NACA

RESEARCH MEMORANDUM

PREPARATION AND PHYSICAL PROPERTIES OF METAL SLURRY FUELS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

A preliminary investigation of the physical properties of slurries and of the use of a metal-soap additive to prepare stable slurries of commercial magnesium, aluminum, and boron powders in a MIL-F-5624 grade JP-3 base fuel has been made. The slurries were prepared and their properties determined in ordinary chemical laboratory apparatus. Data are reported on slurry density, apparent viscosity, apparent surface tension, stability, and fuel-flow characteristics, as affected by slurry composition.

Several of the prepared slurries have physical properties acceptable for combustion-research evaluation and limited flight use; however, further investigations are required to establish the suitability of slurries for extended storage and operational field use.

INTRODUCTION

An analytical and experimental evaluation of metals and metal-hydrocarbon slurries as potential fuels for jet-propulsion systems is being conducted at the NACA Lewis laboratory. Metals and metal-hydrocarbon slurries offer potential advantages over petroleum fuels in terms of available thrust, range, and operating limits. Evaluations of the combustion properties of metallic fuels in the form of wires, powders, solid fuel beds, and suspensions of finely divided powder in a liquid petroleum carrier are reported in references 1 to 5. An analytical evaluation of the air- and fuel-specific-impulse characteristics of aluminum, magnesium, and boron metals and of metal-hydrocarbon slurries is reported in references 6 to 8.

In the experimental investigation of magnesium-hydrocarbon slurries (reference 5), the slurries gave a higher thrust and an increased operational range over that obtainable with the reference hydrocarbon. They were mixed, metered, and injected in a semiconventional fuel system. Mechanical agitation was required to keep the metal particles suspended in the fuel tank, and recirculation of the slurry fuel was necessary to prevent metal deposition in the fuel lines. Since the agitation and recirculation requirement reduces the practicability of metal-hydrocarbon slurries for flight applications, methods of stabilizing the metal-hydrocarbon slurries were surveyed. A majority of the chemical additives used to stabilize paints, inks, and ore-bearing slurries are unsuitable for slurry fuel stabilization either because of reactivity with the metal powders or incompatability with the hydrocarbon fuel. Polyisobutene has been used to stabilize aluminum-kerosene fuel slurries (reference 9), but only limited information on the stability characteristics is available.

An investigation was initiated at the NACA Lewis laboratory to prepare stable slurries and to investigate the properties of these slurries containing commercial magnesium, aluminum, and boron powders suspended in a hydrocarbon fuel carrier. As the result of a preliminary study, a metallic soap, aluminum octoate, was selected for use as the slurry-stabilizing additive in this study. Reported herein are the preparation and the physical-property evaluation of metal-slurry fuels. The experimental work was conducted in ordinary chemical laboratory apparatus from May 1950 to May 1951. Data are presented for:

(a) Particle size, shape, and size distribution as determined by photomicrographs, microscopic, and sieve analysis for commercial magnesium, aluminum, and boron powders

(b) The range of slurry densities obtainable with commercial magnesium, aluminum, and boron powders in MIL-F-5624 grade JP-3 fuel

(c) The variation of apparent viscosity with slurry composition

(d) The variation of apparent surface tension with slurry composition

(e) The weight flow of JP-3 fuel and of magnesium, aluminum, and boron slurries through a fuel system and injection nozzle as a function of a conventional flow parameter

(f) The stability of the metal slurries as a function of gross particle size, additive composition, and storage temperature.

DESCRIPTION OF POWDERS AND CARRIER FUEL

Eight commercial powders, three magnesium, two aluminum, and three boron, were used in the investigation. A classification of the powders and an estimate of their composition is as follows:

Powder	Estimated metal weight (percent)	Estimated oxide weight (percent)
Magnesium, superfine	97	3
Magnesium, fine	99	1
Magnesium, ball-milled	87	13
Boron, amorphous	86	1
Boron, crystalline, 100 mesh	96	--
Boron, crystalline, 200 mesh	96	--
Aluminum, 200 mesh	98	2
Aluminum, 400 mesh	97	3

Representative photomicrographs of the fine and superfine atomized magnesium, ball-milled magnesium, amorphous boron, and 200- and 400-mesh atomized aluminum powders are presented in figures 1 to 3. The superfine and fine magnesium powders shown in figures 1(a) and 1(b), respectively, are spherical in form and differ chiefly in the distribution of particle size. The ball-milled magnesium and the amorphous boron shown in figures 2(a) and 2(b), respectively, are very irregular in shape. The crystalline boron powders when examined under a microscope appear to be so similar to the amorphous boron particles that a presentation of the photomicrographs was unwarranted. The 400- and 200-mesh aluminum powders shown in figures 3(a) and 3(b), respectively, appear to be irregularly shaped particles with smooth surfaces.

The particle-size distributions of six powders were determined by microscopic and sieve analysis methods (reference 10) and are shown in figure 4. The weight-percent size-distribution determination for particles smaller than 37 microns was made by microscopic analysis; sieve analysis was used for determination of the particle size range from 37 to 75 microns. The median-particle size, as indicated by the 50-percent-by-weight points of figure 4, for the powders studied are:

	Particle size (microns)
Magnesium, fine	66
Magnesium, ball-milled	45
Aluminum, 200 mesh	42
Magnesium, superfine	24
Boron, amorphous	21
Aluminum, 400 mesh	9

The results of this investigation are reported for these powders only, and deviation from these particle sizes is known to have a marked influence on the stability and related physical properties of the slurries.

A carrier fuel conforming to specification MIL-F-5624 grade JP-3 was used throughout this investigation. The specifications and analysis for this fuel are indicated in table I.

PREPARATION OF SLURRIES

A preliminary study was conducted on the stabilizing effect of various additives on slurries. This investigation included various commercial fatty acids, amines and esters of fatty acids, tertiary amines, quaternary ammonium compounds, alkyl aryl sulfonates, metallic soaps, and polyisobutene. The most desirable fuel-spray-atomization and stability characteristics were obtained by the use of metallic soaps. Aluminum octoate was the metallic soap selected as the stabilizing additive for this investigation because it exhibited better stabilizing characteristics at lower concentrations than the other metallic soaps studied. The chemical analysis of the aluminum octoate showed the moisture content to be 0.85 percent; total ash, 17 percent; and free acid, 9.24 percent. Other samples of aluminum octoate deviating from this analysis gave different results.

A single mixture of metallic soaps and turpentine in JP-3 fuel was prepared for all stabilizing additive tests. Approximately 10 gallons of a mixture containing 96 percent JP-3 fuel, 3 percent aluminum octoate, 0.9 percent turpentine, and 0.1 percent magnesium stearate by weight were prepared by stirring and heating the mixture to approximately 85° C for 1 hour in a 30-gallon glass-lined reactor at total reflux. The magnesium stearate controlled the gel thickening and the turpentine improved the homogeneity of the gel. The physical properties of the gel were apparently unaffected by 6-months storage in sealed tin cans. The total weight percent of aluminum octoate, magnesium stearate, and turpentine, hereinafter, will be called the additive concentration or percent additive and will be based on the total slurry weight unless otherwise stated.

A specific mixing procedure was followed for all slurries except where otherwise noted: Samples were prepared in 500- to 1000-gram batches. The metal powder was weighed into a glass beaker and JP-3 fuel was added until all the powder was wetted. The gel, whenever used, was added with the remaining JP-3 fuel. Small losses of the more volatile components of the JP-3 fuel that occurred during the mixing procedure were kept constant by mixing each sample for 30 minutes. All tests were started immediately after completion of the stirring.

In the investigation of the slurry densities and in the study of the slurry flow characteristics, the effect of a "dispersing-agent" additive was studied. This dispersing agent was a commercial aluminum naphthenate preparation containing 50 percent aluminum naphthenate, 2.5 percent water, and 47.5 percent mineral spirits.

PROPERTIES OF METAL SLURRIES

The physical properties of the metal slurries investigated were density, viscosity, surface tension, flow rate, and stability. The range of density available over the full range of metal concentration is a measure of the packing ability of the powder and is indicative of the useful range of metal concentration for that powder. The flow properties of the slurries were evaluated by means of viscosity and flow-rate measurements. Knowledge of the surface tensions of slurries may be an aid in the estimation of spray and atomization characteristics and thereby may aid in the design of slurry fuel-injection systems. Stability measurements indicate the homogeneity of the suspended powders after an elapsed time and were the primary means used to evaluate the effect of the stabilizing additive.

Density

The samples used in the density determination were prepared and weighed in calibrated, stoppered, graduated cylinders to prevent vapor loss. The dry powder samples were tapped by hand until the volume remained constant for 2 minutes of tapping. As small amounts of JP-3 fuel were added, part of the air spaces or voids between the packed particles were displaced by the liquid and the density of the total increased. When sufficient JP-3 fuel had been added to fill all the voids, the density reached a maximum and decreased with further increases in liquid concentration. The results of the density investigation are presented in figure 5 for magnesium, boron, and aluminum powders. The theoretical densities of the slurries calculated from equation (1) are presented for comparison. Equation (1) represents volume additions of the individual liquid and metal fractions. Since the theoretical metal volume is based on the solid-metal density, the presence of unfilled voids in the powders accounts for the deviation of the slurry densities from the theoretical.

$$\frac{1}{\rho_t} = \frac{x}{\rho_m} + \frac{(1 - x)}{\rho_l} \tag{1}$$

where

ρ_t slurry density

ρ_m solid-metal density

ρ_l liquid hydrocarbon density

x weight fraction of metal powder

$(1 - x)$ weight fraction of remaining constituents

For the magnesium slurries (fig. 5(a)) the fine magnesium containing the larger spherical particles gave the greatest maximum density and the irregularly shaped ball-milled magnesium particles gave the lowest maximum density. The maximum densities of the crystalline boron powders are essentially equal (fig. 5(b)). The amorphous boron gave the highest maximum density, 1.3 (g/ml) at a 64 weight-percent boron concentration. The 200-mesh aluminum gave a higher maximum density than the 400-mesh powder (fig. 5(c)).

In a preliminary study using aluminum powders, it was noted that low concentrations of dispersing agent caused increases in density of high metal-concentration slurries. A mixture containing 2.5 percent dispersing agent and 97.5 percent JP-3 fuel was prepared and added in varying amounts to the aluminum powders (fig. 5(c)). The maximum densities of both the 200- and 400-mesh powders were increased over those of the slurries without dispersing agent. The maximum density of the 400-mesh powder with dispersing agent increased to a value greater than that of the 200-mesh powder with dispersing agent. The maximum density of the superfine magnesium powder was not affected appreciably by the dispersing-agent additive (fig. 5(a)).

The maximum density and corresponding concentrations for the metal slurries are given in the following table:

Powder	Powder in slurry (percent)		Slurry density (g/ml)
	By weight	By volume	
Magnesium, superfine	74	55.3	1.30
Magnesium, fine	82	66.3	1.40
Magnesium, ball-milled	68	48.0	1.22
Aluminum, 400 mesh	76	47.0	1.65
Aluminum, 200 mesh	80	52.9	1.77
Aluminum, 400 mesh, with dispersing agent	84	59.5	1.83
Aluminum, 200 mesh, with dispersing agent	83	57.8	1.79
Boron, amorphous	64	36.7	1.30
Boron, crystilline, 100 and 200 mesh	55	28.5	1.20

Viscosity

Viscosities were determined at 20±0.5° C with a Stormer viscometer. The unit was calibrated with National Bureau of Standards viscosity oils and silicone oils of known viscosity. Readings were taken by decreasing the shear from a high to a low rate, and repeat determinations were made until checks were obtained. The data for the calibration fluids and some representative slurries are plotted in figure 6 as fluidity against time for 100 revolutions. The time for 100 revolutions is proportional to the reciprocal of the shear rate. The fluidity of the Newtonian calibration fluids remained nearly constant as the shear rate was varied. The slight deviations probably were caused by friction in the instrument. The three sample mixtures, JP-3 fuel with 1.14 percent additive, the 50-percent-magnesium slurry, and the 30-percent-magnesium slurry containing 1.14 percent additive, all became more fluid as the shear rate increased.

It was desired to assign a single value of apparent viscosity to each fluid. Values of fluidity for all samples were therefore taken at a constant shear rate represented by 25 seconds per 100 revolutions. This is the highest shear rate that can be determined accurately with the instrument used. High shear rates are more representative of the flow conditions encountered in actual fuel systems. A curve of viscosity against fluidity at the constant shear rate was plotted for the calibration fluids and was used for converting fluidities to apparent viscosities for the sample liquids.

The apparent viscosities of various slurries are listed in table II.

The increase in apparent viscosity with increasing percentages of superfine magnesium powder in JP-3 fuel without additive is shown in figure 7. At a composition of 60 percent superfine magnesium, the apparent viscosity is over 5,000 centipoises. The apparent viscosity of the 70-percent slurry was too great to be determined with the instrument used.

The increase in apparent viscosity with increasing additive concentration for JP-3 fuel and for JP-3 fuel with 30 percent superfine magnesium is shown in figure 8. The 30-percent-superfine-magnesium slurries with additive exhibit much higher viscosities than the mixtures containing only JP-3 fuel and additive at additive concentrations greater than 0.4 percent.

The variation of apparent viscosity with storage time for a 50-percent-superfine-magnesium slurry with 0.8 percent additive is shown in figure 9. The slurry was restirred before each viscosity determination. The apparent viscosity increased for 2 days then decreased slowly, indicating that the gel was breaking down. The apparent viscosities of mixtures of additive and JP-3 fuel with no metal powders remained constant with storage time.

Surface Tension

Data on surface tension were obtained by the ring method using a calibrated precision tensiometer. All tests were made at a temperature of 26±1° C, and one platinum ring was used. Corrections for ring dimensions and for volume of liquid raised were omitted, and the data are presented as apparent surface tensions. Values of apparent surface tension for various slurries and liquid carriers are listed in table II.

The variation of apparent surface tension with percent additive for the slurries of 30 percent superfine magnesium is shown in figure 10. The change of apparent surface tension with additive concentration is similar to the viscosity variation. Small increases in apparent surface tension were noted to approximately 0.4 percent additive. Further increases in additive were accompanied by large increases in the apparent surface tension.

Flow-Rate Study

A comparison of the flow properties of the JP-3 base fuel with the various metal slurries was made in a simulated fuel system. Control of the fuel flow rate was obtained by the use of pressurized nitrogen gas with a pressure regulator and gage. The nitrogen gas was supplied to a slurry container 2 feet long and $1\frac{1}{2}$ inches in diameter. The slurry was discharged through a 1/4-inch valve and a 6-inch run of 1/4-inch pipe to an injection nozzle. The injection-nozzle throat diameter was 0.040 inch, and the approach angle was 45°. The fuel tank was filled and the nitrogen pressure preset. Data were taken on the time of flow, weight flow, and the nitrogen pressure. The results were plotted as the weight of flow per unit time against the conventional flow parameter $(\rho\ \Delta p)^{1/2}$, where ρ is the slurry density in grams per cubic centimeter and Δp is the measured nitrogen pressure in pounds per square inch gage.

The weight flow rates of various slurries are presented in table II as average percentage values of the weight flow rate of the JP-3 base fuel.

The results of all flow measurements are plotted in figure 11. The JP-3 base fuel determined the straight line correlation of flow rate with the conventional flow parameter. All metal concentrations of superfine magnesium powder in JP-3 fuel without additive correlated with the JP-3 fuel up to a magnesium concentration of 50 percent. Slurries of 55, 60, and 70 percent magnesium without additive fell progressively below the correlation line. Although the 70 percent magnesium without additive was of a semisolid consistency and had an apparent viscosity well over 5,000 centipoises, the flow rate was 60 percent of the value established by the reference correlation line. The addition of 1.5 percent dispersing agent to the 70-percent-superfine slurry reduced the viscosity to 225 centipoises and caused the flow rate to rise to the JP-3 fuel correlation line.

The 30-percent-superfine-magnesium slurries correlated with the JP-3 fuel-flow characteristic for additive concentrations up to 1.0 percent. The flow rate of a slurry containing 30 percent superfine magnesium plus 1.2 percent additive and showing an apparent viscosity of 220 centipoises was about 90 percent of the flow rate determined by the JP-3 fuel correlation line.

The flow rates of the 30-percent-amorphous-boron slurry with 0.56 percent additive and the 30-percent-aluminum (400-mesh) slurry with 0.56 percent additive were about 90 percent of that determined by the JP-3 fuel correlation line although their apparent viscosities were relatively low.

The flow rate of a highly viscous 65-percent-superfine-magnesium slurry with 1.04 percent additive was 66 percent of that indicated by the correlation line.

Stability

A quantitative measure of slurry stability was required. It was observed, when a slurry "broke," that a single phase of clear liquid was left on the top of an apparently homogeneous metal-liquid phase and that the clear liquid phase increased in depth as a function of time. Consequently, the time required for the metal-liquid level to drop to some arbitrary percentage of the total height was taken as a measure of the slurry stability.

Immediately after a slurry was mixed, it was poured into a 29- by 150-millimeter flat-bottom glass test tube to a height of about 6 inches, stoppered, and placed in a rigid test tube rack. The liquid and the metal-liquid levels were determined by a cathetometer to the nearest 0.01 inch. All settling data were taken at room temperature except where otherwise indicated. The stability curves were plotted as a settling ratio h/h_t, where h is the metal-liquid phase height at time t and h_t is the total liquid-slurry height, against time from pouring. For convenience in plotting, a logarithmic time scale was used for all settling data. When slurries are compared by means of the settling ratio - time history curves, an increase in time required for the metal-liquid level to drop to a given settling ratio will be referred to as "an increase in stability or a decrease in settling rate." The time required for the metal-liquid level to drop just below the liquid level, or just below a settling ratio of 1, will be referred to as "the stability time for that slurry."

Metal concentration and stability. - The settling ratio - time history at five metal concentrations is shown in figure 12 for superfine magnesium powder in JP-3 fuel without additive. The stability of the slurries increased with increasing percentage of metal over the range from 10 to 60 percent magnesium.

Particle size and stability. - A comparison of the settling rates for fine and superfine magnesium, 200- and 400-mesh aluminum, and for amorphous boron slurries, as indicated in figure 13, shows the effect of particle size on stability. At a fixed metal composition, the stability is increased as particle size is decreased. For a fixed particle size distribution, stability increases with an increase in metal content from 30 to 50 percent (fig. 13). This increase was previously noted in figure 12.

Particle shape and stability. - As can be seen from figure 13, the irregularly shaped ball-milled magnesium slurries have a greater stability than the spherically shaped fine magnesium slurries for the same metal concentration. These powders have the same solid density and similar size distributions. The same effect may be seen by comparing the superfine magnesium and the amorphous boron slurries at the same metal concentration. The irregularly shaped amorphous boron slurries exhibit greater stability than the spherical superfine magnesium slurries even though the boron has the greater solid density and the powders have similar size distributions. From these limited data, it would appear that as the particle shape deviates from spherical, the stability of a slurry of the powders is increased.

Additive concentration and stability. - The settling ratio - time history for 30 percent superfine magnesium in JP-3 fuel at several additive concentrations is shown in figure 14. Addition of 0.16, 0.32, or 0.40 percent additive to a slurry of 30 percent superfine magnesium actually decreased the slurry stability from that with no additive; additive concentrations of 0.48 percent and above produce great increases in slurry stability. A slurry containing 1.2 percent additive has been stable for over 2,000 hours. Figure 15 shows the rapid increase in stability time with percentage additive for three high settling ratios; this figure is a cross plot of a portion of the data of figure 14.

The settling ratio for six commercial powders in JP-3 fuel with 0.56 percent additive is presented in figure 16. This additive concentration was insufficient to stabilize the fine magnesium and the 200-mesh aluminum for an appreciable interval of time. The 400-mesh aluminum and the amorphous boron were stable for the entire period of observation, over 800 hours.

It is desirable to be able to predict the additive concentration required to stabilize a slurry containing a given weight-percent metal. Accordingly, tests were made on the settling ratio - time history of 30- and 50-percent-superfine-magnesium powders in JP-3 fuel with no additive and with 0.56 percent additive, and a 50-percent-superfine-magnesium slurry with 0.80 percent additive. The results are presented in figure 17. The 50-percent-magnesium slurry with 0.56 percent additive was less stable than with no additive, although the 0.56 percent additive increased the stability of the 30-percent-magnesium slurry over that without additive. The 50-percent-magnesium slurry with 0.80 percent additive was slightly more stable than the comparable slurry with no additive. It is apparent that a critical additive concentration is required to stabilize a slurry of given weight-percent metal. Increases in metal composition may require additional additive to achieve stabilization.

A slurry containing 65 percent superfine magnesium and 1.04 percent additive was prepared in an effort to produce a high-density, stable slurry with acceptable flow characteristics. The slurry was stable for the entire period of observation, over 1000 hours. The flow rate was low but not necessarily prohibitive for practical use (fig. 11).

Viscosity and stability. - Increases in additive concentration above a critical minimum, increase both the viscosity and the stability of slurries. The stability increase is not solely dependent on the viscosity characteristic of the slurry, as can be seen in figure 18. A slurry of 30 percent magnesium in mineral oil with an apparent viscosity of 118 centipoises was less stable than a metallic soap-stabilized slurry with an apparent viscosity of 39 centipoises.

Temperature and stability. - The settling ratio - time history for a 30-percent-superfine-magnesium slurry at three temperatures is shown in figure 19. The stability decreases rapidly with increasing temperature in the range of normal storage temperatures.

SUMMARY OF RESULTS

The physical properties of metal-hydrocarbon slurries were investigated by measurements of slurry density, apparent viscosity, apparent surface tension, stability, and flow characteristics. The following results were obtained:

1. Less than 2 percent by weight of a metallic soap-additive mixture containing aluminum octoate, magnesium stearate, and turpentine greatly improved the stability of slurries of commercial magnesium, aluminum, and boron powders in JP-3 fuel. Variations in the chemical composition of the metallic soaps or in the constituents of the mixture resulted in different physical properties of the slurries.

2. Certain minimum ratios of the additive to metal concentration must be exceeded before achieving an appreciable increase in stability with the attendant increase in apparent viscosity and surface tension.

3. The storage stability characteristics of magnesium slurries containing additives were adversely affected by high storage temperatures.

4. Metal-hydrocarbon slurries stabilized with the metallic-soap additive were more stable than metal-hydrocarbon slurries of comparable viscosities without metallic soaps.

5. The maximum densities of slurries of available commercial magnesium and aluminum powders in JP-3 fuel were attained at metal concentrations of about 80 percent by weight. For boron, the maximum density occurred at a metal concentration of 64 percent.

6. The flow rates of most of the slurries tested were equivalent to those of the reference petroleum fuel MIL-F-5624 grade JP-3. The flow rate of a high metal-concentration slurry was equivalent to that of the reference fuel when a dispersing agent was used.

CONCLUSIONS

The following conclusions were drawn from the investigation of the metal slurry fuels:

1. Slurries of commercial magnesium, aluminum, and boron powders in MIL-F-5624 grade JP-3 fuel with a low-metallic-soap-additive concentration have been prepared that have properties which are acceptable for combustion-research evaluation and limited flight applications.

2. Additional research will be required to prepare slurry-type fuels that have physical properties which are acceptable for all operational field conditions and for the total range of metal concentration.

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TABLE I - SPECIFICATIONS AND ANALYSIS OF CARRIER FUEL

MIL-F-5624 GRADE JP-3

	Specification	Analysis
A.S.T.M. distillation D 86-46 ($^{\circ}$F)		---
Initial boiling point		124
Percent evaporated		---
5		156
10		180
20		220
30		252
40		282
50		312
60		344
70		378
80		408
90	400(min.)	447
Final boiling point	600(max.)	498
Residue (percent)	1.5(max.)	1.0
Loss (percent)	1.5(max.)	0.5
Specific gravity 60/60° F	0.728(min.)	0.760
Reid vapor pressure (lb/sq in.)	5 to 7	6.2
Hydrogen-carbon ratio		0.170
Net heat of combustion (Btu/lb)	18,400(min.)	[a]18,724

[a] Aniline point correlation.

TABLE II - COMPOSITIONS AND SOME PHYSICAL MEASUREMENTS OF VARIOUS METAL SLURRIES AND LIQUID CARRIERS

Metal powder (a)	Metal (percent by weight)	MIL-F-5624 fuel (percent by weight)	Additive (percent by weight)	Apparent surface tension (dynes/sq cm)	Apparent viscosity (cps, 20° C)	Flow rate correlation (average percent weight flow of JP-3 fuel flow)
Mg SF	10	90	0	26.3	1.1	100
Mg SF	30	70	0	26.6	5.6	100
Mg SF	40	60	0	26.3	58	100
Mg SF	50	50	0	41.4	255	100
Mg SF	55	45	0	47.0	495	94
Mg SF	60	40	0	65.7	> 5000	89
Mg SF	70	30	0	>100	(b)	62
Mg SF	30	69.84	.16	26.7	5.1	100
Mg SF	30	69.76	.24	26.8	7.3	100
Mg SF	30	69.68	.32	27.0	9.7	100
Mg SF	30	69.60	.40	27.5	17	100
Mg SF	30	69.52	.48	28.6	27	100
Mg SF	30	69.44	.56	30.0	39	100
Mg SF	30	69.36	.64	32.7	46	100
Mg SF	30	69.20	.80	37.7	110	100
Mg SF	30	69.00	1.00	55.6	175	100
Mg SF	30	68.80	1.20	>100	220	90
Mg SF	50	49.52	.48	28.4	80	---
Mg SF	50	49.20	.80	51.9	115	---
Mg SF	70	28.5	1.5[c]	----	225	100
Mg SF	30	(d)	----	34.2	118	---
Mg SF	65	33.96	1.04	----	----	66
Mg F	30	69.44	.56	27.4	23	100
Mg BM	30	69.44	.56	33.1	74	100
Al 200	30	69.44	.56	26.9	37	92
Al 400	30	69.44	.56	27.5	85	93
B Amor.	30	69.44	.56	29.4	155	98
-------	--	96.00	4	31	380	---
-------	--	98.28	1.72	27.2	70	---
-------	--	98.86	1.14	27.0	29	---
-------	--	99.43	.57	26.7	5.0	---
-------	--	(e)	----	33.5	59	---

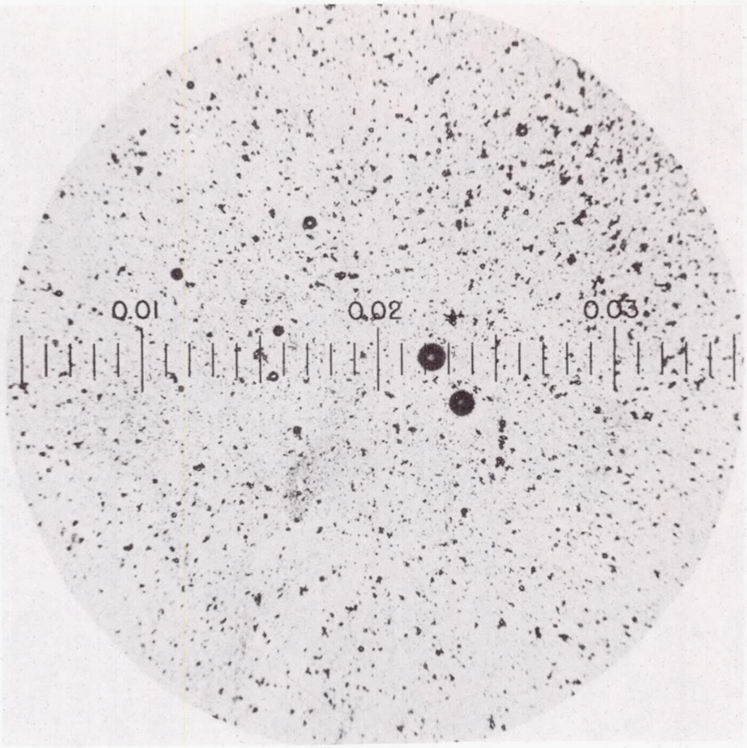
[a] SF, superfine; F, fine; BM, ball-milled; 200 and 400, mesh size; Amor., amorphous.

[b] Unobtainable.

[c] Dispersing agent.

[d] 70 percent mineral oil.

[e] 100 percent mineral oil.

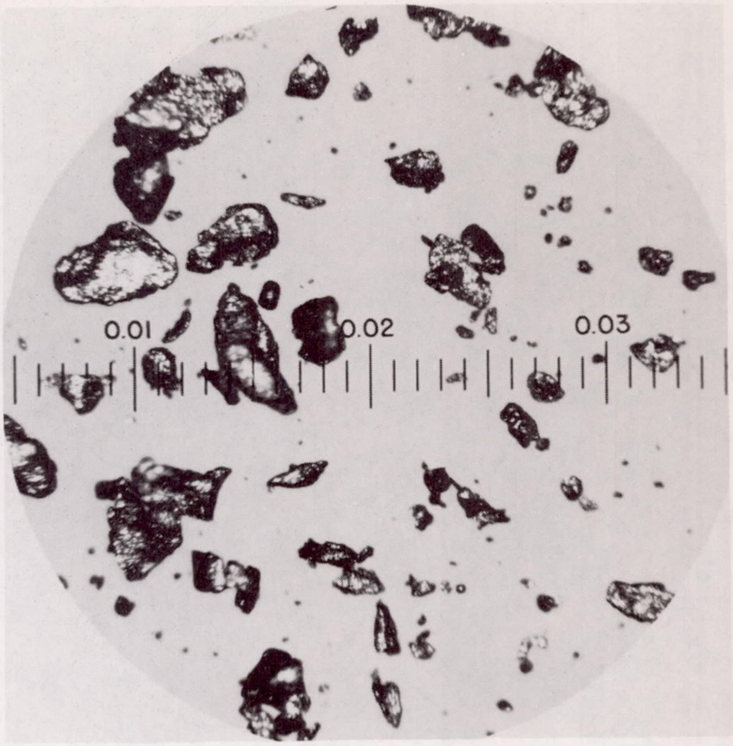


(a) Superfine.

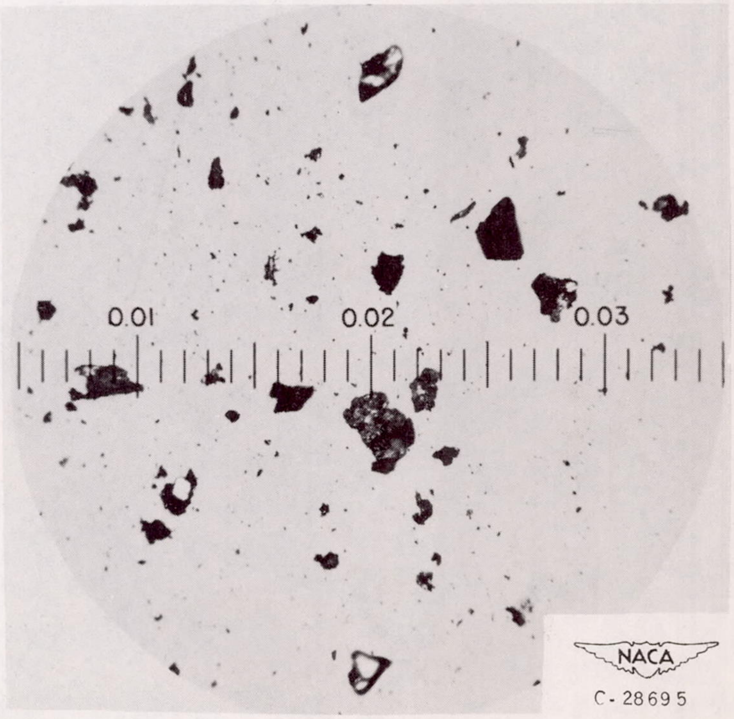
C-28694

(b) Fine.

Figure 1. - Photomicrographs of atomized magnesium particles (scale in inches).



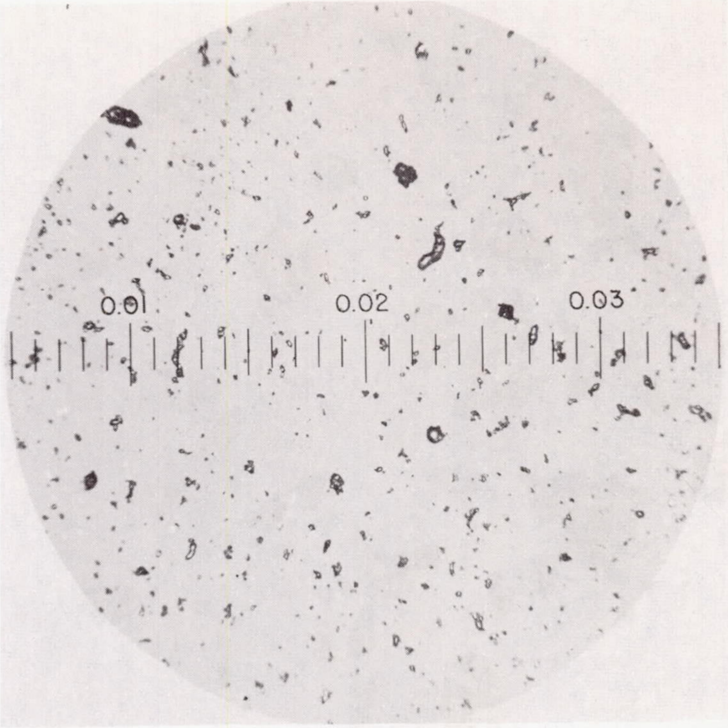
(a) Magnesium, ball-milled.



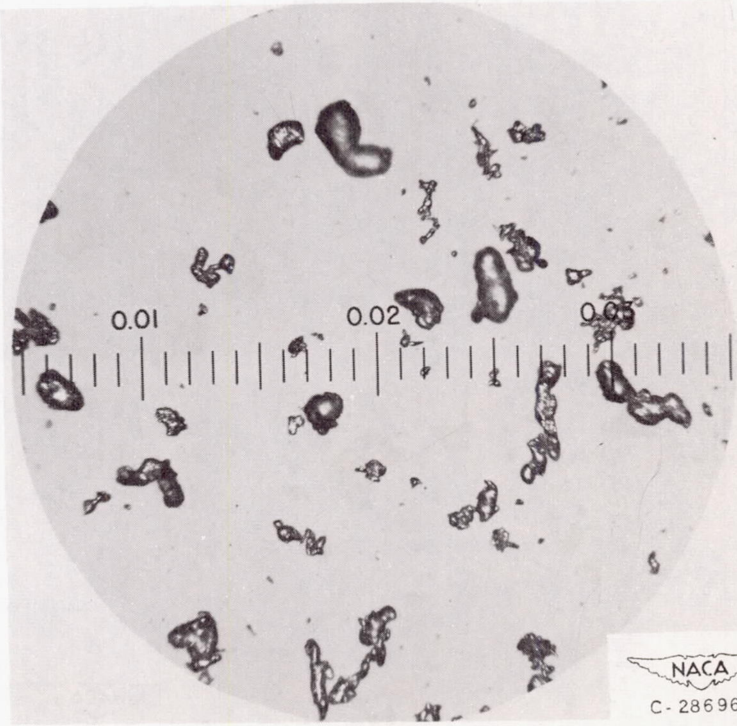
NACA
C-28695

(b) Boron, amorphous.

Figure 2. - Photomicrographs of ball-milled magnesium and amorphous boron particles (scale in inches).



(a) 400 mesh.



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(b) 200 mesh.

Figure 3. - Photomicrographs of atomized aluminum particles (scale in inches).

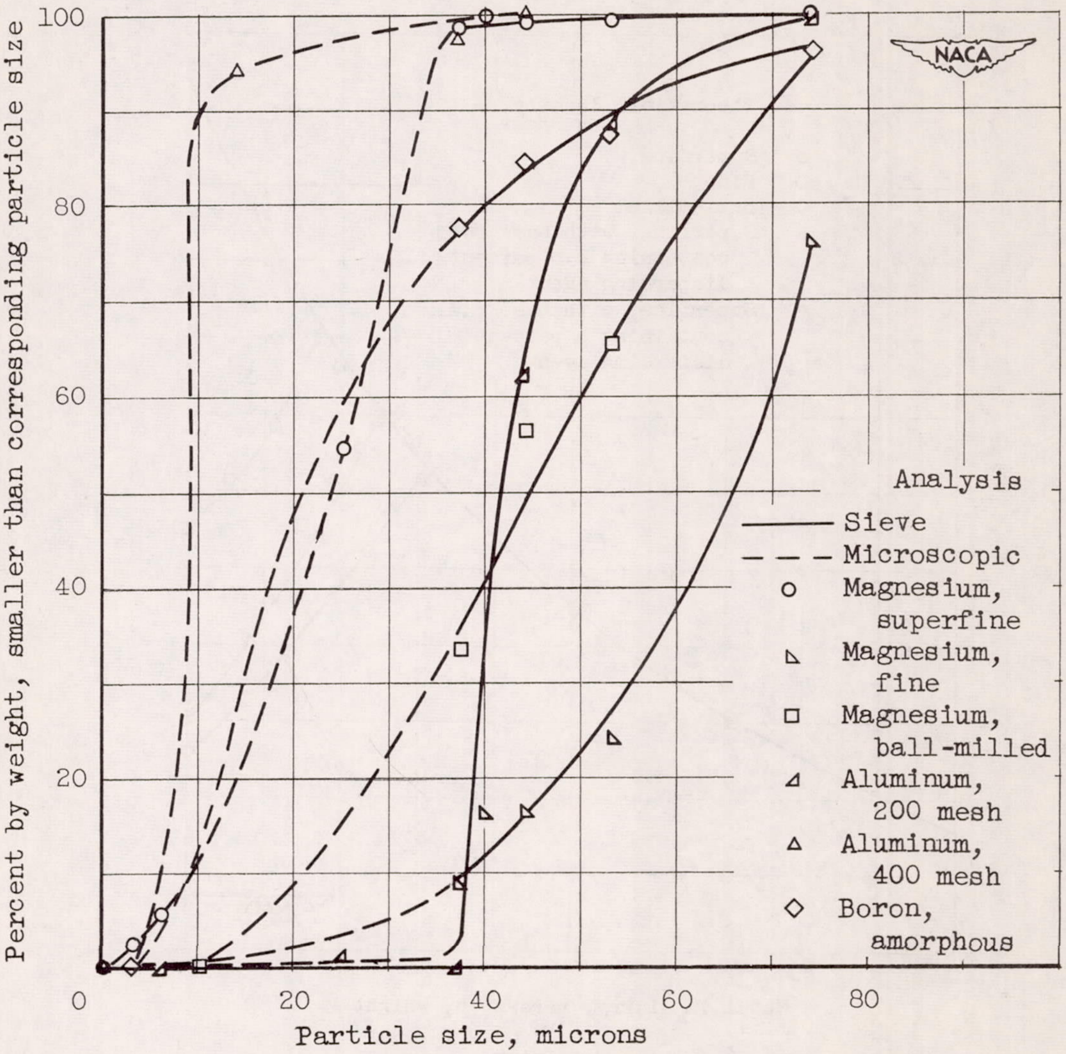
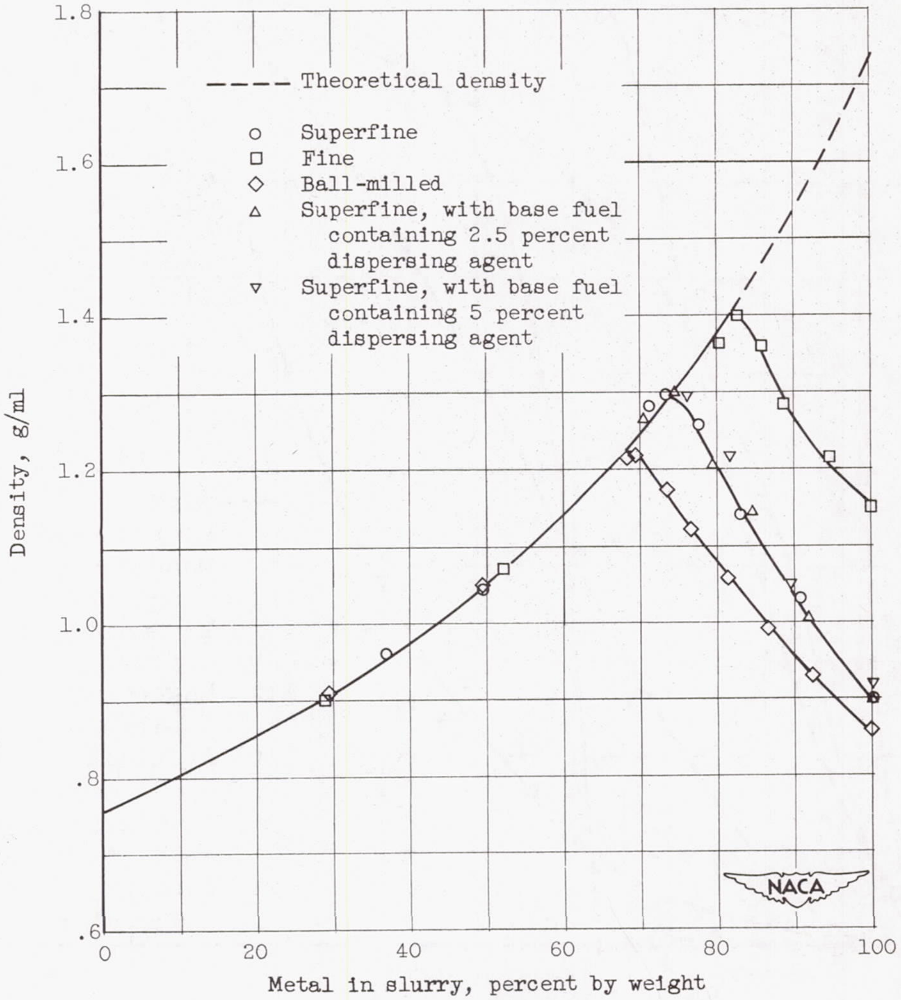
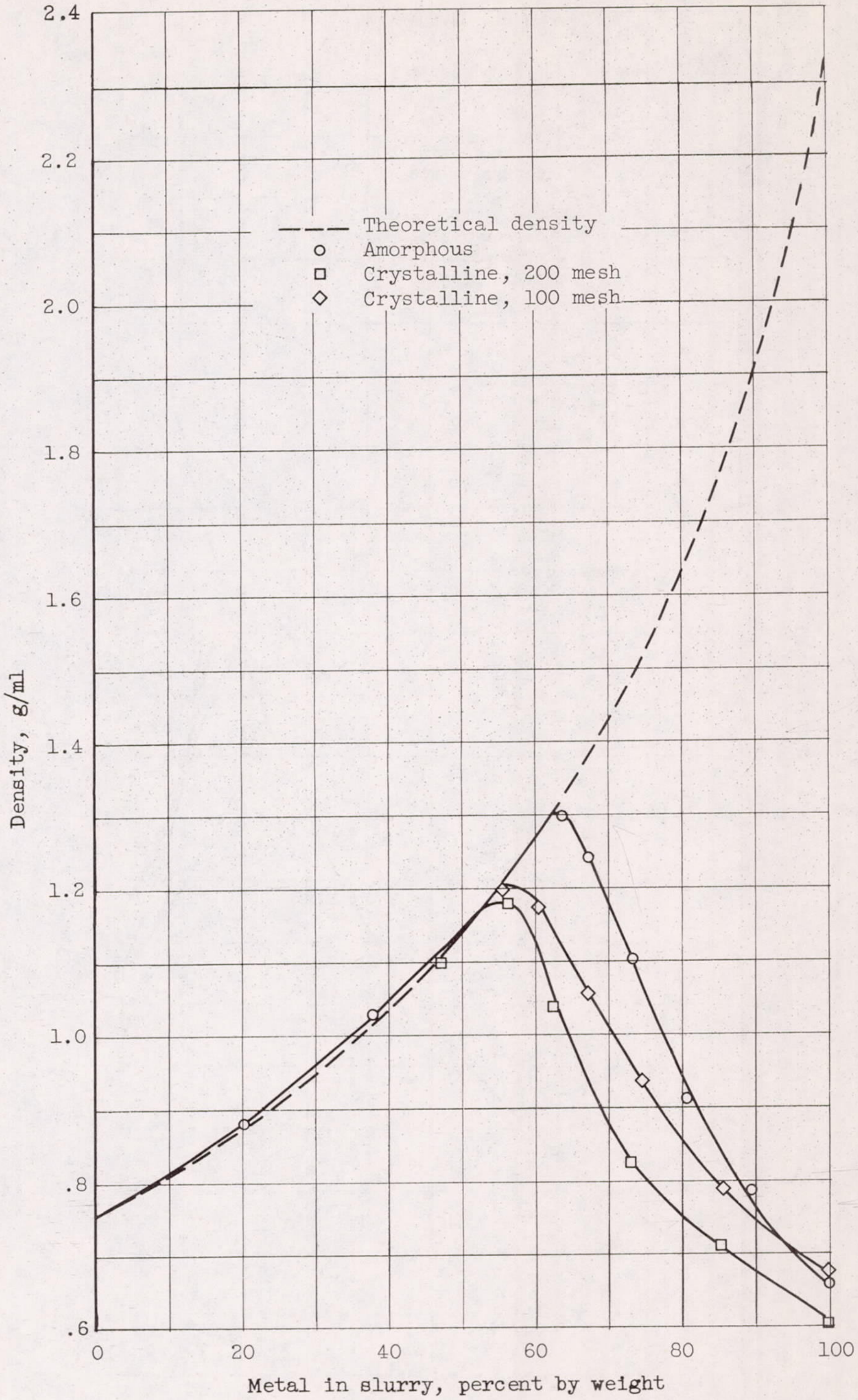


Figure 4. - Particle-size distribution of metal powders from microscopic and sieve analysis.



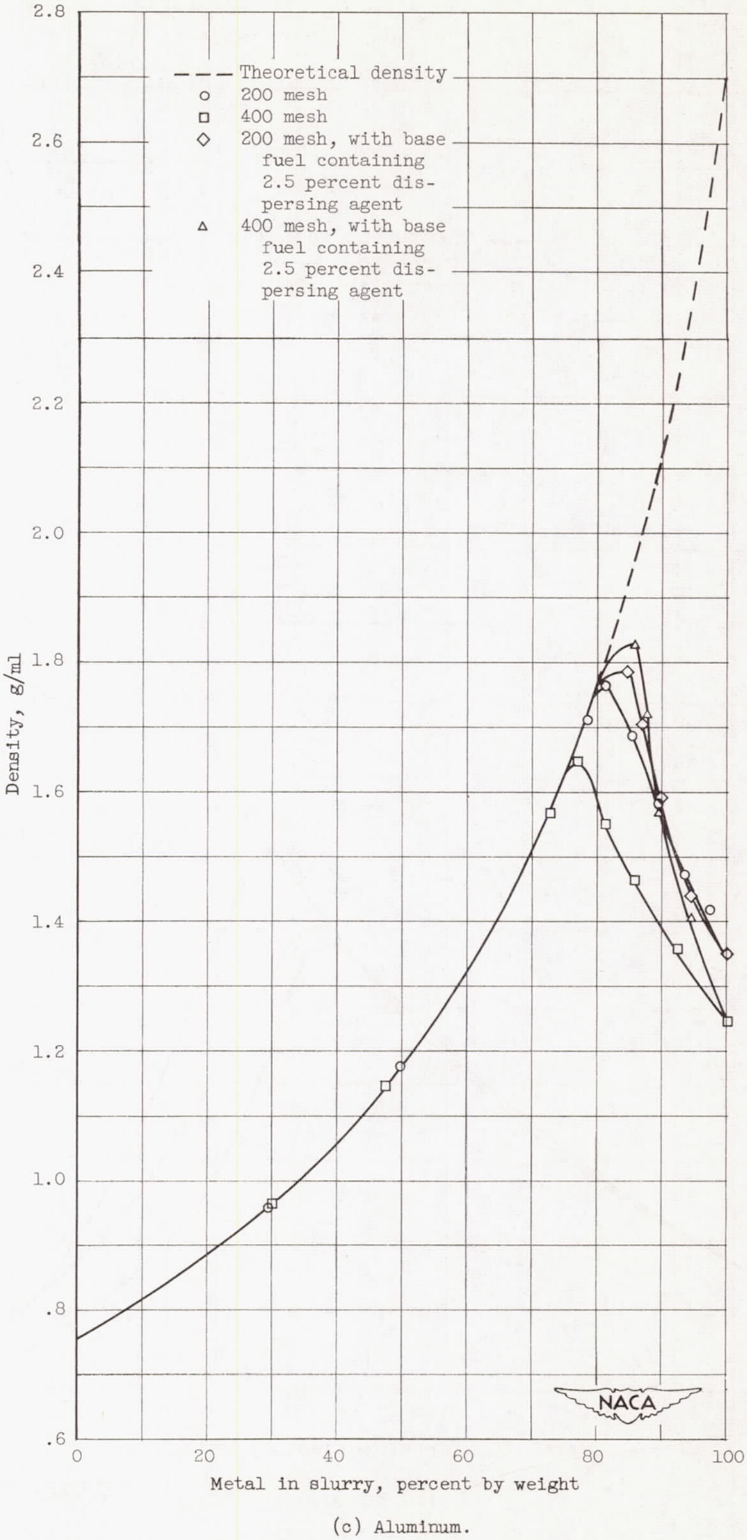
(a) Magnesium.

Figure 5. - Variation of slurry density with metal concentration. Base fuel, MIL-F-5624 grade JP-3.



(b) Boron.

Figure 5. - Continued. Variation of slurry density with metal concentration. Base fuel, MIL-F-5624 grade JP-3.



(c) Aluminum.

Figure 5. - Concluded. Variation of slurry density with metal concentration. Base fuel, MIL-F-5624 grade JP-3.

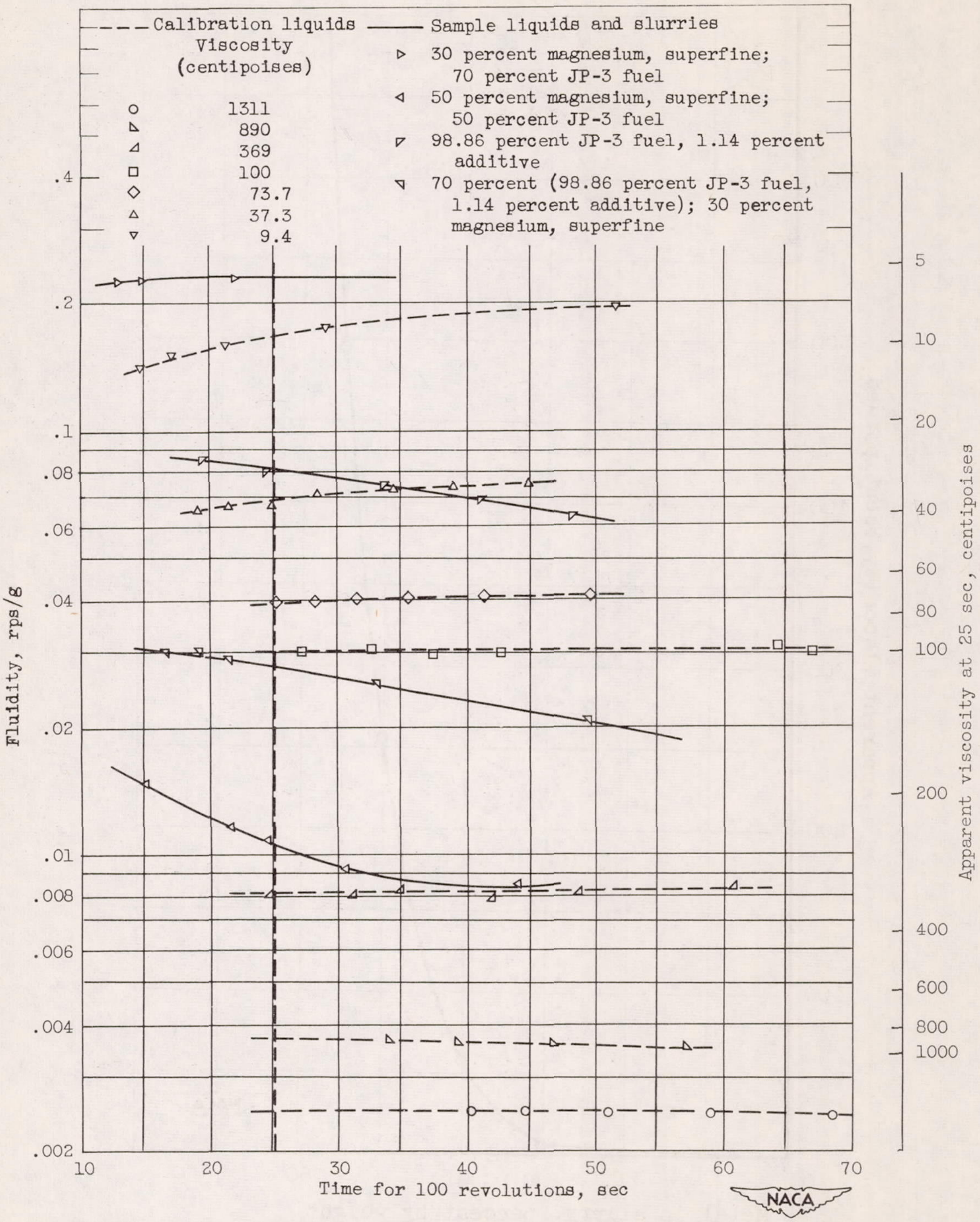


Figure 6. - Viscosity characteristics of calibration liquids, slurries, and MIL-F-5624 grade JP-3 fuel containing additive.

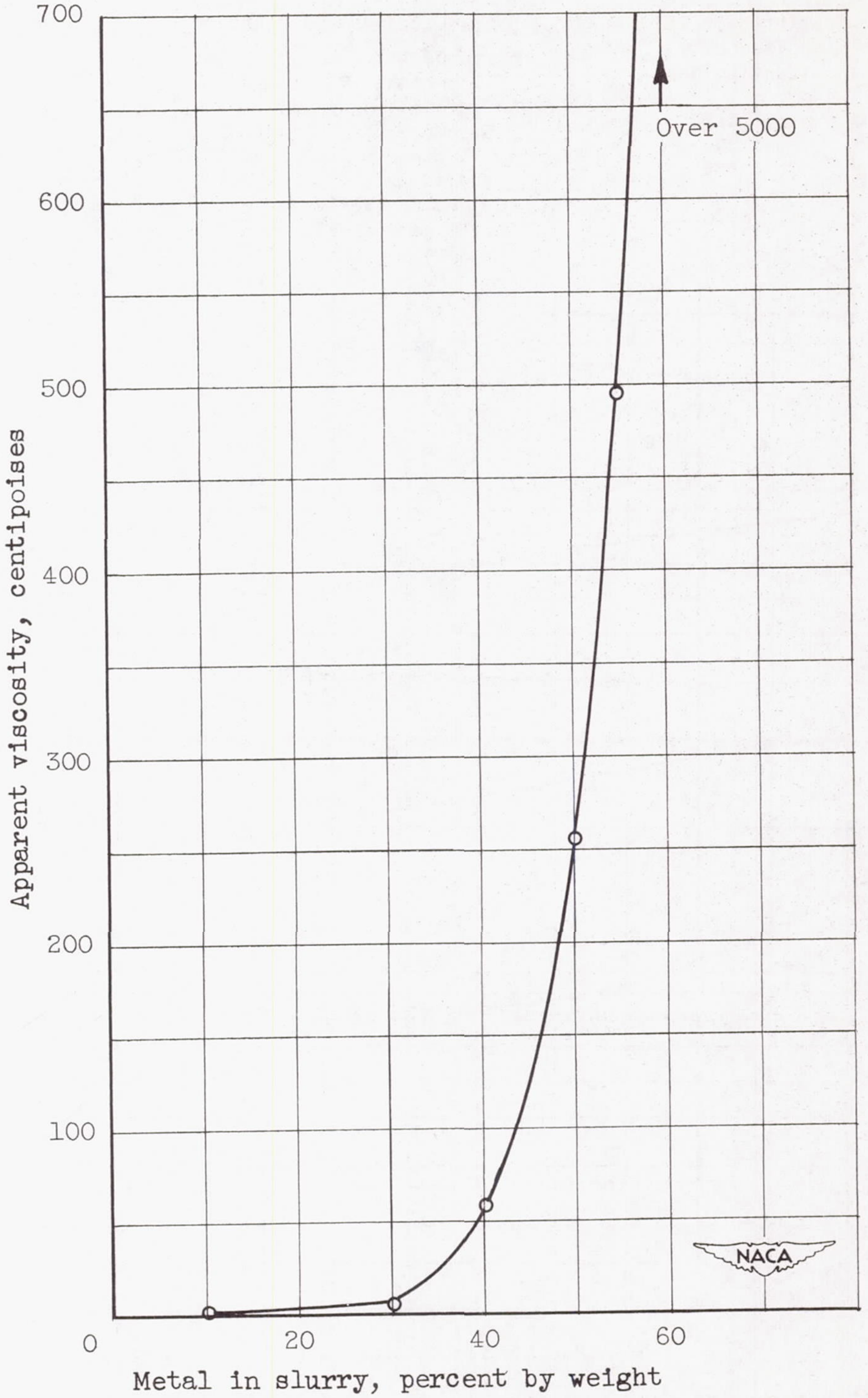


Figure 7. - Variation of apparent viscosity with superfine magnesium concentration in slurry. Base fuel, MIL-F-5624 grade JP-3; no additive present.

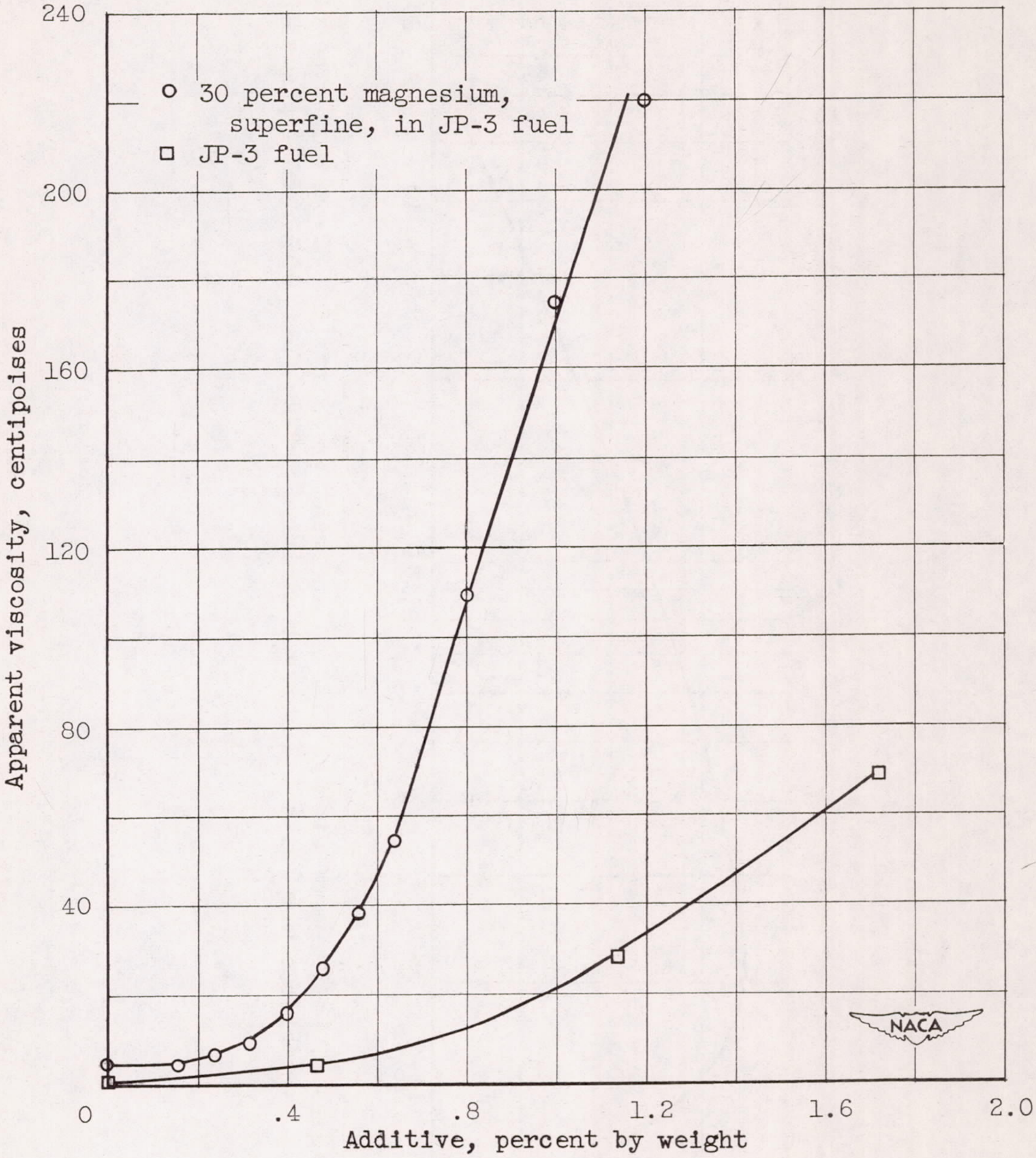


Figure 8. - Effect of additive concentration on viscosity of 30-percent-superfine-magnesium slurries and on viscosity of JP-3 fuel. Base fuel, MIL-F-5624 grade JP-3.

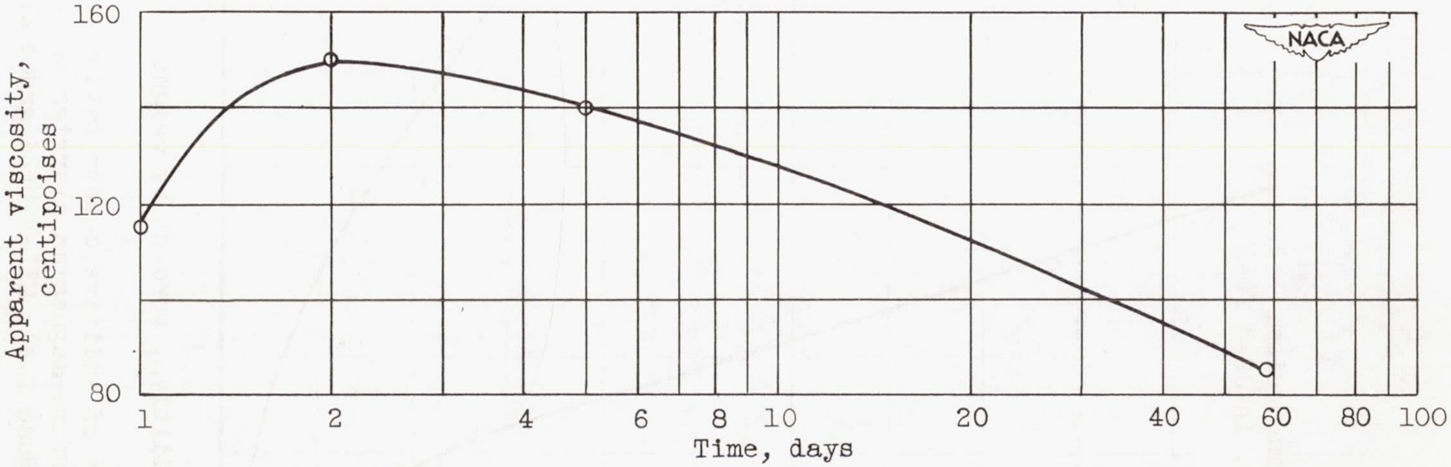


Figure 9. - Effect of storage time on apparent viscosity for 50-percent-superfine-magnesium slurry with 0.8 percent additive. Base fuel, MIL-F-5624 grade JP-3.

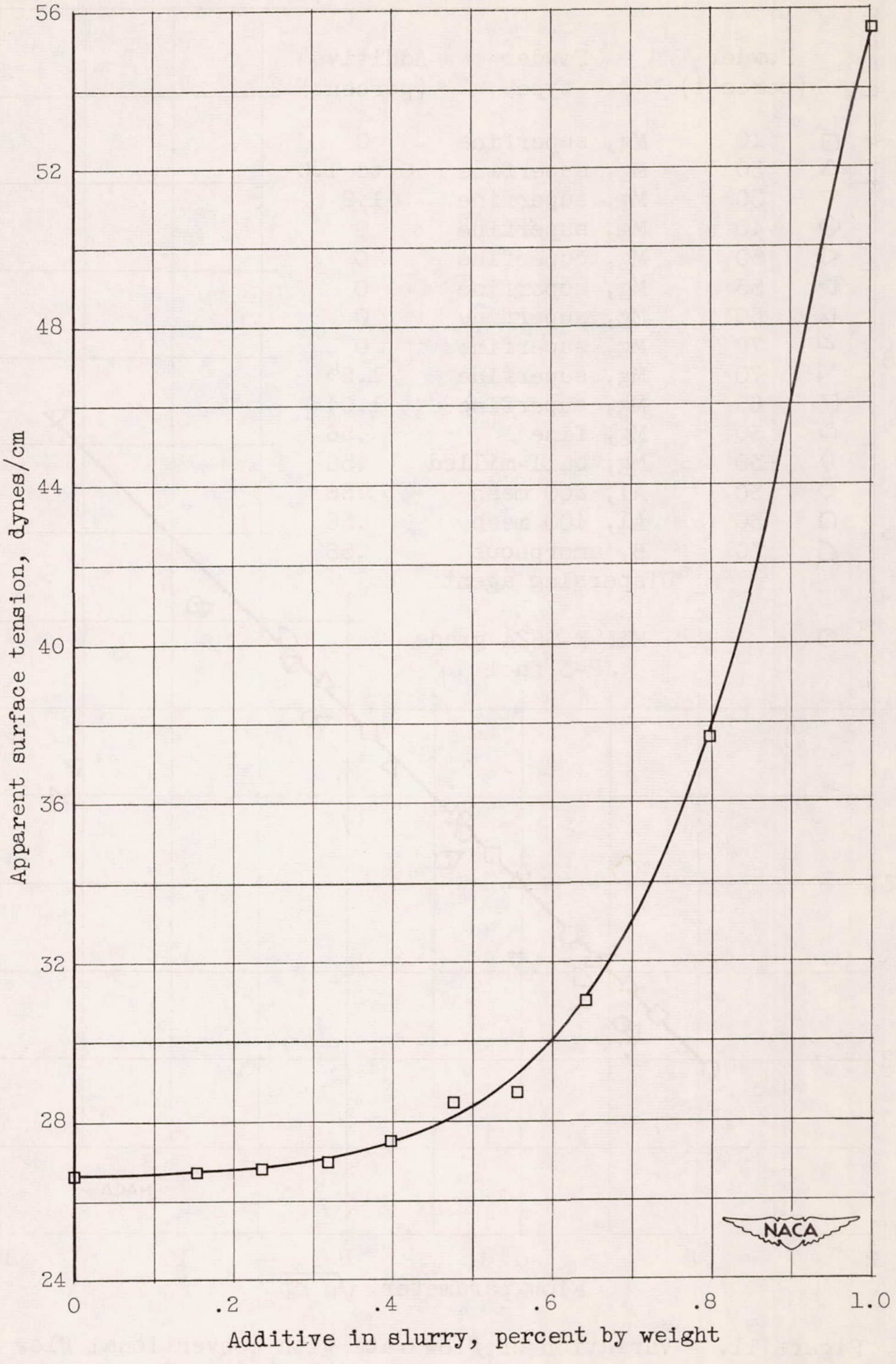


Figure 10. - Variation of apparent surface tension with additive concentration for 30-percent-superfine-magnesium slurry. Base fuel, MIL-F-5624 grade JP-3.

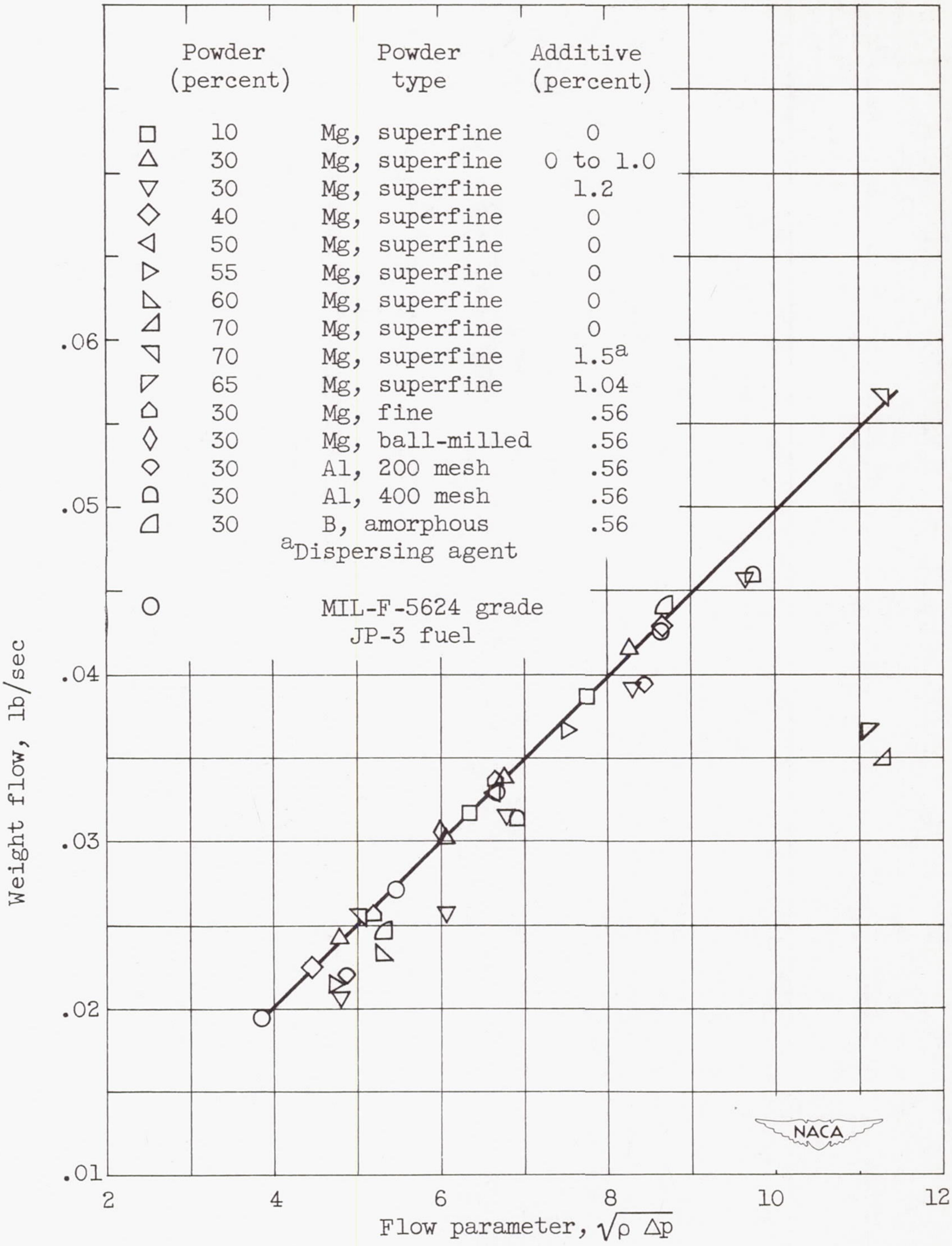


Figure 11. - Variation of flow rate with conventional flow parameter for slurries. Approach orifice, 45°; orifice throat, 0.040 inch.

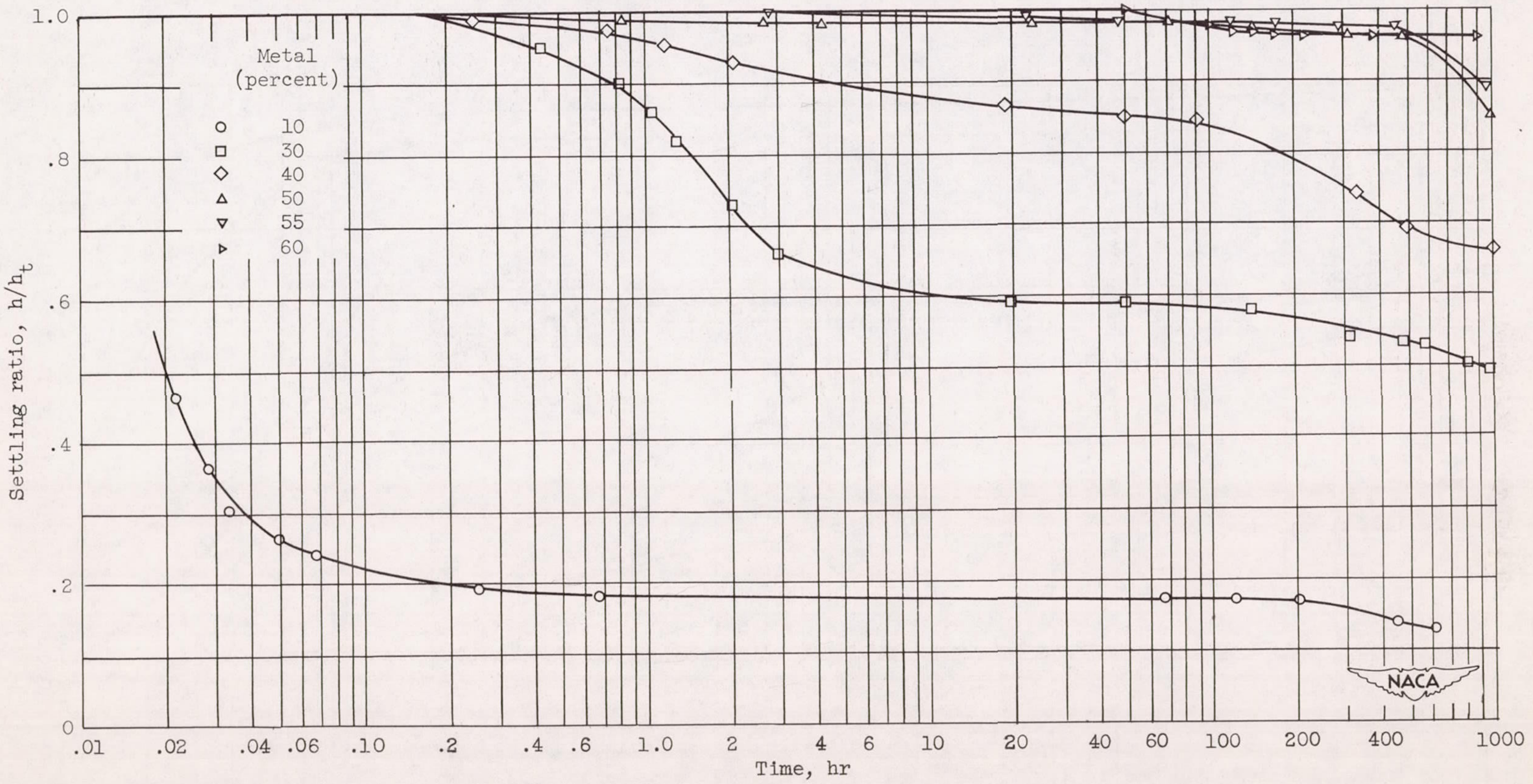


Figure 12. - Settling characteristics for superfine magnesium slurries. Base fuel, MIL-F-5624 grade JP-3; no additive present.

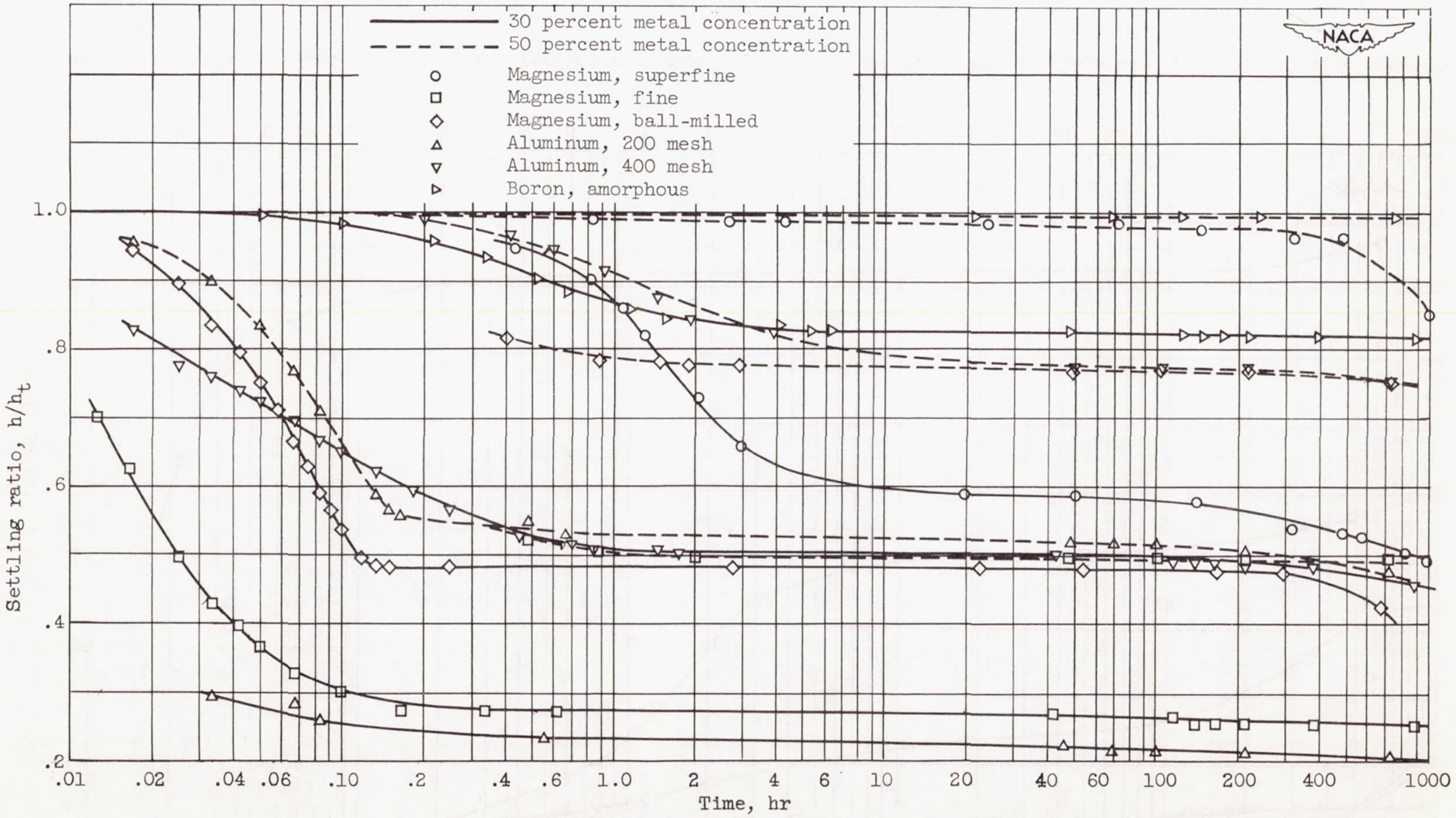


Figure 13. - Settling characteristics of six slurries of 30 and 50 percent metal concentration. Base fuel, MIL-F-5624 grade JP-3; no additive present.

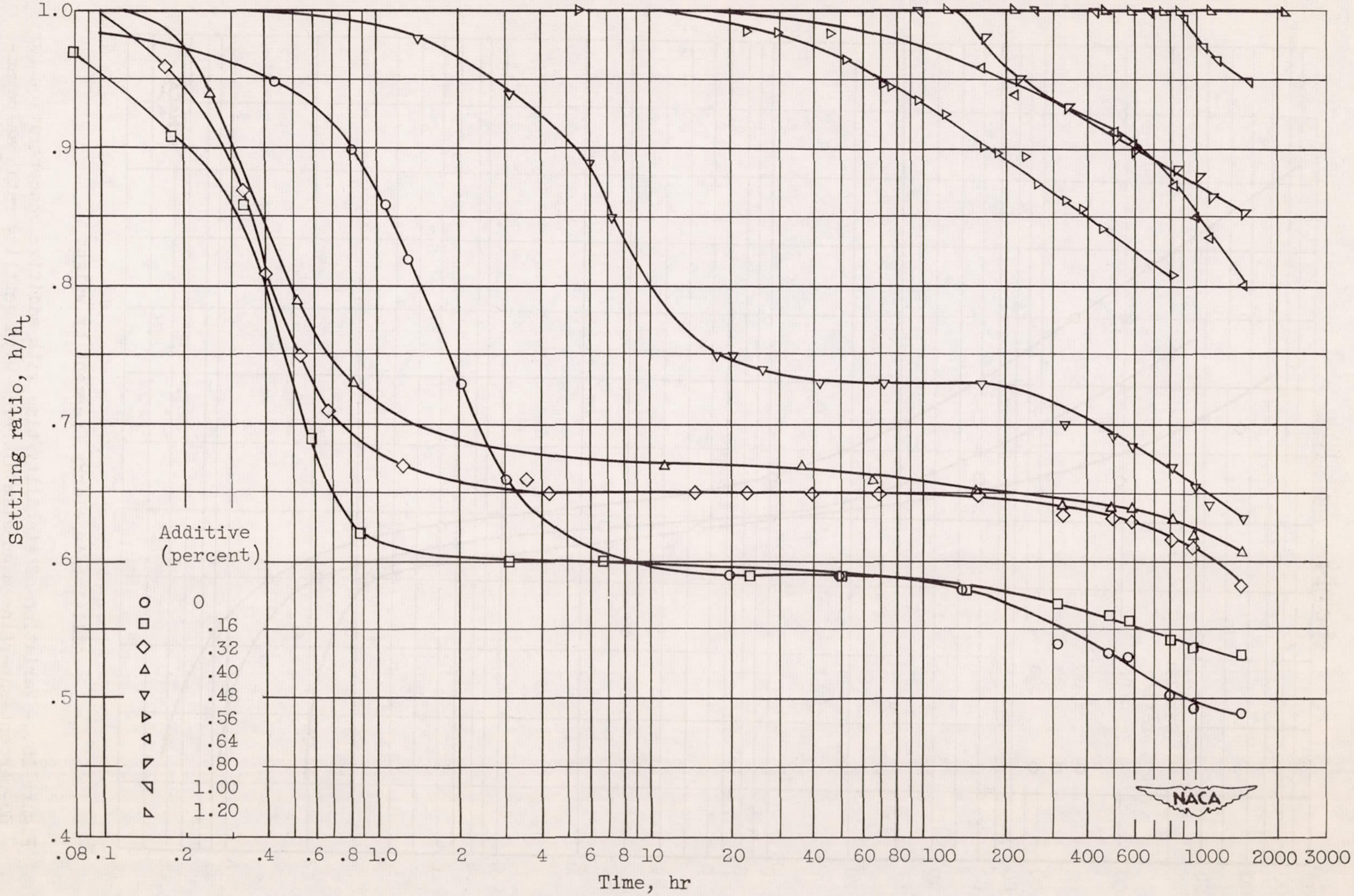


Figure 14. - Settling characteristics of 30-percent-superfine-magnesium slurries for various additive concentrations. Base fuel, MIL-F-5624 grade JP-3.

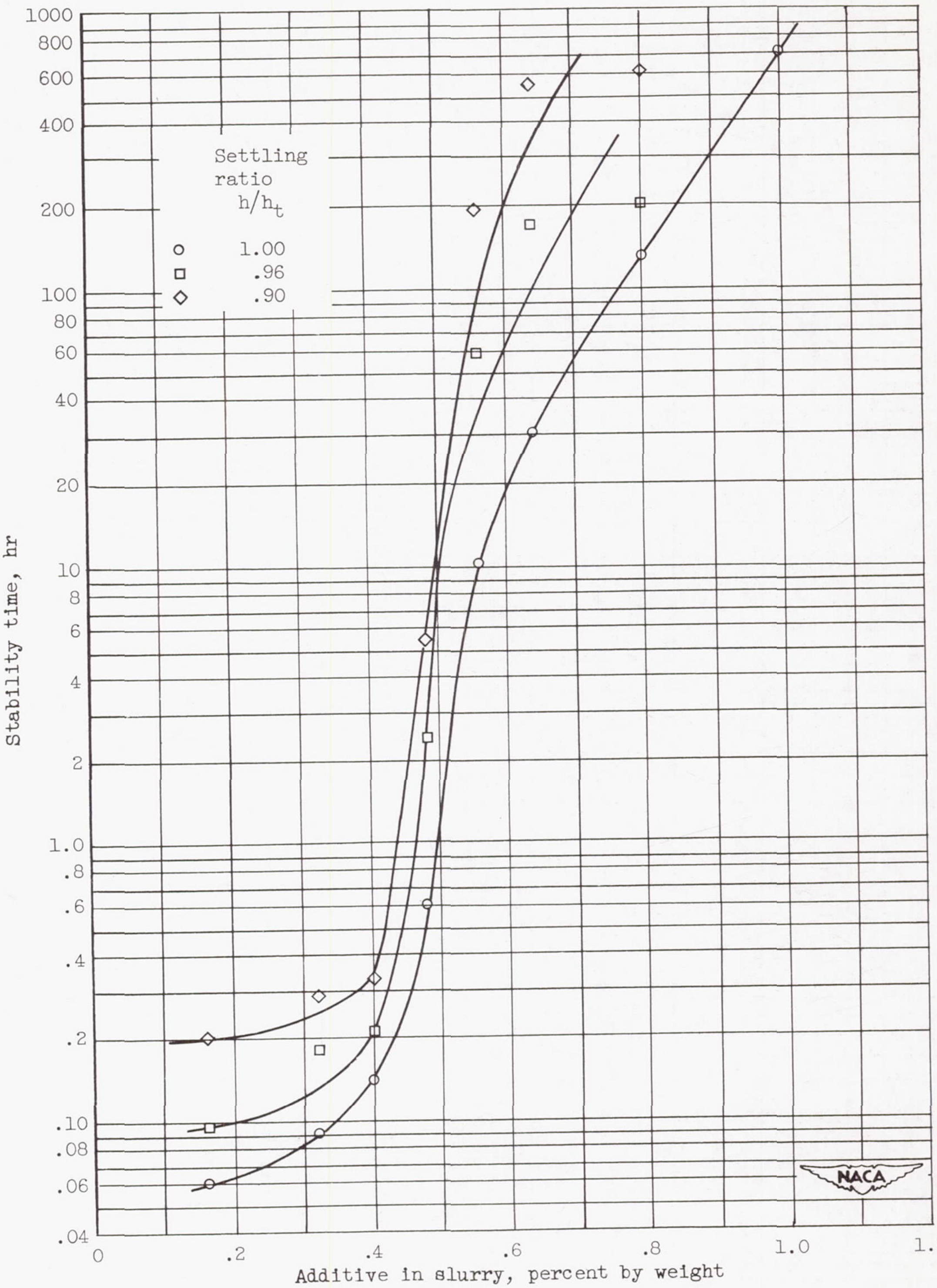


Figure 15. - Variation of stability time with additive concentration for 30-percent-superfine-magnesium slurries with settling ratio as parameter. Base fuel, MIL-F-5624 grade JP-3.

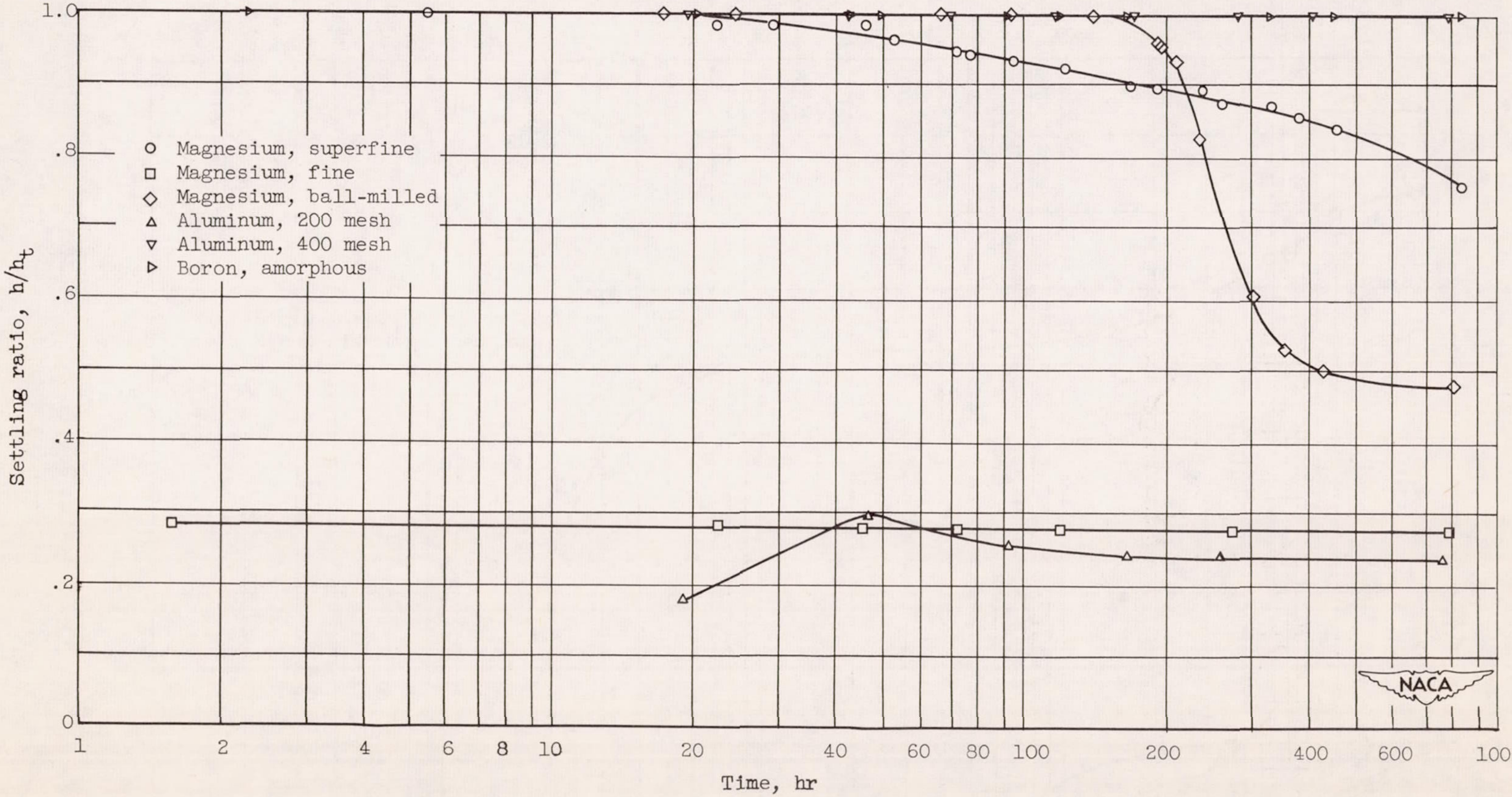


Figure 16. - Settling characteristics for six slurries of 30 percent metal concentration. Base fuel, MIL-F-5624 grade JP-3; additive concentration, 0.56 percent.

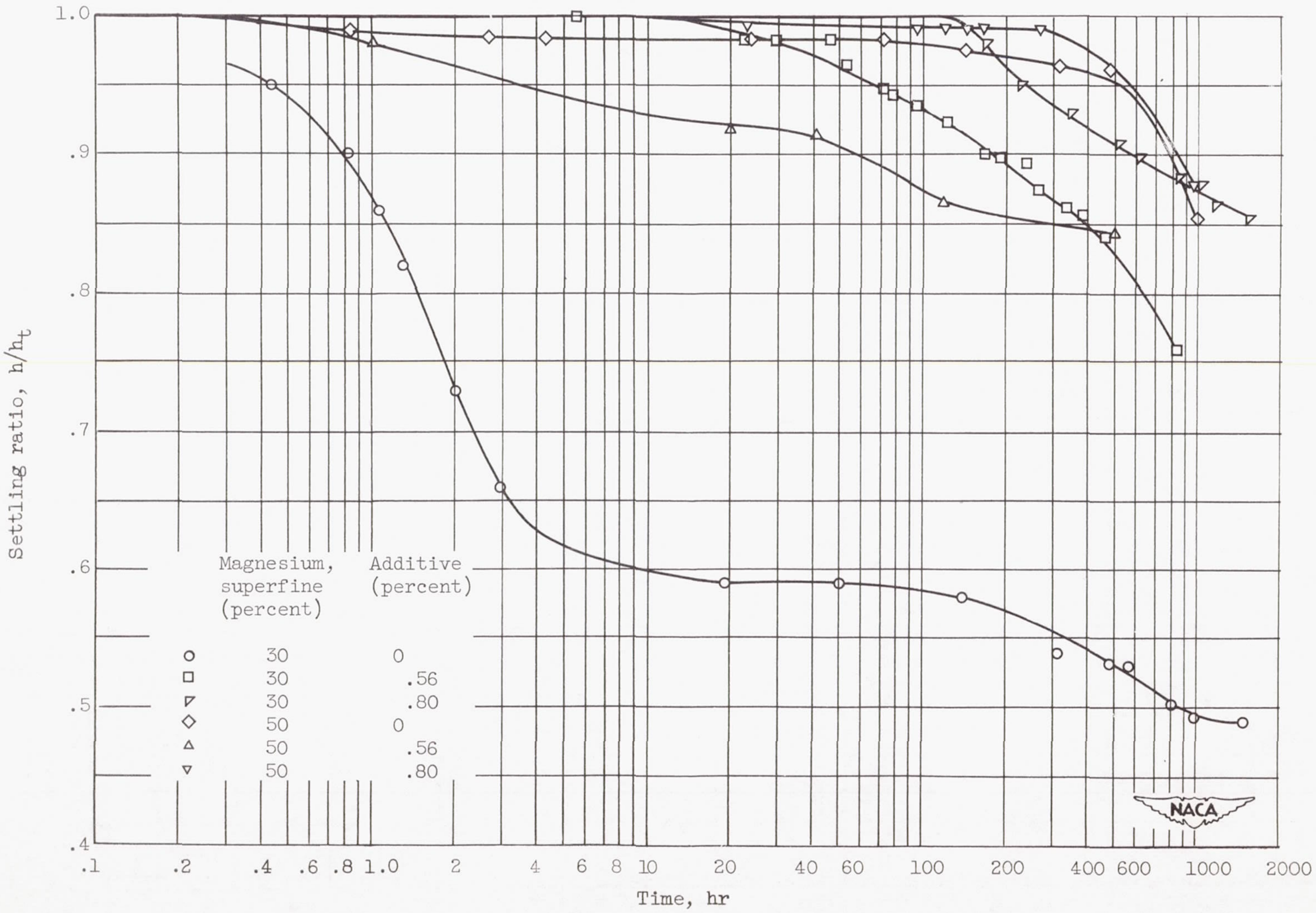


Figure 17. - Settling characteristics for 30- and 50-percent-superfine-magnesium slurries with additive concentration as parameter. Base fuel, MIL-F-5624 grade JP-3.

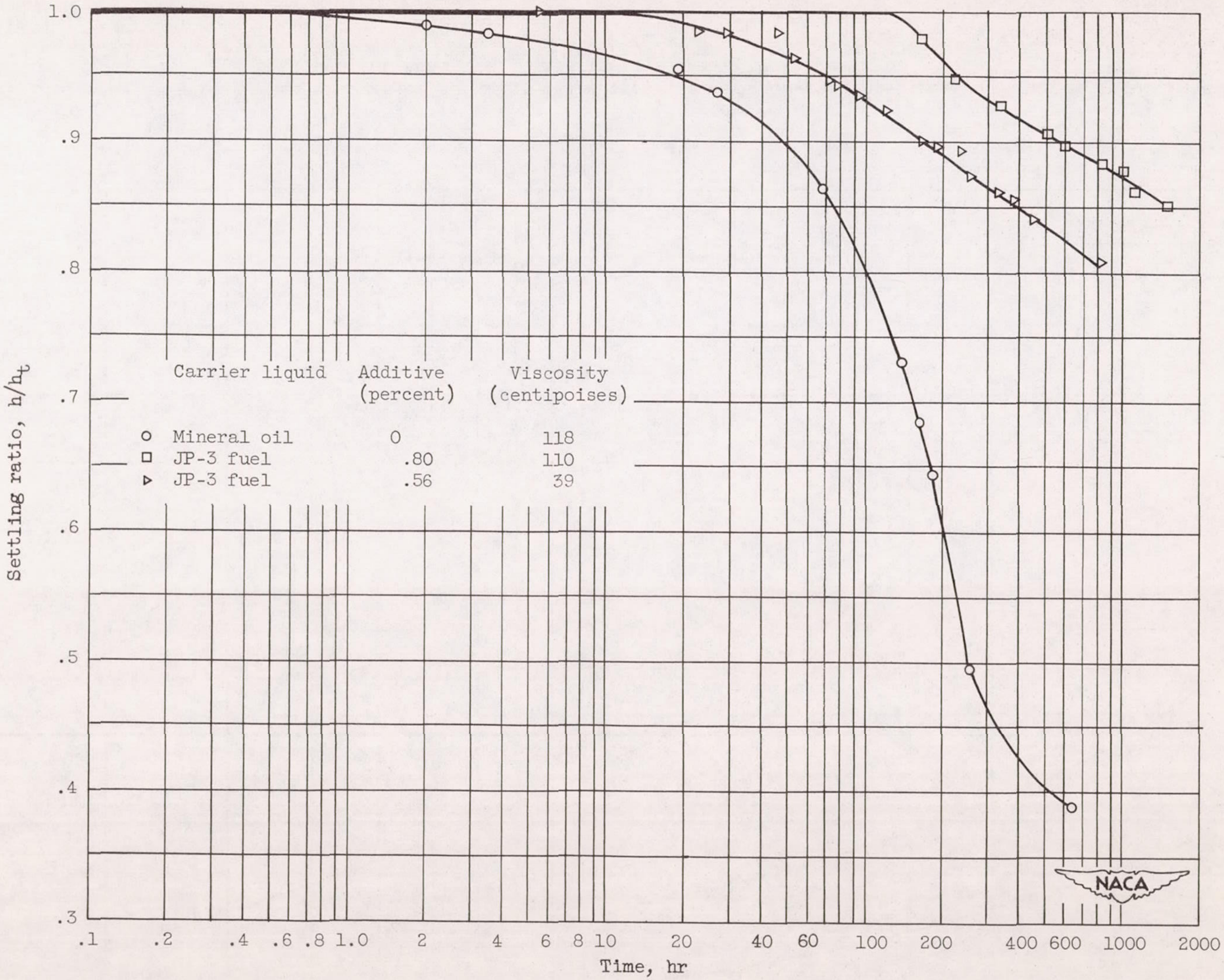


Figure 18. - Settling characteristics of slurries of 30 percent superfine magnesium in mineral oil and in MIL-F-5624 grade JP-3 fuel with additive.

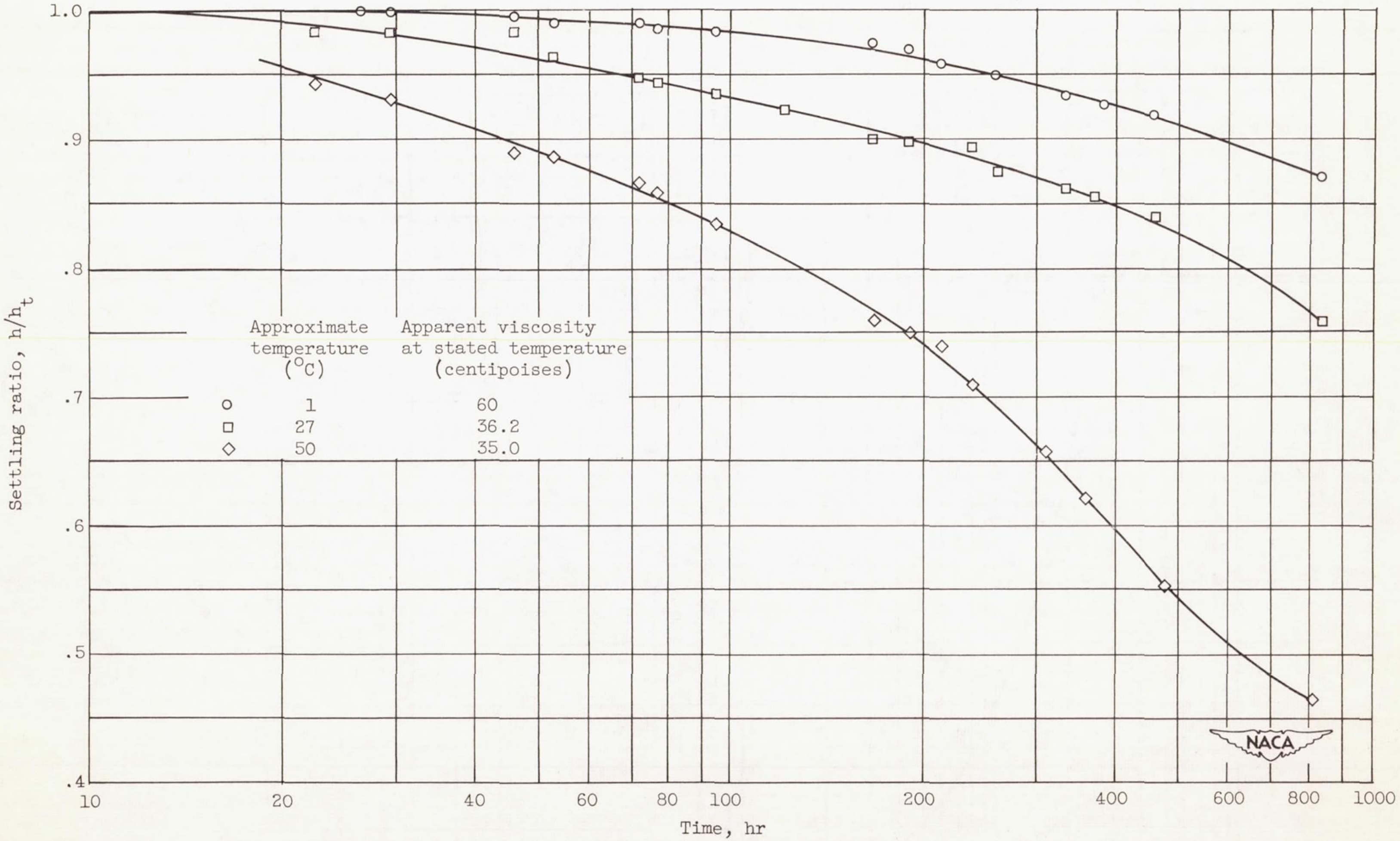


Figure 19. - Influence of storage temperature on settling characteristics for 30-percent-superfine-magnesium slurries with 0.56 percent additive. Base fuel, MIL-F-5624 grade JP-3.