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THE NACA MIXTURE ANALYZER AND ITS APPLICATION TO MIXTURE-DISTRIBUTION MEASUREMENT IN FLIGHT

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SUMMARY

The NACA mixture analyzer was developed as a research instrument for the continuous indication of fuel-air ratios of aircraft-engine installations throughout the range of engine operation. It has been evaluated by using it to measure the mixture distribution of a nine-cylinder radial aircraft engine in flight.

The mixture distribution among the cylinders in flight was obtained at normal operating conditions for the engine at an altitude of 5000 feet. Some limited data were also obtained at an altitude of 20,000 feet. Results of these flight tests showed that the NACA mixture analyzer is a satisfactory and dependable instrument for continuous indication of the mixture in flight at all engine conditions regardless of altitude and temperature.

INTRODUCTION

Operation at known fuel-air-ratio values makes possible the control of the fuel consumption and power of an aircraft engine and consequently the attainment of maximum economy and range. Because the effective fuel-air ratio of the engine is the average of the fuel-air ratios of each cylinder, the operating condition of each cylinder becomes important. In radial and in-line engines the design of the intake system may cause some cylinders to receive a leaner charge than other cylinders. When the lean mixture is enriched by carburetor adjustment, the mixtures in other cylinders are necessarily enriched, which increases the fuel consumption and reduces the range of the aircraft. When a cylinder operates at high powers and lean mixtures, detonation may occur, resulting in power loss and possible engine failure. Operation of the engine in flight for best performance, that is, for maximum power, maximum economy, and maximum safety, requires exact knowledge and control of the mixture strength or fuel-air ratio of the mixture in the engine cylinders at all times.

Among the methods that have been used for determining the mixture strength of an aircraft engine are: (1) chemical analysis of the exhaust gas in flight or collection of exhaust-gas samples and analysis after flight and (2) continuous exhaust-gas analysis in flight by commercially developed instruments of the thermal-conductivity and catalytic-combustion types.

Collection of the normal exhaust gas to be analyzed later in the laboratory is unsatisfactory because it does not give an immediate value and because each complete analysis requires several hours and expensive fragile equipment. This method, which was used in reference 1 in the study of mixture distribution in a single-row radial engine, is suitable principally as a check on other methods to be discussed.

Numerous investigations of the mixture distribution in multicylinder engines have been made by the NACA using oxidized exhaust gas, as proposed in reference 2. This method involves the oxidation of normal exhaust gas and chemical analysis of the resultant carbon-dioxide content of the gas. The fuel-air ratio is readily obtained from a graph correlating carbon-dioxide percentage with fuel-air ratio or from a simple stoichiometric equation. The method is quick and satisfactory for laboratory investigations but in flight the varying ambient pressures make difficult the determination of the carbon-dioxide content of the exhaust gas. This problem has been satisfactorily overcome by incorporating the method proposed in reference 2 into a continuous-indicating mixture analyzer of the thermal-conductivity type.

Mixture analyzers of the thermal-conductivity type have been previously developed for determining the over-all mixture strength of engines during flight but their operation is dependent upon the amount of hydrogen present, which confines the range to mixtures richer than the chemically correct mixture (one with neither excess fuel nor air). When used on mixtures leaner than the chemically correct mixture, these instruments reverse their direction of indication and indicate a richer mixture. Reference 3 discusses the characteristics of such exhaust-gas analyzers.

The catalytic-combustion type instrument (reference 4) has a serious limitation in that the platinum filament is affected by leaded fuels and the calibration changes with changes in engine operating conditions (speed and power).

In consideration of the limitations of the different methods and instruments, the NACA developed a mixture analyzer of the thermal-conductivity type that gives a correct indication of fuel-air ratio over the entire range of engine operation regardless of altitude, temperature, and fuel. An investigation of the accuracy and dependability of the mixture analyzer as a flight instrument, covering a range of normal operating conditions of an aircraft engine (60-percent cruise, 70-percent cruise, and rated power) at various altitudes, was conducted at the NACA Cleveland laboratory and the data are presented herein.

NACA MIXTURE ANALYZER

The NACA mixture analyzer (fig. 1) was primarily designed to indicate the mixture strength or fuel-air ratio of aircraft power plants in flight but can be used in the laboratory or in the field. The complete instrument consists of the analyzer and the indicator electrically interconnected with a multiconductor cable. The indicator is scaled for fuel-air ratios from 0.03 to 0.125. The instrument operates on the nominal 24-volt direct-current system used in aircraft and is calibrated at $27 \pm 1\frac{1}{2}$ volts as best representing the actual voltage of aircraft. The average operating current is 3.5 amperes, although a maximum current of 6 amperes is drawn intermittently when the electric heaters operate. A short time lag (less than 1 min) exists between change in mixture strength and final meter indication. The indications of the analyzer are not critically dependent upon the hydrogen-carbon ratio of the fuel. For instance, at mixtures that yield maximum engine power, a change in the hydrogen-carbon ratio of the fuel from 0.188 to 0.160 (normal range for aviation fuels) results in a change in the fuel-air ratio from 0.080 to 0.078. The instrument is calibrated for a fuel having a hydrogen-carbon ratio of 0.173, which best represents fuels used in aircraft. The gas circuit and the arrangement of components of the instrument are shown diagrammatically in figure 2.

The operation of the instrument is based on the fact that the total carbon content of the exhaust gas is essentially proportional to the fuel-air ratio of the incoming charge in an internal-combustion, jet, or Diesel engine (reference 2). The products of combustion that may be present in the normal exhaust gas are carbon monoxide, carbon dioxide, saturated and unsaturated hydrocarbons, hydrogen, oxygen, nitrogen, and water. If these products are mixed with an excess of air and then oxidized, the resulting products are carbon dioxide, water, and air (oxygen and nitrogen) and the amount of carbon dioxide is proportional to the fuel-air ratio. In the NACA mixture analyzer, desiccated exhaust gas and desiccated air, both at the same pressure, are mixed in equal volume by a proportioning pump and then passed over an incandescent heater to permit oxidation. The water of combustion is removed and the amount of carbon dioxide is then determined by a thermal-conductivity bridge.

The thermal-conductivity bridge consists of four similar cells in a massive metal block that is maintained at constant temperature by an electric heater and thermostat. Each cell contains a platinum filament and the four filaments are connected in a Wheatstone bridge circuit supplied with constant current through a current-regulating tube. The current through each filament raises its temperature by an amount that is determined principally by the thermal conductivity of the gas between the filament and the wall of the cell. Two of the cells, whose filaments are in diagonally opposite sides of the Wheatstone bridge, are analysis cells, exposed to the oxidized and dried exhaust gas. The other two cells are reference cells, connected in series with the intake to the proportioning pump. Thus, the two reference cells contain only dry air, whereas the two analysis cells contain dry air plus an amount of carbon dioxide proportional to the fuel-air ratio. Because the thermal conductivity of carbon dioxide is less than that of air, the analysis filaments assume a higher temperature than the reference filaments. Inasmuch as the platinum filaments have a high temperature coefficient of resistance, an electrical unbalance of the Wheatstone bridge is produced. This unbalance operates the indicator from which fuel-air ratio can be read directly. The electrical zero of the instrument may be set by operating a solenoid valve to shut off the exhaust-gas supply to the proportioning pump, allowing dry air to pass through all four cells of the bridge. A switch and a rheostat in the bridge circuit are provided for zero adjustment.

In order that the temperature of the cell filaments will be determined solely by the thermal conductivity of the surrounding gas, it is necessary that flow past the filaments be negligible. This minimum flow is accomplished through the design of the cell block, which provides for delivery of gas to the cells essentially by diffusion.

The mixture analyzer was checked for accuracy of indication by passing through it a synthetic mixture of known composition of carbon dioxide, methane, and air. Another method used to check the accuracy of indication was to extract a sample of the gas discharged from the analyzer and measure its carbon-dioxide content with an Orsat analyzer. The following table, determined experimentally, shows the relation of carbon dioxide to fuel-air ratio:

Carbon dioxide in gas discharged from analyzer (percent)	Mixture strength (fuel-air ratio)
2.1	0.02
4.2	.04
6.3	.06
8.5	.08
10.7	.10
12.9	.12

Servicing the instrument requires only the periodic changing of the desiccators in front of the analyzer after each 30 hours operation. The degree of deterioration of the desiccators is shown by wetting of the desiccant on the transparent plastic holder. (The desiccant chosen should be one that does not absorb carbon dioxide.)

FLIGHT INSTRUMENTATION AND METHODS

Installation

The mixture analyzer was tested by using it to measure the mixture distribution of a nine-cylinder engine in flight. The engine has a normal rating of 1000 brake horsepower at an engine speed of 2300 rpm and a take-off rating of 1200 brake horsepower at 2500 rpm. It has a single-stage, two-speed supercharger and an injection-type carburetor, which is standard for the engine.

The fuel used for the entire program was a blend of aviation gasoline that complied with the minimum requirements of specification AN-F-28. The hydrogen-carbon ratio of the fuel was 0.173, as determined in this laboratory by the combustion method.

The NACA mixture analyzer was so located in the right wheel well immediately behind the engine that the short gas-sampling tubes minimized the time lag between change in mixture strength and final meter indication. Stainless-steel sampling tubes 1/4-inch in outside diameter were welded into the center of each exhaust stack within $1\frac{1}{2}$ inches of the exhaust valve. Samples of the exhaust gas from the tail pipe were obtained with a similar tube located in the center of the tail pipe about 36 inches from the exit of the gases to the atmosphere. A diagrammatic sketch of the exhaust-gas sampling system used for the flight tests is shown in figure 3.

Methods of Analysis

The three methods used to determine the fuel-air ratio of the mixture in each cylinder and tail pipe are designated (1) the Orsat method, (2) the laboratory method, and (3) the analyzer method. The first two methods were used to check the third. In methods (1) and (3) the analyses were performed in flight; in method (2) samples were collected in flight and the analysis was performed in the laboratory.

The Orsat method, as described in reference 2, consists in passing the normal exhaust gas through a tube containing copper oxide heated to a temperature of 1200° to 1400° F in which the carbon-containing gases are oxidized to carbon dioxide. In the setup used in the present investigation, the copper-oxide tube was located in the tail pipe to eliminate the fire hazard. At low engine power, the temperature of the copper oxide was too low to oxidize the gases and therefore part of the heat added to the copper oxide was electrically obtained. Because an Orsat analysis requires considerable time, only the gas in the tail pipe was analyzed. The fuel-air ratio was obtained from the carbon-dioxide content of the oxidized exhaust gas (reference 2). Three Orsat analyzers were used to lessen the possibility of error caused by breakdown of any one of them during flight.

The laboratory method consists in collecting normal exhaust-gas samples in pipettes during flight and analyzing these samples in the laboratory. The analysis was made by oxidizing a normal exhaust-gas sample in the combustion pipette of an Orsat apparatus developed by the National Bureau of Standards (reference 5) and by determining the fuel-air ratio from the carbon-dioxide content after oxidation (reference 2). Air was used in the oxidizing procedure.

The analyzer method consists in passing the normal exhaust gas during flight into the NACA mixture analyzer and reading the fuel-air ratio directly from the indicator.

The Orsat method was so used during flight that the oxidized gas from the electric oxidizing furnace in the tail pipe passed through a water trap, then through a calcium-chloride desiccator, and finally to the three Orsats. The laboratory method was used to sample gas from the exhaust stack of each cylinder and the tail pipe. The exhaust-gas samples were collected in glass sampling pipettes, each approximately 300 cubic centimeters in volume. Twenty of these pipettes were so located in a rack that during any flight two samples of the gas from each cylinder and also two from the tail pipe could be obtained. The analyzer method was used on each exhaust stack; a water trap and a calcium-chloride desiccator were utilized to remove excess water from the gas before it entered the NACA mixture analyzer. Because only one mixture analyzer was used, the flow of exhaust gas from each cylinder was switched to the analyzer by electrically operated valves in the sampling lines. Figure 3 shows the system used.

Instruments indicating engine speed, manifold pressure, altitude, fuel-air ratio, and oxidizing furnace conditions were mounted on a panel (fig. 4) and the data were obtained by photographing this panel. The panel installed in the airplane, the three Orsat analyzers, and the sampling pipettes are shown in figure 5.

The analyses were made over a range of engine speeds, manifold pressures, and mixture settings (manual lean setting is below automatic lean) at altitudes of 5000 and 20,000 feet as shown in the following table:

TEST-ENGINE FLIGHT OPERATING CONDITIONS

Test series	Engine speed (rpm)	Manifold pressure (in. Hg absolute)	Mixture setting	Altitude (ft)
1 60-percent normal cruising power	1900	26	Full rich Auto. rich Auto. lean Manual lean	5,000
2 70-percent normal cruising power	2000	32	Full rich Auto. rich Auto. lean Manual lean	5,000
3 Rated power	2300	37	Full rich Auto. rich Auto. lean	5,000
4 70-percent normal cruising power	2000	29.5	Auto. rich Auto. lean	20,000

The conditions at which the engine was operated are the ones most frequently used in the operation of the engine during cruise and rated power. No test data were taken until the engine conditions had become stabilized, which generally required about 5 minutes. A complete test run required approximately 11 minutes.

RESULTS AND DISCUSSION

A correlation of data obtained by the Orsat method in flight and that obtained by the laboratory method is shown in figure 6; the correlation of the data obtained by the laboratory method and by the NACA mixture analyzer method is shown in figure 7. The engine data were obtained at various speeds, manifold pressures, and altitudes. The average error in fuel-air ratio was found to be 0.001. Comparison of all three methods was considered necessary because the Orsat method is considered a standard test method of obtaining engine mixture data. A greater amount of data appears in figure 7 than in figure 6 because for each run there are 10 readings by the laboratory method, 9 by the analyzer method, and 1 by the Orsat method.

Comparison of the three methods of obtaining engine mixture data in flight is presented in figure 8. On the average the difference between the analyzer reading and the laboratory or Orsat reading is no greater than the difference between the laboratory and Orsat readings. Consequently, the NACA mixture analyzer may be considered a satisfactory instrument for continuous indication of fuel-air ratio of an engine in flight. The analyzer required merely an occasional bridge zero adjustment and took less than 1 minute to reach correct mixture indication. The Orsat method required considerably more time, space, and effort to arrive at the fuel-air ratio.

The mixture-distribution patterns obtained with the NACA analyzer are plotted in figure 9 to show the effect of mixture setting, pressure altitude, and power, as determined by engine speed and manifold pressure. It will be noted that all these factors have a bearing on the distribution of the mixture among the cylinders.

SUMMARY OF RESULTS

A flight investigation using the NACA mixture analyzer to indicate the mixture strength or fuel-air ratio of the power plant showed that the instrument is reliable over the entire range of engine operation, regardless of altitude and temperature.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, September 19, 1946.

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1. Gerrish, Harold C., and Voss, Fred: Mixture Distribution in a Single-Row Radial Engine. NACA TN No. 583, 1936.

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5. Shepherd, Martin: An Improved Apparatus and Method for the Analysis of Gas Mixtures by Combustion and Absorption. Res. Paper 266, Bur. Standards Jour. Res., vol. 6, no. 1, Jan. 1931, pp. 121-167.

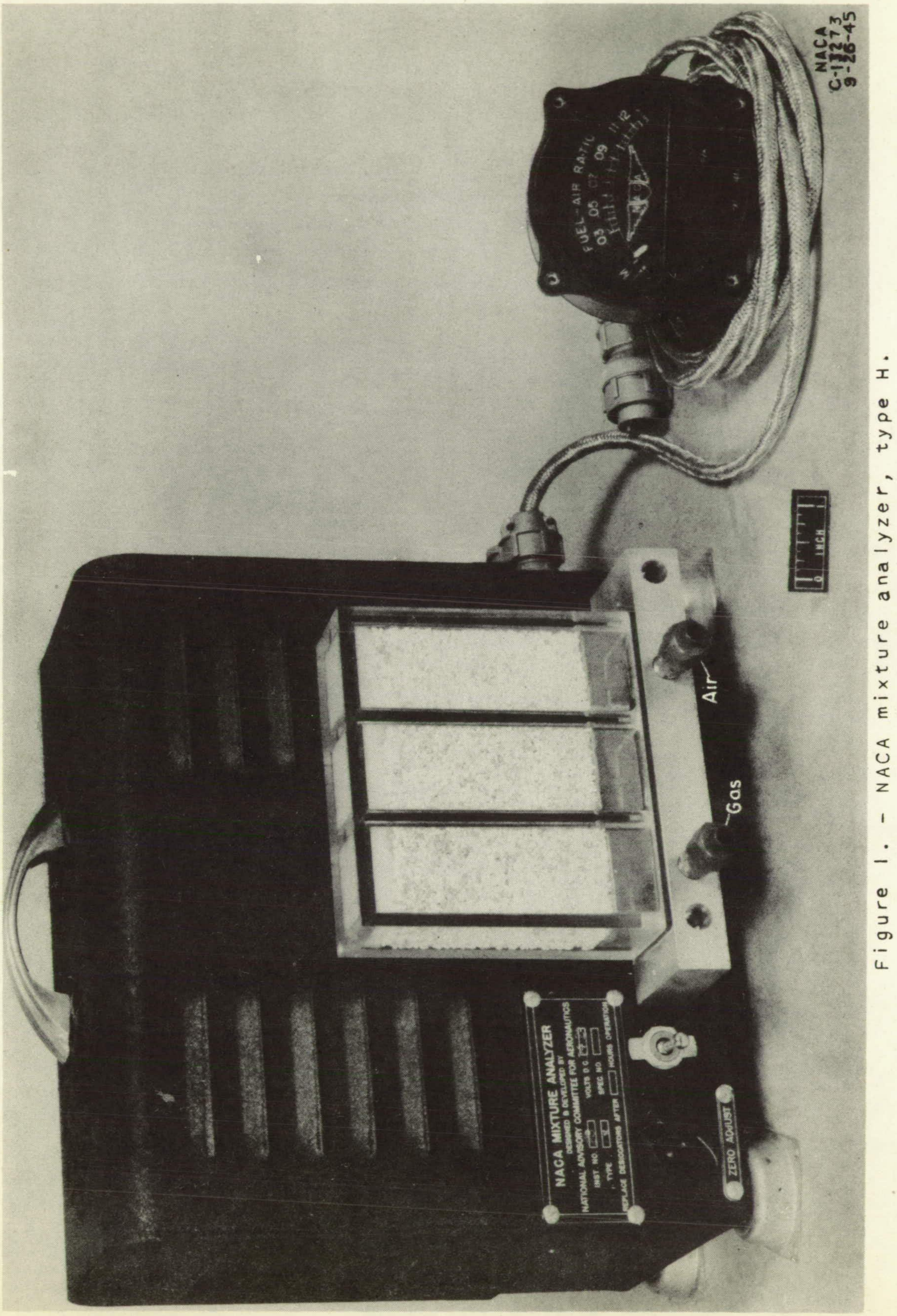

Figure 1. - NACA mixture analyzer, type H.

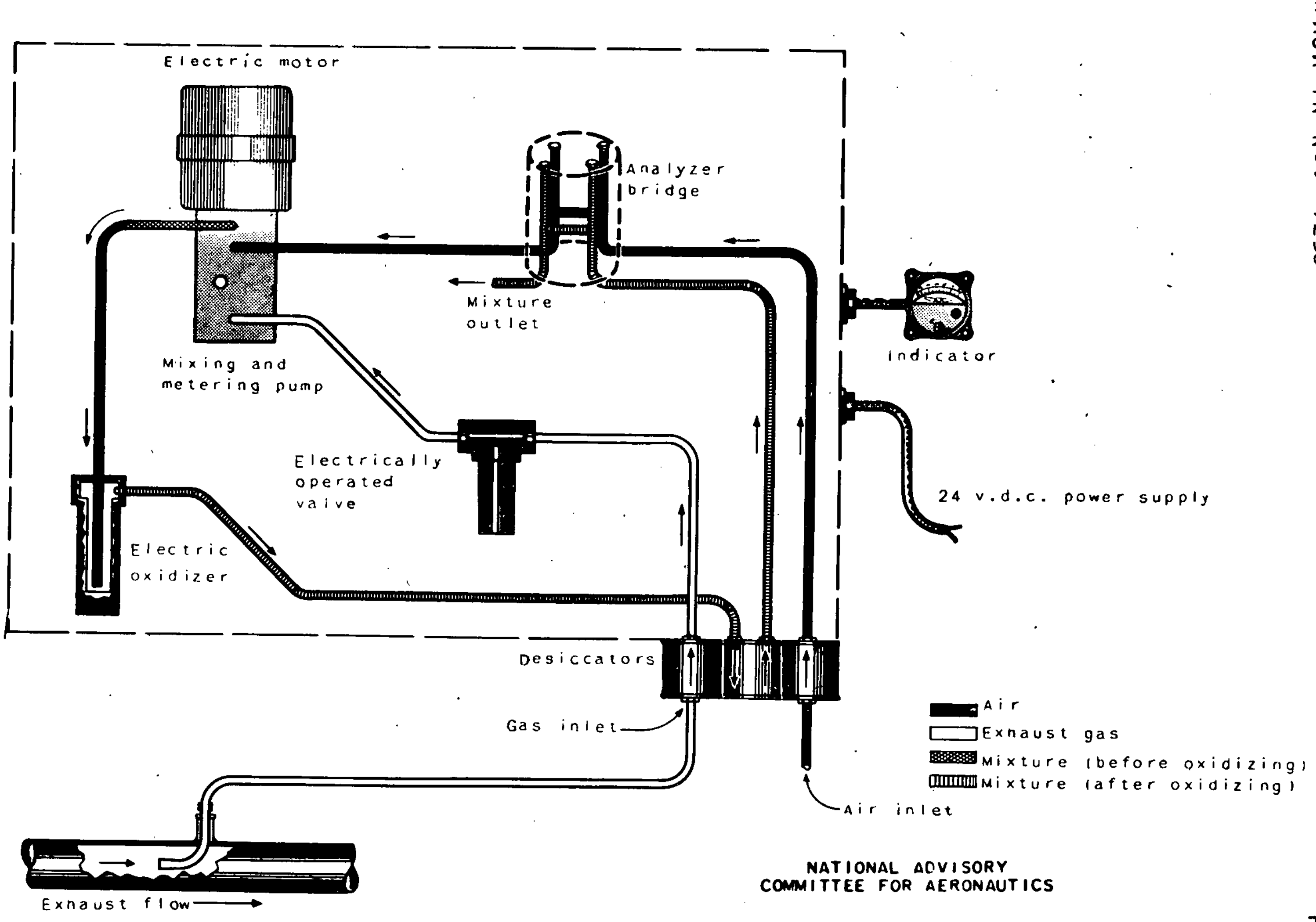

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Figure 2. - Diagrammatic sketch of exhaust-gas and air circuits in NACA mixture analyzer, type H.

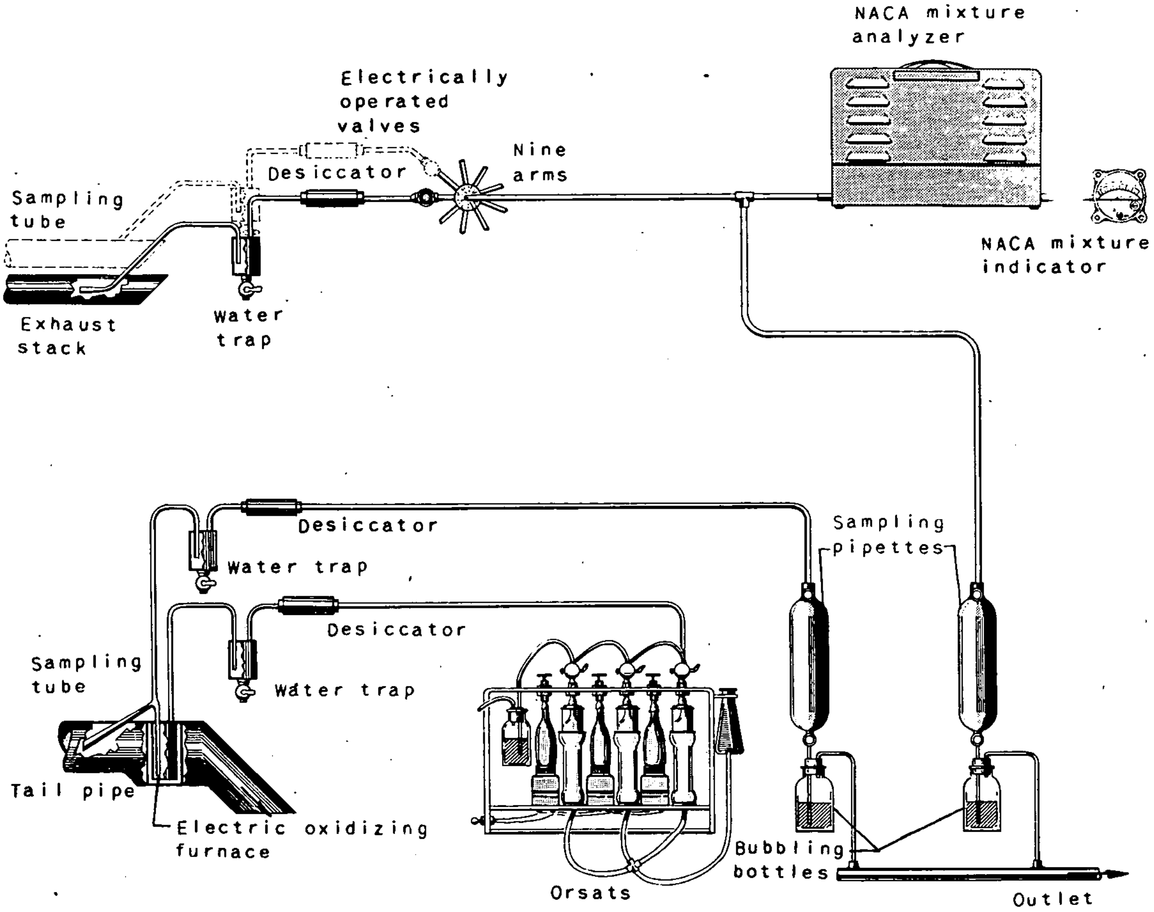

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Figure 3. - Diagrammatic sketch of exhaust-gas sampling system for flight tests.

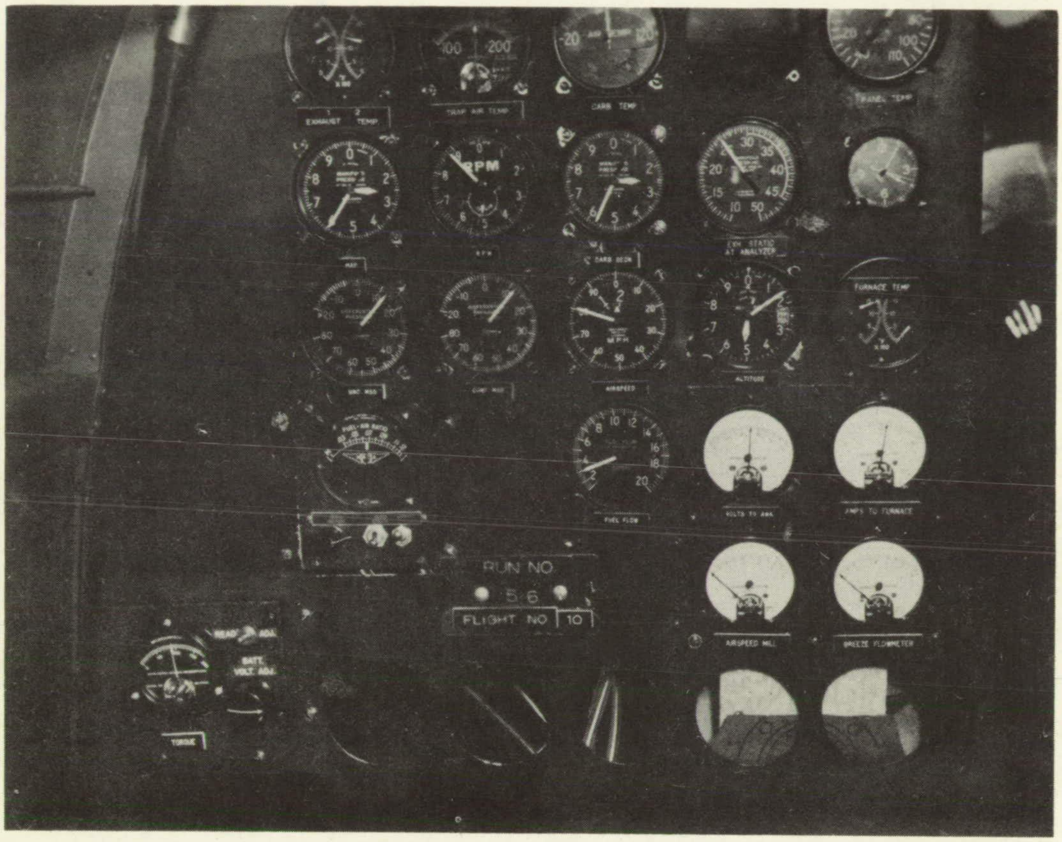

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Figure 4. - Instrument panel of flight-test installation.

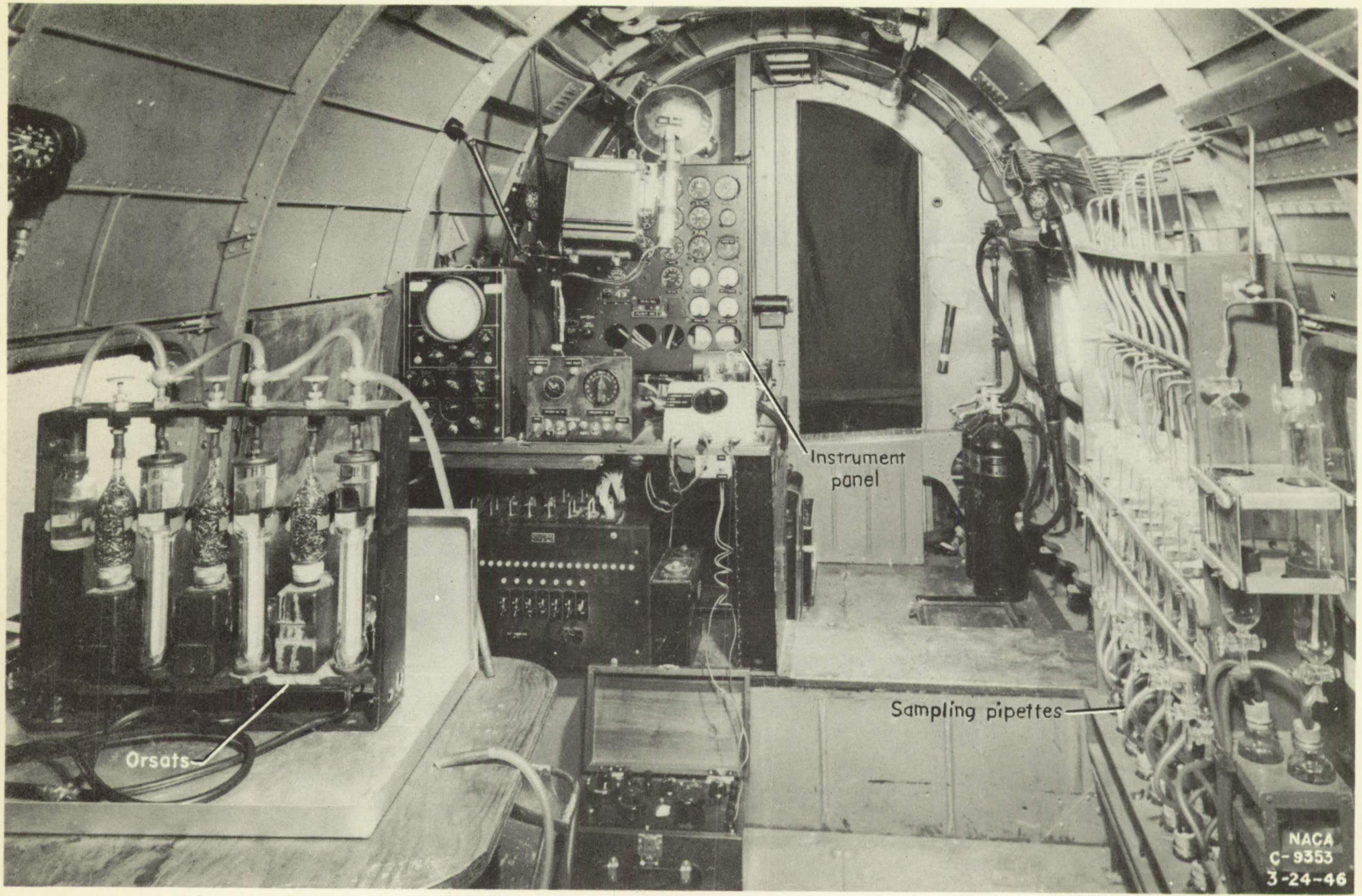


Figure 5. - Location of test instruments and apparatus in airplane.

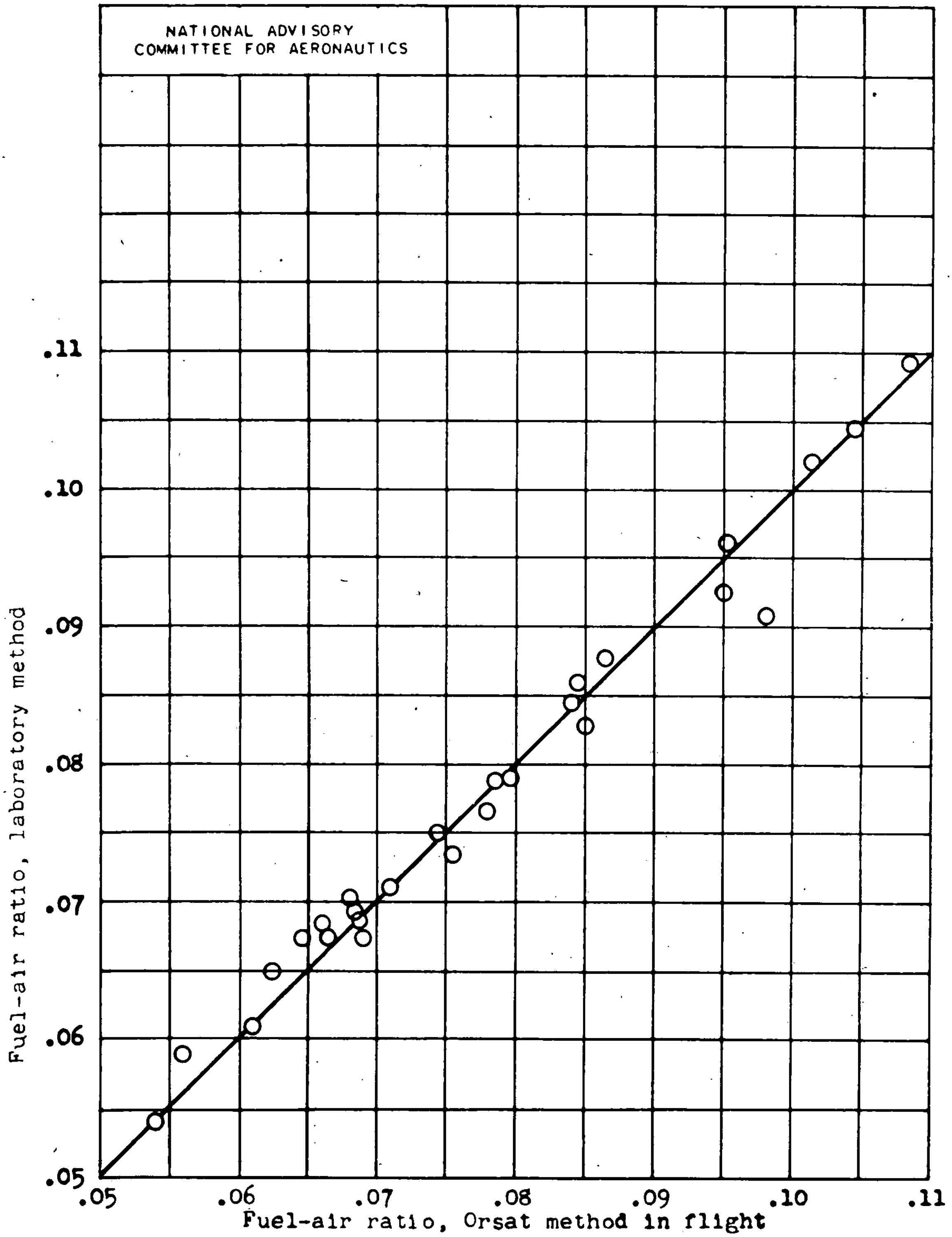


Figure 6. - Correlation of data from laboratory analysis and Orsat analysis in flight.

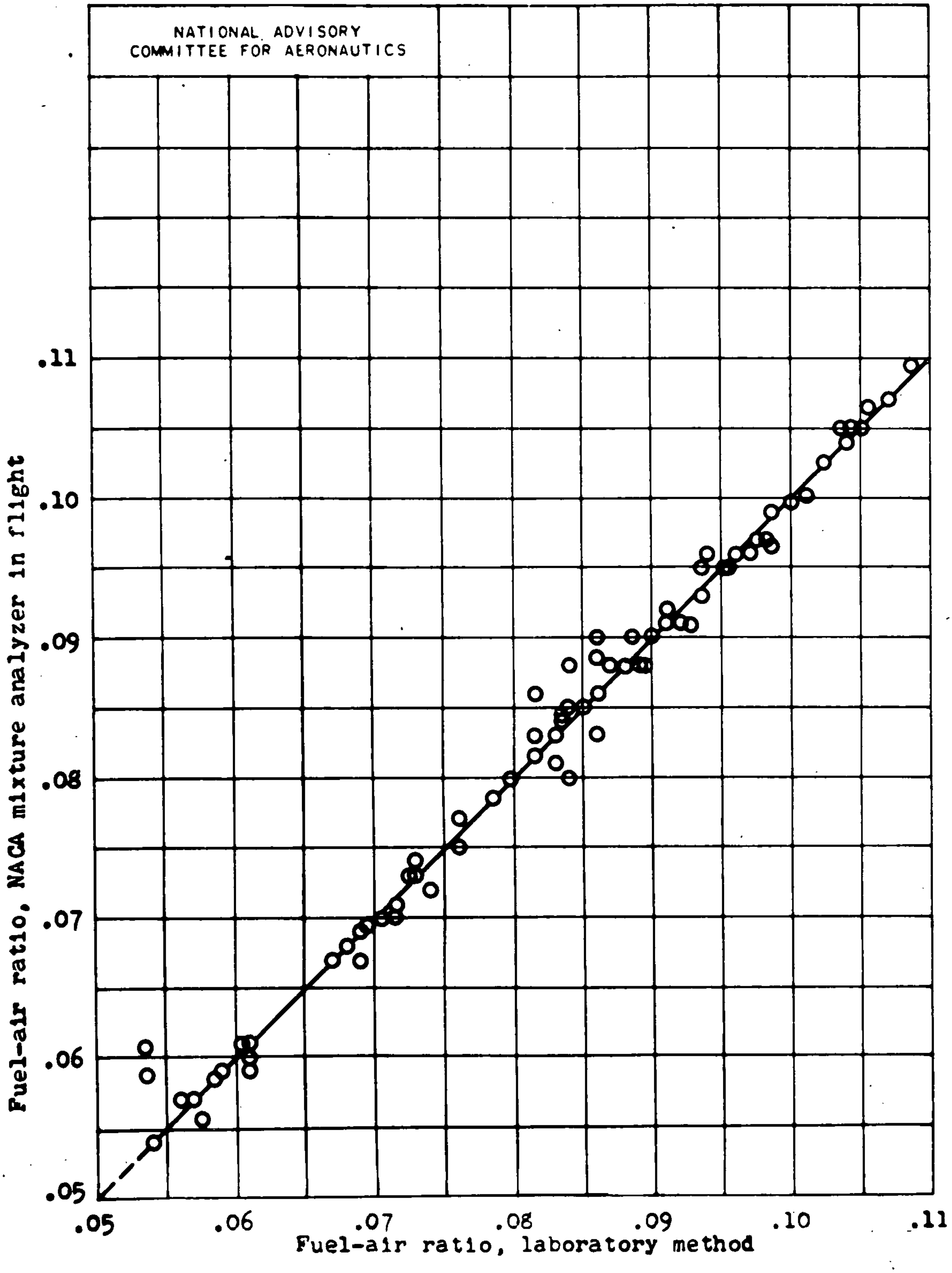


Figure 7. - Correlation of data from NACA mixture analyzer in flight and from laboratory analysis.

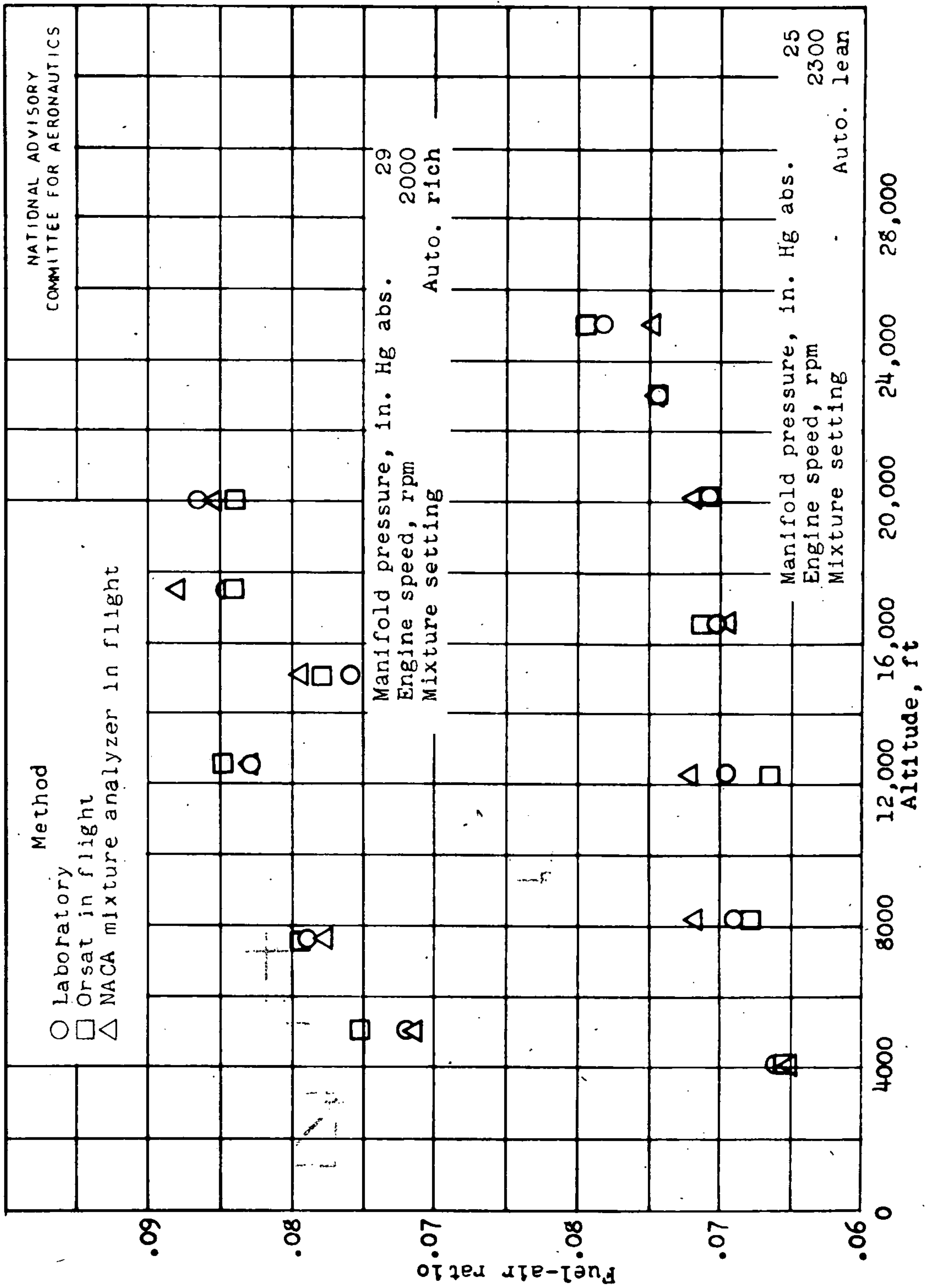
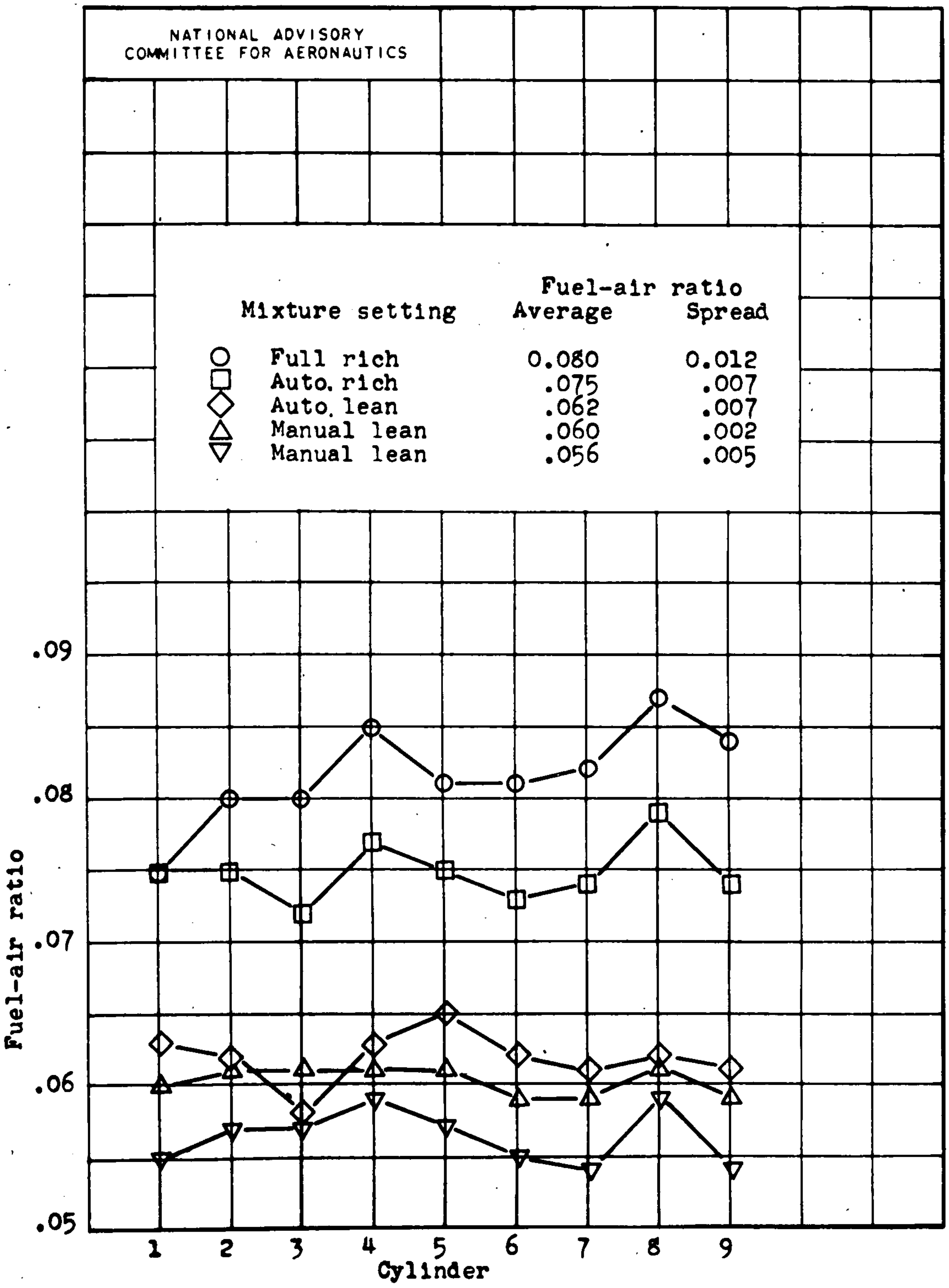
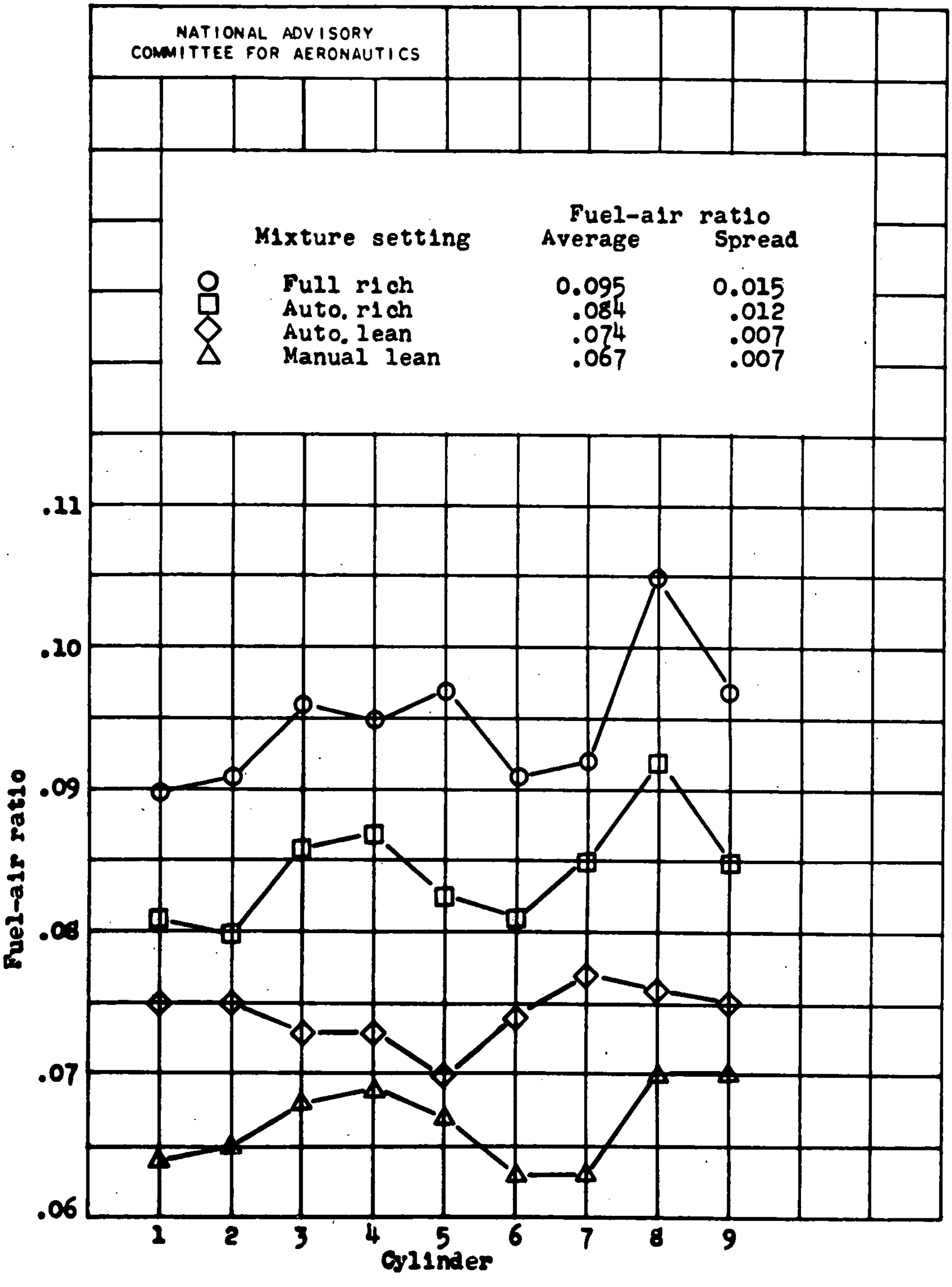


Figure 8. - Comparison of three methods of obtaining engine mixture data.



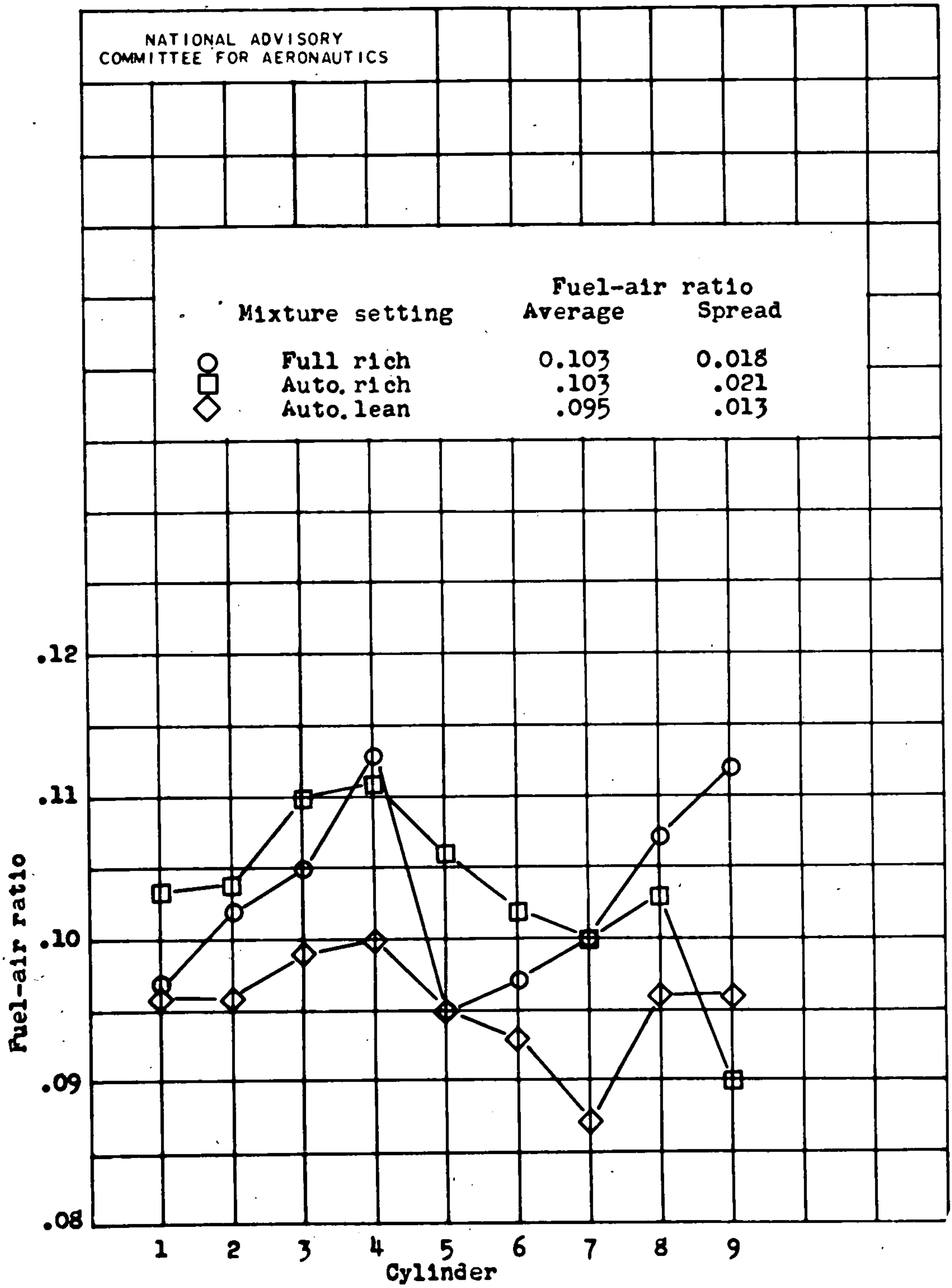
(a) 60-percent normal cruising power: engine speed, 1900 rpm; manifold pressure, 26 inches mercury absolute; pressure altitude, 5000 feet.

Figure 9. - Mixture distribution of nine-cylinder engine in flight obtained with NACA mixture analyzer.



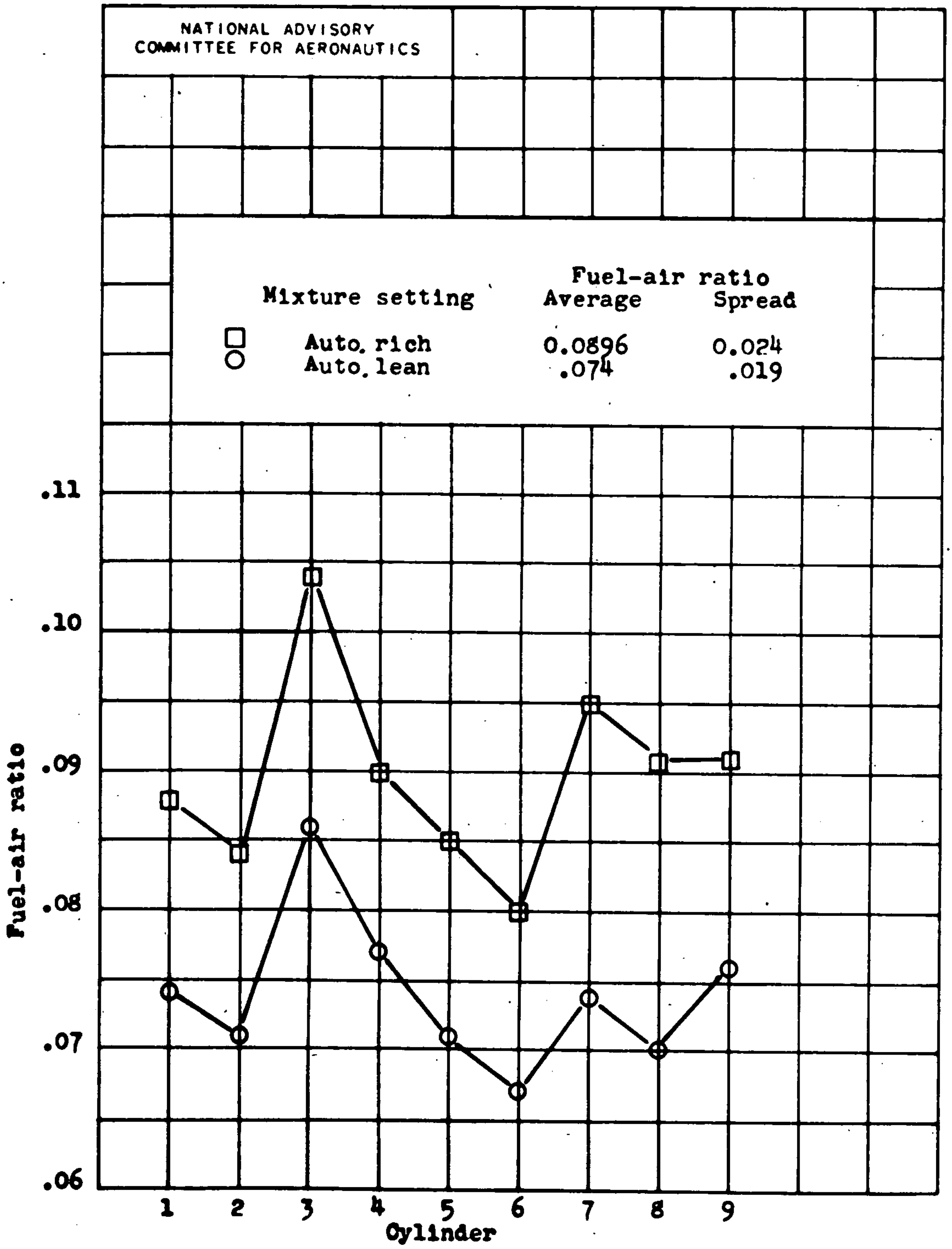
(b) 70-percent normal cruising power: engine speed, 2000 rpm; manifold pressure, 32 inches mercury absolute; pressure altitude, 5000 feet.

Figure 9. - Continued. Mixture distribution of nine-cylinder engine in flight obtained with NACA mixture analyzer.



(c) Rated power: engine speed, 2300 rpm; manifold pressure, 37 inches mercury absolute; pressure altitude, 5000 feet.

Figure 9. - Continued. Mixture distribution of nine-cylinder engine in flight obtained with NACA mixture analyzer.



(d) 70-percent normal cruising power: engine speed, 2000 rpm; manifold pressure, 29.5 inches mercury absolute; pressure altitude, 20,000 feet.

Figure 9. - Concluded. Mixture distribution of nine-cylinder engine in flight obtained with NACA mixture analyzer.