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COMPARISON OF EXHAUST EMISSIONS OF A LOW-TIME JT8D-11 ENGINE: HIGH-SMOKE VERSUS LOW-SMOKE COMBUSTION CHAMBER CONFIGURATIONS

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16. Abstract

Engine-core exhaust emissions were measured on a low-time JT8D-11 engine in both high-smoke and low-smoke configurations. Changing from the high-smoke to the low-smoke configuration considerably reduced the visible smoke, 55 to 90 percent, as measured using the Society of Automotive Engineers (SAE) smoke number. Carbon monoxide was reduced by up to 40 percent. Total unburned hydrocarbons were reduced by 40 percent at idle power, while the production of oxides of nitrogen was increased by 60 percent at the high power setting. These percentages are absolute with no consideration for time in mode, according to the Environmental Protection Agency (EPA) landing/takeoff cycle.

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INTRODUCTION

PURPOSE.

Aircraft exhaust emissions tests were conducted to study the variation in emissions levels between a Pratt and Whitney JT8D turbofan engine with modified, or low-smoke, combustion chambers and unmodified, or high-smoke, combustion chambers. A fixed-probe sampling system was employed to minimize variation due to sample acquisition, and the data used herein was screened to minimize variation due to changes in ambient conditions.

BACKGROUND.

In a continuing effort to minimize air pollution, studies of aircraft-caused environmental effects have been conducted as far back as 1964. At that time a United States Senate Subcommittee held a "clean-air" hearing (reference 1). Air pollution from jet engine operation was recognized generally as contributing in some degree to the national problem, specifically the problem existing in the vicinity of airports.

Various studies conducted in subsequent years gathered more evidence showing that jet aircraft contribute substantial amounts of pollutants to large urban areas, particularly in the Los Angeles Airport area as noted in reference 2. This fact led to the passage of the National Air Quality Standards Act of 1970 (reference 3), which specified air quality standards, and the Clean Air Amendments of 1970 (reference 4), which authorized the Environmental Protection Agency (EPA) to establish aircraft-engine pollution control standards if and when they were deemed necessary to protect the public health and welfare.

Since the EPA had determined that aircraft pollution control had become a necessity, a set of proposed standards for the control of air pollution from aircraft engines was drafted and subsequently published. The Clean Air Amendments of 1970 specified that the Department of Transportation (DOT) and the Federal Aviation Administration (FAA) promulgate regulations enforcing the EPA aircraft emissions standards. However, precise specification of emissions standards for aircraft turbine engines is difficult to define since present data from turbine engine emissions measurements show significant variability throughout studies performed by EPA and industry.

A joint EPA/FAA study was undertaken to determine the cause of this variability in engine emissions measurements. During the conduct of this variability study, a related engine emissions factor from a Boeing 727-100 aircraft with and without modified combustion chambers was investigated. The modified combustion chambers were designed to minimize smoke. Retrofitting of the JT8D engine with the modified combustion chambers appeared to resolve the smoke pollution problem with this engine.

As part of the turbine engine variability investigation, the National Aviation Facilities Experimental Center (NAFEC) undertook an experimental effort to compare the smoke and gaseous emissions from a JT8D engine with and without modified combustion chambers to quantify the changes resulting when the modified and unmodified combustion chambers were installed in the same engine sequentially.

DISCUSSION

DESCRIPTION OF TEST ARTICLE.

Emissions measurements reported herein were obtained from a low-time, JT8D-11 turbofan engine. This engine was an axial-flow, mixed-flow, twin-spool engine of moderate bypass ratio utilizing a six-stage low compressor and a seven-stage high compressor; the low compressor being driven by a three-stage turbine and the high compressor being driven by a single turbine through concentric shafting. The combustion section of the engine consists of nine combustion chambers arranged annularly, each containing a duplex spray fuel nozzle. The ratio of fan air to gas-generator air is approximately one to one at cruise and takeoff power.

Modified, or low-smoke, combustion chambers and fuel nozzles had been installed in the engine at the factory. The low-smoke chambers, as seen in figure 1, differ from the original, high-smoke chambers, shown in figure 2, by the location of inlet air holes. The primary difference in these two combustors is in the amount of air used in the primary combustion zone; i.e., in the dome portion, relative to the overall flow. The primary zone combustion is accomplished with a leaner fuel-air ratio. Fuel nozzles for the low-smoke configuration were modified, along with fuel flow changes between primary and secondary fuel flow rates. A swirling entry pattern for the fuel nozzle air was also used. This may be seen by comparing figure 3, which is a view of the nozzle used in the high-smoke configuration, and figure 4, which is a view of the nozzle used in the low-smoke configuration. The JT8D-11 and late model engines incorporate the low-smoke configuration as standard equipment. The high-smoke parts were standard on the early JT8 engines. Subsequently, all JT8D models have been retrofitted to incorporate the low-smoke combustion chambers.

Testing was conducted on an engine mounted in a static, sea-level test cell, as may be seen in figure 5. A calibrated, short-radius, American Society of Mechanical Engineers (ASME) bellmouth was attached to the engine inlet for calibrated airflow measurement, and a Pratt & Whitney Aircraft (P&WA), fixed-area, test exhaust nozzle was used in place of the standard flight nozzle.

Emission measurements were obtained by installing four multihole, averaging (or integrating), stainless steel sample rakes as shown in figure 6. Each rake contained three inlet-sampling orifices, 0.030 inches in diameter. The rakes were installed in the test exhaust nozzle on chords of the engine-core exhaust

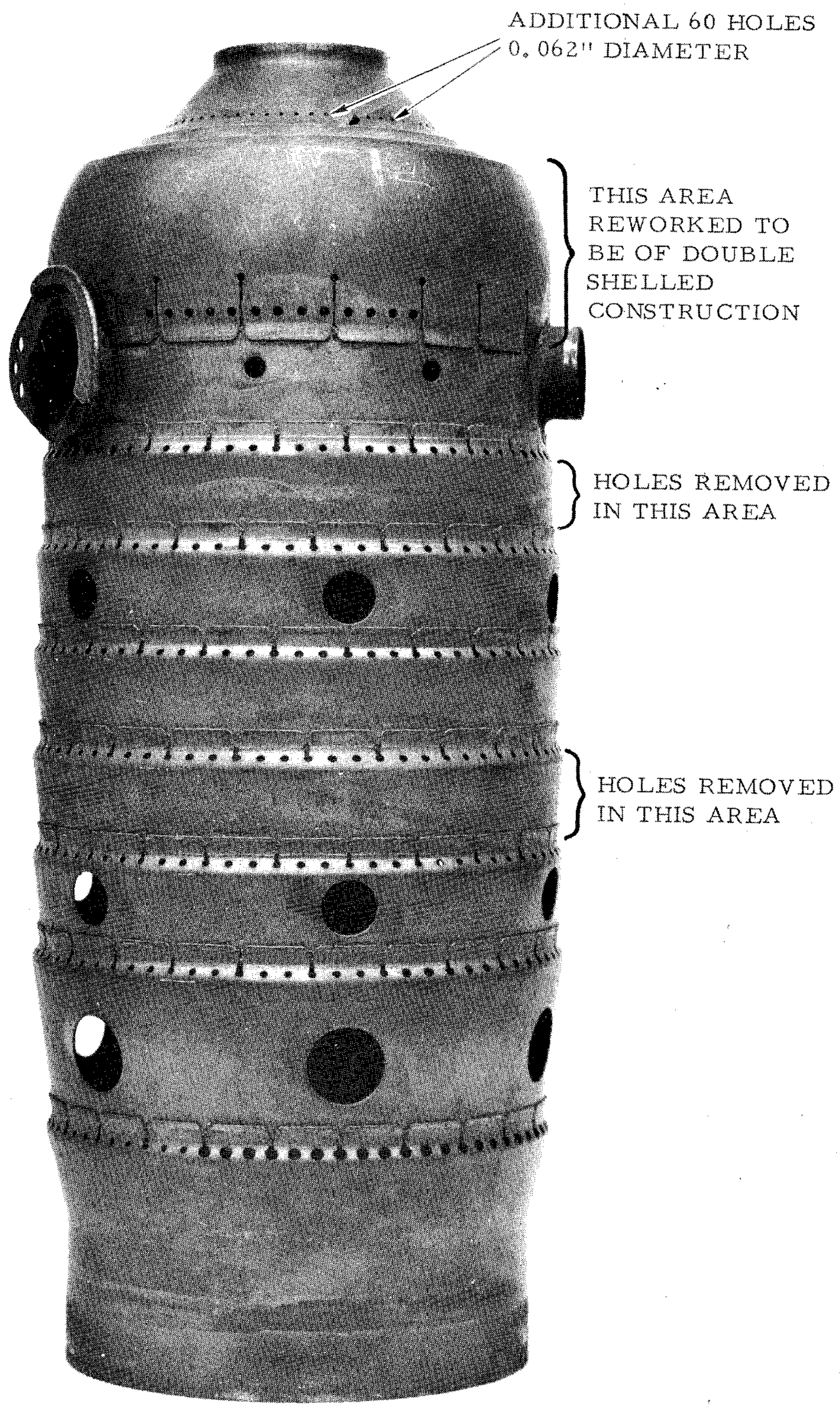

FIGURE 1. LOW-SMOKE COMBUSTION CHAMBER FOR JT8D-11 ENGINE (STANDARD - 11 PART NUMBER)

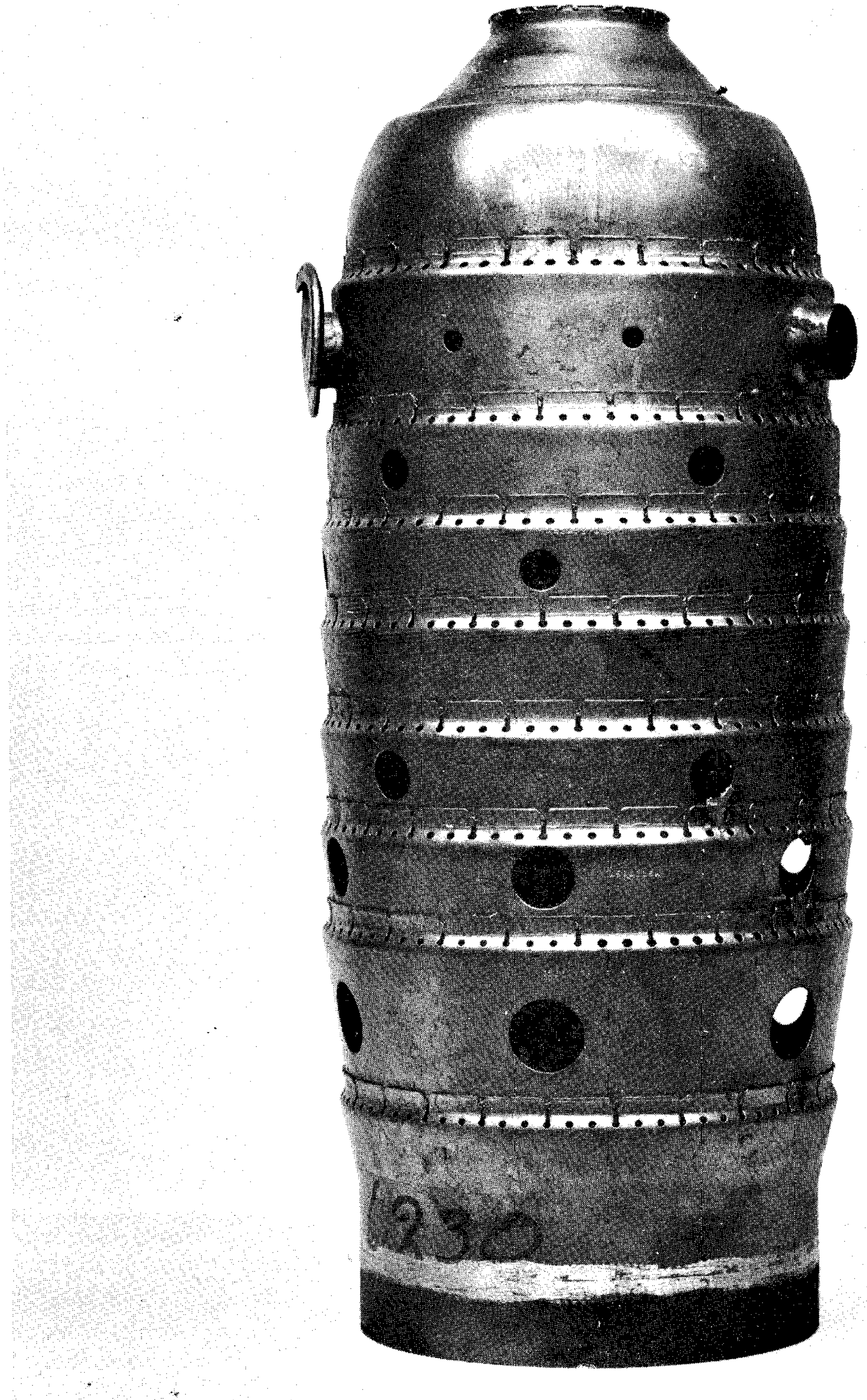

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FIGURE 2. HIGH-SMOKE COMBUSTION CHAMBER FOR JT8D-11 ENGINE (P&WA PART NUMBER 566319)

APPROXIMATE SCALE = 2:1

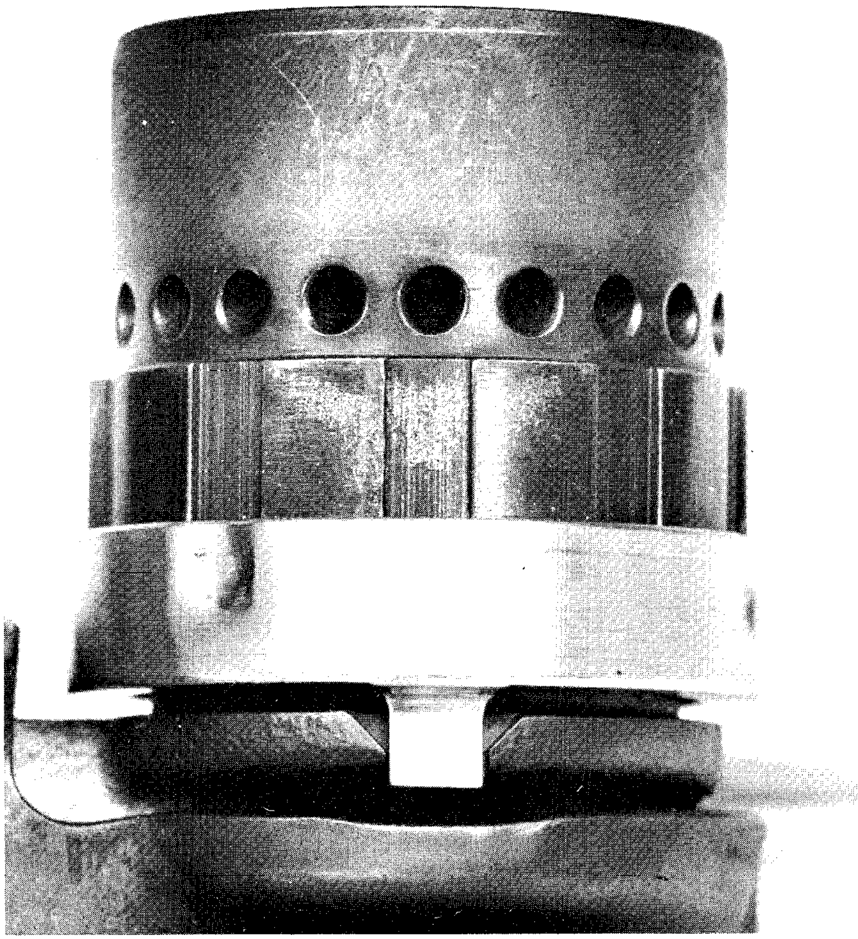

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FIGURE 3. TYPICAL FUEL NOZZLE FOR THE HIGH-SMOKE CONFIGURATION (P&WA PART NUMBER 462074)

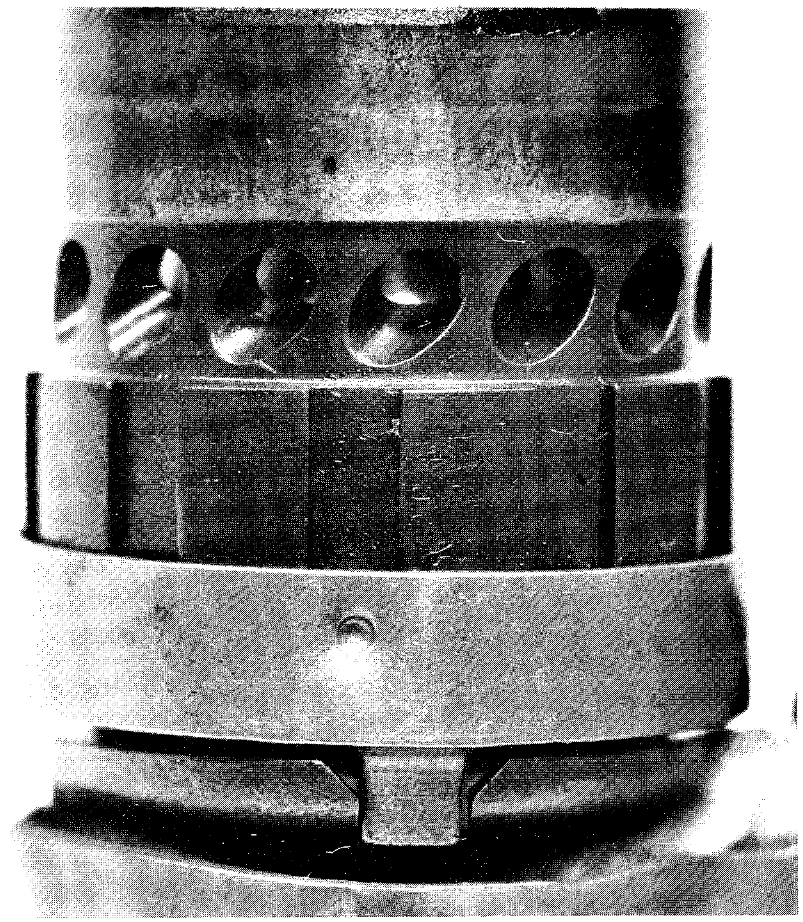

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FIGURE 4. TYPICAL FUEL NOZZLE FOR THE LOW-SMOKE CONFIGURATION (STANDARD - 11 PART NUMBER)

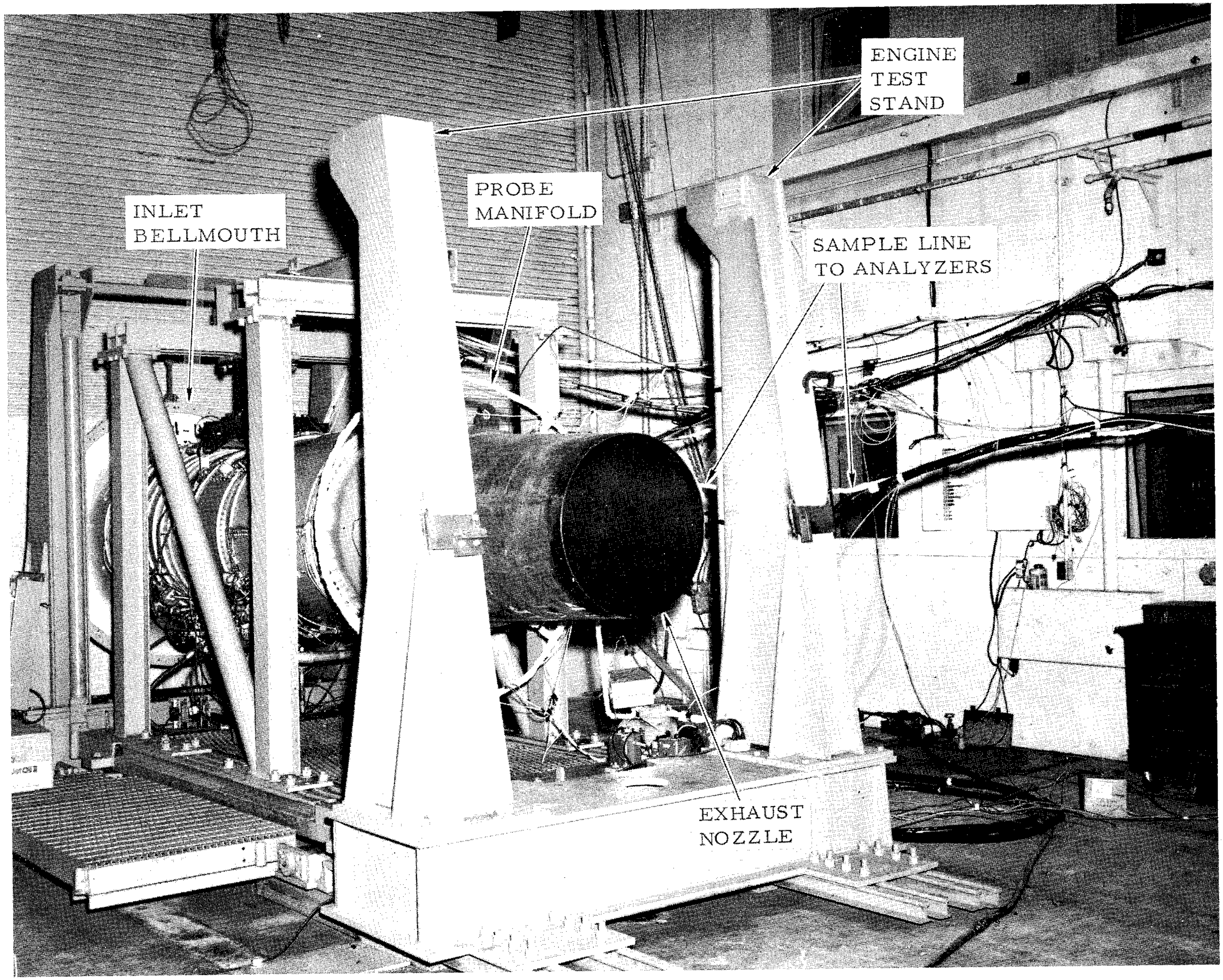

FIGURE 5. JT8D-11 TEST ENGINE INSTALLED IN ENGINE TEST STAND

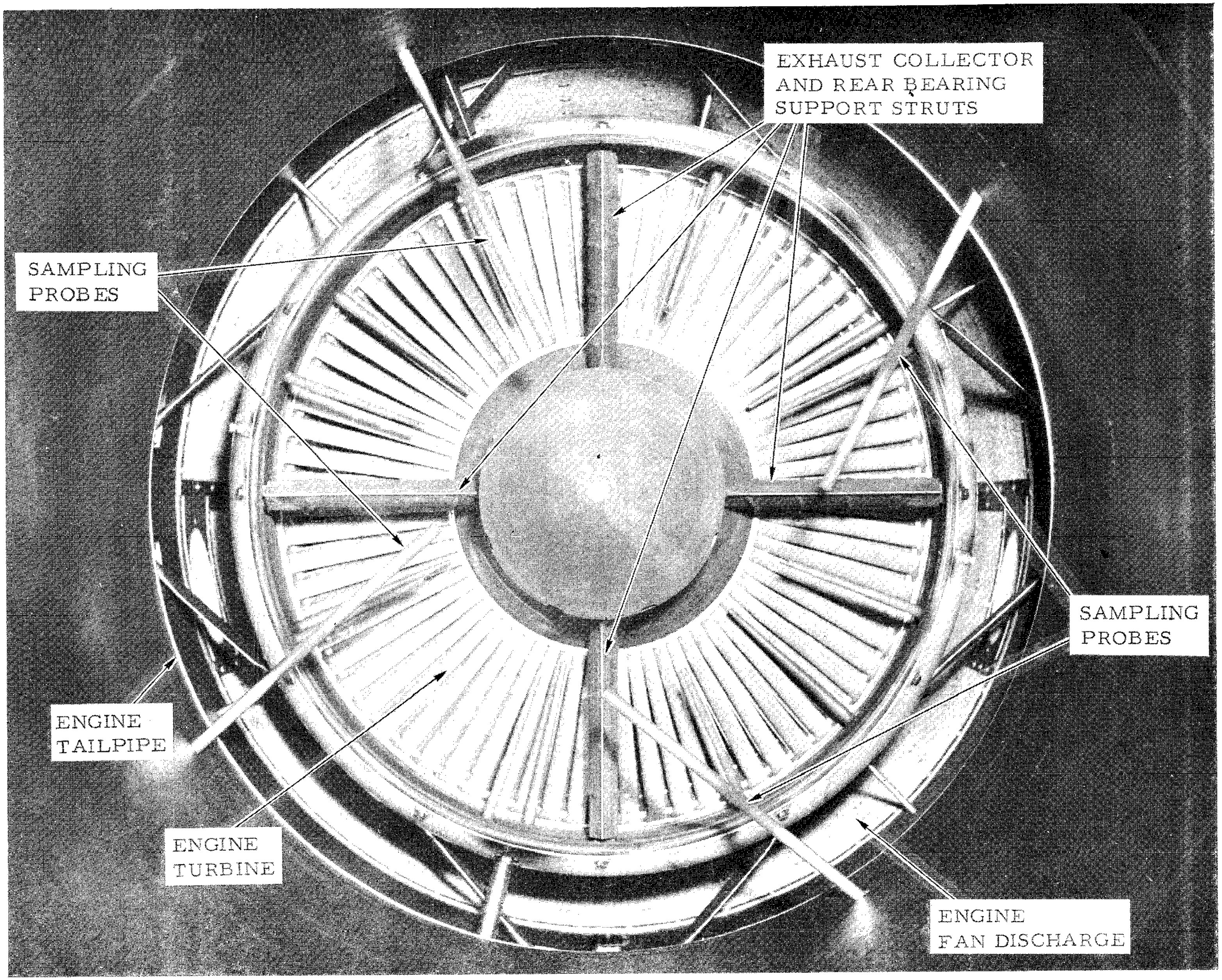

FIGURE 6. SAMPLING PROBES INSTALLED IN JT8D-11 ENGINE (LOOKING FORWARD AT TAILPIPE)

and were manifolded together by a heated tubular ring as shown in figure 7. A random sampling pattern was achieved by varying the chord angles of each probe and by placing probes of similar orifice spacing adjacent to each other. This arrangement helped to avoid the possibility of the symmetry of emissions affecting the resultant readings. It should be noted that, due to the location of the exhaust sampling probes, measurements reported herein represent core emissions; therefore, the values cannot be directly applied or compared to the EPA turbine-engine exhaust standards.

Test runs 1 through 95 were made using the as-delivered engine (low-smoke combustion chambers). Test runs 96 through 154 were made after the modified, low-smoke combustion chambers and fuel nozzles were replaced with the original, unmodified, high-smoke combustion chambers. This replacement was made at the NAFEC test facility by authorized P&WA service personnel.

Data reported herein has been prescreened to minimize the variability due to changes in ambient temperature and humidity. A report describing the effects of temperature and humidity on engine emission will be published at a future date. For the test runs reported, ambient temperature ranged from 25°F to 36°F, and specific humidity ranged between 7 and 8 grains of water per pound of dry air.

TEST PROCEDURE.

Data presented herein consisted of two up-calibration runs; one each for modified and unmodified combustion chambers, and two down-calibration runs, one each for modified and unmodified combustion chanbers for the smoke data only. A calibration run consisted of one reading at each standard power setting between idle and takeoff powers.

Data recorded at power conditions arrived at by increasing power is termed an "up calibration"; decreasing power data points are termed a "down calibration." A full calibration consists of both "up" and "down" calibrations.

Standard power settings for turbine engine testing were idle, approach, landing, cruise, maximum continuous, and takeoff, with intermediate power settings of "part power" inserted where required to obtain a given range of readings. Engine stabilization times at power settings were variable but at no time less than 10 minutes, with the exception of takeoff power, which was limited by the manufacturer to a maximum of 5 minutes continuous operation at this power level. Engine stabilization was determined using the usual parameters of exhaust gas temperature, rotor speed, fuel flow, thrust, and engine pressure ratio, but an additional assurance was gained by monitoring the gaseous emission traces on a continual basis. When stabilization was reached, the gaseous emissions variation became random; whereas, during stabilization, these traces would show a steadily increasing or decreasing trend with time. The gaseous emission traces referred to, include carbon dioxide, carbon monoxide, and total hydrocarbons and oxides of nitrogen. Carbon dioxide and total hydrocarbons appeared to be the best indicators of engine stabilization.

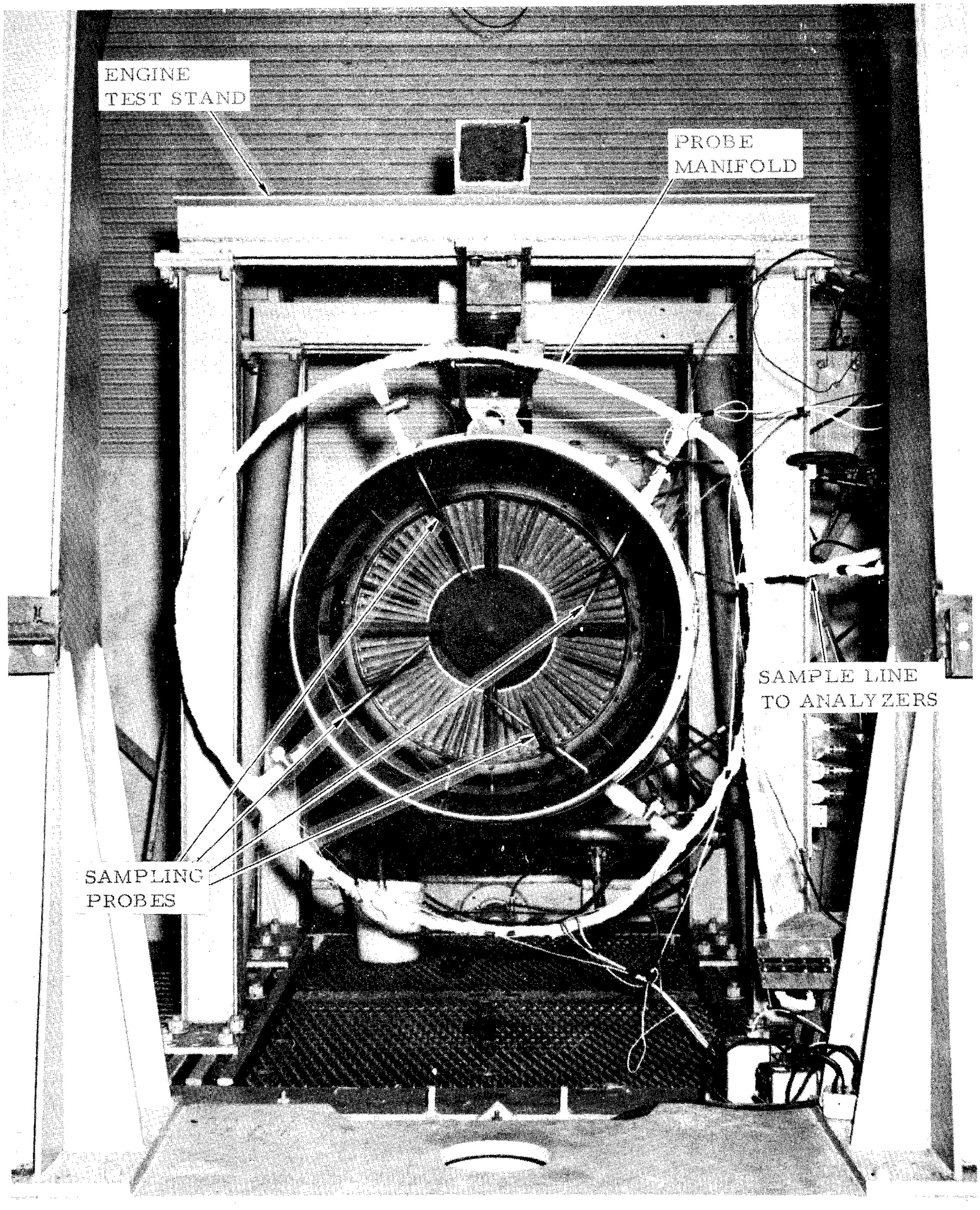

FIGURE 7. PROBE MANIFOLD INSTALLED IN JT8D-11 ENGINE
(LOOKING FORWARD AT ENGINE TAILPIPE)

Prior to each emissions measurement at a power setting, the emissions measuring equipment was calibrated to assure consistent readings. This calibration consisted of passing a known zero gas (either zero-grade nitrogen for all analyzers except the hydrocarbon analyzer or zero-grade air for the hydrocarbon analyzer) through the sampling system and noting the reading on each instrument. If the reading was other than zero, a notation was entered into the operators log, and the instrument was readjusted, provided the initial variation was within the instrument manufacturer's published zero-drift tolerance for that instrument. A similar procedure was followed in checking an upscale calibration point. For instruments with nonlinear ranges, more than one upscale standard was used during some between-reading calibration checks. All upscale calibration gases were certified to be within 1 percent of the specified concentration. The instrumentation for gaseous emissions analysis is shown in appendix A.

After engine stabilization was reached, engine and emissions data were recorded simultaneously to assure proper correlation of the data.

Data presented in this report uses engine pressure ratio (EPR) as a basis for comparison of engine operating conditions. EPR is a standard engine performance parameter used throughout the industry for this type of engine as a measure of engine thrust and therefore used to specify engine power settings. Standard engine power settings for the JT8D-11 engine are related to EPR as shown in table 1.

TABLE 1. ENGINE PRESSURE RATIOS FOR VARIOUS JT8D-11 ENGINE POWER SETTINGS

Idle	EPR $<$ 1.07 (idle flat)
Approach	EPR $\approx$ 1.3
Landing	EPR $\approx$ 1.5
Cruise	EPR $\approx$ 1.7
Maximum Continuous	EPR $\approx$ 1.9
Takeoff	EPR $<$ 2.0

TEST RESULTS.

Figures 8 and 9 show a comparison of smoke emissions from modified and original combustion chambers over the full power range. As can be seen in figure 8, modified combustion chambers achieve a significant decrease (approximately 60 percent at high power settings) in smoke emissions as measured using the Society of Automotive Engineers (SAE) smoke numbers. (See reference 5 for definition of SAE smoke number).

Figure 9 shows the calculated percentage of light transmission through the core exhaust plume over the entire power range. The method used to determine the percentage of transmitted light based on the SAE smoke number is given in reference 6.

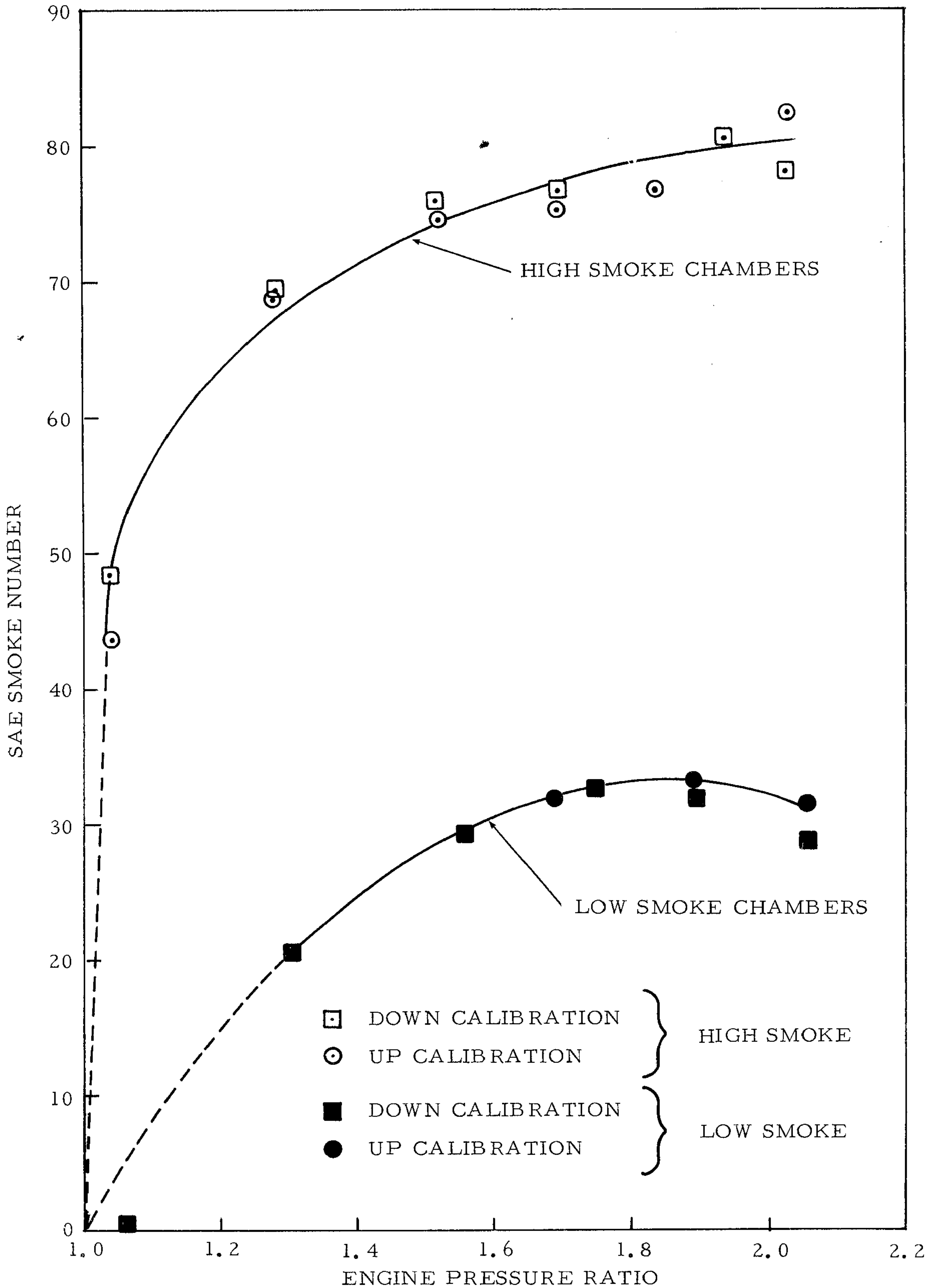

FIGURE 8. RELATIONSHIP BETWEEN THE SAE SMOKE NUMBER AND ENGINE PRESSURE RATIOS FOR HIGH- AND LOW-SMOKE CONFIGURATIONS

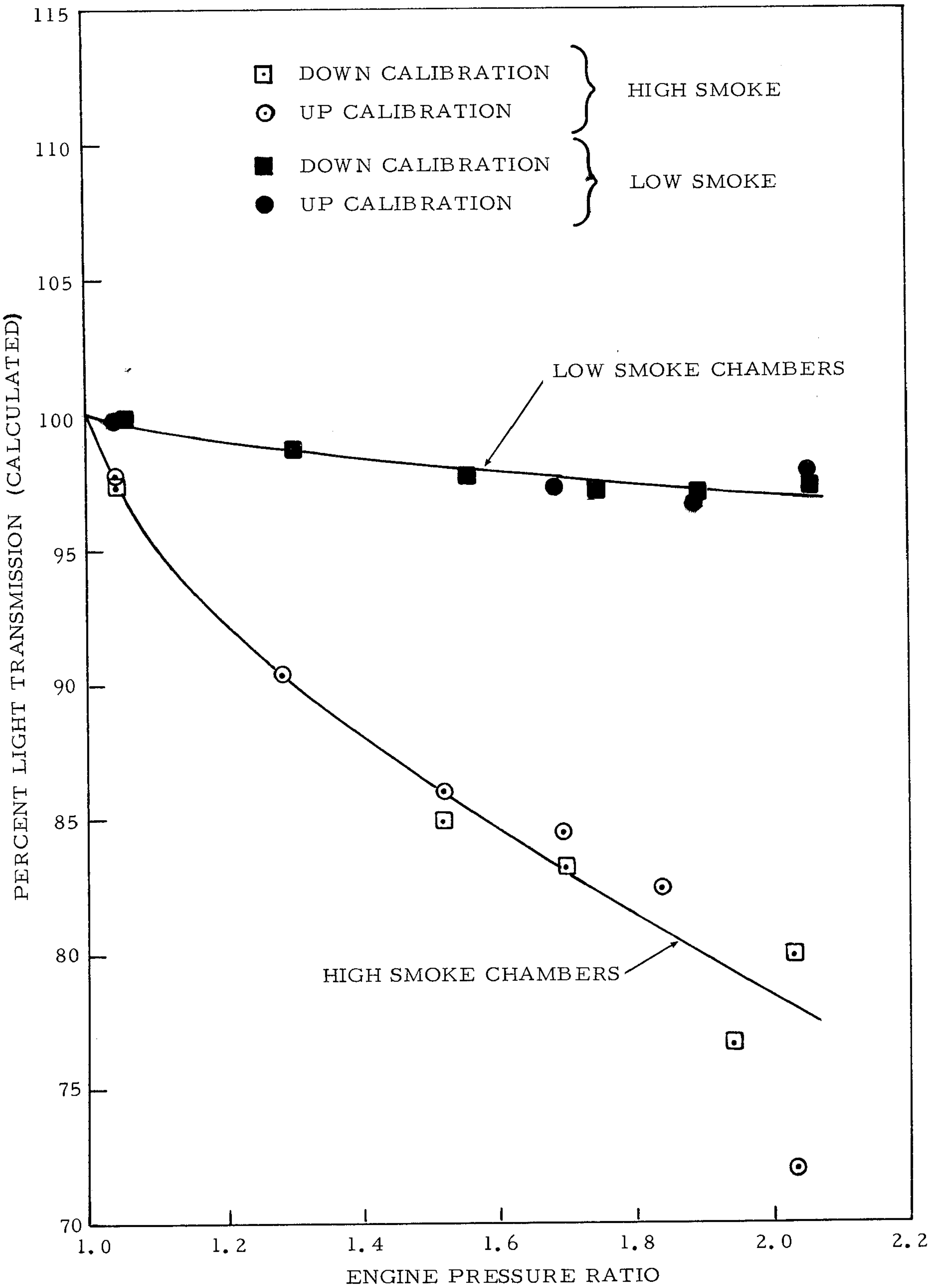

FIGURE 9. RELATIONSHIP BETWEEN THE CALCULATED PERCENT LIGHT TRANSMISSION AND ENGINE PRESSURE RATIO FOR HIGH- AND LOW-SMOKE CONFIGURATIONS

Data presented in figure 10 shows a significant difference in smoke numbers for low-smoke chambers when two different flow systems were used. The lower curve was obtained by branching the smoke sampling line off of the inlet to the gaseous emissions console (flow system 1). The upper curve was obtained by plotting data obtained when the smoke sample line inlet, upstream of the emissions console, was relocated, and the emissions system bypass pump was shut off while smoke measurements were being made (flow system 2). The data from system 1 were used for figures 8 and 9.

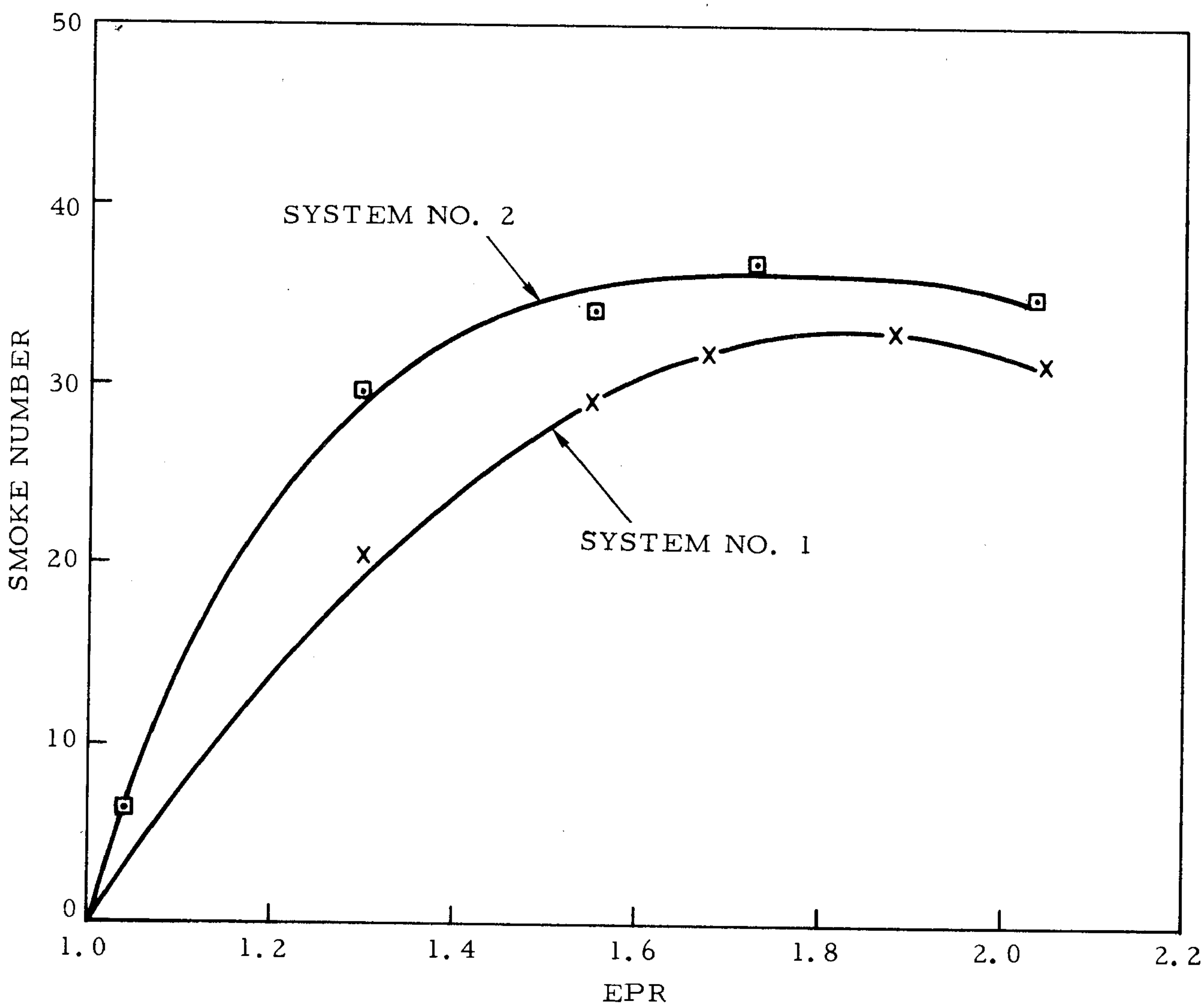

FIGURE 10. DIFFERENCE IN SAE SMOKE NUMBERS FOR SAMPLING SYSTEMS 1 AND 2 FOR LOW-SMOKE CHAMBERS ONLY

Data presented in table 2 shows a decrease in the average carbon monoxide (CO) emissions for the low-smoke chambers at idle power setting. This data presented in tabular form shows the consistently lower emissions through a range of EPR for low-smoke chambers, which is not clearly evident in figure 11.

Figure 11 clearly shows a decrease in carbon monoxide at power settings other than idle.

TABLE 2. IDLE DATA SUMMARY

Idle Reading No.	EPR	CO ppm	THC ppm_C*
	Low-Smoke Configuration		
40	1.024	355	158
41	1.042	372	201
46	1.042	362	201
59	1.040	350	216
61	1.040	350	225
94	1.059	335	189
Mean	1.041	354	198
Standard Dev.	.011	12	23
	High-Smoke Configuration		
96	1.043	420	353
100	1.043	420	317
101	1.043	432	356
110	1.041	432	287
118	1.041	470	305
Mean	1.042	435	323
Standard Dev.	.001	20	30

*ppm_C indicates parts per million of hydrocarbons based on a hydrocarbon with only one carbon atom.

Emphasis should be placed on the improvement in carbon monoxide emissions at idle. Approximately 85 percent of the landing/takeoff (LTO) cycle time in mode according to the EPA specification is at idle power setting, and therefore even a small improvement in low-power emissions would generate a large improvement in the emissions rating of an engine.

Table 2 and figure 12 show a similar trend throughout the power range for total unburned hydrocarbons (THC). Data in the transition region between approach and idle power settings show an increase in hydrocarbon and carbon monoxide emissions for the modified combustion chamber. A possible explaination for this increase is that, with the orginal, unmodified, high-smoke fuel nozzles, the duplex fuel nozzle changeover occurs at a slightly higher power setting; whereas, in the modified fuel nozzles, the changeover occurs earlier. This reversal in the trend of unburned hydrocarbon and carbon monoxide emissions through this range can, in practice, be ignored because engine operation in this range is uncommon.

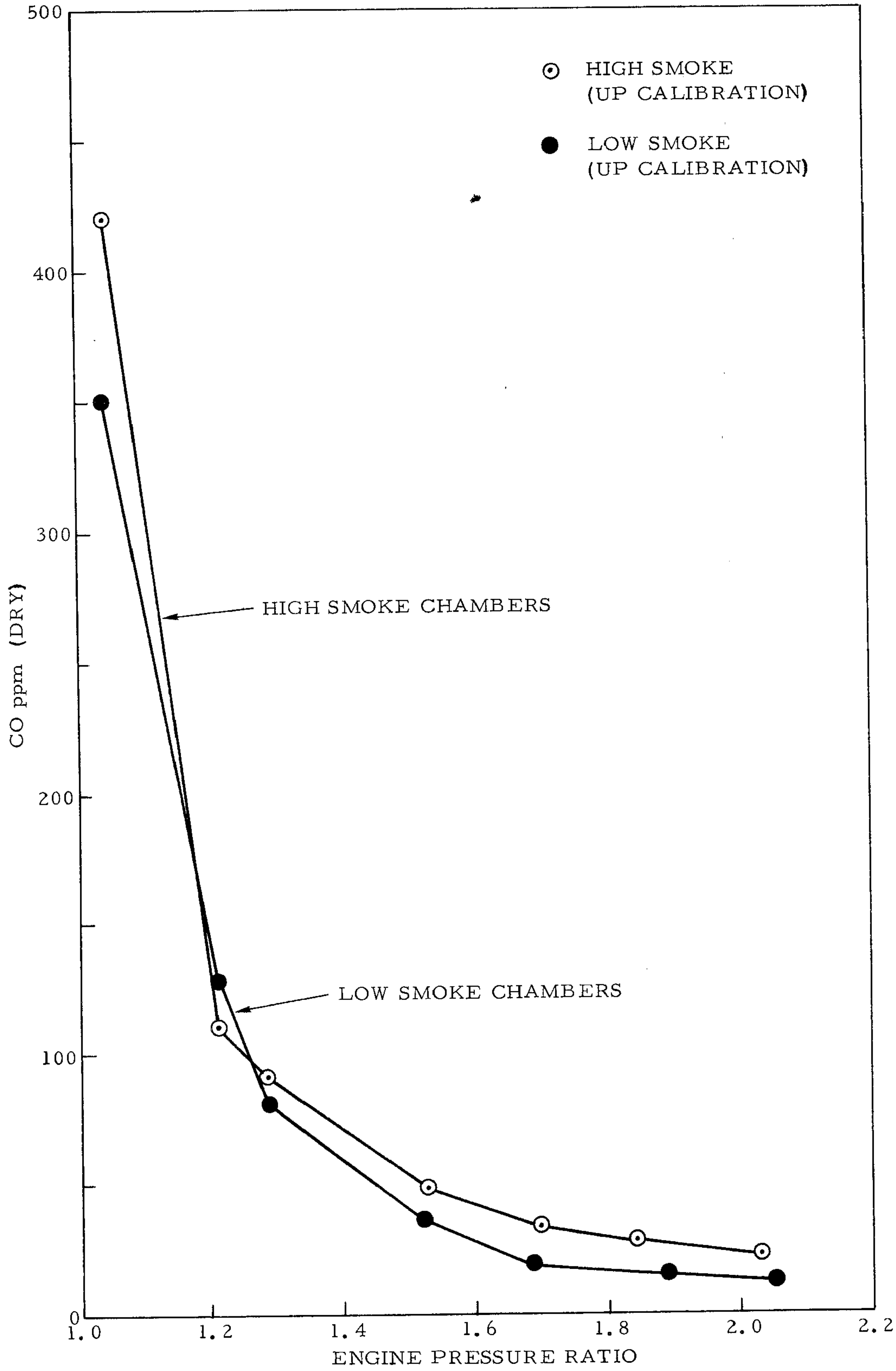

FIGURE 11. CONCENTRATIONS OF CARBON MONOXIDE (DRY) FOR HIGH- AND LOW-SMOKE CONFIGURATIONS

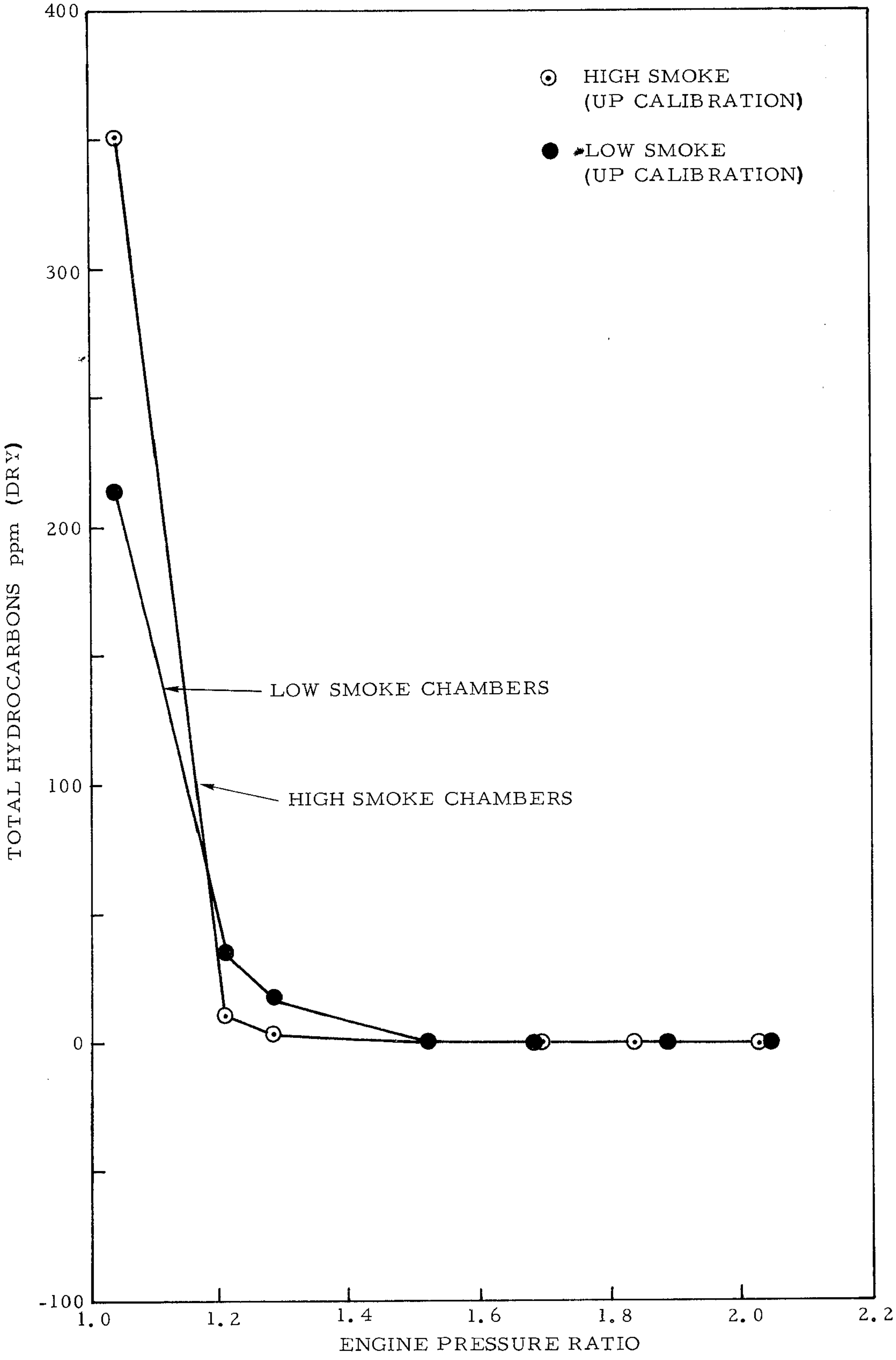

FIGURE 12. CONCENTRATIONS OF TOTAL HYDROCARBONS (DRY) FOR HIGH- AND LOW-SMOKE CONFIGURATIONS

Generally, carbon monoxide and unburned hydrocarbons vary inversely with the efficiency of the combustion process. As efficiency (completeness of combustion) increases, carbon monoxide and total unburned hydrocarbon emissions decrease.

Another indicator of combustion efficiency is carbon dioxide. Figure 13 shows an increase in carbon dioxide production throughout the power range. The overall trend observed from the carbon dioxide curves of figure 13 correlates well with the trends exhibited in figures 11 and 12, the curves for carbon monoxide and total unburned hydrocarbons.

Reduced smoke, carbon monoxide, and hydrocarbon emissions depend on maximum combustion in the primary zone of the combustion chambers. However, this results in higher primary zone combustion temperatures which cause an increase in the formation of oxides of nitrogen (NO_x). Figure 14 shows this increase in NO_x above idle resulting from the modified combustion chambers. The test data show a NO_x increase over the original, unmodified combustion chambers of 59 percent at takeoff power (EPR approximately 2.02) and 22 percent at cruise power (EPR approximately 1.69). At the idle power setting, both the modified and original combustion chambers produced approximately the same low levels of NO_x.

The designation "dry" in figures 11, 12, and 14 indicates that the values are based on exhaust gases without water content.

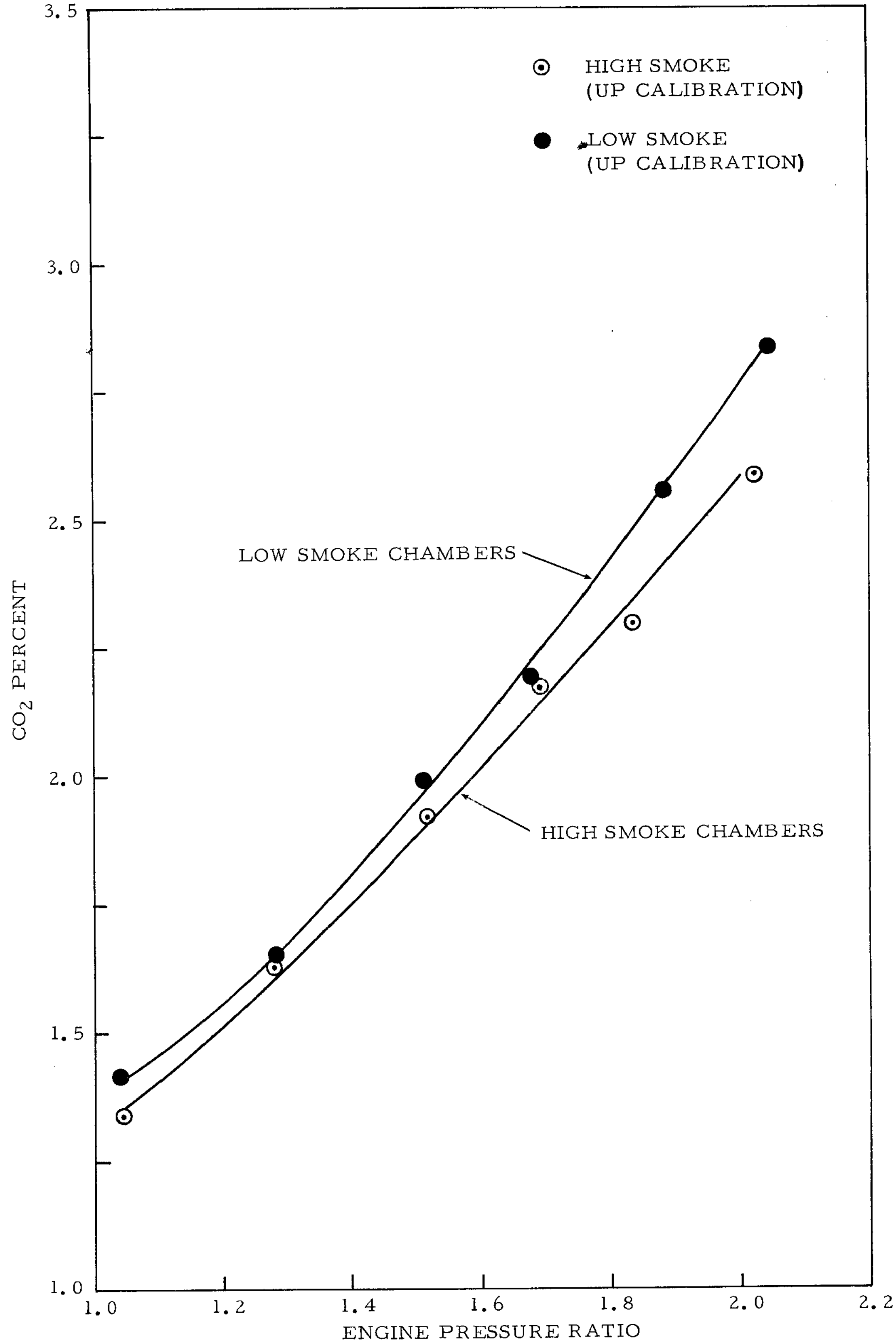

FIGURE 13. RELATIONSHIP OF CARBON DIOXIDE AND ENGINE PRESSURE RATIO FOR HIGH- AND LOW-SMOKE CONFIGURATIONS

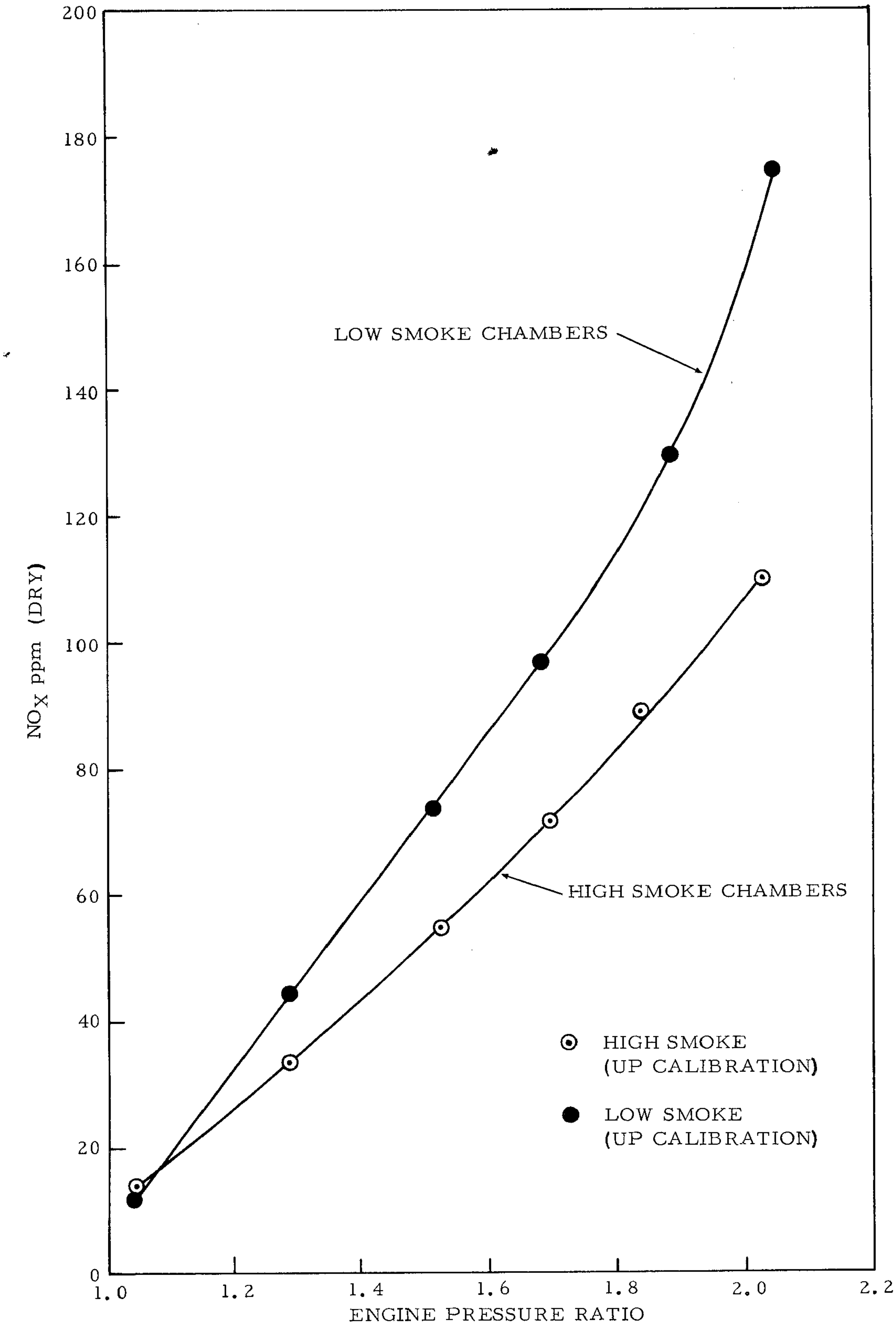

FIGURE 14. CONCENTRATIONS OF OXIDES OF NITROGEN (DRY) FOR HIGH- AND LOW-SMOKE CONFIGURATIONS

SUMMARY OF TEST RESULTS

Modifying the combustion chambers and fuel nozzles of the P&WA JT8D turbofan engine produced a reduction of visible smoke, core emissions, based on the SAE smoke number, by approximately 90 percent at idle and more than 60 percent at high power settings when compared with smoke emissions from the original, unmodified combustion chambers. Carbon monoxide emissions were reduced at idle by 20 percent and at high power settings by approximately 40 percent when compared to the original chambers. Total unburned hydrocarbons were reduced by approximately 40 percent at idle power, while there was no measurable unburned total hydrocarbons at the high power setting with either modified or original combustion chambers. Oxides of nitrogen production increased by approximately 60 percent at high power settings when compared to the original combustion chambers. At idle, there was no measurable difference in oxides of nitrogen between the two configurations.

CONCLUSION

Based on the results of the tests conducted, it is concluded that modification of the combustion chambers and fuel nozzles of a JT8D aircraft engine from a high-smoke configuration (as employed in the JT8D-9) to a low-smoke configuration (as employed in the standard JT8D-11) is effective in reducing smoke and offers significant reductions in carbon monoxide and hydrocarbons, but at a penalty of a significant increase in oxides of nitrogen at high power settings.

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4. Clear Air Amendments of 1970, Public Law 91-604, 91st Congress, H. R. 17255, December 31, 1970.

5. Society of Automotive Engineers Aerospace Recommended Practice Bulletin, ARP-1179, May, 1970.

6. Slusher, G. R., Relationship Between the SAE Smoke Number and Jet Aircraft Smoke Visibility, FAA Final Report No. FAA-RD-71-23.

APPENDIX

EMISSIONS MEASUREMENT SYSTEM

The procedure for the measurement of engine gaseous emissions was essentially the same as described in the Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) Bulletin ARP-1256. A diagram of the emissions measurement system is given in figure A-1. The emissions instrumentation consisted of the following analyzers:

Carbon Dioxide (percent)	Mine Safety Association (MSA) Luft Infrared Analyzer (LIRA), Nondispersive Infrared Analyzer (NDIR) Model 300, calibrated for a range of 0-45 percent.
Carbon Monoxide (parts per million - ppm)	MSA LIRA NDIR Model 200 with dual span; range No. 1 calibrated 0-100 ppm range No.2 calibrated 0-1000 ppm.
Total Hydrocarbons (ppm)	Beckman Model 402 heated Flame Ionization Detector (FID); 0-10,000 ppm with intermediate range selection.
Nitrogen Oxide (NO) (ppm)	Beckman Model 315A, NDIR, range No. 1 calibrated 0-500 ppm range No.2 calibrated 0-100 ppm.
Nitrogen Dioxide (NO_2)	Beckman Model 255, Nondispersive Ultraviolet (NDUV), range No. 1 calibrated 0-500 ppm range No. 2 calibrated 0-100 ppm.

Exhaust samples were obtained through four multihole averaging or integrating rakes as described in the DISCUSSION section of this report. Exhaust samples were routed to a common distribution point through nominal 3/8-inch diameter, stainless steel tubing heated to approximately 150° centigrade (C). From this point, a portion of the sample was plumbed to the FID through 3/8-inch diameter tubing heated to 150°C, while the remainder was plumbed to the other instrumentation through tubing heated to 55°C.

Following the procedure outlined in SAE ARP-1256, the exhaust samples were dried prior to analysis for carbon monoxide and nitric oxide. The drying was accomplished by first passing the exhaust sample through a condenser and then through a dessicant canister.

The sample flow rate through the instruments (except for the FID which was approximately 5 liters per minute) was approximately 2 liters per minute. A sample system bypass was maintained at a rate of 20 liters per minute to insure that the sample transport time from the engine to the analyzers was less than the allowable 2 seconds.

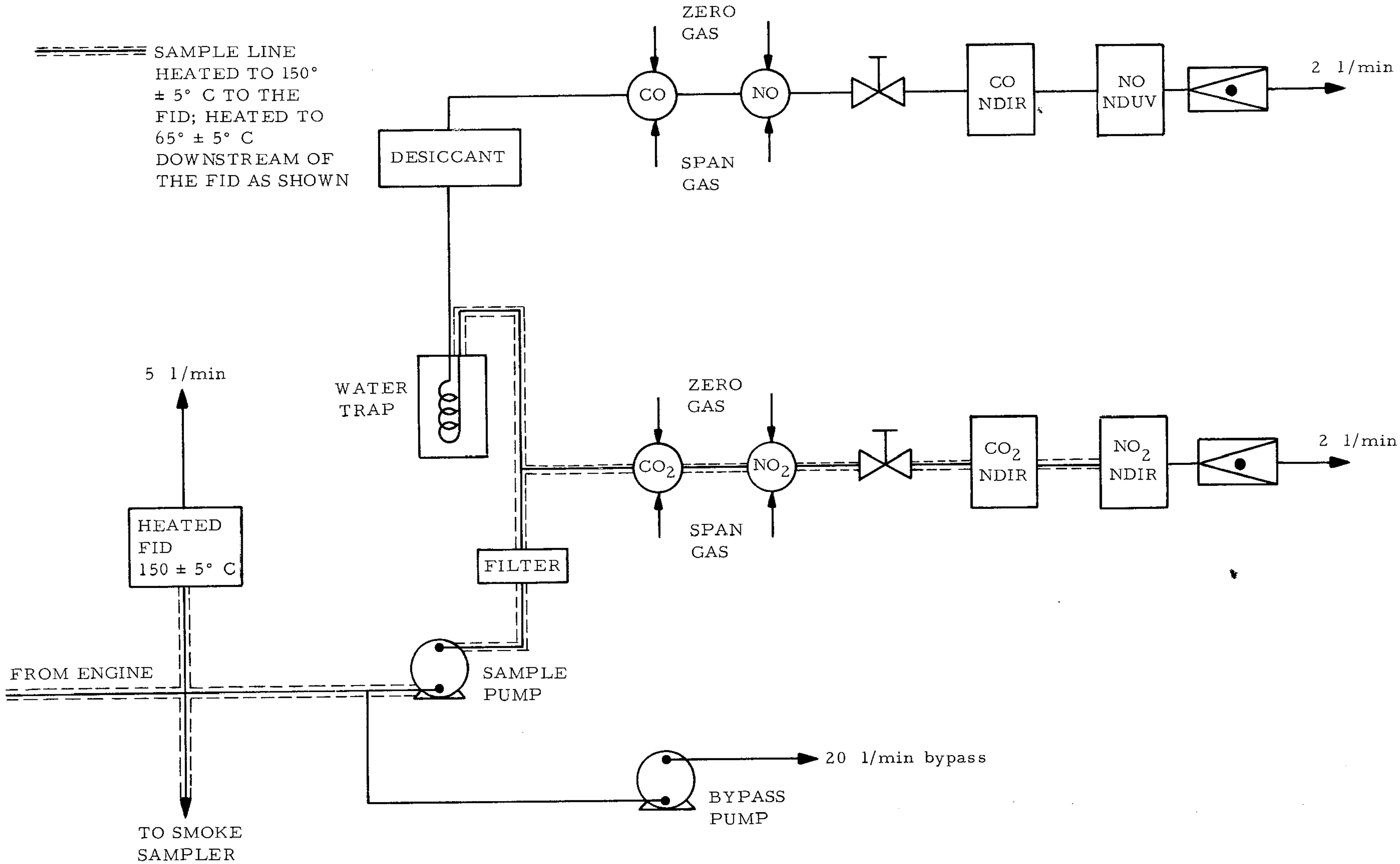

FIGURE A-1. EMISSIONS MEASUREMENT SYSTEM FLOW DIAGRAM

All values for the emissions measurements were visually noted from the instrument meters and manually recorded on data sheets. Also, the electronic output signals from all analyzers were continuously recorded on stripchart recorders in order to allow future error detection if necessary.

The smoke-emissions measurement procedure was essentially as described in the SAE Aerospace Recommended Practice Bulletin, ARP-1179, except for the probe, which was as described in this report.