EPA-AA-SDSB 79-17

Technical Report

Evaluation of HC Control Strategies for General Aviation Piston Engines

by

Richard S. Wilcox

July 1979

NOTICE

Technical Reports do not necessarily represent final EPA decisions or positions. They are intended to present technical analysis of issues using data which are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position or regulatory action.

Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air and Waste Management
U.S. Environmental Protection Agency

I. INTRODUCTION

In support of the current final rulemaking action for aircraft emission standards, the cost effectiveness of controlling hydrocarbon (HC) exhaust emissions from general aviation piston-powered aircraft (P1) is evaluated. Houtman (1976) previously evaluated the cost effectiveness of controlling this source for HC and carbon monoxide (CO). Recent analyses by Jordan (1977) and FAA (1978) have indicated that these aircraft are not major contributors to violations of the National Ambient Air Quality Standard for CO which adversely affect the public health and welfare.

Although HC emissions from general aviation are also small when compared to many other sources, the oxidant problem is so widespread that all reasonable controls should be implemented. Based on this premise, several potentially cost-effective control strategies for these aircraft are evaluated to determine if reductions in HC from general aviation piston-powered aircraft are justified.

II. DISCUSSION

A. Cost Effectiveness

To determine the most cost efficient means of meeting and maintaining the National Ambient Air Quality Standards (NAAQS), potential control strategies are evaluated on the basis of their relative cost effectiveness, i.e., the monetary cost of preventing one ton of emissions. Unfortunately, cost-effectiveness analyses have some associated uncertainties. For example, the point at which a control strategy is not considered to be cost effective has never been precisely defined. Also, when future control strategies are being evaluated, it is important to remember that as the most efficient controls are implemented, each succeeding control increment will have a higher marginal cost. Because of this expected price increase, it is not necessarily correct to make decisions with regard to a potential control strategy by comparing its cost effectiveness to that of other past or presently considered strategies.

These kinds of limitations prevent cost-effectiveness analyses from being used as an absolute decision making device in every instance. Cost effectiveness is most appropriately employed in decision making along with other information. It is also useful, however, as a screening mechanism to eliminate those control strategies whose cost effectiveness is not within the range of values that are generally accepted to be cost efficient.

In this analysis, cost-effectiveness comparisons are used as a screening mechanism. Therefore, a decision will be made to further evaluate HC emission controls for general aviation piston-powered aircraft, only if the cost effectiveness of these controls is reasonably within the range of values for other strategies which are currently being seriously considered. As shown in Table 1, current cost-effectiveness values range up to about $950.

Most of the cost-effectiveness figures contained in Table 1 are based on annual costs. Therefore, to maintain the greatest degree of comparability between those figures and the figures derived in this analysis, the costs of controlling exhaust emissions from general aviation aircraft are annualized. Also, the cost-effectiveness figures contained in Table 1, and the costs which are used throughout this study, are based on 1978 dollars.

The following formula is used to determine the cost-effectiveness values for the control concepts which are reviewed in this analysis.

$$\text{Cost Effectiveness} = \frac{(C_i R_f) + (L_t F_i C_f) + M_i}{P_r L_t}$$

Where: C_i = incremental cost to the consumer;

R_f = capital recovery factor based on 10% interest per annum and 20 year useful life;

L_t = landing and takeoff cycles (LTO's) per year (250);

F_i = increment in fuel consumption in gallons per LTO;

C_f = price per gallon of aviation fuel ($0.97/gal);

P_r = pollutant reduction per LTO; and

M_i = annual maintenance increment.

All of the control costs are attributed to HC since it is the only pollutant being considered for regulation in this study.

B. Baseline Exhaust Emissions

The present standards (promulgated in 1973) were directed predominantly at controlling CO; therefore, the HC standard was set by EPA at a lenient level to preclude HC-CO tradeoffs by some possible control technologies. A review of the baseline (uncontrolled) emissions from these aircraft found that the fleet-weighted average emissions were the same as the present standard of

Table 1

Cost Effectiveness of Strategies for HC Control (1978 Dollars)

Control Strategy with Control Increment	Cost Effectiveness $/Ton	
Degreasing 0-40%	-230	a/
Gravure 0-98%	-60	a/
Gas Terminal 0-67%	0	a/
Acrylonitrile 0-35%	0	a/
Polyethylene 0-95%	0	a/
Charcoal 0-99%	0	a/
Miscellaneous Chemicals 0-35%	0	a/
Dry Cleaning 0-80%	10	a/
Industrial Finishing 0-75%	10	a/
Carbon Black 0-95%	10	a/
Formaldehyde 0-95%	20	a/
Refining 0-67%	10	a/
Arch. Coatings 0-100%	20	a/
GHDV Evap. 5.8-0.5 gm/mi	20	a/ b/
Open Burning 0-25%	20	a/
Ethylene Oxide 0-95%	20	a/
Acrylonitrile 36-99%	40	a/
Ethylene Dichloride 0-95%	40	a/
Paint & Varnish 0-70%	60	a/
Degreasing 41-90%	100	a/
Industrial Finishing 76-97%	110	a/
Gasoline Handling 16-50%	110	a/
Cyclohexanone 0-95%	140	a/
Metal Decorating 0-90%	160	a/
Miscellaneous Chemicals 35-53%	220	a/
Gasoline Distribution 67-99%	300	a/
Coke Ovens 0-80%	490	a/
LDV Exhaust 0.9-0.41 gm/mi	530	a/
Foundries 0-60%	560	a/
Letterpress & Lithography 0-90%	790	a/
Gas Handling 51-91%	780	a/ c/
HDV Gas 90% of baseline	300	d/
HDV Diesel 90% of baseline	162	d/
LDV I/M	955	e/
LDT 1.7-0.8 gm/mi	139-201	f/

---

a/ DOT (1976).

b/ A more recent EPA analysis which supports a regulation yet to be published as a proposal, yields numbers in the range of $70 to $250 per ton.

c/ Agrees reasonably well with a more recent EPA analysis.

d/ EPA (1978).

e/ EPA (1979a).

f/ EPA (1979b).

0.0019 HC lbm/ rated power/cycle. Therefore, the level of control must be more stringent to effectively reduce HC emissions from this source.

The fleet-weighted baseline exhaust emissions per LTO cycle are shown in Table 2.

C. Control Strategies Using Fuel Schedule Enleanment

When the present promulgated standards were issued, EPA identified fuel schedule enleanment as the most practical control technology for these airplane engines. As shown in Figure 1, the fuel-air ratio which is necessary to meet the CO standard is below the fuel-air ratio which is required to attain the HC standard. Therefore, by meeting the CO standard, additional reductions in HC were achieved. The most stringent potential HC reduction reviewed in the analysis of fuel enleanment concepts, is the level of HC control that would result if the present CO standard was attained. (The potential HC reductions attributable to each of the control concepts which are reviewed in this analysis are hereafter referred to as "the HC reduction criteria.")

The fleet-weighted reductions in fuel consumption and gaseous emissions for the most stringent enleanment HC reduction criteria are shown in Table 3. Two enleanment concepts are reviewed: fuel metering tolerance reductions and automatic fuel scheduling.

a) Fuel Metering Tolerance Reduction

The simplest and least expensive control concept is to modify the existing fuel system so that the fuel-air mixture of each engine is calibrated at or near the production lean limit. Specifically, this modification would result in reducing the fuel metering orifice tolerances of the carburetor or fuel injectors. FAA recertification of the engine or airframe would not be required. The cost of this modification has been estimated by one engine manufacturer to be $150 to $200 per engine, excluding the cost of engineering and development (Avco 1977). There is no maintenance increment associated with this hardware.

For the purposes of this analysis, the total incremental cost of the hardware to the consumer is $200. It is unlikely that the hardware could be less expensive after amortizing the costs of engineering and development over the expected production volume; therefore, this is considered the "best case" control cost.

The fuel metering tolerance reduction control technique is incapable of fully attaining the most stringent potential HC reduction which has been identified (Table 3). It is, however, capable of a significant reduction in HC, the level of which can be

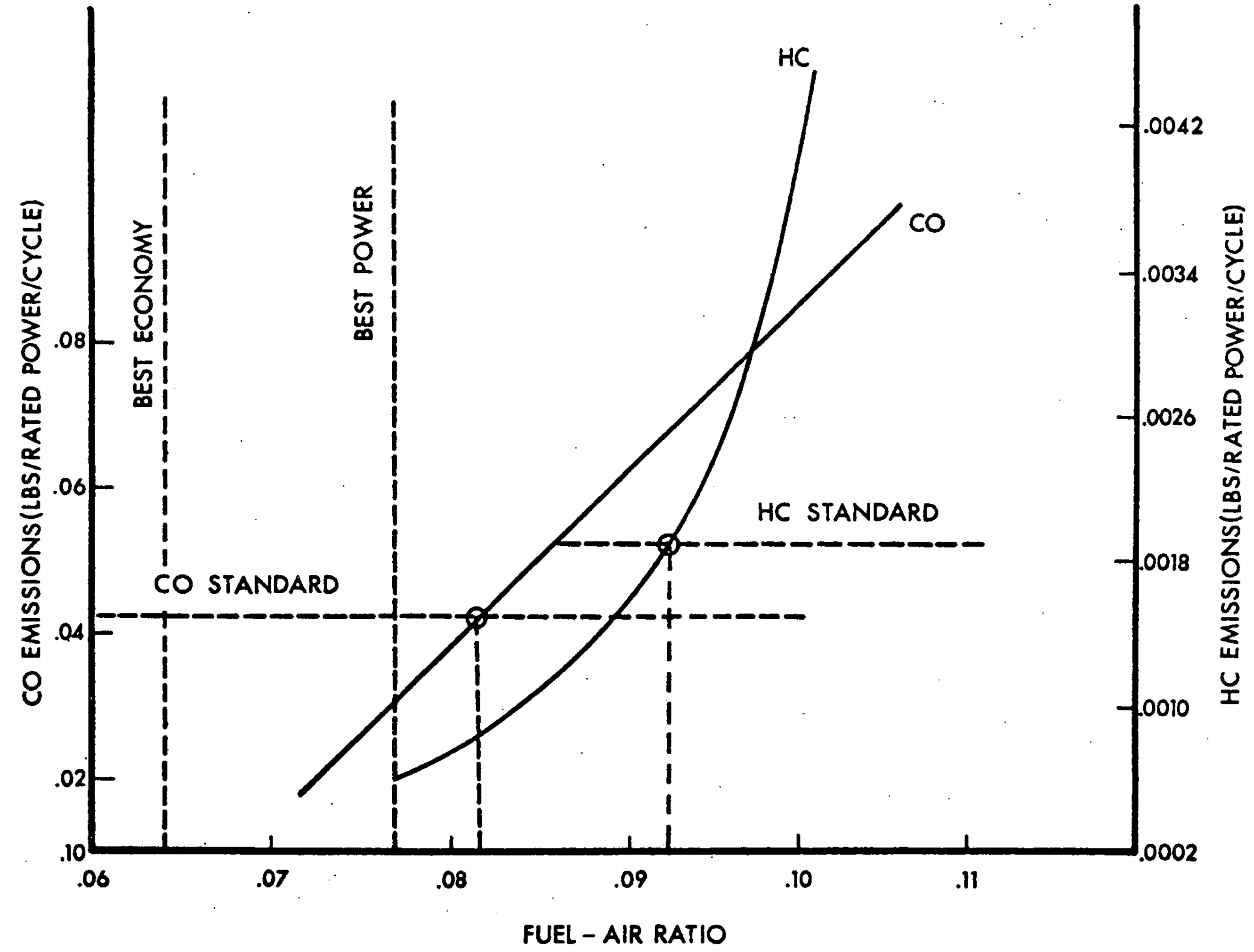
Table 2

Baseline Piston Aircraft Emissions

Engine Model	HC Emissions (lbs/bhp per LTO)	Fraction of Fleet	Weighted HC Emissions
IO-320D	0.00120	0.055	0.00007
IO-360-B	0.00160	0.159	0.00025
O-320-D	0.00159	0.121	0.00019
O-200-A	0.00220	0.285	0.00063
IO-520-D	0.00220	0.129	0.00028
Tiara G 285-B	1.00140	0.141	0.00020
GTSIO-520-K	0.00140	0.072	0.00010
TSIO-360-C	0.00470	0.036	0.00017
Weighted Average			0.00189
Promulgated Standard			0.00190

Source - Data Derived From Deimen (1977).

Figure 1



Source: Houtman 1976.

Table 3

Fleet Weighted Emission Factors (lb/LTO)

	CO	HC	NOx	Fuel
Baseline	15.4	0.32	0.04	0.69
Controlled	8.8	0.21	0.20	0.57
Percent Change	-43%	-34%	+400%	-17%

Source: Houtman (1977).

estimated from information contained in a document prepared by the Avco Corporation (Avco 1977). It is stated that disregarding the obvious variation of the fuel schedules from model to model, the control technique could reduce the baseline CO emissions from the best 0-320 engine tested by 28 percent (from the mean engine setting to the lean limit). As previously stated, enleanment reduces CO and HC together; therefore, for the purposes of this simplified analysis, this same proportion of control is applied to the baseline fleet-weighted average HC emissions.

As shown in Table 3, a 1.0 percentage point reduction in CO corresponds to a 0.79 percentage point change in HC (34/43 = 0.79). Therefore, the 28 percent reduction in CO is equivalent to a 22 percent reduction in baseline HC (28 x 0.79 = 22). Based on Table 3, this would mean a reduction in HC of 0.07 lbm per LTO and a reduction in fuel consumption of 0.08 lbm per LTO. The cost effectiveness is approximately $2,300 per ton of HC reduced. This control technique is not reasonably within the range of costs that have been calculated for other mobile and stationary source control strategies (Table 1).

b) Automatic Fuel Scheduling

Recent information indicates that an engine power control system which automatically schedules the fuel-air ratio may come quite close to achieving the currently promulgated CO standard (Scott 1978). Developed by Woodward Governor Company, Beech Aircraft Company, and Teledyne Continental Motors, the system is referred to as the single lever power control. It has been FAA certified in a Beechcraft Bonanza airframe equipped with a Continental IO-520 engine. Presently, the fuel control is used in conjunction with a constant speed propeller and a continuous fuel injection system. The unit could also be used on turbocharged engines and possibly be adapted to carbureted engines as well (Liseon 1978).

The power control system automatically regulates the fuel schedule above 1500 rpm. During takeoff, the fuel-air ratio is leaned to just slightly rich of "best power." For climbout, the mixture is leaned to "best power," and for approach it is near "best economy." (The corresponding fuel-air ratios for these conditions are shown in Figure 1.) The power control unit also compensates for changes in ambient conditions and altitude.

Industry representatives were unable to state the actual cost of this unit to the consumer. They did comment, however, in the context of statements made previously by Helms (1977) regarding the cost of achieving the current EPA standards. Scott (1978), Liseon (1978), and Norsworth (1978) generally agreed that in limited production quantities, i.e., 500-1000 units, the cost of the single lever power control may be close to or greater than the \$1,500 to \$3,000 as cited by Helms (1977). If the unit were widely used as emission control hardware, there was agreement that the price would be reduced, perhaps by 33 percent.

To evaluate the cost effectiveness of this hardware, the "best possible" emission control case will be examined. Although no emission tests have been conducted (Wilkinson 1978), it is assumed that because the power control unit might nearly achieve the existing CO standard, it will achieve the suggested HC reduction criteria (a 34 percent reduction from baseline emissions). Also it is assumed that if the unit was widely used for pollution control, the incremental cost to the purchaser of a new aircraft would be \$1,000 per engine with no accompanying maintenance penalty.

By using the emission and fuel reduction information contained in Table 3, the cost effectiveness is calculated to be over \$8,000 per ton of HC reduced. This is significantly greater than the currently accepted range of values for other control strategies (Table 1).

D. Other Control Strategies

It has been demonstrated that fuel schedule modifications are not cost effective for reducing HC exhaust emissions alone. A variety of other control techniques for light airplane piston engines have been evaluated by NASA and EPA contractual efforts, and will now be considered.

The two previous examples illustrate that the cost effectiveness of any HC control strategy for this source is very sensitive to the total cost of the system. Therefore, in considering other control techniques, a low cost will be the primary concern. All of the remaining control techniques are able to provide a significant degree of HC control.

a) Air Injection System

Renzy (1976) has ranked various control concepts based on a variety of criteria as shown in Table 4. Air injection ranks first as the least expensive, and since it is also known to be very effective in reducing HC emissions from piston engines, it will be evaluated for its cost effectiveness. It should also be pointed out that air injection was ranked fourth in overall utility as a control concept (Table 5).

Air injection exhaust after treatment has been well defined as an automotive emission control device. It works by injecting air into the engine exhaust port which, as it mixes with the hot exhaust, oxidizes a portion of the HC and CO remaining in the exhaust stream. The additional air is typically supplied by an engine-driven air pump.

Table 4

Concept Rank Ordering Versus Criteria Importance

Criteria

	Dominant							Secondary				Minor			
	EMISSIONS	SAFETY	PERFORMANCE	COOLING	WEIGHT & 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	5	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

* Not considered an HC control concept in this analysis.

Source: Rezy (1976).

Table 5

Concept Ranking for Emissions

Rank	Concept
1	Hydrogen Enrichment, JPL
2	Honda CVCC
3	Improved Fuel Injection Systems
4	Air Injection
5	Texaco CCS
6	Ford Proco
7	2-Stroke Diesel, McCulloch a/
8	4-Stroke Diesel, Open Chamber
9	Improved Cooling Combustion Chamber a/
10	Variable Camshaft Timing
11	Thermal Fuel Vaporization, Ethyl
12	Ultrasonic Fuel Atomization, Autotronic
13	Variable Timing System a/
14	Multiple Spark Discharge System a/

---

a/ Not considered an HC control technique in this analysis.

Source: Rezy (1976).

Air injection systems were considered to be a potential control technology at the time Federal emission standards for this source were originally proposed. Bendix (EPA 1973) evaluated this concept on a Continental 0-200 engine and concluded that it could meet or exceed the Federal standard for HC and CO emissions. Areas in which further development work was necessary were also identified.

Unlike automotive engines, aircraft piston engines use fuel-air mixtures which are much richer than stoichiometric over most of the flight regime. This means that the exhaust from these engines contains a large quantity of potential energy in the form of HC and CO. Under some conditions, if too much air is injected into the exhaust, overheating of the exhaust manifold could result in its failure. This problem can be alleviated by correctly sizing the injection air flow and installing a thermal sensor to prevent overheating. Under normal operating conditions, the added heat from the exhaust may adversely affect engine cooling. This may require double-wall construction of the exhaust system or a redesign of the engine cooling shroud. It is expected that the air injection pump will fit into the existing engine cowling configuration, however.

Specific HC emission reduction figures for this control concept have been reported by Bendix (EPA 1973) and Renzy (1977) which are based on actual engine tests. Bendix (EPA 1973) tested a Continental 0-200 engine and found that the HC emissions were 67 percent below the existing Federal standard. It was also pointed out that because of the abnormally long residence time of the exhaust before it was sampled, the HC reduction was somewhat inflated. Renzy (1976) tested a Continental 0-200 and applied the results to Continental IO-520-D. For this engine, HC emissions were 35 percent below the standard.

For the purposes of this simplified analysis, a "best case" condition is considered where injection reduces the fleet-weighted HC emissions to a level between the values reported by Bendix (EPA 1973) and Renzy (1977). Hence, the reduction criteria is assumed to be 50 percent of the existing HC Federal standard. Since it has already been demonstrated that the fleet-weighted baseline HC emissions are equivalent to the existing Federal standard (Table 2), the assumed reduction criteria can be directly applied to these baseline values. Therefore, a reduction of 0.16 lbm of HC per LTO is used in the cost-effectiveness formula.

The literature which was reviewed as part of this analysis contained only one reference to the cost of installing an air injection system on an aircraft piston engine. Northern Research (1971) reported that the new engine price increment would be $200. This price may seem somewhat high when current automotive experience is considered as a benchmark. In a document prepared for the

EPA (Lindgren 1978), the price of an automotive air injection system is $32.

There are several factors which would increase the system price for a light piston aircraft. These include: 1) higher pass-through costs since more corporate entities are involved (i.e., a minimum of hardware, engine, and airframe manufacturers); 2) FAA certification costs for the engine and airframe; 3) development costs for a larger number of engine families; 4) a lower economic volume over which to amortize nonrecurring expenses; and 5) added costs due to additional cooling and over temperature safety control considerations. If the above factors are considered, a cost of $200, in 1978 dollars, does not appear to be unreasonable.

Other costs will be incurred by this control technique throughout its useful life in addition to the first cost. Although automotive air injection systems do not require maintenance during the useful life of the car (5 years or 50,000 miles), it is conceivable that some direct and indirect maintenance will be required by the aircraft system because its useful life is much longer (20 years). Operating the air injection system will also increase fuel consumption slightly by absorbing a small amount of horsepower from the engine to drive the pump. Northern Research (1971) estimated that these costs would average a total of $30 per year. This cost is equivalent to about $45 in 1978 dollars.

The cost effectiveness of the air injection system can now be calculated by inserting into the formula: (1) $200 as the incremental cost to the consumer, and (2) a yearly expenditure of $45 for added maintenance and increased fuel consumption. This control concept requires $3,000 to reduce one ton of HC; it is much more expensive than any cost-effectiveness value that has been calculated for other control strategies (Table 1).

E. Remaining Concepts

Since air injection has a very high cost-effectiveness value and it is ranked as the least costly control concept (Table 4), as well as one of the better HC emission reduction techniques (Table 5), all other potential control concepts can be eliminated from further consideration since they will be even less cost effective.

III. SUMMARY AND CONCLUSION

The cost effectiveness of alternative strategies for controlling HC exhaust emissions from piston-powered aircraft ranges from $2,300 to $8,000 per ton. These values were based primarily on industry supplied data. Although EPA considers the cost information to be reasonably representative, the actual expense of pollution control may be somewhat lower if a rigorous independent analysis were made. The costs, however, would have to be significantly reduced to bring the cost-effectiveness values for these aircraft within the range of other implemented or planned control strategies. A reduction of that size seems unlikely based on the information which is currently available. Therefore, controlling the HC emissions from piston-powered aircraft is not considered to be cost effective at this time. In the future, however, as the marginal costs of controlling air pollution increase, this source may again be considered for control.

IV. REFERENCES

Avco Corporation. 1977. The Past Development and Future Development of the Avco Lycoming Aircraft Piston Engines for Reductions in Exhaust Emissions. Avco Lycoming Williamsport Division, Williamsport, Pa.

Bastress, E.K., R.C. Baker, C.F. Robertson, R.D. Siegal, and G.E. Smith. 1971. Assessment of Aircraft Emission Control Technology. Northern Research and Engineering Corporation. Report No. 1168-1. EPA Contract No. 68-04-0011.

Datwyler, W.F., A. Blatter, and S.T. Hassan. 1973. Control of Emissions from Light Piston-Engine Aircraft. The Bendix Corporation. EPA Report No. APTD-1521.

Deimen, J.M. 1977. Aircraft Emissions at Selected Airports 1972-1985. TSR AC77-01. Emission Control Technology Division, EPA, Ann Arbor, MI.

Department of Transporation, Interagency Task Force on Motor Vehicle Goals Beyond 1980. 1976. Air Quality, Noise and Health.

Environmental Protection Agency. 1978. Proposed Gaseous Emission Regulations for 1983 and Later Model Year Heavy-Duty Engines: Draft Regulatory Analysis. Emission Control Technology Division, EPA, Ann Arbor, MI.

______________. 1979a. Cost Effectiveness of Portland I/M Program. Memo from Catherine O'Rourke to Janet Becker. Emission Control Technology Division, EPA, Ann Arbor, MI.

______________. 1979b. Gaseous Emission Regulations for 1983 and Later Model Year Light-Duty Trucks. F.R. 44(135): 40784-40839.

Federal Aviation Administration. 1978. General Aviation emission measurements at Lakeland, Florida. Memo from Chief, High Altitude Pollution Staff, FAA, to Director, Environmental Quality.

Helms, J.L. 1976. Summary of the General Aviation Manufacturers' Position on Aircraft Piston Engine Emissions. Presented at the 1976 Aircraft Piston Engine Exhaust Emission Symposium, NASA Lewis Research Center. NASA CP-2005.

Houtman, W.H. 1976. Development of EPA Aircraft Piston Engine Emission Standards. Presented at the 1976 Aircraft Piston Engine Exhaust Emission Symposium, NASA Lewis Research Center. NASA CP-2005.

IV. REFERENCES (cont'd)

______________. 1977. Reevaluation of the Need for Aircraft Piston Engine Emission Standards. TSR AC77-03. Emission Control Technology Division, EPA, Ann Arbor, MI.

Jordan, B. C. 1977. An Assessment of the Potential Air Quality Impact of General Aviation Emissions. Office of Air Quality Planning and Standards, EPA, Research Triangle Park, N.C.

Lieson, P. Woodward Governor Company. 1979. Telephone Communication with R. S. Wilcox, Emission Control Technology Division, EPA, Ann Arbor, MI.

Norsworthy, J. Woodward Governor Company. 1979. Telephone Communication with R. S. Wilcox, Emission Control Technology Division, EPA, Ann Arbor, MI.

Rezy, B. 1976. TMC Aircraft Piston Engine Emission Reduction Program. Presented at the 1976 Aircraft Piston Engine Exhaust Emission Symposium, NASA Lewis Research Center. NASA CP-2005.

Scott, O. W. Beech Aircraft Corporation. 1979. Telephone communication with R. S. Wilcox, Emission Control Technology Division, EPA, Ann Arbor, MI.