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NASA TM X-3227

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GAS SAMPLING METHOD FOR DETERMINING POLLUTANT CONCENTRATIONS IN THE FLAME ZONE OF TWO SWIRL-CAN COMBUSTOR MODULES

Robert A. Duerr

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1975

1. Report No. NASA TM X-3227	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle GAS SAMPLING METHOD FOR DETERMINING POLLUTANT CONCENTRATIONS IN THE FLAME ZONE OF TWO SWIRL-CAN COMBUSTOR MODULES		5. Report Date May 1975
		6. Performing Organization Code
7. Author(s) Robert A. Duerr		8. Performing Organization Report No. E-8211
		10. Work Unit No. 505-04
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s)) Measurement of gaseous pollutants Jet engines Combustion	18. Distribution Statement Unclassified - unlimited STAR Category 07 (rev.)		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 24	22. Price* $3.25

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

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INTRODUCTION

This report discusses a three-degree-of-freedom gas sampling probe which has been developed for measuring the pollutant formations in the primary zone of gas turbine combustors. Primary zone concentrations of gaseous pollutants are reported for two different swirl-can combustor module designs.

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas

of concern have been expressed: urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons and carbon monoxide during idle and taxi, and oxides of nitrogen and smoke during takeoff and landing. Oxides of nitrogen are also considered to be the most predominant emission products formed during altitude cruise.

Altering gas turbine combustor designs to make substantial reductions in oxides of nitrogen will be an extremely difficult task (ref. 1). Oxides of nitrogen are formed during any combustion process involving air. The amount formed is reaction-rate controlled and is a function of flame temperature, dwell time of the combustion gases at high temperature, concentrations of nitrogen and oxygen present, and the combustor pressure. Flame temperatures increase as the primary zone fuel-air ratio approaches stoichiometric values. Dwell time is affected by combustor primary zone length and reference velocity. Trends in combustor operating conditions indicate a steady increase in inlet temperature and pressure due to increasing compressor pressure ratios (ref. 2).

A detailed probing of the primary zone of a combustor should help in understanding how various combustor design features affect the combustion reaction and the formation of gaseous pollutants. For this reason a gas sampling probe was constructed for making measurements in the primary zone of a segment combustor which consisted of a single swirl-can module. For information on the swirl-can combustor, see references 3 to 9. Two different swirl-can module designs were tested. Combustor test conditions were held nominally at an inlet-air temperature of 590 K, a pressure of 6 atmospheres, and reference velocities of 23 and 30 meters per second. Fuel-air ratios were held nominally at 0.02.

APPARATUS AND PROCEDURE

Test Facility

The tests in this report were conducted in a closed-duct test facility capable of supplying air to a combustor at flow rates up to 1 kilogram per second and at pressures up to 7.5 atmospheres. A schematic of the flow system is shown in figure 1. Ambient temperature combustion airflow is measured by a square-edged orifice installed according to ASME standards. The high-pressure inlet air may be indirectly preheated to 750 K in a counterflow heat exchanger using methane for fuel. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. In these tests, the hot exhaust gases from the combustor were cooled in a water quench upstream of the exhaust valve.

Combustor Test Section

The test section, designed for a single swirl-can module, is shown schematically in figure 1. The fuel tube for each swirl can was centered in the combustor housing and passed out of the combustor through an upstream flange. The combustor liner was 6.91 centimeters in diameter and was not cooled with combustor air. The swirl-can modules were each centered in the liner and were located approximately 9.5 centimeters from the downstream end of the liner. A 20-joule ignitor plug was inserted through the water-cooled outer jacket around the test combustor and was located so that the spark would pass through a hole in the liner approximately 4 centimeters downstream of the swirl-can module.

Swirl-Can Module Designs

A typical swirl-can module is shown schematically in figure 2. Each module consists of three components: a cup, an inner swirler, and a flame stabilizer. In operation, the module performs several functions. Each module mixes fuel with air, swirls the mixture, stabilizes the combustion in its wake, and provides large interfacial mixing areas between the bypass air around the module and combustion gases in its wake.

Pollutant emission measurements were made on two swirl-can module designs. Details of the designs are presented in table I. In calculating the percent blockage, which is related to the pressure drop, the swirler discharge coefficient was assumed equal to 1. Figures 3 and 4 depict the two modules tested. Figure 3 shows the model 1 design which uses a hexagonal plate as a flame stabilizer. The inner swirler is mounted so that the swirler face and the hexagonal plate are coplanar. Figure 4 shows the model 2 design in which the fuel is injected downstream of the inner swirler against the circular disk shown in the center of the module. The swirler face was recessed 0.56 centimeter from the flame stabilizer. Each figure shows two of the three pieces of tubing that were attached to the carburetor for the purpose of centering the swirl-can module in the test section.

Emission Measurements

Concentrations of total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and carbon dioxide were obtained with an on-line gas sampling and analysis system. The gas sample was drawn at axial locations varying from 2.5 to 25 centimeters from the face of the swirl-can module at radial locations varying from 0 to 4 centi-

meters from the centerline of the module, and at four equally spaced azimuthal locations.

Gas sample probe actuator assembly. - The gas sample probe could be located at any position in the flame zone through the combination of three remotely controlled actuator systems. Command potentiometers could be set to the desired positions for the axial, radial, and azimuthal directions and separate control systems, each with its own motor, would drive the probe to the appropriate position. Probe position could be constantly monitored in the control room through feedback potentiometers and digital electronic displays. A water-cooled ball socket attached to the outside of the test rig served as pivot point of operation for the probe actuator assembly as shown in figure 1.

Gas sample probe. - The gas sample probe, shown in figure 5, was located downstream of the swirl can in such a manner as to allow gas samples to be taken at any location in the flame zone. The probe was constructed of five concentric pieces of stainless-steel tubing in order to allow passages for water and steam cooling of the probe. The sample gas entered the probe through four ports of 0.12 centimeter diameter located on the outer diameter of the probe approximately 1 centimeter from the tip of the probe. This design inhibited the entry of soot into the probe at close range to the swirl can. In the original probe design, which provided for entry of the sample along the central axis of the probe, soot tended to collect inside the probe and impede the flow of sample gas. With the side-entry probe, however, much of the soot has enough momentum to carry it past the sample ports. The gas sample temperature at the probe exit was maintained between 410 and 450 K by use of both steam and water cooling.

Gas analysis system. - A picture of the gas analysis instrumentation and a schematic of the system are shown in figures 6 and 7, respectively. The sample collected by the probe was transported through 0.64-centimeter-diameter stainless-steel line to the analytical instruments. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated. Sample line pressure was nominally maintained at 2 atmospheres at the instruments in order to supply sufficient pressure to operate the instruments. Excess sample was vented at the instruments.

The exhaust gas analysis system is a packaged unit consisting of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. The hydrocarbon content of the exhaust gas is determined by a Beckman Instruments Model 402 Hydrocarbon Analyzer. This instrument is of the flame ionization detector type. The concentration of the oxides of nitrogen is determined by a Thermo Electron Corporation Model 10A Chemiluminescent Analyzer. The instrument includes a thermal reactor to reduce nitrogen dioxide to nitric oxide and was operated at 972 K. Both carbon monoxide and carbon

monoxide and carbon dioxide analyzers are of the nondispersive infrared (NDIR) type (Beckman Instruments Model 315). The carbon monoxide analyzer has four ranges: 0 to 100 ppm, 0 to 1000 ppm, 0 to 1 percent, and 0 to 10 percent. These ranges of sensitivity are accomplished by using stacked cells of 0.64 centimeter and 34 centimeters in length. The carbon dioxide analyzer has two ranges: 0 to 5 percent and 0 to 15 percent, with a sample cell length of 0.32 centimeter.

Analytical procedure. - All analyzers were checked for zero and span prior to and during each test run. Solenoid switching within the console allows rapid selection of zero, span, or sample modes. Therefore, it was possible to perform frequent checks to ensure calibration accuracy without disrupting testing.

Where appropriate, the measured quantities were corrected for water vapor removed. The correction included both inlet-air humidity and water vapor from combustion. The equations used were obtained from reference 10.

Test Conditions

The swirl-can modules were each tested at nominal test conditions of 6 atmospheres pressure, 590 K inlet temperature, 23 and 30 meters per second reference velocities, and a fuel-air ratio of 0.02. These test conditions were selected to simulate operating conditions of an actual gas turbine engine.

RESULTS AND DISCUSSION

For each set of test conditions with each swirl-can model, detailed probing was done at axial planes 5, 10, and 15 centimeters downstream of the test combustor. Data were taken at the geometric centerline and at four radial locations from the centerline of the combustor at four equally spaced azimuthal locations.

Contour Plots

The results of the data scans are displayed in figures 8 to 10, for concentrations in parts per million of hydrocarbons, carbon monoxide, and oxides of nitrogen, respectively. Figure 11 shows the ratio of the local fuel-air ratio based on gas analysis to the metered fuel-air ratio (FARR), which was calculated for each position. The contour maps are based on a 7-centimeter-diameter view around the geometric centerline looking axially upstream toward the swirl-can combustor module.

These contour maps were constructed from the data obtained at the 17 locations of the gas sampling probe at each axial location as described previously. Time did not permit a more detailed probing, and therefore these contours are best estimates only. As a result they should not be considered a detailed mapping, but rather indicate trends in the primary zone of each combustor module.

For each axial position, contour maps compare the distribution of the parameter for each of the two swirl-can models tested, and the values of the contour lines are shown between the two plots. To the immediate right of each contour map, the integrated average value of the parameter for that map is shown. The integration is based on area weighting of the data taken at the various radial locations and averaged over the four azimuthal locations and also indicate trend values rather than exact averages over the entire cross section.

The contour maps for all four parameters show a general symmetry about a point somewhat lower than and to the left of the geometric center. This is a dominant trend near the combustor which tends to fade as the distance from the combustor increases. The probable cause for this phenomenon is the hole in the inner liner through which the ignitor passed, approximately 4 centimeters from the combustor. It is located in the upper right section of the liner as seen from downstream and is about 0.8 centimeter in diameter. Since the static pressure inside the liner is slightly less than the static pressure in the "dead zone" between the inner liner and the outer liner, a recirculation flow could develop in which gases are drawn around the downstream end of the inner liner and back into the mainstream flow through the ignitor hole. As the distance from the combustor increases, the flow recovers from this disturbance and approaches the geometric centerline.

Unburned Hydrocarbons Emissions

The integrated values of the hydrocarbon concentration shown in figure 8(a) indicate a slightly higher level at the 5-centimeter scan for model 1 over model 2, but a lower value for the 10- and 15-centimeter locations. Figure 8(b) shows higher levels for the 5- and 10-centimeter positions for model 2 over model 1, but a lower value at 15 centimeters. The model 2 contours for figure 8(b) indicate some hydrocarbon toward the top of the test section which suggests that the fuel spray angle of model 2 apparently is wide enough to deposit fuel on the walls of the inner liner which then collects at the downstream edge of the liner and burns there. This conclusion was supported by visual indication of flame seating on the end of the liner. The integrated values also show lower levels of concentrations at the 30-meter-per-second condition than at 23 meters per second at all positions for both models which indicates that the

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higher pressure drop at the 30-meter-per-second condition improved atomization of the fuel for quicker combustion. Also, the general irregularity of the contours indicate a nonhomogeneous distribution of fuel around the combustor modules.

Carbon Monoxide Emissions

In figure 9(a), the integrated values of the carbon monoxide concentrations show higher levels for model 1 over model 2 at the 5- and 10-centimeter locations, but a lower value for model 1 at the 15-centimeter position. In figure 9(b), the integrated values are higher at the 5-centimeter location for model 1, but model 2 has higher levels for the two downstream positions. This indicates a longer burning zone for model 2 which is consistent with the previous observation of flame seating on the end of the liner. With the exception of the 10-centimeter position for model 1, the integrated values were higher for 30 meters per second than for 23 meters per second which also indicates a longer burning zone for the higher reference velocity condition as expected.

A comparison of figure 8 with figure 9 indicates a substantial contrast between the hydrocarbon contours and the carbon monoxide contours. The carbon monoxide contours are surprisingly symmetric in comparison with the contours of hydrocarbons. This indicates intense mixing of combustion gases in the wakes of the two models.

Nitrogen Oxides Emissions

The nitrogen oxides concentration levels shown in figure 10 reflect the prinicple that higher residence times lead to higher concentrations of nitrogen oxides in that the integrated values for the 23-meter-per-second condition are generally higher than those for the 30-meter-per-second condition with one exception. That exception is the level for model 2 at the 15-centimeter position for the 30-meter-per-second condition. The very high levels of nitrogen oxides at this condition are not at all consistent with the other contours. There might have been an error in the measurements, but without a more detailed probing of the combustion zone a definite answer is not possible. The combustion zone does appear to be longer for model 2 than model 1 as shown by the carbon monoxide contours and this is reflected by nitrogen oxides concentrations slightly higher for model 2 over model 1. There is also evidence of hot spots in the contour plot for model 2 at 23 meters per second and the 5-centimeter position; this is reflected in the high integrated value at that position. Another phenomenon that can be distinguished is the peaking of the integrated values near the 10-centimeter position and the downstream dilution effects which lower the concentration levels.

Ratio of Local- to Metered-Fuel-Air Ratios (FARR)

Figure 11 indicates the contours and integrated values of the FARR parameter. Comparison of the values for the two combustor models and the two reference velocities does not result in any clear trends, except that the integrated values decrease with increasing distance from the combustor module. The combustion zones mix as they move downstream, and tend toward homogeneity which would be represented by a constant FARR value of 1.0 over the entire cross section. Again, the 15-centimeter position for model 2 at 30 meters per second seems inconsistent with the other 11 contour plots indicating unusually low values of FARR. With limited information available, no conclusive explanation can be made.

Evaluation of Probing Techniques

The previous measurements of gaseous pollutants in the combustor primary zone successfully demonstrate the feasibility of designing a gas sampling probe to withstand the adverse environment inside a combustor. The probe was adequately cooled for all locations in the combustor. Clogging of the gas sampling ports with carbon was successfully prevented by locating the ports on the side of the probe. The traverse mechanism provided remote control movement of the probe tip to any desired location in the combustor.

The previous tests also indicate that, due to the large spatial gradients, probing in much more detail than was done is necessary in order to obtain desired information on how gaseous pollutants are formed in the combustor primary zone. With a single point probe as the one used in these tests, this detailed probing will require a substantial amount of test time.

SUMMARY OF RESULTS

Gas samples were obtained with a three-degree-of-freedom probe connected to an on-line gas analysis system. This technique successfully demonstrated probing of the primary zone of a research combustor for the purpose of studying the formation of gaseous pollutants and their spatial distribution.

However, the primary zone of a combustor must be probed in much more detail

than was done here due to the large spatial gradients that exist in order to quantitatively determine the formation of gaseous pollutants in the combustor process.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 28, 1975,
505-04.

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TABLE I. - DESCRIPTION OF SWIRL-CAN COMBUSTOR MODULES

Model	Percent blockage in 6.91-cm-diam duct	Inner swirler description	Flame stabilizer description	Fuel injection description
1	47.8	Stamped swirler, 12 blades, 45° angle at tips; tip diameter, 3.25 cm; hub diameter, 1.59 cm; open area, 2.36 cm^2	Hexagon of side L = 2.79 cm; full area, 20.3 cm^2	Fuel tube centered in can; 0.13-cm-diam orifice at end of tube 0.32 upstream of inner swirler; fuel sprayed through inner swirler
2	60.3	Stamped swirler, 12 blades, 45° angle at tips; swirler face recessed 0.56 cm from flame stabilizer; tip diameter, 3.33 cm; hub diameter, 1.91 cm; open area, 2.30 cm^2	Stamped swirler, 24 blades, 45° angle at tips; swirler blades of opposite rotation from inner swirler; tip diameter, 5.79 cm; hub diameter, 4.57 cm; open area, 2.90 cm^2; swirler shroud diameter, 5.95 cm	Fuel tube attached to center of inner swirler hub; 0.13-cm-diam orifice through hub; fuel passes through orifice and splashes against 1.97-cm-diam disk mounted 0.16 cm from inner swirler hub
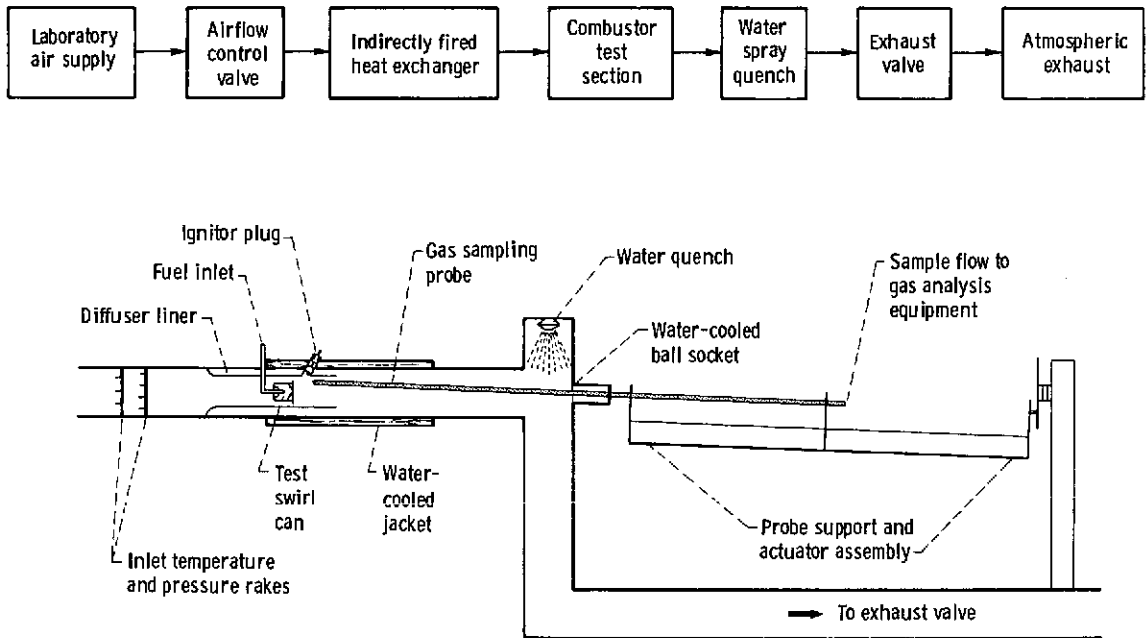
Figure 1. - Test facility and combustor test section schematics.
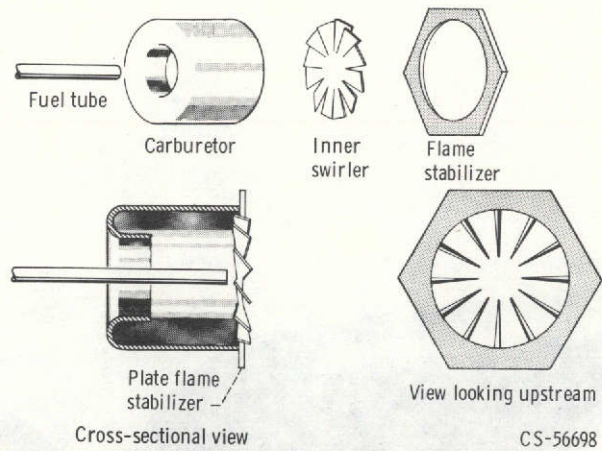
Figure 2. - Typical swirl-can combustor module details.

Figure 3. - Model 1.

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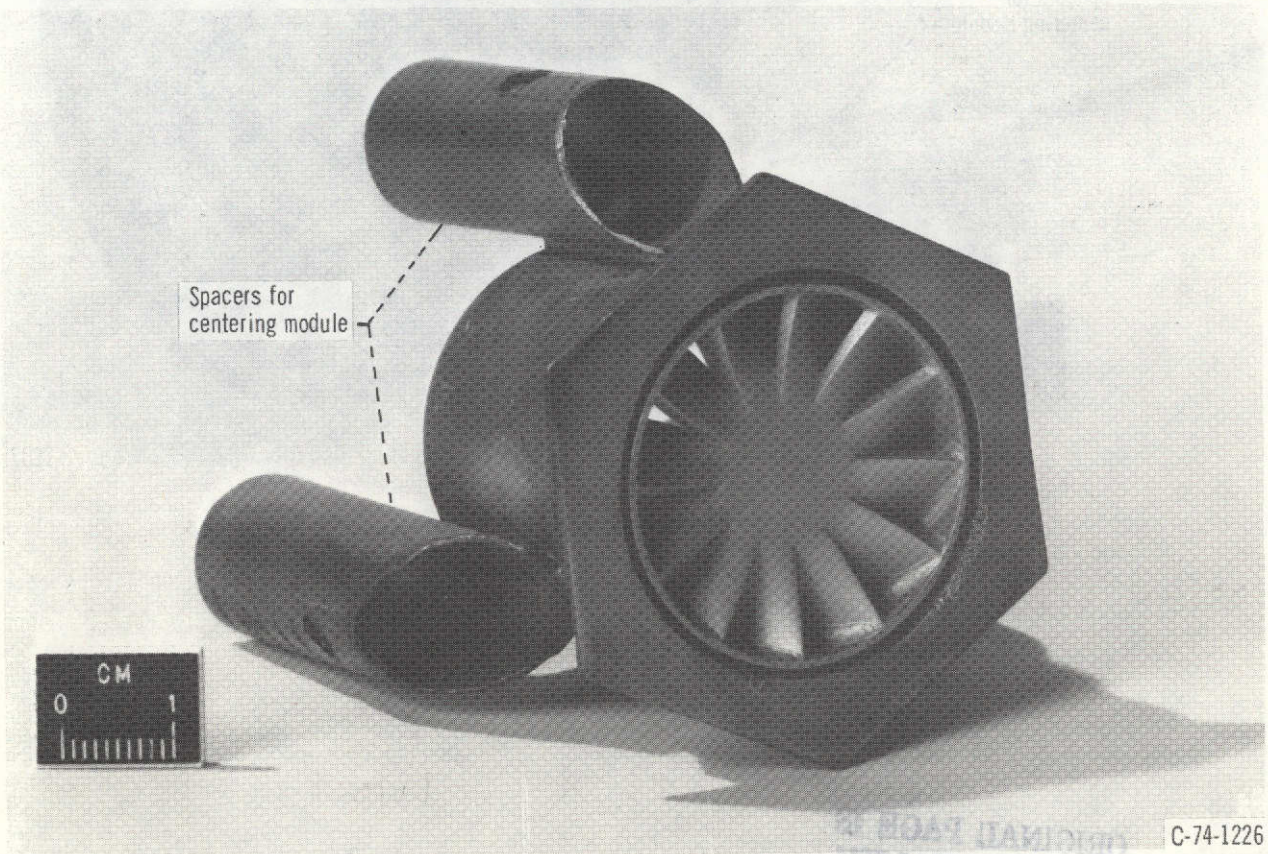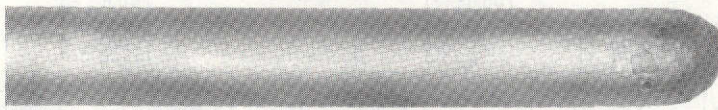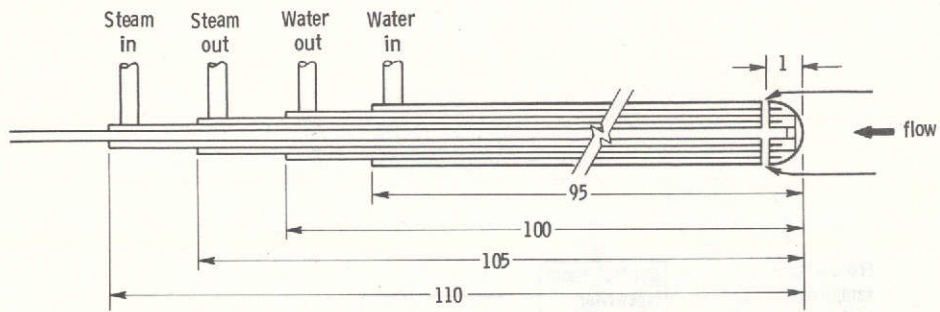
Figure 5. – Gas sampling probe. Probe tubing diameters, 1.27, 0.95, 0.64, 0.48, and 0.32. (Dimensions in cm.)
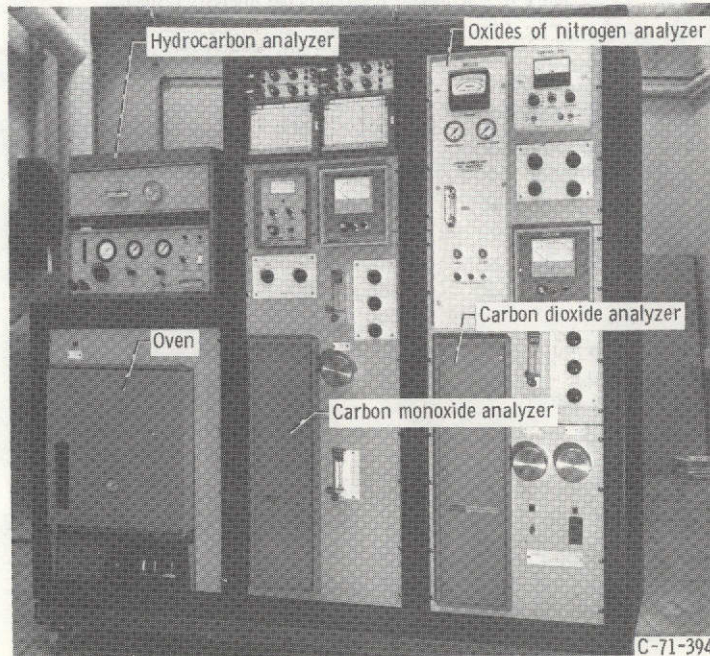
Figure 6. – Gas sampling instrument console.
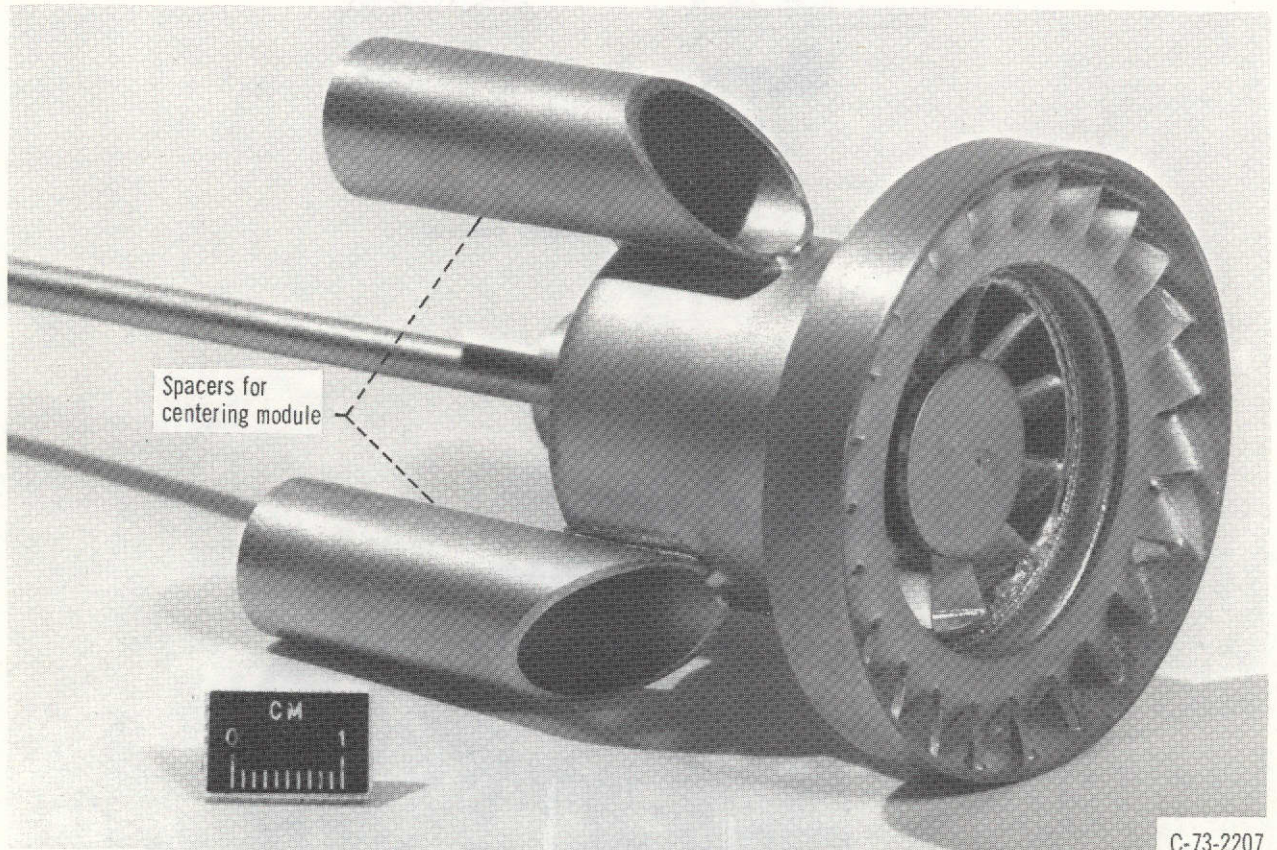
Spacers for
centering module

CM

0   1

C-73-2207

Figure 4. - Model 2.
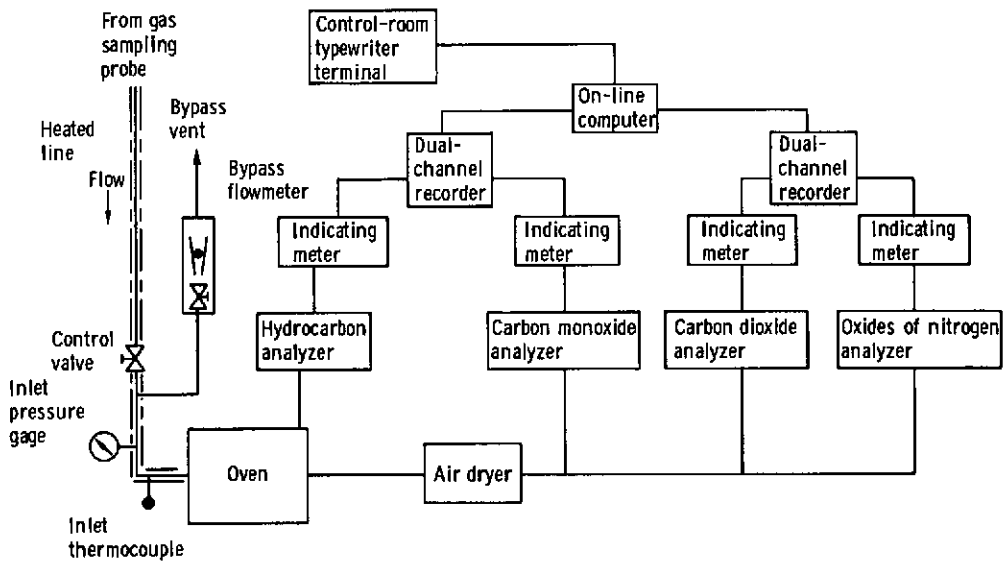
Figure 7. - Schematic diagram of gas analysis system.

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Unburned hydrocarbon
concentration,
ppm

A	5000		A	3000	A	1000
B	4000		B	2000	B	750
C	3000		C	1200	C	500
D	2000		D	600	D	250

3400

1300

460

(a-1) Model 1.

3200

1400

500

5

10

15
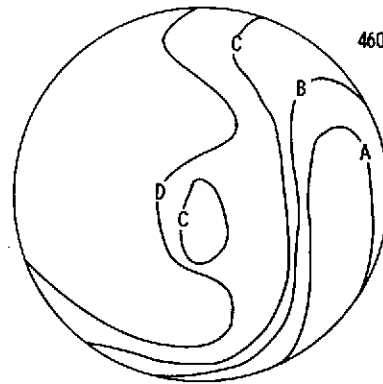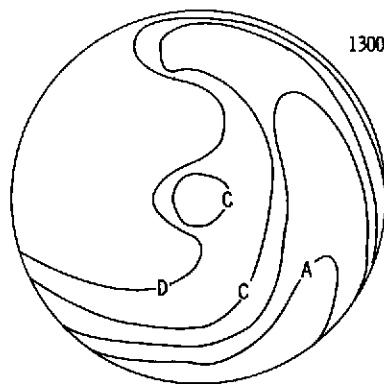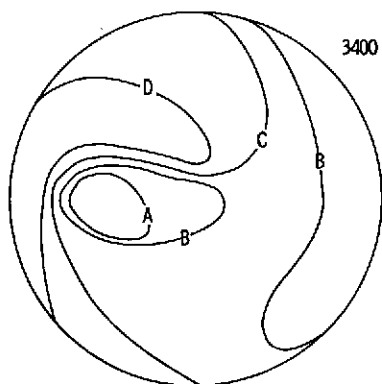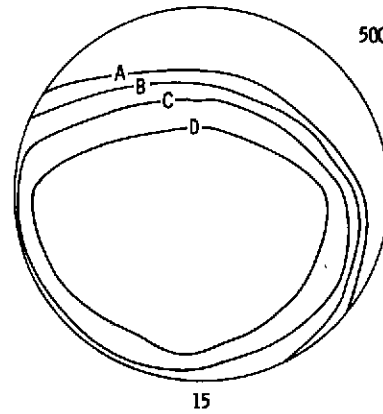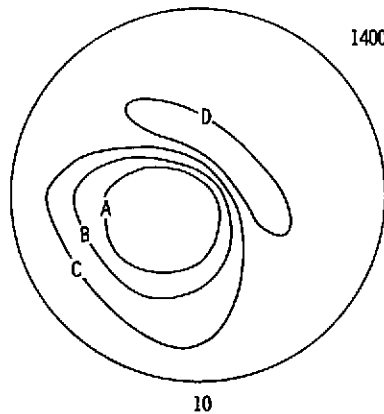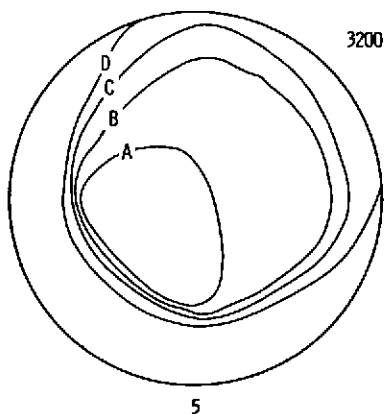
Axial distance from swirl can, cm

(a-2) Model 2

(a) Reference velocity, 23 meters per second.

Figure 8. - Contours of unburned hydrocarbon concentration. The integrated value for each contour is given at the upper right of each plot.

Unburned hydrocarbon
concentration,
ppm

A	6000	A	3000	A	800
B	4500	B	2000	B	400
C	3000	C	1000	C	200
D	1500	D	500	D	100
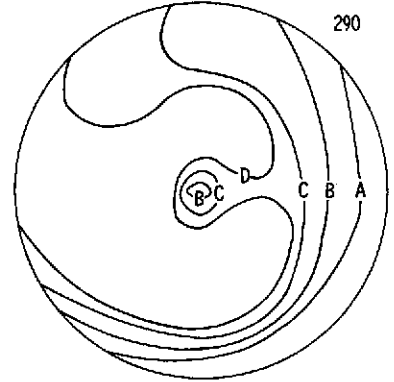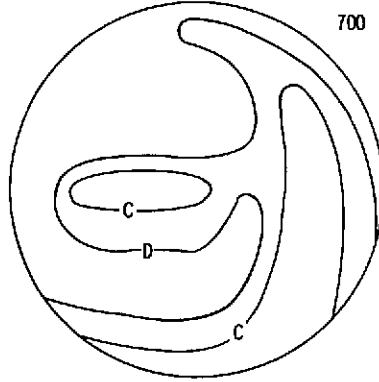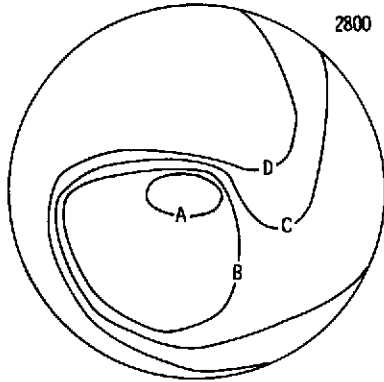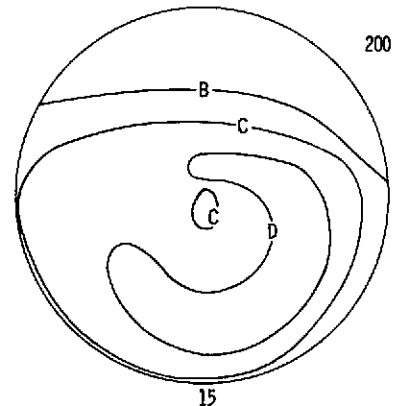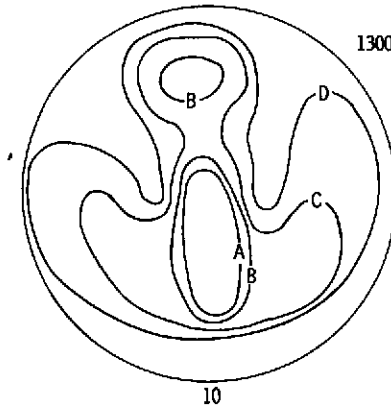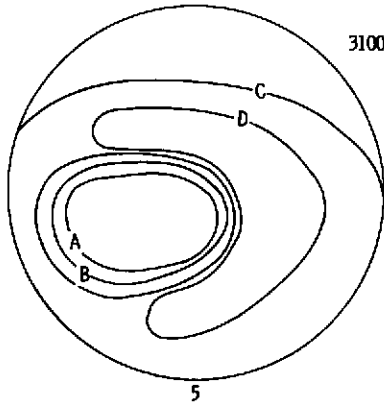
(b-1) Model 1.

Axial distance from swirl can, cm

(b-2) Model 2.

(b) Reference velocity, 30 meters per second.
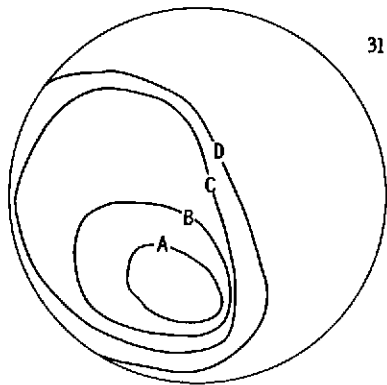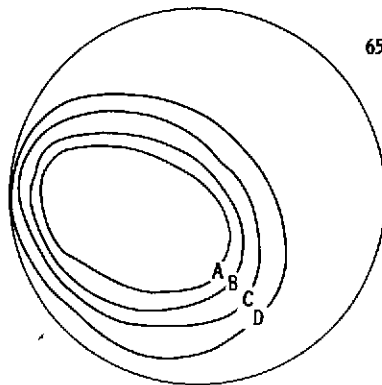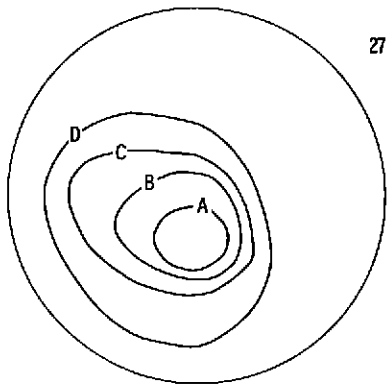
Figure 8. – Concluded.

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Carbon monoxide
concentration,
ppm

|						
A	90 000		A	60 000	A	5000
B	60 000		B	40 000	B	2500
C	30 000		C	20 000	C	1000
D	15 000		D	10 000	D	500

30 000

16 000

700

(a-1) Model 1.

25 000

15 000

3000

5

10

15

Axial distance from swirl can, cm

(a-2) Model 2.

(a) Reference velocity, 23 meters per second.

Figure 9. – Contours of carbon monoxide concentration. The integrated value for each contour is given at the upper right of each plot.

Carbon monoxide
concentration,
ppm

A	90 000
B	60 000
C	30 000
D	15 000

A	60 000
B	40 000
C	20 000
D	10 000

A	20 000
B	15 000
C	10 000
D	5 000
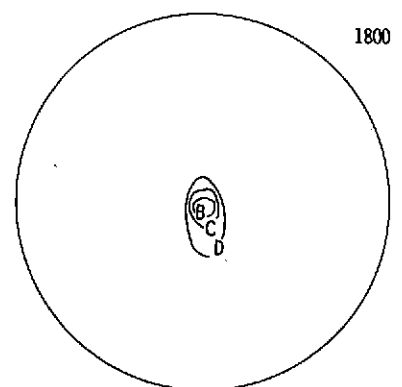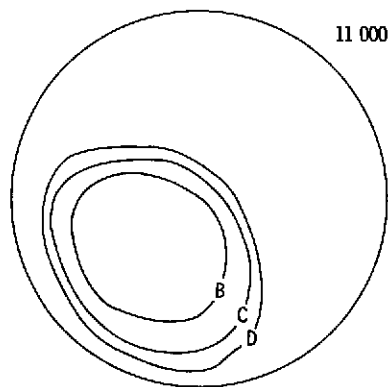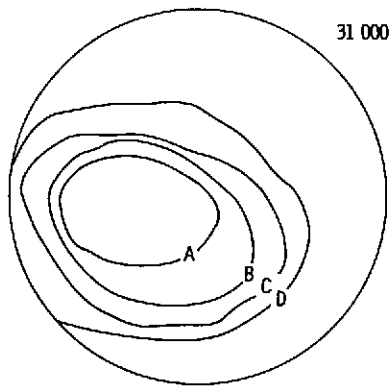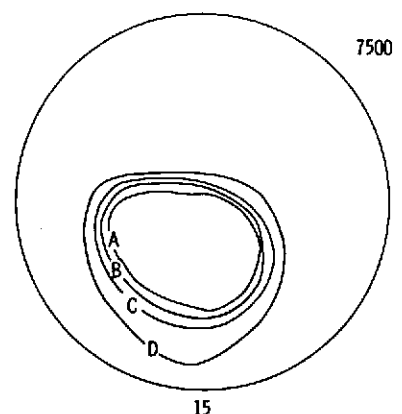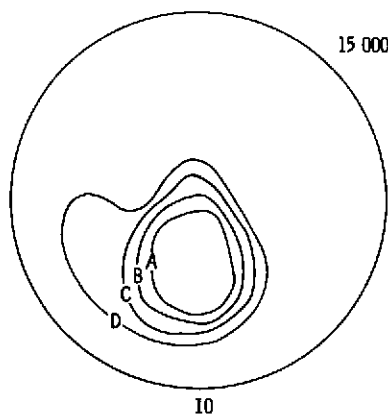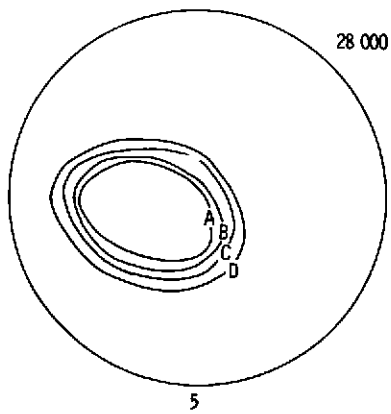
31 000

11 000

1800

(b-1) Model 1.

28 000

15 000

7500

5

10

15

Axial distance from swirl can, cm

(b-2) Model 2.

(b) Reference velocity, 30 meters per second.

Figure 9. – Concluded.

Nitrogen oxides
concentration,
ppm

A	100	A	180	A	120
B	75	B	120	B	90
C	50	C	80	C	60
D	25	D	40	D	30
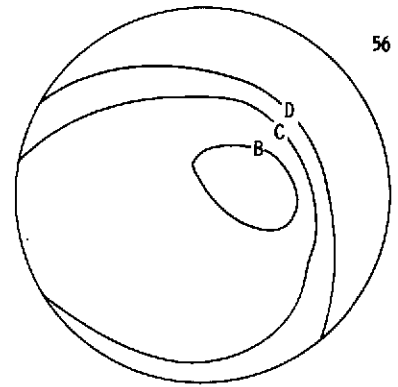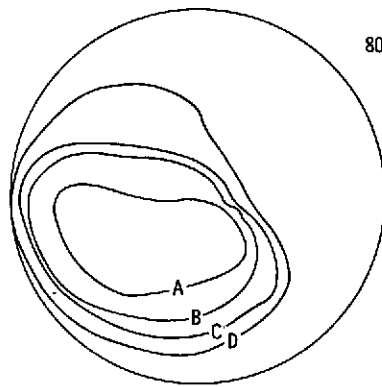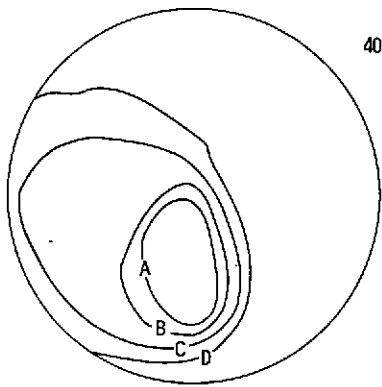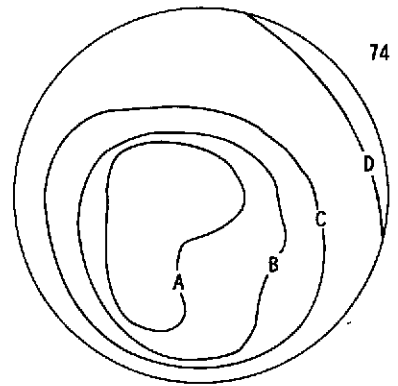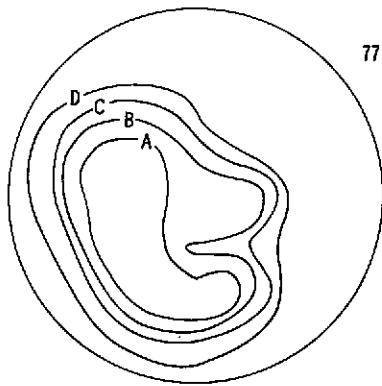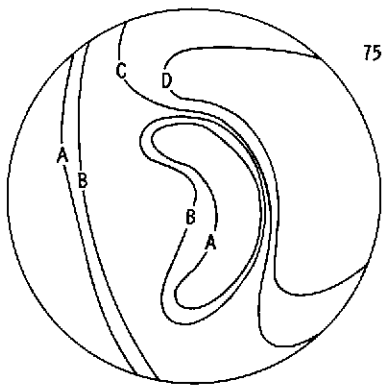
(a-1) Model 1.

Axial distance from swirl can, cm

(a-2) Model 2.

(a) Reference velocity, 23 meters per second.

Figure 10. - Contours of nitrogen oxides concentration. The integrated value for each contour is given at the upper right of each plot.

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Nitrogen oxides
concentration,
ppm

A   80
B   60
C   40
D   20

A   120
B   90
C   60
D   30

A   240
B   160
C   80
D   40
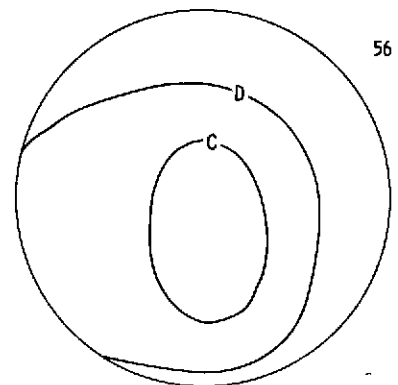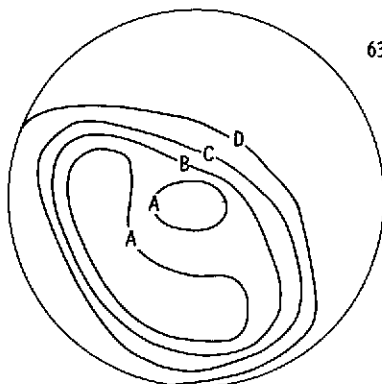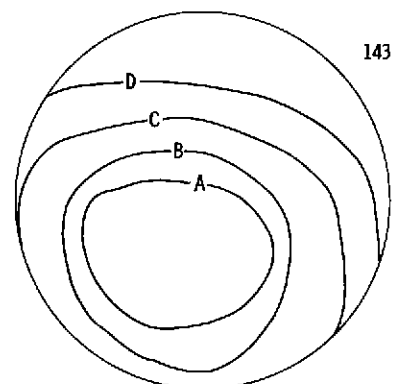
(b-1) Model 1.

Axial distance from swirl can, cm

(b-2) Model 2.

(b) Reference velocity, 30 meters per second.

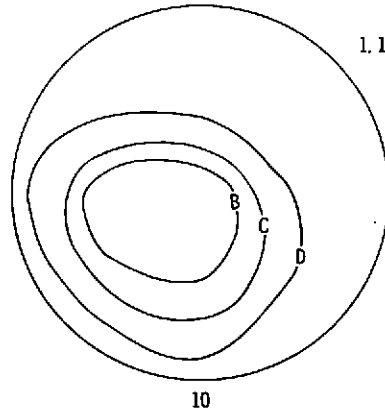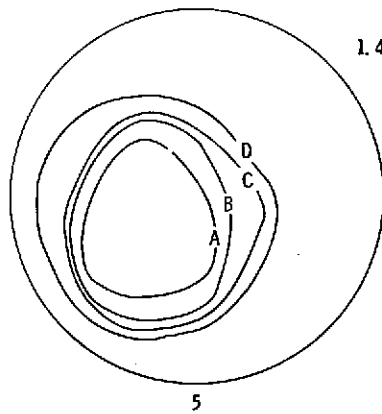Figure 10. - Concluded.

20

Ratio of local- to metered-
fuel-air ratio

A	4
B	3
C	2
D	1

A	3.5
B	2.5
C	1.5
D	.5

A	1.75
B	1.25
C	1.00
D	.50
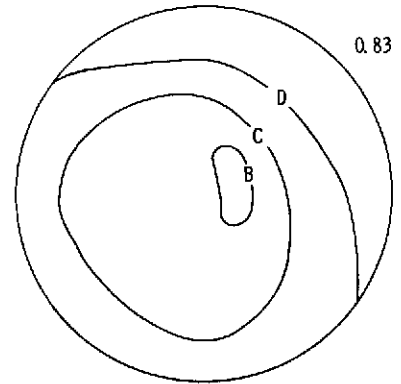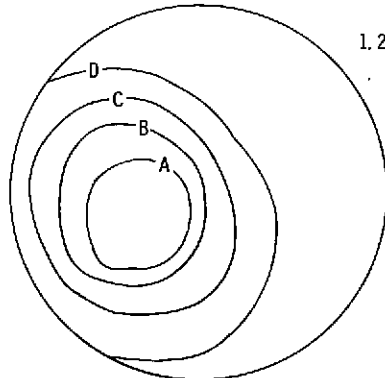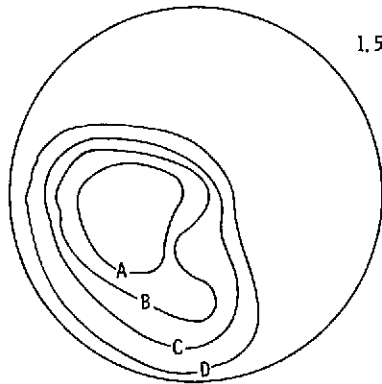
(a-1) Model 1.

Axial distance from swirl can, cm

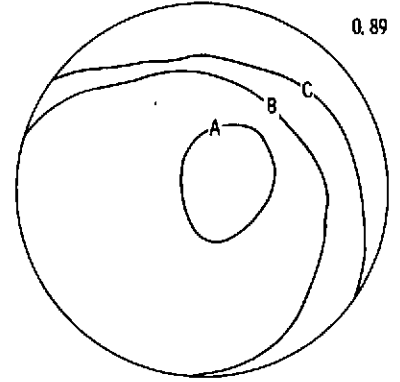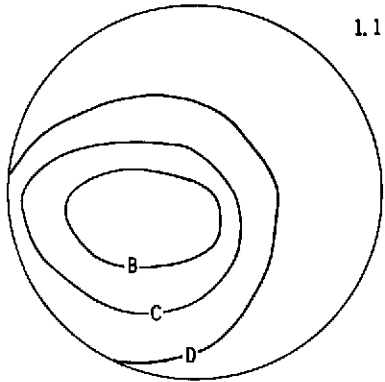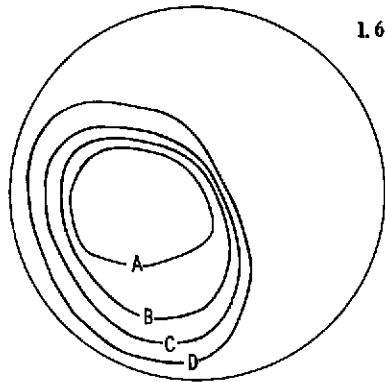(a-2) Model 2.

(a) Reference velocity, 23 meters per second.

Figure 11. – Contours of ratio of local- to metered-fuel-air ratio. The integrated value for each contour is given at the upper right of each plot.
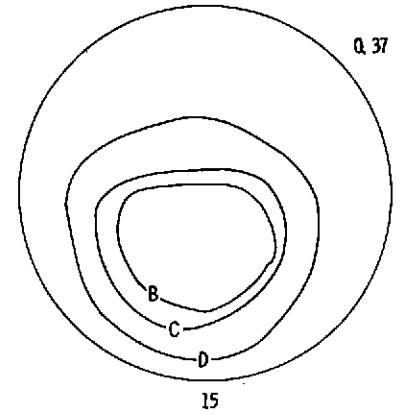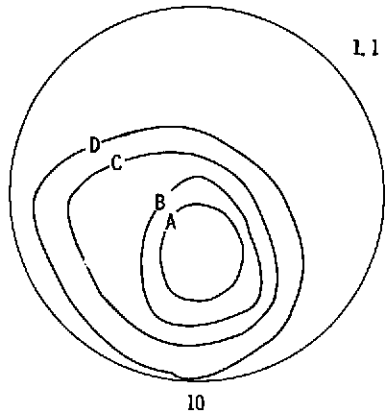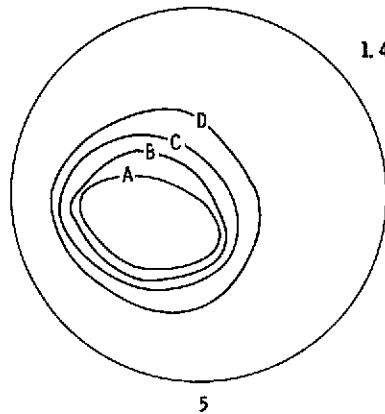
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Ratio of local- to metered-
fuel-air ratio

A	4	A	3.5	A	1.25
B	3	B	2.5	B	.75
C	2	C	1.5	C	.50
D	1	D	.5	D	.25

(b-1) Model 1.

Axial distance from swirl can, cm

(b-2) Model 2.

(b) Reference velocity, 30 meters per second.

Figure 11. - Concluded.