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RESEARCH MEMORANDUM

PREPARATION AND HANDLING OF MAGNESIUM-HYDROCARBON

SLURRIES FOR JET-ENGINE APPLICATIONS

By Henry C. Barnett, A. M. Lord, and P. H. Wise

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SUMMARY

During the past eight years the NACA Lewis laboratory has conducted research on high-energy fuels. In the course of this research considerable information has been accumulated on the preparation, characteristics, and handling of metal-hydrocarbon slurries. This report has been prepared primarily to make this information available to industries concerned with the problem of utilization of slurries in aircraft. The discussion in this report emphasizes magnesium - jet-fuel slurries, since this type of slurry is currently of major interest for afterburner applications. Included in the discussion are details of slurry preparation, physical properties, storage, experimental fuel systems, disposal of solid combustion products, flammability hazards, and physiological hazards.

INTRODUCTION

As early as 1944 it was realized that greater range and thrust than those available from hydrocarbon fuels could be achieved by use of certain nonhydrocarbon materials. For this reason, the NACA Lewis laboratory has explored the possibilities of using these nonhydrocarbon materials as fuels for jet-propulsion engines. Preliminary studies indicated that the greatest gains to be made in energy content and combustion temperatures could be achieved by the use of metals, hydrogen, and combinations of the two.

Of the metals considered, boron, because of its high heat of combustion, is of interest for flight range improvement. On the other hand, aluminum and magnesium, although they have low heats of combustion, will burn to high temperatures and therefore may be useful for thrust improvement.

Little or nothing was known regarding methods of combustion of metals in jet engines; consequently, the investigations were conducted to evaluate

combustion characteristics in experimental laboratory burners and full-scale ram-jet combustors and afterburners (refs. 1 to 10). The results of these investigations indicated that magnesium could be more easily utilized than boron or aluminum because its oxide has properties which would minimize deposits in the combustion and exhaust zones. Moreover, the availability of magnesium enhanced its value as a possible jet-aircraft fuel.

Early studies were made with solid and powdered metals; however, handling difficulties indicated that slurries of metal powder and liquid hydrocarbon fuels might be a more satisfactory means for use of metallic fuels in aircraft fuel systems and engines. It was further evident that the applications of metals as aircraft fuels in the near future would probably be in the form of auxiliary fuels for thrust augmentation with afterburners. In this application the problem of solid exhaust products would not be as critical. For the same reason, application as a primary fuel for ram jets is also probable. It is possible, however, that sometime in the future liquid high-energy fuels may be developed to supplant slurries as fuels for afterburners and ram jets.

The information that has been accumulated in the preparation and handling of magnesium - jet-fuel slurries can serve as an aid to engine manufacturers in the development of slurry-fuel afterburners. Although the subject of slurry preparation is discussed in several reports, handling practices relating to metering, pumping, and safety have not been documented. For these reasons, the present report was prepared to provide a single reference source describing slurry preparation, physical properties, storage, experimental fuel systems, disposal of solid combustion products, flammability hazard, and toxicity.

It is obvious that the use of slurries as aircraft fuels has introduced many new problems not associated with liquid fuels. As study continues and as more data are accumulated in this field of study, it is anticipated that greater reproducibility of results will be achieved and a more quantitative picture of slurry characteristics will emerge. Consequently, the material presented herein must in many instances be considered to be of an interim nature. Much of the uncertainty in this field is attributed to the lack of suitable instruments to evaluate properties of slurries. It is apparent in the succeeding portions of this report that progress in the field will be dependent upon the development of better instruments.

PHYSICAL AND THERMAL PROPERTIES OF MAGNESIUM-SLURRY COMPONENTS

Magnesium slurries used in combustion studies conducted to date have been prepared as mixtures of hydrocarbons, metal, and additives. The hydrocarbon component serves as the carrying agent, the metal is the

carried component, and the additives aid in permitting a high concentration of metal to be added to the mixture while providing for a satisfactory fluidity. The properties of all three components influence the suitability of the final slurry insofar as handling and combustion are concerned.

Hydrocarbons

The hydrocarbon materials used in preparing slurries conform to past, and current jet-fuel specifications. The specifications for these fuels are shown in table I. Any one of these fuels might be used for slurry preparation; however, the MIL-F-5624B specification for JP-4 and JP-5 fuels is representative of the type fuel that would be available in a military emergency.

Generally speaking, JP-1 is a kerosene type fuel, whereas JP-5 fuel might be termed a high-flash kerosene, or light distillate fuel oil. On the other hand, JP-3 fuel is a high-volatility wide-cut fuel drawn from the gasoline, kerosene, and distillate oil petroleum fractions. The composition of JP-4 fuel is similar to that of JP-3 fuel but has fewer high-volatility constituents and consequently a lower vapor pressure.

Although the specifications in table I indicate the limiting values for various physical properties, it should be recognized that any single property may vary appreciably and still meet the requirements of the specification. This fact is substantiated by data in table II from references 11 and 12. For example, as shown in this table, the spread in specific gravities may be as great as 10 percent and in viscosities at low temperature (-40° F) as great as 300 percent.

Metals

Physical and thermal properties of magnesium and its oxide are presented in table III (also refs. 13 to 16). Properties for the oxide have been included because it is of interest in the problem of exhaust products. As can be seen in this table, the melting point of magnesium oxide is 5074° F. Therefore, the magnesium oxide will most probably exist in the solid state in the exhaust of an engine, since the temperatures there will not exceed 5074° F.

PROPERTIES OF MAGNESIUM SLURRIES

In order to obtain the greatest benefit from the combustion properties of metals, it is, of course, desirable to maintain a high concentration of metal in the hydrocarbon carrier. However, the maximum concentration of metal is determined by the properties of the final slurry that

will affect the handling characteristics. For example, the suspension of metal in hydrocarbon must be stable enough to permit long-term storage without settling, and it must have a sufficiently low viscosity to permit pumping and atomization. Unfortunately, the pure metal-hydrocarbon mixture usually does not satisfy these requirements. Consequently, the study of additives has become an important part of slurry investigations. The additives investigated fall into two general classes, namely, thickening agents to improve stability, and wetting agents to allow for increase of metal concentration with control of fluidity. Also important in the preparation of slurries are the effects of metal-particle size and shape. The influence of these two factors, together with the effect of additives, is discussed in the succeeding paragraphs.

Effect of Metal Concentration on Properties of Magnesium Slurries

Density. - A preliminary study of the influence of magnesium concentration on slurry density is reported in reference 17. Three types of magnesium used for this study are briefly described in the following table:

Magnesium type	Median particle size, μ	Estimated pure metal, percent by weight	Estimated oxide content, percent by weight
Atomized	66	99	1
Ball-milled	45	87	13
Atomized	24	97	3

The particle-size distributions in the preceding table were determined by microscopic and sieve analysis methods (ref. 18). The median particle sizes are based on the 50-percent (by weight) points of the distribution curves shown in figure 1. These particle sizes are considerably larger than those of magnesium used in more recent investigations; however, at the time the density studies (ref. 17) were made, the smaller particle sizes desirable for combustion were not readily available.

In order to determine the density of the metal-hydrocarbon slurries (ref. 17), samples of the dry powders were placed in sample tubes and the tubes were tapped until a minimum metal volume was established. Small amounts of JP-3 fuel were then added and successive weighings were made. As the JP-3 fuel was added, the density of the total increased. When all the voids were filled, further additions of JP-3 lowered the density. These changes in density are illustrated in figure 2 for magnesium-hydrocarbon slurries. Theoretical densities for the metal-hydrocarbon slurries calculated from the following equation are included for comparison:

$$\frac{1}{\rho_t} = \frac{x}{\rho_m} + \frac{(1-x)}{\rho_e} \quad (1)$$

where

- ρ_t slurry density
 ρ_m solid metal density
 ρ_e liquid-hydrocarbon density
 x weight fraction of metal powder
 $(1 - x)$ weight fraction of liquid hydrocarbon

The measured densities (fig. 2) agree well with the theoretical curve (eq. (1)) up to metal concentrations of approximately 70 percent (by weight). Since that concentration is probably in excess of concentrations to be applied in aircraft slurries, the theoretical density equation is a convenient tool for estimation purposes.

More recent data indicate that small-particle-size magnesium produced by the vapor condensation method (ref. 19) exhibits density variations similar to those illustrated in figure 2. An analysis of one sample of magnesium powder produced by this method showed 33 percent by weight of particles finer than 1 micron and 73 percent finer than 2 microns. Electron micrographs (fig. 3) of this powder indicated no consistent particle shapes. Some particles were roundish in shape, whereas others were hexagonal or possibly cubical. The translucence of some particles indicated that these particles were in the form of thin plates less than 500 angstrom units in thickness.

Viscosity. - Viscosities of slurries have been determined with three types of viscometers, Stormer, Brookfield, and Severs. Of these types, the Stormer viscometer is probably the most applicable to slurry analyses; however, the Brookfield instrument has been used extensively by the NACA because of the rapidity with which determinations can be made. The three types of viscometers are described in appendix A.

The influence of magnesium concentration on Brookfield viscosities of metal-hydrocarbon slurries is illustrated in figure 4 (also ref. 20). These slurries were stabilized with a petrolatum designated petrolatum E in table IV. As the metal concentration was increased to 15 percent by weight (fig. 4), the Brookfield viscosity increased approximately forty-fold. Above this concentration the viscosity increased more slowly to a concentration of about 40 percent metal. Further increases in magnesium concentration resulted in a higher rate of viscosity increase. No explanation can be offered for the plateau in the middle of the viscosity curve (fig. 4); however, check data substantiated this portion of the curve.

Viscosity data (ref. 17) obtained with a Stormer viscometer for slurries with no petrolatum show little or no increase in viscosity up to a magnesium concentration of 30 percent. Above this concentration viscosity increases sharply.

Stability. - The influence of metal concentration on stability of slurries is illustrated in figure 5. This figure is based upon data reported in reference 21, but settling is expressed in terms of a settling ratio h/h_t rather than the sedimentation ratio used in the reference. In the settling ratio, h_t is the total slurry height before any settling occurs. As settling takes place at a given time, h is equal to the height of a phase containing settled metal particles and liquid.

The data presented in figure 5 show that the settling rate becomes much slower as the metal concentration is increased. For the 60-percent slurry little or no settling occurred during the first five days, and after 23 days only about 3 percent of the slurry had settled.

Effect of Particle Size and Shape

Density. - The effect of particle size and shape on density is illustrated in figure 2. Although no regular trend is indicated, it is apparent that the size or shape has no effect on the agreement between theoretical and actual densities. The size and shape of the particles affect the point at which the voids in the metal powder are completely filled by the JP-3 fuel. This effect is indicated by the points on the curve where the density decreases upon further increase of metal concentration.

Viscosity. - The effect of particle size on apparent viscosity of petrolatum-stabilized magnesium - JP-4 slurries is indicated in figure 6 (also ref. 21). As particle size increases, viscosity decreases. Recent unpublished NACA data confirm this trend and indicate that slurries made with particle sizes less than 2 microns may have viscosities considerably higher than those shown in figure 6.

For the curves representative of metal concentrations of 30, 40, and 50 percent, a minimum viscosity is shown. However, it is doubtful whether much significance can be attached to this result. The powder samples used had the average particle sizes shown, but it is obvious that these values are dependent upon the particle-size distribution. Consequently, it would be possible to have several very different distributions and still have identical average particle sizes. Moreover, the manner in which the metal particles disperse through the liquid would influence the viscosity. That is, if a considerable quantity of small particles were present, the voids between large particles of metal would be filled and a more compact mass would result.

Stability. - The effect of particle size on stability (ref. 21) is illustrated in figure 7. As shown in this figure, stability increases as particle size is decreased. This result is confirmed by data in reference 21 for other metal concentrations and also by reference 7, in which magnesium slurries with various grades of fuel oil were evaluated.

Effect of Additives

As part of the over-all evaluation of slurries, the effects of additives on physical properties of slurries has also been of considerable importance because concurrent satisfactory stability and fluidity must be obtained. Investigations of additives have included thickening agents and surface-active wetting agents, the former to improve stability and the latter to reduce viscosity.

Viscosity. - The petrolatums and aluminum soaps of C_8 acids that were used as thickening agents (to improve stability of slurries) affect viscosity; this is shown for the petrolatums in figure 8.

The results in figure 8 show an increase in viscosity as the petrolatum concentration increases. The rate of viscosity increase with concentration varies among the petrolatums investigated. Both apparent and residual viscosities are shown in figure 8. The apparent viscosities at low shear rates were measured with the Brookfield viscometer, but at high rates of shear a Severs Extrusion Rheometer was used (appendix A). The residual viscosity has been defined (ref. 22) as the apparent viscosity extrapolated to an infinite rate of shear. The apparent viscosities used for this extrapolation are obtained by the Severs method. Physical properties of the petrolatums used in this investigation are given in table IV.

Slurries containing petrolatum as a thickening agent are quite sensitive to temperature variations (ref. 20). The Brookfield apparent viscosity of a slurry containing 50 percent magnesium and 18 percent petrolatum E changed from approximately 150 centipoises at 110° F to 92,000 centipoises at 28° F (fig. 9). Similar behavior was found for a slurry containing 26 percent petrolatum B. From the standpoint of handling and storing fuel over wide ranges of temperature, this variation in viscosity could be a handicap; but, in the case of thick slurries, increased temperature could be a means of obtaining a thinner slurry in fuel-system operations.

The results of tests with thickening agents are reported in reference 23. The thickening agents used were aluminum soaps of C_8 acids. With only one exception, all soaps increased slurry viscosity as the concentration increased. The results of reference 23 are illustrated in figure 10 for a test with several concentrations of one soap.

Fifty surface-active additives used to reduce viscosity have been evaluated in magnesium-slurry studies (ref. 24). The properties of these additives are given in table V. The effect of surface-active additives is opposite to that of thickening agents in that the viscosity decreases sharply as additive concentration increases. This effect is illustrated for three additives in figure 11. As the additive concentration is increased, the slurry becomes so fluid that on standing the magnesium settles and packs into a dense cake.

Of the additives investigated (ref. 24), those with a hydroxyl group together with an ester, metal salt, or polyoxyethylene group in the molecule produced the most fluid slurries. Other factors having a significant effect on viscosity were slurry age, magnesium characteristics, and moisture content.

Stability. - Tests with aluminum soaps of C₈ acids (ref. 23) showed that very stable slurries could be achieved. Table VI presents the results of a test in which a slurry containing 0.6 percent soap remained relatively stable for a period of about 30 days. Duplicate samples of the slurries evaluated are represented by columns A and B in table VI. Although the initial viscosities of the slurry appear to be high, it should be realized that applications of shear would increase the fluidity. More recent experience with slurries of this type indicates good stability for periods as great as 2 or 3 months.

PREPARATION OF MAGNESIUM SLURRIES

Experience at the NACA Lewis laboratory has shown that the properties of slurries are influenced by the technique of preparation. For example, upon several occasions considerable difficulty has been encountered in preparing by identical procedures large batches of slurries that have been previously prepared successfully in small batches. For this reason, the following information is included to illustrate the procedures used for preparing 50-percent-magnesium slurries in jet fuels. This particular concentration of magnesium is selected because it is probably the same as that of slurries that will ultimately be applied in service operation with afterburners.

Experience to date indicates that magnesium slurries do not require both thickening agents and fluidizing agents. Preparation of slurries containing aluminum octoate as a thickening agent is described in reference 23. Slurries prepared from vaporized magnesium (ref. 19) remain reasonably stable without thickening agents and require only the fluidizing type of additives.

It is expected that magnesium slurry fuels prepared from vaporized magnesium will be supplied by the manufacturer as a stable fluidized

mixture suitable for experimental use. The slurry would contain at least 50 percent (by weight) magnesium with sufficient wetting agents added to provide suitable fluidity.

If the slurry is provided as described, any further additives can be blended into the slurry by means of a mechanical mixer such as the one shown in figure 2 of reference 25, or a colloid mill or other unit to give intensive mixing and extreme shear. This high-speed mixer (fig. 2, ref. 25) provides sufficient shear to break down lumps and produce a uniform composition by repeated passage of the material through the slots in the mixing head. Mixing units of this type are available in larger sizes for work on quantities larger than can be handled in bench-scale apparatus.

When a magnesium slurry is being mixed, contact with air should be prevented to avoid degradation of the metal by reaction with oxygen. An atmosphere of helium, argon, or petroleum gases is satisfactory for this purpose. Nitrogen cannot be relied upon if there is any possible source of ignition because finely divided magnesium powder will react with a nitrogen atmosphere if there is a source of heat to initiate the reaction.

If the magnesium slurry prepared from vaporized magnesium exists as a wet clay-like mass (ref. 19), the mixing and blending problems are somewhat more difficult. This condition describes a slurry which contains 50 to 70 percent by weight of solid and no wetting agent to promote fluidity.

The most convenient way to start the blending process is to add 0.5 percent by weight of surface-active agent (glycerol sorbitan laurate) to the pasty solid contained in a pail with a tight cover. Then shake the mixture on a paint shaker for 20 to 30 minutes. This will give a fluid slurry that may contain some lumps, which can be broken down by using the mixer (ref. 25). A sample should be taken to determine total solids. The solids may then be adjusted to 50 percent (by weight) by blending the calculated amount of hydrocarbon carrier into the slurry by further use of the mixer. Additional surface-active agent (up to a total of 2.0 percent by weight) may be blended, if required, until the Brookfield apparent viscosity of the slurry is in the range of 5000 to 10,000 centipoises.

For preparing large quantities, the paint-shaker equipment is obviously not suitable. Ribbon mixers, dough mixers, or ball mills could be used for the first step to break down the clay-like mass and incorporate a wetting agent. After the initial breakdown, the preparation of the slurry can be completed in a kettle by using the mixer or the slurry may be pumped through a colloid mill for final processing prior to use.

In any preparation where a colloid mill has not been used, the slurry should be passed through a screen before it is used in order to remove lumps that might later plug orifices and nozzles.

FUEL SYSTEMS FOR EXPERIMENTAL SLURRY-FUEL COMBUSTION RIGS

The unique physical properties of slurries have created many problems which must be considered by designers of handling devices such as pumps, meters, valves, or injectors. Several problems faced in the design of slurry-fuel systems are:

(1) Metal particles tend to clog passageways and orifices even though the openings may be considerably larger than the maximum particle size. Milled magnesium powder is particularly prone to bridge across large openings, whereas atomized metal powder is much less troublesome in this respect. Flow restriction caused by this kind of clogging is often progressive and does not always result in complete flow blockage. The effect may be intermittent so that the flow rate and pressure will vary unpredictably.

(2) Metal particles will adhere to valve seats unless one of the surfaces is of rubber or the mating surfaces are wiped clean before contact as in tight-fitting plug valves.

(3) Metal particles tend to enter clearance space between sliding and rotating surfaces. As the parts move, the particles become wedged in and weld to the surfaces until the mechanism jams.

(4) If the ambient temperature reaches the boiling point of the carrier fluid, a hard, impermeable cake of dry powder can form. This type of clogging, which is most likely to occur when the fuel flow is interrupted for a period of time, is due to fuel drying and is found most frequently in injection nozzles or adjacent piping. These parts are exposed to radiation from the flame zone or are often in a stream of preheated combustion air. The attachment of nozzles and piping to duct walls and combustors results in additional heating by conduction.

In order to overcome the preceding difficulties, it has been necessary to evaluate certain types of equipment to determine whether the fuel systems are satisfactory for use with slurry fuels. In some cases, existing commercial equipment has been adapted for this purpose and in other cases custom-built equipment has been utilized. The following sections describe some of the experiences encountered in the use of this equipment.

Pumps

Initial efforts to pump slurries with gear-type pumps were unsuccessful. A 5-gallon-per-minute gear pump with all-metal parts seized on the

first revolution with an aluminum-powder slurry. A positive-displacement screw-type pump with steel rotor and stator behaved similarly with magnesium slurries.

A 0.26-gpm/100-rpm pump with tool steel rotor and synthetic-rubber stator has a useful life of several hours when operated with magnesium slurry at a speed of 700 to 800 rpm and a pressure of 200 to 250 pounds per square inch. This particular slurry was prepared with JP-3 fuel having an aromatic content of 20 percent by volume. Because of the high aromatic concentration the rubber stator swelled and was then abraded to uselessness in about 5 hours. The swelling and resulting abrasion were reduced by using a JP-3 fuel containing only 10 percent aromatics. This difficulty can also be reduced by use of rubber less susceptible to attack by aromatics. Further improvement in stator life was achieved by using a 0.86-gpm/100-rpm pump to provide the same flow rate at lower speed. A variable-speed drive was installed to permit rotor operation at the lowest speed necessary. This pump was installed in a recirculating fuel system described in reference 2.

Other tests with magnesium slurry were conducted with a centrifugal fuel booster pump. The aluminum impeller was driven by an air turbine and was intended normally for use in pumping jet fuel to an afterburner. After several hours of pumping slurry containing 50 percent magnesium by weight, the seal began to leak and permitted slurry to enter the bearings. The bearings seized after 17 hours total running time. It is possible that this type of failure could be avoided if the space between the bearings and seal were pressurized with a lubricant so that the leakage of slurry through the seal would be blocked.

This particular pump delivered 180 pounds of slurry per minute at a discharge pressure of 300 pounds per square inch gage. Excessively thick slurries cavitated at the inlet and permitted the pump to overspeed causing the bearings to fail. There was no evidence of abrasion on the impeller surfaces.

In order to eliminate damage to seals and bearings during use of suitable slurries, a vertical centrifugal slurry pump was designed at the NACA Lewis laboratory (fig. 12). The storage tank and pump housing are integral. A double shrouded 6-inch-diameter impeller is used and the shaft is driven with gears by a 2.5-horsepower air motor. Outlet pressures of 70 pounds per square inch gage were reached at an impeller speed of 3600 rpm. Unstable slurries could be maintained in suspension by recirculating a portion of the flow.

The maximum slurry level was kept well below the seal, but when the bearings were disassembled after short running periods, it was always found that slurry had penetrated the seal and damaged the bearings. Several types of seals were tried without success. As in the case of the

centrifugal booster pump previously discussed, it is felt that a method of pressurizing the bearing chamber would make it possible to keep it free of slurry. The impeller showed no signs of abrasion from magnesium slurry after several hours of operation.

Displacement Systems

Diagrams of three systems for pumping slurries by displacement with a hydraulic fluid are shown in figure 13. Jet fuel was used as the pumping medium and to flush the slurry system after a test run.

In systems involving tight-fitting pistons (figs. 13(a) and (b)), if leakage occurred around the pistons during pumping of very viscous slurries, the jet fuel channeled through the slurry and flowed directly to the discharge mixing only slightly with the slurry. The cylinders used in figure 13(a) (also ref. 10) had an inside diameter of 5 inches. On the piston were two 1/4-inch-thick O-rings of $5\frac{1}{8}$ -inch outside diameter. The jet fuel caused the O-rings to swell. Excessive swelling will over a period of time cause piston seizure.

The displacement system shown in figure 13(c) was used where a large volume of slurry fuel was needed and the extent of the test program did not warrant the expense of machining a close-fitting piston and cylinder. The piston was a loose-fitting wooden disk whose density was adjusted so that the disk floated between the slurry and the jet fuel. The displacement systems were not suitable for unstable slurries since none of them provided for recirculation or agitation of the slurry.

Preliminary work has been done on a displacement system in which a low explosive (Cordite) is used as a source of high-pressure gas to propel the piston. This system has been used in flight tests of missiles. Design and performance data on such a system are given in reference 26.

Valves for Slurry Systems

The problem of finding suitable valves for slurries was not so imposing as the development of suitable pumping equipment. Spring-loaded plug valves with manual or mechanically linked shutoff have been used successfully. These valves, which may be obtained with 2-, 3-, or 4-way bodies, did not leak at a pressure of 125 pounds per square inch and were not damaged by magnesium particles. Unfortunately, however, such valves do not permit fine regulation of flow.

For flow regulation, commercially available valves with rubber membranes that can be moved to vary the flow-passage opening were used. Positive shutoff is reliable because the rubber can close tightly over

the metal particles that are trapped on the closure or valve-seating surfaces. Also, the membrane seals the sliding metal valve parts from contact with the slurry.

The pressure-relief valve shown in figure 14 was used in the recirculating fuel system described in reference 2. Operation with this valve was entirely satisfactory.

Flow and Pressure Measurement

A discussion of the physical and hydraulic properties of slurries that affect flow and pressure measurement is given in appendix B. Sharp-edged orifices and Venturi tubes can be used to meter slurries, but the success of such devices is dependent upon the development of pressure gages that will not be affected by solid particles. Ordinary gages have Bourdon tubes, bellows, or diaphragm chambers which contain stagnant zones in which slurries may settle. The resulting sediment impedes the motion of the indicating linkage and is extremely difficult to remove.

In order to avoid these difficulties, several methods have been used to provide for an indirect measurement of slurry flow. For the displacement pumping systems described previously (fig. 13), the jet fuel is metered and the slurry flow rate is determined from the ratio of the densities of the slurry and jet fuel.

The slurry fuel system described in reference 8 had a fuel tank suspended from a strain gage connected to a strip recorder. Instantaneous fuel weight and rate of change of fuel weight were recorded. This type of setup is suitable for tests requiring high flow rates for short periods of time and for tests in which flow is continually changing and instantaneous readings may be required.

A rotating-vane flow meter was used in the investigation reported in reference 9. The meter was modified by the manufacturer to incorporate additional clearance in the bearings and bleed holes for continuously flushing the bearings. The slurry passed through this meter at a rate of 0.275 to 0.8 pound per second. The inside diameter of the meter was $3/8$ inch. A smaller-size meter clogged with a 50-percent-magnesium slurry. A permanent magnet in the rotor of the flowmeter sets up in a coil an alternating potential having a frequency proportional to the flow.

Pressures in slurry fuel-flow systems have been measured by means of diaphragm-sealed pressure gages. As indicated in figure 15, the slurry is not in contact with the pressure-measuring instrument. The pressure of the slurry acting on the diaphragm is transmitted to the gage.

Differential pressures across the orifices or Venturi flowmeters are usually measured by remote-indicating diaphragm-actuated pressure pickups, such as the arrangement described in reference 2. The pickup is protected by a series of settling chambers (fig. 16) which are filled with a clear fluid of lower density than the slurry. By flushing the chambers between tests, the slurry was prevented from entering the pressure pickup.

Slurry Fuel Injectors

The creation of a homogeneous fuel-air mixture at the entrance to a combustor flame seating zone is one of the requirements of good combustor design. In turbojet afterburners the duct length available for fuel-air mixing before the flame holders is severely limited by weight and size considerations.

In the case of slurry fuels, the problem of obtaining a homogeneous mixture at the flame seat is further complicated by the extremely viscous nature of the slurry which tends to promote coarse atomization and uneven fuel-spray distribution. High-speed photographs of slurry sprays (refs. 2 and 7) illustrate the magnitude of the particle-size difference between conventional and slurry fuels (fig. 17) and indicate that spray patterns and distribution are influenced by slurry viscosity. Additional tests (ref. 2) indicated that air could be used to promote better atomization. Details of air-atomizing nozzles that have been used successfully are shown in figure 18 (also refs. 2 and 10).

With nozzles of the air-atomizing type, the air stream serves to shield the slurry from the high temperatures of the combustion zone as well as to atomize the fuel. If the atomizing-air supply is shut off after the slurry flow is interrupted and before the combustor has cooled, the jet-fuel carrier in the slurry quickly boils off and leaves a hard plug of dried powder clogging the injector. Where fuel is injected without air atomization, it is often necessary to provide a means of cooling the fuel injector. A water-jacketed slurry injector is illustrated in figure 19 (also ref. 2). Water cooling may be unnecessary, however, if the slurry injection is preceded by jet-fuel injection. The jet fuel cools the injector, and, if slurry is introduced at a high flow rate, the injector remains cool. Slurry injection may be followed by jet-fuel flow to flush the injector.

Slurries have been atomized by impinging a jet on a splash plate or sleeve (ref. 8).

DISPOSAL OF SOLID PRODUCTS FROM MAGNESIUM-SLURRY COMBUSTION

Although the problem of disposal of solid combustion products has no direct bearing on the use of slurries in aircraft, the subject is very important in ground research facilities and, consequently, of considerable interest to the increasing number of organizations entering the field of slurry fuel research. For this reason, the following section is included to describe the techniques used by the NACA to cope with this problem.

The exhaust gases from combustion of magnesium slurry are laden with finely divided magnesium oxide and, frequently, with unburned magnesium and coarse aggregates of metal and oxide. The large particles are formed on the combustor surface where the solids collect and flake off at intervals. Where unburned metal is present, the oxide particles are fused together as the unreacted metal freezes. These deposits are dark in color, quite hard, and may grow to considerable size before eroding. Under conditions that favor complete combustion, the solid deposits are soft and chalky in appearance and grow only to a thin layer before flaking off the walls.

A portion of the magnesium oxide passes through the combustor in the form of very finely divided particles. It is difficult to completely remove these particles from the exhaust stream with water sprays. Moreover, a small concentration of such particles in the waste water causes a conspicuous discoloration and if discharged into surface streams or rivers may raise serious objections from adjacent communities.

A settling and filtration basin (fig. 20) has been constructed at the NACA Lewis laboratory to clarify the waste water before discharge into storm sewers. The waste water enters a plenum where large particles settle and jet-fuel droplets float to the surface. The liquid then flows into a filter bed containing a top layer of 12 inches of washed plasterer's sand. From there the liquid passes through a 12-inch layer of 1/4-inch crushed stone and then through a 24-inch layer of 1/4-inch crushed stone. The rate of filtration is about 1 gallon per minute per square foot of filter surface, and at this rate the filtered waste water is discharged clear. The top layer of sand accumulates a foamy, gelatinous deposit, greasy to the touch, which penetrates no more than 1/2 inch into the sand layer. This deposit is removed periodically.

Additional precautions are necessary when combustor test conditions favor incomplete combustion because unburned magnesium may be carried into the settling and filtration basin and react with water. This reaction generates hydrogen and may cause the evolution of hydrogen over the filter basin for a period of several days.

HAZARDS AND PRECAUTIONS IN HANDLING MAGNESIUM

POWDERS AND SLURRIES

Flammability Hazards

It is well known that magnesium is a highly flammable solid and this fact becomes even more important where there is handling of magnesium in a finely divided state, for example, in slurry preparation. Fine powders of magnesium, if ignited, can cause violent explosions; consequently, the use of the dry powders should always be considered a serious hazard. Instructions given in reference 27 suggest that dry magnesium powders be stored in cool, well-ventilated areas, away from potential sources of ignition. All such containers should be kept closed and plainly labelled.

Magnesium fires may be smothered with calcium carbonate. Materials such as foam, water, carbon tetrachloride, or carbon dioxide should never be used on magnesium fires.

Physiological Hazards

Magnesium powders imbedded in skin wounds will cause gas gangrene (ref. 27). Inflammation is quite severe and is accompanied by blebs which may last for months. Gas gangrene can be halted by removal of the offending metal particles. Irritation to mucous membranes may result from breathing magnesium powder. However, the irritation can be stopped by cessation of exposure. Metal fume fever is caused by magnesium oxide, and this too may be stopped by cessation of exposure. Dermatitis resulting from work with magnesium is rare.

Occasional ingestion of small quantities of the metal or the oxide should not be harmful.

Precautions

The preceding discussion of hazards from use of magnesium suggests certain precautions that might be incorporated into formal safety regulations. No effort will be made at this point to list such regulations. However, for guidance in the handling of powders and slurries, the NACA Lewis laboratory has developed the regulations given in appendixes C and D. These regulations apply specifically to NACA operations, but many of the requirements are generally applicable to any organization working with magnesium powders in relatively small quantities.

REQUIREMENTS OF MAGNESIUM-HYDROCARBON SLURRIES FOR
AFTERBURNER APPLICATIONS

Much of the current interest in the use of metal-hydrocarbon slurries for aircraft fuel is directed toward applications in afterburners. Most of the research conducted by the NACA has resulted in the conclusion that magnesium is perhaps the most promising metal constituent in slurries for afterburner applications. Furthermore, this research has indicated that for the immediate future this slurry should probably be restricted to a composition of 50 percent (by weight) magnesium and 50 percent jet fuel.

The choice of a "50-50" slurry is not fixed, but is for the present the best compromise between handling and preparation characteristics and combustion characteristics.

There is, of course, no existing specification for a magnesium slurry to be used in service. Moreover, it is not the intention of this report to establish a specification that should be adopted for general usage. However, the expanding effort in the field of slurry application to afterburners may be expedited by a definition of the limits on physical properties of slurry as indicated by current knowledge. These limits are shown in table VII.

In this table, the values placed on each item are based upon considerations of both handling and combustion characteristics. Most of the limits are on the conservative side in order to minimize the possible difficulties that might develop upon introduction of slurries to actual service. For example, it is probable that the limit on viscosity is low, but this limit should not be increased until there is certainty that pumping and atomizing can be adequately achieved. It is also probable that for improved engine performance a higher metal concentration should be used; this may be possible if the handling problems can be solved. In view of these examples, it is obvious that these suggested limits are of an interim nature and must be altered as research continues. Furthermore, problems that arise from application of slurries to full-scale engines and aircraft will, in time, provide the basis for establishing practical limits on composition and physical properties.

In regard to the limit placed upon the absolute viscosity, in table VII it is emphasized that the value of 5.0 poises (appendix B) bears no relation to the value of 6000 centipoises indicated in the footnote for a Brookfield viscometer. Analysis of flow in an experimental fuel system indicated that a slurry having an absolute viscosity of 5.0 poises could be handled satisfactorily. Because use of the Stormer viscometer to measure the absolute viscosity is time consuming, the more easily determined Brookfield value is included as an alternate limit. The value of 6000 centipoises for Brookfield viscosity is judged to be a reasonable

maximum in the light of experience to date with various experimental fuel systems. The same comments apply to the Severs viscosity requirements included in the footnote of table VII.

It is equally difficult to define the limitations on metal particle sizes. Every known instrument and method available for measurement of particle sizes of powder samples has very definite limitations. Generally speaking, the method becomes more difficult and time consuming as the need for more descriptive information about the sample increases. Hence, for simplicity and ease of use, it is suggested in table VII that the Fisher Sub-Sieve Sizer be used. This method results in an average-particle-size determination but gives no indication of the particle-size distribution or particle shape. For powders supplied in suspension, some type of sedimentation analysis or turbidimetric analysis is necessary. Such methods are generally very time consuming and require extremely refined techniques for reliable results.

Determination of maximum particle size in a given batch of powder is difficult but of prime importance. If, for example, there are a few very large particles in a given batch of powder, these might not appear in a sample withdrawn for analysis. Obviously these undetected large particles could clog an orifice in a fuel system. The possibility of large particles occurring in powder batches may necessitate sieving procedures for large quantities of material.

CONCLUDING REMARKS

The possible use of slurries in aircraft has introduced new problems not associated with liquid fuels, and final solutions to many of these problems are yet to be achieved. For this reason the material presented is in many instances of an interim nature. Regardless of this shortcoming, the results are sufficiently advanced to offer guidance to those industries concerned with the practical problems of handling slurries in aircraft.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 6, 1955

APPENDIX A

VISCOSITY MEASUREMENT

The Brookfield Synchro-lectric rotational viscometer (fig. 21(a)) is a direct-reading instrument used for viscosity measurements at very low rates of shear. Four rotational speeds and four spindles make it possible to vary the shear rate somewhat, but the instrument is generally used for one-point readings. In this work the number 3 spindle was run at 12 rpm (estimated shear rate, 10 sec^{-1}) for viscosities up to 10,000 centipoises. The number 4 spindle at 6 rpm (estimated shear rate, 0.5 sec^{-1}) was used for higher viscosities. Determinations were made at 30° C , and viscosities were read after a 30-second rotation of the spindle. The 30-second interval was arbitrarily fixed to provide a degree of procedure standardization.

The Severs Extrusion Rheometer (fig. 21(b)) may be used to determine variations in shearing stress with rate of shear, based on changes in flow rate through a tubular orifice with stepwise variations in applied pressure. It is particularly suited to operation at relatively high rates of shear (1,000 to 20,000 sec^{-1}). The weight of slurry flowing through the orifice in a measured time is recorded for each of several successively applied air pressures. The volume rates of flow, along with pressure readings and the known dimensions of the orifice, may be used to calculate shear stresses, shear rates, and, from these, apparent viscosities. The calculations are based on the following equations:

$$\text{Shearing stress} = \frac{Pr}{2L}, \text{ lb/sq in.}$$

$$\text{Rate of shear} = \frac{4Q}{\pi r^3}, \text{ sec}^{-1}$$

$$\text{Apparent viscosity} = \left(\frac{\text{Shearing stress, psi}}{\text{Rate of shear, sec}^{-1}} \right) (6.89 \times 10^6), \text{ centipoises}$$

$$= \frac{Pr}{2L} \left(\frac{\pi r^3}{4Q} \right) (6.89 \times 10^6)$$

where

P applied pressure

r radius of orifice

- L length of orifice
- Q volume rate of flow of slurry through orifice, M/pt, cc/sec
- M weight of slurry flowing through orifice in t seconds, g
- ρ density of slurry, g/cc
- t time, sec

The Stormer rotational viscometer (fig. 22) is a modified version of the standard instrument. It may be operated at moderate shear rates, up to approximately 1200 sec^{-1} , and allows for stepwise variation in shear rate by the successive addition of weights. The modification consists of replacement of the standard bob and cup by the following:

- Cylindrical brass cup. Diameter, 1.1395 inches; length, $2\frac{5}{8}$ inches.
- Cylindrical solid stainless steel bob. Diameter, 1.0225 inches; length, 1.577 inches.
- Clearance between bob and cup, 0.0585 inch or 1.49 minutes.

The procedure may be generalized as follows: The bob is centered and immersed in a small quantity of slurry in the cup, and the whole is brought to constant temperature. Starting with a weight on the holder sufficient to rotate the bob at the rate of at least 2 rpm, the time required to rotate the bob a whole number of revolutions (2, 5, 10, 20, 50, or 100) in a convenient length of time (no more than 2 min) is measured by stop watch. This step is repeated as rapidly as possible with successive additions of 50 or 100 grams until a rotational speed of 15 to 20 rps is attained or a maximum total weight of 2000 grams has been applied, whichever occurs first. The reverse procedure is started immediately by removing weights in the same steps and measuring rotational speeds, as before. Data are plotted as rps against weight applied. From these data and the dimensions of the bob and cup, shearing stresses and shear rates may be calculated, which, in turn, are used to compute viscosities.

APPENDIX B

PROPERTIES OF SLURRIES RELATED TO FLOW AND PRESSURE

MEASUREMENT IN FUEL SYSTEMS

Clogging of Small Passages and Orifices

Metal slurry particles tend to collect into aggregations that can be redistributed by stirring or milling, but these lumps can be sufficiently rigid to stop the flow when lodged in small passages or orifices. Three different processes by which such aggregations form in fuel systems have been observed.

(1) Some slurries made with fine powders of about 1-micron size or less take on a granular appearance when undisturbed for a period of time. The size and number of these granules can be seen when an object is wetted with a thin film of the slurry. The aggregations are generally larger than the thickness of the film and give the surface a lumpy appearance. Slurries made with milled magnesium form aggregates faster than those made with atomized powder.

(2) Layers of compacted powder are formed during the flow of slurries through pipe elbows and other points of irregular flow. The segregation of large particles generally occurs where the stream turns suddenly and a sheltered zone exists for the particles to collect. The segregated material occasionally breaks off and is carried by the stream until it reaches a constriction where the flow is blocked.

(3) When the flow is stopped in a fuel system carrying an unstable slurry, a layer of settled material forms which can partially or completely block the system.

Non-Newtonian Flow

Slurries differ from Newtonian fluids in that their viscosity varies with shear rate. A discussion of non-Newtonian fluids, methods for computing their flow and pressure relations, and the use of capillary and rotational viscometers for these fluids is given in reference 28.

All the slurries made with milled magnesium powder were dilatant; hence, they increase in viscosity with increase in shear rate. Because of a tendency to clog fuel lines, dilatant slurries cannot be handled satisfactorily in fuel systems.

Slurries made with atomized powder (powder made by freezing a spray of liquid magnesium in a helium atmosphere) are pseudoplastic or plastic.

Pseudoplastic slurries decrease in viscosity with increase in shear rate. Plastic slurries require a finite initial shear stress before they will flow. Parameters for describing the hydraulic properties of both types are described in reference 28. The parameters were used to analyze the flow in three slurry fuel piping systems. These were stationary test installations with relatively long pipe runs and transition sections such as elbows, valves, and orifices. However, on the basis of current knowledge an analysis of the flow of slurries in a fuel system must be limited to consideration of straight pipe sections only. The slurry viscosities at the shear rates prevailing in these systems were of the order of 0.2 to 5.0 poises. The Reynolds numbers showed that in most cases the flow was laminar in the straight-pipe sections.

It was estimated that the shear rates could be 30 to 50 percent higher than those computed for Newtonian fluids. In the three piping systems the flow rates ranged from 500 to 4600 pounds per hour. At a system pressure drop of 100 psi the effective velocities ranged from 90 to 350 centimeters per second with an effective shear rate of approximately 800 to 6000 sec^{-1} in the straight-line sections.

Flow in typical fuel-injection orifices is estimated to be well into the turbulent zone, and the contribution of friction pressure loss to the total pressure drop of fuel injectors will be quite small. Test results consistent with the estimate are reported in reference 17, where the flow-pressure relation of a slurry was measured with a fuel system having a short direct approach to an injector with a large area-contraction ratio.

APPENDIX C

INSTRUCTIONS TO NACA EMPLOYEES FOR HANDLING SLURRIES

All personnel engaged in the work of the slurry program at the NACA Lewis laboratory are expected to use the following equipment and clothing as needed in the course of the working day, and to follow exactly all the instructions set down.

Each man should consider himself responsible for the safety of his fellow workers as well as himself.

General Precautions

- (1) Each man has been provided with work clothes ("suntans") for wear during working hours. A regular change (at least weekly) is imperative.
- (2) Canvas work gloves will be disposed of, rather than laundered, when dirty.
- (3) A daily shower is urged for all personnel having contact with these materials during the working day.
- (4) Good housekeeping is essential in all laboratory operations. All rooms must be kept clean and free of spilled slurries and powders.
- (5) When in doubt about any course of action, ask the engineer in charge how to proceed.
- (6) There should be at least two persons present on every job involving slurry preparation or handling.
- (7) Conductive-sole leather shoes fully covering the feet should be worn on the job. Crepe or rubber soles are not recommended; build-up of static charge is dangerous.
- (8) Know the material you are working with before undertaking a job. Different materials and different jobs require different precautions. In case of doubt, ask the engineer in charge.

Dry-Powder Handling

- (1) Each man should wear the following items of protection when transferring relatively inactive powders (such as boron and the coarser magnesium powders) through the atmosphere:

- (a) Dust respirator
- (b) Rubber gloves
- (c) Face shield
- (d) Laboratory coat or fireproof suit
- (e) Grounding garters

All equipment must be grounded.

(2) The following items of personal protection are to be worn when working with highly reactive powders (such as magnesium, aluminum, and magnesium-aluminum alloy powders of average particle diameter less than 5μ):

- (a) Face shield
- (b) Rubber gloves
- (c) Flameproof smock or fireproof suit

(Note: These powders must not be exposed, in the dry state, to the atmosphere.) If it is found necessary to dispose of quantities of the dry, highly reactive powders, the standard inerting procedure described in appendix D should be used and the hydrocarbon suspension should be dumped from the drums and burned according to prescribed conventional waste-slurry disposal procedures.

Storage

(1) Dry powders in sealed drums may be stored in the powder storage shed. The highly reactive powders are sealed under an inert atmosphere.

(2) Quantities of slurry in excess of 1 gallon should be stored in metal cans or drums to prevent breakage.

(3) Large drums of slurry may be stored outdoors under a tarpaulin or other similar shelter.

Removal of Powder or Slurry Spillage

If a powder or slurry is spilled, the first step is to completely wet the spillage with a nonvolatile hydrocarbon, such as Varsol, JP-5 fuel, or light fuel oil.

When the spillage has been made sufficiently fluid, it can be cleaned up with a mop made from ordinary cotton waste and thoroughly wetted with hydrocarbon. The mop may be wrung out (not dry) into the bucket or drum containing hydrocarbon and re-used until the spillage has been cleaned up. The mop is immediately disposed of by dropping it into the same bucket or drum of hydrocarbon. The entire contents may then be dumped and burned in an open, isolated pit.

In case of a very large slurry spillage, a shovel should be used, if possible, to pick up most of the material. A long-handled, spark-proof (e.g., brass) shovel is recommended for this purpose. After the major portion of the spillage has been shoveled into a drum containing hydrocarbon and the shovel has been rinsed clean in hydrocarbon, the mopping procedure just described should be used to finish the job.

The cleaning procedure, as described, is satisfactory if the surface on which the spillage occurs is of a very smooth and nonporous material, for example, metal or smooth concrete. Such materials are recommended for floors or outdoor platforms where there is to be slurry preparation and handling.

If spillage occur outdoors on the ground, the area should be isolated, covered with hydrocarbon, and thoroughly burned out.

Equipment Disassembly

(1) Any person disassembling equipment containing reactive-powder slurry fuel must wear the following protective items:

- (a) Fireproof jacket and trousers
- (b) Face shield
- (c) Canvas gloves (asbestos palms)

(2) After the equipment is disassembled, it must be cleaned as follows:

(a) Each part and fitting that is removed must be immediately immersed in a Varsol or no. 2 fuel-oil bath, scrubbed with a brush, then washed inside and out with a pressurized oil stream.

(b) Each part must then be removed to an isolated area (while still wet with oil), washed by remote control with a high-pressure cold-water jet for 20 minutes, and finally washed with a high-pressure steam jet for 20 minutes. (Note: Steam cleaning must not be used unless the preliminary treatments have preceded it.)

Fire Regulations

In case of magnesium or magnesium-slurry fire:

(1) Localize the fire by throwing magnesium "flux powder" over it. Allow it to burn itself out.

(2) Call the fire department. Small localized fires can be handled by you, but the fire department should be called, in any event, for your own protection.

(3) Never put water on a metal-powder fire. It would probably spread the fire.

(4) Never use the Cardox system or any carbon-dioxide fire extinguisher on a metal-powder fire. It will not be effective and could spread the fire.

APPENDIX D

PROCEDURE FOR INERTING POWDERS ($< 4\mu$) IN CLOSED DRUMS

A conventional magnesium powder drum has been modified by the installation of a $1\frac{1}{4}$ -inch pipe, welded through the bottom, and anchored to the side of the drum. Argon lines have been connected through a T to the wall of the pipe and through the bottom of the drum.

The following steps are suggested as a guide for inerting powders:

(1) The modified drum is placed on top of the drum containing powder and weighted down with a 50-pound weight. The entire system is on a platform scale. The 50-pound weight has been used for expediency, but special clamps would be preferable.

(2) Argon is flooded into the system and flow is maintained through the entire operation.

(3) The beryllium-copper punch is inserted through the pipe, allowing it to rest on the powder-drum lid. Several sharp blows on the punch will puncture the lid.

(4) Remove the punch and immediately insert the spray nozzle and start spray of the desired liquid.

(5) After the correct amount of material has been sprayed into the drum (determined by weighing), the spray nozzle is removed.

(6) The 50-pound weight and modified drum are removed (surface-active agent solution, if required, is added at this point).

(7) A rubber stopper, cut to fit the hole in the drum lid, is inserted and sealed in by the application of several coats of Glyptal.

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TABLE I. - JET-FUEL SPECIFICATIONS

Physical and chemical properties	MIL-F-5616			MIL-F-5624B, amendment 1	
	JP-1	JP-3	JP-4	JP-5	JP-5
A.S.T.M. distillation, D86-52, °F					
Percentage evaporated					
10	410 (max.)	---	---	---	400 (max.)
20	---	240 (max.)	270 (max.)	---	---
50	---	350 (max.)	370 (max.)	---	---
90	---	470 (max.)	470 (max.)	---	---
End point	490 (max.)	---	---	---	550 (max.)
Residue, percent	572 (max.)	---	---	---	1.5 (max.)
Loss, percent	1.5 (max.)	1.5 (max.)	1.5 (max.)	1.5 (max.)	1.5 (max.)
	1.5 (max.)	---	---	---	---
Freezing point, °F	-76 (max.)	-76 (max.)	-76 (max.)	-76 (max.)	-40 (max.)
Reid vapor pressure, lb/sq in.	---	5.0 to 7.0	2.0 to 3.0	---	---
Aromatics, percent by volume	20.0 (max.)	25.0 (max.)	25.0 (max.)	25.0 (max.)	25.0 (max.)
Bromine number	3.0 (max.)	---	---	---	---
Total sulfur, percent by weight	0.2 (max.)	0.4 (max.)	0.4 (max.)	0.4 (max.)	0.4 (max.)
Mercaptan sulfur, percent by weight	---	0.005 (max.)	0.005 (max.)	0.005 (max.)	0.005 (max.)
Potential gum, mg/100 ml	8.0 (max.)	14.0 (max.)	14.0 (max.)	14.0 (max.)	14.0 (max.)
Existent gum, mg/100 ml	5.0 (max.)	7.0 (max.)	7.0 (max.)	7.0 (max.)	7.0 (max.)
Heat of combustion, Btu/lb	---	18,400 (min.)	18,400 (min.)	18,400 (min.)	18,300 (min.)
Aniline-gravity product	---	5,250 (min.)	5,250 (min.)	5,250 (min.)	4,500 (min.)
Gravity, 60°/60° F	0.850 (max.)	---	---	---	---
Specific	---	50 to 60	---	---	35 to 45
A.P.I.	---	---	45 to 55	---	---
Viscosity, centistokes	---	---	---	---	16.5 (max.)
-30° F	---	---	---	---	---
-40° F	10.0 (max.)	---	---	---	---
Smoke volatility index	---	---	---	---	---
Smoke point, mm	---	54 (min.)	54 (min.)	---	20 (min.)
Flash point, °F	---	---	---	---	140 (min.)
Explosiveness, percent	110 (min.)	---	---	---	50 (max.)
	---	---	---	---	---

TABLE III. - PHYSICAL AND THERMAL PROPERTIES OF
MAGNESIUM AND MAGNESIUM OXIDE^a

Property	Magnesium		Magnesium oxide	
	Temperature, °F	Specific heat	Temperature, °F	Specific heat
Melting point, °F	1204		^b 5074	
Boiling point, °F	2030		^b 5571	
Specific gravity	1.74		3.65	
Gross heat of combustion				
Btu/lb	10,810		----	
Btu/cu ft	1,174,000		----	
Heat of combustion at stoichiometric fuel-air ratio				
Fuel-air ratio	0.353		----	
Btu/lb air	3816		----	
	Temperature, °F	Specific heat	Temperature, °F	Specific heat
Specific heat, (Btu/lb)/°F ^c	1205	0.317	1160	0.287
	1340	.321	1340	.292
	1700	.332	1520	.297
	1880	.337	1700	.302
	2048	.342	1880	.306

^aData from ref. 13 unless otherwise specified.

^bValues from ref. 14.

^cValues for Mg from ref. 15; values for MgO from ref. 16.

TABLE IV. - PHYSICAL PROPERTIES OF PETROLATUMS USED IN
STABILIZATION OF MAGNESIUM SLURRIES

[Ref. 20.]

Petrolatum	A.S.T.M. melting point, °F	Saybolt viscosity at 210° F, sec	A.S.T.M. penetration at 77° F, tenths of millimeter ^a	Specific gravity, 60/60° F	Color
A	121	66	220	0.864	Amber
B	121	68	191	^a .865	Amber
C	141	91	111	.871	Dark brown
D	145	65	215	.871	Dark green
E	161	101	80	^a .871	Dark green

^aEstimated.

TABLE V. - COMPOSITION AND PHYSICAL PROPERTIES OF ADDITIVES^a
 [Ref. 24.]

Additive	Composition	Polar groups in molecule of additive	Purity or active ingredient, percent	Approximate molecular weight	Density, g/cc or specific gravity (at approx. room temp.)
A100	Alkylaryl sulfonate, amine salt (details unavailable)	-----	90+	390	1.03
A101	Aluminum hydroxynaphthenate	Hydroxyl, metal salt of carboxylic acid	b50	---	.9
A102	Aluminum hydroxydi(2-ethylhexoate)	Hydroxyl, metal salt of carboxylic acid	Technical	330	Approx. 1
A103	Bisphenol-epichlorohydrin condensate	Hydroxyl, ether	Approx. 100	---	---
A104	n-Butyl ether	Ether	Technical	130	.77
A105	Cetyl alcohol	Primary amine	Technical	242	.80
A106	Lehydroabietyl amine	Primary amine salt	Technical	290	1.0
A107	Lehydroabietyl amine stearate	Carboxylic acid	Technical	570	1.0
A108	2-Ethylhexoic acid	Hydroxyl, ester, ether	97+	144	.90
A109	Glycerol sorbitan laurate	Hydroxyl, ester	Technical	330	1.00-1.05
A110	Glycerol monooleate	Halide	Technical	165	.95
A111	n-Hexyl bromide	Hydroxyl, ester, -Ti-O-Ti-O-	Technical	---	1.17
A112	Hydroxytitanium stearate	Metal salt of carboxylic acid	b75	---	1.0
A113	Iron naphthenate	Ester, -Ti-O-Ti-O-R	Technical	---	1
A114	Isopropoxytitanium stearate	Ester, tertiary amine	b50	---	1
A115	Lauryl methacrylate-diethylaminoethyl methacrylate copolymer (details unavailable)	Metal salt of carboxylic acid	b60	493	1.1
A116	Lead di(2-ethylhexoate)	Metal salt of carboxylic acid	b85	---	1.2
A117	Lead dinaphthenate	Ester, hydroxyl, quaternary ammonium	c100	780	.75
A118	Lecithin (derived from soybeans)	Hydroxyl, tertiary amine	Technical	600	.95
A119	Linoleic acid, dimerized	Hydroxyl, secondary amine	Technical	209	1.03
A120	n-Methylbenzyl diethanolamine	Hydroxyl, secondary amine	Technical	165	1.08
A121	n-Methylbenzyl monoethanolamine	Primary amine	Approx. 90	269-353	.83
A122	Mixed tert-alkyl primary amines, C18 to C24	Nitro	Approx. 100	123	1.2
A123	Nitrobenzene	Primary amine	c100	276	.8
A124	n-Octadecylamine	Hydroxyl	Technical	130	.89
A125	n-Octyl alcohol	Hydroxyl, Ti-O-R	b50	---	1
A126	Octylene glycol titanate	Carboxylic acid	U.S.P. XII	262	.85
A127	Oleic acid	Hydroxyl, polyoxyethylene	97+	270	1
A128	Polyoxyethylene dodecyl alcohol, 2 moles ethylene oxide				

^aData either supplied by manufacturer or estimated from other information.

^bRemainder is mainly hydrocarbon solvent. Sufficient additive used in slurries to give desired concentration of active ingredient.

^c65 Percent lecithins, 35 percent soybean oil.

^d85 Percent dimer, 12 percent trimer, 3 percent monomer.

^e93 Percent n-octadecylamine, 6 percent n-hexadecylamine, 1 percent n-octadecylamine.

TABLE V. - Concluded. COMPOSITION AND PHYSICAL PROPERTIES OF ADDITIVES^a
[Ref. 24]

Additive	Composition	Polar groups in molecule of additive	Purity or active ingredient, percent	Approximate molecular weight	Density, g/cc or specific gravity (at approx. room temp.)
A129	Polyoxyethylene dodecyl alcohol, 4 moles ethylene oxide	Hydroxyl, polyoxyethylene	97+	360	1
A130	Polyoxyethylene dodecyl alcohol, 8 moles ethylene oxide	Hydroxyl, polyoxyethylene	97+	540	1
A131	Polyoxyethylene dodecanethiol, 3.5 moles ethylene oxide	Hydroxyl, polyoxyethylene, thioether	Technical	360	1.0
A132	Polyoxyethylene sorbitol tetraoleate	Hydroxyl, polyoxyethylene, ester	97+	1500	0.92-0.98
A133	N,N' Polyoxyethylene hydrogenated tallow amide, 5 moles ethylene oxide	Polyoxyethylene, amide, hydroxyl	Technical	490	1.03
A134	N,N' Polyoxyethylene hydrogenated tallow amine, 5 moles ethylene oxide	Polyoxyethylene, tertiary amine, hydroxyl	Technical	470	.97
A135	Sodium alkylaryl sulfonate (details unavailable)	-----	-----	---	1
A136	Sodium dioctyl sulfosuccinate	Ester, metal salt	Approx. 100	444	.73
A137	Sorbitan monooleate	Hydroxyl, ester, ether	97+	450	1.00-1.05
A138	Soybean oil (fatty acid triglycerides)	-----	-----	---	---
A139	Stearic acid	Ester	Technical	885	.9
A140	Stearylamine salt of stearylamidophosphoric acid, monoalkyl ester	Ester, secondary amine, amine salt	U.S.P. XII	270	.85
A141	Substituted oxazoline (details unavailable)	-----	Technical	650-750	.9
A142	Triethanolamine oleate	-----	-----	---	1
A143	Triethylene glycol dimethyl ether	Ester, tertiary amine	Technical	941	.9
A144	Proprietary product. Composition unavailable	Polyoxyethylene	Technical	178	.9
A145	Proprietary product. Composition unavailable	-----	b93	---	.88
A146	Proprietary product. Composition unavailable	-----	b77	---	.97
A147	Proprietary product. Composition unavailable	-----	Approx. 100	437	1
A148	Proprietary product. Composition unavailable	-----	-----	---	.99
A149	Proprietary product. Composition unavailable	-----	b40	---	.89
		-----	b37	---	.91

^aData either supplied by manufacturer or estimated from other information. Remainder is mainly hydrocarbon solvent. Sufficient additive used in slurries to give desired concentration of active ingredient.

^bProbably consists of approximately 60 percent stearic acid and 40 percent palmitic acid.

TABLE VI. - BROOKFIELD APPARENT VISCOSITY - AGE
 DATA FOR 50-PERCENT MAGNESIUM SLURRIES
 STABILIZED WITH 0.6-PERCENT-BY-WEIGHT
 CONCENTRATION OF SOAP III

[Ref. 23; gelation temperature, about 110° F.]

Age of slurries, day	Brookfield apparent viscosity, centipoises	
	A	B
1	79,000	81,000
2	77,000	77,500
5	86,700	80,800
7	87,200	81,400
12	78,000	72,300
14	65,700	59,400
16	60,000	59,000
19	50,400	46,200
21	44,200	45,800
23	36,900	38,300
26	31,000	34,800
28	28,000	29,200
30	(a)	24,700
33		18,600
36		14,100
40		8,000
42		6,800
44		2,100
47		1,200
50		900
54		800
57		800
61		800
64		900
68		800
72		800
75		500

^a Sample was destroyed in other tests.

TABLE VII. - SUGGESTED LIMITS ON VALUES OF COMPOSITION AND PHYSICAL PROPERTIES OF A 50-PERCENT SLURRY OF MAGNESIUM WITH JP-4 AND JP-5 FUELS

		Property	Limitation and remarks
Slurry component	Magnesium powder	Influence of preparation method	Vaporization or atomization preparation best; milling procedures result in dilatant slurries
		Concentration	50 To 55 percent by weight
		Particle size ^a	0.1 Percent (max.) > 40 μ
		Average particle diameter ^a	4 μ (max.) < 2 μ (preferable)
	Fluidizing additive	Concentration	2.0 Percent by weight (max.) (glycerol sorbitan laurate)
	Hydrocarbon carrier	All properties	Should conform to MIL-F-5624B, amendment 1, specification for JP-4 or JP-5 fuel
Complete slurry		Absolute viscosity at 25° C ^b	5.0 Poises (max.)
		Specific gravity at 60° F	1.04 to 1.12

^aAll particles should pass through a 200-mesh screen. Particle diameter should be measured by Fisher Sub-Sieve Sizer for dry powders. If powder is supplied in suspension (probable for vaporized-magnesium powders), a sedimentation analysis combined with microscopic examination will be necessary to determine particle-size distribution. Complete deflocculation is essential for significant results in sedimentation analysis. (See additional discussion of table VII in text.)

^bAbsolute viscosities may be measured by Stormer Rotational Viscometer. If less-time-consuming methods are required, Brookfield or Severs viscometers may be used with the following limitations imposed on the slurry:

- (1) Brookfield (no. 3 spindle, 12 rpm, at 86° F), 6000 centipoises (max.)
 - (2) Severs, continuous flow under 10-psi-gage pressure head and through 1-mm-diameter capillary 2 in. in length
- (See additional discussion of table VII in text.)

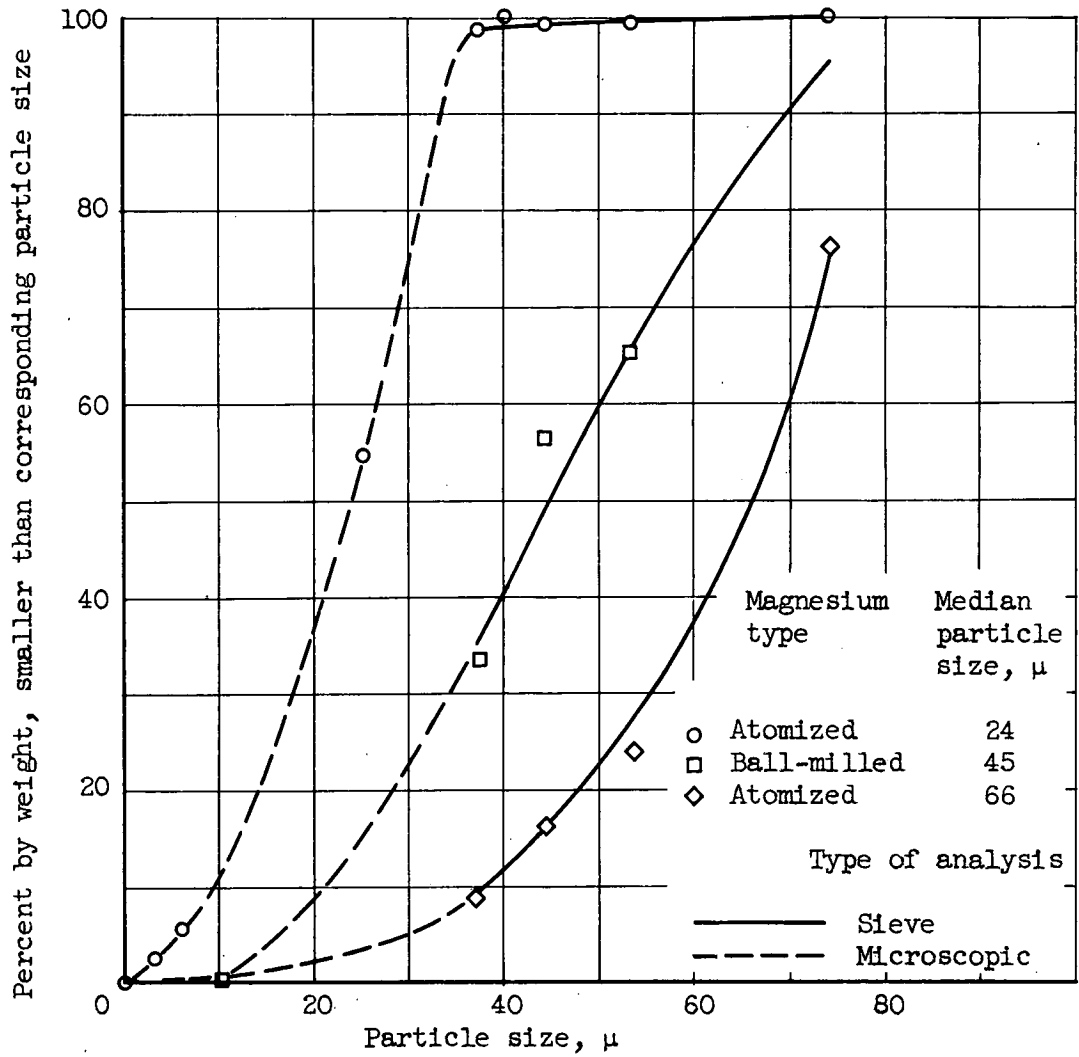


Figure 1. - Particle-size distribution of magnesium powders from microscopic and sieve analyses (ref. 17).

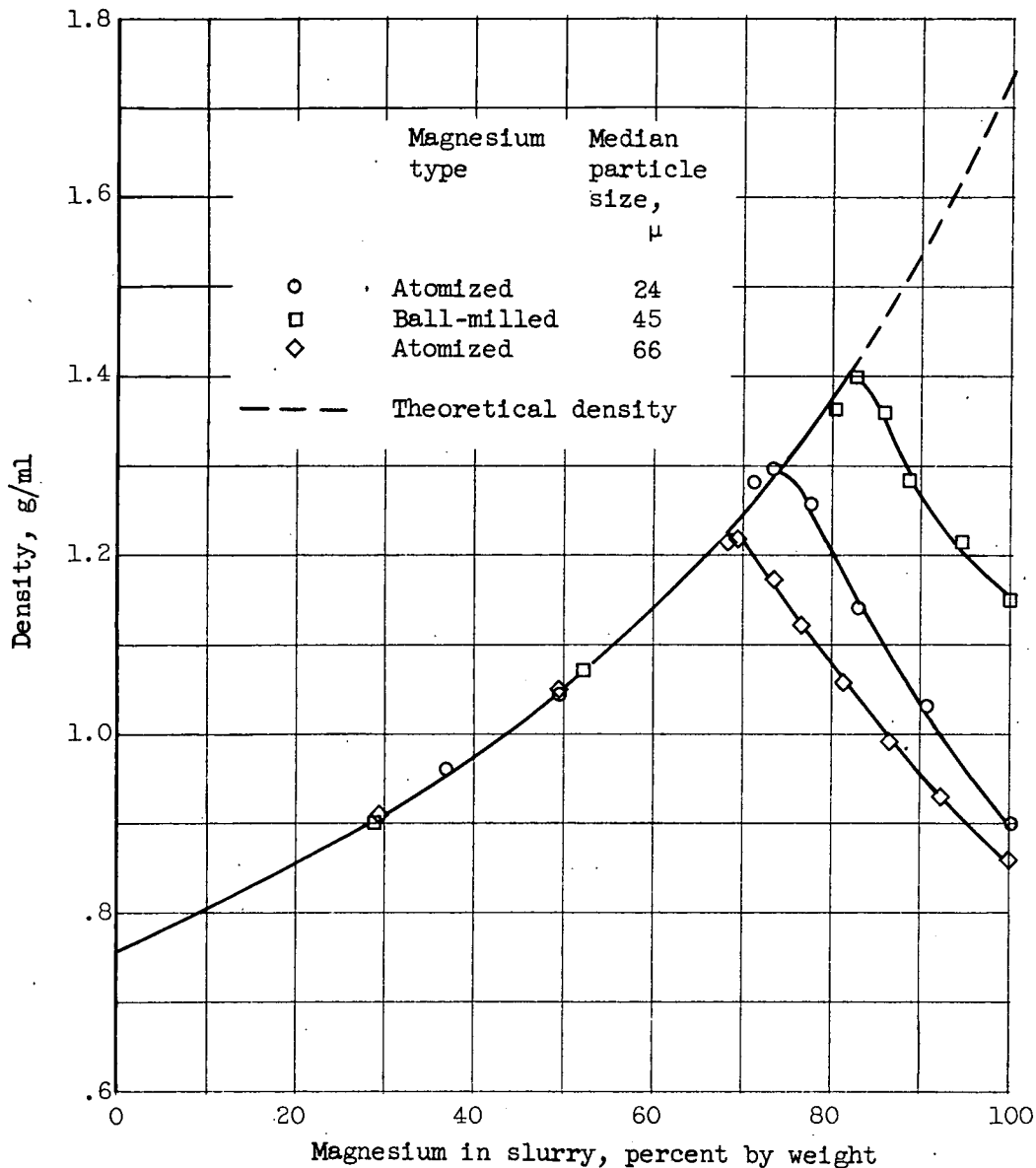


Figure 2. - Variation of slurry density with magnesium concentration (ref. 17). Base fuel, MIL-F-5624 grade JP-3.



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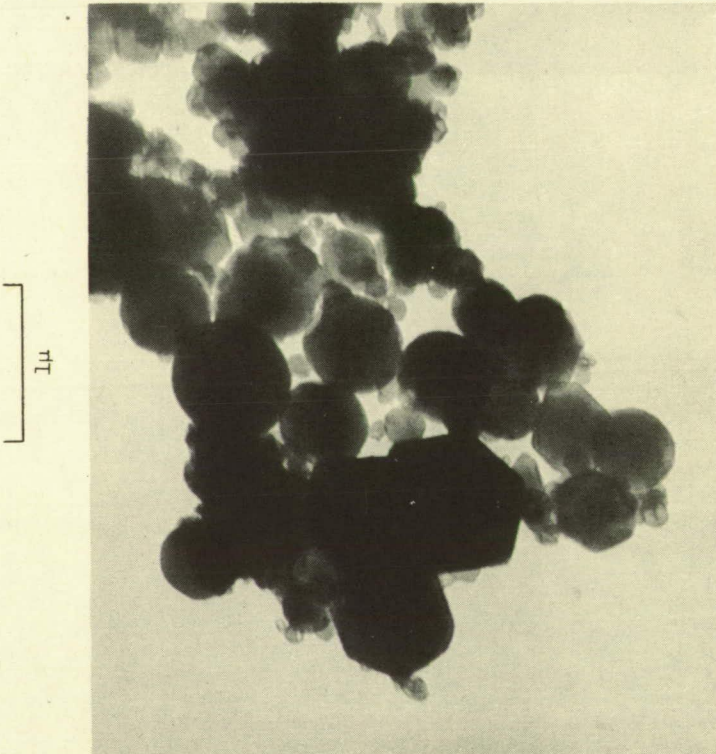


Figure 3. - Electron micrographs of two representative fields of magnesium particles magnified 25,000 times (ref. 19).

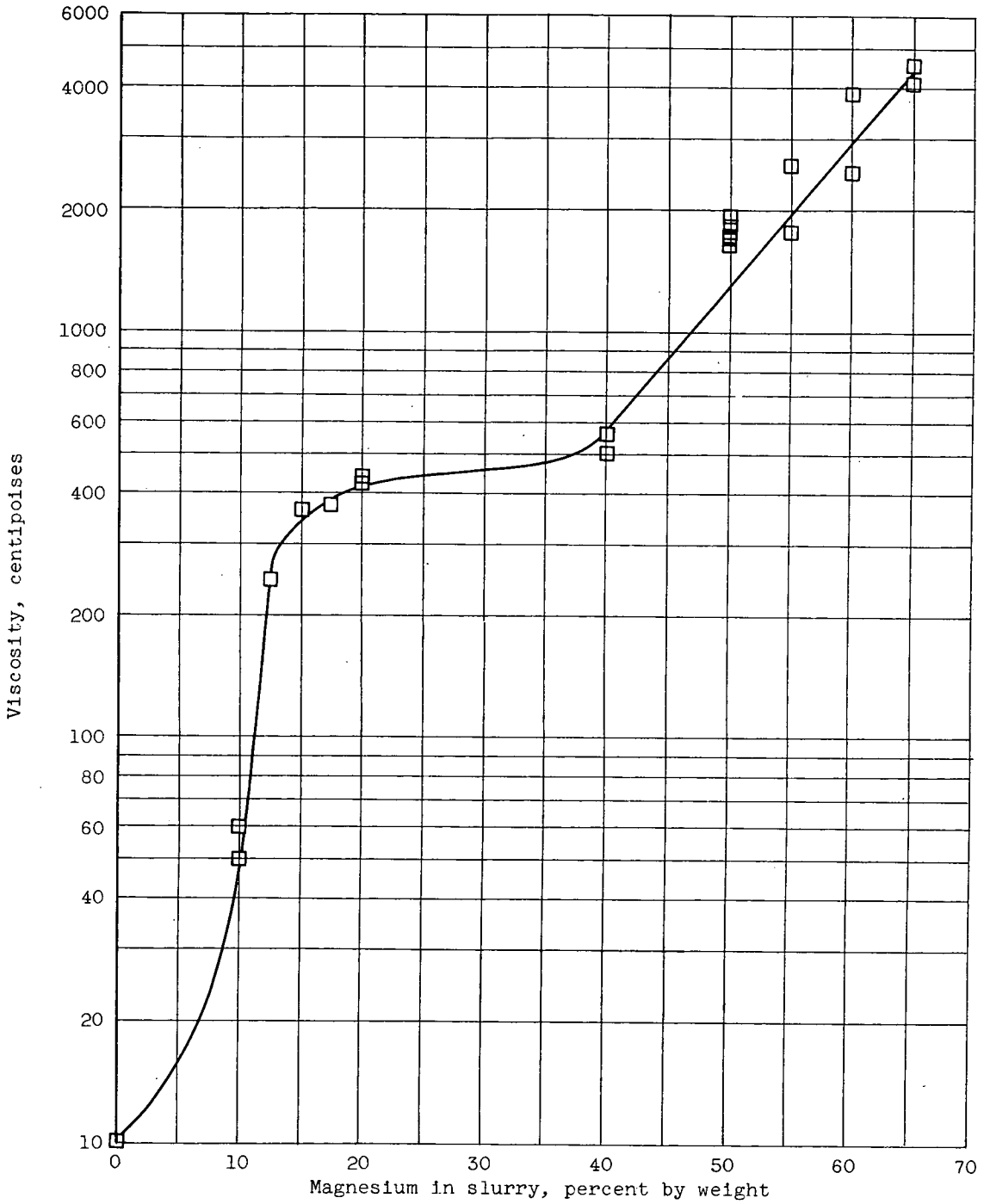


Figure 4. - Effect of magnesium concentration on Brookfield viscosity of magnesium slurries stabilized with petrolatum (ref. 20). Hydrocarbon carrier, 28 percent petrolatum E (table IV) and 72 percent MIL-F-5624A grade JP-4 fuel by weight; temperature, 86° F.

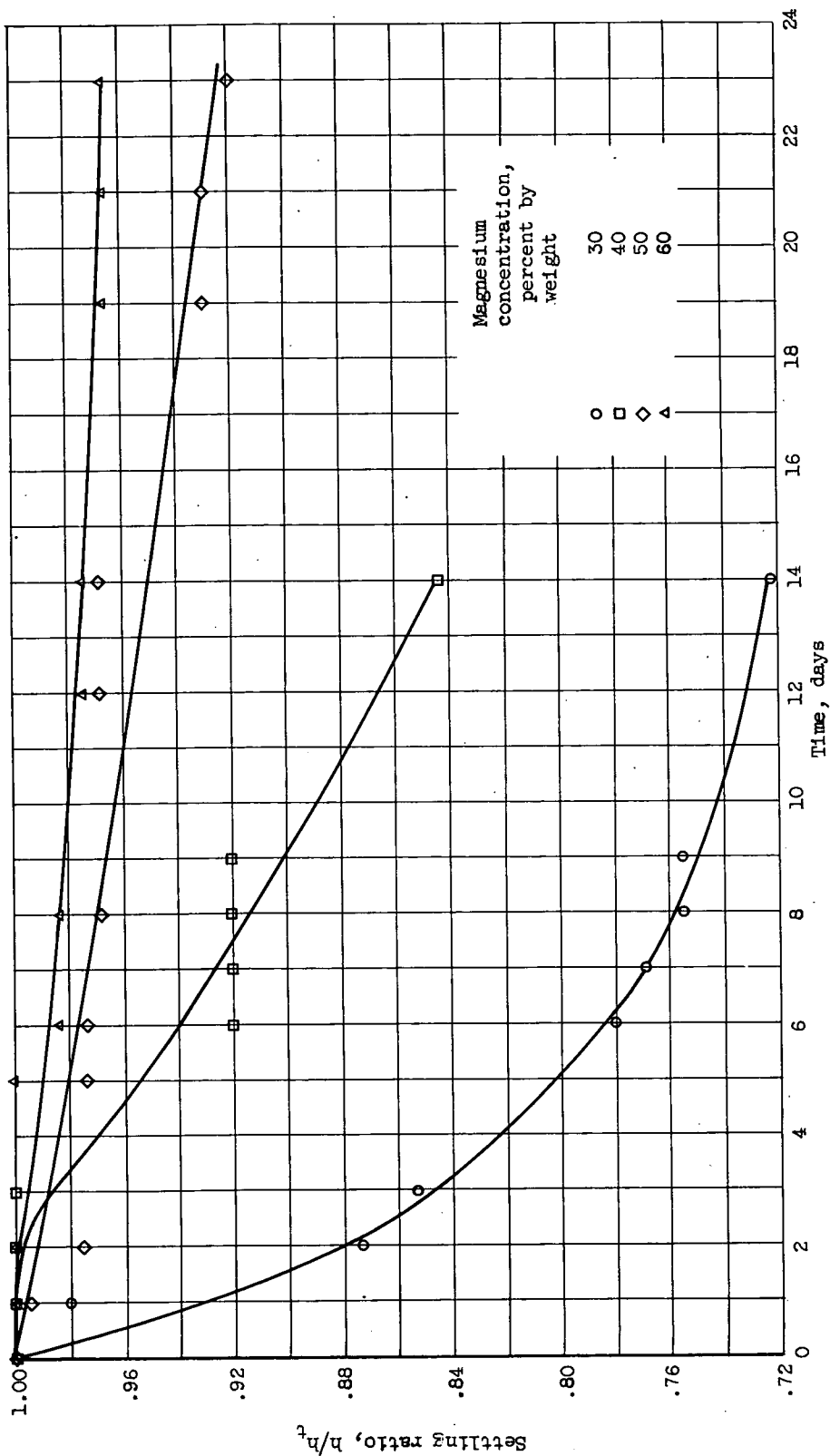


Figure 5. - Effect of magnesium concentration on settling ratio of slurries (ref. 21). Average magnesium particle size, 2.8 microns; hydrocarbon carrier, 40 percent petrolatum A (table IV) and 60 percent MIL-F-5624A grade JP-4 fuel by weight. h_t , height of column before settling; h , height of phase containing settled metal particles.

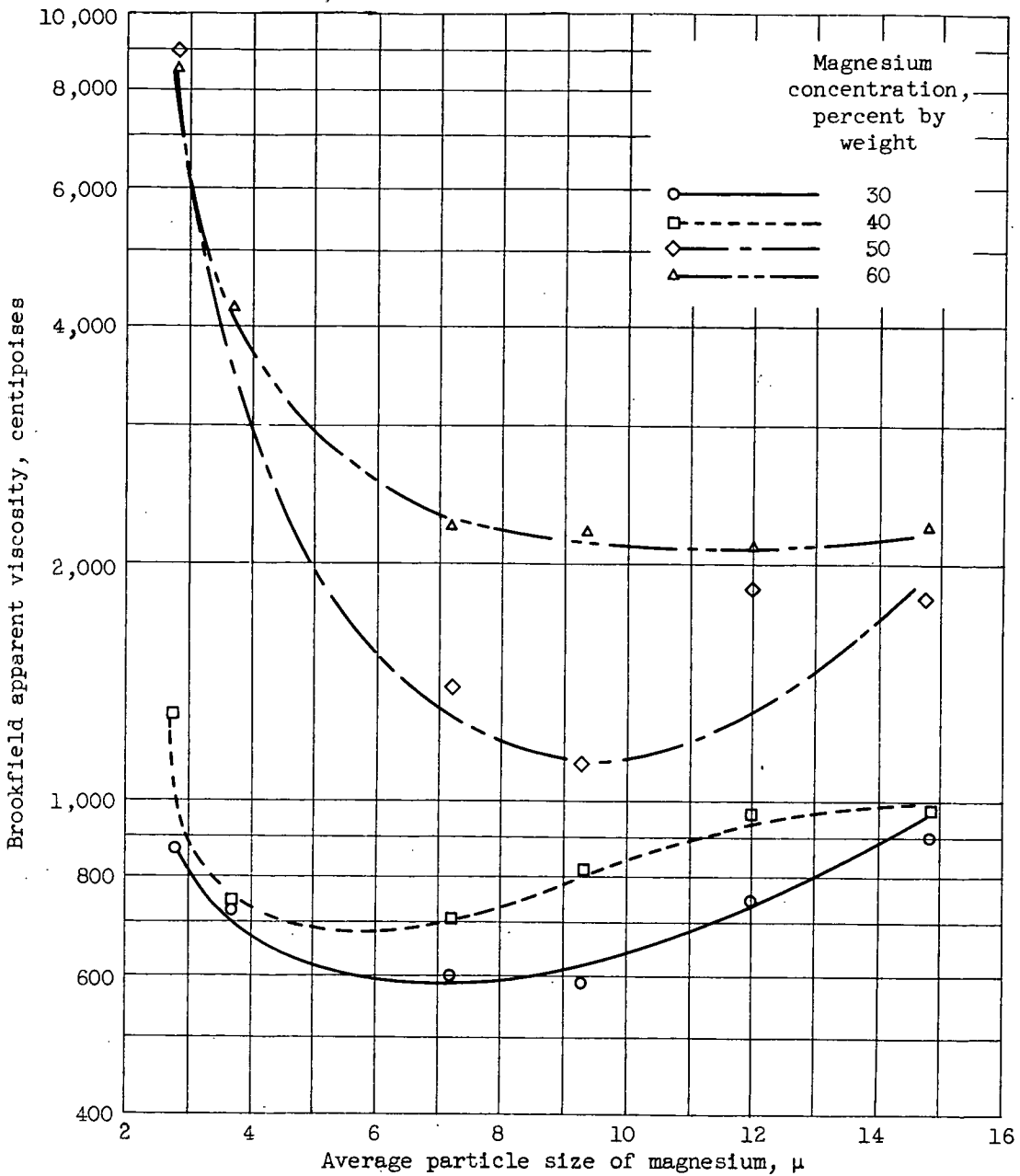


Figure 6. - Effect of average particle size on viscosity of petrolatum-stabilized magnesium slurries (ref. 21). Hydrocarbon carrier, 40 percent petrolatum A (table IV) and 60 percent MIL-F-5624A grade JP-4 fuel by weight; temperature, $86^{\circ} \pm 1.0^{\circ}$ F.

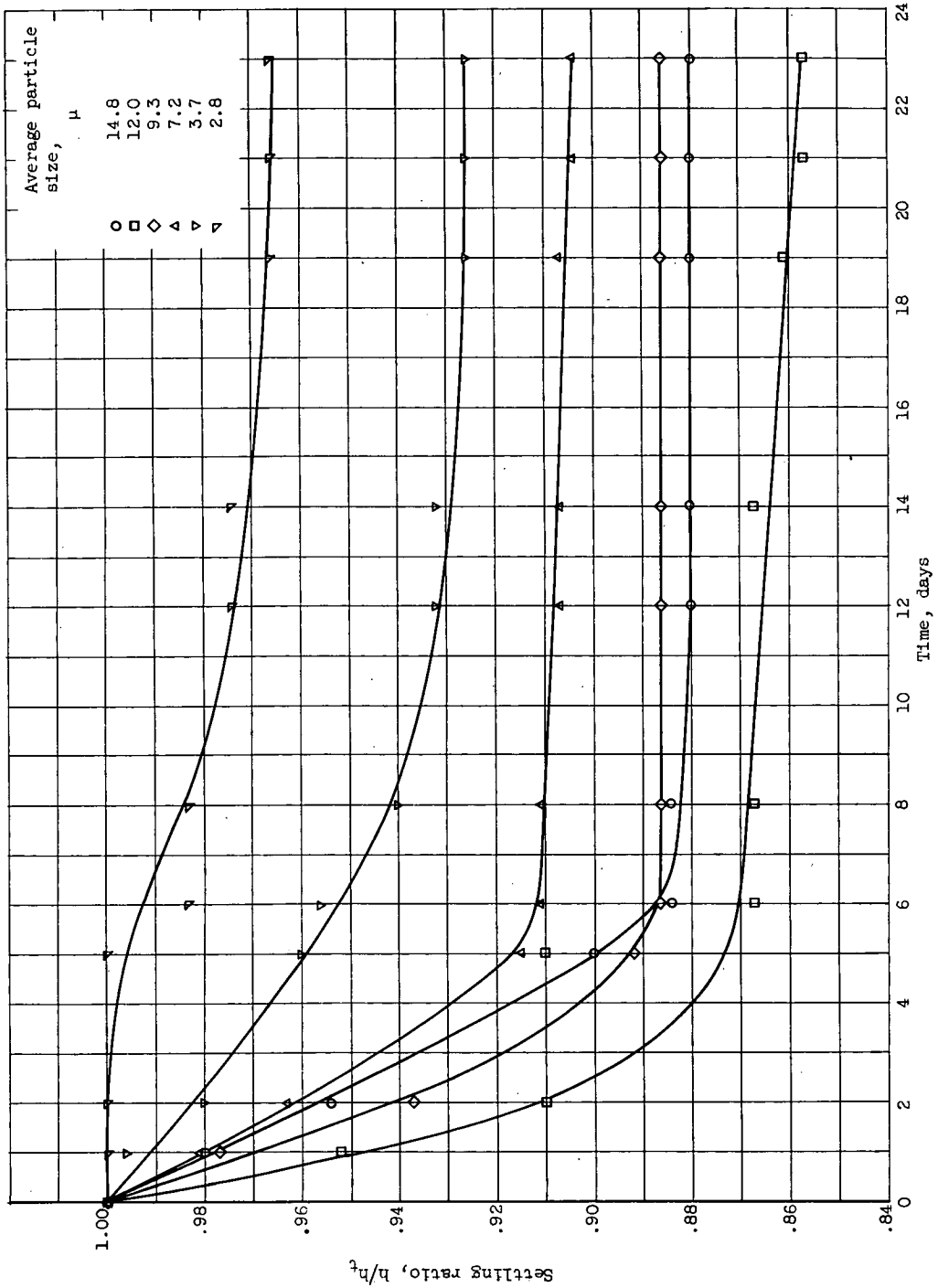
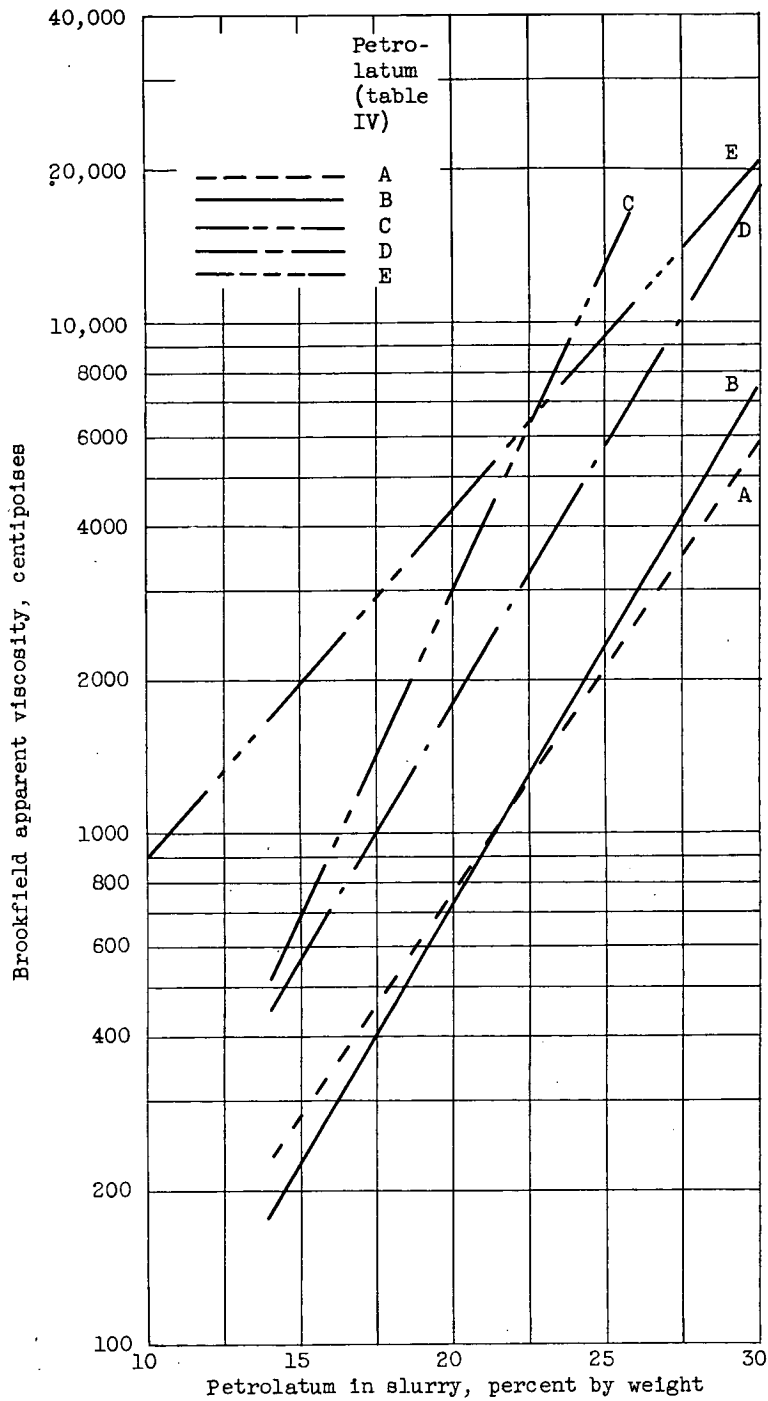
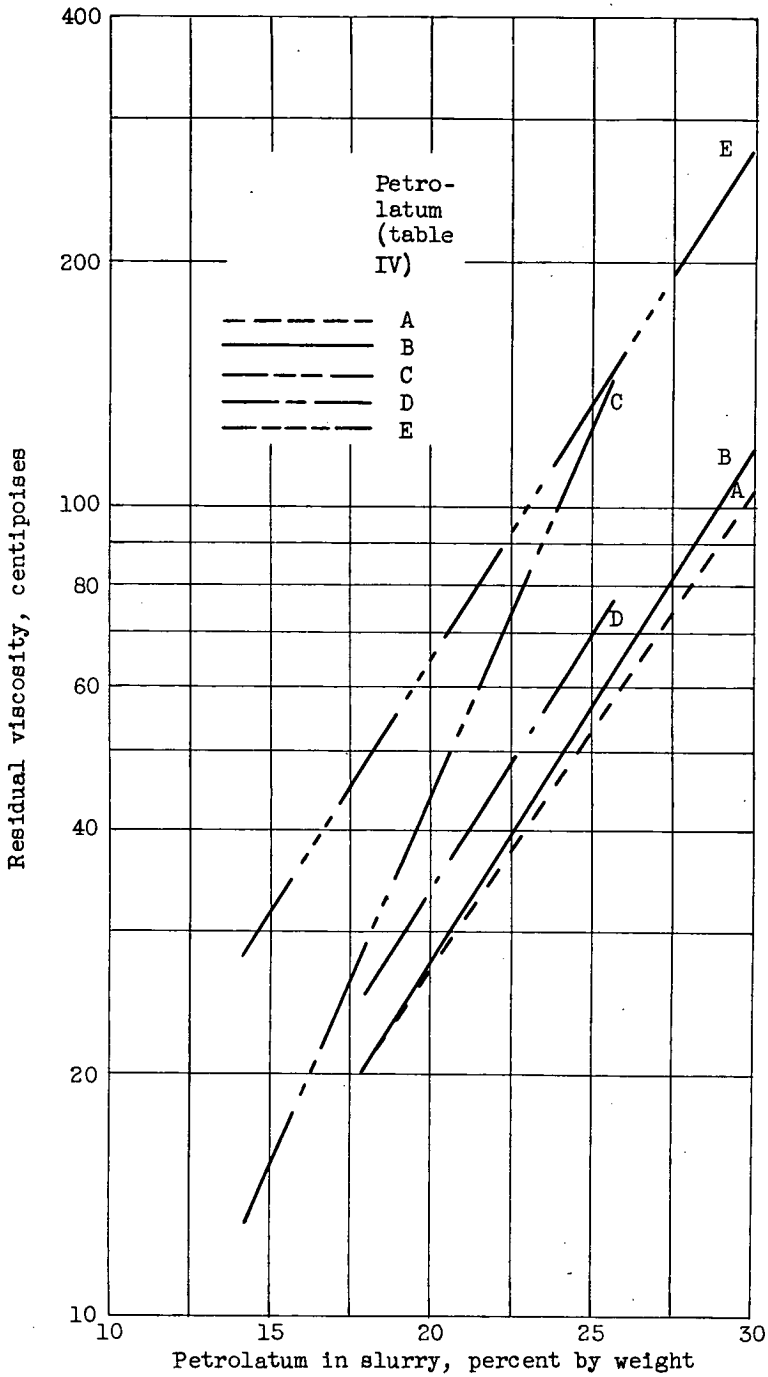


Figure 7. - Effect of magnesium particle size on settling ratios of slurries (ref. 21). Magnesium concentration, 60 percent by weight; hydrocarbon carrier, 40 percent petrolatum A (table IV) and 60 percent MIL-F-5624A grade JP-4 fuel by weight.



(a) Apparent viscosities. Temperature, 86° F.

Figure 8. - Summary of effect of petrolatum concentration on apparent and residual viscosities of 50-percent-magnesium slurries (ref. 20). Hydrocarbon carriers, petrolatum and MIL-F-5624A grade JP-4 fuel.



(b) Residual viscosities. Temperature, 75° to 86° F.

Figure 8. - Concluded. Summary of effect of petrolatum concentration on apparent and residual viscosities of 50-percent-magnesium slurries (ref. 20). Hydrocarbon carriers, petrolatum and MIL-F-5624A grade JP-4 fuel.

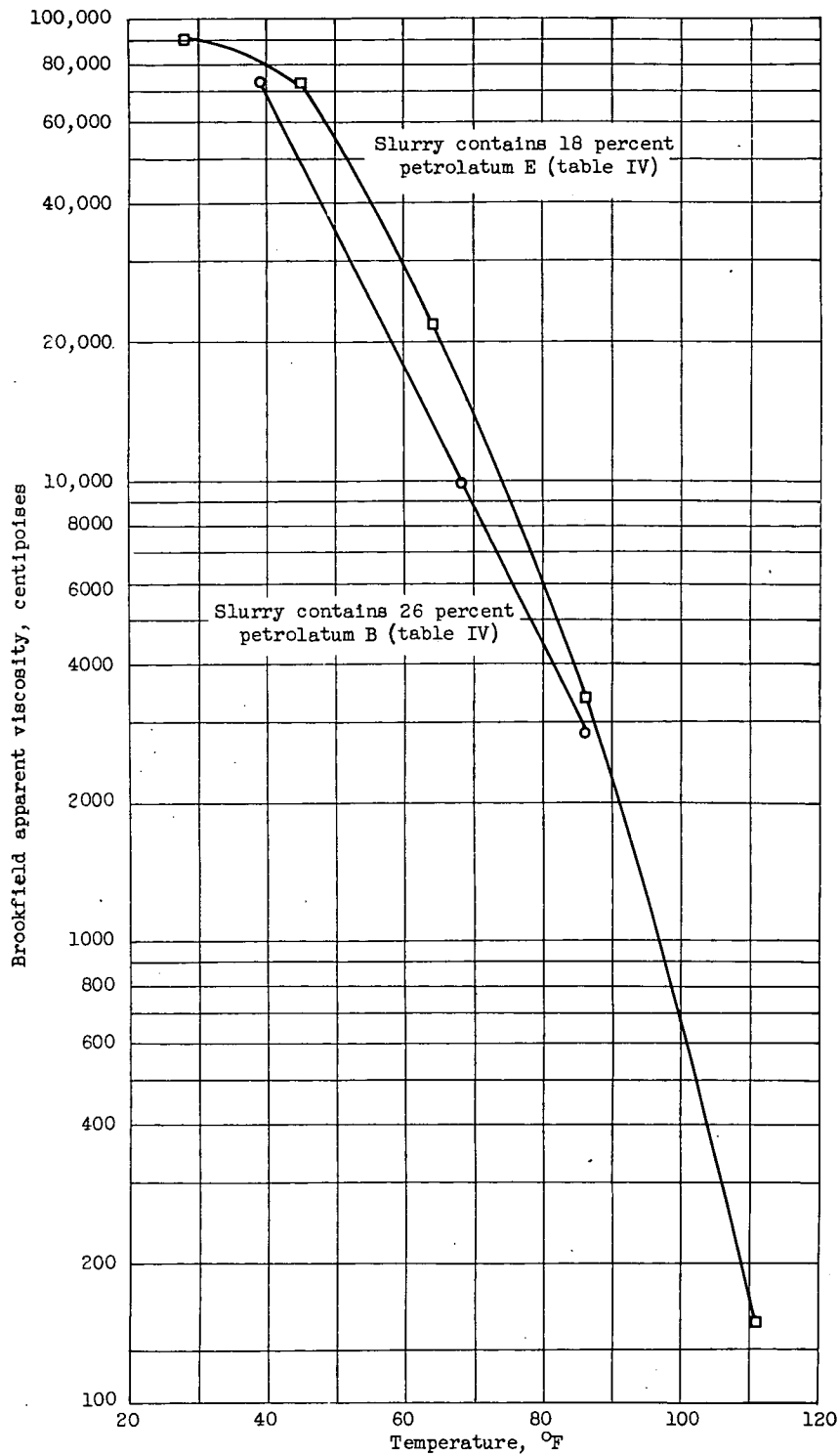


Figure 9. - Effect of temperature on Brookfield apparent viscosity of 50-percent-magnesium slurries stabilized with petrolatum (ref. 20). Hydrocarbon carrier, petrolatum and MIL-F-5624A grade JP-4 fuel.

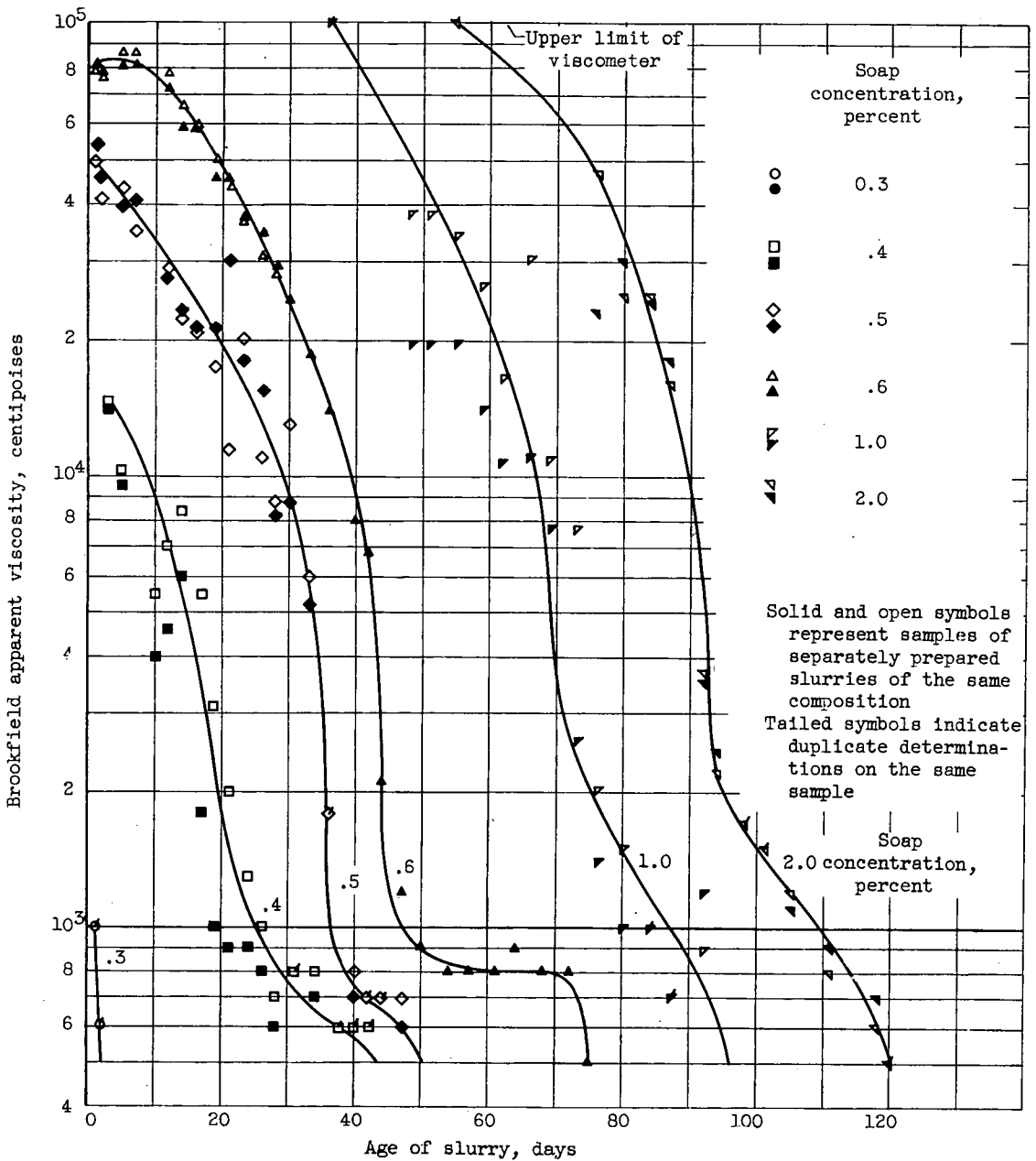


Figure 10. - Viscosity-age profiles of 50-percent-magnesium - JP-4 slurries stabilized with various concentrations of a C₈ soap. Gelation temperature, 110° F (ref. 23).

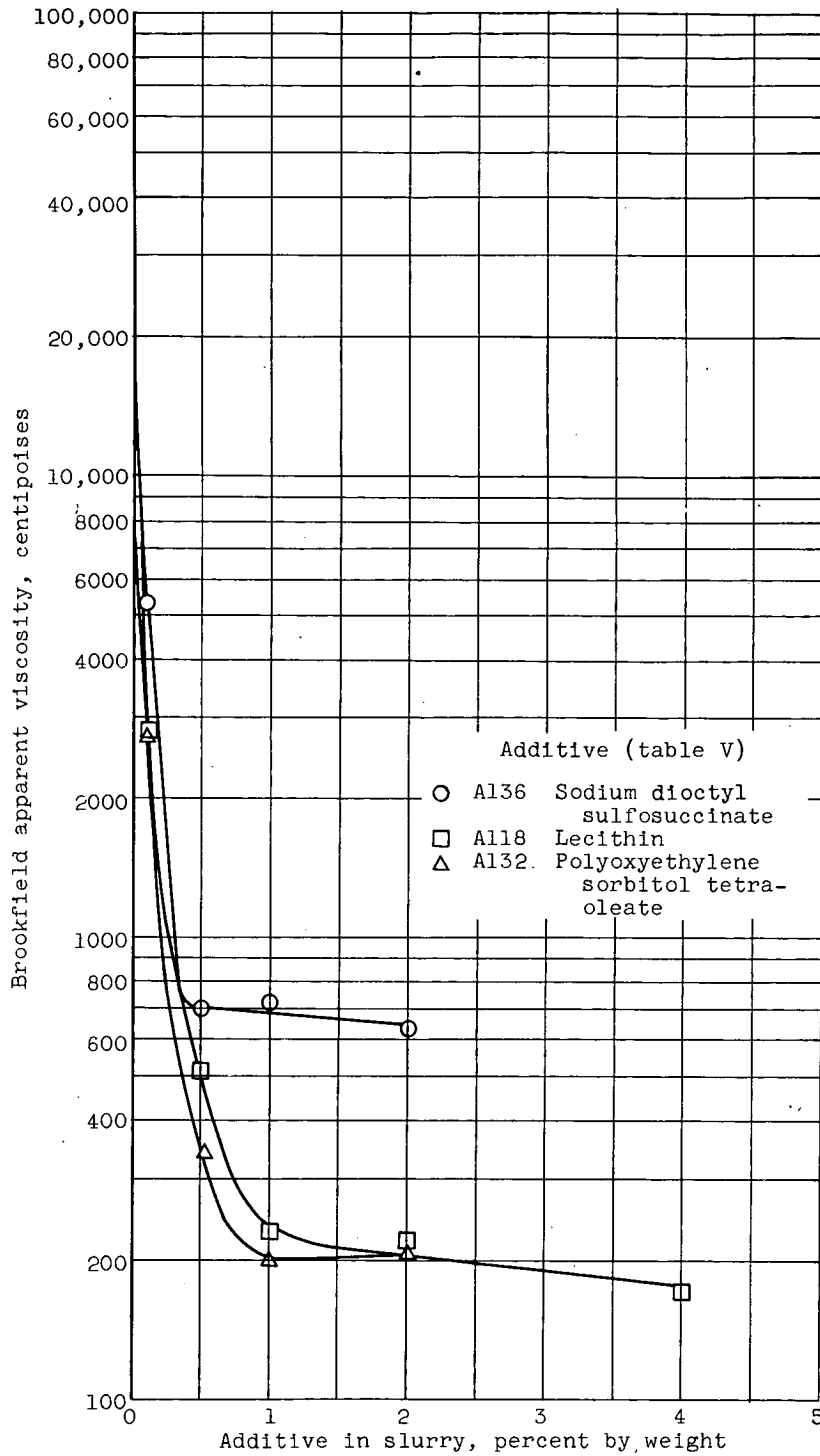


Figure 11. - Effect of concentration of surface-active additives on Brookfield apparent viscosity of 50-percent-magnesium slurries (ref. 24). Additive molecules are bulky and have multiple polar groups.

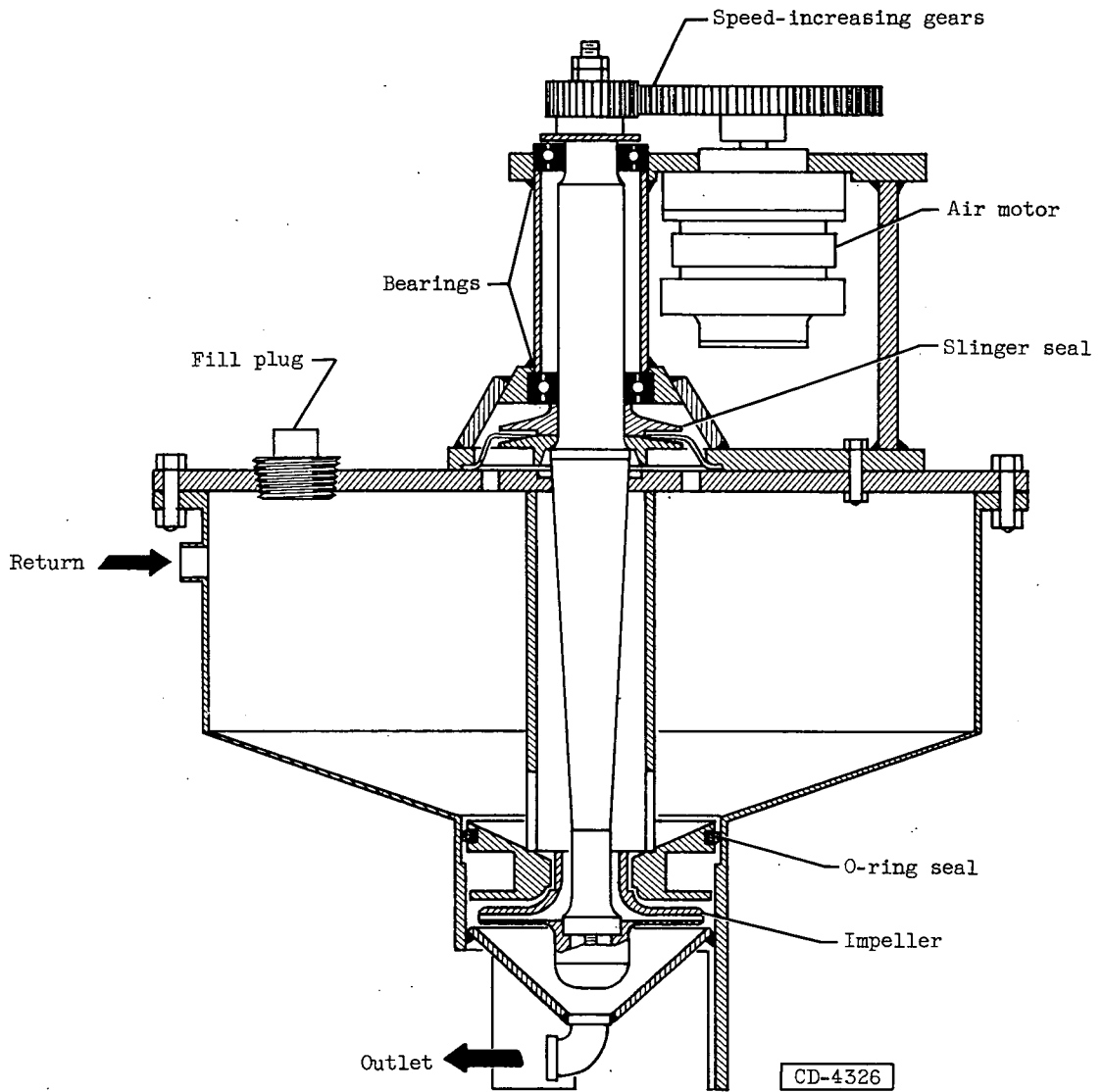
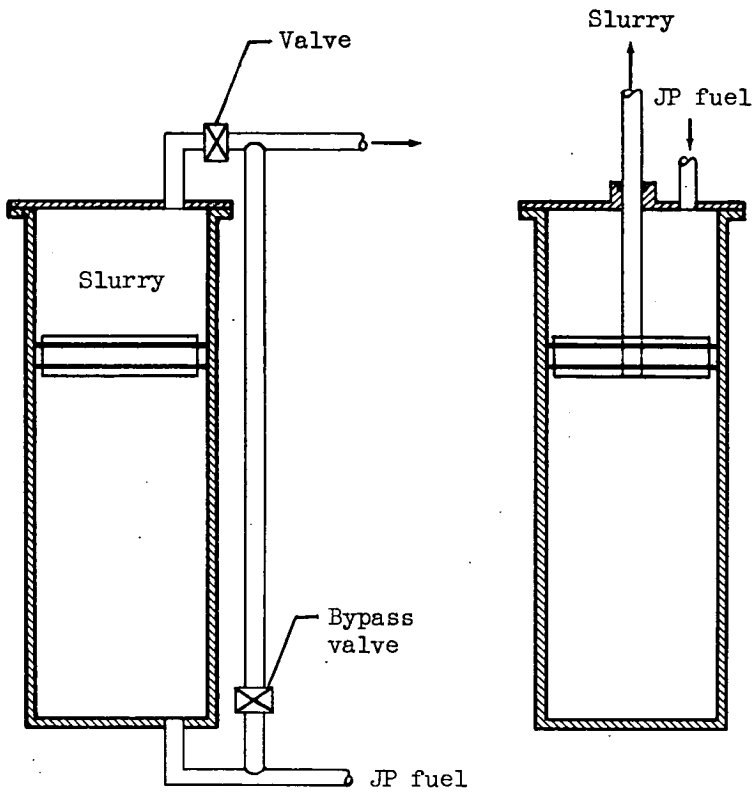
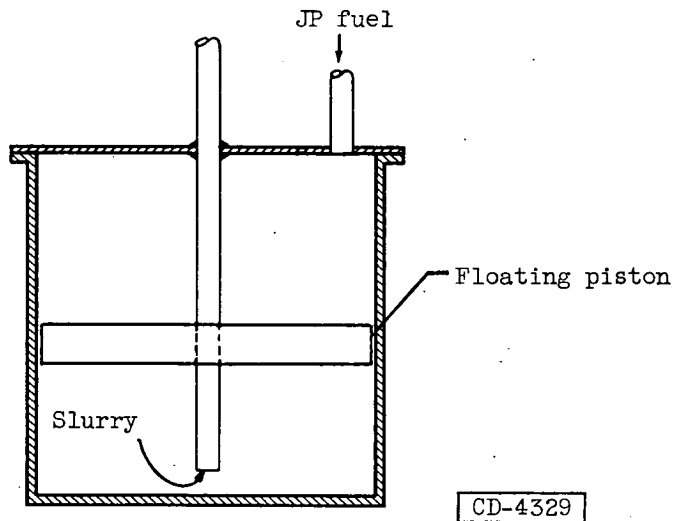


Figure 12. - Vertical centrifugal slurry pump.



(a) Free piston.

(b) Discharge through piston.



(c) Floating piston.

Figure 13. - Slurry displacement systems.

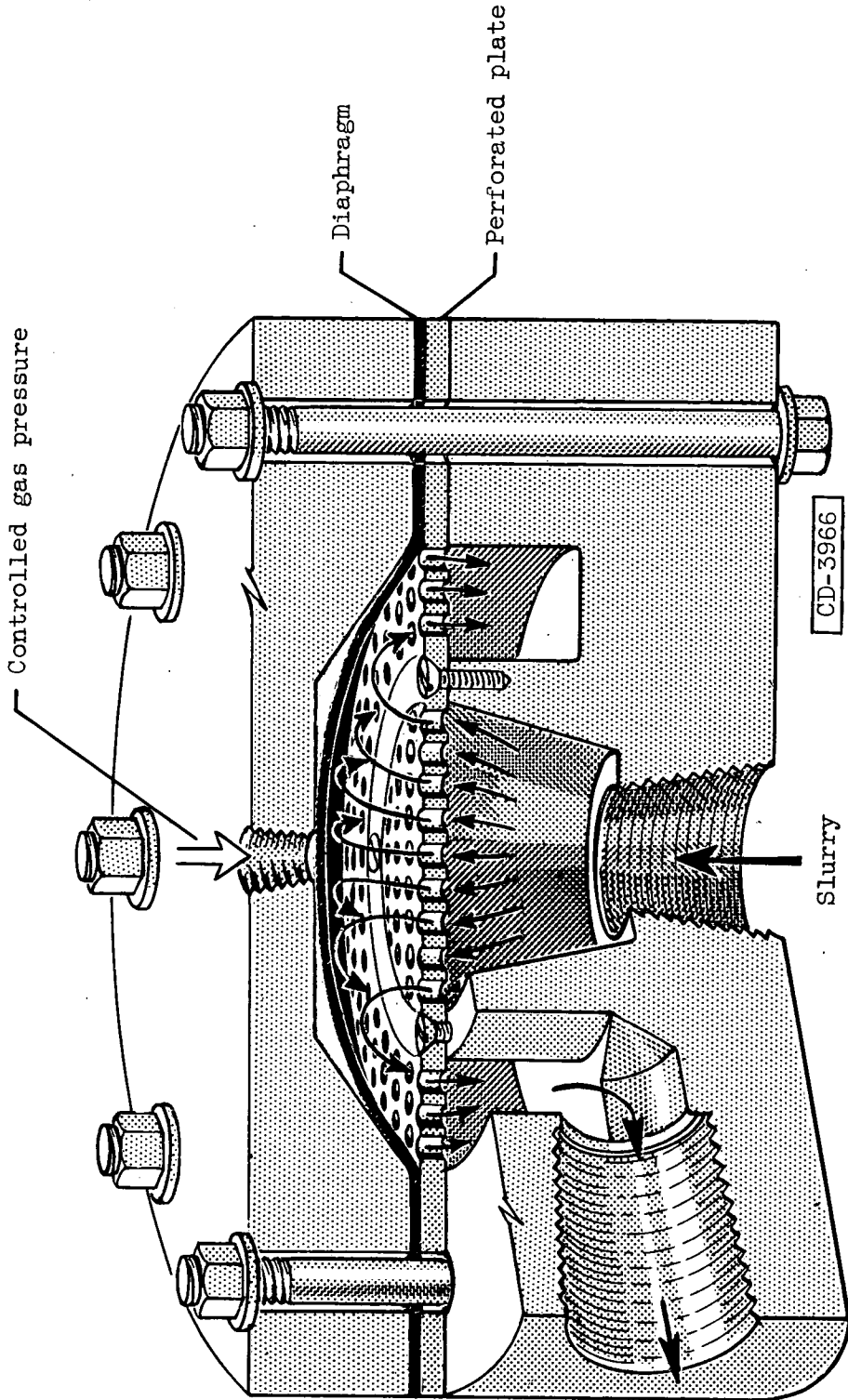


Figure 14. - Pressure-relief valve.

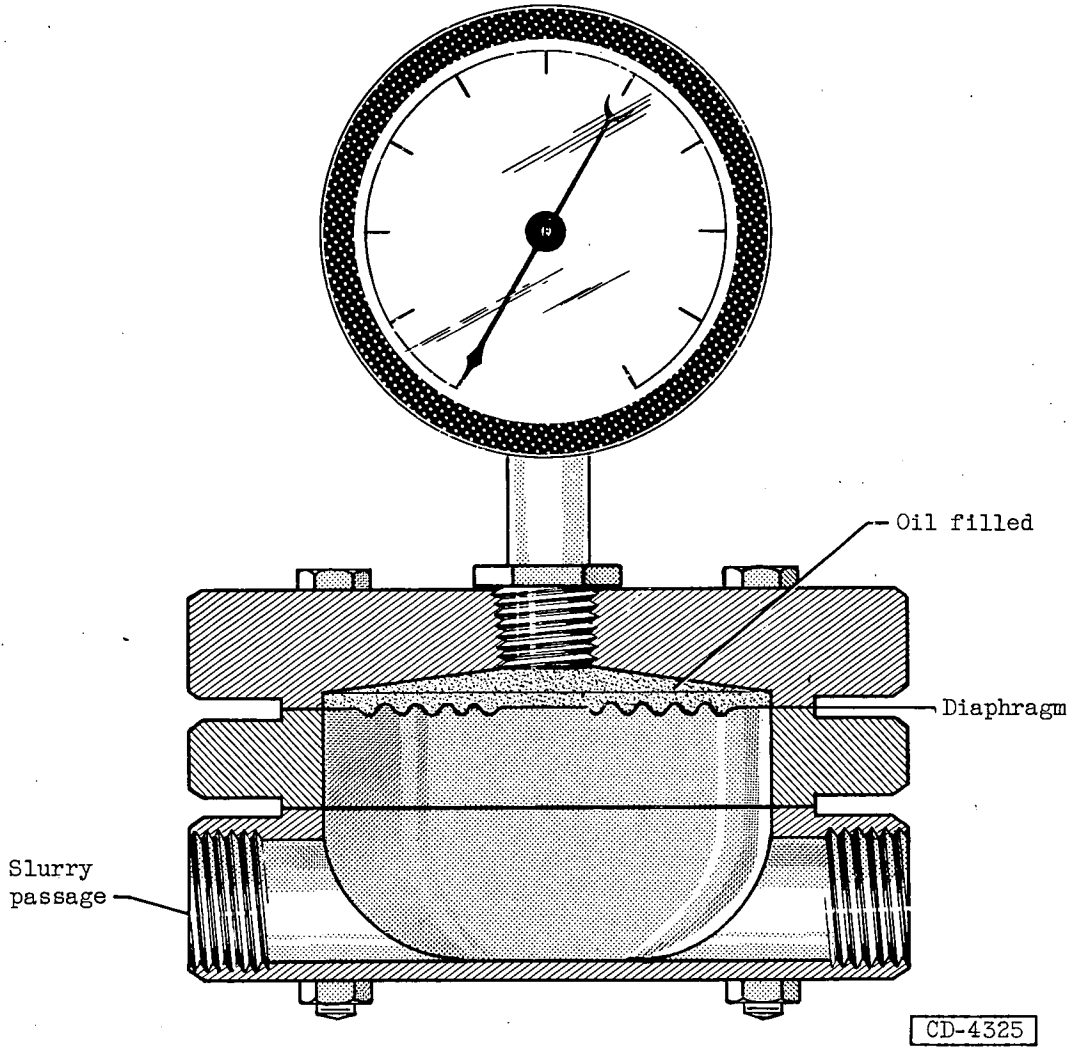


Figure 15. - Diaphragm-sealed pressure gage.

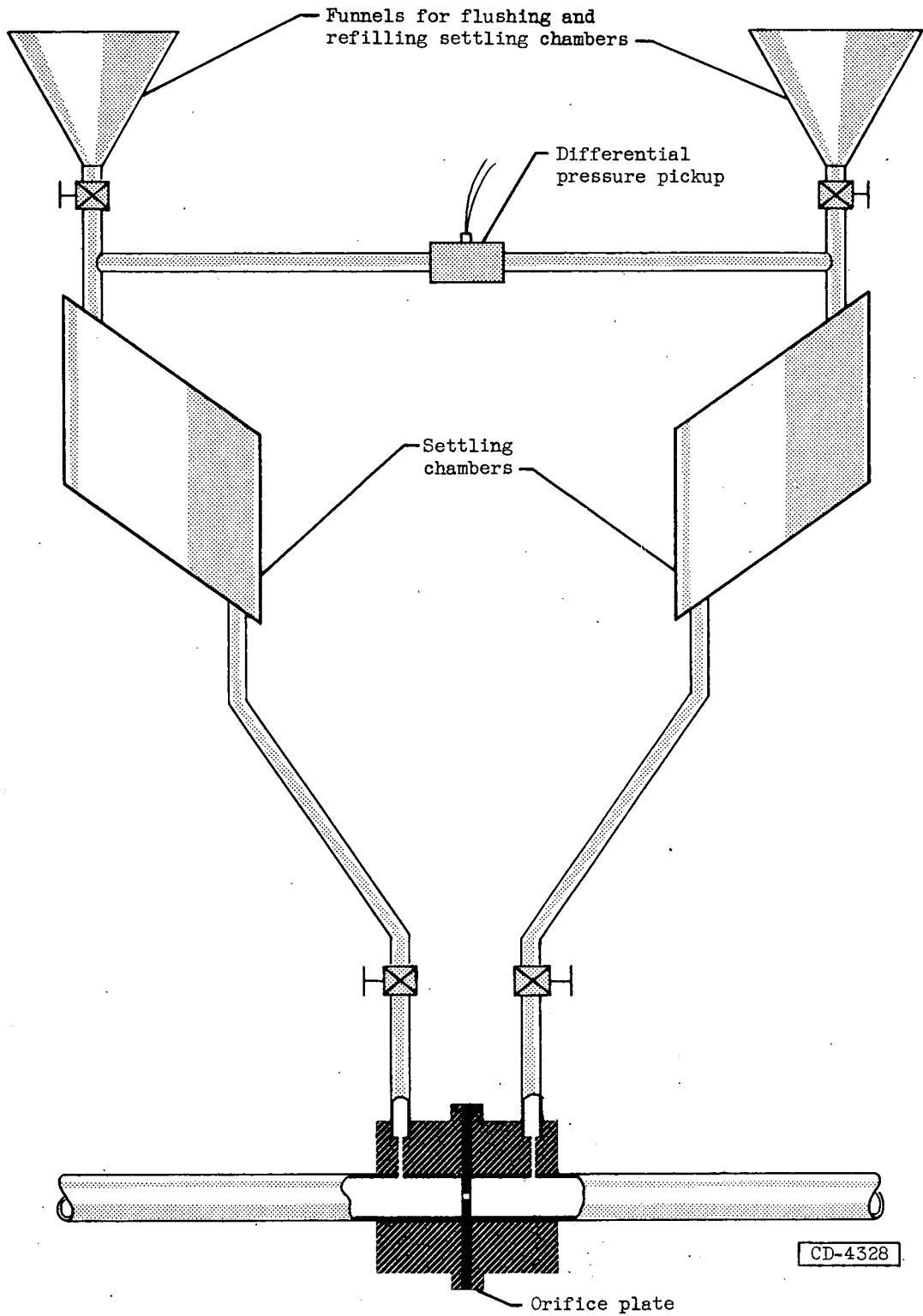


Figure 16. - Settling chambers for differential pressure gage.

→
Air flow



(a) Clear MIL-F-3624 JP-3 fuel; viscosity, 4 centipoises.

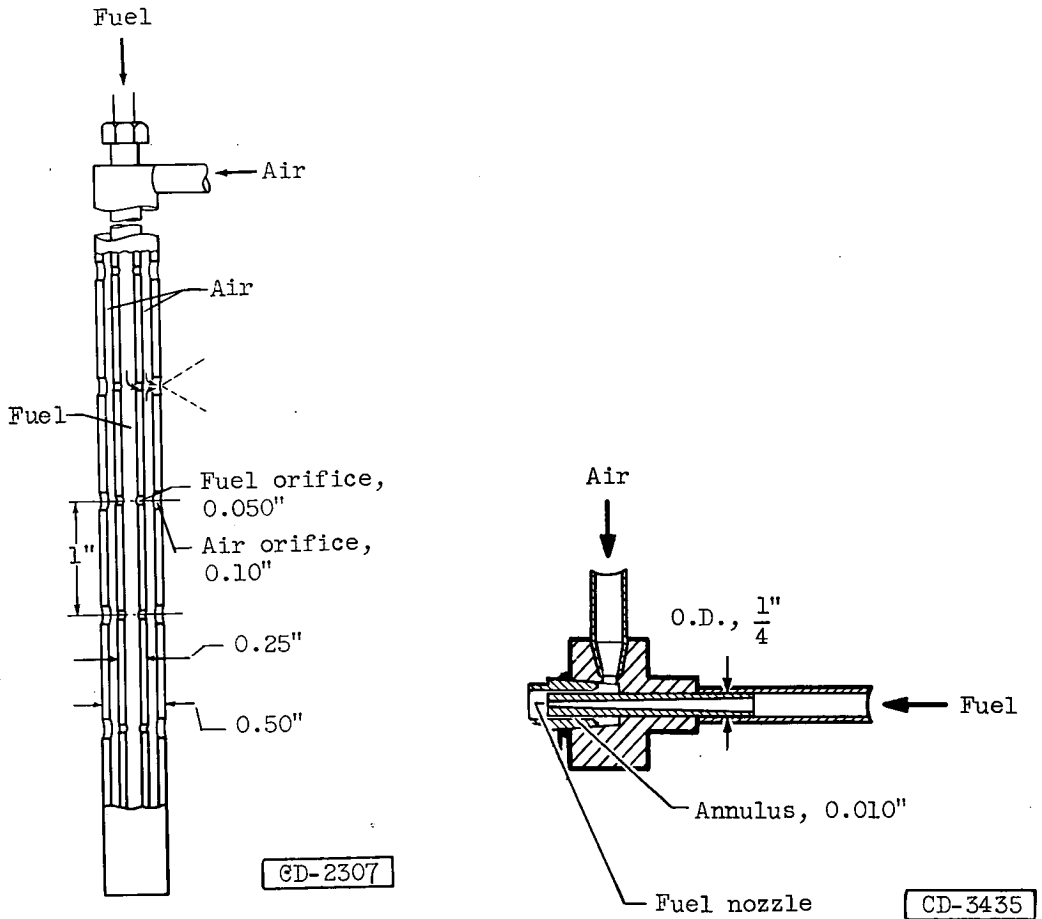


(b) 30-percent slurry of magnesium containing gelling agent; apparent viscosity, 300 to 400 centipoises.



(c) 30-percent slurry of magnesium containing gelling agent; apparent viscosity, 800 to 1600 centipoises.

Figure 17. - Photographs showing effect of gelling agents on spray formation (ref. 2). Inlet-air velocity, 400 feet per second; fuel jet velocity, approximately 26 feet per second; inlet-air temperature, 80° F; inlet-air density, 0.048 pound per cubic foot.



(a) Aspirating spray bar.

(b) Air-atomizing nozzle.

Figure 18. - Air-atomizing devices for slurry fuels (refs. 2 and 10).

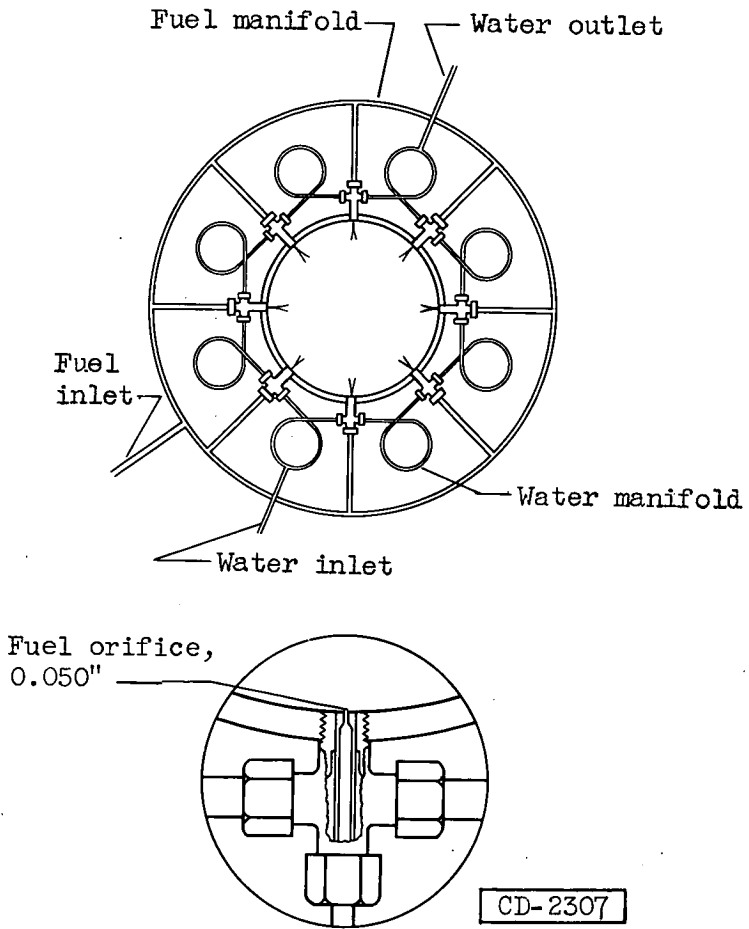


Figure 19. - Water-jacketed fuel injector (ref 2).

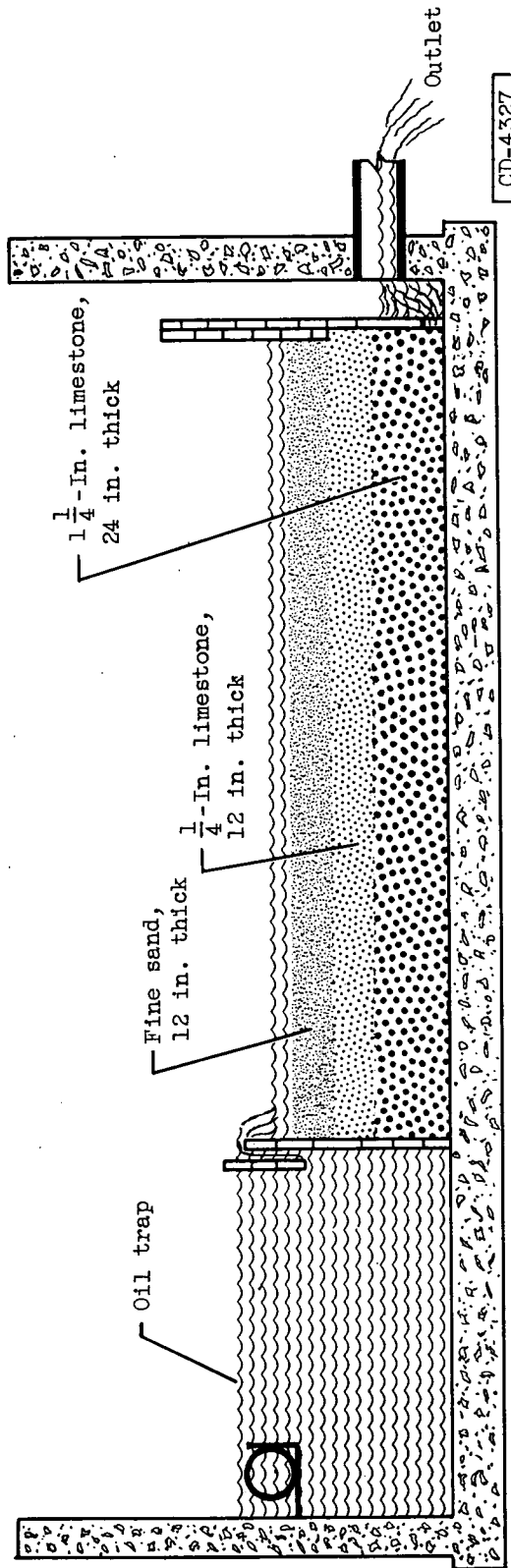
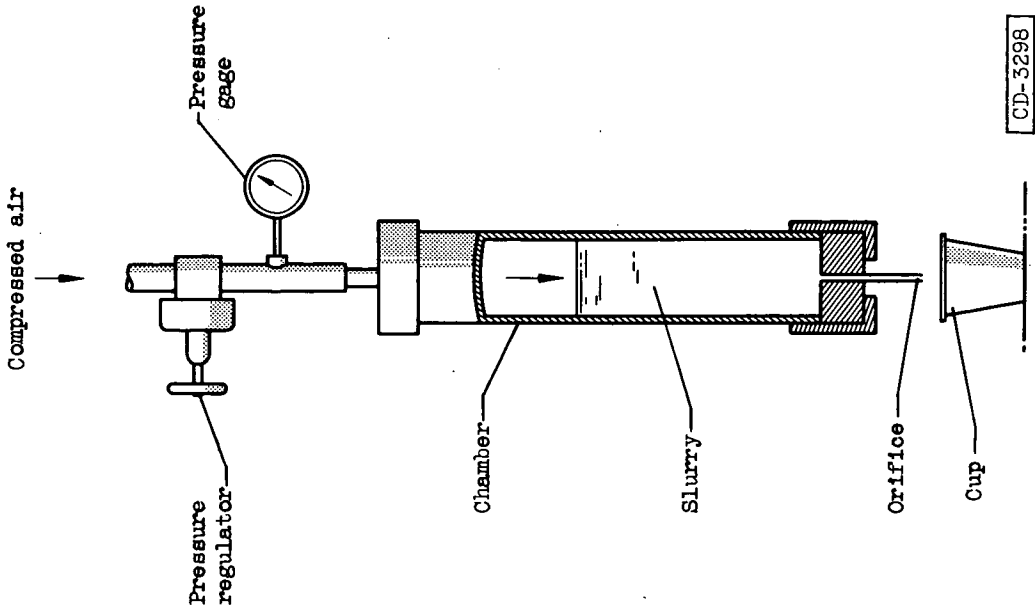
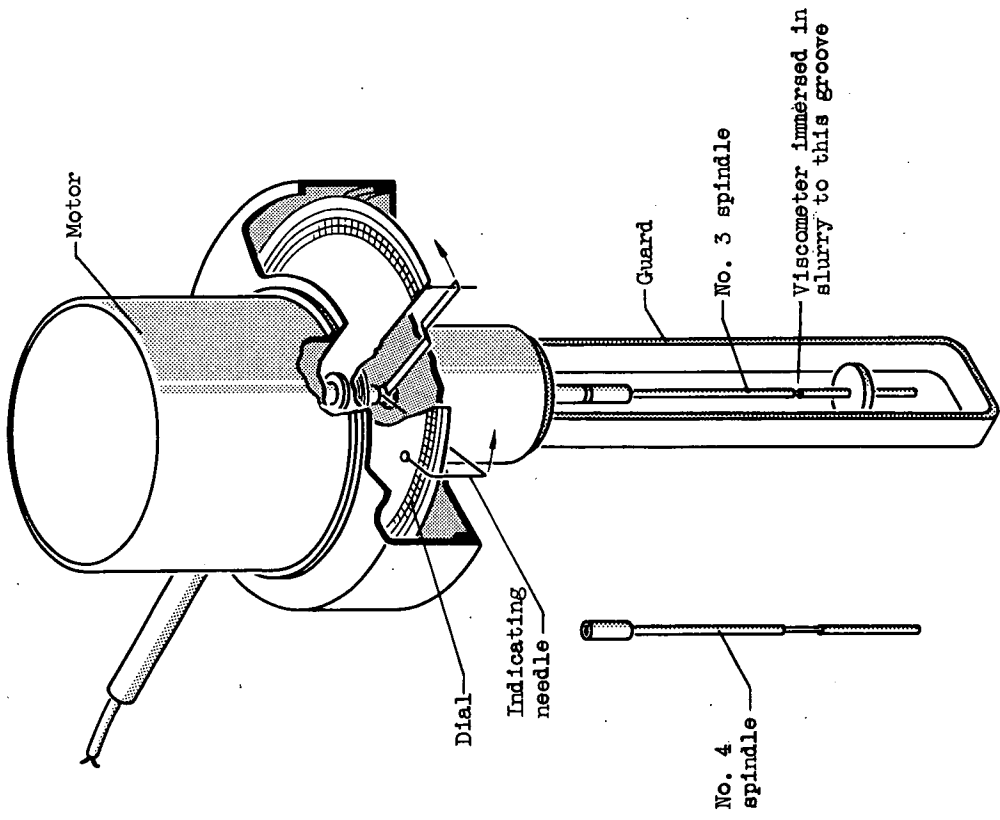


Figure 20. - Settling and filtration basin for exhaust products.



(b) Severs Extrusion Rheometer.

Figure 21. - Viscometers used to study magnesium-hydrocarbon slurries (ref. 20).



(a) Brookfield Synchro-lectric viscometer.

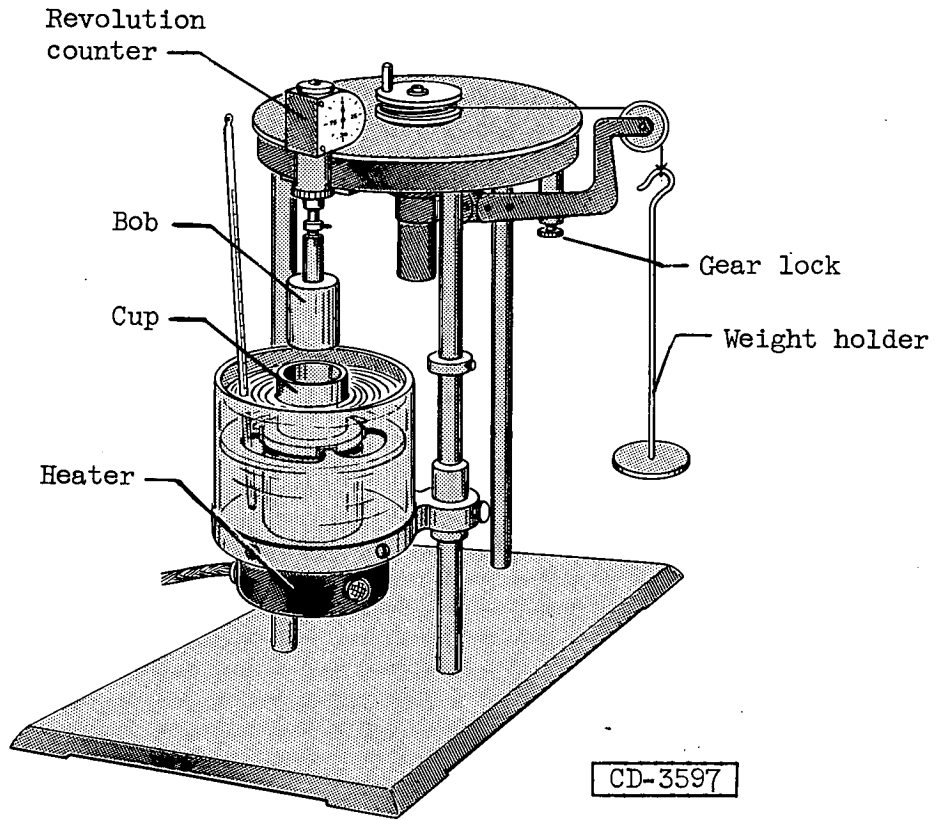


Figure 22. - Stormer rotational viscometer.

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