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RESEARCH MEMORANDUM

COKING OF JP-4 FUELS IN ELECTRICALLY HEATED METAL TUBES

By Arthur L. Smith, William P. Cook, and Vincent F. Hlavin

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RESEARCH MEMORANDUM

COKING OF JP-4 FUELS IN ELECTRICALLY HEATED METAL TUBES

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SUMMARY

A limited exploratory investigation of the rate of coking of four JP-4 fuels in electrically heated metal tubes was conducted in order to provide design information for fuel prevaporizers for turbojet-engine combustors. The fuels tested included two production and two minimum-quality JP-4 type fuels. The heating tube was operated at fuel pressures of approximately 500, 400, and 50 pounds per square inch. The operating fuel temperature was varied between approximately 600° and 1200° F.

Two production JP-4 fuels were heated over a period of approximately 70 hours to fuel temperatures of about 1000° F at fuel pressures of approximately 400 pounds per square inch without depositing sufficient coke to increase appreciably the pressure drop across an 8.5-foot-long, 3/8-inch-diameter tube. When two minimum-quality JP-4 fuels were tested at 50 pounds per square inch over a temperature range of 600° to 1200° F, coke plugged the tube after an operating period of 6 to 20 hours. These fuels were high in aromatic and gum contents. The investigation did not establish well-defined relations between the rate of coke formation and any of the several variables studied because of the poor reproducibility of data obtained and the limited number of tests conducted.

INTRODUCTION

Research at the NACA Lewis laboratory has shown that the performance of aircraft jet-engine combustors can be markedly improved at high-altitude conditions by using vaporized fuel in the combustor (ref. 1). Coke formation may be expected to be the most serious problem in the design of heat exchangers for prevaporizing liquid hydrocarbon fuels in these combustors.

The high temperatures to which fuels would be subjected in heat exchangers in a vaporizing-type-combustor application alter the chemical composition of jet fuels. At sea-level pressures, fuel temperatures of the order of 500° F are required to obtain complete vaporization of a typical JP-4 type fuel. The required temperature will increase as the desired fuel

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pressure is increased. This increased temperature requirement for vaporizing the fuel can result in cracking and, subsequently, in pyrolysis of the fuel, which eventually leads to the formation of coke and tar. Coke formation on the walls of the heat exchanger and vaporizing tubes would be expected to result in a decrease in the heat-transfer rate and in the flow area, which would increase pressure drop through the heat exchanger.

The literature lacks quantitative information regarding the effects of temperature, pressure, fuel type, contact time, and construction materials on the rate of coking for the fuels and temperatures of interest. Since this information is necessary for the design of prevaporizers, an exploratory program aimed toward providing some of this information was conducted at the NACA Lewis laboratory. The influence of such factors as temperature, pressure, residence time, and fuel type on the rate of pyrolysis of two production and two "minimum-quality" JP-4 fuels were investigated in 3/8-inch-diameter electrically heated metal tubes. Fuel temperatures varied from approximately 600° to 1200° F. Inlet fuel pressures of about 500, 400, and 50 pounds per square inch were investigated. The residence time of the fuel in the heating tube was controlled by regulating the fuel flow and fuel temperature. Much of the data was obtained with an average residence time of 27 seconds. With this residence time, fuel velocities were estimated to be less than 1 and about 53 feet per second in the liquid and gaseous phases, respectively.

The limited coking data obtained with the fuels are presented in terms of the change in tube pressure drop with test duration. The influence of fuel type on the coking tendency of the fuels investigated is discussed.

FUELS

Laboratory analysis of the fuels used in the investigation are presented in table I. NACA fuels 53-39 and 52-288 were production JP-4 fuels, while 52-291 and 54-41 were minimum quality JP-4 fuels that did not meet the maximum gum-content specification for MIL-F-5624C fuels.

Thermal-stability test data were obtained with three of the JP-4 type fuels in a "Fuel Coker" of the type described in reference 2. "Goodness ratings" for each fuel, and the test conditions used, are presented in table II.

APPARATUS AND INSTRUMENTATION

A schematic diagram of the test apparatus is shown in figure 1. A low-pressure (20 lb/sq in. gage) and a high-pressure (1000 lb/sq in. gage) constant-speed pump connected in series were used to force the fuel through the heater section, a fuel cooler, and finally through a separator, where the liquid portion was passed into a receiving tank and the gaseous portion was vented to the atmosphere. The fuel was not recycled.

The fuel-flow rate was adjusted and measured by appropriate throttle valves and a calibrated rotameter located in the flow circuit. The fuel pressure in the heating tube was controlled by a valve located downstream of the heating tube. A filter element was installed downstream of the cooling section to prevent particles of coke from clogging the fuel pressure-control valve. A mercury pressure switch controlling a relief valve and an "overtemperature" sensing device were used to protect the system from excessive pressures and temperatures.

Fuel pressures at the inlet and outlet of the heating section were measured with static-pressure taps connected to strain-gage pickups. Fuel inlet and outlet temperatures were measured with iron-constantan and chromel-alumel thermocouple probes, respectively, connected to automatic balancing potentiometers.

The heating tube was either Inconel tubing of 3/8-inch diameter with 0.065-inch wall or type 347 stainless-steel tubing of 3/8-inch diameter with 0.064-inch wall. The length of the heating section was $8\frac{1}{2}$ feet. Copper mounting plates were fastened to the heating tube at both ends for the electrical connections. The portion of the tube between these mounting plates was insulated with five layers of asbestos tape. Alternating current was passed through the tube, which then functioned as a resistance heater.

Temperature gradients along the tube were determined by using the instrumented tube shown in figure 2. This arrangement permitted the measurement of tube-wall and fuel temperatures at various stations along the tube. The tube shown in figure 1 was of the same construction as that shown in figure 2 without the thermocouples in position.

Electric power was supplied to the heating tube from an autotransformer. Current through the heating tube was controlled by varying tap position on the transformer, thus varying the voltage supply to the tube. An ammeter was provided in the heating tube electric circuit for measuring the current flow.

PROCEDURE

The heating tube was operated at pressures of approximately 500, 400, and 50 pounds per square inch gage and temperatures of approximately 600° to 1200° F. Prior to the coking tests the heating tube was calibrated to determine the transformer settings required to attain selected outlet fuel temperatures. Calibrations were obtained at various fuel-flow rates and pressures using the instrumented tube shown in figure 2. Fuel and tube-wall temperatures at various stations along the tube were also measured for each fuel at each test condition.

During each coking run, fuel-flow rate and pressure were maintained constant at the selected transformer setting. Test data were recorded at half-hour intervals. The runs, which were interrupted at the close of each working day and started again the following morning, were concluded by either the tube plugging with carbon or the accumulation of a long test period with no indication of plugging. Pressure-drop increase across the heating tube was the criterion for judging the formation of coke. Rapid increases in pressure-drop values indicated tube plugging, and at this time the test was concluded. After the conclusion of a test, the heating tube was cut into seventeen 6-inch lengths to examine the condition of the inner surface and to locate areas of plugging.

Residence time of the fuel in the heating tube was determined by assuming that the fuel existed as liquid over one-half the length of the heating tube and as a vapor over the remaining half. This approximation was made since, although fuel temperatures along the length of the tube were known, the change in phase of the various components of the fuel could not be readily determined. The density of the liquid fuel at the inlet temperature was determined by using density data presented in reference 3. Compressibility-factor data from reference 4 were used to determine gas densities at the tube outlet. The velocity of the liquid through the tube varied from 0.29 to 1.32 feet per second for a variation in fuel flow from 17 to 77 pounds per hour, respectively; the velocity of the vapor at a temperature and pressure of approximately 900° F and 400 pounds per square inch, respectively, varied from 3.5 to 15.1 feet per second for this variation in fuel flow.

Discoloration of the minimum-quality fuel 54-41 was observed in the fuel rotameter during the test with this fuel. It was necessary to clean and recalibrate the rotameter frequently with this fuel, because of contaminates which deposited on the wall of the rotameter tube.

RESULTS AND DISCUSSION

Tube-wall and fuel temperatures measured along the length of the heating tube for the various fuels at the various test conditions are presented in table III and in figure 3. At the low-pressure test condition temperature differences between the tube wall and the liquid are relatively large near the inlet of the tube where nonboiling, forced convection occurs. As nucleate boiling begins the temperature differences become somewhat less because of the increased rate of convective heat transfer induced by the agitation of the vapor bubbles that are formed.

Near the end of the tube the fuel enters a film-boiling region and temperature differences tend to increase because of the thermal resistance of the vapor film. The curves obtained at the low-pressure condition (figs. 3(a) and (b)) are similar in shape to the curves reported in reference 5 for boiling water. The curves obtained at high pressures (figs. 3(c) and (d)) are not consistant in shape with the curves obtained at low pressure. This inconsistency may be attributed, at least in part, to the variation in the heat-transfer process in the tube as the fuel pressure is increased. Data presented in reference 6 suggest that the heat-transfer process tends to pass from nonboiling forced convection directly into film boiling as fuel pressure is increased to a value near 500 pounds per square inch absolute.

The data obtained in the fuel coking tests are presented in table IV. Data are presented in 1-hour increments for tests that did not exceed 14 hours. For tests that exceeded 14 hours, but were less than 21 hours, data are presented in 2-hour increments. For tests that exceeded 21 hours, data are presented in 3-hour increments. The initial tests were conducted with production JP-4 fuels (NACA fuels 53-39 and 52-288) at a heater-outlet fuel temperature of about 800° to 900° F. The change in pressure drop across the heating tube with test duration is plotted in figure 4. NACA fuel 53-39 was tested only at high pressures (400 and 500 lb/sq in. gage), while fuel 52-288 was tested at 50 and 400 pounds per square inch gage. Although some increase in pressure drop due to coke formation occurred during the tests with these fuels, no plugging occurred. NACA fuel 52-288 was tested for 70 hours at an outlet fuel temperature of 800° F, and 40 hours at an outlet temperature of 1000° F. Fuel residence time in the heating tube varied from 4 to 25 seconds. Examination of the heating tube at the completion of the tests indicated slight traces of deposit on the inner walls starting approximately $3\frac{1}{2}$ feet from the upstream end and dispersing erratically over the remaining length.

The results obtained with the minimum-quality fuels 52-291 and 54-41 at a pressure of 50 pounds per square inch gage and a fuel residence time of approximately 27 seconds are presented in figure 5. With fuel 52-291 and an outlet fuel temperature of 1025° F a rapid rise in pressure drop occurred after about 20 hours of run time, and the tube was completely plugged after 28 hours (fig. 5(a)). Tests with minimum-quality fuel 54-41 were conducted at temperatures from 650° to 1160° F in an effort to define a temperature-against-time relation for coke formation. The results (fig. 5(b)) indicate no consistent relation between coking time and fuel temperature at the residence time and pressure conditions tested. In the Inconel tube plugging time decreased when the fuel temperature was increased from 650° to 890° F; however, a further increase in temperature to 1060° F increased the time for plugging by $3\frac{1}{2}$ hours. This apparent reversal may be due, at least in part, to the irreproducibility of the data. Included in figure 5(b) are results obtained in two runs in stainless-steel tubes at very similar temperatures, 1140° and 1160° F. The time required for the tube to plug varied by 3 hours.

Coking tests were conducted in Inconel and stainless-steel tubes. However, because of the poor reproducibility exhibited by the data, and because of the limited number of tests, no conclusion could be obtained concerning the effect of tube materials on coking.

Information presented in reference 7 suggests that coke formation in turbojet combustors may be expected to increase as the aromatic and gum contents of the fuel increase above the allowable military specification limit. Comparison of the data obtained in figures 4 and 5 with the analytical data presented in table I indicates that the fuels with high aromatic and gum contents plugged the heating tube, while the fuels low in these properties did not plug the tube at the conditions tested.

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The C.F.R. Fuel Coker is a laboratory apparatus being studied for possible use in predicting the thermal stability of jet fuels. In the C.F.R. coking unit fuel is heated (ref. 2) in an annular passage formed by a tubular electrical immersion heater centrally located in an approximately 3/8-inch-diameter tube, $12\frac{1}{2}$ inches long. The hot fuel is then passed through an electrically heated, sintered, stainless-steel filter located downstream of the heat exchanger. Insoluble sediment that is formed during the heating operation deposits on the filter. The time required to attain a given pressure drop (25 in. Hg) across the filter within a 300-minute time period then is related to a fuel "goodness number." Fuels with high goodness rating are more stable, thermally, than fuels with low goodness rating. Comparison of the data presented in figures 4 and 5 and the goodness ratings in table II indicates that the fuels with the lowest goodness rating in the Fuel Coker had the fastest plugging time in the heating tube.

The heating tubes were examined at the completion of the test runs with the minimum-quality fuels to locate the regions in the tube where plugging occurred. The regions plugged in tests with fuel 54-41 are indicated in figure 6 on a plot of fuel and tube-wall temperature against distance along this tube. The regions of coking with fuel 52-291 were very similar. The data suggest that, with fuel 54-41, plugging occurred at fuel temperatures above 600° F. This temperature might be expected to vary with fuel pressure, since pressure influences thermal cracking. The initial and the end boiling points on the distillation curve for this fuel, corrected (ref. 8) for an operating pressure of 50 pounds per square inch, are approximately 410° and 900° F, respectively. The coking regions indicated in figure 6, in general, occur above the 30-percent-evaporation point on the A.S.T.M. distillation curve.

CONCLUDING REMARKS

In order to obtain design information for heat exchangers in vaporizing-type combustor applications, the influence of various factors on coke formation in electrically heated metal tubes was investigated with four JP-4 fuels. The results show that fuel prevaporization with fuel temperatures of the order of 1000° F borders on serious coke formation. For tests where operations were successful at fuel temperatures of the order of 1000° F, pressures of about 400 pounds per square inch were maintained. The tests were not sufficiently extensive, however, to indicate the nature of the pressure requirements. With two JP-4 fuels high in aromatic and gum contents, a sufficient amount of coke was formed in a 3/8-inch-diameter tube to plug it completely after 6 to 20 hours of operation at a fuel pressure of 50 pounds per square inch and temperature which varied between 600° and 1200° F. In the test apparatus used the reproducibility of the data was too poor and the number of tests conducted was too limited to establish definite relations among the several variables investigated.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 22, 1956

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TABLE I. - ANALYSES OF JP-4 FUELS

	NACA FUEL			
	53-39	52-288	52-291	54-41
A.S.T.M. distillation, D86-46, °F				
Initial boiling point	142	144	151	146
Percent evaporated				
5	195	198	211	198
10	218	243	256	235
20	239	287	313	278
30	258	308	347	312
40	269	322	369	339
50	285	334	394	359
60	300	347	413	393
70	319	361	439	434
80	339	379	459	477
90	373	411	482	521
95	415	437	518	---
Final boiling point	464	487	570	572
Residue, percent	1.4	1.0	---	1.2
Loss, percent	0.6	1.0	---	0.8
Freezing point, °F	---	---	-60	<-76
Accelerated gum, mg/100 ml	---	2.6	27.5	75
Air-jet residue, mg/100 ml	---	0.7	11.7	27
Aromatics, percent by volume				
A.S.T.M. D875-46T	9.7	10.0	28.5	26.5
Silica gel	---	10.8	32.3	31.0
Gravity, °API	54.2	50.4	39.7	39.0
Specific gravity, 60°/60° F	0.762	0.778	0.826	0.825
Bromine number	------	------	3.5	7.0
Reid vapor pressure, lb/sq in.	2.7	2.0	2.0	2.3
Hydrogen-carbon ratio	0.172	0.167	0.148	0.159
Net heat of combustion, Btu/lb	18,700	18,675	18,400	18,300
Aniline point, °F	131.7	138.9	108.1	------

TABLE II. - ERDCO THERMAL STABILITY TEST RESULTS

[Ref. 2.]

Test Conditions	52-288	52-291	54-41
Preheater temperature, °F	400	400	400
Filter temperature, °F	500	500	500
Fuel flow, lb/hr	3.13	3.34	3.32
Residence time, sec	30	30	30
Fuel pressure, lb/sq in.	153	153	153
Time to obtain pressure drop of 25 in. Hg, min	51	47	[a]20
"Fuel goodness ratings"	95	88	38

[a] Estimated.

TABLE III. - TEMPERATURE SURVEY DATA OBTAINED WITH FOUR JP-4 FUELS IN ELECTRICALLY HEATED METAL TUBES

	Test series					
	A	B	C	D	E	F
NACA Fuel	53-39	52-288	52-291	54-41	54-41	54-41
Fuel flow, lb/hr	60	18	10	10	10	10
Inlet fuel pressure, lb/sq in. gage	390	424	50	50	50	50
Inlet fuel temperature, °F	54	64	68	90	90	90
Outlet fuel temperature, °F	1010	994	1027	1040	825	1140
Thermocouple position[a]	Temperature, °F					
1	420	452	453	405	327	440
2	460	458	456	365	300	433
3	780	785	622	587	500	640
4	830	852	768	625	515	883
5	1060	1070	1072	973	625	1287
6	1040	1058	1068	990	710	1247
7	1230	1244	1300	1285	890	1495
8	1110	1125	1172	1235	935	1373
9	1285	1301	1382	1410	1105	1587

[a] See fig. 2.

TABLE IV. - COKING OF JP-4 FUELS IN ELECTRICALLY HEATED METAL TUBES

Test series	Fuel flow, lb/hr	Heating-tube fuel inlet temperature, °F	Heating-tube fuel outlet temperature, °F	Heating-tube fuel inlet pressure, lb/sq in. gage	Heating-tube pressure drop lb/sq in. gage	Heating-tube running time, hr	Remarks
NACA fuel 53-39							
1	86.7	70	805	480	1.4	0	
	86.7	75	830	480	1.4	1	
	85.5	72	830	475	1.5	2	
	91.4	75	790	470	1.5	3	
	85.7		840	470	1.5	4	
	88.0		795	490	1.4	5	
	85.5		805	490	1.4	6	
	92.0		755	470	1.4	7	
2	60.4	76	1007	380	1.0	0	
	61.2	85	1015	374	1.1	1	
	60.5	85	1020	373	1.3	2	
	58.5	85	1034	372	1.4	3	
	60.5	85	1000	383	1.3	4	
	58.2	88	1025	380	1.4	5	
	59.4	87	1001	387	1.4	6	
	58.5	89	1009	384	1.4	7	
3	16.9	80	920	452	0.5	0	
		105	950	373		1	
		105	940	371		2	
		102	929	382		3	
		105	930	380		4	
		95	980	362		5	
		74	935	394	.8	6	
		75	942	425	1.0	7	
		75	990	413	.8	8	
NACA fuel 52-288							
4	77	87	998	380	1.7	0	
		85	940	383	1.7	3	
		85	973	388	1.9	6	
		85	982	424	2.0	9	
		85	981	366	2.4	12	
		82	980	374	2.5	15	
		81	941	406	2.3	18	
		80	952	393	1.9	21	
		83	966	398	2.0	24	
		83	935	404	1.5	27	
		83	932	361	2.0	30	
		85	925	390	2.0	33	
		81	917	379	1.5	36	
		82	918	410	2.0	39	
		85	995	390	3.0	42	
5	23	82	781	349	.1	0	
		85	806	406	.2	3	
		86	832	371	.1	6	
		85	812	377	.1	9	
		86	820	371	.1	12	
		86	815	395	.1	15	
		86	795	375	.1	18	
		85	815	386	.1	21	
		86	806	413	.2	24	
		86	800	422	.1	27	
		88	726	390	.1	30	
		87	782	410	.1	33	
		90	805	390	.1	36	
		88	786	405	.2	39	
		92	770	424	.2	42	
		90	788	400	.1	45	
		93	770	420	.2	48	
		90	752	406	.2	51	
		90	780	390	.1	54	
		90	755	409	.1	57	
		90	754	391	.1	60	
		90	782	372	.1	63	
		89	758	411	.1	66	
6	10	72	700	50	3.0	0	
		73	807		3.3	2	
		72	814		3.0	4	
		77	804		3.0	6	
		74	785		3.0	8	
		75	790		5.0	10	
		75	801		3.0	12	
		77	786		4.0	14	
		77	788		3.0	16	
		77	805		4.0	18	
		76	799		4.5	20	
		77	800		5.0	22	
		77	778		4.0	24	
		78	792		3.0	26	
		78	797		3.0	28	
NACA fuel 52-291							
7	10	68	995	50	1.4	0	
		70	1022	52	1.4	2	
		70	1038	54	1.7	4	
		69	1046	50	1.4	6	
		72	1021	50	4.4	8	
		74	1024	50	4.5	10	
		72	1026	44	5.0	12	
		68	985	47	5.9	14	
		70	989	46	7.1	16	
		68	994	50	9.1	18	
		71	1034	61	9.8	20	
		70	1028	50	13.0	22	
		65	1025	47	14.7	24	
		67	1028	50	16.0	26	
		68	1045	52	40.0	28	Tube plugged
NACA fuel 54-41							
8	10	80	600	47	2.0	0	
		80	640	40	2.0	2	
		80	665	56	2.0	4	
		85	640	45	3.4	6	
		85	662	50	3.4	8	
		87	655	50	3.8	10	
		80	630	48	8.5	12	
		80	665	50	4.7	14	
		85	665	52	4.5	16	
		90	700	49	15.6	18	
		90	660	50	35.0	20	Tube plugged
9	10	79	1075	50	10.7	0	
	10	80	1086	50		1	
	11.5	82	1090	35		2	
	12.2	81	1670	56		3	
	10	83	1080	70		4	
	9.4	83	1075	44		5	
	10	85	1059	72		6	
	10	82	1017	70	11.5	7	
	10	85	1048	63	13.0	8	
	10	85	1055	47	19.0	9	
	10	85	1050	50	17.0	10	
	11.2	85	1055	50	22.5	11	
	10	85	1050	60	22.3	12	
	10	85	1065	50	35.0	13	Tube plugged
10	10	81	1036	35	11.5	0	
		85	1027	50	11.5	1	
		85	1035	40	11.5	2	
		85	1025	50	11.5	3	
		85	1037	55	11.5	4	
		85	1030	50	11.7	5	
		86	1031	40	12.3	6	
		80	1024	50	13.8	7	
		82	1035	83	14.4	8	
		80	1046	50	28.0	9	
		81	1032	50	35	10	Tube plugged (approx. time)
11	10	75	926	50	14.0	0	
			880	50	14.3	1	
			865	50	14.4	2	
			884	50	14.6	3	
			878	57	14.8	4	
			867	47	16.0	5	
			900	47	18.0	6	
		72	870	50	23.7	7	
		70	903	53	33.5	8	
		--	---	50	35	9	Tube plugged (approx. time)
12	11	85	1160	50	2.7	0	Stainless-steel tube
			1160	50	2.7	1	
			1165	50	3.5	2	
			1178	35	2.7	3	
			1165	50	2.7	4	
		90	1165	50	2.7	5	
		85	1160	50	5.0	6	
		90	1180	50	10.4	7	
		85	1140	49	13.0	8	
		85	1135	67	35.0	9	Tube plugged (approx. time)
13	10	85	1125	50	4.0	0	Stainless-steel tube
		85	1135	40	6.0	1	
		90	1145	40	7.0	2	
		85	1135	40	7.5	3	
		85	1150	40	9.5	4	
		85	1150	36	17.5	5	
		90	1155	50	35	6	
		90	1155	50	35+	7	Tube plugged (approx. time)

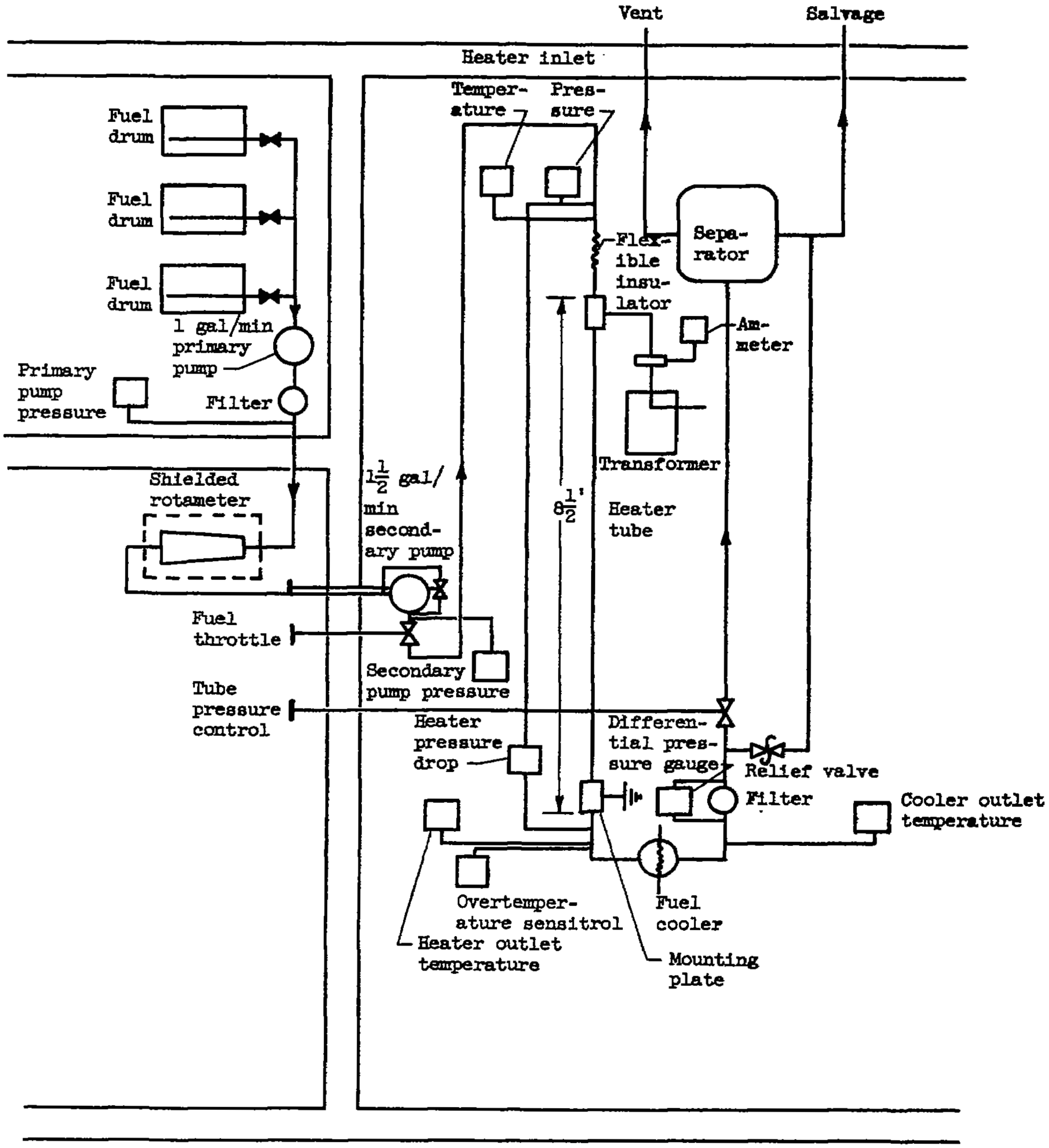
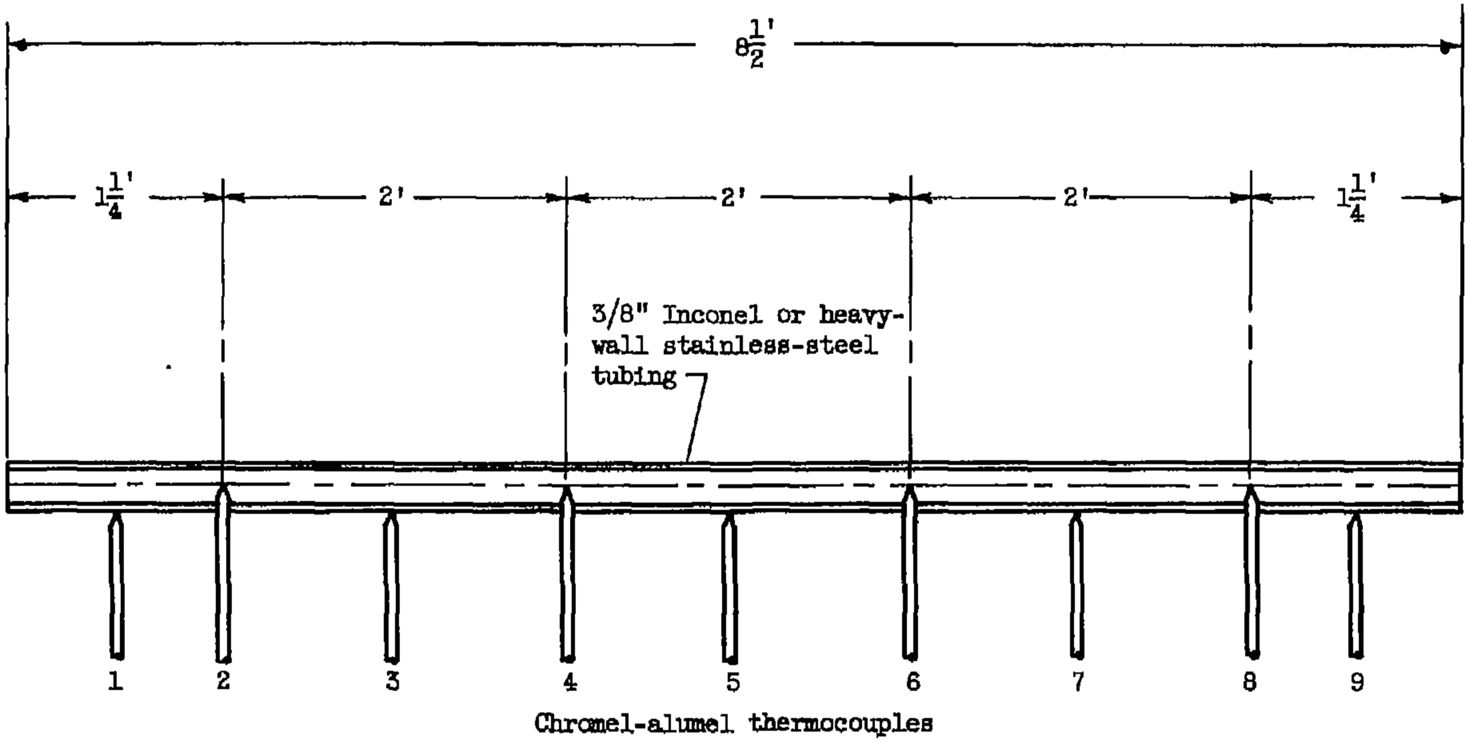
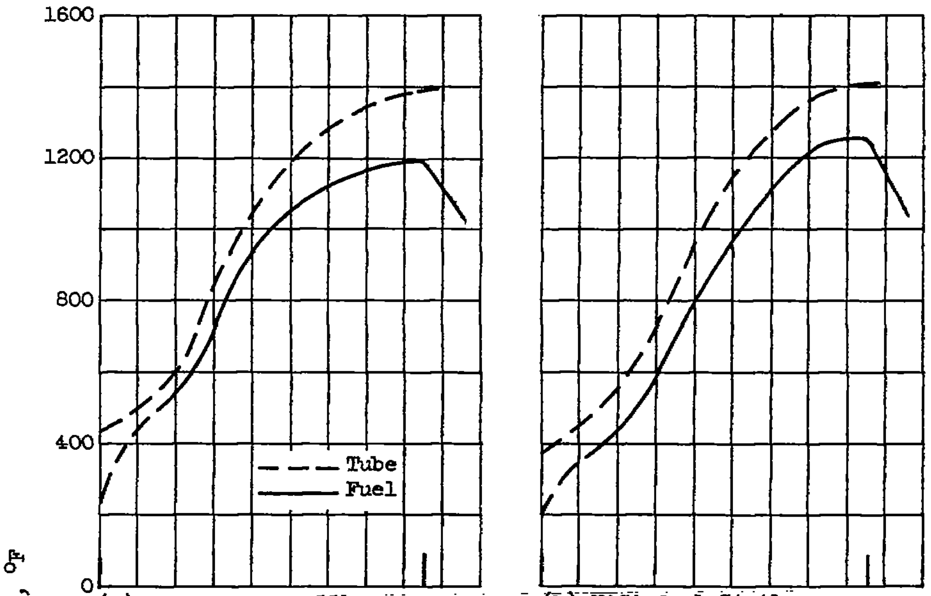


Figure 1. - Schematic diagram of fuel system and heater-tube installation.



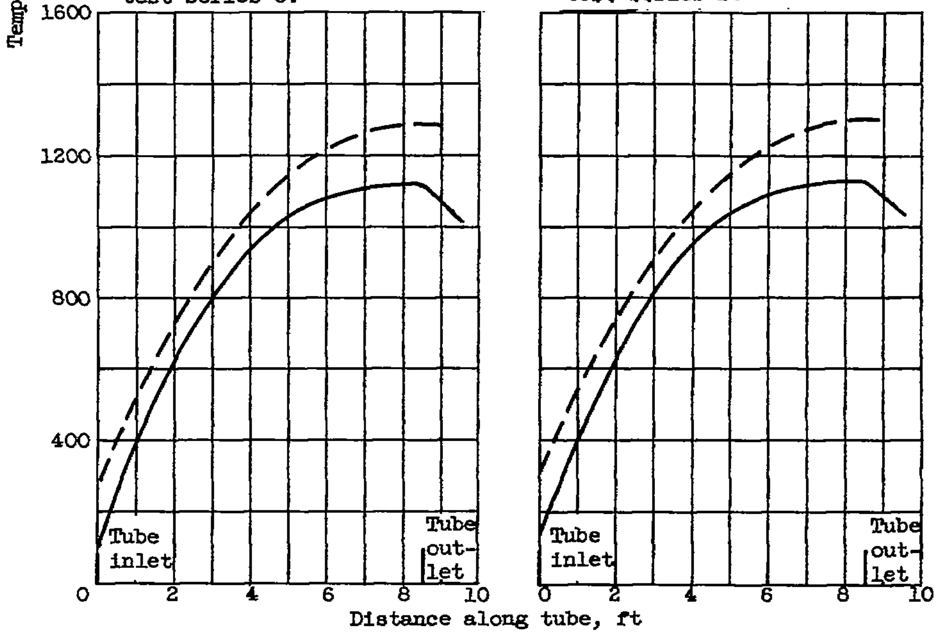
Odd-numbered couples are bare-wire couples welded to surface of tube. Even-numbered couples are shielded couples positioned in center of tube.

Figure 2. - Cross section of heater tube used for recording temperature gradients.



(a) NACA fuel 52-291; pressure, 50 pounds per square inch; residence time, 28 seconds; test series C.

(b) NACA fuel 54-41; pressure, 50 pounds per square inch; residence time, 27 seconds; test series D.



(c) NACA fuel 53-30; pressure, 390 pounds per square inch; residence time, 4 seconds; test series A.

(d) NACA fuel 52-288; pressure, 424 pounds per square inch; residence time, 15 seconds; test series B.

Figure 3. - Temperature survey along heating tube for four JP-4 type fuels. Fuel outlet temperature, approximately 1000° F.

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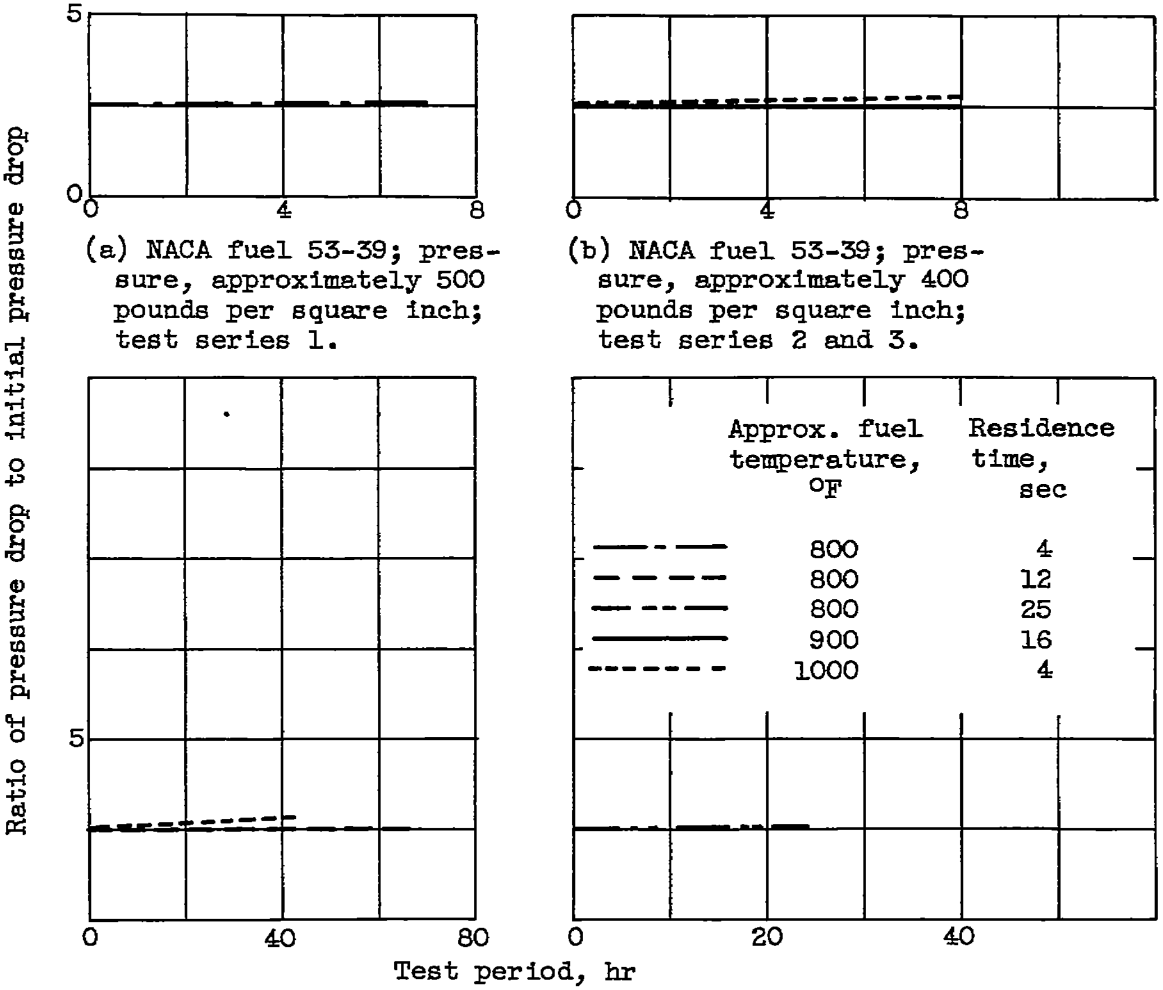

(a) NACA fuel 53-39; pressure, approximately 500 pounds per square inch; test series 1.

(b) NACA fuel 53-39; pressure, approximately 400 pounds per square inch; test series 2 and 3.

(c) NACA fuel 52-288; pressure, approximately 400 pounds per square inch; test series 4 and 5.

(d) NACA fuel 52-288; pressure, approximately 50 pounds per square inch; test series 6.

Figure 4. - Pressure-drop variation with time in electrically heated metal tube for two production JP-4 fuels.

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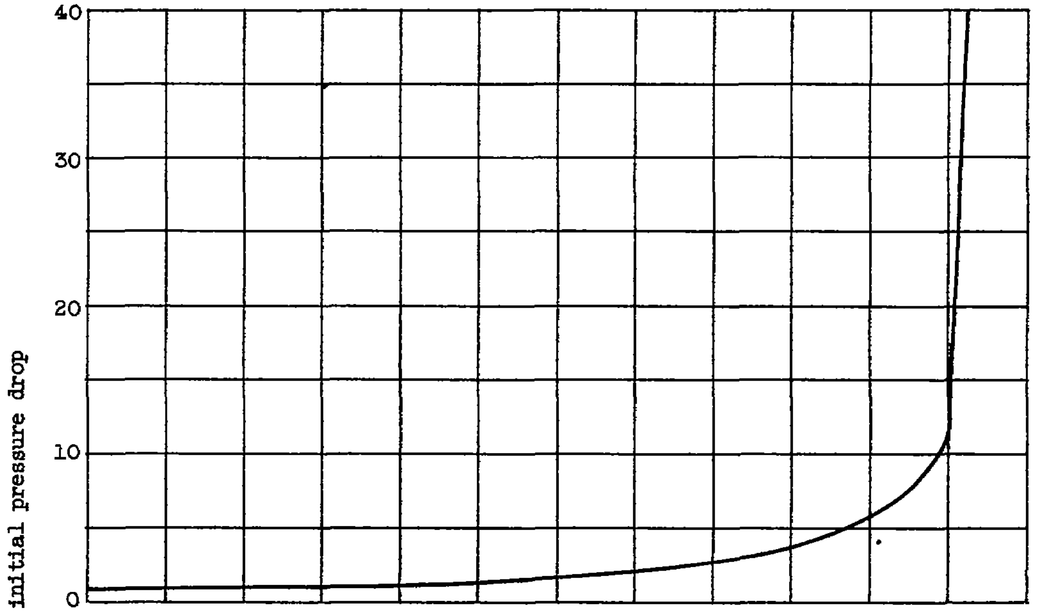
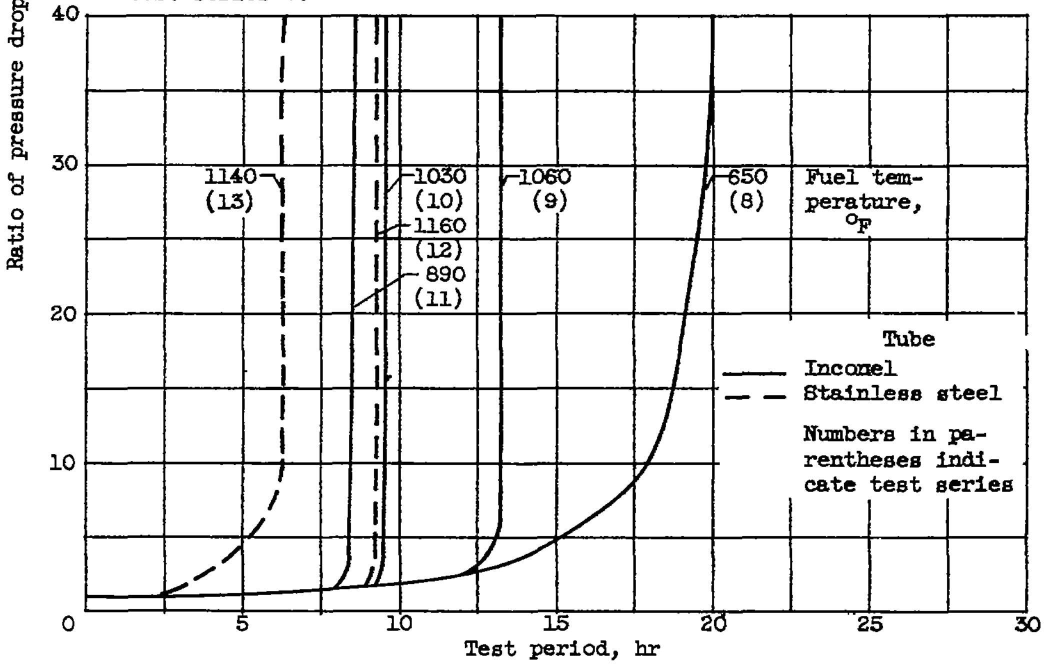


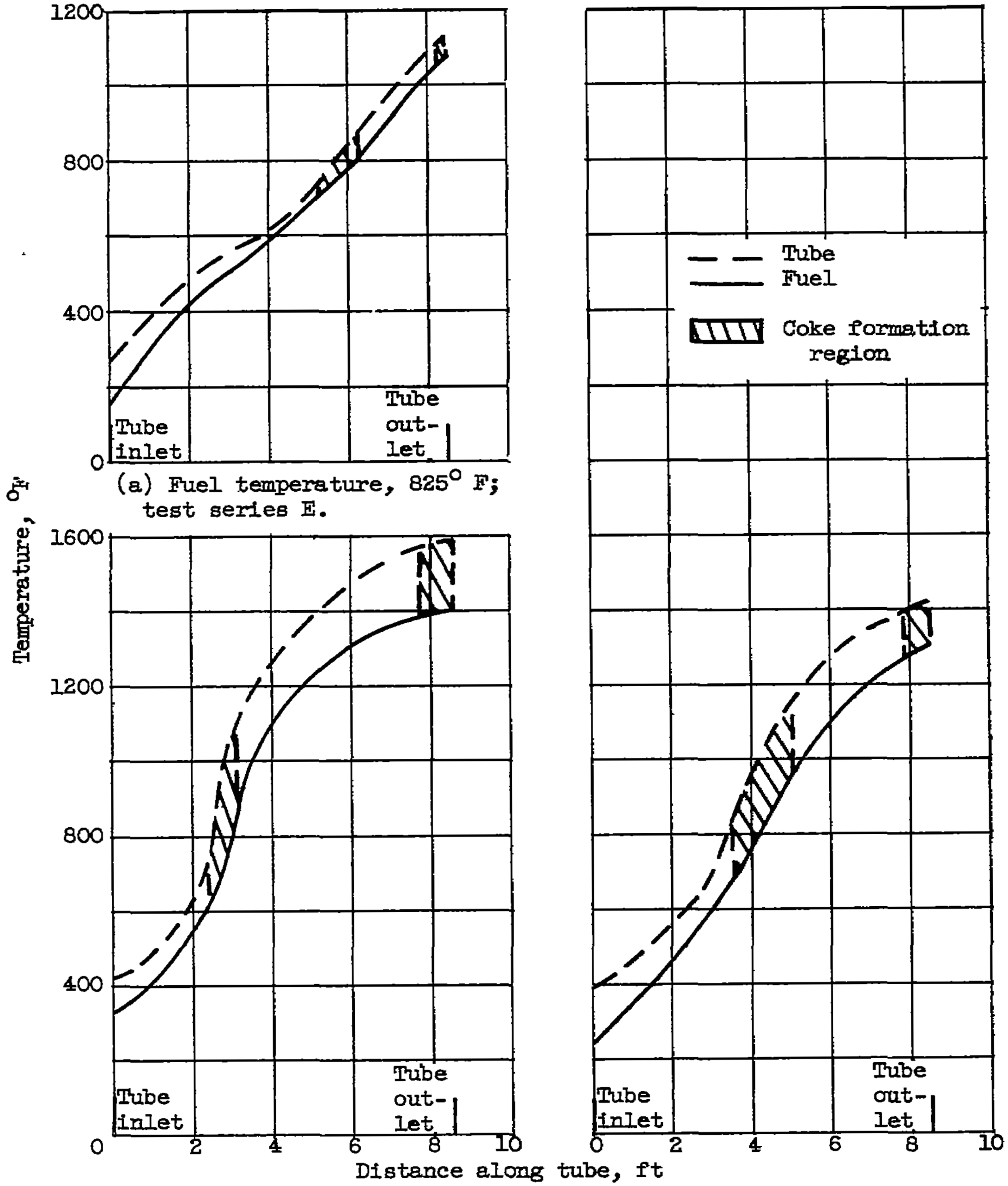
(a) NACA fuel 52-291; residence time, 27 seconds; temperature, 1025° F; test series 7.



(b) NACA fuel 54-41; residence time, approximately 27 seconds.

Figure 5. - Pressure-drop variation with time in electrically heated metal tube for two minimum-quality JP-4 fuels. Inlet fuel pressure, 50 pounds per square inch gage.

[redacted]



(a) Fuel temperature, 825° F; test series E.

(b) Fuel temperature, 1140° F; test series F.

(c) Fuel temperature, 1040° F; test series D.

Figure 6. - Coking region in electrically heated tubes operating with minimum quality JP-4 fuel (NACA 54-41). Pressure, 50 pounds per square inch gage; residence time, approximately 27 seconds.

[redacted]