most promising engine for future research and technology concentration.

IN-HOUSE RESEARCH AND TECHNOLOGY

The in-house work currently in progress is focused on two promising engines that have not been examined extensively for aircraft application - the Stirling and diesel engines. As discussed previously, our principal goals in diesel engines are to reduce specific weight and to increase specific power. The primary focus of our effort will be on low-compression, highly turbocharged, four-stroke diesel engines. This is similar to the work being done at the University of Michigan in that the principal problem lies in developing an acceptable system for starting and low-speed operation. Our approach, as shown in figure 16-1, is different:

    (1) Objective: To develop technology for diesel engines that will permit substantial improvement in specific weight and power and further reduce fuel consumption and exhaust emissions

    (2) Approach:

        (a) Analyze highly turbocharged, low-compression-ratio diesel engine system with low-speed turbine augmentation to facilitate start and low-speed operation; define potential performance and technology problem areas

(b) Purchase and install a single-cylinder diesel research en-
engine that will be used to test the concepts defined in
the analysis

(c) Experimentally test key components such as the low-speed
turbine augmentation combustion system

(d) Experimentally examine the possibility of reducing oxides-
of-nitrogen(NO_x) emissions by introducing high-latent-heat
fluids such as water or methanol

(3) Status: Preliminary system analysis complete; test cell being
prepared; single-cylinder research engine built and acceptance
test scheduled; combustion system in test

Instead of heating the inlet air, we propose to use a semi-independent
turbocharger to provide higher engine inlet flows and pressures at start.
The basic new element in the system is a catalytic combustor that can
provide turbine-drive gas even when the diesel engine is not operating.
During full-power operation, the diesel exhaust would be routed through
the catalytic combustor, but no fuel would be added. This should pro-
vide for cleanup of any hydrocarbons in the diesel exhaust before re-
lease to the atmosphere. A single-cylinder AVL research diesel engine
has been purchased and is now ready for acceptance testing. This will
serve as the primary test bed for defining the design parameters of the
low-compression semi-independent turbocharged diesel engine. The com-
bustion system will be tested and developed separately before combining
it with the engine system. We also plan to examine the effect of addi-
tions such as water or methanol on NO_x formation. Proper introduction
of these high-latent-heat fluids, either mixed with the fuel or sepa-
rately introduced, may lower peak combustion temperature and hence NO_x
production without reducing efficiency significantly.

Our Stirling engine technology program is outlined as follows:

(1) Objective; To become familiar with Stirling engine concepts,
determine technology needs, and define a pertinent research
and technology program

(2) Approach:

(a) Obtain Stirling-type engine for test

(b) Develop computer models for engines

(c) Test engines to define performance and control character-
istics and to calibrate and verify computer programs

(d) Define desirable component characteristics and begin work
on component technology

(2) Status: Helium performance tests complete on 8-hp rhombic-
drive engine (GMC-GPU3); engine being reconditioned in prepa-
ration for hydrogen tests; NASA computer simulation being re-
vised to include effects of mechanical friction and seal
leakage; 6-kW, free-piston engine has not yet achieved rated
power; contractor will perform a detailed analysis to define
the problem and determine a solution

Our primary objectives are to become familiar with Stirling engine con-
cepts, to determine the technology needed to bring the concept to matur-
ity for aircraft application, and to define a research and technology
program that fulfills these needs. Our first step in this effort was to
obtain appropriate Stirling engines for testing. Concurrently, we worked
on the assembling of computer engine simulation models for these engines.
Our plans are to test the engines over a wide range of operating param-
eters and to compare the results with those obtained from the engine
simulation program. The intent is to use these data to develop, verify,
and calibrate computer simulations that will correspond accurately to
the actual engines. As we gain confidence in our ability to simulate
the engines and in our understanding of component behavior and cycle
relationships, we will begin work on advancing component technology.

We have on hand two GMC-GPU3 Stirling engines, which are rhombic-
drive machines rated at about 8 horsepower. One has been refurbished and
tested to obtain performance data with helium working fluid. This engine
is now being reconditioned in preparation for tests with hydrogen work-
ing fluid. The other engine will require extensive refurbishment before
testing. We have also contracted for a 6-kilowatt, free-piston Stirling
engine, which we plan to use in extending our understanding. The engine
has been designed and fabricated and set up for acceptance testing. It
has not yet been able to achieve rated power. The reasons for this de-
ficiency are not clear. The contractor will perform a detailed analysis
using his newly developed proprietary simulation program in order to de-
fine the problem and determine a solution.

SUMMARY

In summary, the overall objective of the program is to determine
which alternative engines are most promising for possible future appli-
cation, to define the research and technology program required to bring
them to the required state of maturity, and to carry out that program.
Our approach includes both in-house and contractual effort and both an-
alytical and experimental work. It involves generating the required
characteristics data for candidate engines and applying these data to an
overall aircraft-mission study to define the most promising engines. In
addition, the required research and technology program for the selected
engine will be defined and implemented. The overall program is progress-
ing about as planned; both in-house and contractual efforts are well un-
der way - with some exceptions as noted previously.

DISCUSSION

Q - F. Riddell: Why do you continue to talk about seal problems with the Stirling engine? Aren't 10 000 hours of service life enough?

A - W. Tomazic: Seal life has to be proven over a longer period of time with more engines. We are having seal problems in testing our engines. People are concerned about high-pressure hydrogen stored in the engine and so forth. There is still some question about the proprietary coating process that Phillips uses to prevent hydrogen diffusion. The problem still seems to exist.

COMMENT - F. Riddell: Part of the hydrogen problem was settled as a result of Ford's requirements, you know. Ford requires that there be no hydrogen addition in 50 000 miles. They also require going from idle to 90 percent of full load torque in 0.6 second. Neither of those requirements would apply to an aircraft engine.

COMMENT - W. Tomazic: No, I agree the design requirements are quite different. That is one of the reasons we would like to look specifically at the aircraft engine. As far as seals are concerned, a good deal of development is still required. Roll-sock seals are not wholly satisfactory, primarily because of the complicated pressure regulation system required to prevent overloading the seal. If the roll-sock seal fails, the failure is catastrophic. Sliding seals are being looked at again.

COMMENT - F. Riddell: I saw the sliding seals. Phillips has done quite a bit of work on them and gotten good service life. It is a Teflon type of dry seal with liquid cooling on the outside of the cylinder. There is little friction or frictional loss from the seals. They do receive some heat from the cylinder barrel, so Phillips cools them. The seals have been working very nicely according to the people at Phillips.

Q - C. Rembleske: I know that Cessna has flown a rotary engine. What have they actually done in rotary engine research?

A - H. Nay: Approximately 4 1/2 years ago the Curtis-Wright, two-chamber, 185-horsepower automotive engine was tested in a Cessna Cardinal with a two-stage reduction gear system. This was a 5000-rpm engine with a propeller rpm of about 2200. This program was part of the quiet engine program. The engine had a very massive exhaust muffler system. After a great many hardware difficulties, the aircraft was successfully flown. It is basically a four-place aircraft carrying 50 gallons of fuel, which gave it about 5 hours of cruise endurance. The water-cooled engine and that particular two-stage reduction gear system resulted in basically a one-place aircraft with test instrumentation and a moderate amount of fuel on board. It was also tested in another configuration in a joint program with Curtis-Wright. The first program was sponsored by the Navy with NASA involvement. The second program was a joint program between Curtis-Wright and Cessna and was aimed at a more practical evaluation of the aircraft. A single-stage reduction system was used with the propeller rpm at 2700, which was the rpm of the basic

Cardinal airplane with the 0-360 Lycoming carbureted 180-horsepower engine. The engine did not develop the full 185 horsepower. The best result, as I recall, were 155 to 160 horsepower. The aircraft provided demonstration rides for a number of us, as a two-place aircraft with considerable degradation in takeoff and climb performance. The general conclusion was that the level of aircraft engine technology was very definitely not acceptable. An electronic ignition system was used and proved extremely troublesome. It resulted in two forced landings before we finally got it working satisfactorily. Nothing that I can say here could give any definitive conclusions on the long-term viability of the rotary combustion aircraft engine. Without qualification, that engine as tested was operationally unsatisfactory and totally unacceptable from a weight and performance standpoint.
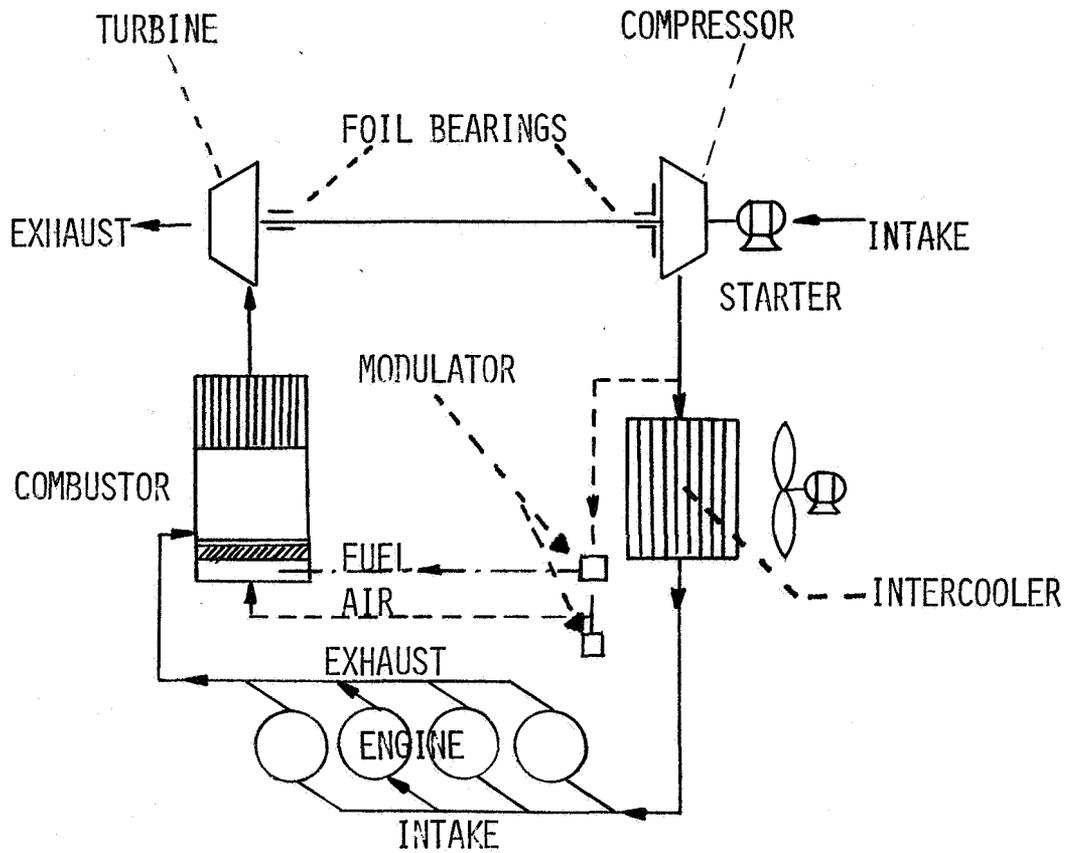
Figure 16-1

EXHAUST PRODUCTS + AIR + FUEL (AS REQUIRED) INTO CATALYTIC COMBUSTOR

- PRODUCES DRIVING GAS FOR TURBINE
- CLEANS UP HC IN EXHAUST
- ALLOWS HIGH POWER FROM LOW CR ENGINE

17. SUMMARY OF THE GENERAL AVIATION MANUFACTURERS'

POSITION ON AIRCRAFT PISTON ENGINE EMISSIONS

J. Lynn Helms

Piper Aircraft Corporation
Lock Haven, Pennsylvania

The members of the General Aviation Manufacturers Association are
pleased to participate in this symposium and wish to express their
appreciation to NASA, particularly the Lewis Research Center, for host-
ing the meeting. A technical meeting, with representation from all
groups associated with aircraft piston engine emissions, is particularly
appropriate at this time. A considerable amount of technical results
from the laboratory, test stands, and flight tests is now available.
This meeting fills a need for an update to all concerned on what is
known and not known about aircraft piston engine emissions and the re-
sultant installation and operational unknowns.

The standards governing the emissions of aircraft piston engines
were established nearly 3 years ago. Those standards were established
without a valid technical basis applicable to aircraft engines. In the
public hearings held at that time, the General Aviation Manufacturers
Association pointed out the extremely small contribution to atmospheric
pollution made by piston engine aircraft. It was pointed out that the
gains in environmental quality would be extremely small (completely un-
measurable) and the costs extremely high in proportion to any benefits.
On the basis of the tests completed since then, and the considerably
greater (but still incomplete) knowledge that we have today, the conclu-
sions we expressed in the 1973 public hearings have been reinforced.

We strongly recommend that the EPA rescind the aircraft piston
engine emissions regulations currently on the books. This should be done
because of the very small emission reduction potential and the very poor
benefit-cost ratio involved in this form of emission reduction. The
limited resources of this industry can far better be devoted to items of
much greater benefit to the citizens of this country - reducing noise,
improving fuel efficiency (which will incidently reduce exhaust emis-
sions), and improving the safety, operational, and economic aspects of
our aircraft, all far greater contributions to our total national trans-
portation system.

I have summarized the position of the General Aviation Manufacturers Association. We believe it is based on the facts, and it is the same position we held in 1973. However, we recognize that, regardless of our position and regardless of the facts as we see them, the regulations regarding aircraft piston engine emissions are on the books. We have been working hard to respond to these regulations to determine if it is possible to meet the regulations or to determine what level can be approached and to define an orderly program for compliance.

Up to now the research effort on reducing aircraft piston engine emissions has primarily been concentrated on operating with leaner fuel-air mixtures to reduce hydrocarbons and carbon monoxide. Other approaches, such as modifications to spark timing, which could possibly be implemented within the next several years, have not shown promise. For the en route phase of flight, the current mixture leaning practices provide near-optimum fuel-air ratios from both standpoints of fuel economy and exhaust emissions. Development efforts on reducing engine emissions have properly been concentrated on operations in the vicinity of the airport where most richer than optimum mixture operations occur. The research results show that although some fuel-injected engines might operate satisfactorily with leaner than current fuel scheduling in the initial climb and approach modes they still would not meet EPA standards. Also, there appears to be a possibility that with the addition of complex and costly automatic mixture control devices some further reduction in emission levels might be obtained. Fully effective devices are many years away. It is not possible to predict, with confidence, how close these changes could bring the body of aircraft piston engines toward meeting the existing standards. There is considerable variation from one engine model to another of a given class, and the effects of production tolerances, test conditions, engine hour accumulation, and aircraft installation constitute additional unknowns.

Let me emphasize that the practicality of the emission reduction approaches which have been tentatively identified have yet to be proven. In the case of some of the automatic mixture control devices, the implementing hardware technology has yet to be developed and tested. Current aircraft fuel control systems have evolved over many years of development and refinement based on field experience. Certainly much can be done on the test stand and on in-flight tests. However, before we deliver an aircraft with a new fuel scheduling system to a customer it must be tested over the full spectrum of conditions expected in operation including time. We must have a firm handle on all of the operational, environmental, and manufacturing variables involved and their effects on safety and operation of the aircraft. In the case of modified fuel scheduling, this requires a costly and time consuming process using current types of injector systems. In the case of automatic mixture control devices, it would require a much longer and more costly development program and this would result in a major increase in production costs for very little benefit.

Based on current information, a projection has been made of the emission reductions possible, and rough estimates of the costs involved have been established. Currently, aircraft piston engines make up approximately 0.1 percent of the total atmospheric hydrocarbon, carbon monoxide, and NO_x pollution. Based on an estimated potential of a 30 percent reduction in emissions during the landing-takeoff cycle, where 5 to 10 percent of aviation fuel is burned, a reduction of approximately 2 percent in total emissions is projected for a typical piston engine aircraft with a modified fuel system. By the year 2000 roughly one-half of the fleet would be made up of aircraft powered by modified engines. On this basis, a reduction in total atmospheric pollution of the order of 0.001 percent is projected for the year 2000. These numbers could easily be off by a factor of two, five, or even greater in either direction. However, the point remains - the contribution of any possible aircraft piston engine emission reduction to the total atmospheric pollution reduction is dramatically miniscule and unmeasurable.

If we look at the economics, it is estimated that a 5 to 15 percent increase in product cost to the consumer would probably be necessary for the engine and aircraft modifications required to provide the emissions reductions assumed previously. With a $1 billion average annual sales rate for piston engine aircraft, the cost is estimated to be $50 to $150 million per year, or at least $1 to $2 billion in this time period. Thus, the benefit to cost ratio works out to be approximately 0.000001 percent per million dollars spent. Surely other far more important needs exist for these resources.

It is clear on the basis of what we know today (disregarding the cost-benefit aspect) that it will be impossible to meet the existing standards by December 31, 1979, either as to levels or time. If it is not possible to rescind or indefinitely postpone the applicability of the standards, then it is clear that both the industry and the government agencies represented at this meeting need to aggressively continue research and development efforts to provide the information upon which realistic standards, and a practical schedule for their implementation, can be based. As a part of this effort, we feel that it is important that good, definitive information regarding implementation costs and schedules be developed so that a practical program reflecting cost-benefit trades can be devised.

As the industry began preparing for this symposium several months ago, it was hoped that sufficient information would be available to enable us to make a concrete proposal to modify the standards and the implementation schedule. Unfortunately, as we have seen during the past two days of discussion, sufficient knowledge is not available to allow the definition of realistic standards. We plan to continue our efforts toward the goal of establishing realistic standards and a workable implementation program. Even if the standards are rescinded, our industry will continue with a meaningful program. It is necessary that this effort be continued and that new standards and schedules be established

in the near future in order to avoid serious dislocation within the industry because of the long lead time commitments necessary on many purchased items, such as engines, and the long flow time in the aircraft manufacturing process.

We feel that the symposium has been extremely worthwhile in providing a free exchange of information on what is known and not known on aircraft piston engine emissions. The hidden spectre throughout is the potential impact on flight safety. It seems very likely we will reverse the positive trend of 60 years if we continue on this present path; that is, we will have less flight safety.

Based on all the information available to us today we can draw the following conclusions:

(1) Sufficient testing has now been accomplished to confirm trends of expected results.

(2) The technology does not exist to meet the present EPA standards or schedule.

(3) We do not yet know what limits can be met.

(4) System technology to achieve automatic mixture control is presently unknown.

(5) The impact of emission reduction efforts on time between overhaul and engine reliability are completely unknown.

(6) Flight safety requirements prevent the adoption of any system requiring manual leaning during the taxi phase.

(7) Wide and unpredictable excursions exist in production tolerances.

(8) Each aircraft installation is different and not completely predictable.

(9) No technical option exists that is compatible with production and tooling lead times.

(10) Achieving the EPA emissions standards would only reduce atmospheric pollution by approximately 0.001 percent.

(11) Costs of tens to hundreds of millions of dollars per year will result for the extremely small reductions obtained.

(12) There will be an adverse impact on flight safety, though we do not know how to quantify.

Differences with these conclusions can exist only in degree, not subject matter.

We live in complex times with ideas and opinions subject to extreme criticism or appraisal by either genuine evaluators or purposeless dissidents. These cultural environmental characteristics are exacerbated by the political events of the day and single-interest groups, either pro or con to an idea.

None of these, however, relieve our joint responsibility for fulfilling the established requirements of our respective offices. Just as industry has a firm responsibility to take a leading role in a national environment improvement effort so also does the federal government and its included agencies and bureaus have an equal responsibility to stand up and be counted when it is time to acknowledge the need for change. Government need not do so with any feeling of valid condemnation from industry or outspoken critics. Equally, our congressional committee system clearly establishes a recognition by the Congress for the need to continually review and revise laws and their applicability.

It is now clearly evident that when these standards were established in 1973 the national mood of cleaning up the environment overwhelmed our knowledge of what could be done and the safety aspects affected by establishing aircraft piston engine emission standards. We now have a joint responsibility to redirect the two most vital resources we have - talent and time - toward solving problems with a much higher potential pay out to our nation's citizenry. Cost is merely our way of accounting for use of these two more vital resources.

It is time we clearly state that the potential benefit of even massive efforts to reduce aircraft piston engine emissions is unmeasurable at best and an extremely poor use of our national resources. Aside from the economic impact of large scale unemployment and plant reductions, it is a case whereby simple logic confirms that what we get is not worth the effort. It was not the intent of Congress when it enacted the Clean Air Amendment of 1970 to arbitrarily establish a basis to waste tens of millions of dollars for a benefit so small that even this nation's advanced technology cannot measure. Congress fully expects the responsible government organization to bring such situations to their attention.

We thereby recommend that -

(1) The emissions requirements specified for aircraft piston engines be rescinded, and

(2) A joint industry-government task force compile a report containing all of the data obtained (which substantiates the recommendation for recision) with that report made available to all interested parties, whether dissidents or supporters, rather than engage in continuing rhetorical debate, or

(3) If the previous two recommendations cannot be accepted, then the emissions levels and schedule for aircraft piston engines must be indefinitely postponed until such testing has been completed as to allow the establishment of meaningful values and dates.

DISCUSSION

COMMENT – J. Barriage: Speaking for the FAA, I appreciate the provisions and the excellence of the discussions and presentations which we have experienced these past 2 days. Each of us recognizes that there is a great deal more to be done. I think each of us also recognizes that we need to continue defining the work that needs to be done and to define the manner in which we are able to arrive at a solution. Obviously, as has been brought out, there are differences of views, but it's healthy to bring them out and discuss them. We appreciate NASA-Lewis having this symposium and handling it so beautifully.

COMMENT – G. Kittredge: We, too, appreciate the opportunity to have been able to take part in this symposium. In my own case, it's the first chance I've had to get together with such a complete spectrum of talent from the aerospace industry and associated government agencies. We look forward to the publication of the proceedings. We'll study these very carefully and with thoroughness. We want to respond to your comments, Mr. Helms. To do them justice, we would like to study them more thoroughly on an agency basis before we comment. I have a few impromptu comments which are my own only. I do want to restate, with regard to our air quality arguments, that certainly what you say is correct in so far as nationwide impact is concerned. With respect to general aviation operations, we're really mostly concerned with the local impact, largely that of carbon monoxide in reasonably close proximity to heavily used general aviation airports. With regard to the very valid points brought up by Mr. Helms and discussed more completely yesterday on testing and measurement problems, we accept that these have delayed work on actual reduction of engine emissions. Since the session yesterday, the FAA and myself have talked this over. We will make an effort to get a meaningful industry/government group to work on this within the next several weeks. The SAE committee I referred to yesterday is scheduled to meet within 2 weeks. Our proposal is to set up a subgroup that would include the people who've spoken on this subject here during the past 2 days and to work to fill in some of the gaps in the present emissions measurement procedures. We don't see this as a formidable problem, because of the excellent base that now exists as a result of your 3 years of experience. One comment on engine cost. This morning's session was the first exposure I'd had to actual cost estimates as to implementation of this program for the very wide array of engine models and aircraft types that you have to deal with. I do feel, in a somewhat defensive way, that since the approaches that have been talked about most seriously for use in meeting the standards do result in fuel economy benefits as well, that the costs of the total program can be spread over the presumed fuel economy advantages to your customers as well as to air quality control. You said it the other way around in your presentation. It's equally valid either way. One other comment that really wasn't brought out by Mr. Helms, but did come out this morning, has to do with old engines and old aircraft. I should have said this morning that we have this comment in hand from the turbine engine manufacturing segment of the industry. It was presented at our public hearings on this

subject in February 1976. We have to respond to it. But engines that
are likely to be made in relatively limited quantities in the future to
serve for replacement purposes in existing old design aircraft will have,
presumably, minimum impact on air quality and justify some sort of exemp-
tion or delay or something of that nature. I can assure you that this is
being worked on.

COMMENT - G. Banerian: This concludes the formal presentation of our
program. As all of you know, the purpose of the meeting wasn't to de-
bate the merits of the regulations, but to provide data for future regu-
latory action and petitioning for change if deemed necessary. I want
to thank all of you for participating as you did and presenting your
material in a most professional way. I, also, thank the Lewis Research
Center for a good job in arranging this meeting. As you know, the action
items for regulatory action are with FAA and EPA and not with NASA. We'll
do what we can to assist them, but the initiative is with them.

APPENDIX A

REVIEW OF MEASUREMENT AND TESTING PROBLEMS[*]

Avco Lycoming
Williamsport, Pennsylvania

PROBLEMS EXPERIENCED

I. Instrumentation – Good instrumentation is required to obtain reliable and repeatable baseline data. Problems have been encountered in developing such a total system.

    A. Accurate airflow measurement at all modes is essential. Leanout curve trends have substantial dependence on this quantity.

    B. Precise fuel flow measurement is required to maintain good fuel/ air ratio agreements. The small flows typical of the idle/taxi modes demand extreme accuracy.

    C. The instrumentation used for pollutant measurement has proven to be susceptible to frequent malfunctions and has required certain modifications.

        1. Changes to console pumps, filters, and gas sample path have been made in an attempt to comply with the 2 second response time.

        2. Modifications to the NO/NO_x analyzer have been recommended to eliminate possible water condensation in the reaction chamber.

        3. The instrument pump in the FID was replaced with a larger unit to improve response time.

        4. An oxygen analyzer has been added to the sample analysis instrumentation to permit computation of the carbon balance. There is no requirement or specification for this instrument by the EPA, Part 87.

        5. Frequent instrument and component failures, some requiring lengthy trouble shooting and repair periods have been encountered throughout the test program. A partial list of the failures follows:

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[*]Material distributed but not presented at the Symposium.

Instrument	Problem
HC FID	Pressure regulator failed
HC FID	Pressure gage failed
HC FID	Thermistor failed
HC FID	Heater failed
HC FID	Meter readout miswired
NO/NO$_x$ chem.	Thermistor switch failed, resulting in heater failure
NO/NO$_x$ chem.	Photomultiplier tube cracked
NO/NO$_x$ chem.	Meter readout failed
CO	Detector failed
Heated sample line	Thermistor failed

6. During low power operation (idle/taxi) there is considerable fluctuation in indicated pollutant concentrations, as recorded by the plotter. No determination has yet been made as to whether this variation is inherent in the instrumentation or reflects pulses in the exhaust sample. At present Avco Lycoming approximates the mean of the recorded plotter output as the measured pollutant concentration. Of course, each signal could be electrically dampened or averaged; however, some determination must be made to evaluate the true average and isolate the cause of the fluctuations.

II. Span Gases - Span gas quality has a significant effect on emissions test results.

A. The rejection rate of incoming span gases based on a ±2 percent tolerance is approximately 15 percent.

B. Until sufficient test experience was accumulated, it was often difficult to identify span gas discrepancies and divorce them completely from instrumentation problems.

C. The Scott Reference Service is performed only four times a year. Such variables as span gas replacement and instrumentation changes must be considered. In addition, this service publishes an average value from the reported results of the participants. No allowance is made for an abnormal pattern in results for a given test period. The Scott Service provides an indication of major span gas discrepancies and should be used in that manner.

D. NAFEC has established its own cross reference service. Sample periods have been increased to one a month; however, this service has been limited to only four sample periods. In addition, the baseline engine test program was completed prior to receipt of the first sample. It will be extremely difficult to use these results to improve correlation of past testing.

III. Engine Condition - It has been shown that the mechanical condition of the test engine can affect the test results substantially.

    A. Prolonged low power operation in the idle/taxi modes without interceding extensive higher power operation is not considered to be normal of in-service engine operating conditions.

        1. Such extended operation at idle/taxi results in fouled spark plugs and glazed cylinder barrels.

        2. If the barrel glazing condition is severe, oil will move past the rings into the combustion chamber, resulting in oil fouled plugs or plugged fuel nozzles.

        3. An engine in this condition may exhibit high oil consumption, moderate to extreme roughness or a loss of ignition in one or more cylinders.

    B. The engine condition should be closely monitored for any possible mechanical malfunctions throughout all modes of operation.

    C. Emissions data taken on an engine experiencing mechanical difficulties cannot be used to predict baseline characteristics.

        1. Emissions data reflecting extremely poor combustion characteristics for the idle/taxi modes is not representative of actual in-service engine operation.

        2. Constant effort should be made to ensure that the test engine is maintained in satisfactory condition.

IV. Test Procedure - Test procedures have been shown to have considerable effect on emissions test results.

    A. The required test procedures as specified by the EPA, Part 87, are incomplete and do not promote the adoption of one unified test procedure by all test facilities. Additional description on the following should be provided:

        1. An acceptable method of performing the precycle warmup should be noted.

        2. Specific description of the required exhaust collection system should be made. There is no system representative of all aircraft models in the general aviation fleet.

        3. The sample transport and response time should be changed to a time representative of the test system and state-of-the-art instrumentation.

4. An instrument specification for the oxygen analyzer should be included if it is to be an optional piece of equipment.

5. If the cycle is to be run consecutively with no intervening operating points, the allowable length of time for operation at the initial idle/taxi modes should be specified to prevent possible deterioration in engine condition.

6. The specified cyclic power settings are at best unrepresentative of typical in-service engine operation. The percent power for the climb mode should be specified, not 75 to 100 percent.

7. There is no specification regarding standard inlet conditions at the entrance to the injector or carburetor or for cooling air supplied to the engine.

8. Some minimum requirement should be noted for the exhaust gas temperature of the sample at the probe inlet to prevent loss of hydrocarbon sample.

B. If the EPA is unable or unwilling to make these specifications, industry and other facilities involved with this testing should formulate and approve a well-defined procedure.

C. Avco Lycoming has experienced problems with air leakages in both the induction and exhaust systems.

1. Since the induction air system is pressurized above ambient pressure, leakages between the air flow measuring system and engine result in the observed air flow readings being higher than the quantity of flow being used by the engine.

2. Cracks forming in the exhaust system usually permit air leakage into the exhaust sample. The resultant pollutant concentrations show signs of dilution or higher than normal oxygen values.

3. Avco Lycoming has found that the data affected by these system discrepancies can be minimized by careful attention to quantities and trends of the fuel/air ratio agreement (utilizing the Spindt Method for carbon balance). However, this requires that all data be reduced daily and reviewed completely.

D. The total emissions data system is fairly complex and Avco Lycoming has experienced substantial "down" time for system maintenance and repair.

V. Calculation Procedure – The required calculation procedure, as speci-
fied by the EPA, Part 87, for reducing raw emissions data leaves
several intermediate steps to "good engineering practice."

   A. It is possible that some differences in reported emissions values
between test facilities can be attributed to differences in cal-
culation procedures. A well-defined procedure for determining
the following variables should be specified by the EPA:

      1. Some method for determining the correction factor for
ambient and combustion formed water vapor should be
specified.

      2. The calculation procedure for the exhaust molecular weight
should be defined.

      3. Acceptable methods to perform the required carbon balance
should be specified. The 5 percent agreement, as specified,
is considered excessively intolerant when dealing with the
low air and fuel flows of the idle/taxi modes.

   B. Again, if the EPA cannot or will not make well-defined require-
ments in these areas, industry together with other facilities in-
volved with the actual testing should specify acceptable proce-
dures.

   C. Correction factors for the effect that nonstandard conditions
have on cyclic emissions totals should be developed between
facilities and approved.

      1. Avco Lycoming has developed in-house correction factors for
the effect of temperature and variations in power output on
emissions when reduced to a pound/mode basis.

      2. However, correction factors for the effect that humidity or
temperature variations have on pollutant formation (ppm or
percent by volume) are needed.

RECOMMENDATIONS

I. Engine Test Procedures

   A. The engine must be maintained in good condition for the entire
test program to ensure that representative data is obtained.

      1. A performance calibration should be made to ensure that the
engine is within production limits and typical of that par-
ticular model. The calibration should consist of the follow-
ing types of runs: full throttle performance, mixture dis-

tribution at rated speed, variable manifold pressure at rated speed, fuel metering response with varying propeller load, oil consumption. Additional testing may be included, if necessary.

2. Daily inspections of the engine and sampling system should be made to inspect for possible discrepancies. The inspection procedure currently used by Avco Lycoming is described in attachment I.

3. During operation, frequent magneto checks should be made to ensure that the ignition system is functioning properly.

4. Cylinder head temperatures should be monitored closely for signs of engine problems. For idle and taxi modes, a comparatively low head temperature could be indicative of ignition or fuel nozzle problems. Comparing cylinder head temperature trends for the takeoff, climb, and approach mode leanout runs can also be used in the same manner.

5. The engine must be constantly monitored for abnormally rough or uneven operation, particularly in the idle/taxi modes. Prolonged running at low power conditions causes deterioration in engine condition such as fouled spark plugs and glazed cylinder barrels which are not representative of an engine in good condition.

   a. A possible indicator of glazed cylinder barrels is higher than normal engine oil consumption.

   b. Frequent magneto checks will show a high rpm drop between magnetos or highly uneven cylinder head temperatures when on single ignition as indicative of possible fouled spark plugs.

   c. Corrective actions are prolonged periods of operation at high power conditions. Badly fouled spark plugs may require removal and cleaning.

   d. A period (10-20 min) of continuous operation at takeoff power should precede a baseline run to improve spark plug and cylinder barrel conditions. Avco Lycoming has found that this procedure tends to minimize data scatter in the idle/taxi modes for the baseline cycle.

   e. Once the baseline cycle has been initiated, the modes must be run in sequence with no "clearing" between modes.

f. The only time a brief period (2-5 sec) of engine clearing is permitted between consecutive idle or taxi runs is during a leanout test when engine deterioration is suspected due to prolonged low power operation. The engine should be briefly cleared after each run.

B. Two types of tests are currently employed to determine the emissions characteristics of an engine model:

1. The baseline cycle consists of a seven-mode test program run consecutively with stabilized engine conditions at each mode. The following are the engine speeds and power settings for each mode :

Mode	Engine speed	Power, percent
Idle	600	--
Taxi	1200	--
Takeoff	Rated	Full throttle
Climb	90% rated	80
Approach	87% rated	40
Taxi	1200	--
Idle	600	--

2. The leanout run shows the effects of mixture variations on emissions output and vital engine parameters for each mode. The results of the leanout run when plotted on a pounds/mode or percent pollutant concentration versus fuel/air ratio basis can be used to identify emissions trends, formulate possible temperature or humidity correction factors or construct improved or optimum baseline cycles based on leaner fuel schedules.

II. Emissions Instrumentation

A. It is required by the EPA, in Part 87, that the following exhaust emissions concentrations be measured:

CO	(Carbon monoxide)
CO_2	(Carbon dioxide)
NO/NO_x	(Oxides of nitrogen)
HC	(Hydrocarbons)

In addition to the above quantities, measurement of the O_2 concentration in the exhaust sample is necessary to complete the carbon balance calculation procedure (Spindt Method) currently in use.

1. Avco Lycoming has experienced several instrumentation difficulties since the initiation of testing.

   a. The instrumentation employed is basically sensitive laboratory test equipment. Usage for extended periods of time results in the need for frequent adjustment or in equipment malfunctions.

   b. Careful daily monitoring of instrument response characteristics provides aid in determining the onset of · instrumentation difficulties.

2. Avco Lycoming essentially follows the procedures outlined in the EPA, in Part 87; however, revisions are necessary to update and improve the required test procedures.

   a. Revisions for improving and updating instrument calibration procedures and specifications are necessary.

   b. It has been stated by the EPA that changes will be made to the 2 second sample response time. Such a revision is necessary and should also include a well defined procedure for determining this response time.

B. The exhaust collector and sample probe should be designed and fabricated in accordance with the requirements by the EPA in Part 87.

   1. The exhaust system should be made of a suitable material and designed to permit no exhaust gas dilution but minimize engine power loss. Carefully fitted slip joints are permitted but may require additional sealing to guard against dilution.

   2. The sample probe is fabricated from 1/4 inch diameter stainless steel tube with 5 inlet holes approximately 1/16 inch diameter located evenly across the tailpipe. The sample probe inlet holes are positioned into the exhaust flow, although testing has shown no difference in measured concentrations for other rotated positions.

   3. The sample probe should be located far enough downstream to allow for good mixing in the tailpipe. However, the EPA in Part 87 specifies that the sample path to and through the Hydrocarbon Analyzer must be maintained at 302° F (150° C) to prevent the loss of heavy hydrocarbons in the sample line. Therefore, the minimum allowable EGT at the inlet of the sample path is 302° F. Avco Lycoming has noted that failure to maintain sufficient exhaust gas temperature at the sample probe inlet results in similar losses. In addition, low EGT's are often indicative of exhaust sample dilution.

III. Span Gases

    A. Maintaining a set of good quality working span gases is important in obtaining accurate and repeatable emissions data.

        1. Comparative services such as the Scott Reference Service and the NAFEC Cross Reference Service can be used as indicators of possible span gas discrepancies.

            a. Due to the 3 month period between samples with the Scott Service other factors such as changes in instruments and depletion and replacement of span gases must be considered.

            b. The Scott Service uses the average of the reported values as a basis for comparison. This average could be influenced in a specified test period by an abnormal reporting pattern from the participants. It is invalid to use this average as the absolute value of the sample gas in an attempt to revise span gas values.

            c. A review of the Scott Service results between facilities shows no definite relative trends. It is difficult to justify the use of either service to formulate correlation correction factors either for past or present testing.

        2. Avco Lycoming has established an in-house quality control procedure for testing working span gas accuracy. A set of master grade span gases have been purchased to be used as comparative standards. Periodically, all in-house working span gases will be checked against two or more of the master standards. At present, details as to frequency of testing, acceptable tolerances, etc., are being formulated.

IV. Computational Procedure

    A. The basic computational procedure employed by Avco Lycoming is as specified by the EPA in Part 87, Federal Register. Figure A-1 shows a flow diagram summarizing the data reduction process. Shown in attachment II is a complete detailed description of the procedure currently used.

        1. The EPA, in Part 87, does not require that the inlet air pressure, temperature, or humidity be controlled to a specified range. Differences in mass of induction air flow between varying ambient conditions can be substantial. As the air flow quantity is involved directly in the calculation for pollutant pound/mode, some effort should be made to

correct for varying ambient conditions. At present, Avco Lycoming is investigating possible correction factors which will improve data agreement.

2. In addition to affecting air flow mass, temperature and humidity differences can affect pollutant concentration output. Avco Lycoming has made limited effort at defining correction factors for these effects. Other facilities such as NASA Lewis, which have the ability to fully control ambient test conditions, should provide better controlled data trends for a complete analysis.

B. Although the basic calculation procedure for reduction of raw emissions data is specified by the EPA in Part 87, some of the intermediate steps are not defined adequately.

1. The method for determining exhaust molecular weight should be specified.

2. The procedure for calculating water correction factors for both combustion formed water and ambient water vapor should be outlined.

3. A method for performing the required carbon balance should be included.

V. Data Analysis Criteria

A. In emissions testing, the review and analysis of data trends and quality becomes a complex procedure because of the large number of values recorded as input parameters.

1. Some method of carbon balance must be used to identify possible data discrepancies. At present the Spindt Method is used by all facilities involved in the piston aircraft emissions program.

a. The Spindt Method provides a comparative computational procedure for fuel/air ratio based on measured emissions concentrations.

b. The fuel/air ratio agreement is obtained by comparing the measured and calculated fuel/air ratios. The EPA, in Part 87, requires that this agreement be within ±5 percent for all modes. Although this requirement is realistic for the higher power and taxi modes, compliance for the idle mode is difficult where low air and fuel flow values as well as small changes in engine speed necessitates extremely precise measurements.

2. Avco Lycoming has found that emissions data with considerable scatter in fuel/air ratio agreements usually produces the same scatter when plotted on a pound/mode versus fuel/air ratio basis. In addition, the best data correlations between facilities, or even in-house testing, are obtained when the fuel/air ratio agreements are well within the tolerance.

3. Experience has shown that the fuel/air ratio agreement between measured and calculated fuel/air ratios is possibly the most valuable indicator in recognizing and locating discrepancies in the emissions system. Recognizing these trends or variations in trends in the fuel/air ratio agreement is most important.

CHECK LIST TO PERFORM BEFORE BEGINNING EMISSIONS TESTING - (Daily)

1. <u>Sample System</u>:

   Please remove heated sample line from probe. Remove covering from teflon section of line and inspect for any heat damage. If teflon has become discolored, replace section. Check all fittings for tightness. Cap off end of sample line and turn on console pump to leak check.

   Remove stainless steel probe and inspect for cracks. Check exhaust system from exhaust ports to probe location for cracks. Reconnect all parts of line and reinstall probe.

2. <u>Induction Air</u>:

   Please inspect induction air hose for leaks. Check clamp at airbox for tightness.

3. <u>Magneto Timing Device (if installed)</u>:

   Please check connecting arm for tightness. Inspect around magneto base for oil leakage or gasket slippage. Tighten slightly if necessary. Check position indicator cable connector for tightness.

4. <u>Torquemeter</u>:

   Please check for oil leakage around any portion of the torquemeter, adapter plates or propeller. Inspect restraining wires to torque-meter to make sure they are in good condition.

R. Moffett

DATA REDUCTION TECHNIQUES EMPLOYED BY AVCO LYCOMING

The following data reduction techniques are currently employed by Avco Lycoming:

1. Water Correction Factors - to account for the water vapor condensed from the analyzed exhaust samples

2. Exhaust Molecular Weight - to convert the volumetric percentages read from the exhaust analyzers to a gravimetric percentage

3. Exhaust Volume Technique - to calculate the total mass exhausted from the engine based on the mass percentage of the individual pollutants and the total gas flow through the engine

4. Carbon Balance - to verify that those pollutants detected by the exhaust gas analyzers are indicative of the fuel-air mixture supplied to the engine

WATER VAPOR CORRECTION

Water vapor in the exhaust sample originates from two sources:
(1) combustion formed water vapor, (2) water vapor contained in ambient induction air. Avco Lycoming has developed independent correction factors for each source.

Correction Factor for Combustion Formed Water Vapor

Considering a general equation for the combustion process at equilibrium in the form

$$a_o C_c H_h + a_1 [O_2 + 3.76 \ N_2] \rightarrow a_2 CO_2 + a_3 CO + a_4 H_2 O + a_5 H_{1.85} C + a_6 H_2 \quad (1)$$
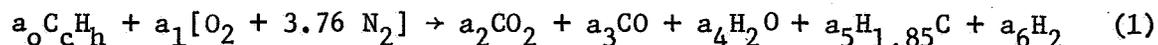
where

$$\sum_2^n a = 1$$

a carbon balance yields

$$a_o = \frac{a_2 + a_3 + a_5}{c} \tag{2}$$

and a hydrogen balance yields

$$a_o = \frac{2a_4 + 1.85a_5 + 2a_6}{h} \tag{3}$$

Combining (2) and (3) and solving for a_4 gives

$$\frac{a_2 + a_3 + a_5}{c} = \frac{2a_4 + 1.85a_5 + 2a_6}{h}; \qquad \frac{h}{c} = \alpha$$

$$\alpha(a_2 + a_3 + a_5) = 2a_4 + 1.85a_5 + 2a_6$$

At this point the relationship $0.51\,a_3 = a_6$ or $0.51\,CO = H_2$:

reference: "Relation of Exhaust Gas Composition to A/F Ratio," B. A. D'Alleva and W. G. Lovell, SAE Journal (Trans.), Vol. 38, No. 3

Therefore

$$a_4 = \frac{\alpha}{2} a_2 + a_3 \left(\frac{\alpha}{2} - 0.51\right) + a_5 \left(\frac{\alpha}{2} - \frac{1.85}{2}\right) \tag{4}$$

At this point because equation (4) is still in terms of mol fractions we can substitute the chemical terms for a_2, a_3 . . . to simplify the equation. Of course, the CO and CO_2 quantities are measured dry and represent such in the equation, so they must be converted to wet concentration $(1 - H_2O)$.

$$H_2O = \frac{\alpha}{2} (1 - H_2O)CO_2 + CO(1 - H_2O) \left(\frac{\alpha}{2} - 0.51\right) + \frac{HC}{10^4} \left(\frac{\alpha}{2} - \frac{1.85}{2}\right)$$

$$= (1 - H_2O) \left[\frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] + \frac{HC}{10^4} \left(\frac{\alpha}{2} - \frac{1.85}{2}\right)$$

$$= \left[\frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] - H_2O \left[\frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right]$$

$$+ \frac{HC}{10^4} \left(\frac{\alpha}{2} - \frac{1.85}{2}\right) \tag{5}$$

$$H_2O = \frac{\left[\frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] + \frac{HC}{10^4}\left(\frac{\alpha}{2} - \frac{1.85}{2}\right)}{\left[1 + \frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right]} \qquad (6)$$

By definition

$$C_w = 1 - H_2O$$

Finally,

$$1 - \frac{\left[\frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] + \frac{(\alpha - 1.85)HC}{2\times10^4}}{\left[1 + \frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right]} \qquad (7)$$

equals the water correction factor C_w for that contribution arising from the combustion process.

Correction Factor Ambient Water Vapor Development

Previously it was assumed that the fuel was represented by a specific fuel molecule. However, this approach, while allowing calculation of the water contained in the air, fixed the definition too rigidly. With little or no difference in the final result a more general approach was adopted that is based on the assumption that the water contained in the intake mixture does not enter into any combustion reaction and simply passes directly through the engine. Expressing this in a word equation

(Water in exhaust - lb/hr) = (Air flow into engine - lb/hr)(% humidity)

$$(1)$$

Dividing each side of the equation by the total flow through the engine, air plus fuel, yields the percentage of water in the exhaust due to humidity.

In a final form the humidity correction becomes

$$\text{Fraction water} = \frac{(\text{Air flow})(\% \text{ humidity})}{(\text{Air flow} + \text{Fuel flow})} = \frac{M_{air}\left(0.622 \frac{\text{Vapor press.}}{\text{Patm} - \text{Vapor press.}}\right)}{(M_{air} + M_{fuel})}$$

$$(2)$$

or

Water correction factor]$_{Humidity}$ = 1 − Fraction water   (3)

The total water correction factor, therefore becomes a multiplicative combination of the two individual contributions.

The exhaust molecular weight computation is based on "Procedure and Charts for Estimating Exhaust Gas Quantities and Compositions" − GMR 372, B. A. D'Alleva, May 15, 1960. Figure A-2 shows the variation of exhaust molecular weight with fuel/air ratio, as determined by this method.

Exhaust Volume Calculation Procedure

The method specified by the EPA for treating the emissions measurements is specified in the Federal Register, Part 87.99, Vol. 38, 7-17-73. As stated in this section, par. 3, "The engine exhaust volume shall be calculated in accordance with good engineering practice from actual air and fuel flow measurements . . ."

The exhaust volume can be equated as

$$V_e = \frac{W_a + W_f}{D}$$

where

W_a airflow, lb/hr

W_f fuel flow, lb/hr

D   density of exhaust

The exhaust density can be expressed as

$$D = \frac{0.075 \ E_m}{28.96}$$

where

0.075   density of air

28.96   molecular weight of air

E_m exhaust molecular weight

At this point it is necessary to provide the exhaust molecular weight. Figure A-2 shows the relationship between exhaust molecular weight and A/F ratio as derived according to "Procedure and Charts for

Estimating the Exhaust Gas Quantities and Compositions," GMR 372, by B. A. D'Alleva.

Substituting the value for E_m and working according to the calculation procedure in the Federal Register, the mass emission rate of any exhaust component is

$$\text{Pollutant} = \frac{(P)}{100} V_e P_p$$

where

(P)   the pollutant concentration in percent

P_p the pollutant density at standard conditions and is specified in the Federal Register

This yields the emission rate in pounds/hr. To convert to lb/mode it is necessary to multiply by one of the corresponding mode times:

Idle	0.0167 hr
Taxi	.1833 hr
Takeoff	.005 hr
Climb	.083 hr
Approach	.100 hr
Taxi	.05 hr
Idle	.0167 hr

Summing the emissions for each mode for the three pollutants and dividing by the rated horsepower of the engine gives the desired end result in pollutant lb/hp-hr, which corresponds to the limits set by the EPA.

Carbon Balance

The intent of the carbon balance technique is to verify that those concentrations indicated by the exhaust analysis equipment are representative of the actual pollutant levels present. This is accomplished by calculating an operating fuel/air ratio ingested into the engine on the basis of the measured exhaust gas components. A measured fuel/air ratio obtained from actual air and fuel flows serves as the standard for comparison.

To predict the fuel/air ratio from the concentrations of the exhaust gas components the procedure of Spindt (SAE Paper 650507) was chosen. This method assumes that a fraction (F_b) of the fuel supplied to the engine is involved in a combustion process that proceeds to completion and the remaining fuel (F_u) passes through the engine essentially unchanged. That is to say, for the total mixture introduced into the engine,

$$F_u + F_b = 1$$

or

$$\frac{(HC)}{(CO) + (CO_2) + (HC)} + \frac{(CO) + (CO_2)}{(CO) + (CO_2) + (HC)} = 1$$

where the measured exhaust concentration of each specie is indicated by the parentheses.

In terms of CO, CO_2, O_2, and HC, the air/fuel ratio is expressed by

$$A/F = F_b \left[11.492 \ F_c \left(\frac{1 + R/2 + Q}{1 + R} \right) + \left(\frac{120 \ F_n}{3.5 + R} \right) \right]$$
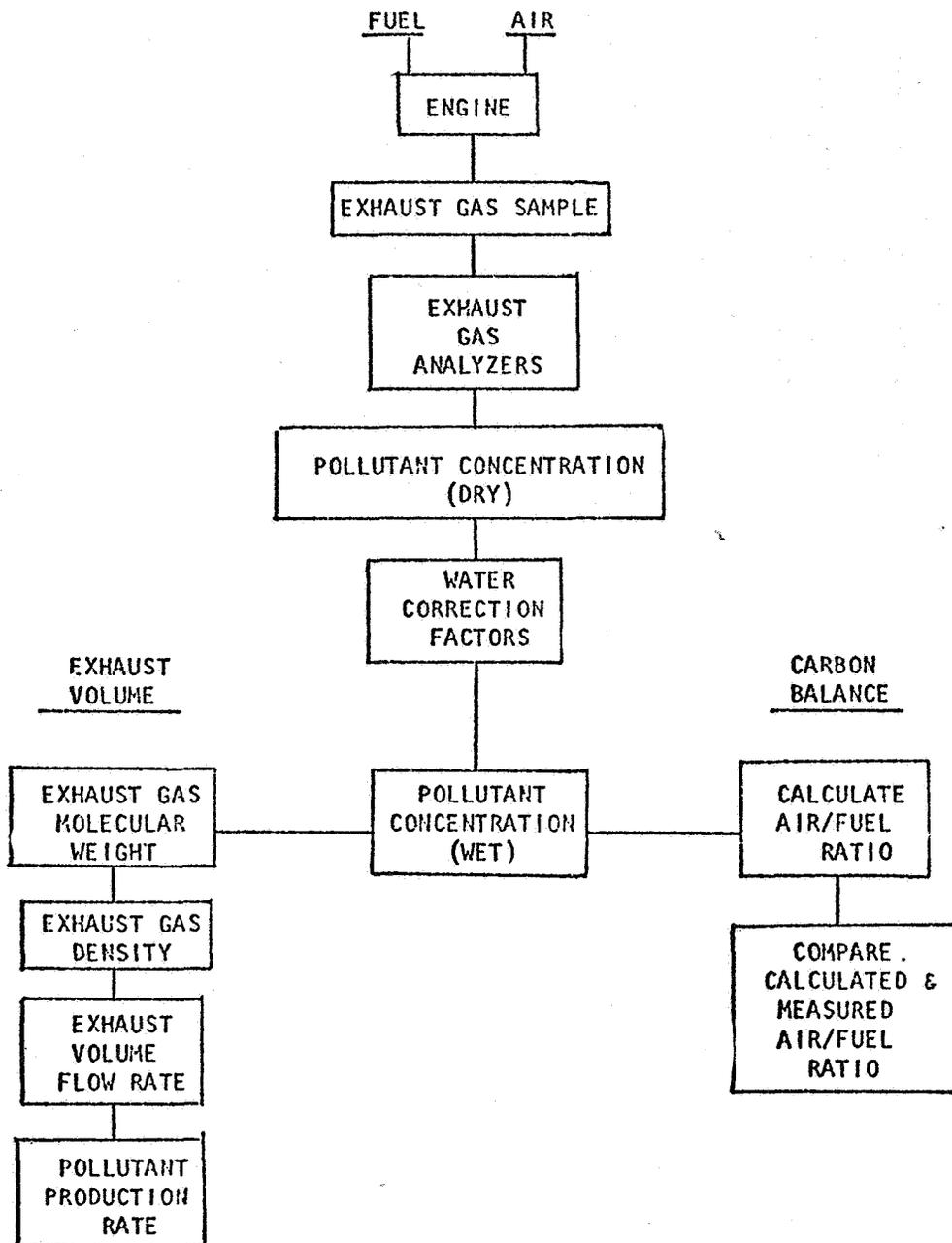
where

F_c fraction of carbon in fuel
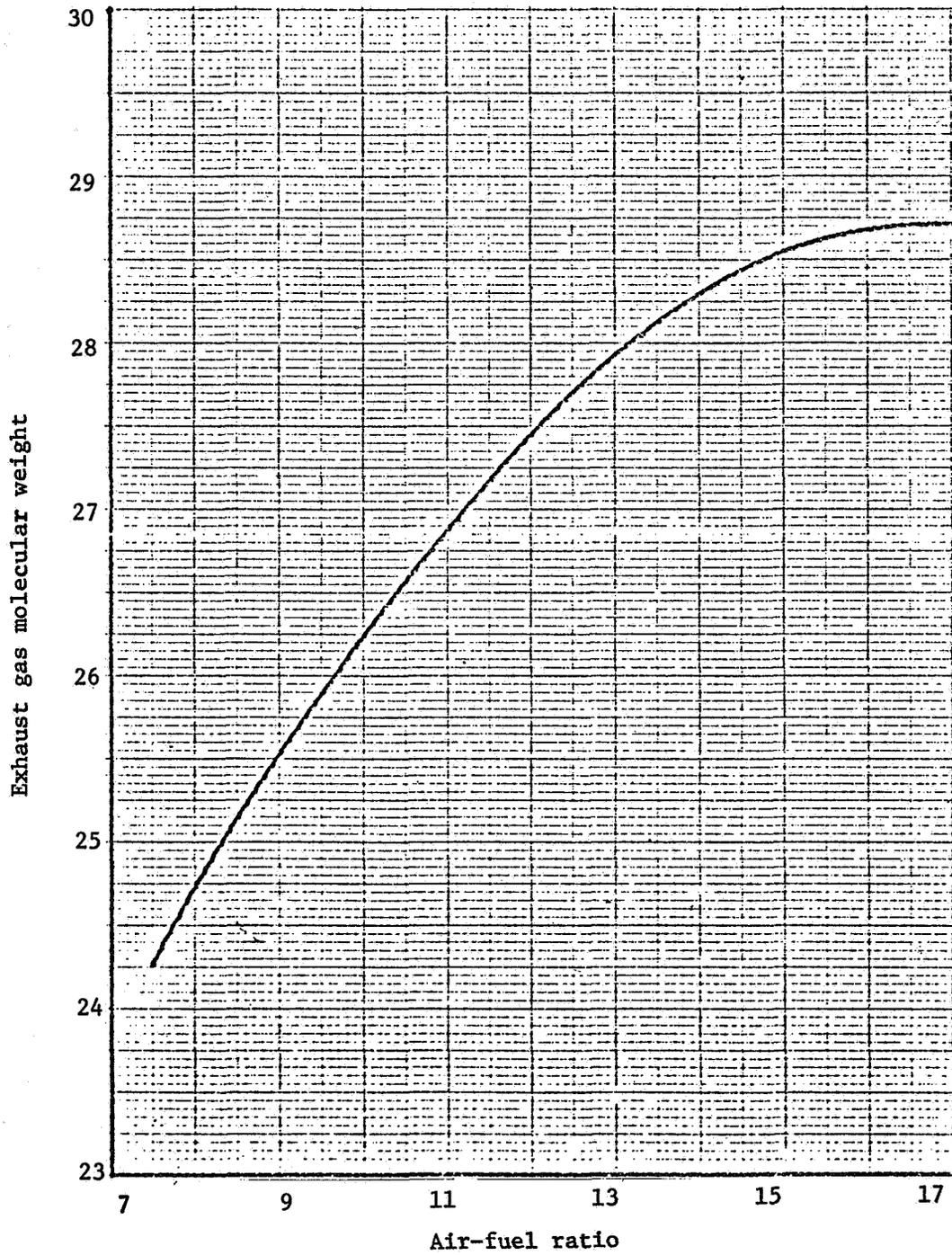
F_n fraction of hydrogen in fuel

R $(CO)/(CO_2)$

Q $(O_2)/(CO_2)$

AVCO-LYCOMING
EXHAUST EMISSION DATA
REDUCTION SCHEMATIC

Figure A-1

AVCO–LYCOMING

EXHAUST MOLECULAR WEIGHT VERSUS AIR/FUEL RATIO

FROM GMR 372

Figure A-2

APPENDIX B

REVIEW OF MEASUREMENT AND TESTING PROBLEMS*

Teledyne Continental Motors
Mobile, Alabama

APPARATUS AND RELATED PROCEDURE

Background

Teledyne Continental Motors experience with the measurement of ex-
haust emissions from aircraft piston engines goes back to the latter part
of 1971 when five engines of each of four different models were tested
under contract to the Environmental Protection Agency. Additional test-
ing was accomplished in late 1971 and early 1972 on an inhouse program to
evaluate the emissions of an exhaust-air-injected, turbocharged engine.

Subsequently, a contract was awarded on June 28, 1974, which was
jointly funded by both the FAA and NASA (DOT FA74NA-1091).

This review of measurement and testing problems presents an overview
of work in this area from the beginning of the FAA contract.

Exhaust Emissions Measurement Equipment

Attachment I presents a concise list and description of problems en-
countered with the exhaust emissions measurement analyzers and the attend-
ant sample handling systems.

The problems have been attributable mainly to emission analyzer dur-
ability and design. Some problems early in the contract were the result
of the learning process. In effect all of the participants in the NAFEC
Contract were required to custom make a total system package which would
comply with the requirements of the Federal Register, Volume 38, Number
136, Part 87.93.

While equipment development continues and durability problems have
not entirely been overcome, we believe that our present system is capable
of being maintained in accordance with Part 87.

Testing Problems

Throughout the contract, testing problems have been encountered

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*Material distributed but not presented at the Symposium.

which resulted in lack of data repeatability, both inhouse and between TCM and NAFEC. These repeatability problems stem basically from the fact that testing conditions were not and could not be held constant with current test cell equipment.

It was agreed that, for each operating mode, the controlled variables fuel flow, engine speed, manifold pressure, induction air inlet pressure, and engine cooling air pressure would be held to specified values. The variables leading to poor data repeatability which were recorded but not controlled were induction air and cooling air temperatures, induction air humidity, and exhaust back-pressure. These lead to variations in engine power, cylinder head temperature, induction air flow and, most importantly, emissions.

In addition, the specification of the amount of cooling air pressure to be supplied being fixed at a constant value does not lend itself to sound judgmental values of cylinder head overtemperature safety limits. The question continually arose as to the expected variability of these safety limits in a variety of actual airframe installations. The matter was considered important enough to be investigated under a supplement to the Phase I contract in the form of a flight test program.

It is clear at this point in time that more satisfactory, repeatable results would have been obtained had the uncontrolled variables been controlled. Since, to date, no universal correction factors are available to account for variations in emissions due to humidity, temperature, and pressure of induction air, it is apparent that future testing of this sort should include requirements aimed at maintaining the induction air inlet conditions to a set of some, yet unspecified, standard atmospheric conditions.

Engine-Related Problems

During the course of the NAFEC contract, TCM has tested five engines ranging in horsepower from 100 to 435. These engines vary in complexity from the simple O-200-A, a carbureted engine with a fixed pitch propeller, to the highly complex GTSIO-520-K, which is geared, turbocharged, fuel injected, intercooled, and has sonic venturi bleed air provisions for cabin pressurization.

The basic problem to which the contract terms addressed themselves was a matter of how to measure emissions for all these engines on a common basis so that the results would be comparable. This involved selecting various parameters for each individual engine which would comply with both the intended airframe requirements on the one hand and consistency with contract goals on the other. As a result, the contract specifications had to be reevaluated and changed to accommodate the variations among the five engines as experience was gained on the emissions test stand. Still, it cannot be said that every engine was treated on an

equal basis with the others.

As an example, the O-200-A engine was operated at the same conditions for takeoff and climb modes as is normal for that engine. The GTSIO-520-K, however, which has a 5-minute takeoff rating at full power was operated at 80 percent power, 90 percent speed in the climb mode. The O-200-A, which was equipped with a typical fixed-pitch flight prop, could not develop full power (full rpm) in the static test stand condition, whereas the remaining four engines were equipped with constant speed propellers allowing prop governor adjustments so that full rpm could be attained.

All TCM engines are designed to operate most efficiently at the higher power modes. While the engines would idle satisfactorily for long periods of time, the inappropriate valve and spark timing and induction system characteristics caused widely variable exhaust emissions values to be measured in this mode of operation. As a consequence a large degree of data scatter was observed and poor repeatability resulted.

Air Flow Measurement

In addition to the exhaust emissions measurement equipment problems discussed previously, there was little reason to suspect any difficulties with our engine operating parameter measurements. Initially in the program when testing the O-200-A engine, an airflow measurement device was used that later was suspected to be inaccurate due to data reduction result crosschecks. The valve device was replaced with a modern laminar flowmeter which is compensated for pressure and temperature. Subsequent cross-calibration with other devices including a gas flowmeter, a sharp-edged orifice, a calibrated laminar flow standard, and two turbine-type flowmeters have shown the laminar flowmeter to be the most accurate single device covering the widest range of engine airflow requirements.

Retest of the O-200-A has been accomplished using the laminar flowmeter.

Summary

While the phase I contract completion date has been extended by additions to the work plan to gather more data, the principal reason for delays beyond the initial phase I completion date of September 1, 1975, has been attributable to long periods of inactivity because of exhaust emissions measurement equipment durability problems and delays due to the additional effort involved in sorting out these and other problems with the measurement system.

Systematic checks and calibrations of the instrumentation have reduced the above measurement and testing problems to a minimum. The data presented in this report are considered representative of the engines

tested.   Absolute values may differ from facility to facility, but in no instance has this difference changed the trends or conclusions presented herein.

EXHAUST EMISSIONS CALCULATION PROCEDURE

Background

The Federal Register, Volume 38, Number 136, Part II, dated July 17, 1973, sets forth the requirements for the control of air pollution from all aircraft and aircraft engines. Subparts E and I and appendix B deal with the requirements for compliance with the law regarding exhaust emissions from aircraft piston engines.

The exhaust emission test is designed to measure hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) concentrations (percent or parts ~~per million~~ by volume) and determine mass emissions through calculations during a simulated aircraft landing-takeoff (LTO) cycle.

The calculations required to convert exhaust emission concentrations (raw emissions measurements) into mass emissions are the ~~subject of this~~ discussion.

Combustion Equation

The chemical equation for the combustion of a hydrocarbon fuel in air can be represented symbolically by

$$Fuel + Air \rightarrow Products\ of\ combustion$$
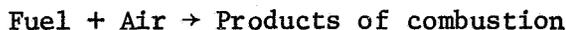
To be able to deal mathematically with the combustion equation it must be written in a form such that the coefficients, representing the quantities of each constituent, are known by virtue of measurement or are calculable using the principles of mass conservation or chemical equilibrium.

The combustion equation used as the basis for the emissions calculations is

$$
(M_f) \cdot \underbrace{C_x H_y}_{\text{Fuel}} + (M_a) \underbrace{[O_2 + (3.72744)N_2 + (0.04451)Ar]}_{\text{Air}} + (M_w) \cdot \underbrace{H_2O}_{\substack{\text{Atmospheric} \\ \text{humidity}}} \rightarrow
$$

$$
\rightarrow (M_1) \cdot H_2O + (M_2) \cdot CO_2 + (M_3) \cdot CO + (M_4) \cdot NO + (M_5) \cdot O_2
$$

$$
+ (M_6) \cdot C_p H_q + (M_7) \cdot H_2 + (M_8) \cdot N_2 + (M_9) \cdot Ar
$$

$$
+ (M_{10}) \cdot NO_2 + (M_{11}) \cdot C
$$

where

M_i number of lbm-moles of ith constituent; 1 lbm-mole (lb-mass mole) of a substance is quantity of that substance in pounds-mass (numerically equal to the molecular weight of substance in atomic mass units): 1 lbm-mole of water (H_2O), therefore, would have mass of (2)(1.008) + 16 = 18.016 lbm

$C_x H_y$ pure hydrocarbon fuel containing x atoms of carbon and y atoms of hydrogen in each molecule

O_2 oxygen

N_2 nitrogen

Ar   argon

H_2O water (vapor)

CO_2 carbon dioxide

CO   carbon monoxide

NO   nitric oxide

NO_2 nitrogen dioxide

$C_p H_q$ unburned hydrocarbon exhaust product containing p atoms of carbon and q atoms of hydrogen in each molecule

H_2 hydrogen

C   solid carbon

Examining each constituent of the equation, it is necessary to determine what can be measured, what can be calculated, and what assumptions must be made in order to calculate mass emissions values of HC, CO, and NO_x.

Fuel and Air

We have represented the fuel $C_x H_y$ as a pure hydrocarbon molecule. In reality, gasoline is a blend of many hydrocarbon products of refined crude oil and contains, in addition, antiknock agents such as tetraethyl lead, deposit modifiers, antioxidants, detergents, antirust agents, dyes, and anti-icing agents which contain elements other than hydrogen and carbon. These other elements are ignored in the combustion equation as they are deemed negligible. The fuel molecule $C_x H_y$ then is representative of a nominal or average hydrocarbon molecule with a ratio of hydrogen to carbon atoms of y/x. Although the actual values of y and x

for the gasoline varies considerably and no specific values can be assigned to them in our simplified fuel molecule, the ratio of hydrogen to carbon atoms in 100/130 octane aviation gasoline can be measured and remains relatively constant at a value of about 2.125.

Likewise, the unburned hydrocarbon constituent in the exhaust may contain several species of hydrocarbons, but a ratio of q/p of 1.85 has been suggested to represent the average ratio of hydrogen to carbon in the exhaust hydrocarbon pollutant. This value, however, for the purpose of this analysis will be considered unknown.

The fuel flow is measured using a Cox Vortex Flowmeter, Model #4271.

At TCM, airflow is measured by a Merriam laminar flowmeter which gives a linear relationship between mass flow and pressure drop and compensates for temperature and pressure. The total mass flow measured includes the atmospheric humidity.

Humidity is calculated from measured values of wet and dry bulb temperatures and is given in terms of pounds-mass of water vapor per pound-mass of dry air.

Products of Combustion

The products of combustion as shown in the combustion equation are again simplified in that the nonhydrocarbon fuel additives are ignored.

The exhaust constituents which are measured include CO_2, CO, NO, NO_2, O_2 and $C H_{q/p}$. The constituents which are known, a priori, are Ar and N_2. Those constituents which are not measured are C, H_2 and H_2O.

The formation of solid carbon C is the result of rich combustion of fuel (fuel burned in the presence of insufficient air) and to a varying extent, depending on engine age and condition, the burning of the oil lubricant entering the combustion chamber along the piston rings or valve guides. Chemical equilibrium calculations have shown that below fuel-air equivalence ratios of about 3.0 (fuel-air ratio of 0.20), solid carbon as a product of combustion is negligible compared to the remainder of the gaseous products. Aircraft piston engines do not normally run at overall equivalence ratios over 2.0 (fuel-air ratio of 0.13). The chemical equilibrium calculations, however, assume homogeneity of the fuel-air mixture. The lack of perfect mixture uniformity in a real engine would lead to some production of solid carbon due to localized rich mixtures within the combustion chamber.

At the present time solid carbon is not measured and is assumed for calculation purposes to be negligible. There is currently no equipment available to measure solid carbon production on a real-time basis.

Free hydrogen (H_2), which is present in the exhaust products in

small but significant quantities, is also not measured. Real-time measurement equipment for H_2 is available.

While there are systems on the market which will measure water (H_2O) vapor content in the exhaust, they are expensive. Calculative procedures are available to estimate the quantity of water vapor in the exhaust.

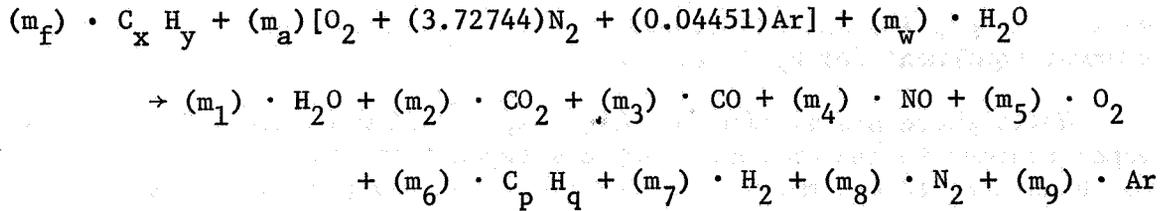Table B-1 outlines the equipment currently used by TCM to determine those exhaust products which are measured.

TABLE B-1

Exhaust product	Measuring instrument	Method used by measuring instrument
CO	Beckman Model 864 (NDIR)	Measurement of differential absorption of infrared light
CO_2	Beckman Model 864 (NDIR)	Measurement of differential absorption of infrared light
NO, NO_2	Beckman Model 951 H(CL)	$NO + O_3 \rightarrow NO_2 + Light$; measurement of light intensity due to reaction
O_2	Scott Model 150	Measures effect of paramagnetic oxygen in gas sample on magnetic field
$C_p H_q$	Scott Model 215 (FID)	Measures effect on electrostatic field of ionized hydrogen and carbon from gas sample

Balancing Combustion Equation

By the principle of conservation of mass we know that the atomic quantities introduced into the engine induction system must also be present in the exhaust even though they are rearranged into different molecules by the combustion chemical reaction. Hence, all the carbon atoms entering the engine in the form of hydrocarbon fuel molecules must be present in the exhaust in the form of CO, CO_2, and $C_p H_q$. This atom-balancing technique provides us with a system of equations by which we may solve for unknown quantities.

Going back to the original combustion equation, we eliminate solid carbon (C) and nitrogen dioxide (NO_2) (it has been found that NO_2 does not exist in any significant quantity for our engines). We then divide each molar value on both sides of the equation by the sum of the molar values on the right side. The equation then becomes

$$(m_f) \cdot C_x H_y + (m_a)[O_2 + (3.72744)N_2 + (0.04451)Ar] + (m_w) \cdot H_2O$$

$$\rightarrow (m_1) \cdot H_2O + (m_2) \cdot CO_2 + (m_3) \cdot CO + (m_4) \cdot NO + (m_5) \cdot O_2$$

$$+ (m_6) \cdot C_p H_q + (m_7) \cdot H_2 + (m_8) \cdot N_2 + (m_9) \cdot Ar$$

where

$$m_i = \frac{M_i}{M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 + M_9}$$

Thus, every molar coefficient on the right side of the equation is now expressed in mole fractions such that

$$m_1 + m_2 + m_3 + m_4 + m_5 + m_6 + m_7 + m_8 + m_9 = 1.0$$

This is done for convenience and the reason for it will be demonstrated later.

The nine products of combustion represent an estimated 99.998 percent of the chemical composition of an equilibrium mixture at exhaust gas temperatures below 3000° R.

An oxygen balance results in

$$2m_a + m_w = m_1 + 2m_2 + m_3 + m_4 + 2m_5 \tag{1}$$

or

$$m_1 = 2m_a + m_w - 2m_2 - m_3 - m_4 - 2m_5$$

A carbon balance gives

$$x \cdot m_f = m_2 + m_3 + p \cdot m_6 \tag{2}$$

or

$$m_f = \frac{m_2 + m_3 + p \cdot m_6}{x}$$

Since our measurement of $C_p H_q$ is in ppm carbon equivalent, we can represent $C_p H_q$ as $CH_{q/p}$. Equation (2) then becomes

$$m_f = \frac{m_2 + m_3 + m_6}{x}$$

The remaining atomic balances are as follows:

Hydrogen balance: $\quad y \cdot m_f + 2m_w = 2m_1 + \dfrac{q}{p} m_6 + 2m_7$ \hfill (3)

Nitrogen balance: $\quad (3.72744)(2)m_a = m_4 + 2m_8$ \hfill (4)

Argon balance: $\quad (0.04451)m_a = m_9$ \hfill (5)

Water Correction Factor

Since CO, CO_2, and O_2 are measured on a dry volumetric basis (water vapor being removed from the exhaust sample before measurement) and HC and NO are measured on a wet volumetric basis, we must determine the amount of water vapor removed from the dry sample in order to correct all measured values to either a dry or a wet volumetric basis for calculative purposes. In doing this we are solving for one of the unknowns – m_1 (H_2O).

We can define the fuel to dry air mass ratio as

$$\frac{f}{A} = \frac{m_f(12.011x + 1.008y)}{m_a(138.2689)}$$ \hfill (6)

where

$$(12.011x + 1.008y) = \text{fuel molecular weight}$$

and

$$138.2689 = \text{pounds-mass of air per lbm-mole of oxygen}$$

The specific humidity, or water vapor to dry air mass ratio, is

$$\frac{W}{A} = \frac{m_w(18.016)}{m_a(138.2689)}$$ \hfill (7)

Substituting equations (2), (6), and (7) into equation (1) and rearranging the terms gives

$$m_1 = \left[2 + 7.67478 \frac{W}{A}\right] \frac{(m_2 + m_3 + m_6)\left(12.011 + 1.008 \frac{y}{x}\right)}{138.2689\left(\frac{f}{A}\right)}$$

$$- 2m_2 - m_3 - m_4 - 2m_5 \qquad (8)$$

For clarity, equation (8) may be rewritten using chemical symbols to represent the mole fraction for each constituent:

$$H_2O = \left[2 + 7.67478 \frac{W}{A}\right]\left[\frac{(CO_2 + CO + HC)\left(12.011 + 1.008 \frac{y}{x}\right)}{138.2689\left(\frac{f}{A}\right)}\right]$$
$$- 2CO_2 - CO - NO - 2O_2 \qquad (9)$$

Equation (9) then represents the total water vapor (humidity plus water of combustion) contained in the exhaust gas with each constituent measured on a wet basis.

Defining the water correction factor as

$$C_w = 1.0 - H_2O \qquad (10)$$

we can convert the entire equation (9) to dry basis measurements by dividing by $(1.0 - H_2O)$:

$$\frac{H_2O}{1 - H_2O} = \left[2 + 7.67478 \frac{W}{A}\right]\left[\frac{\left(CO_{2\ dry} + CO_{dry} + \frac{HC_{wet}}{1 - H_2O}\right)\left(12.011 + 1.008 \frac{y}{x}\right)}{138.2689\left(\frac{f}{A}\right)}\right]$$
$$- 2CO_{2\ dry} - CO_{dry} - \frac{NO_{wet}}{1 - H_2O} - 2O_{2\ dry} \qquad (11)$$

where

$$CO_{2\ dry} = \frac{CO_{2\ wet}}{1 - H_2O} \quad \text{etc.}$$

The solution to equation (11) may be obtained iteratively by assuming a value for H_2O on the right side of the equation, solving for H_2O on the left side, using this new value for H_2O on the right side and repeating the process until satisfactory agreement has been obtained between the assumed and calculated values. Using this scheme, convergence is obtained usually within four iterations.

A more expansive chemical equilibrium calculation was made over the normal range of fuel-air ratios, considering the products of combustion to include C, Ar, CO, CO_2, H_2, H_2O, N_2, O_2, O, OH, H, NO, N, NH_3, and CH_4. The maximum error determined in the calculation of water vapor using our abbreviated product of combustion equation was less than one-half of one percent.

The solution to the wet correction factor then was obtained by using five equations ((1), (2), (6), (7), and (10)) involving five unknowns (m_a, m_w, m_1, m_f, and C_w). The assumptions made in order to effect a solution to the water correction factor are

(1) The combustion equation represents all of the elemental constituents involved in the actual combustion process.

(2) The ratio of hydrogen to carbon atoms for all 100/130 octane aviation gasolines remains constant at (y/x).

While there are similar methods which can be used to calculate the water correction factor, it is believed that this method involves the use of the least number of assumptions leading to the most accurate estimate of C_w based on the quantities currently being measured.

Calculation of Mass Emission Values

As mentioned previously, the raw emissions are measured on a volumetric basis in percent or ppm. In order to determine the emissions based on the requirements of the EPA Standards, these volumetric values must be converted to volumetric flow rate and then to mass flow values in accordance with

$$
\begin{array}{l} \text{Pollutant} \\ \text{mass} \\ \text{emission} \\ \text{rate} \end{array} = \begin{array}{l} \text{Exhaust} \\ \text{volumetric} \\ \text{flow} \\ \text{rate} \end{array} \times \begin{array}{l} \text{Pollutant} \\ \text{volumetric} \\ \text{concentration} \end{array} \times \begin{array}{l} \text{Pollutant} \\ \text{density} \end{array} \quad (12)
$$

For this equation, the pollutant densities are specified in the Federal Register at a standard pressure and temperature of 760 mm H_g and 68° F. The values of pollutant volumetric concentrations (CO, HC, NO_x) are measured, and in order to calculate the mass emission rates the exhaust volumetric flow rate must be known.

The EPA Standards state that the exhaust volumetric flow rate "shall be calculated in accordance with good engineering practices."

Two methods are used by TCM to calculate the exhaust volumetric flow rate — one is called the Exhaust Volume Method and the other, the Carbon Balance Method.

The basis for the Exhaust Volume Method is in the calculation of the exhaust volumetric flow rate at the standard pressure and temperature of 760 mm H_g and 68° F using the assumption that the exhaust gas follows the ideal gas equation of state:

$$
\dot{V}_{EXH} = \frac{R \dot{m} T}{M_{EXH} P} = \frac{R(f + A')T}{M_{EXH} P} \quad (13)
$$

where

$\dot{V}_{EXH}$ exhaust volumetric flow rate, ft^3/hr

R universal gas constant, 1545.33 $ft\text{-}lbf/lbm\text{-}mole\text{-}^{o}R$

$\dot{m}$ total exhaust gas mass flow (also equal to total induction mass
flow of fuel and air by principle of mass conservation), lbm/hr

T absolute temperature, 528° R $(68^{o}$ F)

M_{EXH} exhaust gas molecular weight

P exhaust pressure, 2116 lbf/ft^2 (760 mm H_g)

f fuel mass flow, lbm/hr

A' humid air mass flow, lbm/hr

In equation (13), R, T, and P are given values and $\dot{m}$ is measured.
The value of the exhaust gas molecular weight can be calculated from ex-
haust products.

$$M_{EXH} = \sum m_i M_i \qquad (14)$$

where M_{EXH} is the "apparent molecular weight" of the exhaust gas. M_i
is the molecular weight of each constituent and m_i is the mole fraction
of each constituent which can be determined from measured concentrations
and solution of equations (2) to (7). Solution of equation (14) further
requires an assumption of exhaust hydrocarbon hydrogen to carbon ratio
q/p. Studies have indicated, however, that extremely unreasonable values
of calculated fuel-air ratio are obtained when the sum of the exhaust gas
mole fractions are constrained to unity.

Therefore, the method used by TCM for estimating the exhaust gas
molecular weight is based on chemical equilibrium calculations and as-
sumes that chemical equilibrium exists among the exhaust products for a
given measured fuel-air equivalence ratio. This assumption is reasonable
since the major constituents which contribute to the exhaust molecular
weight (e.g., N_2, CO_2, H_2O, CO) do not vary significantly from equilib-
rium predictions. The calculation of mass emissions of carbon monoxide
as an example would be as follows by substituting equation (13) into
equation (12):

$$\dot{m}_{CO} = \left[\frac{R(f + A')T}{M_{EXH}P} \right] \times [\rho_{CO}] \times [CO] \qquad (15)$$

Since, by the ideal gas assumption,

$$\rho_{co} = \frac{M_{co}P}{RT} \qquad (16)$$

Substituting equation (16) into (15) yields

$$\dot{m}_{co} = \left[\frac{R(f + A')T}{M_{EXH}P}\right] \times \left[\frac{M_{co}P}{RT}\right] \times [CO]$$

or

$$\dot{m}_{co} = \left(\frac{M_{co}}{M_{EXH}}\right)(f + A')(CO) \qquad (17)$$

where

$\dot{m}_{co}$ mass emission rate of CO, lbm/hr

M_{co} molecular weight of CO, 28.011 lbm/lbm-mole

M_{EXH} exhaust gas molecular weight, lbm/lbm-mole

$(f + A')$ total induction mass flow rate, lbm/hr

CO   wet volume fraction of CO in exhaust

The Carbon Balance Method of calculating exhaust volumetric flow rate is also used by TCM. This method provides a cross-check on the Exhaust Volume Method and is the same method used in the calculation of turbine engine emissions.

The Carbon Balance Method is believed to be the more accurate as measurement of airflow A and estimation of exhaust gas molecular weight M_{EXH} are not required. The Carbon Balance Method accounts for all the carbon atoms in the combustion equation, and by conservation of mass, the carbon introduced into the engine in the molecular form of fuel must be accounted for in the carbon-containing exhaust product molecules CO, CO_2, $C_p H_q$.

As with the Exhaust Volume Method, the assumption is made that the ideal gas equation of state applies.

The derivation of the Carbon Balance Method is as follows. From equation (2), the carbon balance equation,

$$m_f = \frac{m_2 + m_3 + m_6}{x} = \frac{\text{moles of fuel}}{\text{moles of wet exhaust}}$$

The volumetric flow rate of the exhaust can then be calculated as follows:

$$\dot{V}_{EXH} = \frac{\dot{m}_{EXH}}{\rho_{EXH}} = \frac{\dot{M}_{EXH} M_{EXH}}{\rho_{EXH}} \tag{18}$$

where

$\dot{M}_{EXH}$ molar flow rate of exhaust, lbm-moles/hr

M_{EXH} molecular weight of exhaust, lbm/lbm-mole

ρ_{EXH} exhaust gas density, lbm/ft^3

We define

$$\dot{M}_{EXH} = \frac{f}{m_f M_f} \tag{19}$$

where

f   mass fuel flow, lbm/hr

M_f molecular weight of fuel

m_f from carbon balance eq. (2), moles of fuel/moles of wet exhaust

From the ideal gas equation of state

$$\frac{M_{EXH}}{\rho_{EXH}} = \frac{RT}{P} \tag{20}$$

Substituting equations (19) and (20) into (18) gives

$$\dot{V}_{EXH} = \frac{f}{m_f M_f} \left(\frac{RT}{P} \right) \tag{21}$$

Substituting this result into equation (12) and using carbon monoxide as an example gives

$$\dot{m}_{CO} = \left[\frac{f}{m_f M_f} \left(\frac{RT}{P} \right) \right] \times [\rho_{CO}] \times [CO] \tag{22}$$

The density of CO (ρ_{CO}) by ideal gas consideration is

$$\rho_{co} = M_{co}\left(\frac{P}{RT}\right) \qquad (23)$$

and the molecular weight of the fuel is

$$M_f = x\left(12.011 + 1.008\,\frac{y}{x}\right) \qquad (24)$$

We can substitute equations (23), (24), and (2) into equation (22) to obtain

$$\dot{m}'_{co} = \frac{fM_{co}CO}{\left(12.011 + 1.008\,\frac{y}{x}\right)(HC + CO + CO_2)} \qquad (25)$$

Note that the value x in equation (24) cancels with the x in equation (2) so that it is not necessary to know the molecular form of the fuel but only the H/C ratio y/x.

This method is attributable to Stivender (see SAE Paper 710604) and has the advantage of producing an exhaust volumetric flow rate calculation independent of measured air flow which is a source of some probable error in the Exhaust Volume Method. It is instructive to look at the difference between these two methods. In order to do this we can take the ratio of Carbon Balance to Exhaust Volume mass flow values for CO using equations (25) and (17):

$$\frac{\dot{m}'_{co}}{\dot{m}_{co}} = \frac{(f/A)(M_{EXH})}{\left(12.011 + 1.008\,\frac{y}{x}\right)(HC + CO + CO_2)\left(1.0 + \frac{W}{A} + \frac{f}{A}\right)} \qquad (26)$$

This indicates that any differences between the two methods ($\dot{m}'_{co}/\dot{m}_{co} \neq 1.0$) are a function of fuel-air ratio and measured values of HC, CO, and CO_2 (the value of M_{EXH} as used by TCM is a function of f/A only). Therefore, the ratio of these two values is a good indicator of the measurements of fuel flow, airflow, and HC, CO, and CO_2. TCM experience has shown that while this ratio is not equal to unity for most engines, a general range of values can be established for a particular engine model and operating mode.

As an example, when testing the Tiara 6-285-B engine, the ratio of $\dot{m}'_{co}/\dot{m}_{co}$ was near 0.97 for the takeoff modes. A point was observed to have a value of this ratio of 1.33. Upon rechecking the recorded emissions data it was found that an error had been made in reading the value of CO_2.

These two methods of calculating exhaust mass emissions provide a good check on the accuracy of measured values. In addition, the Carbon Balance Method provides a convenient means for the measurement of exhaust

emissions in a field survey or flight test situation, as measured airflow is not required.

Calculation of Fuel-Air Ratio

The Exhaust Emissions Standards require a check on accuracy of measured data which involves the calculation of fuel-air ratio from exhaust gas constituents. This calculated fuel-air ratio must be within ±5.0 percent of the measured fuel-air ratio in order for the test to be valid. (See Part 87.96, subparagraph (b) of the Regulation.)

An example of this method is given in the text "Internal Combustion Engines and Air Pollution" by E. F. Obert, page 353. The method is simple and reliable if the molecular form of the fuel and exhaust hydrocarbons is known, that is if we know the values x, y, p, and q in $C_x H_y$ and $C_p H_q$.

To this point in the analysis we have scrupulously avoided assumption of these values by using equations in the form such that only the value of y/x must be known. This value has been measured and thus eliminates a possible source of error.

An alternative method for calculating fuel-air ratio has been developed by R. S. Spindt in SAE Paper 650507 which requires the use of ratios including y/x, eliminating the assumption of fuel molecular form, and avoiding the errors encountered by previous investigators.

A subsequent SAE Paper (660118) entitled "An Evaluation of Techniques for Measuring Air-Fuel Ratio" by L. C. Broering, Jr., shows that the Spindt Method is accurate to within ±5.0 percent at a fuel-air ratio of 0.067. This conclusion, however, was based on a limited data base using an automotive engine.

The derivation of the Spindt Method will not be covered here except to say that the required input values are O_2, CO, CO_2, HC, y/x, and the assumption of the water-gas equilibrium parameter, K_p. Equation (27) is the Spindt equation:

$$\frac{f}{A} = \frac{1.0}{FB\left[(11.492)FC \frac{1.0 + E/2 + D}{1 + E} + \frac{120(1 - FC)}{(K_p + E)}\right]} \tag{27}$$

where

f/A   calculated fuel-air ratio

FB $(CO + CO_2)/(CO + CO_2 + HC)$

FC $(12.011)/(12.011 + 1.008 \, y/x)$, fraction of carbon in fuel, $C_x H_y$

E CO/CO_2

D O_2/CO_2

K_p $(H_2O)(CO)/(H_2)(CO_2)$

The water-gas equilibrium parameter comes from the chemical equation

$$H_2 + CO_2 \rightleftarrows H_2O + CO \tag{28}$$

where

$$K_p = \frac{(H_2O)(CO)}{(H_2)(CO_2)} \tag{29}$$

Basically, chemical equilibrium dictates through the "mass action law" that when a chemical system is in equilibrium at a constant temperature the mole fractions of the reactants (H_2 and CO_2) and products (H_2O and CO) take on values such that the value K_p in equation (29) remains constant.

Another way to look at this phenomenon is that in equation (28) the rate of change of $H_2 + CO_2$ into $H_2O + CO$ is equal to the rate of change of $H_2O + CO$ into H_2 and CO_2.

The basis for this assumption in the combustion process is that as the exhaust gases expand and cool in the expansion and exhaust strokes, the rates of reaction decrease to a very small value due to the sudden decrease in temperature and the water-gas equilibrium reaction is essentially "frozen" at the higher temperature values. This assumption is invalid in that the temperatures of the exhaust gases at the start of the expansion stroke vary considerably with engine operating mode and fuel-air ratio. For the most part, at least at the higher power modes of the aircraft emissions cycle (takeoff, climb, approach), TCM has found that measured values of fuel-air ratio agree to within the required ±5.0 percent of those calculated by the Spindt Method.

Having taken all reasonable steps necessary to assure the accuracy of the data collected from the five different engines investigated to date, the conclusion has been reached that the Spindt Method is not accurate to within ±5.0 percent at low power modes (taxi/idle). In addition, it has been determined that the requirement that measured and calculated fuel-air ratios be within ±5.0 percent is not sufficient to prove that the measured emissions data is accurate. A case in point is the takeoff mode data point mentioned previously where a reading error was discovered in the value of CO_2 on the Tiara 6-285-B engine. The error was made evident by noting an unusual value of Carbon Balance against Exhaust Volume mass emissions data. The calculated fuel-air ratio for that data point was well within ±5.0 percent of the measured value.

A thorough investigation of the source of error in the Spindt Method led to the discovery that the assumption of a constant value of the water-gas equilibrium parameter is in error. Spindt used a value of 3.5 as it best fit his data. Indications from TCM data show that the value of K_p may vary from 2.1 to 4.4. A specific value of the water-gas equilibrium constant may be applicable in comparing similar engine operating conditions, but in general it would not be valid to assume it as a constant for all modes of operation.

When using the Spindt Method for calculating fuel-air ratio with a constant value for K_p, it seems inappropriate to eliminate a lower power data point where calculated and measured fuel-air ratios are not within the prescribed ±5.0 percent tolerance.

Unless another calculative procedure is developed with the promise of greater accuracy in predicting fuel-air ratios at lower power modes, it seems unlikely that the requirements of data validity can be met.

Exhaust Emissions Standards

Once the mass emission values of CO, HC, and NO have been determined, the calculation of exhaust emissions relative to the EPA standards (table B-2) is straightforward.

TABLE B-2. - EPA EMISSIONS REGULATIONS REQUIREMENTS

Mode	Mode name	Time in mode, min	Power, percent	Engine rpm, percent
1	Taxi/ idle-out	12.0	(a)	(a)
2	Takeoff	.3	100	(100)
3	Climb	5.0	75-100	(a)
4	Approach	6.0	40	(a)
5	Taxi/ idle-in	4.0	(a)	(a)
Total cycle		27.3	---	---

[a]Manufacturer's recommendation.

This table shows the required five-mode LTO cycle. In each mode, run consecutively, the mass emissions are calculated in lbm/mode. The sum of these values, lbm/cycle, is then divided by the engine rated brake horsepower so that the final emissions values are given in lbm/bhp/cycle. The Standards specify as maximum allowable values: CO, 0.042 lbm/bhp/cycle; HC, 0.0019 lbm/bhp/cycle; NO_x, 0.0015 lbm/bhp/ cycle.

TCM Emissions Measurement System Modifications

<u>Date</u>: 9/3/74 to 10/25/74.

<u>Problem</u>: Loss of sample flow due to interaction of 3 analyzer pumps being connected to common suction line.

<u>Correction</u>: Balancing valves and surge chambers fitted to improve this condition.

<u>Problem</u>: Strip chart recorders out of calibration with no means of calibrating.

<u>Correction</u>: Instrumentation designed and constructed for 6 channels incorporating a standard cell for calibrating 0 - 1 mV scale.

<u>Problem</u>: No means of measuring sample flow response and residence times.

<u>Correction</u>: Event markers and chart speed switching installed on each strip chart recorder.

<u>Date</u>: 12/2/74 to 2/10/75.

<u>Problem</u>: Exhaust sample residence time excessively slow.

<u>Correction</u>: Two 20-foot heated lines from exhaust sampling pipe to analyzers provided by Scott. One of these removed to agree with the EPA Federal Register (issue July 17, 1973, p. 19099, Sec. 87.93). Rewiring and plumbing effected to maintain a temperature in this line of 310° F.

<u>Problem</u>: Standby sampling of cell air in cold weather caused the temperature of the 20-foot heated line to drop.

<u>Correction</u>: Heater installed in the standby air inlet with control hardware to maintain inlet air at 310° F.

<u>Problem</u>: Difficulty in calibrating analyzers when only one span gas per analyzer available.

<u>Correction</u>: Fourteen additional gases purchased and connected into the system with appropriate changeover valves for calibrating 25, 50, 75, and 100 percent of instrument scales.

<u>Problem</u>: No means of measuring sample air on input to induction air system.

<u>Correction</u>: Sample line and filter installed with necessary change-over valves and fittings as requested by NAFEC.

<u>Date</u>: 5/6/75 to 6/26/75.

Problem: Sample lines to NO_x analyzer and dryer unit in main console not heated causing moisture problems.

Correction: Heating apparatus installed to maintain sample lines at 180° F.

Problem: Sample flow not being maintained when sampling exhaust gas. Insufficient capacity of pumps to overcome restriction of line heated filter due to exhaust contaminants.

Correction: Higher capacity pump installed in the downstream end of the 20-foot heated line. This gave only a partial correction to problem.

<u>Date</u>: 10/20/75 to 11/26/75

Problem: Sample flow still unstable.

Correction: All pumps replaced by one master pump situated near exhaust sampling pipe at upstream end of 20-foot heated line. Excess sample gas relief valve installed downstream of 20-foot heated line with flow gage. This has effectively stabilized flow rates.

Problem: CO and CO_2 flow gages hard to read at required flow rate of 3.0 CFH.

Correction: 24 CFH gages replaced with 5 CFH gages.

TCM 215 HC Analyzer Modifications

<u>Date</u>: 10/14/74 to 10/21/74.

Problem: Detector bench temperature exhibits lack of control (i.e., $\pm6^o$ F).

Correction: Control updated by Scott to control within $\pm2^o$ F.

<u>Date</u>: 12/2/74 to 12/20/74.

Problem: HC sample pump (MB21) gave insufficient sample flow (i.e., 3 CFH max.).

Correction: Higher capacity pump (MB115) fitted to give 10.5 CFH.

Date: 5/6/75 to 6/26/75.

Problem: HC analyzer calibration nonlinear on 50 K and 100 K ranges.

Correction: Fine wire inserted into detector capillary tube to reduce flow rate.

Problem: Restriction to flow caused by vapor condensing in HC sampling tubes and flowmeter downstream of detector.

Correction: Interior temperature of HC analyzer raised from 80° to 120° F by disconnecting fan, closing all vents, and insulating flowmeter from front panel.

Problem: Particles getting into system and partially blocking detector capillary tube.

Correction: Heated filter (310° F) installed in input to HC analyzer.

TCM NO_x Analyzer Modifications

Date: 9/3/74 to 10/25/74.

Problem: Cannot maintain Scott 325 analyzer sample flow rates.

Correction: Changed sample pump from MB21 to Model MB41.

Problem: All NO_x measurements measured dry as per design of equipment.

Correction: Scott 325 was replaced with a Beckman 951 (unheated analyzer). Sample lines to the 951 heated and pipe work rerouted to bypass dryer.

Date: 12/2/74 to 2/15/75.

Problem: Beckman 951 (unheated version) giving low readings of NO_x.

Correction: Replaced 951 with Model 951H.

Date: 5/6/75 to 6/26/75.

Problem: 951H exhibiting a progressively reduced readout due to moisture entering the reaction chamber.

Correction: Temperature of reaction chamber raised from approximately 80° to 110° F by disconnecting heat control fan and insulating reaction chamber. Thermocouple was installed to record temperature.

Problem: NO$_2$ could not be measured because of pressure difference at input of reaction chamber when switching from converter to bypass of converter.

Correction: Balance valve which consisted of crude clamp pinching the tube gave unstable results and was replaced with needle valve and pressure gage connected to the capillary tube.

Date: 12/18/75 to 1/12/76.

Problem: Instrument could not be calibrated. Reaction chamber was starved of ozone. Ozonator Teflon lamphousing was cracked and capillary tube to ozonator was partially blocked due to distortion of Teflon tubing.

Correction: Lamphousing was replaced and capillary tubing was replaced with needle valve. Beckman has advised replacing Teflon housing every 6 months.

Ozone, which reacts with impure Teflon, is normally always present even when the analyzer is not in use as there is no provision in the instrument for purging.

Capability of purging the ozonator with nitrogen has been installed and is now a routine procedure.

Problem: Instrument calibration was nonlinear at high values of span gas. Reaction chamber flow rates had changed from 693 cc/min to 500 cc/min, due to the capillary tube becoming partially restricted.

Correction: Reaction chamber capillary tubing was replaced with a 1/8-inch tube and a needle valve.

Problem: There was a zeroing problem – the 951H unlike the 951 had no provision for feeding in zero gas. Zero point adjusted when the oxygen is turned off. This gives a zero point somewhat lower than when using a zero gas.

Correction: Solenoid valve with tubing and switching was installed to allow zero gas to be introduced into the analyzer.

Date: 6/22/76 to 7/26/76.

Problem: Sent instrument to Beckman to be modified free of charge with promised return of 1 week. After modification, Beckman found problem with noise signal on output due to faulty photomultiplier tube. Tube was replaced at TCM expense. Upon return the unit was found to have water vapor condensation internally – a problem which had not existed before sending the unit.

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