# SURVEY OF AIRCRAFT EMISSIONS AND RELATED INSTRUMENTATION

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**16. Abstract**

This technical memorandum presents the preliminary results of a survey of transportation systems emissions monitoring requirements. Emissions of carbon monoxide, hydrocarbons, oxides of nitrogen and particulates from aircraft power plants, with emphasis on gas turbine engines, are considered. Measurement rationale for various types of aircraft is summarized. Instrumentation available for measuring these emissions is reviewed and a tabulation made of those techniques in current use. Instrumentation requiring further engineering development is briefly discussed.

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CONTENTS

# CONTENTS (Continued)

# AIRCRAFT EMISSIONS SURVEY
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## 1.0  INTRODUCTION

Studies undertaken at three major commercial airports in the United States (refs. 1,2,3) indicate that the contribution of aircraft emissions to the degradation of air quality in the urban environment is small.  The fact that this contribution is only about 1 to 2 percent of the total of all emissions must be weighted by consideration of additional factors.

(a)  The reduction of emission levels from stationary sources and motor vehicles, coupled with the forecast growth in air traffic (Figure 1) will increase the relative contribution of aircraft emissions to the total of all emissions.

(b)  The effect of these emissions on the airport and its environs has not yet been studied in depth (refs. 1,2,3,4).

(c)  The Congress has shown its desire that the level of aircraft emissions be controlled and reduced by passage of the Clean Air Act of 1967 and the Clean Air Amendments of 1970 (ref. 5).

In this survey, engine exhaust emissions of the following are considered:  long range jet, medium range jet, turboprop, piston, and the superjet.  Table I lists representative examples of each craft and its powerplant.

To facilitate analysis of the nature of aircraft emissions, use will be made of the operational landing-take-off cycle (LTO). This cycle includes engine start-up and idle, taxi, take-off run, climbout to 3000 ft, approach below 3000 ft, and landing rollout. The choice of a 3000-ft altitude "ceiling" implicitly assumes

1-1

that all emissions below this altitude diffuse back to ground level and those above this level do not affect the immediate surroundings.  While not rigorously valid for all cases, it is a useful model for study.  Figure 1 illustrates the annual activity, in terms of LTO cycles, at all U.S. FAA-controlled terminals projected through 1979.  These data indicate a doubling of air carrier activity over this decade and a projected three-fold increase in civil activity.

TABLE I.- REPRESENTATIVE AIRCRAFT POWERPLANTS

| Type | Example | Engine |
|------|---------|--------|
| Long-Range Jet | 707, DC8 | JT3D (Pratt and Whitney) |
| Medium-Range Jet | 727, 737, DC9 | JT8D (Pratt and Whitney) |
| Turboprop | Electra | Allison 501-D13 |
| Piston | DC6, Convair 440 | R2800 (Rolls Royce) |
| Superjet | 747 | JT9D (Pratt and Whitney) |

Aircraft emissions to be considered include carbon monoxide (CO), hydrocarbons (HC), nitric oxide (NO), sulfur dioxide ($SO_2$), and particulates.  Exhaust gases from piston engines are higher in CO and HC concentration, but lower in NO concentration compared to the emissions of jet aircraft.  Particulate emissions consist primarily of lead from piston planes and carbon from jet aircraft. Table II gives emission indices for each of these pollutants for each type of airplane under various operating conditions.  This table is taken from reference (6) and updated by TSC to reflect most recent data available (ref. 7).

In 1967, the gross total of emissions from all aircraft operating at FAA-controlled fields (ref. 6) was as follows:

$$CO - 2564 \text{ tons/day}$$
$$HC - 415 \text{ tons/day}$$
$$NO_x - 42.8 \text{ tons/day}$$
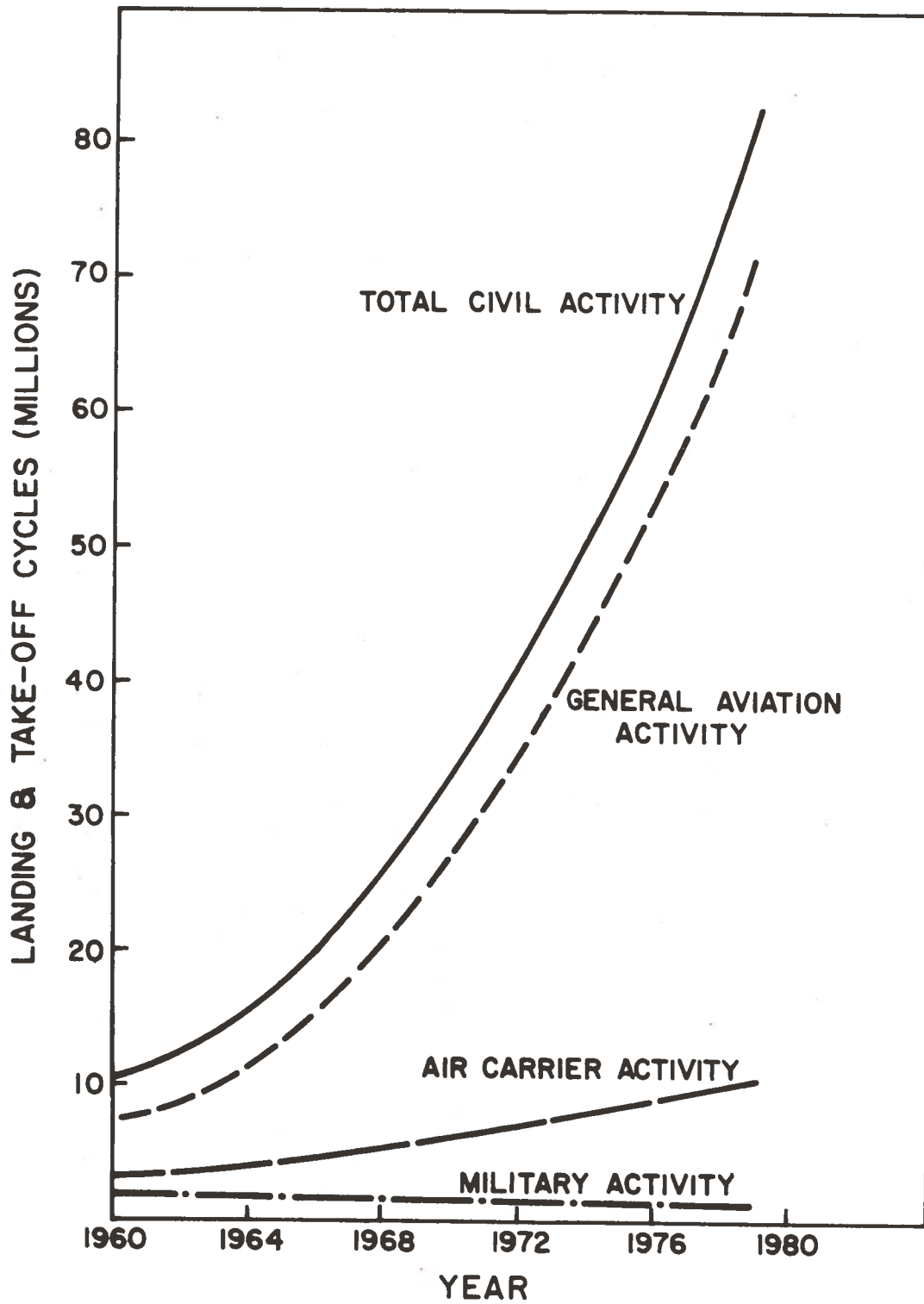$$Particulates - 17.3 \text{ tons/day}$$

Figure 1.- Source:  Federal Aviation Administration

A projection of these figures due to anticipated growth in air traffic indicates increases as follows:

$$1970 - 25\%$$
$$1975 - 60\%$$
$$1980 - 100\%$$

Table III is taken from data presented by Kittredge and McNutt (ref. 8) to illustrate the wide variations which have existed in reported emissions data. It demonstrates quite explicitly the need for standardication of measurement and reporting methods.

TABLE II.- EMISSION INDEX (PER ENGINE, LBS/1000 LBS FUEL)

### Idle and Taxi

| Aircraft | Fuel Usage/hr | CO | HC | $NO_x$ | $SO_2$ | Part |
|---|---|---|---|---|---|---|
| LRJ | 1090 lbs | 91.5 | 64. | <1.3 | | |
| MRJ | 920 | 77.3 | 14.9 | 1.3 | | |
| TP | 587 | 118. | 11.5 | 2.0 | 0.1 | 1.0 |
| Piston (Idle) | 345 | 600. | 160. | 0 | 2.0 | 0.2 |
| Piston (Taxi) | 345 | 900. | 90. | 3 | 2.0 | 0.2 |
| SJ | | 60.8 | 15. | 1.3 | | |

### Landing, Takeoff, Climbout

| Aircraft | Fuel Usage/hr | CO | HC | $NO_x$ | $SO_2$ | Part |
|---|---|---|---|---|---|---|
| LRJ | 8350 | 0.99 | 0.23 | 5.2 | | |
| MRJ | 6550 | 0.86 | 0.04 | 4.0 | | |
| TP | 1660 | 2.3 | 3.2 | 3.1 | 0.8 | 1.0 |
| Piston | 1200 | 800. | 6.0 | 5.0 | 2.0 | 1.0 |
| SJ | | <.07 | <.05 | 6.8 | | |

### Approach

| Aircraft | Fuel Usage/hr | CO | HC | $NO_x$ | $SO_2$ | Part |
|---|---|---|---|---|---|---|
| LRJ | 5840 | 5.7 | 1.8 | 2.7 | | |
| MRJ | 4120 | 4.6 | 0.19 | 2.1 | | |
| TP | 1225 | 1.6 | 0 | 2.9 | 1.0 | 1.0 |
| Piston | 700 | 800. | 60. | 5.0 | 2.0 | 1.0 |
| SJ | | 5.1 | 5.0 | 2.4 | | |

TABLE III.- EMISSIONS (LBS/LTO CYCLE)

| | CO | Hydrocarbons and Organic Gases | $NO_x$ | Particulates |
|---|---|---|---|---|
| George, et al. (ref. 1) | 16.0 | 18.3 | 6.3 | 6.2 |
| Northern Research (ref. 6) | 10.6 | 2.7 | 2.1 | 1.3 |
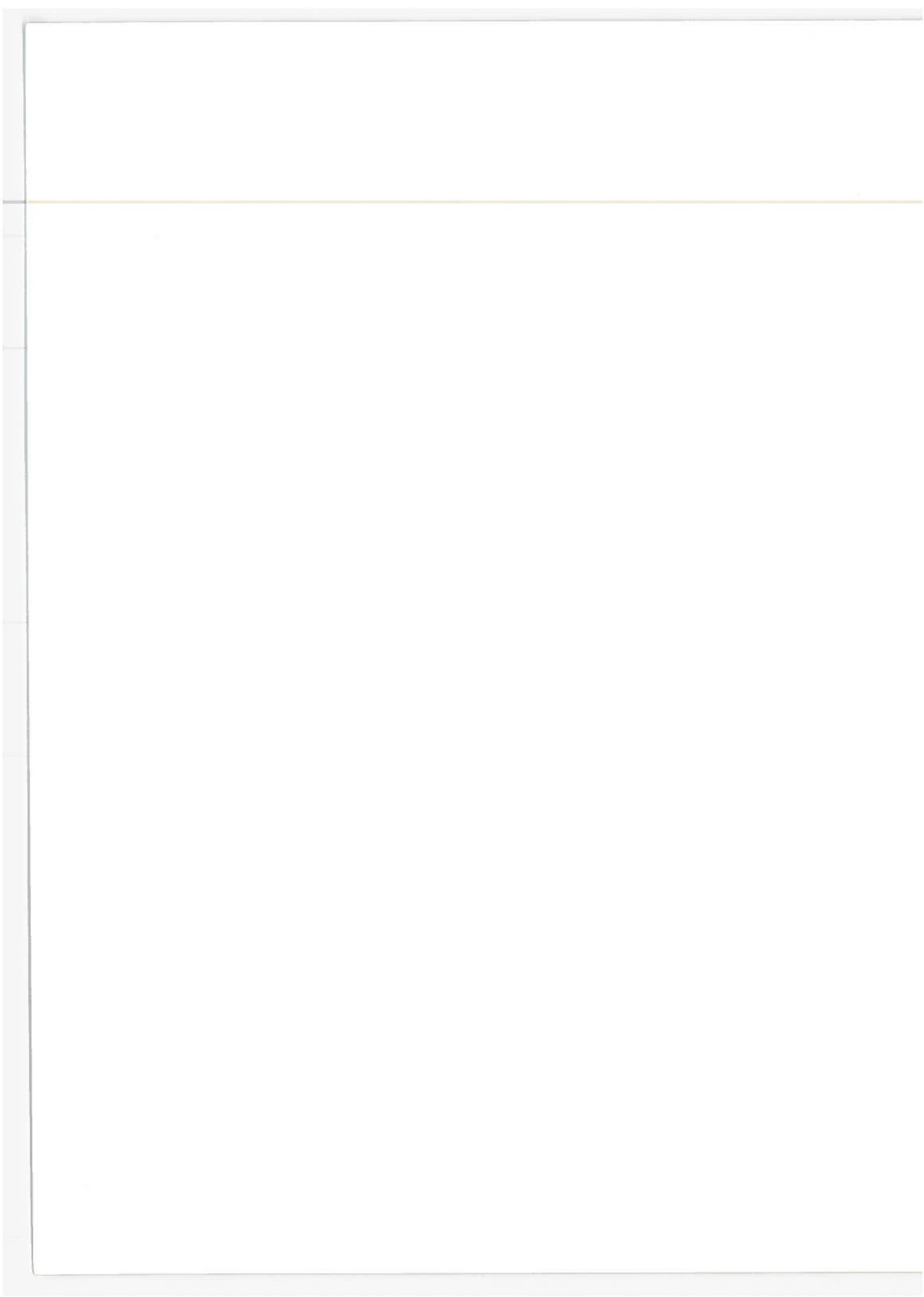
## 2.0 BACKGROUND

This section presents background information relative to measurements of carbon monoxide, hydrocarbons, oxides of nitrogen and particulate emissions from different classes of engines.

## 2.1 THE NATURE OF AIRCRAFT EMISSIONS

### 2.1.1 Carbon Monoxide

Carbon monoxide has a debilitating effect on the oxygen-transport abilities of the blood. The affinity of hemoglobin for CO is approximately 200 times that for oxygen (ref. 9) and exposure to ambient levels in excess of 200 ppm for periods in excess of one hour can result in significant impairment to the body's ability to function. Longer-term exposure to smaller concentrations of CO has been observed to result in adaptive effects, such as increased hemoglobin level in animals and may have similar effects on humans. There is no evidence to indicate that exposure to CO over long periods has cumulative effects.

With jet aircraft, CO emission is highest during ground operation, when the engine is least efficient. With present operating procedures, much of this emission occurs in the vicinity of the terminal, or is directed toward following aircraft on a taxi strip, presenting an undesirable situation. Definitive measurements of ambient CO levels at a variety of airports under these specific conditions have not yet been made and the extent of this problem is thus undefined. Recognizing this problem, the FAA has laid plans to undertake an analysis of ground operation at airports. Part of this effort will include measurements of ambient emissions levels and a detailed examination of operating procedures which can minimize these levels. Many airfields have also adopted a policy of granting "cold-engine clearances" in order to minimize the amount of time spent at idle awaiting take-off.

## 2.1.2  Hydrocarbons

The aliphatic and alicyclic hydrocarbons are, in general, biochemically inert.  No debilitating effects have been reported with exposure to levels below 500 ppm.  The aromatic hydrocarbons are biochemically active, but do not seem to produce undesirable effects from exposure to levels below 25 ppm.  Hydrocarbons do, however, play a role in the photochemical smog complex and produce membrane and eye irritation through formation of formaldehyde, acrolein, peroxyacl nitrates, and peroxylbenzoyl nitrate.

Hydrocarbons emitted from aircraft engines are the product of incomplete oxidation and cracking of the fuel.  These emissions are most serious at low-power settings, when the combustion efficiency of the engine is low.  Emission of hydrocarbons from piston engines follows a similar pattern with their relative contribution being much higher.  As with CO, it is hoped that improved operating procedures coupled with new design philosophies will help minimize these emissions from both piston and turbine engines.

## 2.1.3  Oxides of Nitrogen

The oxidation of NO by atmospheric oxygen produces Nitrogen Dioxide.  $NO_2$ is a highly toxic compound with an $LC_{50}$ (lethal concentration for 50 percent of small animals exposed) of 320 ppm for one-hour exposure.  Data on cumulative effects are sketchy, though some have reported toxic effects on workmen exposed to levels as low as 2.8 ppm for 3 to 5 years (ref. 11).  $NO_2$ also participates heavily in the photochemical smog complex and produces membrane and eye irritation.

Nitrogen Oxide (NO) is a product of combustion at high temperatures arising from the oxidation of atmospheric nitrogen.  In contrast to emissions of CO and HC, NO concentration is highest during high-power operation when the engine is operating most efficiently.  It is of interest to note that the new JT8D

engines equipped with smokeless burner cans do not show an increase in $NO_x$ production over the older versions. The FAA is presently investigating the production of $NO_x$ by gas turbines to better understand the dynamics of $NO_x$ production (ref. 10).

## 2.1.4  Sulfur Dioxide

$SO_2$ levels present in aircraft engine emissions are quite low compared to other emission sources due to the burning of low-sulfur fuel. A recent survey within the Boston Metropolitan Air Pollution Control District (ref. 12), for example, indicates that aircraft contribute 0.1 percent of the total $SO_2$ emissions. Though the $SO_2$ emission problem is not considered to be of major importance, the projected increase in number of aircraft in service coupled with the adverse effects of $SO_2$ on engines themselves make it desirable to further reduce the sulfur content of jet fuels, to the extent practical.

$SO_2$ in concentrations of greater than 5 ppm can produce bronchoconstriction in humans. Of greater annoyance is sulfuric acid, a potent irritant formed by the reaction of $SO_2$ with water and oxidation by atmospheric oxygen. The effects of sulfuric acid are dependent upon the droplet size. Present data are insufficient to provide a quantitative assessment of the health hazard with regard to aircraft emissions alone.

## 2.1.5  Particulates

Particulate engine emissions from piston aircraft are composed mostly of lead which results from the breakdown of tetraethyl lead used as an additive to enhance fuel octane ratings. Carbon particles form the majority of particulate emissions from gas turbines.

Substantial efforts have been directed toward the reduction of smoke from jet aircraft in an effort to reduce the visibility of the plume. This smoke consists of particles in a size range below 1.0-micron diameter and, though they are in the respirable

range, no toxic effects have been documented at the low concen-
trations produced by aircraft alone and encountered in airport
surroundings.  These factors aside, smoke particles have a high
degree of unacceptance by the public for obvious reasons, and
claims and complaints about their soiling properties are not
uncommon.

JT8D engines in current use are being retrofitted, with
newly developed "smokeless" burner cans, as the original equip-
ment fails.  This retrofit reduces total particulate emission by
about a factor of three with a resulting marked decrease in
plume visibility.  The retrofit program should be "substantially"
completed by late 1972.  JT9D and GE4 engines have been designed
for low smoke visibility.  Pratt and Whitney expects to have a
retrofit for the JT3D and JT4D engines available within 1.5 to
2 years (ref. 7).

In the design of gas turbine engines, production of "smoke"
was historically kept to a moderate level, since particulate
production is indicative of incomplete combustion.  Though design
of these engines resulted in combustion efficiencies in excess
of 99 percent, smoke levels remained objectionable to the public,
and particulate emissions from gas turbines accounted for a sub-
stantial fraction of total particulate concentrations in the
vicinity of commercial airports.  Recently, new engine designs
have minimized "smoke" emissions from gas turbines and retrofit
kits have been developed for the JT8D engine.

Since particulate emissions are generally measured by
weighing filters and the mass of a particle is proportional to
the cube of its diameter, a question arises as to whether
"smokeless" engines merely produce greater quantities of small
particles instead of fewer, larger particles.  This answer must
be developed through analysis of experimental data which have yet
to be obtained.

## 2.1.6 Odor

The odors produced by unburned aircraft fuels and engine exhaust products are objectionable, especially where concentration of these odorants are high (ref. 13). With increased air activity this problem will become worse and is expected to be a subject of some concern in the future as the air quality of urban areas is improved through reduction of other emissions from stationary and mobile sources.

Little work has been performed in the area of odors produced by gas turbines, though Lozano, et al. (ref. 14) report an odor dilution threshold varying from 15 to 1000 depending upon engine type and power setting. It is expected that further study of this area would make use of techniques which have been successfully applied to the characterization of diesel exhaust (ref. 15).

## 2.2 MEASUREMENT RATIONALE

As mentioned earlier, recent legislation reinforces the requirement for rapid, meaningful aircraft exhaust emission measurements. Specifically, the Clean Air Amendments of 1970 require that the Administrator of the Environmental Protection Agency, in cooperation with the Secretary of Transportation, prescribe aircraft "emission standards applicable to emissions of any air pollutant from any class or classes of aircraft or aircraft engine which in his judgement contribute or are likely to cause or contribute to air pollution which endangers the public health or welfare" (ref. 5). The Secretary of Transportation has been given specific responsibility for issuance of regulations to insure compliance with such standards. Four separate measurements are discussed in this section; their associated problems are defined and recommendations for alleviating these difficulties are discussed.

## 2.2.1 Commercial Turbine Engines

Because of their large number and high frequency of operation, accurate measurement of the emissions of commercial turbine engines presents perhaps the most immediate need. As emission standards are prescribed, it is reasonable to expect that these engines will either be acceptable as presently equipped, or with recommended improvements (e.g. "smokeless" burner cans.) A question arises as to what initial measurements should be made to check compliance with future emission standards and what measurements will be required to insure continued compliance.

Certainly, future engine types will be uniquivocally required to meet emission standards, both upon certification and throughout their "useful life." Unfortunately, there seems to exist *no published data on the statistical difference in emission levels for a large number of identical engines*. If anything, recent data (ref. 8) indicate that published levels of engine emissions do not agree within as much as a factor of six. Further, there seems to exist *no published data on the change in emission level as a function of time* on an individual engine, due to an apparent *a priori* judgement that they do not degrade with time.

Given this lack of data, the following program is deemed appropriate. Initial measurements must be made on a large number of turbines. A representative (small) sample of each type should then be followed and tested at periodic intervals for emission level while accurate documentation of their mechanical histories is maintained. With these data, well founded decisions may be made relative to the frequency and kind of measurements required to insure regulatory compliance of each engine type.

## 2.2.2 General Aviation

"General Aviation" here is taken to mean light aircraft employing one or more small piston engines. The assessment of

emissions from such engines requires further study, and is receiving some attention from NAPCA. By far, the civil fleet outnumbers the commercial fleet (by 50:1) and is projected to grow by at least 70% over the next 8 years, (ref. 6) as shown in Figure 1. While these numbers are impressive, it does not intuitively seem that civil aircraft present the same type of contribution to a deterioration of air quality as does the commercial fleet.

For one thing, the operations of this segment are not such that they tend to create intensive activity in a few major centers. In addition, even relatively busy general aviation terminals do not see the enormous fuel consumption per unit time that is common at commercial fields. Hence, the immediate effect of light aircraft engine emissions on the environment is small. The future potential of these emissions cannot, however, be neglected.

As with the commercial turbines, data are lacking on the engine emissions as a function of time, and variations of emission within a type. Since these engines are subject to the same type of normal deterioration in efficiency as the automobile, a periodic examination of individual emission levels seems required. This would occur after each major overhaul and at least once between major overhauls. Many of the older engines may have to be exempted from regulation (Unless some type of afterburning exhaust system can be installed at reasonable cost), but new engines will certainly be required to meet future standards in order to obtain type certification. The type of measurement required should borrow heavily from the automobiles' periodic motor vehicle inspection (PMVI) technology. It must be a rapid, inexpensive measurement made on reasonably priced equipment operable by relatively unskilled personnel.

## 2.2.3 Other Aircraft

Military aircraft present some unusual problems. While the military fleet in many respects is similar to the commercial

fleet and amenable to a similar measurement philosophy, many attack and fighter aircraft, along with supersonic bombers, employ afterburners. The undesirable effect produced by some of these power boosting devices is a marked increase (perhaps by a factor of 2 to 5) in emissions. The difficult measurement environment (mean exhaust stream temperature of approximately 3500°F and exhaust velocity near Mach 2.5) presented by these aircraft requires specially engineered instrumentation and sampling techniques. It does not seem reasonable to further consider these special problems in this discussion, since their contribution to the total of aircraft mass emissions is relatively minor. These aircraft should be treated as other turbines and certified for compliance when the afterburners are not in operation (as is usually the case).

## 2.2.4   The Airport and Its Environs

Though the total of aircraft emissions contributes only on the order of one percent of the atmospheric pollution in an urban environment, its most serious effects are felt in the immediate vicinity of the commercial airport. This fact is the result of a combination of activities: (a) the jet engine is least efficient and has the highest emission index during ground operations within the typical landing-take-off (LTO) cycle, (b) there is a heavy concentration of vehicular traffic in the airport area for pickup and discharge of passengers and freight, and (c) the airport itself is an industrial complex. Clearly, the latter two factors cannot be ameliorated by reduction of aircraft emissions. They are mentioned to illustrate the difficulty in actually assessing the contribution of the aircraft alone.

The FAA will shortly undertake an analysis of aircraft ground operations which will better define this situation. What is needed at present is an effort to monitor, on a continuous and on-going basis, ambient levels of aircraft exhaust constituents and pertinent atmospheric and meteorological factors at a number

of commercial airfields.  Such data would be invaluable.  Aside
from the normal meteorological records, these data should include
comprehensive data on cloud cover (for studies of contrail
formation), CO level, $NO_x$ level, $C_y H_x$ level, $SO_2$ level, and
particulate level (with size distribution).  These data should
be amenable to analysis with Continuous Air Monitoring Program
(CAMP) data and should include a few baseline statistics
(especially cloud cover) from areas outside the airport surroundings
as well as some measurements in various locations of the airport
itself.
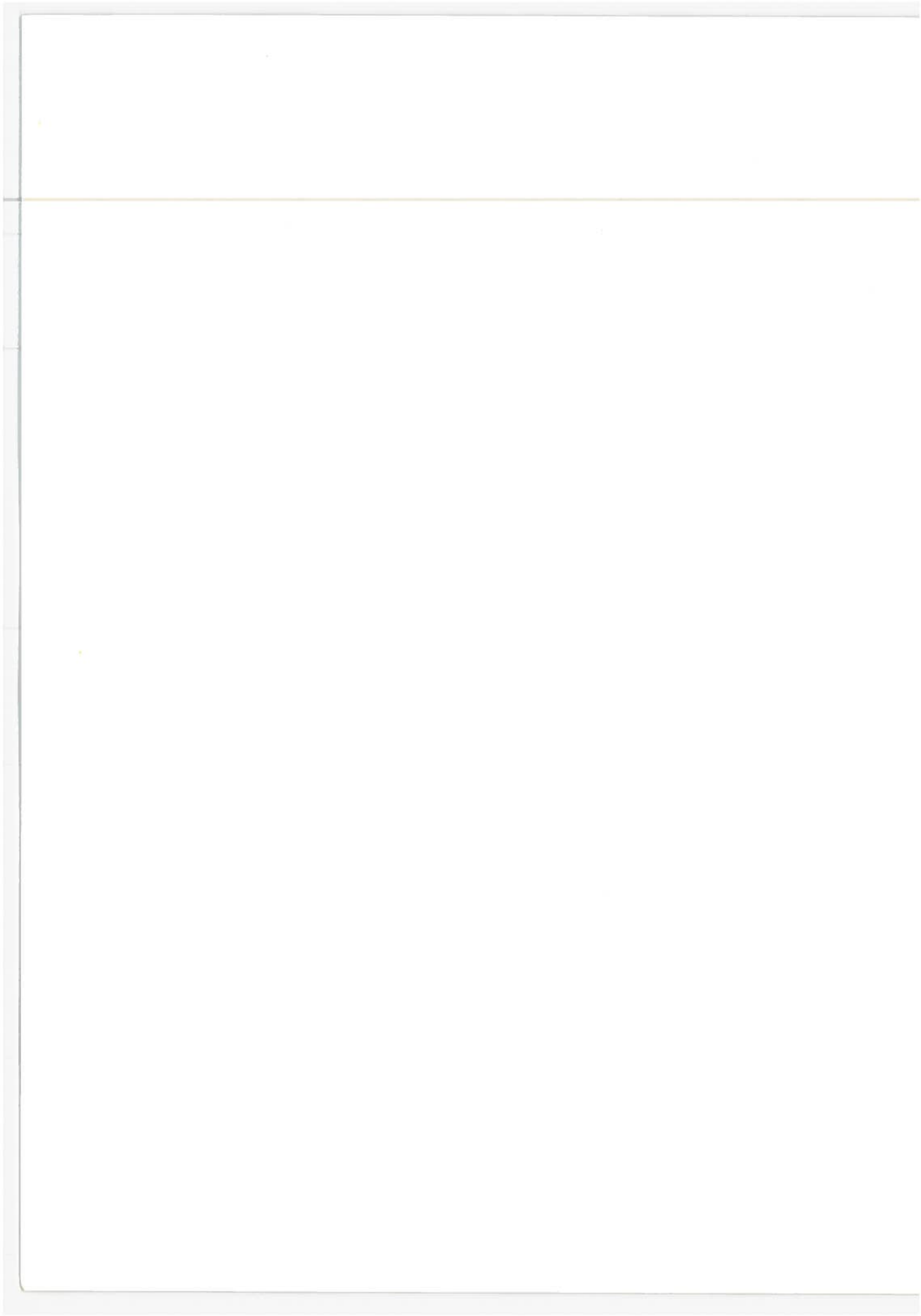
## 3.0 INSTRUMENTATION

Over the last few years, government and industry groups have intensified efforts to develop measuring equipment and techniques for quantitatively analyzing aircraft mass emissions. Especially noteworthy are the efforts of the Society of Automotive Engineers Committee E-31, "Aircraft Exhaust Emission Measurement" and those of the Coordinating Research Council's (CRC) "Aircraft Exhaust Study Group." The former has produced an "Aerospace Recommended Practice" covering the measurement of visible smoke emitted from turbines under test-cell conditions.

The CRC work is of more particular interest, in that it includes a continuing program of evaluating aviation emission measurement techniques. The latest data published by this group (ref. 16) emphasize the poor precision and accuracy of many existing measurement techniques. Precision of a given technique can be established through careful engineering of the instrumentation and good measurement technique. What is completely lacking in almost every measurement program at the present time is a solidly based determination of the absolute accuracy of the measurement.

Recently, several authors have pointed to disparities existing in published emission data, but do not seem to dwell on the cause of this problem. It is suggested here that a fundamental defect in virtually all present measurement methods is their requirement for physically sampling the exhaust plume for subsequentlanalysis. None of the measurements are made directly on the exhaust plume; all of the measurements, therefore, are carried out on a somewhat modified exhaust sample. After a brief discussion of the available measurement techniques, recommendations will be made for improving the accuracy of these data through development of advanced measurement techniques.

## 3.1 INSTRUMENTATION AVAILABLE

This section will review the current status of measuring techniques for each exhaust constituent.

### 3.1.1 Carbon Monoxide

Measured concentrations of CO from jet exhausts range from 800 ppm at idle and taxi to less than 20 ppm at maximum power settings. Instruments currently available for measuring CO include nondispersive infrared analyzers (NDIR), electro-chemical analyzers, mercury vapor analyzers, and gas chromato-graphs.

NDIR.- This is the generally accepted method for monitoring CO. Ranges usually extend from 50 to 1000 ppm full-scale, and accuracies are usually quoted as ±1 percent of full-scale reading. This instrument does not readily lend itself to measurements of the low ambient levels at airports and their environs. For measurements of jet engine emissions, two problems are encountered: (1) wide variations in CO concentrations with varying power settings in jet exhaust lead to a requirement for extremely wide dynamic range, and (2) high concentrations of $CO_2$ and water vapor frequently interfere with measurement of the CO in the exhaust plume.

The first problem can be overcome by careful choice and/or modification of the instrumentation and use of supplemental measurement techniques to insure accuracy. The second problem, water vapor and $CO_2$ interference, can be minimized by use of filter cells, optical filters, absorbing and drying agents, and condensation techniques. Many of the commercially available instruments incorporate such features; however, all of these techniques lower instrument sensitivity and/or response time. On the positive side, this instrument lends itself well to operation by unskilled personnel, is portable, and requires no wet chemicals for operation.

In an SAE report written by the Coordinating Research Council (ref. 16), the NDIR instrument compared quite favorably with a gas chromatograph. However, its poor accuracy at low CO concentrations is of concern in view of the substantial reduction in CO emissions presently sought. It may be necessary, in measuring turbine exhausts, to supplement the NDIR readings by use of other instruments, especially at high power settings.

Recently, a significant advance in NDIR instrumentation was made by Arkon Scientific Company of Berkeley, California. They use an infrared fluorescent cell containing normal and isotopic carbon monoxide as the source for the absorption measurement instead of the conventional blackbody source. The fluorescent radiation passes through the sample cell, through a chopper containing two small gas cells, and on to the detector. The gas cells on the chopper contain normal carbon monoxide and isotopic carbon monoxide, respectively. The fluorescence of the normal carbon monoxide exactly matches the absorption lines of the carbon monoxide in the sample cell, thereby leading to increases of sensitivity over conventional NDIR of up to two orders of magnitude. The isotopic fluorescence is not at all absorbed in the sample cell; it is used to provide a reference signal. The chopper with the two gas cells serves to differentiate between the absorption and the reference signal. Because the absorption and reference signals occupy (but do not intersect in) the same frequency band, any interferences from water vapor or carbon dioxide are automatically subtracted out. Two prototypes of this instrument have been delivered to date. Comprehensive field testing of the technique remains to be accomplished.

Electrochemical Analyzers.- These instruments employ a wet-chemical technique using the reaction $5CO + I_2O_5 \xrightarrow{150°C} 5CO_2 + I_2$, where the liberated $I_2$ is measured by galvanic or coulometric techniques. The instrument can be quite accurate at low concentrations (to 1 ppm) if care is taken to control temperature

and gas flow.  In the measurement of turbine exhaust, care must be taken to eliminate water vapor interference.  Considering these disadvantages, operation by skilled personnel would be required and the technique seems to hold little promise for future improvement.

   Mercury Vapor Techniques.- This technique involves the reaction $CO + HgO \xrightarrow{210°C} CO_2 + Hg$ and subsequent measurement of Hg. Advantages of this instrument include its ability to measure CO to levels as low as 0.025 ppm.  Therefore, this instrument may be useful as a supplemental technique in connection with an NDIR instrument.  Unfortunately, it is susceptible to interference from hydrocarbons.  It may be necessary, therefore, to employ sophisticated sampling techniques and cooled sample lines to alleviate this problem.  Again, skilled operation would be required, but here the basic technique shows definite promise.

   Gas Chromatograph.- This instrument measures gas concentrations from 0.1 to 1000 ppm.  It requires skilled operation and more readily lends itself to laboratory use.  Sampling is not continuous, as is the case with other CO measuring instruments, and analysis time is on the order of several minutes.  Chromatographic data are difficult to interpret, but recent advances in computerization could help alleviate this problem.  Small, special purpose instruments, such as the Fisher Partitioner, lend themselves quite well to field use, but it is felt that the gas chromatograph is best used in the laboratory for verification of measurements made in the field.

## 3.1.2  Hydrocarbons

   Measured levels of HC from jet exhausts vary from 400 ppm at idle and taxi to less than 2 ppm at full power.  Among the instruments currently available to measure HC concentrations are flame ionization detectors and optical spectrometers for total hydrocarbon content, with gas chromatography and mass

spectroscopy techniques being used for measurement of specific hydrocarbon concentrations.

Flame Ionization Detectors (FID).- The increase in ion current produced by burning hydrocarbons in a clean hydrogen flame is indicative of the number of carbon atoms present in a sample. Based on this principle, the operation of the instrument is continuous and response is rapid. The FID is capable of measuring from less than 1 ppm to percentage level concentrations of HC. Its disadvantages include nonlinear response to different organic compounds (the FID measures the total number of carbon atoms present) and uncertain calibration procedures. In measuring turbine engine exhausts, it is imperative to heat the sample lines to avoid condensation of hydrocarbons, a problem which was well demonstrated during the CRC evaluation (ref. 16), where discrepancies of as much as 25 percent were produced by varying the sample inlet line temperature. Commercial instrument manufacturers recognize this problem and now offer temperature controlled sample inlet lines operating at about 400°F.

The CRC evaluation also documented problems encountered at low concentrations of HC (<10 ppm). These problems were attributed to lack of good calibration gases, leaks, noise, electronics drift, and random vibrations.

It should be noted that the EPA recognizes the FID as an acceptable tool for hydrocarbon determination.

Spectrophotometric Methods.- These are usually used for concentrated samples which may be prepared by freeze-out or other collection techniques. Again, complicated calibration procedures present a severe problem. It is doubtful that this technique would be useful for measuring jet plumes without substantial instrumentation engineering, but its basic suitability for the task leads one to encourage such development.

Gas Chromatography and Mass Spectroscopy.- Gas chromatography
is the only available, proven technique that can specifically
measure hydrocarbons, but if suffers from the same problems out-
lined under CO measurements in subsection 3.1.1.

The mass spectrometer can differentiate between hydrocarbons
but suffers from the same problems as the GC, i.e., high cost,
tedious data reduction, and need for highly-trained personnel.

3.1.3 Oxides of Nitrogen

$NO_x$ is generally present in aircraft exhaust emissions in
amounts varying from the neighborhood of 10 ppm at low-power
settings to 100 ppm at high-power settings.  Generally, $NO_x$
concentration is measured in one of the following ways.

Wet Chemistry.- These techniques all depend on a visual or
spectrophotometric measurement of color intensity produced by a
chemical reaction in the presence of $NO_x$.  Examples of such tech-
niques include the Saltzman method (ref. 17) and the PDS (phenol
disulphonic acid) procedure (ref. 16).  The analyses are slow,
do not yield real time data, and are of dubious accuracy when
performed in the field by unskilled personnel.  The Saltzman
method is perhaps the most widely used and permits measurements
to be made over an extremely wide range of concentrations; that
of Jacobs and Hochheiser (ref. 19) is also commonly employed.

Nondispersive Infrared (NDIR).- This technique produces
reasonably good data at high $NO_x$ concentrations if the instrument
is well designed to eliminate interferences from water vapor.  At
low concentrations, presently available instruments yield data of
poor quality.

Chemiluminescence Reactions.- Instrumentation recently
developed with EPA support (ref. 19) and just now becoming
available shows promise of being widely accepted.  An extremely
accurate, sensitive, real-time technique for measurement of $NO_x$
concentrations, it makes use of the fact that NO reacts with ozone

giving off a visible glow at low pressures ("airglow") which
can be optically measured. The technique is applicable to con-
centrations from 0.01 ppm to 1000 ppm. Its only drawback is a
required vacuum pump, but this is deemed of little significance
since the unit need only be a small (say 1/3 HP) forepump.

### 3.1.4 Sulfur Dioxide

Of the 28 million tons of $SO_2$ emitted into the atmosphere
in 1966, jet and piston aircraft accounted for approximately
0.14 and 0.05 tons, respectively. $SO_2$ emissions from turbines
vary in the neighborhood of from 5 to 10 ppm (JT8D/JP-5 fuel)
and are almost totally a function of the sulfur content of the
fuel. Since sulfur can have a deteriorating effect on engine
components, the present sulfur content of fuels is quite low –
less than 0.04 percent.

In view of the fact that emissions of sulfur oxides are not
the result of the combustion process *per se*, but arise from fuel
impurities, measurements of $SO_2$ are not normally emphasized, since
calculated values are in good agreement with experimental
determinations. Present measurement techniques are adequate for
most purposes, though they involve wet chemistry. The accepted
method for $SO_2$ measurement in the range of 0.002 to about 10 ppm
is the West–Gaeke method (ref. 20). This is a colorimetric
measurement, which has been packaged for automated, continuous
readout of $SO_2$ levels (ref. 21). Other methods include conductivity
measurements and post-collection sample analysis. Remote monitoring
of $SO_2$ is possible through correlation spectrometry with the
Barringer spectrometer, but the device is quite costly and has
yet to be adequately field tested. Further development of these
measurement techniques is not deemed necessary for aircraft
emissions monitoring.

### 3.1.5  Particulates

The measurement of particulate concentrations in aircraft exhaust emissions is generally accomplished through use of one or more of the following techniques.

Filtration.- Filtration is perhaps the most widely used technique for particulate monitoring.  It is generally useable in the range from 0.1 to 10 micron particle diameters, with special purpose membranes available to extend this range down to the region of .05 micron diameter.

If the instrument scheme employs single filters, as does a Hi-Vol Sampler, particle mass is determined by direct weighing. Paper Tape Samplers employ light transmission or reflectance as a measure of particulate mass collected on exposed filter paper strips.  The Los Angeles County Air Pollution Control District instruments employ filters if the nature of the sample is appropriate.

Impingement.- Impingement techniques are based on the fact that particle momentum will tend to carry a particulate sample onto a collector while the sampled air stream is deflected. These impactors are used in either single or multiple stages and may employ either liquid or dry surface collectors.  Centrifugal separators, for separation of large particles, may be used in series with impactors as in the case with the Scientific Advances Cascade Impactor.

Both filtration and impingement techniques require post collection data analysis and generally provide only limited particle size information due to the laborious data reduction required.  Neither technique is amenable to real-time data display and neither is useful for particles of less than about 0.1 micron diameter.

Particle Mass Monitor Systems.- These systems have been developed and are commercially available (ref. 22) which utilize

vibrating piezoelectric crystals in an electronic circuit to provide real-time, continuous, automatic readout of total particle mass concentration in the .01 to 10 micron range.

Optical Scattering.- These techniques hold promise for providing much needed data on size distribution of particulate emissions. Several instruments are available which can provide real-time size data in the range of 0.3 to 10 micron diameter (ref. 23). Generally, these instruments have poor dynamic range (both in terms of size and concentration) and repeatability. If reasonably well engineered and properly used, this class of instruments can fill a significant gap in our knowledge of particulate emissions. They are further discussed in subsection 3.2.2.

Condensation Nuclei (CN) Counters.- These counters are used for real-time determination of total particle (CN) concentration in the size range of from 0.001 to 1.0 micron diameter. Commercially available instruments (ref. 24) seem to provide reliable data on total particle count in the 0.001 to 0.1 micron range. These data are not reported in characterization of aircraft exhaust emissions, but there is growing reason to believe CN are of fundamental importance in the overall photochemical smog complex (ref. 25). The technique is further discussed in subsection 3.2.1.

Electrical Mobility Analyzers.- These analyzers present a means for real-time counting and sizing submicron particles in the range of approximately 0.005 to 1.0 micron diameter. The technique is based on a measurement of the rate of attraction of charged particles to a metal surface of opposite charge. Commercially available instruments (ref. 22) are bulky and not portable but provide the basis for further development as discussed in subsection 3.2.1.

The current state of development of real-time particle counting and sizing instruments does not permit routine data taking under field-measurement conditions, especially in the submicroscopic range. These instruments should be further developed in order to provide data on size distribution of particulate emissions especially in the range below 0.1 micron diameter.

3.1.6  Instrumentation in Present Use

In the course of this survey, several organizations were contacted to determine the type of measurement technique employed for aircraft engine emission measurements. These organizations, whose cooperation is gratefully acknowledged, include:

- Arnold Engineering Development Ctr. (Dr. Templemeyer)

- Avco/Lycoming (Mr. P. Rubins)

- General Electric, Evendale (Mr. W. Shaffernocker)

- L.A. County Air Pollution Control District (Mr. J. Nevitt)

- National Aviation Facilities Experiment Center
  (Mr. W. Westfield, FAA)

- Naval Air Propulsion Test Center (Mr. L. Magitti)

- NASA, Lewis Research Center (Mr. J. Grobman)

- Pratt and Whitney Aircraft (Mr. C. W. Bristol)

- Scott Research Laboratories (Dr. W. Zegel)

Table IV is a compilation of measurement methods employed by these organizations by compound and number of users. Some organizations employ more than one method for one or more compounds and not all measure the same constituents.

TABLE IV.- METHODS OF ANALYSIS FOR NINE ORGANIZATIONS

Carbon Dioxide
   Flame Ionization (after          (1)
   conversion to methane)

   Gas Chromatography               (1)

   NDIR                             (7)

Carbon Monoxide
   Flame Ionization (after          (1)
   conversion to methane)

   Gas Chromatography               (1)

   NDIR                             (9)

Hydrocarbons
   Flame Ionization with heated     (6)
   (~350-400°F) sample line

   Flame Ionization, unheated       (5)
   (<300°F line)

Nitric Oxide
   NDIR                             (7)

   Saltzmann Method                 (1)

   Electrochemical Cell             (2)

Nitrogen Dioxide
   NDUV                             (2)

   NDIR (by conversion to NO)       (1)

Nitrogen Oxides
   Electrochemical Cell             (2)

   NDUV                             (2)

   PDS                              (1)

Particulates
   Mass Determination               (2)

   Mass Determination and sizing    (2)
   by electron microscope

   Mass Determination and wet       (1)
   chemical analysis

Smoke
   Per SAE, ARP 1179                (6)
   Other                            (1)

## 3.2   INSTRUMENTATION REQUIRING FURTHER ENGINEERING DEVELOPMENT

This section discusses measuring techniques which are believed to merit further engineering development.  The first two instruments consider particulates and, as such, cannot be "remote" in the sense of "noncontact" or "nonsampling".  The third and fourth techniques both provide similar data - completely remote, quantitative determination of aircraft exhaust constituents.

### 3.2.1   Condensation Nuclei Measurements

While the existing data vary by more than an order of magnitude, it is clear that the bulk of particulate engine emissions is in the size range below one micron diameter.  With the advent of "smokeless" engines, the number of "smoke" particles will be decreased to a point where the plume is all but invisible.  The remaining particulate emissions are in the respirable range in addition to playing a key role in visibility reduction and the photochemical smog complex.  These extremely fine particles are frequently referred to as condensation nuclei (CN), since they can form the nucleus for condensation of water, sulfuric acid, and other common atmospheric constitutents  Though their role in the environment is yet to be completely understood, recent data indicates that they are key elements in a deterioration of air quality (refs. 25,26).

Definitive data are presently lacking on the size distribution of CN in the airport environment and in aircraft exhaust.  Some data exist on total particulate emissions, but such information is insufficient to reasonably assess the problem.  A key point is that the size distribution of these emissions is of real importance because of the chemical reactivity of these particles coupled with their slow rate of vertical diffusion and resulting wide horizontal dispersion.  Presently needed is baseline data on airport ambient size distributions as well as emissions data

on turbine engines, whose relative contribution to total urban concentrations is not well documented but could be as high as 10 percent (ref. 25).

To fulfill this need, a laboratory model of a portable CN spectrometer is currently under development at TSC. This instrument, in various configurations, is expected to be directly applicable to the gathering of most of the data which are presently lacking. It is designed to measure CN with the following performance objectives as goals:

Size Range:  0.001 to 1.0 micron diameter
Concentrations:  10 to $10^6$ particles/cc
Input Air Ambient Pressure:  1.0 to 0.05 atm.
Air Intake Temperature:  200°C to −60°C
Spectrum:  10 size ranges
Accuracy:  10%

### 3.2.2  Aerosol Particle Analysis

In conjunction with the development of a CN spectrometer, a need is recognized for improvement of the more conventional portable light scattering aerosol analyzers, measuring particles of about three tenths of a micron diameter and larger.  Major problems with available devices include a lack of dynamic range, poor sensitivity for small particles, poor size resolution, and poor stability.  Work funded by NASA (presently being completed by TSC personnel) on the development of an aerosol analyzer for spacecraft cabin atmosphere studies has pointed the way to improvements attainable over the present design of light scattering analyzers.  These improvements would take the form of modifications in two areas, as discussed below.

In the light scattering aerosol analyzer, an air sample is drawn through the instrument causing individual particles to pass sequentially through the scattering volume, a point of intense illumination.  Each particle scatters light onto an

optical detector, the amount of scattered light being indicative of its size (diameter). By employing a new type of lens system to better collect this scattered light, in conjunction with the use of a laser for illumination in place of the normal white light, considerable improvements are possible in the sensitivity, stability, and size resolution of the device.

Improvements in dynamic range of the instrument should be achievable by employing rapidly switched optical attenuators in the illumination beam. These attenuators would permit the use of an intense laser source for optimized sensitivity with small particle diameters while reducing markedly the tendency of the instrument to saturate at large particle diameters.

The availability of such an improved aerosol analyzer would greatly facilitate field measurements of ambient aerosol levels without the need for extensive post-measurement laboratory analysis to determine size distribution. It will prove rapid, accurate assessment of emissions from aircraft and, in conjunction with the CN spectrometer, provide a meaningful basis for issuance of standards and methods for compliance testing.

### 3.2.3  Remote Raman Spectroscopy

Remote Raman spectroscopy is a newly-developed technique for remote, quantitative trace gas analysis. It is expected to be developed specifically for exhaust emission analysis under contract through the Aero-Propulsion Laboratory at Wright-Patterson Air Force Base. Additional development of the technique is presently underway at TSC. The technique holds great promise for providing an accurate method of remote, noncontact exhaust emission analysis.

Without going into great detail, the Raman process may be viewed as essentially a scattering phenomenon, wherein light incident on a molecule is absorbed and immediately re-emitted at a slightly shifted frequency. This difference in frequency

corresponds to a particular moecular vibration frequency and, since each species has its own unique set of vibration frequencies, the Raman spectrum yields positive identification of the scattering constituent. In a *remote* Raman spectrometer, for engine emissions analysis, the light source is a pulsed laser which illuminates the exhaust plume. Scattered light is collected by a telescope, generally located beside the laser, and analyzed by a frequency sorting device. The output of this device is directed onto a phototube which supplies a voltage to a signal processing device for analysis. By using a pulsed laser and specially synchronized time-gated electronics, the technique can be used to locate the scattering molecules with respect to the detector for studies of spatial variation of exhaust constituents. Knowledge of the pulse length, along with the field of view of the telescope, permit the volume of gas examined to be quantitatively analyzed.

At present, this instrumentation is considerably more complex and expensive than is desirable. With advances in laser technology, it is expected that the technique will develop into a more routine method of analysis for use in accurate emission measurements useful in obtaining good quantitative data. It is not expected that the technique is amenable to simplification to the extent that it would become useable in routine compliance inspection. Its value is seen to lie in its use as a reference point from which the accuracy of other measurement techniques may be measured.

### 3.2.4 Tuneable Diode Spectroscopy

Recent work (ref. 27) in the development of tuneable semiconductor diode lasers at Lincoln Laboratories holds promise for the development of new instrumentation techniques for highly sensitive and specific quantitative analysis of trace gas analysis. The diodes require substantial additional engineering development and have potential application to many of the measurement problems

presently existing or anticipated by the various modes of DOT, including emission analysis of transportation system exhausts, gathering of ambient concentration levels of exhaust constituents, and quantitative, in-situ determination of stratospheric ambient levels of exhaust constituents.

The devices under development at Lincoln Laboratories are lead-tin-telluride diodes which emit light in a very narrow wavelength band, the center of which is "tuneable" over a relatively wide range of wavelengths. Since the diodes may be chemically tailored to emit anywhere within a broad band of wavelengths, individual diodes can be matched to coincide with infrared absorption bands of specific gases of interest. The extremely narrow width of this emission line leads to good specificity in gas analysis. For example, it is likely that individual species of hydrocarbons could be separately monitored by instrumentation which makes use of the diodes' narrow band-width. As implied above, the diodes themselves do not constitute a complete instrument. Examples of a few types of instrumentation which could employ these devices are described as follows.

Remote Resonance Raman Spectrometer.- Using the laser diode as a light source in the infrared, a remote Raman spectrometer may be conceived which makes use of the "resonance" effect, which occurs when the laser wavelength closely approaches an absorption band of a compound, thereby yielding enhanced sensitivity by as much as a factor of $10^6$ over non-resonant Raman spectroscopy under similar conditions.

Heterodyne Emission Spectroscopy.- Using a laser diode much like the local oscillator in a conventional radio set, an instrument is envisioned which can be "tuned" to a specific monitor wavelength and remotely measure the concentration of emitting exhaust constituents.

NDIR Instruments.- The diode laser would permit fabrication of an extremely sensitive and accurate NDIR instrument. Such a unit could be made for each exhaust constituent and would probably be specific in HC monitoring.

The development of these diodes, along with the general progress of laser technology, can be expected to yield improved instrumentation for remote monitoring of exhaust constituents. The potential return offered by development of this technique is quite impressive, but the time required is on the order of 3 to 5 years before producing the actual instrumentation.
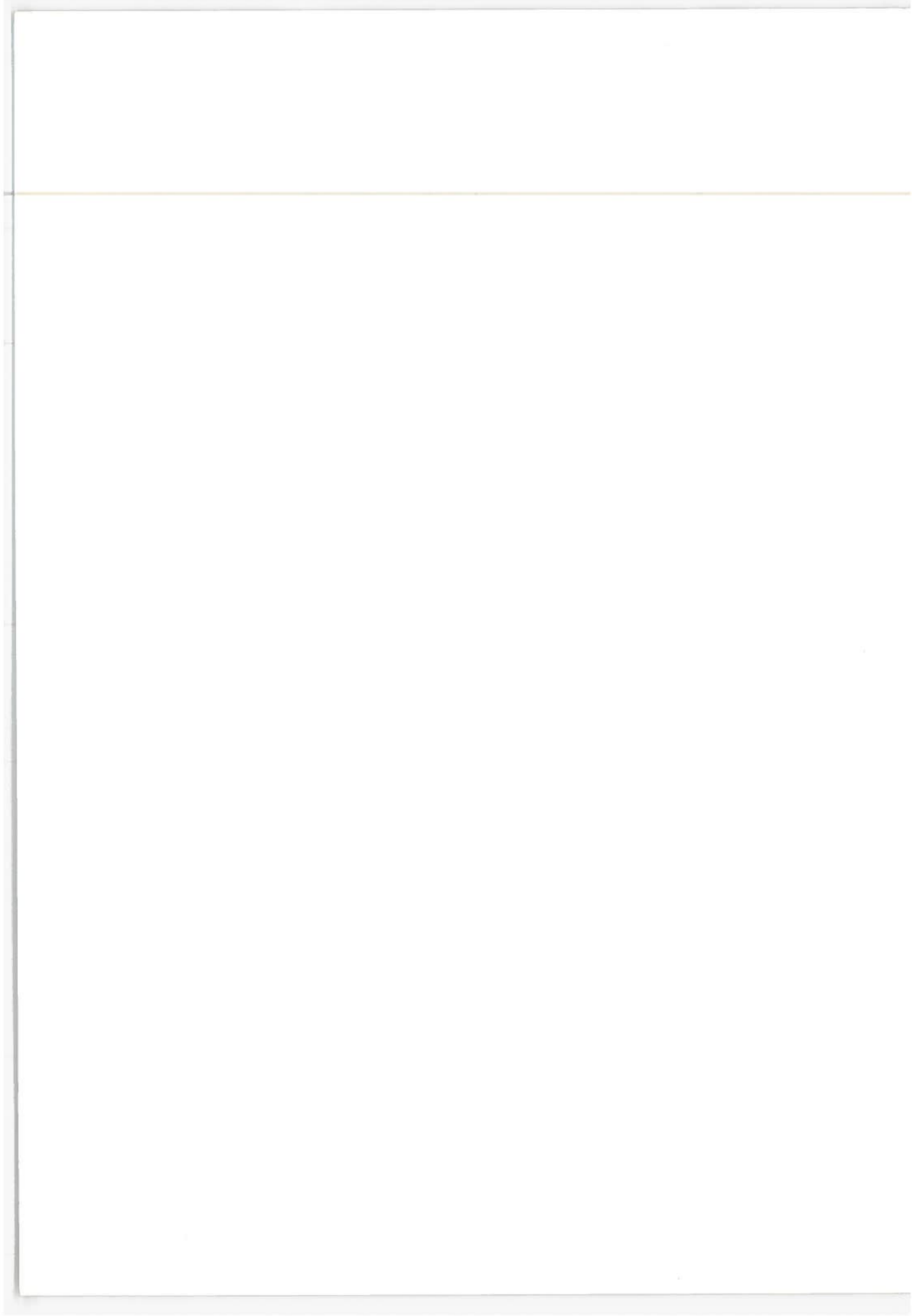
## 4.0 CONCLUSIONS AND RECOMMENDATIONS

Emissions from aircraft engines constitute a small fraction of total emissions in an urban area but have a major polluting effect on the airport area and its immediate surroundings. Present data are neither obtained nor presented in a consistent manner. It is difficult to make a fair assessment of the general problem, though studies at individual airports have documented the necessity for better control of aircraft emissions.

There are no data available on the deterioration of an aircraft engine as a function of time, and the resulting change in its emission index. In addition, there are no data available in the literature on the expected variation in emission index for a number of engines of identical design. These data are needed in order to establish a starting point from which emission standards may be written.

Measurement methods vary widely for exhaust constituents considered in this survey. Standardization of these methods, and a presently being pursued by the Society of Automotive Engines E-31 committee, will be of considerable help in future work.

All emission measurements are presently made by direct sampling of the exhaust plume. It is recommended that development of instrumentation of remote (non-sampling) analysis of the exhaust stream be supported in order to provide a means of independently checking results obtained by direct sampling. The most promising techniques for immediate development are remote Roman spectroscopy and tuneable diode spectroscopy.

Considerable attention is presently given to measurements of smoke levels in the exhaust plume. It is recommended that, in addition, more attention be given to measurements of particulate concentration as a function of size. These measurements should

be extended to the range below 0.1-micron particle diameter,
where the number of particles emitted from engines is quite
substantial.

Measurement of $NO_x$ is presently accomplished by wet chemical
means, and measurements of NO by NDIR.  It is recommended that
evaluation and field testing of the chemiluminescense technique
be carried out as soon as possible with an eye toward its
adoption as a standard method.

Measurement of total hydrocarbons is presently carried
out by means of flame ionization detectors.  Heated sample lines,
now commercially available, should be used with this instrument
for aircraft engine emission measurements of best accuracy.

Efforts to define the problem of odors caused by aircraft
engine exhaust should be undertaken in order to provide means
for regulating these emissions for the public welfare.

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