Explosion of a cereal silo

August 20, 1997

Blaye – [Gironde]

France

Explosion
Food handling facility
Port silo
Cereal
Explosive atmosphere
Dust removal circuit
Casualties

THE INSTALLATIONS INVOLVED

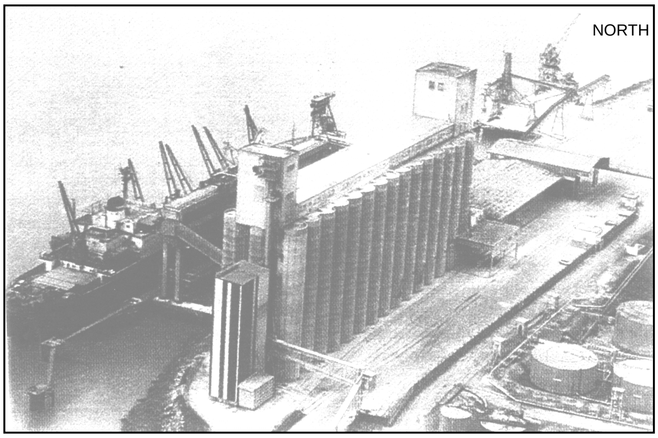
The site

The company's facilities are located at the port complex within the municipality of Blaye, on the right bank of the Gironde Estuary, and constitute one of the largest cereal storage centres in the entire Gironde department, with a total capacity of 130,000 tons of cereals, 90,000 tons in flat storage in metal hangars and the remaining 40,000 tons within a vertical silo. The company is primarily engaged in handling and storing cereals intended for maritime export, with delivery to the site arriving almost exclusively by truck. The facility employs a workforce of 21. However, a bagging operation and key cargo vessel loading tasks require hiring temporary personnel (some 75 temp employees per 24-hour period).

The closest neighbouring firm houses a number of storage tanks containing, among other things, caustic soda, aromatic oils and molasses. The property boundary lies 25 m from the silo cells, with the nearest tank at a distance of approximately 40 m and the administrative buildings at 210 m. The closest residences are located 230 m east of the silo.

Layout of the installations

The silo is composed of 44 circular reinforced concrete cells, arranged in 3 rows, for a total capacity of 47,240 m³ (37,200 tons when filled with wheat).



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Partial aerial view of the vertical silo infrastructure

Two vertical concrete annexes rising to a height of 53 m are laid out on each end of the silo and then connected to one another by an 80-m long, concrete-walled gallery running over the cells and housing conveyor belts. The northern annex lies at the summit of the material handling tower, which contains bucket elevators that enable vertically manipulating the cereals received via the bulk delivery pit. The southern annex or south tower, above the cells, houses a grading machine and two grain cleaners-separators. The space below the cells on the lower part of the silo contains, among other things, chain conveyors.

South of the vertical silo, within a few meters of the last cells, a metal frame tower encompasses corn dryers. One of the metal frame hangars used to store cereals is connected to the vertical silo by means of two belt conveyors.

A shed, built at the base of the vertical cells, on the Gironde Estuary side, has been allocated for bagging operations, particularly when organizing humanitarian shipments.

The administrative and technical offices spanning 3 floors, including the control room, are located on the north side, for the most part as an extension to the storage cells and handling tower.

Description of the vertical silo

The silo, built in two segments in 1970 and 1974, creates a volume of approx. 100 m long by 20 m wide and 40 m high. The concrete, circular cross-section vertical cells (internal diameter: 6.20 m; shaft height: 36.5 m; storage height: 33 m, 2.5 m of which occupies the lower conical part, also known as the "silo nose"), juxtaposed over 3 rows, feature a reinforced concrete cover composed of 7-cm thick pre-slabs topped by an 8-cm slab ; this slab configuration serves as the floor of the upper connecting gallery between the northern and southern annexes. The cover slab is not bonded to the vertical walls. The intervening hoppers (or more familiarly "ace of diamonds") are set up with a 32-m storage height and 4.20 m dimension at their widest internal diameter.

The first silo segment (northern side) is composed of 20 cells and 12 intervening hoppers, yielding a storage volume of 20,904 m³, while the second segment accounts for 24 cells and 14 hoppers (volume: 26,336 m³). The two hoppers positioned at the intersection of the two silo sides are not used for storing cereals, but instead remain open over their lower part (space beneath the cells) and blocked over their upper part (by the gallery floor above the cells).

Both the cells and hoppers are fitted with a filling trap that contains a counterweight, along with an inspection gate, a manhole with autoclave locking, a manually-controlled drainage valve and, for the second segment storage units, a pneumatically-controlled series valve (so-called "grain cutoff"). The cells built during the second segment may be ventilated by injecting air at the cell base and have been equipped with an air extraction system over their upper part, except for three cells located at the southern end of the silo; air is discharged to the outside without any special filtration procedure.

The two cereal delivery pits (unit capacity: 45 tons) are connected to the elevator pit of the northern handling tower, via an underground gallery that encompasses chain conveyors.

The northern tower, which is positioned in continuity with the vertical cells, houses the bucket elevators as well as components of the centralized dust removal circuit (fan, set of filters and a dust bin). The openings (3 m x 2.5 m) introduced in the flooring between stories to allow moving equipment are partially covered with metal sheets, yet a void measuring several m² is a permanent fixture on each floor. The tower communicates directly with both the over-cell gallery and the under-cell space. The tower facades contain glazing units to allow natural light to enter; these components, which are capable of acting as vents, represent a surface area on the order of 80 m², i.e. 4% of the total sidewall surface area for a tower whose volume equals approximately 5,000 m³.

The southern tower, built with a rectangular cross section (6.5 m x 11 m), houses a set of two cleaners-separators and one grading machine fitted with their own dust removal system (fan, cyclone, exhaust duct leading to the roof). Ambient air on the tower's first level, which is positioned as an extension to the over-cell gallery, is discharged to the outside without filtration by means of an extractor hood.

The over-cell gallery primarily comprises 3 silage conveyor belts and one material handling conveyor to provide a connection between the vertical silo and an adjoining hangar. The ducts associated with the central cell air exhaust system, built as part of the second segment crossing the gallery over its full height, thus create a regular succession of obstacles. The concrete slab forming the floor of this gallery fully covers the central cells and intervening hoppers, plus a portion (one-third of the diameter) of side cells. The vertical walls contain 26 glass surfaces (measuring 3 m x 1 m) to ensure that natural light enters the building; these bay openings occupy a total surface area of roughly 80 m² and are indeed capable of acting as vents, in representing 3% of the sidewall surface area of a gallery whose volume equals 3,500 m³. Moreover, 8 evenly-spaced circulation fans serve to discharge the atmosphere of this gallery to the outside.

The aboveground under-cell space mainly contains the conical silo noses of the cells, along with 10 chain reclaim conveyors and air blowing unit accessories at the base of the 24 cells making up the second segment of this facility. The ambient air contained in this space is discharged to the exterior by means of 4 fans installed at the level of the first segment.

In addition to the set of equipment cited above, silo dust removal is performed by means of a centralized air suction network set up at several points along the cereal circuit using a fan positioned in the upper part of the northern handling tower and connected to an exposed sleeved filter apparatus ; breaking a sleeve could therefore cause dust to be released over all tower stories. The dust is recovered within a bin fitted with level detection, yet the centralized dust removal circuit does not include any means for measuring pressure drops or rises downstream of the fan. An employee is assigned to clean this system as part of overall installation maintenance.

An automatic monitoring system makes it possible to control temperature in all cells, with the threshold alarm (both lights and sound) being adjusted depending on the time of year. The hoppers are not equipped with thermometric probes.

The silo has no built-in protection, along the lines of fire detectors or explosion vents. No device has been installed to detect and collect foreign bodies when accepting product deliveries, nor has any magnetic apparatus been introduced to recover metallic objects that may eventually enter the cereal circuit.

Administrative situation

The facility is regulated according to prefecture order pronounced June 12, 1984, indicating the various conditions applicable that were initially elaborated in the August 11, 1983 ministerial decree, given the prior construction date of the silo, as well as in respect of complementary orders dated October 1987 and July 1990. An order adopted on September 20, 1994 authorizes the operations of a second dryer.

THE ACCIDENT, ITS CHRONOLOGY, EFFECTS AND CONSEQUENCES

The accident

The explosion occurred on Wednesday August 20, 1997 around 10:15 am. A dumper truck with an attached trailer was unloading corn into the delivery pit situated closest to the administrative and technical offices.

The previous truck had already unloaded wheat into the other delivery pit and had just left the site. The presence of a mix of barley and wheat on a conveyor belt connected to the elevator pit would suggest that the pit was empty at the time of the accident and that the wheat delivery had been completed.

In the under-cell space, two chain conveyors seemed to be running with barley. One was likely emptying a cell in order to transport barley to a hangar, while the other was probably performing an internal transfer of cereal in preparation of transhipment to a hangar as well.

The silo was nearly full and the hoppers accounted for the majority of empty storage capacity.

The consequences

- ✓ Casualties

The accident gave rise to 11 deaths (7 company employees, 3 subcontractors and a fisherman) and 1 serious injury.

In the three days following the explosion, 10 victims were found in the administrative and technical premises located at the base of the silo or their immediate vicinity. The victims inside the buildings were found at their workstation, apparently unable to react (due to the sudden nature of the accident and the likely absence of any warning signs or identifiable indication of a seriously deteriorated situation).

The eleventh victim, the fisherman, was found on September 3, not until 14 days after the accident, buried underneath rubble on the Gironde riverbank side.

- ✓ Material damage

a) Damage to company installations

The vertical silo collapsed over its central and northern parts, with the northern part effectively burying the installation offices. Only 16 of the 44 cells were still for the most part intact after the accident, 9 on the south side and 7 on the north. One characteristic of this disaster was the collapse of two sets of cells: the first on the northern end, which had abutted the material handling tower; and then the central section of the silo (see photo).

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The northern handling tower, as well as the immediately adjacent cells, were almost entirely destroyed. Over roughly half of its initial height, just a curved half-shell of this tower was still standing, as the tower's sides that had formed the walls of adjacent hoppers were slammed backwards, onto the shaft of a neighbouring cell. This observation indicates the presence of an explosion within the handling tower, which would have occurred after the eventual explosions taking place inside the adjacent storage units.

The over-cell gallery was totally destroyed, an air extraction device was found 30 meters from the silo.

The southern tower slumped onto the tops of cells. Components of the cleaners-separators (rubber balls from the sieves) found calcinated at the surface reveal the passage of fire or expansion of burnt gases in this tower.

In the northern part of the silo, the under-cell space (primarily composed of the central cell shaft) showed limited signs indicating the presence of fire or expansion of burnt gases. On the other hand, underneath the compact block of the 9 cells left standing in the silo's southern zone, many traces of combustion could be noted (melted plastic components, burnt dust deposits, etc.), and this was especially so under 3 of the central cells. Within this zone, the air blowing ducts running at the base of cells were found, in large part, completely unfastened, having been projected in a north-south direction. This observation points to the high dust content present in the circuit.

To an overall extent, the elevator pit retained its original geometry and no sign of combustion could be detected on the inside. The same can be said for the cereal delivery pits and the underground connecting gallery, although the cover slab of this gallery had collapsed under the weight of the rubble.

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Southern silo zone

The elevators located inside the handling tower sustained heavy damage; the observations that could be recorded indicate that the drive pulleys showed no traces of slipping, as the axles of these elevators did not seem blocked in their main bearings, and the scraps of metal duct found had neither swollen nor burst; moreover, the pieces of bucket straps recovered showed no signs of combustion. The elevators located in the southern part of the silo were rather damaged by the collapse of surrounding concrete structures; no trace of combustion could be identified on these facilities other than a mark roughly a meter long on the external part of an elevator duct. The reclaim conveyors in the under-cell space were damaged by collapse of the storage units. A good number of upper covers on cases housing these conveyors were blown off. In the northern part of the silo, a conveyor displayed unmistakable signs of friction at the head (leading part) and many blades on the conveyor chain were missing.


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Northern silo zone

Although earthworks and dredging operations on the Gironde River were carried out, very few components of the centralized dust removal circuit were actually found, despite the large size of such components, like the dust bin (which occupies a volume of 25 m³).

Other silo-related installations were also destroyed or damaged (maintenance shops and bagging room, ship loading crane, hangars).

b) Third-party damage

Many projectiles hit various nearby company-owned storage tanks, and transfer pipes between the tanks and public piers were broken.

Damage to residences lying outside the port zone was noticed at distances reaching around 500 meters from the silo, as evidenced by broken glass, falling plaster, etc.

✓ Projectiles

Large projectiles (metal, concrete or glass elements) were observed at distances of up to a hundred meters from the silo. Meter-sized pieces of reinforced concrete were found at a radius reaching some 50 m from the silo and smaller-sized debris (i.e. weighing less than a kilogram) was projected out to 140 m.

European scale of industrial accidents

By using rating rules applicable to the 18 parameters of the scale officially adopted in February 1994 by the Member States' Competent Authority Committee for implementation of the '*SEVESO*' directive on handling hazardous substances, this accident can be characterized by the four following indices, in light of the amount of information available.

The parameters composing these indices and their corresponding rating protocol are available from the following Website: http://www.aria.developpement-durable.gouv.fr

The value of 2 ascribed to the "Dangerous materials released" index corresponds to a TNT equivalent of between 100 and 1,000 kg (broken windows observed at distances extending to around 500 m - parameter Q2).

The level 4 reached by the "Human and social consequences" index is due to the death of 11 people (parameter H3).

The 4 rating ascribed the "Economic consequences" index stems from the material damage estimate at 160 million francs in 1997 (parameter €15).

THE ORIGIN, CAUSES AND CIRCUMSTANCES OF THE ACCIDENT

The investigation undertaken required 8 months and 2 full-time agents working with an independent body, as mandated by the Ministry of the Environment, in a supporting function to hazardous site inspections (1/3 full-time equivalent of an inspector).

The investigation method adopted was based on collecting witness accounts, certifiable observations on the equipment and state of failure (complicated by the extent of destruction), analyses of products recovered (grains, dust, level of calcination), and studies involving a hierarchy of causes.

Activities at the silo when the accident occurred

An initial elevator was feeding corn into an unidentified storage unit, which most likely was one of the intervening hoppers. This storage capacity, which could be considered nearly empty, was open onto the over-cell gallery given that the grain handling operation was underway.

A second elevator was being used to drain a barley storage cell, probably within a transit cell being prepared for a grain transfer operation into a hangar, in which case the transit cell was also open onto the over-cell gallery.

A third elevator enabled the "transhipment" operation towards the hangar. It is plausible to assume here that this elevator was being fed by the cereal drained from a second barley cell and by direct discharge of the transit cell.

Moreover, the placement of wheat into silo storage had just been completed, in which case the access door to the cell being loaded might still have been open onto the over-cell gallery. The location of this cell cannot be accurately identified, but must have been 2/3 empty regardless.

Therefore, two (and possibly three) cells could communicate between the roof of storage units and the over-cell gallery, and this would be the case for the barley transit cell. The other two storage units must have been just about empty and at least 2/3 empty for the corn and wheat.

Sequencing of the explosion phenomenon

The first-hand accounts collected served to determine that the explosion originated in the northern handling tower before propagating into the over-cell gallery and was able to reach the southern end of this gallery, as evidenced either by a return of dust into suspension or a dusty atmosphere, or a combination of both.

The flames from this explosion, most likely in the form of a flame burst, wound up entering two, or even three, of the open storage units.

The burst of flames penetrating the storage units, which contained airborne dust as a result of silo loading operations, then caused a violent explosion. The geometry of these storage units, in particular their elongated shape, no doubt contributed to enhancing the pressure effects. This remark would apply especially to the hopper that could have contained the corn. Given that the height-to-hydraulic diameter ratio was in the vicinity of 10, it is altogether possible that this condition, in combination with the reactivity of corn, accounted for a considerable share of the damage recorded in the central part of the silo.

Furthermore, destruction of the over-cell gallery and notably its floor allowed for communication between this gallery and the space below cells where the hoppers are positioned at the intersection of the two distinct silo segments.

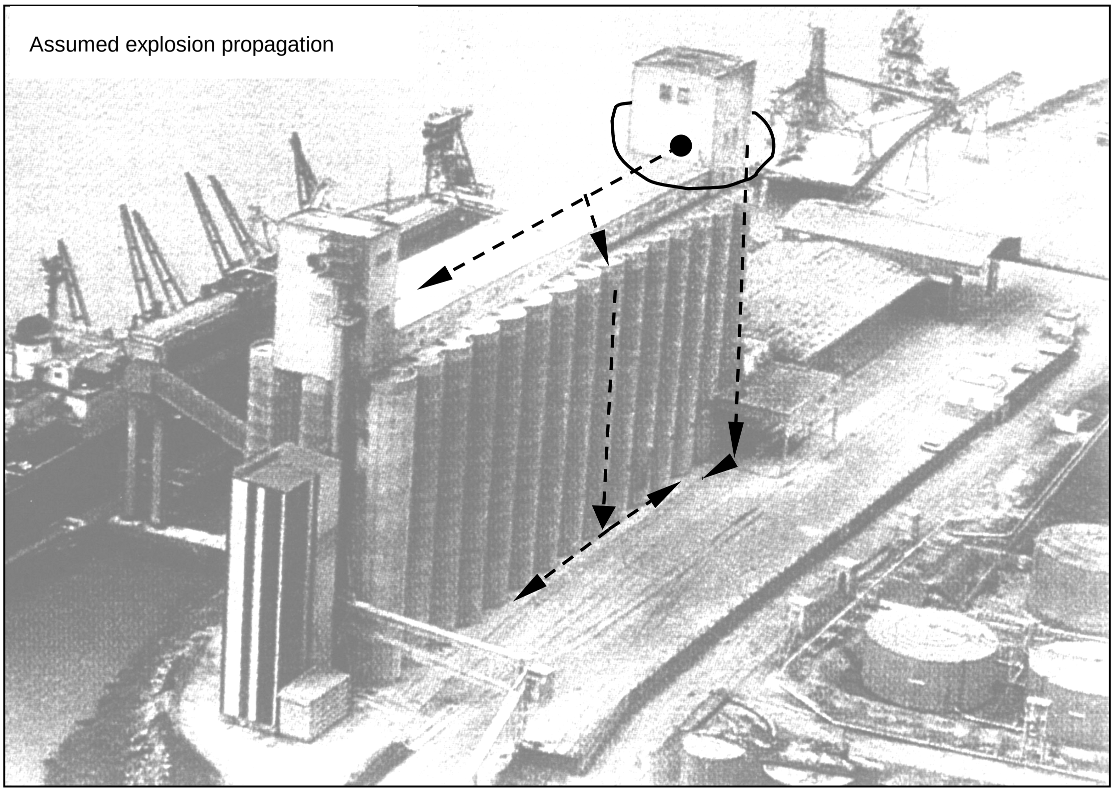
Propagation of the explosion via this opening seems feasible, as this volume had never undergone special cleaning and dust deposits on the sidewalls were therefore likely.

At the northern handling tower and simultaneous to bursting of the transit cell, the explosion gathered strength from top to bottom. The pressure level reached could not be contained due to the absence of venting surfaces, resulting in destruction of the northern handling tower. The vector of propagation was neither the elevator ducts nor the centralized dust suction circuit pipes. This propagation therefore probably took place within the tower volume, a finding that still presumes however the presence of an inflammable cloud within this space. In excluding the presence of eventual deposits, only an accidental dust spreading mechanism could have given rise to suspending these dust particles from top to bottom in the handling tower. The only foreseeable process capable of spreading a significant quantity of dust in this manner consists of a break downstream of the dust suction fan, under the hypothesis of a break in the dust bin.

The explosion spread to the under-cell part, either via the base of the handling tower or most likely, according to the independent investigators, via the hoppers positioned at the intersection of the two building segments. With this last hypothesis, propagation of the explosion via the hoppers would enable the flame to accelerate sharply, due to the geometric configuration (an H/D ratio near 10), while inducing sizable pressure effects. Under such conditions, the pressure waves emitted at the lower hopper outlet can easily be intensive enough to destroy the adjacent storage units and, to a large extent, the concrete shell separating the under-cell gallery from the outside. These openings at the level of the under-cell gallery, just a short time before the flame struck, were able to serve as vent surfaces, thereby limiting the pressure surge reached within this same under-cell gallery.

Destruction of the concrete shells of the under-cell gallery could thus stem from pressure waves created by either top-to-bottom propagation of the explosion or the actual structural collapse. This sequencing is consistent with the fact that the destruction of the concrete shells in the under-cell space occurred towards the end of the explosion process, as reported by witnesses.

The photo below shows a schematic depiction of the supposed explosion path. Overall, the explosion phenomenon could have lasted several seconds.



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The building collapse could have been facilitated by eventual structural vulnerabilities (partial collapse of the sidewall of an external cell had already occurred in 1988, thereby revealing the insufficient or poor position of concrete reinforcement on a number of cells). Collapsing and falling equipment invariably caused short-circuiting, and this is especially true at the level of the transformer room located in the first basement of the administrative and technical offices, which might have been at the origin of localized fires subsequent to the explosion.

The cell fires, reported at the upper storage surface, could have been ignited by the falling of lighted combustible equipment following passage of the flame. From this perspective, conveyor belts were unable to resist fire propagation.

Causes of the accident

The search to determine accident causes entailed specifying the conditions under which an explosive atmosphere could form as well as identifying the inflammation source.

Regarding the formation of an explosive atmosphere, two possibilities were set forth:

- ✓ the formation of combustible gases in the storage unit roof, provoked by a deteriorated situation such as self-heating, fermentation or the outbreak of fire;
- ✓ the presence of an explosive atmosphere containing a dust and air mix.

Following closer examination, only the second hypothesis was adopted. This situation has been commonly encountered during other accidents. Based on first-hand accounts collected and observations recorded, the explosion began either in the dust removal circuit or within a structural volume of the silo itself, since a source in the "product" circuit can reasonably be excluded. The assessment of potential inflammation sources, as listed below, led to designating sources internal to the dust removal circuit as plausible inflammation sources.

To the extent that working at hot spots could quickly be excluded, the following causes of inflammation sources were examined in detail: sparks or mechanical heat build-up (including hot surfaces), static electricity, electrical sparks, self-inflammation of dust accumulation. An analysis of the various possibilities and the fact that dust collection installation components were not found led to choosing the following as plausible origins of the explosion-generating inflammation:

- ✓ either shocks or mechanical friction at the level of the centralized dust removal circuit fan,
- ✓ or the outbreak of a fire by means of self-induced heat rise at the level of the dust bin.

LEGAL RAMIFICATIONS

The Bordeaux criminal court sentenced the Facility Director to 18 months of jail time with suspension and a fine of 58,000 francs by underscoring in its February 26, 2001 ruling: "*An analysis of the facts… has demonstrated both the lack of rigor and precision in the plant's safety organization, procedural shortfalls, no real equipment maintenance monitoring program, the absence of a bona fide preventive and systematic control protocol, and uncertainty regarding maintenance work, poor or nonexistent training offered and deficient information transmission among staff on explosion causes other than fire and on inflammable sources other than hot spots (e.g. cigarettes, welding arcs)…*

The company, as an corporate body, was fined one million francs and is under judicial surveillance during three years.

THE LESSONS LEARNED

A specialized environmental inspection mission, ordered by the Environment Minister, returned in March 1998 a report concluding the necessity to update the regulations dating from 1983 in order to ensure proper application to silos built previously. The essential guidelines pertained to:

- ✓ completion of a hazard study devoted to existing installations,
- ✓ an adequate distance maintained by third parties from the occupied premises,
- ✓ creation of venting surfaces and separation of the various silo structures,
- ✓ assignment of non-essential personnel far from silos.

The independent body, as mandated by the Environment Ministry, included in its report the primary lessons learned from this accident. Their findings relate to several topics, listed hereafter in order of the explosion process:

Prevention of the formation of an explosive atmosphere:

- ✓ monitor temperature within the hoppers as for the cells,
- ✓ make use of video monitoring techniques, whether combined or not with detection methods for notifying abnormal dust accumulation,
- ✓ determine safe operating limits of the dust suction system, especially for centralized type systems,
- ✓ continuously check the suction efficiency of a centralized dust removal system by means, for example, of a pressure drop measurement,
- ✓ ensure that filtering sleeves are covered or introduce an equivalent system that enables preventing against any risk of dust spreading into the predominantly closed installations. The most suitable procedure would consist of installing this equipment outside of any confined space, i.e. in the open air,
- ✓ isolate, to the greatest extent possible, the various parts of the silo from one another (the term "parts of the silo" could, for example, designate the handling tower, the over-cell gallery or the under-cell space). This would also hold for each of the various tower stories.

Pressure surge of potential inflammation sources:

- ✓ generalize, within silos built prior to 1983, the stone removers and metallic part collection devices;
- ✓ install, on the main pieces of equipment, spark detectors or any equivalent feature to control equipment shutoff;
- ✓ introduce an abnormal temperature detection on some facilities (e.g. fan bearings on the centralized dust collection system);
- ✓ strengthen controls relative to electrical equipment.

Propagation of the explosion:

- ✓ separate the various silo structures so as to limit explosion propagation (which also leads to limiting explosion effects);
- ✓ install the centralized dust collection systems, to the extent possible, away from confined machinery, i.e. in open air.

Limitation of adverse effects:

- ✓ perform a regular diagnostic assessment of cell strength (e.g. once every 10 years);
- ✓ lay out vents on the structures that house grain handling equipment as well as on the storage units;
- ✓ determine the procedures and limitations with venting calculations for elongated structures, during inflammation caused by a burst of flames;
- ✓ prohibit (and deactivate) or limit the use of capacities with a high length-to-diameter ratio (i.e. greater than 5), especially for intervening hoppers.

Mitigation of consequences:

- ✓ study, on a case-by-case basis, the minimum distance separation of buildings occupied by third parties, with the value of 1.5 times the silo height needing to be set as the minimum distance;
- ✓ move away from the silo all individuals whose activity is not essential to direct silo operations.

Other lessons:

- ✓ install fire/smoke detectors in those zones with a known fire risk due to the presence of combustible materials other than cereals;
- ✓ regularly clean the air blowing circuit pipes located at the base of cells;
- ✓ adapt the storage temperature alarm threshold to outdoor climatic conditions, provided technical justification in incorporating kinetics of the self-heating phenomenon.

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Subsequent to the accident, the prescriptions set forth in the Ministerial decree adopted on August 11, 1983 relative to silos were updated. A July 29, 1998 decree would then set the new regulatory obligations with respect to the general layout and organization of installations, facility design and risk prevention. The scheduling for installation applications would also be prescribed.