

# SUGAR DUST EXPLOSION AT MHLUME: A CASE STUDY

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## Abstract

The dust explosion which took place recently in the Mhlume refined sugar conditioning plant is described, possible causes are discussed and the resulting damage is listed. International design standards for minimising the consequences of a dust explosion are briefly discussed, as are the steps taken at Mhlume to rectify design flaws.

## Introduction

The Mhlume sugar production facility is situated in the north-eastern Swaziland lowveld, close to both the Mozambique and South African borders. Mhlume Sugar Company produces some 70% of the 1,3 million tons of cane that are milled each year to produce around 165 000 tons of sugar. All sugar produced in Swaziland is marketed through the Swaziland Sugar Association which is a body comprised of equal representation by the Grower and Miller Associations. Some 50% of Mhlume's production will, from this season onwards, be refined sugar for sale to the southern African market. The remaining raw sugar will be sold to various overseas markets, some of which enjoy preferential pricing.

In early 1995, it was decided by the Swaziland Sugar Association that a sugar refining facility should be constructed at Mhlume. In deference to market expectations, it was also decided to construct a sugar conditioning plant, together with a 20 000 ton capacity warehouse for bagged sugar. To date six sugar conditioning plants have been installed at refineries in southern Africa.

## Process overview

### Sugar conditioning

A sugar conditioning plant reduces the sugar moisture from around 0,05% to 0,03% or less. This is done simply to improve the keeping quality of refined sugar, that is, to reduce the risk of lump formation and to retain its free flowing nature. The emphasis here is on *reducing* the risk and not eliminating it altogether, which would be almost impossible to achieve due to the hygroscopic nature of sugar. There are three categories of moisture present in sugar (Rogers and Lewis, 1963):

- *Free moisture* is the more or less dilute sugar solution surrounding all sugar crystals leaving the centrifugal separators. This moisture is easily removed by conventional dry-

ers. The moisture level will typically decrease from around 1% to around 0,05% during the drying process.

- *Bound moisture* is moisture on the surface of the crystal and is more difficult to remove, requiring the sugar to be maintained under dry conditions for a comparatively long time, such as during the conditioning process. Caking of refined sugar occurs when this bound sugar migrates through the total mass of sugar and collects in the coldest areas, particularly when the temperature in these areas subsequently rises, thus displacing the collected moisture. The target moisture for sugar after conditioning is 0,03%. Thus a ton of sugar will lose some 200 to 300 grams of moisture over the conditioning period.
- *Inherent moisture* consists of minute pockets of moisture which have become trapped during the growth of the crystal. It is possible that this moisture may diffuse through the crystal to the surface, but at an extremely slow rate. This moisture is unlikely to have any practical effect on caking.

A sugar conditioning plant consists of four major plant areas:

- The *air-conditioning plant* which provides air of the desired quality and quantity to condition the sugar. This consists of two complete systems, one working and one standby.
- The *service tower* which contains all the transport equipment, flow direction change points and provides access for maintenance personnel.
- The *conditioning silo* or tower which provides the residence time required to condition the sugar successfully.
- The *dust removal system*.

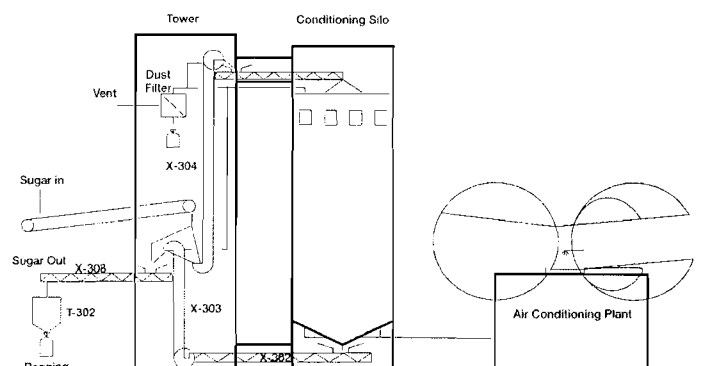


Figure 1. Simplified process flow diagram.

*The air plant*

The air-conditioning plant is the core of the sugar conditioning process. Early experimental work and plant scale trials have resulted in well established operating parameters.

These are:	Air flow	1,62 m <sup>3</sup> /ton sugar/hour
	Air temperature	42°C
	Relative humidity	20%

Note that the ambient relative humidity at which sugar will absorb moisture from the atmosphere has been determined experimentally (Excell, 1984) to be 76%.

The air system at the blower discharge is pressure limited to 200 kPa but usually operates at 175 kPa.

*The Service Tower*

Refined sugar exiting the refinery drier passes through a batch weigher and is transferred via a ribbon flight type screw conveyor onto the aero conveyor and is conveyed to the conditioning plant service tower. Sugar is elevated to the top of the tower and discharges into a screw conveyor which meters the sugar rateably into a rotary distributor located in the penthouse of the sugar silo. The rotary distributor ensures an even distribution of the sugar to a ring of 12 inlet pipes. This ensures that the sugar is layered in the silo rather than forming a cone. The sugar level is continuously monitored.

*The conditioning silo*

The sugar silo is sized to permit a normal conditioning time of 60 hours, which in the case of Mhlume resulted in a structure (excluding the penthouse) of 8 m diameter by 30 m high, including 5 m of ullage. Under normal operating conditions the silo will contain 1 200 tons of sugar at a bulk density of 800 kg/m<sup>3</sup>.

At the base of the silo there are 16 outlet cones arranged in two rings, plus a central cone. Sugar discharges through these cones and associated piping via a rotary valve into the discharge screw conveyor. The outlet pipes are equipped with flow sensors to ensure that flow occurs at all times. This is necessary to draw the sugar down as uniformly as possible. From the screw conveyor the sugar is elevated either to the bagging bin feed conveyor as demanded by the bagging rate or to recycle back to the silo. It is always necessary to turn over a proportion of the sugar in the silo to ensure full conditioning. That is, if there is no demand for sugar at the bagging plant (for example, scale malfunction, conveyor breakdowns etc), conditioned sugar is re-circulated through the silo. Feed is not stopped until the level of sugar in the silo exceeds a predetermined amount. Once this level is reached, production is stopped but recycling continues. Sugar may bypass the conditioning process in the event of equipment breakdown.

The silo is equipped with over/under pressure relief devices and 16 explosion panels of 2 x 1m, to protect the integrity of the silo structure. The silo is kept at a small negative pressure (5 kPa below atmospheric) at all times. This is in con-

trast to the service tower which is kept at a slight positive pressure by means of fans, the objective being to maintain a dirt free environment. Both the service tower and the conditioning silo are constructed of reinforced slip-form concrete 300 mm thick.

*Dust removal*

The slight under-pressure in the conditioning silo is maintained by means of a dust aspiration and filtration system which was situated one level below the silo penthouse level. Dust removed from the air is bagged and physically returned to the refining process. Under normal circumstances, approximately 25 kg of dust is removed from the conditioning silo per eight hour shift. In addition, a dust removal system designed to aspirate dust from the conveyors, elevators and change-over systems was also installed. The aspiration and filtration system is identical to that of the conditioning silo and was also expected to serve as a standby to the silo dust system.

**Explosive properties of sugar**

The best measure of the explosibility of a dust is the  $K_{st}$  value. This value is an indication of the violence of an explosion. It is also used in the sizing of explosion protection equipment.

$K_{st}$  is defined as:

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

Where  $(dP/dt)_{max}$  is the maximum rate of pressure rise and V is the volume of the reactor vessel.

A literature survey recently undertaken indicates little commonality amongst researchers other than temperature of ignition. It can, however, be stated that sugars dust is a St 1 dust ( $K_{st} < 200$ ). The minimum ignition energy is less than 50 mJ and the explosion limit is not less than 15 g/m<sup>3</sup>.

**Table 1. Explosion data as determined by various researchers.**

Researchers	Particle size (microns)	K <sub>st</sub> (bar m/s)	P max (bar)	Explosive limit (g/m <sup>3</sup> )	Temperature/energy reqd
Eckhoff (1991)	19				470°C
Schütz (1987)	30	138	8,50		480°C
	32	123	9,00	30	480°C
Field (1982)			7,60	15	30 mJ
Bartknecht (1981)		59	8,20		
		165	9,40		
Rafferty (1974)				15	48 mJ
Kessler and Knoetze (1996)	63	143	8,10		

The discrepancies between the values obtained by the various researchers can be explained by differences in particle sizes and experimental conditions. Other possible causes are whether the sugar is derived from sugar cane or sugar beet, the moisture content (and possibly the type thereof) and sugar purity.

### Early design precautions

Refined sugar dust is known throughout the industry to be potentially explosive. Precisely how explosive it is appears thus far to have been a matter of guesswork in southern Africa. At the time of designing the plant, there were no known incidents of sugar dust explosions in the region. However, in the light of our very scant knowledge, the following (over and above the dust removal system) was done in an attempt to make the plant safe.

- Prior to any design work, it was recognised that the service tower and conditioning silo were indeed potentially hazardous and were classified as Class II Division 2 (now Zone 21).
- This requires that all electrical and instrumentation fittings should be of IP65 (dustproof) standard.
- All conveyors were fitted with covers to reduce the passage of dust to the surroundings and also to prevent contamination of the product.
- Explosion panels were built into the conditioning silo in the ullage space to protect the integrity of the construction.
- Smoke detectors were fitted at strategic points in the service tower.
- It was specified that the bucket elevators were to be fitted with explosion relief panels.
- All casing panels were to be connected with earthing wire and all interconnected transport equipment properly earthed.
- The plant was designated a hot-work permit area prior to the first attempt at commissioning.

Thus, while some cognisance was taken of the explosive nature of sugar dust, the steps taken have subsequently been proved to be highly inadequate.

### Events leading up to the incident

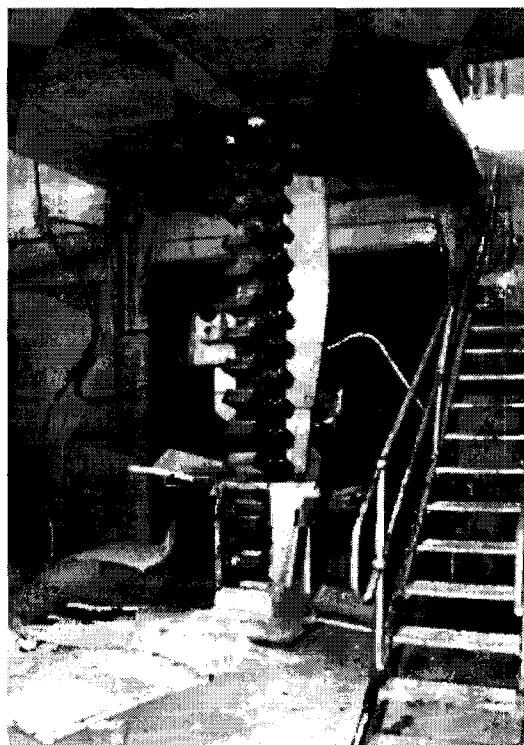
The refinery project was very fast track indeed. Consultants were appointed to do the design and project management in May 1995 and the refinery was due to start on 15 July 1996. Due to numerous design and installation problems the first refined sugar was made more than two months later on 24 September. However, the conditioning plant was not ready to run until November 1996. The initial commissioning was aborted by Mhlume because of the hopelessly inadequate conveyor dust removal, which after only two days, left the entire inside of the service tower covered in sugar dust, in many places centimetres thick. In view of the continuing difficulties being experienced with the refinery operation and the rapidly approaching end of season, it was decided to bypass conditioning and not to restart until the following season.

Some five weeks after starting up the refinery, it was decided to commission the conditioning plant once again. The refinery was stopped while conveyors, general plant and interlocks were being checked. The explosion took place shortly before 7.00 pm on 25 June 1997 in the silo outfeed

bucket elevator, termed X-303. There were five people in the service tower at the time. A fitter and helper who were working on the silo feed elevator, termed X-304, a process foreman and the plant operator, who happened to be in the personnel lift at the time. A project engineer employed by our consultants was also present. It was indeed fortunate that no one was seriously injured. The only physical injury that resulted from the incident was a minor cut on the ankle of the fitter as he was making his way out of the service tower. The damage to the plant was extensive and there is little doubt that, had anyone been in the basement or on the ground floor, serious injury and possibly even fatalities would have occurred.

### The damage

- The casing elevator of X-303 in the basement and ground floor area was completely blown apart and ballooned in the upper segments. The explosion relief panel did not rupture.
- The silo outfeed screw conveyor (X-302) motor was blown off the speed reducer by the force of the blast. Shafting was bent. The covers of this conveyor were blown off.
- All the ground floor access doors were blown off.
- The personnel lift doors were slightly damaged.
- Cable racking was buckled and cabling and fittings damaged.
- Handrails on the basement access stairway were severely bent by a flying elevator casing segment.



**Figure 2.** View of the service tower basement following the explosion.

### The cause

The Fire and Explosions Programme of the Division of Building Technology of the CSIR was contacted by Mhlume (Swaziland) Sugar Company Limited to investigate an incident at their facility. An indication of a possible cause of the explosion could be delivered, given the observations made. It was clear that the explosion caused the most damage in bucket elevator X-303. No damage was observed in bucket elevator X-304. The pressure of the explosion also moved panels in X-308, X-302 and T-302. From these observations, it is clear that the explosion originated in bucket elevator X-303.

Virtually no sign of heat damage was observed and no fire occurred after the explosion. This is an indication of a lower limit explosion. Only a small quantity of dust participated in the explosion. Indications of charring of sugar were found at the bottom of elevator X-303.

The most likely scenario for the explosion is that some of the dust that was clinging to the sides of the elevator and to the buckets dislodged. This could have happened while maintenance was performed on bucket elevator X-304. As this dust cloud fell down the elevator, it came into contact with an ignition source of appropriate energy and an explosion resulted. A metal bolt falling down the elevator could also have caused the explosion.

A hot surface somewhere in the elevator has the potential to initiate an explosion. Electrical sparks can also act as an ignition source. Given the circumstances of the explosion, neither of these two scenarios seem likely. Static discharges are also not expected to be generated by falling sugar within earthed equipment (Thorpe *et al.*, 1985). The pattern of charring of the sugar on one of the panels at the bottom of the elevator suggests that hot sugar was present in this area. This could have been the ignition source.

The fact that the exact cause of the explosion could not be identified conclusively is not satisfactory, but seems to be in line with international experience. In a study of grain dust explosions in the United States (Kauffman, 1987), the cause of the explosion could not be determined in 41% of the incidents.

### The aftermath

Obviously an incident such as the dust explosion warrants extensive investigation. In total, some 15 independent opinions were sought.

These included:

- Earthing specialist, who were satisfied with the installed earthing protection.
- Electrical and instrumentation specialists who inspected motors, fittings and instrumentation. All motors (except one, which could not have caused the explosion) were found to be of the correct type. However, the same could not be said of the wiring, electrical fittings and some of the instrumentation, where the IP65 standard had been ignored.

- Explosion experts both scientific and commercial.
- Conveyor experts.
- Other sugar consultants, particularly on the precautions required in dealing with the threat of sugar dust explosions.
- Dust extraction experts.
- Mhlume's project consultants.
- An investigator, whom, while employed by our project consultants, had previously investigated an incident at our plant and was held in high regard by Mhlume management.

What was soon apparent from all those consulted, with the exception of the explosion experts, was the lack of knowledge of explosions and how to deal with them in terms of design parameters. The usual sugar industry consultants and conveyor manufacturers had no design criteria for effective explosion venting.

The most important points arising from the investigator's report (personal communication) are:

- The plant was not designed according to the recommendations of the National Fire Protection Agency (NFPA) of the United States of America.
- The mechanical design regarding bucket elevator explosion protection and protection against misaligned belts was found to be suspect. The explosion hatches on both bucket elevators were inadequately sized and incorrectly located.
- The dust extraction ducting design was found to be incorrect, in that there are long vertical piping runs (flow upwards) and connections with poorly designed headers. The system is likely to be prone to blockages and can give rise to dumping fine sugar powder into equipment. There is no means of balancing or monitoring the operation of the system.
- The design philosophy of whether to contain dust within bucket elevators or to extract the dust to minimise explosive pockets must be established. Both are acceptable in accordance with NFPA 61, although the latter is preferred as it minimises the size of the dust explosion pocket and thus the extent of the explosion.
- The location of the dust extraction bag filters at a high elevation in the service tower is incorrect, in that they present a high explosion risk and should be relocated to a safe position outside the building at ground level.

Of further interest is the report from our consultants mechanical engineer, who was involved in the project design. His report (personal communication) mentions, *inter alia*:

- The clearances on the elevators were too small to be sure of trouble-free running under typical operating conditions.
- It is normal practice to crown the head pulley, particularly for tall elevators.
- Belt width should be wider than the buckets, although there is a danger that friction could generate sufficient heat to ignite the dust.

- Mechanical contact type belt tracking detectors could have metal to metal contact with the buckets, giving rise to a spark of sufficient intensity to ignite dust. Some run out detectors were missing.
- The provision of the blow out panel on the top of the elevator was of inadequate area and was inappropriately located for any effective protection.
- Tail pulley was unlikely to run true.
- Buckets are of crude manufacture with excess material not trimmed off.
- The elevator belts were too long.
- Inaccurate belt splicing

### Rectification

#### Overall considerations

The overall philosophy adopted is to maintain the entire plant as free of dust as possible and to provide for explosion relief in the high risk areas.

- Area classification was confirmed at Class II Division 2 as per SABS 0108. Equipment must now be Dust-ignition-proof (DIP) to SABS 969. This also means that the electrical and instrumentation installation must be certified by an accredited inspecting body.
- As far as practicable, the rectified plant should comply with National Fire Protection Association standard NFPA 61 "Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Products Facilities", (1995). Other useful publications are NFPA 68, "Guide for Venting Deflagrations" (1994) and NFPA 69, 'Standard on Explosion Prevention Systems' (1997).
- Dust extraction from the silo and the transport equipment were separated. This ensures stable conditions in the silo.
- The isolation of equipment in the event of an explosion is extremely important, since this will prevent a possible explosion from propagating through the entire plant. The bifurcating chutes between elevators X-303 and X-304 should suffice. The feed into the silo is isolated from the rest of the plant by rotary valves on both the feed and discharge. Slide valves with up and downstream pressure sensors are suitable (but expensive) if the space required for a rotary valve is not available. This is being considered for the only remaining weak spot in the system, which is the feed to the bagging bin (T-302).
- A separate vacuum cleaning system for the service tower and silo penthouse and basement areas has been provided.
- All dust filters have been located in a separate building and sited such that venting outside the building is possible.
- Lightning protection for the service tower and silo was rechecked and found to be inadequate, in view of the very high risk rating in the Swaziland lowveld. This has been rectified.
- Plant operating and interlocking philosophy was re-examined and operating manuals are being rewritten with much greater emphasis being placed on plant cleanliness.

- Selected electrical staff have been trained for working on IP65 equipment.
- Motors in the conditioning plant are painted a different colour to those in the remainder of the plant.
- Signage and security are being greatly improved.
- Conveyor inspection hatches should be equipped with alarms to prevent them being left open accidentally, thus giving rise to dust escaping (and possible product contamination).
- While unfortunately not possible in the Mhlume plant, it is highly desirable to be able to provide for explosion venting on the outside of the building or, at very least, to site the explosion vents such that the risk to personnel is minimised. This must be carefully considered when designing a new installation.

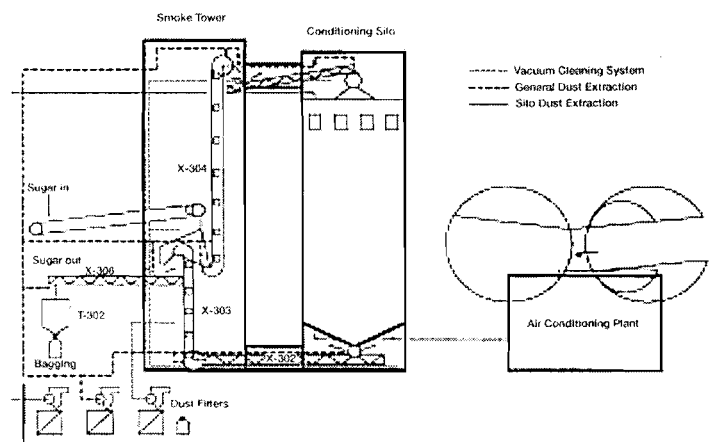


Figure 3. Process flow diagram following modifications.

#### Bucket elevators

The most hazardous areas in the plant are the bucket elevators and the dust extraction system. Bucket elevators are particularly hazardous because explosive mixtures are continuously present in the elevators while they are in operation. If an ignition source is present, it is indeed possible for an explosion to occur. Faults on an elevator should be identified and rectified as soon as possible. The following are the minimum specification/recommendations for elevators associated with sugar silos (Dupire, 1988).

- Anti-static and flame resistant elevator belts.
- Stainless steel or anti-static plastic type buckets should be fitted. The latter have proved to be unsuccessful in the Mhlume refinery. (It should be mentioned that most vendors will verbally assure that their buckets are anti-static but none have so far been prepared to provide a written guarantee.) Note that 3Cr12 is not suitable because of the high iron content, and with aluminium there is the risk of a thermite reaction taking place and thereby increasing the risk of explosion.
- X-303 has been completely rebuilt and clearances designed in such a manner as to reduce the danger of spark formation. The belt width is 100 mm wider than the

centrally located buckets and the free space between the belt and the casing is 50 mm on either side.

- Accurate, non-contact belt tracking devices such as infra-red sensors must be provided to warn of belt misalignment and hence the danger of buckets striking the casing, thereby possibly causing a spark. These should be connected to the alarm/trip system.
- Belt tensioners should also be provided to assist in preventing belt misalignment.
- Drive pulleys should be crowned to assist in the belt running true.
- Elevator bearings should be installed outside the casing in order to prevent ignitions due to overheating, and temperature detection fitted and connected to the alarm/trip system.
- Blockage detection ('bindicators') must be provided on the feed and discharge chutes of elevators as well as any flow direction change point in the plant. Again, these should be connected to the alarm/trip system.
- As already mentioned, a separate dust removal system for conveyors, elevators and directional changes has been installed. As far as bucket elevators are concerned, it is vital to remove the dust from the feed and discharge regions.
- Overload protection on the elevator motor should be carefully set as it is necessary to reduce the risk of a belt breaking. This could cause an explosion.
- If the inside of the bucket elevators must be painted, care must be taken to ensure that the paint does not form an insulating layer on the inside of the elevator. This could lead to static electricity problems.
- It is important that all the elevator casing panels are properly earthed. Care must be taken to ensure that there is indeed metal to metal contact between the strapping lugs and the panels.
- Commercially obtainable explosion relief panels (0,625 m square) have been installed on both elevators; 10 on X-303 and 15 on X-304. Burst pressure is 15 kPa.
- Bucket elevators in the refinery proper have also been modified as described.

#### *Dust extraction system*

The dust extraction system is also a high risk area because of the fine particles involved and the possibility that an explosion could propagate through the pipes and ducting.

- Filter bags should be made of anti-static material and should never be allowed to become electrically insulated. The type of bag that incorporates carbon fibre is recommended. Bags with wire are not recommended. Sparks can result when the wires in the bag break.
- The filter units are housed in a separate building.
- The plant dust extraction system has been designed in such a way that the dust concentration in the ducting is below the lower explosion limit of sugar dust. Dust concentrations in the ducting should thus not be higher than 15 g/m<sup>3</sup>. Explosible dust concentrations will, however, be

present in the filter unit from time to time. It is necessary to install filters that protect against the effect of possible explosions by venting.

- The elevators must tie into the extraction system as close as possible to the filter unit. The tie into the dust extraction system should be at an angle to reduce the risk of explosions propagating upstream.
- The installation of a flame front diverter upstream of the filter units will isolate the filter units from the rest of the ducting and from the plant. The diverter must function in both directions, that is, protect the filter unit from external explosions and protect the extraction system from explosions originating in the filter unit. The possible flame from the flame front diverter should be vented to the outside of the building.
- The ducting must be properly earthed to prevent static build up. The precautions mentioned above should be followed.
- This has been interlocked such that the entire conveying system will be shut down in the event of filter failure.

#### *Secondary explosions*

These are perhaps the greatest danger in any plant in terms of potential damage. When a secondary explosion occurs, dust in the plant outside of equipment is disturbed and ignited. Suck an explosion could destroy the entire building. It is essential that good housekeeping practices be strictly adhered to. All dust should be removed as regularly as possible, also from beams and walls. Every effort should also be made to decrease the amount of dust in the plant. This can be achieved by carrying out regular maintenance on the plant and by decreasing the speed of transport. The vacuum cleaning system will also assist in achieving this aim.

The cost of rectification is in the order of R1 500 000.

### **Conclusion**

While there may be some disagreement on the exact explosive properties of sugar dust and more experimental work may be required to establish these, it is clear that sugar dust is indeed hazardous and that extreme care should be taken in the design of the process equipment. It is believed that the modifications mentioned above, together with closely monitored, effective dust removal, equipped with the necessary alarms and interlocks, will reduce the risk of explosion to negligible levels.

### **Acknowledgements**

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