X. GENERAL AVIATION PISTON-ENGINE EXHAUST EMISSION REDUCTION

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The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), the Environmental Protection Agency (EPA), and the general aviation engine manufacturers are actively involved in a program to reduce exhaust emissions from aircraft piston engines. Last September, 14-15, 1976, an Aircraft Piston Engine Exhaust Emission Symposium was held at the Lewis Research Center 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 paper briefly summarizes and updates some of the topics covered in the symposium and reported in reference 1.

DEVELOPMENT OF EPA PISTON-ENGINE AIRCRAFT EMISSIONS STANDARDS

Influence of Piston-Engine Aircraft Emissions on Air Quality

In the studies supporting the promulgation of the aircraft regulations (refs. 2 and 3), two airports were examined, Van Nuys and Tamiami. Based on these studies, it was determined that the carbon monoxide (CO) emissions from piston-engine aircraft have a significant influence on the

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CO levels in the ambient air in and around airports, where workers and travelers would be exposed. To remedy this pollution problem, emissions standards were promulgated on July 17, 1973, for control of emissions from aircraft piston engines manufactured after December 31, 1979.

The EPA has recently begun a reevaluation of the need for controlling these emissions based on current data. This evaluation expands the original study to include additional general aviation airports. The contribution of piston-engine aircraft to air pollution is shown in table X-1.

As readily noted, the CO emissions dominate. The total unburned hydrocarbon (THC) and oxides of nitrogen (NO_x) emissions from aircraft contribute to the overall metropolitan pollution problem, but when compared to other sources they would have to be considered of low priority for control. Carbon monoxide emissions, on the other hand, are critical near the source, at points of heavy concentration. For example, in the vicinity of the Van Nuys airport, which is a known CO "hot spot," the piston-engine aircraft contribution is about 10 percent of the total CO emissions, affecting a population of 67 000 people. More sophisticated air quality modeling techniques are being used to determine if this contribution is likely to cause violations of the ambient air quality standards at the airport and in the surrounding area.

Selection of Emissions Standards

The piston-engine standards selected were based on a technologically feasible and economically reasonable control of carbon monoxide. The approach to selecting the standard is illustrated by figure X-1. The baseline studies revealed that piston-engine aircraft operate over a wide range of fuel-air ratios. Engines typically operate at fuel-air ratios of 0.08 to 0.14 during ground operations. After reviewing a variety of potential control systems, it was concluded that substantial CO reductions could be realized if this range of typical fuel-air ratios could be narrowed. Thus, improvements in fuel management were determined as reasonable controls to impose on a source that has minimal impact on National air quality but clearly significant impacts at certain critical locations. The selection of the actual levels of the standards were based on figure X-1. Fuel-air ratios of 0.077 to 0.083 were chosen as reasonable mixture ratios for engine operation, especially since some engines already performed in this range. Thus, from these values and other baseline engine characteristics, the EPA standards for CO, THC, and NO_x were calculated.

The fuel-air mixture ratio cannot be arbitrarily leaned without consideration of overall operational requirements. A modal breakdown of CO emissions during the landing and takeoff operation is shown in figure X-2. As noted, the climbout phase is dominant and the takeoff phase can be ignored. Thus, to reduce CO emissions, leaning of the taxi/idle, climbout, and approach power settings is required. Emissions design requirements must be considered in a trade-off with other requirements in these modes for the best fuel-air ratio. At the taxi/idle and approach conditions, acceleration pumps may have to be substituted for rich mixtures previously used in order to maintain smooth running while advancing the throttle. During climbout, improved cooling methods may have to be substituted for excess fuel cooling.

Future of the Standards

The standards promulgated on July 17, 1973, were considered necessary and reasonable based on technology that was feasible for piston-engine-powered aircraft, namely, improved fuel management (ref. 4). The EPA has continued to monitor the progress of the industry and supporting government agencies in their attempt to develop engines capable of complying with the EPA standards. This continuing assessment of progress has been recently intensified as a result of a petition submitted to the EPA by the General Aviation Manufacturers Association. To properly address the petition, additional information has been sought from the various manufacturers. Upon receipt, this information will be analyzed and reported. If rule-making action is determined to be appropriate by the EPA Administrator a notice of proposed rule making will be published seeking comments from all interested parties, which normally include the affected manufacturers, their trade organizations, environmental groups, and private citizens. On the basis of these comments and with consideration of the goals of clean air as well as other social constraints, if it is determined that changes to the standards are appropriate, such action can be expected.

Independent of the petition action, there is one aspect of the piston-engine standards that is presently being considered for proposed changes. The piston-engine regulations are primarily directed to CO control. The THC 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 emissions 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 that had been made. This same argument can be considered relative to the piston-engine aircraft regulations. Carbon monoxide is the pollutant of concern. Standards for THC and NO_x were set to establish "trade-off boundaries." Removing these standards altogether would allow greater flexibility for the selection of emissions control systems.

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

Whether EPA as an organization will consider removing the existing limitations on THC and NO_x emissions from piston-engine aircraft engines is uncertain. We, at the technical staff level, are merely dealing with the possibility. The potential air quality impact of any such change must be weighed before even proposing it to the executive levels of the EPA. The removal of the THC 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 through the use of 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 imposed on present control system developments.

FAA INVESTIGATION OF PISTON-ENGINE EXHAUST EMISSIONS

The EPA has described its basis for setting piston-engine emissions standards (ref. 4). The public law that authorized EPA to investigate and set standards also required the Department of Transportation, Federal Aviation Administration (DOT/FAA) to issue regulations to implement and enforce the EPA standards, should they be required.

In issuing the standards, EPA made recommendations that improved fuel management could be employed to allow the piston engines to meet the standards. FAA, following guidelines drawn between NASA and FAA, interpreted this fuel management to mean that leaner fuel schedules and altered spark timing, or combinations thereof, could achieve the goals. NASA and FAA were to split the research requirements. FAA would concentrate on minor modifications that could be applied to present designs; NASA would look at advanced-technology improvements. The leaner fuel schedules and timing work fit nicely into this division of effort for FAA.

FAA was concerned that the application of leaner fuel schedules could cause operational problems that would be hazardous. Accordingly, contracts were awarded to Teledyne Continental Motors (TCM) and AVCO Lycoming to conduct tests on engines that were considered representative of their manufacture. NASA shared in the funding of this initial effort. In addition, a contract was awarded to the University of Michigan to conduct separate, independent research on various promising aspects of emission controls and to develop calculational and analytical procedures.

The two manufacturers, AVCO and TCM, selected five engines each, ranging in type from carbureted to injected to turbocharged; measured the baseline emissions on these engines; and then operated them with leaner fuel schedules in order to document emissions. The engines were then sent to the National Aviation Facilities Experimental Center (NAFEC), an FAA facility near Atlantic City, New Jersey, where the baseline and leanout tests were repeated to establish the validity of the data. NAFEC also carried the leanout procedures farther than the manufacturer in order to investigate with what margins of safety the engines could be leaned. In this process, as many as 300 data points were collected on each engine at NAFEC.

Test Results

None of the engines as received could meet the EPA limits in either the full-rich or production-lean fuel schedule configurations (fig. X-3). When the engines were operated with the fuel schedule leaned to give optimally low emissions without encountering operational problems, such as excessive cylinder head temperatures, detonation, and poor acceleration, all engines met the EPA standards, with the exception of the turbocharged engines (fig. X-4). The TCM GTSIO-520-K has not yet been tested at NAFEC, but the data received from the manufacturer support the fact that it will be over the standards.

These data are representative of what will be achieved on the test stand and at sea-level conditions. Although the engines were not selected under any special conditions, there is no assurance that the data are typical of all engines of the same manufacture. Furthermore, the data are not indicative of what one could expect from an actual operational aircraft engine; such effects as may be produced by even minor maintenance, such as changing spark plugs, are unknown at this time.

Test Problems

The major problem areas encountered in the conduct of the tests to date are

(1) Instrumentation
(2) Emissions measurement equipment
(3) Calibration gases
(4) Calculational and analytical procedures
(5) Engine operating procedures

The overall effort was to take 18 months. The first phase of the program has taken over 2 years to complete, so the delays caused by these problems are significant.

The first major problem was the instrumentation. Four facilities were involved, and all four were fairly new to emissions measurement. The impact of airflow and fuel flow measurement inaccuracies is magnified; and since all four facilities used different techniques of acquiring the data, considerable time was spent in cross-correlating the data to assure credibility. The emissions measurement equipment, though off-the-shelf hardware, was nevertheless still laboratory-type equipment. Many months of modification, alteration, and redesign were spent to get the equipment to function properly in an operational environment. In similar fashion the calibration gases presented problems that in turn created delay and forced retracing of progress. Such instances are illustrated by gas calibration value changes with time, the effect of storage cylinder material on the concentrations, and repeatability. In the course of testing to date, procedures for proper use of the instrumentation, emissions equipment, and calibration gases had to be developed.

The calculational procedures used initially have been changed considerably with the insertion of proven values of various constants rather than the average values based on automotive emissions work. The analysis also has become much more sophisticated, an area where the University of Michigan contract has been most useful.

The final and probably most significant problem area was in the engine operating procedures themselves. Stabilization times at various power conditions could drastically alter the emissions results. Unfortunately, the most troublesome area was in the taking of data at idle power. Any extended operation at low power could result in totally erroneous data at the next, or taxi, condition because of the tendency of the engine to "load up" with oil. It eventually became obvious that this situation at idle would have to be overcome. Data were taken under the procedures defined in the beginning of the program. Data taken at seven power modes were compared with data taken on the same engine but with the idle data points deleted; no significant change in result was noted (fig. X-5). These two procedures are shown in tables X-2 and X-3. The times for the idle-out and idle-in modes were reassigned to the corresponding taxi-out and taxi-in modes. As a result of this process, the FAA feels it is reasonable to recommend deletion of any requirement to take data at the idle condition.

Future FAA Activities

The FAA's work to date has been summarized. The FAA is presently examining the test stand data with respect to followon efforts on

(1) Time-degradation factors for piston-engine exhaust emissions
(2) Flight simulation of a modified low-polluting engine
(3) Flight demonstration of a low-polluting engine

Operation at altitude will probably increase emissions levels unless some way to control overtemperature of cylinder heads is developed. The reduced density at altitude also tends to increase exhaust gas temperatures. These, as well as other potential operating problems, will be addressed in simulated and actual flight tests in the next several years.

The final subject to be mentioned is in response to the EPA requirement that engines in service continue to meet the emissions levels throughout their lifetimes. FAA is studying the rate at which emissions change with operating time. A pilot program is underway at NAFEC using two aircraft to establish what requirements will be put into the statement of work for a competitive request for proposal to be issued in about 2 months. Based on the results of this 2-year program, the effects of operating time as well as of minor or major overhaul or maintenance will be determined for inclusion in the FAA regulations.

STATUS OF PISTON-ENGINE EXHAUST EMISSIONS REDUCTION TECHNOLOGY AT AVCO LYCOMING

The test programs now in progress at AVCO Lycoming to determine viable exhaust emissions reduction techniques are as follows:

(1) FAA-NAFEC contract (and similar in-house programs)
(2) Effect of production tolerances on emissions
(3) Evaluation of low-drag cylinder heads

(4) Emissions testing of other engine models

(5) NASA Lewis Research Center contract

The first four programs are near-term studies, where relatively quick turnaround conclusions can be made. For a long-term development program, a contract has been made with the NASA Lewis Research Center to examine and define new or advanced concepts and applications for aircraft piston engines. This discussion updates the conclusions and the status of the various investigations now under way at AVCO Lycoming.

Near-Term Studies

The results of the NAFEC contract were discussed previously. However, additional engines have been tested at Lycoming. The larger, more powerful engines, which are usually turbocharged, exhibited higher pollutant outputs per rated horsepower than their smaller, normally aspirated counterparts. This trend has also been indicated in the NAFEC data.

The NAFEC data are mainly from one engine, and the variation of engine-to-engine emissions within the same model is another problem to be considered. AVCO Lycoming has thus tested several production engines of the same model, and the results show that variations do exist between engines. Insufficient data have been collected to fully apprise the magnitude or the cause of the problem other than the direct effect of production tolerances on fuel flow.

The AVCO Lycoming data have been collected on a flight test stand. Although a flight test stand does simulate, to some extent, actual engine operation, it is not absolutely reflective of aircraft operation, for instance, in the controllable amount of air available for engine cooling. Also, no aircraft engine cowling is used. To provide an exhaust sampling point, the exhaust from each cylinder is ducted into a common runner, and a portion of the exhaust stream is extracted for analysis. Therefore, while serving as an ideal test bed for engine research, the flight propeller test stand does not fully duplicate an airframe-installed application of the engine. In fact, any attempt to use a production exhaust system or engine cowling is wholly impracticable because of the many different engine models in use.

Flight Test Program

In an attempt to separate some of the influences these differences between test-stand and installed-engine operation may have, a flight test program to evaluate an "emission controlled" engine was started. Essentially, the main objective of this flight test was to evaluate a revised fuel schedule in different aircraft with fuel-injected engines. The standard fuel schedule for this type of injector features a virtually flat fuel-air ratio maintained over the power range of the engine. At low powers (idle and taxi), some enrichment is available through a separate flow circuit. The revised flight test incorporated a fuel-lean midpower region and automatic mixture compensation to offset the variations in day-to-day ambient conditions and those due to altitude. At both ends of the power spectrum, that is, idle and takeoff, fuel enrichment was available.

Each test flight was arranged to identify any problems associated with a lean fuel schedule. Engine cooling, detonation, and response to throttle movement were of primary importance in these tests. The results of these tests are as follows:

(1) Significant reductions in emissions were attainable with a breadboard fuel injection system. These reductions were of the order of a 50-percent differential or more; that is, where a level of 200 percent of the Federal standards existed previously, with this system a 150-percent level would result.

(2) Density compensation is required to ensure that the tailored fuel schedule is maintained throughout the normal range of ambient conditions for aircraft.

(3) Some cooling problems were encountered on certain aircraft for the 80-percent power climb at best power, but no detonation was detected.

(4) No problems were indicated with rapid accelerations, but a hesitation or flat spot was encountered during slow accelerations.

(5) Turbocharged engines show definite problems with leaner schedules.

At this point, it may be well to digress a minute to clarify and enforce these conclusions. The data obtained from these tests are from a breadboard model. Currently, no density compensation, like the one tested here, is available on a production basis. A major development program would be required to accomplish this seemingly small task. Also the fact that some aircraft experienced cooling problems enforces the unique character established in marrying an engine and an airframe. The solution of each of these problems could possibly require both an engine and airframe recertification program for each aircraft now in production. While that immediate task is insurmountable, we are addressing ourselves to it in a stepwise fashion; that is, extracting as much benefit from the research as can be reasonably expected without sacrificing either safety, reliability, or performance. Conclusion 5 from the flight test program deals with a large, turbocharged engine. This engine could not tolerate the lean fuel schedule, and from this first attempt the simple "leanout" technique does not appear feasible. However, work on this type of engine is continuing.

Low-Drag Cylinder Head

In other programs the development of a low-drag cylinder head for better cooling (fig. X-6) has produced indirect benefits in the exhaust emissions reduction program. The low-drag head dissipates heat more efficiently than the standard cylinder head design. This improved efficiency allows the use of leaner fuel-air ratios where cylinder head cooling was previously a problem. Consequently, lower emissions, especially of CO and THC, result. But this low-drag cylinder head design may not be the optimum - a third design may be even better.

Near-Term Study Conclusions

The conceptually feasible conclusions drawn from the AVCO Lycoming near-term test are as follows:

1. Exhaust pollutants can be significantly reduced by lean operation. To accomplish this without engine or airframe recertification, a reduction in fuel system tolerances toward the lean production limit is being pursued.
2. Existing fuel systems can be modified to incorporate density compensation with a tailored fuel schedule.
3. A new fuel system should be developed with total density compensation and adjustable valves to set a precise fuel flow schedule.

4. Flight test programs are essential to determine the fuel schedule limits for acceptable aircraft performance.

5. Cooling fin design should be optimized to provide the maximum cooling efficiency.

NASA Contract

To further the long-term research and development of piston aircraft engines, AVCO Lycoming has entered into a contract with the NASA Lewis Research Center. This contract, while having reduction of exhaust emissions as its primary goal, also rated improved engine fuel economy, safety, and other parameters on an equal level. As a result of an in-house feasibility study, AVCO Lycoming has begun work on three individual concepts: variable valve timing, ultrasonic fuel vaporization, and ignition systems. Variable valve timing is a major engine change designed to optimize the valve timing for each engine power setting. To accomplish this, both valve overlap and timing are variable. Ultrasonic fuel vaporization is being investigated to improve cylinder-to-cylinder fuel-air distribution in carbureted engines. This improvement would allow the use of leaner operating fuel-air mixtures in aircraft. Improving combustion at low powers and reducing the potential if misfire, both of which produce high THC pollutant levels, is the aim of the ignition systems studies. Both of the latter concepts are minor changes to the engine.

Variable valve timing has been proposed to optimize the power output of the engine, or to optimize its "breathing," at all conditions. This will ensure that the maximum benefit of the fuel supplied to the engine is being withdrawn from each intake charge. For such a concept to become effective, both the valve overlap and the occurrence of the valve opening and closing need to be variable. This was accomplished (fig. X-7) by designing a special camshaft equipped with movable lobes and gearing. Tests of this concept are now under way.

Ultrasonic fuel vaporization was chosen to improve cylinder-to-cylinder distribution of the fuel-air mixture to the engine. In a typical engine (fig. X-8), fuel and air rise vertically into a plenum chamber and are then distributed to each cylinder. With this design, there is a chance of maldistribution since the larger fuel droplets may not be able to "turn" the corners in the manifold. Installing an ultrasonic atomizer in the system (fig. X-9) enhances breakup of large liquid droplets and allows an improved, more uniform flow of the mixtures throughout the system.

Investigation of ignition system components is directed at improving the initiation of the combustion process for more consistent firing of the intake charge. Along with such devices as multiple spark and capacitive discharge systems, other variables such as spark plug tip penetration (fig. X-10) are also being surveyed.

In conclusion, the programs being conducted at AVCO Lycoming to reduce the pollutant emissions from aircraft piston engines are a combination of both near- and far-term programs. These programs have been chosen to approach the task of cleaning the environment in a stepwise manner. The most readily available techniques will be addressed first and the "fine tuning" will follow. It is planned that each concept, applied in the correct sequence, will not only benefit the emission reduction plan, but will also optimize the fuel consumption characteristics of the engine.

TELEDYNE CONTINENTAL MOTORS (TCM) PISTON ENGINE EMISSIONS REDUCTION PROGRAM

NASA Contract

Teledyne Continental Motors is currently under contract with the NASA Lewis Research Center to establish and demonstrate the technology necessary to safely reduce general aviation piston-engine exhaust emissions to meet the EPA 1979 emissions standards with minimum adverse effects on cost, weight, fuel economy, and performance. The contract is intended, first, to provide a screening and assessment of promising emissions reduction concepts; and, second, to provide for the preliminary design and development of those concepts mutually agreed upon. These concepts will then go through final design, fabrication, and intregration with a prototype engine or engines. Verification testing will then be performed at TCM.

Teledyne Continental Motors has completed the following tasks under the NASA contract:

(1) Task II: screening analysis and selection of three emissions reduction concepts

(2) Task III: preliminary design of three selected concepts

A technical report (ref. 5) has been published detailing the results of task II. The results obtained during tasks II and III are summarized here.

In the screening analysis, 10 basic concepts were evaluated: stratified-charge combustion chambers, improved cooling combustion chambers, diesel combustion chambers, variable camshaft timing, improved fuel injection systems, ultrasonic fuel atomization, thermal fuel vaporization, ignition systems, hydrogen enrichment, and air injection. As part of the analysis, we conducted a detailed literature search and contacted firms considered expert in their respective fields. Our objective was to obtain raw emissions data for the specific aircraft model conditions for as many concepts as possible. The data were then input to the TCM aircraft cycle emission deck. Where adequate raw emissions data were not available, the concepts were evaluated by analyzing their impact on emissions as applied to the IO-520-D engine. A graphical representation of engine emissions as a function of time-weighted fuel-air equivalence ratio is shown in figure X-11. Note that only a narrow band of seven-mode, timed and weighted equivalence ratios (1.03 to 1.13) exists where all three regulated pollutants are at or below EPA standards.

Based on the results of the concept-criteria trade-off analysis, improved fuel injection systems, improved cooling combustion chambers, and exhaust air injection were approved by the NASA Lewis Research Center for further development.

The adaptability of all three concepts provides a means for many possible integrated emissions reduction packages, as shown in figure X-12. An improved fuel injection system and an improved cooling combustion chamber complement each other in reducing emissions by overcoming the associated problems of operating at leaner than present fuel-air ratios. An exhaust port liner coupled with air injection provides a means of aftertreatment of the exhaust products, ensures a cooler cylinder head, and suggests leaner fuel-air ratio operation.

An improved fuel injection system will be a timed, airflow-sensitive system capable of supplying fuel at moderate pressure 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 and density) sensitive system is required to maintain the desired fuel-air ratio, which controls the emissions levels, and together with proper cylinder distribution, provide better engine transient response. A servomechanical controlled system is currently being evaluated.

An improved cooling combustion chamber will include an exhaust port liner. A detailed heat transfer analysis has shown port liners, coupled with an air gap, to be the most effective means of reducing cylinder head temperatures.

TCM Future Development Programs

In considering the present knowledge of exhaust emissions at TCM and the work that lies ahead to achieve the substantial emissions reductions needed to meet EPA standards, we have planned programs utilizing concepts that have the promise of earliest success. These programs generally will attempt to enhance existing engine systems, exploiting their potential for emissions reduction as far as is compatible with retaining the well-established features in them that are in current production. This approach will minimize development times and retain much of existing know-how that is always vital in ensuring technical performance and safety in production engines. The intended programs identified to date in the area of new concepts are a fuel injection system, evaluation of the accelerator pump, and variable spark timing.

TCM fuel injection system. - Density compensation capability will be developed for the TCM fuel-injection system. The potential benefit of better fuel-air ratio control over a temperature range would be, for instance, in reducing the 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.

Evaluation of accelerator pump. - The limitation in leaning idle, taxi, and approach modes is the inability to accelerate from those conditions. Temporary augmentation of fuel flow by accleration pumps may have the potential to provide safe operation in the transient condition between steady-state leaned conditions.

Variable spark timing. - The lean misfire limits can be extended by varying ignition timing but, although misfiring has not yet imposed a limitation on leaning, this limit will be met as further leaning is attempted. An automatically controlled variable spark timing could be beneficial, particularly 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 concept.

To provide the information needed for a full definition of the emissions reduction task in TCM engines, baseline emissions must be surveyed, the effects of production tolerances and cumulative operational time determined, flight tests made, and the effect of inlet manifold tuning evaluated.

Survey of baseline emissions of TCM engine range. - The emissions levels for the basic engine models not tested to date must be determined.

Effect of production tolerances. - The difference between baseline and case 1 emissions has shown that the effect of fuel flow tolerance is very significant. (Baseline is defined as the average fuel flow rate established by the fuel system production tolerance band when operated with the mixture control at the fuel-rich position. Case 1 is defined as the minimum allowable fuel flow rate established as the engine type certificate.) It is probable that other effects are significant also, one possibility being varying hydrocarbon emissions having as a source the lubricating oil that passes into the combustion chamber. Consistent control of lubricating oil in the first few hours of engine life is notoriously difficult especially in air-cooled engines. Understanding of tolerances is clearly vital.

Effect 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.

Flight testing. - 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 information on the performance penalties incurred by improved cooling. Also further data are required to project uninstalled engine results for the actual aircraft installation. Flight service testing will also be required to assess the effect on engine time between overhaul and reliability.

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

OVERVIEW OF NASA LEWIS RESEARCH CENTER GENERAL AVIATION PISTON-ENGINE RESEARCH AND TECHNOLOGY DEVELOPMENT PROGRAM

After the EPA issued exhaust emissions standards for general aviation engines in 1973, NASA embarked on a program to establish and demonstrate the technology necessary to safely reduce general aviation piston-engine exhaust emissions to meet the EPA 1979 standard and to reduce fuel consumption. The emissions reduction program has three major elements. The first is the joint FAA/NASA contractual effort previously discussed. The second is the NASA contractual effort that would screen and assess more significant modifications and carry through to actual demonstration those concepts showing the most promise. Cost-shared contracts to TCM and AVCO Lycoming were let in late 1975. The status of these contracts was presented in the preceding sections of this paper. The third major effort, to be conducted in-house at the Lewis Research Center, concentrates on longer term solutions requiring additional or new analytical and/or experimental technology. Specific in-house areas that are presently active are

(1) Temperature-humidity correlations
(2) Lean-operation fuel injection
(3) Otto-cycle program development
(4) Instrumentation development

Temperature-Humidity Correlations

It was recognized early in the FAA/NASA 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 correlate these data. Therefore, NASA Lewis 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, a four-cylinder, naturally aspirated engine; and the second was the Teledyne Continental Motors TSIO-360-C, a six-cylinder, turbocharged, fuel-injected engine.

Figure X-13 shows the TSIO-360 installed in the test stand. The engine is coupled to a 300-horsepower dynamometer through a fluid coupling in the drive shaft. Engine cooling and induction air is 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 relative humidity range from 0 to 80 percent. The cooling air was always at the same conditions as the induction air and was directed down over the engine by an air distribution hood.

Two basic types of tests were conducted for each engine. The seven-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 landing/takeoff, seven-mode cycles were run at the full-rich fuel-air ratio.

Comparing the temperature and humidity test results at 100° F and 80-percent humidity with those at 50° F and no humidity shows that, with the increased temperature and humidity, CO emissions increase by a factor of 1.6, HC emissions increase by a factor of 2.2, and NO_x emissions decrease by a factor of 3.5 (ref. 1).

Present-day aircraft engines do not use a temperature-density-compensated fuel system. Hence, the cited changes in the exhaust emissions are primarily the result of richer fuel-air ratios, which occur at the higher air temperatures and humidities. Ambient conditions can also affect the induction vaporization and basic combustion process, thereby influencing the HC and NO_x emissions. Therefore, a series of tests were performed to establish these effects for a fixed fuel-air ratio.

To illustrate the test findings, figure X-14 shows how the taxi-mode HC emissions expressed as a percentage of the EPA standard varied over the range of temperature and the two extreme relative humidity conditions, 0 and 80 percent. For the 80-percent-relative-humidity case, the HC emissions varied from 38 to 120 percent of the EPA standard over the temperature range tested. For the 0-percent-relative-humidity case, the HC emissions varied from 35 to 40 percent of the standard. The fuel-air ratio varied from 0.093 at the 50° F, 0-percent-relative-humidity condition to 0.11 at the 100° F, 80-percent-relative-humidity condition.

Figure X-15 compares the results with 80-percent relative humidity for a varying fuel-air ratio (upper curve) and a fixed fuel-air ratio of 0.093 (lower curve) over the tested temperatures. The 0.093 fuel-air ratio was obtained at 50° F and 0-percent relative humidity. The plot shows both the increase in emissions due to combustion effects and the increase in emissions due to a change in fuel-air ratio.

The CO, HC, and NO_x emissions for each mode are being correlated on the basis of fuel-air ratio. An overall correlation of the raw emissions and modes will then be attempted, and finally comparisons will be made between the two engines.

Fuel Injection

Another in-house effort is being made to determine and demonstrate the potential of an optimized inlet-port fuel injection system to reduce exhaust emissions and fuel consumption. It is believed that any basic research program that endeavors to accomplish these goals must necessarily include fuel atomization studies. The effects of atomization on internal-combustion-engine performance are not well known. Conflicting studies (ref. 6) exist as to how the degree of atomization influences the extension of the lean limit. Multicylinder engine experiments show an extension of the lean limit with proper atomization. However, it has not been determined whether this results from reduced cylinder-to-cylinder variations due to good atomization or from a better combustion process because of the homogeneity. Conversely, single-cylinder studies indicate that heterogeneous and not homogeneous fuel-air mixtures lead to leaner limits. Likewise, a reduction in exhaust emissions from a more homogeneous charge has not been fully substantiated. Claims that HC and CO emissions may be reduced by optimum vaporization of the fuel are contradicted by claims that NO and HC emissions are increased in that way.

Therefore, NASA is attempting to determine the effects of the various injection-controlling parameters (droplet size, distribution, and velocity; spray pattern; injection timing; and nozzle position) on aircraft engine emissions and performance. This program will be accomplished in four phases: droplet studies, manifold flow visualization studies on a single cylinder, single-cylinder performance and emissions tests, and full-scale engine tests. Present activities include injector characterization and manifold visualization studies using photography. Figure X-16 is a photograph of a current aircraft injector's spray characteristics at idle and takeoff/climb. It illustrates the problem of poor atomization at higher powers.

Otto Cycle

The Otto-cycle modeling effort is believed to have the potential of becoming an uniquely valuable tool. If NASA is successful in developing a realistic computer simulation of engine operation, rapid and inexpensive engine performance mapping would thereby reduce the testing required in research activities. The present program code (ref. 7) incorporates such important features as (1) NO_x and CO predictions, (2) finite combustion rates, (3) three heat transfer models, and (4) complete chemical kinetics on the burned gas. Work is under way to include HC predictions, a lesser dependence on experimental report data, realistic valve timing, and cycle-to-cycle variations.

Instrumentation

In order to supply experimental engine data to support development of the analytical model, instrumentation has been designed and built to determine on a per-cycle, per-cylinder basis, real-time measurements of

(1) Mass of charge burned
(2) Combustion interval and ignition lag
(3) Indicated mean effective pressure (IMEP)
(4) Pressure-volume diagram
(5) Average and standard deviations for items 1 to 3

Bargraphs of 100 consecutive cycles of IMEP for engine operation at the same rpm and power but at two different equivalence ratios are shown in figure X-17. The left bargraph is for a equivalence ratio of 1 and displays very uniform combustion; the rather dramatic presentation of both slow combustion and misfire at the lean limit is shown at the right. Further information on this subject can be found in references 1 and 8.

CONCLUDING REMARKS

This paper has only briefly presented the status of various programs related to reducing exhaust emissions from aircraft piston engines. The EPA standards are local (airport area) standards. They are based on appeciable pollution contributions from general aviation aircraft observed and/or projected in the vicinity of numerous airports. Initial testing of many production engines, under joint FAA/NASA sponsorship, revealed that current models exceed the EPA standards by factors of 2 or 3. Subsequent testing with leaner fuel schedules (as premised by EPA in calculating the numerical standards) did show significant emissions reductions. In many cases, however, this was accompanied by undesirable side effects such as overheating at high powers and unsatisfactory throttle response. Therefore, the recent emphasis in the NASA program has been to define and promote the timely development of an advanced-technology base that could be used by industry for problem-free, environmentally acceptable engines in the future. Both AVCO and TCM have now tested several advanced-technology concepts with encouraging results. Also, because post-1979 engines must meet the emission standards throughout their lifetimes, the FAA is beginning efforts to determine the rate at which emissions change with operating time. Based on the results of this 2-year program, the effects of operating time as well as of minor or major maintenance and overhaul will be determined for inclusion in the FAA regulation.

For the longer term, NASA is beginning a program including (1) the evaluation of alternative engine concepts such as rotary or lightweight diesel; (2) the development of technology needed by these as well as advanced-spark engines; and (3) the continuing improvement of analytical techniques, diagnostic instrumentation, and test facilities.

In addition to NASA's exhaust emissions program, a related advanced propulsion concepts program for general aviation is under way.

Advanced engines that are environmentally acceptable, are tolerant of expected future fuels, and have improved economic and performance characteristics are needed for the health of the domestic general aviation industry. Many of the advanced engine concepts being considered include unconventional design or cycle features. The technology base to evaluate and assess such candidates (e.g., a stratified-charge rotary engine) for general aviation use is incomplete. NASA's involvement in this area will provide the focus (1) to obtain characteristic data on candidate alternative engines; (2) to assess, define, and carry out needed research on the promising candidate engines as an aid in their evaluation; (3) to perform unified systems studies to evaluate the candidates in terms of their performance in an airplane and to select the most promising engine or engines; and (4) to assemble the key technology into an experimental engine or engines to verify readiness for commercial development by the late 1980's.

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AIR POLLUTION CONTRIBUTION OF PISTON ENGINE AIRCRAFT AT FIVE SELECTED AIRPORTS

	RANK	yr	TONS/yr*		
			HC	CO	NO_X
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.

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Table X-1.

7-MODE TEST FOR EMISSIONS

POWER	ENGINE SPEED, rpm	TIME AT POWER,[a] min
IDLE(OUT)	600	1
TAXI(OUT)	1200	11
TAKEOFF	[b]2700	.3
CLIMB	[b]2430	5
APPROACH	[b]2350	6
TAXI(IN)	1200	3
IDLE(IN)	600	1

[a] FOR CALCULATION PURPOSES ONLY.

[b] NOMINAL.

Table X-2.

5-MODE TEST FOR EMISSIONS

POWER	ENGINE SPEED, rpm	TIME AT POWER,[a] min
TAXI(OUT)	1200	12
TAKEOFF	[b]2700	.3
CLIMB	[b]2430	5
APPROACH	[b]2350	6
TAXI(IN)	1200	4

[a] FOR CALCULATION PURPOSES ONLY.

[b] NOMINAL.

Table X-3.

PISTON ENGINE EMISSION CHARACTERISTICS

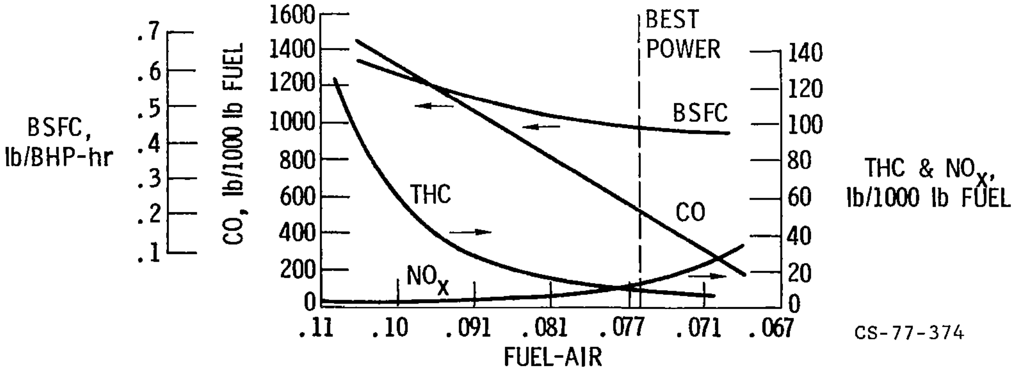

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Figure X-1.

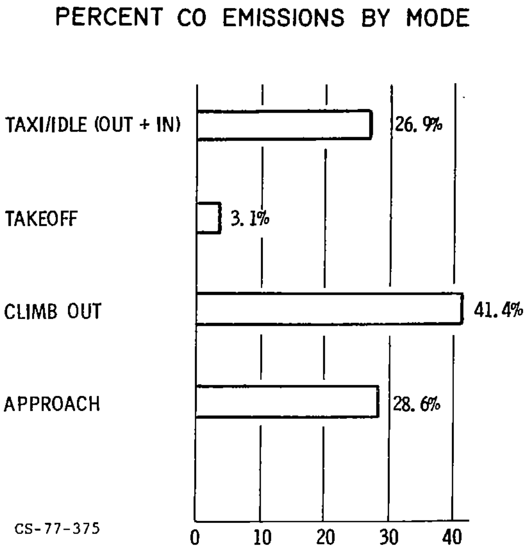

Figure X-2.

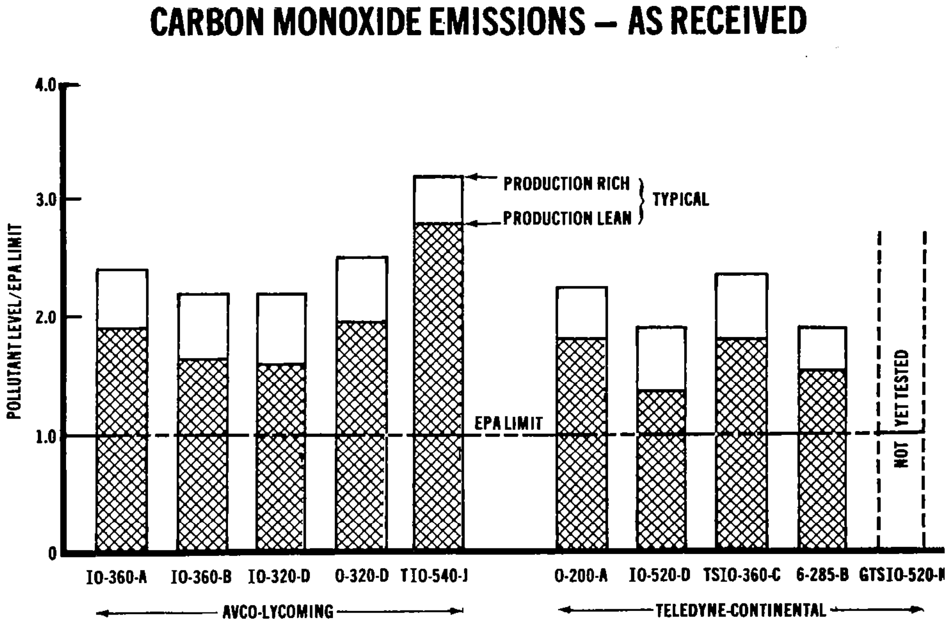

Figure X-3.

CARBON MONOXIDE EMISSIONS - LEANED FUEL SCHEDULE

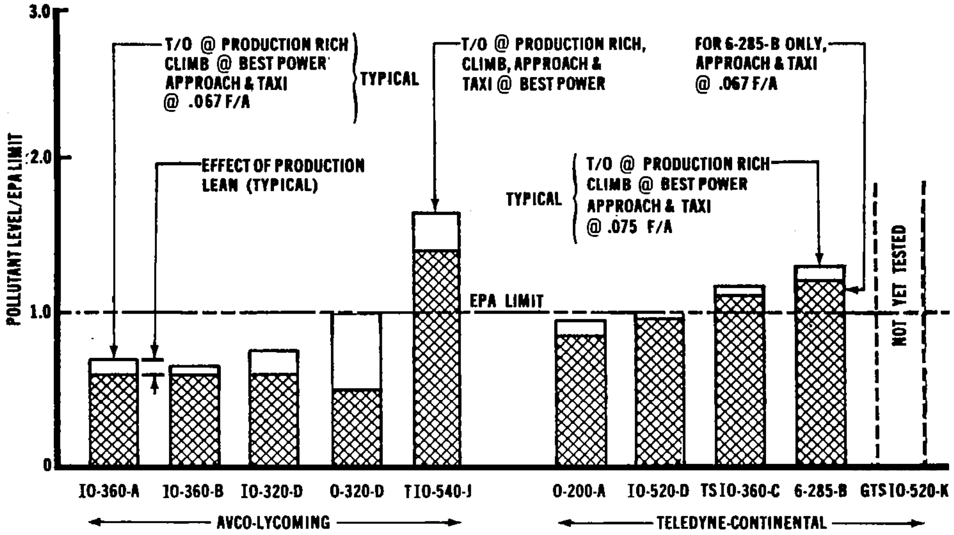

Figure X-4.

EFFECT OF DELETION OF IDLE MODE ON EMISSIONS CALCULATIONS

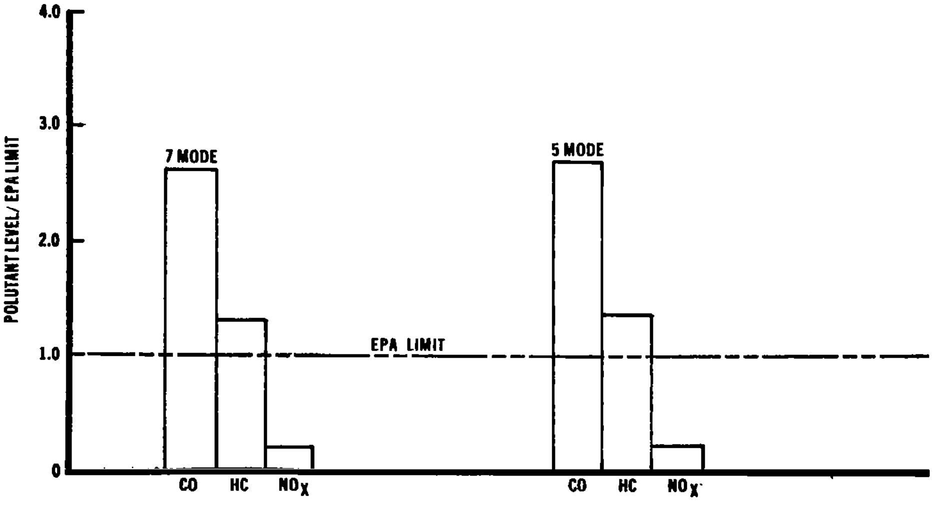

Figure X-5.

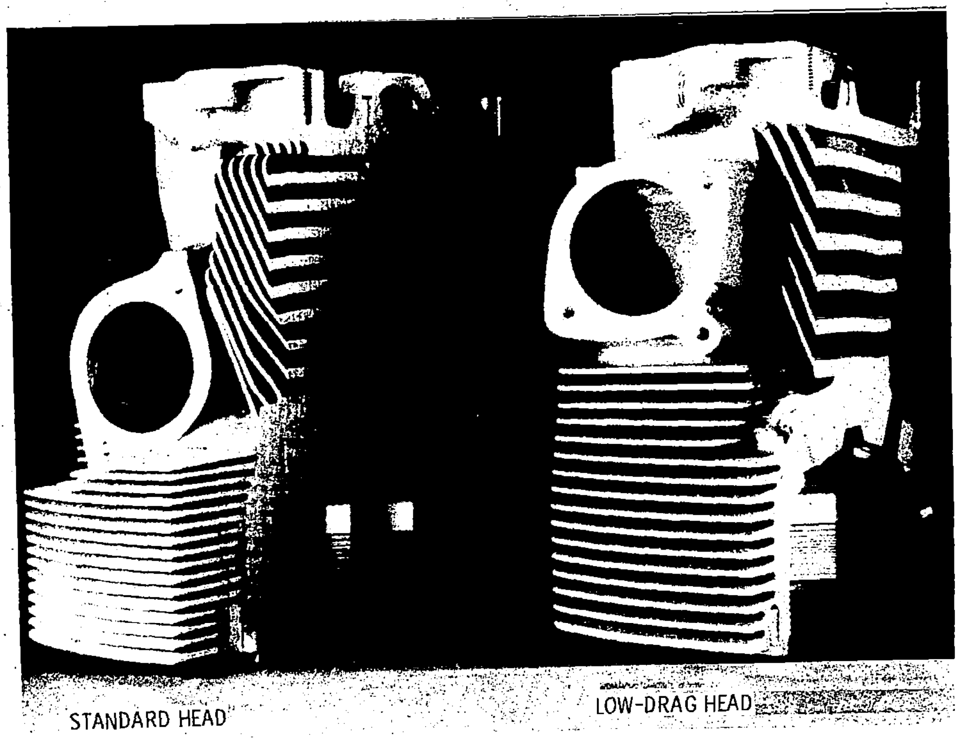

Figure X-6.

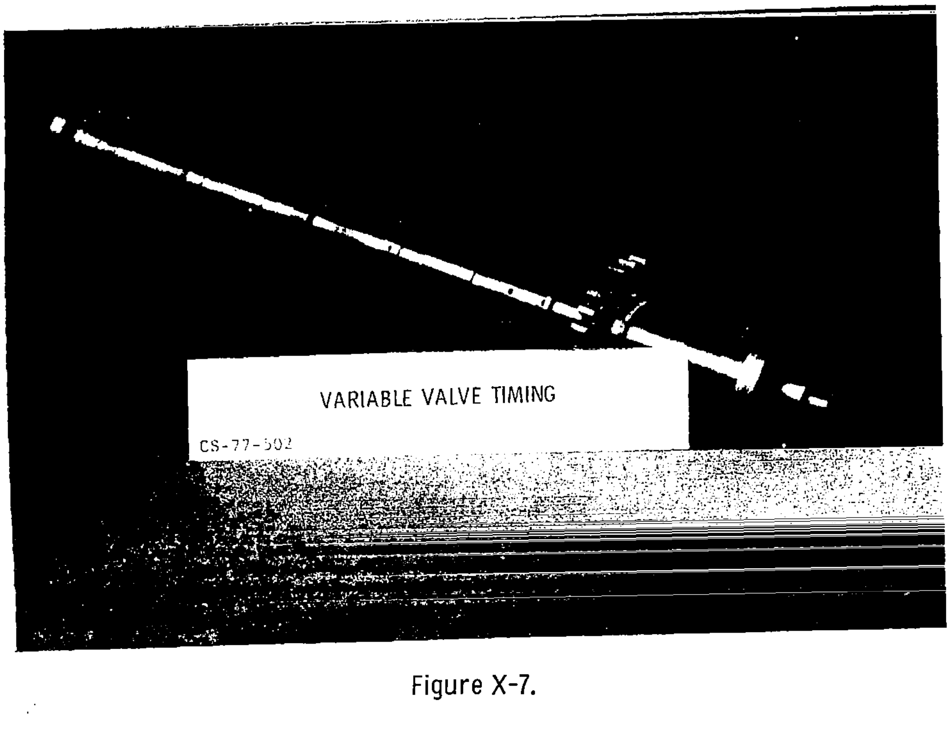

Figure X-7.

CARBURETOR INDUCTION SYSTEM

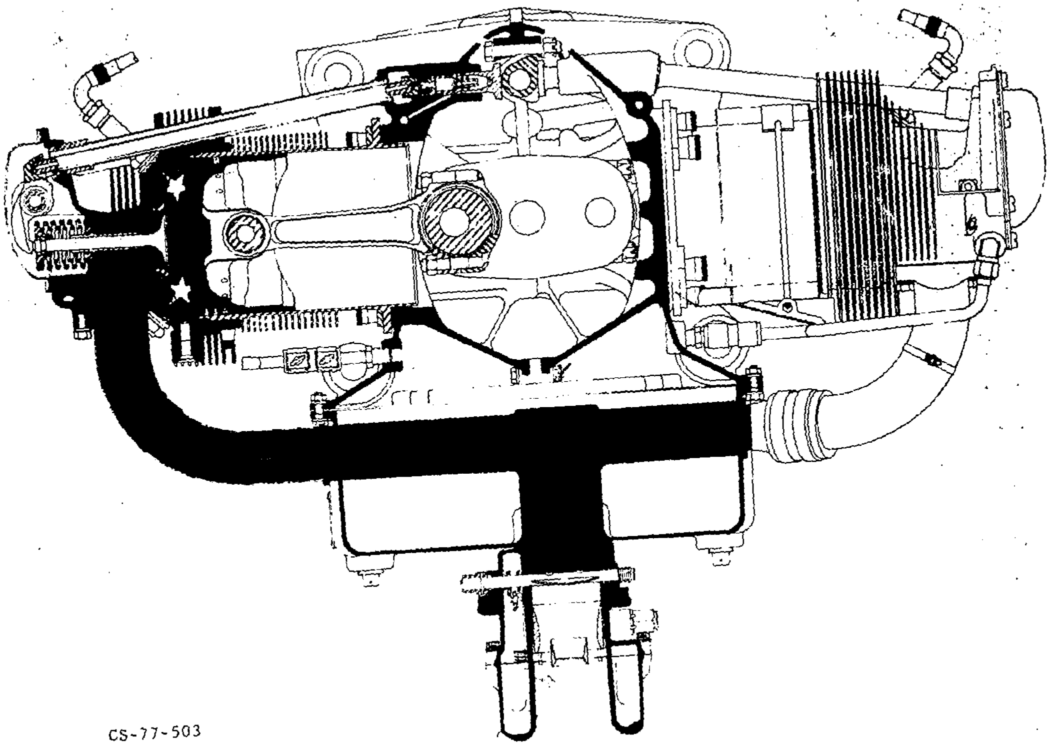

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Figure X-8.

ULTRASONIC FUEL VAPORIZATION

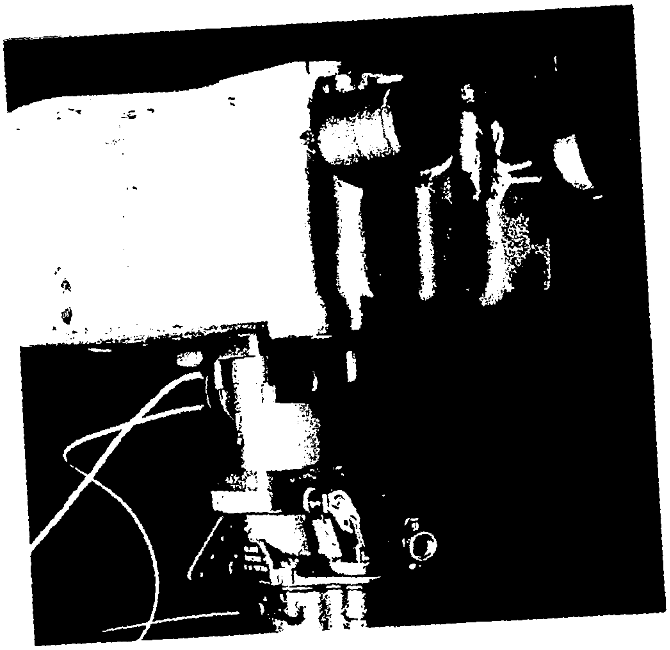


Figure X-9.

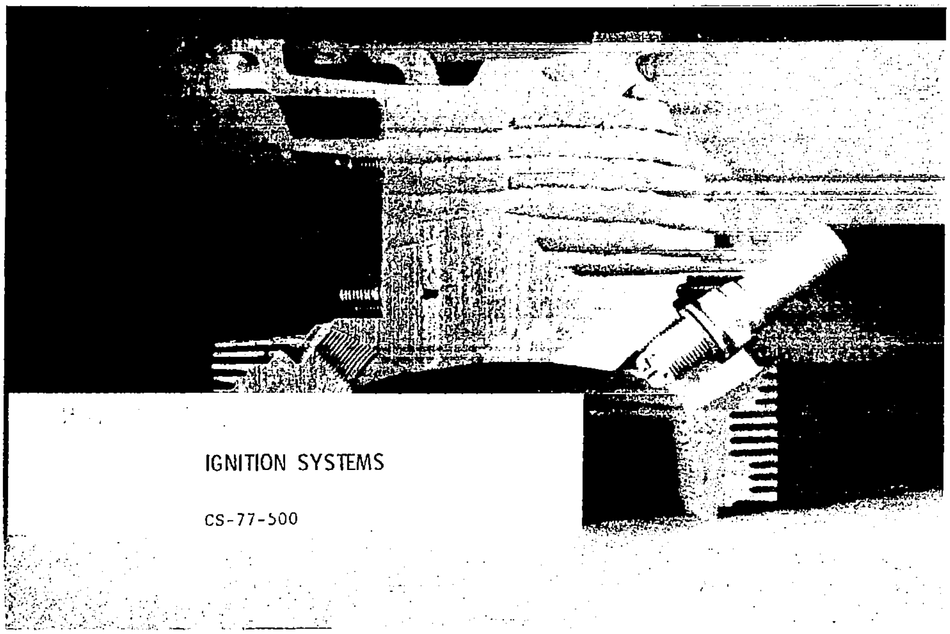
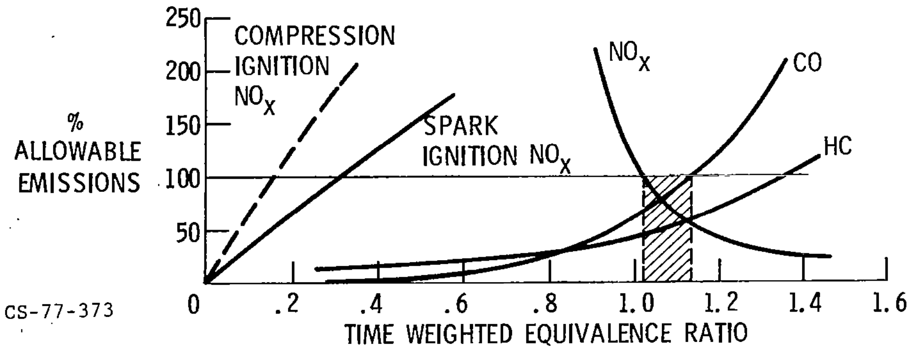


Figure X-10.



PERCENT ALLOWABLE EMISSIONS VERSUS TIME WEIGHTED EQUIVALENCE RATIO

ENGINES EVALUATED ON 7-MODE AIRCRAFT EMISSION CYCLE

Figure X-11.

CONCEPT INTEGRATION

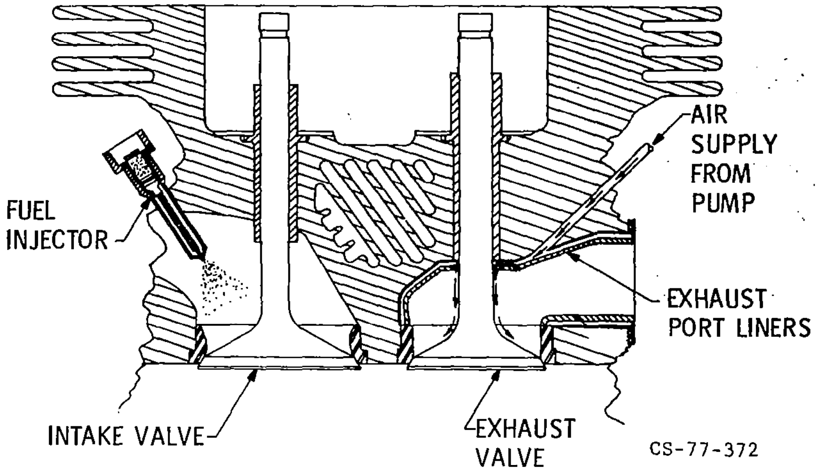


Figure X-12.

TEST CELL

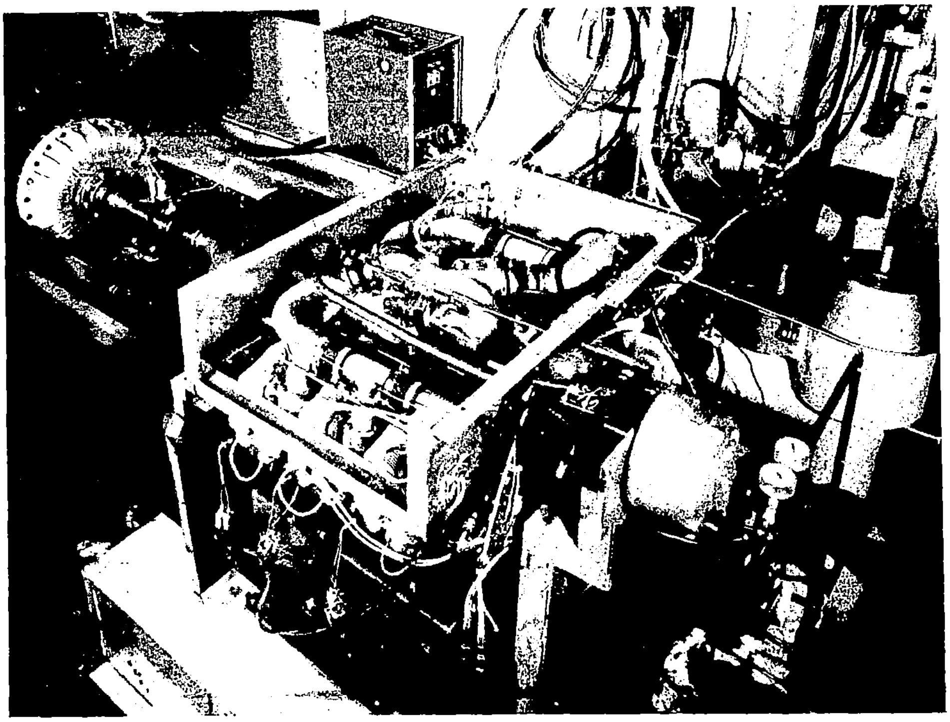


Figure X-13.

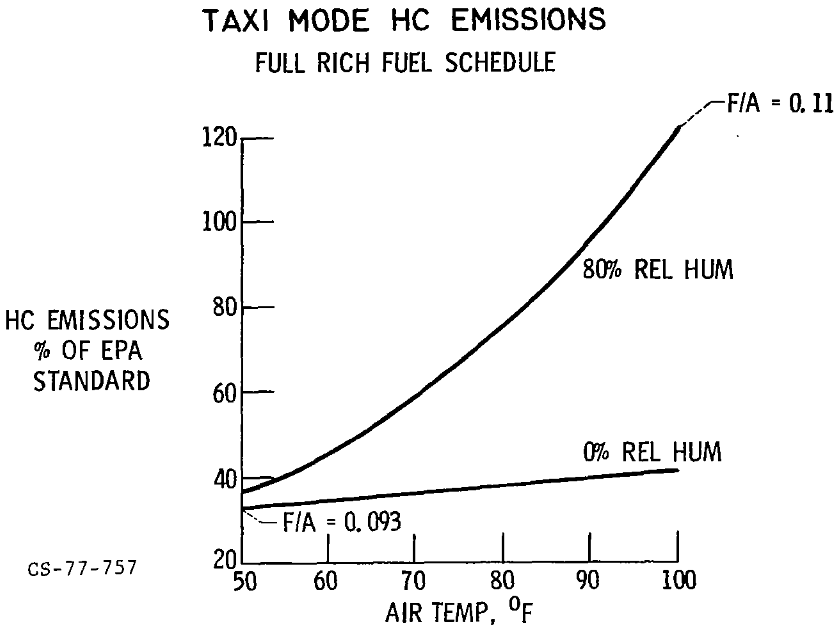


Figure X-14.

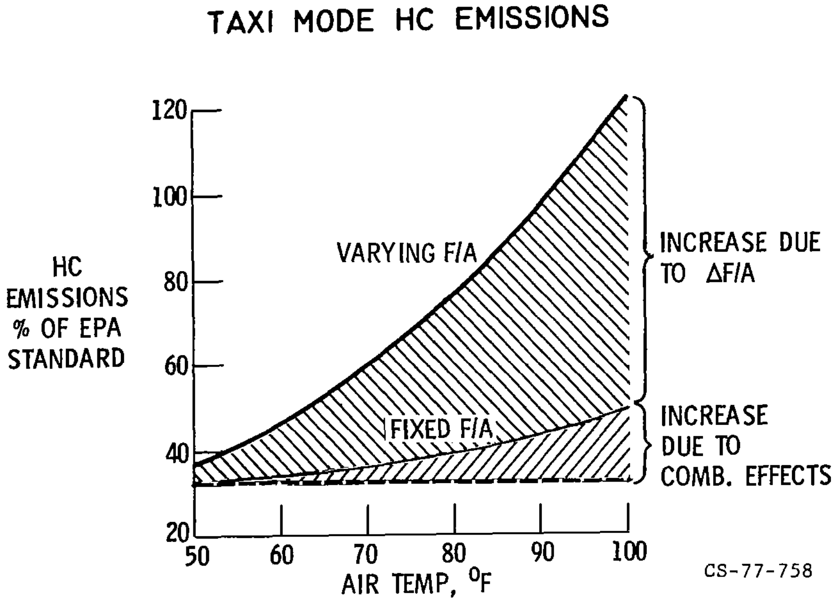


Figure X-15.

AIRCRAFT FUEL INJECTION PROBLEMS

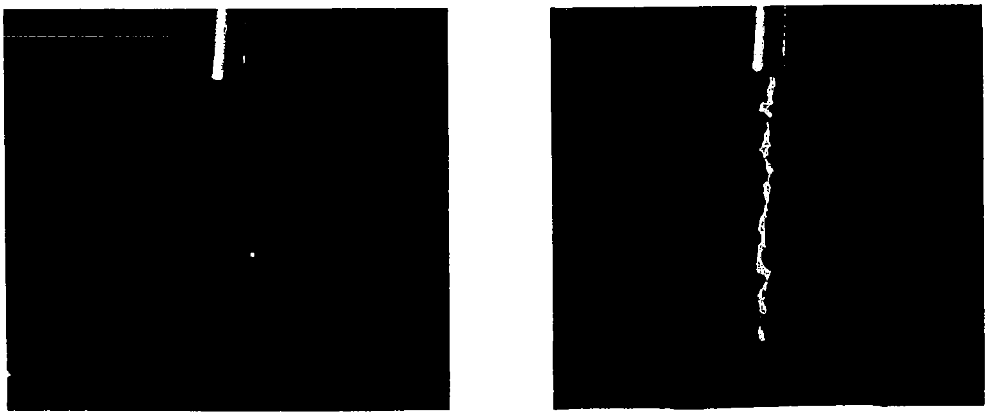

CS-77-748 IDLE/TAXI TAKEOFF/CLIMB

Figure X-16.

IMEP INSTRUMENTATION

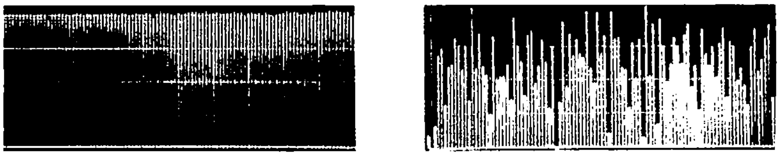

CS-77-747

Figure X-17.