

Dust Combustion Safety Issues For Fusion Applications

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ABSTRACT

This report summarizes the results of a safety research task to identify the safety issues and phenomenology of metallic dust fires and explosions that are postulated for fusion experiments. There are a variety of metal dusts that are created by plasma erosion and disruptions within the plasma chamber, as well as normal industrial dusts generated in the more conventional equipment in the balance of plant. For fusion, in-vessel dusts are generally mixtures of several elements; that is, the constituent elements in alloys and the variety of elements used for in-vessel materials. For example, in-vessel dust could be composed of beryllium from a first wall coating, tungsten from a divertor plate, copper from a plasma heating antenna or diagnostic, and perhaps some iron and chromium from the steel vessel wall or titanium and vanadium from the vessel wall. Each of these elements has its own unique combustion characteristics, and mixtures of elements must be evaluated for the mixture's combustion properties. Issues of particle size, dust temperature, and presence of other combustible materials (i.e., deuterium and tritium) also affect combustion in air. Combustion in other gases has also been investigated to determine if there are safety concerns with "inert" atmospheres, such as nitrogen. Several coolants have also been reviewed to determine if coolant breach into the plasma chamber would enhance the combustion threat; for example, in-vessel steam from a water coolant breach will react with metal dust. The results of this review are presented here.

SUMMARY

This report presents some data on metal dust explosions, and limits of metal dust combustibility. Fusion experiments generate armor tile and metal-component dusts during plasma-material interactions, and these dusts accumulate in the vacuum vessel. The safety issues with these dusts are examined here. The dusts tend to be chemically toxic, neutron activated, and may contain tritium if the fusion experiment uses tritium fuel. Past chemical reaction work has examined the oxidation-driven mobilization of solid wall materials, because these materials comprise the majority of the in-vessel inventory. The dust may actually react before the bulk wall materials due to its higher surface area and its dispersion in the vacuum vessel volume. Loss of vacuum accident (LOVA) modeling has shown that dust can be lofted within the vacuum vessel by inrushing air, and there are a number of possible ignition mechanisms energetic enough to initiate a dust deflagration event. The ignition mechanisms identified here are electrostatic discharge, radiant heating of particles, laser ignition, and plasma heating antenna arcing. Since the fusion conditions are elevated temperature and dust-air mixtures at one atmosphere pressure, industrial studies also apply to fusion LOVA dust analyses.

Most of the metal dusts require reasonably high temperatures for autoignition (i.e., 500 – 700°C), or spark ignition energies in the 1 millijoule range. Metal dusts will deflagrate, that is, combust with a subsonic combustion wave front. Some industrial tests have demonstrated that aluminum and other metal dusts can detonate (combust with a supersonic combustion wave front), but only under very high energy conditions of using high explosives as the ignitor. Fusion should not have such high energy ignitors, so the safety work should focus on deflagrations. Some dusts are difficult to ignite, such as carbon, copper, and nickel. These might serve as diluent material that suppresses a dust explosion, if the temperatures and ignition energies can be kept low. Metal dusts can also react with steam, so an in-vessel water coolant leak also poses a concern for dust combustion. Reactions with atmospheres other than air were also reviewed to determine if there are any other safety issues or potential means to mitigate dust combustion events.

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ACRONYMS

DDT	deflagration to detonation transition
DOE	Department of Energy
HEPA	high efficiency particulate air filter
FIRE	Fusion Ignition Research Experiment
ITER	International Thermonuclear Experimental Reactor
J	joules
K_{st}	dust deflagration index
LMIE	Lowest minimum ignition energy
LOCA	loss of coolant accident
LOVA	loss of vacuum accident
MEC	Minimum Explosive Concentration
MIE	Minimum ignition energy
Nd:YAG	neodymium: yttrium-aluminum-garnet laser
NFPA	National Fire Protection Association
PVC	polyvinyl chloride

DUST COMBUSTION SAFETY ISSUES FOR FUSION APPLICATIONS

1.0 INTRODUCTION

The combustion of dust particles in air has been a serious safety concern for the agricultural, mining, manufacturing, and energy production industries (Echhoff, 1997). Several large-scale accident events have occurred that resulted in loss of life and substantial property damage; grain silos and food processing plants have experienced explosions, textile dust and pharmaceutical dusts have exploded, and coal dust in mines and in power plants has also exploded. Such events have prompted industries to study dust combustion characteristics to seek the means to preclude or mitigate the effects of dust combustion. Industrial safety lore maintains that if there is enough dust present on a surface to leave a visible mark when writing in the dust with one's finger, then there is enough layered dust present to pose a dust-layer combustion hazard.

There are two possible outcomes of a dust combustion event. If the dust is suspended in air as a dust cloud, it could explode under the proper conditions. Such an explosion, even in a confined chamber, is generally a deflagration. A deflagration is characterized by a subsonic combustion wave front and relatively modest overpressure and energy release. In contrast, a detonation is a supersonic combustion wave front with very high overpressure and energy release. It is unlikely, but possible, that a deflagration can "run up", or transition, to detonation due to factors that increase the combustion wave front speed. This phenomenon is called deflagration-to-detonation transition (DDT). The DDT for metal dusts will be reviewed to determine if there is any likelihood of occurrence in fusion situations. The other possible outcome is if the dust resides in layers on a surface, the layer could combust. This combustion reaction is often a slow-acting, smoldering combustion rather than a visible diffusion flame combustion. The heat and combustion product release in smoldering combustion can slowly overpressurize a chamber, but no impulsive overpressure would be generated since there is no moving combustion wave front. Smoldering combustion allows more time to mitigate the consequences of combustion.

There are several safety consequences of explosions. The greatest damage caused by explosions in most industrial situations results from the shock wave forces applied onto nearby equipment and structures (Beveridge, 1998). As the dust cloud combusts, the deflagration combustion wave front compresses the air ahead of the wave, creating a sharp increase in pressure, often more than two atmospheres. This pressure is dissipated through impulsive force loading on objects the wave front encounters. The maximum rate of pressure rise in a dust explosion is an important parameter to assess the potential damage from the explosion's shock wave impulse. After the combustion wave front, the trailing combustion products are hot and create a pressure lower than the wave front compression but still higher than ambient. For deflagrations, this pressure can be perhaps

an atmosphere or two above ambient. Thus, after impulsive force loading, there is a new, higher overall pressure in the chamber or room. The next concern is the heat and flame from the combustion, which can create secondary fires and other heat damage in the debris created by the shock wave. A third concern is that small objects, such as debris created by the overpressure of the combustion wave and impulsive force loading, will be propelled by the high-pressure combustion wave; further damage is caused when these 'debris missiles' impact structures, equipment, or people. An example of missile creation during an industrial explosion is the commonplace event of the pressure wave breaking windows. The broken window panes become propelled glass shards that are very injurious to people (Norville, 1999).

Dust layer combustion consequences may not be as severe as those for dust cloud explosions. Dust layer fires are slower acting and less energetic than explosions. The fire releases heat and combustion products from the high temperature flame, but at oxygen diffusion speeds rather than speeds near the sound speed. The heat release can lead to damage of surrounding structures and equipment. The combustion products are generally oxides of the metals combusting; the oxides can be toxic. The combustion products also contaminate the area by plating out oxide particles. If the metal dust is radioactive, oxidation and the mobilization of frangible oxide layers is a challenge to the facility confinement barriers.

The two atmospheres of concern that might enter a vacuum vessel are air and steam. Table 1 outlines the potential accident sequences. Atmospheric air would enter from a loss of vacuum accident (LOVA), such as a vessel port penetration that breaches and allows room temperature air to rush in to the vessel. In that case, the vessel is already compromised, so releases from the vessel are possible if an overpressure event drives radioactive/toxic products from the vessel. Steam would come from a water coolant line (e.g., plasma heating antenna or wall armor tile cooling) breach inside the vessel, which is referred to as the in-vessel loss of coolant accident (LOCA). For the in-vessel LOCA event, the vacuum vessel itself is still intact, so for accident propagation past the vacuum vessel boundary the dust combustion event would need to breach the vessel.

Table 1. Possible accident scenarios to consider

Oxidant Ingress Scenarios	Combustion safety issues
<p>Air ingress while the machine is in operation, a loss of vacuum accident (LOVA). Ingress air is assumed to terminate the plasma by a disruption.</p>	<p>Plasma disruption creates new dust, adding to dust inventory.</p> <p>Will turbulent inrush of air loft enough dust into the vessel volume for combustion in air? Will dusts that are difficult to ignite dilute combustible dust concentrations below the minimum explosive concentration?</p> <p>If there is insufficient dust in the vessel atmosphere to combust, will the remaining dust layer combust in air?</p> <p>What damage would dust combustion cause to the vessel?</p>
<p>Steam ingress from an in-vessel water coolant line breach (in-vessel LOCA). Ingress water / steam terminates the plasma in an intense disruption (Merrill, 1991).</p>	<p>Plasma disruption creates new dust.</p> <p>Does the turbulent inrush of steam into vacuum lofts enough dust for combustion in steam?</p> <p>If not, will the dust layer combust in steam?</p> <p>Will dust combustion serve to ignite solid metals in the vessel?</p>
<p>Air-steam-mist ingress from an ex-vessel water line breach. Plasma runs on, burns out in-vessel cooling lines to allow formation of an ex-vessel-to-in-vessel LOCA. Ingress air / steam terminates the plasma in a disruption.</p>	<p>Plasma disruption creates new dust.</p> <p>Will the turbulent inrush of very humid air into the vacuum vessel through several small tubes loft enough dust for combustion?</p> <p>If not, will dust layer combust in humid air?</p>

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2. METAL COMBUSTION PHENOMENON

Metal dust is thought to be more chemically reactive than solid metal samples, yet the INEEL Fusion Safety Program has invested considerable effort to study oxidation-driven mobilization of bulk materials used in fusion vessels. Bulk solid materials have been studied because these materials comprise the majority of tokamak in-vessel material. Steam and air reaction tests with coupon samples of a variety of solid materials have been conducted over the last 15 years. Overall results show that oxidation reactions will occur, and that the reaction rate increases as the sample temperature increases.

2.1 Bulk Metal Combustion

Experiment results have shown that solid metal sample volatility in air begins to occur quite slowly at temperatures over 500°C for many metals, shifting from a slow protective oxidation to more aggressive oxidation (Druyts, 2002). For example, copper alloys tend to increase their volatilized mass at temperatures above 600°C (McCarthy, 1996). As the temperature increases, shorter exposure times at the temperature are needed to volatilize the material. At 600°C, at least 1 to 5 hours of testing were required for copper to begin to oxidize. For an austenitic stainless steel and a ferritic steel, tests showed that temperatures above 800°C would be required to mobilize any radiologically significant fractions of activated material (Piet, 1986). Vanadium alloy tests showed that at 600°C, a 100-hour test in air did not form a molten phase and the mass release was barely detectable, but a 700°C test for 100 hours resulted in complete oxidation (Smolik, 1996). Vanadium at 800°C in air required 5 to 20 hours to obtain appreciable mass releases, tests at 1000°C required only 1 to 5 hours, and 1200°C tests required only 0.25 to 1 hour for oxidation. Tantalum alloy tests (Smolik, 2001) in air showed that after 81 hours at 500°C, a thin dark oxide formed. After 55 hours at 600°C, a light yellow oxide had formed and some oxide particles could be seen in the test chamber. At 700°C for 55 hours, a specimen had its oxide turn completely into powder. After 48 hours at 800°C a specimen had developed a very thick oxide layer; the oxide caused a considerable volume expansion of the specimen, and large spall pieces (i.e., flakes) had dislodged from the specimen. After only 8 hours at 900°C, oxide scales spalled from the specimen surfaces, which proved to be an important mobilization mechanism from the test specimen. Test times were further reduced with elevated temperature: 6 hours at 1,000°C, 4 hours at 1,100°C, and only 2 hours at 1,200°C. Tungsten samples slowly began oxidizing at ~600°C and oxidation was more prominent at 800°C (McCarthy, 1996a).

These experimental results suggest that the higher the temperature, the faster the reaction in air or steam with bulk materials on the chamber walls. For bulk materials, the oxidation below 400°C is very slow, in general taking many days to react the exposed surfaces. The experiments do prove that bulk fusion materials do react with air and steam, so finely divided fusion materials may react more easily and influence the combustion process.

Graphite has also been tested because of its use as an armor tile material. Pyrolytic graphite will combust and release heat after it has been ignited in air, but the energy requirement to ignite the graphite is high (O'Brien, 1988). Carbon fiber composites behave in a similar manner (Marshall, 2002). At low temperatures, below 600°C, the graphite coupon would not ignite for over 12 hours in the test apparatus. Surface oxidation was very slow in the CFC tests. Finely dividing the graphite could affect the reaction by increasing the reaction rate at a given temperature, or reducing the temperature that the graphite will begin to react.

2.2 Dust Combustion

Metals have several unique properties compared to other flammable materials. The heat of oxidation of metals is generally quite high, often twice the value for wood fuels or other flammables. Metal thermal conductivity is also very high, often orders of magnitude higher than for other flammables. Consequently, to ignite a large block of metal in air, essentially the entire block must be raised to the ignition temperature or the block simply conducts heat through the block. Bulk metal combustion can be categorized in two ways; metals that combust via surface reactions, and those metals whose vapors burn above the metal surface. Titanium and zirconium are examples of metals that burn by surface combustion (i.e., oxygen adsorption onto the metal surface), because the metal boiling point is higher than the metal's flame temperature. Carbon also combusts in this manner, since carbon does not vaporize until it reaches over 3900°C. Other metals will boil below their flame temperatures, thus these metals can release vapors that will burn over the molten metal surface (like hydrocarbons and many other flammable materials) (Friedman, 1998). Early work to define the character of dust explosions (Nagy, 1983) stated that oxygen had to diffuse to the surface, whether the dust was in a layer or dispersed in air. The reaction between a gaseous fuel, such as methane, and air is molecular, but dust particle-air reactions are surface-dependent. In general, dust combustion has been shown to be slower-acting than gas combustion. This difference has been attributed to the need for oxygen diffusion to the particle surface (Nagy, 1983; Friedman, 1998). For this reason, dust explosions are considered to be subsonic deflagration events rather than detonation events.

Eckhoff (1997) surveyed the literature and suggested that metal dusts may undergo both heterogeneous (oxygen diffusing through any oxide layers on dust particles to give a gaseous oxygen and solid metal fuel heterogeneous mixture) and homogeneous ignition. Homogeneous ignition is the case where metal vapor mingles in air above the particle surface, so that the fuel vapor and the oxidizer are both in the same physical state above the particle. Chatrathi (2000) pointed out that most experimental studies provide evidence of heterogeneous ignition, and there is only limited evidence of homogeneous ignition. Sun (2000) also noted experimental evidence of heterogeneous combustion in iron dust. Considering the small spark energies needed to provide ignition for many

types of dust, the heterogeneous ignition model is compelling. In later stages of a combustion process, when the combustion wave front is sufficiently hot, it seems more likely that a combination of processes is possible.

Dust that is lofted by turbulent inrush air from tile surfaces, castellations in tiles, spaces between tiles, etc., will react more easily in air than bulk materials due to the greatly increased surface area (Eckhoff, 1997). Finely divided dust generally does not require the high temperatures described above to ignite combustion. Even small energy spark discharges arising from electrostatic charge buildup of flowing particles can initiate dust cloud combustion. For the International Thermonuclear Experimental Reactor (ITER), a representative large tokamak, an estimate of dust inventory residing in the vacuum vessel is 200 kg carbon, 100 kg beryllium, and 100 kg tungsten (IAEA, 2002). If a sufficient amount of combustible dust is lofted during air or steam ingress, it will combust at low temperatures, lower than the 500 to 600°C reaction threshold for solids determined by the experiments described above. The dust cloud will burn quickly since it is a small amount of fuel of high surface area suspended within a copious supply of oxygen (either as steam vapor or air). It is possible that this dust cloud explosion could supply enough heat to further elevate the wall temperatures, that is, it may produce surface heating that could raise the temperature of the solid surfaces closer to short-duration oxidation reactions. Thus, the accident model may require two stages for adequate description, the initial inrush of air or steam and dust combustion, followed by the slower-paced, bulk wall material surface reactions. The combustibility parameters of some elemental metal dusts that could be found in fusion are given in Table 2. These data have come from 20-liter test chamber apparatus; each dust was tested separately. For the selected elements tested, the dust particle size range is given. The reader will recall that for a given mass of dust, most of the mass is found in a small number of the largest diameter particles; there will be many, many more small diameter particles that contribute only a small fraction of the total mass. Next, the minimum explosive concentration of dust in air is given for two ignition energies (2,500 and 5,000 Joules). The ignitors were pyrotechnic units composed of zirconium (40%), barium nitrate (30%), and barium peroxide (29%) initiated by an internal fuse wire. The maximum pressure obtained in the test chamber (the chamber pressure before explosion was 1 bar, absolute) is given. The size-normalized maximum rate of pressure rise is given for these short duration deflagration events. Then the maximum adiabatic temperature (calculated from ideal constant pressure combustion theory) is given. Actual temperatures will be lower than the ideal values due to heat losses by radiation and convection to the chamber walls. Dust particle sizes can change the overall severity of an explosion; in general, the smaller the dust particle diameter the more violent the explosion.

Data in Table 3 (Jacobson, 1964) show some of the element parameters for dust cloud and dust layer fires. It should be noted that the dust cloud concentrations are large, on the order of 100 g/m³. Such concentrations are much larger than permissible exposure concentrations for humans in the workplace, which are usually in the milligrams/m³

range. The Table 3 concentrations would exist inside ducts, piping, or vessels rather than in human-habited rooms (Hinds, 1999) where engineering controls (ventilation, filtration, etc.) are used to reduce worker exposures. In workspaces, dust layers can present hazards as well. If the dust layer is heated to temperatures suggested in Table 3, the dust can begin to smolder. Zinkle (2000) has shown that a variety of refractory materials for fusion can easily operate in the 200 to 700°C range, which can ignite dust layers if air ingress occurs. High temperature operation has not presented problems to date since fusion experiments do not presently operate at greatly elevated temperatures, and the vessels are also under vacuum. When the vessel is accessed, the temperature is reduced to room temperature, and the vessel is first filled with dry nitrogen gas to preserve vacuum cleanliness before venting to air. If there is a mechanical impact event, unusual equipment vibration, room air sweep, etc., that suspends dust from the layer, the resulting dust cloud may be ignited.

The potential for dust explosions or fires depends on several factors, including: metal chemistry, specific surface area (i.e., particle size and porosity), tendency to accumulate a static charge, surface coatings, gaseous environment, and moisture. The particle size tends to be the most important factor in chemical reactions (McCarthy, 1998; Eckhoff, 1997) and hence explosion energy release. For a fixed volume of metal, as the individual metal particle diameter decreases, the overall surface area of the set of particles increases. The increased area allows more modest energies to initiate more complete chemical reactions. Also, as particle diameter decreases, the particles can remain lofted in the air

Table 2. Explosibility data for elemental dusts

Element	Size range (μm)	MEC @ 2 kJ (g/m^3)	MEC @ 5 kJ (g/m^3)	P_{max} (bar)	$(dP/dt)_{\text{max}} V^{1/3}$ (bar-m/s)	$T_{\text{ad,max}}$ (K)
B	0.5 – 10	~110	~50	7.0	35	2850
C (test 1)	0.2 – 2	90	90	5.5	~10	2320
C (test 2)	4 – 10	F	70	~5	~6	2320
C (test 3)	4 – 30	NF	NF	1.1	~0	2320
C (test 4)	10 – 200	-	NF	1.1	~0	2320
Ti	10 – 60	70	60	5.7	35	3450
Cr	4 – 40	~F	~600	~3	~3	2840
Fe (test 1)	1 – 8	220	~160	4.5	29	2250
Fe (test 2)	10 – 80	~500	~300	3.1	3	2250
Ni (test 1)	3 – 8	-	NF	1.0	~0	2240
Ni (test 2)	20 – 40	-	NF	1.0	~0	2240
Cu	10 – 50	-	NF	1.0	~0	1510
Nb	10 – 60	~420	~350	~4	~4	3060
Mo	3 – 6	-	NF	1.0	~0	-
Sn	2 – 20	~450	~350	4.3	~16	-
Ta	4 – 30	~400	~250	~4	~7	3290
W (test 1)	≤ 1	~700	~550	~3.3	~5	2670
W (test 2)	5 – 25	-	NF	1.0	~0	2670

Note: Data taken from Cashdollar (1994). An F indicates flammable but a Minimum Explosive Concentration (MEC) could not be determined. NF indicates the dust was nonflammable or non-ignitable.

Table 3. Dust cloud and dust layer combustion parameters

Element	Average Particle Size (microns)	Dust cloud Ignition Temperature (°C)	Dust Layer Ignition Temperature (°C)	Dust Cloud MIE (mJ)	Dust Layer MIE (mJ)	Limiting Oxygen Concentration (%)
Be, with 1.2% BeO	5	no ignition	650	--	--	--
Be, with 2.4% BeO	5	no ignition	680	--	--	--
Be, with 8.1% BeO	1	910	450	--	--	--
B, 85% pure	44	470	400	60	--	--
B, ~97% pure	44	730	390	--	--	--
Cr, 97% pure	53 (99%), 74 (1%)	900	670	no ignition	1,280	--
Cu, 94% pure	44	700	no ignition	no ignition	no ignition	--
Fe, 98% pure	53	320	290	80	160	11
Mo, 99.8% pure	74	720	360	--	--	--
Ni, 99% pure	44	no ignition	no ignition	no ignition	no ignition	--
Ta	44	630	300	120	3.2	--
Ti, 99% pure	104 (94%)	330	510	0.024	--	--
Sn, 96% Sn, 2% Pb	53 (97%), 74 (1%), 149 (2%)	630	430	80	1,280	16
V, 86% pure	74 (100%)	500	490	60	--	--
W	44 (99%) 15 (1%)	730	470	no ignition	no ignition	--

(or other atmosphere) for longer periods of time after they are initially suspended. Increasing the surface area for reaction allows reactions to progress rapidly and completely, releasing more heat energy and combustion products (usually gaseous phase oxides of the metals involved). Smaller particles tend to require smaller ignition energies, and they also yield higher overpressure and higher thermal energy release. For

this reason, any testing information on specific metal dusts must note the particle size distribution tested, and the analyst must verify that the test particle size distribution is close to the process particle size distribution or range. Otherwise, published test results may not be strictly applicable to the process under analysis. Cashdollar (2000) studied 4 micron and 45 micron median diameter iron particle explosions in a Hartmann laboratory apparatus. There was a difference of about 200 K in the peak flame temperature, a peak factor of about 10 difference in rate of pressure rise, and about 1 atmosphere higher peak explosion pressure for the smaller diameter particles. Obviously, the smaller particles yielded a more severe explosion in every sense.

Fusion dusts have been characterized in existing experiments (Carmack, 2000; Peacock, 1999; Chappuis, 2001; Sharpe, 2003). Particle sizes are typically small, in the 0.1 to 10-micron diameter range. This particle size raises three separate classes of safety concerns. The first concern is that because of the small diameters, these irradiated, tritiated, toxic dusts are very easily mobilized and carried on air currents. Therefore, lofted dust could escape confinement if the confinement were breached. Takase (2001) used an analytical model to predict the amount of 10-100 micron diameter tokamak dust mobilized outside the vessel by turbulent air inrush and then exchange flow through a 0.02 m² vessel opening. The results were: beryllium, 1.7%; carbon, 0.7%; stainless steel, 0.5%; copper, 0.4%; and tungsten, 0.1%. Each dust type was less than 2%. Takase found that as the breach size increased, so did the mobilization percentage. At a 0.5 m² breach, the dust mobilization was about 2.5%, and at 1.5 m², the mobilization was about 3.5%. However, Takase's work shows that nearly all of the dust is entrained by turbulent air inflow within the vacuum vessel. The second concern is for personnel occupational safety, since these dusts are respirable size. Maintenance errors or confinement loss during work on the vacuum system components could expose workers to these dusts. This issue has been recognized by Moshonas (2001); precautions can be taken to protect workers from dust inhalation and to provide temporary confinement barriers and ventilation control when working on vacuum system components. The third concern is that these dusts are potentially combustible in layers or when suspended in air during conditions where the machine is hot and air is allowed to enter; that is, a LOVA during, or immediately following, plasma operation. The overpressure from a combustion reaction may not completely vent through the same breach opening – the pressure increase can depend on the ignition location and combustion wave front propagation around the torus. Goranson (1992) presented an initial model of gas combustion wave propagation in a torus; for an ignitor at the outboard wall, the wave could simultaneously propagate in two directions toroidally around the torus. A dust deflagration could behave in a similar manner. Portions of the confinement barrier may receive explosion loads from the dust deflagration pressure wave. Similarly, steam from a water coolant, either from wall tiles or plasma heating antennas, could enter the hot vessel. In that case, the dust is likely to react before the solid walls, and the combustion pressure will put stress on the vessel walls.

For the ITER early safety studies, activated in-vessel dusts were determined to be an important radiological inventory. The ITER reference events (i.e., design basis accidents) showed that the so-called wet bypass (vacuum vessel inventory released with steam/water through a port that bypasses the cryostat confinement boundary) was more consequential than the LOVA that released dust and tritium. The design event was a 0.02 m² vacuum vessel penetration experiencing failure of all windows. Air ingress terminated the plasma and a one-hour loss of offsite power was assumed to occur with this event. The vacuum vessel and the room containing the port equalized in pressure after 25 minutes. The vacuum vessel heated up but remained below 200°C throughout the event. Chemical reactions did not occur due to the low temperature, but dust and tritium did leave the vessel. When the tokamak venting system actuated, no further dust or tritium left the vessel, they were scavenged by the venting system (IAEA, 2002). Environmental releases for the LOVA were a factor of 8 below the project release limits.

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3.0 METAL DUST COMBUSTION EVENTS

A review of the literature has identified several metal dust combustion events from which lessons can be taken for fusion. The fusion conditions are anticipated to be a high temperature environment, with air or steam mingling with the dust, and hydrogen isotopes adsorbed or absorbed in the dust. The combination of a hot environment, metal dust, and air is easily arrived at in many industries. A few industries have hybrid explosions, where combustible dusts are mixed with combustible gases. Some published events are described below.

3.1 Industrial events

There have been several events of interest that have occurred in various industries. Selected metal fire and explosion events are discussed individually in this section.

Lembo (2001) discussed several aluminum dust explosions in the Italian Verbano Cusio Ossola region's industrial centers over the 1990-2000 time frame. For 27 facilities that finish aluminum and aluminum alloy parts in that region, there were 6 explosions over the time interval, resulting in 2 fatalities and 16 injuries. The aluminum dust was sampled for particle size. Two distinct particle shapes were found, the first was described as a 'belt shaped' particle of average dimensions 200 by 20 by 20 microns, and isometric particles with smaller dimensions, usually less than 5 microns. Igniters were not discussed, but some of the explosion events led to secondary explosions of aluminum dust. The initial, or primary, explosion dispersed enough dust that a secondary explosion took place. Several of the explosions discussed by Lembo occurred when maintenance or cleaning operations were in progress on the process equipment (e.g., grinders, lappers, etc.) or the dust collection equipment.

Pratt (1999) described an event that occurred during aluminum powder unloading from a transport truck. A facility that produces aluminum powder in varying sizes for industrial applications had produced a batch of ~10 micron aluminum powder and loaded it into a transport truck to be taken to a railhead. The transport truck was designed to use its diesel exhaust as the pneumatic gas to move the aluminum; the exhaust is well below the minimum oxygen concentration for aluminum explosions. The rail cars are inerted with nitrogen before the powder is loaded. In this event, the order for the 10-micron aluminum powder was cancelled and the truck had to be returned to the facility so the powder could be ground further and reclassified to fill a different order. This was a highly unusual event; there was no procedure. The truck returned, and workers learned that its transfer hose was too short to reach the facility input. Workers put an extension hose onto the truck hose and duct taped the two together. Now the truck hose was no longer grounded, but the workers were unaware of grounding issues. The workers also realized that they were using a longer hose length and that the extension hose was a larger diameter than the truck hose, so they added a compressed air line through the duct tape

seal between hoses to inject some more pneumatic gas that would help move the powder along. They were unaware of the reason for using diesel exhaust to move the powder. Just after transfer operations began, the aluminum powder exploded. Investigation revealed that an electrostatic scenario was favorable. The extension hose was estimated to have a ground resistance of $\sim 10E+10$ ohms and a capacitance of ~ 30 picoFarads. The streaming current for the aluminum was estimated to be 10 micro-amperes. Using Ohm's Law, the breakdown voltage would be $V = (\text{streaming current})(\text{hose resistance})$ or $1E+05$ Volts. Using this rather high breakdown voltage for the hose, the breakdown spark energy would be $W = 0.5C(V^2) \sim 0.5(30E-12 \text{ F})(1E+05 \text{ V})^2$ or 150 millijoules. The minimum ignition energy for aluminum dust is on the order of 50 millijoules, so there was more than enough energy to ignite the powder/compressed air mixture in the hose line. This explosion caused considerable damage to the truck and the side of the facility, but no fatalities were reported. The event serves to show that electrostatic discharge is a credible ignition scenario with metal dust.

May (1987) also discussed aluminum dust fires. Three events were described. The first was an aluminum dust fire in the dust collector room of an industrial manufacturing facility. The room was not kept clean; there was dust buildup on the rafters, floor, on the room thermal insulation and the eaves. Maintenance repairs in an adjacent room used an acetylene torch. The heat from the torch conducted through the wall and ignited the aluminum dust (70 % of this dust was less than 75 microns). An ABC dry type portable fire extinguisher was used to extinguish the flames, but the extinguisher dry powder stream simply disturbed more dust and allowed the flame to spread. The second event involved a grinder at a parts manufacturer. The grinder would operate on either stainless steel or aluminum parts, whichever was in production at the time. Grinder dusts and debris were captured in a dust collector. The collector housed about 50% aluminum and 30% iron dusts. Eighteen percent of the dust was less than 150 microns in size. While grinding steel parts, the operator noticed a red glow from the dust collector. He attempted to remove the glowing mass. At that time, an explosion occurred in the dust collector. In the third event, several aluminum dust explosions were described at a firm that manufactured molding strips. One event was a dust explosion when workers removed an ungrounded duct from the dust collection system. Another was the explosion of a dust collector. The speculated ignitor was heat and sparks from the use of a hand held dressing stone. The force of the explosion caused the explosion wall (made weaker than other walls) to yield and collapse, sheared bolts, and shifted concrete blocks. The explosion also propagated through the dust collection ducts, where it knocked duct work to the floor and injured personnel. The dust involved in that event was nearly 85% aluminum. Particle size was not given.

Eckhoff (1997) discussed several aluminum powder explosions in various industrial plants that either produced aluminum powder or handled it as part of the process. Eckhoff noted that due to the severity of damage from the aluminum explosions, a study was performed for aluminum flake powder. The results showed that aluminum flakes on

the order of 0.1 micron thick had spark ignition energies on the order of 0.1 mJ, and maximum rate of pressure rise in a Hartmann apparatus of 2600 bar/second. Both of these values are extreme. The aluminum flake had a specific surface area of about 7.5 m²/g, which enhanced the ignition sensitivity and the explosion severity.

A tantalum powder fire was reported by Matsuda (2000). An industrial plant manufacturing tantalum powder for use in compact, high-performance tantalum electrolytic capacitors suffered a dust explosion in 1997. One worker was killed and another was severely injured in the explosion. The plant performed crushing operations on tantalum chips to produce powder that is generally less than 10 microns in diameter. Any tantalum emitted from the process is collected by a bag filter unit in the ventilation system. Dust cannot penetrate the filter bags and accumulates in the filter unit housing. When 40 kg of dust accumulates in the housing, it is collected from a hopper at the bottom of the unit to be returned to the process. Two workers were operating the sliding valve at the bottom of the hopper and pouring Ta dust into polyethylene collection bags. The second bag had roughly 25 kg of Ta powder in it when a vigorous flash fire occurred. The workers' clothing quickly caught fire and both men were killed. The 36 filter bags in the housing were burned out, but there was no overpressure damage to the unit or surrounding equipment. This was a very low overpressure deflagration event. A year earlier, hot Ta particles from the grinding mill had entered this filter unit and caught fire; as a result, a nitrogen gas blanketing system had been installed and was in use to prevent fires. The nitrogen gas system had been turned off during dust recovery operations to prevent an inert gas suffocation hazard. The company investigated the event to determine the cause of dust ignition. They eliminated tantalum-to-steel mechanical sparks (they could not force the Ta to spark on steel even with vigorous force applied), open flames (none were present in the area), and self-heating from oxidation (nitrogen was present, the Ta was at low temperature, and the Ta had been passivated with a few percent of oxygen before entering the filter unit) as causes. The investigation did show that electrostatic charge buildup occurred easily in flowing Ta powder. A charge per unit weight of powder was measured at 0.1 micro-coulomb per kg. The polyethylene collection bag with over 20 kg of collected dust would have had a charge of over 2 micro-coulombs. If this powder charge were to discharge to the bag or among the powder itself, the potential could increase up to 10 kV. The investigators' ignition tests showed that Ta dust is very sensitive to small ignition energies, even less than 0.2 mJ sparking into a layer of Ta dust. The layer minimum ignition temperature was found to be 573 K, which agreed with literature values. The dust cloud minimum ignition temperature was found to be 883 K (as opposed to a literature value of 903 K), and the minimum spark ignition energy was found to be 14 mJ (as opposed to 120 mJ in the literature). The authors stated that they may have used different dust samples and testing methods. The investigation of the Ta dust did show that the dust particles had a "coral-like" appearance; the dust can be fragile or brittle, easily broken into smaller sizes that strongly affect the explosion sensitivity by increasing surface area and presenting a smaller heat sink. Overall testing showed that the Ta dust had a lower explosive limit of

$\sim 0.2 \text{ kg/m}^3$, and testing was halted at 5 kg/m^3 . Explosion time to peak pressure was highest for the lower limit, about 65 ms, while the 3 kg/m^3 and higher concentrations were between 10 and 20 ms. Explosion overpressure ranged from 50 kPa at the lower explosive limit to $\sim 700 \text{ kPa}$ at 5 kg/m^3 .

Senecal (1991) described a manganese dust explosion in an industrial facility. In 1989, a process dust explosion occurred in a mill facility. On the day of the event, the vibrating classifier screen deck became plugged with a large quantity of very fine powder, < 74 microns in diameter. The material had backed up in the mill and consequently was ground much finer than its normal sizes of 0.595 mm or 0.354 mm. Workers investigating the plugged classifier threw an emergency switch to 'safe' the system for their approach. This was not an approved procedure; perhaps it was done in the interest of saving time. This switch also deactivated the nitrogen purge gas system and the oxygen monitoring system; this fact was not understood by the workers who had operated the switch. While two workers used aluminum shovels to clear the classifier deck of fine powder, an explosion occurred. A flame ball and cloud of brownish-orange dust were ejected from the ball mill chute. The two workmen evaded the flames but were enveloped in dust. The operations shift workers in the rest of the plant also evaded the flames that exited via two of the 0.28 m^2 pressure relief vent panels on the 14-m tall bucket elevator. Even though the highest two of the four panels released to relieve explosion pressure, there was enough overpressure and velocity in the explosion wave front to mechanically damage the 2.77 mm-thick sheet steel at the top of the bucket elevator. The accident investigators studied the ignition source for the dust explosion. The most likely cause of ignition was attributed to self-heating from surface oxidation when the fine Mn dust was exposed to inleakage air. The manganese thermochemistry reaction that the investigators considered was:



The investigators reasoned that, because of these high heats of reaction, only a modest amount of oxygen adsorption in a thin layer of fine dust would raise the dust temperature to the point of smoldering or flaming. The dust layer, although not very deep, is a very poor thermal conductor and would increase temperature near the surface of the dust rather than conduct heat to the mill apparatus. The investigators also reviewed the performance of the four overpressure relief vent panels. They concluded that the panels were too few in number, and each panel was too small in surface area, to effectively protect the bucket elevator. The explosion propagated upward in the elevator; the first panel was found to be intact, the second panel was bulged, the third panel was opened, and the fourth panel was blown off the elevator. As the explosion progressed up through the 1 m x 1 m x 14 m elevator structure, the pressure increased and acted on the relief panels.

A search of the Chemical Incident Reports Center (see www.chemsafety.gov) of the US Chemical Safety and Hazard Investigation Board revealed the incidents described in Table 4. Only metal and carbonaceous dust events are listed in the table; other events cited wood dust, pharmaceutical dust, agricultural dust, and plastic dust. These recent events illustrate several points - even small dust fires can prove to be very consequential, dust fires and explosions are occurring at small companies and a few at large corporations, and that dust combustion events remain an ongoing safety concern in industry.

There have been some bulk metal fires in industry as well. Titanium metal has caught fire during oxy-acetylene weld cutting processes (Mahnken, 1997; Prine 1992; Meidel, 1970). In one event, the metal fire spread rapidly and burned through the holdings of a scrap metal dealer – even though the local fire department arrived in a timely manner and fought the fire.

Table 4. Recent Dust Fires and Explosions in US Industries

Event Date	Location	Narrative Description of Event
04/26/2003	Nikiski, AK	<p><u>Electrician suffers burns in accident at refinery</u></p> <p>A Kenai man was in satisfactory condition at the Harborview Medical Center in Seattle Monday where he was taken after being burned in an industrial accident Saturday. David Ramsey, a Tesoro electrician, suffered second- and third-degree burns to his right arm while doing electrical maintenance work at the company's Nikiski refinery Saturday morning. Ramsey was performing turnaround maintenance work on electrical switch gear that had been de-energized, according to refinery manager Rodney Cason. Dust from the cleaning procedure, however, apparently flashed when it came into contact with a nearby switch that still had electricity going to it. Ramsey, who was wearing leather gloves and fire retardant clothing, suffered second-degree burns to his forearm and third-degree burns to his elbow through the protective clothing. He was given immediate first-aid care at the scene and taken by Nikiski Fire Department ambulance to Central Peninsula General Hospital. From there, he was flown to the Burn Care and Plastic Surgery Clinic of Harborview for additional care. Cason said he spoke to Ramsey Monday and the Tesoro employee "is doing really well." "He said he wants to get back and get golfing," Cason said. CSB record 2003-6517.</p>
04/09/2003	Richmond, IN	<p><u>Imperial Products catches fire; no one hurt</u></p> <p>Indiana-Richmond firefighters continued battling a stubborn fire inside a dust collector atop the Imperial Products plant at 451 Industries Road this morning. The factory was evacuated while firefighters poured tons of water into the top the collector. No one was injured. The water was pouring out the bottom of the rooftop collector and swirling down a drain in the middle of the plant's parking lot. There were no visible flames, but there was smoke in the area. Firefighters were trying different strategies to attack the fire. "It's in too confined a space," Battalion Chief Tim Brown said. A 5-inch water line was run from a hydrant on the northeast corner of the Imperial property across the front of the building and down the south side of the plant. Firefighters contacted Indiana-American Water to boost water pressure in the area. The dust collector is on the roof at the rear of the factory. The alarm was received at about 6:30 a.m. today. Firefighters were still at the scene at 9:30 a.m. Three fire companies were fighting the fire. A relief company was sent shortly before 9 a.m., fire department officials said. Cause of the fire has not been determined, fire officials said. Imperial Products produces doors and employs about 140 people. Because the fire is confined inside the Imperial plant, it did not threaten any neighboring businesses at the industrial park. CSB record 2003-6494.</p>

Table 4. Recent Dust Fires and Explosions in US Industries (continued)

Event Date	Location	Narrative Description of Event
03/17/2003, 2:42 pm	Stambaugh, PA	<p><u>Fire in dust collection system causes about \$5,000 in damages.</u> Employees helped extinguish a small fire that evacuated Stambaugh Metal Inc. Thursday evening. The fire started in a dust collection system and ignited a dust bin and several filters, said Hanover fire commissioner James Roth. He estimated damage at about \$5,000. Ten employees were working at the company, polishing metal parts for Harley-Davidson motorcycles when the fire broke out at 6:47 p.m. Polisher John Moore was cleaning the main room of the High Street facility when he saw fire in a metal dust bin. He and three other employees doused the fire with extinguishers before Hanover firefighters arrived and evacuated the plant. Firefighters found light smoke throughout the building and the fire contained in the dust bin, Roth said. A dry chemical extinguisher within the dust collector did not put out the fire, but it did trigger the fire alarm, plant manager Ivan Goss said. Firefighters extinguished the fire by 7:20 p.m., Roth said. The dust collector vacuums dust away from the stations where workers polish the parts, Goss said. "It's easy for the system to suck up a spark too, which is probably what happened Thursday night," Roth said. He ruled the fire was accidental. "This happens in all these types of shops like this," Roth said. Goss said the workers would clean up the room Thursday night so they could continue polishing luggage racks and engine guards. CSB record 2003-6424.</p>
3/15/2003	Blendon Township, MI	<p><u>Dust in machine ignites steel polishing plant.</u> A fire ripped through a Borculo steel polishing plant Friday, destroying the building and its contents after dust in a machine sparked flames that couldn't be knocked down by employees. Fire officials said Borculo Polishing Inc., 9442 Henry Court in Blendon Township, was a complete loss from the fire, which started at about 2:30 p.m. Blendon Fire Chief Ken Haveman said the building was engulfed in flames when they arrived on scene. "There was nothing to save," Haveman said. "When we got here, the building was fully involved from end to end." The fire investigation points the source of the flames to a polishing and buffing machine that turns raw metal into polished steel plates, the fire chief said. "This is a dangerous industry," Haveman said. "This is highly combustible material. It just takes a spark to ignite." Four or five employees tried to put the fire out with extinguishers before firefighters arrived, but were quickly driven back, according to one employee. "I heard someone yell 'Fire' and saw a bunch of smoke, so I grabbed a fire extinguisher and ran over there," said Pat Shoulders, an employee from Allendale. "We had to leave the building less than five minutes after we saw fire. It went that fast." "It was amazing how fast it went up," said</p>

Table 4. Recent Dust Fires and Explosions in US Industries (continued)

Event Date	Location	Title and Narrative Description of Event
3/15/2003 (continued)	Blendon Township, MI	<u>Dust in machine ignites steel polishing plant.</u> (continued) Richard Dalman, an employee from Zeeland. Employees originally thought they contained the fire because they couldn't see flames, but quickly fled the building when they were overcome by smoke and heat. "Smoke was rolling from floor to ceiling, you just couldn't see," Dalman said, "There was nothing we could do." Firefighters initially tried an aggressive interior attack, but the heat and flames forced them to retreat and fight from the outside, according to Jim Harkess of the Allendale Fire Department. Extinguishing the fire was complicated by the difficulty of transporting water to the scene. The closest hydrant was several hundred yards away. It is unknown whether the business plans to rebuild. Blendon firefighters called for assistance from eight local departments. CSB record 2003-6348.
03/03/2003, 2:03 pm	Portland, OR	<u>2-alarm fire hits hoppers at north-side pipe plant.</u> A two-alarm fire on Monday afternoon caused about \$10,000 damage to two dust-collection hoppers at a North Portland steel pipe manufacturer. The fire started shortly after noon as workers blasted grit and rust off a 60-foot-long water pipe inside a building at Northwest Pipe Co. in the 12000 block of North Burgard Way, said Neil Heesacker, a Portland Fire Bureau spokesman. Two of the facility's three metal hoppers caught fire, but the flames remained inside the machines, Heesacker said. The second alarm was sounded at 12:17 p.m. because the first firefighters arriving at the scene feared they would have trouble reaching the flames, Heesacker said. It took 60 firefighters about 30 minutes to contain the fire. Company officials said no employees were injured. As a precaution, 13 workers were evacuated from the lining and coating building where the hoppers are located, said Carol Grant, a Northwest Pipe safety manager. The hoppers were expected to be operating again today, Grant said. Pipes are blasted before a paint coating is applied, she said. It was the second time in less than a year that firefighters were called to the plant to extinguish a fire in one of the hoppers. Heesacker said a small fire occurred about six months ago. An investigation was under way, but Heesacker said the investigator suspects a faulty bearing in a fan. CSB record 2003-6410.
02/10/2003	Rothschild, WI	<u>Explosion shuts down power plant unit.</u> A coal dust explosion Monday forced Wisconsin Public Service Corp. to shut down one of its electrical generators at the Weston Power Plant, the utility said. No one was hurt. The explosion occurred at 10:30 a.m. in the ductwork of one of six coal pulverizers, plant manager Roger Zimmermann said. "We don't know yet what caused the ignition of the coal dust," he said Monday afternoon. Unit 3 at the power plant will

Table 4. Recent Dust Fires and Explosions in US Industries (continued)

Event Date	Location	Title and Narrative Description of Event
02/10/2003 (continued)	Rothschild, WI	<p><u>Explosion shuts down power plant unit.</u> (continued) remain shut down until the cause of the blast is known and repairs are made. The company hopes to be producing power again sometime today, WPS spokeswoman Kelly Zagrzebski said. Four workers were in an area nearby when the explosion occurred, she said. They described the incident as a "fireball flash." The explosion did not cause a fire. Managers and other company officials investigated the plant's piping Monday afternoon to analyze the problem and check for damage, Zagrzebski said. The nature of the failure caused the plant to shut down automatically. WPS said it will replace the electricity lost by purchasing power on the open market. The Wisconsin Public Service Commission approves rates charged by WPS for power. "If we have to purchase power at triple what it takes to produce at Weston, that's a loss to our company and not something customers have to pay for," Zagrzebski said. Officials called Rothschild fire and ambulance crews to the plant as part of their standard operating procedures after an explosion, although they were not needed for emergency services. CSB record 2003-6348.</p>
01/14/03 5:20 pm	Twinsburg, OH	<p><u>Explosion at plant causes evacuation.</u> An explosion in a dust collector at Commercial Alloy Sales on Highland Road ignited a fire about 5:20 p.m. Tuesday. No major injuries were reported, and a damage estimate was not available Tuesday night. The Twinsburg Fire Department reported the explosion came from duct work in the building and from the dust collector unit outside the building. The dust collector was blown apart, with heavy fire and flames coming from the unit, according to the Fire Department. All employees evacuated the building at 1831 Highland Road. The cause of the explosion is under investigation. Firefighters from Northfield Center, Hudson and Macedonia responded in support of the township department. CSB record 2003-6280.</p>
06/06/2002	Hempfield Township, PA	<p><u>Fire Breaks Out at Carbidie Plant</u> Three people suffered minor injuries in a two-alarm fire Thursday evening (6/6/2002) at the Carbidie Corp. plant along Arona Road in Hempfield Township. Two of the victims were treated at the scene; the third was transported to a hospital, said Dan Stevens, Westmoreland County 911 public information officer. "The injuries appeared to be smoke inhalation-related," he said. Stevens said the fire started at about 7:05 p.m. in a dust collector. A spark from a nearby machine apparently got into the collector, setting fire to cobalt and tungsten dust that was being collected to be recycled. The company recycles cobalt because of its expense, he said. There was no damage to the building. The plant</p>

Table 4. Recent Dust Fires and Explosions in US Industries (continued)

Event Date	Location	Title and Narrative Description of Event
06/06/2002	Hempfield Township, PA	<u>Fire Breaks Out at Carbidie Plant</u> (con't) was evacuated, but nearby homes were not. Stevens said there was little environmental danger from the blaze. Risk of explosion made warranted two-alarm status for the blaze. The company, a Kennametal subsidiary, produces tungsten carbide preforms for the tool industry. More than 100 people work at the facility. CSB record 2002-5685.
04/13/2002	Saylor Township, IA	<u>Four Injured in Dust Explosion.</u> Workers at the Dee Zee Manufacturing plant in Saylor Township were recovering Sunday after being injured in a dust explosion Saturday (4/13/2002) morning. More than 200 workers were at the plant when the fire erupted in a confined section of the plant. About 10 workers were buffing and sanding metal while equipment was being cleaned, sparking the explosion, company officials said. Company President Ron Shivers said four workers were taken to area hospitals; two were kept overnight because of smoke inhalation and burns. No one was seriously injured, he said. Dee Zee manufactures truck accessories. CSB record 2002-5548.
03/06/2002 7:00 pm	West Pittsburg, PA	<u>Fire In Magnesium Storage Shed</u> Fire continued to burn Thursday morning at a plant storing magnesium, a metal that can explode if it comes into contact with water. Fire officials said they had no choice but to let the fire burn out, which could possibly take days, at the Remacor Inc. storage facility in Lawrence County. The fire began shortly after 7 p.m. Wednesday (3/6/2002), apparently when a drum containing magnesium reacted with moisture, which caused it to explode. The explosion caused an electric line to catch fire, which in turn caused more fires. No injuries were reported and no one had to be evacuated, officials said. Remacor develops products for use in the steel industry. Magnesium powder is used in steel refining. The West Pittsburg facility is located about 35 miles northwest of Pittsburgh. CSB record 2002-5458.
Note: The CSB database contains reports on other dust explosions as well - in agricultural, manufacturing (resins, etc.), pharmaceutical, and food processing facilities. All of these types of dust explosions have occurred in the last several years in the US, which indicates that dust explosions are an ongoing safety concern.		
Disclaimer: <i>The Chemical Incident Reports Center (CIRC)</i> is an information service provided by the U.S. Chemical Safety and Hazard Investigation Board (CSB). Users of this service should note that the contents of the CIRC are not intended to be a comprehensive listing of all incidents that have occurred; many incidents go unreported or are not entered into the database. Therefore, it is not appropriate to use the CIRC database to perform statistical analysis that extends conclusions beyond the content of the CIRC. Also, although the CSB never knowingly posts inaccurate information, the CSB is unable to independently verify all information that it receives from its various sources, much of which is based on initial reports. Users of data from the CIRC are requested to attach this disclaimer to the data and cite http://www.chemsafety.gov/circ as the source.		

3.2 US Department of Energy events

The US Department of Energy (DOE) occurrence reporting and processing system was searched for metal dust combustion events. Alkali metals (i.e., lithium, sodium, potassium, rubidium, cesium, and francium) were not included here since most of these metals in bulk solid form are reactive in air and water; it is obvious that finely divided powder of these metals in air will also lead to chemical reactions. Pyrophoric metals are defined (DOE, 1994) as heavy metals (i.e., uranium, thorium, plutonium, etc.), and were not included here since these metals should not be found in any significant quantity within tokamak dust. Uranium has been successfully used as a getter material in tritium storage beds, but the safety of uranium beds is outside of the scope of this report. With these restrictions in place, the results of the ORPS search are few. The reports are summarized below.

In the ORPS report RL--PNNL-PNNLBOPER-1993-0037, November 11, 1993, several staff members were conducting an experiment to determine the effects of fine particles of indium phosphide (InP) on small animals. The experimental apparatus consisted of a laboratory dust disburser inside a fiberglass glovebox. The generated aerosol is transported through plastic tubing to exposure chambers in an adjacent room. About 20 minutes after starting the experiment, a small explosion and small flash fire occurred. The damage was confined to the glovebox and its attachments. The spread of indium phosphide (InP) was confined to the laboratory rooms in the immediate vicinity. The probable cause of the event was an explosion in the InP dust that had accumulated on the high efficiency particulate air (HEPA) filter at the end of the distribution line. The explosion probably occurred when an explosive quantity of InP collected in the vicinity of the HEPA filter and an electrostatic spark or sparks ignited it. The aerosol distribution system was built using polyvinyl chloride (PVC) piping. Similar PVC distribution systems are known to generate static electricity. In the future, the staff will take precautions: design the dust transport system using standard NFPA 654 (Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids), bond and ground the transport piping system, and reduce the concentration of dust needed.

In the ORPS report CH--AMES-AMES-1995-0001, December 30, 1994, a metal fire occurred in a 35-gallon barrel used for the storage of metal scrap in a machine shop. Machinists noticed an ammonia-like smell, and saw flames extending twenty inches over the top of the barrel. The Machine Shop Manager, following the information contained in the Material Safety Data Sheet for neodymium, use powdered lime from a bulk fire extinguisher to extinguish the fire. The barrel was rolled to a nearby dock. The barrel contained materials from normal machine shop activities; fines, turnings and chips of aluminum, brass, copper, stainless steel, cutting fluid, floor sweepings and wood, plus neodymium turnings. Investigators believed that the neodymium turnings reacted with the water-based cutting fluid, or with moisture in the air, to rapidly oxidize. Neodymium is not pyrophoric, but it is water-reactive. It seems likely that the fire suppression was

quick enough that none of the other fines or chips of metal were ignited, or the barrel could not have been approached and moved to the outside dock location.

In the ORPS report ID--LITC-TOWN-1995-0002, January 13, 1995, a laboratory technician received minor burns on his hands, arms, and abdomen after a small quantity (about 50 grams) of aluminum and copper oxide powders used in welding-related research ignited inside a bottle in a lab room. The individual was shaking a 250 ml polyethylene bottle to mix the two 325-mesh (44 micron) powders when ignition occurred. The two materials had been mixed several times before without incident. The individual was transported to the hospital and was treated and released. The investigation revealed that the Al-Cu₂O thermite compound was usually mixed in the same bottle, but that the bottle was usually 50 to 70% full, rather than this occasion where the bottle was only about 10% full. The shaking process to mix the two powders may have been more aggressive than typically used. The investigators believed that the aluminum dust cloud in the bottle began to react with air in the bottle headspace, then subsequently the heat from oxidation ignited the thermite reaction between the aluminum and copper oxide. The most probable ignition source of the aluminum-air reaction was static electrical discharge. Residues at the scene were mainly aluminum oxide and copper metal, and small quantities of copper oxide.

Chapter 3 References

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4.0 DUST COMBUSTION ISSUES IN FUSION

Research on dust explosions has taken place in the laboratory using small size test chambers. It is impractical and expensive to conduct full scale dust explosion tests, and any actual explosions rarely have instruments in place to record the progression of the event. Therefore, the small scale lab test results must be scaled up to apply to actual situations. This chapter discusses the nature of dust explosions and dust layer fires, including the scaling process from test data to actual chambers, ignition sources and energies, particle size effects, presence of other combustibles with the dust (such as tritium), and the effects of dust explosions.

4.1 Dust hazard categorization

Combustible dusts have been assigned three hazard categories, corresponding to the severity of their deflagration in air (NFPA, 2002). These categories are:

<u>Hazard Class</u>	<u>K_{st}, Deflagration Index for dust (bar-m/sec)</u>	<u>Maximum Pressure (bar)</u>
1	~200	10
2	201 – 300	10
3	> 300	12

The deflagration index is described by the empirical relation (Bartknecht, 1989):

$$(dP/dt)_{\max} \cdot V^{1/3} = K_{st} \quad (1)$$

where P is the pressure from the explosion (1 bar ≈ 1 atmosphere)

t is the time duration of the explosion

V is the test chamber volume

K_{st} is the deflagration index, a constant for a given type of dust (Bartknecht, 1989)

The subscript ‘st’ stands for “staub”, whose German to English translation is ‘dust’. The K_{st} value is not a strict constant for a given material; it can vary somewhat with dust diameter and dust size distribution, initial dust temperature, the moisture content of some types of dusts, the ignitor energy (in this case, 10 kJ), and other factors. This equation is referred to as the “Cubic Law” for explosion evaluation. Experimental evidence has shown that the maximum pressure obtainable is constant in dust explosions (Bartknecht, 1989; Baker, 1991). Therefore, this basic relation indicates that as the chamber volume increases, the maximum rate of pressure rise decreases. The relation does appear to account for the subsonic dust combustion wave that must travel through larger and larger volumes while keeping the combustion pressure at a relatively constant value. Hazard classes for some specific types of dust are given in Table 5.

4.2 Dust Explosion Scaling

Laboratory testing has been used to determine the basic combustibility of dusts, and the combustibility of mixtures of dusts with diluent materials. As stated earlier, it is impractical to conduct tests on industrial scale dust-air clouds, so smaller scale testing apparatus are used. The original apparatus is an instrumented, reinforced metal cylindrical chamber, and is called the Hartmann apparatus in honor of Mr. Irving Hartmann of the US Bureau of Mines, who devised the apparatus to test coal dusts in the mid-1900's (Baker, 1991). The original chamber was cylindrical, with a volume of 1.2 liters. Not long after the Hartmann apparatus was in wider use, a 20-liter chamber was built for the purpose of examining effects of scale. Since that time, larger apparatus of 1 m³ have been used to determine applicability of the "Cubic Law" scaling rule (Going, 2000). Testing in these vessels serves to establish upper bounds on deflagration explosion pressures and the maximum rates of pressure rise for 'compact' enclosures (that is, chambers whose dimensions are about equal – spheres, cubes, and short cylinders) (Baker, 1991). A typical pressure increase after ignition of a dust explosion begins slowly in the first milliseconds of combustion; the pressure curve follows a nearly cubic increase with time. The pressure reaches its peak value at the end of combustion, then decreases as heat is lost to the chamber walls. While deflagrations are considered to be more modest energy events than detonations, pressure increases of ten times the pre-explosion pressure can create large amounts of damage and personnel injuries, as seen from the operating experiences described in previous chapter.

Kuchta (ISA, 1999) states that the cubic law is an idealized equation, and for spherical chambers can give rather accurate results. Generally, actual pressures are less than those predicted by the equation since flame propagation is rarely spherical – even in a spherical industrial chamber, the ignition rarely occurs exactly in the center of the chamber. Heat losses to walls increase as flame fronts reach close to chamber walls, causing the combustion to cool and slow. Also, the burning velocity is not truly constant in constant volume processes. Fuel buoyancy in air can also affect the maximum pressure obtainable in the combustion process due to concentration changes and restricted flame propagation (i.e., upward, horizontal, or downward). Also, if the fuel-air mixture is not at the

Table 5. General dust hazard classes

Type of Dust	Dust Hazard Class
Aluminum	3
Calcium/silicon alumina	2
Coal dust	1
Copper	na
Ferrochromium	1
Ferromanganese	1
Graphite (99.5% C)	1
Graphite fiber (99% C)	1
Hard metal (TiN, WC, VC, Mo)	1
Iron	1
Magnesium	3
Manganese	1
Niobium	1
Silicon	1
Steel (6% Cr)	2
Titanium	3
Titanium carbide	2
Titanium hydride	1
Titanium monoxide	2
Tungsten	na
Vanadium	1
Zinc	1
Zirconium	na

Notes: na stands for not available

Table compiled from information in Bartknecht (1989), Eckhoff (1997), and NFPA (2002a). Class 0 is ‘no explosion’; 1 is weak explosion; 2 is strong explosion, and 3 is very strong explosion. These dusts were ignited by a 10 kJ ignition source.

stoichiometric proportions, the enthalpy of the reaction is reduced and the burning velocity is reduced (ISA, 1999).

The cubic law is useful for setting credible values of the maximum pressure obtainable in a dust explosion. The analyst must recognize the uncertainties created when

extrapolating from 20-liter and 1-m³ chambers to very large chambers. Baker (1991) pointed out that coal dust tests in a 1-m³ chamber and test results in a full-scale coal mine (used for such experiment purposes) compared well. Other dust explosion tests performed in grain silos (with a length to diameter ratio of 6:1) did not compare so favorably to the test chambers. Kumar (1992) described a 10 m³ cylindrical test chamber (aspect ratio of 3.8:1) set up specifically to allow better extrapolation to industry; however, this chamber has been used to test cornstarch and coal dusts since these are dusts of concern. The results agreed well for cornstarch, but the coal dust experiment results showed K_{st} values lower than reported by smaller chambers. The authors theorized that the intensity of air turbulence needed to keep the dust aloft was altering the outcome of the explosion. There are issues involved with scaling; however, for many applications, it is not possible to conduct a full-scale test, and the small scale tests do provide a point for extrapolation. The analyst must use care when extrapolating; for example, the ITER chamber is 3880 m³ (Topilski, 1997). Such large fusion chambers would mean extrapolating several orders of magnitude. An error bound should be used.

4.3 Ignition of Combustion

In general, a safety analysis will assume an ignition source simultaneously exists when an oxidizer and a fuel are both present in a configuration that will allow combustion. The traditional safety analysis is deterministic, assuming that accidents will occur. The safety analysis calculates the largest consequence for a given type of event, then identifies protective measures to mitigate the consequence. In the case of dust and gas explosions, the ignition energy can be less than a Joule, which can be realized in many ways, so the ignition is simply assumed to occur. A probabilistic safety assessment will give a probability of ignition (Fullwood, 2000). In actual events and in accident investigation, the source of ignition is sought to identify if the source can be eliminated or altered to preclude ignition in other industrial situations.

Some typical sources of ignition in industry have been static electricity discharge, where a charge accumulated from flowing the substance through an orifice or along a pipe (Baker, 1991). Arc welding also creates electrical current and often enough heat to ignite a dust-air explosion. Open flames (e.g., pilot light on gas equipment, bunsen burner, acetylene welding) can also ignite dust-air mixtures (NFPA, 2002a).

There have been several subtle sources of ignition in gas cloud and dust explosions that apply to fusion chambers. For example, Baek (1994) discussed a radiant heating situation where hydrogen gas was mixed in a 1:1 volume ratio, with 100-micron inert particles suspended in the gas mixture. Radiant heating from the chamber walls at 1800 K heated the inert particles, which in turn conducted heat to the gas mixture; Baek assumed the gas was transparent to radiant heat, which is quite reasonable if the gas does not have any water vapor or other suspended material. Under that assumption, the particles were always at a higher temperature than the surrounding gas until combustion

was initiated by the localized heat transfer in the region of each 100-micron particle. Each inert particle served as a micro-ignitor location for the gas-air mixture. Baek's study is relevant to large fusion vessels. For fusion, the intruding air is expected to be cool (i.e., room temperature) and will likely begin cooling any entrained particles, while the protective tiles on the vessel walls will radiate heat as the rest of the machine cools down. If a plasma disruption followed the LOVA event, then the walls would be radiating at temperatures higher than the typical operating values, perhaps in the 500 – 700°C range, which may transfer enough heat for autoignition of some of the constituents of fine dust (see Table 3). The entrained particles will experience the radiant heat flux from the walls and their temperature will increase accordingly. This method of ignition needs further study.

Another subtle ignition source is ignition by laser heat. Laser ignition of suspended particulate has also been performed in laboratories (Marion, 1996). Zhang (1992) experimented with fiber optic cables. He discovered that even 100 mW continuous wave energy optical cables, which are slightly above communication cable energies, could heat inert particles enough to ignite combustible gases in the air. Welzel (2000) describes an experiment where laser energy was routed along a fiber optic cable into a chamber containing propane-air. The end of the fiber in the combustible atmosphere was coated with iron oxide so that the laser light would heat the iron oxide coating. The heated coating would radiantly heat and ignite the gas-air mixture. Welzel pointed out that nearly any combustible material could accept radiant heat. For the gases tested, radiant heat in the range of 50 mW was sufficient to cause ignition in the ~0.01 m³ test chamber. In fusion, the Thomson scattering diagnostic uses a set of lasers to determine ion or electron temperature and density. Some typical values of these systems are the DIII-D reactor using six neodymium:yttrium-aluminum-garnet (Nd:YAG) lasers at 20 hertz, 1 joule, 15 nanosecond pulse and 1064 nm wavelength (Carlstrom, 1997), and the Large Helical Device using ten Nd:YAG lasers, each with a maximum power of 30 Watts and a repetition rate of 50 hertz (Narihara, 1997). If the laser energy is deposited on dust particles, local concentrations of particles can be ignited; a dust ignition experiment performed on aluminum and other, non-metal dusts has used a Nd:YAG laser with a 60 Watt output and 1064 nm wavelength (Proust, 2002). The only metal dust tested, aluminum dust of 15 microns size, required 4.5 Watts of laser power to ignite. It is true that the laser ignition experiments were performed in small chambers under controlled conditions, not the highly turbulent environment of a large-scale fusion chamber breach. However, enough evidence exists to suggest that run-on of a Thomson scattering diagnostic laser system might be able to ignite dust particles crossing the laser paths. Therefore, the diagnostic lasers must be shut down when an off-normal event occurs.

Another issue is plasma heating antennas. The ion cyclotron and electron cyclotron heating systems use megawatts of power. If the antennas were to be bombarded by dusts, the electric fields around the antennas can cause ionization and the dust particles can create paths to ground the antenna energy to other parts of the vacuum vessel. This

situation could lead to electrical arcs that would serve as ignitors. If a heating system was to run-on, emitting radiofrequency energy into the dust-air mixture in the vessel, it is possible that there would be enough heating to create an ignition. Fortunately, the plasma heating systems use appreciable amounts of electrical power, and they are interlocked to quickly shut down if the plasma deviates from normal conditions. Considering the time scales of air ingress for different breach sizes, 10's to 100's of seconds (Takase, 2001), the plasma heating systems would be de-powered before there was a significant amount of air mixing with the dust. Timely shut down of plasma heating is important since these systems use megawatts of power and could be considered to be strong (e.g., kJ energy delivery) ignition sources.

Another subtle ignitor is described in the US National Fire Protection Association (NFPA) standards. Iron oxide, forming in steel chambers, will eventually become dislodged from the walls and be swept downstream with the process material. If the iron oxide strikes a pipe, duct, or chamber wall, it may cause the ignition of confined combustibles. The standard also mentions aluminum paint. If flakes of aluminum paint were to become dislodged or were struck by a foreign object, the heat of the impact could be sufficient to ignite the aluminum particle, subsequently initiating a fire in the combustible materials present (NFPA, 2000). While fusion should only use stainless steel, it is possible that particles of iron oxide could be formed during construction of a fusion device, so ignition protection makes another reason to thoroughly clean the vacuum vessel. Since aluminum is a reasonable material to use to reduce tritium migration, the use of any aluminized paint should be considered for its impact sensitivity.

The electrostatic charging issue is a concern. A tokamak is a highly “ionic” environment, where particle collisions, erosion, electric fields, and magnetic fields can create ions from particles composed of armor tile and other materials. In a LOVA, the dust is lofted and swirled around in a strong magnetic field; kilogram quantities of ~10 micron dust particles that collide with each other and with the chamber walls. The dust particles can acquire electrostatic charge during this turbulent flow, which is roughly similar to an industrial cyclone separator that is known to generate electrostatic charge (Pratt, 1997). These charges and any pre-existing positive and negative electrostatic charges (Winter, 2001, speculates that decay of adsorbed tritium also leads to charge establishment in dust particles) accumulate within the dust cloud. An electric field is created in the particle cloud when the charges are disbursed throughout the cloud (Pratt, 1997). This creates a condition where an electrostatic discharge can occur to some conductive part of the tokamak interior. Drysdale (1985) states that the electrical spark supplies some of the ions necessary for completing the intermediate steps of the combustion reaction, as well as raising the temperature of a localized volume near the spark. Most dusts require an electrostatic discharge on the order of 1 mJ to 1 J, while combustible gas-air mixtures usually require less than a mJ (Barton, 2002). The dust cloud can accumulate enough charge to yield a spark ignition, as discussed in aluminum explosion event in Chapter 2.

The effects of the tokamak's magnetic field on dust combustion are not well defined. Wakayama (1996) states that experiment evidence shows that magnetic fields over 1 Tesla can affect the direction and growth of diffusion flames, but not the flames in pre-mixed combustion systems. The dust lofted into air would be a 'pre-mixed' system, where the fuel is dispersed into air, while a dust layer fire would be a diffusion flame system, the oxygen diffusing onto the fuel surfaces. Mizutani (2001) experimented with a 5 Tesla field and a bunsen burner diffusion flame, seeing some magnetic field induced effects in bending the flame and slight decreases in the rate of nitrogen oxide formation. Combustion products are known to be ionized in the high temperature process, so bending the 'gas bag' of the diffusion flame and altering the slower chemical processes of combustion (e.g., NO formation) are reasonable effects from a strong magnetic field.

4.4 Dust Particle Size in Combustion

The literature sources all agree that as the size of the dust decreases, the energy released in an explosion increases (Bartknecht, 1989; Eckhoff, 1997; Barton, 2002). Surveying the particle characterization work performed thus far for fusion shows that there is cause for concern over energy release in an in-vessel dust explosion.

Winter (1999) has described graphite and iron dust particles found in the TEXTOR tokamak. Images of the dust particles show the surface texture and roughness, and the high surface area that is available for reaction with air. Carmack (2000), Chappuis (2001), Patel (1999), and Sharpe (2001) have characterized dusts collected from existing tokamaks and other experiments, with the large majority of the dust being under 20 microns. The dust particulate appears to be originating mainly from the armor tile materials, so much of the dust in existing machines is composed of graphite, but the Alcator machine dust was composed mainly of molybdenum. The molybdenum dust was sized similarly to the graphite and other dusts found; it was most often between 1 and 10 microns in diameter, with some submicron dust and a few larger particles at ~100 microns.

Sweis (1987) studied the effect of mixtures of particle sizes when igniting a dust cloud. He studied oil shale dust and sugar particles, conducting several series of experiments in a furnace apparatus. He found that when coarse particles (~230 micron average) were mixed with fine particles (~69 micron average) for a total concentration of 1 gram/liter, the finer particles were ignited first, and if the fine particles were up to 30% of the weight of the dust, then the autoignition temperature would be reduced by 20 to 30% from the larger particle value. van der Wel (1991) studied the effect of particle size and pore size on dust ignition and explosion energy. He found that for the mild explosions graphite can produce, there was no difference between activated carbon (with 20-30 times the surface area) and graphite dust. van der Wel's team theorized that only the largest and most easily accessible pores on the surface of dust particles effectively increase the reaction surface area available during explosion propagation.

Baker (1991) states that particles with diameters up to 500 microns can be considered explosible dusts. The Uniform Fire Code (UFC, 2000) also defines combustible dust as finely divided solid material which is 420 microns or less in diameter and could be ignited in air by a flame, spark, or other ignitor. Baker points out that dusts must be significantly confined with the oxidizer to produce a deflagration. Unconfined dust clouds can be ignited, and a flame can propagate through the cloud, producing a large fireball. A fireball will create heat and light, and poses a safety concern, but a fireball does not generate an overpressure wave that damages chambers or structures. Combustible dust clouds can be deflagrated, but not *detonated*, from “soft ignition”, meaning low energy ignitors such as sparks (Baker, 1991). Eckhoff (1997) also gives this discussion, but points out that aluminum dust has been detonated in air by using several kilograms of high explosive as the ignitor. Such high energy, intense ignition (hundreds of kJ in ms time frames) is outside the realm of fusion power applications. Dust cloud detonation is not a concern for fusion power plant safety, only deflagrations pose a concern. Deflagrations are serious enough threats to vessels and piping.

4.5 Dust Layer Combustion

Lees (1996) describes dust layer fires as two types, flaming or smoldering. Flaming fires usually require that the dust fuel evolve some form of combustible vapor due to heating, either metal vapor or metal oxide vapor (and the oxide reacts in air to become a higher oxide). Then an easily-recognizable luminous flame forms in the vapor above the dust layer; the flame color will be characteristic of the material burning. Metal dusts can create flames during combustion, but the dusts usually do not evolve vapor unless lower oxides are vaporized from the surface under combustion temperatures. Smoldering combustion is usually favored in metal dust deposits. Layers of some types of dust tend to insulate hot surfaces, and smoldering may begin at the hot surface under the dust, or at some point within the dust layer, where sufficient air has infiltrated into the layer and the thermal conductivity of the dust has held the temperature at a high value. While metals are usually high thermal conductivity, metal dust layers have lower conductivity than bulk solids due to the particle packing factor and resistances of particle contacts in the layer. Larger particle sizes tend to reduce the smoldering rate. The minimum depth of typical dusts to allow sustained smoldering is 2 mm (Lees, 1996). The NFPA states that dust layers have several classifications. If the true color of the hard surface under the dust is discernable through the dust layer, the dust is not thought to pose a hazard and there is no classification for electrical equipment enclosures and sparks, etc. If a dust layer is less than 3 mm thick and the true color of the surface is not discernable, the electrical equipment classification is Division 2 in the electrical code. If the dust layer is over 3 mm thick, the electrical equipment classification is Division 1 in the electrical code (NFPA, 1997).

A dust deposit can smolder in air for very long periods of time. Lees states that it is known in industry that large dust piles can smolder for years. In this regard, fusion may have an advantage that as the vessel is evacuated, smoldering should be significantly retarded due to starvation of air. Granted, fusion vessels are baked out to release water vapor that clings to walls, thus reducing ‘virtual’ leaks in the vacuum system, but bakeouts for tens of hours at ~200°C are not an issue for metals dusts that might reside in the vessel; Table 3 shows that layer ignition is on the order of 300°C and higher.

Sichel (1995) described experiments where the behavior of a dust layer was studied. The dust layer was exposed to a dust cloud explosion, the heat and pressure served to entrain layered dust, mix it in air, and ignite it. The combustion wave front, being fueled by the added dust from the layer, accelerated up to detonation (i.e., supersonic) velocity during tests for wood, wheat, cornstarch, and other non-metal dusts. Full scale experiments in a coal mine suggest that the laboratory results are at least qualitatively applicable to industrial scale facilities. While dust does settle to the bottom of fusion chambers, it is noted to find its way under tiles, into castellations between tiles, into ports, into vacuum valves and pumps, etc.. The dust is eroded from tiles, but generally does not reside in any mm depths on the large surface area faces of plasma-facing tiles. The dust layer prompting a deflagration-to-detonation transition does not appear to be applicable to fusion chambers.

4.6 Temperature Effects

As the temperature of the dust or powder increases, the ignition energy usually decreases (Eckhoff,, 1997; Barton, 2002). A high temperature furnace, the Godbert-Greenwald furnace apparatus, generally tests dusts at 800°C, but can test up to 1000°C. Usually a dust sample of 0.2 gram is used, dispersed in the furnace by an air blast (Barton, 2002). Eckhoff also showed that the minimum spark energy needed for dust cloud ignition and the minimum explosive dust concentration decreases as the dust cloud initial temperature increases. Minimum spark ignition energies can decrease by up to a factor of ten over the temperature range of 20 to 1000°C. Some dusts showing a factor of 1.5 to 2 decrease in concentration over a temperature range of 20 to 200°C. Eckhoff also showed that the higher the temperature of the dust cloud, the lower the peak explosion pressure. This result is due to the oxygen concentration for a given volume decreasing with increasing temperature. Eckhoff showed that many experimental results showed this relationship: $(T_{amb}/T_i) = (P_i/P_{amb})$, where temperature subscript “amb” refers to ambient temperature of 323 K and subscript “i” refers to the dust cloud initial condition of elevated temperature. The pressure subscript “i” refers to the peak explosion pressure at elevated temperature, and “amb” refers to the maximum explosion pressure at 323 K.

4.7 Hybrid Combustion

Hybrid combustion is defined as having combustible dust and a combustible gas both mixed in air. In general, having the combustible gas present means the combustion requires less ignition energy and also propagates more easily than dust alone. Usually combustible gases have lower spark ignition energies than dusts, and the combustion of gas and oxygen adds heat to the mixture (Barton, 2002).

For fusion dusts, the situation is more complex. The dust particles may contain tritium and deuterium that has adsorbed to the particle surface or absorbed into the particle mass. Knipe (2001) discusses results of tests of carbon dust and flakes from the Joint European Torus. The tritium thermally desorbed from carbon flakes at $\sim 800^{\circ}\text{C}$, to a level of 1.2 TBq/gram of carbon. The desorption process is measured in hours; Knipe presented a graph of GBq/h that peaked at a rate of 1TBq/h at about 500°C and then decreased again. With particle combustion to oxide form, the process of desorption might be somewhat faster – the particle surface will be consumed, liberating some tritium. Tritium that is adsorbed to the dust surface could easily combust, but the bound tritium in the particles may not combust as easily.

4.8 Combustion in Gases Other than Air

The metal dusts considered likely to be found in fusion facilities were examined to determine if they might undergo reactions in any gases other than air. A primary concern was nitrogen gas, if the metal would undergo a nitride reaction. For the most part, the nitride reactions were found to occur at high temperatures above $\sim 600^{\circ}\text{C}$. Table 6 gives the results of some testing with different metal dusts in nitrogen and carbon dioxide. Of course, argon gas is ‘noble’, that is, non-reacting with other elements. If there is an accumulation of dust in a vessel, operations approaches could either allow the vessel to cool to low temperature and then purge the vessel with nitrogen gas, or if the purge must occur quickly, then purge with the much more expensive argon gas at higher temperatures.

Metal dusts are unique in that they will often react with steam to form oxides, for example, $2\text{Al} + 3\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2 + 819 \text{ kJ}$ (Friedman, 1998). Such reactions were discussed in Chapter 2. Other, non-metal dusts (agricultural, pharmaceutical, etc.) have used steam as an inerting gas. Steam has the drawbacks of incompatibility with some dusts (i.e., leads to caking and unwanted chemical reactions), condensation on cool surfaces leads to a loss of inert atmosphere, and potential non-availability during plant startup and shutdown (Barton, 2002). For fusion, with its metal dusts, safety analyses have recognized the issue that the dust layer will likely react before the solid wall materials. Gaeta (1997) calculated steam reactions with 50 micron beryllium dust, for in-vessel LOCA events, and found that the reaction would generate ~ 2 kg of hydrogen gas in the vacuum vessel for ITER.

Table 6. Combustion of metal powder layers in gases other than air.

Element	Characteristics of the Combustion System		
	Particle size (microns)	Ignition temperature in Nitrogen gas (°C)	Ignition temperature in Carbon Dioxide gas (°C)
aluminum	8-9 and also 0.03	tested up to 1080°C, no ignition	360, and 420
beryllium	0.1	504 to 527	25
boron	0.02 to 0.06	tested up to 893°C, no ignition	tested up to 920°C, no ignition
chromium	44	tested up to 1170°C, no ignition	870
copper (94% pure)	44	no ignition (chemically reacted at 700°C, but no ignition or fire)	no ignition
iron (98% pure)	53	no ignition (chemically reacted at 200°C, but no ignition or fire)	tested up to 850°C, no ignition
manganese	44	tested up to 1316°C, no ignition	696
tin (96% pure)	53 and 74	900	no ignition (chemically reacted at 720°C, but no ignition or fire)
titanium	1 to 5	830	670
Ti mixture: 67.8% Ti, 8% Al, 2.5% Si, 3.5% Fe, &1% Cu	44 to 74	500	470
titanium hydride	44	750	710

Notes: Table values taken from Rhein (1965) and Jacobson (1964)

There is little industrial testing information published about steam reactions; apparently there are few industrial situations where metal powders or dusts contact a steam atmosphere. While steam is used as a diluting gas for some powders that can tolerate the moisture (Eckhoff, 1997; Barton, 2002), it is not used with metal dusts because the steam will easily react with elevated temperature dust or powder to form oxides and hydrogen, as discussed above for aluminum. Steam-dust reactions in fusion vessels need further study and experimentation to determine the reaction timing, completeness of reactions of dust layers with steam, production of hydrogen, and other issues.

Another concern is the hydrogen created from the metal dust-steam reaction. If the dust is mostly consumed when forming oxides in the reaction with steam, there is little concern for dust-hydrogen hybrid reactions. Hydrogen generation is a safety concern that must be accounted for in the design of the vacuum vessel and vacuum system.

It has been noted that copper dust is not highly explosive in air or in other atmospheres. Copper will react at high temperatures, but as a slow-paced chemical reaction rather than an explosion. In fact, copper powder has been used as an extinguishing agent for lithium fires (Leonard, 1994). Therefore, for machines that will have copper dust, such as the Fusion Ignition Research Experiment (FIRE), the copper may act as a diluent material during a LOVA event if the temperatures are kept low, under 700°C.

4.9 Combustion Suppression

Bartknecht (1987) has discussed the spectrum of measures to suppress explosions. These are:

- Avoiding explosible dust-air mixtures. For most dusts, the lower explosive limit is 20 to 60 g/m³, and the upper explosive limit is in the range of 2 to 6 kg/m³. Care must be taken that dust layers are not whirled up into the air to form an explosive concentration.
- Inerting the atmosphere. Many dusts will be safely inerted by nitrogen gas. Since the oxygen concentration can be dependent on the size of the dust test chamber, it is recommended to use a maximum allowable oxygen concentration for a dust that is 2% by volume lower than the concentration found experimentally. For many types of dust (agricultural, coal, pharmaceuticals, organics, etc.) an 8% volume of oxygen will preclude dust explosions. Some metals dusts require markedly lower oxygen concentrations. Hartmann (1951) showed for ~18 micron titanium dust in a spark ignition apparatus, when diluted by additional nitrogen to reduce the oxygen content in air, the oxygen volume percentage to suppress combustion was 6%. When argon gas was used, the oxygen percentage had to be 4%. Bartknecht (1987) stated that for hybrid mixtures of dust and combustible gases, the component with the lowest oxygen requirement sets the allowable oxygen concentration. Bartknecht also states that inerting will not preclude dust layer fires.

- Inerting through vacuum. Bartknecht (1987) suggested a level of 5000 Pa or lower pressure. Either an explosion is precluded by lack of oxygen, or if the pressure is high enough to provide sufficient oxygen for an explosion to occur, then the maximum explosion pressure generated in the subatmospheric chamber is less than 1 atmosphere. Damage would be greatly reduced in that situation, where the peak explosion pressure just balances the air pressure.
- Inerting with solids. In this process, non-combustible (inert) solid materials are admixed with the combustible dust or powder. The minimum ignition energy increases with increasing inert material concentration. A general concentration of inert matter needed to prevent an explosion is around 50% by weight (Bartknecht, 1987). Barton (2002) suggested that the effective range is higher, in the 60 to 80% range. Information for inerting combustible dusts was sought; Dastidar (1999) discussed that for an aluminum dust of 17 micron average diameter, monoammonium phosphate was needed in a concentration of 65%, and sodium bicarbonate was needed in a concentration of 60%. Other metal dusts have not been treated by adding solids. Presumably, for industrial applications, purity is a concern so inert gases near room temperature appear to have been favored for inerting, as seen in chapter 2.

Bartknecht (1987) also described ways to prevent ignition of the dust. He pointed out that for most industrial situations, the so-called ‘trivial’ sources of ignition (hot work such as welding or grinding, tobacco smoking, etc.) can be prevented through procedures and organizational measures. Other means of ignition are:

- Mechanical sparks. These sparks occur only when metallic materials are moved against each other or against certain types of stone at relative velocities > 1 m/s.
- Hot surfaces. Direct contact with hot surfaces can ignite dust cloud explosions and dust layer fires. Heated carbon steel and stainless steel alloy surfaces are often likely to cause ignition in industrial situations.
- Glowing accumulations of particles. Dust layers on hot surfaces can self-ignite and create glowing accumulations of dust. These hot accumulations of dust particles that are insulating dust-air mixtures from directly contacting the hot surface can become a source for ignition of dust-air mixtures.
- Static electricity. Static discharges through charged conductors can ignite dust-air mixtures if the energy from the voltage and capacitance is larger than the minimum ignition energy requirement of the dust. A number of dusts can be ignited as easily as combustible gases; that is, with milli-joule discharge energies. For example, in chapter 2, the ignition energy for aluminum dust was given as ~ 50 mJ, while the breakdown spark

energy was roughly calculated to be 150 mJ. Static could be an important ignitor for fusion vessels.

Chapter 4 References

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5. CONCLUSIONS

There are a number of conclusions that have been reached in the course of this review. The first is that metal dusts, in general, do combust and are known to pose serious safety issues in a number of industries. Dust combustion must be addressed in energy technology; either it is not a safety concern for a particular design, or it is a concern and is mitigated in some manner. The second conclusion is that dust explosions tend to become more energetic and have greater rates of pressure rise as the dust particle diameter is reduced from hundreds of microns to only a few microns. Unfortunately for fusion facilities, most of the erosion dust created in tokamaks is under 20 microns, which means that any explosion or combustion that could potentially occur would be rather energetic. Even though the explosions are energetic, they are still subsonic deflagration events. Only strong ignition sources (high explosives, gas combustion wave front, etc.) can drive metal dusts to supersonic detonation events. Fusion should not have any of these high energy drivers. The third conclusion is that dusts can be ignited by several means in fusion. A leading ignition mechanism in industry is static electrical discharge. Flowing dust gathers an electrical charge, and when the charge builds to a high level, the dust stream will discharge to a ground. The spark ignition energies are small for dusts (< 1 joule), and static discharges can easily contain enough energy to ignite dusts. Fusion also has several other possible sources of ignition besides static discharge. The first is the radiant heat from the divertor and first wall. Small dust particles in furnaces, drifting in air and experiencing a radiant heat flux, have warmed enough to serve as micro-ignition sites for combustible gases. It is also possible that the radiant heat could ignite a cloud of dust itself, unless wall temperatures are kept low. Lasers have been used to study dust combustion. Fusion diagnostics, such as the often-used Thomson scattering diagnostic for plasma particle density measurement, employ similar types of lasers of similar power levels. A Thomson scattering laser might be pulsed at 15 nanoseconds, delivering a joule of energy per pulse. It is theoretically possible that a diagnostic run-on after a LOVA could ignite the dust swirled into the air, if the beam can contact a particle long enough and the beam is not dispersed by the multitude of particles lofted into the atmosphere. Another issue is the plasma heating devices. The radiofrequency antennas for plasma heating should de-power when the plasma departs of nominal conditions. If the system were to run-on, it is possible to see a 'sparkdown' or arc event due to ionized dust on and near the antennas. The arc, driven by high power in the radiofrequency system, could ignite dust.

These findings are counterbalanced by the fact that two fusion dusts, carbon and copper, are not very reactive. At modest temperatures, these two elemental dusts may serve as diluent materials. The diluent materials provide two key features to preclude a dust explosion, they intersperse between the combustible metal dust particles to dilute the concentration of combustible dusts so that a combustion wave does not propagate in the lean mixture, and they also absorb heat that might otherwise raise the temperature of combustible dust particles for combustion. Carbon is known for its ability to absorb heat. The combustible dusts can pose a hazard in fusion vessels. The simple LOVA accident should include dust combustion as part of the accident analysis. It is possible, for a machine like ITER that has as much carbon dust as metal dust, that a dust combustion

reaction is precluded by dilution if the temperatures and ignition energies are kept below those of carbon. For a machine like FIRE, with copper dust, the same conclusion may also be drawn. Individual scenarios would have to be analyzed to verify that combustion is not possible.

Data collected for this report also shows that metal dusts can also react with other gaseous atmospheres, as well as with steam. Generally, reacting with a nitrogen atmosphere requires very high temperatures above 500°C for fusion materials. The dust combustion in an in-vessel water coolant breach is also important to examine for its possible damage to the reactor vessel. Steam reactions have not been examined as thoroughly as air reactions in the industrial testing. Steam-dust reactions need further study and experimentation to determine the reaction timing, completeness of reactions of layers of dust with steam, production of hydrogen, and other factors.