2. APPLICATION OF AUTOMOBILE EMISSION CONTROL TECHNOLOGY TO LIGHT PISTON AIRCRAFT ENGINES

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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 powerplants 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 powerplant, 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 experimentally the levels of emissions achievable by modifying light aircraft 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 operating 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 successful in reducing emissions, to varying degrees, but not with sufficiently greater effectiveness to offset their added expense, weight, and bulk. The study concluded that "further investigation of piston engine emissions should initially emphasize fuel and air management over exhaust treatment as the most promising approach to the control of emissions 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 distribution for more precise control of the mixture in individual cylinders. This would allow increased average leanness with minimum increases in individual 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 interest 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 requirements 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 aircraft powerplants which tend to work in favor of achieving and maintaining 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 combustion 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 engines 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 approaches 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 enleanment 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 standpoint alone, even if there were no concern for emission control.

During the Landing Take-Off (LTO) cycle, current light piston aircraft (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 acknowledged 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 associated 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 vapor, liquid and droplet forms. For efficient engine performance, the manifolding must deliver under both steady-state and transient conditions an accurate, equal portion of this mixture to each cylinder. Unfortunately, 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 intake manifold runners of LPA engines are significantly longer than automotive 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, current systems at low flow conditions frequently emit the fuel as a weak stream or dribble. Curing this problem is considered to be a straightforward 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 intake 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 features 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 increases 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 efficiency.

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 energy 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. Enleanment to reduce emissions will increase the cooling requirements and in some installations overtemperature conditions may be experienced. A solution 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 between 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 fundamental limiting condition in the ability of LPA engines to cool satisfactorily 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 during 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 except 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 characteristics and applies a hard nickel alloy coating to the surfaces exposed to wear. While it is recognized that the most critical overheating 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 material 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 conserving the exhaust gas heat the effectiveness of afterreaction techniques 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 exhaust 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 exhaust gas temperature. Another means of raising exhaust gas temperature is through the use of exhaust port liners.

Discussed in the previous section as means of alleviating overheating 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 performance, cooling, cost, reliability, etc.

A - D. Tripp: EPA realizes that the industry has looked at these techniques. 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 valuable 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. Approximately 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.

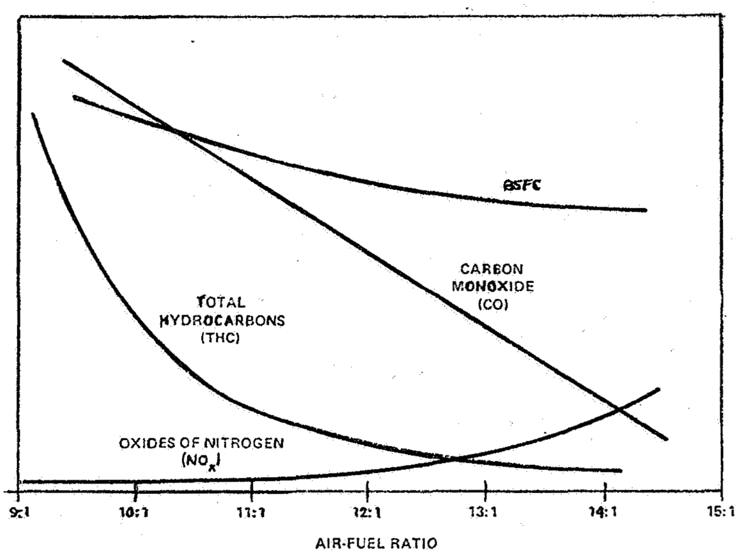
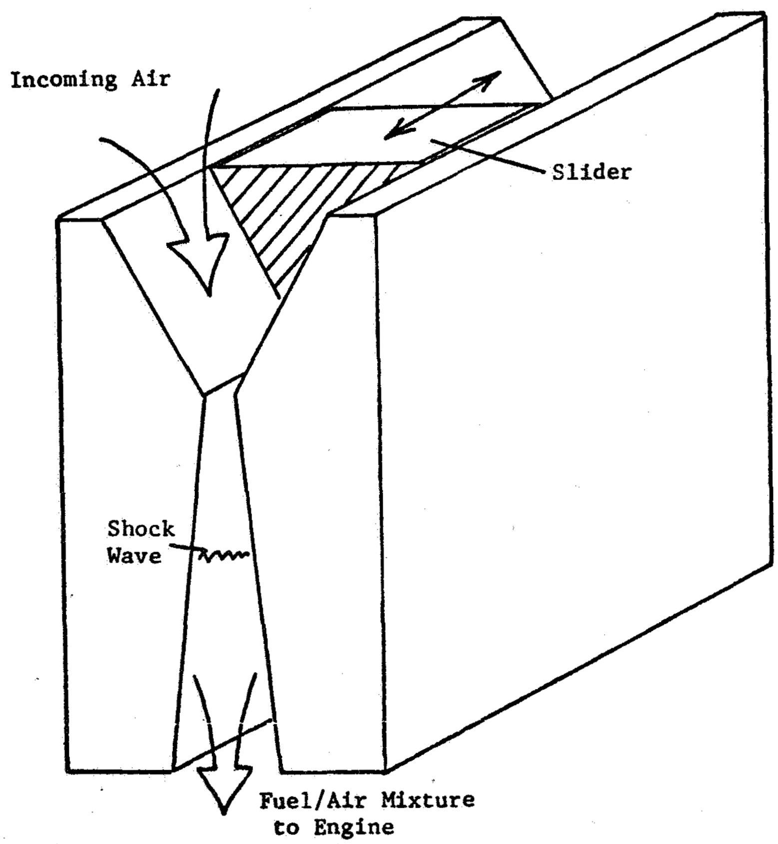
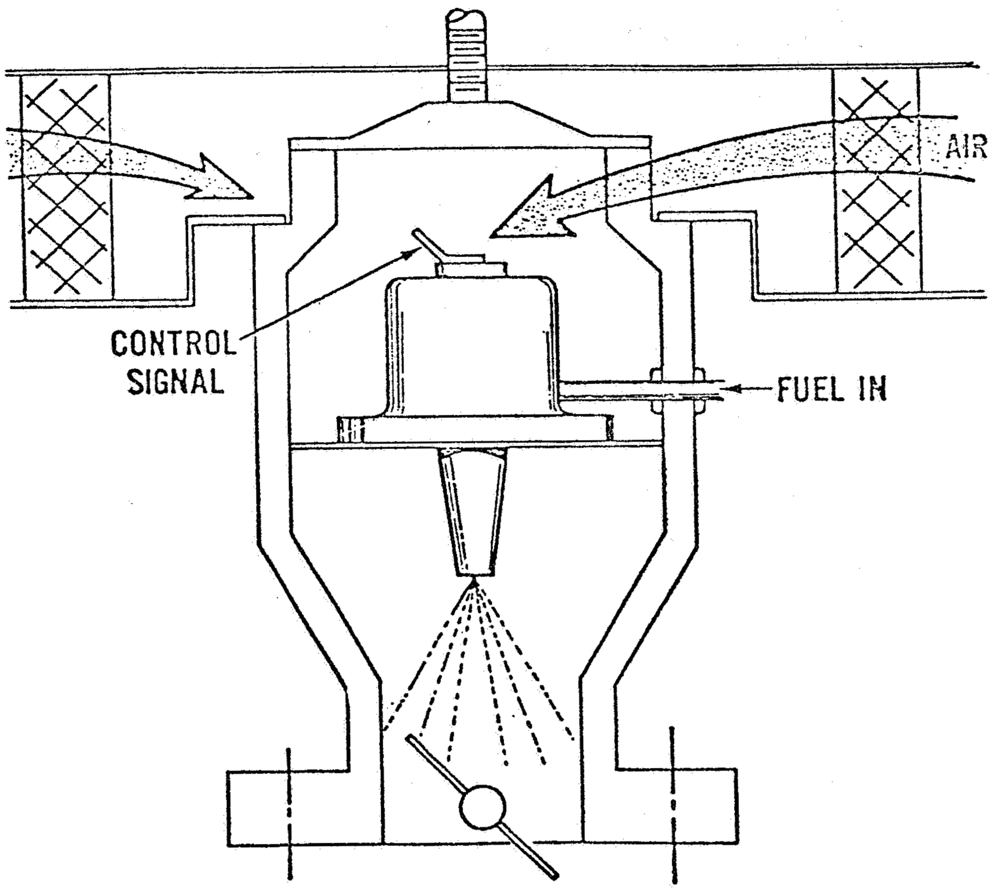


Figure 2-1



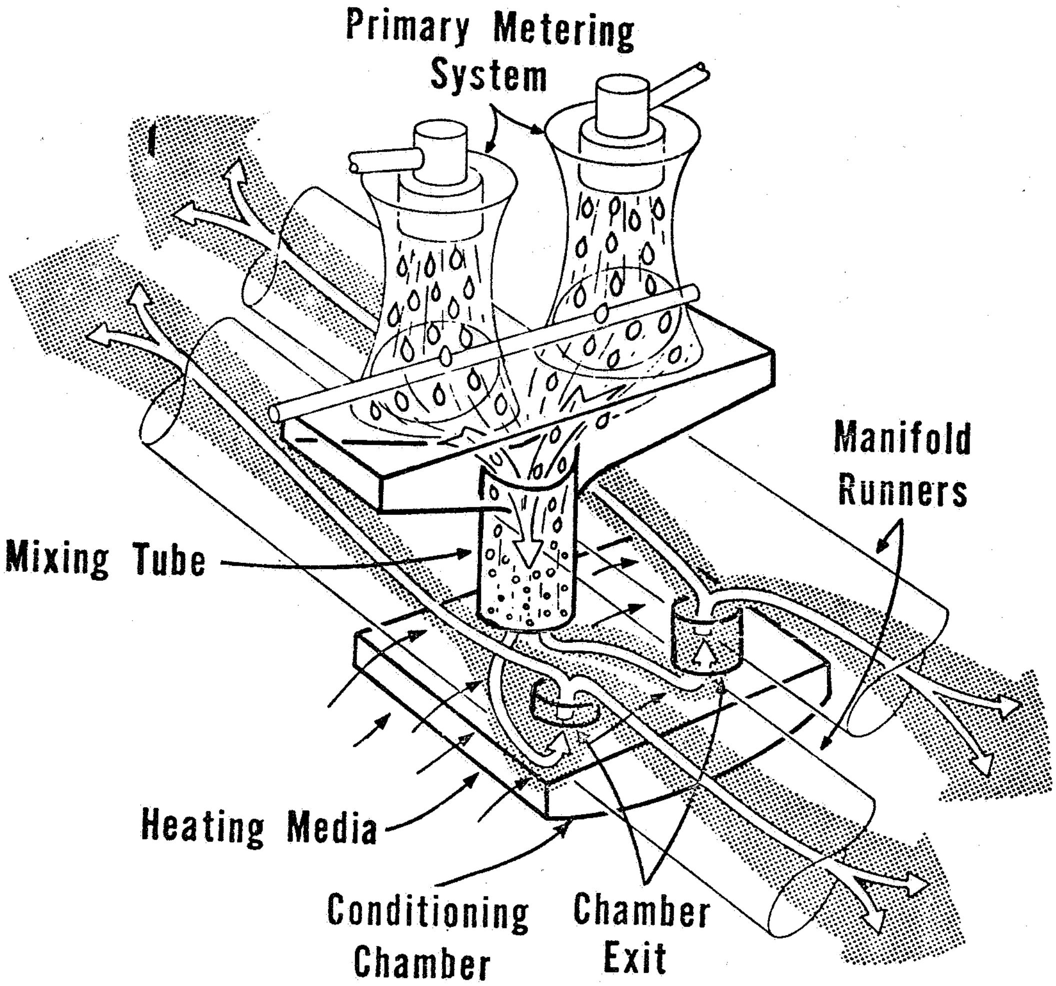
Sonic Fuel Metering

Figure 2-2



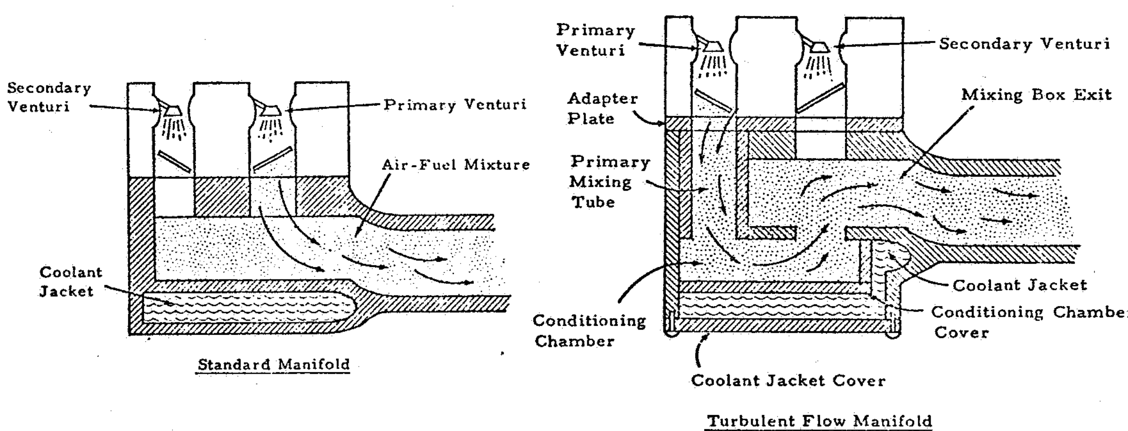
Single Point Injection

Figure 2-3



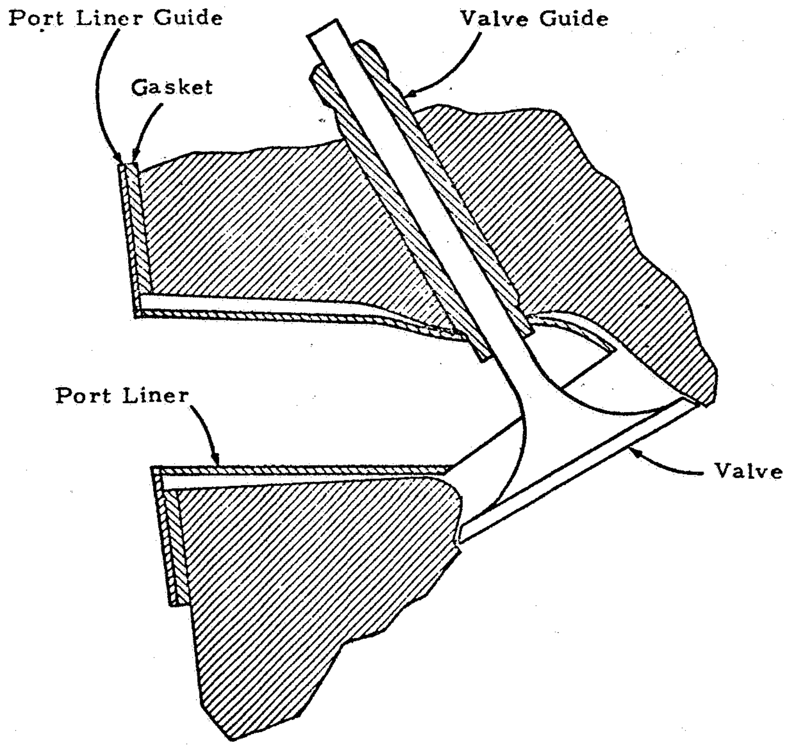
Turbulent Flow System (TFS)

Figure 2-4



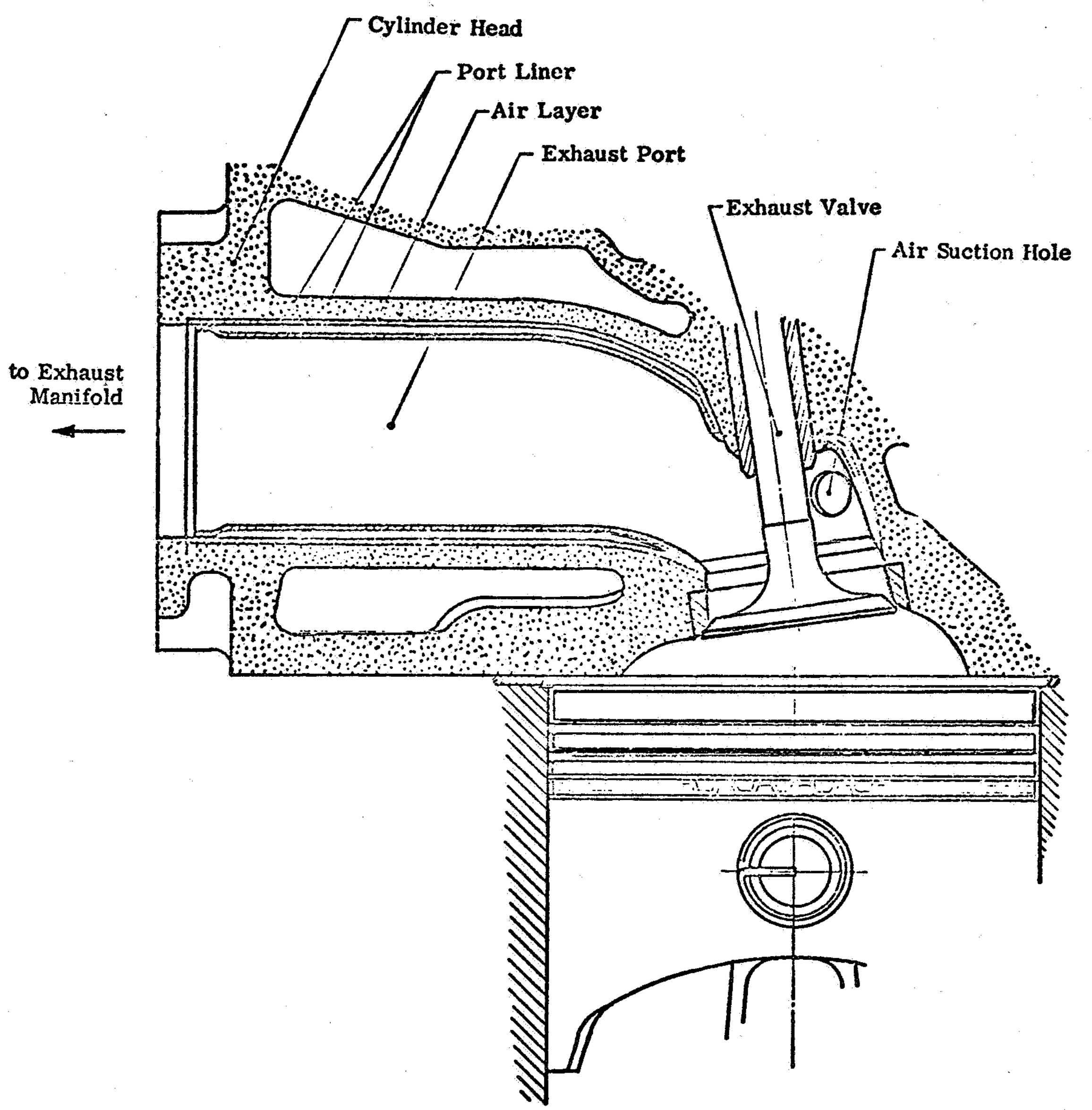
Comparison of TFS with standard manifold

Figure 2-5



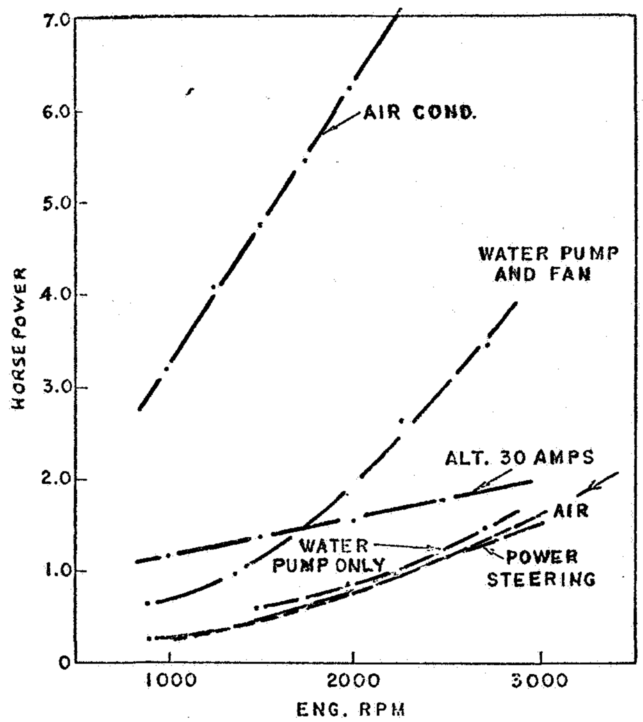
Exhaust Port Liner

Figure 2-6



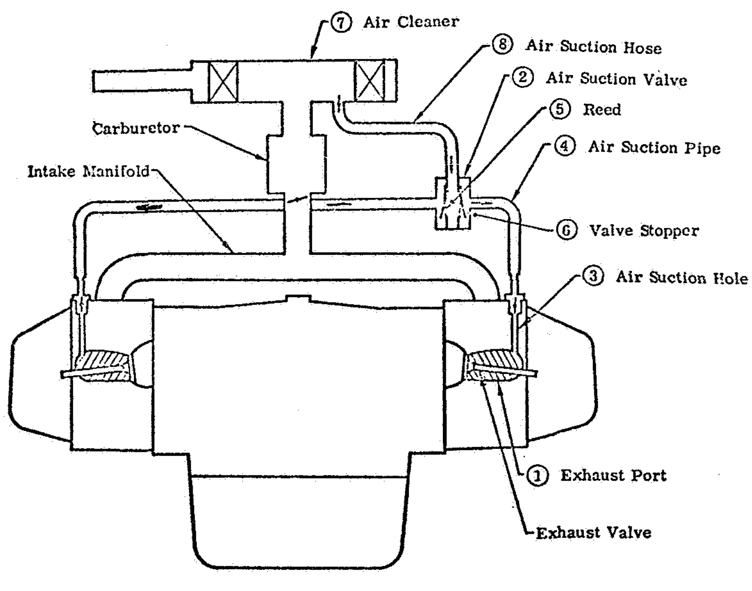
Exhaust Port Liner

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

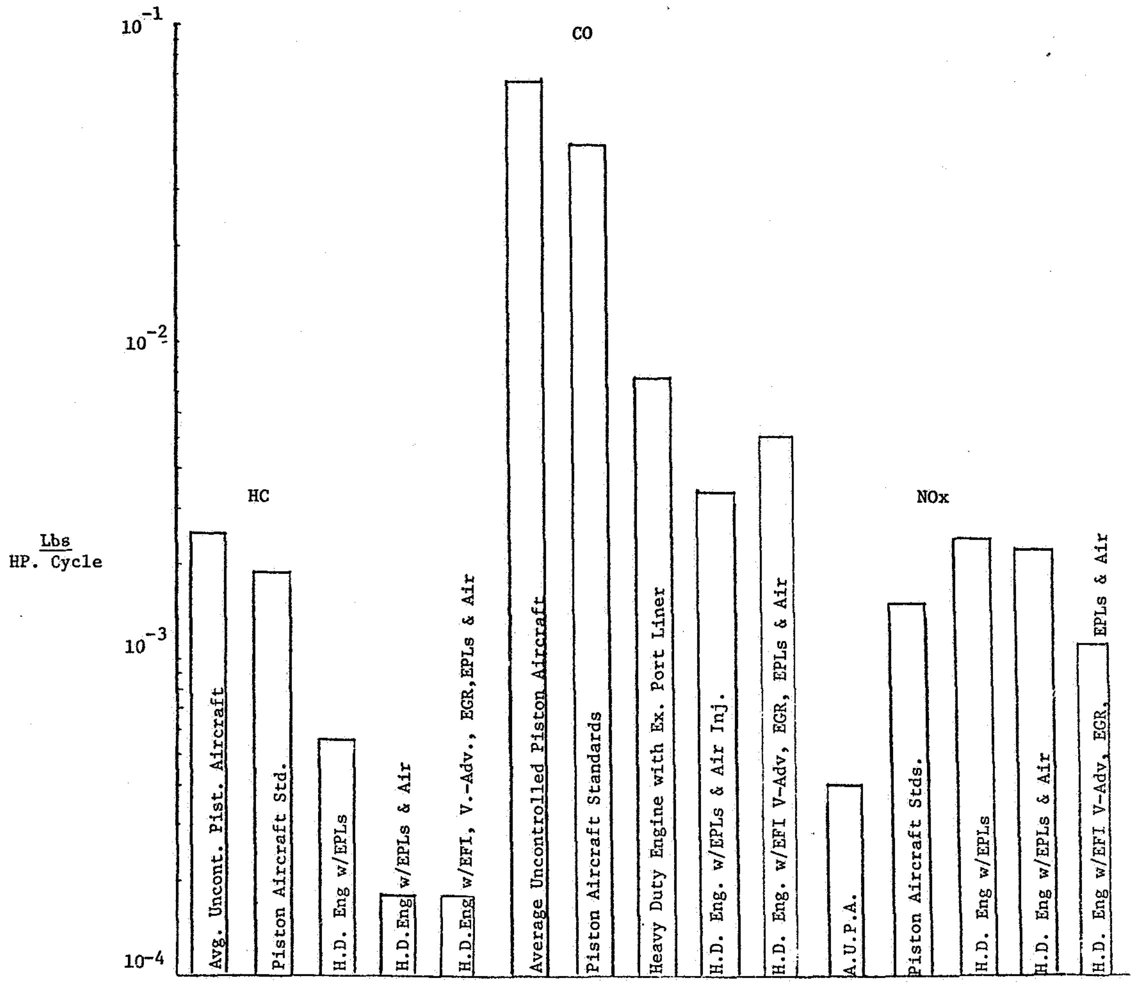


Figure 2-10