

DUST EXPLOSION IN SUGAR SILO TOWER: INVESTIGATION AND LESSONS LEARNT

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On 21 July 2003 a dust explosion occurred in the Sugar Silo Facility at British Sugar Refinery in Cantley, Norfolk. The plant was not operational at the time of the explosion and was actually undergoing maintenance. This paper is produced by HSE/HSL and British Sugar and describes:

- i. The circumstances of the explosion in terms of the formation of the explosive atmosphere, the source of ignition and development of the explosion.
- ii. The physical consequences of the explosion in terms of damage to the plant, the travel of the explosion through the plant, and the subsequent fire.
- iii. The consequences for British Sugar during the days following the explosion and their close cooperation with HSE during the subsequent investigation.

The paper will also discuss lessons learnt from this incident, in terms of practical considerations of explosion prevention, the practicalities of complying with DSEAR, and the protection of industrial systems such as bucket elevators from the effects of such explosions.

1. INTRODUCTION

On 21 July 2003, a dust explosion occurred in the Sugar Silo facility at the British Sugar Refinery in Cantley, Norfolk. The explosion propagated through large parts of the facility, having its greatest impact in the bucket elevators and dust extraction system. At the time of the explosion, the plant was not operational but was undergoing maintenance and modifications which involved welding on one of the bucket elevators known as the Silo Feed bucket elevator, to attach support frames onto the elevator casing for out of alignment detectors. Incidents such as this clearly cause extensive damage, injury and even death and when they occur and it is essential to learn as much as possible from them. It is for this reason that HSE/HSL and British Sugar decided to produce this paper, which describes key features of the explosion and its impact on the site.

The Sugar Silo facility at Cantley is an extensive facility consisting of six silos, a bucket elevator tower and conveyers top and bottom for transferring sugar into and out of the silos. The initial explosion appears to have occurred in the bucket elevator tower at the east end of the Sugar Silos, which is the area where the welding work was taking place at the time. The photograph in Figure 1 shows the bucket elevator tower and adjacent silos.



Figure 1. Photograph showing bucket elevator and adjacent silos

The elevator tower is approximately 52 m high and the transfer of sugar from the base of the tower to the top, uses two linked elevators known as the Production and Silo Feed elevators.

Within the tower, the lower Production/Bulk Export elevator was a single casing that housed the two separate bucket elevators to carry crystallised sugar from ground level to a height of approximately 20 m. At this point, sugar from the Production Elevator transferred to a second elevator known as the Silo Feed elevator via a chute and sugar from the Bulk Export Elevator transferred to the bulk export area of the plant in an adjacent building. Although the two elevators shared the same casing, they operated in independent channels separated by a central wall. The combined elevator was fitted with two explosion relief vents to protect it in the event of an explosion. The lower explosion vent was in a vertical orientation, fitted approximately 5 m above ground level on the up leg of the elevator. It was designed to operate at 0.1 bar with a tolerance of 25% and was actually made up of 4 individual vent panels. The top explosion vent was horizontal and was directed out through the tower wall via a right-angled duct. Again the vent was made up of four individual panels of the same size as the lower vent.

The Silo Feed elevator took crystallised sugar from the top of the Lower Production Elevator to the top of the storage silos discharging into the silo feed scroll and then onto a

series of belt conveyors feeding the storage silos. This elevator was 38.4 m in height. This elevator was again fitted with explosion vents, the lower of which was a vertically orientated approximately 5.7 m from the base of the up leg of the elevator. This vent was made up of four individual panels, designed to operate at 0.1 barg with a tolerance of 25%. The second vent was horizontal at the top of elevator and feed out through the tower wall via a right-angled duct and was made up of two individual vents.

In addition to propagating through the two bucket elevators, the explosion also propagated through other parts of the plant, including the dust extraction system ducting which terminated at an Airmaster bag filter/dust collector system. The Airmaster filter body was fitted with two explosion relief vents, which used a membrane of 'Flexotalic Glingerite' with an estimated static bursting pressure of 0.05 barg. The dust collector was housed in a separate building. The ducting system was complex, connecting almost all parts of the plant. It was badly damaged by the explosion which propagated through the ductwork.

2. THE CAUSE OF THE INCIDENT

As already described, the work underway involved the welding of metal frames to the outside of the casing of the Silo Feed Elevator. Figure 2 shows a close up of a typical weld. This work was carried out under a permit and a risk assessment had been carried out. However, this risk assessment assumed that there was no potential for an explosive atmosphere because the plant was not operational, and hadn't been for some time, and the work was been carried out on vertical sections of the elevator well away from areas where any material may have settled.



Figures 2 & 3. Close up of weld on outside and inside of case showing burnt sugar residue around weld and second area away from weld

Figure 3 shows a photograph of a typical weld viewed from reverse side, inside the elevator, which clearly shows that the heat of the welding process had transmitted through to the inside of the casing. In addition, the photograph shows black residues of charred sugar. Almost every weld examined showed similar charred residues.

A metallurgical examination was performed on the section of the elevator being worked on at the time which showed that during the welding, molten metal had penetrated through onto the inside of the casing producing temperatures approaching 1500°C. This penetration (stainless steel through mild steel) is clear from the section through one of the welds shown in Figure 4.

For thoroughness, given the serious nature of the explosion, it was important to establish that the explosive atmosphere was in fact sugar dust. This involved firstly establishing that the sugar that was likely to be in the system could have formed an explosive

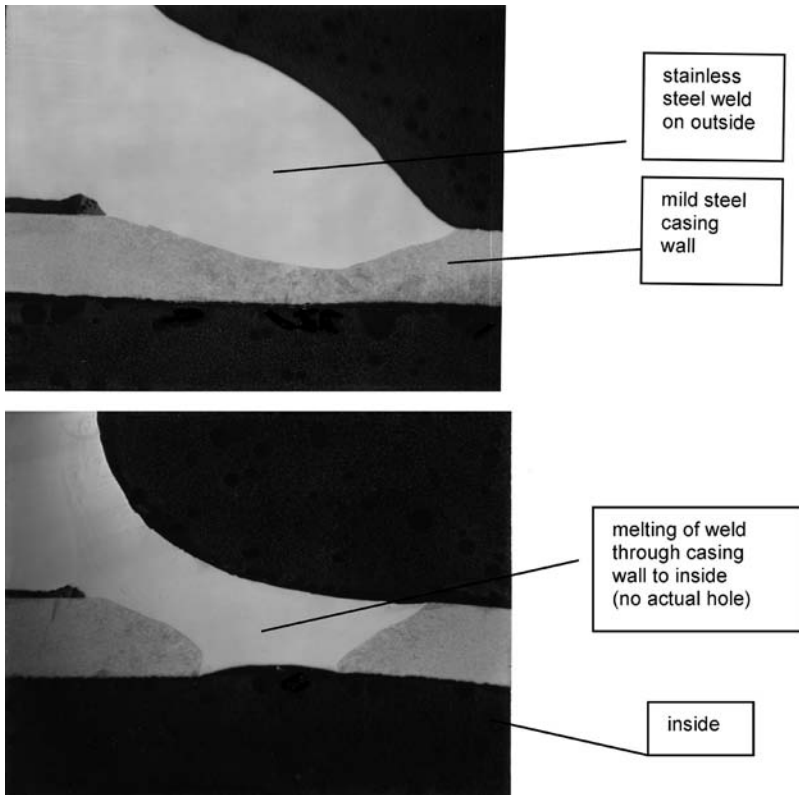


Figure 4. Sections through welds on sample

Table 1. Results of 20 litre sphere & BAM oven test

Maximum explosion pressure	8.6 bar
Maximum rate of pressure rise	650 bar/s
Specific material constant (K_{st})	176 m.bar/s
Dust classification	ST1
Lowest oven temperature for ignition	372°C
Lowest surface temperature for ignition	335°C

atmosphere and had typical characteristics of such an explosive atmosphere. Representative samples were taken from the material filtered out by the dust extraction system as these were unaffected by the explosion and were representative of the fine material that could have become airborne during transfer through the bucket elevator systems. The results of the 20L sphere and BAM oven test are given in Table 1.

At the time of the explosion the plant was not operational. As already mentioned, there was evidence of sugar on the vertical surfaces inside the elevator system. The Lower Explosive Limit (LEL) for icing sugar/sugar fines is around 60 to 100 g/m³ (according to the BIA Report)¹. In this incident it was assumed that explosive atmosphere was provided from the sugar coating the interior of the walls of the elevator, ignoring any sugar dust on the elevator belt or in the buckets. Based on the dimensions for the elevator section the amount of sugar required was calculated to be approximately 12 g/m² of surface area. Using a volume packing fraction of 50%, this gives a layer thickness of approximately 0.5 mm to achieve the LEL. Figure 5 shows a photograph taken looking into the up leg of Import/Export elevator which was not involved in the explosion. Clearly, there is considerably more than 0.5 mm of sugar coating the inside of the elevator, and so if the Silo Feed Elevator were similar the LEL would easily have been achieved. Figure 6 shows evidence of similar deposits after the explosion in the Silo Feed elevator.

Figure 7 shows a series of frames from a video recording of a test heating a sugar sample on a 1.5 mm thick metal plate. The plate is heated below with an oxy-acetylene welding torch. The sequence of events shown is (1) the heating chars the sugar and produces flammable vapours, (2) When the metal beneath reaches red heat (as would have the case in the incident) the vapours ignite and cause sustained burning of the layer even when the welding torch beneath is removed. The third frame in the sequence (bottom left) shows the moment of ignition, a small flame kernel starting around the hot spot on the plate.

3. THE DAMAGE CAUSED

The damage to the plant was extensive and the route taken by the explosion complex. It seems, as already discussed that the explosion started in the Silo Feed Elevator propagating up and then across the tops of the silos through the Silo Feed Scroll and Silo Feed



Figures 5 & 6. Photographs taken looking into the hatch on the Import/Export Elevator showing heavy build up of sugar on walls and up-leg of Silo Feed Elevator through hatch at Level 2.5 showing residual sugar fines on casing wall and bucket and less evidence of caramelisation

Conveyers. It also propagated down into and through the Production and Bulk Export elevators and to the Import/Export area of the plant and the Under Silo Elevators. The sections below summarise the explosion damage in the plant following the most likely routes for the explosion to progress from the Silo Feed Elevator, concentrating on the equipment in the elevator tower as the main areas of interest.

3.1 SILO FEED ELEVATOR TO SILO FEED SCROLL AND SILO TOP FEED BELTS

Although the Silo Feed Elevator was the area where the explosion appears to have been initiated, it had suffered comparatively little damage. Caramelised sugar could be seen inside the elevator, appearing more severe on the down leg than the up leg.

The explosion propagated out of the top of the elevator through the Silo Feed Scroll and along the conveyers blowing off the side cases and venting into the space outside. Caramelised sugar could be seen lying on the bottom of the conveyers. Explosion damage, such as displaced room/compartment doors and wall cladding material was observed along the full length of the walkway spanning the top of the elevators. On the top level of the tower the heavy steel door to the outside (access to the top of the silos and an emergency exit) which had been secured by a flat mild steel bolt of approximate size 25 mm × 5 mm, had been blown open, bending the bolt and distorting the door.

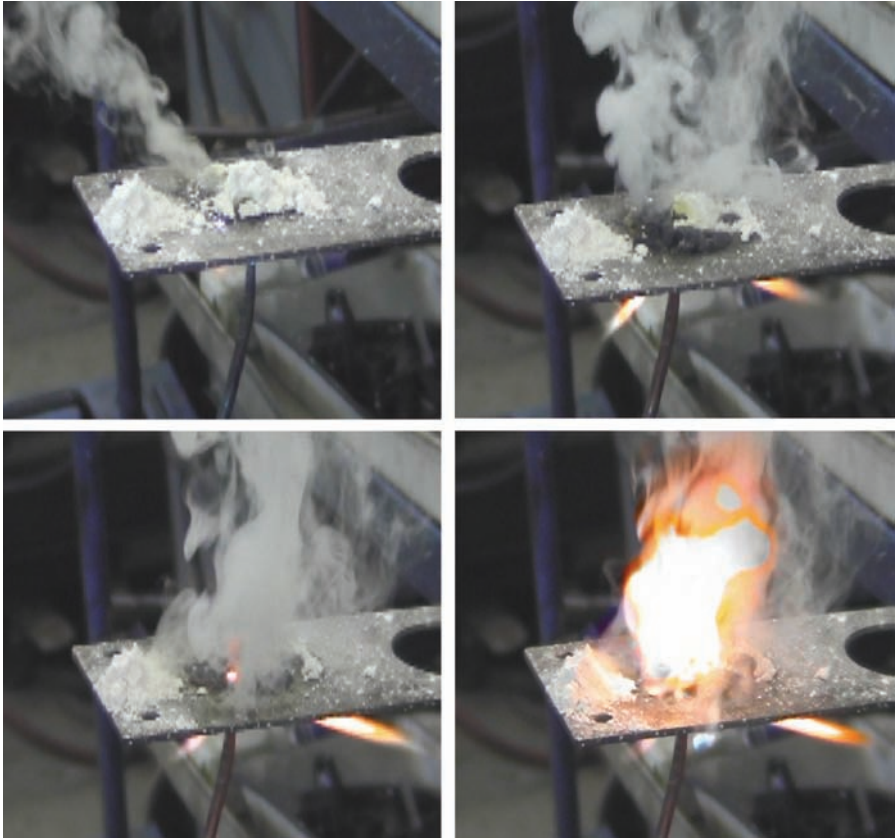


Figure 7. Frame grabs from video of heating of sugar deposits leading to ignition

3.2 PRODUCTION ELEVATOR/BULK EXPORT ELEVATOR

These two elevators are contained in a single casing, but are separated by a central steel wall. The most direct route for the explosion to have propagated into these elevators is via the chute connecting the Production Elevator to the Silo Feed Elevator. The explosion may well have then developed in the production elevator before linking into the adjacent Bulk Export Elevator.

The explosion damage to the combined elevator becomes progressively more severe towards the base. At the top there was little, if any, damage apparent to the top (head) of the elevator. Moving down the elevator at level 2 where the damage is more apparent, both legs are clearly distorted and some panels have become partially detached on the up leg.



Figures 8 & 9. Damage to Production/Bulk Export Elevator on level 2 to Production/Bulk Export Elevator just above ground level

Figure 8 show the elevator one floor level above the base where the bottom panel shown has opened up on the up and down legs. Figure 9 shows the damage to this elevator just above ground level. The elevator case opened up here and vented the explosion into the area at the base of the tower destroying the wooden partitions, entering adjacent rooms, blowing the exterior door off in this area causing injury to a worker who was close by. It also pushed down the exterior wall, caused other structural damage indicating that the flat roof in this area lifted and then resettled.

3.3 UNDER-SILO AREA

The door into the silo discharge area had been blown off its hinges and was lying on the floor at a distance of approximately 10 metres. The side and top panels on the conveyor from the silos had been blown off. The top covers had also been blown off the conveyor leading to the bagging shed, hitting the roof in several places. The fusible link on the drop down fire door on the conveyor had operated allowing the door to close part way where it had jammed, presumably as a result of the explosion.

3.4 DUCT SYSTEM AND AIRMASTER DUST COLLECTOR

The duct system on the plant is extensive and complex linking to most of the items of equipment. As such it provided a very effective means for the explosion to propagate through the plant.

The key areas of the ductwork were in the Import/Export area where the damage was severe. In terms of actual explosion damage to other items in this area, it seemed fairly limited. However, the explosion did lead to a fire in this area.



Figure 10. Building housing Airmaster filter. Note damaged ductwork at 3-way junction

At the end of the duct system is the Airmaster dust collection system. Both explosion vents on this system had operated and the filters and filter housing were disrupted. The doors of the building housing the dust collector had been blown off their hinges (see Figure 10). The ducting in this area was severely damaged. At the rear of the building a hole had been blown in the cladding where a piece of the ducting from inside had been blown through the wall and projected for tens of metres across the area outside.

4. ASSESSMENT

4.1 SOURCE OF IGNITION AND EXPLOSIVE ATMOSPHERE FORMATION

The source of ignition in this incident was the welding that was taking place on the outside of the Silo Feed Elevator in the tower. Evidence indicates that molten metal penetrated through to the inside of the elevator casing. This in theory could have directly ignited any explosive sugar dust cloud present.

However, it is also possible that the explosion did not commence immediately. A viable alternative sequence of events is that the sugar in contact with the heated region charred and then began to flame as demonstrated in the tests shown in Figure 6. This flaming could have persisted for several seconds and then ignited a cloud produced after a delay. This would have provided time for the welding work to finish and further work to

begin which then disturbed the sugar to produce the explosive cloud, e.g. an impact on the elevator casing. Based on work by Gummer and Lunn (2003)³, for this second mechanism to be viable, the sugar would almost certainly need to have been flaming, as simply smouldering material does not appear to provide such an effective ignition source.

It is clear that this work should never have been attempted without first ensuring there was no potential for an explosive atmosphere inside the elevator. However, there would clearly be problems in achieving this with the present situation, as any activity involving dismantling the bucket elevator would disturb the sugar coating within the elevator, causing an explosive dust cloud inside it and possibly outside. Care would therefore be required to ensure that ignition sources were not present. The action was and still is to ensure a flammable atmosphere does not exist, this can be by washing or cleaning a section and installing fire blanket barriers etc.

A better approach for consideration, which would be much more in keeping with the ALARP principle and Section 6 of the DSEAR regulations (2002)⁷, would be to try and eliminate the potential for an explosive atmosphere to occur in the first place. To achieve this would require a means to prevent or at least limit the build of sugar fines on the inside of the casing. It may be that this has already been considered, but dismissed due to the limited occurrence of an explosive atmosphere because activities that disturb the sugar fines are so infrequent. This is partially achieved through dust extraction, but the nature of transporting sugar does result in fines formation because crystal damage occurs.

4.2 EXPLOSION DEVELOPMENT AND DAMAGE

Once ignited, the explosion was a classical self-feeding dust explosion in the sense that the pressure wave/air flow and vibration produced by the explosion disturbed dust to propagate it through the plant (See Eckoff, 2003)². The initial explosive cloud was probably produced by disturbance of the coating in the area where the modification work was being carried out.

Evidence suggests that from the very early stages the explosion progressed through the system in both directions. Because of the linking chute, the pressure in the Production/Bulk Export Elevators would also have increased during these early stages and airflow and vibration would begin to stir up sugar fines to form an explosive cloud.

Work done by Holbrow et al (2002)⁴ gives guidance on the venting requirements for dust explosions in bucket elevators. As a basic requirement they recommend vents (100 mbar static opening pressure) within 6 m of the boot (base) and in the head (top) and of area equal to the cross-sectional area of the elevator. This would appear to be the case here.

However, other important findings reported by Holbrow were:

- i. The K_{st} value is of key importance to determine if and how the dust explosion develops. K_{st} values greater than 150 bar m s⁻¹ will propagate explosions, and vents additional to those in the head and boot are required on elevators (discussed further

- below) to limit the reduced explosion pressures* obtained. No extra vents were incorporated on either elevator.
- ii. The operation of the buckets had no significant effect on the reduced explosion pressure.
 - iii. Ignition position has little effect on measured reduced explosion pressures.
 - iv. The bucket spacing has an important effect on the reduced explosion pressures obtained. A smaller spacing tends to result in lower reduced explosion pressures.

From the data presented by Holbrow et al (2002)⁴ it is possible to estimate that a fully developed explosion in the Silo Feed elevator would have produced a reduced explosion pressure of approximately 1 bar. This is based on the K_{st} of 176 bar m s⁻¹ reported in Section 2.2.3 and a vent spacing greater than 10 m. An explosion pressure of 1 bar might be expected to cause some deformation of a structure such as this elevator casing, but generally does not appear to have done so. This suggests that the explosion did not develop fully in all parts of the elevator as indicated by the reduced level of caramelised sugar/heating on the up leg. Reasons for this may be that the concentration of sugar fines was not ideal, the relatively close spacing of the buckets may have impeded early development and also that the explosion was able to vent into the Production/Bulk Feed Elevator below thus limiting the pressure.

Considering the Production/Bulk Feed Elevator, clearly much greater damage occurred suggesting a greater reduced explosion pressure was achieved than in the Silo Feed Elevator. From Holbrow et al (2002)⁴, an explosion in this elevator in isolation could again be expected to produce a reduced explosion pressure of approximately 1 bar using the same approach as above.

However, the damage to this elevator was much more severe because:

- i. The effects of the explosion in the Silo Elevator vented into and so pre-pressurised the interior of the Production/Bulk Export Elevator and produced a turbulent dust cloud. Although the authors know of no work on the effects of dust explosions in linked bucket elevators, the general principles of explosions in linked vessels are described by Holbrow et al (1999)⁵ entitled "Dust explosion protection in linked vessels: guidance for containment and venting". The high turbulence and higher pre-explosion pressurisation in the second vessel (in this case the second bucket elevator) combine to give a much higher K_{st} value. This in turn impacts on the effectiveness of the vents, much larger areas being required. This effect is illustrated by reference back to Holbrow (2002)⁴, which shows that for a K_{st} of 211 bar ms⁻¹ (20% increase) the reduced explosion pressure for a 12 m vent spacing is 3 bar and increases for greater vent separations. This in itself explains the severity of the damage. Note that secondary

*Reduced explosion pressure is the pressure in the system even with the limiting effects of the vents. Without the explosion vents the pressure inside the elevator could reach the maximum explosion pressure reported section 3.2.3 assuming the elevator was strong enough.

explosions in totally enclosed linked vessels have been shown to easily lead to a doubling of the K_{st} value (Lunn et al, 1996).

- ii. The bucket spacing on the Production Elevator is much greater than for the Silo Feed Elevator, which would lead to greater explosion pressures according to Holbrow (2002)⁴.
- iii. Because of the wider casing of this elevator and apparently similar bolt spacing to the Silo Feed elevator, the former is probably weaker and so more susceptible to damage.

Because the casing of the Production/Bulk Export Elevator failed, the explosion vented in to the space at the base of the tower causing damage and injury. In addition, the explosion entered the Import/Export area of the plant causing damage and starting a fire. The explosion then propagated through to the Airmaster filter system where again pressure-piling and enhanced turbulence would have led to higher K_{st} , so that explosion vents were inadequate and reduced explosion pressure was greater than allowed and damage resulted.

5. SUMMARY

While this was clearly a very unfortunate incident, it was a good reminder of the dangers posed by explosive dusts, and in particular the hazards they pose even in plant that is not operational. It demonstrates the need to have a thorough risk assessment based on a very good understanding of the plant in question, and the potential hazards. More specifically, this incident also demonstrates the importance of a means of preventing explosions from propagating between different pieces of equipment. Such equipment could include rotary valves and fast acting valves. Suppression systems are an option, but consideration may be needed to ensure that such systems do not project a dust cloud outside the equipment/elevator at junctions in the conveyers etc. If the plant had been fitted with some means of isolation, then this explosion would have been confined to the Silo Feed Elevator. The Silo Feed Elevator may have suffered more severe damage, but this could be allowed for by adding further explosion vents.

If isolation is not fitted, then vent sizes should be increased, to allow for the higher K_{st} that should be expected during secondary explosions. There may be practical limits to this approach as reference to Holbrow et al (2002)⁴ shows that for a K_{st} of 211 bar m s⁻¹ vents at 3 m spacing (meeting other criteria described in Section 4.2) would only limit the reduced explosion pressure to 0.6 bar.

Specific recommendations that came out of this incident, but which probably have wider applications, are:

1. Greater care is required when carrying out hot work to avoid a repeat of this incident. In particular, consideration should be given to the presence or creation of a flammable/explosive atmosphere inside equipment when performing work on the outside.
2. Based on the K_{st} value measured for the sugar dust and guidance in the literature (Holbrow 2002)⁴, the level of explosion venting on the elevators needs to be increased.

3. In plant where the risk of explosions is recognised, extra measures must be taken to prevent or limit the effects of propagation between interconnected items of equipment. Preferably this should be achieved using explosion isolation. However, if explosion venting is to remain as the means of explosion prevention, vent sizes should be increased to allow for the enhanced rates of pressure that will occur in secondary explosions.
4. Consideration should be given to prevent or limit the build-up of sugar inside the elevators at source (general principle set out in section 6 of DSEAR regulations, 2002) rather than having to deal with the dust build-up prior to maintenance with the associated risk of creating an explosive atmosphere.

Following the incident and during various reviews with explosion protection suppliers, the authors would also recommend the following points:-

1. Ensure that evaluations are undertaken of the strength of equipment that is to be protected by explosion protection equipment. The guidance available in the public domain for applying protection systems assumes strength data, which therefore could result in the incorrect level of protection being applied. For the correct application, actual strength data is required.
2. The design of explosion vents are also critical, ducts with bends or long ducts can render the vent ineffective.
3. Use recognised experts to advise on practical methods of explosion propagation protection. British Sugar believed they were being supplied with suitable systems for conveying to and from bucket elevators. For new installations they now have recognised industry consultants to sign off their designs/installations.
4. A team approach to high hazard activities is recommended, it avoids assumptions and ensures the right people are involved. They now also ensure that Safety Personnel, Explosion Risk Trained Personnel, Plant Managers and the Supervisor involved with Hot Work activities are present during Risk Assessments, Method Statement Generation as opposed to just Permit Issue.

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