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RESEARCH MEMORANDUM

EFFECT OF INLET-AIR AND FUEL PARAMETERS ON SMOKING CHARACTERISTICS OF A SINGLE TUBULAR TURBOJET-ENGINE COMBUSTOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted to determine the effect of systematic variations in inlet-air and fuel parameters on the smoking characteristics of a single tubular turbojet-engine combustor. For comparison purposes, a series of tests was conducted at static sea-level conditions over a range of engine speeds with a full-scale turbojet engine having combustors similar to the single-tube unit investigated. The concentration of smoke in the combustion gases was determined by means of a filter technique whereby smoke particles were deposited on a special filter paper. The optical density of the deposit as determined by a transmission densitometer served as an indication of the amount of smoke in the exhaust gas.

The most pronounced effect on smoke was observed with increases in inlet-air pressure which produced large increases in smoke concentration. As fuel-air ratios were increased, smoke densities increased, passed through a maximum, and finally decreased. Increases in inlet-air velocity reduced maximum smoke densities. The effect of inlet-air temperature and fuel volatility on smoke densities was small. Increases in fuel-inlet temperature increased smoke formation slightly. In the full-scale engine, smoke density increased with increasing engine speed and with decreasing exhaust-nozzle area.

The results obtained during this investigation suggest that carbon is formed in the primary zone of a turbojet combustor and is subsequently partly burned in passing through the flame zone, the unburned portion emerging as smoke. Thus, those factors that either tend to reduce carbon formation in the primary zone, such as decreases in pressure and in primary zone fuel-air ratios, or tend to bring about increased burning of smoke in the flame zone such as increased flame length and combustion-gas temperature, will reduce the concentration of smoke in the exhaust gases.

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INTRODUCTION

The formation of carbon in turbojet combustors presents a number of major engine operational problems. Previous investigations (references 1 and 2) and operational experience have shown that carbon deposition on walls, fuel-injection nozzles, and ignitors affects combustion efficiency, altitude operational limit, and ignition characteristics of the combustor. Also, the distorted air-flow and fuel-flow patterns which result from carbon deposits frequently cause warping and burning of the combustor liners. Carbon dispersed in the gas stream as smoke does not, in general, impair combustor-performance characteristics, but is objectionable in military operations where smoke trails remaining in the wake of jet-powered aircraft may be easily detected by the enemy.

Research is being conducted at the NACA Lewis laboratory to determine the effects of operating variables on carbon deposition and smoke and to gain a better understanding of the mechanism, or mechanisms, by which these formations occur. The information thus obtained will then aid in the formulation of basic combustor design principles which should result in the elimination of these problems. It has not yet been established whether carbon deposits and smoke result from similar processes or whether they occur under similar operating conditions. The investigation described herein is concerned only with the formation of carbon in the combustion gases as smoke.

At the present time the mechanism of smoke formation is not known. According to one recent theory (reference 3) smoke results from polymerization of fuel molecules at high temperatures and subsequent dehydrogenation forming large carbon aggregates. Additional work on smoke formation has been done by Spalding (reference 4) who studied the burning rates of liquid droplets and by Topps (reference 5) who investigated the rate of evaporation and combustion of liquid drops falling through a high-temperature furnace. Smoke formation has also been studied in laboratory burners (reference 6) and in smoke lamps (reference 7) with principal emphasis on the effect of fuel properties. Research on combustion of smoke in laboratory burners has been conducted by Clark (reference 8) who found that appreciable quantities of admixed smoke can be burned in both diffusion and Bunsen burner flames. In addition, considerable effort has been expended on the smoke problem in Diesel engines (references 9 and 10), but most of the research has been of an applied nature and little basic information has resulted. Some consideration has been given to the smoke problem in turbojet-engine combustors by Lloyd (references 11 and 12), but as yet insufficient quantitative data describing the events occurring inside a turbojet combustor (atomization and evaporation of the fuel, mixing of fuel and air, and initiation of combustion) are available to explain the problem of smoke formation in accordance with existing theories.

The investigation reported herein was conducted in order to determine the characteristics of smoke formation in a turbojet combustor through a study of the effect of combustor operating variables on smoke concentration. Accordingly, the effects of systematic variations in inlet-air parameters (pressure, temperature, and velocity) and fuel parameters (temperature and volatility), as well as fuel-air ratio, on smoke were determined in a single tubular turbojet combustor. For comparison, exhaust-gas smoke concentrations were measured at static sea-level conditions over a range of engine speeds on a full-scale engine having combustors similar to the single-tube unit investigated.

APPARATUS AND PROCEDURE

Combustor

A single tubular combustor from a J47 turbojet engine was used for the investigation reported herein. The installation of the combustor was similar to that described in reference 2. Air flow and fuel flow to the combustor were measured by means of an adjustable orifice and calibrated rotameters, respectively; temperature and pressure of the inlet air were determined by two single-junction iron-constantan thermocouples and two three-point total-pressure rakes, respectively. Fuel-inlet temperature was measured by an iron-constantan thermocouple located in the common-flow passage of the duplex fuel nozzle. Exhaust-gas temperatures were measured by seven banks of five-junction single-shielded chromel-alumel thermocouples (reference 2) located in a plane corresponding approximately to the position of the turbine blades in the full-scale engine. A sketch of the combustor installation showing location and arrangement of the instrumentation planes is shown in figure 1.

Smoke Measurement

Smoke measurements were obtained by means of a filter technique whereby a metered volume of exhaust gas was drawn through a filter disk with the resultant deposit on the paper of all smoke particles suspended in the gas. The optical density of the smoke on the filter paper was considered a measure of the amount of smoke in the sample.

Smoke samples were obtained from the combustor by means of a sampling probe located immediately downstream of the exhaust-gas thermocouples (plane D, fig. 1). Preliminary tests in which the circumferential position of the sampling probe in the exhaust section (fig. 1), as well as the distance from the combustor exit, was varied indicated that smoke concentration was relatively uniform and that the position of the probe was not critical. The probe consisted of a section of 1/4-inch outside diameter Inconel tubing, closed at one end and having four

drilled holes of 1/8-inch diameter located at the centers of equal areas and facing upstream. From the probe the exhaust gases passed to the smoke meter through 1/4-inch Inconel tubing. A bypass line located immediately upstream of the smoke meter provided continuous purging of the sampling line and served to reduce the exhaust-gas pressure at the 2449
smoke meter.

The smoke meter was a modification of a commercially available smoke tester and is shown diagrammatically in figure 2. It consisted essentially of an air-cooled filter press containing a paper filter disk and an automatic metering device. Automatic metering was accomplished by a sonic-flow orifice and a vacuum pump controlled by an electric timer. Constant upstream orifice pressure and temperature, necessary for accurate metering, were attained by means of a pressure regulator and by an air cooler incorporated in the filter press, respectively. A solenoid valve, operated by the timer, provided instantaneous stoppage of the gas flow at the end of each cycle. Location of all control equipment downstream of the filter minimized any deposition of smoke particles in the sampling system ahead of the filter.

The optical density of the smoke-covered filter disks was determined by a transmission densitometer which measured the amount of light transmitted through the filter. Densitometer scale deflections are a logarithmic function of the amount of light absorbed by the filter paper and hence can be considered a measure of the amount of smoke in the sample. An attempt to determine the weight of smoke in a given sample and thus to calibrate densitometer readings in terms of weight of carbon per unit volume of exhaust gas produced excessive scatter of data because of the extremely small weights of carbon involved. However, the results indicated that densitometer scale deflections did not increase linearly with smoke concentration, but increased at decreasing rates. This trend undoubtedly results from the reduction in uncovered filter area as the deposition of smoke progresses; thus, the first particles of smoke are more effective in reducing light transmission than those deposited later. For the purpose of this investigation, however, the differences in transmission density readings between the smoke-covered and the clean filters were considered a sufficiently accurate measure of the amount of smoke in a given sample and are plotted as "smoke density" throughout the report. Photographs indicating the range of filter-paper smoke depositions obtained are shown in figure 3.

Combustion Efficiency

Combustion efficiencies were also calculated for each test condition. Combustion efficiency was based on the ratio of actual enthalpy rise across the combustor to the heat supplied by the fuel and was computed by the method described in reference 13.

Test Conditions

Inlet-air and fuel parameters were varied over a wide range as shown in table I. At each condition the fuel-air ratio was varied to give average combustor-exit temperatures from 800° to 1600° F.

In order to verify some of the conclusions reached during the investigation, a special experiment was conducted in which a restriction was placed in the secondary air passage of the single combustor to force more air into the primary combustion zone.

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In order to compare single combustor performance with that of a full-scale engine, a series of tests was conducted with a full-scale engine operating at static sea-level conditions over a range of engine speeds and at three different exhaust-nozzle openings. Smoke samples were obtained by means of a single 1/4-inch outside diameter Inconel total-pressure probe located in the tail-cone section of the engine.

Fuels

Investigations of the effects of varying inlet-air conditions on smoking tendency were conducted with MIL-F-5624A grade JP-3 fuel. Tests of the effects of fuel volatility on smoking tendency were conducted with several paraffinic-type hydrocarbon fuels, in addition to the JP-3 fuel. Pertinent properties of these fuels are shown in the following table:

Properties	Fuel			
	MIL-F-5624A grade JP-3	2,3 dimethyl-butane	2,2,4 trimethyl-pentane	Paraffinic Diesel fuel
Boiling range (°F)	113-473	136	208	480-574
Specific gravity at 60°F/60°F	0.742	0.665	0.696	0.799
Hydrogen-carbon ratio by weight	0.172	0.194	0.188	0.171
Net heat of combustion (Btu/lb)	18,764	19,192	19,065	18,762
Aromatics, A.S.T.M. D875-46T (percent by volume)	approx. 9	0	0	0

RESULTS

Reproducibility of Smoke Measurements

In order to determine the reproducibility of results, daily checks were made not only of the smoking tendency of the combustor, but also of the performance of the smoke meter. Reliable smoke-meter performance essentially required that a constant volume of exhaust gas be passed across the filter under all conditions. Daily tests with a wet-test meter showed that a constant rate of flow of exhaust gas through the smoke meter could be maintained by means of the sonic orifice. In order to determine any variation in smoking tendency of the combustor, daily tests were conducted at one condition of inlet-air temperature, pressure, and velocity over a range of fuel-air ratios. Results of these tests (fig. 4) indicate that maximum deviations from the average curve were less than ±20 percent. 2449

Effect of Fuel-Air Ratio and Inlet-Air Parameters on Smoke Density

The data obtained in the investigation of the smoking characteristics of the single combustor and the full-scale engine are summarized in tables II and III.

The effect of variations in fuel-air ratio on smoke density is shown for a range of air velocities and at three combinations of combustor inlet-air pressure and temperature in figure 5. At low velocities, smoke density increased with increasing fuel-air ratio, passed through a maximum, and then decreased. As the velocity was increased, maximum smoke concentrations were obtained at successively lower fuel-air ratios. At the same time, the effect of changes in fuel-air ratio on smoke concentration was greatly reduced.

The effect of inlet-air velocity on smoke density is also shown in figure 5. At low fuel-air ratios, smoke densities increased with increasing velocity, whereas at high fuel-air ratios the reverse occurred. Maximum smoke densities, however, decreased with increasing velocity.

The effect of inlet-air pressure on smoke density is shown in figure 6, which was cross-plotted from figure 5 at two velocities and at two fuel-air ratios. The increases in pressure were accompanied by slight increases in inlet-air temperature. Smoke density increased rapidly with increasing pressure under these conditions.

The effect of inlet-air temperature on smoke density at constant pressure and mass flow is shown in figure 7. Since inlet-air pressure and mass flow were held constant, increases in temperature were accompanied by proportional increases in velocity. On the average, smoke densities decreased slightly as the inlet-air temperature was increased, the effect being most pronounced near the peak of the fuel-air ratio curve. The observed effect of increasing inlet-air temperature was no greater, however, than would be anticipated for the effect of the concurrent increasing inlet velocity; hence no definite conclusion can be drawn regarding the effect of inlet-air temperature on smoke density except that the effect is very small.

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Effect of Fuel Parameters on Smoke Density

The effect of fuel volatility on smoke is shown in figure 8 for four fuels of essentially paraffinic composition. Only very small changes in maximum smoke density were observed as the fuel volatility was increased. The most pronounced effect was the occurrence of maximum smoke densities at successively lower over-all fuel-air ratios as volatility was increased.

The effect of fuel-inlet temperature on smoke is shown in figure 9. In general, increases in fuel temperature resulted in a slight increase in smoke formation.

Full-Scale Engine Tests

Results of tests of the full-scale engine operating at static sea-level conditions over a range of engine speeds and at three different exhaust-nozzle openings are shown in figure 10. Although the combustor-inlet conditions in full-scale engine tests are fixed by compressor and turbine characteristics and thus cannot be varied at will as in single-combustor tests, the data so obtained can be used to verify some of the trends indicated by the single-combustor tests. Thus, from figure 10, the smoke density increased with increasing engine speed as well as with decreasing exhaust-nozzle opening. Increases in engine speed at constant altitude result in increased mass flow through the engine together with increased combustor-inlet pressures and temperatures and increased combustor-exit temperatures. Single-combustor tests showed these effects to be in opposition to each other; that is, increases in pressure resulted in large increases in smoke density, while increases in velocity and combustor-inlet temperature reduced smoke density. However, the effect of increased pressure was by far the most pronounced and, hence, may be assumed to be primarily responsible for the increase in smoke with increased engine speed. The slightly higher smoke densities obtained with the smaller exhaust-nozzle openings can also be ascribed to the effect of increased combustor pressure with the reduced exhaust-nozzle opening.

Combustion Efficiency

Combustion-efficiency measurements made at each test condition indicated no loss in efficiency attributable to smoke. Because of the high-pressure conditions investigated, combustion-efficiency values were, in general, very high, averaging above 93 percent (table II).

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DISCUSSION OF RESULTS

In order to analyze the effect of inlet-air and fuel parameters on smoke concentration, it is necessary to consider those variables that are the result of variations of these parameters, but which affect the combustion process more directly. Some of the more important of these variables and their predicted effect on smoke concentration are shown in the following table:

Variable	Expected effect on smoke concentration with increase in variable
Primary-zone fuel-air ratio	Increase
Fuel boiling point	Slight increase
Fuel atomization	Decrease
Flame length	Decrease
Flame temperature	Decrease

In addition, the degree of mixing of fuel and air may be an important variable, but its effect on smoke concentration is not readily predicted.

Increases in primary-zone fuel-air ratio generally result either from increased over-all fuel-air ratios or from increased rates of vaporization of the fuel and can be expected to increase smoke formation in the primary combustion zone. Experiments with laboratory burners (reference 6), as well as in Diesel engines (reference 10), have shown that smoke increases with increasing fuel-air ratio. Thus a well-aerated Bunsen burner flame will be blue; as the fuel-air ratio is increased, the color will gradually change from blue to yellow, and, eventually smoke may be emitted. In addition, the experiment (described in PROCEDURE) in which more air was forced into the primary zone of the single combustor by means of a restriction in the secondary air passage showed that reduction of smoke concentration can be effected by reducing the primary-zone fuel-air ratio.

Increases in fuel boiling point result from increases in pressure and from the use of fuels of lower volatility. According to Spaulding (reference 4), who investigated the burning rates of liquid droplets and who found that the smoke formation increased as the temperature of the film surrounding the liquid droplet was increased, increases in fuel boiling point should result in increased smoke formation. Other investigators (reference 6), however, found that the effect of boiling point on smoke formation was very slight. This effect of boiling point is substantiated by the results of figure 8, which showed no noticeable reduction in smoke as fuel volatility was increased.

Improved fuel atomization, in general, results from increased flow through the fuel nozzle and should reduce smoke formation because of the greater penetrating power of the improved spray and the resultant elimination of fuel-rich pockets. Conversely, deterioration of spray characteristics is experienced at very low fuel flows. Since a duplex fuel nozzle was used during this investigation, the effect of low fuel flows probably was not as pronounced as it would have been with a single-flow nozzle.

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Increases in flame length result, among other causes, from increases in fuel flow and may be expected to decrease smoke concentrations because of the greater amount of smoke burned in its passage through the flame zone. Similarly, increases in the average temperature in the flame zone, brought about by increases in fuel-air ratio, should result in decreased smoke concentration because of the greater amount of smoke burned by the hotter flames.

On the basis of the preceding discussion, the effect of the inlet-air and fuel parameters on smoke concentration can now be interpreted more easily. The initial increase in smoke density with increasing over-all fuel-air ratio may thus be attributed to concomitant increases in primary-zone fuel-air ratios, while the decrease in smoke density with further increases in over-all fuel-air ratio may be considered to be the result of increased flame length and flame temperature. Since increases in inlet-air velocity were brought about by increases in mass air flow with attendant increases in fuel flow, the decreases in maximum smoke concentration with increases in velocity can be attributed primarily to the effect of increased flame length and improved fuel-spray characteristics.

The large increase in smoke concentration with increases in pressure cannot readily be associated with any changes in the secondary variables discussed previously, such as the effect of increased boiling point, since the varying fuel-volatility tests showed no noticeable increase in smoke density due to increases in boiling point. It is possible that the increase in pressure affected the chemistry of the combustion process rather than the physical characteristics of the combustion zone. The pressure effect has been confirmed by Lloyd (reference 11) who found that smoke increased with pressure in turbojet engines and by Schweitzer (reference 9) and Landen (reference 10) who observed increased smoke in Diesel engines as compression ratios and cylinder pressures were increased.

The slight increase in maximum smoke densities with increasing fuel temperature may have been caused by attendant increases in primary-zone fuel-air ratios. Similarly, the occurrence of maximum smoke densities at successively lower over-all fuel-air ratios as fuel volatility was increased may be attributed to increases in primary-zone fuel-air ratios although no noticeable increase in the magnitude of maximum smoke concentrations was observed.

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The results of the investigation showed that increases in pressure brought about large increases in smoke density, while increases in inlet-air velocity or mass flow reduced smoke density. The results further indicated that those variables which increase the primary-zone fuel-air ratio will increase smoke formation, whereas those factors which tend to lengthen the flame zone or increase the flame temperature will decrease smoke concentration in the exhaust gases.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effects of inlet-air and fuel variables on the exhaust-gas smoking characteristics of a single tubular turbojet-engine combustor and from comparison tests in a full-scale turbojet engine:

1. The most pronounced effect on smoke was observed with increases in inlet-air pressure, which produced large increases in smoke concentration.

2. As fuel-air ratios were increased, smoke densities first increased, passed through a maximum, and finally decreased. The effect of variations of fuel-air ratio on smoke decreased with increasing velocity; also maximum smoke densities decreased and occurred at successively lower fuel-air ratios as inlet-air velocity was increased.

3. The effect of inlet-air temperature on smoke density was very small.

4. As fuel volatility was increased, maximum values of smoke density did not change appreciably, but were obtained at successively lower fuel-air ratios. Increases in fuel temperature resulted in slight increases in smoke formation.

5. The results of comparison tests in a full-scale turbojet engine indicated that the factors which increased combustion-chamber pressure, such as increased engine speed and decreased exhaust-nozzle area, also increased exhaust-smoke concentration.

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TABLE I - RANGE OF TEST CONDITIONS

Inlet air				Fuel	
Pressure (in. Hg)	Temperature (°F)	Velocity[a] (ft/sec)	Specific mass flow (lb/(sec)(sq ft))	Specification	Temperature (°F)
35.0	180	30, 40, 50, 60 70, 80, 90	Varied with velocity	MIL-F-5624A Grade JP-3	Ambient
50.9	250	30, 40, 50, 60 70, 80, 90	Varied with velocity	MIL-F-5624A Grade JP-3	Ambient
65.0	305	30, 40, 50, 60, [b]70	Varied with velocity	MIL-F-5624A Grade JP-3	Ambient
65.0	100, 150, 200, 250, 300, 350, 400	Varied with temperature	4.51	MIL-F-5624A Grade JP-3	Ambient
65.0	100	30	4.51	MIL-F-5624A Grade JP-3	76, 200, 300 400
65.0	100	30	4.51	MIL-F-5624A Grade JP-3; 2,3 dimethylbutane; 2,2,4 trimethylpentane; Paraffinic Diesel fuel	Ambient

[a]Based on maximum cross-sectional area of combustor housing (0.48 sq ft) and density of air at combustor inlet.

[b]Air preheater capacity limitations restricted velocity to maximum value of 70 ft/sec.

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TABLE II - PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

Run	Fuel	Combustor-inlet total pressure (in. Hg abs.)	Combustor-inlet temperature (°R)	Air flow (lb/hr)	Combustor reference velocity (ft/sec)	Fuel flow (lb/hr)	Fuel temperature (°R)	Fuel-air ratio	Mean combustor-outlet temperature (°R)	Mean temperature rise through combustor (°F)	Combustion efficiency (percent)	Fuel-nozzle pressure differential (in. Hg)	Smoke density
Effect of fuel-air ratio and inlet-air pressure and velocity													
129	MIL-F-5624A Grade JP-3	64.8	755	5,899	30.0	40.1	Ambient	0.0068	1245	490	97.7	20.1	0.17
130		65.0	758	5,829	29.6	55.4		.0095	1455	697	101.5	38.2	.49
131		65.1	758	5,855	29.7	72.9		.0125	1650	892	101.1	66.6	.69
132		65.0	766	5,914	30.4	94.8		.0160	1855	1089	97.9	111.5	.89
133		65.1	758	5,799	29.4	118.2		.0204	2075	1317	95.3	158.2	.85
134		65.0	762	7,797	39.8	53.5		.0069	1270	508	100.6	34.2	.24
135		65.0	760	7,797	39.7	76.6		.0098	1465	705	99.5	72.8	.52
136		65.1	765	7,828	40.1	100.2		.0128	1660	895	98.8	123.6	.76
137		65.0	764	7,791	39.9	127.5		.0164	1880	1116	98.5	166.5	.92
138		65.0	758	7,783	39.5	155.2		.0199	2060	1302	96.1	182.8	.82
139		64.9	766	9,742	50.1	65.2		.0067	1260	494	100.2	52.6	.37
140		64.8	766	9,734	50.1	97.0		.0100	1470	704	98.0	115.8	.52
141		65.0	766	9,728	50.0	127.7		.0131	1675	909	98.1	166.5	.82
142		65.0	760	9,759	49.7	159.8		.0164	1870	1110	97.8	182.8	.80
143		65.1	764	9,715	49.7	193.1		.0199	2085	1321	98.0	201.0	.72
144		65.0	764	11,682	59.8	80.8		.0069	1265	501	98.5	81.0	.51
145		65.0	764	11,634	59.6	118.7		.0102	1480	716	97.5	158.3	.72
146		65.0	762	11,658	59.5	151.8		.0130	1660	898	97.5	178.7	.72
147		65.0	764	11,647	59.6	189.2		.0162	1865	1101	97.8	197.0	.75
148		65.1	760	11,631	59.2	228.3		.0196	2070	1310	98.3	217.3	.62
149		64.9	760	13,573	69.3	96.5		.0071	1275	515	98.6	113.7	.63
150		65.0	751	13,717	69.0	139.9		.0102	1465	714	97.0	174.6	.65
151		64.8	748	13,646	68.6	182.8		.0134	1680	932	98.4	195.2	.65
152		65.0	749	13,676	68.6	231.3		.0169	1899	1150	98.3	-----	.47
153		65.2	749	13,597	68.1	242.1		.0178	1955	1206	98.5	223.3	.51
164		50.8	713	4,950	30.3	38.9		.0079	1255	542	93.6	17.8	.07
165		50.8	712	4,942	30.2	51.9		.0105	1470	758	99.8	32.1	.28
166		50.9	714	4,931	30.2	65.9		.0134	1670	956	100.9	52.3	.57
167		51.0	714	4,937	30.1	83.0		.0168	1855	1141	97.6	84.8	.65
168		51.0	714	4,920	30.0	104.0		.0211	2075	1361	94.8	131.6	.55
169		50.9	714	6,560	40.1	48.9		.0075	1255	541	98.3	27.9	.09
170		50.8	714	6,577	40.3	69.9		.0106	1470	756	98.4	60.6	.27
171		50.9	715	6,543	40.0	88.7		.0136	1665	950	98.7	97.1	.57
172		50.8	712	6,554	40.0	111.3		.0170	1870	1158	98.2	152.2	.67
173		50.9	715	6,560	40.2	136.5		.0208	2075	1360	96.2	172.4	.50
174		50.9	712	7,808	47.6	59.0		.0076	1260	548	98.3	42.1	.19
175		50.9	713	7,777	47.5	83.8		.0108	1480	767	98.6	86.9	.32
176		50.9	710	7,808	47.5	108.0		.0138	1660	950	96.9	141.9	.54
177		50.9	708	7,815	47.4	133.2		.0170	1860	1152	97.2	168.4	.62
178		50.9	714	7,830	47.9	163.2		.0208	2080	1366	96.4	184.7	.37
179		50.9	708	9,876	59.9	76.9		.0078	1265	557	97.1	72.7	.37
180		50.8	710	9,867	60.1	107.0		.0108	1465	755	96.3	140.0	.39
181		50.9	714	9,876	60.4	138.0		.0140	1670	956	96.6	172.4	.51
182		51.0	706	9,899	59.7	167.7		.0169	1850	1144	97.0	186.6	.46
183		50.9	714	9,899	60.5	205.2		.0207	2080	1366	96.9	205.0	.21
184		50.9	707	11,469	69.4	89.7		.0078	1265	558	96.7	97.1	.36
185		50.8	706	11,534	69.8	124.0		.0108	1460	754	97.0	160.3	.47
186		50.8	706	11,534	69.8	160.0		.0139	1655	949	96.5	182.7	.48
187		50.9	706	11,546	69.8	198.8		.0172	1880	1174	98.2	201.0	.32
188		51.1	707	11,443	69.0	226.7		.0198	2025	1318	97.3	215.0	.12
189		50.8	708	13,199	80.2	102.5		.0078	1260	552	96.4	127.8	.35
190		51.0	708	13,123	79.4	142.7		.0109	1470	762	97.0	174.4	.38
191		51.0	710	13,123	79.6	182.9		.0139	1680	970	98.3	192.7	.36
192		50.9	713	13,098	80.0	222.4		.0170	1870	1157	98.1	213.2	.27
193		51.0	712	14,793	90.0	115.8		.0078	1275	563	97.7	154.0	.34
194		50.8	714	14,811	90.7	156.2		.0105	1455	741	97.1	180.7	.32
195		50.7	718	14,722	90.8	205.7		.0140	1685	967	97.9	203.2	.32
196		51.0	720	14,780	91.0	228.0		.0154	1770	1050	97.1	215.1	.22
202		35.0	644	3,798	30.4	33.7		.0089	1270	626	95.5	11.2	.05
203		34.9	646	3,736	30.1	42.4		.0113	1460	814	98.8	19.5	.18
204		35.0	642	3,763	30.1	54.0		.0144	1665	1023	100.1	33.6	.34
205		34.9	650	3,757	30.5	68.1		.0181	1870	1220	96.7	54.1	.37
206		35.0	640	3,720	29.6	82.5		.0222	2060	1420	93.8	82.5	.32
207		35.1	640	5,036	40.0	42.2		.0084	1255	615	99.1	19.3	.01
208		35.0	640	5,033	40.1	56.8		.0113	1455	815	99.3	37.7	.12
209		35.0	640	5,000	39.8	73.3		.0147	1675	1035	99.3	64.2	.29
210		35.0	640	5,017	40.0	92.7		.0185	1865	1225	95.2	102.8	.32
211		35.0	640	5,006	39.9	111.4		.0225	2060	1420	93.5	149.7	.19
212		34.9	640	6,263	50.0	54.0		.0086	1265	625	98.0	33.7	.04
213		35.0	640	6,271	50.0	72.5		.0116	1460	820	97.7	62.1	.08
214		35.1	640	6,267	49.8	92.1		.0147	1660	1020	97.5	102.7	.18
215		35.0	644	6,271	50.3	115.8		.0185	1865	1221	95.0	153.7	.15
216		35.0	644	6,284	50.4	137.2		.0218	2060	1416	95.0	170.0	.06
217		35.0	644	7,512	60.2	64.0		.0085	1260	616	97.7	49.9	.07
218		35.1	638	7,502	59.4	88.2		.0118	1465	827	97.0	94.6	.14
219		35.1	644	7,532	60.2	114.2		.0152	1675	1031	95.8	151.6	.20
220		35.0	642	7,522	60.1	140.8		.0187	1870	1228	94.3	172.1	.12
221		35.1	644	7,512	60.1	167.3		.0223	2080	1436	94.6	184.2	.07
222		35.0	645	8,786	70.6	78.8		.0090	1280	635	95.9	74.3	.08
223		35.0	645	8,802	70.7	104.9		.0119	1465	820	95.0	131.3	.18
224		35.1	644	8,780	70.2	134.0		.0153	1670	1026	94.7	167.9	.14
225		35.0	640	8,802	70.1	163.8		.0186	1860	1220	94.1	182.2	.08
226		35.0	646	8,796	70.7	197.0		.0224	2105	1459	95.8	198.5	.02
227		35.0	645	10,061	80.8	90.4		.0090	1270	625	94.1	98.8	.12
228		35.0	644	10,076	80.8	118.2		.0117	1455	811	95.3	155.8	.11
229		35.1	644	10,074	80.6	153.7		.0153	1655	1011	93.2	178.1	.15
230		35.0	642	10,089	80.6	187.0		.0185	1860	1218	94.4	194.5	.03
231		35.0	642	10,097	80.7	222.3		.0220	2060	1418	94.4	212.8	.02
232		35.0	642	11,282	90.2	99.2		.0088	1255	613	94.2	119.1	.12
233		35.0	640	11,267	89.8	132.8		.0118	1450	810	94.7	166.0	.14
234		35.0	640	11,267	89.8	174.2		.0155	1670	1030	93.8	186.3	.06
235		35.0	640	11,282	89.9	224.2		.0199	1920	1280	93.1	212.8	0

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TABLE II - PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTION - Concluded

Run	Fuel	Combustor-inlet total pressure (in. Hg abs.)	Combustor-inlet temperature (°R)	Air flow (lb/hr)	Combustor reference velocity (ft/sec)	Fuel flow (lb/hr)	Fuel temperature (°R)	Fuel-air ratio	Mean combustor-outlet temperature (°R)	Mean temperature rise through combustor (°F)	Combustion efficiency (percent)	Fuel-nozzle pressure differential (in. Hg)	Smoke density
						Effect of inlet-air temperature							
84	MIL-F-5624A Grade JP-3	65.5	564	7686	28.8	68.1	Ambient	0.0089	1255	691	104.9	56.0	0.57
85		65.0	560	7649	28.7	92.8		.0121	1480	920	104.1	101.3	.82
86		65.2	562	7791	29.3	117.5		.0151	1660	1098	101.8	154.1	.92
87		64.8	564	7760	29.4	144.9		.0187	1880	1316	100.7	174.8	.82
88		64.7	562	7754	29.4	170.8		.0220	2090	1528	101.1	187.2	.66
89		65.2	612	7712	31.6	66.3		.0096	1270	658	103.3	52.3	.39
90		65.2	610	7641	32.0	88.3		.0113	1455	845	103.0	72.6	.67
91		65.2	612	7795	31.9	113.1		.0145	1670	1058	102.2	152.0	.97
92		64.9	610	7734	31.7	140.0		.0181	1885	1275	100.9	172.7	.86
93		65.0	610	7829	32.0	166.3		.0212	2065	1455	100.0	184.8	.74
94		64.9	660	7815	34.6	61.2		.0078	1255	595	102.7	44.4	.27
95		65.2	665	7807	34.7	83.9		.0108	1465	800	102.5	84.9	.59
96		65.1	664	7801	34.7	108.0		.0138	1670	1006	102.2	142.0	.75
97		65.1	664	7750	34.4	133.6		.0172	1860	1196	99.5	168.4	.90
98		64.8	664	7790	34.8	162.8		.0209	2070	1406	98.5	183.0	.65
99		64.8	710	7828	37.4	58.5		.0075	1270	560	101.6	40.5	.24
100		65.2	710	7756	36.8	78.7		.0102	1465	755	102.7	76.7	.63
101		65.1	712	7807	37.2	104.6		.0134	1670	958	100.6	133.6	.82
102		65.0	711	7789	37.1	129.8		.0167	1865	1154	99.6	166.5	.85
103		65.0	708	7776	36.9	158.6		.0204	2060	1352	97.3	182.8	.68
104		64.8	756	7809	39.7	51.7		.0066	1250	494	101.3	32.3	.22
105		64.9	758	7790	39.7	76.0		.0098	1460	702	99.6	70.9	.39
106		65.0	757	7776	39.4	100.2		.0129	1670	913	100.1	123.7	.76
107		65.0	760	7821	39.8	124.8		.0160	1855	1095	98.9	164.5	.80
108		65.1	759	7813	39.7	154.7		.0198	2060	1301	96.7	180.6	.68
109		65.0	808	7832	42.4	47.3		.0060	1250	442	99.6	26.0	.32
110		65.0	812	7845	42.7	71.2		.0091	1460	648	99.2	64.7	.39
111		64.8	812	7782	42.5	98.8		.0127	1675	863	96.6	119.9	.67
112		65.0	810	7787	42.3	123.8		.0159	1870	1060	96.6	164.5	.70
113		65.1	805	7774	41.9	150.8		.0194	2075	1270	96.7	180.6	.73
114		65.0	858	7787	44.8	43.2		.0055	1260	402	99.0	21.9	.32
115		65.0	860	7787	44.9	67.3		.0086	1470	610	98.4	58.6	.40
116		65.1	858	7760	44.6	91.4		.0118	1665	807	97.5	105.3	.52
117		65.0	860	7856	45.3	118.2		.0150	1860	1000	96.5	158.3	.69
118		65.1	860	7773	44.8	147.5		.0190	2090	1230	96.3	178.6	.75
						Effect of fuel volatility and temperature							
417	2,2,4-trimethylpentane	65.0	562	7821	29.4	68.9	Ambient	0.0058	1260	698	104.9	64.7	0.76
418		65.2	565	7834	29.6	89.8		.0115	1460	895	105.3	113.4	.81
419		65.1	562	7828	29.4	112.3		.0144	1660	1098	105.2	158.2	.87
420		65.0	563	7783	29.4	139.5		.0179	1890	1327	104.2	174.6	.79
421		64.8	564	7811	29.8	163.8		.0210	2080	1516	103.6	185.0	.50
432	Paraffinic Diesel fuel	65.0	558	7795	29.1	77.6	Ambient	0.0100	1280	722	97.8	60.6	0.13
433		65.1	568	7801	29.7	95.8		.0123	1470	902	100.9	89.0	.22
434		64.8	562	7783	29.4	117.2		.0151	1660	1098	101.9	126.0	.59
435		64.8	563	7785	29.5	140.5		.0181	1855	1292	102.0	134.1	.77
436		65.0	568	7801	29.7	171.2		.0219	2100	1532	101.8	148.2	.81
447	2,3-dimethylbutane	64.8	562	7792	29.4	66.8	Ambient	0.0086	1250	688	105.5	64.9	0.51
448		65.1	560	7798	29.2	90.4		.0116	1480	920	106.5	123.8	.75
449		65.2	558	7817	29.2	111.0		.0142	1670	1112	107.0	164.3	.74
450		64.9	564	7799	29.5	138.1		.0177	1890	1326	104.7	180.8	.50
451		65.0	560	7798	29.2	159.9		.0205	2080	1520	105.5	193.0	.36
509	MIL-F-5624A Grade JP-3	64.9	557	7780	29.1	69.9	536	0.0090	1265	708	106.2	64.7	0.49
510		64.9	559	7787	29.2	91.9	536	.0118	1465	906	105.4	109.5	.61
511		65.5	563	7751	29.0	116.6	535	.0150	1685	1122	104.6	141.4	.92
512		65.6	560	7811	29.1	140.5	536	.0180	1870	1310	104.0	153.5	.89
513		64.8	561	7775	29.3	163.7	536	.0211	1850	1489	102.8	164.5	.80
514		64.9	556	7730	29.0	68.4	659	.0085	[a]----	[a]----	[a]-----	70.8	.79
515		64.8	558	7793	29.2	91.5	666	.0117	----	----	-----	121.9	.91
516		64.8	560	7812	29.4	113.8	656	.0146	----	----	-----	140.2	1.01
517		64.7	562	7831	29.6	138.0	663	.0176	----	----	-----	156.6	.98
518		64.8	565	7774	29.5	165.4	651	.0213	----	----	-----	176.9	.72
519		64.8	560	7748	29.2	69.2	766	.0089	----	----	-----	93.3	.88
520		65.4	561	7757	29.0	93.0	760	.0120	----	----	-----	102.9	.98
521		65.0	563	7771	29.3	115.3	760	.0148	----	----	-----	127.6	1.07
522		66.0	560	7765	28.7	134.0	772	.0173	----	----	-----	149.0	1.00
523		65.4	560	7750	28.9	162.0	748	.0209	----	----	-----	167.9	.89
532		64.6	563	7909	30.0	67.5	860	.0085	----	----	-----	148.4	.84
533		65.2	563	7777	29.3	84.8	892	.0109	----	----	-----	202.8	.83
534		65.1	563	7811	29.4	109.2	868	.0140	----	----	-----	213.2	.94
535		65.2	563	7811	29.4	136.8	843	.0175	----	----	-----	219.3	1.17
536		65.1	564	7802	29.4	150.0	868	.0192	----	----	-----	258.1	1.09

[a]Equilibrium not established at these conditions because of lag in fuel preheater.

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TABLE III - PERFORMANCE DATA OF FULL-SCALE ENGINE

Run	Engine speed (rpm)	Compressor discharge pressure (in. Hg abs.)	Compressor discharge temperature (°R)	Turbine-inlet temperature (°R)	Air flow (lb/sec)	Fuel-air ratio	Exhaust-nozzle area (sq ft)	Smoke density
35	7954	132.7	950	2133	84.6	0.0168	2.27	0.82
36	7577	125.9	921	2006	83.0	.0151		.70
37	7197	117.8	892	1894	80.1	.0139		.59
38	6820	109.2	863	1793	75.7	.0127		.54
39	6427	99.2	831	1693	70.9	.0116		.42
40	6047	88.7	799	1609	65.0	.0109		.36
41	5310	70.4	740	1484	53.7	.0100		.24
42	7946	122.6	916	1732	85.6	0.0114	3.06	0.61
43	7570	116.9	891	1639	84.6	.0101		.53
44	7188	110.2	863	1552	81.6	.0093		.53
45	6435	93.6	809	1422	72.3	.0081		.42
46	5678	75.7	756	1353	60.8	.0077		.26
47	6584	109.1	866	2061	71.0	0.0167	2.01	0.63
48	6435	103.9	853	1993	68.7	.0158		.50
49	6058	91.6	817	1853	62.8	.0142		.38
50	5304	71.7	753	1667	52.2	.0124		.23

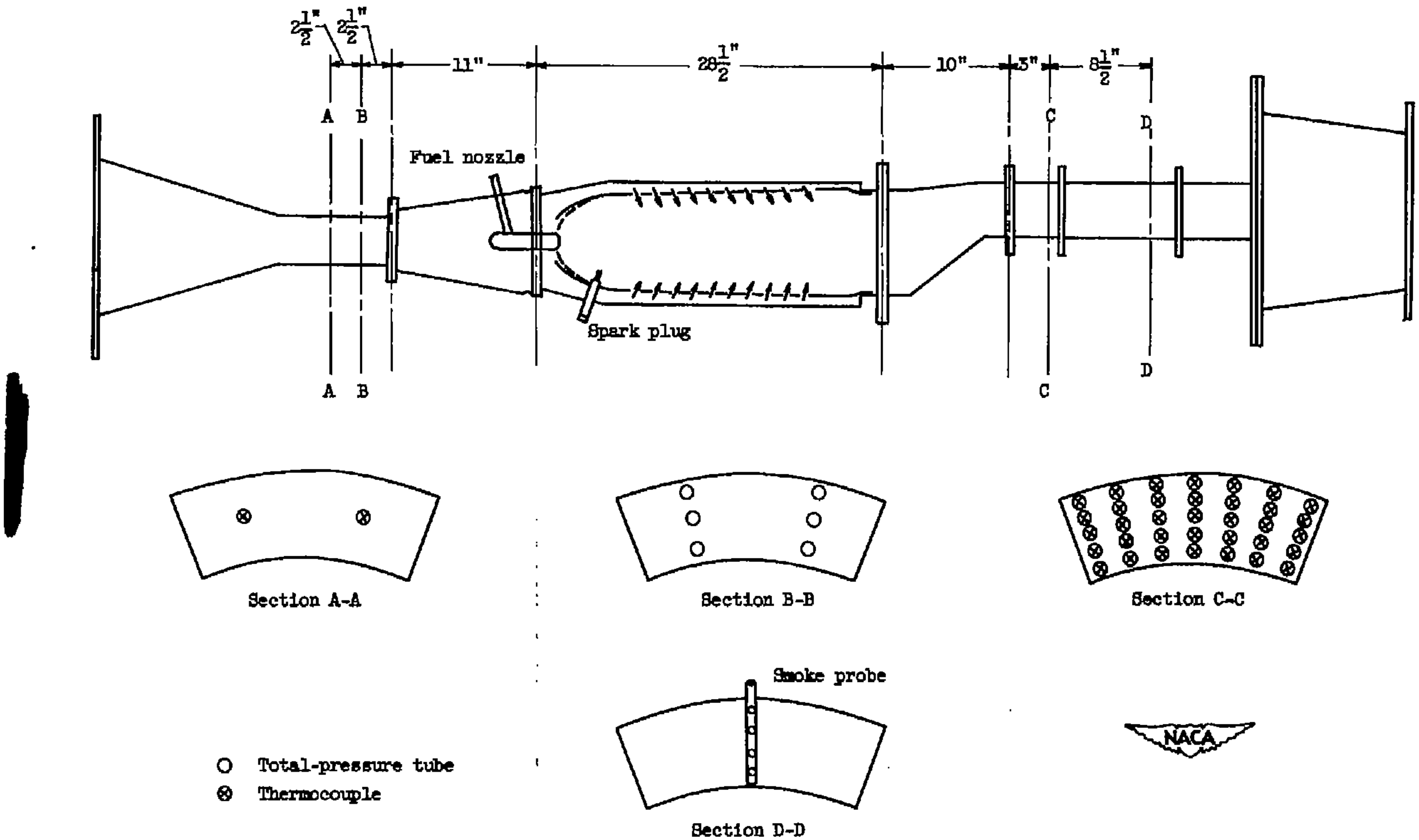

Figure 1. - Single tubular combustor installation including location and arrangement of instrumentation planes.

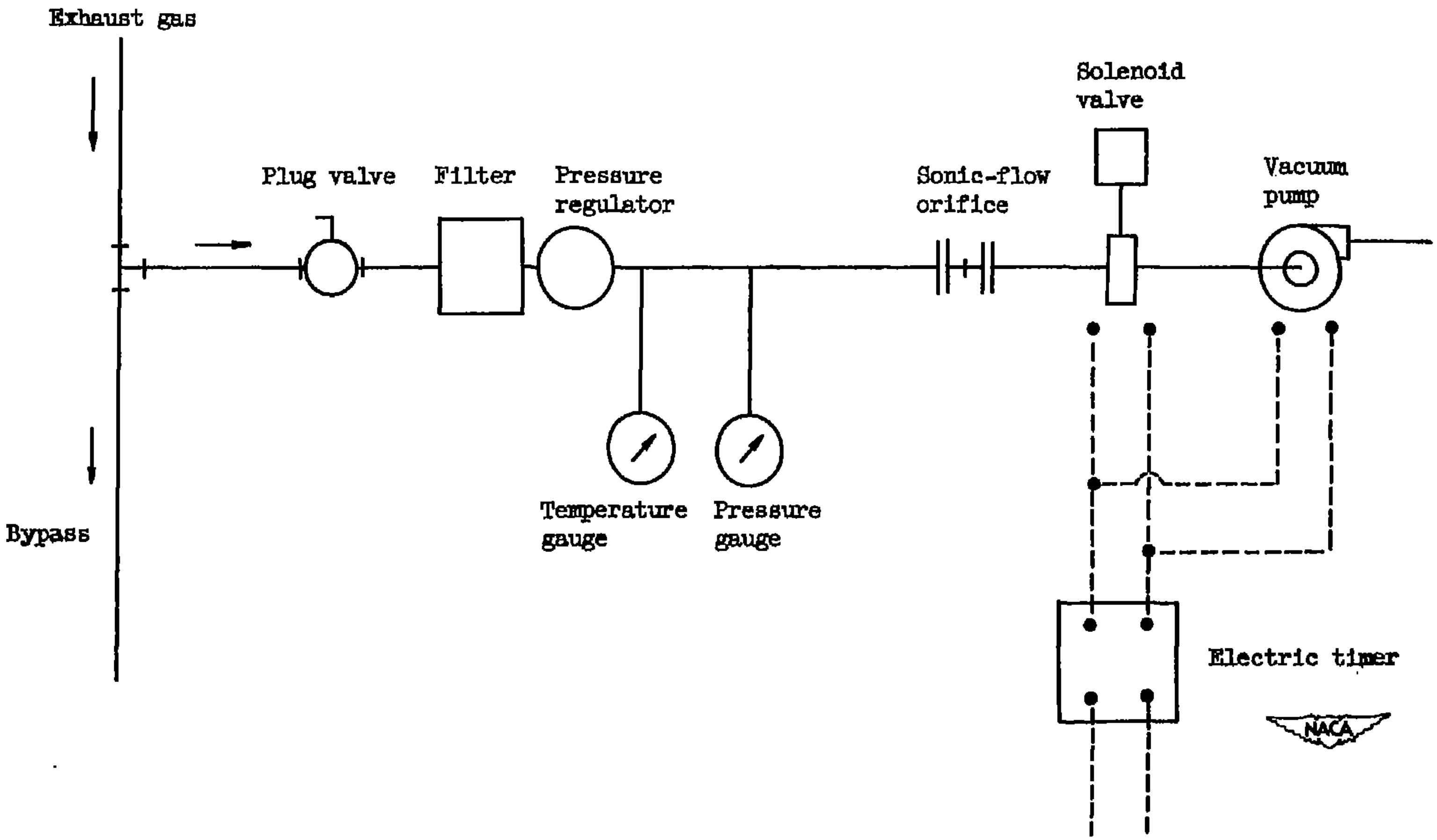

Figure 2. - Diagram of smoke meter.

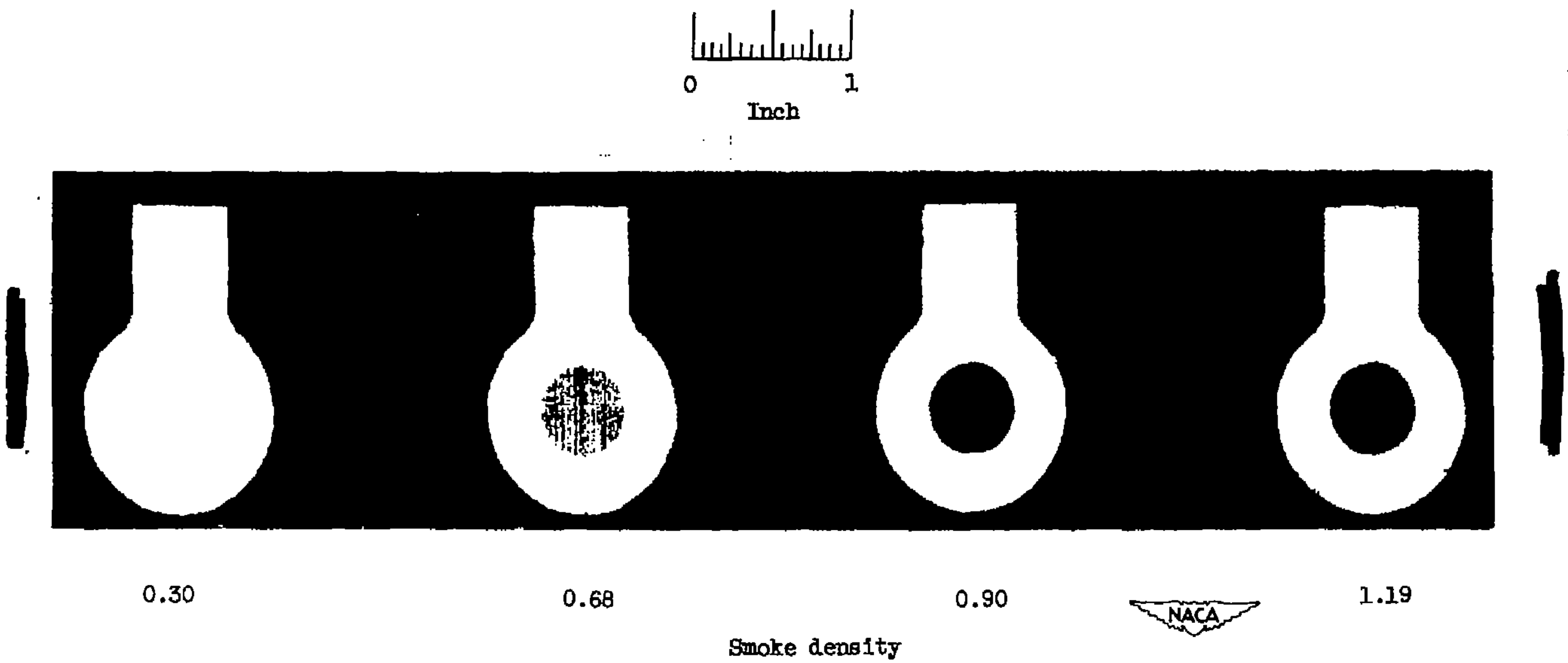

Figure 3. - Smoke-covered filter papers.

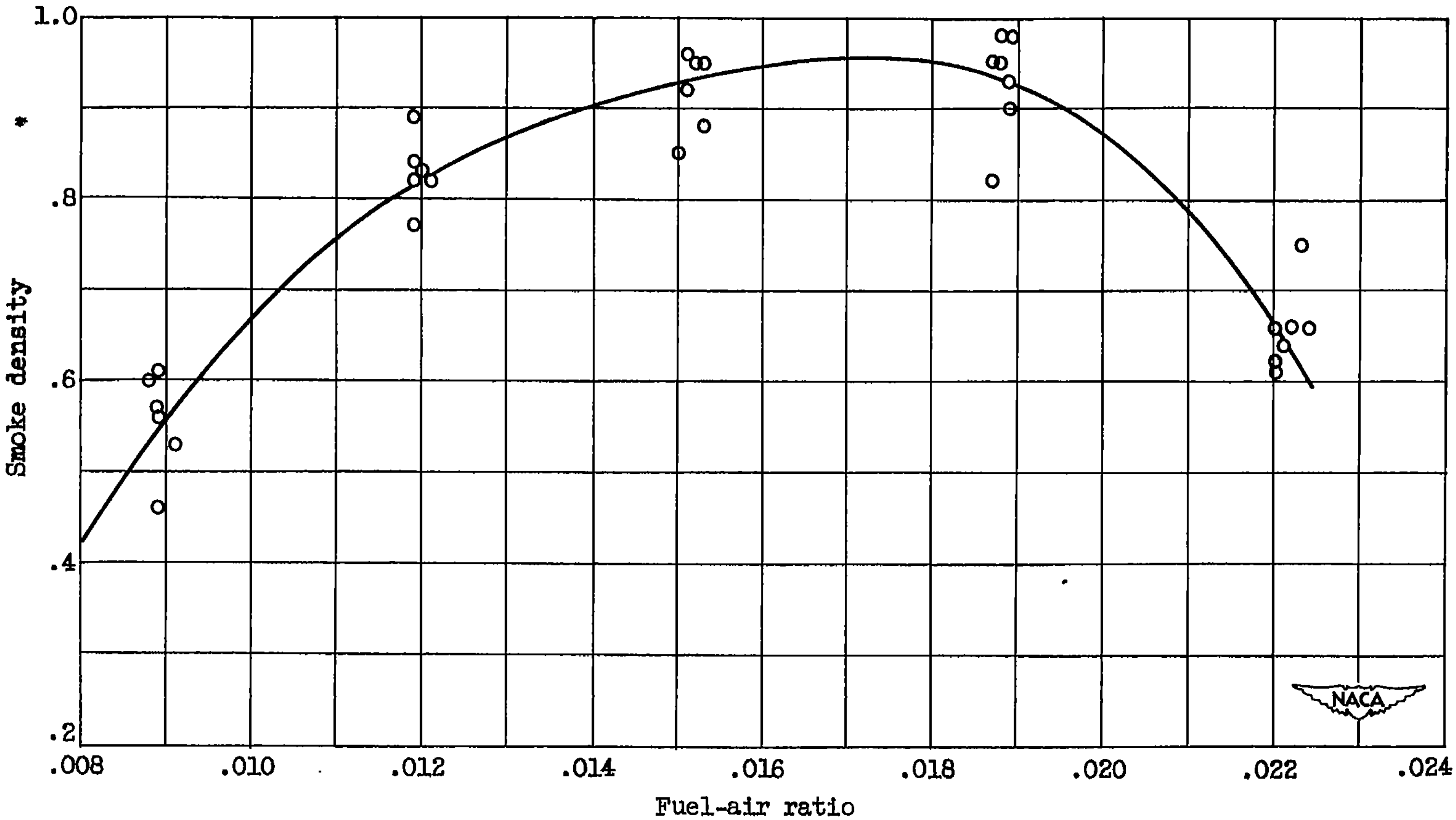

Figure 4. - Reproducibility of smoke-density data in single tubular combustor. Inlet-air pressure, 65 inches of mercury; inlet-air temperature, 100° F; inlet-air velocity, 30 feet per second; fuel, MIL-F-5624A, grade JP-3.

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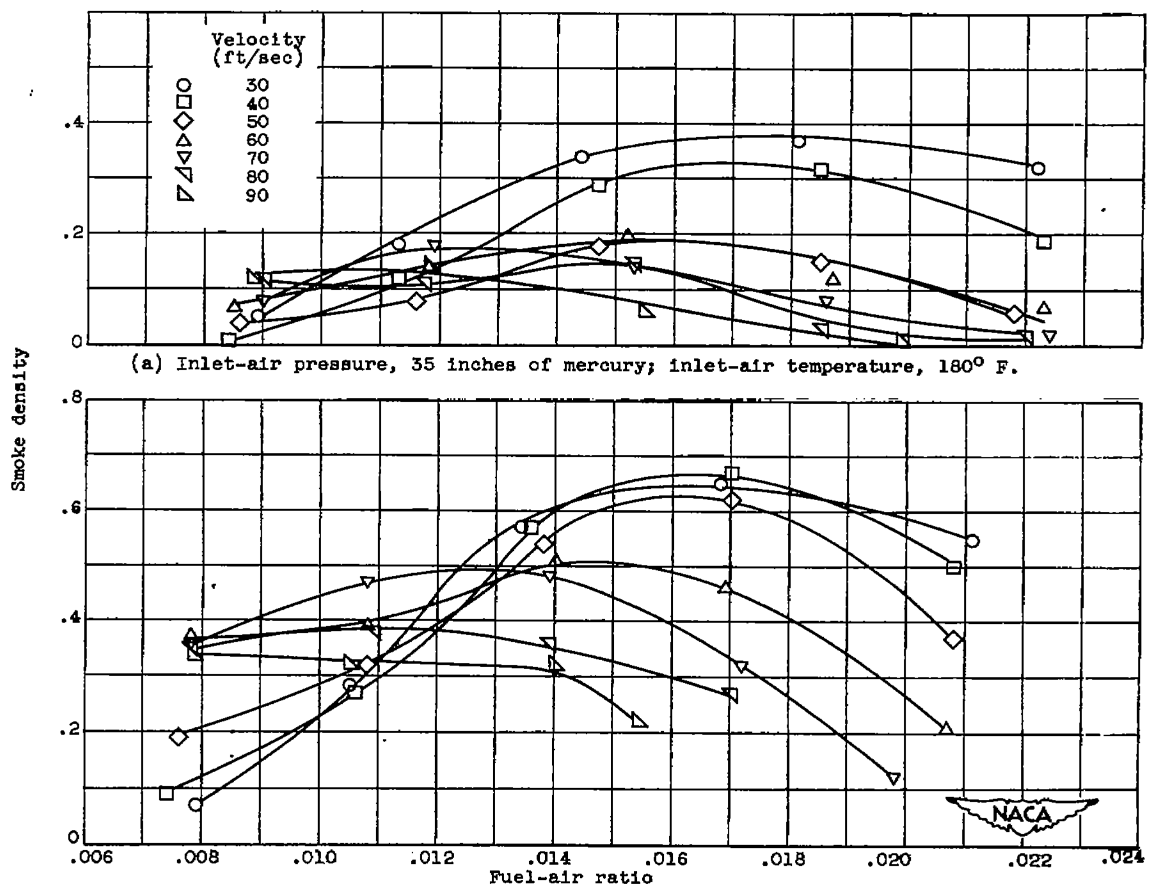
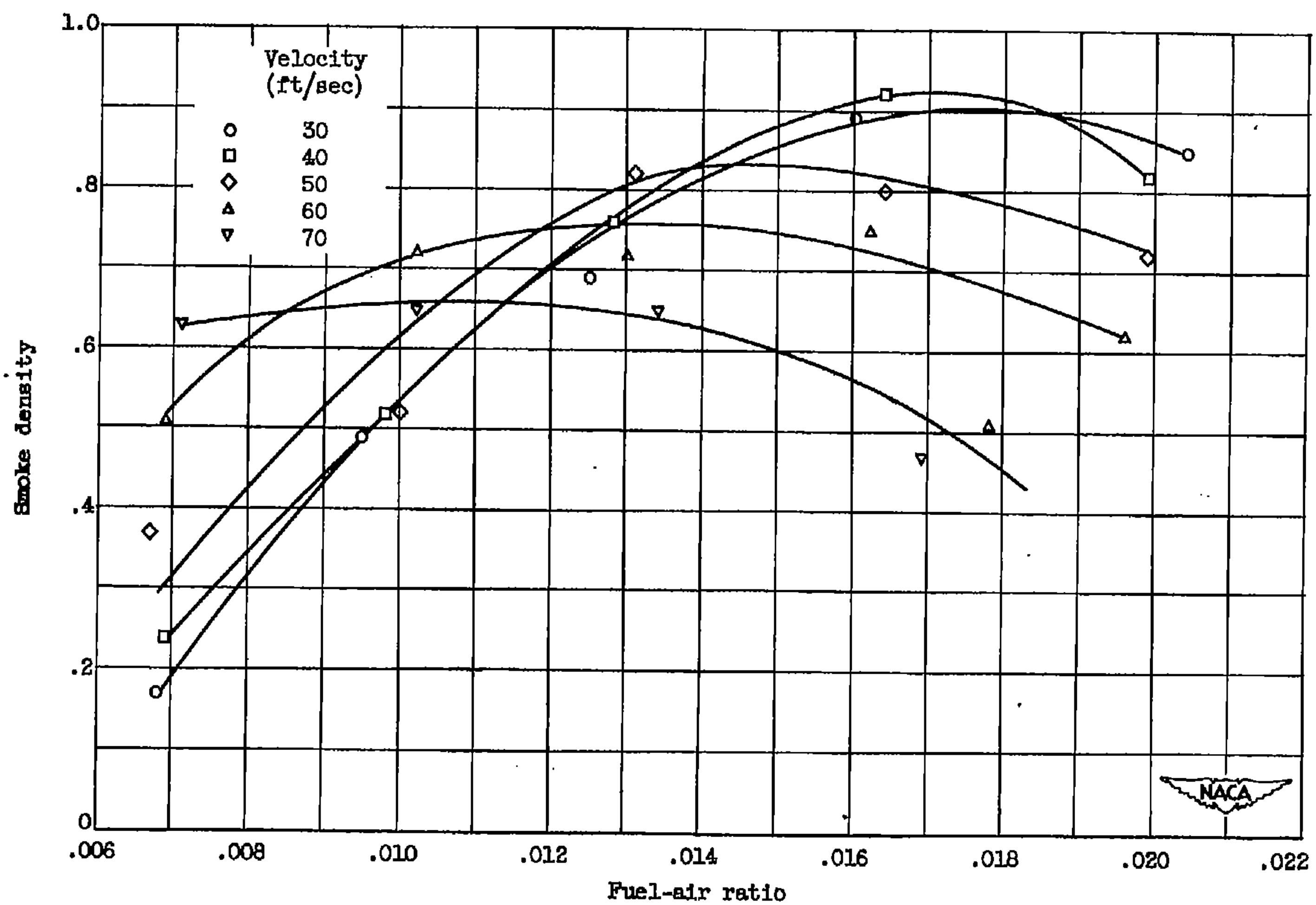


(a) Inlet-air pressure, 35 inches of mercury; inlet-air temperature, 180° F.

(b) Inlet-air pressure, 50.9 inches of mercury; inlet-air temperature, 250° F.

Figure 5. - Effect of fuel-air ratio and inlet-air velocity on smoke density in single tubular combustor at several inlet-air pressures and temperatures. Fuel, MIL-F-5624A, grade JP-3.

[redacted]



(c) Inlet-air pressure, 65 inches of mercury; inlet-air temperature, 305° F.

Figure 5. - Concluded. Effect of fuel-air ratio and inlet-air velocity on smoke density in single tubular combustor at several inlet-air pressures and temperatures. Fuel, MIL-F-5624A, grade JP-3.

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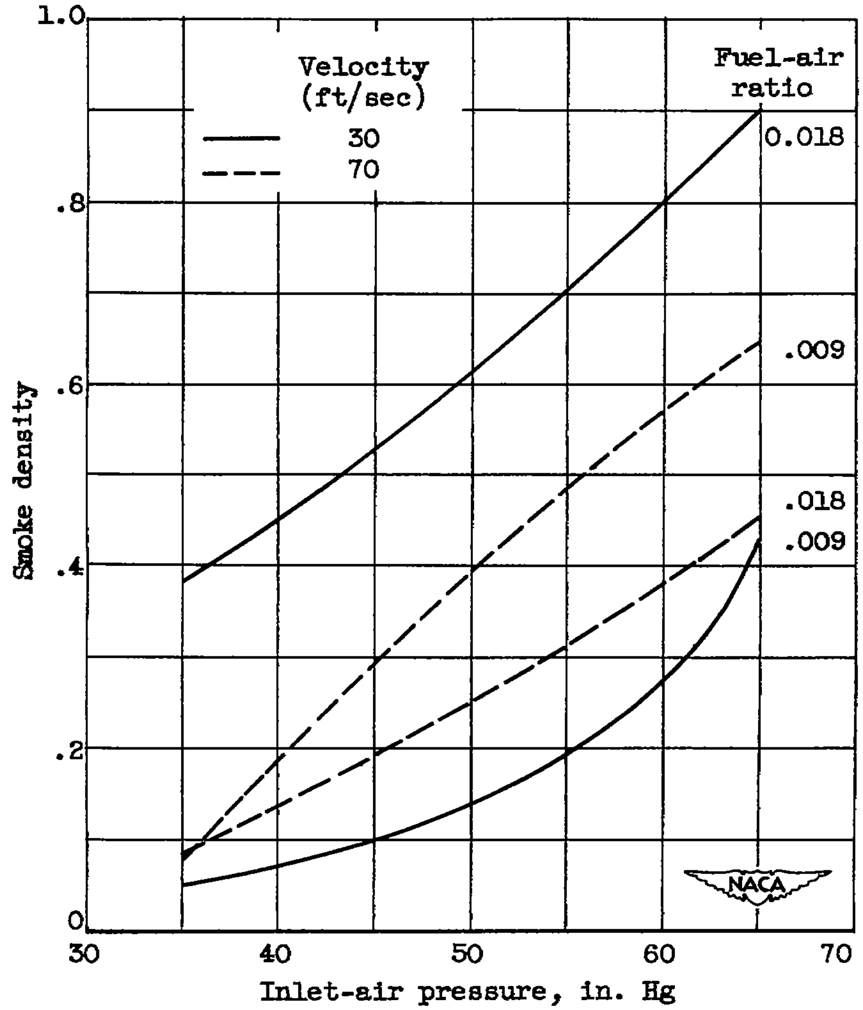

Figure 6. - Effect of inlet-air pressure on smoke density in single tubular combustor at two inlet-air velocities. Fuel, MIL-F-5624A, grade JP-3.

[redacted]

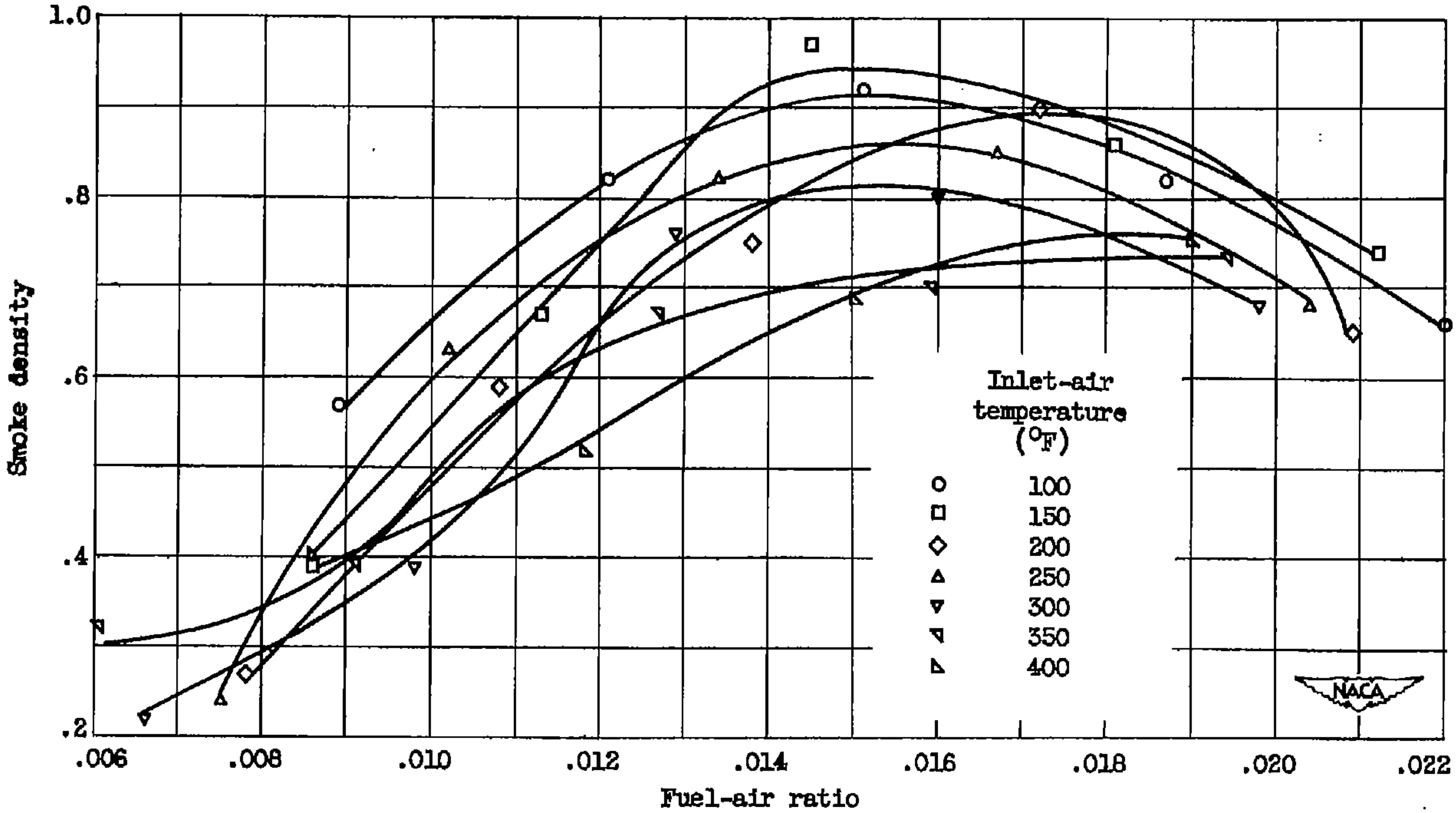

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Figure 7. - Effect of inlet-air temperature on smoke density in single tubular combustor. Inlet-air pressure, 65 inches of mercury; specific mass-air flow, 4.51 pounds per second per square foot; fuel, MIL-F-5624A, grade JP-3.

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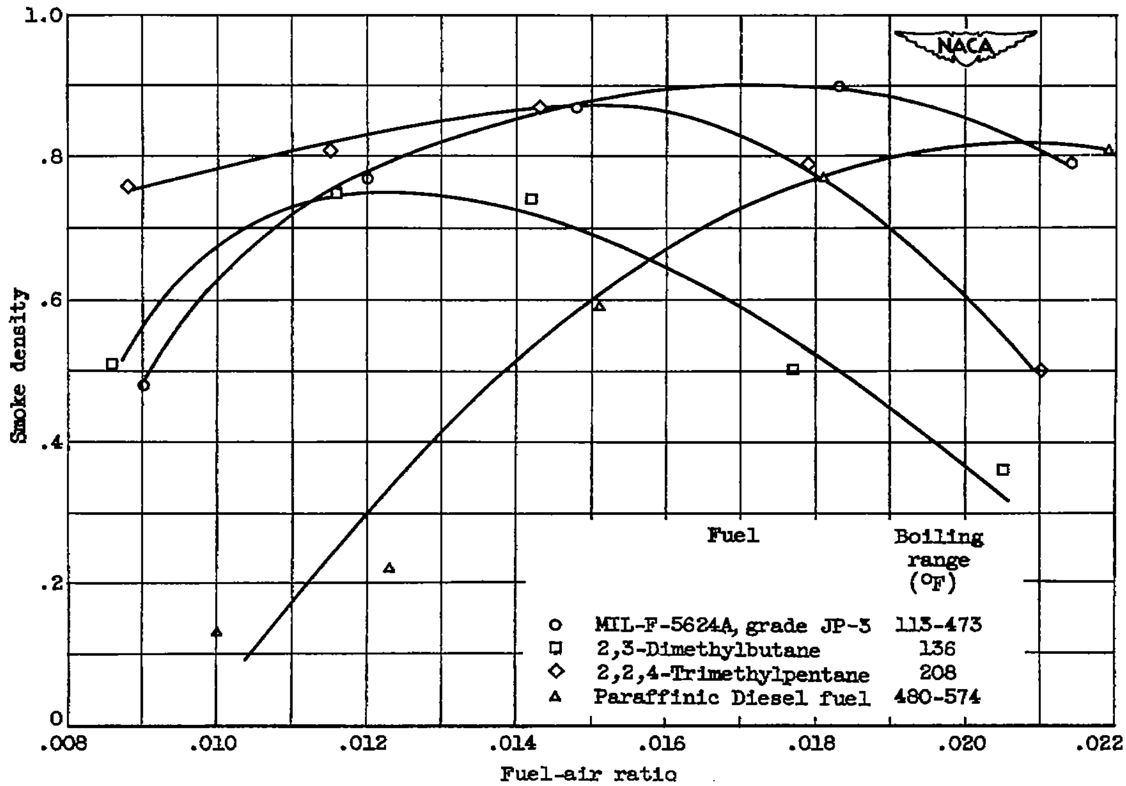

Figure 8. - Smoke density of fuels of varying volatility in single tubular combustor. Inlet-air pressure, 65 inches of mercury; inlet-air temperature, 100° F; inlet-air velocity, 30 feet per second.

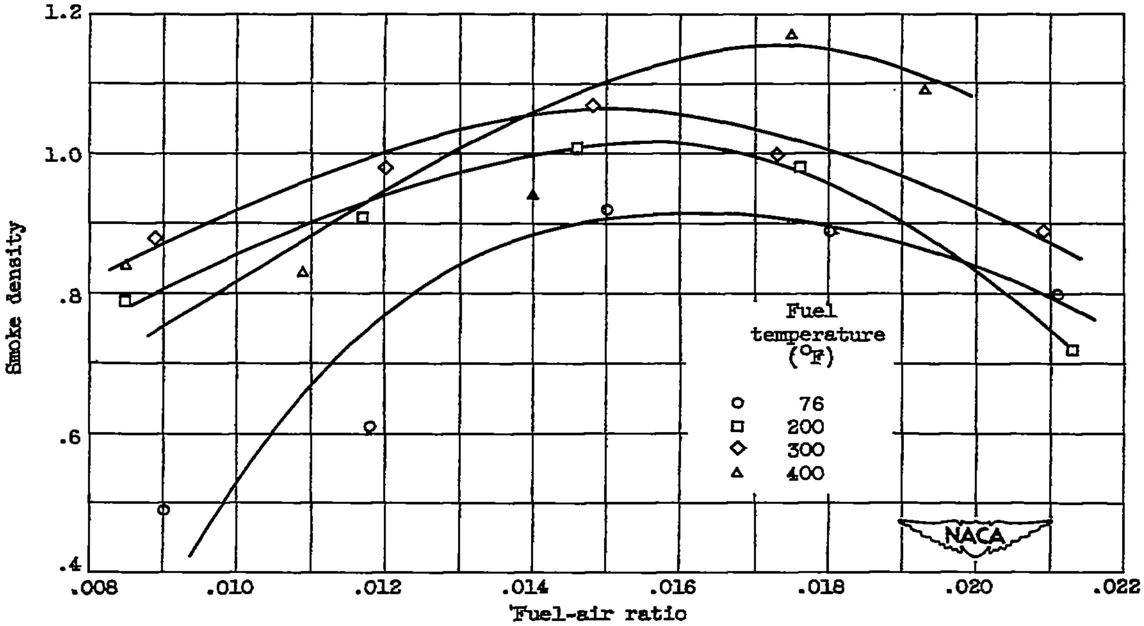

Figure 9. - Effect of fuel temperature on smoke density in single tubular combustor. Inlet-air pressure, 65 inches of mercury; inlet-air temperature, 100° F; inlet-air velocity, 30 feet per second; fuel, MIL-F-5624A, grade JP-3.

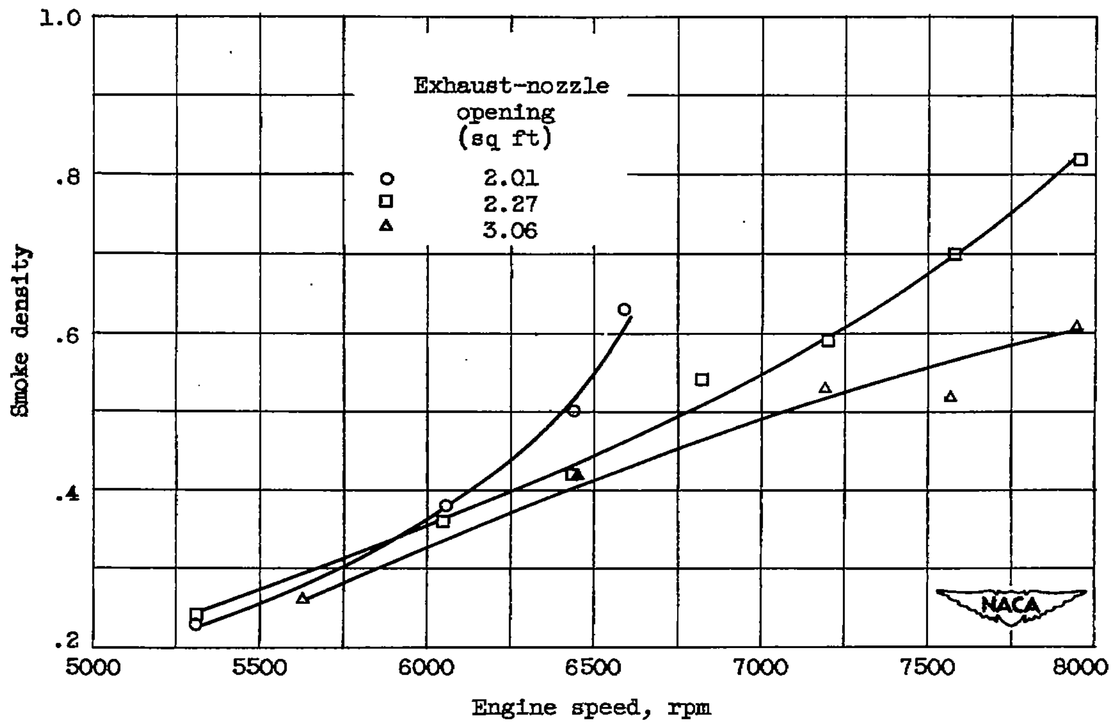

Figure 10. - Effect of engine speed and exhaust-nozzle opening on smoke density in full-scale engine operating at sea-level conditions. Fuel, MIL-F-5624A, grade JP-3.

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