A STUDY OF EXHAUST EMISSIONS FROM RECIPROCATING AIRCRAFT POWER PLANTS

Prepared for

AIR POLLUTION CONTROL OFFICE
ENVIRONMENTAL PROTECTION AGENCY

SCOTT RESEARCH LABORATORIES, INC.
P. O. BOX D-11
PLUMSTEADVILLE, PENNSYLVANIA 18949

A Study Of Exhaust Emissions From Reciprocating Aircraft Power Plants

APCO (Formerly NAPCA) Project CPA 22-69-129
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Prepared for

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Division of Motor Vehicle Research & Development
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5 Research Drive
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SCOTT RESEARCH LABORATORIES, INC.
P. O. Box D-11
Plumsteadville, Pennsylvania 18949

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SUMMARY

Under contract with the Air Pollution Control Office (formerly National Air Pollution Control Administration), Scott Research Laboratories has documented the exhaust emissions of light, piston engine aircraft and investigated the phenomena of natural afterburning of the exhaust gases on contact with the ambient air. The approach used in this study was to measure the exhaust emissions of representative aircraft as they were flown in a normal manner. At the same time, the extent of afterburning was measured by sampling the exhaust plume downstream of the exhaust stack and comparing the plume composition, corrected for dilution, to the composition of the stack gases.

The exhaust emissions from nine light aircraft were determined using a 9-mode takeoff-cruise-landing (TCL) cycle developed for this study. Exhaust component concentrations and fuel consumption rates were measured for each mode during ten test flights per aircraft. The pollutant concentrations were converted to emission rates per pound of fuel, per minute, per mode, per TCL cycle, and per landing-takeoff (LTO) cycle. A summary of light aircraft emissions is given below.

Summary of Emissions from Nine Light Aircraft

Rate Parameter	CO	CO_2	Total HC (as hexane)	NO_x (as NO_2)
Pounds per Pound of Fuel	0.847	1.74	0.0210	0.0102
Pounds per Minute	0.614	1.27	0.0152	0.0074
Pounds per TCL cycle	21.0	43.3	0.520	0.254
Pounds per LTO cycle	14.1	25.5	0.431	0.128

The rich mixtures employed during most operations resulted in incomplete combustion as demonstrated by the high ratio of carbon monoxide to carbon dioxide recorded. During lean cruise operation carbon monoxide and hydrocarbons were substantially lower and nitrogen oxides were much higher than at the normal rich mixture operation. The difference in exhaust composition from one rich mode to another was small.

The fuel injected engines tested emitted much higher concentrations of hydrocarbons than the normally aspirated engines. Exhaust composition differences due to engine age, size and airframe design were minor.

No afterburning of exhaust carbon monoxide and hydrocarbons was found for any of the test aircraft at any mode. Apparently the exhaust temperatures at the stack exit were too low for burning to occur. Means for enhancing afterburning are discussed. The application of automobile exhaust reactors to light aircraft is considered, and design problems which must be solved are noted.

1.0 INTRODUCTION

This report describes the work performed by Scott Research Laboratories, Inc. on the Air Pollution Control Office's project, "A Study Of Exhaust Emissions From Reciprocating Aircraft Power Plants" (Contract No. CPA-22-69-129). This project was sponsored by the Division of Motor Vehicle Research and Development of the Air Pollution Control Office.

1.1 PROJECT OBJECTIVES

The general objective of the contract was to study the exhaust emissions of light utility, piston engine aircraft. The specific objectives of the study were:

1. Document the emissions of carbon monoxide, hydrocarbons and nitrogen oxides from light aircraft under typical use conditions.
2. Determine the extent of natural afterburning in the emitted exhaust and consider means of increasing the extent of afterburning under typical use conditions.
3. Reach conclusions regarding the potential usefulness of exhaust system reactors in general, and the need for alternative methods for reducing carbon monoxide and organic gases emitted by light aircraft.

The general approach used in reaching these objectives consisted of monitoring the exhaust constituents of representative aircraft as they were flown in a normal manner. This approach was used because simulation of normal flight in a test cell was considered extremely difficult.

1.2 OUTLINE OF REPORT

This report has been organized into six sections following the introduction.

Section 2 supplies the background to this study.

Section 3 describes the aircraft tested during this study and the reasons for their selection.

Section 4 describes the equipment and methodology used in conducting this study.

Section 5 presents the results of the study.

Section 6 discusses the results and presents the conclusions and recommendations.

The report concludes with references in Section 7 and an appendix of data collected during test operations.

2.0 BACKGROUND

Atmospheric contaminants emitted by aircraft constitute a small but significant contribution to air pollution in the form of carbon monoxide, nitrogen oxides, particulates and various organic compounds. These are basically the same pollutants as those emitted by highway vehicles. In 1965 a study by the Los Angeles County Air Pollution Control District found that non-military aircraft were responsible for between one and two percent of all organic gases, carbon monoxide, and oxides of nitrogen, and approximately ten percent of all aerosols emitted in Los Angeles County.[1] The nationwide figures[2] indicate that civil aircraft were responsible for about one percent of all organic gases and carbon monoxide emitted in the United States. This percentage will increase, however, as controls are tightened on other pollution sources and the aircraft population increases. The development of high speed aircraft with greater fuel consumption rates will also increase this percentage.

A great deal of attention has been given to the emissions of large turbojet engines. This is due to their optically dense plume, characteristic odor and their concentration around major air terminals. The turbojet aircraft are generally large, multi-engined commercial aircraft. Several programs are underway to determine the amount and type of emissions from turbojets and the best way to reduce the quantities emitted.

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1. Page 1 of Ref. 1
2. Table 43, page 283, Ref. 2

The general aviation category of aircraft, however, consists primarily of light, piston engine aircraft. They are large in number and relatively dispersed across the country. The emissions of this type of aircraft have not been well documented, particularly the emissions under true flight conditions. These aircraft engines are very similar to automobile engines in their manner of operation. The basic element is the combustion chamber in which fuel and air mixtures are burned and from which energy is extracted through a piston and crank mechanism that drives a propeller. Nearly all aircraft piston engines have two or more cylinders and are generally classified according to their cylinder arrangement. The arrangement in general use is the opposed configuration. Some radial engines are still in use in older large transport aircraft.

All of the emission control techniques applicable to automobile engines are applicable, in principle, to aircraft piston engines. However, the techniques vary widely in their practicability. Some reduction in emissions from piston engined aircraft was believed to occur as a result of natural afterburning of hot exhaust gases as they enter the atmosphere. Natural afterburning would reduce the amount of carbon monoxide, organic gases and perhaps carbonaceous particulates emitted. Little documentation of the existence and effect of this afterburning can be found. The enhancement of afterburning is potentially a simple, effective means of reducing emissions from aircraft piston engines.

3.0 DESCRIPTION OF TEST AIRCRAFT

Aircraft tested under this contract were selected to represent typical engines, exhaust system geometries and airframes found in the present light aircraft population. From talks with consultants, aircraft dealers, pilots and engine manufacturers, it was determined that the engines in the present population were almost exclusively of horizontal, opposed cylinder configuration, with four or six cylinders. It was also determined that most of the engines had a single exhaust stack, and the most popular airframe was a single-engine monoplane with fixed tricycle landing gear.

The characteristics of the test aircraft are summarized in Table 3-1. All the engines in these aircraft had a horizontal, opposed cylinder configuration. These aircraft were selected so that they could be grouped in various ways to show the effect of certain variables on exhaust emissions and afterburning:

1. Engine Operating Time - The effect of total engine operating time was studied by testing a group of three Cessna 172's with four cyclinder engines and a group of two Cessna 182's with six cylinder engines.
2. Airframe Design - The effect of airframe design was investigated by comparison of a Piper PA-23, a low wing, twin-engined aircraft with retractable landing gear, with a Cessna 172, a high wing, monoplane with a fixed tricycle landing gear. Both aircraft were powered by similar engines.

AIRCRAFT				ENGINE INFORMATION							
Test No.	Manufacturer	Model	Reg. No.	Manufacturer	Model	No. of Cylinders	Engine Operation Time	HP	Propeller Type	Fuel-Air System	Exhaust System
1	Cessna	Skyhawk 172K	N78658	Lycoming	0-320-E2D	4	140 Hrs.	150	Fixed Pitch	Normal Aspiration	Single Stack
2	Cessna	Skyhawk 172D	N2360U	Continental	0-300-D	6	295 Hrs.	145	Fixed Pitch	Normal Aspiration	Dual Stack
3	Cessna	Skyhawk 172I	N8410L	Lycoming	0-320-E2D	4	672 Hrs.	150	Fixed Pitch	Normal Aspiration	Single Stack
4	Cessna	Skyhawk 172K	N7048G	Lycoming	0-320-E2D	4	105 Hrs.	150	Fixed Pitch	Normal Aspiration	Single Stack
5	Beechcraft	Bonanza 36	N1697A	Continental	IO-520-B	6	334 Hrs.	285	Variable Pitch	Fuel Injected	Dual Stack
6	Cessna	Skylane 182H	N1976X	Continental	0-470-R	6	1053 Hrs.	230	Variable Pitch	Normal Aspiration	Single Stack
7	Cessna	Skylane 182N	N92687	Continental	0-470-R	6	53 Hrs.	230	Variable Pitch	Normal Aspiration	Single Stack
8	Piper	Apache PA-23	N1314P	Lycoming	0-320-A	4	423 Hrs.	150	Variable Pitch	Normal Aspiration	Single Stack
9	Cessna	Centurion T210F	N6739R	Continental	TS-520-C	6	900 Hrs.	285	Variable Pitch	Turbo-chgd. & Fuel Inj.	Single Stack

Table 3-1. Characteristics of Test Aircraft

3. Engine Design Variables - Common engine design variations were represented by the Beechcraft Bonanza 36 with fuel injection, the turbocharged Cessna 210 with fuel injection, and the Cessna 182 with natural carburetion. A supercharged aircraft was not tested because they are relatively rare. Supercharging has been replaced almost entirely by turbocharging in the newer aircraft.

4. Exhaust System Geometry - Exhaust geometries represented included the six cylinder Cessna 172 with a dual exhaust, the Piper PA-23 with a venturi-ejector exhaust and the Cessna 172 and 182 with the more common single exhaust stack.

The fuel used by all the aircraft except #5 and #9 was 80 octane. The fuel injected aircraft used 100 octane fuel. The specifications for both these fuels are presented in Table 3-2.

The aircraft tested were obtained from three local aircraft dealers and air taxi operators. The aircraft available from these sources were well maintained and inspected every 100 operating hours.

The aircraft selected for this program represented 68.5% of the eligible* aircraft in the national population based upon FAA categories presented in Reference 5. The only major class not represented was the small (one to three place) aircraft because of limited room for our instrumentation. Table 3-3 presents the FAA categories, the number of aircraft in each category, and the aircraft tested in each category.

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* Aircraft that are both registered and carry a valid airworthiness certificate.

Table 3-2. Specifications for Aviation Gasolines

(ASTM D910-70)

	Grade 80-87	Grade 100-130
Knock value, min, octane number, lean rating	80	100
Knock value, min, octane number, rich rating	87	Isooctane plus 1.28 ml of tetraethyllead per gallon
Color	Red	Green
Dye content:		
Permissible blue dye, max, mg per gal	0.5	4.7
Permissible yellow dye, max, mg per gal	none	7.0
Permissible red dye, max, mg per gal	8.65	none
Tetraethyllead, max, ml per gal	0.5	3.0
Net heat of combustion, min, Btu per lb	18 720	18 720

Requirements for All Grades	
Distillation temperature, deg F	
10 per cent evaporated, max	158
50 per cent evaporated, max	221
90 per cent evaporated, min	212
90 per cent evaporated, max	257
Final boiling point, max, deg F	338
Sum of 10 and 50 per cent evaporated temperatures, min, deg F	307
Distillation recovery, min, per cent	97
Distillation residue, max, per cent	1.5
Distillation loss, max, per cent	1.5
Acidity of distillation residue	Shall not be acid
Vapor pressure, max, lb	7.0
Potential gum (5 hr aging gum), max, mg per 100 ml	6
Visible lead precipitate, max, mg per 100 ml	3
Sulfur, max, per cent	0.05
Freezing point, max, deg F (deg C)	- 72 (-58)
Water tolerance	Volume change not to exceed ± 2 ml
Permissible antioxidants, max, lb per 1000 bbl (42 gal)	4.2

Table 3-3. United States light aircraft population as categorized by the FAA.

FAA Category (by total rated engine takeoff power)	Eligible Aircraft*	Aircraft Tested
Single Engine		
100 hp and less	28,262	
101-200 hp	47,018	Cessna 172
201-350 hp	31,231	Cessna 182, 210 & Beechcraft 36
351-500 hp	1,328	
501-700 hp	559	
over 700 hp	235	
2 - Engine		
500 hp and less	5,533	Piper Apache
501-800 hp	8,220	
Total	122,386	

* Aircraft that are both registered and carry a valid airworthiness certificate.

4.0 TEST EQUIPMENT AND PROCEDURES

In order to accomplish the objective of the study, it was necessary to monitor the concentration of carbon monoxide, hydrocarbons and nitrogen oxides in the exhaust stack and the concentrations of carbon monoxide and hydrocarbons in the exhaust plume after any afterburning had occurred. Ideally, all monitoring should be done by an analytical instrument system installed in the aircraft. Since this was not practical because of weight, volume and power constraints, an optimal combination of a limited analytical system in the aircraft for continuous analysis of the stack samples and laboratory analysis of the dilute exhaust plume sample was used. Table 4-1 summarizes the analytical techniques used in this study.

Table 4-1

Analytical Techniques For Aircraft Exhaust

Compound(s)	Method Used for Stack Samples	Method Used for Plume Samples
Carbon Monoxide	Continuous Infrared Analyzer in aircraft	Gas Chromatography of bag sample in laboratory
Carbon Dioxide	Continuous Infrared Analyzer in aircraft	Gas Chromatography of bag sample in laboratory
Total Hydrocarbons	Continuous Flame Ionization Detector in aircraft	Bag sample by Flame Ionization Detector in laboratory
Nitrogen Oxides	Continuous Electrochemical Analyzer in aircraft	

4.1 AIRCRAFT ANALYTICAL INSTRUMENT SYSTEM

The primary considerations in the design of an aircraft analytical instrument system are accuracy, power consumption, weight and volume. Most of the aircraft tested under this contract were light, four place aircraft with minimum baggage space. Since the flight crew consisted of the pilot and an engineer to operate the instrument system, the space available for equipment was limited to the remaining seating and baggage area and had to weigh no more than two people (340 lbs) plus the baggage allowance. The equipment also had to remain operable in an airborne environment with its attendant shock and vibration field, and temperature and altitude variation. The aircraft tested generally had little electrical power available beyond that needed for aircraft operation. For this reason and to avoid fluctuating voltage due to engine speed and aircraft electrical load variations, the instrumentation was powered by an independent auxiliary power supply.

The instruments chosen were two Mine Safety Appliance Corp. LIRA Model 300 infrared analyzers for 0-10% carbon monoxide and 0-15% carbon dioxide, a Beckman Model 109A flame ionization detector and a Whittaker Model NX110 nitrogen oxides analyzer. The responses of these instruments as well as that of the thermocouples mounted on the exhaust probes, were recorded continuously on battery powered Esterline Angus Model T-171B strip chart recorders. The instruments were powered by a heavy duty storage battery using a 250 VA inverter to convert the 12 volts DC to 115 volts AC at 60 Hertz. A diaphram pump mated to a 12 volt DC motor was used to drive the sample through the analyzers.

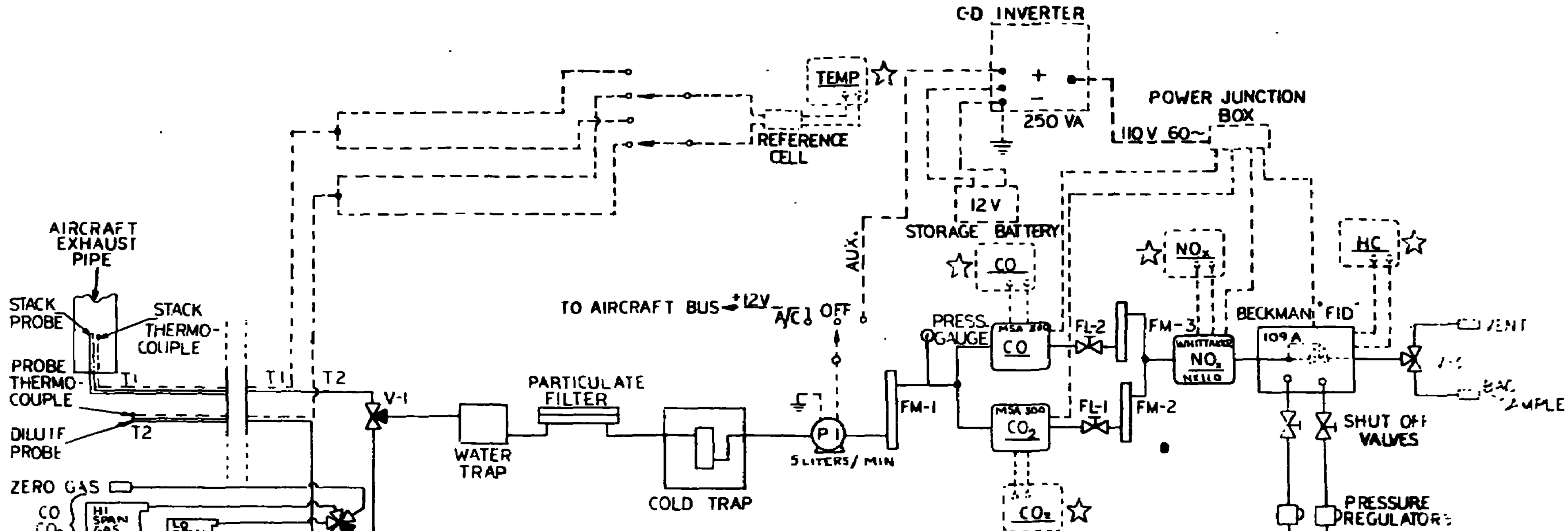
The pump was powered by the aircraft electrical system since voltage variations would not seriously affect its operation. When the engine was not running, such as before start up and after shut down, the pump was powered by the auxiliary power supply.

Figure 4-1 shows a schematic of the flow and electrical systems of the airborne analytical instrument package. Inputs to the system were selected by valves V-1 and V-2. The possible inputs were: 1. stack probe, 2. plume probe, 3. zero gas, 4. hi-span gas and 5. low-span gas. The exhaust sample was taken at a rate of five liters per minute and passed through a water trap, a particulate filter and a cold trap in an ice bath. The flow rate was monitored by flowmeters FM-1, FM-2, and FM-3 and controlled by valves FL-1 and FL-2. The pressure at the inlets of the infrared analyzers was measured and logged throughout the test. After passing through the infrared analyzers and flow control equipment, the sample passed through the nitrogen oxides monitor and the hydrocarbon analyzer. Valve V-3 then directed the sample to a vent or to the connection where Tedlar bags were filled for subsequent laboratory analysis.

4.2 INSTALLATION OF AIRCRAFT ANALYTICAL INSTRUMENT SYSTEM

Prior to installation of the equipment, all seats but the pilot's were removed. The equipment was grouped into modules in order to facilitate handling. The five recorders, NO_x analyzer, thermocouple reference cell and thermocouple selector switch were mounted in a rack made of aluminum angle. The selector valves, water trap, particulate filter and pump switch were mounted on a small flow control panel. This panel was usually attached to the forward end of the recorder rack within easy reach of the operator. The rack and flow control panel are shown in Figure 4-2.

NOTES:
1. - - - - - - - ELECTRICAL WIRING & INSTRUMENTS
☆ 2. (5) STRIP CHART RECORDERS ESTERLINE ANGUS MODEL T-171B (BATTERY POWERED)



FLOW & ELECTRICAL SCHEMATIC FOR AIRCRAFT EXHAUST SAMPLING SYSTEM

Figure 4-1

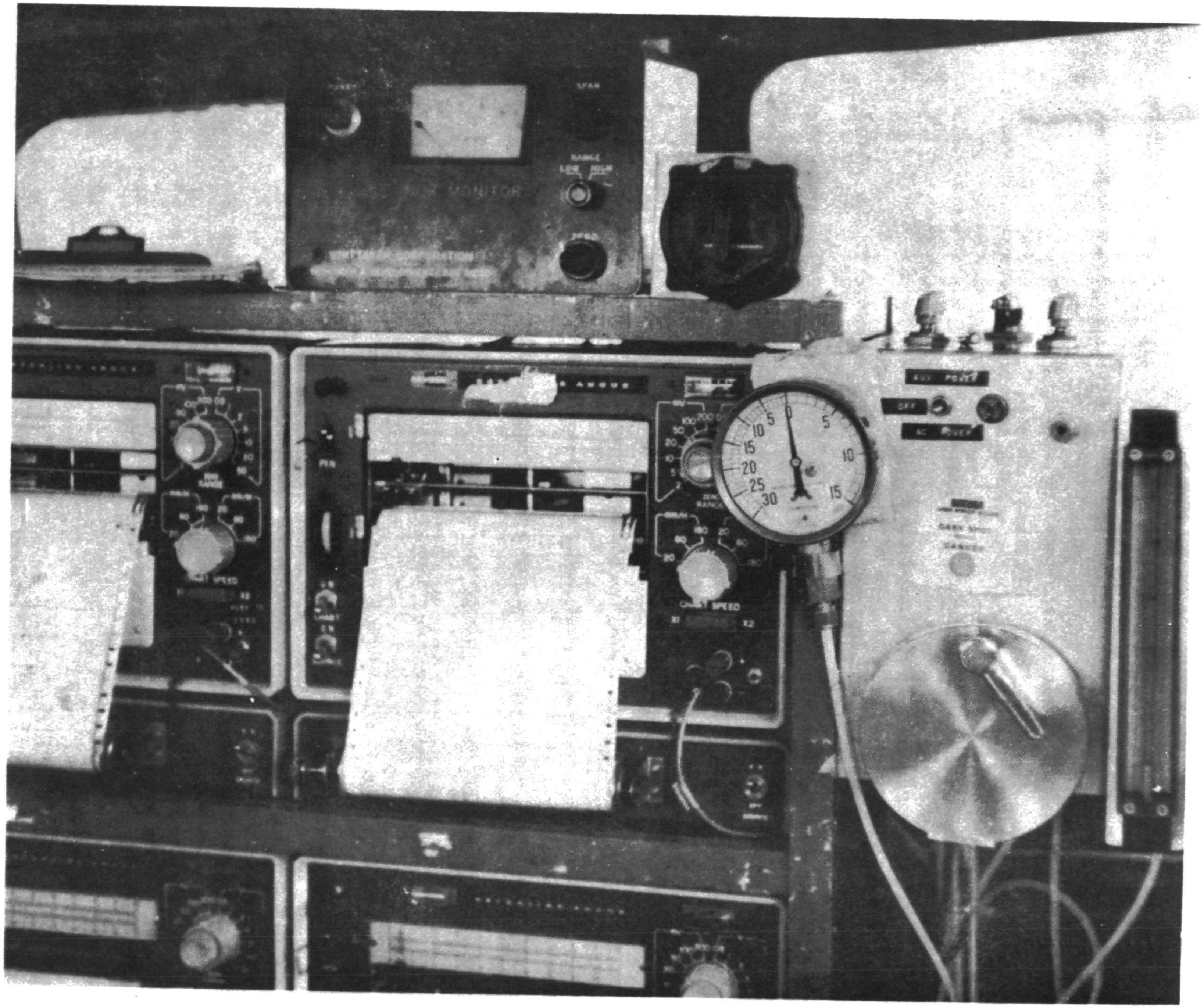


Figure 4-2. Recorder Rack, NO_x Monitor and Flow Control Panel Installed in a Cessna 210.

The two MSA infrared analyzers and the Beckman 109A FID were bolted together and shock mounted as a unit on an aluminum pallet as shown in Figure 4-3. This assembly also held the nitrogen-hydrogen fuel and compressed air cylinders for the FID as well as the two flow control valves (F_1, F_2 in Figure 4-1) and two flowmeters (FM_1, FM_2). The pump and motor were likewise shock mounted on an aluminum pallet. The operator's seat, a storage battery holder and the inverter were mounted on a plywood floor panel. The floor panel was then placed in the rear seat/baggage area and bolted to the seat rails and seat belt attachment points. The recorder rack was then attached to the plywood floor panel. The operator occupied the right rear seat area and the recorder rack occupied the left rear seat area. The inverter and storage battery occupied the baggage area and are shown in Figure 4-4.

The shock mounted analyzer package was attached to the right front seat rails and seat belt anchor points. The pump module was fastened down in whatever space remained - either to a seat rail or to the plywood floor panel. Interconnecting tubing and wiring completed the cabin installation.

Exhaust gases were collected by a probe that was custom-made for each installation. It contained two gas sampling points, one well within the exhaust stack to sample the stack gases and a second usually about four inches below and four inches downstream of the exhaust stack exit to sample the plume gases. The probe used on aircraft #9 is shown in Figure 4-5. Thermocouples were located near each sampling point to monitor the gas temperature at the two probe inlets. The exhaust sample was brought into the cabin through the existing inspection hatch located on the aircraft belly using Teflon and stainless steel tubing. The length of tubing from the sampling points to the analyzers was approximately ten feet.

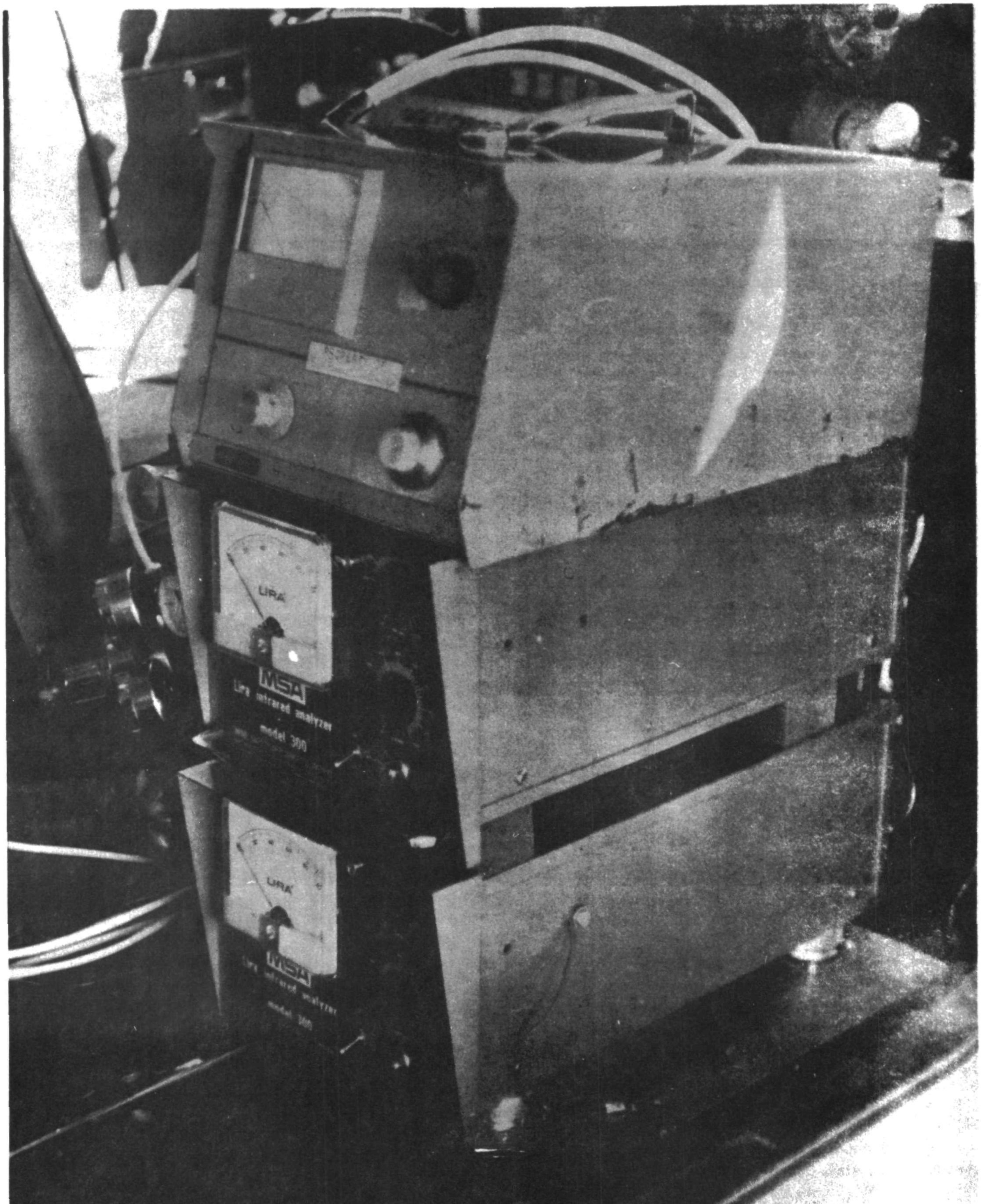


Figure 4-3. Infrared Analyzers and Flame Ionization Unit Mounted on Aluminum Pallet in a Cessna 210.

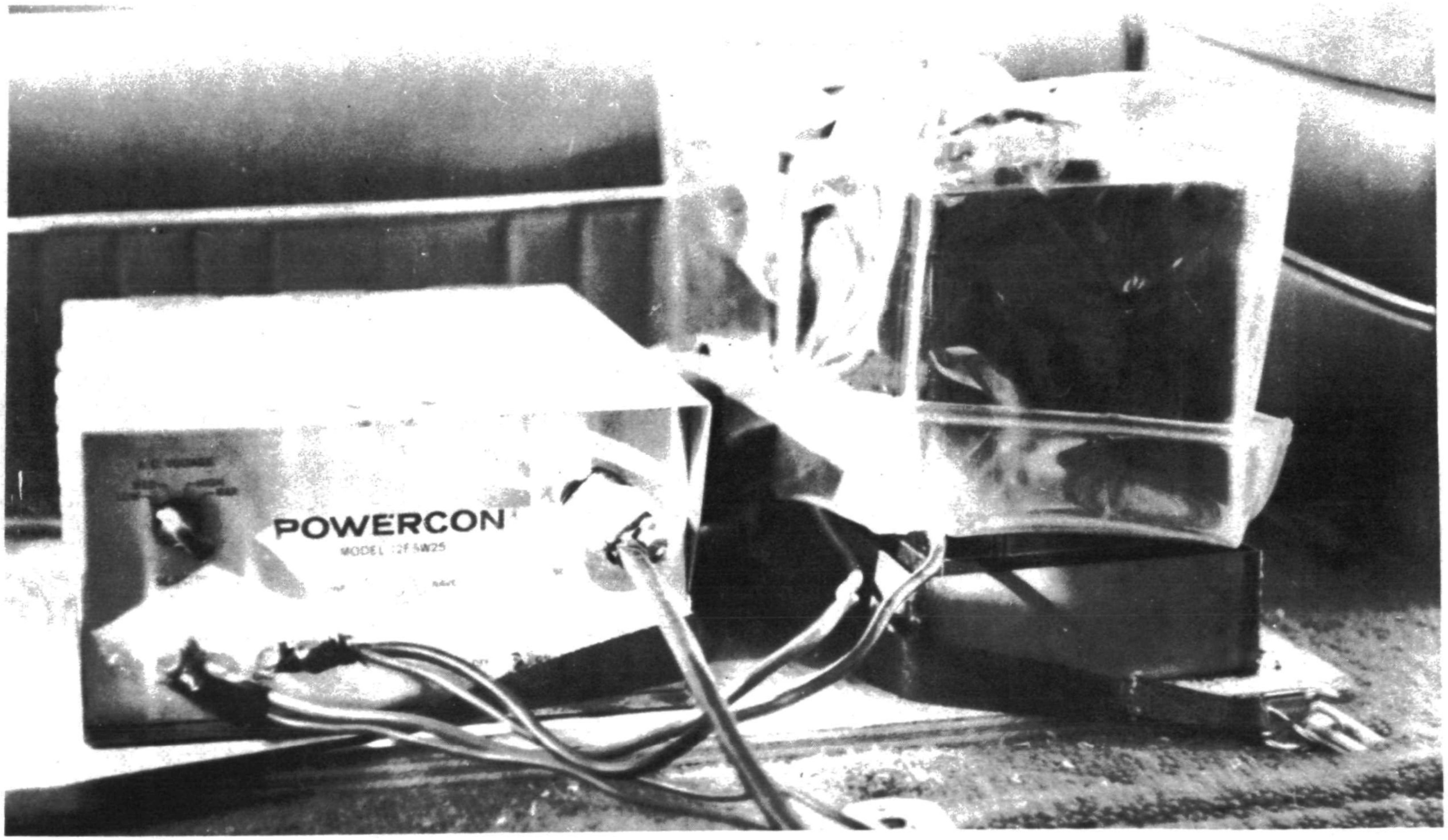


Figure 4-4. Inverter and Storage Battery in Baggage Area of a Cessna 210.

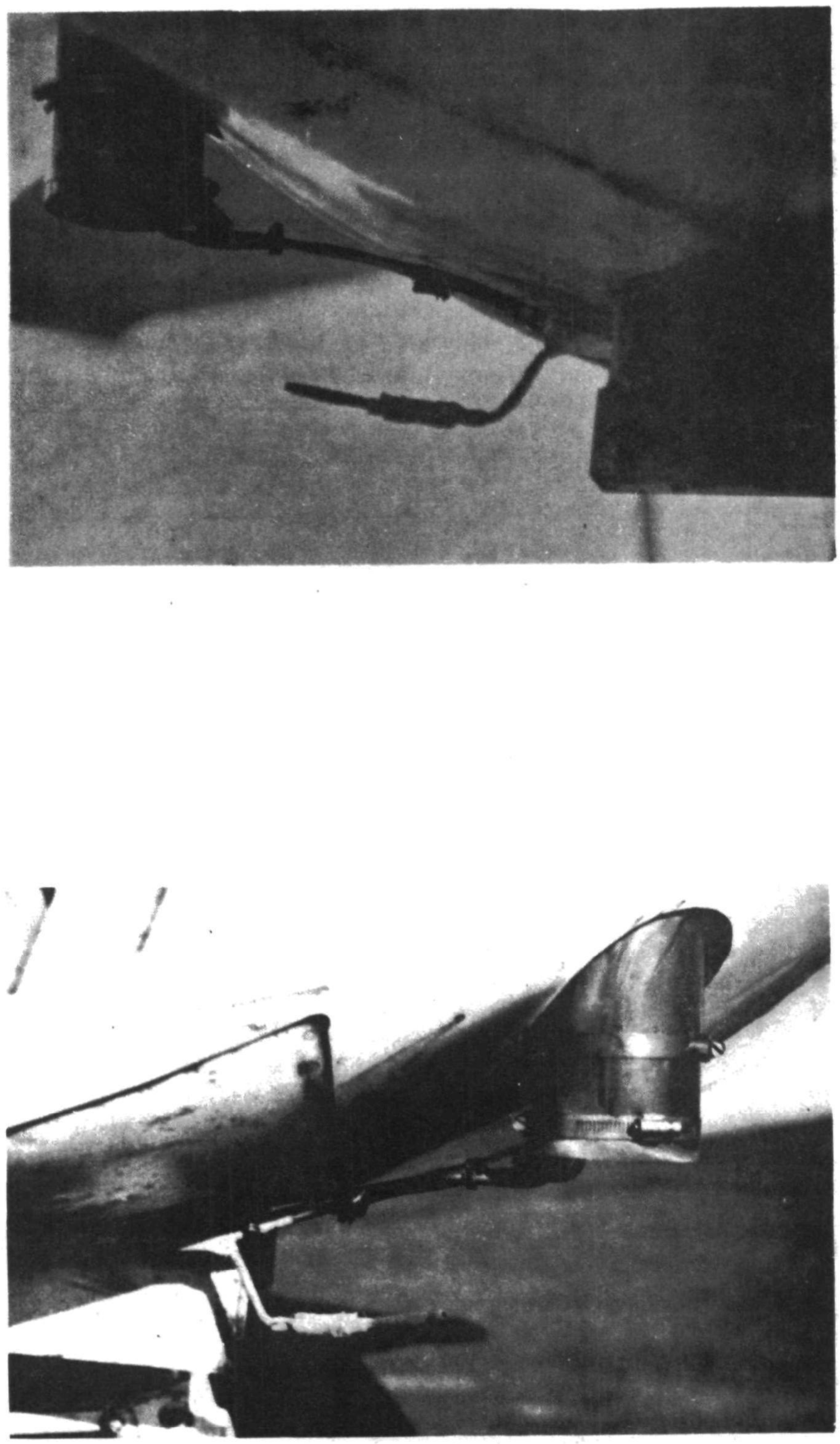


Figure 4-5. Sampling Probe Installed on the Exhaust Stack of a Cessna 210 (two views).

When the installation of the exhaust analysis equipment was complete as shown in Figure 4-6, the FAA was notified and a request for aircraft recertification was made. The aircraft was then inspected by an FAA representative and recertified in the Experimental category. In this category an airplane may be flown only by the project crew and only within a specified low population density area.

After completing the testing on the aircraft, the equipment was removed and the aircraft returned to the standard configuration. At that time application was made to the FAA for certification of the aircraft into Standard category. The aircraft was then inspected and certified by the FAA, and returned to the owner.

4.3 AIRCRAFT TESTING PROCEDURES

The test program was performed at Central Bucks Airport, Doylestown, Pennsylvania. Approximately ten test flights were conducted for each aircraft. A typical test flight lasted about a half hour from engine start to engine shutdown. During each mode of the takeoff-cruise-landing (TCL) cycle, the on-board instruments continuously monitored the stack gases. During part of each steady-state mode, Tedlar bag samples and nitrogen oxide readings were taken of the exhaust plume. The bag samples were taken to Scott's Plumsteadville laboratory for analysis at the end of the flight. The steady-state modes were taxi, ascent, cruise and descent. Modes such as takeoff and landing were non-steady-state because the engine conditions changed rapidly due to loading variations as well as adjustments by the pilot. Calibrations were performed using on-board calibration bags three times during each flight, one a at the end of the initial taxi, another during the cruise mode and the last

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Figure 4-6. Complete Instrument System Installed in a Beechcraft Bonanza 36.

after shutdown. Randomly selected bag samples of the stack gases were taken for laboratory analysis as a cross-check on the aircraft analytical system. Samples of the ambient air were also taken during the flight and brought to the laboratory for analysis with the other bag samples.

Fuel flow data were obtained by two methods. For aircraft with a gravity fuel feed, a calibrated rotometer was inserted in the fuel line. The readings were logged as the aircraft was flown through the various operating modes. If the aircraft had a fuel pump, a calibrated turbine meter was installed in the fuel line and its readings logged. The stainless steel turbine meter had a flow range of 3.5 to 45 USGPH. The turbine meter could only be used on aircraft with fuel pumps because the pressure drop across the meter restricted the gasoline flow of gravity fed aircraft.

4.4 LABORATORY ANALYSIS

The Tedlar bag samples of the exhaust plume returned to the Plumsteadville Laboratory were analyzed for carbon monoxide, carbon dioxide and total hydrocarbons. The concentrations of the carbon oxides were determined by gas chromatography. The hydrocarbon concentration was measured using a Beckman Model 109A flame ionization detector operated under laboratory conditions. The stack samples were analyzed in a similar manner. The ambient air samples were analyzed only for carbon dioxide and hydrocarbons since normal carbon monoxide levels are extremely low.

4.5 DATA REDUCTION AND CALCULATIONS

The continuously recorded strip charts indicating temperature, carbon monoxide, carbon dioxide, hydrocarbons and nitrogen oxides were reduced by a manual procedure. This procedure consisted of marking off the various modes of the flight utilizing the hack marks recorded by the operator, and taking an average reading for each mode. These raw values were corrected for altitude and converted to concentrations via calibration curves made for the in-flight instrument calibrations. The resultant concentrations were averaged over the flight to arrive at an average pollutant concentration per mode per plane. Table 4-2 summarizes the calculations performed on the data.

The average stack concentrations were then reduced to a molar carbon basis and emission rates in pounds per pound of fuel and pounds per minute for each pollutant calculated. This calculation is shown in Table 4-2. Also illustrated in Table 4-2 are calculation procedures to determine the amount of afterburning. The plume analyses for CO, CO_2 and THC were adjusted for background levels and then for dilution, and compared with the appropriate stack concentrations. Afterburning would result in an increase in carbon dioxide levels with corresponding decreases in carbon monoxide and hydrocarbon levels.

Table 4-2. Calculation Procedures Used in the Reduction of the Raw Data.

ALTITUDE CORRECTION OF AIRBORNE INSTRUMENT READINGS:

$$\frac{\text{Sea Level Bar. Pressure (atm.)}}{\text{Bar. Pressure at altitude (atm.)}} \times \text{Instrument reading at altitude} = \text{corrected reading}$$

MASS EMISSION CALCULATIONS FOR POLLUTANT A:

$$\text{lb of A/lb Fuel} = \frac{\text{Wt \% C in Fuel}}{100} \times \frac{1}{12} \times \frac{(\text{Vol \% A in exhaust}) \times M_A}{\text{Vol \% C in exhaust}}$$

where:

Wt % C in fuel = Weight percent carbon in fuel

Vol % C in exhaust = Volume percent of carbon containing compounds in exhaust

= (Vol % CO_2 + Vol % CO + Vol % THC as methane)

Vol % A in exhaust = Volume percent of A in exhaust

M_A = Molecular weight of A

Also:

lb of A/min = (lbs of A/lb Fuel) x (lb Fuel/min)

CORRECTION OF PLUME SAMPLES FOR DILUTION:

$$\text{Dilution Factor} = \frac{(\text{Vol\%}CO_2+\text{Vol\%CO}+\text{Vol\%THC(as methane)) in stack}}{(\text{Vol\%}CO_2+\text{Vol\%CO}+\text{Vol\%THC(as methane)) in plume} - (\text{Vol\%}CO_2+\text{Vol\%THC(as methane)) in air}}$$

Corrected Plume Value for A = Dilution Factor X (VOL%A in plume - Vol%A in air)

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5.0 RESULTS OF AIRCRAFT EMISSIONS TESTS

5.1 TAKEOFF-CRUISE-LANDING (TCL) CYCLE

In order to compile meaningful emissions data, it was first necessary to establish an operating cycle for light aircraft. The takeoff-cruise-landing (TCL) cycle described in Table 5-1 was developed based on discussion with pilots and several test flights. The cycle was representative of light aircraft operation at Central Bucks Airport. However, since it may not be representative of operations at other airports, additional cycle definition may be needed.

The time in each mode shown in Table 5-1 is approximate and may vary from aircraft to aircraft. Each mode has its own characteristic power and mixture setting. The power setting is a combination of a throttle and propeller pitch setting, or in the case of an aircraft with a fixed pitch propeller, a throttle setting alone. The mixture setting determines the engine air-fuel ratio.

All modes are reasonably steady-state except for run-up, cruise pattern and final approach. These three modes are not steady because of changing engine loads and pilot adjustments. The rich cruise mode is used during relatively short trips. For longer trips the air-fuel mixture is leaned to reduce fuel consumption once cruise altitude had been reached.

The cruise altitude during tests was usually 3,000 feet MSL. Since higher performance aircraft, such as those with fuel injection and turbocharging, generally cruise at higher altitudes, aircraft Nos. 5, 7, 8 and 9 were tested at a cruise altitude of 5,000 feet.

Table 5-1. Takeoff-Cruise-Landing Cycle
Used in Study of Emissions from Light Aircraft.

Mode	Description	Approximate Time in Mode (minutes)
Taxi	Startup of engine and taxi to end of runway	4.5
Run-up	Checkout procedure at end of runway, includes a run-up of the engine	1.5
Ascent	Takeoff and ascend to cruise altitude	6
Cruise, Rich	Rich cruise at cruise altitude	6.5
Cruise, Lean	Lean mixture cruise at cruise altitude	2.5
Descent	Descend to landing pattern altitude	7.5
Cruise Pattern	Hold in landing pattern	2
Final Approach	Descend and land	2
Final Taxi	Taxi back to hangar	1.7

5.2 EMISSION TEST RESULTS

The concentrations of carbon monoxide, carbon dioxide, hydrocarbons and nitrogen oxides found in the exhaust of the nine test aircraft are summarized in Table 5-3 along with stack gas temperatures. Data are presented for the minimum, maximum and average for each of the nine modes in the TCL cycle. Detailed data for each aircraft are given in the Appendix.

The reported emission values are subject to random error due to differences in atmospheric conditions and pilot settings, and to random error inherent in the overall instrument system. There is also a small systematic error introduced by the instrument system. The systematic error was minimized by careful calibration of the system. The magnitude of the random error is indicated by the standard deviations of the data for individual flights. The deviations were a function of the compound being measured, because of differences in the instruments used and the levels being measured, and the mode of operation, since certain modes were more reproducible than others. The indicated precision of the emission data is shown in Table 5-2.

Table 5-2. Precision of Emission Data

Parameter	Precision*, %	
	Steady-State Modes	Non Steady-State Modes
Carbon Dioxide	8	8
Carbon Monoxide	12	12
Hydrocarbons	11	30
Nitrogen Oxides	30	50

* One sigma limits (1S% as defined in ASTM Recommended Practice E177).

Table 5-3. Summary of Exhaust Composition Data for Nine Light Aircraft

Mode	CO (%) Min.	CO (%) Max.	CO (%) Avg.	CO_2 (%) Min.	CO_2 (%) Max.	CO_2 (%) Avg.	Total HC (ppm-C) Min.	Total HC (ppm-C) Max.	Total HC (ppm-C) Avg.	NO_x (ppm) Min.	NO_x (ppm) Max.	NO_x (ppm) Avg.	Stack Temp. (°F) Min.	Stack Temp. (°F) Max.	Stack Temp. (°F) Avg.
Taxi - Initial	5.20	11.69	8.42	6.78	11.82	9.18	3270	15180	7950	71	280	128	113	907	635
Idle (Run up)	6.41	10.35	8.13	6.60	10.66	9.43	2150	13080	5820	86	1220	355	188	1150	849
Ascent	6.86	9.91	8.08	8.48	13.34	10.77	990	3090	2140	138	600	334	215	1500	1220
Rich Cruise	5.43	10.19	7.82	7.93	12.15	10.13	987	2730	1850	80	612	213	208	1450	1190
Lean Cruise	0.47	4.80	2.66	11.35	14.75	13.06	207	1770	966	674	4750	2200	221	1550	1289
Descent	5.72	10.98	8.99	5.08	11.44	8.06	906	29000	6660	162	703	291	221	1380	970
Pattern	5.38	10.89	7.86	7.20	11.08	9.45	1140	5160	2950	125	458	254	228	1290	1090
Final Approach	4.30	8.39	6.64	4.70	10.57	7.79	2300	35000	16300	79	326	157	199	1010	759
Taxi - Final	3.62	10.00	7.50	7.14	11.15	8.78	4080	27700	10500	77	808	237	170	889	642

5.3 EMISSION RATES

The exhaust composition data were utilized to compute emission rates on a basis of pounds of pollutant emitted per pound of fuel consumed. An average fuel composition of 85 weight % carbon and 15 weight % hydrogen was assumed. The computed emission rate data were converted to pounds of pollutant emitted per minute using the measured fuel consumption rates.

Summaries of emission rates on a per pound of fuel basis and a per minute basis are presented in Tables 5-4 and 5-5, respectively. The minimum, maximum and average emission rates for each operating mode are given. Detailed data for each aircraft are included in the Appendix.

The air-fuel ratios shown in Table 5-4 and the Appendix were estimated from the ratios of carbon monoxide to carbon dioxide measured in the the exhaust. The estimates were based on composition data for an aircraft engine given in Figure 10-6, Page 317 of Reference 4.

The total emissions per TCL cycle were calculated using the time per mode shown in Table 5-1. The emissions for a Landing-Takeoff (LTO) cycle were also calculated by omitting the cruise modes. Total emission data for each pollutant are presented in Table 5-6 for each mode and test cycle. Data for each test aircraft are given in the Appendix.

Table 5-4. Summary of Exhaust Emission Rates
for Nine Light Aircraft, lb/lb fuel

Mode	Air-Fuel Ratio* (lb/lb)	Emissions (lb/lb Fuel)											
		Carbon Monoxide			Carbon Dioxide			Hydrocarbons (as Hexane)			Nitrogen Oxides (as NO_2)		
		Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Taxi - Initial	11.4	.629	1.170	.910	1.07	2.08	1.58	.00175	.0819	.0426	.00122	.00565	.00235
Idle (Run-up)	11.6	.746	1.167	.896	1.21	1.90	1.63	.0123	.0680	.0322	.00233	.0235	.00660
Ascent	11.9	.677	.953	.849	1.59	2.04	1.77	.00521	.0053	.0115	.00226	.0127	.00607
Rich Cruise	11.8	.740	1.073	.859	1.40	1.95	1.75	.00518	.0163	.0104	.00136	.0137	.00422
Lean Cruise	14.0	.0792	.560	.326	2.22	3.01	2.60	.00179	.0110	.00615	.0135	.0977	.0463
Descent	11.0	.662	1.186	1.011	0.90	2.08	1.43	.00536	.168	.0384	.00288	.0130	.00535
Pattern	11.7	.778	1.175	.917	1.22	1.89	1.64	.00645	.0245	.0182	.00214	.00855	.00477
Final Approach	11.6	.561	.993	.825	1.18	1.96	1.52	.0148	.189	.1036	.00137	.00699	.00343
Taxi - Final	11.6	.475	1.098	.853	1.23	2.30	1.61	.0247	.147	.0590	.00140	.0195	.00502

* Estimated

Table 5-5. Summary of Exhaust Emission Rates
for Nine Light Aircraft, lb/minute

	Emissions (lb/min)											
	Carbon Monoxide			Carbon Dioxide			Hydrocarbons (as Hexane)			Nitrogen Oxides		
Mode	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Taxi - Initial	.126	.407	.223	.218	.727	.387	.00343	.0374	.0116	.000335	.00167	.000597
Idle (Run-up)	.351	.733	.483	.571	1.388	.885	.00691	.0440	.0184	.000666	.00996	.00329
Ascent	.724	1.747	1.044	1.73	3.09	2.13	.00590	.0251	.0144	.00232	.0139	.00718
Rich Cruise	.621	1.685	.943	1.31	2.94	1.85	.00606	.0231	.0115	.00127	.0115	.00417
Lean Cruise	.0568	.665	.291	1.81	3.87	2.22	.00128	.0150	.00555	.0205	.0912	.0376
Descent	.279	1.109	.536	.236	1.468	.806	.00378	.0439	.0147	.000752	.00439	.00234
Pattern	.306	1.256	.694	.742	1.486	1.10	.00253	.0259	.0146	.00102	.00734	.00413
Final Approach	.131	.407	.188	.246	.550	.325	.00286	.0881	.0240	.000344	.00131	.000647
Taxi - Final	.0893	.396	.196	.231	.652	.363	.00478	.0606	.0161	.000288	.00376	.00103

Table 5-6. Summary of Exhaust Emissions from Nine Light Aircraft during Typical Operating Cycles

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	1.00	1.74	.0521	.00269
Run-up	1.5	.725	1.33	.0276	.00493
Ascent	6	6.27	12.81	.0862	.0442
Rich Cruise	6.5	6.13	12.00	.0747	.0271
Lean Cruise	2.5	.764	5.80	.0150	.0988
Descent	7.5	4.02	6.05	.110	.0651
Pattern	2	1.39	2.32	.0820	.00827
Final Approach	2	.394	.678	.0452	.00144
Taxi - Final	1.7	.334	.617	.0274	.00174
Total-TCL Cycle*	34.2	21.0	43.3	.520	.254
Total-LTO Cycle**	25.2	14.1	25.5	.431	.128

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

6.0 DISCUSSION OF DATA COLLECTED

The composition of the exhaust from a light, piston engine aircraft is a complex function of the various fixed aircraft parameters, such as engine type and airframe design, and the operating mode of the aircraft. The aircraft selected for testing and the modes defined in the takeoff-cruise-landing (TCL) cycle allow evaluation of the effects of many of these variables on the exhaust composition and the emission rates.

6.1 EFFECT OF OPERATIONAL MODE ON EXHAUST EMISSIONS

Light aircraft are generally operated with a rich mixture setting during all operations except long cruise modes in which case the mixture may be leaned to reduce fuel consumption. Rich mixtures are employed to protect the engine through cooler operation and to provide for greater safety through more stable engine operation with less chance of stalling than with stoichiometric mixtures. In addition, the pilot does not have to adjust the mixture control during the critical operations of takeoff and landing.

The exhaust composition resulting from the rich mixture setting was relatively high in carbon monoxide as shown in Table 5-3. The differences in carbon monoxide among the various rich modes were small. The hydrocarbons varied to a greater extent with the lowest concentrations found at the high power settings used for ascent and cruise, and the higher concentrations found at low power modes such as descent, final approach and taxi. The highest hydrocarbon concentrations occurred during final approach, a mode in which the engine absorbed energy through the propeller while idling as the aircraft lost altitude. Nitrogen oxides concentrations showed little change from one rich mixture mode to another.

When the mixture was leaned during the cruise mode, a substantial reduction in carbon monoxide occurred along with a moderate reduction in hydrocarbons, a moderate increase in carbon dioxide and a very large increase in nitrogen oxides. The emission rate of nitrogen oxides at lean cruise exceeded the sum of the emission rates at the other eight modes.

As the aircraft's altitude increases, the decrease in ambient air pressure might be expected to produce a richer air-fuel mixture and thus less complete combustion. However, the comparison data shown in Table 6-1 indicate that cruise altitude had little effect on exhaust emissions expressed as pounds per pound of fuel. On the other hand, it was noted that fuel consumption increased with altitude thereby producing greater emissions per unit time.

Table 6-1. Effect of Cruise Altitude on Exhaust Emissions

	lb pollutant/lb fuel		
Aircraft #3	CO	CO_2	THC
Cruise @ 1,200'MSL	1.16	1.24	0.0258
Cruise @ 3,000'MSL	1.17	1.23	0.0231
Aircraft #1			
Cruise @ 3,000'MSL	1.02	1.44	0.0280
Cruise @ 4,500'MSL	1.11	1.36	0.0328

During warm, humid weather ice can form in the induction system as an aircraft descends from cool air aloft into the humid air below or as it passes through clouds. To prevent ice from forming, the intake air to the carburetor is heated in a heat exchanger using exhaust gas as the source of heat. Heating the intake air reduces the air-fuel ratio and thus produces higher emissions. This is illustrated in Table 6-2 where both carbon monoxide and hydrocarbons were about 30% higher when the carburetor intake was heated than when it was not. However, since carburetor heat is generally used only for short periods of time, the increase in total emissions is small.

Table 6-2. Effect of Carburetor Heat on Exhaust Composition

Aircraft #8	Air-fuel Ratio (lb/lb)	CO (%)	CO_2 (%)	THC (ppm-C)
Descent with Carburetor Heat	10.6	10.6	8.0	3300
Descent without Carburetor Heat	11.5	8.3	10.3	2500

6.2 THE EFFECT OF AIRCRAFT PARAMETERS ON EXHAUST EMISSIONS

The aircraft tested in this program were selected to allow an assessment of the effect of design differences on exhaust emissions. Of particular interest was the effect of engine operating time, engine size, engine induction system and airframe design on the composition of the exhaust. To quantify the comparisons made in this section, the exhaust emissions as pounds of pollutant per pound of fuel were averaged over the most reproducible rich modes of operation, specifically the ascent, rich cruise, descent and final taxi modes. These comparisons are limited to exhaust composition and do not take into account differences in fuel consumption rates.

6.2.1 THE EFFECT OF ENGINE OPERATING TIME

The effect of engine operating time, that is the total number of hours the engine has been operated since its manufacture or last major overhaul, is indicated by examining the emissions data for three similar four cylinder and two similar six cylinder craft. The data shown in Table 6-4 indicates that the effect of engine age is small. The differences in pollutant levels are probably due to engine settings rather than engine use.

6.2.2 THE EFFECT OF ENGINE SIZE

The Cessna 172 and 182 have similar airframes, but the 182 is heavier and has a larger engine. The data presented in Table 6-4 indicates combustion in the larger engines is more efficient. The two Cessna 182's emitted an average of 15 percent less carbon monoxide and 49 percent less hydrocarbons per pound of fuel than the three 172's.

Table 6-4. Effect of Engine Use and Size on Exhaust Emissions

Aircraft	Engine Power (HP)	Number of Cylinders	Engine Use (hrs)	Average Emissions During Steady-State Modes (lb/lb Fuel)			
				CO	CO_2	THC (as Hexane)	NO_x (as NO_2)
#3 Cessna 172	150	4	672	0.820	1.78	0.0227	0.00604
#1 Cessna 172	150	4	140	0.928	1.62	0.0184	0.00822
#4 Cessna 172	150	4	105	1.011	1.46	0.0304	0.00265
#6 Cessna 182	235	6	1053	0.766	1.88	0.0128	0.00207
#7 Cessna 182	235	6	53	0.789	1.87	0.0104	-

6.2.3 THE EFFECT OF ENGINE INDUCTION SYSTEM

A comparison of emission data for six cylinder engines with fuel injection and normal aspiration is made in Table 6-5. The fuel injected engines in the Beechcraft 36 and Cessna 210 emitted 23 percent more carbon monoxide and 307 percent more hydrocarbons per pound of fuel than the Cessna 182's with normal aspiration. There was little difference between the emissions from the turbocharged Cessna 210 and the Beechcraft 36 without turbocharging.

Table 6-5. Effect of Engine Induction System on Exhaust Emissions

			Average Emissions During Steady-State Modes (lb/lb Fuel)			
Aircraft	Induction System	Engine Power (HP)	CO	CO_2	THC (as Hexane)	NO_x (as NO_2)
#6 Cessna 182	Normal Aspiration	230	0.776	1.88	0.0128	0.00207
#7 Cessna 182	Normal Aspiration	230	0.789	1.87	0.0104	-
#5 Bonanza 36	Fuel Injection	285	0.994	1.43	0.0462	0.00232
#9 Cessna 210	Fuel Injection, Turbocharged	285	0.955	1.49	0.0482	0.00360

6.2.4 THE EFFECT OF AIRFRAME DESIGN

Two distinctly different airframes with similar engines were included in the test program. Both the Cessna 172 and Piper PA-23 utilized 4 cylinder, 150 HP engines. The Cessna 172 was a high wing monoplane with fixed tricycle landing gear, while the Piper PA-23 was a low wing twin-engine aircraft with retractable landing gear.

The Piper also had an ejector type exhaust. The ejector exhaust is a venturi-shaped duct placed around the exhaust stack with the stack ending at the venturi throat. The rear end of the duct is open to the atmosphere and the front end is open to the engine compartment. The high speed flow from the engine exhaust stack draws ambient air over the engine thereby cooling it with little or no additional drag. The air also passes over the exhaust stacks and cools the exhaust gases. This is evident by the temperatures of approximately 200°F found at the stack sampling point.

The data presented in Table 6-6 show that the emissions from the Piper were slightly lower in carbon monoxide and hydrocarbons than any of the three Cessna 172's. However, it is not possible to draw firm conclusions based on one aircraft.

Table 6-6. Effect of Airframe Design on Exhaust Emissions

			Average Emissions During Steady-State Modes (lb/lb Fuel)			
Aircraft	Airframe Design	Engine Use (hrs)	CO	CO_2	THC (as Hexane)	NO_x (as NO_2)
#3 Cessna 172	High wing mono-	672	0.820	1.78	0.0227	0.00604
#1 Cessna 172	plane with fixed	140	0.928	1.62	0.0184	0.00822
#4 Cessna 172	landing gear.	105	1.011	1.46	0.0304	0.00265
#8 Piper Apache	Low wing twin engine with retractable landing gear and exhaust ejector.	423	0.736	1.93	0.0163	-

6.3 COMPARISON OF EMISSIONS FROM LIGHT AIRCRAFT AND AUTOMOBILES

The engines and fuels used in light aircraft are similar to those employed in automobiles so that a comparison of emissions from these two sources may be made. The emission rates for light aircraft obtained in this study are compared to present and projected rates for automobile exhaust in Table 6-7 on a basis of pounds of pollutant per pound of fuel.

Table 6-7. Comparison of Light Aircraft and Automobile Emissions

	lb pollutant/lb fuel consumed		
	Carbon Monoxide	Hydrocarbons as Hexane	Nitrogen Oxides as Nitrogen Dioxide
Present Uncontrolled Light Aircraft*	0.847	0.0210	0.0102
Uncontrolled Automobiles**	0.525	0.066	0.018
Automobiles Meeting 1972 Federal Stds.**	0.176	0.015	No Standard
Automobiles Meeting Proposed HEW 1975 Federal Standards**	0.050	0.002	0.0041

* Average value for aircraft operated over TCL cycle described in Table 5-1.
** Reference 6 - Average values for automobiles operated over new Federal urban driving cycle assuming 12 miles per gallon of gasoline.

Carbon monoxide emissions from light aircraft were approximately 60 percent higher than uncontrolled automobiles and nearly five times as high as allowable emissions for 1972 automobiles. Hydrocarbon emissions from current aircraft were only slightly higher than 1972 automobile standards. However, ground operations of aircraft produced hydrocarbons at approximately twice the rate of the TCL cycle. Nitrogen oxides emissions from aircraft, expecially on the ground, were not much higher than proposed 1975 standards. However, continued attention must be paid to nitrogen oxides since control techniques for carbon monoxide and hydrocarbons could increase aircraft nitrogen oxides emissions.

6.4 AFTERBURNING

Afterburning can take place when very hot exhaust gases containing high concentrations of carbon monoxide and hydrocarbons come in contact with air. This combustion could eliminate much of the carbon monoxide, hydrocarbons, hydrogen and carbonaceous particles present in the exhaust. Natural afterburning at the end of the aircraft exhaust stack would provide a convenient means of pollution control. It would be expected that afterburning would occur most readily at the high exhaust temperatures and rich mixtures present during the ascent and rich cruise modes.

Samples of the exhaust plume were taken downstream of the exhaust stack during the initial taxi, ascent, rich cruise and descent modes. The plume composition was corrected for dilution by carbon balance after correcting for ambient air concentrations of carbon dioxide and hydrocarbons. The corrected plume concentrations are compared to the corresponding stack values in Table A-37 in the Appendix. A frequency distribution of the net change in carbon dioxide concentration is shown in Figure 6-1. The figure shows a near normal distribution of data points. The difference between corrected plume and stack data was ten percent or less for ninety percent of the test points. This range covers the expected level of random error. A study of those points showing a carbon dioxide increase of fifteen percent or more indicates that they are widely distributed over aircraft and operating modes and thus the result of random data error and not afterburning.

The changes in hydrocarbons given in Table A-37 exhibit greater dispersion than the changes in carbon dioxide and carbon monoxide. This is due to greater fluctuation of hydrocarbons during steady-state modes and less precision in the plume measurements. However, there is no evidence of any consistent reduction in hydrocarbon emissions for any aircraft or operating mode.

The fact that no afterburning was found in this study is plausible when the exhaust gas temperatures are examined. The highest temperatures occurred during ascent and cruise where values as high as 1500°F were recorded at the stack sampling point. Cooling undoubtedly occurred between the sampling point and the end of the stack. Thus, the temperature at the point where air needed for afterburning first came in contact with the exhaust was too low for burning to take place.

One means of enhancing afterburning would be to minimize the distance from the engine manifold to the exhaust vent. This exhaust configuration was used on many radial piston engine aircraft for which visible afterburning was reported at the exhaust vents. Afterburning might also be enhanced by insulation of the exhaust system.

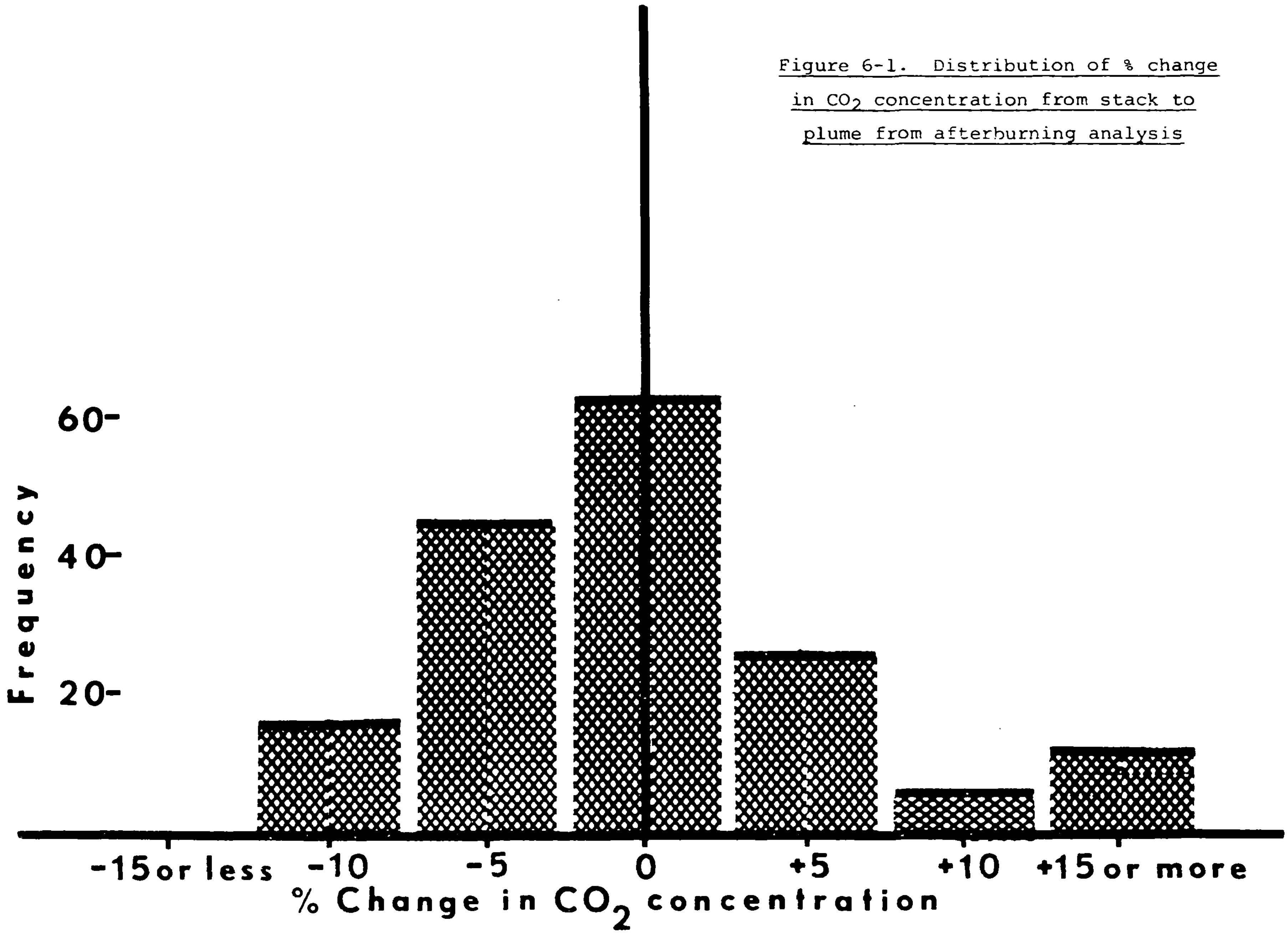

Figure 6-1. Distribution of % change in CO_2 concentration from stack to plume from afterburning analysis

6.5 CONTROL TECHNIQUES FOR AIRCRAFT EMISSIONS

In addition to natural afterburning, techniques which have been applied to automobile exhaust are potentially applicable to aircraft exhaust. However, greater constraints are placed on the design of an aircraft control system as compared to one suitable for automobiles. Aircraft safety must not be impaired in any manner. This means that engine performance cannot be reduced, any heat generated must be safely dissipated, and additional weight and power requirements must be minimal. On the other hand, high temperatures must be maintained and substantial amounts of air added to achieve combustion of exhaust products.

While leaning of the engine mixture was shown to result in substantial reductions in carbon monoxide and hydrocarbons at the cruise mode, this cannot be done safely with the present engine design at the high performance modes such as ascent. The mixture could possibly be leaned during ground operations, but a large increase in nitrogen oxides emissions would be anticipated.

Exhaust reactors can be applied in principle to aircraft emissions. The volume of air required for complete combustion of the carbon monoxide, hydrocarbons and hydrogen in the exhaust would be as great as 50 percent of the total exhaust volume at rich modes. A pump capable of supplying this large volume of air would be heavy and require additional power thus limiting its practicability. It would appear that the air would best be supplied by the ram air pressure generated by the aircraft motion. The incoming air would have to be heated, preferably in a heat exchanger with heat supplied by the reactor effluent, in order to maintain combustion in a thermal reactor. This may prove difficult at ground level modes where exhaust temperatures are relatively low. A catalytic reactor could be used to obtain combustion at lower temperatures, but with added catalyst bed weight and cost. The lead present in the exhaust would limit catalyst life but this could be overcome by the use of unleaded fuel.

In summary, the technology which has been developed for controlling automobile exhaust emissions will be valuable in developing control techniques for aircraft emissions. However, a number of constraints unique to aircraft will make it necessary to carry out additional design efforts to adapt the techniques and hardware utilized for automobiles for satisfactory performance in aircraft. In the meantime, proper engine maintenance and setting of the air-fuel mixture to the minimum richness required for safe operation would be beneficial in minimizing aircraft exhaust emissions.

6.6 CONCLUSIONS

As a result of this study of nine light aircraft, the following conclusions can be drawn:

1. The light piston engine aircraft tested emitted exhaust containing levels of carbon monoxide higher than uncontrolled automobiles and substantially higher than standards set for 1972 vehicles in terms of pounds of pollutant per pound of fuel. Hydrocarbon emissions from the test aircraft were in the range emitted by current controlled automobiles. Aircraft nitrogen oxide emissions were low except during lean mixture operation.

2. Carbon monoxide and hydrocarbon emissions can be substantially reduced by leaning the aircraft air-fuel mixture, but this is not done because it increases the possibility of engine stalling.
3. Fuel injected engines of current design emitted much higher concentrations of hydrocarbons than normally aspirated engines. The effect of other aircraft parameters such as use time, engine size, and airframe design, on exhaust composition was small.
4. No natural afterburning of carbon monoxide or hydrocarbons occurred in the exhaust from the light aircraft tested during any operating mode.
5. Analytical instrumentation packages are available to monitor exhaust emissions of light aircraft during actual flight operation.

6.7 RECOMMENDATIONS FOR FUTURE STUDIES

Future investigations related to light aircraft emissions should be concentrated in two areas: the contribution of light aircraft emissions to pollution levels in the vicinity of airports and the feasibility of various control techniques for reducing exhaust emissions.

Work on aircraft contributions to pollution levels should obtain information on typical operations at a number of airports and thus improve upon the TCL cycle developed in the current study. Special emphasis should be placed on operations at or near ground level with attention also focused on the dispersion of pollutants in the atmosphere surrounding the airports.

The evaluation of control techniques should investigate the potential schemes discussed in the previous section. It should include enhancement of natural afterburning via increased temperatures at the stack vent. Both thermal and catalytic reactors should be tested. Because of the importance of temperature in control device performance, and because actual inflight heat transfer is difficult to simulate in a test cell, the evaluations would best be accomplished in actual flight tests.

7.0 REFERENCES

1. "Nature and Control of Aircraft Engine Exhaust Emissions" Report of the Secretary of Health, Education & Welfare to the United States Congress; December, 1968.

2. "Nature and Control of Aircraft Engine Exhaust Emissions" Report prepared by Northern Research and Engineering Corporation for the National Air Pollution Control Administration under Contract No. PH22-68-27.

3. "Standard Specifications for Aviation Gasolines" ASTM Standards (D910-70), Part 17, November, 1970.

4. "Internal Combustion Engines Analysis and Practice" Second Edition by Edward F. Obert.

5. "Aviation Statistics (Interum Report)", Office of Management Systems, Information and Statistics Division, FAA/DOT, September, 1970.

6. "Congressional Record-Senate", September 21, 1970, pg. S16113.

Appendix of Data

Table A-1

Composition of Light Aircraft Exhaust

MODE: Taxi - initial

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	8.68	7.79	4650	74	630
2. (Right) - Cessna 172D	10.85	7.03	9450	109	643
2. (Left) - Cessna 172D	10.45	7.02	4050	88	653
3. Cessna 172I	5.20	10.92	3780	157	631
4. Cessna 172K	11.69	6.78	14670	107	774
5. Bonanza 36	8.46	9.60	15180	99	747
6. Cessna 182H	6.97	11.82	3630	71	907
7. Cessna 182N	7.92	10.82	3270	90	753
8. Piper Apache	7.39	8.51	3525	280	113
9. Cessna 210	8.88	9.50	16020	171	512

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Table A-2

Composition of Light Aircraft Exhaust

MODE: Run-up

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	-	-	-	-	-
2. (Right) - Cessna 172D	10.35	6.81	5670	360	849
2. (Left) - Cessna 172D	9.69	6.40	4410	120	892
3. Cessna 172I	6.41	10.39	3540	292	855
4. Cessna 172K	8.53	8.71	8460	320	1030
5. Bonanza 36	8.63	9.72	13080	140	916
6. Cessna 182H	8.09	10.66	3810	86	1150
7. Cessna 182N	7.23	10.45	2150	260	967
8. Piper Apache	7.78	8.89	3300	1220	188
9. Cessna 210	8.33	10.01	7080	280	815

Table A-3

Composition of Light Aircraft Exhaust

MODE: Ascent

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	6.88	8.48	1550	600	1320
2. (Right) - Cessna 172D	8.34	8.15	3180	485	1340
2. (Left) - Cessna 172D	7.76	8.85	2350	678	1360
3. Cessna 172I	9.41	10.83	2610	483	1210
4. Cessna 172K	8.64	9.64	1640	217	1405
5. Bonanza 36	8.64	10.10	2840	201	1320
6. Cessna 182H	7.39	12.45	1740	138	1500
7. Cessna 182N	6.86	12.43	990	202	1400
8. Piper Apache	6.96	13.34	2050	–	215
9. Cessna 210	9.91	11.14	2770	247	1220

Table A-4

Composition of Light Aircraft Exhaust

MODE: Rich Cruise - 3,000'

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	5.43	9.14	1250	612	1260
2. (Right) - Cessna 172D	7.31	8.46	2580	330	1290
2. (Left) - Cessna 172D	8.36	7.39	2520	387	1290
3. Cessna 172I	7.45	10.49	1970	164	1220
4. Cessna 172K	7.30	9.99	1320	85	1350
5. Bonanza 36*	10.19	8.48	2730	85	1240
6. Cessna 182H	7.35	11.80	1370	80	1450
7. Cessna 182N*	8.75	10.6	987	112	1430
8. Piper Apache*	7.28	12.15	2060	-	208
9. Cessna 210*	8.83	10.61	2370	208	1260

* Cruise at 5,000', all others at 3,000'

Table A-5

Composition of Light Aircraft Exhaust

MODE: Lean Cruise - 3,000'

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	0.47	11.35	207	2050	1410
2. (Right) - Cessna 172D	-	-	-	-	-
2. (Left) - Cessna 172D	2.64	11.41	1520	1880	1440
3. Cessna 172I	2.24	13.38	879	2030	1310
4. Cessna 172K	3.09	13.40	795	1910	1470
5. Bonanza 36 *	4.80	12.12	1770	1360	1340
6. Cessna 182H	3.02	14.75	789	2900	1550
7. Cessna 182N *	1.61	14.29	435	4750	1530
8. Piper Apache *	3.20	13.64	696	-	221
9. Cessna 210 *	2.91	13.36	1580	674	1310

* Cruise at 5,000', all others at 3,000'

Table A-6

Composition of Light Aircraft Exhaust

MODE: Descent

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	9.32	6.32	4630	180	743
2. (Right) - Cessna 172D	9.50	5.07	30400	945	1100
2. (Left) - Cessna 172D	9.92	5.09	27700	460	1130
3. Cessna 172I	9.28	7.42	6180	385	803
4. Cessna 172K	10.98	6.77	7170	162	894
5. Bonanza 36	10.41	7.25	4410	162	1150
6. Cessna 182H	8.08	10.48	1900	186	1330
7. Cessna 182N	5.72	11.44	906	-	1380
8. Piper Apache	6.83	9.76	1970	-	221
9. Cessna 210	10.57	7.99	3720	256	1090

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Table A-7

Composition of Light Aircraft Exhaust

MODE: Pattern

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	-	-	1410	-	-
2. (Right) - Cessna 172D	8.07	9.30	4650	500	1290
2. (Left) - Cessna 172D	8.78	7.84	5670	415	1270
3. Cessna 172I	7.55	9.64	3030	255	1070
4. Cessna 172K	6.88	8.50	3780	324	1170
5. Bonanza 36	9.63	8.78	3390	150	1190
6. Cessna 182H	8.20	10.66	2460	125	1260
7. Cessna 182N	7.04	10.89	1140	-	1290
8. Piper Apache	6.73	9.70	2160	-	228
9. Cessna 210	10.89	7.20	3990	212	1040

Table A-8

Composition of Light Aircraft Exhaust

MODE: Final Approach

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (°F)
1. Cessna 172K	6.54	7.31	14900	120	558
2. (Right) - Cessna 172D	-	-	-	-	-
2. (Left) - Cessna 172D	5.09	4.70	14500	185	729
3. Cessna 172I	4.30	9.47	15100	326	740
4. Cessna 172K	6.26	7.20	27600	182	809
5. Bonanza 36	8.26	7.11	35000	79	1010
6. Cessna 182H	5.38	10.57	9570	86	995
7. Cessna 182N	7.87	9.13	9450	-	995
8. Piper Apache	7.70	7.97	2300	-	199
9. Cessna 210	8.39	6.62	18500	121	800

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Table A-9

Composition of Light Aircraft Exhaust

MODE: Taxi - Final

Plane	CO (%)	CO_2 (%)	THC (ppm-C)	NO_x (ppm)	Stack Temp. (^oF)
1. Cessna 172K	7.66	8.31	4080	140	551
2. (Right) - Cessna 172D	9.88	7.16	10500	280	599
2. (Left) - Cessna 172D	9.78	7.12	7350	145	623
3. Cessna 172I	3.62	11.15	4500	288	594
4. Cessna 172K	10.00	7.18	11700	126	690
5. Bonanza 36	8.07	8.49	24100	83	768
6. Cessna 182H	6.74	10.8	4350	77	889
7. Cessna 182N	8.18	9.70	4620		840
8. Piper Apache	4.88	8.31	4290	808	170
9. Cessna 210	8.50	7.94	27700	158	667

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Table A-10

Light Aircraft Exhaust Emissions

MODE: Taxi - Initial

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel): Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	11.0	1.022	1.44	.0280	.00143
2 (Right)	Cessna 172D	10.3	1.150	1.17	.0513	.00190
2 (Left)	Cessna 172D		1.166	1.23	.0231	.00200
3	Cessna 172I	12.8	0.629	2.08	.0233	.00312
4	Cessna 172K	10.0	1.170	1.07	.0751	.00176
5	Bonanza 36	11.5	0.862	1.54	.0792	.00166
6	Cessna 182H	12.3	0.726	1.94	.0194	.00122
7	Cessna 182N	11.9	0.829	1.78	.0175	.00155
8	Piper Apache	11.6	0.907	1.64	.0222	.00565
9	Cessna 210	11.4	0.887	1.49	.0819	.00281

Table A-11

Light Aircraft Exhaust Emissions

MODE: Run-up

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel): Carbon Monoxide	Emissions (lb/lb Fuel): Carbon Dioxide	Emissions (lb/lb Fuel): Hydrocarbons (as Hexane)	Emissions (lb/lb Fuel): Nitrogen Oxides (as NO_2)
1	Cessna 172K	-	-	-	-	-
2 (Right)	Cessna 172D	10.3	1.165	1.20	.0327	.00666
2 (Left)	Cessna 172D		1.169	1.21	.0272	.00238
3	Cessna 172I	12.3	0.746	1.90	.0211	.00558
4	Cessna 172K	11.3	0.941	1.51	.0478	.00580
5	Bonanza 36	11.5	0.876	1.55	.0680	.00233
6	Cessna 182H	11.9	0.844	1.75	.0203	.00147
7	Cessna 182N	12.0	0.806	1.83	.0123	.00476
8	Piper Apache	11.5	0.913	1.64	.0198	.0235
9	Cessna 210	11.7	0.872	1.65	.0380	.00482

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Table A-12

Light Aircraft Exhaust Emissions

MODE: Ascent

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	11.7	.885	1.71	.0102	.0127
2 (Right)	Cessna 172D	11.4	.986	1.52	.0230	.00942
2 (Left)	Cessna 172D		.919	1.65	.0143	.0132
3	Cessna 172I	11.6	.916	1.66	.0130	.00772
4	Cessna 172K	11.5	.935	1.64	.00909	.00386
5	Bonanza 36	11.6	.906	1.66	.0153	.00346
6	Cessna 182H	12.3	.737	1.95	.00886	.00226
7	Cessna 182N	12.5	.706	2.01	.00521	.00342
8	Piper Apache	12.6	.677	2.04	.0102	–
9	Cessna 210	11.5	.927	1.64	.0133	.00380

Table A-13

Light Aircraft Exhaust Emissions

MODE: Rich Cruise

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	12.3	.737	1.95	.00862	.0137
2 (Right)	Cessna 172D	11.3	.910	1.66	.0164	.00675
2 (Left)	Cessna 172D		1.042	1.45	.0161	.00793
3	Cessna 172I	12.0	.820	1.81	.0111	.00296
4	Cessna 172K	11.9	.836	1.80	.00772	.00160
5	Bonanza 36 *	10.8	1.073	1.40	.0147	.00147
6	Cessna 182H	12.2	.760	1.92	.00726	.00136
7	Cessna 182N *	11.5	.898	1.71	.00518	.00189
8	Piper Apache *	12.3	.740	1.94	.0107	–
9	Cessna 210 *	11.7	.895	1.69	.0123	.00346

* Cruise at 5,000', all others at 3,000'.

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Table A-14

Light Aircraft Exhaust Emissions

MODE: Lean Cruise

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel): Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	15.1	.0792	3.01	.00179	.0566
2 (Right)	Cessna 172D	13.9	-	-	-	-
2 (Left)	Cessna 172D		.371	2.52	.0110	.0434
3	Cessna 172I	14.3	.286	2.67	.00575	.0426
4	Cessna 172K	13.8	.372	2.54	.00490	.0377
5	Bonanza 36 *	13.1	.560	2.22	.0106	.0261
6	Cessna 182H	14.0	.338	2.59	.00451	.0533
7	Cessna 182N *	14.8	.202	2.81	.00279	.0977
8	Piper Apache *	13.8	.378	2.53	.00420	-
9	Cessna 210 *	13.9	.353	2.55	.00985	.0135

* Cruise at 5,000', all other at 3,000'.

Table A-15

Light Aircraft Exhaust Emissions

MODE: Descent

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel): Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	10.4	1.155	1.23	.0294	.00366
2 (Right)	Cessna 172D	9.8	1.076	.90	.176	.0176
2 (Left)	Cessna 172D		1.113	.90	.159	.00848
3	Cessna 172I	10.7	1.069	1.34	.0364	.00729
4	Cessna 172K	10.2	1.186	1.15	.0397	.00288
5	Bonanza 36	10.4	1.147	1.26	.0249	.00293
6	Cessna 182H	11.8	.860	1.75	.0104	.00325
7	Cessna 182N	12.7	.662	2.08	.00536	-
8	Piper Apache	12.0	.812	1.82	.0120	-
9	Cessna 210	10.6	1.114	1.32	.0200	.00443

Table A-16

Light Aircraft Exhaust Emissions

MODE: Pattern

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	-	-	-	-	-
2 (Right)	Cessna 172D	11.3	.903	1.64	.0266	.00919
2 (Left)	Cessna 172D		1.019	1.43	.0337	.00791
3	Cessna 172I	11.8	.861	1.73	.0177	.00478
4	Cessna 172K	11.7	.871	1.69	.0245	.00674
5	Bonanza 36	11.0	1.025	1.47	.0185	.00262
6	Cessna 182H	11.8	.856	1.75	.0132	.00214
7	Cessna 182N	12.2	.778	1.89	.00645	-
8	Piper Apache	12.0	.807	1.83	.0133	-
9	Cessna 210	10.3	1.175	1.22	.0220	.00376

Table A-17

Light Aircraft Exhaust Emissions

MODE: Final Approach

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	11.5	.851	1.49	.0992	.00256
2 (Right)	Cessna 172D	11.1	-	-	-	-
2 (Left)	Cessna 172D		.904	1.31	.131	.00540
3	Cessna 172I	12.8	.561	1.94	.101	.00699
4	Cessna 172K	11.6	.770	1.39	.174	.00368
5	Bonanza 36	10.9	.874	1.18	.189	.00137
6	Cessna 182H	12.7	.635	1.96	.0578	.00167
7	Cessna 182N	11.6	.875	1.60	.0538	-
8	Piper Apache	11.3	.966	1.57	.0148	-
9	Cessna 210	10.8	.993	1.23	.112	.00235

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Table A-18

Light Aircraft Exhaust Emissions

MODE: Taxi - Final

Aircraft Number	Aircraft Type	Air-Fuel Ratio (lb/lb)	Emissions (lb/lb Fuel) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	11.4	.933	1.59	.0254	.00280
2 (Right)	Cessna 172D	10.5	1.090	1.24	.0591	.00507
2 (Left)	Cessna 172D		1.106	1.27	.0426	.00270
3	Cessna 172I	13.4	.475	2.30	.0302	.00620
4	Cessna 172K	10.5	1.087	1.23	.0651	.00225
5	Bonanza 36	11.4	.849	1.40	.130	.00143
6	Cessna 182H	12.2	.748	1.88	.0247	.00140
7	Cessna 182N	11.6	.890	1.66	.0257	-
8	Piper Apache	12.4	.715	1.91	.0322	.0195
9	Cessna 210	11.1	.883	1.30	.147	.00270

Table A-19

Light Aircraft Exhaust Emissions

MODE: Taxi - Initial

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	.204*	.208	.294	.00571	.000292
2 (Right)	Cessna 172D	.204*	.236	.245	.00759	.000398
2 (Left)	Cessna 172D					
3	Cessna 172I	.204*	.128	.424	.00475	.000636
4	Cessna 172K	.204	.239	.218	.0153	.000359
5	Bonanza 36	.472	.407	.727	.0374	.000784
6	Cessna 182H	.177	.126	.343	.00343	.000216
7	Cessna 182N	.216	.179	.384	.00378	.000335
8	Piper Apache	.296	.268	.485	.00657	.00167
9	Cessna 210	.243	.216	.362	.0199	.000683

* Fuel Flow estimated from measurements on Aircraft #4.

Table A-20

Exhaust Emission Rates

for Light Aircraft

MODE: Run-up

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	-	-	-	-	-
2 (Right)	Cessna 172D	.470*	.548	.571	.0141	.00212
2 (Left)	Cessna 172D					
3	Cessna 172I	.470*	.351	.893	.00992	.00262
4	Cessna 172K	.470	.442	.710	.0225	.00273
5	Bonanza 36	.647	.567	1.003	.0440	.00151
6	Cessna 182H	.455**	.382	.793	.00920	.000666
7	Cessna 182N	.562**	.453	1.028	.00691	.00268
8	Piper Apache	.424**	.387	.697	.00840	.00996
9	Cessna 210	.841**	.733	1.388	.0320	.00405

* Fuel Flow estimated from measurements on Aircraft #4.

** Fuel Flow estimated from measurements on other aircraft.

Table A-21

Exhaust Emission Rates

for Light Aircraft

MODE: Ascent

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	1.093*	.967	1.87	.0111	.0139
2 (Right) / 2 (Left)	Cessna 172D / Cessna 172D	1.093*	1.041	1.73	.0204	.0124
3	Cessna 172I	1.093*	1.001	1.81	.0142	.00844
4	Cessna 172K	1.093	1.022	1.79	.00994	.00422
5	Bonanza 36	1.479	1.340	2.46	.0226	.00512
6	Cessna 182H	1.028	.758	2.00	.00911	.00232
7	Cessna 182N	1.133	.800	2.28	.00590	.00387
8	Piper Apache	1.069	.724	2.18	.0109	
9	Cessna 210	1.885	1.747	3.09	.0251	.00716

* Fuel Flow estimated from measurements on Aircraft #4.

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Table A-22

Exhaust Emission Rates

for Light Aircraft

MODE: Rich Cruise

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	0.842*	.621	1.64	.00726	.0115
2 (Right)	Cessna 172D	0.842*	.822	1.31	.0137	.00618
2 (Left)	Cessna 172D					
3	Cessna 172I	0.842*	.690	1.52	.00935	.00249
4	Cessna 172K	0.842	.704	1.52	.00650	.00135
5	Bonanza 36	1.57	1.685	2.20	.0231	.00231
6	Cessna 182H	.933	.709	1.79	.00677	.00127
7	Cessna 182N	1.17	1.051	2.00	.00606	.00221
8	Piper Apache	.648	.648	1.70	.00936	-
9	Cessna 210	1.74	1.557	2.94	.0214	.00602

* Fuel Flow estimated from measurements on Aircraft #4.

Table A-23
Exhaust Emission Rates
for Light Aircraft

MODE: Lean Cruise

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	.717*	.0568	2.16	.00128	.0406
2 (Right)	Cessna 172D	.717*	.266	1.81	.00789	.0311
2 (Left)	Cessna 172D					
3	Cessna 172I	.717*	.205	1.91	.00412	.0305
4	Cessna 172K	.717	.267	1.82	.00351	.0270
5	Bonanza 36	1.187	.665	2.64	.0126	.0310
6	Cessna 182H	.826	.279	2.14	.00373	.0440
7	Cessna 182N	.933	.188	2.62	.00260	.0912
8	Piper Apache	.758	.287	1.92	.00318	-
9	Cessna 210	1.52	.537	3.87	.0150	.0205

*Fuel Flow estimated from measurements on Aircraft #4.

Table A-24

Exhaust Emission Rates

for Light Aircraft

MODE: Descent

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	.261*	.302	.322	.00769	.000957
2 (Right)	Cessna 172D }	.261*	.286	.236	.0439	.00341
2 (Left)	Cessna 172D					
3	Cessna 172I	.261*	.279	.351	.00953	.00191
4	Cessna 172K	.261	.310	.300	.0104	.000752
5	Bonanza 36	.967	1.109	1.218	.0241	.00283
6	Cessna 182H	.648	.557	1.134	.00674	.00211
7	Cessna 182N	.706	.467	1.468	.00378	-
8	Piper Apache	.505	.410	.919	.00606	-
9	Cessna 210	.991	1.104	1.308	.0198	.00439

* Fuel Flow estimated from measurements on Aircraft #4.

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Table A-25

Exhaust Emission Rates

for Light Aircraft

MODE: Pattern

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	-	-	-	-	-
2 (Right)	Cessna 172D	.859 *	.825	1.319	.0259	.00734
2 (Left)	Cessna 172D					
3	Cessna 172I	.859*	.740	1.486	.0152	.00411
4	Cessna 172K	.859	.748	1.452	.0210	.00579
5	Bonanza 36	.889	.911	1.307	.0164	.00233
6	Cessna 182H	.476**	.407	.833	.00628	.00102
7	Cessna 182N	.393	.306	.742	.00253	-
8	Piper Apache	.446**	.360	.816	.00593	-
9	Cessna 210	1.069	1.256	1.304	.0235	.00420

* Fuel Flow estimated from measurements on Aircraft #4.
** Fuel Flow estimated from measurements on other aircraft.

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Table A-26

Exhaust Emission Rates

for Light Aircraft

MODE: Final Approach

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	.188*	.160	.280	.0186	.000481
2 (Right)	Cessna 172D	.188*	.170	.246	.0246	.00102
2 (Left)	Cessna 172D					
3	Cessna 172I	.188*	.150	.364	.0190	.00131
4	Cessna 172K	.188	.144	.261	.0326	.000690
5	Bonanza 36	.466 **	.407	.550	.0881	.000638
6	Cessna 182H	.206 **	.131	.404	.0119	.000344
7	Cessna 182N	.216	.189	.346	.00333	-
8	Piper Apache	.193 **	.186	.303	.00286	-
9	Cessna 210	.240 **	.238	.295	.0269	.000564

* Fuel Flow estimated from measurements on Aircraft #4.
** Fuel Flow estimated from measurements on other aircraft.

Table A-27

Exhaust Emission Rates

for Light Aircraft

MODE: Taxi - Final

Aircraft Number	Aircraft Type	Fuel Flow Rate (lb/min)	Emissions (lb/min) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
1	Cessna 172K	.188*	.175	.299	.00478	.000526
2 (Right)	Cessna 172D	.188*	.206	.236	.00956	.000730
2 (Left)	Cessna 172D					
3	Cessna 172I	.188*	.0893	.423	.00568	.00117
4	Cessna 172K	.188**	.204	.231	.0122	.000423
5	Bonanza 36	.466	.396	.652	.0606	.000666
6	Cessna 182H	.206**	.154	.387	.00509	.000288
7	Cessna 182N	.216	.192	.359	.00555	-
8	Piper Apache	.193**	.138	.369	.00621	.00376
9	Cessna 210	.240**	.212	.312	.0353	.000648

* Fuel Flow estimated from measurements on Aircraft #4.
** Fuel Flow estimated from measurements on other aircraft.

Table A-28. Exhaust Emissions During
Normal Operating Cycles for
Aircraft Number 1 - Cessna 172K

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	0.936	1.323	0.0257	0.00131
Run-up	1.5	-	-	-	-
Ascent	6	5.80	11.22	0.0666	0.0834
Rich Cruise	6.5	4.04	10.66	0.0472	0.0748
Lean Cruise	2.5	0.142	5.40	0.00320	0.102
Descent	7.5	2.27	2.42	0.0577	0.00718
Pattern	2	-	-	-	-
Final Approach	2	0.320	0.560	0.0372	0.000962
Taxi - Final	1.7	0.298	0.508	0.00813	0.000894
Total-TCL Cycle*	34.2	-	-	-	-
Total-LTO Cycle**	25.2	-	-	-	-

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-29. Exhaust Emissions During Normal Operating Cycles for Aircraft Number 2 - Cessna 172D

Mode	Mode Time (Min.)	Mode Emissions (lb.)			
		Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	1.062	1.103	0.0341	0.00179
Run-up	1.5	0.822	0.857	0.0212	0.00318
Ascent	6	6.25	10.38	0.122	0.0744
Rich Cruise	6.5	5.34	8.52	0.0891	0.0402
Lean Cruise	2.5	0.665	4.53	0.0197	0.0778
Descent	7.5	2.15	1.77	0.329	0.0256
Pattern	2	1.65	2.64	0.0518	0.0147
Final Approach	2	0.340	0.492	0.0492	0.00204
Taxi - Final	1.7	0.350	0.401	0.0163	0.00124
Total-TCL Cycle*	34.2	18.63	30.69	.732	.2410
Total-LTO Cycle**	25.2	12.62	17.64	.624	.1230

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-30. Exhaust Emissions During
Normal Operating Cycles for
Aircraft Number 3 - Cessna 172I

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	0.576	1.91	0.0214	0.00286
Run-up	1.5	0.527	1.34	0.0149	0.00393
Ascent	6	6.01	10.86	0.0852	0.0506
Rich Cruise	6.5	4.49	9.88	0.0608	0.0162
Lean Cruise	2.5	0.513	4.78	0.0103	0.0763
Descent	7.5	2.09	2.63	0.0715	0.0143
Pattern	2	1.48	2.97	0.0304	0.00822
Final Approach	2	0.300	0.728	0.0380	0.00262
Taxi - Final	1.7	0.152	0.719	0.00966	0.00199
Total-TCL Cycle*	34.2	16.14	35.82	.2207	.1770
Total-LTO Cycle**	25.2	11.14	21.16	.1496	.0845

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-31. Exhaust Emissions During Normal Operating Cycles for Aircraft Number 4 - Cessna 172K

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	1.076	0.981	0.0689	0.00162
Run-up	1.5	0.663	1.065	0.0338	0.00410
Ascent	6	6.13	10.74	0.0596	0.0253
Rich Cruise	6.5	4.58	9.88	0.0423	0.00878
Lean Cruise	2.5	0.668	4.55	0.00878	0.0675
Descent	7.5	2.33	2.25	0.0780	0.00564
Pattern	2	1.50	2.90	0.0420	0.0116
Final Approach	2	0.288	0.522	0.0652	0.00138
Taxi - Final	1.7	0.347	0.393	0.0207	0.000719
Total-TCL Cycle*	34.2	17.56	33.28	.4193	.1266
Total-LTO Cycle**	25.2	12.33	18.85	.3682	.0504

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-32. Exhaust Emissions During
Normal Operating Cycles for
Aircraft Number 5 - Bonanza 36

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	1.83	3.27	0.168	0.00353
Run-up	1.5	0.851	1.51	0.0660	0.00227
Ascent	6	8.04	14.8	0.136	0.0307
Rich Cruise	6.5	10.95	14.3	0.150	0.0150
Lean Cruise	2.5	1.66	6.60	0.0315	0.0775
Descent	7.5	8.32	9.14	0.181	0.212
Pattern	2	1.82	2.61	0.0328	0.00466
Final Approach	2	0.814	1.10	0.176	0.00128
Taxi - Final	1.7	0.673	1.11	0.103	0.00113
Total-TCL Cycle*	34.2	26.92	54.4	1.044	.348
Total-LTO Cycle**	25.2	14.31	33.5	.863	.256

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-33. Exhaust Emissions During
Normal Operating Cycles for
Aircraft Number 6 - Cessna 182H

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	0.567	1.54	0.0154	0.000972
Run-up	1.5	0.573	1.19	0.0138	0.000999
Ascent	6	4.55	12.0	0.0547	0.0139
Rich Cruise	6.5	4.61	11.6	0.0440	0.00826
Lean Cruise	2.5	0.698	5.35	0.00933	0.110
Descent	7.5	4.18	8.51	0.0506	0.158
Pattern	2	0.814	1.67	0.0126	0.00204
Final Approach	2	0.262	0.808	0.0238	0.000688
Taxi - Final	1.7	0.262	0.658	0.00865	0.000490
Total-TCL Cycle*	34.2	16.52	43.3	.2329	.295
Total-LTO Cycle**	25.2	11.21	26.4	.1796	.177

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-34. Exhaust Emissions During Normal Operating Cycles for Aircraft Number 7 - Cessna 182N

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	0.806	1.73	0.0170	0.00151
Run-up	1.5	0.680	1.54	0.0104	0.00402
Ascent	6	4.80	13.7	0.0354	0.0232
Rich Cruise	6.5	6.83	13.0	0.0394	0.0144
Lean Cruise	2.5	0.0470	6.55	0.00650	0.228
Descent	7.5	3.50	11.0	0.0284	-
Pattern	2	0.612	1.48	0.00506	-
Final Approach	2	0.378	0.692	0.00666	-
Taxi - Final	1.7	0.326	0.610	0.00944	-
Total-TCL Cycle*	34.2	18.40	50.3	0.1583	-
Total-LTO Cycle**	25.2	11.10	30.8	0.1124	-

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-35. Exhaust Emissions During
Normal Operating Cycles for
Aircraft Number 8 - Piper Apache
(1 Engine)

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	1.21	2.18	0.0296	0.00752
Run-up	1.5	0.581	1.046	0.0126	0.0149
Ascent	6	4.34	13.1	0.0654	-
Rich Cruise	6.5	4.21	11.1	0.0608	-
Lean Cruise	2.5	0.718	4.80	0.00795	-
Descent	7.5	3.08	6.89	0.0455	-
Pattern	2	0.720	1.63	0.0117	-
Final Approach	2	0.372	0.606	0.00572	-
Taxi - Final	1.7	0.235	0.627	0.0106	0.00639
Total-TCL Cycle*	34.2	15.47	42.0	.2499	-
Total-LTO Cycle**	25.2	10.54	26.1	.181	-

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-36. Exhaust Emissions During
Normal Operating Cycles for
Aircraft Number 9 - Cessna 210

Mode	Mode Time (Min.)	Mode Emissions (lb.) Carbon Monoxide	Carbon Dioxide	Hydrocarbons (as Hexane)	Nitrogen Oxides (as NO_2)
Taxi - Initial	4.5	0.972	1.63	0.0895	0.00307
Run-up	1.5	1.10	2.08	0.0480	0.00608
Ascent	6	10.48	18.5	0.151	0.0430
Rich Cruise	6.5	10.12	19.1	0.139	0.0391
Lean Cruise	2.5	1.34	9.68	0.0375	0.0513
Descent	7.5	8.28	9.81	0.149	0.0329
Pattern	2	2.51	2.61	0.470	0.00840
Final Approach	2	0.476	0.590	0.00538	0.00113
Taxi - Final	1.7	0.360	0.530	0.0600	0.00110
Total-TCL Cycle*	34.2	35.64	64.5	1.149	.1861
Total-LTO Cycle**	25.2	24.18	35.8	.973	.0957

* Cycle as defined in Section 5.1.
** Landing-Takeoff Cycle - as TCL cycle without cruise modes.

Table A-37. Comparison of Stack and Corrected Plume Analysis to Detect Afterburning

Aircraft	Flight	Mode	Stack CO (%)	Stack CO_2 (%)	Stack HC (PPMC)	Corrected Plume CO (%)	Corrected Plume CO_2 (%)	Corrected Plume HC (PPMC)	Dilution Factor	% Change in Conc. CO	% Change in Conc. CO_2	% Change in Conc. HC
1	1	Ascent	6.85	9.60	450	6.54	9.89	528	11.33	-4.48	3.12	17.45
1	2	Cruise	4.84	8.70	380	5.05	8.44	808	48.58	4.38	-2.93	112.73
1	3	Cruise	6.50	8.65	480	6.58	8.58	286	17.20	1.37	-.80	-40.35
1	3	Descent	5.43	3.20	555	5.30	3.24	1294	7.33	-2.22	1.46	133.31
1	4	Ascent	7.30	9.68	425	7.67	9.27	671	18.33	5.18	-4.16	58.10
1	4	Descent	6.40	2.60	1070	5.94	3.07	876	13.15	-7.08	18.18	-18.04
1	6	Ascent	6.96	8.41	640	5.63	9.76	366	55.22	-19.07	16.10	-42.70
1	6	Cruise	5.75	8.12	540	2.55	11.33	347	40.18	-55.62	39.62	-35.70
1	6	Descent	6.90	2.88	2960	5.75	4.16	1601	15.01	-16.63	44.58	-45.90
2	4	Taxi	10.40	6.80	2640	8.01	9.25	2000	27.92	-22.97	36.08	-24.23
2	4	Ascent	8.32	7.86	1305	8.68	7.48	1365	37.25	4.42	-4.75	4.60
2	4	Cruise	6.52	8.16	920	6.53	8.15	831	33.75	.23	-.08	-9.53
2	5	Taxi	11.70	7.15	6200	12.16	6.92	3784	18.31	4.00	-3.17	-38.96
2	5	Ascent	11.72	11.70	1280	10.92	12.38	2419	58.10	-6.80	5.83	89.00
2	5	Cruise	8.38	10.90	945	7.98	11.24	1378	44.98	-4.66	3.18	45.85
2	7	Ascent	8.00	8.00	1210	7.61	8.20	3027	32.68	-4.81	2.54	150.20
2	7	Cruise	7.00	8.50	780	7.23	8.14	1989	4.82	3.39	-4.21	155.08
2	8	Ascent	7.40	9.70	820	7.37	9.57	2318	55.67	-.38	-1.25	182.73
2	9	Ascent	8.00	9.10	730	7.54	9.39	2333	53.46	-5.63	3.18	219.62
2	9	Cruise	8.40	7.47	825	8.23	7.48	2310	48.50	-1.95	.20	180.08
2	10	Ascent	7.62	8.70	775	7.67	8.49	2211	40.46	.74	-2.30	185.31
2	10	Cruise	8.20	7.25	800	7.52	7.76	2442	43.11	-8.24	7.06	205.25
2	10	Descent	9.04	5.25	12400	9.67	5.04	8179	86.42	6.97	-3.97	-34.03
2	11	Ascent	8.00	7.90	810	7.91	7.81	2528	39.12	-1.11	-1.04	212.20
2	12	Cruise	7.34	8.72	790	7.97	7.92	2372	29.05	8.67	-9.11	200.29

Table A-37 Continued

Aircraft	Flight	Mode	Stack CO (%)	Stack CO_2 (%)	Stack HC (PPMC)	Corrected Plume CO (%)	Corrected Plume CO_2 (%)	Corrected Plume HC (PPMC)	Dilution Factor	% Change in Conc. CO	% Change in Conc. CO_2	% Change in Conc. HC
3	1	Ascent	9.28	9.73	980	9.70	9.11	2866	48.05	4.55	-6.37	192.47
3	1	Cruise	8.02	9.65	740	7.96	9.54	2341	42.07	-.62	-1.13	216.38
3	1	Descent	7.80	8.42	1103	7.39	8.64	2891	38.22	-5.21	2.61	162.14
3	4	Ascent	9.38	9.40	870	10.08	8.53	2521	19.44	7.48	-9.25	189.80
3	4	Cruise	7.72	9.60	660	7.34	9.83	2120	22.64	-4.87	2.39	221.27
3	4	Descent	8.17	7.80	1590	8.70	7.09	3314	23.56	6.49	-9.10	108.45
3	5	Ascent	9.87	11.97	905	10.29	11.33	3021	57.39	4.26	-5.34	233.84
3	5	Cruise	7.90	11.38	640	7.92	11.13	2829	66.36	.29	-2.19	342.13
3	6	Ascent	8.68	11.17	840	9.37	10.26	3002	58.13	7.96	-8.14	257.38
3	6	Cruise	6.93	10.59	630	7.25	10.01	3109	62.64	4.67	-5.47	393.57
3	7	Descent	10.37	6.82	2360	10.50	6.43	4797	18.19	1.34	-5.71	103.28
3	8	Ascent	9.50	11.10	890	9.99	10.38	3086	60.95	5.16	-6.48	246.84
3	8	Cruise	7.92	10.59	680	7.93	10.37	2690	63.10	.23	-2.07	295.71
3	11	Taxi	6.39	10.44	1055	6.02	10.60	3044	41.66	-5.85	1.53	218.43
3	11	Cruise	7.45	11.80	650	7.64	11.42	2435	64.70	2.66	-3.22	274.71
3	11	Descent	11.24	7.00	2170	10.96	6.98	5122	23.75	-2.48	-.28	136.05
4	2	Taxi	11.17	6.51	4650	10.26	7.02	8590	64.62	-8.12	7.83	84.73
4	2	Cruise	6.18	10.39	595	6.32	10.17	1279	36.94	2.35	-2.11	115.09
4	4	Ascent	8.50	10.08	640	9.12	9.34	1791	35.37	7.34	-7.34	179.92
4	4	Cruise	7.41	10.32	415	7.81	9.77	1761	28.57	5.49	-5.32	324.37
4	4	Descent	10.84	6.91	2000	10.78	6.84	3108	20.50	-.46	-1.01	55.43
4	5	Taxi	10.60	7.91	2040	10.98	7.07	6509	59.76	3.62	-10.61	219.11
4	5	Ascent	8.78	10.00	580	9.54	9.13	1609	38.64	8.66	-8.70	177.42
4	5	Descent	11.39	6.83	3800	10.86	7.43	3013	20.27	-4.64	8.78	-20.68
4	6	Taxi	12.74	7.25	5700	12.84	6.61	10960	73.10	.81	-8.82	92.28
4	6	Ascent	8.77	11.00	560	9.52	10.20	907	36.82	8.62	-7.27	62.02
4	6	Cruise	7.61	10.52	500	7.96	10.07	1488	31.24	4.60	-4.27	197.68
4	6	Descent	10.70	7.68	1330	10.46	7.78	2629	22.16	-2.19	1.30	97.70
4	7	Ascent	9.05	9.98	520	8.73	10.15	1884	38.73	-3.43	1.70	262.34
4	7	Cruise	7.76	10.65	420	7.13	11.16	1541	33.78	-8.05	4.78	267.10
4	7	Descent	13.02	6.52	2800	11.97	6.84	10018	23.87	-8.02	4.90	257.80
4	8	Cruise	6.88	9.51	420	7.42	8.88	1244	26.13	7.87	-6.62	196.41
5	1	Taxi	8.78	8.74	27000	10.36	8.59	12599	22.82	18.06	-1.71	-53.33
5	1	Ascent	8.33	11.04	2391	8.91	10.40	2911	42.41	7.03	-5.79	21.76

Table A-37 Continued

Aircraft	Flight	Mode	Stack CO (%)	Stack CO_2 (%)	Stack HC (PPMC)	Corrected Plume CO (%)	Corrected Plume CO_2 (%)	Corrected Plume HC (PPMC)	Dilution Factor	% Change in Conc. CO	% Change in Conc. CO_2	% Change in Conc. HC
5	2	Taxi	8.88	9.09	12771	9.53	8.58	11309	21.75	7.36	-5.61	-11.44
5	2	Cruise	9.30	9.32	2220	9.50	8.98	3505	60.82	2.21	-3.64	57.91
5	2	Descent	8.99	8.35	2739	8.49	8.78	3354	71.92	-5.51	5.14	22.47
5	3	Ascent	8.46	9.75	2400	7.71	10.48	2477	17.48	-8.78	7.48	3.21
5	3	Cruise	9.68	8.72	2520	9.02	9.27	3569	65.33	-6.79	6.30	41.65
5	3	Descent	8.92	11.21	2709	9.74	10.22	4270	78.16	9.27	-8.83	57.65
5	4	Taxi	8.86	9.81	12600	9.14	9.62	11610	41.03	3.24	-1.93	-7.84
5	4	Descent	12.40	6.21	5709	11.64	6.10	14314	48.58	-6.12	-1.77	150.74
5	5	Ascent	8.80	9.71	3960	8.83	9.79	2769	16.82	.39	.82	-30.06
5	5	Cruise	11.09	7.49	3330	11.26	7.10	5407	51.18	1.58	-5.20	62.38
5	5	Descent	10.34	7.18	3960	10.32	7.17	4133	58.51	-.12	-.13	4.37
5	6	Taxi	8.30	8.45	21300	7.68	9.36	18319	43.41	-7.46	10.76	-13.99
5	6	Ascent	8.88	10.19	2370	8.12	10.76	4102	37.41	-8.47	5.59	73.09
5	6	Descent	10.70	6.92	3435	10.91	6.41	6404	73.92	1.97	-7.36	86.46
5	7	Taxi	9.00	10.10	18540	9.97	9.51	14658	25.23	10.82	-5.84	-20.93
5	7	Ascent	8.94	10.24	3534	9.29	9.91	3200	17.23	4.01	-3.22	-9.44
5	7	Cruise	10.59	8.73	3000	11.00	8.13	4777	54.51	3.93	-6.87	59.25
5	8	Taxi	8.01	10.48	9900	8.89	9.58	9977	28.11	11.07	-8.58	.78
5	8	Ascent	8.40	10.53	2790	8.48	10.41	3072	45.42	1.01	-1.13	10.12
5	8	Cruise	9.82	9.37	2775	10.01	9.03	4177	68.88	1.99	-3.62	50.53
5	8	Descent	9.82	6.85	5100	10.31	6.52	3344	50.94	5.06	-4.81	-34.42
5	9	Ascent	8.50	9.87	2340	8.63	9.68	2876	15.83	1.55	-1.92	22.94
5	9	Cruise	9.80	8.62	2580	9.50	8.71	4582	56.12	-2.98	1.04	77.59
5	10	Taxi	8.14	9.99	15600	9.01	9.51	11522	25.05	10.79	-4.80	-26.13
5	10	Ascent	8.54	10.25	2400	8.59	10.18	2578	15.28	.58	-.68	7.42
5	10	Cruise	9.52	8.91	2490	9.58	8.66	4284	60.64	.71	-2.80	72.05
5	10	Descent	10.48	6.51	6000	10.87	6.35	3629	50.66	3.74	-2.45	-39.50
6	1	Taxi	6.91	10.47	4074	7.06	10.42	2995	17.22	2.26	-.47	-26.47
6	1	Ascent	7.78	10.89	2154	7.23	11.48	1611	17.02	-6.99	5.41	-25.17
6	1	Cruise	7.68	11.20	1404	7.48	11.37	1619	20.32	-2.58	1.51	15.31
6	2	Taxi	6.70	11.11	4050	6.57	11.38	2527	14.87	-1.81	2.43	-37.59
6	2	Ascent	7.55	11.02	1695	7.40	11.17	1571	15.93	-1.93	1.36	-7.25
6	2	Cruise	7.78	10.87	1440	7.70	10.92	1604	17.90	-.96	.45	11.44
6	2	Descent	8.52	10.39	2520	8.18	10.77	2035	24.93	-3.96	3.65	-19.20
6	3	Taxi	5.79	11.99	2190	6.14	11.61	2445	16.75	6.06	-3.16	11.65
6	3	Ascent	7.73	11.64	1752	8.18	11.17	1858	15.40	5.91	-4.03	6.06
6	3	Descent	7.40	10.12	2142	7.26	10.29	1755	23.52	-1.79	1.67	-18.05
6	4	Taxi	7.71	11.72	4200	7.96	11.52	3580	19.15	3.32	-1.70	-14.75
6	4	Ascent	7.81	12.61	1980	8.47	11.98	1642	17.92	8.48	-4.99	-17.04

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Table A-37 Continued

Aircraft	Flight	Mode	Stack CO (%)	Stack CO_2 (%)	Stack HC (PPMC)	Corrected Plume CO (%)	Corrected Plume CO_2 (%)	Corrected Plume HC (PPMC)	Dilution Factor	% Change in Conc. CO	% Change in Conc. CO_2	% Change in Conc. HC
6	4	Cruise	8.07	11.86	1428	8.30	11.62	1485	16.56	2.87	-2.02	3.99
6	4	Descent	8.52	10.65	1920	8.53	10.64	1863	31.77	.16	-.09	-2.96
6	5	Taxi	7.10	11.44	3660	7.13	11.47	2979	18.70	.52	.26	-18.59
6	5	Ascent	7.80	12.11	1833	7.89	12.04	1539	21.19	1.20	-.57	-16.02
6	5	Cruise	7.55	11.50	1404	7.37	11.74	1437	25.38	-2.32	2.08	2.41
6	5	Descent	7.87	10.25	2079	7.86	10.27	1892	23.76	-.09	.19	-8.94
6	6	Taxi	7.08	11.21	4110	7.36	11.06	2748	23.30	3.97	-1.33	-33.13
6	6	Ascent	6.51	13.08	1686	7.84	11.75	1613	17.05	20.45	-10.16	-4.27
6	6	Cruise	7.04	11.74	1251	6.82	11.94	1331	16.11	-3.06	1.70	6.46
6	7	Ascent	7.11	13.15	1545	7.33	12.92	1540	18.86	3.14	-1.74	-.30
6	7	Cruise	7.14	12.02	1260	6.94	12.20	1344	20.17	-2.70	1.49	6.70
6	7	Descent	8.37	10.33	1692	8.23	10.46	1701	24.09	-1.67	1.25	.58
6	8	Taxi	6.99	11.06	4260	7.54	10.62	3071	20.61	7.92	-3.97	-27.90
6	8	Ascent	6.99	12.26	1710	7.36	11.90	1518	16.75	5.42	-2.93	-11.18
6	8	Cruise	6.70	11.57	1284	6.85	11.41	1280	17.87	2.26	-1.38	-.28
6	8	Descent	7.80	9.84	1806	7.82	9.83	1619	22.60	.26	-.10	-10.31
6	9	Ascent	7.19	13.85	1695	8.19	12.84	1653	18.86	14.02	-7.29	-2.45
6	9	Cruise	6.02	13.00	1206	6.26	12.75	1256	24.80	4.04	-1.92	4.16
6	9	Descent	6.64	11.52	1866	6.86	11.31	1612	25.33	3.43	-1.82	-13.59
6	10	Cruise	7.88	13.23	1500	8.04	13.06	1488	19.41	2.12	-1.28	-.78
6	10	Descent	8.70	11.28	1971	8.66	11.33	1740	29.68	-.34	.44	-11.69
7	1	Cruise	8.60	10.70	1140	8.90	10.37	1296	14.96	3.54	-3.08	13.74
7	3	Taxi	6.30	10.80	2370	6.86	10.27	2024	18.58	8.95	-4.90	-14.56
7	3	Ascent	5.90	11.60	570	6.00	11.47	742	12.05	1.84	-1.12	30.34
7	3	Cruise	10.60	10.50	720	8.99	12.06	1132	5.84	-15.16	14.85	57.28
7	3	Descent	5.10	11.60	570	5.17	11.50	744	12.08	1.53	-.86	30.68
7	4	Taxi	6.20	9.90	2580	6.06	10.12	1725	17.62	-2.18	2.22	-33.10
7	4	Ascent	5.80	10.10	900	5.14	10.77	700	11.17	-11.31	6.63	-22.20
7	4	Cruise	7.10	10.10	900	7.04	10.15	930	5.52	-.82	.49	3.43
7	5	Ascent	8.50	13.50	1110	9.69	12.27	1314	14.49	14.11	-9.11	18.39
7	6	Taxi	12.90	11.30	2820	10.48	13.69	2957	25.95	-18.69	21.15	4.86
7	6	Descent	8.20	12.50	990	9.41	11.29	907	12.32	14.80	-9.68	-8.34
7	6	Ascent	6.80	10.70	2160	6.46	11.23	1808	26.33	-4.86	4.95	-16.30

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Table A-37 Continued

Aircraft	Flight	Mode	Stack CO (%)	Stack CO_2 (%)	Stack HC (PPMC)	Corrected Plume CO (%)	Corrected Plume CO_2 (%)	Corrected Plume HC (PPMC)	Dilution Factor	% Change in Conc. CO	% Change in Conc. CO_2	% Change in Conc. HC
7	7	Taxi	7.30	10.50	3000	7.52	10.37	1982	18.37	3.12	-1.23	-33.90
7	7	Cruise	6.50	11.70	780	6.63	11.41	2243	10.07	2.10	-2.47	187.64
7	7	Descent	6.20	10.60	840	6.17	10.56	1473	13.82	-.40	-.37	75.45
7	8	Taxi	9.30	11.20	6600	10.41	10.43	3062	26.41	11.99	-6.87	-53.60
7	8	Cruise	9.40	10.80	1320	9.38	10.83	1112	5.71	-.17	.34	-15.74
7	8	Descent	5.00	13.10	720	5.45	12.54	1692	13.91	9.07	-4.27	135.11
7	9	Taxi	8.10	11.30	4500	9.15	10.40	2878	24.83	13.03	-7.96	-36.02
7	9	Ascent	9.50	10.80	1350	7.43	12.73	2701	15.46	-21.74	17.87	100.11
7	9	Descent	5.80	12.00	900	4.86	12.95	697	15.97	-16.11	7.91	-22.52
7	10	Taxi	8.10	11.40	3180	8.64	10.88	2865	18.49	6.71	-4.56	-9.89
7	10	Cruise	9.80	13.60	1320	11.16	12.21	1543	7.77	13.89	-10.22	16.93
7	10	Descent	5.70	14.00	1020	6.10	13.63	688	19.88	7.05	-2.64	-32.45
8	1	Taxi	8.25	7.10	3900	6.91	8.56	2594	20.76	-16.17	20.56	-33.47
8	2	Taxi	6.60	9.35	3330	6.59	9.46	2190	21.70	-.04	1.17	-34.22
8	2	Ascent	6.25	13.80	2460	6.79	13.37	1265	18.70	8.65	-3.11	-48.56
8	2	Cruise	6.20	12.30	1785	4.69	13.87	1010	18.49	-24.22	12.76	-43.38
8	2	Descent	6.60	10.80	1710	5.72	11.60	2334	19.03	-13.19	7.40	36.50
8	3	Taxi	9.60	7.35	3825	7.76	9.23	3316	19.28	-19.13	25.57	-13.30
8	3	Ascent	6.50	13.40	1545	5.54	14.36	1380	18.74	-14.64	7.16	-10.66
8	4	Taxi	6.65	9.90	3270	7.55	9.03	2854	17.00	13.65	-8.78	-12.69
8	4	Ascent	6.95	14.40	2160	5.42	15.84	3002	15.42	-21.96	10.06	38.98
8	4	Cruise	8.10	12.80	2280	5.97	15.00	1496	13.05	-26.27	17.18	-34.35
8	5	Cruise	6.30	11.60	2025	5.40	12.57	1180	11.97	-14.21	8.36	-41.69
8	5	Descent	7.35	9.05	2205	7.07	9.34	1972	11.76	-3.67	3.20	-10.52
9	3	Ascent	10.70	10.50	1680	10.64	10.47	2485	4.38	-.53	-.22	47.94
9	3	Cruise	8.95	10.00	900	8.19	10.67	1621	16.77	-8.40	6.79	80.16
9	4	Taxi	8.25	9.22	16800	8.98	9.51	6434	14.33	8.96	3.22	-61.70
9	4	Ascent	9.15	11.20	2790	8.37	12.04	2088	4.67	-8.42	7.51	-25.14
9	4	Cruise	8.00	9.70	2235	7.65	10.08	1864	15.98	-4.34	3.96	-16.59
9	9	Taxi	7.70	10.10	14100	8.10	9.44	16636	61.40	5.26	-6.52	17.98
9	9	Ascent	10.75	11.00	2160	11.29	10.38	2863	4.09	5.07	-5.59	32.55
9	9	Cruise	9.60	9.80	2580	9.44	9.98	2239	16.51	-1.61	1.92	-13.18
9	10	Taxi	7.80	8.65	16350	7.60	8.88	15976	25.12	-2.50	2.68	-2.28
9	10	Ascent	9.35	11.10	3240	9.43	11.08	2543	3.95	.90	-.13	-21.50
9	10	Cruise	8.10	10.30	2295	7.91	10.50	2054	13.91	-2.25	2.00	-10.48
9	10	Descent	8.65	8.20	3930	7.95	8.89	3983	72.91	-8.03	8.41	1.37