NACA

RESEARCH MEMORANDUM

PERFORMANCE OF FOUR EXPERIMENTAL HIGH-BTU-PER-GALLON FUELS IN A SINGLE TURBOJET COMBUSTOR

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SUMMARY

Performance characteristics of four experimental hydrocarbon fuels having high volumetric energy contents were determined in a single tubular turbojet combustor. Carbon deposits, exhaust-gas smoke formation, and combustion efficiency were measured at conditions simulating operation of a 4-pressure-ratio engine at 20,000-foot altitude and zero flight speed. Carbon deposits and combustion efficiencies were also measured at conditions simulating a 7-pressure-ratio engine at sea level and a flight Mach number of 0.87. Additional efficiency tests were conducted with two of the experimental fuels at conditions simulating a 5-pressure-ratio engine at 56,000-foot altitude and a flight Mach number of 0.6. For comparison, similar performance data were obtained with MIL-F-5624B, grades JP-4 and JP-5 fuels.

The high-Btu-per-gallon fuels generally produced larger carbon deposits and more exhaust-gas smoke than did the JP-4 and JP-5 fuels. Data indicated that the use of a fuel-oil additive may reduce deposits with the experimental fuels to a tolerable level; the additive will not alleviate the exhaust-gas smoke problem, however.

Significant differences in combustion efficiency among the fuels were observed only at the high-altitude (56,000 ft) cruise condition. At this condition, efficiencies with JP-4 fuel were slightly higher than those with JP-5 fuel, and significantly higher than those with the experimental fuels. Although not investigated, modifications in the design of the combustor and the fuel injector would be expected to improve performance of the combustor with the experimental fuels.

INTRODUCTION

The range of an aircraft is markedly affected by the energy content of its fuel. A fuel releasing the most energy from the smallest and lightest package would provide maximum range. Unfortunately, for hydrocarbon fuels that are available in large quantities, an increase in energy content per unit volume is accompanied by a decrease in energy content per unit weight. The relative importance of volume and weight of the fuel load to aircraft performance will therefore determine the required compromise in heating values.

Aircraft that are being developed for high-speed flight may, in some applications, be volume limited; that is, because of external drag, the volume of the aircraft components may be more critical than their weight. In such cases it would be desirable to use fuels with high-volumetric-energy contents. Three hydrocarbon fuels having high-volumetric-energy contents were tested in a single turbojet combustor (ref. 1); they gave reduced combustion efficiency, poorer altitude ignition characteristics, and increased carbon deposits, compared with conventional jet fuel. These fuels were pure hydrocarbons that would not be available in sufficient quantities for large-scale use. 3857

The Wright Air Development Center procured three high-volumetric-energy-content fuel blends having greatly improved potential availabilities. The volumetric-energy contents of these fuels were from 10 to 18 percent greater than MIL-F-5624B, grade JP-4 fuel. Combustion performance investigations with these fuels and with a No. 2 furnace oil having a 9-percent-higher volumetric-energy content than JP-4 fuel were conducted at the NACA Lewis laboratory in a single tubular turbojet combustor. The results are presented herein. Combustion efficiencies were determined at inlet-air conditions simulating operation in a 5-pressure-ratio engine at 56,000-foot altitude, 85-percent rated engine speed, and 0.6 flight Mach number. Combustor carbon deposits were measured at the following two simulated engine operating conditions: (I) 4-pressure-ratio engine, 90-percent rated engine speed, 20,000-foot altitude, and zero flight Mach number; and (II) 7-pressure-ratio engine, rated engine speed, sea level, and 0.87 flight Mach number. Limited data obtained with a fuel additive that reduced deposits of fuels in previous tests are reported. In addition to combustion-chamber deposits, exhaust-gas smoke concentrations were measured at condition I.

The data obtained with the four experimental fuels are compared with similar data obtained with MIL-F-5624B, grades JP-4 and JP-5 fuels.

FUELS

The fuels tested included experimental high-Btu-per-gallon fuels A, B, and F54-19 procured by the Wright Air Development Center, a No. 2 furnace oil used at the Lewis laboratory for carbon-deposit studies, two JP-4 fuels, and two JP-5 fuels.

Analyses of the fuels are presented in table I. The volumetric and gravimetric heating values are compared in figure 1. Included in this figure are the heating values of three high-Btu-per-gallon pure hydrocarbon fuels, tetralin, decalin, and monomethylnaphthalene, reported in reference 1. Fuels tested in the present investigation had volumetric heating values to 143×10^3 Btu per gallon, or approximately 18 percent higher than that of JP-4 fuel. A decrease of about 7 percent in Btu per pound accompanied this increase.

The two JP-4 fuels varied in their physical and chemical properties; NACA fuel 52-288 was a "high quality" JP-4 fuel, NACA fuel 52-76, a "minimum quality" JP-4 fuel. The two JP-5 fuels were very similar (see table I).

APPARATUS AND PROCEDURE

Carbon-deposit and combustion-efficiency tests were conducted with the J33 liner and dome assembly shown in figure 2. This combustor was designed for, and is currently being operated with MIL-F-5624B, grade JP-4 fuel. No modifications to the combustor or the fuel injector were made for tests with the experimental fuels. The combustor liner and dome assembly was installed in the facility shown in figure 3(a) for carbon-deposit and combustion-efficiency tests at relatively low inlet-air pressures and temperatures. A combustor liner and dome assembly from the same model engine was installed in the facility shown in figure 3(b) for carbon-deposit tests at a higher inlet-air pressure and temperature condition.

Air-flow and fuel-flow rates to the combustors were measured with square-edged orifice plates (installed according to ASME specifications) and calibrated rotameters, respectively. Combustor-inlet and -outlet total pressures were measured with total-pressure probes connected to either manometers or strain-gage pickups. Combustor-inlet and -outlet temperatures were measured with bare-wire iron-constantan, chromel-alumel, or platinum-rhodium - platinum thermocouple probes connected to self-balancing potentiometers. More complete details concerning the test installations and instrumentation are presented in references 2 and 3.

Carbon Formation

Carbon-deposit tests were conducted at the following combustor operating conditions:

	Condition	
	I	II
Inlet-air pressure, lb/sq in. abs	26.5	141.0
Inlet-air temperature, $^{\circ}F$	271	640
Air-flow rate, lb/sec	2.87	12.0
Outlet-gas temperature, $^{\circ}F$	1100	1800
Combustor reference velocity, ft/sec	110	130
Run time, hr	4	1.5
Simulated full-scale engine conditions:		
Pressure ratio	4	7
Engine speed, percent rated	90	100
Altitude, ft	20,000	0
Flight Mach number	0	0.87

The combustor reference velocities listed in the table are based on the maximum cross-sectional area of the combustor, the weight flow of air, and the density of the air at combustor-inlet conditions. The run time was decreased to $1\frac{1}{2}$ hours at condition II because of limited life of the combustor liner at this condition.

The four high-Btu-per-gallon fuels, one JP-4 fuel (52-76), and one JP-5 fuel (53-87) were tested at condition I. Only one of the high-Btu-per-gallon fuels B (54-224), one JP-4 fuel (52-288), and one JP-5 fuel (54-35) were tested at condition II. Limited tests were conducted at both conditions to determine the effectiveness of a fuel-oil additive in reducing deposition tendencies of high-Btu-per-gallon fuels. The additive chosen contained lead and copper and previously gave the largest reduction in deposits with No. 2 furnace oil (ref. 4). This additive (additive A, ref. 4) was blended into fuels B (NACA fuel 54-224) and F54-19 (NACA fuel 54-225) in a concentration of 1 gallon of additive per 1000 gallons of fuel for tests at condition 1. The same concentration, of the same additive, was tested in JP-5 fuel 54-35 at condition II. The fuels used for these additive tests were chosen for their high carbon-forming tendencies.

Prior to each test run the combustor liner and dome assembly, including the ignition plug, was cleaned with rotating brushes and weighed on a torsion-type balance. After the prescribed period of operation, the assembly was reweighed; the difference in weight, plus the weight of any carbon collected from the fuel nozzle tip, is the amount of carbon deposit reported herein.

The relative concentration of exhaust-gas smoke formed with each fuel was measured at condition I. Exhaust-gas samples were withdrawn from a single total-pressure probe, which was centrally located in the exhaust duct, through the "smoke meter" described in reference 5. The amount of carbon deposited on a paper filter disk was considered to be representative of the concentration of smoke in the exhaust gases. The optical densities of the smoke-covered filter disks from the smoke meter were determined with a transmission densitometer. The differences in optical density readings between the smoke-covered and clean filters are reported herein as "smoke density".

Combustion Efficiency

Combustion efficiencies were calculated for the carbon-formation tests at conditions I and II. In addition, more detailed studies of combustion efficiency were conducted with JP-4, JP-5, and two of the high-Btu-per-gallon fuels B and F54-19 (54-224 and 54-225) at the following combustor operating conditions:

	Condition	
	III	IV
Inlet-air pressure, lb/sq in. abs	7.37	7.37
Inlet-air temperature, °F	230	230
Air-flow rate, lb/sec	0.75	0.966
Combustor reference velocity, ft/sec	98	126

These inlet-air conditions simulated operation of a 5-pressure-ratio engine at 56,000-foot altitude, 85-percent rated engine speed, and a flight Mach number of 0.6. The air velocity at condition III is representative of velocities in current production engines; that at condition IV, of velocities in engines having higher capacity compressors.

At conditions III and IV combustor performance data were recorded over a range of outlet-gas temperatures. Combustion efficiencies were computed, by the method of reference 6, as the ratio of the actual to the theoretical increase in enthalpy across the combustor (stations 1 to 2, fig. 3) multiplied by 100. The enthalpy of the exhaust gases was based on the arithmetic mean of 16 thermocouple indications at station 2.

RESULTS

Carbon Formation

Carbon-deposit data obtained with the test fuels are presented in table II. The data for the JP-4 fuels and the No. 2 furnace oil were obtained in previous investigations (refs. 4, 7, and 8). At condition I the four high-Btu-per-gallon fuels gave larger deposits than did the

JP-4 and JP-5 fuels. Reproducibility with the high-Btu-per-gallon fuel F54-19 was extremely poor, the deposits varying from 18.1 to 46.7 grams. Deposits obtained with fuels B and A were found, by spectroscopic analysis, to contain metallic compounds, principally lead (table II). At condition II, only one of the high-Btu-per-gallon fuels, B, was tested. The deposits were about the same as those obtained with the "high quality" JP-4 fuel (52-288). There was no visual indication that the fuel B deposits at this condition contained metallic compounds; spectroscopic tests of the deposits were not conducted.

Deposit data with fuels containing an organo-metallic fuel-oil additive are presented in table III. The additive tests were conducted at each condition with fuels giving the largest deposits at that condition. At condition I only a minor reduction was obtained with fuel B. Somewhat larger reductions were obtained with the high-Btu-per-gallon fuel, F54-19. The significance of this reduction is questionable, however, because of the wide variation in deposit values obtained with the fuel containing no additive. The largest reductions were observed with JP-5 fuel 54-35 and No. 2 furnace oil (data of ref. 4).

Exhaust-gas smoke data were obtained only at condition I; these data are presented in table IV. The highest smoke concentration was observed with fuel F54-19, which had the highest Btu per gallon. The lowest smoke concentration was observed with fuel A, which had an intermediate value of Btu per gallon. No smoke data were obtained with the JP-4 fuels. The effect of the additive on smoke concentration was not consistent for the two fuels tested; the effect in any case was not large.

Combustion Efficiency

The data obtained in combustion-efficiency tests with JP-4, JP-5, and two experimental high-Btu-per-gallon fuels at conditions III and IV are presented in table V. Combustion efficiencies at conditions III and IV are plotted against temperature rise across the combustor in figure 4. At condition III maximum combustion efficiencies of about 87 to 90 percent were obtained at a temperature rise of about 1200° F. The increased air velocity at condition IV reduced efficiencies significantly and caused flame blow-out at values of temperature rise around 1150° to 1250° F. Peak efficiencies at condition IV were obtained at lower temperature-rise values.

Combustion performance data recorded during the carbon-deposit tests at conditions I and II are also presented in table V. At condition I data were recorded 5 minutes after the start of the test and at the end of the test. At the high-pressure condition II reliable data were obtained only at the beginning of the test run because of rapid deterioration of the exhaust-gas temperature probes. The data show that, at these higher combustor pressures, differences among the fuels are diminished. At the intermediate pressure (condition I) JP-4 and JP-5 fuels gave efficiencies that were 3 to 7 percent higher than those of the high-Btu-per-gallon fuels. There was no consistent change in efficiency with run time, or, hence, with carbon build-up. At the highest pressure condition II the spread in efficiency was about 6 percent with the high-Btu-per-gallon fuel B giving the highest efficiency.

DISCUSSION

Carbon Formation

Large increases in the volumetric energy content of hydrocarbon jet fuels are generally accompanied by increases in the polycyclic hydrocarbon content. In the investigation of reference 1, polycyclic monomethylnaphthalene formed 26 times as much carbon as did AN-F-58, grade JP-3, fuel, which probably contained very little polycyclic material. Also, relations established between deposits and the NACA K factor (ref. 9) predict that the inclusion of polycyclic hydrocarbons with their higher boiling temperatures and their lower hydrogen-carbon ratios will result in larger deposits. It is not surprising, then, that the fuels with higher Btu per gallon tested in this investigation gave larger deposits. In figure 5 carbon deposits at condition I are plotted against volumetric energy content of the fuel. Experimental fuel F54-19 had the highest Btu per gallon, about 18 percent higher than JP-4 fuel, and gave the largest deposits; they were about four times those obtained with a "minimum quality" JP-4 fuel. Increased deposits were not caused directly by increased Btu per gallon, but rather by accompanying changes in volatility and composition of the fuel. As noted in table II, the deposits with fuels A and B contained lead, which may mean, from previous studies (ref. 4), that the deposits with these fuels were erroneously low. The lead contamination may have resulted from the use of storage or shipping containers used previously for leaded gasoline. At condition II one of these fuels, B, with a 12-percent increase in Btu per gallon, gave less deposits than did either JP-4 or JP-5 fuels. The deposits with this fuel at condition II did not appear to contain metal contaminants. A similar inconsistency noted in reference 8 was attributed to one of two factors: (1) the high inlet-air temperature at condition II may have vaporized the lead contaminant (probably tetraethyl lead) so rapidly that no significant quantity reached the liner walls; or (2) only a portion of the fuel shipment may have been contaminated. Since the addition of an organo-metallic additive to JP-5 fuel (54-35) did not produce any visual evidence of metal in the deposits at condition II, the first factor appears more likely.

The process by which lead and other metallic compounds reduce deposits is not known; the beneficial effects may not require that the material actually reach the walls.

The addition of an organo-metallic additive reduced deposits in all cases. At condition I the largest reduction (74 percent) occurred with the No. 2 furnace oil (ref. 8). With the additive, this fuel, which has a 9-percent higher Btu per gallon than JP-4 fuel, gave less deposits than did the JP-4 fuel. The additive was considerably less effective with the other high-Btu-per-gallon fuels. Reduced effectiveness with experimental fuel B would be expected since this fuel showed evidence of lead contamination in tests without the additive. Even without contamination, however, variations in the effectiveness of the additive with different base fuels have been observed (ref. 4). At condition II the additive reduced deposits with JP-5 fuel (54-35) about 78 percent, the largest reduction obtained in any of the tests (table III). With the additive the JP-5 fuel gave considerably less carbon than did JP-4 without additive.

Average deposits obtained at condition I are plotted against three empirical fuel factors in figure 6. These factors, smoke-volatility index (SVI), smoke point, and NACA K factor (table I), have been used in previous investigations to correlate carbon deposits (ref. 8). The solid symbols in figure 6 denote deposits that showed evidence of metal contamination. The correlation curves from reference 8 are presented in figure 6; these curves satisfactorily correlated deposit data obtained at condition I with 20 JP-3 and JP-4 fuels. The correlation curve for smoke point applies reasonably well to the data obtained with the high-Btu-per-gallon fuels (fig. 6(b)). The curves for SVI and NACA K factor (figs. 6(a) and (c)), however, do not; deposits from the high-Btu-per-gallon fuels were lower than would be predicted. Separate K factor and SVI curves are faired through the high-Btu-per-gallon fuel deposits in figures 6(a) and (c); deposits that showed evidence of contamination were not considered. While these curves appear to correlate the high-Btu-per-gallon fuel data reasonably well, the data are very limited.

Examination of deposit data at condition II for the JP-5 and experimental high-Btu-per-gallon fuels indicated no satisfactory correlations with the fuel factors. Similar results were obtained in reference 8 with JP-3 and JP-4 fuels. As noted in reference 8, deposits at condition II form in less regular patterns within the combustor and are not as reproducible as those formed at condition I.

The relative exhaust-gas smoke densities observed with the JP-5 fuel and the experimental high-Btu-per-gallon fuels varied from 0.12 to 0.40. Experimental data relating these densities to the visual intensity of smoke in engine exhaust gases are not available. It is known that production JP-4 fuels produce excessive smoke in some current jet engines. The smoke densities of a series of JP-4 fuels, measured in the same test facility and at the same conditions as used for the present investigation, varied from 0.05 to 0.15 (ref. 8). Since smoke densities with JP-5 fuel and three of the high-Btu-per-gallon fuels were considerably greater, 0.16 to 0.43, it may be assumed that these fuels will seriously aggravate the smoke problem. Additives that effectively reduced carbon deposits in this and in a previous investigation (ref. 4) have not shown any promise of alleviating the exhaust-gas smoke problem. It may be necessary, then, to rely on combustor design modifications for reducing exhaust-gas smoke with the high-Btu-per-gallon fuels. One such modification is described in reference 5.

Combustion Efficiency

Combustion efficiencies of the test fuels were significantly different only at inlet-air conditions simulating high altitude (56,000 ft) and 85-percent engine speed operation (conditions III and IV). Their efficiencies at these conditions are compared in figure 7. At condition III (fig. 7(a)) the efficiencies varied by about 8 percent at low temperature rise and by only 3 percent at maximum efficiency conditions. At condition IV (fig. 7(b)) the variation in efficiency among the fuels was again about 8 percent at low temperature rise, but was considerably greater at high temperature rise.

At velocity conditions representative of current operation (condition III) the highest combustion efficiencies were obtained with JP-4 fuel. The efficiency with this fuel was about 84 percent at the 680° F temperature rise required for 85-percent engine speed operation. At these same conditions the two experimental high-Btu-per-gallon fuels gave efficiencies 5 to 9 percent lower than JP-4 fuel. In reference 1 AN-F-58 fuel (equivalent to MIL-F-5624B, grade JP-3) operated with an efficiency of about 81 percent in the same combustor at similar conditions (altitude, 56,000 ft, 90-percent rated engine speed, and a flight Mach number of 0.6). The efficiency of the high-Btu-per-gallon fuel tested in reference 1, monomethylnaphthalene, was 25 percent lower at the same operating conditions. Thus, experimental fuel F54-19 gave considerably higher efficiencies. In addition, its volumetric energy content was about the same as that of monomethylnaphthalene, and its gravimetric energy content was 3 percent higher.

Some consideration has been given to the use of JP-5 fuel in future jet-powered aircraft. As seen in figure 1 this fuel has a significantly higher Btu per gallon accompanied by little, if any, reduction in Btu per pound. In addition, its lower volatility would result in less evaporation loss at high altitudes. At the high altitude condition III (fig. 7(a)) and at the temperature rise required for 85-percent engine speed operation, JP-5 fuel gave efficiencies only 3 percent lower than JP-4.

At values of temperature rise that would be required for rated engine speed operation at condition III (about 1200° F), the efficiencies with the JP-4 fuel, the experimental fuels, and the JP-5 fuel were within 3 percent of each other. At rated engine speed the combustor-inlet pressures would also be somewhat higher, and the differences among the fuels would tend to be even less.

Increasing combustor air velocity by 30 percent (condition IV) had a detrimental effect on combustion efficiency and flame blow-out limits. The poor performance at high values of temperature rise indicates an over-rich mixture condition in the primary combustion zone. As would be expected, this was particularly severe with the most volatile fuel (JP-4). The higher velocities probably altered the distribution of air between the primary and secondary zones of the combustor.

The combustor used in this investigation was not designed for the high-boiling-temperature fuels tested, nor was it designed for the high air velocity at condition IV. Design modifications to the combustor and to the fuel injector would be expected to improve performance characteristics. Data of reference 10, obtained with JP-4 fuel and a high-Btu-per-gallon hydrocarbon (monomethylnaphthalene) show that the use of a vaporizing-type combustor tends to diminish effects of fuel properties on efficiency. An experimental vaporizing combustor that provided excellent combustor performance characteristics is described in reference 11. In this combustor, the fuel is preheated and vaporized in a flame-immersed heat exchanger and sprayed in a conventional manner from the upstream end of the combustor. This combustor may improve combustion efficiencies with the high-Btu-per-gallon fuels considerably.

A problem that may be encountered in vaporizing combustors operating on high-Btu-per-gallon fuels is coke formation within the vaporizing tubes. In reference 12, a single-tube Mamba vaporizing combustor was operated with a fuel (W-42) having properties similar to those of fuel F54-19. Prohibitive amounts of deposits were formed within the vaporizing system. While the severity of this problem will depend upon the design at the vaporizing system, an increased tendency toward deposition with the high-Btu-per-gallon fuels is expected.

SUMMARY OF RESULTS

Carbon formation and combustion efficiencies were determined with JP-4 and JP-5 fuels and four experimental high-volumetric-energy-content fuels in a single tubular turbojet combustor. The following results were obtained:

1. In general, larger carbon deposits were obtained with the high-Btu-per-gallon fuels than with the JP-4 and JP-5 fuels. A single curve

correlated deposits of JP-3, JP-4, JP-5, and the experimental high-Btu-per-gallon fuels with smoke points of the fuels. Significant reductions in carbon deposits were obtained with the addition of a commercial fuel-oil additive.

2. The JP-5 fuels and three of the four experimental high-Btu-per-gallon fuels produced more exhaust-gas smoke than did JP-4 fuel in previous tests. No consistent effect of the fuel-oil additive on smoke was observed.

3. At conditions simulating low-altitude engine operation in carbon-deposit tests, there were no significant differences in combustion efficiency among the test fuels. At high-altitude (56,000 ft) cruise conditions, efficiencies with JP-4 fuel were about 3 percent higher than those with JP-5 fuel, and 5 to 9 percent higher than those with the experimental fuels.

CONCLUDING REMARKS

Experimental high-volumetric-energy-content fuels generally gave larger carbon deposits, more exhaust-gas smoke, and lower combustion efficiencies at severe operating conditions than JP-4 or JP-5 fuels. However, the turbojet combustor used for these tests was not designed for the kinds of fuels included in the investigation. It is believed that the observed performance deficiencies may be reduced to a tolerable level by design modifications to the combustor and the use of fuel additives, or both.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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TABLE I. - FUEL ANALYSES

	JP-4 fuel		JP-5 fuel		No. 2 furnace oil	A	B	F54-19
NACA fuel	52-288	52-76	53-87	54-35	53-193	54-232	54-224	54-225
A.S.T.M. distillation, D86-52, °F								
Initial boiling point	139	142	370	360	374	390	490	430
Percent evaporated								
5	224	201	387	373	422	417	510	462
10	253	220	394	382	434	427	510	468
20	291	244	402	399	462	439	516	474
30	311	263	416	409	484	449	524	480
40	324	283	424	419	504	459	530	488
50	333	304	435	429	520	470	536	494
60	347	324	440	439	534	482	544	500
70	363	348	452	449	548	496	554	512
80	382	381	465	459	564	515	566	526
90	413	438	484	473	591	542	586	552
End point	486	494	532	502	627	592	619	612
Residue, percent	---	1.2	1.4	1.0	1.5	1.3	1.5	1.0
Loss, percent	---	0.8	0	1.0	0	0.2	0	0
Freezing point, °F	<-76	<-76	---	-48	-13	<-76	-72	-14
Reid vapor pressure, lb/sq in.	2.7	2.3	---	---	---	---	---	---
Aromatics, percent by volume	10	24	13.8	13.7	31.5	30.0	39.4	86.0
Bromine number	--	--	----	----	7.8	----	----	----
Accelerated gum, mg/100 ml	--	3	----	5	48	30	117	406
Existent gum, mg/100 ml	--	1	----	1	7	10	31	130
Hydrogen-carbon ratio[a]	0.168	0.156	0.162	0.160	0.145	0.148	0.144	0.099
Heat of combustion[b], Btu/lb	18,675	18,475	18,625	18,600	18,400	18,350	18,325	17,400
Heat of combustion, Btu/gal $\times 10^{-3}$	121.0	121.4	126.9	126.6	132.2	133.0	135.9	142.8
Aniline-gravity product	6950	5133	6430	6271	4402	3776	3517	------
Specific gravity, 60°/60° F	0.776	0.787	0.816	0.815	0.861	0.868	0.888	0.983
Gravity, °A.P.I.	50.8	48.2	42.0	42.2	32.8	31.6	27.8	12.5
Aniline point, °F	136.8	106.5	153.1	148.6	134.2	119.5	126.5	<20
Smoke-volatility index[c]	68.3	51	30.5	32.1	13.0	13.3	11.0	4.5
Smoke point, mm	[d]32.0	[d]16.5	[d]23.1	[e]23.3	[e]12.0	[e]12.0	[e]11.0	[e]4.5
Flash point, °F	----	----	170	170	----	160	175	255
NACA K factor[f]	278	316	335	340	423	398	434	518

[a] Determined by combustion furnace.

[b] Estimated from aniline-gravity constant.

[c] Smoke volatility index = Smoke point + 0.42 (volume percent of fuel boiling under 400° F).

[d] Determined by modified Davis factor lamp (ref. 13).

[e] Determined by method 2107 of specification VV-L-791.

[f] Ref. 9.

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TABLE II. - SINGLE COMBUSTOR DEPOSITS

Fuel type	NACA fuel	Carbon deposits, g			Average deposits, g	Average variation, percent (a)	Remarks
Condition I							
JP-4	52-76	----	----	----	7.4	--	(b)
JP-5	53-87	5.3	5.0	----	5.2	3	---
No. 2 furnace oil	53-193	20.7	20.6	20.1	20.5	1	(c)
B	54-224	10.0	14.2	----	12.1	17	(d)
F54-19	54-225	46.7	24.1	18.1	29.6	38	---
A	54-232	9.5	8.8	----	9.2	4	(e)
Condition II							
JP-4	52-288	3.3	2.4	----	2.9	16	(f)
JP-5	54-35	4.3	4.6	----	4.5	3	
B	54-224	2.7	2.2	----	2.5	10	

[a] Arithmetical average percent variation of individual carbon deposit values from average deposit.

[b] Data from ref. 7.

[c] Data from ref. 4.

[d] Gray, brown, and yellow deposits. Spectroscopic analysis indicated high concentration of lead, with some copper and magnesium.

[e] Dark gray deposits. Spectroscopic analysis indicated high concentration of lead with some iron, zinc, and silicon.

[f] Data from ref. 8.

TABLE III. - DEPOSITS WITH FUELS CONTAINING ADDITIVE[a]

Fuel type	NACA fuel	Condition	Carbon deposits, g	Average deposits, g	Average variation, percent (b)	Average deposit reduction, percent of base fuel deposit
B	54-224	I	[c]10.1	[c]10.1	--	17
F54-19	54-225	I	[d]22.6	[d]22.6	--	24
No. 2 furnace oil	53-193	I	[e]4.9,[e]5.6	[e]5.3	[e]7	[e]74
JP-5	54-35	II	0.7,1.2	1.0	25	78

[a] Additive A (ref. 4), 1 gal/1000 gal of base fuel.

[b] Arithmetical average percent variation of individual carbon deposit values from arithmetical average deposit.

[c] Brown deposits with some gray-green areas.

[d] Brownish cast to deposits.

[e] Data from ref. 4.

TABLE IV. - EXHAUST-GAS SMOKE DATA, CONDITION I

Fuel type	NACA fuel	Smoke density (a)	Average smoke density
JP-5	53-87	0.29,0.24,0.21, 0.26,0.28,0.18	0.24
No. 2 furnace oil	53-193	0.19,0.19,0.27, 0.21,0.16,0.32, 0.27,0.19,0.19	0.22
B	54-224	0.21,0.28,0.26, 0.25,0.22,0.22	0.24
B	54-224 and additive	0.15,0.17,0.16	0.16
F54-19	54-225	0.37,0.36,0.35 0.48,0.48,0.48, 0.39,0.29,0.41	0.40
F54-19	54-225 and additive	0.39,0.40,0.51	0.43
A	54-232	0.17,0.07,0.12, 0.15,0.12,0.12, 0.08,0.10,0.11	0.12

[a] Determined by method of ref. 5.

TABLE V. - COMBUSTION PERFORMANCE DATA

Run	Fuel type	NACA fuel	Condition	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet total temperature, $^{\circ}$F	Air-flow rate, lb/sec	Combustor reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, $^{\circ}$F	Mean temperature rise through combustor, $^{\circ}$F	Combustion efficiency, percent
1	JP-4	52-288	IV	14.9	226	0.970	126	86.2	0.0247	1365	1139	68
2				14.9	230	.967	126	61.2	.0176	1215	985	80
3				15.0	233	.962	125	48.0	.0139	1015	782	79
4				15.0	234	.966	126	41.4	.0119	900	666	77
5				15.0	236	.965	126	51.2	.0147	1090	854	82
6				15.0	236	.965	126	69.0	.0199	1295	1059	77
7	JP-4	52-288	III	15.0	232	0.750	98	63.1	0.0234	1595	1363	87
8				15.0	230	.751	97	50.6	.0187	1390	1160	90
9				15.0	230	.751	97	40.8	.0151	1180	950	89
10				15.0	228	.747	97	28.9	.0107	880	652	84
11				15.0	228	.751	97	37.6	.0139	1090	862	87
12				15.1	228	.750	96	48.4	.0179	1350	1122	90
13				15.0	228	.746	97	57.8	.0215	1505	1277	87
14	JP-5	54-35	IV	15.0	220	0.947	121	76.0	0.0223	1420	1200	79
15				15.0	226	.947	122	59.4	.0174	1240	1014	84
16				15.1	230	.946	122	48.7	.0143	1035	805	79
17				15.0	230	.946	123	40.6	.0119	880	650	76
18				15.0	232	.944	123	53.3	.0157	1120	888	80
19				15.1	235	.945	123	64.0	.0188	1320	1085	84
20	JP-5	54-35	III	14.9	231	0.752	98	67.2	0.0248	1660	1429	86
21				15.0	230	.751	97	52.8	.0195	1390	1160	86
22				14.8	230	.758	100	44.3	.0163	1200	970	85
23				14.8	230	.758	100	34.8	.0128	990	760	83
24				14.8	230	.757	100	31.0	.0114	890	660	80
25	JP-5	54-35	III	15.1	230	0.757	99	40.6	0.0149	1125	895	85
26				15.2	230	.759	97	49.0	.0179	1325	1105	88
27				15.0	231	.760	99	58.4	.0214	1505	1274	88
28				15.0	235	.757	99	52.4	.0192	1400	1165	88
29				15.1	233	.756	98	59.6	.0219	1525	1292	87
30	B	54-224	III	15.0	216	0.746	95	68.6	0.0256	1645	1429	85
31				15.0	218	.750	96	55.5	.0206	1445	1227	88
32				14.8	220	.754	98	45.4	.0167	1200	980	85
33				15.0	220	.747	96	37.4	.0139	1000	780	80
34				15.0	220	.751	96	33.9	.0125	885	665	75
35	B	54-224	III	15.0	220	0.747	96	41.9	0.0156	1110	890	82
36				15.0	221	.747	96	51.6	.0192	1350	1129	86
37				15.0	222	.748	96	62.0	.0230	1555	1333	87
38				15.0	224	.753	97	71.0	.0262	1715	1491	87
39	B	54-224	IV	15.1	230	0.966	125	76.0	0.0219	1410	1180	80
40				14.9	232	.962	126	62.0	.0179	1220	988	80
41				15.0	234	.964	126	51.3	.0148	1015	781	75
42				15.0	234	.966	126	45.8	.0132	890	656	70
43				15.0	234	.966	126	56.9	.0164	1120	886	78
44				15.0	235	.966	126	69.8	.0201	1320	1085	80
45				15.0	235	.964	126	90.2	.0260	1480	1245	72
46	F54-19	54-225	III	15.0	230	0.746	97	65.5	0.0244	1520	1290	83
47					230	.741	96	50.0	.0187	1310	1080	88
48					231	.746	97	43.2	.0161	1115	884	83
49					232	.753	98	34.2	.0126	915	683	80
50					231	.748	97	39.2	.0146	1050	819	84
51					230	.748	97	48.4	.0180	1225	995	84
52					230	.743	96	55.9	.0209	1415	1185	88

TABLE V. - Concluded. COMBUSTION PERFORMANCE DATA

Run	Fuel type	NACA fuel	Condition	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet total temperature, °F	Air-flow rate, lb/sec	Combustor reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent
53	F54-19	54-225	IV	15.0	235	0.970	127	76.5	0.0219	1300	1065	75
54				15.0	236	.963	126	62.7	.0181	1135	899	75
55				15.0	236	.964	126	48.7	.0140	885	649	68
56				15.1	236	.966	126	55.4	.0159	1015	779	73
57				15.0	236	.967	127	70.1	.0201	1210	974	74
[a]649	JP-4	52-76	I	53.9	271	2.87	110	127.3	0.0123	1135	864	97
[b]651										1130	859	96
[a]654										1135	864	97
[b]656										1135	864	97
[a]659										1130	859	96
[b]661										1120	849	95
[a]822	JP-5	53-87	I	53.9	271	2.87	110	127.3	0.0123	1170	899	100
[b]824										1120	849	94
[a]827										1125	854	95
[b]829										1130	859	95
[a]575	No. 2 furnace oil	53-193	I	53.9	271	2.87	110	127.3	0.0123	1040	769	86
[b]579										1050	779	87
[a]580										1080	809	90
[b]582										1080	809	90
[a]585										1085	814	91
[b]587										1090	819	92
[a]520	B	54-224	I	53.9	271	2.87	110	127.3	0.0123	1095	824	93
[b]522										1085	814	91
[a]525										1100	829	94
[b]527										1090	819	92
[a]545	F54-19	54-225	I	53.9	271	2.87	110	127.3	0.0123	1040	769	91
[b]547										1045	774	91
[a]550										1040	769	91
[b]552										1030	759	90
[a]555										1005	734	86
[b]557										1015	744	88
[a]530	A	54-232	I	53.9	271	2.87	110	127.3	0.0123	1085	814	91
[b]532										1100	829	93
[a]535										1085	814	91
[b]537										1085	814	91
[a]540										1130	859	97
[b]542										1080	809	91
[a]420	JP-4	52-288	II	286.9	640	12.03	130	778	0.0180	1750	1110	95
[a]422	JP-4	52-288		286.9	650	11.97	131	778	.0181	1750	1100	93
[a]425	JP-5	54-35		286.5	648	12.04	132	776	.0179	1725	1077	92
[a]428	JP-5	54-35		287.0	654	12.01	132	773	.0179	1740	1086	93
[a]413	B	54-224		286.5	650	12.05	132	790	.0182	1805	1155	99
[a]416	B	54-224		287.7	648	11.93	130	790	.0184	1805	1157	98

[a] 5 Min. from start of test.

[b] 240 Min. from start of test.

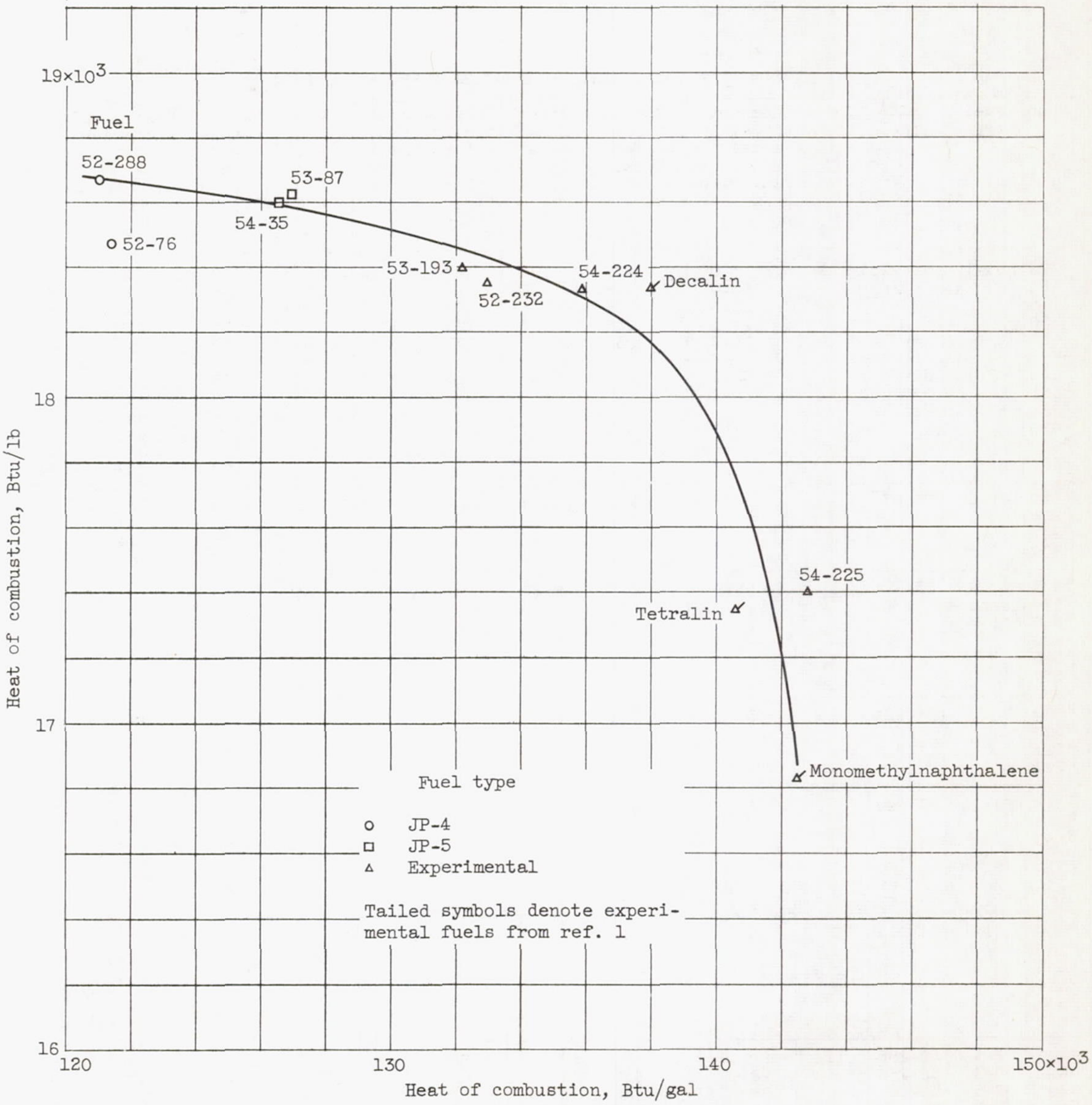

Figure 1. - Volumetric and gravimetric heating values of test fuels.

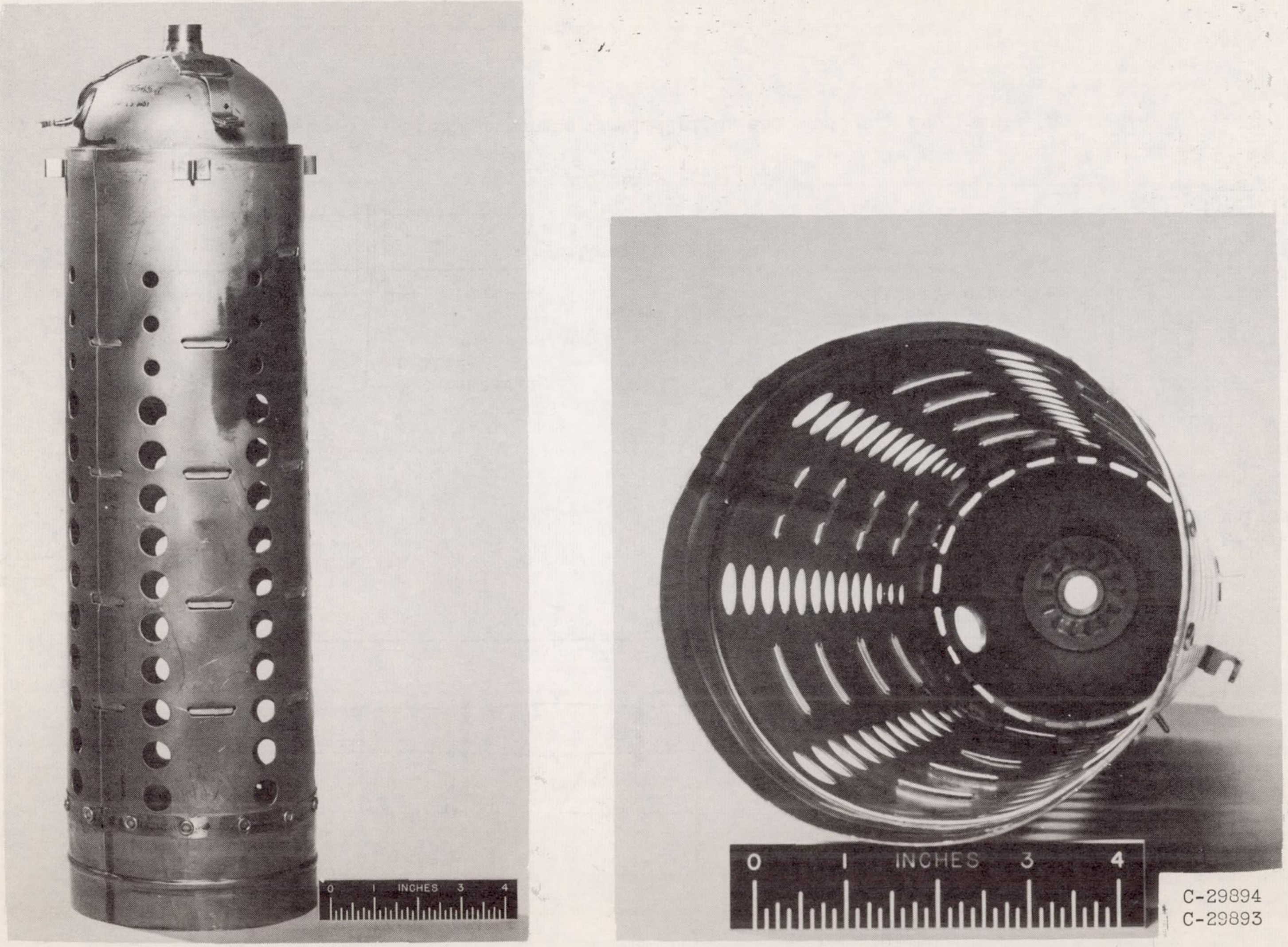

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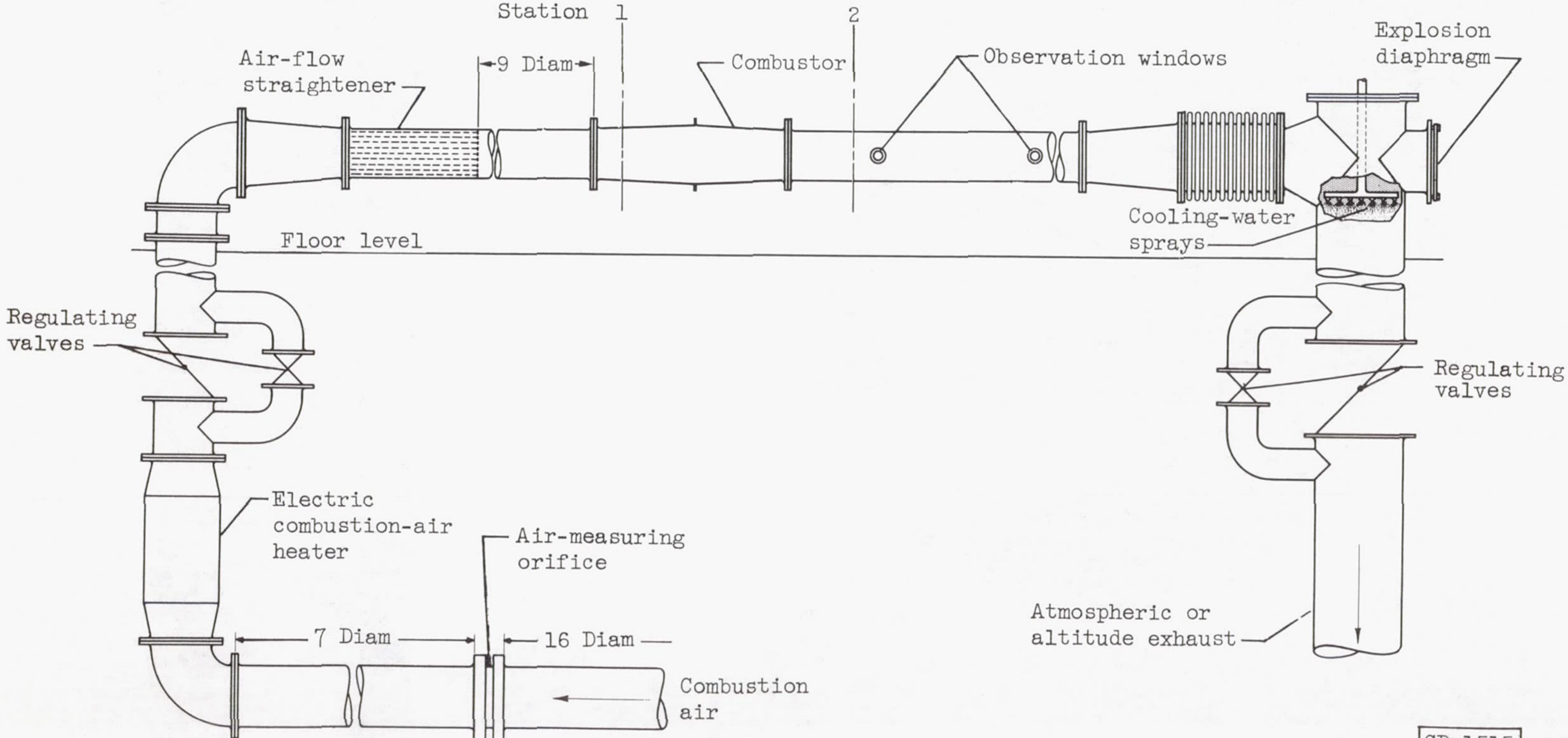
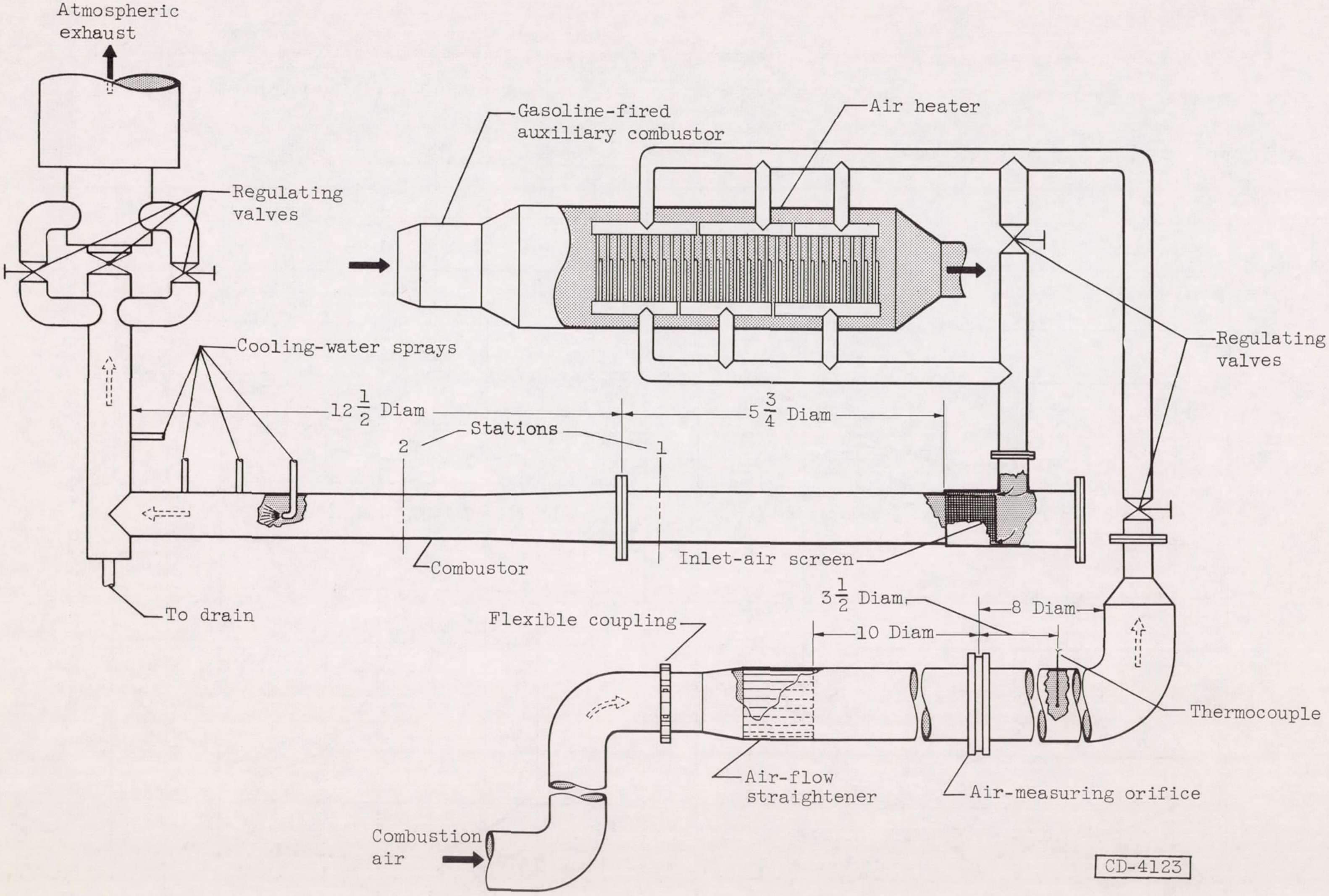
Figure 2. - Inner liner and dome of single combustor used in carbon-deposition and combustion-efficiency investigation.



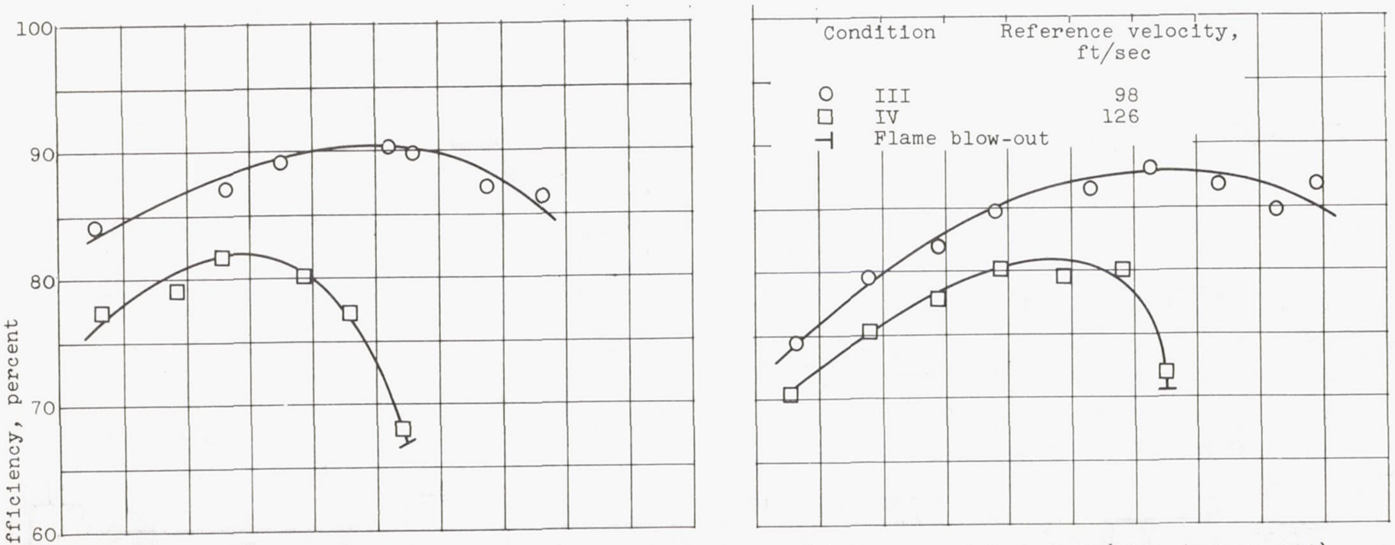
(a) Low-pressure facility.

Figure 3. - Single-combustor installation and auxiliary equipment.



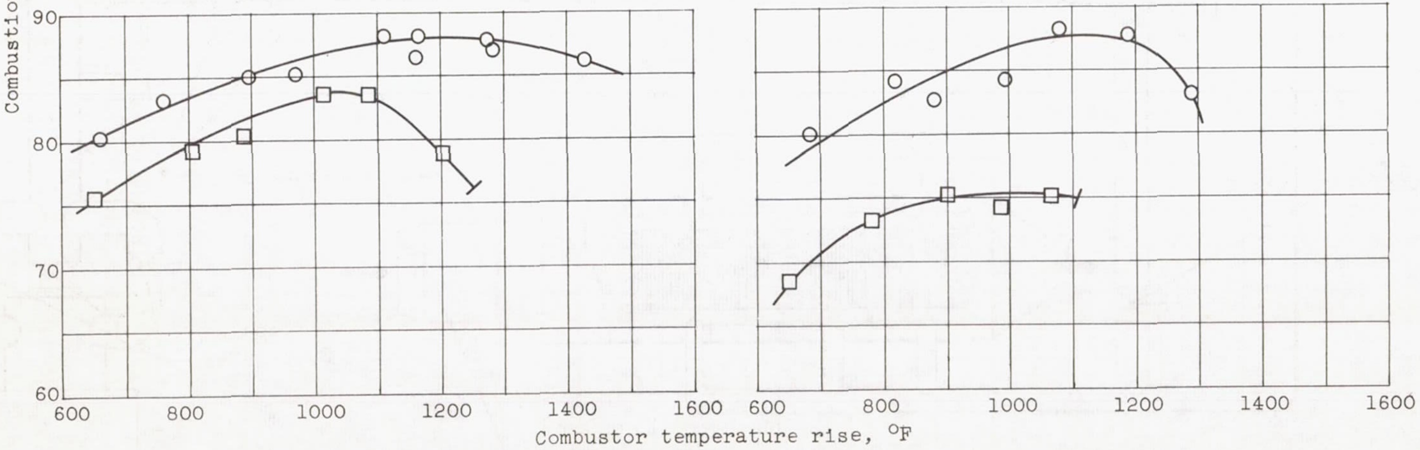
(b) High-pressure facility.

Figure 3. - Concluded. Single-combustor installation and auxiliary equipment.



(a) JP-4 fuel (NACA fuel 52-288).

(c) Experimental fuel B (NACA fuel 54-224).



(b) JP-5 fuel (NACA fuel 54-35).

(d) Experimental fuel F54-19 (NACA fuel 54-225)

Figure 4. - Variation of combustion efficiency with combustor temperature rise for JP-4, JP-5, and two experimental high-Btu-per-gallon fuels.

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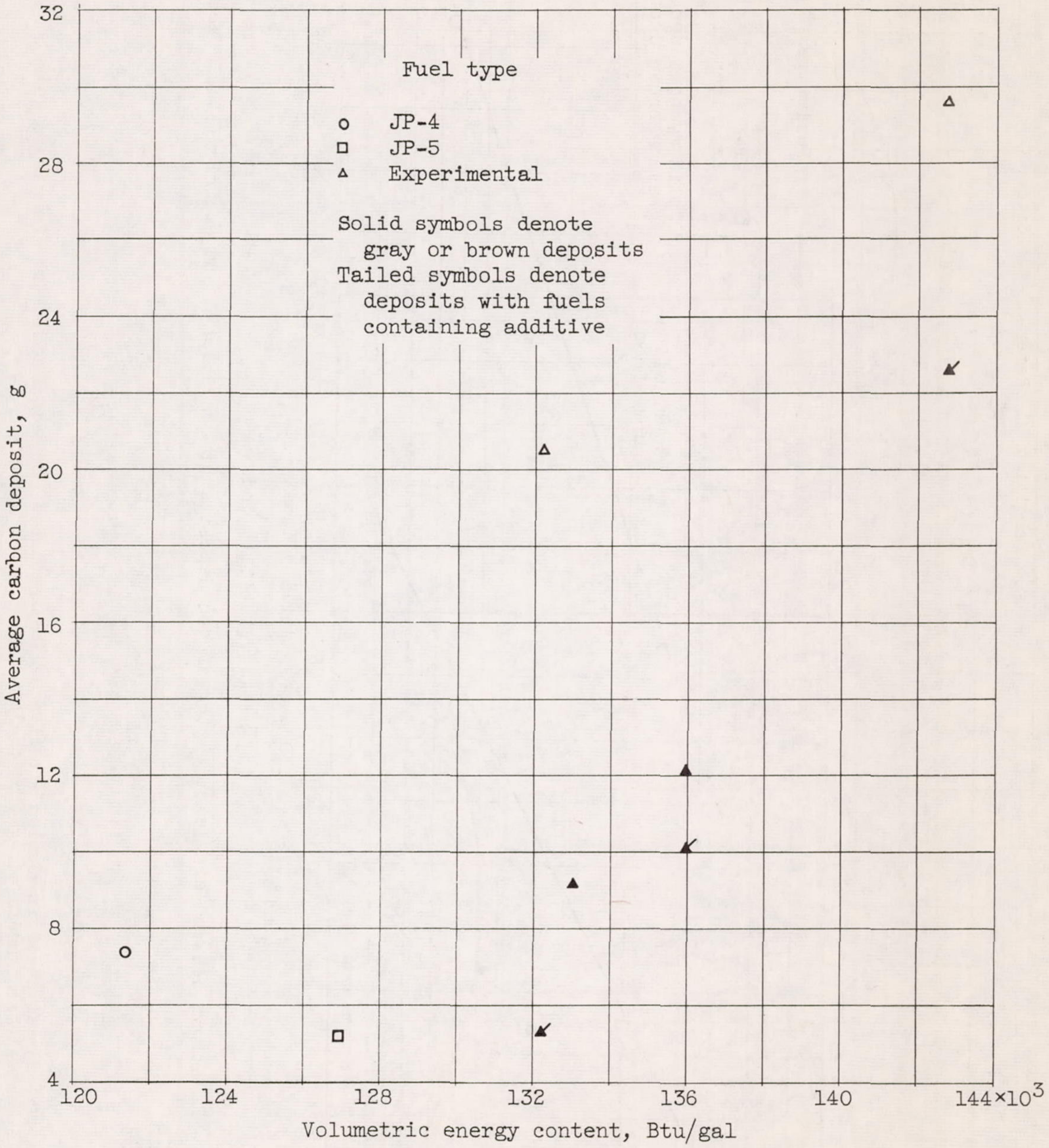
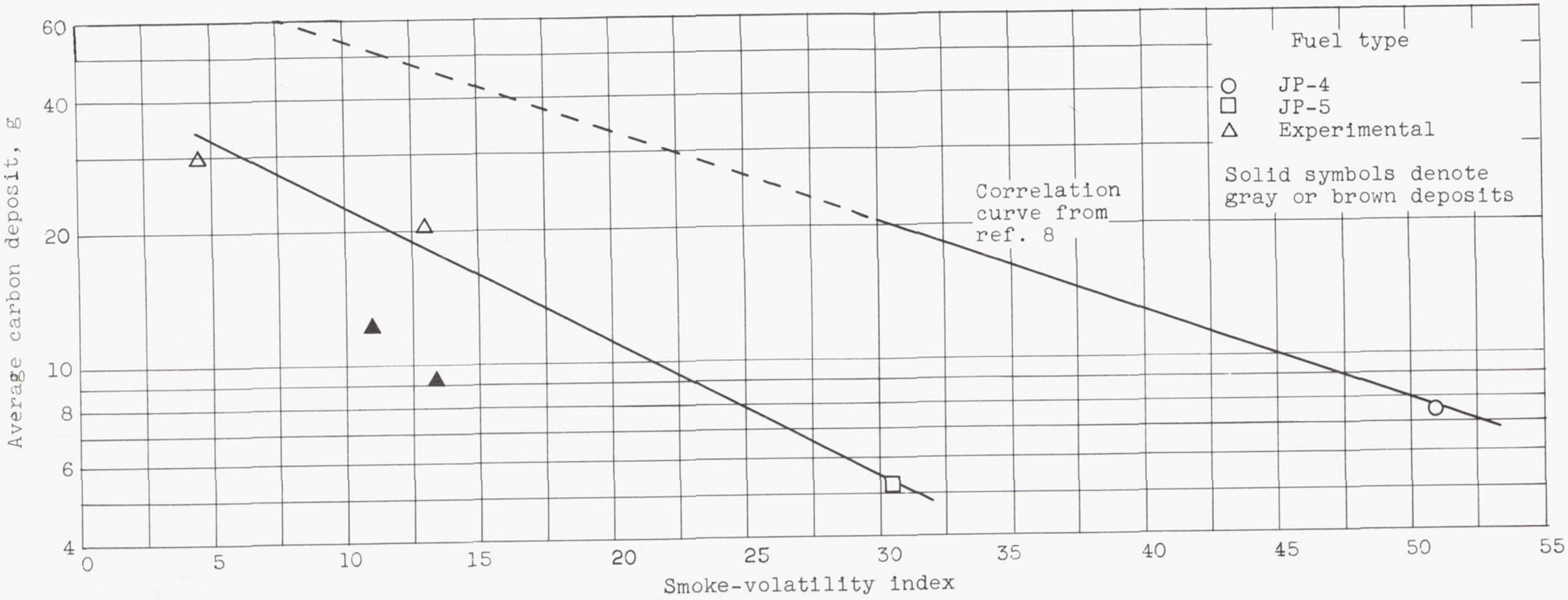
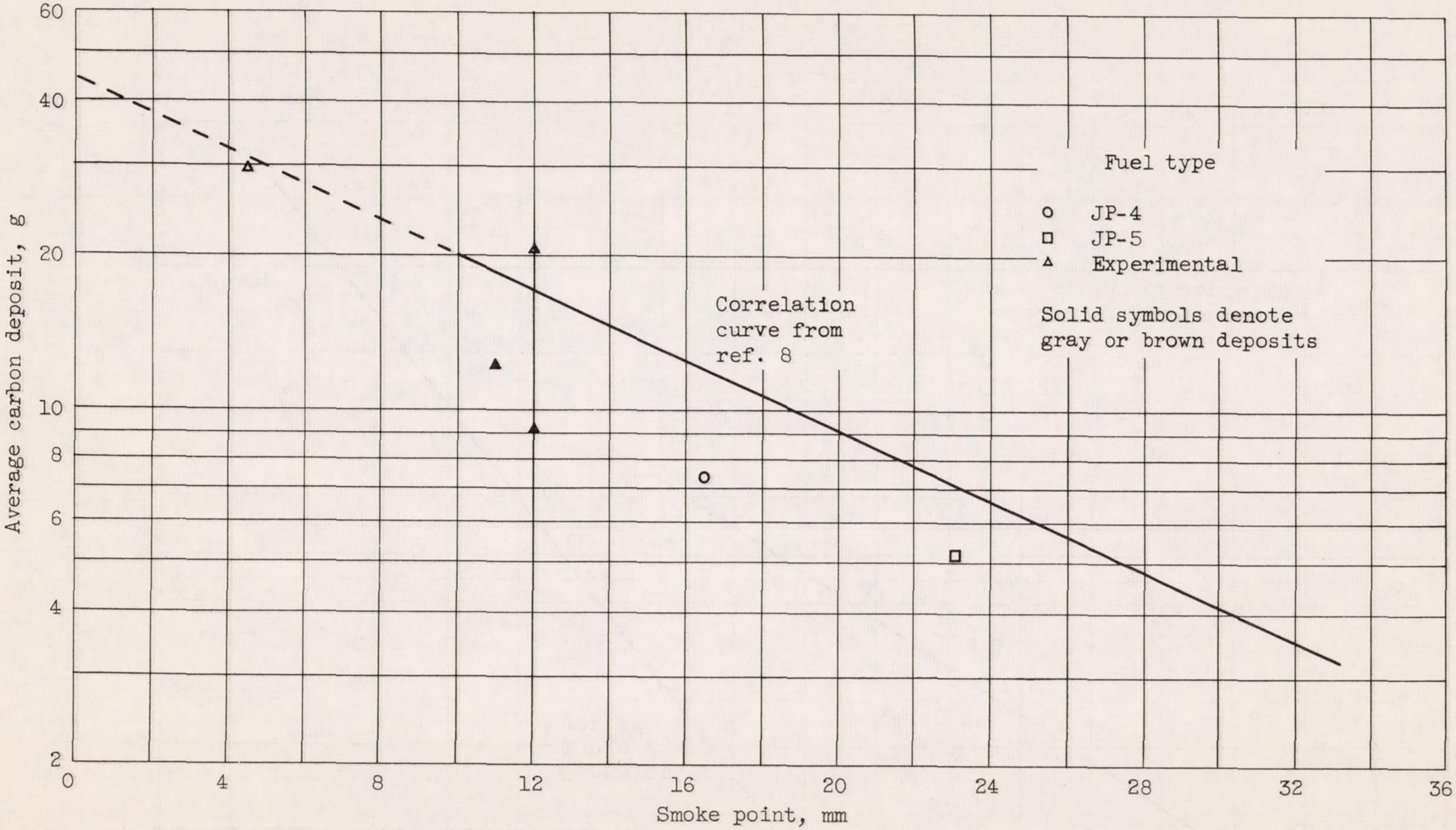


Figure 5. - Relation between single-combustor carbon deposits at condition I and volumetric energy contents of fuels.



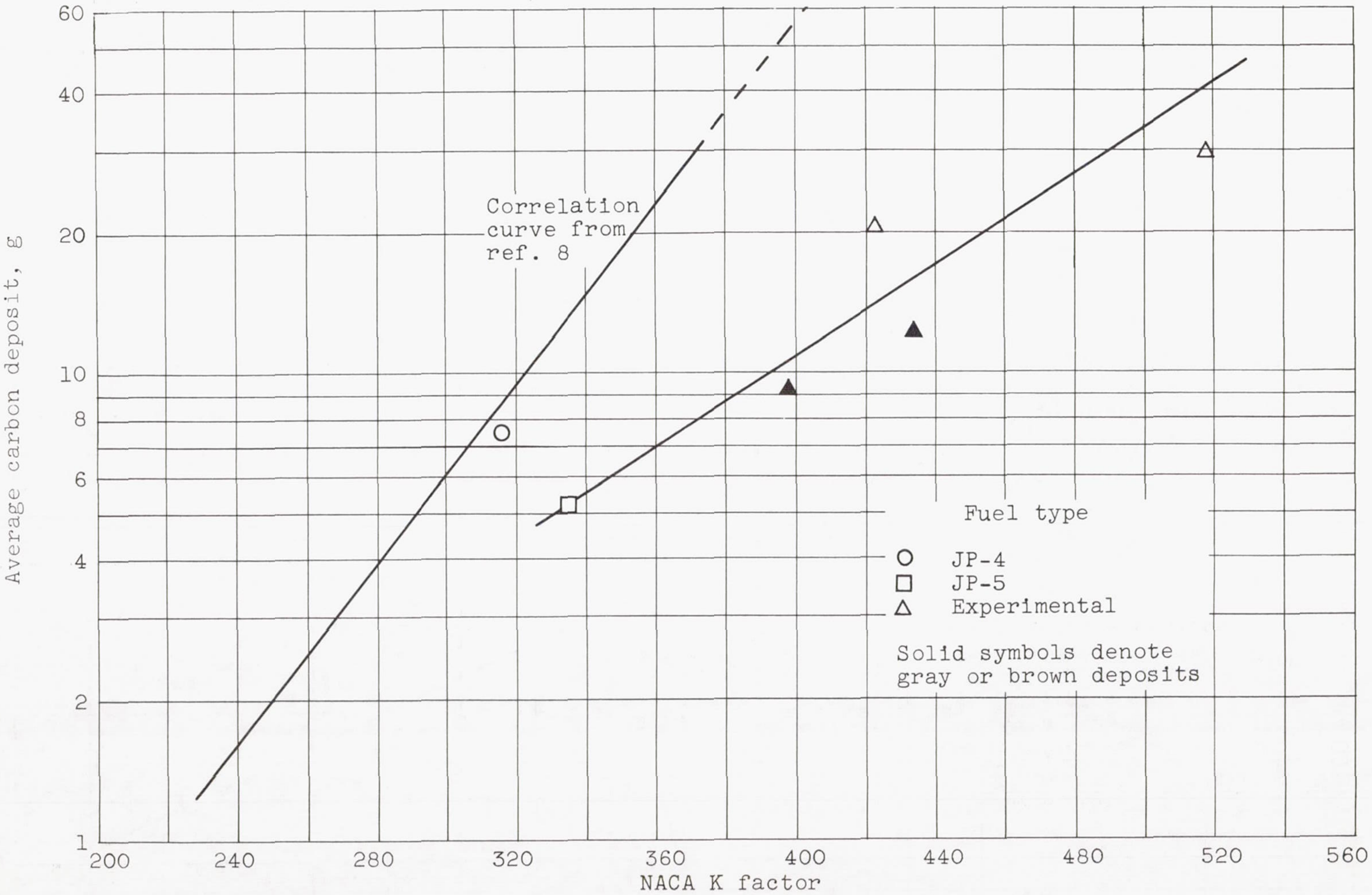
(a) Smoke-volatility index.

Figure 6. - Relations between single-combustor carbon deposits at condition I and empirical fuel factors.



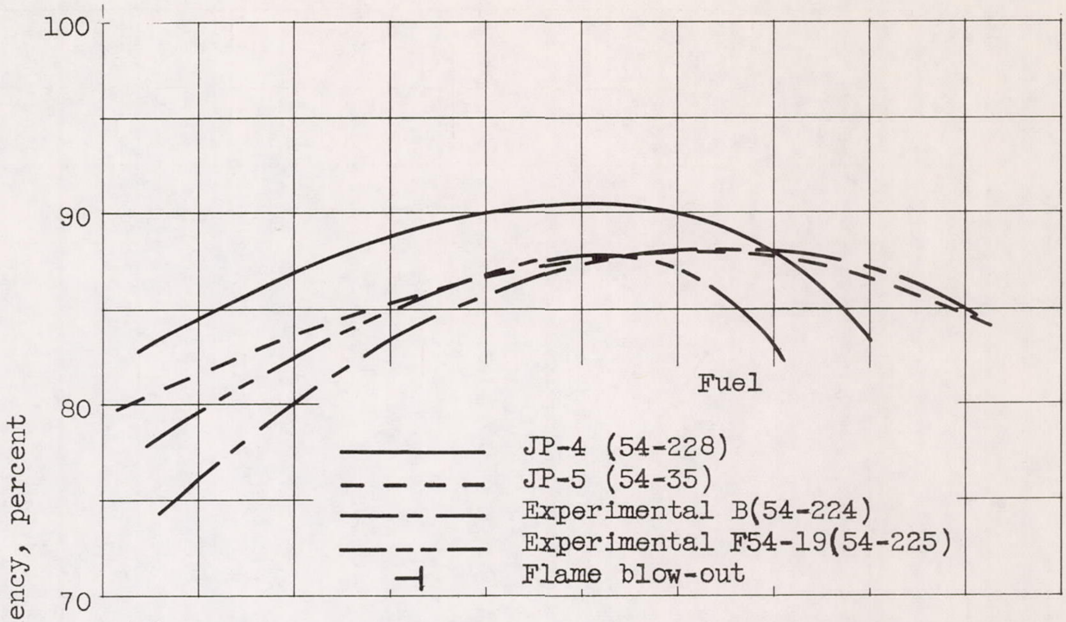
(b) Smoke point.

Figure 6. - Continued. Relations between single-combustor carbon deposits at condition I and empirical fuel factors.

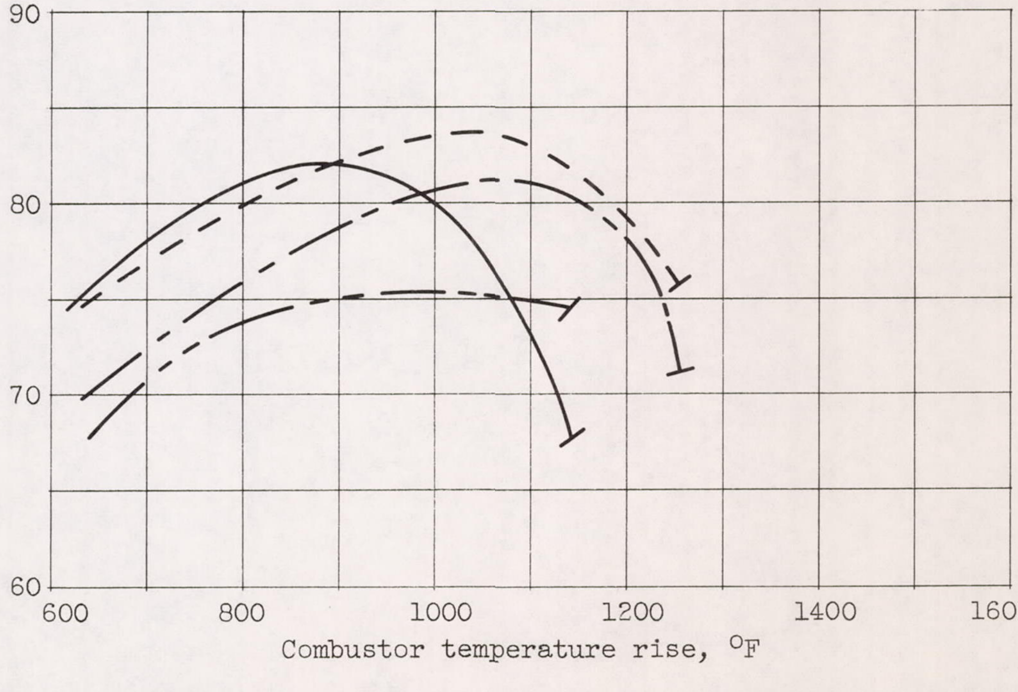


(c) NACA K factor.

Figure 6. - Concluded. Relations between single-combustor carbon deposits at condition I and empirical fuel factors.



(a) Condition III; reference velocity, 98 feet per second.



(b) Condition IV; reference velocity, 126 feet per second.

Figure 7. - Comparison of combustion efficiencies obtained with JP-4. JP-5, and two experimental high Btu-per-gallon fuels.

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