CHAPTER XIII

COKE DEPOSITION AND SMOKE FORMATION IN TURBOJET ENGINES

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INTRODUCTION

In the early development of jet engines, it was occasionally found that excessive amounts of coke or other carbonaceous deposits were formed in the combustion chamber. Sometimes a considerable amount of smoke was noted in the exhaust gases. Excessive coke deposits may adversely affect jet-engine performance in several ways. The formation of excessive amounts of coke on or just downstream of a fuel nozzle (figs. 116(a) and (b)) changes the fuel-spray pattern and possibly affects combustor life and performance. Similar effects on performance can result from the deposition of coke on primary-air entry ports (fig. 116(c)). Sea-level or altitude starting may be impaired by the deposition of coke on spark-plug electrodes (fig. 116(b)), deposits either grounding the electrodes completely or causing the spark to occur at positions other than the intended gap. For some time it was thought that large deposits of coke in turbojet combustion chambers (fig. 116(a)) might break away and damage turbine blades; however, experience has indicated that for metal blades this problem is insignificant. (Cermet turbine blades may be damaged by loose coke deposits.) Finally, the deposition of coke may cause high-temperature areas, which promote liner warping and cracking (fig. 116(d)) from excessive temperature gradients and variations in thermal-expansion rates. Smoke in the exhaust gases does not generally impair engine performance but may be undesirable from a tactical or a nuisance standpoint. Appendix B of reference 1 and references 2 to 4 present data obtained from full-scale engines operated on test stands and from flight tests that indicate some effects on performance caused by coke deposits and smoke.

Some information about the mechanism of coke formation is given in reference 5 and chapter IX. The data indicate that (1) high-boiling fuel residuals and partly polymerized products may be mixed with a large amount of smoke formed in the gas phase to account for the consistency, structure, and chemical composition of the soft coke in the dome and (2) the hard deposits on the liner are similar to petroleum coke and may result from the liquid-phase thermal cracking of the fuel.

During the early development period of jet engines, it was noted that the excessive coke deposits and exhaust smoke were generally obtained when fuel-oil-type fuels were used. Engines using gasoline-type fuels were relatively free from the deposits and smoke. These results indicated that some type of quality control would be needed in fuel specifications. Also noted was the effect of engine operating conditions on coke deposition. It is possible that, even with a clean-burning fuel, an excessive amount of coke could be formed at some operating conditions. In this case, combustor redesign could possibly reduce the coke to a tolerable level. This chapter is a summary of the various coke-deposition and exhaust-smoke problems connected with the turbojet combustor. Included are (1) the effect of coke deposition on combustor life or durability and performance; (2) the effect of combustor design, operating conditions, inlet variables, and fuel characteristics on coke deposition; (3) elimination of coke deposits; (4) the effect of operating conditions and fuel characteristics on formation of exhaust smoke; and (5) various bench test methods proposed for determining and controlling fuel quality.

COKE DEPOSITION IN TURBOJET ENGINES

The coke deposits in a turbojet-engine combustor are formed on the liner walls from 2 to 6 inches downstream of the dome, in the dome, on the fuel nozzle, and on the spark plug (fig. 116(e)). The deposits on the liner are generally hard and of a medium gray color, show erosion marks or streaks caused by the hot gases, and adhere strongly to the liner walls. The dome and nozzle deposits are sometimes softer than liner deposits and generally darker in color. These deposits are probably not heated to as high temperatures as are the liner deposits. The amount of coke deposit obtained in one tubular combustor of a full-scale engine has been as much as 170 grams (fig. 116(a)); 250 grams has been obtained from full-scale annular combustors. Although most investigators consider deposit weight as a measure of the amount of coke, it is possible that volume instead of weight should be considered.

Effect of Coke on Combustor Life and Performance

As stated previously, large deposits on liner walls can cause severe temperature gradients that may result in warping and cracking of the liner. Coke deposits on or just downstream of the fuel nozzle may cause alterations in the fuel-spray patterns with possible effects on performance.

Life or durability. - Severe liner warping that occurred just downstream of a large coke formation is shown in figure 116(d). Figure 1 of reference 6 also indicates quite clearly the effect of coke formations on liner warping. Information presented in reference 6, which was obtained from military flight bases and overhaul stations, indicates that severe coke deposition can cause liner failure in as little time as 30 hours. In some engines, five out of eight liners had failed at the 30-hour check time. Generally, flight stations that reported heavy coking in their engines had much higher rates of liner replacement than did stations that reported only small amounts of coke build-up. In some cases where the coke deposition was generally quite low, liner life was as long as 200 hours. Liner life can also be shortened because of a distortion or deflection of the fuel spray by coke formations that causes actual burning of part of the liner. This type of failure is also reported in reference 6.

Combustion efficiency and stability. - Loss in fuel heating value due to coke formation in the combustion chamber is unimportant even under the worst conditions. As explained in chapter IX, for such conditions, the loss due to coke deposition is only of the order of 0.004 percent. However, coke formation can affect efficiency by other means. For example, an increase in efficiency at low fuel-air ratios accompanied the formation of coke on fuel nozzles in an early type tubular combustor (fig. 117). The periods of operation shown in this figure were conducted under various test conditions. This unexpected increase in efficiency was attributed to a change in the fuel-spray characteristics. Photographs of the fuel sprays in still air, obtained before and after the coke had been deposited, indicated that the deposits caused a large increase in fuel-spray angle and provided improved fuel drop distribution at low fuel-flow rates. It is noted that cleaning the fuel nozzle after $6\frac{1}{2}$ hours of operation reduced combustion efficiency to the original values. The insertion of a nozzle shield that prevented the formation of coke on the nozzle tip resulted in constant combustion efficiency with run time. An opposite effect of coke deposits on full-scale-engine performance is reported in reference 6. It was reported from one flight station that if the domes and liners were not cleaned, a significant loss in engine power and efficiency (increased tail-pipe temperature for a given engine speed) was observed within 60 hours.

Results of an investigation reported in reference 7 show the effect of coke deposits on altitude limits of a single tubular combustor. The altitude limits were

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determined before and after an 80-hour test run, during which the coke deposit pictured in figure 118 was accumulated. The operational limits were reduced somewhat as a result of the coke deposits, as shown in figure 119. In general, there seems to be no reason to expect coke deposits to improve either the efficiency or the altitude limits of well-designed combustors. Decreases in efficiency and altitude limits would appear more likely, although adequate substantiating data are not available.

Effect of Combustor Design and Operating Conditions on Coke Deposition

The coke deposits in a combustor are affected by combustor design and operating conditions or inlet variables. The amount of the coke deposit is determined by the operating time and by the rates of formation, burning, and erosion. These rates are in turn affected to different degrees by design and by inlet variables. As previously mentioned, coke deposits may result from liquid-phase thermal cracking of the fuel on the liner walls. The softer coke found in the dome is probably high-boiling fuel residuals mixed with a larger amount of smoke that was formed in the gas phase. Therefore, a combustor design that permits a large amount of liquid fuel to impinge on the hot liner walls should accumulate more coke, provided that the temperature of the liner walls is proper for thermal cracking of the liquid. Preventing the liquid fuel from getting to the liner walls or using vapor-fuel injection should decrease the coke deposits.

The direct effects of engine operating conditions or combustor-inlet variables on combustor deposits are somewhat obscured by the interdependence of these variables, which include inlet-air pressure, temperature, velocity, and fuel-air ratios. Investigators employing small-scale or full-scale single tubular combustors have tried to determine the singular effect of pressure, for example, by holding mass air flow, temperature, and fuel-air ratio constant. In this case, the inlet-air velocity varies with pressure. Then to determine whether the pressure or velocity is affecting the quantity of deposits, tests must be made with constant pressure, temperature, and fuel-air ratio and varying velocity. The change in mass air flow, to vary velocity, requires a change in fuel flow to maintain constant fuel-air ratio which in turn requires tests to determine the effect of total fuel flow on deposition. Because of the large number of tests required, most investigators have not determined the singular effects of all the combustor-inlet variables. From the available data, however, some indications can be obtained as to whether or not the effect of the inlet variables on combustor deposits is in agreement with the deposit formation mechanisms previously postulated.

Combustor design. - Several investigators have determined the effect of change in "air wash" along the liner walls on coke deposition. Data of reference 8 show a 58- to 77-percent reduction in weight of coke deposits in a small-scale combustor when the gaps in the liner-wall louvers were increased from 0.030 to 0.050 inch. Information presented in reference 9 (full-scale tubular combustor) indicated an appreciable increase in coke deposition when one-third of the liner louvers were closed. Unpublished NACA data (full-scale single combustor) show a reduction in coke deposits from about 30 grams to 1 gram when the combustor was modified so that an annulus of air was directed downstream surrounding the fuel spray. This annulus of air was obtained by modifying the upstream end of the combustor dome as follows: A 3-inch-diameter hole was cut in the end of the dome, and a flat plate $2\frac{1}{2}$ inches in diameter was installed at the back of the fuel nozzle so that the plate was centered in the 3-inch opening. The primary air entering the $\frac{1}{4}$-inch annulus ($1\frac{1}{4}$ in. from the fuel nozzle) prevented most of the liquid fuel from impinging on the liner walls. This method also decreased the amount of liquid fuel recirculating into the dome; smoke formed in the gas phase could not adhere as readily to the dome surface.

Injection of vaporized fuel (considered as part of combustor design) has an effect on coke deposits, as shown by data presented in reference 10. Less liner deposit was obtained in a small-scale tubular fuel-vaporizing combustor than in a similar design of a fuel-atomizing combustor operated at comparable conditions. However, if the fuel is not completely vaporized, the liner deposit may be increased over the values obtained with the atomizing combustor. Also, deposits may form in the vaporizing tubes and cause a decrease in fuel flow that will probably result in tube failure.

Inlet-air pressure. - Increasing the pressure increases the smoke-forming tendency of hydrocarbon flames (ref. 11); thus, combustor deposits should increase with increase in inlet pressure. This is generally substantiated by information presented in references 12 and 13 (small-scale tubular combustors; fuel-atomizing and -prevaporizing, respectively) and reference 14 (full-scale single tubular combustor). For example, data in figure 120 show a continued increase in total deposit weight with increase in pressure. In this case, velocity, temperature, and fuel-air ratio were relatively constant while fuel flow varied. Deposit weight per unit of fuel, which tends to minimize the variable-fuel-flow effect, also increased with pressure, but at a decreasing rate. This leveling off of combustor deposits at higher pressures is similar to the pressure effect on the rate of smoke formation shown in reference 11. This may be caused, in part, by an increased rate of erosion with increase in air density.

Inlet-air temperature. - An increase in the combustor inlet-air temperature should decrease combustor deposits because of the increased evaporation rate of the liquid fuel from the liner walls and the resultant decrease in fuel residence time. Investigations reported in references 13 and 15 (small-scale tubular combustors; fuel-vaporizing and -atomizing, respectively) and reference 16 (full-scale single tubular combustor) were conducted to determine the effect of inlet-air temperature on coke deposition. Results of these investigations are somewhat conflicting regarding the temperature effect on combustor deposits. For example, data taken at a constant air velocity (ref. 13) show that the flame-tube deposit of a high-deposit fuel increased with increase in air temperature up to 250° F, then decreased as temperature was further increased up to 400° F. Similar data (ref. 15) are shown in figure 121(a). The data were obtained in a small-scale tubular fuel-atomizing combustor at constant mass air flow. Increase in the air temperature from 100° to 250° F increased the amount of deposits; however, further increase in temperature to 325° F caused a decrease in deposits. Data for a full-scale single tubular combustor (ref. 16) for both constant mass air flow and constant inlet-air velocity indicate a decrease in deposits as inlet-air temperature was increased from 100° to 300° F. As the air temperature was increased from 300° to 500° F, the deposit quantity increased. Data obtained in a small-scale tubular fuel-atomizing combustor (ref. 17) at constant reference air velocity show an increase in deposits as air temperature was increased from 100° to 350° F. The inlet-air pressure was varied from 20 to 50 pounds per square inch absolute. Varying inlet-air temperature from 200° to 860° F (ref. 18) caused a decrease in deposits at inlet pressures from 60 to 173 pounds per square inch absolute, as shown in figure 121(b). The data were obtained at constant reference air velocity and fuel-air ratio.

It is apparent that the processes that cause combustor deposits are affected to different degrees by change in inlet-air temperature. With some particular inlet-air temperature, combustor geometry, and fuel, one process may predominate;

with other combinations another process may predominate. In some cases the increase in temperature will increase the vaporization rate of the fuel, thereby decreasing the fuel residence time on the walls; in other cases the thermal-cracking rate (with increase in inlet-air temperature) may become greater, relative to the vaporization rate, and therefore deposits will increase. Of course, if the inlet-air temperature is high enough, the liner temperature will be above the minimum temperature at which coke will burn, and, therefore, combustor deposits will not build up on the liner (fig. 121(b)).

Inlet-air velocity. - An increase in the inlet-air velocity would be expected to decrease combustor deposits because (1) the increased scrubbing action of the air on the liquid fuel decreases fuel residence time on the walls, (2) less fuel impinges on the liner walls, and (3) the erosion of deposits is greater. Conversely, the fuel recirculation increases with increase in air velocity, and the greater amount of liquid fuel in the dome may increase deposits. The relative importance of these different processes is not known. Data of references 14 and 19 (full-scale single tubular atomizing combustors) show an increase in deposits as the velocity was increased. Information presented in reference 17 for a small-scale tubular atomizing combustor indicates a decrease in deposits as velocity was increased. Data shown in figure 122 indicate that, depending on the fuel-air ratio, there will be either an increase, no change, or a decrease in combustor deposits with increasing inlet velocity, which is proportional to mass air flow. It is apparent that the effect of inlet velocity on combustor deposits is similar to the inlet-air-temperature effect. Depending on the operating conditions and combustor geometry, combustor deposits may increase or decrease with increase in velocity.

Fuel-air ratio. - Increase in fuel-air ratio of fuel flow should increase combustor deposits because of higher local fuel-air ratios and the increased amount of residual wall fuel. The increased primary-zone temperature resulting from the increased fuel-air ratio should cause either an increase in deposits through increased thermal cracking or a decrease in deposits because of increased burning and erosion of the deposits. Investigations reported in reference 13 (small-scale fuel-vaporizing tubular combustor) and references 14 and 19 (full-scale single tubular combustors) indicate a general increase in combustor deposits with increase in fuel-air ratio. Data presented in figure 123 show an increase in total combustor deposits with increase in fuel-air ratio, with all other variables constant except, of course, exhaust-gas temperature. However, deposit weight per unit of fuel is constant with increase in fuel-air ratio. Data shown in figure 122 also indicate an increase in combustor deposits with increase in fuel-air ratio.

Run time. - The amount of deposit in a combustor depends on the length of the run time. However, because of increased burning and erosion of deposits as the deposit quantity increases, deposition rate remaining constant, the rate of deposit build-up decreases, and finally at some value of run time a maximum quantity of deposits is obtained. This tendency is shown in figure 124.

Summary of effects of combustor design and operating variables. - In summary, it is noted that certain changes in combustor design and inlet variables affect combustor deposits in the way expected. For example, increased "air wash" along the liner walls or injection of vaporized fuel caused a decrease in amount of deposits. Increases in inlet-air pressure and fuel-air ratio both generally caused increases in coke deposits. Deposit weight increased with run time until an equilibrium level was reached; the rate of erosion and burning becomes approximately equal to the deposition rate. Increases in inlet-air temperature or velocity, or both, were expected to decrease deposits. However, results were conflicting; in some cases deposits increased and in others decreased as air temperature was increased. If the air temperature was high enough (>850° F), little deposit was formed. The inlet-air-velocity effect on deposits was similar to the temperature effect; depending on the operating conditions and combustor design, the deposits either increased or decreased with increase in velocity.

Effect of Fuel Characteristics on Coke Deposition

A substantial quantity of data has been obtained by numerous investigators describing the effects of various fuel properties on combustor deposits. Since all inlet variables or operating conditions can be maintained relatively constant, the direct effect of fuel type on combustor deposits can be determined.

Volatility. - It is indicated earlier in this chapter that combustor deposits are smaller with gasoline-type fuels than with higher-boiling fuels. This result is in agreement with the supposition that more easily vaporized fuels should produce less combustor deposits because of the decrease in fuel residence time. Other data that substantiate this theory are given in references 9 and 19 (full-scale single tubular combustors), reference 20 (small-scale tubular combustor), and reference 21 (full-scale annular combustor, $10\frac{3}{8}$-in. diam.). For example, information presented in figure 125(a) shows a considerable increase in combustor deposit with increase in the volumetric average boiling temperature (decrease in volatility) at constant hydrogen-carbon weight ratio. This result suggests that decreasing the liquid-fuel residence time on the liner walls results in decreased combustor deposits. Hence, it would seem that the use of vapor fuel would eliminate deposits. However, as indicated in reference 22, some deposits were obtained on the vapor-fuel nozzle and in the combustor dome when a vapor fuel (propane) was used. These deposits were formed during incomplete combustion of the fuel in the complete absence of a liquid phase.

Fuel composition. - The effect of hydrocarbon type or composition on the tendency of diffusion flames to produce smoke is presented in chapter IX. The fuel types in order of decreasing tendency to smoke are naphthalene and substituted naphthalene compounds, aromatics, alkynes, olefins, and normal paraffins. The aromatics are about 12 times as smoky as the olefins and about 24 times as smoky as the normal paraffins. Naphthalene, with its high smoking tendency would be expected to cause large amounts of combustor deposit. Data of reference 21 (full-scale annular combustor, $10\frac{3}{8}$-in. diam.) show that 139 grams of coke was obtained with a mixture of α- and β-monomethylnaphthalene, 88 grams with triisopropylbenzene, 34 grams with benzene, and 2 grams with a normal paraffin fuel. Other investigators have shown that aromatic-type fuels generally cause a large amount of coke deposit. Some of this data is reported in references 9, 23, and 24 (full-scale single tubular combustors) and references 12, 20, and 25 (small-scale tubular combustors). An example of these data is shown in figure 125(b), where the combustor deposits increase with increase in aromatic content for constant values of volumetric average evaporated temperature. Some investigators have surmised that the highest-boiling fraction of the aromatic portion may be causing much of the combustor deposits. Information presented in reference 12 (small-scale tubular combustor) shows that combustor deposits increase as the percentage of aromatics boiling above 420° F increases. However, the quantity of coke deposits was not necessarily the same for different types of fuels that had the same percentage of aromatics boiling above 420° F.

Information concerning the effects of normal paraffins, isoparaffins, and cycloparaffins on combustor deposits indicates that these different fuel types have about the same coke-forming tendencies and that the amount deposited is appreciably less than that obtained from aromatic-type fuels. As shown in chapter IX, except for the normal paraffins, olefinic-type hydrocarbons have the lowest values of smoking tendency. In spite of these low values, larger deposits could possibly form because of the polymerizing characteristics of olefins. However, data from investigations reported in references 9, 23, and 26 (full-scale single tubular combustors) and reference 18 (full-scale annular combustor, $10\frac{3}{8}$-in. diam.) show that the quantity of deposits obtained with olefinic fuels is similar to that obtained from paraffin fuels of the same boiling range. One investigator (ref. 27) reported heavy deposits in a full-scale single tubular combustor from a fuel containing a considerable amount of diolefins. Unreported investigations conducted in a full-scale single tubular combustor with a fuel blend consisting of 50 percent JP-3 fuel and 50 percent dipentene showed an increase of about 25 percent in combustor deposits over those obtained with JP-3 fuel alone. For the same operating conditions, an aromatic fuel blend with an average boiling point of about 380° F caused an increase in deposits of about 230 percent over those for JP-3 fuel.

Nonhydrocarbon fuel components. - Sulfur compounds and gum are minor nonhydrocarbon components present in petroleum-derived aviation fuels that can have an effect on combustor deposits. Investigations conducted to determine the effects of sulfur on combustor deposits indicate that the quantity of sulfur in the fuel can be increased a considerable amount above the present specification MIL-F-5624C maximum of 0.4 percent before an appreciable increase in deposits is obtained. Results of some of these (full-scale single tubular combustor) investigations are shown in the following table:

Fuel	Additive for increasing sulfur content	Sulfur in fuel, percent by weight	Weight of deposit, g	Reference
Straight-run kerosene	None	0.05	4.1	9
		.5	3.1	
		1.0	5.0	
		3.0	7.2	
AN-F-58	None	0.034	3.1	28
	Thiophene	.39	2.3	
	Thiophene	.91	1.2	
	Disulfide oil	1.00	3.6	
MIL-F-5624A, grade JP-3	None	0.04	7.0	26
	Disulfide oil	.55	8.8	
	Disulfide oil	1.03	8.4	
	None	.04	5.6	
	Mixed butyl mercaptans	1.05	6.5	

It is noted that the sulfur content of a fuel can be increased to 1 percent or more before a significant increase in combustor deposits is obtained. Thiophene added to a fuel in amounts of 1 and 3 percent (0.39 and 0.91 percent sulfur) actually caused a decrease in deposits.

The majority of investigations that have been conducted to determine the effect of gum, either existent or potential, on combustor deposits show, in general, that the specification MIL-F-5624C maximum limits of 7 and 14 milligrams per 100 milliliters of fuel may be increased several times before an appreciable effect on combustor deposits is obtained. The following data were obtained from some of these investigations:

Fuel	Combustor	Gum, mg/100 ml		Weight of deposit, g	Reference
		Existent	Potential		
MIL-F-5624A, grade JP-3	Full-scale single tubular	7	12	12.6	26
		77	445	14.7	↓
		165	560	15.4	↓
MIL-F-5624A, grade JP-3	Full-scale single tubular fuel-vaporizing	9	12	2.1	26
		95	103	2.6	↓
AN-F-58	Full-scale single tubular	6.5	3.5	4.3	28
		4.3	4.2	3.3	↓
		21.1	25.3	4.1	↓
		34.1	55.8	4.8	↓

The existent and potential gum contents were determined by the A.S.T.M. Standards D381-46 and D525-46, respectively. It can be seen that a large increase in gum content is possible before any significant increase in combustor deposits is obtained. In the data from reference 26, the gum content of the fuels was increased without any appreciable change in other fuel characteristics. Information obtained from reference 29 showing the effect of existent gum content of fuels on deposits in small-scale tubular combustors (fuel-atomizing and fuel-vaporizing) is presented in the following table:

Fuel	Existent gum, mg/100 ml	Deposit weight, mg/hr			
		Atomizing-combustor flame tube or liner	Vaporizing combustor		
			Flame tube or liner	Outside vaporizer tube	Inside vaporizer tube
A174 (base)	6.1	260	9.0	1.5	16.2
A76	58.5	---	81.2	7.5	377.5
A84 (base)	5.2	216	16.6	7.0	13.5
A98	59.2	185	49.0	16.5	425.0

The data indicate that an existent gum content of about 8 or 9 times the maximum specification limit may cause large increases in the deposits in the vaporizing-combustor flame tube or liner and inside the vaporizer tube. Information presented in reference 30 shows that the vaporizing tubes plugged after about $1\frac{1}{2}$ hours of operation with a low-aromatic fuel with a gum content of 100 milligrams per 100 milliliters of fuel. This plugging caused rough burning and unsatisfactory operation of the combustor. Continued combustion with a plugged vaporizer tube would probably result in a complete tube failure.

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Elimination of Coke Deposits

The effects on combustor deposits of changes in combustor design and fuel injection, variation in combustor inlet-air variables, and changes in fuel quality can be qualitatively estimated from deposit formation mechanisms previously presented. From these considerations, methods for decreasing or eliminating combustor deposits can be proposed.

Combustor design. - Any design changes in the combustor that decrease or prevent liquid-fuel impingement on the liner walls decrease combustor deposits. Among the design changes by which deposit reduction may be effected are provisions for (1) fuel prevaporization, (2) increased "air wash" to the liner walls, (3) change of fuel-spray angle, and (4) liner temperatures either low enough to prevent thermal decomposition of the fuel or high enough to burn off the deposits. With fuel prevaporization, additional problems are encountered, such as plugging of vaporizing tubes, and these problems may overshadow the advantages of decreased combustor deposits. Increased "air wash" and changed fuel-spray angle may have adverse effects on combustion efficiency, stability, or altitude blow-out. It may be impracticable to keep liner temperatures below the fuel-decomposition temperature, and very high liner temperatures shorten liner life (ref. 18). It is apparent that the final combustor design must be a compromise involving several factors, and combustor coke deposition is only one of these factors.

Fuel-quality control. - Combustor deposits can be greatly affected by choice of fuel. As previously shown, deposits generally increase as the state of the fuel is varied from vapor to liquid and as the type of the fuel is varied from high to low volatility or from paraffin to aromatic. From the standpoint of reducing combustor deposits, the vapor fuel would be best. As previously mentioned, the special equipment needed to obtain vaporized fuel may be sensitive to coke deposits. However, continued research may overcome this problem. High-volatility fuels cannot be used in aircraft because tank losses due to fuel boiling and slugging become excessive (ref. 31). For liquid-fuel-atomizing combustors, the paraffin-type fuels cause less deposits than aromatic fuels. However, the availability of paraffin or nonaromatic fuels is limited. It can be seen that the final fuel will be a compromise depending on the amount of importance that is assigned to the various considerations.

Fuel additives. - Another means of reducing combustor deposits is by use of fuel additives. Additives effective in reducing or eliminating coke from commercial furnaces and Diesel engines may also be effective in turbojet combustors. Data of reference 32 (full-scale single tubular combustor) show a decrease in deposits when small amounts of tetraethyl lead were added to the fuel. Deposits decreased about 45 percent with a lead concentration of about 0.002 percent. Further increases in lead concentration eventually cause an increase in deposits because of increased amounts of lead oxides. With the need of JP fuels and military aviation gasoline in a national emergency estimated as about 1,000,000 and 300,000 barrels per day, respectively, the metallic lead needed per day for JP fuels (0.002 percent by weight) would be about $2\frac{3}{4}$ tons and lead required for aviation gasoline (4.6 ml TEL/gal) would be 55 tons per day. Other additives that reduced deposits were lead naphthenate, secondary amylnitrate, and commercial fuel-oil additives (refs. 16, 32, and 33; full-scale single tubular combustors). In small-scale combustors (refs. 34 to 36), the decreases in deposits were negligible with additives such as lead naphthenate, U.O.P. Inhibiter No. 5, amylnitrates, ditertiary butyl peroxide, and a commercial additive. Aviation tetraethyl lead in a concentration of 4 cubic centimeters per gallon (0.12 percent lead by weight) caused a considerable increase in deposits because of the lead deposits added to the coke. Reference 37 presents data for a large number of

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additives tested in small-scale atomizing and vaporizing combustors. The additives consisted of halogen compounds, antioxidants, organometallics, silicates, carbonyls, high-molecular-weight organics, and water. Tetraethyl lead (0.01 percent by volume) and iron pentacarbonyl (0.1 percent by volume) were the only additives that caused any appreciable decrease in combustor liner deposits, and water was the only additive that caused a decrease of fuel-vaporizer-tube internal deposits.

The results of various investigations to decrease combustor deposits by special fuel additives are not conclusive enough at the present time to determine whether the advantages are sufficient to offset such problems as storage stability, deleterious effects on engine fuel systems and hot engine parts, and perhaps availability. The over-all benefits must be determined by further research.

SMOKE FORMATION IN TURBOJET ENGINES

As previously indicated, smoke formation in turbojet combustion is less important than is coke deposition. There is no measurable loss in performance due to smoke, and, in fact, operating conditions conducive to smoke formation are the same conditions that yield generally high combustion efficiencies. For this reason, less work has been done in the field of smoke research in full-scale engines and in single combustors than has been done in the study of coking. The reverse has been true in bench-scale experimentation (ch. IX).

Bench-scale studies reported in chapter IX have shown that smoke can be formed only in a fuel-rich environment. The primary zone in turbojet combustors certainly contains local areas that are fuel-rich under most operating conditions, and it is likely that smoke is often generated in considerable quantities. The fact that smoke is not found in much higher concentrations in the turbojet exhaust indicates that much of this material is consumed in passing through the burner. This theory is confirmed by electron microscopy studies of turbojet smoke (ch. IX).

Smoke formation has been determined qualitatively in full-scale engines and single combustors by visual observation. Smoke has been determined quantitatively by either filtration and optical measurements or by collection and weighing. In the filtration method, the exhaust is passed through a filter at a given rate for a given time, and the darkening of the filter is then determined by either visual rating or by optical methods. This method was used in references 13, 14, 20, and 38. In references 27, 39, and 40, the smoke was trapped by bubbling the exhaust gases through water, and the smoke was weighed after filtration and drying. There has been no attempt to report absolute smoke values by either method; the data only indicate the effect obtained when a small and unreported fraction of the exhaust gas is sampled. Comparison between laboratories on an absolute basis is obviously impossible, and the results reported herein are given only as trends.

Effect of Operating Variables on Smoke Formation

A systematic study of the effect of inlet variables on smoke production was made in a full-scale tubular combustor using the filter-darkening technique (ref. 38). With a typical JP-3 fuel, the exhaust smoke increased from two- to tenfold as the inlet pressure increased from 35 to 65 inches of mercury absolute. The controlled variables were fuel type, inlet temperature, fuel-air ratio and inlet-air velocity. This effect of a marked increase in smoke with increasing pressure is also reported in reference 14 for pressures up to 350 inches of mercury absolute and in reference 13 for pressures up to 150 inches of mercury absolute. This effect of pressure is also fully confirmed in the bench-scale work reported in reference 11 and by the fact that, in flight, turbojet-powered aircraft leave the heaviest smoke trails at low altitudes.

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With the other variables constant, it was also shown in the work of reference 38 that smoke production increased from two- to four fold as the fuel-air ratio increased from 0.008 to 0.016. Above a fuel-air ratio of 0.016, there was a slight decrease in smoke up to a fuel-air ratio of 0.022. In the tests of reference 13, fuel-air ratios were varied up to 0.015 and in the tests of reference 20 up to 0.020. In both cases, the smoke production increased with increasing fuel-air ratio up to the highest ratios tested. These values are over-all fuel-air ratios, and the smoke was obviously formed in much richer mixtures. Bench-scale data plotted in figure IX-4 show that smoke continually increases with increasing fuel-air ratio. In general, there is agreement that smoke increases with increasing fuel-air ratio. The slight decrease at higher ratios reported in reference 38 is accounted for by the probability that increasing flame length at high fuel-air ratios consumed a large fraction of the smoke that was initially formed.

Both references 13 and 38 show that smoke formation is substantially independent of inlet-air temperature over the range between 100° and 400° F. This result is in full agreement with the bench-scale work reported in reference 41.

It is difficult to fully isolate the effect of inlet-air velocity as a variable in reference 38 since other air parameters vary simultaneously. However, it appears that smoke increases slightly with increasing velocity at low fuel-air ratios and decreases slightly with increasing velocity at high fuel-air ratios. Reference 13 shows a considerable decrease in smoke with increasing velocity at low fuel-air ratios, but the data are few and scattered. The effect of inlet-air velocity on smoke would be expected to be a function of combustor geometry, but little agreement is likely between investigators regarding this relation.

Smoke tests have been made on a full-scale engine running at near-sea-level conditions with a JP-3 fuel (ref. 38). Engine speed and exhaust-nozzle area were the controlled variables and fuel-air ratio and inlet-air pressure, temperature, and velocity were the dependent variables. Because the various inlet parameters cannot be independently varied in full-scale-engine testing, the independent effect of the parameters on smoke cannot be determined. In the tests of reference 38, smoke increased 3 to 4 times as engine speed increased from 5300 to 8000 rpm. Smoke increased to a lesser extent as nozzle area was decreased by 33 percent. The changes in engine operating conditions that increased smoke also increased fuel-air ratio, pressure, and temperature. It seems probable that increases in fuel-air ratio and pressure were the main factors contributing to increased smoke, a theory confirmed by the observations from both bench-scale and single-combustor studies.

Effect of Fuel Quality on Smoke Formation

A small amount of work has been done in several laboratories relating smoke formation to fuel quality. Four fuels of low aromatic content but of varying volatility were tested in a full-scale single combustor (ref. 38). As fuel volatility increased, the maximum values of smoke density did not change appreciably, but the fuel-air ratio at which maximum smoke was produced shifted to lower ratios. Data presented in references 19 and 20 and chapter IX indicate that smoke formation is less dependent on fuel volatility than on other fuel factors. Chapter IX shows that smoking tendency does not vary greatly with molecular weight in the range of molecular weights covered by the usual petroleum-derived fuels. However, the effect of hydrocarbon type on smoke production is quite pronounced, the aromatic fuels yielding considerably more smoke than the nonaromatic ones. References 19, 20, and 40 show this effect in combustor studies, and chapter IX shows it for bench-scale flames.

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Liner coke is quite dependent on both the hydrocarbon type and the volatility characteristics of fuels, the latter presumably being important since it relates to the residence time of liquid fuels on combustor walls. Smoke, on the other hand, is largely dependent on hydrocarbon type but is little affected by fuel volatility. Therefore, a poor correlation might be expected between the coking and smoking tendencies of fuels, and this poor correlation is, in fact, noted in references 20, 27, and 40.

EVALUATION OF FUEL DEPOSIT-FORMING CHARACTERISTICS

Since the influence of fuel quality on coke deposition is a matter of considerable importance affecting the performance and reliability of turbojet engines, it would be desirable to have laboratory tests that could be used to evaluate and control the quality of such fuels. In general, the most accurate deposit-forming evaluation of fuels is made by operating complete engines under service conditions. This approach is prohibitively expensive, and easier methods have been sought.

A fairly close approach to the prototype testing of turbojet fuels has been made by taking single combustors from full-scale engines and using these in connected-duct facilities. A considerable amount of deposit-formation work has been done in such test units. In order to determine whether results of tests with single full-scale combustors can be related to full-scale-engine coke deposition, several full-scale-engine tests were conducted. The full-scale engines were operated on test stands (refs. 2 and 4). Results of some flight test data are also available and can be used for comparison (appendix B of ref. 1 and refs. 3 and 6). The results show, in general, a good relation between deposits in full-scale single combustors and full-scale engines. However, even full-scale single-combustor testing is too costly in terms of facilities, power, fuels, and time to permit its use for the control of fuel quality by manufacturers.

Therefore, considerable effort has gone into the development of either a simple bench-scale test which will correlate with the performance of fuels in engines or the correlation of other easily determinable fuel properties with full-scale-engine performance. Since little quantitative full-scale engine data are available on the coke-forming tendencies of turbojet fuels, much of this effort has been toward correlating bench-scale results with the results from single-combustor testing. There has been no complete agreement concerning the best correlating test. The following discussion describes the progress that has been made to date.

Correlation of Fuel Properties With Coke Deposit Formation

Certain fuel characteristics and related properties are considered to affect coke deposits. These include hydrogen-carbon ratio, aromatic content, A.S.T.M. distillation temperatures, gravity, and aniline point. These properties have been used singly and in combinations to help indicate the coke-forming tendency of a fuel. One drawback to the use of fuel properties to relate combustor deposits to the fuel is that these properties do not give any indication of the effect of special fuel additives on deposits.

Hydrogen-carbon ratio and volatility. - Early investigators attempted to relate the carbon and hydrogen contents of a fuel and some measure of its volatility to combustor deposits. Deposits from several fuels obtained in a small-scale combustor (ref. 20) were empirically related to the fuel as follows:

$$\text{Weight of deposits} = \frac{\log\,(n_C/n_H + C_1)}{C_2} + \frac{T}{C_3} + C_4 \qquad (1)$$

where

$C_1 \ldots C_4$ constants

n_C/n_H ratio of carbon atoms to hydrogen atoms

T A.S.T.M. 10-percent distillation temperature, $^{\circ}F$

The fuels varied from low-boiling or high-volatility cycloparaffins to low-volatility aromatics, and also included high- and low-volatility fuel blends. In general, the combustor deposits increased with an increase in the value of equation (1), although a considerable scatter was obtained.

The logarithm of the combustor-deposit values obtained from 19 fuels (ref. 21; full-scale annular combustor, $10\frac{3}{8}$-in. diam.) were empirically related to the fuels by a factor designated as the NACA K factor and shown as

$$\text{Log of combustor deposits} = a + b\,K \qquad (2)$$

$$K = (t + 600)(0.7)^{\frac{H/C - 0.207}{H/C - 0.259}} \qquad (3)$$

where

a,b constants

t fuel volumetric average evaporated temperature, $^{\circ}F$

H/C hydrogen-carbon weight ratio

The fuels consisted of high- and low-volatility paraffins, olefins, aromatics, and fuel blends. Examples of the relation of the NACA K factor to deposits of various fuels obtained in a small-scale tubular combustor, a full-scale single tubular combustor, and a full-scale tubular combustor engine are shown in figure 126. The deposits from most of the fuels can be estimated by this relation, although some fuel deposits show wide variations.

Aromatic content and volatility. - Both the total aromatic content of a fuel and the aromatics boiling above 400° or 420° F have been used in attempts to relate combustor deposits to fuel properties. Some of this type of data is presented in references 12 (small-scale combustor) and 23 (full-scale single combustor). The full-scale-combustor data show a regular increase in deposits with increase in total aromatic content. Although the small-scale-combustor data indicate an increase in deposits with aromatics and aromatics boiling above 420° F, the increase does not show any regular trend, and different fuels with the same aromatic content gave different deposit values.

Other investigators have used aromatic content of a fuel and some measure of volatility as a means of relating combustor deposits to the fuels. For example, as shown in reference 23 (full-scale single tubular combustor), the logarithms of the

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combustor-deposit values of several fuels are plotted against the percentage of aromatics by weight plus one-tenth of either the 80- or 90-percent A.S.T.M. distillation temperature. The combustor deposits of some fuels can be estimated with reasonable accuracy by this relation; however, wide variations are obtained with other fuels.

Volatility, density, and aniline-gravity constant. - Fuel properties such as specific gravity or density, volatility, and aniline point are easily determined and therefore are desirable for use in a bench or control test to determine the combustor deposit-forming tendency of fuels. Data of reference 19 (full-scale single tubular combustor) show how combustor deposits of several fuels vary with molal average boiling point of the fuel and Universal Oil Products (U.O.P.) characterization factor.

$$\text{U.O.P. factor} = \frac{(T_b)^{1/3}}{\text{Sp.gr. } 60^\circ/60^\circ \text{ F}} \tag{4}$$

where

T_b mean average boiling point, $^\circ$R

There is a general trend of increased combustor deposits with decrease in U.O.P. factor, although some fuels vary from this trend. Information presented in reference 40 for a full-scale single tubular combustor also shows a similar relation of combustor deposits to the U.O.P. characterization factor.

The U.O.P. characterization factor, the hydrogen-carbon ratio, and, to some extent, gravity are all related to the aromaticity of a fuel. Therefore, different combinations of these various fuel properties should give about the same trend of deposits with fuel.

The aniline-gravity constant (product of the aniline point in $^\circ$F and the A.P.I. gravity) is another fuel property that has been used to rate fuels for their coke-forming tendencies (ref. 1, full-scale single tubular combustors). With this fuel property there was wide variation in the data.

The A.P.I. gravity has been used to estimate the coking tendency of fuels. Data presented in reference 1 (full-scale single tubular combustors) show examples of a general decrease in deposits with increase in A.P.I. gravity (decrease in sp. gr.) and other examples where this trend is not so evident. Data of reference 42 show a regular decrease in deposits with increase in A.P.I. gravity.

Laboratory Measurement of Fuel Coke-Forming Characteristics

There does not appear to be a chemical or physical or combination chemical-physical property of a fuel that will consistently give an accurate estimation of the coke-forming tendency of a fuel. Therefore, investigations were conducted to determine whether some type of laboratory combustion test would give a satisfactory coke-forming rating among fuels.

The investigations included smoke-lamp, flame-plate, and small-pot-burner methods. Although small-scale combustors could be classed as laboratory equipment, for the data presented herein, they are discussed along with the full-scale combustors.

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Smoke-lamp method. - One simple bench test that has been used by several investigators is the fuel smoke-point determination by some type of smoke lamp. A simple wick lamp is used to determine the maximum height of a smoke-free flame of a particular fuel. The different types of lamp and test procedure are described in chapter IX. The smoke point is defined as the maximum height of a smoke-free flame in millimeters h; smoking tendency of a fuel is defined as $\frac{320}{h}$. Information presented in references 1 (full-scale single tubular combustors) and 12 (small-scale tubular combustor) shows a trend of increasing deposits with decrease in the smoke point; however, there is considerable variation in the data. The average deviation of some of the deposit data of reference 1 from a curve faired through the data is about 16 percent. The data from reference 12 indicate an average deviation of about 60 percent. An example of some of these data is given in figure 127, which is a plot of smoking tendency (320/h) and combustor deposits of 16 fuels tested in a full-scale single tubular combustor. This figure indicates some relation between smoke point and combustor deposits, although some of the data show wide variations. The smoke-point test is not affected by small amounts of special fuel additives (ch. IX), but combustor deposits may be decreased by addition of small amounts of these same additives.

In an attempt to eliminate variations in the data, investigators have included the boiling point of a certain fraction of the fuel or a certain function of the boiling point. Data in reference 43 show the relation of combustor deposits obtained with 16 fuels in a full-scale annular combustor ($10\frac{3}{8}$-in. diam.) to a function of boiling temperature and smoke point. A somewhat different relation is presented in reference 44 (small-scale tubular combustor) relating combustor deposits to a function of smoke point and boiling point. Coke deposits are related to

$$0.1\ \left(\begin{array}{l}\text{90-Percent distil-}\\ \text{lation temperature, }{}^{\circ}\text{F}\end{array}\right) + \frac{\begin{array}{l}\text{100 (Volume percent boil-}\\ \text{ing above 400}^{\circ}\text{ F)}\end{array}}{\begin{array}{l}\text{Smoke point of fuel boil-}\\ \text{ing above 400}^{\circ}\text{ F, mm}\end{array}} - \text{smoke point, mm} \qquad (5)$$

The average deviation of data from a faired curve was about 21 percent for the annular combustor (ref. 43) and about 14 percent for the small-scale combustor (ref. 44).

The following relation for Smoke Volatility Index (SVI) (ref. 15) has been used with some success to determine which fuels will produce above average amounts of combustor deposits in full-scale engines:

$$\text{SVI} = \text{smoke point} + \frac{\begin{array}{c}\text{volume percent of fuel boiling under 400}^{\circ}\text{ F}\\ \text{A.S.T.M. distillation temperature}\end{array}}{2.4} \qquad (6)$$

This relation is used in current military procurement fuel specification MIL-F-5624C, grades JP-3 and JP-4, to limit the carbon-forming tendency of these fuels. The specification requires that fuels have SVI values greater than 54. Figure 3(a) of reference 46 shows the SVI values of 21 fuels plotted against deposits obtained in a full-scale single combustor. The average deviation from a faired curve is about 27 percent. Data showing the relation of the SVI and liner deposits obtained in a full-scale single fuel-vaporizing combustor are given in reference 30. These data indicate a much larger average deviation.

Flame-plate method. - Another bench test that has been used to determine the coke-forming tendency of a fuel is known as the flame-plate test. Fuel is delivered dropwise to the surface of a tared stainless steel plate maintained at a constant elevated temperature. The vaporized fuel is ignited by a bunsen burner pilot, and, after a specified amount of fuel is burned, the plate is reweighed to determine the amount of deposits. The apparatus and procedure are more fully described in references 12, 47, and 48. Results presented in reference 48 show good agreement between the deposits obtained from the flame-plate test and deposits obtained from the same fuels tested in a full-scale single tubular combustor. The effect of such fuel properties as gravity, percent aromatics, and percent aromatics boiling above 420° F on flame-plate-deposit quantity is shown in reference 12. In reference 35, information is presented showing the effect of special fuel additives on flame-plate deposits. Use of tetraethyl lead, U.O.P. Inhibitor No. 5, and amylnitrate resulted in decreased flame-plate deposits of 50 to 90 percent. Small amounts of tetraethyl lead and secondary amylnitrate also reduced deposits in full-scale single combustors. However, the effect of amylnitrate and U.O.P. Inhibitor No. 5 on deposits in a small-scale combustor appeared negligible. One drawback to this bench test is the considerable amount of time required to complete the test ($6\frac{1}{2}$ hr).

Pot-burner method. - Another bench test apparatus that has been used to a limited extent is the "pot burner" (ref. 49). Fuel is fed to a small combustion chamber at a known rate and burns as it enters the chamber. The weight of deposit is determined by weighing the residue scraped from the combustion chamber after a predetermined run time.

Summary of laboratory tests. - In summary, several laboratory and bench tests have been used for determining the deposit-forming tendency of fuels. The tests included methods using the smoke point, the smoke point in combination with a particular boiling point, a flame plate, and a "pot burner." None of the methods listed consistently predicts the combustor-deposit-forming characteristics of various fuels. However, a method that can be used as a first approximation is the smoke-point method with some function of the distillation temperature. This type of test also has the advantage of requiring simple apparatus and only a little time for the determination. The Smoke Volatility Index defined by equation (6) appears to give as consistent results as do any of the methods.

SIGNIFICANCE OF COKE DEPOSITION AND SMOKE-FORMING RESEARCH IN APPLICATION TO JET-ENGINE FUEL SPECIFICATION AND COMBUSTOR DESIGN

The information presented in chapters IX and XIII indicates that coke in a jet-engine combustor liner may be formed from liquid-fuel cracking on the hot liner walls. The softer coke in the dome appears to be a combination of high-boiling fuel fractions and partly polymerized products mixed with a large amount of smoke.

A high-volatility paraffin-type fuel will cause the least deposits. Decrease in fuel volatility causes an increase in combustor deposits but has no significant effect on exhaust smoke. Increase in aromatic content of a fuel causes large increases in combustor deposits and also exhaust smoke. Minor fuel components, such as sulfur and gum, have no effect on combustor deposits until their concentrations are considerably above the maximum permitted by present fuel specifications.

Combustion-chamber inlet-air variables of pressure and fuel-air ratio cause increases in combustor deposits and exhaust smoke; however, the effects of combustor inlet-air temperature and velocity on deposits are not conclusive. Future turbojet engines will have higher inlet-air pressures and mass air flows; these are both conducive to combustor-deposit formations. The higher mass air flows which require more fuel cause an increase in combustor deposits. Because of these considerations, it may be more practical to use special fuel additives to hold the deposits down to a tolerable level. In some investigations very small amounts of tetraethyl lead and lead naphthanate (0.002 percent lead) caused a significant decrease in combustor deposits.

Any combustion-chamber and fuel-injector design that prevents liquid fuel from impinging on the combustor walls or decreases the residence time of liquid fuel on the hot combustor liner walls will decrease combustor deposits. For example, increasing "air wash" to liner walls should decrease fuel residence time, and, therefore, combustor deposits. Combustion with a properly designed vapor-fuel-injection system should be relatively free of liner deposits.

As previously indicated, a high-volatility paraffin-type fuel will give the least combustor deposits. However, considerations of availability require the final fuel to be a blend of the various types. In an attempt to determine whether the deposit-forming tendency of various fuel blends can be related to fuel properties, investigations were made of properties such as aromatic content, aromatics and volatility, hydrogen-carbon ratio and volatility, density, and aniline-gravity constant. Of these properties, a function of hydrogen-carbon ratio and the 50-percent-evaporated temperature seemed to give the best relation of fuel properties to combustor deposits.

Laboratory and bench test methods for determining the coke-forming characteristics of fuels include the smoke-point method with some measure of volatility, the flame-plate method, and the "pot-burner" method. The Smoke Volatility Index

$$\left(\text{smoke point} + \frac{\text{volume percent boiling under } 400^{\circ}\text{ F A.S.T.M. distillation temperature}}{2.4}\right)$$

seemed to be the best method because of the accuracy of the results, the simple equipment needed, and the short time required for the determination.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 7, 1955

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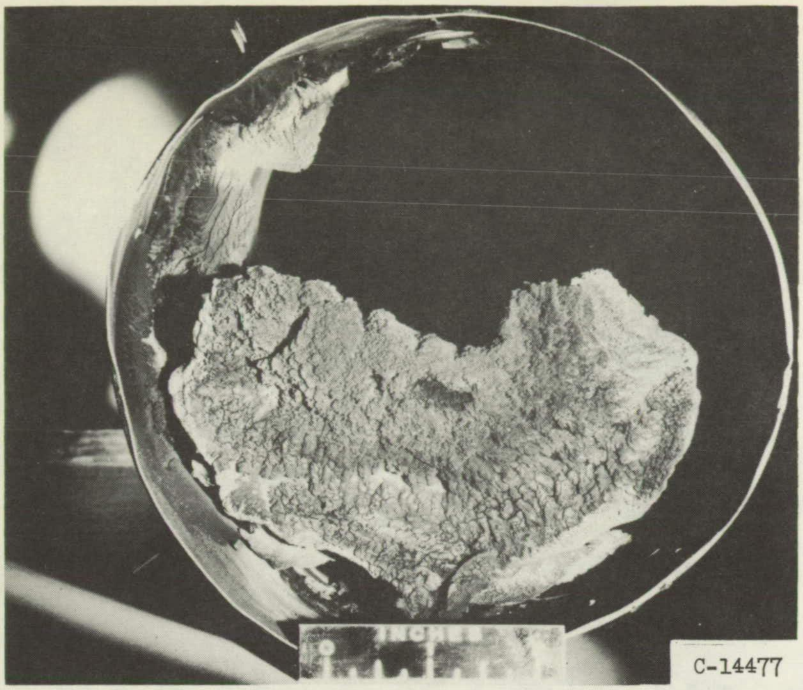
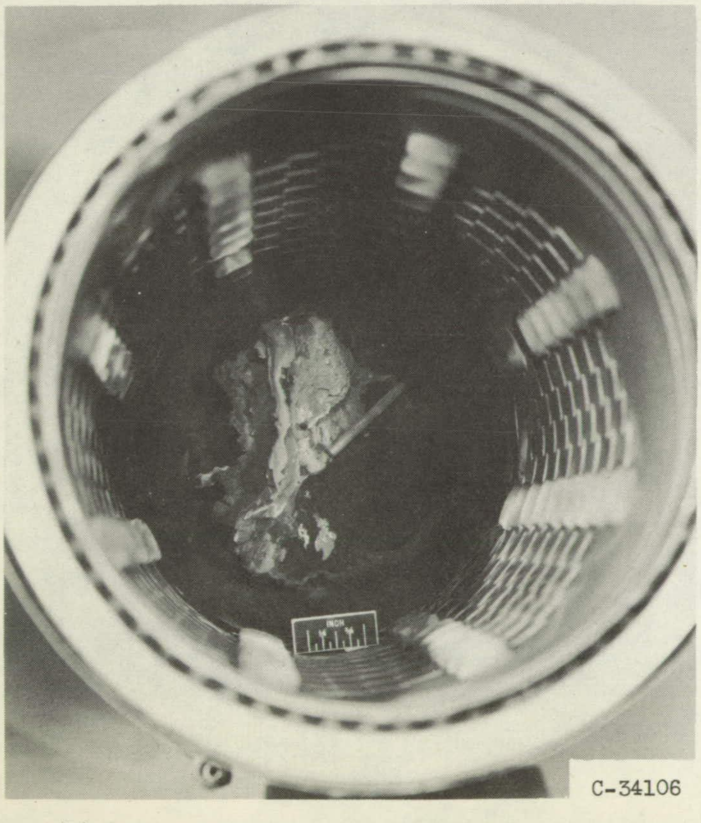
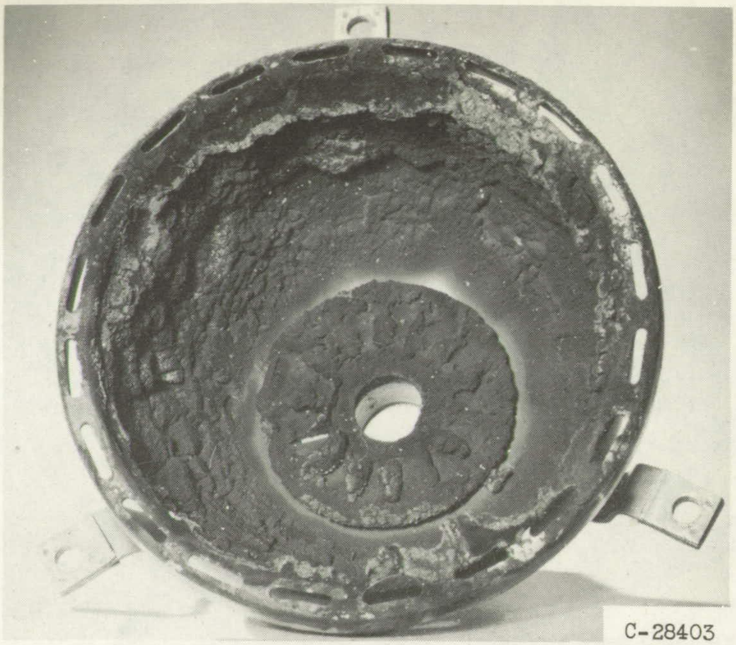


(a) On liner after 2-hour run with Diesel fuel oil (ref. 50).

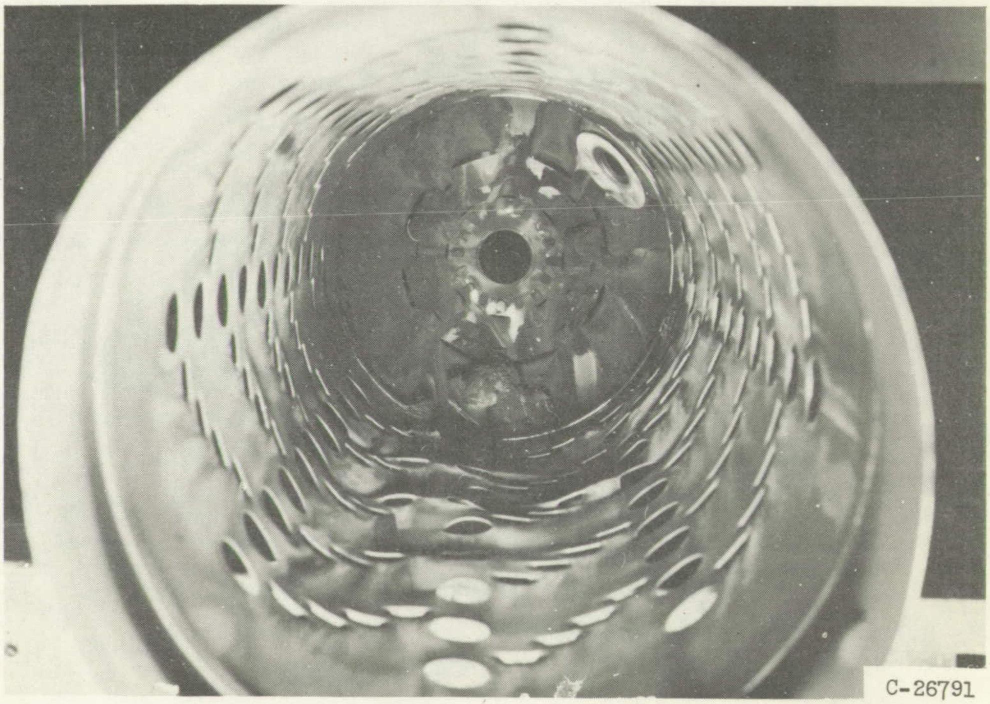


(b) On liner after 25-hour run with JP-4 fuel.

Figure 116. - Coke deposits in full-scale-engine combustors.


C-28403

(c) On dome and primary-air entry ports after 30-hour run with JP-3 fuel.


C-26791

(d) On liner near warped and cracked area after 25-hour run with JP-3 fuel (ref. 4).

Figure 116. - Continued. Coke deposits in full-scale-engine combustors.

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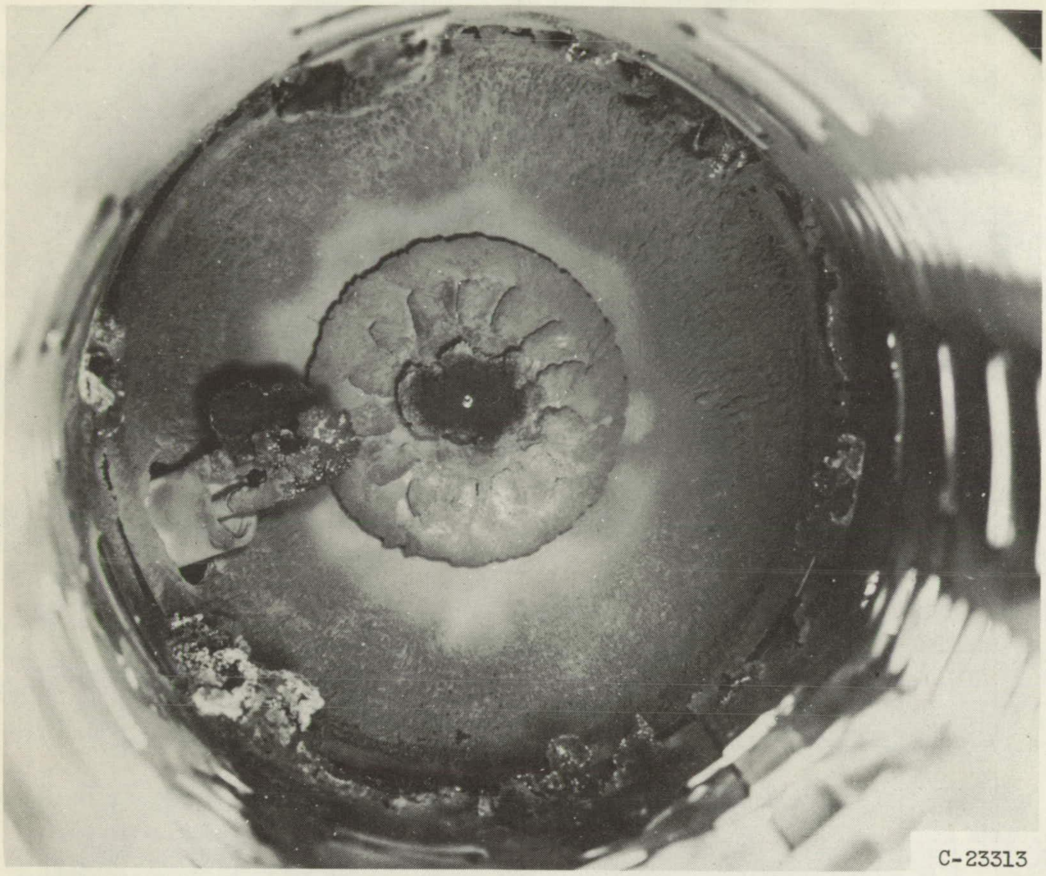


C-23313

(e) On liner, fuel nozzle, primary-air entry ports, and spark plug after 12-hour run with aromatic fuel (ref. 51).

Figure 116. - Concluded. Coke deposits in full-scale-engine combustors.

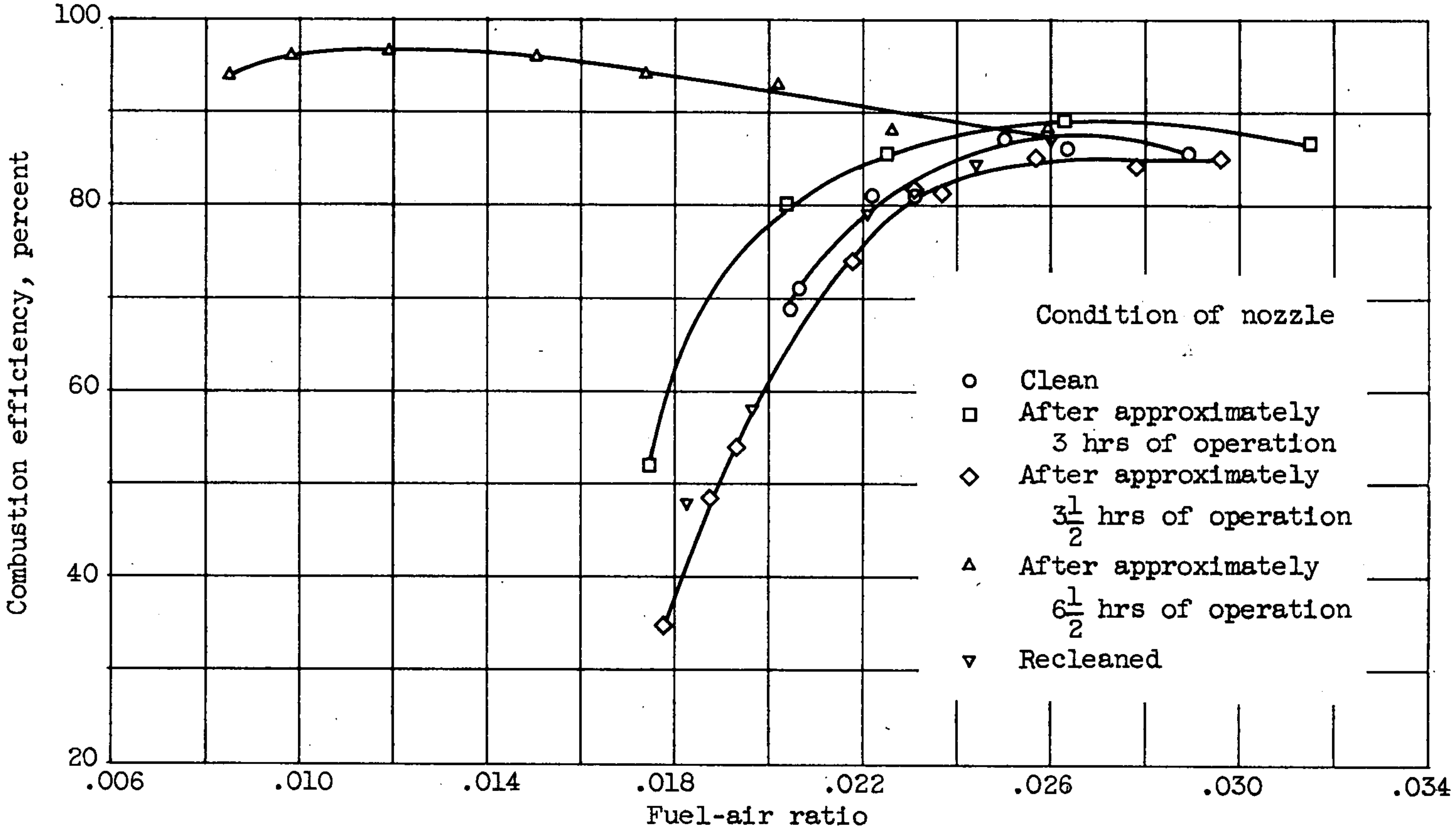
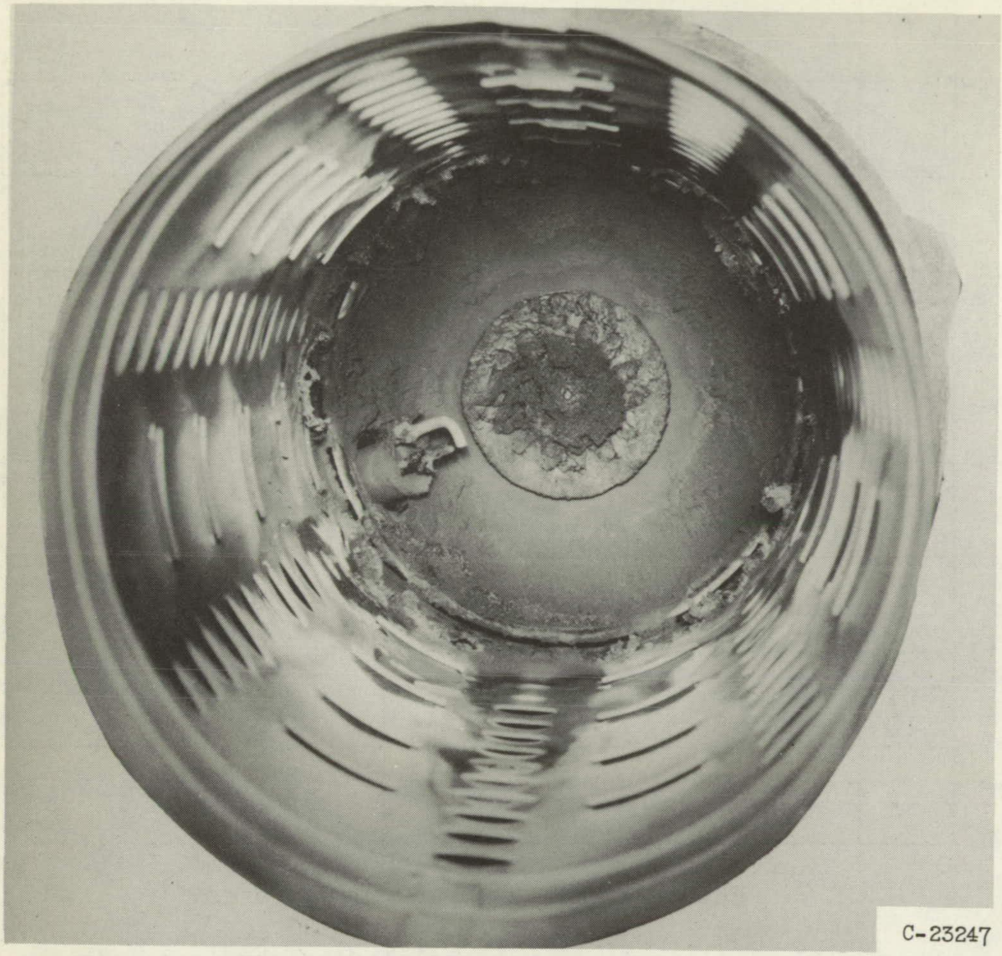


Figure 117. - Variation of combustion efficiency with fuel-air ratio as affected by coke formation on fuel nozzle of single tubular turbojet combustor. Inlet-air pressure, 6.1 pounds per square inch absolute; inlet-air temperature, 550° R; air-flow rate, 0.457 pound per second (ref. 52).



C-23247

Figure 118. - Coke deposits obtained in single tubular combustor during 80-hour test run. Fuel, high-aromatic MIL-F-5624A, grade JP-3; engine conditions: altitude, 20,000 feet; 90-percent normal rated engine speed; flight Mach number, zero (ref. 7).

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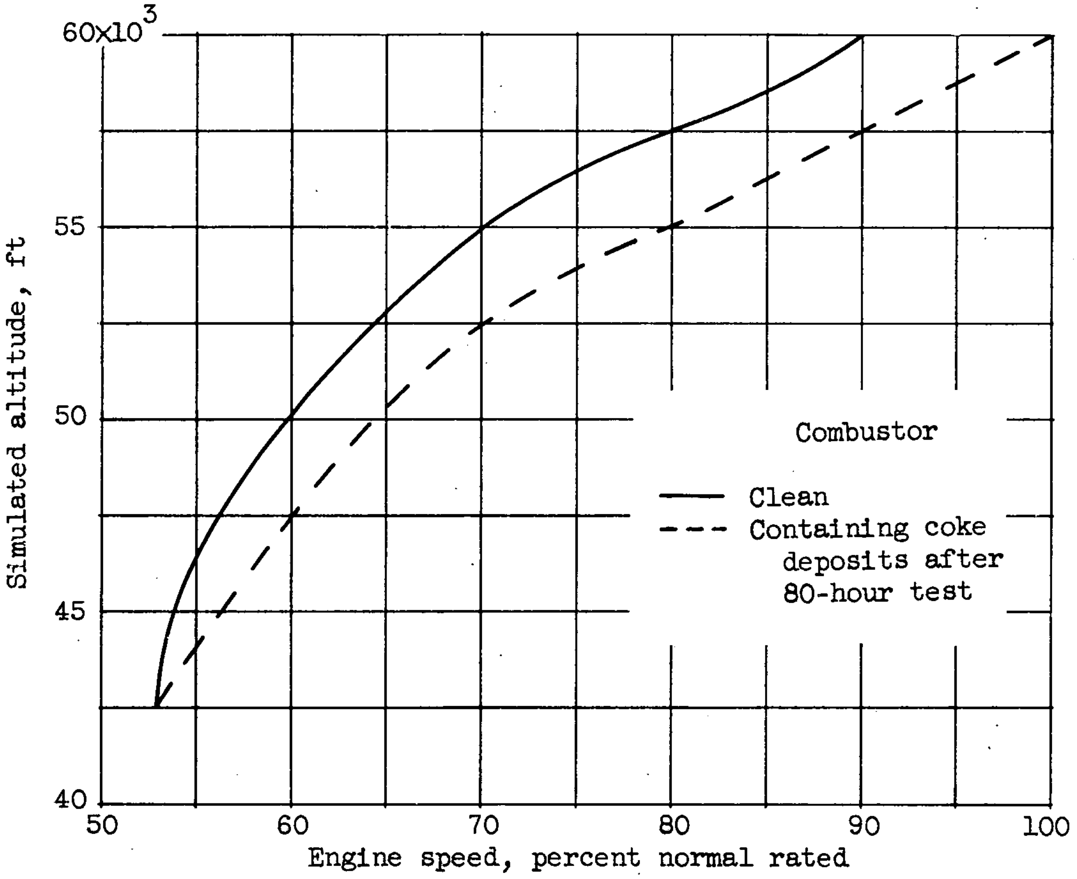


Figure 119. - Altitude operational limits obtained in clean single tubular combustor and in combustor containing coke deposited during 80-hour test. Fuel, minimum-quality MIL-F-5624A, grade JP-3 (ref. 7).

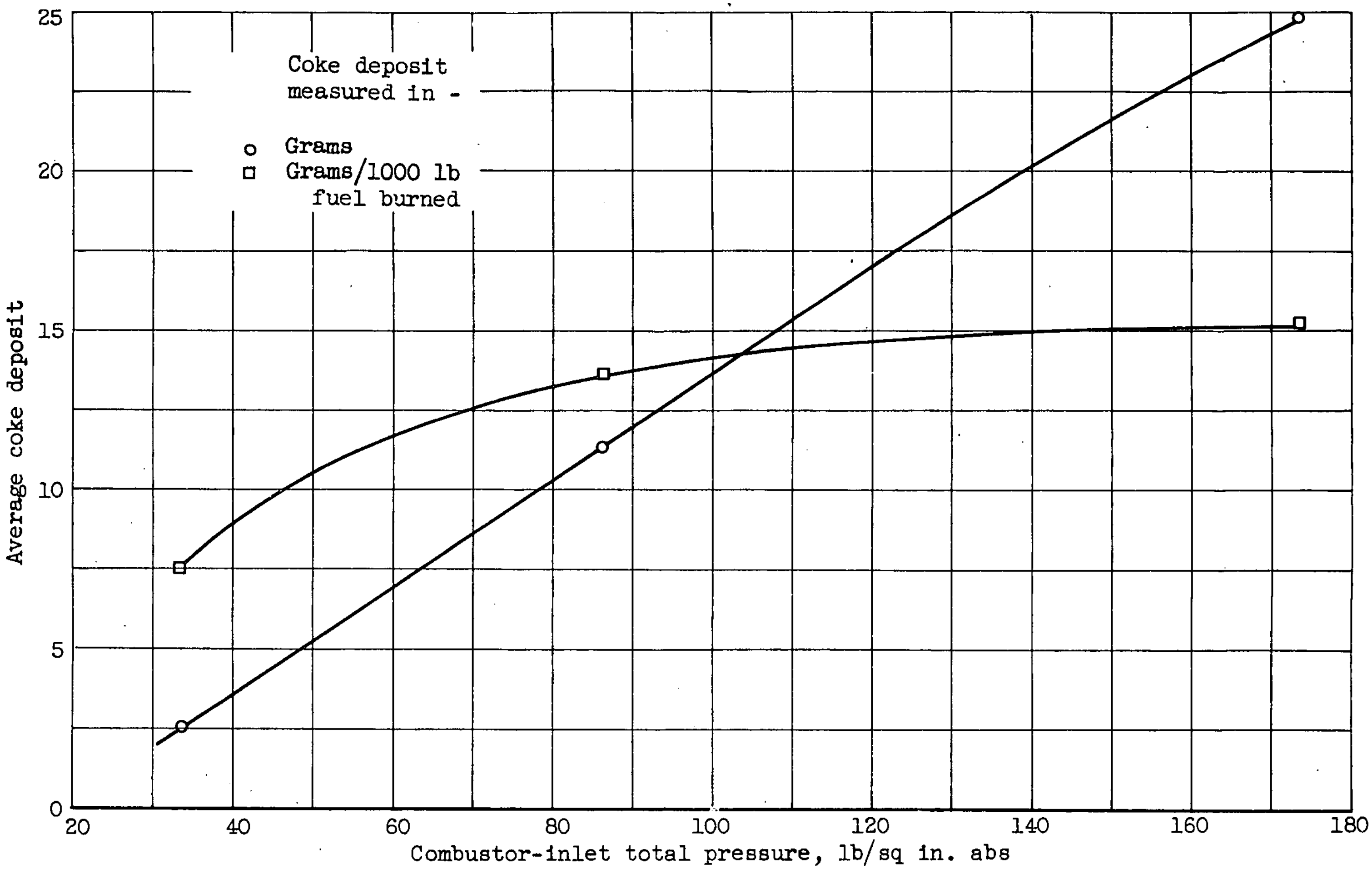
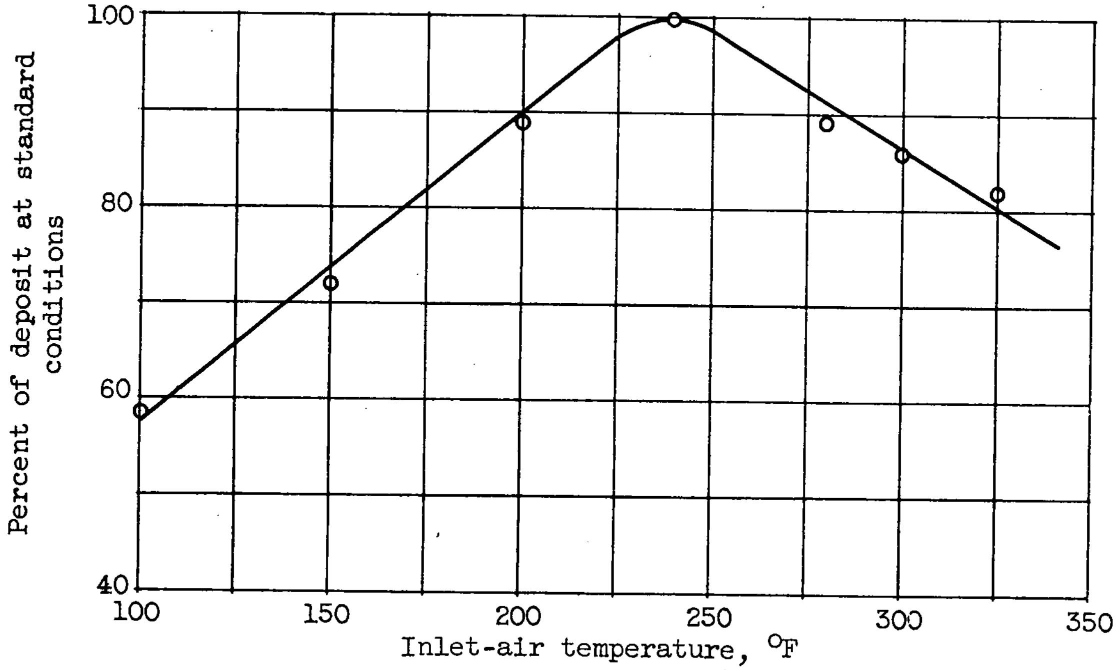
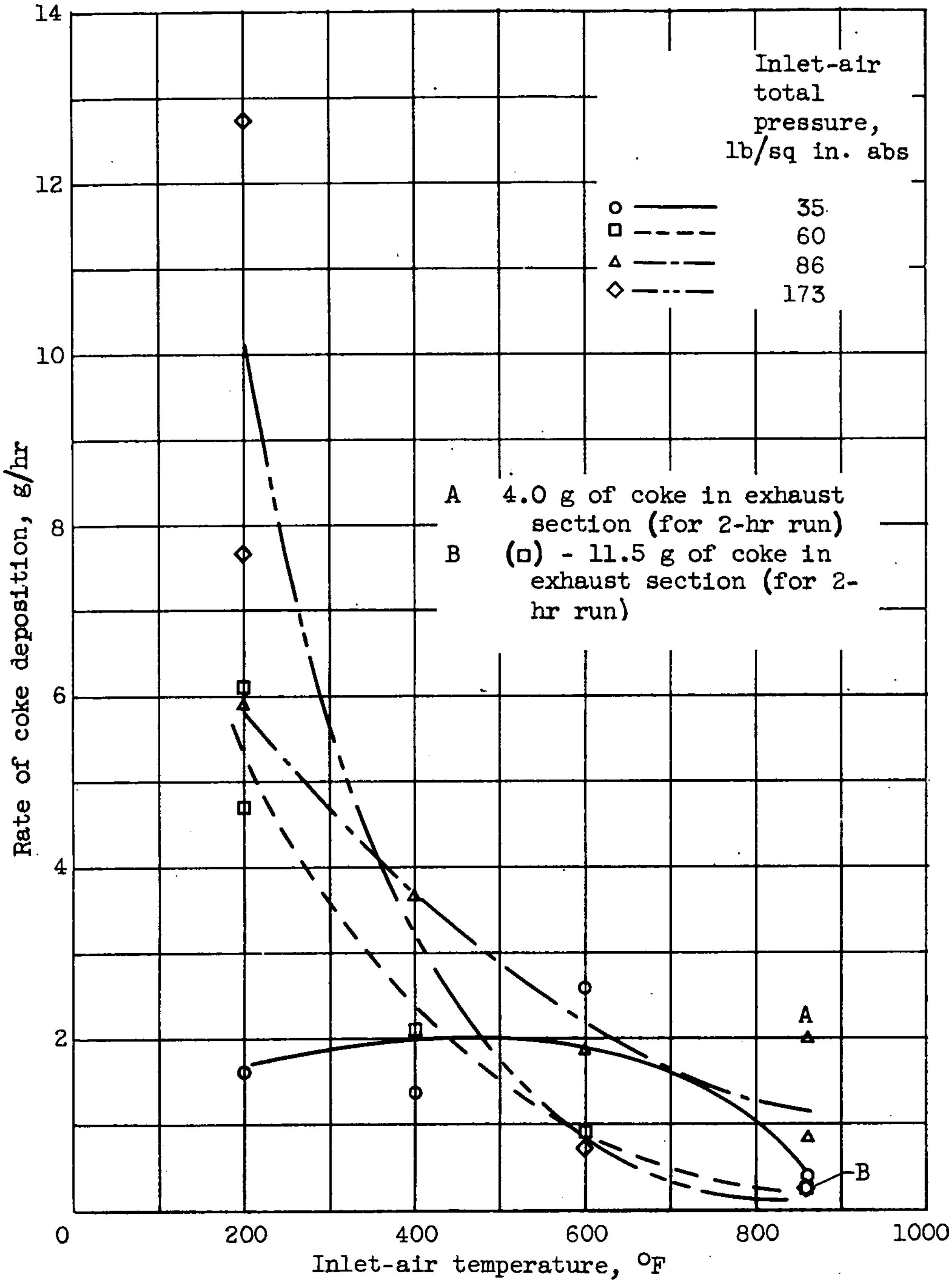


Figure 120. - Effect of combustor-inlet total pressure on coke deposition in full-scale single tubular combustor. Combustor reference velocity, 78 feet per second; inlet-air temperature range, 218° to 253° F; fuel-air-ratio range, 0.0166 to 0.0174; JP-4 fuel; run time, 2 hours (ref. 14).



(a) Small-scale combustor. Inlet pressure, 48 inches of mercury absolute; total mass air flow, 435 pounds per hour; fuel-air ratio, 0.0133; JP-1 fuel; run time, 2 hours (ref. 15).

Figure 121. - Effect of inlet-air temperature on coke deposition in tubular combustors.



(b) Full-scale single combustor. Inlet reference velocity, 78 feet per second; combustor temperature rise, 1165° F (ref. 18).

Figure 121. - Concluded. Effect of inlet-air temperature on coke deposition in tubular combustors.

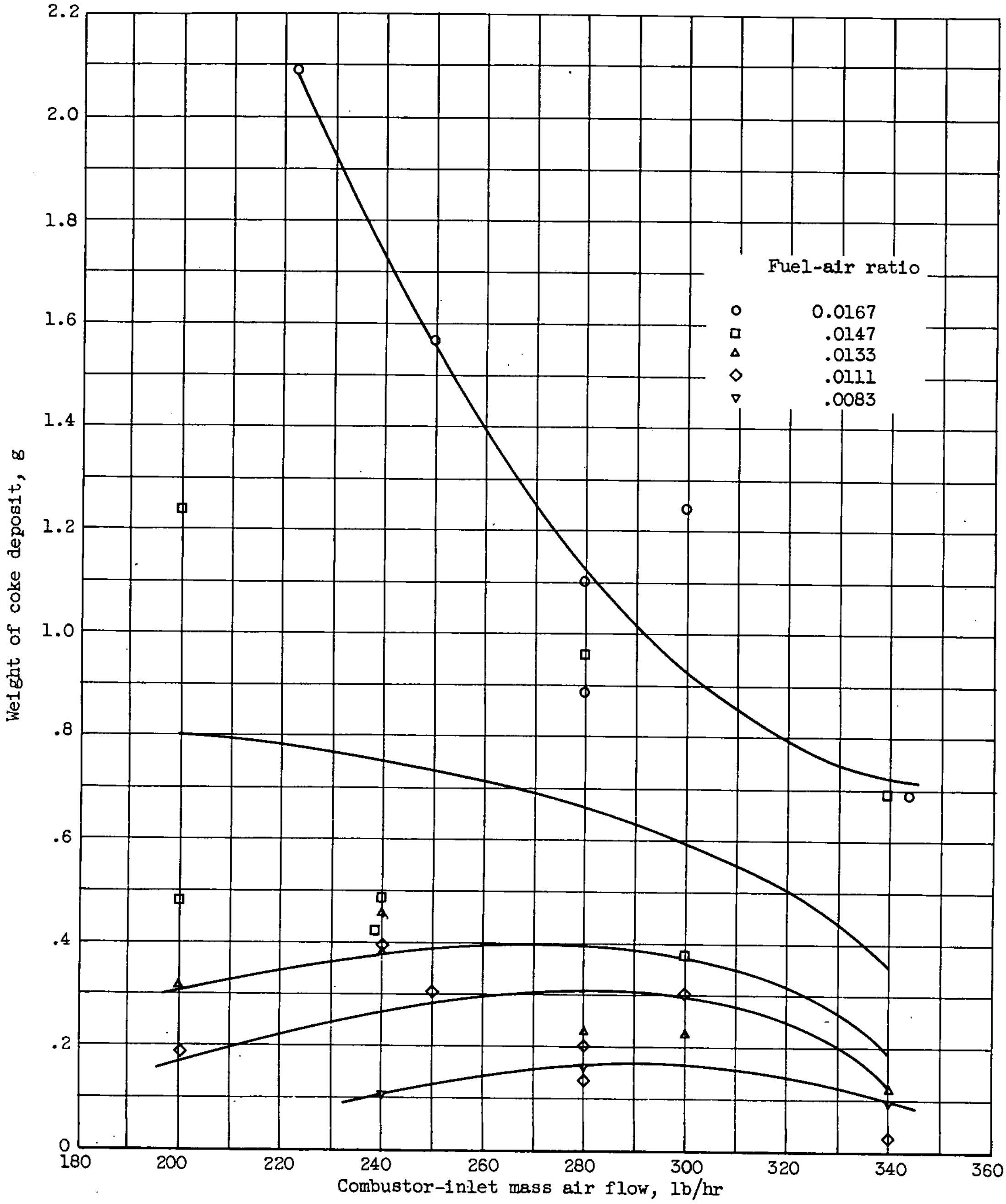


Figure 122. - Effect of combustor-inlet mass air flow and fuel-air ratio on coke deposition in small-scale tubular combustor. Combustor-inlet pressure, 20 pounds per square inch; JP-1 fuel; run time, 15 minutes (ref. 20).

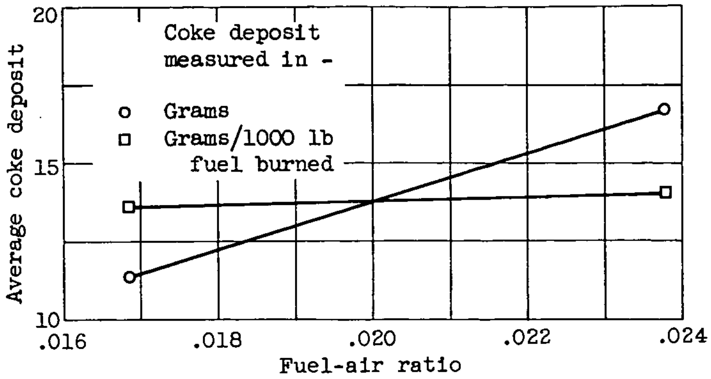


Figure 123. - Effect of fuel-air ratio on carbon deposition in full-scale single tubular combustor. Inlet-air total pressure, 86.2 pounds per square inch absolute; combustor reference velocity, 78 feet per second; inlet-air temperature range, 239° to 246° F; JP-4 fuel; run time, 2 hours (ref. 14).

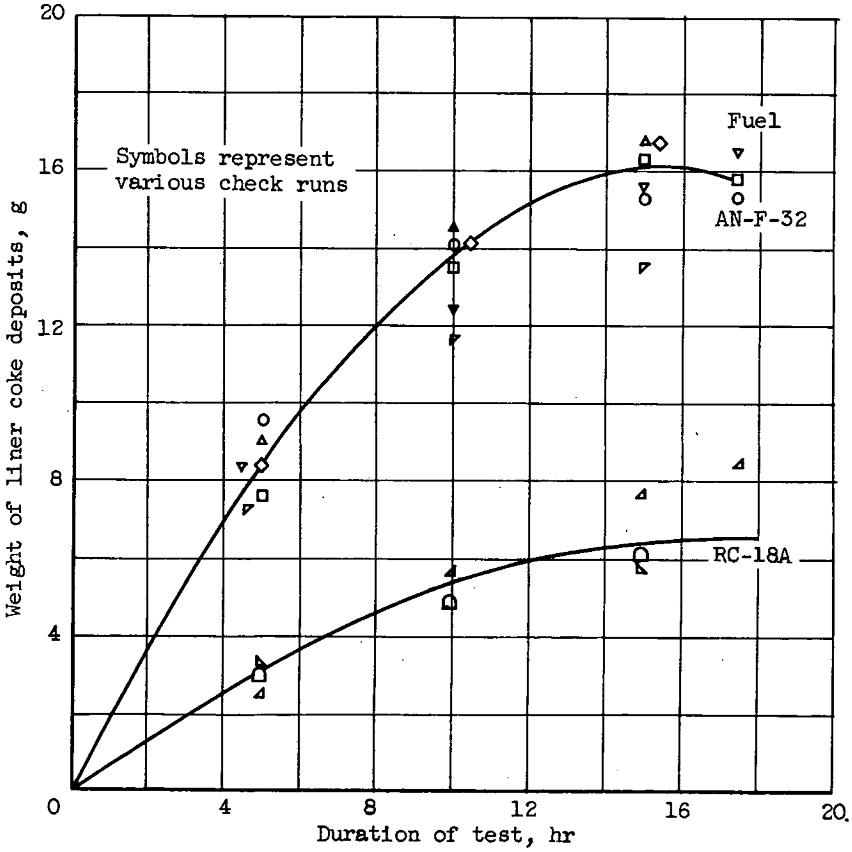
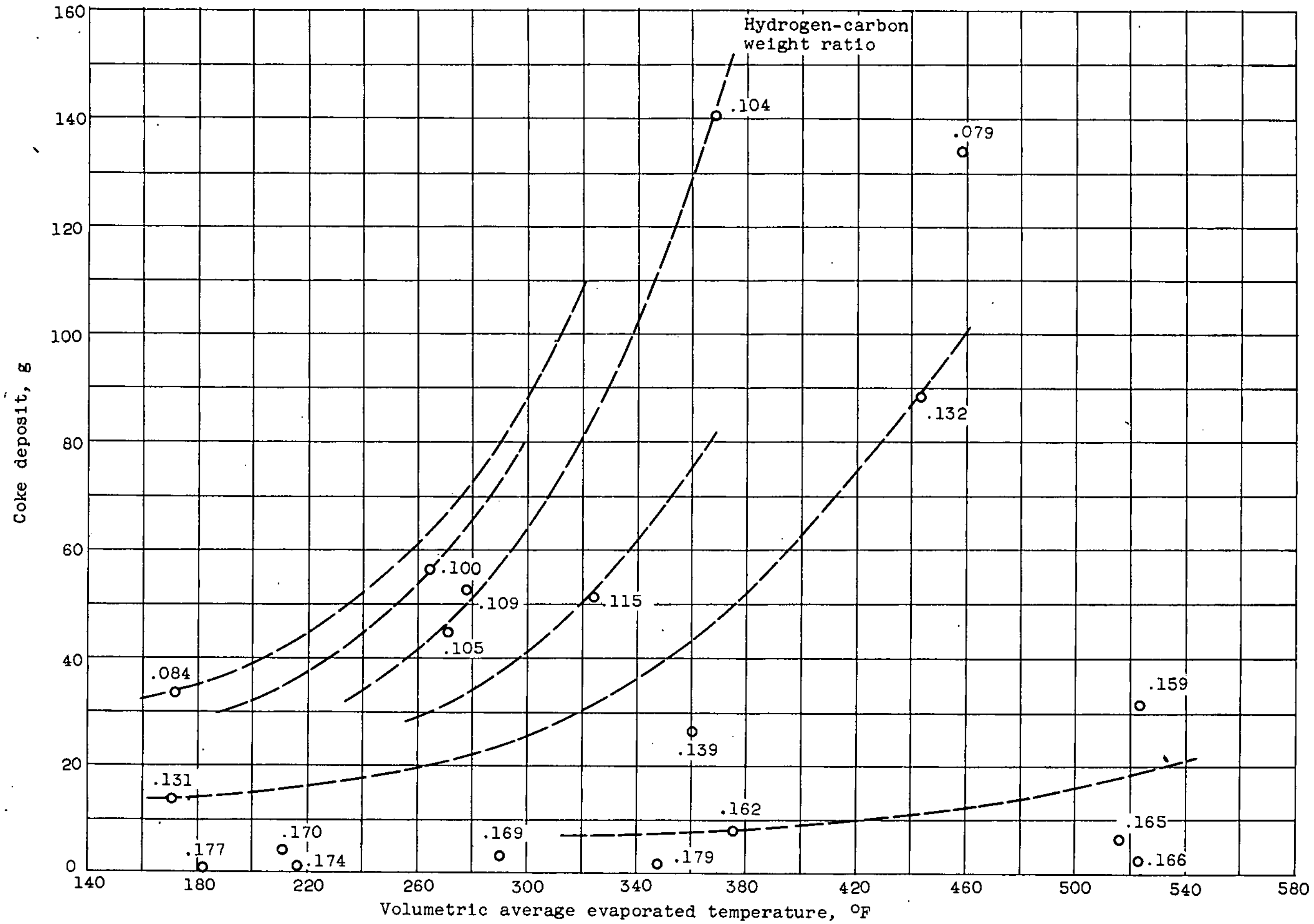
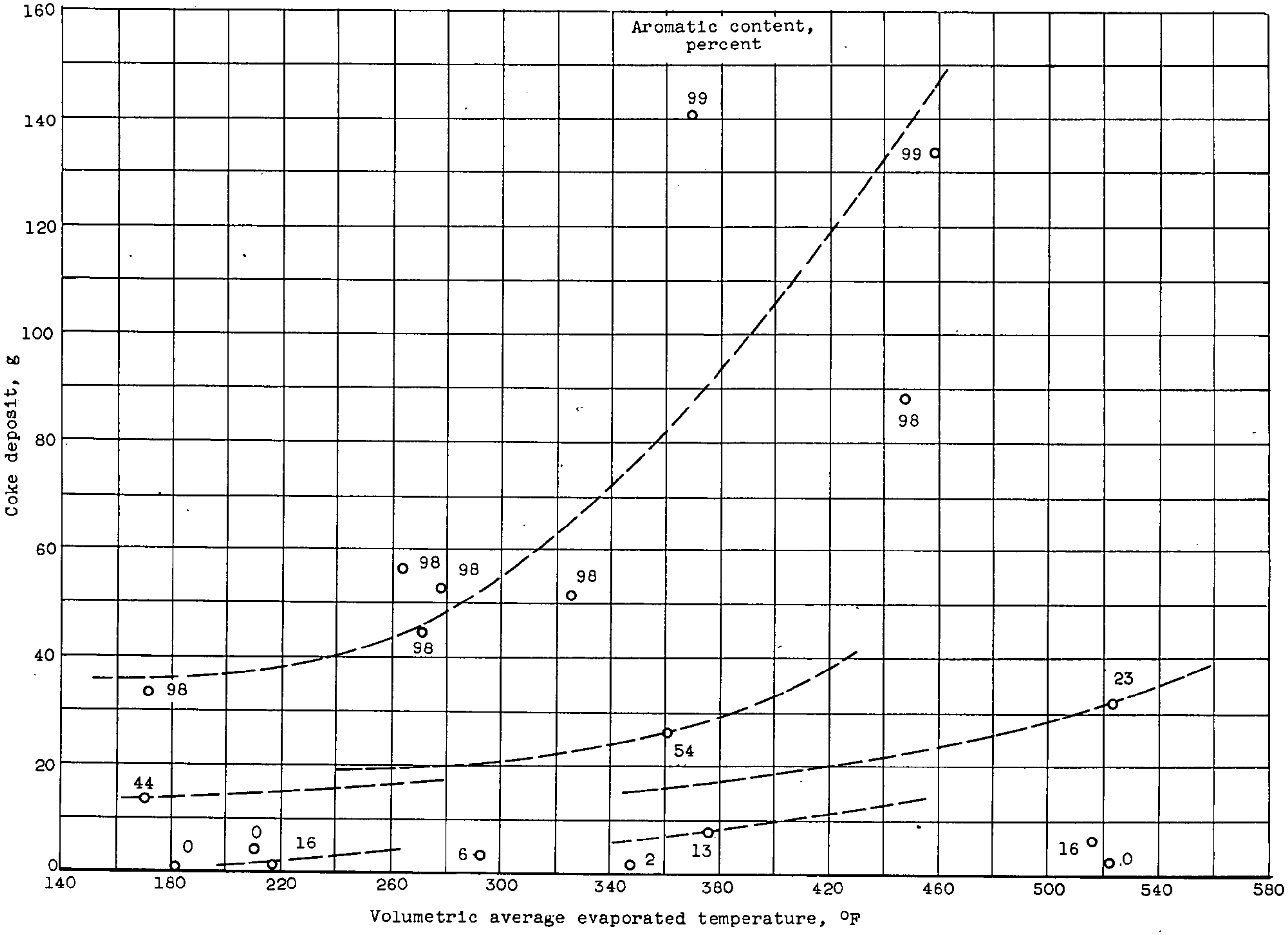


Figure 124. - Effect of run time and fuel type on coke deposition in full-scale single combustor. Combustor operated at cyclic conditions (ref. 28).



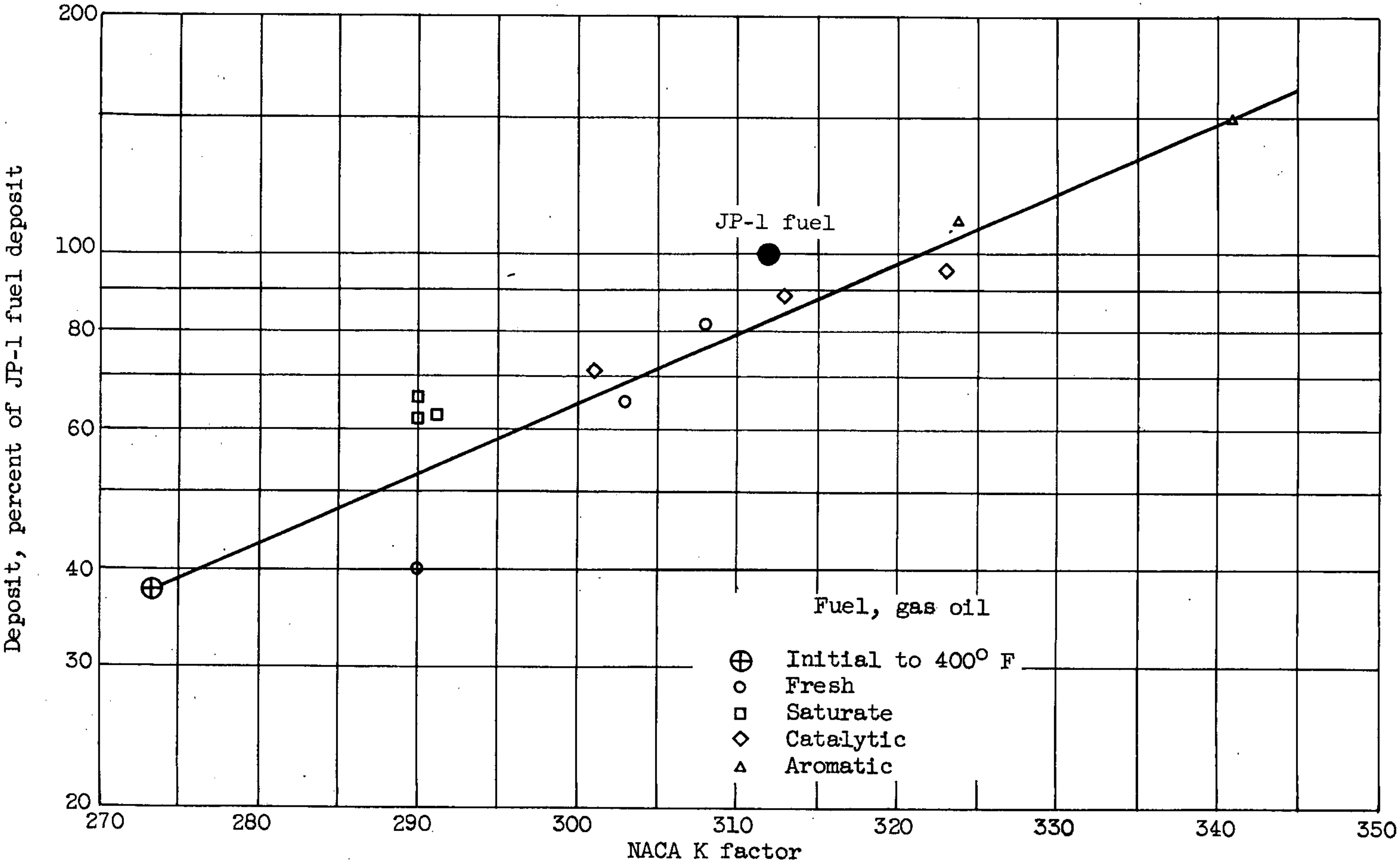
(a) As function of hydrogen-carbon weight ratio.

Figure 125. - Coke deposition of 19 fuels as determined by volumetric average evaporated temperature. Annular-combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; fuel-air ratio, 0.0175; run time, 2 hours (ref. 21).



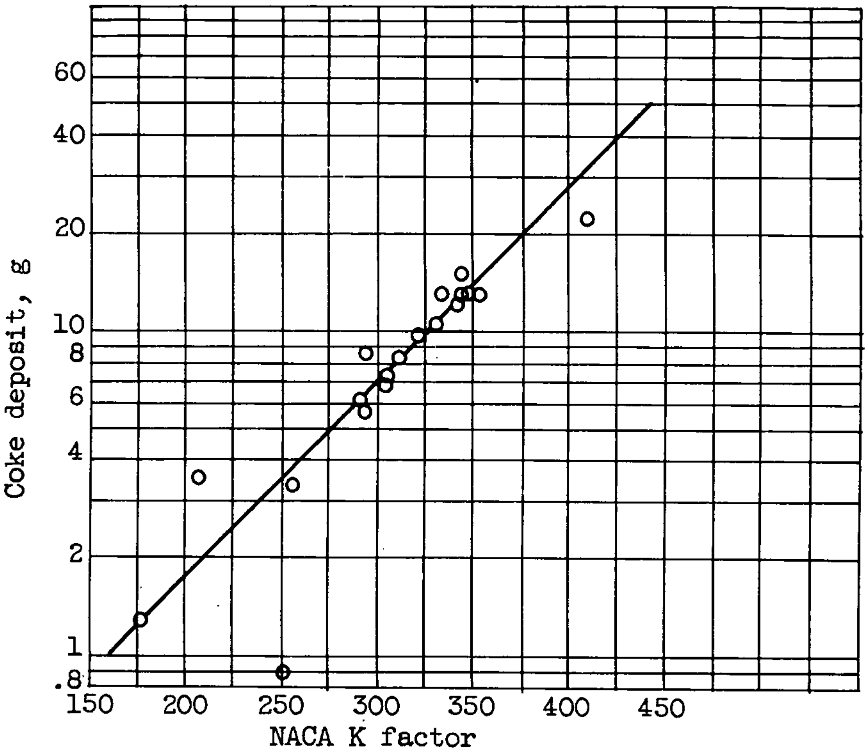
(b) As function of aromatic content.

Figure 125. - Concluded. Coke deposition of 19 fuels as determined by volumetric average evaporated temperature. Annular-combustor diameter, $10\frac{3}{8}$ inches; inlet-air total pressure, 40 inches mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; fuel-air ratio, 0.0175; run time, 2 hours (ref. 21).



(a) In small-scale tubular combustor. Combustor-inlet air pressure, 48 inches of mercury absolute; inlet-air temperature, 240° F; total mass air flow, 435 pounds per hour; fuel-air ratio, 0.0133; run time, 2 hours (ref. 44).

Figure 126. - Effect of NACA K factor on coke deposition of several fuels.



(b) In full-scale single tubular combustor. Combustor-inlet air total pressure, 53.9 inches of mercury absolute; inlet-air temperature, 271° F; fuel flow, 127.0 pounds per hour; fuel-air ratio, 0.0123; run time, 4 hours (ref. 1).

Figure 126. - Continued. Effect of NACA K factor on coke deposition of several fuels.

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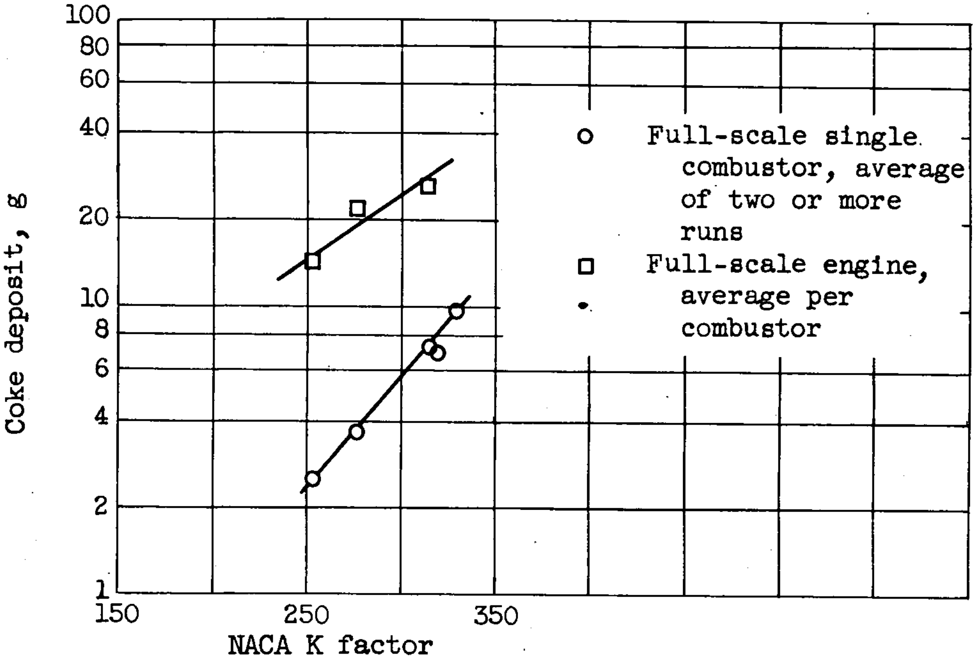

(c) In full-scale single combustor and in full-scale engine. Single combustor-inlet total pressure, 53.9 inches of mercury absolute; inlet-air temperature, 271° F; fuel flow, 127.0 pounds per hour; fuel-air ratio, 0.0123. Full-scale engine cyclic running schedule, 15 minutes at take-off speed and 5 minutes at idle speed; total run time, about 50 hours (ref. 2).

Figure 126. - Concluded. Effect of NACA K factor on coke deposition of several fuels.

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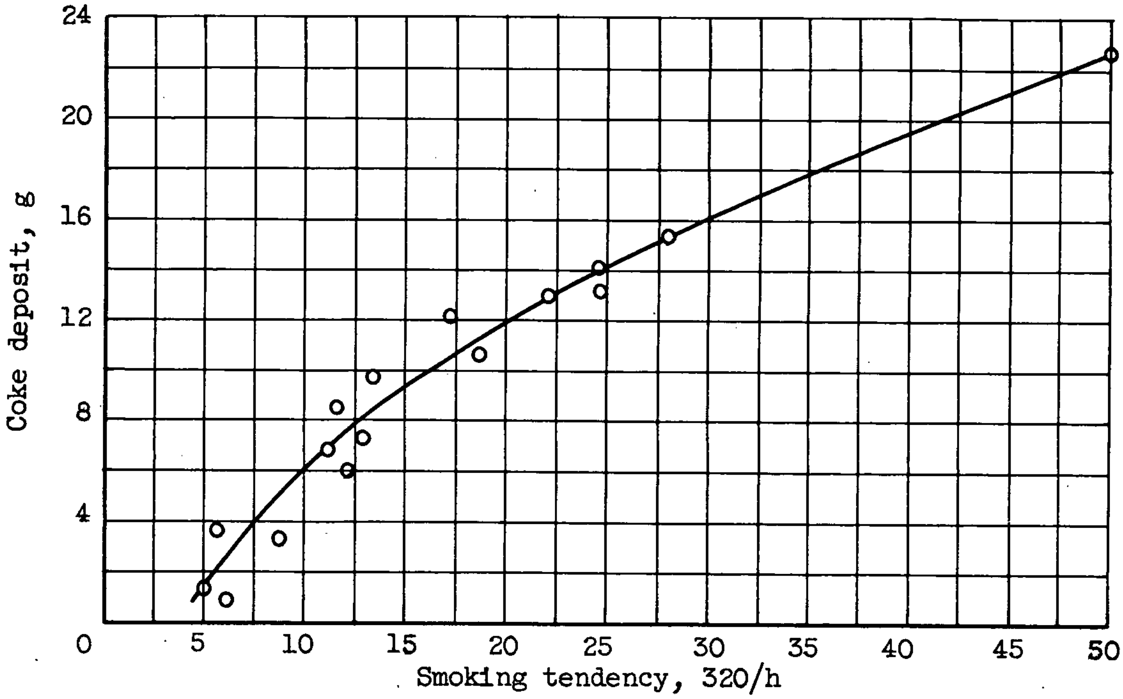

Figure 127. - Effect of smoking tendency on coke deposition of several fuels in full-scale single tubular combustor. Combustor-inlet total pressure, 53.9 inches mercury absolute; inlet-air temperature, 271° F; fuel flow, 127.0 pounds per hour; fuel-air ratio, 0.0123; run time, 4 hours (ref. 1).