

RESEARCH MEMORANDUM

A PRELIMINARY STUDY OF THE PREPARATION OF SLURRY FUELS

FROM VAPORIZED MAGNESIUM

By Walter R. Witzke, George M. Prok
and Thomas J. Walsh

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

February 4, 1954
Declassified June 20, 1957

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUMA PRELIMINARY STUDY OF THE PREPARATION OF SLURRY FUELS FROM
VAPORIZED MAGNESIUM

By Walter R. Witzke, George M. Prok, and Thomas J. Walsh

SUMMARY

Slurry fuels containing extremely small particles of magnesium were prepared by concentrating the dilute slurry product resulting from the shock-cooling of magnesium metal vapors with a liquid hydrocarbon spray. A complete description of the equipment and procedure used in preparing the fuel is given. Ninety-five percent by weight of the solid particles formed by this process passed through a 100-mesh screen. The particle-size distribution of the screened fraction of one run, as determined by sedimentation analysis, indicated that 73 percent by weight of the metal particles were finer than 2 microns in equivalent spherical diameter. The purity of the solid particles ranged as high as 98.9 percent by weight of free magnesium. The screened product was concentrated by means of a bowl-type centrifuge from 0.5 to more than 50 percent by weight of solids content to form an extremely viscous, clay-like mass. By the addition of a surface-active agent, this viscous material was converted into a pumpable slurry fuel.

INTRODUCTION

Theoretical combustion studies at the NACA Lewis laboratory with concentrated suspensions of magnesium particles in hydrocarbon indicated that greater thrust is obtained with these slurry fuels than with conventional jet fuels (ref. 1). This was confirmed experimentally in a simulated afterburner with the additional advantage of better combustion stability (ref. 2). Further investigations indicated that higher blow-out velocities and higher metal combustion efficiencies result as the particle size of the magnesium is decreased (refs. 3 and 4). Since no commercial sources of a sizable quantity of very fine magnesium metal powder were found, an investigation was undertaken to develop a practical method of preparing slurry fuels containing particles of magnesium approximately 1 to 2 microns in diameter.

Various methods for preparing fine particles were studied. Milling operations were not entirely satisfactory because of the long milling time, poor yields, and the flattened shape of the product. A commercial

product prepared by atomization of the molten metal gave only very small yields in the desired particle-size range. The method of preparing extremely small magnesium particles by vapor condensation held the greatest assurance of successful results (ref. 5). This method consisted in passing hot vapors through a jet or spray of a cold fluid to cool the vapor rapidly to a low temperature. Very fine particles (0.1 to 0.6 μ) of solid were reported to form as a result of the sudden quenching.

The vapor-condensation method has been used in the commercial production of metallic magnesium primarily to inhibit the reoxidation of the magnesium; but an undesirable effect, from a refining viewpoint, was the formation of a crude product of extremely fine powder (ref. 5). The method discussed in reference 5 consists in quenching magnesium vapors with cold natural gas instead of hydrogen as used in the original Hansgirg process. The process was further modified by substituting a volatile liquid as the quench medium (refs. 6, 7, and 8). Various phases of the latter modification were adapted for the present investigation because the finely divided product was similar to that desired for fuel preparation; the use of a liquid hydrocarbon as the condensing medium was especially desirable since the final product was in the form of a slurry requiring only concentration and the addition of additives to make it suitable for combustion studies.

This report describes the equipment and materials used in vaporizing the magnesium metal, rapidly condensing its vapor, separating the metal particles and hydrocarbon from the inerting gas, and concentrating the magnesium suspension. The work covered in this report was carried on from August, 1952, to August, 1953.

DESCRIPTION OF PROCESS AND APPARATUS

Process

Magnesium metal was vaporized by heating the material to about 2000° F. Hot helium gas was used to maintain the vaporizing pot at a pressure of approximately 3.5 pounds per square inch gage. The hot vapors were passed through a heated orifice and into the path of a series of hydrocarbon sprays where condensation of the magnesium vapor into minute particles of solid took place. The solid particles were carried by hydrocarbon liquid into collectors following separation from the helium gas and some vaporized hydrocarbon. A vacuum was maintained downstream of the orifice.

Apparatus

The equipment in the magnesium vaporization unit was arranged as shown in the flow sheet and schematic diagram (figs. 1 and 2). The unit

consisted of a vaporizing furnace, a shock-cooling condenser, a means for separating and collecting the product, and auxiliary equipment. The equipment to be described was developed as a result of test runs with several earlier designs.

An Inconel resistance heater preheated the helium, which entered the vaporizing furnace through the $\frac{1}{2}$ -inch pipe in the top of the pot. Power was supplied to the Inconel tubing from a 300-ampere d-c welding unit and was controlled by adjusting the voltage and amperage.

The vaporizing furnace was a mild-steel pot surrounded by asbestos insulation and heated by induction (fig. 3). The pot was constructed by welding plates on the ends of a 9-inch section of standard 4-inch pipe. Threaded openings were provided at the top of the pot for entry of a $\frac{1}{2}$ -inch feed pipe and several thermocouples. A side outlet was centered $7\frac{1}{4}$ inches from the bottom plate.

The pot was heated by means of a 30-kilowatt high-frequency induction unit. A magnetic field developed around an eight-turn coil, which had a $5\frac{7}{8}$ -inch inside diameter and was made of $\frac{1}{4}$ -inch copper tubing. A $\frac{3}{8}$ -inch spacing between turns was maintained by blocks of asbestos cement.

The vaporizing pot was connected through the side outlet to the shock-cooling condenser by a $\frac{1}{4}$ -inch pipe nipple containing a replaceable $\frac{1}{4}$ -inch converging-diverging stainless-steel orifice. Because of condensation of the metal vapors at the orifice and in the piping between the pot and the shock-cooling condenser, the induction coil was extended to heat this section (fig. 3). This portion of the induction coil had a $2\frac{7}{8}$ -inch inside diameter, six turns, and $\frac{1}{2}$ -inch spacing between turns.

The shock-cooling condenser was designed to provide a curtain of coolant in the path of the hot metal vapors coming from the pot without cooling the intervening piping (fig. 3). Three hollow-cone spray nozzles, one rated at 10.5 gallons per hour (60° included spray angle) and two at 21.5 gallons per hour (80° included angle), were installed to spray downward at right angles to the metal vapor flow. The nozzle with the narrow spray angle was nearest the inlet to the spray chamber so that liquid did not strike and cool the inlet duct. The condensing medium was taken from a 55-gallon drum and passed through a flow control valve to the spray nozzles by means of a gear pump.

Separation of the product from the inerting gas was accomplished by collecting the unvaporized hydrocarbon and part of the condensed magnesium particles in a 20-gallon drum below the spray chamber. The hydrocarbon vapors with the portion of magnesium particles not already removed by the first collector were condensed in a pair of ice-water-cooled Heliflow coils and collected in a second 20-gallon drum.

In order to prevent any loss of the metal particles from the system, the inerting gas was passed through a bath of hydrocarbon followed by a felt filter. A water-cooled heat exchanger was situated in the line to condense any hydrocarbon vapors passing the filter. The final piping was connected to a 4-inch vacuum line serviced by a 225-cubic-foot-per-minute Beach-Russ vacuum pump.

The concentration of the vapor-condensation product was carried out as a separate operation with a bowl-type laboratory centrifuge. Although this unit was designed principally for liquid-liquid separation, it was found capable of concentrating small batches to approximately 50 percent solids content by weight, with a clear liquid discharge, at rotor speeds of 30,000 to 40,000 rpm.

Instrumentation

The instruments employed on the magnesium vaporization unit consisted of temperature, pressure, and flow measuring devices. Self-balancing potentiometers were used for recording and indicating temperatures of thermocouples at various points in the system. Thermocouple wells protected the thermocouples extending into the magnesium in the pot. All thermocouples were grounded to the instrument case by means of a 1-microfarad condenser to eliminate alternating current disturbance from the induction coil. The pot pressure and after-spray pressure were indicated by a 30-pound-per-square-inch gage and a 36-inch U-tube mercury manometer, respectively; these pressures were also recorded by a self-balancing potentiometer with the aid of pressure-sensing elements. The flow of helium and hydrocarbon was measured by means of rotameters. Power input to the induction unit was measured by a wattmeter.

DESCRIPTION OF MATERIALS

Magnesium

Various forms of magnesium were used for charging the pot. Among these was atomized cell powder of 99.8 percent purity with a particle size ranging from 16 to 200 mesh. Small magnesium chips were also employed. A more satisfactory pot charge was found in 1-inch strips of 1/8-inch magnesium wire. The wire had a purity of approximately 99 percent free magnesium.

Condensing Medium

The hydrocarbon mixture used as the condensing medium in the majority of the runs was MIL-F-5616 grade JP-1 fuel (table I). A few initial runs were made with a mixture of 90 percent n-heptane and 10 percent JP-1.

Helium

Analysis of the helium indicated it to be free of water and oxygen.

PROCEDURE

Preparation for a test run, following assembly of the equipment, consisted in filling the pot with about 3 pounds of magnesium and inspecting the unit for leaks. The system was evacuated, purged with helium to remove all oxygen, and pressurized to about 3.5 pounds per square inch gage with the inert gas.

With no flow of materials through the system, power was applied to heat the pot, the helium, and the orifice section. Sufficient heating of these three items was required before flow was initiated to prevent condensation of the metal vapors before they reached the shock-cooling condenser.

When the liquid-magnesium temperature reached 1400° F, flow was started through the apparatus as follows: (1) Helium was passed through the resistance heater and into the pot; (2) the pressure was reduced downstream of the orifice by means of the vacuum pump; and (3) the hydrocarbon was sprayed into the shock-cooling condenser. As the vapor pressure of the metal increased with further temperature rise, the pressure in the pot was kept constant through manual adjustment of the helium flow. The pressure downstream of the orifice was held constant by a manually controlled air bleed valve at the vacuum-pump inlet. Shutdown required the cutting off of power to the induction heater and reduction of the helium temperature. When the magnesium temperature decreased below 1200° F, the helium heater was turned off and the flow of the gas reduced; the vacuum pump and the condensing liquid spray were stopped and the magnesium allowed to cool to 200° F. A slight positive pressure of helium was maintained throughout the cooling period.

The product from the vapor-condensation process was pumped through a 100-mesh screen, which removed the coarse particles. After thorough mixing with a turbine stirrer, samples of the product were taken for analysis. Concentration of the mixture from 0.5 percent to 50 percent by weight of solids followed in the laboratory centrifuge at a feed rate of about 500 cubic centimeters per minute.

Special precautions. - A certain degree of hazard was involved in the disassembly and cleaning of equipment and in the storage of the product. Several fires started when the piping at the orifice and the spray chamber was opened. Steam cleaning was employed for removing the magnesium deposits in the piping and usually resulted in ignition of the magnesium. During the cleaning and disassembly operations, protection for the face and hands was necessary. Cleaning of the slurry collectors was advisable as soon as possible after removal of product since evaporation of the hydrocarbon resulted in spontaneous ignition of the exposed magnesium particles. The principal precaution taken in storing the concentrated product was keeping the material in a closed container and the magnesium particles covered with liquid hydrocarbon.

Chemical analysis of solid product. - The analytical determination for free magnesium content in the solid product was carried out gravimetrically. The slurry was treated with acid, and the liberated hydrogen was converted to water by passing it through a combustion train containing cupric oxide. The weight of free metal was calculated on the basis of the weight of water collected. The total magnesium content was determined gravimetrically by precipitating the metal from the acid solution with 8-hydroxyquinoline. The accuracy of the method was found to be within ± 0.1 percent, with magnesium sulfate used as a standard.

Particle-size analysis by sedimentation. - Data for the size distribution of the magnesium particles in the product were obtained according to the modification of the Casagrande method of particle-size analysis proposed in reference 9 with a long-arm centrifuge. This method had to be further modified to accommodate the lower densities of the materials involved. The specific-gravity determinations were made using a Westphal balance instead of a hydrometer.

OPERATIONAL AND DESIGN PROBLEMS

The vaporization unit described in this report and operated at the present time is the design evolved from the solution of problems encountered in several attempts to produce high-purity, submicron magnesium particles by vapor condensation. A discussion of these problems and their solution is believed desirable to aid others who may wish to prepare fuels by this method.

Atomized magnesium powder served as the starting material in the pot until it was found that high helium flows carried the powder from the pot, causing clogging of the orifice and contamination of the product with large particles. Magnesium chips also produced clogging of the orifice. Short strips of magnesium wire were too heavy to be affected by the gas flow and therefore proved to be a satisfactory charge material for the vaporizing pot.

The first vaporizing pot was constructed from graphite to withstand the high temperatures and attack from the magnesium vapors. Its porous structure required an enclosing shell which also contained the induction coil and high-temperature insulation. The system was operated under vacuum conditions, and helium was used to pressurize the pot shell. With this arrangement, severe arcing across the induction coil was caused by the presence of helium.

Revision of the furnace to the design described in the Apparatus section in this report eliminated the difficulty of arcing. An AISI type 347 stainless-steel pot was used in this second assembly, but the magnesium vapor reacted sufficiently with the alloyed nickel to cause a leak. Consequently, a third pot made of mild steel was installed. Although limited in service by the severe oxidation of the exterior of the pot resulting from the high-temperature operation, the mild-steel pot proved satisfactory.

Clogging of the section between the pot and the spray area was a constant problem. In the initial runs with no restriction at the outlet of the pot, a coke plug formed as a result of the thermal cracking of the hydrocarbon spray. This apparently arose from the diffusion of the organic vapors into the hotter portions of the apparatus. The coke formation was completely eliminated through the installation of an orifice between the pot and the spray area.

Further clogging in the piping, before the condensing spray, was caused by condensation of magnesium in this section. The condensation was related to the design characteristics and temperature of the orifice and condenser sections. By heating the piping between the pot and the spray chamber to a temperature above the melting point of the magnesium, metal deposition in the orifice was practically eliminated. Replacement of the sharp-edge orifice, used in most of the runs, with a converging-diverging one further alleviated clogging in this section.

Clogging at the spray-area inlet, where a temperature transition occurs, varied with the design of the shock-cooling condenser. Prior to adoption of the spray-chamber type shown in figure 3, the condenser usually consisted of a nozzle spraying the hydrocarbon upstream or downstream in the pipe leading from the pot. (This type of design is illustrated by the double-Y condenser shown in fig. 4.) The spray-chamber design was based on the assumption that the rapid build-up of a magnesium plug in the double-Y condenser had been due to the cooling effect of the spray on the walls of the piping and to the narrowness of the passage. The spray chamber proved satisfactory in that only a small amount of magnesium was deposited in the inlet area.

Separation of the product from the helium was first performed by a 2-inch cyclone separator. The separating efficiency of this unit was not

very high based on the amount of solid accumulated in the felt filter following the cyclone separator. Furthermore, the interior of the cyclone showed a build-up of sludge on the walls. A more efficient separator was found in the Heliflow coils. The effect of this equipment was to condense all the hydrocarbon vapor and thereby to wash out the solid particles in the gas stream. A hydrocarbon bath and felt filter were effective in removing the final traces of solid particles.

The use of a mixture of 90 percent n-heptane and 10 percent JP-1 fuel (volume basis) as the condensing medium in the first few runs proved undesirable at the low operating pressures. With the after-spray pressure (downstream of orifice) below 2 pounds per square inch absolute, the n-heptane showed a tendency to boil. The JP-1 fuel itself, being less volatile, gave good results as the condensing medium in later runs.

DISCUSSION OF RESULTS

The data and results obtained in the vapor condensation of magnesium are shown in tables II and III, respectively. The on-stream time is the interval of operation from the initiation of flow until the induction heating was discontinued. The magnesium distillation rate is the loss in weight of the crucible and its contents during the run divided by the on-stream time. All temperatures and pressures were averaged on a time-weighted basis during the on-stream time. The power requirements for the induction unit included the heating of the orifice section as well as the vaporizing pot and magnesium charge.

A limitation in the amount of power available affected the distillation rate of the magnesium, because the induction unit when operated at full capacity did not supply a sufficient amount of energy to produce boiling of the magnesium in the vaporizing pot. As an aid to the magnesium distillation, helium was employed to sweep the metal vapors from the pot into the shock-cooling condenser.

Helium flows up to 23.7 pounds per hour were employed. Initially, the flow of this inert gas into the pot served to maintain sonic conditions at the orifice to stop clogging. However, it was later found (in run 29) that a mass velocity of the helium and magnesium vapors as low as 287 pounds per hour per square inch of cross-sectional area (somewhat below sonic velocity) did not lead to clogging by magnesium in the heated orifice. It was further noted in run 35 with a 3/32-inch orifice that the helium flow could be decreased to zero during the vaporization of the magnesium without any deleterious effects. However, the continued use of helium was considered necessary for the startup and shutdown of the unit.

During a number of runs in which helium was used throughout the operation, the effect of the helium temperature from 1200° to 1700° F was

observed with respect to clogging. The helium temperature had no effect on clogging as long as it was kept above the melting temperature of the magnesium. Below this temperature, one run (run 27) plugged completely within 3 minutes following the shutdown of the helium heater.

Operation of the system with pot pressures below atmospheric pressure resulted in a product containing solid particles of low free-metal content. This was presumed to be due to oxidation of the magnesium by air which leaked into the apparatus. When the pot pressure was raised above atmospheric pressure, high product purity was achieved.

The flow rate of the condensing medium was varied between 190 and 400 pounds per hour to determine its effect on the quantity of large particles formed. Under the existing operating conditions, no definite relation could be established between the flow rate of the hydrocarbon spray and the percentage of condensed magnesium particles retained by a 100-mesh screen.

It was originally estimated that about 20 pounds of liquid hydrocarbon, of which 1 pound was relatively nonvolatile, would be required to condense and cool each pound of magnesium vapor. Vaporization of all but 1 pound of the hydrocarbon should then have resulted in a 50 percent by weight magnesium slurry. These results were never realized with the shock-cooling condensers used because of the high temperatures occurring downstream of the condenser and the consequent requirement of hydrocarbon flows 5 to 25 times theoretical.

The amount of fine particles that passed through a 100-mesh screen was used as a measure of the efficiency of the condensation process. The 100-mesh screen was selected because this screen contained openings smaller than those of any orifice which might be used in a fuel system and thereby precluded any future stoppage of slurry fuel flow. The amount of fine particles passing through the screen ranged from 85.0 to 99.7 percent on a weight basis. The average for the runs evaluated was 95 percent by weight. The material passing the 100-mesh screen was used for further analysis.

The shape and size characteristics of the solid-metal particles obtained from the magnesium vaporization were best observed by means of electron micrographs of the product from run 29 (fig. 5). The hexagonal-shaped particles were not seen in earlier electron micrographs of less-pure solid product. Another observation regarding the shape of the particles was made when the poor penetrability of the electron microscope was considered. The electron microscope usually will not penetrate a material greater than 500 angstrom units in thickness. Therefore, it was assumed from the observed translucence of many of the particles that these particles were in the form of thin plates.

The particle-size distribution of the metal particles from run 29 was determined by centrifugal sedimentation analysis. The result indicated that 33 percent by weight of the particles were finer than 1 micron in equivalent spherical diameter and 73 percent by weight finer than 2 microns (fig. 6).

The purity of the solids portion of the vapor condensation product ranged as high as 98.9 percent by weight free magnesium. The values of the solid-product purity in the first collector were usually higher than those in the second collector. This difference in purity was attributed to leakage of air into the system in the vicinity of the second collector. It was noticed that the difference in purity between the product in the two collectors increased as the pressure downstream from the orifice was decreased below atmospheric pressure. In general, the leakage of air into the system through pipe unions, sight gages, and other fittings accounted for the low purities resulting in many of the runs. During the operation of run 34, a leak occurred in the sight gage of the first product collector, while on the completion of run 35 it was noted that an inspection port in the spray chamber was not tightly sealed. Although a consistently high purity product was the ultimate goal, this was not the purpose in many of the runs in which it was more urgent to eliminate the clogging problem.

The concentration of the product from a 0.5-percent slurry to one of 50-percent solids content resulted in a wet clay-like mass that was extremely viscous. When sliced, the exposed surface had a metallic luster similar to sodium metal. The densities and concentrations (calculated as 100 percent free magnesium) of five centrifuged samples were as follows:

Sample	Density, g/cc	Solids, percent
1	1.124	53.7
2	1.155	57.3
3	1.075	47.9
4	0.973	33.5
5	1.129	54.3

A small quantity of concentrated product was fluidized by the addition of a surface active agent. Approximately 1.3 percent by weight of a glycerol sorbitan laurate was required to lower the viscosity of the clay-like mass to between 5000 and 10,000 centipoises. This slurry fuel, with a 53.4 percent by weight solids content, was burned in a small experimental combustor with promising results.

SUGGESTED IMPROVEMENTS

Further improvement in the purity of the product should result from the exclusion of air from the entire system by operating at pressures greater than atmospheric. A vaporizing pot made of a material more resistant to high-temperature oxidation than mild steel and also resistant to attack by magnesium vapor would be desirable for continuous operation of the unit. A larger induction unit for vaporizing the magnesium would improve the performance of the system.

SUMMARY OF RESULTS

The following results were obtained from the preparation of slurry fuels by condensing magnesium vapor with liquid hydrocarbons:

1. Of the solid particles formed by the condensation of magnesium vapor, 95 percent by weight passed through a 100-mesh screen.
2. Sedimentation analysis of the screened fraction from one run indicated that 73 percent by weight of the particles were finer than 2 microns in equivalent spherical diameter.
3. The purity of the solid particles ranged as high as 98.9 percent by weight free magnesium.
4. The concentration of a dilute slurry containing 0.5 percent by weight magnesium to one with a solids content of approximately 50 percent by weight produced an extremely viscous, clay-like mass.
5. A pumpable slurry fuel resulted from the addition of a surface active agent to the concentrated material.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 24, 1953

REFERENCES

1. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. II - Magnesium, and Magnesium-Octene-1 Slurries. NACA RM E51C23, 1951.
2. Tower, Leonard K., and Branstetter, J. Robert: Combustion Performance Evaluation of Magnesium-Hydrocarbon Slurry Blends in a Simulated Tail-Pipe Burner. NACA RM E51C26, 1951.

3. Lord, Albert M., and Evans, Vernida E.: Effect of Particle Size and Stabilizing Additives on the Combustion Properties of Magnesium Slurry. NACA RM E52K12, 1953.
4. Cook, Preston N., Jr., Evans, Vernida E., and Lezberg, Erwin A.: Experimental Investigation of Physical and Combustion Properties of Several Residual Fuel Oils and Magnesium-Fuel-Oil Slurries in a Ram-Jet-Type Combustor. NACA RM E53D30, 1953.
5. Dungan, T. A.: Production of Magnesium by the Carbothermic Process at Permanente. Am. Inst. Mining and Metallurgical Engrs., vol. 159, 1944, pp. 308-314.
6. Dean, R. S.: Annual Report of the Metallurgical Division, Fiscal Year 1939. R.I. 3480, Bur. Mines, Jan. 1940, pp. 49-54.
7. Doerner, H. A., Holbrook, W. Floyd, Dilling, E. Don, and Harris, Dwight L.: Magnesium by Electrothermic Reduction. R.I. 3635, Bur. Mines, May 1942.
8. Wood, C. E., et al.: Construction and Operation of the Dearborn Magnesium Pilot Plant. R.I. 3823, Bur. Mines, Aug. 1945.
9. Norton, F. H., and Speil, S.: The Measurement of Particle Sizes in Clays. Jour. Am. Ceramic Soc., vol. 21, 1938, pp. 89-97.

TABLE I. - ANALYSIS OF MIL-F-5616 GRADE JP-1 FUEL

A.S.T.M. distillation	
D86-52, °F	
Initial boiling point	311
Percentage evaporated	
5	330
10	337
20	334
30	350
40	357
50	366
60	376
70	384
80	394
90	410
95	420
Final boiling point	423
Residue, percent	1.0
Loss, percent	0
Specific gravity, 60/60° F	0.797
Gravity, °A.P.I.	46.0
Viscosity at 32° F, centistokes	2.087

TABLE II. - COMPILATION OF DATA FOR MAGNESIUM VAPORIZATION UNIT

Run	Arrangement of apparatus			On-stream time, min	Flow rate, lb/hr				Temperature, °F				Pressure, lb/sq in. abs		Power, kw		Reason for ending run	
					Helium, average	Magnesium, distillation, average	Hydrocarbon, average	Helium ^m	Magnesium liquid		Magnesium vapor		After-spray ^a	Pot ^a	After-spray ^a	Induction unit input, average		Helium heater input, average
	Range	Average ^a	Range						Average ^a									
1	Graphite	None	(e)	46	0.4	(m)	(m,n)	969	1220-1690	1520	1090-1650	1380	(m)	2.0	(m)	21	(q)	(s)
2	Graphite	None	(e)	25	.3		(m,n)	979	1240-1690	1540	1000-1610	1380	(m)	2.0	(m)	26	(q)	(s,t)
3	Graphite	None	(e)	20	.3		(m,n)	976	1200-1680	1540	1000-1570	1340	80	2.0	(m)	27	(q)	(t)
4	347 Steel	b _{1/8}	(f)	15	.7		(m,p)	974	1240-1540	1380	690-1130	(m)	135	4.1	2.4	30	(q)	(t)
5		b _{1/8}	(f)	3	.2			975	1200-1310	1250	1150-1200	1180	140	3.4	.3	18	(q)	(t)
6		b _{1/4}	(f)	3	2.0			(m) ^q	1200-1300	1250	1160-1260	1210	155	3.5	.6	30	(q)	(t)
7			(g)	12	2.3			971	1190-1600	1400	1000-1200	(m)	185	4.2	.9	16	(q)	(t)
8			(g)	5	1.5			1410	1210-1730	1480	1000-1540	1190	190	2.6	.5	28	(q)	(u)
9			(h)	21	1.7			1310	1210-1900	1640	1000-1680	1400	190	8.5	2.2	21	6.0	(t)
10	Mild steel		(h)	15	2.4			1430	1210-1600	1380	1000-1420	1260	205	5.6	4.8	19	6.0	(t)
11		b, c _{1/4}	(h)	31	2.2			1570	1320-1790	1650	1000-1330	1180	205	7.8	5.6	12	4.0	(t)
12			(i)	32	2.3			1510	1280-1690	1540	1000-1350	1200	205	4.2	1.5	12	4.0	(s)
13			(i)	70	2.3			1400	1230-1760	1640	1000-1460	1240	205	8.1	5.3	12	4.0	(t)
14			(i)	49	2.3			1210	1230-1680	1560	1000-1280	1150	205	3.4	1.8	12	4.0	(v)
15			(i)	43	2.3			1410	1210-1600	1460	1000-1140	1060	205	3.0	1.2	6	3.5	(w)
16		b, c _{1/4}	(i)	3	23.7			1290	1780-1890	1820	1010-1100	1040	>400	37.0	17.5	22	4.5	(x)
17	347 Steel		(i)	43	(m)			1460	1710-2070	2000	1000-2070	1560	290	17.0	(m)	23	5.0	(y)
18	Mild steel		(i)	56	(m)			1790	1580-1900	1800	1120-1580	1490	245	18.7	6.4	28	9.5	(z)
19			(j)	65	(m)			1210	1630-1890	1780	1210-1570	1510	200	18.0	6.0	20	8.0	(z)
20			(j)	42	(m)			1620	1610-2070	1970	1170-1840	1550	200	18.2	4.4	30	8.0	(t)
21			(j)	64	(m)		P200	1120	1670-2080	1900	1220-1780	1550	(m)	18.6	6.3	28	8.5	(t)
22			(j)	56	10.8	0.9	P200	1590	1500-1820	1760	1000-1470	1430	195	17.3	4.8	24	8.0	(t)
23			(j)	37	12.4	1.9	P200	1640	1670-2000	1890	1400-1860	1700	210	17.6	4.4	30+	8.0	(s)
24			(j)	22	12.4	2.2	P190	1600	1610-2060	1900	1310-1870	1610	215	17.5	4.6	30+	8.0	(t)
25			(j)	32	11.6	2.9	P270	1690	1570-2060	1970	1180-1830	1680	205	18.1	4.8	30+	8.0	(t)
26		d, c _{1/4}	(k)	44	13.5	2.3	P400	1650	1500-2000	1900	1250-1790	1640	205	18.2	5.2	30+	8.5	(v)
27		d, c _{1/4}	(k)	31	16.7	1.5	P280	1190	1650-1960	1900	1340-1510	1430	210	18.2	5.1	30	6.5	(t)
28		b, c _{1/4}	(k)	45	11.0	2.2	P400	1640	1410-2070	1880	1050-1790	1560	200	18.1	3.7	30	8.0	(v)
29		d, c _{1/4}	(k)	40	13.2	.9	P360	1640	1350-1930	1810	1000-1700	1520	230	18.2	13.3	30	8.5	(v)
30			(k)	39	11.8	.8	P380	1650	1400-1960	1810	1000-1650	1500	205	16.1	6.2	30	8.5	(v)
31			(k)	60	12.1	1.6	P320	1690	1390-1990	1870	1000-1710	1560	235	18.1	7.0	30	9.5	(v)
32			(k)	51	14.3	1.2	P350	1680	1410-1960	1830	1000-1650	1530	210	17.9	4.7	30	9.5	(v)
33			(k)	50	13.9	1.5	P370	1690	1460-1910	1810	1080-1730	1580	220	17.6	6.5	30+	9.0	(v)
34		b, c _{1/4}	(k)	43	10.5	3.2	P400	1720	1420-2110	1970	1000-1740	1540	200	17.9	3.6	30+	8.5	(v)
35		b, c _{3/32}	(k)	46	r.9	2.1	P260	r1290	1470-2150	1980	1100-2110	1800	160	16.2	.7	30	r3.0	(v)

^aAll temperatures and pressures averaged on time-weighted basis during on-stream period.
^bSharp-edge orifice.
^cOrifice section heated.
^dConverging-diverging orifice.
^e3 Gal/hr nozzle pointed downstream in T.
^f3 Gal/hr nozzle pointed upstream in pipe.
^g3 Gal/hr nozzle pointed downstream in pipe.
^h5 Gal/hr nozzle pointed downstream in Y-fitting.,
ⁱ10.5 Gal/hr nozzle pointed downstream in Y-fitting.
^jTwo 25 gal/hr nozzles pointed downstream in double-Y.
^kChamber containing one 10.5 and two 21.5 gal/hr nozzles spraying at right angle to stream from pot.
^lChamber containing 30 and 21.5 gal/hr nozzles spraying at right angle to stream from pot.
^mNot determined.

ⁿMixture of 9 volumes of n-heptane and 1 volume of JP-1 fuel.
^pJP-1 fuel only.
^qHelium not heated.
^rAverage for first 25 min. of on-stream time; remainder of run with no helium flow.
^sArcing between turns of induction coil.
^tPressure rise in pot indicating clogging in system.
^uHelium heater burn-out.
^vProduct collectors near full capacity.
^wAdjustment of induction unit required.
^xPortion of piping overheated.
^yLeak in pot due to Mg-Ni interaction
^zPot nearly empty.

TABLE III. - ANALYSIS OF PRODUCT OF MAGNESIUM VAPORIZATION UNIT

Run	Purity of solids ^a		Amount of fine particles through 100-mesh screen, percent by weight
	Free Mg in first collector, percent	Free Mg in second collector, percent	
1	^b 37.3	^b 47.5	(c)
2	(b)	(b)	↓
3	(b)	(b)	
4	(c)	(c)	
5	(c)	(c)	
6	14.0	(c)	
7	(c)	51.6	
8		30.1	
9		57.5	
10		66.1	
11		22.3	
12		53.2	
13		62.6	
14		72.1	
15		88.2	
16		55.0	
17		84.9	
18		83.1	
19		83.0	
20		88.4	
21		93.9	↓
22		67.4	97.0
23		89.7	98.9
24		83.0	99.7
25		37.5	88.6
26	↓	76.6	98.7
27	79.4	73.5	97.1
28	98.0	42.8	85.0
29	98.9	97.8	97.7
30	95.6	89.6	94.0
31	81.4	71.7	98.3
32	95.6	75.5	90.8
33	66.7	84.1	93.8
34	56.9	(c)	97.7
35	35.7	(c)	(c)

^aLow solid-product purity, in general, was due to air leaking into system.

^bCarbon present in product.

^cNot determined.

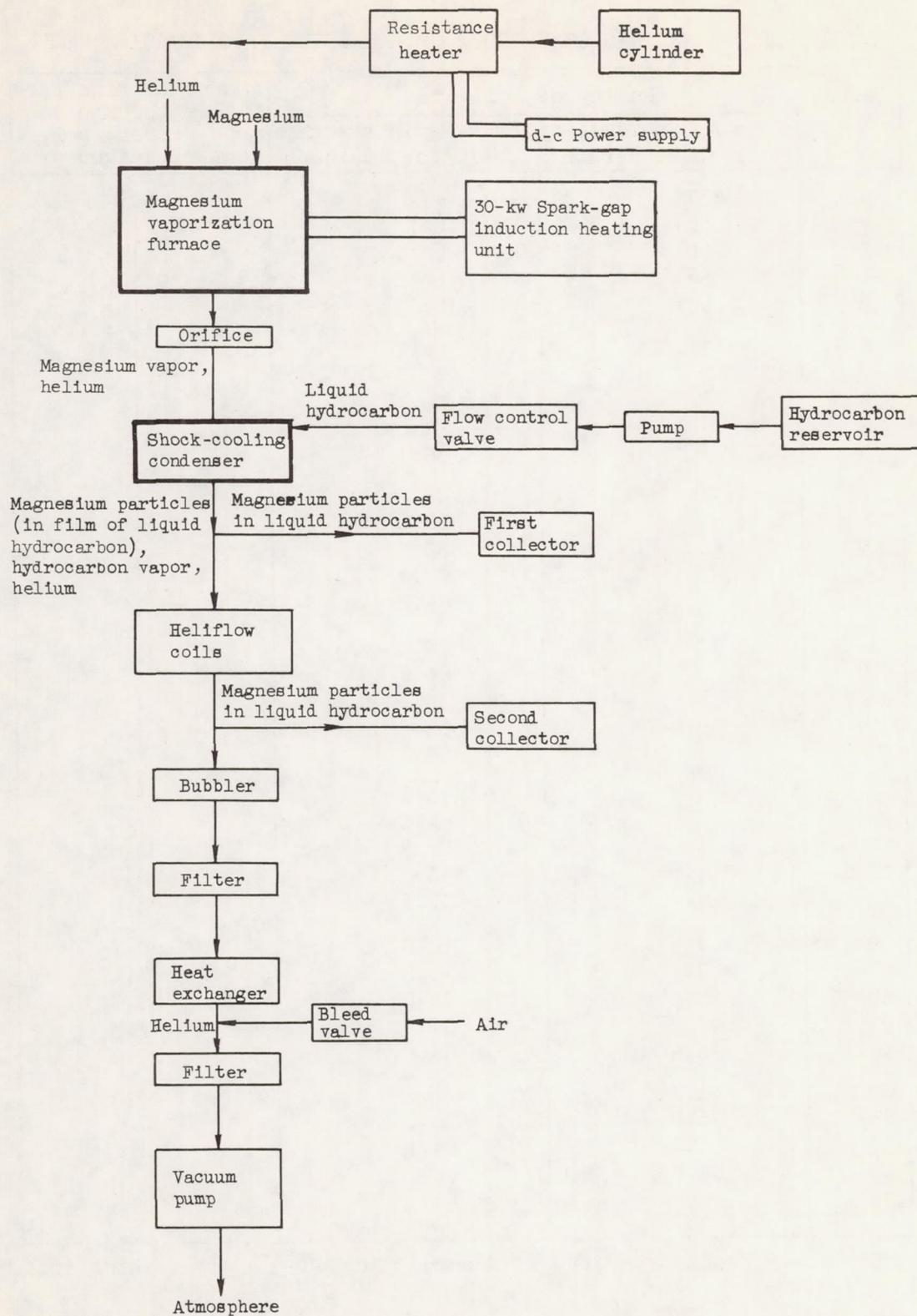


Figure 1. - Flow diagram of magnesium vaporization unit.

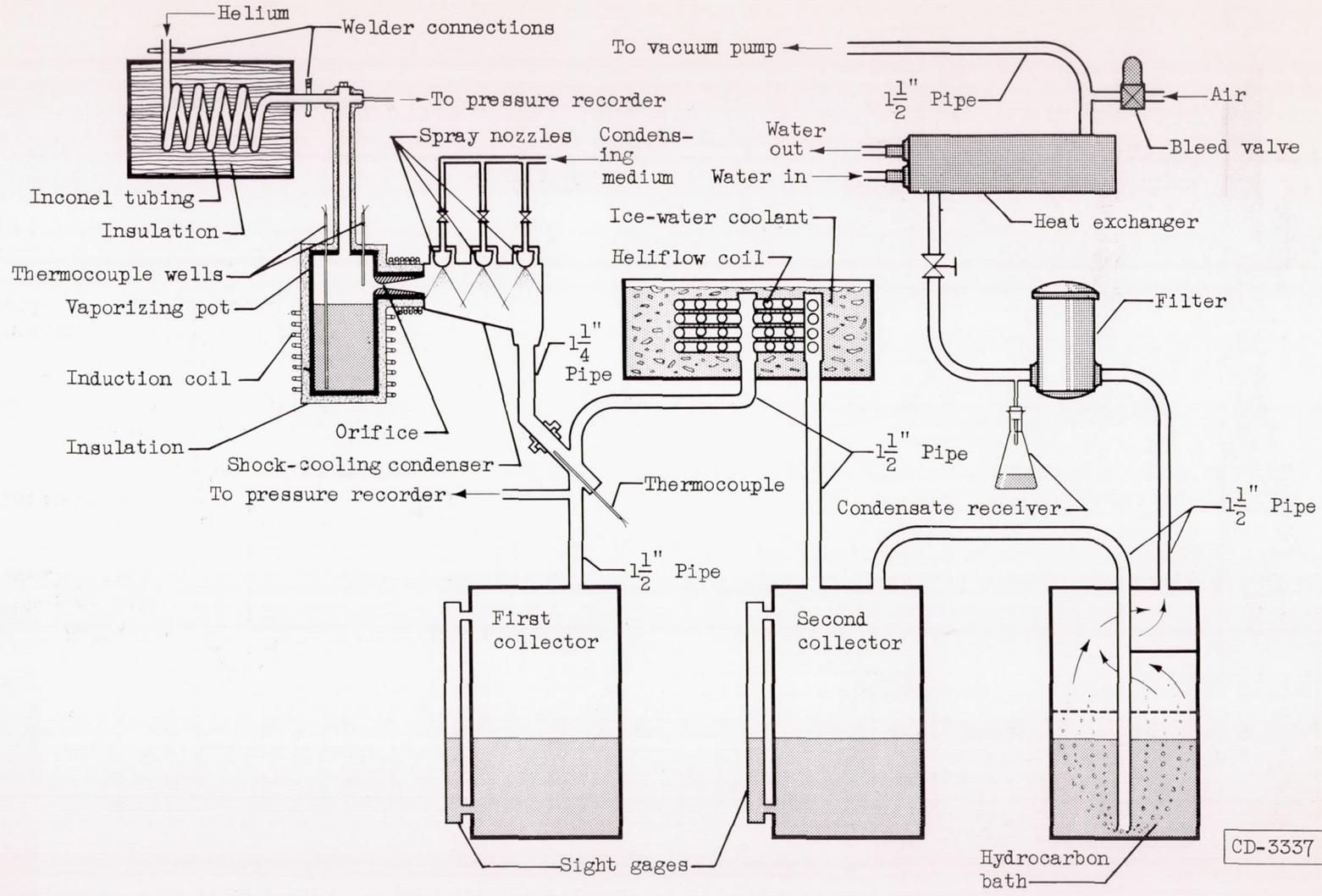


Figure 2. - Schematic diagram of magnesium vaporization unit.

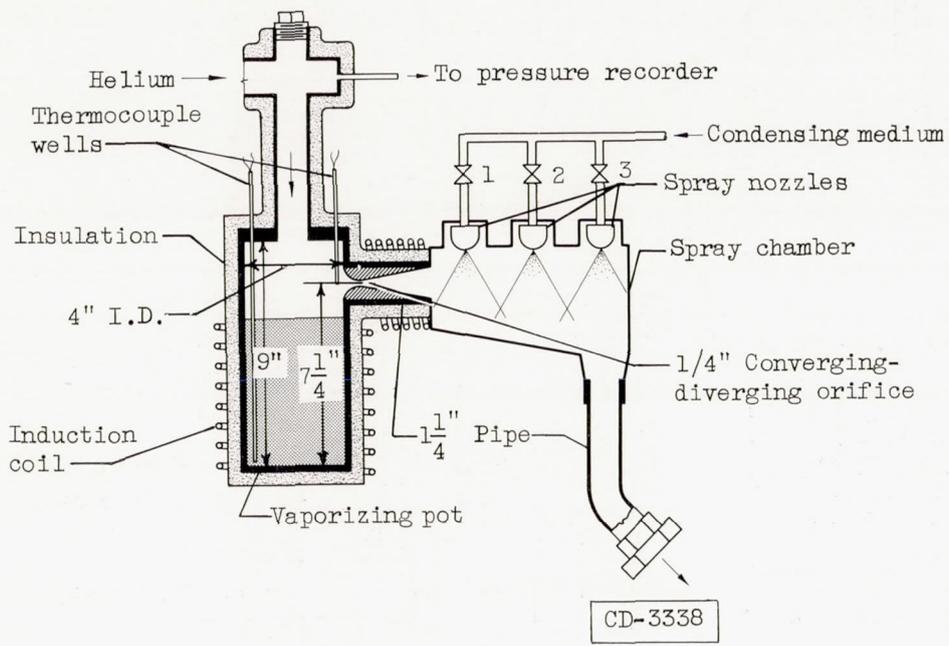


Figure 3. - Vaporizing pot with converging-diverging orifice and spray-chamber condenser.

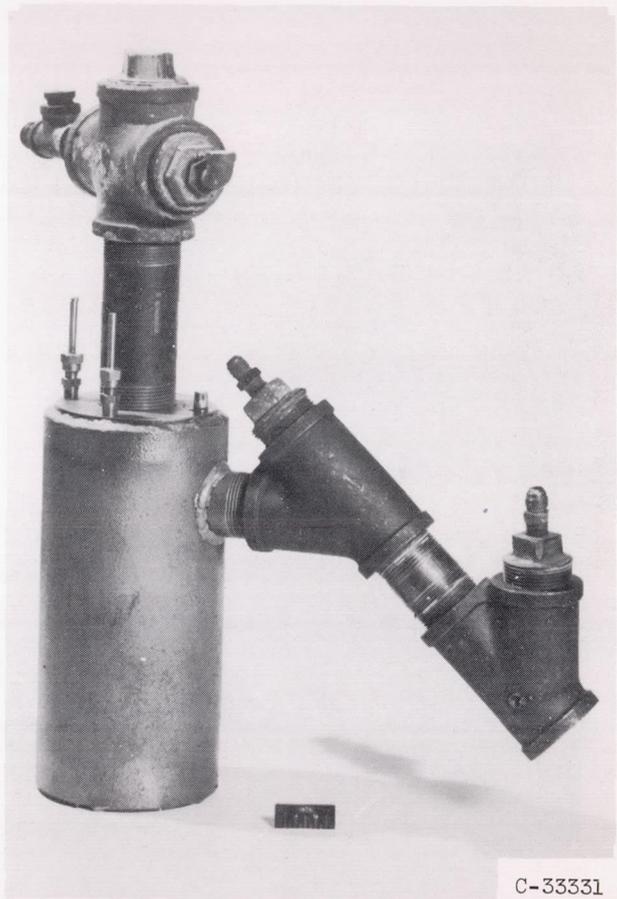
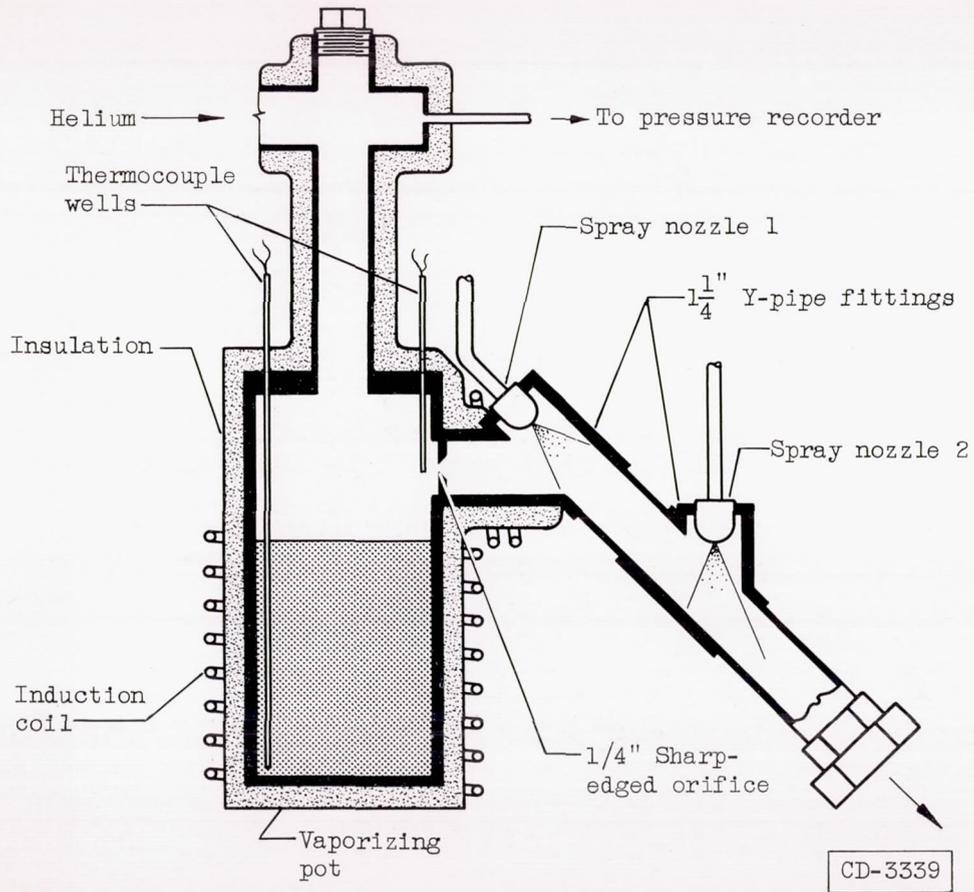


Figure 4. - Vaporizing pot with sharp-edged orifice and double-Y condenser.

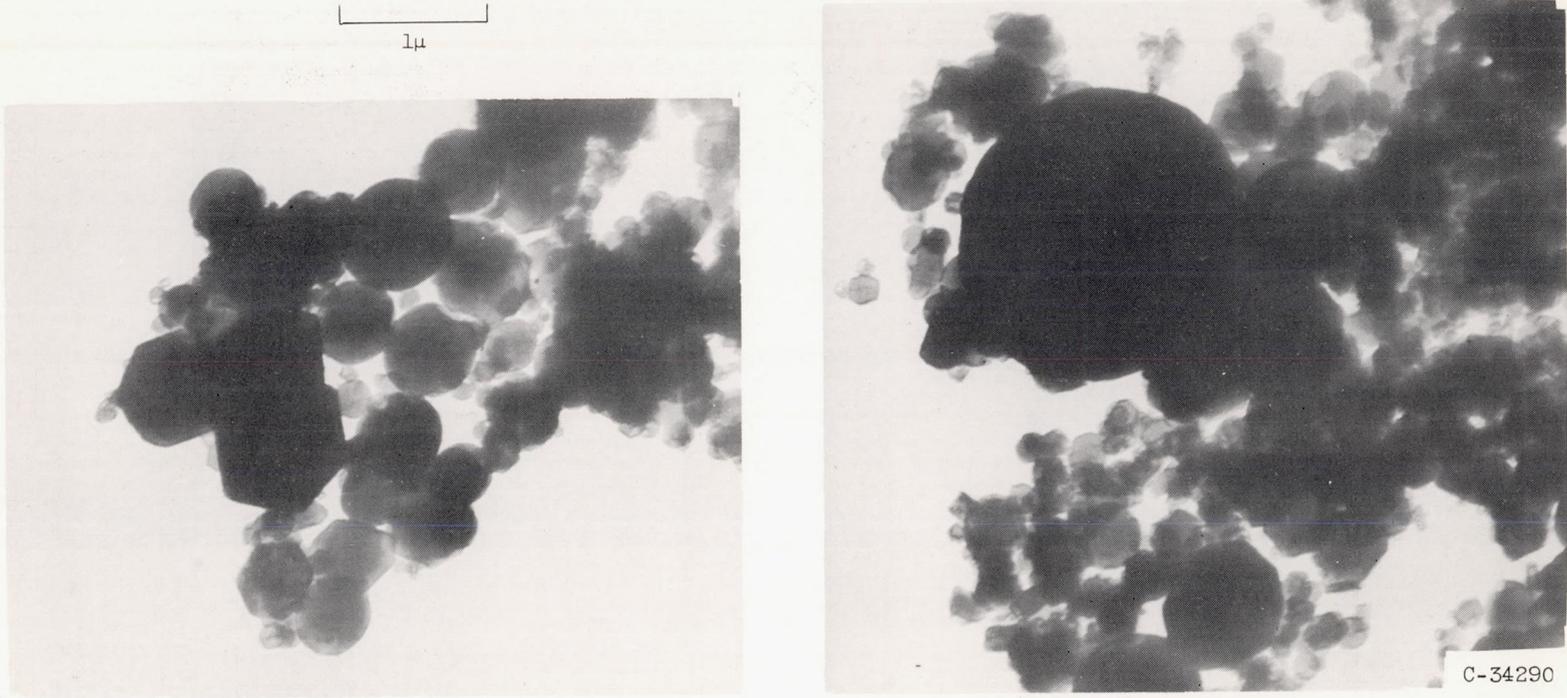


Figure 5. - Electron micrographs of two representative fields of magnesium particles (run 29) magnified 25,000 times.

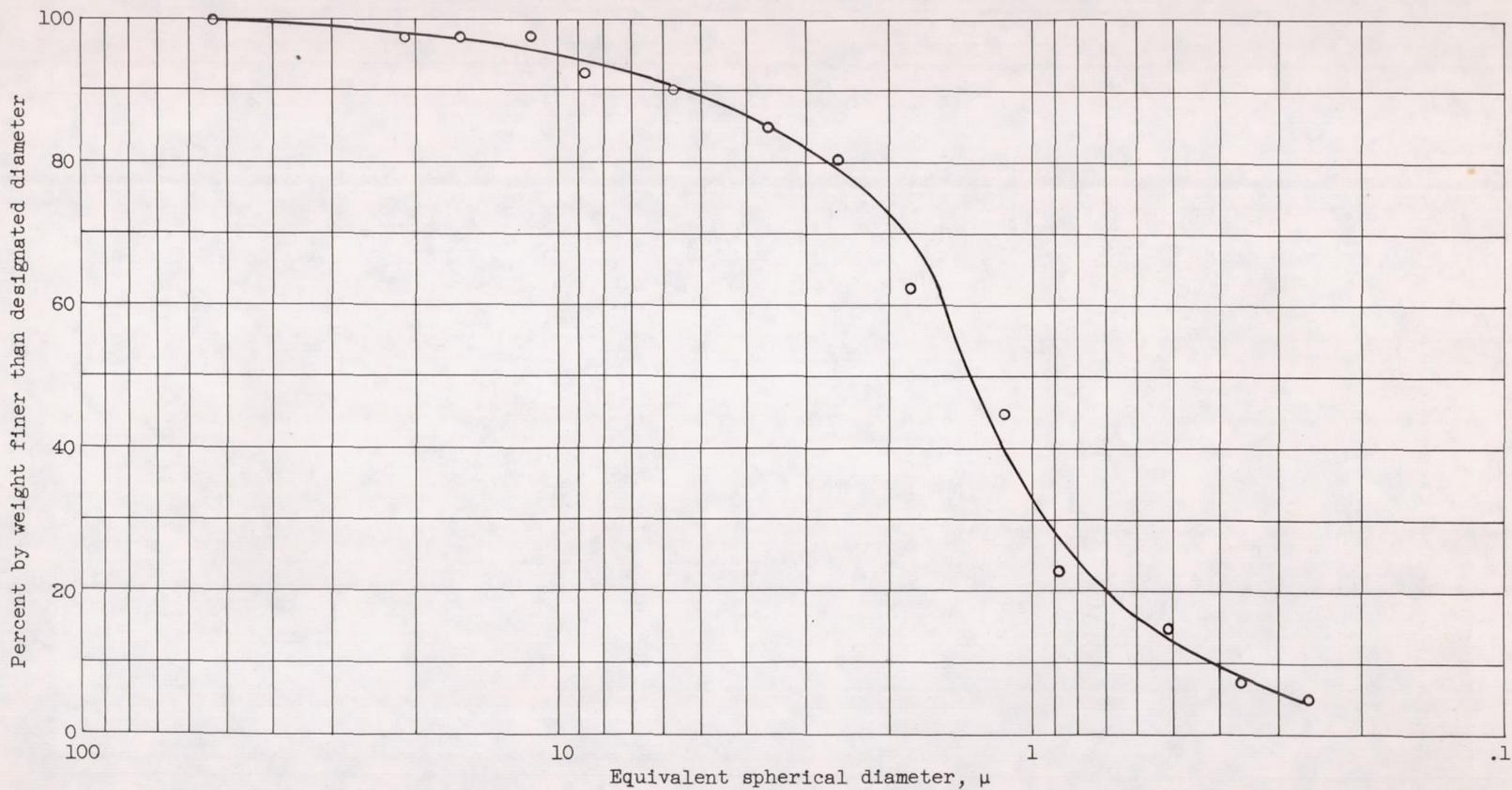


Figure 6. - Particle-size distribution of typical run (29) of magnesium vaporization unit by centrifugal sedimentation.