Taming the Beast - Lessons Learned from 5 Decades of Aluminium Dust Explosions

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This paper describes six aluminium dust explosion incidents which have occurred at AMG's site in Anglesey over the course of 5 decades. The incidents have revealed that the use of good explosion prevention and protection practices at the time was often insufficient and the use of measures over and above what would be expected is necessary. Owing to their very high reactivity and rapid flame propagation, protection from dust explosions with fine aluminium powder is often at the limit of what best available technology can deal with reliably. The site has found it is necessary to restrict access even to explosion protected plant as a result. The incident history has revealed gaps at each stage and enabled them to develop the explosion prevention and protection systems to the point where personnel now have a high level of protection. The paper also re-enforces the huge benefits gained from incident learning in advancing our process safety knowledge and the authors would like to thank AMG for being willing to share their experiences.

Keywords: Aluminium powder, dust explosion, incident learning, case studies

Introduction

AMG Alpoco in Anglesey, North Wales, manufactures fine aluminium powder using melt atomisation, employs 43 people and has been operating since the late 1960's. The powder has a number of end uses ranging from metallic effect pigments to rocket propellant, the latter application making good use of its reactive properties. It is well known that due to these reactive properties, aluminium powder is a combustible dust and can, under the right conditions, exhibit some of the most severe explosion consequences possible in industrial powder handling. Handling such a hazardous material presents challenges to manufacturers such as AMG to ensure the fire and explosion risks are suitably controlled.

Owing to the hazardous nature of the material, the site has a history of dust explosions. Fortunately none of these has resulted in loss of life and the majority have not resulted in significant injury to personnel. The first explosion occurred in 1973 on Line 1 although details of this incident are not well recorded. The most widely known occurred in 1983 when AMG Alpoco (then the Aluminium Powder Company Ltd), had an explosion on a melt atomisation line which caused significant damage to the process and two injuries but no loss of life occurred. When re-building the plant, the company took on board all the lessons learned. The key aim was to prevent recurrence but owing to the high ignition sensitivity of fine aluminium powder and some high energy processes involved in its manufacture, this needed to be combined with measures to ensure that further explosions would not harm personnel. This required incorporation of state of the art (at the time) explosion protection systems. The decision to provide this protection was a good one as since 1983, the site has had further dust explosions or varying severity, and one as recently as 2019. However, in all cases since 1983, the explosion protection measures employed worked as expected and prevented harm to people both on and off site. However, each time an incident occurred, potential deficiencies in existing process safety systems were identified and improvements adopted. The site's explosion safety improvement over the decades has therefore been brought about by a combination of adopting recognised good practice as well as from incident learning which has often driven the need for some innovative solutions above and beyond recognised good practices. In addition, DEKRA (formerly Chilworth Technology Ltd) have provided support and advice on compliance with DSEAR[1] and explosion testing of powders. AMG have taken on board much of this advice which has led to further improvements in explosion safety.

Aluminium powder is widely handled in industry either as a raw material, product or by-product and explosions continue to happen worldwide. This paper describes each incident, its causes and how the lessons learned from each one have positively transformed AMG's dust explosion safety over the past 35 years and which also have widespread applicability. The paper focuses on both the engineering measures employed and improvements in process safety management systems and culture. A photograph of the site is given in Figure 1.

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[1] Dangerous Substances and Explosive Atmospheres Regulations 2002

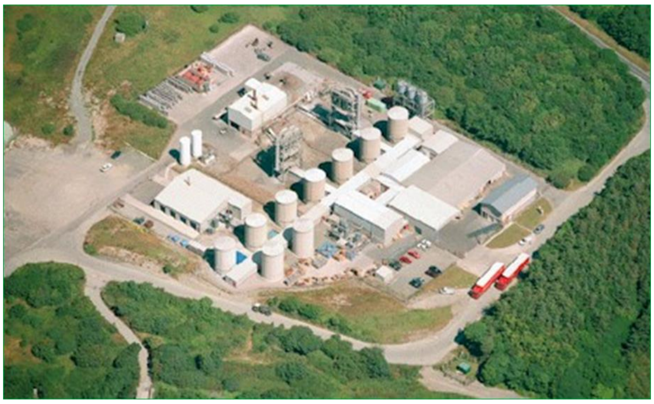

Figure 1: Aerial photograph of the site

Process description

The first step in the manufacture of fine aluminium powder involves melt atomisation. Aluminium ingots are melted in a furnace and the molten aluminium flows into a nozzle where it is atomised using compressed gas. AMG Anglesey site has 4 atomisation lines with Lines 1 and 2 atomising with compressed air, and Lines 3 and 4 atomising with inert gas in a closed loop system with continuous oxygen monitoring. The inert gas used on Lines 3 and 4 is usually nitrogen but other inert gases such as Argon can be used. Other metals such as Zirconium can also be added to the melt although generally in small amounts. The powder is separated from the gas stream using cyclone banks within a restricted access compound where it discharges into a buffer hopper from where it drops into metal bulk containers known locally as e-bins. The e-bin collection for Lines 1 and 2 is at the end of a linear track which provides appreciable separation from where people are present. Conveying air for Lines 1 and 2 is created using a fan located after the cyclone banks which exhausts to atmosphere. On Lines 3 and 4, the conveying fans are located within the closed loop to provide motive force for the circulating gas. Powder collected directly from the atomisation process is locally termed “As Blown” powder or AB for short. This may be sold directly or more commonly sieved and / or mechanically classified to produce tailored particle size distributions. Classification and sieving are carried out in specially designed cylindrical towers (silo towers) with re-enforced walls, doors and weak roofs.

Product is packaged into Type C[2] big bags, medium sized metal drums or paper sacks. Prior to packaging, e-bins are often blended using a tumble blender to ensure product uniformity. There is also a mechanical blender into which product can be pneumatically conveyed using nitrogen, blended in an inert atmosphere with continuous oxygen monitoring and collected directly into Type C big bags. Dust extracted during packing is routed to one of two reverse jet dust extraction filters located outside in a fence off compound with exchange key access. Powder can also be filled into silos and sent offsite in bulk road tankers. The silos are filled pneumatically from e-bins using nitrogen and the silos inerted with continuous oxygen monitoring.

Explosion properties of aluminium powder at AMG

In order to show the hazards of the materials that AMG handles, some of the explosion properties have been provided in Table 1. These are based on actual test data. Owing to the large number of product specifications produced, testing every product is not feasible but the data in Table 1 provides a good flavour of the range of explosion properties encountered.

Table 1: Dust explosion properties of selected aluminium powder produced at AMG

Material Description	**Layer ignition temp. (LIT) °C**	**Minimum ignition temp. (MIT) °C**	**Minimum ignition energy (MIE) mJ**	**Maximum explosion pressure (P_{max}) bar g**	**Explosion severity constant (K_{st}) bar m s^{-1}**	**Minimum explosible conc. (MEC) g m^{-3}**	**Limiting oxygen conc. (LOC) %$^{v}/_{v}$**
6 μm nodular (classifier fines)			10-25				

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[2] A type of big bag with continuous woven conductive threads that needs to be earthed

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Line 3 filter fines	> 400	580	< 5				
30 µm spherical (from atomising with N_2))			25-50				
Line 1 HGAB) (as blown)	310		25-50				
350D - 6µm (ex screen rooms)			25-50				
VAC002 (25µm median)			30-46	10.6	443		
VAC005 (26µm median)			91-122	9.6	231		
CLASS.6.006 (7µm median)				11.6	596		
Data ex Chilworth (7/9/1998)				8.9	327		10
Data ex Chilworth on Line 1 AB powder						40	

Further data was obtained from testing over a period of time. This data showed a range of K_{st} from 64-274 bar.m/s, P_{max} from 3.3 to 11.8 barg, and MEC from 50-1200 g/m^3. The highest K_{st} in the range was from AB powder less than 38µm in median particle size. AB powder greater than 38µm in particle size typically had a Kst less than 100 bar.m/s. The data shows that the aluminium powder produced on site has a range of explosion property values dependent predominantly upon particle size. The very finest powders having a low MIE and high K_{st} reaching well into the St3[3] dust explosion severity category. With an MIE in the 5-25mJ range, the powders are also sensitive to ignition sources such as relatively low energy electrostatic sparks from isolated metal plant and people. Inert gas atomisation can also produce more spherical particles and this also affects the explosion properties. From DEKRA's experience, the level of surface oxidation also has strong influence although this is unlikely to differ considerably at AMG as even in the inert gas lines, a minimum oxygen level of 2% is maintained to ensure surface oxidation is achieved prior to exposing the powder to atmospheric oxygen levels. This is a safety measure employed to avoid possible pyrophoric behaviour (which has never been experienced on site).

Incident description and learning

In this section, six incidents are described and the key lessons learned are highlighted. In addition, the improvements made to the explosion prevention and protection systems are explained. It should be noted that the main author of this report (DEKRA) was not involved in the incident investigations although has carried out several DSEAR assessments for the site and discussed many of the incidents with site personnel in detail. The information presented is therefore based on the outcomes of the AMG internal investigations or external investigations by others in addition to further interpretation by the author and co-authors. The findings from these incidents (with the exception of the 2019 incident due to its recentness) were also used to support the DSEAR assessments.

Incident 1 - Dust explosion in 1973

Details of this incident are not clear due to absence of records of the incident analysis although it is known that at the time [Wright 2001], explosion panels fitted did not have trip wires to stop the plant after the explosion. This was thought to contribute to the severity of the explosion and a key recommendation was to ensure all future explosion vent panels had trip wires linked to plant shutdown.

Incident 2 - Explosion in cyclone banks in 1983

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[3] Kst > 300 bar.m/s

On 16th July 1983, the site had a large dust explosion on the atomisation line which caused substantial damage to the plant and injured two people. The damage can be seen in Figure 2.

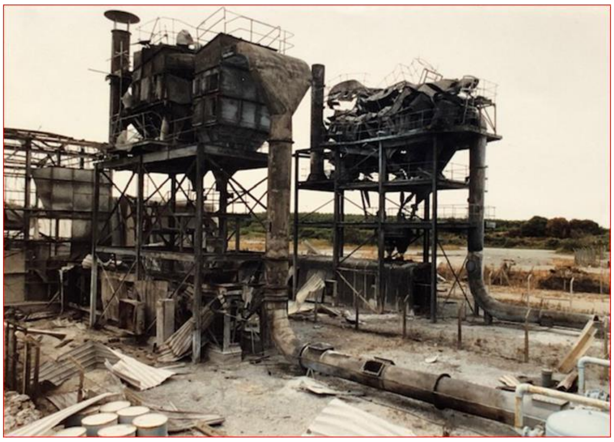

Figure 2: Aftermath of 1983 explosion

This incident was widely reported, mainly because of the level of damage it created. The exact cause of the incident was not fully determined although the most likely ignition source was thought to be an electrostatic discharge. However, details of how or where this occurred remain uncertain. For example, the use of earthing and bonding was already well established on site leading to the conclusion that an electrostatic spark discharge from isolated equipment was unlikely. One theory was the possibility of aluminium powder becoming charged in flight and sparking to the wall of the duct or cyclone. Consultation with an electrostatic expert at the time deemed this unlikely although not impossible. One important point to note was that the plant had explosion venting fitted (as it did in 1973 too) although for a number of possible reasons (as explained later in this section), it did not work as expected and substantial damage occurred even to vented equipment. The incident highlighted the devastating effect of aluminium dust explosions and the new layout, selection of some of the replacement equipment and controls and explosion protection systems was clearly influenced by the lessons learnt from the analysis of this explosion. The company also looked at what other aluminium powder producers were doing from an explosion safety perspective in an attempt to gain further insight. From comments on record [Wright, 2001], it would appear that no significantly different precautions were being taken by other companies. Some of the key learning points and changes as a result of learning from this incident are detailed below. This incident influenced the biggest step change in dust explosion prevention and protection on site.

Explosion prevention improvements

A number of measures were put in place to prevent further explosion through prevention measures such as avoiding flammable dust concentrations, ignition source avoidance or inerting. Some of these are described below.

When the original plant was built in the late 1960's, a production rate (atomising rate) of 750 kg/hr was set in order to comply with the target output required by the management of the day. This became the "Standard" atomising condition even though the atomiser itself could easily produce at a higher rate. It was subsequently found that with the conveying air rates used through the plant, this production rate would keep the dust concentration in the main conveying duct at an average concentration of around 22 g/m^3 which is just above 50% of the MEC of the lowest MEC measured. Although it was known that once in the cyclones, the dust concentration would increase (by design intention), keeping the dust concentration in the main conveying duct below the MEC is important. This is particularly the case at the first point of entry of the molten droplets into the duct where the temperature will be above the MIT (for a short time as cooling is rapid). Whilst it would be better to operate at below 25% of the MEC, this would not be economical and for this reason, the duct is fitted with explosion vents and is within a restricted access compound along with the cyclone banks. However, prior to the incident, the safety benefit of this rate was not considered and although the trend to finer powders meant that using higher production rates was unlikely, it would be easy to exceed this limit in future unless stated as a key part of the basis of safety. The production rate is now a key safety control parameter and the following safety features are present

1. The rate is measured and a local readout provided to the operator. The rate is measured by temperature inference and is therefore not accurate but provides enough accuracy to ensure rates are maintained within safe limits. Rates have typically lowered gradually since 1983 anyway due to the trend towards finer material.
2. Atomisation gas cannot start without the conveying air fan running. The fan has a rotation sensor on its shaft which is interlocked to the atomising air valves.

3. The fan is fitted with continuous vibration monitoring so problems which might affect the airflow performance can be identified quickly.
4. Airflow in the duct is now measured and alarms are present in the atomising furnace rooms – this is a more recent addition as finding a reliable means to do this proved very difficult.

The site now produces at a rate of 600 kg/hr or less on air atomisation Lines 1 and 2 and with an increased conveying air flow of 39600 m^3/hr which has further reduced the 'average' dust concentration to less than 40% MEC.

In addition, the atomising air was filtered and dried to minimise any possibility of moisture ingress which can cause product to stick to surfaces and increase the amount of fuel in the system should an ignition occur. Preventing moisture ingress is also desirable as aluminium powder can react with water (slowly at ambient temperature) to produce hydrogen. With the high air conveying rate through the plant, hazardous hydrogen build up due to moisture in the atomising air would be unlikely. However, elsewhere on site, hydrogen build up could occur and as a result, the site is very careful to avoid water in any of the process areas. This resulted in a policy to exclude any use of water in the processing areas.

The continuous vibration monitoring of the fan can also help identify blade balance issues and bearing issues which may result in mechanical sparking. However, normally, the high efficiency cyclones ensure the dust concentration through the fan is very low. High dust concentration through the fan would result in product loss and so ensuring maximum cyclone performance makes sense for both economic and process safety reasons. The fan is always run for a period after the atomising air has stopped (this is interlocked) to prevent settling of powder which may result in transient increases in dust concentration through the fan upon subsequent start up.

The re-build paid special attention to earthing and bonding particularly as the incident ignition source was considered to be electrostatic discharge. However, it was recognised that earthing and bonding would not necessarily prevent sparks from isolated sections of powder in free flight. However, the site introduced extensive use of equi-potential bonding particularly across flexible connections. One area where use of flexible equi-potential bonding leads had proven to be unreliable was across screen decks. Each deck has a flexible seal and it was found that due to the movement of the screen, wire breakage was common. For that reason, the seals between the decks used static dissipative materials to take way reliance upon wired connections.

The mechanical classifiers used to 'tail' the particle size distribution are operated under an inert gas blanket with a target oxygen level between 2 and 4 % by volume. Although one of the company's competitors had operated similar classifiers with no inert gas for years without incident, having been sensitised by the incident, a decision was made to take extra precautions. This decision proved to be a wise one as the competitor subsequently had an explosion in one of their classifiers. The company even went a step further and built cylindrical explosion protected rooms (locally called towers) with a weak roof to house all vibrating flatbed screens and classifiers (see discussion on explosion protection below).

The explosion highlighted the need to ensure electrical equipment would not be a source of ignition but in 1983 the company had difficulty sourcing much of the electrical equipment in "Dust Tight" designs and certainly not with certified T ratings so wherever possible compressed air operated devices were used for the re-build including vibrator systems etc. As they became more readily available, IP6X electrical equipment became the site standard. The site later introduced formal hazardous classification to the site and when DEKRA (then Chilworth Technology Ltd) visited in 2005 to carry out the first phase of a DSEAR compliance review, the site was already zoned in a fairly stringent way with IP6X[4] standardised within all hazardous areas. Some work has now been done to justify reduction in zone extents which is making hazardous area management easier. In addition, older IP6X equipment is gradually being replaced with ATEX[5] certified equivalents.

Explosion protection improvements

The incident highlighted that a complete re-think of the plant's explosion protection was needed. Some key learnings and improvements made were:-

1. It was found that the close proximity and similar orientation of the two cyclone banks enhanced the level of damage. Therefore Line 1 and Line 2 cyclone structures were re-built at 90 degrees to each other and with a greater separation. This minimises domino effect potential, something which significantly impacted the level of damage in the 1983 explosion.

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[4] IPXX refers to dust and water protection rating with the first number referring to the dust ingress protection and IP6X being the highest level of dust tightness

[5] ATEX refers to EU Directive 2014/34/EU for equipment and protective systems and 1999/92/EC for worker protection

2. The explosion vent location on the cyclone banks was such that vents had obstructions directly in their path. The location of the explosion vents on the re-built plant ensured a much clearer venting path
3. There was no design basis for the explosion vents on the cyclone banks. They were re-designed after the explosion in 1983 using the vent ratio method for St3 dusts. This was chosen over the K_{st} Nomograph method since there were no recognised methods to estimate the pressure shock strength of weak plant at the time and the vent ratio method did not need to know the vessel strength. The vents fitted were pop out panels (due to time constraint to re-instate the plant) which AMG had tested independently for release pressure but the tests were limited to St1 powders. This still left some uncertainty over the performance of the explosion vents. For this reason, a fenced off compound was created around the cyclone banks and conveying duct with access strictly prohibited during operation.
4. Trip wires were fitted to the explosion vents as before.
5. Prior to the explosion, rotary valves were fitted at the base of the cyclones to provide an explosion barrier. The rotary valves fitted had (and still have today) rubber tipped vanes as experience showed that all metal vanes caused unacceptable product compaction. The explosion showed that despite having rubber tipped vanes, the rotary valves did succeed in isolating the explosion. For this reason, rubber tipped rotary valves were retained. This was in an era two decades prior to ATEX and DSEAR and rotary valves certified as an explosion barrier were not available (although some knowledge of rotary valve design for explosion isolation was available). To compensate for this, the product collection e-bins were separated from the operator using a tunnel with a track on which the e-bin was driven by a linear motor. Entering the linear tunnel during operation was strictly prohibited and a strict disciplinary offence.

The cyclone banks and production buffer hoppers on air atomisation Lines 1 and 2 have recently been replaced and fitted with ATEX certified explosion panels. In addition, to the impact on the cyclone banks for the air atomisation Lines 1 and 2, the explosion in 1983 also highlighted some key deficiencies in the safety of the screening operations used at the time. Prior to the 1983 explosion all 4 screens were housed in a single screen room with each machine mounted in its own "protected bay area". These rectangular bays were separate walled compartments with large lockable wooden doors to allow fork truck access. They were open topped and two overhead hoists served two screens each. The design was such that the operators were, in theory, protected whilst they were at ground level from a horizontally directed explosion force. It was necessary for them however to climb to a higher platform level when changing the input bin on any of the 4 screens and since they were then above the protective wall they became vulnerable. Another key problem however was that the layout of the room made it impossible to keep the upper levels including beams etc. clean and free of dust and even light fittings were difficult to maintain. An attempt had been made in the building design to clad the internal walls to avoid horizontal surfaces for dust to settle on, but this proved to be a poor design and powder penetrated behind it. As a result, when the 1983 explosion took place, the primary shock wave shook this building, disturbed settled dust and created a classic secondary dust explosion.

It was therefore clear that the re-built plant would have to include a design which could provide protection at all stages of the operation, would be easy to operate with fork truck access and be easy to maintain and clean. As with the cyclone area previously discussed it was also necessary to create a system that could be stopped and started from a remote, safe position. It was decided that this could only be achieved by treating each screen machine individually and housing it in its own customised room (called a tower), with its own hoist and all equipment to make it a stand-alone unit. The rooms were designed to have a wall strength, including the door, of 0.6 barg and a roof that would lift off at 0.1 barg. In order to achieve this a circular wall construction using reinforced concrete was used and this had the added benefit of allowing internal walls to be smooth and clear of obstructions on which dust would settle i.e. it would be easy to keep clean. Horizontal solid surfaces were kept to a minimum although could not practically be avoided completely. The wall strength was based upon the predicted maximum reduced explosion pressure using the K_{st} Nomograph principles for an St3 powder. This was the best available method at the time. Operators could not enter the room during screening.

The classifiers were installed in identical rooms all of which could be accessed by a common corridor. The screen and classifier rooms were fitted with exchange key interlocks and the classifier rooms now have timed exchange key entry systems that prevent entry to the room until the classifier has stopped. The cylindrical screening and classifier towers are shown in Figure 3. The frequency of housekeeping was also increased and a centralised vacuum system installed to provide a better and safer way of cleaning. However, vacuuming aluminium powder is not without its process safety issues as the next incidents show.

Screen and classifier towers (all cylindrical towers)

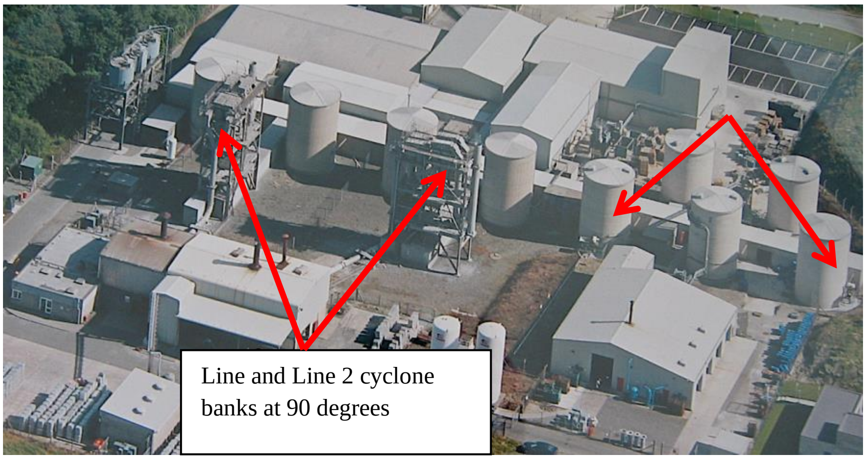

Figure 3: Photo of site showing cyclone banks and screen / classifier towers

Incident 3 - Explosion in vacuum system in 1997

As mentioned previously, maintaining housekeeping in the screen and classifier towers was essential for avoiding secondary explosions. In 1983, portable vacuum cleaners suitable for aluminium powder were not readily available. In addition, the use of portable vacuum cleaners meant the need for electrical sockets within the screen and classifier rooms as well as the fact that an explosion in a unit meant the operator was close to the source. For this reason, AMG decided to install a centralised vacuum cleaning unit with vacuum pipes routed to each screen and classifier tower as well as other powder handling areas. There are two vacuum cleaning circuits with two collection filter units located in a dedicated room with the vacuum pumps and secondary filters.

The site had an explosion in a vacuum cleaning unit in 1997 despite a number of precautions being in place to avoid ignition and protect personnel. These included:-

1. The filter chamber was fitted with “Epitropic Fibre” (Carbon coated) impregnated cloth. Static dissipative filter cloths are particularly important for conductive combustible dusts.
2. To ensure earthing of the filter bags, the filter sleeves were earthed at their fixing point on a manifold at the top and the earth was linked to the main body of the unit. Unreliable earthing of filter bags was identified as the cause of an explosion in the vacuum cleaner at their Minworth site some years before.
3. Secondary filter between the main filter unit and the vacuum pump to avoid dust reaching the vacuum pump (possible ignition source).
4. The filters were fitted with explosion vents suitable for St3 powders and which directed outside into the restricted compound. This ensured people would not be in front of the explosion vents.
5. Vent diverters were fitted on the suction lines with vents directed to a safe area to minimise likelihood of explosion propagation even though suction pipes were of small diameter (less likely to propagate flame).
6. The use of a small collection bin with a daily emptying routine to minimise ‘fuel’ in the filter unit.

The explosion vent on the vacuum filter unit worked as intended but the main consequence that was not expected was substantial propagation of flame back along the suction pipework despite that presence of the vent diverters. This resulted in flame ejection from a number of the suction points which were only sealed with a spring loaded cap.

This incident actually demonstrates phenomena that are better understood now (Taveau 2013, Ing 2018) but perhaps less well understood at the time:-

1. Dust explosions can readily propagate against air flow.

2. Dust explosions can propagate along small pipe even in the absence of limited fuel in the pipe. The suction pipe was approximately 75 mm diameter.

3. Vent diverters are not guaranteed to achieve complete explosion isolation although do provide explosion de-coupling.

As a result of this observed flame propagation, rapid acting valves were installed in each suction line triggered by pressure sensors on the vacuum filter units. An example is shown in Figure 4.

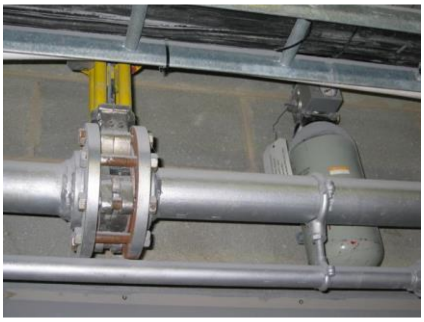

Figure 4: Rapid acting valve in vacuum suction line

There is limited information on what caused the ignition. The suction pipes installed in 1984 are made from mild steel and so the possibility of rust forming on the inner surfaces and a possible thermite[6] spark cannot be ruled out although there was no evidence of rust at the time of the incident or since. In practice the almost constant use of the system and regular passage of powder along most of the sections means that the inner surfaces tend to remain polished which has been confirmed by inspection of limited sections of pipe. Ignition by thermite spark was actually discounted by the investigation team after the 1997 incident although it was concluded that a thermite spark occurring in future could not be totally discounted. The site also excludes any use of water from the process areas which prevents water being sucked into the vacuum lines which would promote rust formation.

The system was therefore modified to protect against this possibility and, since a complete rebuild of the pipe-work system was not deemed practical (it is an extensive network), traps were installed at each inlet entry point of the circuit. These traps were designed to prevent any material other than powder from entering the pipes. Any foreign bodies sucked up are trapped by the internal mesh and are removed by taking the access plug cap off. Since these meshes are not visible without taking this cap off a regular check was implemented to ensure that they were correctly maintained. The other change made to the inlet hose connecting points at that time was to introduce closure caps which are twisted against a cam action retaining collar to create a seal. The caps previously used had a simple spring retainer and relied upon suction in the pipe to keep the cap tightly closed. These naturally presented no barrier to an internal pressure in the pipe and they allowed flame to escape from the system at many points throughout the plant in the 1997 incident. It was also ensured that all vacuum hoses were made from static dissipative material with suitable earthing and bonding.

Incident 4 - Explosion in vacuum system in 2006

Another explosion occurred in the vacuum system on 13th July 2006. This occurred on vacuum plant no.2 whilst the operator was vacuuming gas classifier no.6. The operator noticed a loss of suction and so removed the cap covering the filter trap and upon removing the cap, there was a flash and flames were reported coming out of the opening. At the same time, an operator working in the corridor reported hearing a loud bang and saw smoke and dust outside the door to the vacuum filter room. Nobody received any injuries. The vacuum filter explosion vent had burst and the vent diverter cap had released as can be seen in Figure 5 (LHS showing explosion panel and RHS showing vent diverter). There was no evidence of damage to the filter unit although the secondary filter protecting the vacuum pump was extensively fire damaged. In addition, the rapid acting valve on vacuum system no.2 suction line had shut as can be seen in Figure 6.

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[6] A high temperature spark generated when a reactive metal like aluminium is impacted against iron oxide (rust)

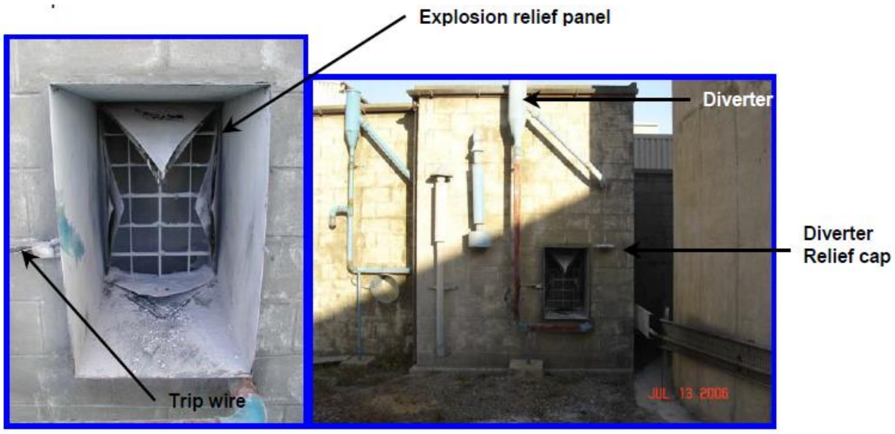

Figure 5: Vacuum filter no.2 explosion panel (LHS) and vent diverter (RHS)

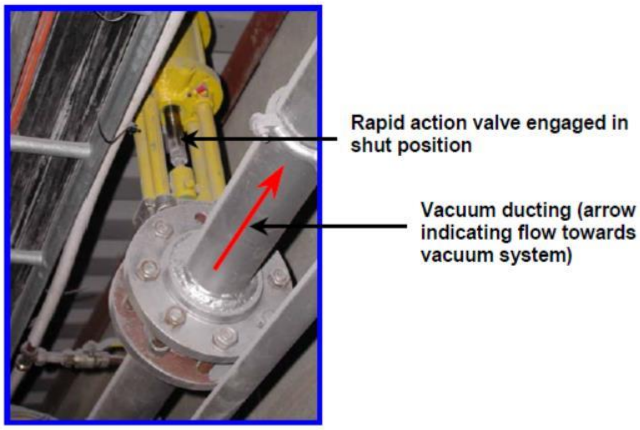

Figure 6: Rapid active valve engaged in shut position

The investigation concluded the following

1. The explosion most likely originated in the pipe near to where the operator removed the cap to inspect for blockage. This resulted in a flash out of the pipe and back to the vacuum filter causing ignition in the vacuum filter.
2. The protection systems all worked as expected and prevented both damage to the vacuum filter unit and significant propagation back to the suction caps. This means the explosion vent panels and rapid acting valve worked as expected.
3. The secondary filter was damaged by fire indicating that flame did propagate through the filter bags in the vacuum unit to the secondary filter. However, the consequences were localised and contained within the vacuum filter room.
4. The ignition source in this case was most likely caused by a thermite spark from a foreign object dislodged from the filter when the operator opened the end cap to clear the blockage. An electrostatic discharge was not considered to be the source of ignition since earthing checks of metal plant, the operator and vacuum hose all indicated adequately low earthing / bonding resistances.

A key change following this incident was to provide more robust access restriction controls to the vacuum filter room using an exchange key system. This now prevents access whilst the vacuum plant is running. Operators were re-trained in the use of the vacuum system and the procedure for inspection and cleaning of the filter traps was reviewed and improved. The vacuum plants have now been running effectively since 2006 without further incident. Prior to this incident, the packaging and blending line dust extraction filters also used a vent diverter principle to avoid propagation back to the workplace. This relied upon weak sections of duct with frequent change of direction in the expectation that the ducting would relieve the explosion and prevent propagation. However, the vacuum incident clearly indicated the need for positive isolation and rapid acting valves were fitted on the inlet to the dust extraction systems. This also allowed a less convoluted duct arrangement preventing dead spots and dust settlement in the ductwork. So lessons have been applied to other parts of the site where similar deficiencies were found.

Incident 5 - Explosion in screen 1 silo tower

At approximately 03.15am on the 8th of June 2015 an explosion occurred within screen room 1. The explosion resulted in the weak roof of the tower being displaced as can be seen in Figure 7 which was the intended function of the roof under explosion loading. The explosion also resulted in some fire damage within the screen silo tower. No personnel were injured.

Figure 7: Roof blown off screen 1 silo tower

The following conclusions were drawn from the investigation:-

1. Fatigue had caused the steel area supporting the bearing to split open. See Figure 8.
2. Once the bearing had pushed through, the continuous motion/rotation of the bearing housing created friction/heat with the surrounding stationary base unit. This is a very credible source of ignition.
3. The impact of the screen unit with the surrounding steel support framework could have created an ignition source.
4. The steel counterbalance on the underside of the unit had caused considerable impact damage to the supporting steel work of the unit. This may also have created an ignition source due to mechanical sparking.
5. All safety systems within the area performed as designed and contained the explosion. For example, the roof lifted as intended and acted as explosion relief, there was no damage to the re-enforced concrete wall of the silo tower and the metal blast doors prevented the explosion entering the occupied corridor area. The decision to install screens and classifiers within these re-enforced towers in 1984 was therefore a very sensible one.
6. The bearing unit was found to be out of line by the engineering team. An external repair to the bearing housing had been undertaken 11 years earlier and this may have been the reason for the failure.

Figure 8: Bearing housing protruding through steel support area

Corrective actions taken were as follows:-

- All the other screen units were removed and inspected for any faults.
- NDT (Non-destructive testing) was undertaken on each screen unit.
- Removing and inspecting the screen units on a 5 year plan is now part of the planned maintenance program.
- Screening silo 1 was replaced with a completely new unit.

- The screen bases are inspected on a regular basis by the Team Leaders and Maintenance team and all checks/findings are recorded.

In addition, the fact the roof was displaced suggested that a secondary explosion had occurred within the screen silo tower. To understand what might have caused this, the site collected powder from surfaces in an adjacent screen room and collected almost 60 kg of powder. If raised by a primary explosion locally to the sieve, this amount of powder could create a dust cloud well above the MEC for the entire volume of the screen silo tower. As a result of this, the site has taken further steps to improve sealing of equipment within the screen and classifier rooms including the type of sealing system used for filling e-bins with screened and classified material. This has been combined with further increases in housekeeping inspections and cleaning frequency.

Incident 6 - Explosion in Line 2 cyclone system

On 10th August 2019, an explosion occurred in the cyclone system on Line 2. Just prior to the incident, the atomising nozzle on Line 2 blocked and so the operator commenced a full line clean out procedure. During this time there was no compressed air to the nozzle but the cyclone conveying fan continued to operate and the discharge of powder into e-bins also continued under automatic control. The explosion happened during the line clean out and although nobody was injured, there was mechanical damage to the cyclones and heat damage from burning of residual aluminium powder in the equipment. The conveying line from the atomising furnace room to the cyclones is approximately 40 metres long and has six explosion panels fitted with restraining cages. All six panels had opened and the retention cages had been displaced and were located on the ground. The duct however, remained intact with no evidence of any mechanical damage. The cyclone structure has 24 blast panels and all these had opened and despite this, there was some mechanical damage to some parts of the equipment as can be seen in Figure 9 as well as fire damage / discolouration most likely from internal burning although also possibly from flame released from explosion vents.

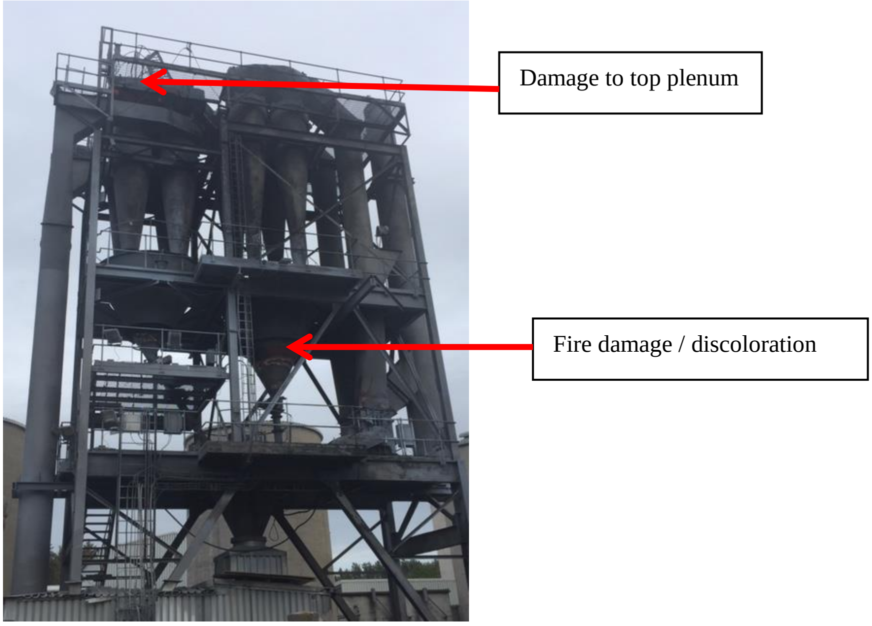

Figure 9: Damage to Line 2 cyclones

The investigation considered whether hydrogen may have generated inside the equipment which first ignited. This was soon dismissed on the basis that the conveying air flowrate of almost 40000 m^3/hr would almost certainly have provided very high dilution. It was concluded therefore that the material which ignited was an aluminium dust cloud which would have been present inside the equipment during automatic emptying even though no fresh powder was being generated. The conveying fan was shown to be without any damage and turned freely indicating that this was not the likely source of ignition. Ingress of water causing an exothermic reaction and heat was also considered but not deemed a likely ignition source. The investigation showed that some of the equi-potential bonding straps were broken with evidence that this breakage occurred before the explosion. The investigation team concluded that an electrostatic discharge due to this break in continuity was the most likely source of ignition. The reason why there was significant damage, particuarly to the northern plenum chamber on the fine cyclones is not fully understood. The explosion panels all opened in the explosion and in theory should have prevented damage. However, there are a number of points to note:-

1. The explosion may have been more violent than the explosion panels were designed for. So for example, the maximum reduced explosion pressure (P_{red})[7] may have exceeded design expectations in some parts of the installation. For example, the K_{st} may have been higher than design. The amount of vent area provided was as much as could be physically fitted to the equipment and with high K_{st} metal powders, this may not always be sufficient to avoid damage altogether.
2. The P_{red} of the equipment may have been overestimated, particularly the northern plenum which was most badly damaged. This had rectangular geometry and so would not be expected to be as strong as the cylindrical cyclones.
3. The design of the cyclone system means that pressure piling within the system e.g. between the coarse and fine collection cyclone banks may have occurred again increasing the explosion severity beyond design intent.
4. The explosion panels may not have lifted at the pressure expected. The panels were ATEX certified panels so if maintained should have a certified burst pressure but factors such as product building up may have affected their ability to open. Prior to the incident, the site did not have a rigorous inspection regime in place for burst panels on the cyclone banks.
5. Explosion vents are not generally intended to prevent mechanical deformation, particularly with weak (non-coded) plant. They key objective is to prevent catastrophic failure and harm to personnel. The level of damage was significantly less than occurred in 1983 indicating the latest protection systems worked far better even if not perfectly. The explosion consequences were also contained within the fenced exclusion zone and linear tunnel justifying the use of these exclusion zones to account for the often unpredictable and severe nature of aluminium dust explosions.

Actions the site has taken since the incident are listed below:-

1. All explosion relief panels on Line 1 (line still operating) immediately removed and inspected to ensure that they were undamaged and free from powder build up.
2. Inspection regime implemented for the explosion panels.
3. Continuous earth monitoring system installed to Line 1 cyclone system (line still operating). Integrated alarming system also installed.
4. Maintenance inspection regime developed for the grounding systems.
5. Restricted automated access gates installed within the linear tunnel areas. This prevents unauthorised access into the ‘hazard’ areas.

Learning related to process safety management systems

The Anglesey site is a sub-COMAH[8] site, but in order to ensure explosion risks are adequately managed and for DSEAR compliance, a level of process safety management is required. Under ATEX / DSEAR, these are commonly referred to as ‘organisational measures’. The incident history of the site as described has led to substantial changes in the ‘engineered’ dust explosion prevention and protection systems employed. However, it has also highlighted a number of improvement opportunities in procedures critical for ensuring the engineering measures remain effective. Whilst this paper cannot cover all relevant management systems, selected ones are discussed below. It should be noted that the site has some very good safety management practices relating to dust explosion prevention and protection, for example, it does not permit hot work anywhere on site except during shutdowns.

Management of change

Up until recently, the site did not have a formal management of change procedure. It had a procedure for handling engineering modifications but not for other types of change. A formal management of change procedure has now been developed and is being used routinely. This is a critical step for the site as the market trend is towards finer and finer product meaning that the adequacy of the explosion prevention and protection systems needs to be continually reviewed.

Training and awareness

An effective means of ensuring staff have sufficient competency to safely operate and maintain the plant is essential and this is no different from any high hazard process plant. It is difficult to be sure how much contribution training and awareness (or lack of it) played in the incidents described. However, the site has improved in this respect over the years. For example, it has developed a good induction training package on the hazardous of aluminium powder which is used for new starters as well as for re-fresher training. This package includes an actual dust explosion demonstration using a vertical tube which the site purchased

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[7] This is the maximum pressure reached in the vented dust explosion
[8] Control of Major Accident Hazards Regulations 2015

from DEKRA. Engineering and technical staff in recent years have attended more in depth training in ATEX and DSEAR and the site has COMPEX trained electricians and maintenance technicians.

Housekeeping

Some of the larger scale incidents have shown that settled dust layers have resulted in a more severe consequence. The site has over the years focused on trying to reduce dust emissions through engineering design but there are limits to how far this can be taken. Aluminium powder is quite an aggressive material and can quickly degrade seals for example. In addition, although dust extraction is used in the packaging areas, dust extraction systems handling aluminium powder present their own significant explosion hazards and so widespread use of dust extraction is not desirable with this material. For this reason, there will always be some reliance on housekeeping to control dust layers. In this respect, the site has made significant progress and operational shifts do not tolerate previous shifts leaving layers of powder on surfaces. This shift from a culture of acceptance to one of non-tolerance is a positive step and this is evident in terms of the standard of housekeeping observed today. It has also allowed a reduction in the extent of some of the ATEX Zone 22 hazardous areas.

Identification of safety critical equipment

The site is well aware of the importance of all its equipment for preventing or protecting against dust explosions and has planned maintenance in place for much of it. For example, it carries out regular checks on earth continuity of flexible leads on moveable plant, calibration of oxygen analysers on inerted plant and has external contracts on active explosion protection devices such as rapid acting valves. However, the recent incident in 2019 highlighted some deficiencies in the coverage of safety critical equipment including inspection of explosion vent panels and testing of equi-potential bonding connections on fixed plant.

Incident investigation and learning (and particularly information retention)

The site now has a rigorous incident investigation process and for the incidents from 2006 onwards, detailed records were available. However, the majority of the information relating to incidents prior to that was obtained from memory of either existing staff or basic information recorded by past staff. Since a substantial part of the basis of safety has been developed organically from the site's incident history, it is vital to retain this information in detail to ensure that future changes do not compromise it. The incident history is also a very useful tool which can be used in training of new staff and refresher training of existing staff.

Succession planning and retention of corporate memory

In many respects, this is strongly linked to the heading above relating to information retention. One of the challenges AMG has at Anglesey is how to ensure knowledge is not lost when people leave the organisation. During one of the author's DSEAR assessment visits to the site, discussions were had with an operator who was working on site when the 1983 incident occurred. The sense of vulnerability of this particular operator was clearly far greater than other operators spoken to. However, the recent efforts to raise awareness of the hazards of aluminium powder and the incident history are starting to have positive effects on the workforce safety culture. Making use of the most recent incident learning in training and awareness to further cement the culture provides a great opportunity. A very useful 'basis of safety' document was created in 2001 by a previous staff member [Wright 2001] which summarised the key explosion prevention and protection measures, their design basis and why they were in place. A substantial amount of knowledge developed since 2001 resides in a few long standing staff members (who are close to retirement) and whilst progress is now being made to pass on knowledge more effectively, creating an updated basis of safety document would further support this. Keeping information in people's brains is certain to result in corporate memory loss.

Conclusions

This paper has described six aluminium dust explosion incidents which have occurred at AMG's site in Anglesey over the course of 5 decades. The following conclusions can be drawn.

1. The incidents have occurred despite the organisation being well aware of the hazards of their materials and an above average (based on DEKRA's experience) level of knowledge on how to prevent and protect against explosions. This highlights the inherently hazardous nature of fine aluminium powder requiring constant vigilance and strong process safety management to adequately control the risk.

2. The incidents have revealed that the use of good explosion prevention and protection practices at the time was often insufficient and the use of measures over and above what would be expected is necessary. Owing to their

very high reactivity and rapid flame propagation, protection from dust explosions with fine aluminium powder is often at the limit of what best available technology can deal with reliably. The site has found it is necessary to restrict access even to explosion protected plant as a result.

3. The site is fortunate to have so many incidents without loss of life and in many cases without injury. But this incident history has revealed gaps at each stage and enabled them to develop the explosion prevention and protection systems to the point where personnel now have a high level of protection.

4. The paper re-enforces the huge benefits gained from incident learning in advancing our process safety knowledge.

References

1. Wright J.W., 2001, Alpoco Plant Layout & Design Philosophy, AMG internal document.

2. Taveau J., 2013, Dust Explosion Propagation: Myths and Realities, FIKE Corporation white paper.

3. Ing A., 2018, Combustible Dust Flame Propagation and Quenching in Pipes and Ducts, Fire Protection Research Foundation Final Report for NFPA