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ODOR INTENSITY AND CHARACTERIZATION STUDIES OF EXHAUST FROM A TURBOJET ENGINE COMBUSTOR

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Abstract

Sensory odor tests of the exhaust from a turbojet combustor operating at simulated idle conditions were made by a human panel sniffing diluted exhaust gas. Simultaneously, samples of undiluted exhaust gas were collected on adsorbent substrates, subsequently removed by solvent flushing, and analyzed chemically by liquid chromatographic methods. The concentrations of the principal malodorous species, the aromatic (unburned fuel-related) and the oxygenated (partially burned fuel) fractions, as determined chromatographically, correlated well with the intensity of the odor as determined by sniffing. Odor intensity increased as combustion efficiency decreased. Combustor modifications which increased combustion efficiency decreased odor intensity.

Introduction

This report presents the results of an investigation designed to determine the intensity and character of the odor of gas turbine combustor exhaust gases. The project was carried out under NASA contract NAS 3-15701[1] by Arthur D. Little, Inc. in cooperation with the Lewis Research Center of the National Aeronautics and Space Administration. The main part of the experimental effort was conducted at the Lewis Research Center in Cleveland.

Although the problem of pollutant emissions from all sorts of fossil-fuel burning sources has received considerable attention over a number of years, concern over the contribution of aircraft to the overall pollution picture has only been voiced in recent years. Since intensity of odor is an aspect of pollution at airports that is readily sensed by the general public, the study of odor problems resulting from the operation of jet aircraft is a very timely one. However, before the odor problems can be attacked vigorously, a method must be established for determining the intensity of malodorous emissions, both at the source and under ambient conditions after dilution.

During the past few years Arthur D. Little Inc., has studied the problem of exhaust odor from Diesel engines[2-5] and has developed techniques which make it possible to characterize the intensity of Diesel exhaust odor from both a sensory and an analytical standpoint. The scope of the present investigation was to adapt the methodology developed for Diesel exhaust to the problem of jet combustor exhaust and to obtain data from a single turbojet combustor over a range of operating conditions with a number of different fuels and with several combustor modifications. Odor intensity evaluations were made both by a human panel sniffing and rating diluted exhaust gas and by means of analytical techniques designed to measure the concentrations of the malodorous components.

Odor Measuring Techniques

In its work with Diesel exhaust A. D. Little, Inc. had pursued two different approaches for determining odor intensity. They were: (1) a human panel sniffing samples of diluted exhaust gas under controlled environmental conditions, and (2) chromatographic separation and analyses of exhaust gas to determine the concentration of the malodorous species. These tests had shown that the concentrations of the oxygenated species, as determined by chromatography, correlated well with the intensity of odor as determined by the odor panel.

To make sensory odor tests for turbojet engine combustors it was necessary to construct an odor room at the test facility and to train a panel of Lewis personnel to recognize and rate odor intensity and character. To make analytical determinations it was necessary to collect sufficiently large volumes of exhaust gas so that the concentrations of the malodorous species could be readily measured with the existing analytical techniques. Previous experience had shown that large volumes of exhaust gas (as much as 500 liters) can be collected in specially prepared traps containing adsorbent substrates and later removed from the substrates by reverse flushing with organic solvents. The traps are filled with solid adsorbent materials (chromosorb 102, a cross linked polystyrene porous adsorbent) which allow the low molecular-weight gases to pass through, but retain most of the high molecular-weight organic compounds containing the malodorous species. The effluent gases from the traps have no significant odor. A schematic diagram showing the various steps employed in the odor tests is presented in figure 1.

Sensory tests. The odor test facility consisted of an air-conditioned chamber approximately 2.4 meters wide, 3.6 meters long, and 2.4 meters high. A manifold with four sniffing ports was located at the rear wall of the chamber. The sniffing ports were normally sealed with a hinged aluminum plate and a deodorized rubber gasket. A hole was cut in each gasket shaped to accommodate the analyst's face such that the nose was in the airstream while the face was pressed against the gasket to minimize flow of dilution air into the manifold. Diluted exhaust gas, with dilution ratios ranging from 6600:1 to approximately 280:1 was constantly circulated through the manifold. Normally five concentrations, each approximately double the previous one, were examined by the panel. The odor chamber and its associated dilution equipment are shown schematically in figure 2 while a photograph of the panel in action is shown in figure 3.

The panelists were trained by A. D. Little, Inc. personnel to recognize and rate odors according to the intensity scale presented in figure 4. In addition to the intensity ratings the panel was asked to describe the character of the odor, using terms such as oily, kerosene like, smoky, burnt etc.

The odor intensity ratings thus obtained were then plotted against concentration on a semilogarithmic plot as shown in figure 5. The odor intensity at a dilution ratio of 1000:1 is termed the

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total intensity of aroma (TIA) and is the intensity value used in all subsequent plots.

Analytical tests. Undiluted exhaust gas samples in volumes as high as 500 liters were passed through the adsorbent traps. The chemical compounds retained on the traps, mainly high molecular weight organic species, were then removed by solvent extraction. Samples of the extract (total organic extract, TOE) were then analyzed by liquid chromatography. The chromatographic separation produced three distinct peaks representing three classes of chemical compounds: the paraffins which are nonodorous, and the aromatics and the oxygenated compounds which are primarily responsible for the odor of the exhaust gases. The aromatic species result from the aromatic content of the fuel while the oxygenate compounds, which are products of partial oxidation, consist primarily of high molecular-weight alcohols, adehydes, ketones, and methoxy compounds. Low and high-resolution mass spectrometry of the aromatic (LCA) and oxygenated (LCO) fractions can give further insight into the chemical composition of these general classes, but is quite time-consuming and generally not warranted.

Test Facility

Combustor. A single-can combustor from a J57 engine was installed in a closed-duct test facility capable of supplying nonvitiated combustion air at pressures up to 10 atmospheres and temperatures to 600 K. The standard J-57 fuel manifold containing 6 Duplex nozzles was used for most of the tests. Fuel flows to the primary and secondary nozzles were metered and controlled separately. The combustor liner was housed in a 30.3 centimeter pipe as shown in figure 6.

Instrumentation. The instrumentation for this investigation consisted essentially of 8 five-point chromel-alumel thermocouples and of 8 five-point steam-cooled sample probes positioned as shown in figure 6. The individual sample probes were connected to a common manifold. Exhaust-gas samples passed from the probes to the instruments through 1.9 centimeters diameter stainless-steel tubing approximately 15 meters long and steam-heated to maintain a gas temperature of about 420 K.

At the monitoring station, the exhaust-gas sample was split into two streams. One portion was fed to the on-line gas-analysis console capable of measuring concentrations of total hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen. Values of combustion inefficiency were derived from these measurements. A description of the instrumentation console is found in reference 6.

The second portion of the exhaust-gas stream was passed through a heated filter to remove soot particles and was processed for odor measurements as shown in figure 1.

Test Program

The test program, shown in figure 7, was set up to determine the effect on odor intensity of the following variables: 1) combustor-inlet conditions, 2) fuel composition, 3) combustor modifications.

At the beginning of the investigation it was felt that the primary problem with odor emissions would occur at the idle condition where combustion efficiency is known to be low. In preliminary tests where combustor-inlet conditions were varied parametrically it was found that essentially two levels of odor intensity could be readily distinguished by the panel: a high level of odor intensity associated with low-efficiency operation and a low level of intensity associated with high-efficiency operation. Thus the combustor-inlet conditions shown in figure 7 were selected for the main part of the program.

In order to determine the effect of fuel composition on odor, several other fuels besides the standard ASTM A-1 fuel were tested. The fuels were selected to give a wide range in volatility and aromatic content.

Combustor modifications were limited to changes in the mode of fuel injection. For effective evaporation and mixing of fuel and air, good fuel atomization is necessary. At idle, fuel flows are so low that, even when only the primary fuel passage of the conventional Duplex nozzle is used, poor fuel atomization results. In a previous investigation[7] it had been found that substantial increases in combustion efficiency at idle can be realized by the use of an air-assisted fuel nozzle. In an air-assisted nozzle fuel flows through the primary passage of the Duplex nozzle while air from an auxiliary compressor flows through the secondary passage, thus helping to atomize the fuel spray. In addition to the Duplex nozzles, a set of Simplex nozzles sized to cover the range of fuel flows encountered was tested.

Procedure

At each test condition, after combustor operation had been stabilized, exhaust gas was presented to the panel in a series of 5 concentrations, each approximately twice the preceding level. Each panelist independently recorded the total intensity of the odor and the primary odor character notes. This required about 2 to 3 sniffs and less than 30 seconds. A pause of several minutes between successive presentations helped to prevent sensory fatigue. After completion of one dose-response series in order of increasing concentrations, the tests were repeated with the same set of concentrations presented in random order. The tests were generally replicated on the following day.

At each concentration the intensity readings recorded by each of the 4 panelists were averaged and the average values plotted against concentration on a semi-logarithmic scale as shown in figure 5. The intensity of aroma at a dilution of 1000:1 (TIA) is the measure of intensity used in all subsequent plots.

While the sensory tests were proceding, samples of the undiluted exhaust gas were collected in the adsorbent traps for subsequent chromatographic analysis at A. D. Little, Inc. facility in Cambridge. At the same time pertinent combustor operating data including on-line gas analysis measurements were recorded on the Lewis data acquisition system.

Results and Discussion

The scope of the present investigation was to obtain odor data over a range of turbojet engine combustor operating conditions with several different fuels and with several combustor modifications to see if the odor data could be correlated with combustion efficiency. The technique employed was essentially that developed by A. D. Little, Inc. for Diesel exhaust. To achieve these results three separate sets of data were taken: 1) combustor performance data, including gas analysis of the exhaust gas to provide combustion efficiency values, 2) sensory odor tests conducted by the human panel, 3) analytical tests carried out with samples of undiluted exhaust collected on adsorbent substrates.

In a number of cases the extracts from the traps were reintroduced into the odor chamber in concentrations approximating the dilution ratios originally presented to the odor panel. The odor intensities of the reconstituted exhaust samples correlated with the odor intensities of the original exhaust.

Effect of combustor-inlet conditions. In the early phases of the investigation combustor-inlet conditions were varied parametrically to establish a range of odor intensities that could be readily distinguished by the panel. The results of these tests, conducted with ASTM A-1 fuel are shown in figure 8 where odor intensity at a dilution ratio of 1000:1 (TIA) is plotted against the logarithm of combustion inefficiency, as determined by gas analysis. Odor intensity correlated well with combustion inefficiency, and as a result the remaining tests were conducted at the combustor-inlet conditions shown in figure 7. Conditions 1 and 3 represented low and high efficiency operation, respectively. Efficiencies at condition 2 generally fell between those of conditions 1 and 3.

In figure 9, odor intensity (TIA) is plotted against the logarithm of the concentration of the oxygenated species (LCO), in micrograms per liter of exhaust, as determined by chromatographic analysis. A good correlation between TIA and LCO was obtained, suggesting that analytical tests might eventually replace the more cumbersome sensory tests conducted by the odor panel. Good correlations were also obtained between TIA and the concentrations of the aromatic species (LCA). However, since the trends were similar, only the LCO plots are presented in this report.

Effect of combustor modifications. Combustor modifications consisted only of changes in the mode of fuel injection since emphasis was placed on idle operation and proper fuel atomization is known to be a critical factor at idle operation. The results presented in figure 10 show that a substantial reduction in odor intensity was achieved through the use of an air-assist nozzle at combustor-inlet conditions where low efficiency and hence high odor intensity was obtained with the standard Duplex nozzle. At combustor-inlet conditions where efficiency with the standard Duplex nozzle was close to 100 percent, no additional reduction in odor intensity was achieved with the air-assist nozzle. For comparison, tests were made with a set of Simplex fuel nozzles, sized to provide fuel flow over the entire flow range with the existing pump capacity. As a result nozzle pressure drops were very low for the low fuel-flow conditions while at the higher fuel flows higher nozzle pressure drops with resultant good fuel atomization were obtained. At the high fuel-flow condition high values of combustion efficiency with correspondingly low values of TIA were attained while at the low fuel-flow conditions low values of efficiency and correspondingly high values of odor intensity resulted. The regression lines shown on figures 8 and 10 were computed from all the data obtained with ASTM A-1 fuel, indicating that the correlation is valid whether the inefficiency is caused by adverse combustor-inlet conditions or by fuel spray characteristics.

The corresponding plot of LCO versus TIA, presented in figure 11, again shows good correlation between odor intensity and the concentration of oxygenates. The regression line was computed from all the data obtained with ASTM A-1 fuel.

Effect of fuel properties. Four fuels in addition to the standard ASTM A-1 fuel were selected to give a wide range in volatility and composition. Natural gas was included because it is a gas and consists primarily of the low molecular-weight methane while the other fuels are liquids containing higher molecular-weight compounds. The data presented in figure 12 show that the correlation between odor intensity and inefficiency established for ASTM A-1 fuel is not appropriate for all fuels. However, the data for JP-4 and for the high-aromatic JP-5 seem to correlate reasonably well with the regression line established for ASTM A-1 fuel. These results are not too surprising since these three fuels are somewhat similar in character while isoctane and natural gas differ greatly from them both in composition and volatility.

The relation between concentration of oxygenates and odor intensity is shown in figure 13. In contrast to the efficiency data, a good correlation between TIA and LCO was obtained, further confirming the potential of using LCO as a measure of odor intensity.

Analytical Liquid Chromatograph (ALC)

The data presented in figures 11 and 13 show that the correlation between the concentration of oxygenates, in micrograms per liter of exhaust, and odor intensity, established for ASTM A-1 fuel, also applies for the case where nozzles as well as fuel composition were the variables. This finding is in good agreement with the large amount of data which A. D. Little, Inc. has collected with Diesel exhaust. This earlier success had led them to search for an instrument which could perform these analytical functions in an automatic manner, thus greatly speeding up the process of obtaining odor intensity data. Such an instrument has now been developed by A. D. Little, Inc. to the prototype stage.

The basic measurement technique which is similar to the manual method depends on chromatographic separation of the aromatic (LCA) and the oxygenate (LCO) fractions for subsequent measurement by an ultraviolet absorbent detector. The magnitude of the detector response is proportional to the quantity of LCA and LCO eluted from the column so that, with proper calibration, the concentrations of aromatics and oxygenates present in the original undiluted exhaust can be computed. A schematic diagram of the prototype ALC system is presented in figure 14 and a typical chromatogram is shown in figure 15.

A more detailed description of the instrument which was developed entirely in the A. D. Little, Inc. Diesel program is given in reference 1. Although the instrumental method has had only limited experimental verification, the results have been sufficiently encouraging to warrant its continuing development and usage as a means of supplementing sensory odor data. Eventually it could be used as a field instrument to minimize the need for human odor panels and to expedite greatly the process of collecting data on odor intensity.

Summary of Results

An investigation was conducted to determine the intensity and character of the odor of exhaust gas from a single-can J57 combustor operating at simulated idle conditions with a number of different fuels and with several combustor modifications and to correlate the odor data with combustion efficiency. The following results were obtained:

1) A group of human beings can be trained to recognize and to identify differences in odor intensity and character when exposed to varying concentrations of diluted exhaust gas under controlled conditions.

2) Intensity of the odor of exhaust decreased as combustion efficiency increased. This was essentially true whether increases in combustion efficiency were brought about by combustor modifications or by operation at less severe combustor-inlet conditions. No correlation between odor intensity and combustion efficiency was obtained with variations in fuel composition. Use of an air-assisted fuel nozzle for idle operation was especially effective in reducing odor intensity.

3) The malodorous constituents of exhaust gas can be collected by passing large volumes (about 500 liters) of the gas through specially-prepared adsorbent traps from which they can subsequently be extracted by means of solvents. Chromatographic separation of the extract from these adsorbent traps has shown that the principal malodorous species in jet exhaust are the aromatic (fuel-related) and the oxygenated (partially burned) fractions. Chromatographic analysis of these extracts has also shown that the concentrations of the oxygenated species, in micrograms per liter of exhaust, correlate well with odor intensity as determined from sensory tests.

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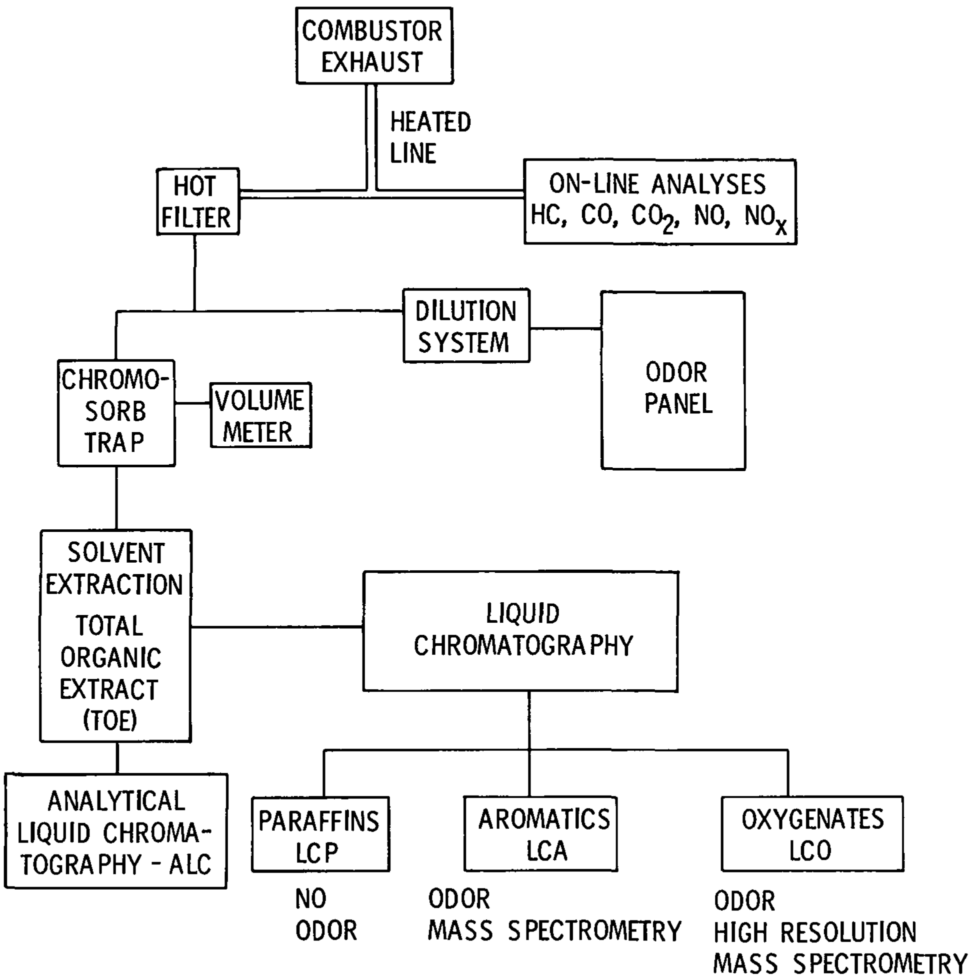

Figure 1. - Exhaust-odor characterization technique.

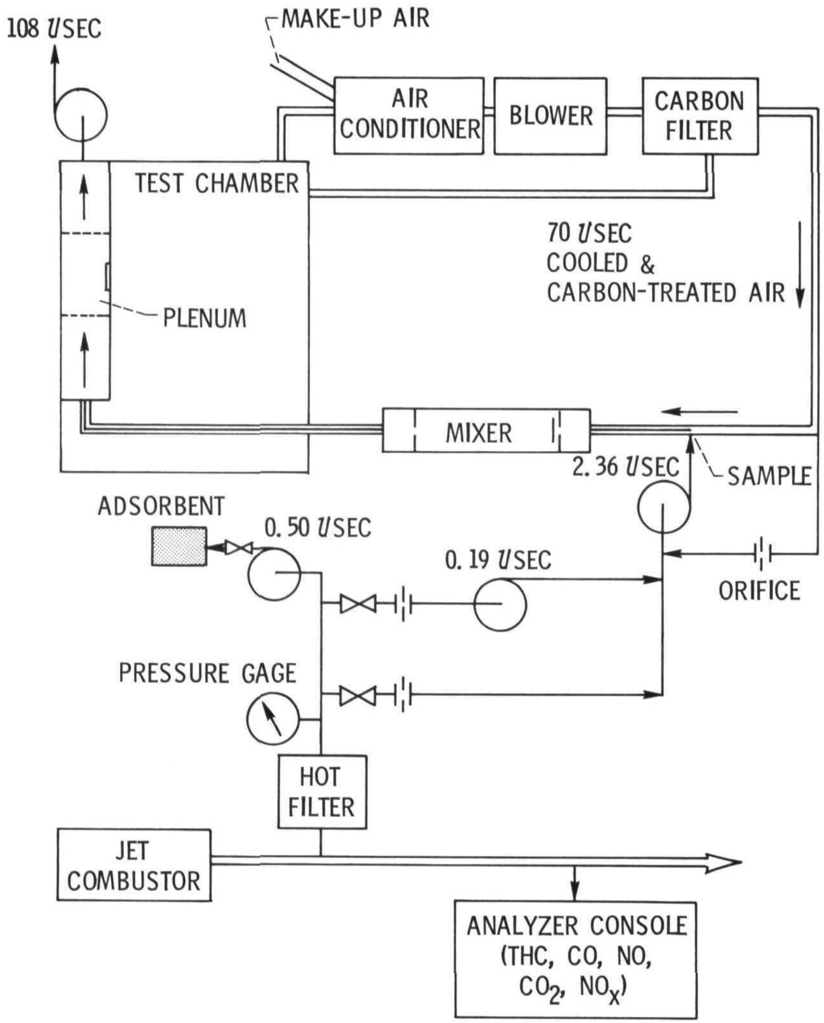

Figure 2. - Schematic arrangement of equipment for NASA odor test facility.

Figure 3. - NASA panel inside odor test facility.

NUMERICAL RATING	INTENSITY
T	THRESHOLD (RECOGNITION)
1/2	VERY SLIGHT
1	SLIGHT
$1\frac{1}{2}$	SLIGHT TO MODERATE
2	MODERATE
$2\frac{1}{2}$	MODERATE TO STRONG
3	STRONG

Figure 4. - Odor intensity scale.

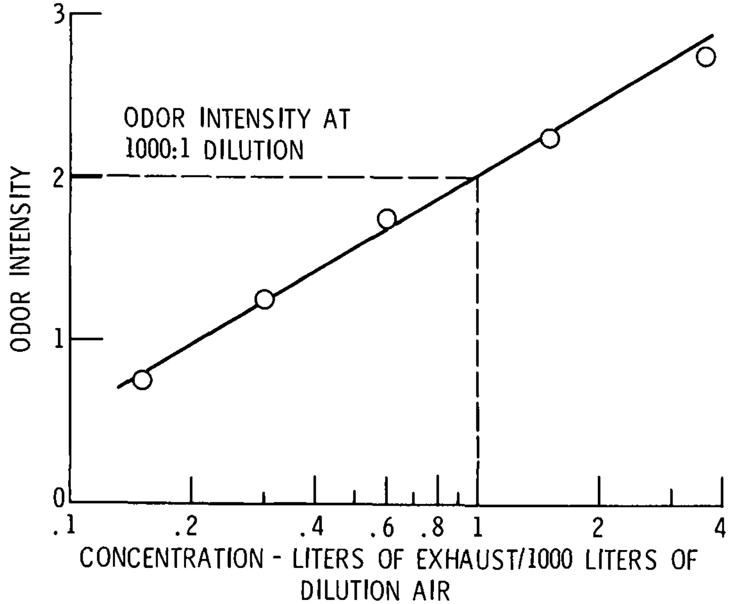

Figure 5. - Typical dose response curve.

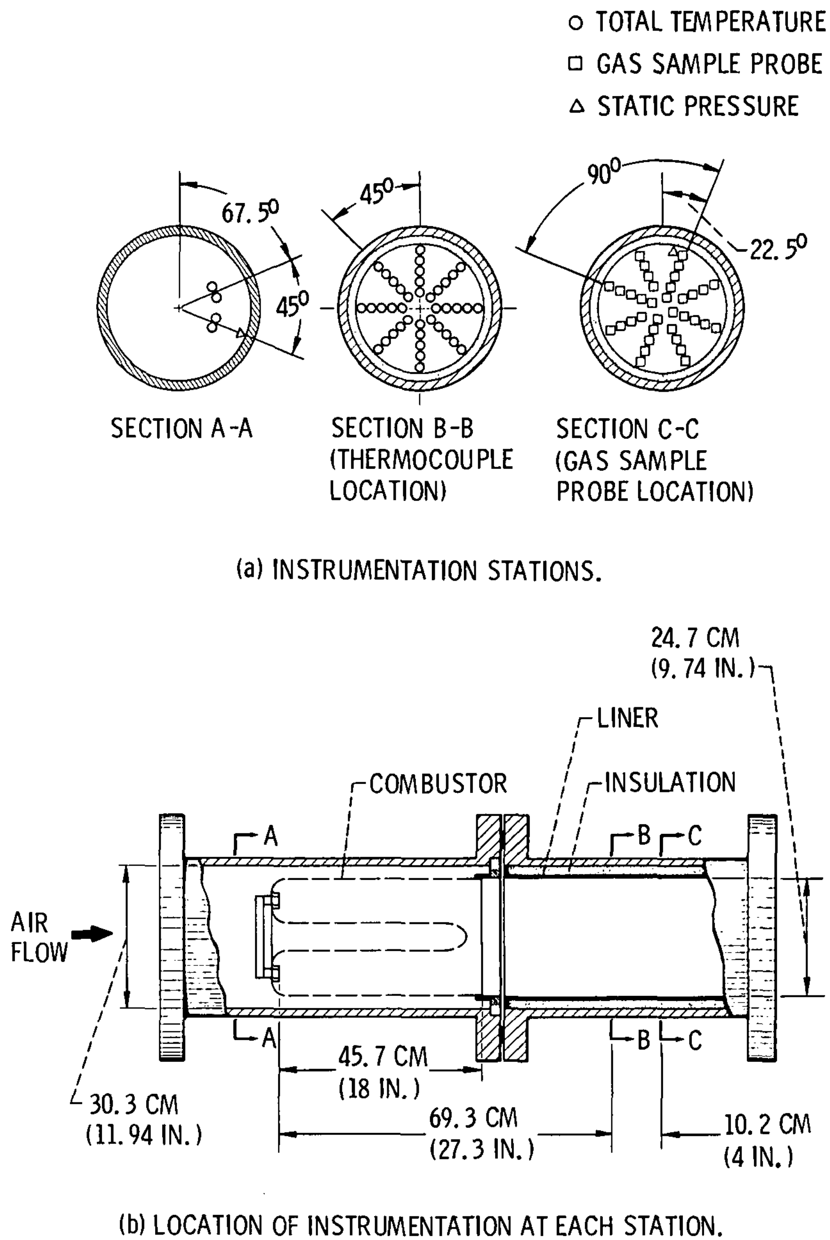

Figure 6. - Combustor test duct.

TEST CONDITIONS

CONDITION	COMBUSTOR-INLET PRESSURE ATMOS	COMBUSTOR-INLET TEMP, ^0K	FUEL-AIR RATIO
1	2	150	0.008
2	2	150	.016
3	4	240	.013

FUELS

ASTM A-1
JP-5 (HIGH AROMATIC)
JP-4
ISOOCTANE
NATURAL GAS

COMBUSTOR MODIFICATIONS

DUPLEX FUEL NOZZLE
AIR-ASSISTED NOZZLE
SIMPLEX FUEL NOZZLE

Figure 7. - Test program.

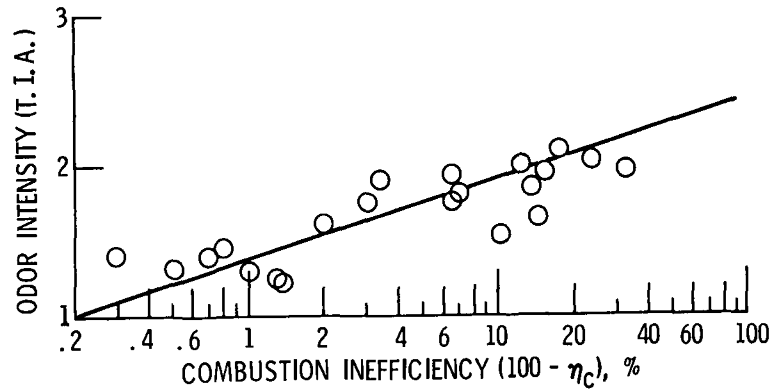

Figure 8. - Correlation between odor intensity and combustion inefficiency. ASTM A-1 fuel; variable: combustor-inlet temperature and pressure, and fuel-air ratio.

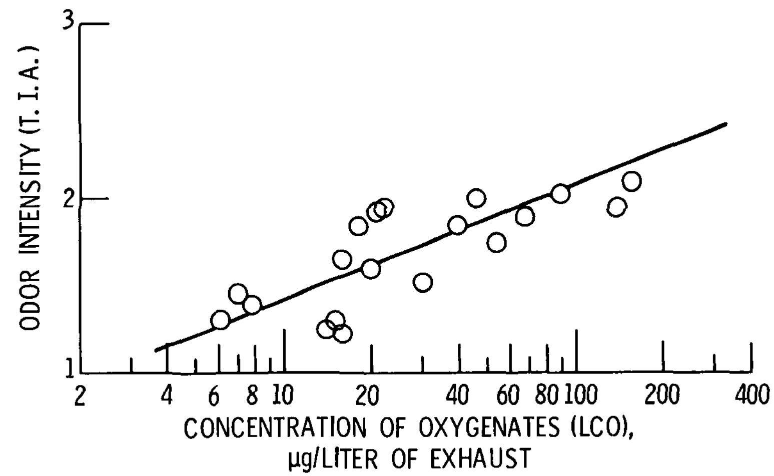

Figure 9. - Correlation between odor intensity and concentration of oxygenates. ASTM A-1 fuel; variable: combustor-inlet temperature and pressure, and fuel-air ratio.

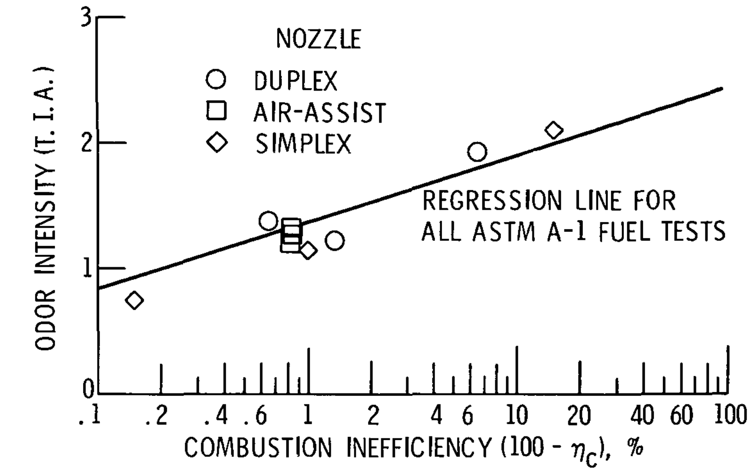

Figure 10. - Correlation between odor intensity and combustion inefficiency for various fuel-nozzle modifications. Fuel, ASTM A-1.

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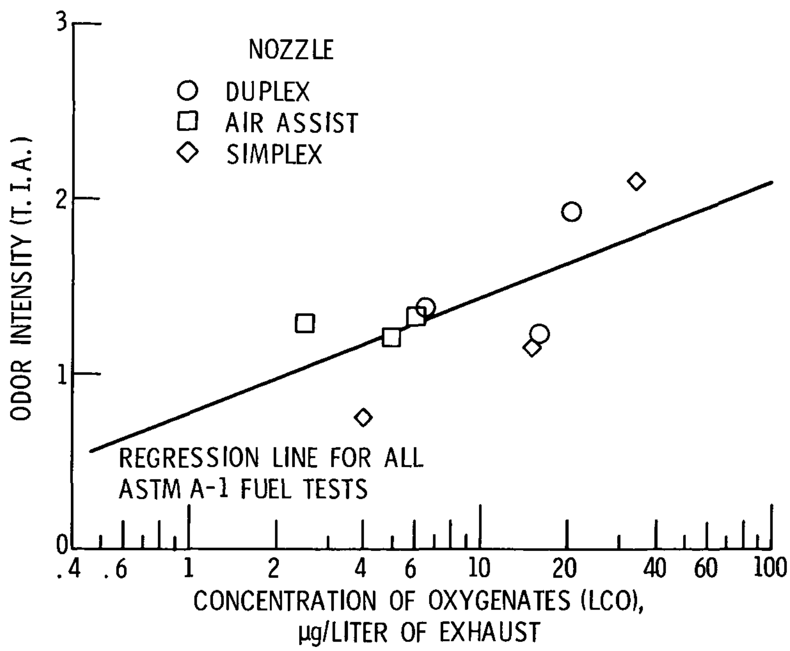

Figure 11. - Correlation between odor intensity and concentration of oxygenates for various fuel-nozzle modifications. Fuel, ASTM A-1.

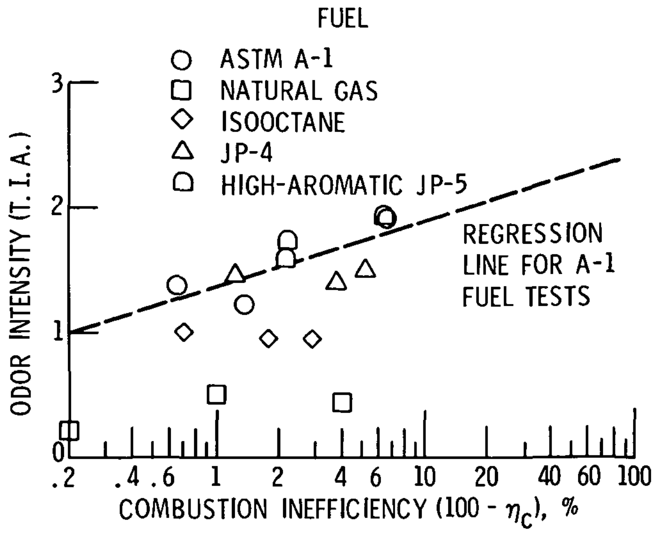

Figure 12. - Correlation between odor intensity and combustion inefficiency for various fuels.

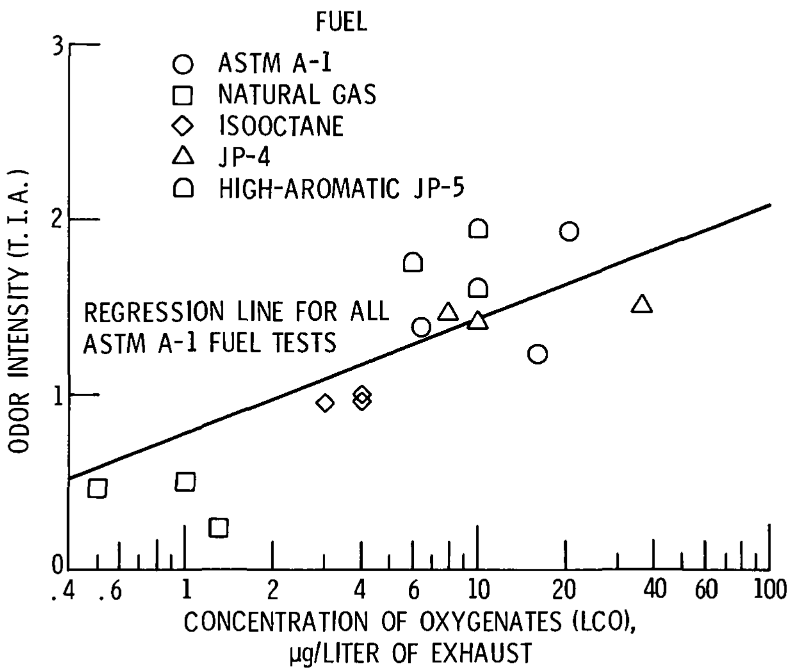

Figure 13. - Correlation between odor intensity and concentration of oxygenates for various fuels.

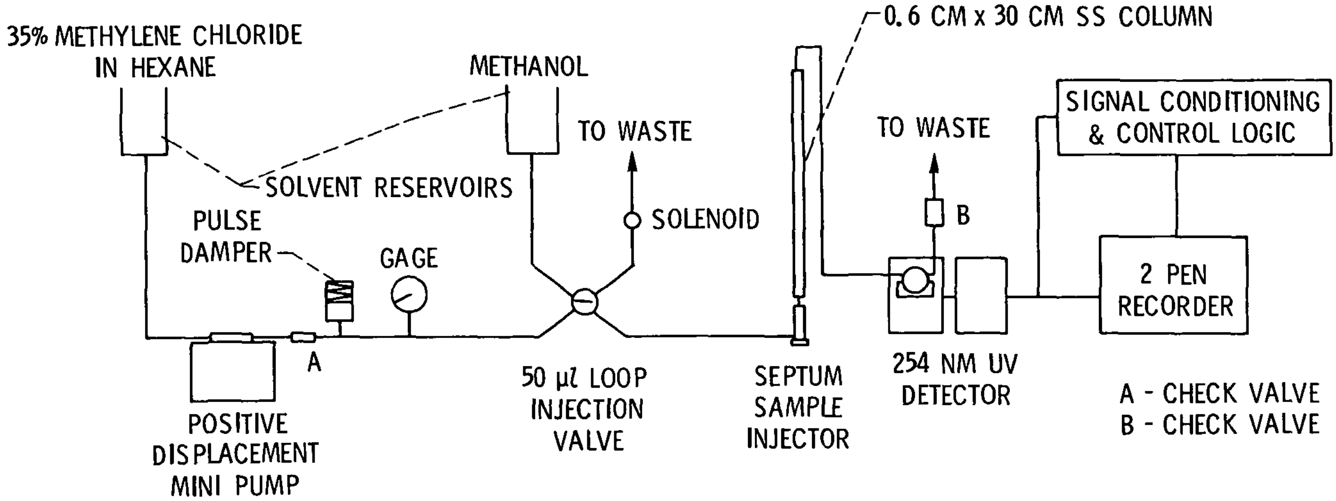

Figure 14. - Analytical liquid chromatograph (ALC) prototype system.

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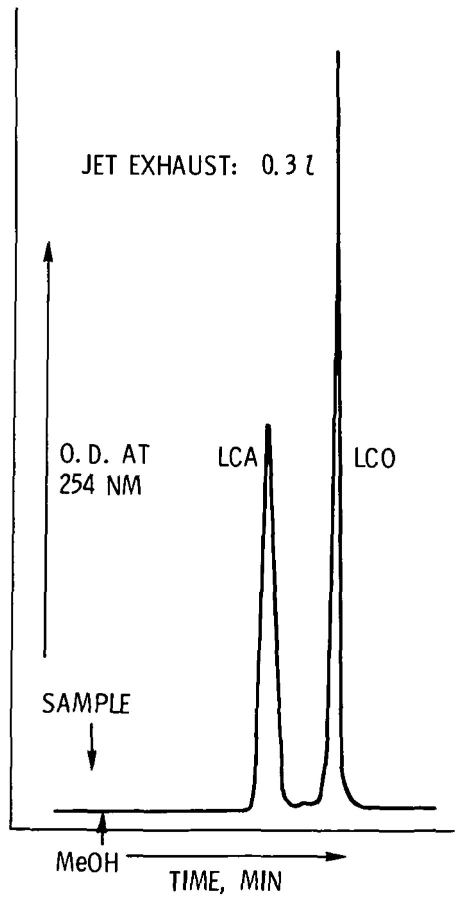

Figure 15. - Typical chromatogram of jet exhaust T.O.E. sample.