

Safety

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In general, all industrial development gives humans both an improved standard of living and increased wellbeing, but there is a darker side to this development, including accidents. The silicon industry has seen serious accidents in which operators or other employees have been harmed, and some have even died from work-related injuries. This chapter gives a short description of some of the specific safety challenges that are present in the production of silicon. It starts with a general presentation of safety and then mentions some examples from other industries.

13.1 General about industrial safety

Process safety is an integrated part of the Health, Safety & Environment (HSE) programmes in industrial production (the acronym EHS is a North American term with the same meaning). Every year there are a huge number of accidents in industry worldwide ('List of Historic Explosions,' n.d.). Fortunately, there has been an increased focus on avoiding injuries, and the safety standard has improved in many countries through systematic safety work. Safety work is a continuous process in which new learning from your own factory, as well as learning from others, improves the standard. Organized safety work is about 100 years old and started because of the huge number of accidents in the early days of industrialization. Injured workers and their families paid the highest price, but it also affected colleagues, the company and society.

Improvement work seeks to minimize risk and remove hazards, unsafe conditions and unsafe behavior, thereby avoiding accidents through improved technical standards, better training, and more effective procedures. To measure injury rates, Norwegian industry uses standardized parameters defined by the Federation of Norwegian Industries (*Norsk Industri*)¹:

- H-value (Frequency) shows the number of lost-time injuries (LTI) per 1 000 000 working hours.
- F-value (Absence)/ DISR (Disabling Injury Severity Rate) gives the number of days lost due to injuries per 1 000 000 working hours.
- A-value (Severity): provides a picture of how serious the accidents are (F-value divided by H-value).

The numbers often include injuries sustained by hired personnel or contractors performing work for the company.

There are several reasons to work on industrial safety, and the most important is to avoid employee harm or death in the workplace. However, there are also other important reasons to prioritize safety:

- Protection of the environment from damage from industrial accidents
- Protection of the business from serious financial loss from damage to plant and machinery
- Elimination of accidents causing work stoppage and production loss.
- Creating awareness of available good practices for the delivery of effective safety instrumented systems

Some claim that there can be a conflict between efficiency and the requirement for safe standards. One example is the understanding that simple ladders are not suited for elevated work. The standard requires the use of solid scaffolding, which is, of course, more time consuming to build than just grabbing a ladder. Here, safety concerns should prevail, as we know that fall injuries from more than 2 metres can easily result in serious injury or fatalities. It has been said that the most common start of an explanation for why short-cuts are made is: 'I was only going to ...'

1 <https://www.norskindustri.no/siteassets/dokumenter/annet/veileder-for-personskadestatistikk-i-norsk-industri.pdf>

Work with better safety standards can improve efficiency at the same time as the working environment improves. One example is a part of safety work called '5S'. 5S stands for the 5 steps: Sort, Set in Order, Shine, Standardize, Sustain. These steps involve going through everything in a space, deciding what is necessary and what is not, putting things in order, cleaning, and setting up procedures for performing these tasks on a regular basis. This not only improves safety, but also efficiency and productivity.

In addition to physical harm to employees and the plant, serious accidents can also cause financial losses or legal consequences for workers, management and owners of the factory. Employees must be given adequate information about risks in their working environment, and the necessary training to do their work safely. Programmes that ensure documented safety training are mandatory for all employees. Special programmes and training for new employees are also necessary.

There are several different types of accidents:

- Near-miss: accidents with no damage or injury are called near-misses.
- Minor accident: accidents with damage that can be easily repaired, or injury with a short healing time.
- Serious accident: accidents with heavy damage and/or serious injury with a long healing time or permanent loss of function.
- Fatal accident: accidents with loss of life.

With serious or fatal accidents, Labour Inspection Authorities and police are often involved in the investigation to find the causes. Documentation showing risk understanding and safety training for all employees will be requested for their investigations.

13.2 General hazards for the silicon industry

The most common industrial accidents are:

- Pinching/crushing
- Fall from heights
- Falling objects
- Moving vehicles and equipment

This is also generally the case for the silicon industry and other metal-producing industries. However, there are other factors that may have a special influence on the silicon industry's safety:

- There are many simultaneous activities in a limited space. In addition, large numbers of workers who may not be familiar with normal factory activities are brought into the workplace for project work or major repair work.
- Many silicon factories are old and may not be well suited for large mobile equipment like payloaders and trucks.
- Work 7/24. Shift work, including nights, carries its own unique type of stress that may be dangerous. Studies have shown that changing sleep patterns can create stress with the potential to impact performance, decision-making skills, and safety.

The accident types listed above will normally have public or governmental safety standards. In the case of an accident, the labour inspection authority will refer to such standards. Penalties may be given if there is serious deviation from applicable safety standards.

There should be a comprehensive evaluation of the safety situation at the factory. This includes simple things like separating pedestrian walkways and vehicle roads.

13.3 Process specific hazards for the silicon industry – energy out of control

The introduction of electricity in the metallurgical process enabled industrial production of silicon and ferrosilicon. Electricity provided an effective means of reaching the very high process temperature needed for the SiO_2 reduction into silicon. Though important for the total process, different types of energy may also cause harm:

- Potential energy – fall from heights – converted to kinetic energy in an accident situation
- Kinetic energy – moving machinery, cars, trucks, tools

- Electrical energy – high and low voltage
- Thermal energy – warm charge, liquid silicon, warm off-gas
- Chemical energy – coal, coke, process gas before combustion, silicon

While all of these can cause serious harm and death, it is the huge amount of thermal and chemical energy that creates the process specific hazards, which can have catastrophic consequences. Another important factor is that the very high temperature may create extreme energy transfer into other forms of energy. In the following, four examples of extremely high energy hazards that are specific to the silicon industry (or, more generally, the metal producing industry) will be discussed.

Eruption of water vapour and process gas from the charge

The eruption of water vapour and process gas from the charge has been the big killer when looking at low-shaft furnaces like the silicon furnace on a global basis (Tveit and Breidenthal, 2020). The use of the word eruption reflects the relatively slow total reaction. A furnace eruption may happen without high pressure build up. However, if the furnace is closed, the large amount of gas during the eruption may create pressure build up inside the furnace hood.

There are several energy sources that may create an eruption:

- The main energy source is the extremely hot charge. If the charge is mixed with water, the heat transfer may be extreme.
- Inside the charge there is process gas that may burn quickly if exposed to air. Normally this is released in a controlled manner and evacuated safely through the off-gas system, but it may also escape uncontrolled together with the water vapour.
- Rapidly heated coal may defragment into very small pieces if rapidly heated (No and Syred, 1990). Fragmentation has been attributed to the pressure build-up within a particle when volatiles released internally cannot escape rapidly through pores in the coal. The defragmented coal may achieve a very high combustion rate. It was found that a 10 mm coal particle would use 100 s for the burn-out, while the 1 mm and 0.3 mm particles used about 1 s and 0.1 s respectively (Agarwal, 1986).

The energy transport out from the furnace may be enabled by either large volumes of water from leakages in the cooling systems or by fresh raw materials that are added too quickly. Figure 13.1 shows the principle of a water leakage out of control. The leakage may come from the furnace hood, the electrode clamps, or other water-cooled parts of the furnace. If the furnace is in full operation, it can tolerate a substantial leakage, as the water is evaporated and does not accumulate or move towards the furnace reaction zone. Evaporation does however have its limits, and if the furnace is stopped, the tolerance is much lower. Figure 13.2 and Figure 13.3 show how the accumulation of water can increase when power is cut and evaporation slows down.

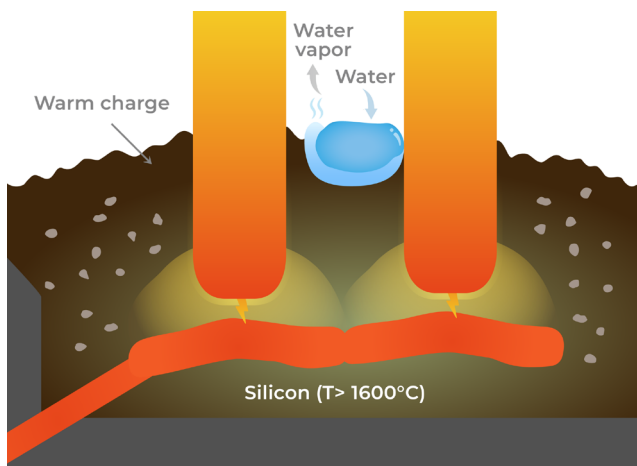


Figure 13.1 shows a water leakage that accumulates in the upper part of the charge.

The water may also mix with the charge, causing a violent boiling process. There are several reports of hearing an ominous rumbling noise.² People seem to never forget such an experience. Another possibility for too much water entering the furnace crater is through the charge itself. The charge will inherently always contain both moisture and volatiles, and levels of these may vary greatly depending on weather conditions, storage, and handling. If large amounts of fresh charge are added in an uncontrolled manner (too much – too

² Private conversation with Ing. Peter Kallfelz, who is a private consultant in metallurgical processes.

quickly), the necessary evaporation will also suffer, allowing water to transit further down into the furnace.

When the main reaction takes place in these types of situations, the eruption of water vapour and process gas far exceeds the capacity of the off-gas system. The normal capacity of the off-gas system is in the order of 12–80 Nm³/sec, dependent on furnace size and off-gas temperature. Calculations have indicated that the amount of water vapour and gas from the volatiles may reach several thousand m³/sec during the eruption. As this overwhelms the off-gas system, it finds other ways out of the furnace through the gates and other openings. If the openings are too small, pressure will build up in the furnace, potentially destroying the furnace.

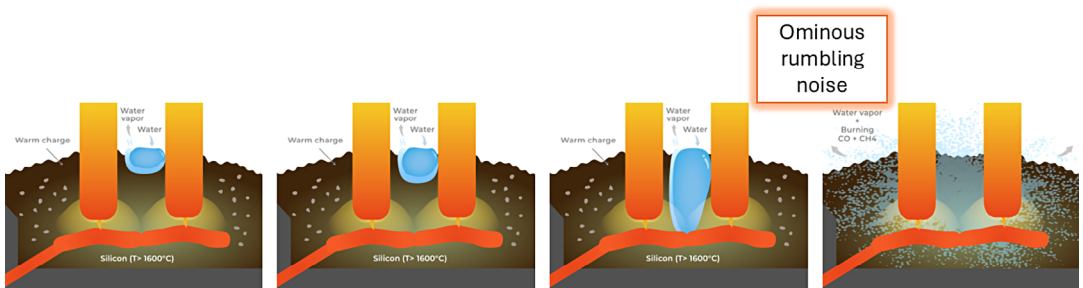


Figure 13.2 shows steps from the start of a water leakage to an eruption.

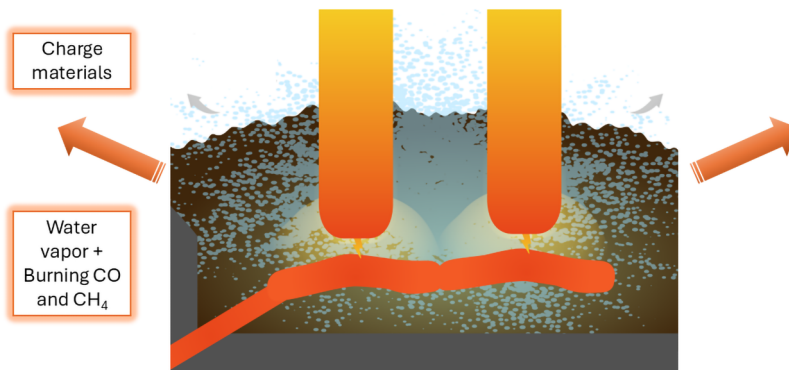


Figure 13.3 shows the eruption. The mixed charge and water create an extreme energy transfer. A deadly mix of superheated water vapour and burning process gas and coal fines stream out from the furnace.

The amount of off-gas from a 10 MW furnace is shown in Table 13.1. This table shows that more gas is needed to cool the off-gas to lower temperatures. Thus, it will totally be more gas when cooling it to 300 than 700°C. The amount of off-gas will vary somewhat with the composition of the charge, such as the amount of coal, coke, and woodchips.

Table 13.1 *The table shows the typical amount of off-gas from a 10 MW silicon furnace where it takes more gas to cool the off-gas to 300°C than 700°C.*

Off-gas temperature	Off-gas volume	Corresponding amount of water vapour at 400°C
300°C	32 Nm ³ /sec	26 kg H ₂ O
500°C	18 Nm ³ /sec	15 kg H ₂ O
700°C	12 Nm ³ /sec	10 kg H ₂ O

Case 1 – the 2006 Elkem Thamshavn accident

On the 12th of April 2006, an eruption took place in Furnace #1. One operator was critically wounded and died four weeks later. The direct cause of the incident was a major water leakage in the electrode cooling system. A comprehensive investigation was carried out to find the root cause of the incident and measures to avoid similar accidents in the future. The investigation identified a continued inflow of water into the furnace after the power was turned off, enabling the accumulation of a high volume of water close to the reaction zone. In line with the Elkem ASA policy of being open with information that may help others avoid serious incidents and injuries, a presentation of the incident was published in 2008 (Tveit *et al.*, 2008). The investigation also included reviews of other similar incidents, showing that water vapour eruptions from silicon and ferro-alloy furnaces did happen occasionally and often resulted in multiple fatalities. The paper describes five known accidents with up to seven fatalities.

Case 2 – the 2010 Elkem Iceland accident

The tragic incident at Elkem Iceland on the 29th of June in 2010 was a reminder of the inherent risk involved with the production of high silicon-containing alloys. A severe eruption of gases from Furnace #1 ignited, killing one young operator. Again, an investigation had to be carried out to find the root causes and how to avoid similar incidents.

The first hypothesis suggested a major water leakage, as in the Thamshavn case, but no water leakages were found, and the furnace was in normal operation when the eruption took place. Video footage from CCTV cameras in the area provided valuable input to the investigation and the modelling of the incident. Figure 13.4 shows time-stamped pictures from the video, which allowed us to see how the eruption progressed. The investigation concluded that the incident was an eruption of process gases from the furnace that ignited on contact with oxygen outside of the furnace. The findings strongly indicate a major furnace cavity collapse, allowing fresh, newly fed charge to fall into the reaction zone before moisture and volatiles were evaporated, as seen in Figure 13.5.

The investigation, modelling and necessary calculations gave a frightening worst-case potential for fatal incidents when substantial amounts of fresh raw materials are mixed with very warm charge material and/or molten silicon. The literature suggests that high-volatile coal may defragment (or explode and be converted into small pieces) if it is heated too quickly. The resulting fragments of coal may release volatiles and have extremely fast combustion, with the release of huge amounts of energy. Several combustion and mixing scenarios were calculated. The worst-case scenario indicated an energy release in the order of 16 GW for 1 second – i.e. the total effect of Norwegian electricity production. This is not the most probable scenario, but all the calculated scenarios resulted in an overload of the off-gas system, according to the observations and measurements.

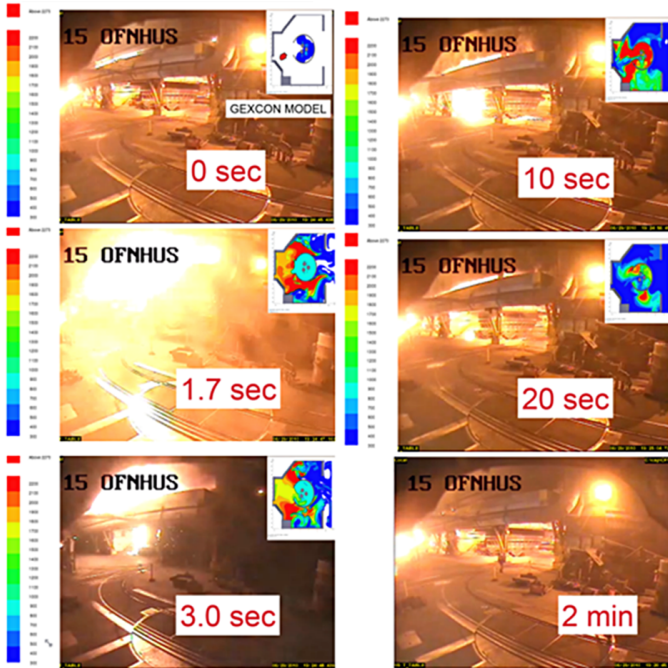


Figure 13.4 The snap from a video shows the speed of the eruption at Elkem Iceland together with the model from Gexcon (2026). There were 2 maxima – after 0.7 and 1.7 sec. The major eruption time was about 1 sec – and after 2 minutes no trace of the accident could be seen on the video.

Both cases mentioned above are extreme examples of what is typically called a furnace blow-out. Gases and materials are ejected with high force through furnace openings when an imbalance occurs in the off-gas evacuation system. Fans that normally create constant evacuation through the chimneys do not have sufficient capacity when the amount of process gas increases rapidly, replacing some of the cooling air and increasing the temperature in the furnace hood. Blow-outs on a smaller scale do happen frequently in silicon furnaces and can be anything from small amounts of smoke and particles exiting the furnace to burning flames and charge materials that can cause damage and fires in the area. This phenomenon will sometimes be heard as slamming of the furnace doors, due to the change of gas pressure and the reversal of the cooling air flow to the furnace.

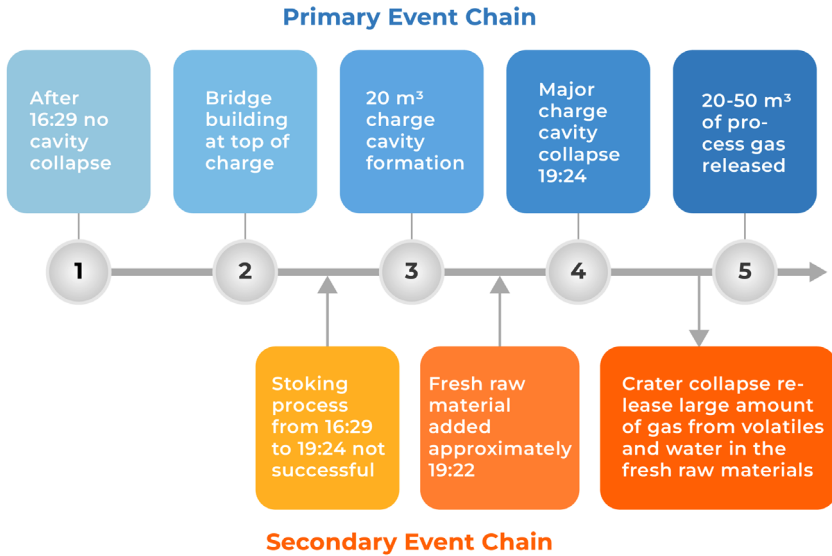


Figure 13.5 shows the most likely chain of events for the Iceland example. The figure is included because a major cavity of 20 m³ was found at the top of the charge. The reason why the cavity did not collapse during the 3 hours of stoking is not fully understood.

The main measures after the Elkem Iceland accident were changes to the charging process and limitations of access to the stoking floor area.



Figure 13.6 shows the destruction of a closed CaSi furnace, where the author was participating in the investigation. The picture shows the extreme destruction when energy comes out of control.

Explosion due to water encapsulated in molten or very hot metals and materials

Liquid water or moisture encapsulated in molten or very hot metal immediately evaporates, as shown in Figure 13.7. This generates sudden expansion and possible pressure build-up, enabling an explosion. The word explosion indicates a sudden pressure build-up with pressure release. The time for an explosion is less than 1 second. The molten substances that were around the water may be ejected with high force and velocity, causing harm to people and equipment in proximity, either by contact or by resulting fire, as illustrated in Figure 13.6.

There is practically no lower limit to the amount of water needed for this type of incident to occur. Any amount of water heating from 25°C to 1000°C will expand 1600 times as it becomes water vapour. This means that there is zero tolerance for water to be trapped in liquid silicon. Situations where this type of explosion can occur in silicon production are many: equipment leakages, rain, snow, or even residual moisture that has not been sufficiently dried in refractory materials or concrete floors have the potential to be encapsulated in liquid silicon or slag.

The phenomena of explosions caused by water enclosed in liquid metal have also been investigated in the steel and aluminium industry (Babaitsev and Kuznetsov, 2001). The explosive effect of 1000 kg of aluminium or steel is presented for different amounts of water entrapped in 2. To visualize the effect of this power, 1 kg of TNT will destroy all windows within a radius of 30 m, 80 kg TNT will destroy all windows within a radius of 250 m and destroy a normal roof at a 40 m distance and all walls at 23 m distance from the explosion.

Table 13.2 *The explosive effect of 1000 kgs of aluminium with amount of water trapped (Babaitsev and Kuznetsov, 2001).*

Amount of water	1 litre	10 litres	100 litres
Explosive power (kg TNT)	3	32	200

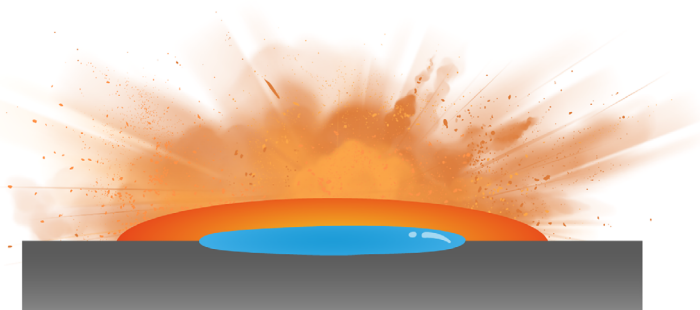


Figure 13.7 shows the principle behind the start of a water explosion – i.e. water enclosed by liquid or hot silicon or slag.

The enthalpy of silicon, both by volume and by mass, is much higher than that of aluminium and iron, so the explosion strength may be higher for silicon, as seen in Table 13.3. This type of explosion can harm people in multiple ways, through both pressure and temperature. A pressure wave can injure people directly, and indirectly by moving debris, particles, and equipment at high speeds. Temperature can injure people directly, through severe burns caused by contact, or through fumes caused by fires.

Table 13.3 shows the enthalpy release through 100 ΔK and solidification ('HSC Chemistry', n.d.).

	Temp in	Temp out	kWh/kmol	kWh/1000 kg	kWh/Nm ³
Al	700	600	–4	–144	–389
Fe	1600	1500	–5	–91	–714
Si	1500	1400	–15	–524	–1221

Dust explosions – primary and secondary explosions or the formation of explosive gases or metal fines after a primary explosion

Most of the dust in primary silicon production facilities is SiO_2 and will not cause dust explosions, as it is inert. It may, however, cause serious health problems with exposure over time (potential to cause COPD) and must therefore be kept under close control. Dust from the further processing of silicon

alloys through crushing and sizing is a different story, as this type of dust is combustible. There will therefore almost always be the potential for combustible dust in a silicon facility, and the silicon industry has experienced dust explosions with fatal consequences (Abbasi and Abbasi, 2007; Eckhoff *et al.*, 1986). There are four conditions that must be in place for a dust explosion to happen, as illustrated in Figure 13.8 and Figure 13.9:

- The dust must be combustible
- Particles must be able to form a cloud exceeding min. explosion concentration
- Dust must be confined
- An ignition source must be present.

Most types of silicon alloy dust are difficult to ignite, but this varies strongly between different types of silicon alloys; the risk is higher with mixtures of ferrosilicon and magnesium or flammable solids. If they do ignite, however, the explosions can be extreme because of the stored energy. Over time, silicon dust will collect on walls and structures if it is not correctly contained and collected. This increases the potential for an explosive dust cloud forming after a primary water/metal explosion, if these processes are operated in the same area, as is often the case at a smelter. A primary metal/water explosion has more than sufficient energy to ignite the dust. In addition to silicon and ferrosilicon dust in the crushing and screening areas, fine carbon materials in the raw materials transportation systems are also candidates for dust explosions in the silicon industry.

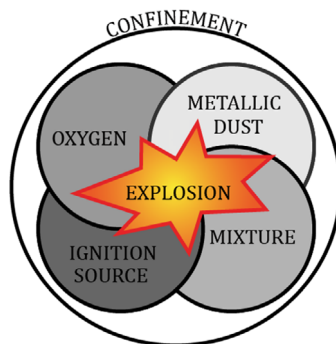


Figure 13.8 shows the necessary conditions for a metallic dust explosion.

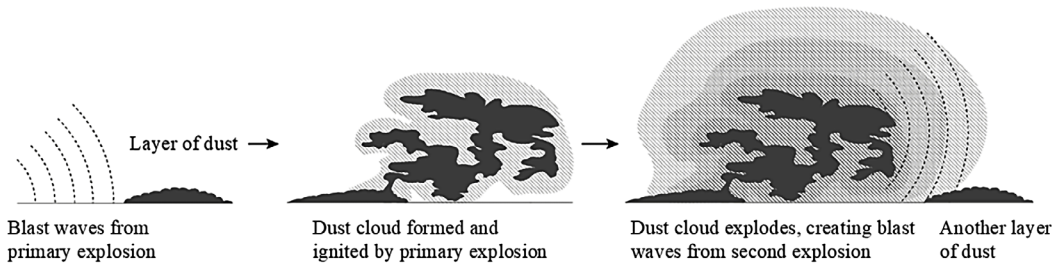


Figure 13.9 shows the potential for a large secondary dust explosion following a smaller one.

Burning of skin due to contact with warm gas or liquid or warm silicon

This type of injury is by far the most common when we experience blow-outs or explosions, and it may range from minor superficial burns to fatal burns. Breathing hot gases can also cause fatal burn injuries, as it may affect a person's throat and lungs. Most of the minor to medium-severity burns in silicon production happen in the tapping and post-taphole areas, where there is close contact between molten silicon and operators. High-pressure process gas ejection from the taphole, or loss of confinement of molten silicon from ladles or casting molds, are the main causes of this type of incident. Fatal burn injuries are more connected to major explosions, like the ones described in case 1 and 2 above.

13.4 Active and passive measures for increased safety

The work for increased safety may be divided into active and passive measures. Active measures are taken to avoid accidents. Eruption-type incidents can be mitigated with instrumented control of cooling water flow, to detect leakages easily before they become critical. Examples of passive measures are preventing access to high hazard areas like the stoking floor, and either making control room windows stronger or removing them completely, and

using camera surveillance instead of direct view through a window. For the type 2 explosions, the main active measure is preventing water from coming close to liquid silicon.

13.5 Conclusion

Production of silicon alloys has an inherent risk of explosion and serious injury because of very high temperatures and very high amounts of energy. Fully understanding the mechanisms behind this risk is of the utmost importance to operate the process safely and prevent harm from happening. Controlling this risk involves fully understanding the process, implementing equipment, automation, and methods to remove operators from dangerous work, and using better personal protective equipment. The more general type of accidents is more frequent. It is important to have a continuous safety focus, with participation of all employees at the silicon plant.

A personal comment from the author of this chapter

I have been working in the metal producing industry all my life. It has been a good and interesting time. Most of the work has been on the positive side – working with good colleagues to improve the process and the environment. Unfortunately, the industry may also show a darker side! Out of ‘people I knew’, friends and colleagues I have lost 8 in work accidents. And I have participated in the investigation of 4 fatal accidents in different countries.

To come to a plant that has suffered a loss of a colleague is to come to a sad plant. It is not easy to describe the feelings when you talk to his working companions. The plant that gave wellbeing to them and their family has suddenly shown a grimmer face. Whole families have suddenly got a sad and uncertain situation. To investigate is to try to find out the root cause of the accident. In that process, you need to study the last hours of the deceased. You get to know a person you will never meet.

This is my background for writing this chapter. If the learning here will contribute to avoiding one single accident with serious harm or death, I will be grateful.

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