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NYO-4869

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HEALTH AND SAFETY

UNITED STATES ATOMIC ENERGY COMMISSION

HEALTH AND SAFETY IN POWDER METAL
HANDLING

By
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April 1957

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New York, New York

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April 1957

ABSTRACT

The use of metal powders of interest to the Atomic Energy Program is discussed. Those properties of powders which present unusual problems of health and safety are presented together with the possible effects which these powders may have on workers and their environment. Protective measures and equipment for controlling fire, explosion, and health hazards are presented.

April 1957

NYO-4869

HEALTH AND SAFETY IN POWDER METAL HANDLING

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The handling of metal powder presents certain problems from the standpoint of health, safety, and fire protection which tend to warrant the consideration of powders as a class, rather than permit distinction by element. There are certain properties which all powdered metals have which are only somewhat modified by the relative position of the metal in the periodic table. These properties have a profound effect on the ability of the metal to produce illness, injury, or property damage. It will be the intent of this discussion to define these properties and to indicate how and under what circumstances they increase the risk. We will also attempt to indicate those materials whose chemical properties emphasize this risk, and point the way to reasonable procedures which may be applied in controlling the various hazards.

POWDER CHARACTERISTICS

The primary characteristics of a metallic powder which differentiate it from other forms of the element are: (1) the small size of the individual pieces, (2) the enormous surface area which it presents, and (3) the fact that it is in pure elemental form. We will discuss each of these properties and see how it tends to influence the potential hazards associated with the material.

The fact that individual particles of a powder are small in size makes it possible for the material to be suspended in the air. Usually, only those materials which have a very low specific gravity, as for example a feather, can be carried on a lightly turbulent air stream. However, as the dimension of the material decreases to below mesh size, terminal velocity, or the maximum rate at which the particle will settle in air becomes slower and slower. For example, a 100 micron particle will settle at a rate of about 60 feet per minute, a 325 mesh (44 μ) particle at about 10 feet per minute, and a 10 micron particle at about 1/2 foot per minute. In view of the fact that all room air is normally in a state of constant motion, and has a resultant turbulent velocity which is of the order of 25 feet per minute, non-directional, it can be seen that particles which are significantly below about 65 microns, and certainly those below mesh size, will tend to be dispersed readily into the air, will tend to float for

long periods, and will resist removal from an air stream. In fact, particles of this nature are scarcely different from air molecules as far as inertial or gravitational effects are concerned, and will follow whatever forces are responsible for air movement, and in effect, behave substantially as a gas.

The ease of removal of a particle from a gas stream, by relatively simple devices is thus a function of the size of the particle. Particles which are below 5 or 10 microns, for example, become almost impossible to remove from an air stream by normal mechanical or centrifugal forces. It is therefore necessary to use other types of stress to induce the particle to become separated from its ambient environment.

On the other hand, small particles which are airborne become easily influenced by controlled air streams, and are therefore readily handled by ventilation. These factors, of course, strongly influence the potential hazard of the material.

The human lung is a rather complex and tortuous series of passages of ever decreasing diameter, with the smallest being of the order of microns. Thus, it is obvious that only the finest of particles can penetrate to the interior, and generally more sensitive, tissues of the lung. The larger particles are removed either by simple mechanical stoppage or blockage or by an inertial effect which causes the particle to deposit before it can reach the lower lung passages.

In addition to the effects of inertia which are so strongly influenced by the physical dimensions of the particle, there is another area in which size has an important bearing on potential hazard. A material of small size inherently has a low heat capacity. Thus, small amounts of heat have a profound effect on the temperature of a particle, and temperature rises tend to be reflected throughout the body of the particle, vastly increasing the possibility of fire. In a large mass of metal the heat applied tends to be rapidly dissipated and lost by being averaged throughout the mass of the material, while in a similar mass of powder, only individual particles will tend to reach ignition temperature. This is accentuated by the insulating quality of the air which is trapped between the particles and which cuts down heat transfer from the mass. Even if only a few have their temperatures so raised, however, the exothermic reaction which generally accompanies combustion will tend to break through the insulating barrier around the individual particles and propagate this combustion throughout the mass.

The fine subdivision of a metal into powder form introduces a new dimension which is called surface area. This can be best appreciated by a specific example. If a cube of metal 1 cm on the side is comminuted into particles of one micron on a side, the resultant surface area would

be 10,000 times as great as the original. Thus, there would be 10,000 fold the surface presented for chemical reaction; either increasing the availability of the material to react with the human system and thus influence its toxicity, or increasing the surface available for oxidation, thereby raising the fire potential.

Most metallic materials, being pure elements, inherently have a high order of chemical reactivity with many other materials. This is generally obscured by the fact that metals are usually available in massive structure and therefore have a relatively small surface area to attack. When metals are finely divided, however, the fact that large surface areas are available for chemical activity significantly increases the possibility of reaction. Thus, rapid oxidation or combination with other elements becomes a major attribute of powders. Such reactions as hydriding, nitriding, carbiding, and halogenation are the rule with many powdered metals, even though they may be the exception when the same metal is in massive form. Most of the finely divided materials with which industry normally deals are salts or compounds in which the metallic element has already reacted and which have therefore become relatively stable. It is the metal in unreacted form which must frequently be isolated from normal working atmospheres to prevent reactions which can be violent, thus introducing novel safety problems.

As a result of the characteristics which have been discussed above, precautions must be exercised in the handling of powdered metals which are somewhat unique in metallurgy. The purpose of these procedures is usually to prevent the material from behaving in a manner adverse to the process or to personnel. The most important of these predictable behaviors can be briefly discussed as follows.

It is usually essential that surface oxidation (or any other surface chemical reaction) be inhibited to insure that the material will handle in a manner satisfactory to the process. This generally has very little health or safety implication except that in some cases even a relatively slow surface oxidation can create a fume which will more readily become airborne than would the original powder. (Fumes are not infrequently less than 0.1μ in diameter.) In addition, of course, slow oxidation can result in the generation of sufficient heat to induce combustion in other materials, such as that of the container, or sometimes a suspending liquid. Conversely, combustion in other materials can induce sufficient heat within a mass of powder to ignite the powder, thereby releasing potentially dangerous aerosols into the breathing atmosphere and initiating a toxicity hazard. This is far more true with powdered materials than with massive metals which require very intense concentrations of heat before oxidation can occur.

A second category of possible danger which might result from the handling of metallic powders is that which involves rapid oxidation. Although it

is difficult to draw a fine line between the speed of reaction which was considered in the previous paragraph and that which would be termed rapid, the difference is probably sufficiently clear. Rapid reaction is one in which the materials tend to flare or explode. Many materials which are unreactive in small pieces are highly flammable when in powder form. Materials which as chips or small pieces are flammable or pyrophoric, in the finely divided state are apt to be explosive. Although it will not necessarily follow that an increased violence of burning would be dangerous, it is something which must be borne in mind whenever powdered metals are handled.

A more important area of potential danger involves the rapid chemical combustion (generally oxidation) of powdered metals which have been transformed by one mechanism or another into air floated dust. In this case, the possibility of explosion with most metals is very real and must be very carefully prevented. Any material which can burn and which is dispersed into the atmosphere as a finely divided dust is a potential explosion hazard. Flour, other powdered foodstuffs, coal and wood dust explosions are characteristic of the violence which can result from combustion which occurs in powdered metals which are suspended in the air. The results of such an event can well be disastrous, both from the standpoint of property destruction and also from the wide-spread dissemination of a toxic compound.

Another area against which protection must be provided during the handling of powdered metals is the possibility of inhalation. There are many materials which have substantially no toxicity except when the material is carried into the lung in a finely divided form. Physical contact with such materials, or their ingestion, even in very large amounts, will have no significant physiologic sequelae, whereas the inhalation of even infinitesimal quantities can cause very serious poisoning. This is true not only of the more exotic materials such as beryllium, but also of many common materials, including cadmium, chromium, and so forth.

GENERAL PROTECTION TECHNIQUES

There are certain basic techniques which can be applied to powdered metal handling procedures which will in most cases prevent any of the disastrous occurrences hinted at above. Although many metals can be handled with safety under most circumstances, most or all of the techniques which will be described may be necessary in order that complete safety will be assured.

The characteristics of the metal powder will determine the extent to which any control might be required. In order to be able to prejudge the dangers, the following characteristics should be especially considered:

1. The minimum particle size of the powder - Obviously from the discussion above, the smaller the particle division, the more controls must be exercised to prevent any unwanted reaction.
2. Reaction rate, especially oxidation - The greater the possible reaction rate of the material with its environment, the greater must be the care which is exerted to prevent such reaction.
3. Toxicity - Materials of high toxicity will obviously require more rigid controls than those whose reaction with the body is negligible.
4. Value of the metal powder - The value of the material as a pure metal powder and the cost of converting it from a compound to the metal must be considered in providing adequate protection. Materials which require costly reprocessing and those whose metallurgy or future use requires that they be in a very pure state should, of course, be kept as clean as possible during the handling.
5. Specific chemical reactivity of the material - This is apt to show itself in very strange ways with powder, and result in unusual phenomena. Some of these are described below.

Materials of low flammability or toxicity which will not react seriously with their environment, may be handled in open containers without any unusual precautions. Where these materials are inexpensive, small amounts of spillage are presumably unimportant and can be swept up and disposed of. Where the materials are costly, however, it may be advisable to provide filtered local exhaust ventilation and cribbing to prevent uncontrolled loss. In the event that such exhaust ventilating equipment is provided, it is essential that the potential hazard of this material in an exhaust system be understood. Dust collection equipment and media should be non-flammable, and every effort should be made to prevent any source of ignition from occurring within the exhaust stream. This may be very difficult because the possibility of static electricity buildup with subsequent sparking resulting from powder suspension is very real. Dust explosions in cyclone collectors, and bag house fires and explosions can be extremely serious even with relatively non-reactive powders.

Where the material being handled is more valuable, reactive, or toxic than most common metals, greater precautions are necessary. These include handling within a completely closed system, working the powder entirely under an inert atmosphere, and sometimes where possible, surface passivation of the metal.

SPECIFIC CHARACTERISTICS

Common Materials - Most materials which are commonly used in industry are also used rather extensively in powder metallurgic processes. These

include copper, brass and bronze, iron, stainless steel, nickel, zinc, and cobalt. These materials are, in general, of a low order of toxicity and are relatively non-reactive with other elements. They will all burn, however, and in general will usually cause some physical disability when the fumes of the combustion are continuously inhaled in concentrations exceeding about 15 mg/M³. (1) It should be unnecessary, however, to provide specific control of the handling of small quantities of material to prevent the dissemination of dust into the atmosphere; exhaust systems, hoods, enclosures, and so forth are usually not required. The hazard from handling materials of this type is almost entirely confined to bulk transferrals. When the powder contains a significant fraction of less than 325 mesh material, dumping of material from container to container, or large scale storage and conveying is apt to create large volumes of finely divided airborne dust which will not only support, but propagate combustion and thus generate fume, and be also potentially explosive. Before using any powdered metal without providing equipment to prevent inhalation, it is wise to be assured that the material possesses no unusual toxicity that is not obvious. For example, there is some indication that inhalation of finely divided nickel over long periods of time can lead to chronic illness and even death.

A second group of common materials which may or may not be involved in powder metal processes are those which bear an inherent toxicity which should be carefully avoided. Permissible concentrations of these materials in the atmosphere run of the order of 1% of those specified above (0.5 to 0.1 mg/M³). (1) Such materials as arsenic, chromium, cadmium, lead, mercury, and tellurium belong in this group. Wherever these materials are handled, provision should be made to maintain airborne concentrations to within specified levels. Usual precautions include hoods and enclosures connected to exhaust ventilating equipment, and finally some type of air cleaning equipment. The latter is usually dictated by economics. The design of equipment of this type is usually dictated more by the specific process than by the material being handled. Such designs are usually best handled by someone experienced in industrial exhaust ventilation engineering, but useful guides may be found in the Manual of Industrial Ventilation. (2)

A third group of potentially dangerous common materials is that which includes aluminum and magnesium. These materials are highly reactive with a large group of other elements, especially oxygen. They should be handled with the utmost respect. Very serious fires and explosions can come about from promiscuous handling of these metals as powder. The common Friedel-Krafts reaction can occur with explosive violence when powdered aluminum contacts organic chlorides under suitable circumstances.

MATERIALS OF INTEREST TO AEC PROGRAMS

Many of the requirements of the atomic energy development and production program involve the use of materials whose metallurgy has only very recently

been understood. These materials will be discussed either individually or in groups of similar substances.

Thorium and Uranium

The two elements which form the major portion of the nuclear fuel supply are thorium and uranium. Uranium, either as the normal material or in some degree of enrichment, is the more important fuel, while thorium is receiving attention as a blanket material from which to breed U 233.

In any event, the properties of these two materials are not sufficiently dissimilar to warrant their separate treatment. As far as potential hazard is concerned, both uranium and thorium have substantially the same specific activity; the permissible body burden according to the International Committee on Radiation Protection, (3) differs only slightly. The value given for natural thorium deposited in the lungs is $2 \times 10^{-3} \mu\text{c}$ while the permissible amount of uranium is $10 \times 10^{-3} \mu\text{c}$. The same source, however, defines the permissible airborne concentration for each as being the same ($3 \times 10^{-11} \mu\text{c/cc}$) for continuous exposure. One would presume this value would be multiplied by three for exposures not exceeding the normal occupational workweek. It should be pointed out that in defining these levels, the ICRP specifies that the curie of natural uranium is considered to correspond to 3.7×10^{10} d/sec from U 238, 3.7×10^{10} d/sec from U 234, and 9×10^8 from U 235. The curie of natural thorium is considered to correspond to 3.7×10^{10} d/sec from Th 232, and 3.7×10^{10} d/sec from Th 230. This would mean that the conversion from curies to d/m would use a factor of 4.5×10^{12} d/m/curie.*

It should be further pointed out that although these values which were accepted by the ICRP in 1954 and presumably will be the accepted figures for use in the United States, they have not yet been transposed by the NCRP into useable values by publication in a revision of Handbook #52, (4) which is now overdue (1957). The permissible level for continuous exposure to uranium as expressed in Handbook #52 is $1.7 \times 10^{-11} \mu\text{c/ml}$ of air, while thorium is not listed. Occupational exposure of 40 hours/week is three times this level ($80 \mu\text{g/M}^3$).

Both uranium and thorium are pyrophoric materials, although uranium is significantly less stable than thorium. A dust cloud of uranium will ignite at room temperature, while the ignition temperature of thorium is 270°C . It is interesting to note in this respect, however, that the minimum energy required for the ignition of thorium is considerably less than that required to ignite uranium, and comparable to that required to set off uranium hydride in a dust cloud. A layer of uranium dust, however, requires the same amount of energy as a layer of thorium dust. (5)

*This multiplied by the value given above yields a MAC about $300 \mu\text{g/M}^3$ for uranium and $400 \mu\text{g/M}^3$ for thorium.

TABLE I

Flammability of Less Than 325 Mesh Powder Layers

<u>Element</u>	<u>Air</u>	<u>Co₂</u>	<u>N₂</u>
U	100	350	410
Th	280	450	500
Zr	190	620	790
Ti	510	550	560

The lower explosive limit for each material is not significantly different, nor is the maximum pressure developed during an explosion. It is obvious from the above that handling of powders either of uranium or thorium requires some isolation to be perfectly safe, although this is much more true for uranium than it is for thorium. It appears that although thorium will ignite very readily, there must be some elevation in temperature before this will happen. (See Table III.)

The usual procedure for isolating such materials from possible combustion is to operate in an inert atmosphere. It should be pointed out, however, that what might be considered to be an inert atmosphere for some materials is not necessarily inert for these particular materials. At elevated temperatures both uranium and thorium will ignite in the presence of pure dry nitrogen or CO₂ (5) while their hydrides will ignite in air at room temperature. Here we see some reversal of the usually expected behavior in that the dust layers are more readily ignitable than the dust clouds. This has been discussed in some length in the literature. It appears likely that a small agglomeration of metal powder is the physical form most susceptible to ignition. The fact that the material is finely divided provides sufficient surface for ignition, and there is strong evidence that a definite minimum quantity of metal in one pile must be exceeded before ignition can take place. This has been likened to spontaneous ignition of oily rags where it is necessary that a minimum mass of material be present before ignition can be expected. Interestingly enough, a 5% oxygen mixture in helium, a 4% oxygen mixture in argon, and 3% oxygen in nitrogen were effective in suppressing dust cloud ignition of these materials, with carbon dioxide being completely ineffective. This was not found to be true for hydrides of these materials where carbon dioxide-air mixtures were the most effective in suppressing ignition.

As far as practical experience with these materials is concerned, there have been more incidents of fire and explosion involving uranium than have been noted with thorium. However, this might be due to the fact that uranium has been used much more extensively, and it might be pointed out that the single serious incident which has come to our knowledge in which thorium powder reacted with explosive violence was much more serious than any of the uranium incidents.

It appears reasonably sure the incomplete densification of uranium powders has resulted in a pyrophoric solid. The ignition of uranium powders and materials resulting from uranium powders appears, however, to be limited to passive burning. Although this can occur without disaster, it must not be concluded that it is without danger. In the first place, conversion of the powder to oxide, once begun, is very difficult to stop. This, of course, results in a degrading of quality and a subsequent monetary loss. In addition, the oxide fume which is formed is of extremely small particle size and is readily made airborne. (6) This results in dissemination of a very fine fume into the air which can readily enter the lung. Fortunately, the conversion is quiescent and therefore the proportion of fume that is thrown into the air is relatively small. Air samples which were taken, for example, in a 30 cubic meter sealed room after the combustion of approximately 100 g of uranium as chips showed average dust concentrations which were below the permissible breathing concentration.

To put the toxicity of uranium into a recognizable frame of reference, it should be pointed out that the maximum permissible concentration for uranium as defined by the NCRP in Handbook #52, and also by CFR 10 Part 20, which is the official AEC standard for licensed operations is 5×10^{-11} $\mu\text{c}/\text{ml}$ for an occupational exposure of 40 hours per week. This value converted to gravimetric quantity is approximately $80 \mu\text{g}/\text{M}^3$. This quantity of material in the air represents a relatively severe restriction inasmuch as the material is very dense, and at the same time is apt to be easily airborne. It does not take much handling of uranium powder to throw considerably more than $100 \mu\text{g}/\text{M}^3$ into the air which can be breathed by workmen.

As a comparison, the maximum permissible concentrations of several of the more toxic metals have been defined by the American Conference of Governmental Hygienists. The most recent revision of these values lists the following:

TABLE II

Typical Maximum Permissible Levels for 8 Hour/Day
Occupational Exposures

<u>Element</u>	<u>$\mu\text{g}/\text{M}^3$</u>
Copper	--
Brass	--
Bronze	--
Iron	15,000 (a)
Stainless	--

Note: (a) as oxide

<u>Element</u>	<u>ug/M³</u>
Ni	7 (b)
Zn	15,000 (a)
Co	--
As	500
Cr	100 (c)
Cd	100
Pb	150
Hg	100
Te	100
Th	-- (110) (e)
U	250 (80) (e)
Zr	5,000 (a)
Ti	15,000 (a)
Be	2 (d)
Pu	0.0001 (e)

- Notes:
- (a) as oxide
 - (b) as carbonyl
 - (c) as CrO₃
 - (d) Rec's of AEC Beryllium Advisory Committee
 - (e) CFR 10 Part 20
 - (f) all other values from ACGIH (1)

Industrial experience which normally involves the handling of uranium powder in completely closed systems under inert atmospheres has been very good. Reasonably large quantities of this material have been handled without any serious incident, and in fact, without any significant loss. It may very well be that the reason for this is that uranium powder is normally prepared by decomposition of uranium hydride. All steps of the preparation leading to the powder are potentially very dangerous. The handling of hydrogen, high temperature conversion both to the hydride and from the hydride to the powder, evolving hydrogen, are all steps requiring great precaution. Therefore, the use of glove box equipment, completely sealed equipment, and relatively elaborate controls for the prevention of the release or ignition are essential to the operating procedure. This undoubtedly has had some bearing on the fact that incidents have been few. One such incident involved an experimental quantity which was being handled in a glove box -- the material was mixed with CCl₄ and almost immediately exploded. The exact cause was never established, although there is some indication that water in the CCl₄ and some unconverted hydride were involved.

The handling of thorium is somewhat more obscure than handling uranium. There have been a couple of very serious incidents which have involved the preparation and processing of thorium powder. The precise nature of the material which entered the reaction is not known, although gross

analyses shown no unusual constituents nor anything which could be directly blamed for the unusual behavior.

The most important of the incidents was one which involved a relatively small quantity of powdered metal which had been prepared during experimental work being pursued to evolve an economical method for powder production. The total quantity involved was something less than 50 pounds of thorium powder. The resulting explosion was almost disastrous. Very serious damage was caused in a very well constructed, fire-proof laboratory building. An idea of the force of the explosion can be gained from the fact that an 18" I beam which supported the floor directly below the explosion area, was permanently deflected about 4 inches, and partitions hundreds of feet from the area were buckled and moved out of place.

The incident consisted of three separate but interrelated explosions. The initial explosion involved about a half pound of material which was deliberately burned to oxide. This material exploded with a detonation sufficiently severe to throw one man about 20 feet across the room. It appears that the subsequent detonations of the larger quantity of material (approximately 40 pounds) were percussive reactions resulting from the initial blast. (7)

Although ignition of thorium is somewhat more difficult than the ignition of uranium, it can be seen from the above that the resulting combustion is apt to be very rapid and creates very severe detonation shock.

The toxicity of thorium according to various authorities, (8) is pegged at the same level as uranium. Although there is some disagreement in this direction resulting from the high degree of insolubility of thorium materials in the body and from a knowledge of the eventual site of their deposition, (9) the similarities between uranium and thorium are sufficiently great to permit an assumption of equivalence as far as health hazards are concerned. Handling procedures are substantially the same as are followed with uranium.

Fire fighting of both of these materials involves procedures which are similar to those used for other metal fires. The slow introduction of burning material into large quantities of water will adequately suppress the combustion. For fires which cannot be handled in this manner, a liberal sprinkling of graphite or one of the commercial metal fire suppressants, such as G-2 powder has proved very effective. Copious quantities of fog can also be used to suppress a relatively small quantity of burning metal. (10)

Zirconium and Titanium

Zr and Ti are materials which are of great interest to the Atomic Energy program because of certain special properties which they possess. These

include relatively low cross section to neutrons, reasonably good strength to weight ratio, high degree of corrosion resistance, and high degree of heat resistance.

Until very recently these materials were considered to be relatively non-hazardous to personnel engaged in their production and fabrication. As more experience became available with them, however, especially in their handling as powders, it became obvious that each of them, particularly Zr, possesses a very unexpected instability under certain, not well defined circumstances. The major Atomic Energy Commission experience with this type of hazard has involved the use of Zr, although there is some indication that Ti will also behave in a similar fashion. There is no intention here to incriminate Ti unnecessarily, but in view of the similarity of the materials, and the Zr experience, it would certainly be advisable to be especially cautious in handling Ti powders.

To point up the similarity, it is well to note at this point one particular phenomenon which has been experienced similarly with Zr, Ti, and uranium. According to Smith, (11) a series of incidents have been experienced involving Zr, U, and Ti, and their alloys which have resulted in an unusual type of surface explosion. This has generally followed acid treatment of the solid material. Witnesses have described explosions of this type as involving a brilliant flash of white light, accompanied by a sound similar to that of a 22 caliber rifle shot. Strangely enough, the surface of these materials appears to be undamaged after the explosion.

Prior to 1954, Zr scrap material consisting of all forms of the metal had been stored in various manners at various sites without significant incident. Since that time, however, there have been three serious explosions at AEC sites. Investigation of these incidents led to the discovery that several other incidents had occurred in other industrial locations. Some indication of the nature and extent of these explosions can be obtained from the following brief summary of several incidents. (12)

1. One pound of wet Zr powder was being poured into a metal drum. An explosion occurred, critically injuring the employee.
2. A mechanical stirrer was being introduced into a 50 pound keg of Zr powder packed in water. The material exploded, critically injuring one employee and seriously burning several others.
3. One-half gram of powdered material was being digested in 150 ml of water with a few drops of nitric acid. Stirring with a glass rod resulted in an explosion which seriously injured the operator.
4. A 5-gallon can of Zr powder fell to the ground during shipment. Powder was spilled which spontaneously ignited.

5. Fine Zr powder which collected in duct work ignited spontaneously causing a \$15,000 fire.
6. A one-gallon can which contained Zr powder with 10% water, exploded spontaneously during the removal of the metal lid. Two men died, and two others were seriously injured. The can was lined with polyethylene.
7. A two-pound sample of powdered Zr wet with carbon tetrachloride was gently heated over a Bunson burner. The material detonated with a blinding flash, very badly burning the operator.
8. Very serious explosions have occurred in vacuum drying equipment drying Zr powders.

The above incidents which have been abstracted from AEC Bulletin TID-5635 (1956) will provide some insight into the unusual qualities of this material. Additional information can be seen in Table III. (13) To date there has been no satisfactory explanation of the precise conditions under which these materials will ignite or explode, but several important points should be stressed. These are:

1. Nitric acid treatment of the powder appears to increase the hazard.
2. The presence of small quantities of water appears to increase the hazard.
3. Storage of powders either as scrap or as raw material is potentially dangerous and should be maintained at a minimum. If the powder is produced wet, it should be kept wet with copious quantities of water. If the powder is produced dry, it should be maintained under an inert gas, preferably argon.
4. Great care should be taken to protect operators involved in the handling of these materials so that should some unusual incident occur, injury to personnel will be minimized.

Beryllium

Quite contrary to the properties of the materials discussed previously, beryllium presents extreme danger from the standpoint of toxicology, while there has been no experience which would indicate a danger from fire or explosion.

The nature of beryllium is such that it is extremely difficult to get strong machinable castings. As a result, it has been found to be more economical to use powder metal techniques where massive shapes are

desired. Because of this, a very large portion of all of the beryllium which is processed is eventually handled as a powder. Beryllium powder is a very light fluffy material which can be very readily dispersed into the air. Procedures leading to the production of the powder and the powder handling must be very rigidly disciplined in order to prevent excessive airborne concentrations.

As far as is now known, the only hazard which must be prevented is that of inhalation of the airborne dust. The maximum permissible concentration of this material in the air, according to AEC recommendations, (14) is $2 \mu\text{g}/\text{M}^3$ as an average daily exposure. The AEC policy further recommends a maximum short term exposure of $25 \mu\text{g}$. To put this in proper perspective it means that if one is handling 25 pounds of powder in a 1,000 cubic meter room (approximately $50' \times 50' \times 12'$), 2×10^{-7} of the initial material if completely dispersed through the room, would exceed the maximum permissible quantity. It is obvious, therefore, that extreme measures must be taken to prevent any dispersion into the atmosphere.

One of the unusual things about beryllium toxicity is that a relatively small portion of the exposed population appear to be susceptible to the disease. To date, however, there is no known method for ascertaining the susceptible individual. It is therefore necessary to protect all.

In order to insure protection of individuals who are engaged in the handling of beryllium powders, there are several basic concepts which must be applied. A few of these can be briefly stated:

1. It is essential that every step in the process be equipped with local ventilation.
2. The size of ventilating hood openings must be as small as possible consistent with accessibility, to prevent the escape of dust and for efficient use of ventilating air.
3. Hoods must be designed so that no operator need place his head inside during normal operation.
4. Air velocities at hood openings should be 150 feet per minute or greater.
5. The use of dust respirators should be discarded except for very infrequent emergency use.
6. Rigid clean-up procedures, preferably by means of industrial vacuum cleaning equipment, should be maintained. The vacuum cleaner exhaust should be to the outside of the building.

7. The air should be monitored for dust levels on a frequent continuing basis.
8. Wherever significant quantities of material are handled, it is advisable to provide some type of air cleaning equipment to prevent discharge of the beryllium out of the building. The recommended outdoor level for the general population is that it not exceed 0.01 $\mu\text{g}/\text{M}^3$. (15)

Plutonium

The handling of plutonium as a powder probably presents more problems than any other known material. The reasons for this may be summarized as follows:

1. Plutonium is pyrophoric.
2. The toxicity of plutonium is among the highest of any known material, being comparable on a weight basis to that of radium.
3. Because of the fact that plutonium is a fissionable material, nuclear safety must be observed throughout the handling procedures.
4. Except during experimental work, plutonium is generally handled in fairly large quantities.
5. It might also be worth noting that depending on the history of the material, plutonium gives off more or less gamma radiation. One authority suggests a maximum limit of 1 1/2 hours/week as the permissible hand contact dose. This, however, will vary with the history, and the radiation level should be measured prior to use.

Inasmuch as each of the above hazards tends to dictate limitations in exposure of this material to the atmosphere, the most satisfactory procedure which has been worked out to date for the handling of plutonium is in suitably constructed glove boxes. These glove boxes are pressurized with some type of inert gas, such as argon or helium, and the operator works through double gloves; one glove being directly on the hands, and the other one providing access to the interior of the box. Again, it is advisable to set down certain basic principles which should be considered prior to the design of a system for handling this material. These are:

1. All operations should be carried out in tight enclosures which provide for manipulation by means of arm length gloves, aided by mechanical devices where necessary.

2. Pressure within the box should be below ambient so that in the event of a leak, leakage will be inward with a velocity of at least 150 feet/minute. The system, however, should be constructed as nearly leakproof as possible.
3. The system should be provided with a dry inert atmosphere. This is especially true where powders are handled.
4. Exposure to air must be limited as far as possible because the material may catch fire or explode.
5. Allowance must be made for radiation which penetrates the gloves and thereby limits the time of exposure to personnel.
6. Criteria of nuclear safety should be carefully studied prior to operation.
7. All gases which leave the system should be filtered on exhaust. The filter should be checked and changed periodically to insure no build-up to critical amount.
8. Rules for safe practice should be adopted in advance, and rigidly adhered to, and the necessary materials, equipment, and personnel for compliance should be provided.

Provision of a facility for meeting the above criteria introduces many unusual techniques. Most of these have been worked out and are available in the literature. (15) Some of the items which should be considered are:

1. Purification and drying of the inert gas.
2. Emergency ventilation in the event of breakdown of the system.
3. Means for insuring a pressure differential on the system.
4. Suitable filters for insuring removal of powder material from the circulating gas system.
5. Adequate system for transfer of materials into and out of the system.
6. Choice of suitable glove material.
7. Development of a suitable glove changing technique.

TABLE III

Ignition and Explosion Properties of Dust Clouds

<u>Element</u>	<u>% thru 270 mesh</u>	<u>Ign. Temp. °C</u>	<u>Conc. Oz./cu. ft.</u>	<u>Max. Pressure Rise</u>	
				<u>psi/sec</u>	<u>secs. to max.</u>
Al	80	645	0.1	2080	0.040
			0.5	5700	0.029
			1.0	2350	0.049
Mg	86	570	0.1	1200	0.060
			0.5	2570	0.048
			1.0	2840	0.040
Fe	99	320	0.2	600	0.061
			0.5	1200	0.044
			1.0	1200	0.047
Si	86	775	0.2	360	0.187
			0.5	1180	0.141
			1.0	940	0.163
Ti	92	480	0.1	430	0.104
			0.5	1120	0.059
			1.0	1640	0.071
Zr	100	70	0.2	140	0.140
				1590	0.091
				2570	0.070
Sb	88	415	0.5	50	0.200
Mn	63	450	0.5	300	0.139
Zn	100	600	0.5	300	0.093
U	100	20	0.060	5100	
Th	100	270	0.075	6100	
Zr	100	20	0.045	5000	0.07
Ti	100	330	0.045	6100	

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