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RESEARCH MEMORANDUM

EFFECT OF FUEL ADDITIVES ON CARBON DEPOSITION IN A J33 SINGLE COMBUSTOR

I - THREE METALLIC-ORGANIC ADDITIVES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted in a J33 single combustor to determine the effects of three fuel additives on the carbon-deposition characteristics of MIL-F-5624A fuel, grades JP-3 and JP-4, and an aromatic fuel blend. The additives considered included a commercial fuel-oil additive (containing cobalt and lead compounds), tetraethyl lead, and lead naphthenate. The combustor was operated for 4-hour periods at simulated full-scale operating conditions at 90 percent of normal rated engine speed, zero Mach number, and 20,000-foot altitude.

Small concentrations of all additives reduced carbon deposition significantly. A 0.1-percent concentration of the fuel-oil additive in JP-3 fuel reduced carbon deposition 23 percent. Of the two lead additives tested, lead naphthenate was the more effective; a 0.005-percent concentration of this additive reduced the carbon deposition obtained with a highly aromatic fuel blend 66 percent. For at least two of the additives tested, there appeared to be optimum concentrations; larger concentrations caused significant metallic-compound deposition which was included in the reported deposition. The effectiveness of the lead naphthenate additive varied considerably for two widely different fuels considered, an aromatic fuel blend and a JP-4 fuel.

INTRODUCTION

Carbon deposition in the combustors of turbojet engines constitutes an important operational problem since such deposition can impair (1) combustor performance by affecting air and fuel distribution, (2) starting performance by fouling ignition electrodes and, (3) liner durability by causing liner cracking and warping. Carbon deposition may be minimized by proper combustor design; air is frequently used to "wash" critical combustor areas to prevent deposition. Carbon deposition may also be minimized by proper choice of fuel properties. Investigations conducted at the NACA Lewis laboratory and at other laboratories have indicated the effects of certain fuel properties on deposition. An empirical function of the hydrogen-carbon ratio and the volumetric average boiling temperature of the fuel (NACA K factor), developed in reference 1, indicates the importance of these particular fuel properties in determining the carbon forming propensity of a fuel.

Control of carbon deposition by combustor design is limited by the extent to which other desirable performance characteristics may be compromised; similarly, control by fuel characteristics is limited by the extent to which other desirable fuel characteristics must be compromised. Because of the contemplated use of higher compression ratios and of fuels of lower volatility, which tend to increase carbon deposition, it is desirable to consider other means of reducing such deposition. A large variety of fuel additives has been suggested for use in fuels to prevent and to remove carbon deposition in commercial furnaces and Diesel engines, and in recent years several investigations in turbojet combustors have indicated at least moderate success with materials such as amyl nitrate, thiopene, and metallic-organic compounds (references 2 to 8). Accordingly, carbon-deposition studies of the more promising fuel additives are being conducted at the NACA Lewis laboratory. The principal objective of the program is the identification of the mechanism by which additives reduce carbon deposition. The program will also further demonstrate the effectiveness of additives in full-scale turbojet combustor operation.

Data previously obtained with metallic-organic additives indicated reductions in carbon deposition which have been partly obscured by the deposition of metallic compounds in cases where relatively large concentrations of the additives were used. The effect of metallic-organic additive concentration on carbon deposition was therefore selected as the subject of the preliminary investigation reported herein. The additives considered included a commercial fuel oil additive, tetraethyl lead, and lead naphthenate, in concentrations as large as 0.21 weight percent. Carbon-deposition tests were conducted in a J33 single combustor with high carbon-forming base fuels. The following combustor operating conditions were chosen: simulated full-scale engine operation at 90 percent rated engine speed, zero Mach number, and 20,000-foot altitude for a 4-hour period.

FUELS

The base fuels used in this investigation of the effects of additives on carbon deposition were as follows:

NACA fuel 49-162 - a "minimum quality" MIL-F-5624A, grade JP-3 fuel

NACA fuel 52-105 - MIL-F-5624A, grade JP-4 fuel plus 10 percent by weight of a mixture of α- and β-monomethylnaphthalene

NACA fuel 49-224 - a high-boiling aromatic fuel blend expected to produce large carbon deposits.

Chemical and physical analyses of these fuels are presented in table I.

The additives, additive concentrations, and base-fuel combinations tested were as follows:

Additive	Additive concentrations (percent by weight)	Base fuel
Commercial fuel-oil additive	0.00, 0.05, 0.10, 0.21	NACA 49-162
Lead naphthenate	.00, .0025, .0050, .01, 0.10	NACA 52-105
Lead naphthenate	.00, .0025, .0050	NACA 49-224
Tetraethyl lead	.00, .00145, .00292	NACA 49-224

Chemical analysis of the ash obtained from the pyrolysis of the commercial fuel-oil additive indicated the principal metallic constituents to be cobalt (approximately 0.6 weight percent) and lead (approximately 0.1 weight percent). No further analysis was conducted to determine the form of these metals in the additive solution. The lead naphthenate used contained 37 percent lead; the tetraethyl lead, 64 percent lead. Thus, the concentrations of lead in fuel 49-224 as lead naphthenate and as tetraethyl lead were similar. The concentrations of tetraethyl lead corresponded to approximately 0.03 and 0.06 milliliter TEL per gallon (1-T aviation mix).

APPARATUS AND PROCEDURE

Combustor installation. - The inner liner and dome assembly of the J33 single combustor used in this investigation is shown in figure 1. This assembly, mounted in a tapered outer shell (7-in. max. I.D.), was installed in the laboratory air-supply and exhaust system as shown schematically in figure 2. Air-flow and fuel-flow rates to the combustor were measured by means of a square-edged orifice plate (installed according to A.S.M.E. specifications) and a calibrated rotameter, respectively. Pressure and temperature data were obtained with manometers and self-balancing potentiometers, respectively.

Test procedure. - Carbon-deposition tests were conducted at the following combustor operating conditions, which gave simulated engine operation at 90 percent normal rated engine speed, zero Mach number, and 20,000 foot altitude:

Inlet-air pressure, in. Hg abs	53.9
Inlet-air temperature, °F	271
Air-flow rate, lb/sec	2.87
Fuel-air ratio	0.0123
Run time, hr	4

These conditions resulted in a combustor-outlet temperature of about 1100° F.

Prior to each test run, the combustor inner liner and dome assembly and the ignition plug were cleaned with mechanical rotating brushes and weighed on a torsion-type balance. After a 4-hour period of operation at the specified conditions, the assembly was reweighed; the difference in weight before and after the test run represented the total deposition reported herein. No attempt was made to determine independently the quantity of carbon and of metal oxides deposited. Further, no quantitative information concerning the geometric distribution of the deposits was obtained.

With each change in fuel blend, a reasonable quantity of the new blend was allowed to flow through the fuel system, prior to a test run, in order to purge any residual fuel blend. The extent to which this purge was effective was not determined.

RESULTS AND DISCUSSION

The results obtained in the investigation of the effects of three fuel additives on carbon deposition in a J33 single combustor are presented in table II. The carbon deposition obtained with the base fuels followed the trend predicted by the NACA K factors. Thus, 6.5 grams of carbon was deposited by fuel 52-105 (K factor, 300), 14.1 grams by fuel 49-162 (K factor, 345), and 25.5 grams by fuel 49-224 (K factor, 455). Duplicate tests were conducted with the base fuels and with several of the additive blends. With the exception of the data for fuel 49-224, the average variations of individual carbon-deposit values from the average deposit values were from 0 to 6 percent. No resonable explanation for the wide variation in deposits obtained with fuel 49-224 (21 percent) could be determined.

As shown in table II, all concentrations of the commercial fuel-oil additive in JP-3 fuel reduced the carbon-deposition tendency of the base fuel. The greatest reduction (approximately 23 percent) was obtained with an intermediate concentration (0.1 percent). Reduced effectiveness of higher additive concentrations may be attributed to deposition of metal or metallic oxides.

Low additive concentrations of lead naphthenate and of tetraethyl lead in fuels 52-105 and 49-224 decreased the carbon-forming tendency of the base fuel. As in the case of the fuel-oil additive, intermediate concentrations of lead naphthenate in fuel 52-105 provided the largest reductions (46 percent) in deposition. Reduced effectiveness at higher additive concentrations may again be attributed to metallic deposits. A 0.1-percent addition of lead naphthenate to fuel 52-105 increased deposits by more than 100 percent. Visual inspection of the combustor liner following the test indicated significant deposits of metallic lead, in addition to yellow-gray combined-lead deposits.

The relative effects of the various concentrations of the lead additives on carbon deposition are illustrated in figure 3. The relative percentage carbon deposition (base fuel = 100) is plotted against the concentration of lead (percent) in the fuel blend in order to compare the different fuels and different lead additives. These data indicate that an optimum concentration of lead exists which will produce maximum reductions in carbon deposition. Although the results did not necessarily determine the precise optimum value, it appears to be approximately 0.002 percent lead (or approximately 0.005 percent lead naphthenate).

Comparison of the data obtained with lead naphthenate additive in fuels 49-224 and 52-105 indicates that a single optimum concentration of lead may possibly be applicable to widely different fuels. However, the effectiveness of the additive may vary in such fuels; thus a 0.005 percent concentration of lead naphthenate in fuel 52-105 reduced carbon deposition 46 percent; whereas a similar concentration in fuel 49-224 reduced the deposition 66 percent.

Comparison of the relative effectiveness of the two forms of lead additions in fuel 49-224 indicates that, for similar concentrations of lead as large as 0.002 percent, lead naphthenate reduced deposition by a significantly greater factor than did the tetraethyl lead. The results obtained with the fuel-oil additive cannot be directly compared in figure 3. It is of interest, however, that the most effective concentration of lead naphthenate in fuel 52-105 corresponded to approximately 9×10^{-8} pound mole of lead per pound of fuel and that the most effective concentration of fuel-oil additive in fuel 49-162 was approximately 11×10^{-8} pound mole of cobalt plus lead per pound of fuel.

As noted, the weight of deposits includes any metallic deposits when metallic additives are used in the fuel. Therefore, the actual reductions in carbon deposits may have been significantly greater than those reported. Since the density of metallic deposits normally exceeds the density of carbon deposits, the volume of deposits may be reduced. The volume, rather than the weight, of deposits probably determines the effects on combustor performance.

A factor which must also be considered in the use of fuel additives is the effect of the additive on other fuel characteristics. Because of the minute concentrations used in this investigation, it would be expected that only such characteristics as preformed gum (air-jet residue) and accelerated gum may be affected. Although this phase of the problem was not studied in detail in the present investigation, the following gum analyses were obtained:

Fuel	Air-jet residue (mg/100 ml)	Accelerated gum (mg/100 ml)
NACA 52-105	3	10
NACA 52-105 plus 0.005 percent lead naphthenate	6	14

The addition of the lead naphthenate apparently caused small increases in both preformed and accelerated gum.

The results presented herein indicate that fuel additives may be used to reduce combustor carbon deposition. However, further research must be conducted with a chosen additive to determine possible deleterious effects on factors such as fuel storage stability and on engine fuel-system parts.

SUMMARY OF RESULTS

From an investigation of the effects of three fuel additives on carbon deposition in a J33 single combustor, the following results were obtained:

1. A 0.1-percent addition of a commercial fuel-oil additive containing cobalt and lead compounds to JP-3 fuel decreased carbon deposition 23 percent.

2. Although small concentrations of both tetraethyl lead and lead naphthenate reduced carbon deposition significantly, lead naphthenate was more effective; a 0.005-percent concentration of the lead naphthenate reduced carbon deposition obtained with a highly aromatic fuel blend 66 percent.

3. For at least the fuel-oil additive and the lead naphthenate additive, there appeared to be optimum concentrations; larger concentrations caused metallic-compound deposition, which was included in the total deposition reported.

4. The effectiveness of the lead naphthenate in reducing carbon deposition varied for two widely different base fuels compared; an aromatic fuel blend and an MIL-F-5624A, grade JP-4 fuel.

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2684

TABLE I - ANALYSES OF BASE FUELS

NACA fuel	49-162 (JP-3)	52-105 (JP-4)	49-224
A.S.T.M. distillation D86-46, °F			
Initial boiling point	109	134	327
Percent evaporated			
5	135	183	352
10	158	204	357
20	210	231	364
30	270	253	372
40	323	272	383
50	358	291	393
60	398	314	406
70	432	343	421
80	462	381	444
90	500	431	482
Final boiling point, °F	584	488	583
Residue, percent	1.0	0.9	1.4
Loss, percent	1.0	0.3	0.3
Freezing point, °F	<-76	<-76	<-76
Accelerated gum, mg/100 ml	16	10	---
Air-jet residue, mg/100 ml	8	3	---
Aromatics, percent by volume			
A.S.T.M. D-875-46T	25	16	87
Silica gel	31	17	96
Specific gravity, 60°/60° F	0.801	0.779	0.907
Bromine number	12	3	-----
Reid vapor pressure, lb/sq in.	4.5	2.6	-----
Hydrogen-carbon ratio	0.150	0.160	0.111
Net heat of combustion, Btu/lb	18,500	18,575	18,475
NACA K factor[a]	345	300	455

[a]Reference 1.

[redacted]

TABLE II - CARBON-DEPOSITION DATA

Base fuel	Additive	Additive concentration (percent by weight)	Metal concentration (percent by weight)	Carbon deposition (g)				Average carbon deposition (g)	Average variation (percent) (a)
				1	2	3	4		
NACA 49-162	Fuel-oil additive	0.00	------	13.9	15.0	13.5	13.8	14.1	4
		.05	0.0004	13.4	----	----	----	13.4	-
		.10	.0007	10.7	11.8	10.9	----	11.1	4
		.21	.0015	13.3	----	----	----	13.3	-
NACA 52-105	Lead naphthenate	0.00	-------	6.4	6.8	6.5	6.4	6.5	2
		.0025	0.00093	3.9	---	---	---	3.9	-
		.0050	.0019	3.5	3.5	---	---	3.5	0
		.0100	.0037	3.6	----	---	---	3.6	-
		.1000	.0370	14.9	13.2	---	---	14.1	6
NACA 49-224	Lead naphthenate	0.00	-------	17.9	22.4	31.1	30.6	25.5	21
		.0025	0.00093	13.0	----	----	----	13.0	--
		.0050	.0019	8.8	----	----	----	8.8	--
	Tetraethyl lead	.00145	.00093	19.6	----	----	----	19.6	--
		.00292	.00187	13.3	----	----	----	13.3	--

[a]Arithmetic average variation of individual carbon-deposit values from arithmetic average deposit value.

[redacted]

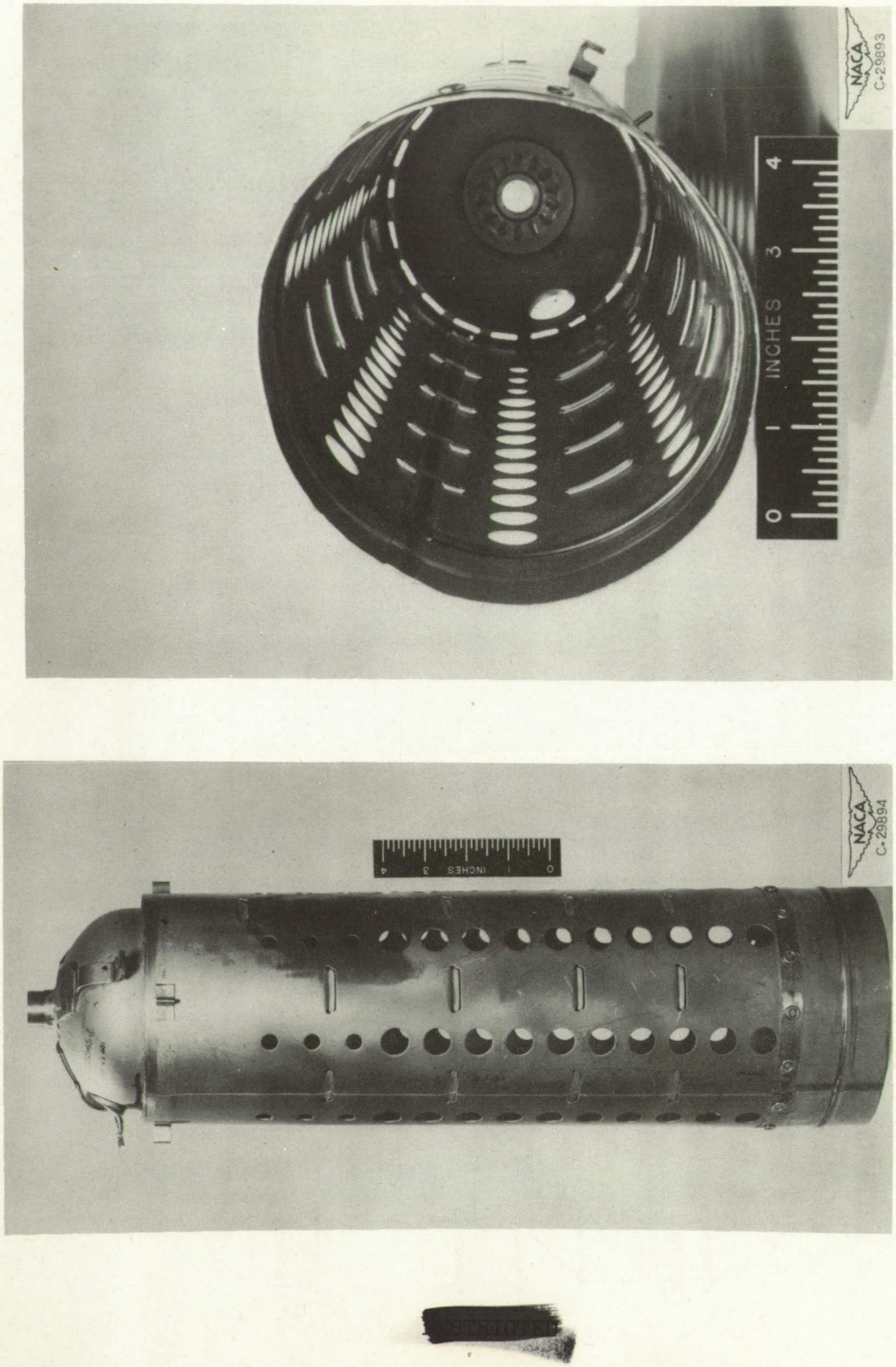

Figure 1. - Inner liner and dome of J33 single combustor used in carbon-deposition investigation.

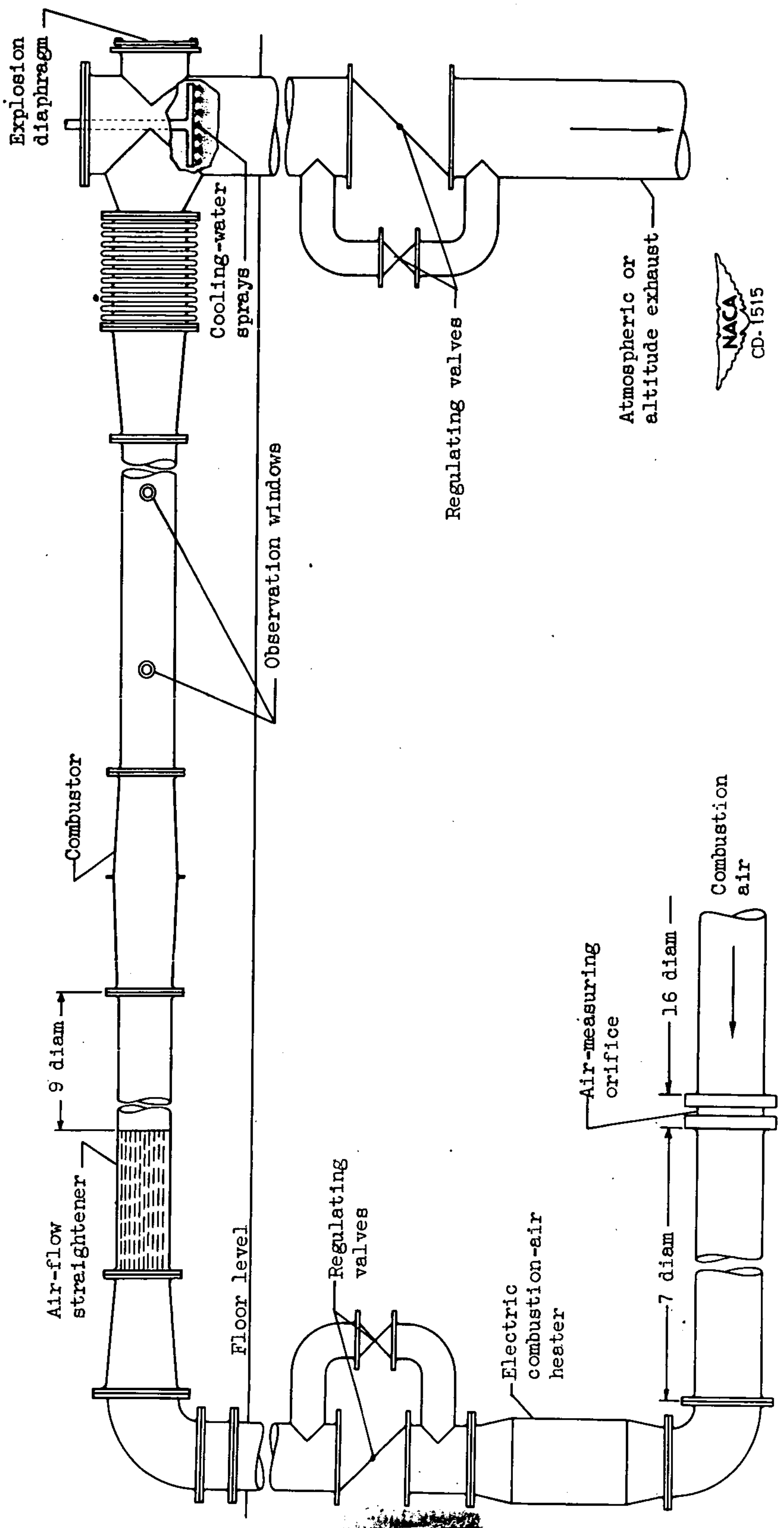

Figure 2. - Single-combustor installation and auxiliary equipment.

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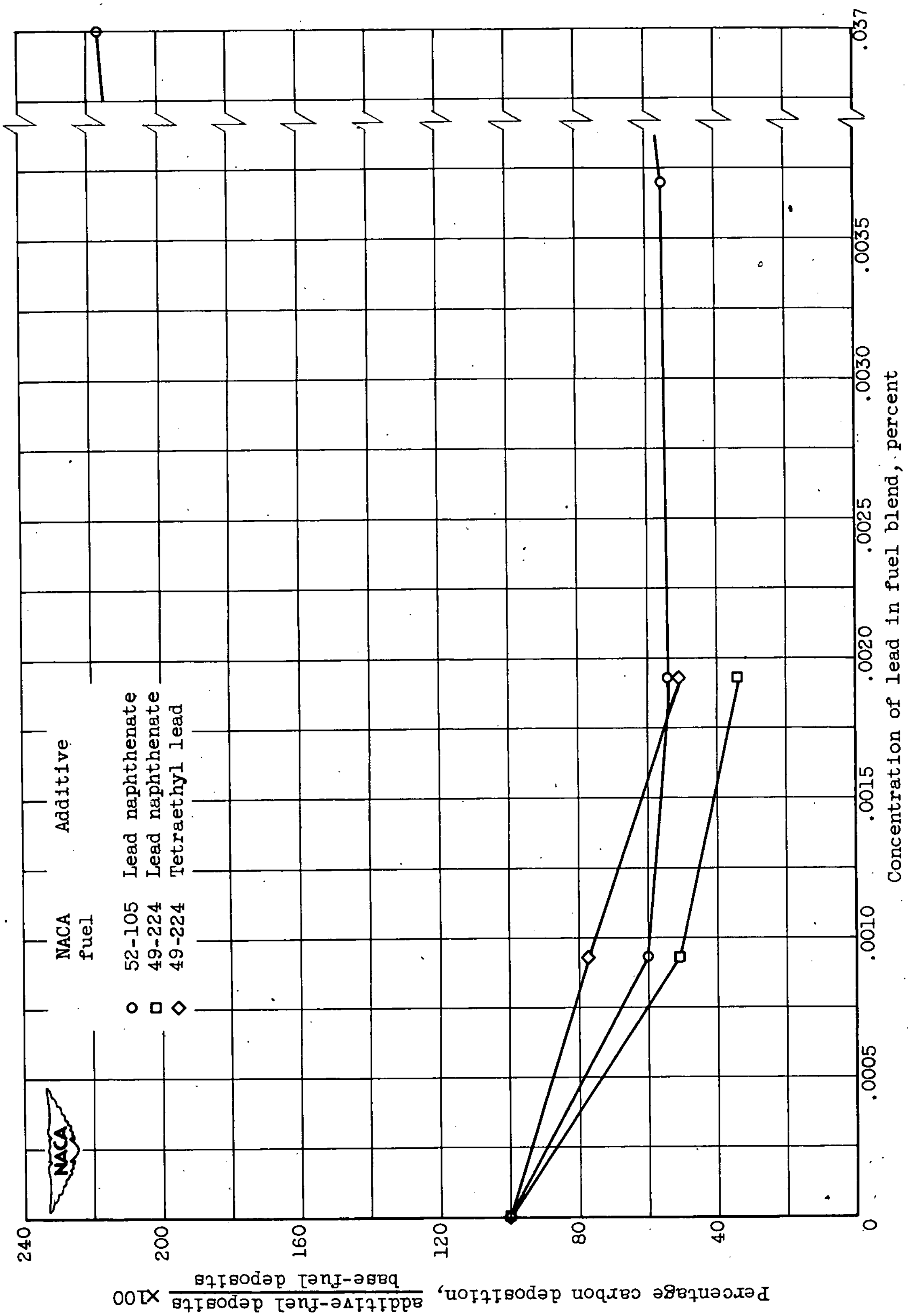

Figure 3. - Effect of lead concentration on carbon deposition in J33 single combustor.

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