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THE EXPLOSIBILITY OF TITANIUM, ZIRCONIUM,
THORIUM, URANIUM AND THEIR HYDRIDES.
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THE EXPLOSIBILITY OF TITANIUM, ZIRCONIUM, THORIUM, URANIUM
AND THEIR HYDRIDES

SUMMARY

At the request of the United States Atomic Energy Commission, a study was made of the explosive characteristics of nine metal and metal hydride powders. The average particle sizes of the powders ranged from 3 to 18 microns.

The investigation disclosed that dust clouds of powders in air constitute severe potential explosion hazards. As some of the samples were definitely pyrophoric, they were stored and handled in a specially constructed inert gas cabinet until shortly before testing.

Layers of uranium hydride and thorium hydride ignited spontaneously at room temperature within a few minutes after exposure in air. Layers of the other powders ignited at temperatures of 100 to 510°C. When heated in carbon dioxide the dust layers ignited at 340 to 710°C., and in nitrogen all except two powders (one zirconium and zirconium hydride) ignited at 210 to 790°C.

Uranium, uranium hydride, and finely divided zirconium ignited at room temperature immediately upon dispersion into air. Clouds of the other powders ignited at 260 to 440°C. In carbon dioxide, dust clouds of uranium, uranium hydride, fine zirconium, and thorium ignited at 560 to 740°C., but in nitrogen none of the clouds ignited on contact with a hot surface at temperatures ranging up to 850°C., the highest tried.

Neither dust layers nor dust clouds ignited in an atmosphere of pure helium or argon up to 850°C., but layers of all the powders ignited at 850°C. (only temperature tried) in a 50-50 percent mixture of air and helium. Dust clouds of several powders could be ignited by high-voltage electric sparks in an atmosphere of carbon dioxide, but none ignited in nitrogen, helium or argon.

Layers of all samples could be ignited by weak electrical condenser discharge sparks having energies ranging from 4 microjoules to 1.5 millijoules. To effect ignitions of dust clouds in air sparks of 3 to 60 millijoules energy were required.

The lower explosive limits of dust clouds in air were determined to be 45 to 120 milligrams per liter (0.045 to 0.120 oz. per cubic foot). Explosions of dust clouds in air within the range of 0.200 to 4.000 oz. per cubic foot were studied in a laboratory test bomb. The pressures developed in these explosions ranged up to 127 psi, the average rates of pressure rise up to 3700 psi per second, and the maximum rates of pressure rise to over 10,000 psi per second.

INTRODUCTION

The investigation was started under a cooperative agreement with the Atomic Energy Commission following correspondence and conferences with Mr. Edward J. Kehoe, Chief, Fire and Accident Branch, Health and Safety Division, of the New York office of A.E.C. The object of the work was to extend present knowledge on the explosive characteristics of metal powders, particularly in the field of current interest to the Atomic Energy Commission. Basically the plan was to make a study similar to that described in Bureau of Mines Report of Investigations 3722 on "Inflammability and Explosibility of Metal Powders," making use of newly developed techniques and information acquired since that report was published.

Through arrangement by Mr. Kehoe the test samples were prepared and supplied by Sylvania Electric Products, Inc., Bayside, Long Island. The company also supplied information on chemical analyses and on particle size distribution of the powders. Detailed descriptions of the samples, their appearance and method of shipment are given below.

The helpful cooperation and interest shown throughout the work by Messrs. E. J. Kehoe, F. L. Brannigan, and Paul Klevin of the New York Office of the Atomic Energy Commission and by Dr. Bernard Kopelman, Sylvania Electric Products, Inc. are gratefully acknowledged.

DESCRIPTION OF SAMPLES

The test samples were numbered and are described here in the order of their receipt at the laboratory.

Uranium (Bureau of Mines No. 1625). - Two pounds of uranium powder was received in a jar under argon gas. When the sample arrived, the upper 3/4-inch portion was blackened whereas the lower part was silver-gray in color. During storage the dark color extended somewhat deeper into the powder. No essential differences were noted in the test results with the black and with the gray portions.

The percentage of oxygen in the sample was reported to be 0.07, and of nitrogen 0.008. The average particle diameter, as determined by

photometer measurements was given as 10.8 microns. The particle size distribution of the powder is given in table 1.

Uranium Hydride, UH_3 (Bureau No. 1626). - Two pounds of this sample was received under argon in a glass jar. The powder was dark gray in color.

The chemical analysis of the sample was not reported. The average particle diameter determined by the sub-sieve sizer was given as 3.6 microns and by the photometer as 3.3 microns.

Zirconium Hydride, ZrH_2 (Bureau No. 1627). - Approximately two pounds of this powder, dark gray in color, was received sealed under argon. The reported analysis gave 0.19% oxygen and 0.022% nitrogen. The average particle diameter by photometer measurements was reported as 4.7 microns.

Zirconium, Fine (Bureau No. 1632). - Two pounds of this sample (Lot 010-1-L) was received in a container under water. It was described as pyrophoric zirconium, but will be designated here for brevity as "fine" zirconium, to differentiate it from the next sample (No. 1633) which was considerably coarser.

The powder was reported to contain 3.0% oxygen, and the average particle diameter by photometer measurements was given as 3.3 microns.

To prepare a sample for explosibility tests, about 30 grams of the material was removed from the liquid and placed in a glass jar. The wet material was washed with ethyl alcohol three times and the excess liquid was drained off. The container was so equipped that it could be evacuated or filled with helium. The sealed container was evacuated while placed in a warm water bath. When the powder appeared to be dry the container was filled with helium and the jar and contents transferred into the inert gas cabinet where the powder was placed into a small glass jar. The dry sample was dark gray in color.

Zirconium (Bureau No. 1633). - One pound of this powder, silver-gray in color, was received under argon. The material was said to contain 0.29% oxygen and 0.025% nitrogen. The average particle diameter by photometer measurements was given as 17.9 microns. This zirconium was prepared from its hydride (Sample No. 1627). It was reported that thermal decomposition of the zirconium hydride (4.7 microns diameter) resulted in marked sintering, yielding zirconium particles of 17.9 microns average diameter.

Titanium (Bureau No. 1648). - About one pound of this powder, dark gray in color, was received under argon. The metal (designated as D-2) was reported to contain 0.08% hydrogen, 0.82% oxygen and 0.062% nitrogen by weight. The average particle diameter by the sub-sieve sizer determination was given as 10.5 microns. The particle size distribution by the

photometer method was reported to be as follows: 24.0% between 0-10 microns, 40.3% between 10-20 microns, 35.7% between 20-40 microns; average 17.8 microns.

Titanium Hydride, TiH_2 (Bureau No. 1649). - One pound of this powder (designated as H-3), dark gray in color, was received under argon. The analysis was given as 2.83% hydrogen, 0.24% oxygen and 0.071% nitrogen. Although this hydride contains only 70% of the theoretical hydrogen for TiH_2 , it was said to behave in many ways as a fully hydrided material.

The average particle diameter by sub-sieve sizer analysis was given as 4.9 microns. Particle size distribution by the photometer method was reported to be as follows: 88.1% between 0-10 microns, 10.0% between 10-20 microns, 1.9% between 20-40 microns; average 5.2 microns.

Thorium (Bureau No. 1652). - Four hundred grams of powder, dark gray in color, was received in an evacuated pyrex bulb. The metal was reported to contain 0.032% hydrogen, 1.20% oxygen and 0.19% nitrogen. The average particle size was given as 7.2 microns by the sub-sieve sizer, and 7.4 microns by photometer determination.

Thorium Hydride, ThH_2 (Bureau No. 1653). - Four hundred grams of this sample was received in an evacuated pyrex bulb. The powder was greenish-gray in color. Analysis was reported to show 0.94% hydrogen, 1.07% oxygen, and 0.16% nitrogen. Theoretical hydrogen percentage for ThH_2 is 0.86. The average particle diameter by the sub-sieve sizer measurement was given as 3.8 microns and by photometer measurement as 2.9 microns.

Particle Size Distribution

The following table contains data on the particle fineness of seven of the samples, as determined by photometer analysis. Information for titanium and titanium hydride was already given.

Table 1. - Particle Size Distribution of Powders

<u>Fineness, microns</u>	<u>Percent by weight</u>						
	<u>No. 1625</u>	<u>1626</u>	<u>1627</u>	<u>1632</u>	<u>1633</u>	<u>1652</u>	<u>1653</u>
0-1	4.0	10.6	10.6	5.9	2.1	2.8	13.5
1-2	—	27.7	20.1	19.2	—	6.5	13.5
2-3	2.0	17.5	14.2	27.3	1.5	13.9	28.2
3-4	3.1	11.9	23.5	18.7	1.2	11.6	19.3
4-5	5.0	8.5	6.3	14.3	1.5	10.9	14.3
5-6	4.8	10.7	7.7	8.5	2.8	8.3	9.6
6-8	14.1	10.3	2.4	3.3	5.0	14.0	8.7
8-10	16.3	2.2	1.8	0.9	7.0	7.4	4.4
10-12	15.6	0.6	3.8	1.7	7.6	5.6	2.0
12-14	13.0	—	2.6	—	7.8	6.2	—
14-16	9.8	—	2.2	—	8.5	4.2	—
16-20	6.0	—	3.7	—	18.3	4.5	—
20-30	4.9	—	1.3	—	26.8	4.1	—
30-40	1.3	—	—	—	10.0	—	—

TEST EQUIPMENT AND PROCEDUREInert Gas Cabinet

Some of the powders were pyrophoric and ignited spontaneously upon exposure in air. To store and handle them safely it was necessary to construct a special cabinet, in which the samples could be stored under inert gas. In this investigation pure helium gas was used; this was obtained from the U. S. Helium Production Company, Amarillo, Texas. Analysis of the gas by mass spectroscopy at Bruceton showed that the maximum percent impurities were 0.08 water, 0.003 oxygen and 0.05 nitrogen.

The design of the cabinet was based on information furnished by the Sylvania Company. It consisted essentially of a main chamber (approximately 24 inches wide, 24 inches high and 30 inches deep) and an airlock or transfer chamber (6 inches by 6 inches by 8 inches in size). The construction was of 1/4-inch steel, welded at all seams. Figure 1 is a general view of the cabinet. The main chamber had a glass viewing window, 3/4 inch thick and 12 inches square, at the front; a 20-inch square relief vent, sealed with a reinforced plastic-impregnated cloth diaphragm comprised the back side. The purpose of the vent was to relieve pressure in event of an accidental explosion within the cabinet. The airlock was welded to the left side of the chamber; the doors of the airlock closed on rubber gaskets, forming airtight seals. In the main chamber there was an analytical balance, a fluorescent light, and necessary tools and jars for working with the powders. All manipulations in the cabinet were performed by an operator wearing special rubber gloves that were sealed to portholes welded to the main section.

Provisions were incorporated in the design of the cabinet (sometimes referred to as a "dry box") and transfer chamber for evacuation and also for filling the entire volume with helium. It was determined by gas analyses in preliminary tests that the system had to be initially evacuated and flushed with helium at least three times to attain a completely satisfactory atmosphere for storage and handling of the powders over a long period of time. The helium gas pressure in the cabinet was maintained between 1-1/2 and 3-1/2 oz. per square inch at all times by means of an electrically controlled solenoid valve on the gas line. A mercury check valve was placed in the system to relieve excess gas pressure.

Following receipt of a sample the original container was placed in the inert gas cabinet and a small quantity was transferred within the inert gas atmosphere to a 2-ounce screw top jar. The original container was then resealed carefully and removed from the cabinet for storage until it was needed again.

Test Procedure

The powders were tested in the fineness and form as received, except that the fine zirconium powder was first dried in batches, as has been mentioned. The equipment and the test procedure were for the most part similar to those described in Bureau of Mines Report of Investigations 3722. In these experiments however, the samples were weighed in the inert gas cabinet and they were removed therefrom only within a few minutes prior to actual testing. A brief outline of the various tests follows:

The ignition temperature of the dust clouds was determined in a vertical, electrically heated, cylindrical tube furnace to the top of which there is connected a small brass chamber or "dust boat" into which a weighed amount of dust can be placed. The dust is projected by compressed air downward through the furnace and ignition is denoted by flame appearing at the open furnace mouth at the bottom. An automatic thermostatic control is a part of the electric heating circuit of the furnace. The lowest furnace temperature at which ignition is obtained is taken as the ignition temperature of the dust cloud. The furnace can be seen at the left side of figure 2; on the right side is an apparatus that is used to study ignitibility of dust clouds by high-voltage electrical induction sparks.

To determine the ignition temperature of dust layers the furnace is used in a modified form. The top is open and a small pile of dust is placed on an aluminum oxide disc at the center of the furnace. A slow stream of air flows upward through the furnace past the heated dust layer. The lowest temperature at which the dust ignites or glows strongly, or at which its temperature shows a sudden rapid rise is taken as the ignition temperature.

To determine the ignition temperatures of dusts in gases other than air the procedures are similar, but before the dust is set in the boat the entire system is carefully flushed with the gas in question and air is kept away from the dust throughout the test.

No determinations were made in this study of the "relative flammabilities" of the dust clouds. Previous experiments on similar metal powders have indicated that these values would probably be 90% or more for the subject samples; in other words, it would require the admixture of about 90% inert dust (fuller's earth) with the metal powders to prevent ignition and flame propagation when the mixture is dispersed into a dust cloud in the presence of an electric spark or through the heated furnace at 700°C.

To measure the minimum energy required for ignition of dust clouds and dust layers experiments were conducted with electrical condenser discharge sparks. In one series of experiments a condenser was charged to a definite potential, and formation of the dust cloud in a cylindrical lucite tube (see figure 3) was synchronized with discharge of the condenser through the primary winding of a step-up transformer. The potential induced in the secondary circuit of the transformer produced a spark between the electrodes in the dust cloud. To find the weakest spark that would produce an ignition condensers of different capacities were tried.

In the experiments on the ignition of dust layers the procedure was similar, except that the condenser was discharged without step-up in voltage directly through the spark gap between a point electrode and a grounded metal disc on which the dust was placed.

The minimum explosive concentration or lower explosive limit of the dusts was found by determining the least average dust concentration in the lucite-tube (2.75 inch I.D., 12 inches long) apparatus which could be ignited and which would propagate flame throughout the dust cloud, as manifested by development of sufficient pressure to break the weak filter paper diaphragm at the top of the tube. The igniting source used in these experiments was a high-voltage continuous electric induction spark, which has an average power of 24 watts.

The maximum pressure and the rates of pressure rise developed during a dust explosion give an indication of the structural damage that might result from it. They also furnish some information concerning the venting requirements in buildings or in equipment in which explosions might occur. The apparatus used for studying the pressures is shown in figure 4. It consists essentially of a chromium plated cylindrical steel test bomb (2.75 inches I.D. and 12 inches long; 1.23 liters volume) in which the dust cloud is formed and ignited, and a pressure manometer mounted above the bomb. The manometer is of the diaphragm type, the deflection of the diaphragm being magnified by an optical system; a record is obtained on a photographic film mounted on a rotating drum.

Figure 5 is an enlarged print of an actual pressure-time record. As can be seen, following ignition of the dust cloud (at point A) the pressure rises at first slowly, then for a time very rapidly (D to F), and then again less rapidly, reaching a maximum value at point C, after which the pressure starts to decrease. The figure illustrates the manner in which the pressure and the rates of pressure rise are computed from the film records. The distance between successive dots on the horizontal time axis represents a time interval of $1/120$ of a second.

A weighed amount of dust to be tested is placed into a specially designed brass cup at the bottom of the bomb. The dust is dispersed upward by the sudden release of a small volume of compressed air. In the recent experiments the compressed air was contained in a 50 cc. cylinder at 100 psi pressure; this arrangement gave better dust clouds, resulting in stronger explosions, than could be obtained with the arrangement used previously (as in Report of Investigations 3722) when the compressed air was placed in a 1.3 liter container at 8-12 psi pressure.

Mention has already been made of the fact that in the laboratory furnace some tests were conducted in gases other than air. These were commercially pure carbon dioxide, commercially pure nitrogen, argon and helium. The ignition temperatures of dust clouds and of dust layers were determined in carbon dioxide and in nitrogen, and in addition the ignitibility of dust layers was studied at 850°C . in a 50-50% mixture of air and helium. Besides these experiments there were prepared a series of mixtures of air and carbon dioxide, air and nitrogen, air and argon, and air and helium, and flammability tests were made in the induction spark apparatus to determine the limiting mixtures that would prevent ignitions and explosion of the dust clouds. A schematic diagram of the apparatus is shown in figure 6. Prior to each test the entire system is flushed thoroughly with the gas mixture, and the spherical glass bulb which contains gas for dispersing the dust through the spark tube is filled with the gas. A weighed quantity of the dust sample is placed in the "dust boat" above the spark tube. The water manometer controls the flow of gas that is slowly bled through the spark tube during the entire test.

The personnel engaged in handling of the powders and in the actual experimental work used protective gloves and performed all operations in such a manner as to prevent contamination by the dusts and fumes. All ignition and explosion tests were made under closed, well-ventilated hoods. Analyses of dust and fume samples by Mr. Klevin of the Atomic Energy Commission showed that under the test conditions, with the small quantities of dust used, the health conditions of the experimenters were entirely satisfactory.

RESULTS OF TESTS

Mr. Kehoe and his associates visited the laboratory on a number of occasions and they were kept informed of the progress of the work. On May 15 the writer presented a preliminary account of the results of the experiments at the Fourth Annual Safety and Fire Protection Conference of the Atomic Energy Commission and Contractors at Washington, D. C. A summary of the final data is presented on the following pages.

Ignition Temperatures

The ignition temperatures of the dust clouds and of the undispersed dust layers were determined in air, in an atmosphere of carbon dioxide and in nitrogen. In working with the dust clouds the dust was projected rapidly through the furnace, passing through the hot zone in less than one second. In the tests with undispersed layers, the dust was kept at the center of the hot furnace for several minutes, up to 15 minutes if no ignition occurred. The test data are given in table 2.

Table 2. - Ignition Temperatures of Powders

<u>Sample</u>	<u>Dust clouds, °C.</u>			<u>Dust layers, °C.(glow)</u>		
	<u>Air</u>	<u>CO₂</u>	<u>N₂</u>	<u>Air</u>	<u>CO₂</u>	<u>N₂</u>
Uranium (1625)	Room temp.	560	N.I.	100	350	410
Uranium hydride (1626)	Room temp.	720	N.I.	Room temp.	360	210
Zirconium hydride (1627)	430	N.I.*	N.I.	340	650	N.I.
Zirconium, fine (1632)	Room temp.	650	N.I.	190	620	790
Zirconium (1633)	350	N.I.	N.I.	300	710	N.I.
Titanium (1648)	330	N.I.	N.I.	510	550	760
Titanium hydride (1649)	440	N.I.	N.I.	500	710	750
Thorium (1652)	270	740	N.I.	280	450	500
Thorium hydride (1653)	260	N.I.	N.I.	Room temp.	340	330

* "N.I." denotes no ignition at 850°C., the highest temperature used in these tests.

In the dust cloud tests normally 1 gram of powder was used. When the samples of uranium, uranium hydride, and fine zirconium (No. 1632) were dispersed through the furnace at room temperature (approximately 20°C.) strong ignitions resulted.

When 1 to 3 grams of uranium hydride powder layers were exposed in the air at room temperature no ignition resulted; 1 gram of powder ignited at 110°C. When 5 grams of uranium hydride were placed on a watch glass at room temperature the surface darkened immediately and a few bright sparks appeared. Within a few minutes a slight popping noise was heard, a yellow flame was seen over the surface, and the entire mass assumed a dull red glow. The residue after the burning was black.

When 3 grams of thorium hydride was exposed in air at room temperature, it ignited within a few minutes. The ignition was characterized by an intense yellow glow. The residue was a powdery white dust.

Small layers of each powder were exposed at 850°C. in an atmosphere of 50% air and 50% helium by volume. All dusts ignited within a few minutes. The test was not made at other temperatures.

In accordance with Mr. Kehoe's request, unused portions of uranium, uranium hydride, thorium and thorium hydride, as well as the solid residues from the explosibility tests were carefully preserved and will be returned to the New York Office of the Atomic Energy Commission.

Minimum Energy Required for Ignition

Table 3 contains the data obtained in the tests with condenser discharge sparks. In the tests with dust clouds in air considerable preliminary work was required to find the optimum conditions for ignition. The minimum energy depends, among other things, on the concentration of the dust cloud and on the time of discharge of the condenser relative to the formation of the cloud. The timing was accomplished with the electronic equipment shown at the left of figure 3. In the background of the figure is shown the luminous tube transformer used for stepping up the voltage in the dust cloud experiments.

Figure 7 shows the effect of the dust concentration on the igniting energy of dust clouds of titanium powder in air.

Minimum Explosive Concentration

The minimum explosive concentrations or lower explosive limits of the dusts in air are given in the last column of table 3. The experimental values depend greatly on the fineness of the dust, on the

uniformity of the dust cloud, on the nature of the ignition source and on other test conditions. For this reason data determined by different investigators are rarely in complete agreement.

Table 3. - Minimum Electrical Igniting Energy and Lower Explosive Limit of Powders

<u>Sample</u>	<u>Minimum energy required for ignition</u>		<u>Lower explosive limit, oz. per cu. ft. **</u>
	<u>Dust cloud, millijoules*</u>	<u>Dust layer, microjoules</u>	
Uranium (1625)	45	4.0	0.060
Uranium hydride (1626)	5	32	.060
Zirconium hydride (1627)	100	64	.120
Zirconium, fine (1632)	15	6.4	.045
Zirconium (1633)	12	240	.045
Titanium (1648)	25	24	.045
Titanium hydride (1649)	60	1600	.080
Thorium (1652)	5	4.0	.075
Thorium hydride (1653)	3	6.4	.080

*1 joule = 1,000 millijoules = 10^6 microjoules = 0.00095 B.t.u. = 0.24 gram-calorie.

**1 oz. per cubic foot is approximately equivalent to 1 gram per liter.

Pressures and Rates of Pressure Rise

The pressure measurements in the 1.23-liter test bomb were made at dust concentrations of 0.200, 0.500, 1.000, 2.000, 3.000 and 4.000 oz. per cubic foot. The test data are plotted for each sample individually on figures 8 to 16. The pressures and the rates of pressure rise developed by the explosions of most samples reach a maximum value at some concentration within the range investigated. However, in general there is no sharp optimum limit at which the pressures and the rates attain definite peak values.

Although it is not definitely known which oxides (in the event that more than one oxide exists) were formed in the experimental explosions, and whether or not any nitrides were also formed, for the sake of interest the stoichiometric concentrations for the oxides are indicated near the bottom of figures 8, 11, 12, 13 and 15.

In the experiments the highest pressures were produced by explosions of titanium hydride and the next highest by zirconium hydride. Explosions of uranium hydride developed average rates of pressure rise in excess of 3,500 psi. per second and explosions of thorium hydride produced average rates of over 3000 psi. per second. Explosions of a number of powders developed maximum rates of pressure rise in excess of 10,000 psi. per second.

IGNITION BY ELECTRIC SPARKS IN INERT GAS ATMOSPHERES

In the manufacture of highly explosive powders it has occasionally been found necessary and practical to perform some operations, as grinding, sieving and conveying in atmospheres of reduced oxygen content. The data on ignition temperatures of the present samples indicate that dust clouds of some of the powders can be ignited at elevated temperatures in carbon dioxide and that layers of nearly all powders can be ignited at elevated temperatures in carbon dioxide and in nitrogen. These gases would therefore be of little if any use as a protection against ignitions of the powders by hot surfaces or by flames. However, in many industrial processes electric sparks of static and other origin constitute the principal igniting sources.

To study the prevention of ignitions by electric sparks, a series of experiments were performed with dust clouds of the powders in various mixtures of air with carbon dioxide, nitrogen, helium and argon. The clouds were formed in the presence of a high-voltage electrical induction spark in the spark tube sketched in figure 6. The results of the experiments are plotted in figure 17. As illustrated, ignitions of dust clouds of the metals and of uranium hydride by electric sparks could be prevented most effectively in atmospheres containing mixtures of air and helium. Mixtures of air and nitrogen and air and argon were about equal in effectiveness, and carbon dioxide was not effective at all in preventing ignitions.

As a protection against ignitions of dust clouds of thorium-, zirconium-, and titanium-hydrides, on the other hand, carbon dioxide-air mixtures were the most effective and argon-air atmospheres the least effective. Helium- and nitrogen-air mixtures were approximately equal in effectiveness. These findings correspond closely to the experimental data for methane gas, as reported by H. F. Coward and G. W. Jones (see Bureau of Mines Bulletin 279, Limits of Inflammability of Gases and Vapors, 1939, figure 22, page 54.) The greater effectiveness of carbon dioxide is attributed to its higher specific heat per unit volume. Helium has a high thermal conductivity, but its specific heat is less than one-half that of carbon-dioxide. The specific heat of argon is slightly higher than of helium, but its thermal conductivity is very much smaller than that of helium.

The results obtained for dust clouds of the five metal powders and of uranium hydride may appear to be puzzling at first. However, the ineffectiveness of carbon dioxide is no surprise, because past work with other metals, including magnesium and magnesium-aluminum alloys, and the present experiments in the furnace have shown that dust clouds of these highly reactive powders can ignite and explode in carbon dioxide. The greater effectiveness of helium in preventing ignitions is evidently due

to its high thermal conductivity. Helium-air mixtures are definitely more effective in preventing explosions of the metal powders than are argon-air mixtures. Even with helium-air mixtures however, the oxygen content of the atmosphere had to be 7% or lower to prevent ignitions, and it is quite probable that in most applications it would be more practical to maintain an atmosphere of pure helium rather than attempt to prepare helium-air mixtures.

CONCLUDING REMARKS

The investigation has shown that the fire and explosion hazards incident to the manufacture and handling of large quantities of the subject powders as tested would be considerable. The hazards are comparable to or even exceed those encountered in the manufacture of finely divided magnesium and of stamped or flaked aluminum powders. It is suggested that any laboratories or plants contemplating production of these powders on any important scale should consult and follow, insofar as possible, the recommendations outlined in the Codes for the Prevention of Dust Explosions in the Manufacture of Aluminum Bronze Powders and of Magnesium Powders, published by the National Fire Protection Association, Boston, Massachusetts. It is recommended further that whenever possible at least some if not all of the manufacturing operations of the more hazardous powders should be performed in an atmosphere of helium or argon.

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Fig. 1 - Inert gas cabinet.

Fig. 2 - Laboratory furnace and spark ignition apparatus.

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Fig. 3 - Apparatus for determining minimum explosive concentrations and minimum igniting energies of dust.

Fig. 4 - Apparatus for determining pressures produced by dust explosions.

Fig. 5 - Pressure-time record of zirconium powder explosion in laboratory test bomb.

Fig. 6 - Spark apparatus for testing dust flammability in various gases.

Figure 8 - Maximum pressure and rates of pressure rise developed by explosions of uranium.

Figure 9 - Maximum pressure and rates of pressure rise developed by explosions of uranium hydride.

Figure 10 - Maximum pressure and rates of pressure rise developed by explosions of zirconium hydride

Figure 11 - Maximum pressure and rates of pressure rise developed by explosions of fine zirconium

Figure 12-Maximum pressure and rates of pressure rise developed by explosions of zirconium.

Figure 13—Maximum pressure and rates of pressure rise developed by explosions of titanium

Figure 15-Maximum pressure and rates of pressure rise developed by explosions of thorium.

Figure 16 - Maximum pressure and rates of pressure rise developed by explosions of thorium hydride.

Fig. 17 Limiting oxygen contents in air-inert gas mixtures for preventing ignition of dust clouds by electric sparks.

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