A SILO STRUCTURE TO RESIST INTERNAL DUST EXPLOSIONS

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Abstract: Over a period of about 12 years a research program on silo structures was going on in Germany, financed by the Deutsche Forschungsgemeinschaft. One of the subjects studied was the straining of silo structures in case of dust explosions, which often occur in silo plants. This was done by experiments and theoretical analysis. The first and third author were engaged in this project. A few years later a very large silo structure was erected, where the third and second author served as check engineers. A short report is given on the basic results obtained in the research and their application at the large silo plant, where in the meantime a dust explosion has occurred.

Keywords: dust explosion, silos, research, theory and experiment, plant execution, occurrence of a dust explosion

1. Dust explosions in silos

Already in ancient cultures, *e.g.* in Egypt, storage facilities had been used to save food for men and animals over periods of time. Nowadays, silo structures of immense dimensions are used for this purpose.

Quite long experience has demonstrated that the content of such silos, depending on the stored material, may explode and destroy the structure, injuring people, buildings and other neighbouring facilities, as shown in Figure 1. This is a silo plant in Blaye, France, with a capacity of 300 000t of grain, after a dust explosion which happened a few years ago. Twelve people were killed and the structure was completely removed. Figure 3 shows the result of a similar event at a silo plant in Germany, near the city of Bremen. The silo structure was also completely destroyed. The intensity of the explosion was equivalent to about 20t of explosives, fourteen people were killed, seventeen heavily injured.

The costs were estimated at 100 million German marks. Windows were shattered within about 2km around the silo. Statistics (Figure 2) show that a significant number of people have been killed over the years by such explosions, not to speak of the combined monetary losses.

Such explosions occur if sufficiently small particles react exothermally with the air oxygen, ignited by an initiating event. A number of the most important initiating events are given in Figure 4.

Table 1. Characteristic values of explosive dust materials

Bulk material	K_{st} value [bar·m/s]	$\rho_{\max}$ [bar]
aluminium powder	1100	13.0
brown coal	63	4.3
fly ash	35	1.9
barley	83	7.7
grain flour	130	9.0
rubber	138	8.5
wood, sawdust	220	10.0
coffee	90	9.0
potato flour	115	8.8
coke	146	8.2
starch (dried)	210	10.0
milk powder	160	9.0
paper	60	9.0
pigments	290	10.0
soya meal	47	7.2
soya flour	120	9.0
mineral coal	80	8.4
wasching powder	270	9.0
sugar	150	9.0

What is unknown to many civil engineers who build silos is the great number of materials which may explode in silos. Only a small selection is given in Table 1. However, even if the initiation of such dust explosions can never be excluded in a silo structure one should try to keep the consequences as limited as possible.

The only means relevant nowadays are:

- explosion suppression,
- explosion resistant structures,
- pressure relief.

While the first is hardly possible in very large localities, the second is extremely expensive, so that only the third can be applied.

2. Theoretical background

Before discussing dust explosions in silos and their structural consequences it is necessary to give a short introduction to the underlying thermodynamical facts. To study the matter in detail the reader is referred to the relevant literature [4, 6, 7].

Figure 1. Silo plant in Blaye, France, after a dust explosion (photo: J. Steiner [1])

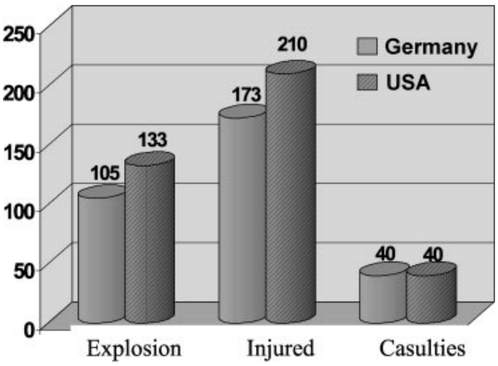

Figure 2. Statistics of dust explosions in the period 1981–1995 [2–5]

Figure 3. Rolands-mill Bremen after dust explosion

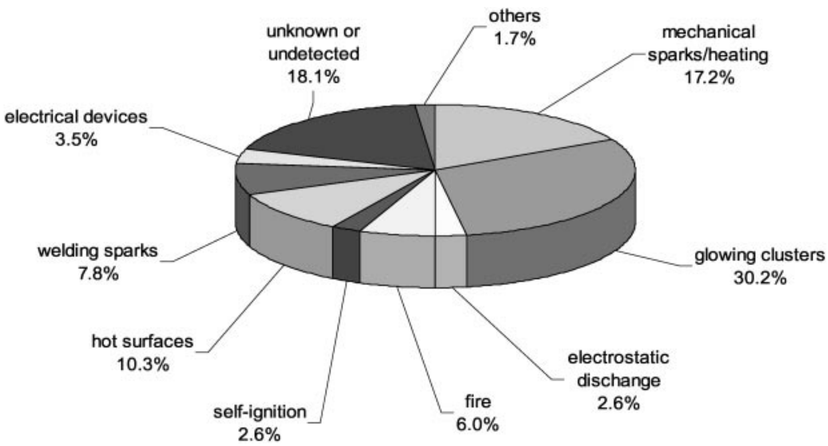

Figure 4. Possible sources of ignition [4, 5]

If heat is incremented in a closed thermodynamical system by dq, the following equation holds:

$$dq = de + pdV, \tag{1}$$

where q – specific heat supply, e – specific internal energy, p – pressure, V – specific volume.

The enthalpy i is determined by:

$$i = e + pV, \tag{2}$$

so that

$$dq = di - V dp. \tag{3}$$

Specific heat capacity is formulated as follows:

$$c = \frac{dq}{dT}, \qquad c = \frac{di}{dT} + p\frac{dV}{dT}, \tag{4}$$

$$c_p = \left(\frac{de}{dT}\right)_{p=\text{const.}} + p\left(\frac{dV}{dT}\right)_{p=\text{const.}}, \quad c_V = \left(\frac{\partial i}{\partial T}\right)_{V=\text{const.}} - V\left(\frac{\partial p}{\partial T}\right)_{V=\text{const.}}, \tag{5}$$

where T – temperature.

Further on the following conservation equations must hold (see section A in Figure 5):

$$\text{mass} \quad \rho_1 v_1 = \rho_2 v_2, \tag{6}$$

$$\text{impulse} \quad p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2 \quad (v_i = \text{velocity}), \tag{7}$$

$$\text{energy} \quad \frac{v_1^2}{2} + i_1 = \frac{v_2^2}{2} + i_2 + q. \tag{8}$$

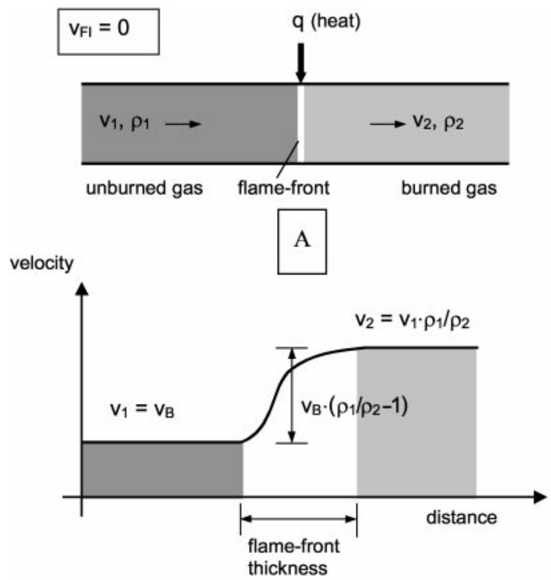

Figure 5. One-dimensional gas flow stationary state [4]

By means of the equations

$$pV = R/\mu \cdot T, \quad (c_p - c_V)\mu = (C_p - C_V) = R \quad \kappa = C_p/C_V, \tag{9}$$

where R – the ideal gas constant, μ – the molar mass, C_p, C_V – molar heat capacities, one finally ends up with the so-called Rankine-Hugoniot equation:

$$\frac{p_2}{p_1} = \frac{\frac{\kappa+1}{\kappa-1} - \frac{\rho_1}{\rho_2} + \frac{2\kappa}{\kappa-1}\frac{q}{c_p T_1}}{\frac{\kappa+1}{\kappa-1}\frac{\rho_1}{\rho_2} - 1}. \tag{10}$$

Considering that $1/V_i = \rho_i$, the equation gives the values of ρ_2, p_2 behind the flame front at the stationary point A (Figure 5) if those before the point are known. It leads to the principal results as shown in Figure 6 [6], with the additional statement that only a burning process can occur. All types of detonations are excluded.

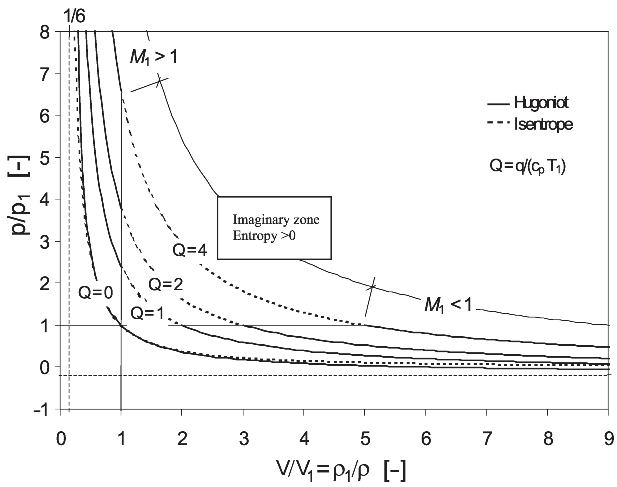

Figure 6. Hugoniot curves at heat addition q for methane-air and starch-air mixtures

3. Experimental and computational investigations

Before discussing the experimental investigations and computations carried out at the Institute für Massivbau and the Engler Bunte Institute[1], a short introduction on dust explosions in general and the relevant terminology has to be given.

This fast burning process is characterised by burn velocity, v_B, and flame velocity, v_{Fl}. In general, the intensity of the process depends on the size of dust particles; the finer the particles, the more vehement the explosion.

Most dust explosions in silos occur due to organic materials, however, metallic dusts generate the highest pressures. Table 1, including a selection of explosive materials, demonstrates that there is a far greater number of dangerous materials than one might expect. The highest intensities of dust explosions occur with dust concentrations of about 200 to 400g/m^3. Of further importance is, of course, the temperature and energy of ignition. A characteristic indicator of the maximum pressure which may be expected is the so-called K_{St} value of a material. According

1. Combustion Institute, Technical University of Karlsruhe, Director Prof. Dr Ing. Leuckel

to a more or less international consensus (see [4, 8]), it is determined in a spherical model container filled with the relevant material (Figure 7), according to the following relation:

$$\left(\frac{dp}{dt}\right)=K_{St}V^{-\frac{1}{3}},$$

where the increase in pressure is measured.

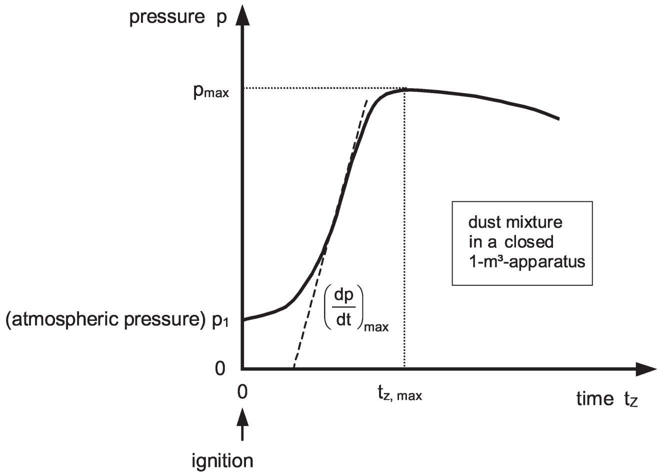

Figure 7. Maximum pressure, $p_{\max}$, measured in a standardised $1\mathrm{m}^3$-apparatus

Designing silo walls for unreduced explosion pressures is practically impossible, because of the costs involved. Therefore, silos are usually designed with p_{red}, reduced pressure due to special relief devices such as covers or lid structures (Figure 8).

The smaller their resistance at opening, the lower their weight and fixing, the lesser the resulting explosion pressure.

To realistically consider all these effects, apart from computation, experiments have also been carried out in Karlsruhe, at the third author's institute [9–11].

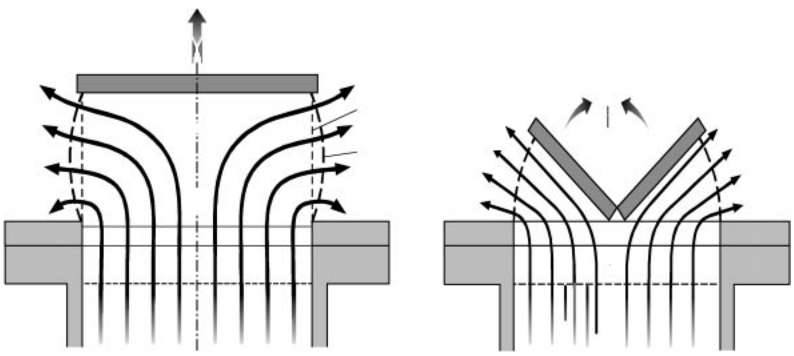

Figure 8. Relief systems

3.1. Experiments carried out

Basing on this knowledge, a special experimental silo structure was built an old limestone quarry. Figure 9 gives a sectional view and a photograph of the test

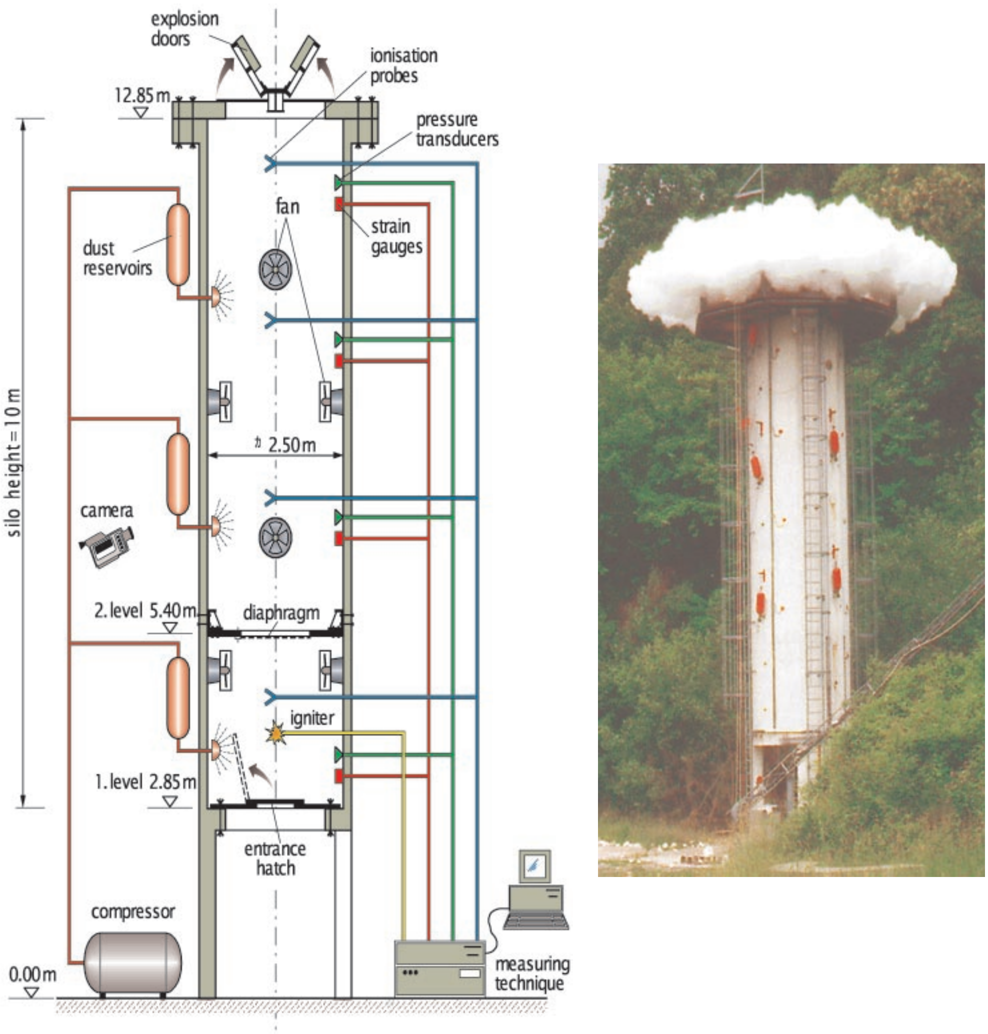

Figure 9. Experimental set-up

silo building. The silo had a diameter of 2.5m and a height of 10m, *i.e.* a height-to-diameter relation of 4. At the top, several ring elements could be arranged to change the pressure relief area from 100% to 75% and 50%. An intermediate floor was installed to reduce the H/D relation and to study ignition transfer through holes into different compartments by means of jet ignition. Dust was spread by ventilators to get an equal, controlled distribution. Many pressure cells and strain gauges were used to register pressure and strain, as well as temperature fields. Pressure was mainly produced by corn dust with a K_{St} value of 210bar·m/s and a maximum pressure of 10bar. For comparison, methane gas was also studied.

Table 2 gives an overview of the tests, with maximum pressures depending on the place of initial ignition.

Pressure reductions of 80% to 95% achievable due to the relief measures could be measured. This pressure reduction is, however, a rather complex phenomenon,

Table 2. Overview of the tests: [1] $D = 2.5$m diameter of silo, [2] H/D for intermediate enclosure, [3] a value at high turbulence, ventilators with 830rpm; ε_R – radial strain, ε_L – longitudinal strain, ω – angular velocity, F_v – vertical reaction force, F_h – horizontal reaction force, a – acceleration, K_G – gas specific characteristic

	cover I $V = 49.1\text{m}^3$ $H/D^{1)} = 4$		exp. doors II $V = 49.1\text{m}^3$ $H/D^{1)} = 4$		exp. doors III $V = 12.5\text{m}^3$ $H/D^{1)} = 1\,(3)^{2)}$		exp. doors IV $V = 36.5\text{m}^3$ $H/D^{1)} = 3$		flow deflector V $V = 51.7\text{m}^3$ $H/D^{1)} = 4$	
	dust	gas	dust	gas	dust	gas	dust	gas	dust	gas
max. p_{red} [mbar]	649 $899^{3)}$	1101	882	1281	980	1267	629	792	1248	1882
max. ε_R [‰]	0.11 $0.14^{3)}$	0.17	0.09	0.13	0.20	0.15	0.03	0.08	0.08	1.65
max. ε_L [‰]	0.028 $0.03^{3)}$	0.04	0.01	0.02	0.01	0.01	0.01	0.02	0.25	0.60
max. v [m/s]	—	20	—	—	—	—	—	—	—	—
max. ω [rad/s]	—	—	15	17	13	12	13	17	—	—
max. v_{Fl} [m/s]	26 $30^{3)}$	27	25	27	70	45	20	20	28	35
max. F_v [kN]	—	1000	120	300	100	35	55	70	270	330
max. F_h [kN]	—	—	—	—	—	—	—	—	180	240
max. a [m/s^2]	—	—	—	—	—	—	—	—	—	17
$(\text{d}p/\text{d}t)_{\max}$ [bar/s]	11.5 $51.6^{3)}$	30.6	9.3	21.9	19.4	22.0	6.6	10.2	22.1	40.0
$(\text{d}p/\text{d}t)_{\max} \cdot V^{1/3}$ ("K_{St}-" or "K_G-value") [bar·m/s]	42.1 $189^{3)}$	112	34	80	45	51	22	34	82	149

depending on the type of fixing, inertia effects and the induced pressure, which means that the air flow conditions have to be studied in great detail.

After an initial pressure build-up due to inertia of the relief devices, a significant pressure reduction follows after an appropriate acceleration of the cover lids. Even below-atmospheric pressure has been observed in steel silos with self-closing relief devices. Therefore, the velocity of lids at opening and the translational velocity of covers had to be taken into account as well.

However, if one intends to reduce pressure by certain relief devices, one also has to study some further problems. Burning dust escapes with high speed from the cells. Fragment formation and the flight of missiles in the space above the cells has to be taken into consideration. Otherwise dangerous projectiles may endanger the plant's surroundings.

Covers and lids must be either fixed or their flight path must be controlled by adequate means.

Significant pressure-time dependent strain changes in the longitudinal reinforcement have been registered as a consequence of changing stress resp. strain profiles over the cross-section of the silo (Figure 11). It became extreme when a device to change the direction of gas flow was accompanied by heavy vibrations of the whole system in the case of flow deflectors being used (Figure 12). Similar effects occurred in the vertical direction when the longitudinal tension on one side of the silo was much

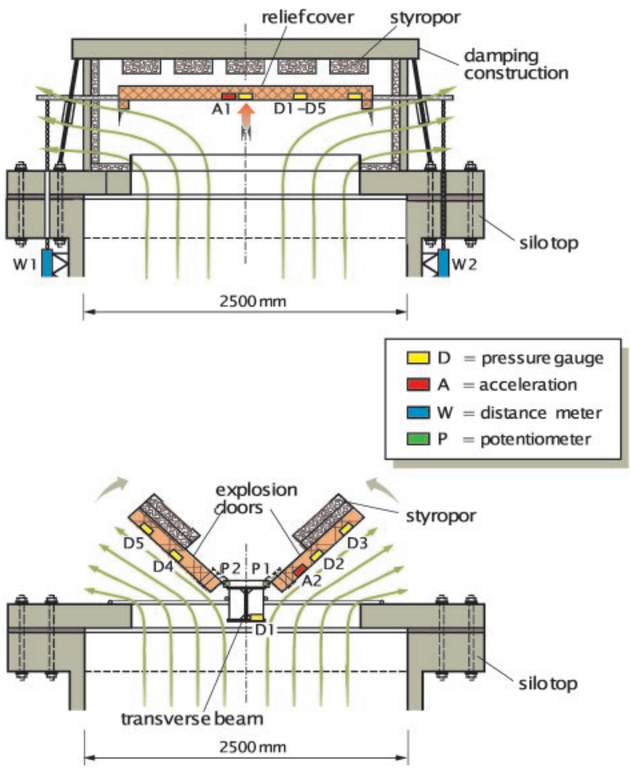

Figure 10. Cover and lid used in the experiments:
top – relief cover and bottom – explosion doors

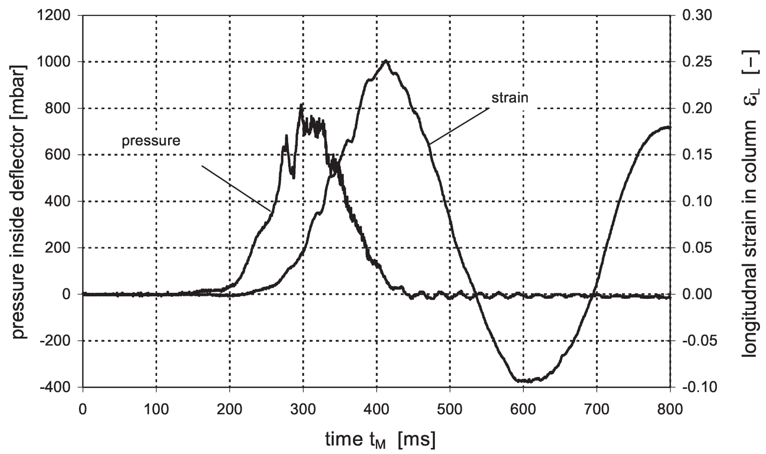

Figure 11. Oscillation of the silo due to venting with a flow deflector

greater than on the other. This effect also induced quite different vertical loads in the supporting columns resp. walls.

The above mentioned experiments were accompanied by Finite Element calculations simulating the whole explosion process. For this purpose the so-called ALE code was used, which allows the coupling of a Lagrangian mesh to model the containment with an Eulerian mesh for the containment space [4].

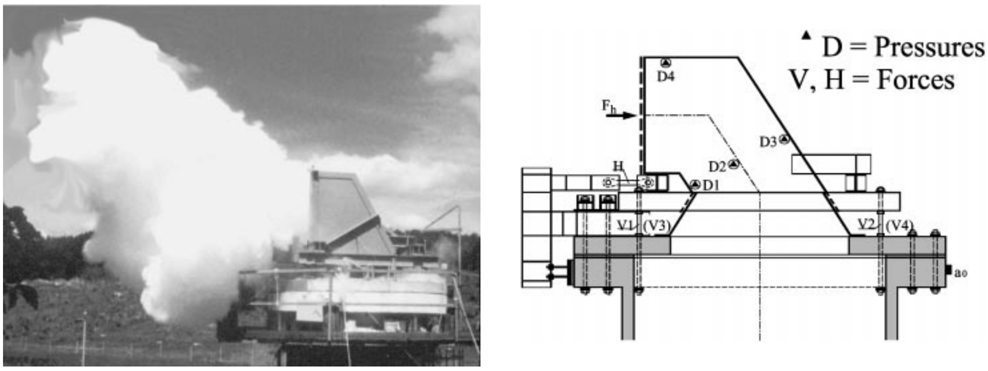

Figure 12. Dust cloud in the case of flow deflector use

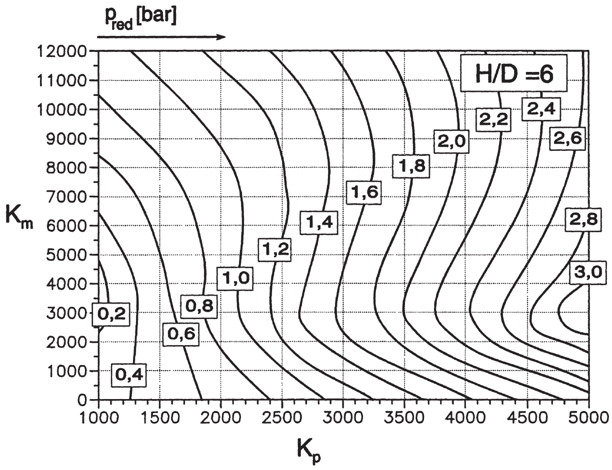

Figure 13. Example chart to find pressure p_{red}

For a general idea of the process, the following may be sketched. Computation starts with an original $p-V$ state and a heat input according to the theory presented in Section 2. In the successive time increments all $p-V$ states in the neighbouring cells are adjusted. A new heat input follows after $v_1 \cdot dt$, where now $v_1 = v_{Fl} - v_B$ (see Figure 5), v_{Fl} being the flame front velocity and v_B – the burning speed. The values of v_{Fl} and v_B result from experiments and depend mainly on dust type and distribution.

Regarding that the values of p_1, ρ_1, e_1, q_1 the set of conservation Equations (6)–(8) are known and that an equation of state, $p \cdot V = nRT$, is available, the four remaining unknowns the system of three conservation Equations (6)–(8) e_2, p_2, ρ_2, v_2 may be determined, as $v_1 = v_{Fl} - v_B$ is also known.

4. Design protection against dust explosions

As a result of these experiments and the FE computation, a simple design proposal was made for the evaluation of pressure distribution by simple charts [4, 9, 10]. This method was also the basis for a new German code of live loads (DIN 1055). A typical example of the many charts developed is given in Figure 13, just for the

Figure 14. Overview of the plant

determination of p_{red}. A further set of charts is available which allows determining the reaction forces for design of flaps and lids. Finally, a wide range of measures for the protection of silos against dust explosions and design proposals for venting devices and their arrangement are suggested [4].

Starting with the input parameters [9, 10], and

$$K_p = \frac{V^{\frac{5}{6}} \cdot K_{St}}{A_E}, \qquad K_m = \frac{m_E^{\frac{1}{2}} \cdot K_{St}^{\frac{5}{4}} \cdot V^{\frac{1}{24}}}{n^{\frac{1}{4}}},$$

the design pressure p_{red} can be taken directly from the chart, depending on K_m and K_p, where V – silo volume, n – number of flap partitions, A_E – area of venting, m_E – weight/m^2 of flap or cover, K_{St} – dust specific characteristic.

5. A silo plant designed against dust explosions

According to these research results, the first big plant designed against dust explosion has been erected (Figures 14–16). The design of the plant against dust explosion was done according the new design method [9, 10] beside existing codes [8, 12, 13]. At the stage reached so far, it has a capacity of 250000t in 64 hexagonal cells for different agricultural products and is situated at the mouth of the river Weser in Germany where large sea-going ships can reach it. The dimensions are as follows: length – 95m, width – 35m, height – 85m.

The advantage of this type of hexagonal cells (Figure 17) is that they are principally designed to resist moments, the latter being not very high due to the short horizontal bending length. At the lower end of the cells steel funnels were attached (Figure 16). Of course, silo cells of this type require more reinforcement than circular ones but have several advantages. Circular cells have interstices between them, in most cases not used, and low reinforcement, which is sensitive to non-uniform loading.

The plant as shown in ground plan (Figure 17) was erected in two stages (part I and part II) with the third author being check engineer for the whole plant and special consultant for the dust explosion layout. Part I was finished in 1981, part II was opened

Figure 15. View from the Weser

Figure 16. Steel funnel

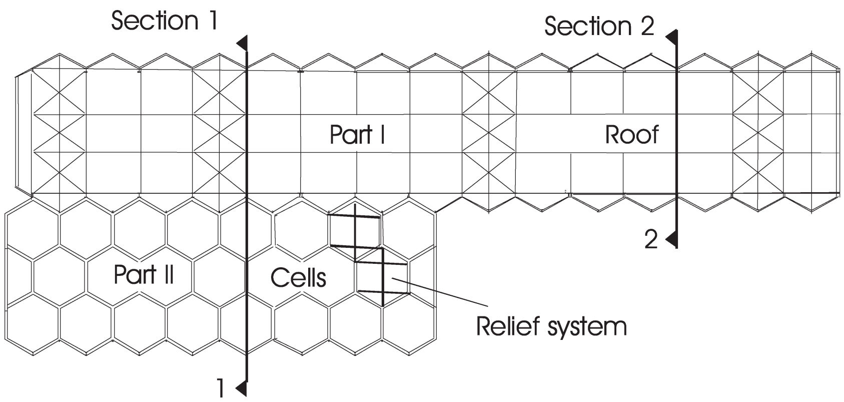

Figure 17. Ground plan

in 2003. Before the latter was completed, a dust explosion happened in 1988. Only minor, almost negligible damage occurred thanks to the chosen dust explosion layout. Nevertheless, this experience led to minor changes to part II, as will be shown.

A first overview of the whole may be seen from the ground plan (Figure 17). For the sake of simplicity, it shows in upper part II a sketch of the roof structure, which is actually the same for both parts of the structure. In the lower part I, a sketch of the concrete cells is given, again relevant to both parts.

The cross-section in Figure 18 gives the original layout for part I; its amendment for part II is shown in Figure 19. Finally, Figure 20 shows the complete structure as it stands nowadays.

Before part II was erected, the upper closure of the cells of part I consisted of light-weight pumice slabs with several layers of sealing sheets, which were designed to

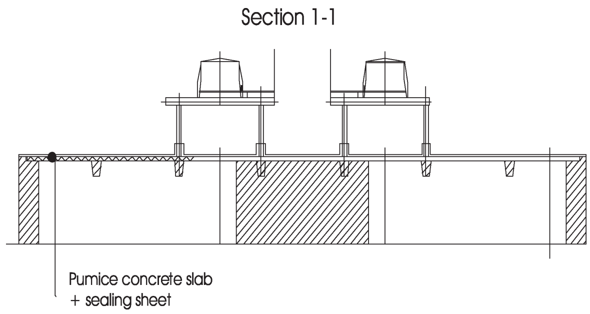

Figure 18. Original part I: section 1-1

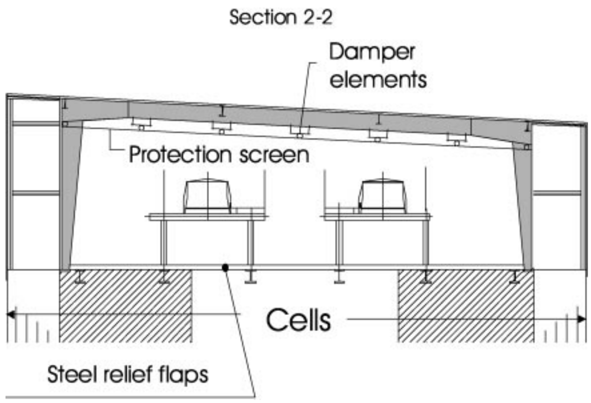

Figure 19. Part II: section 2-2

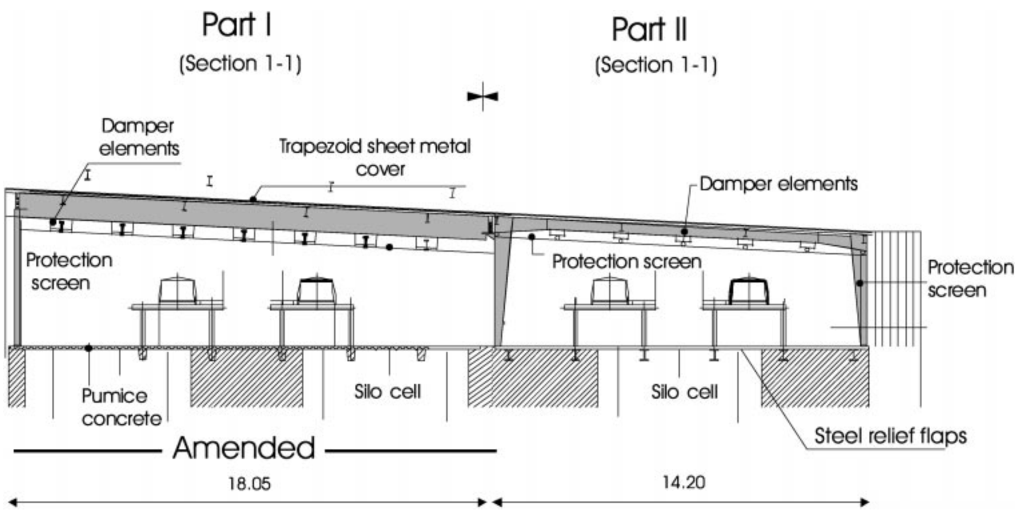

Figure 20. Final version: section 1–1

fly away in case of a dust explosion (Figure 18). The maximum silo pressure in case of an explosion was determined with regard to this light weight structure.

In order to keep fragments of the normal silo operation equipment within the upper enclosure and to prevent them from falling down 80m, a net of steel ropes has been placed below the roofing steel frames. It is fixed on special damper elements

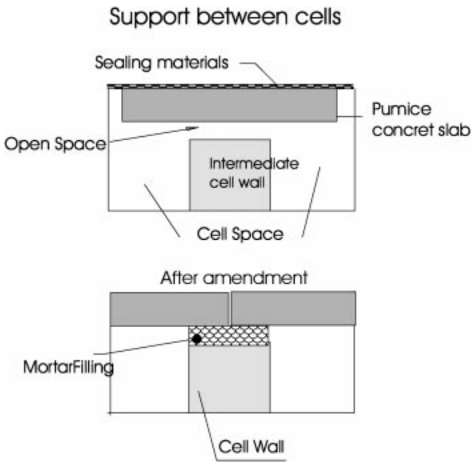

Figure 21. Pumice concrete slabs

to control the rope forces in case of contacting fragments. Metal sheets are the final upper closure.

According to this type of construction and the relevant weight of the covers, respectively of the relief flaps, the structure was designed for the following explosion loads, independently from the usual design loads such as temperature, filling pressure, wind *etc.*:

- overpressure in cells due to explosion: $p = 1.6$ bar,
- maximum pressures at relief opening: $p = 0.05$ bar,
- impulse pressure going out of the cell: $p = 1.15$ bar,
- upper steel net to cover flying fragments,
- wire mesh in the protection screen in part I with 15/25 cm designed for $P = 500$ kN,
- wire mesh in the protection screen in part II with 10/25 cm designed for $P = 2\,000$ kN.

In amendment of part I from its original construction to the final one, the pumice slabs were cut into shorter pieces and the intermediate gaps between the pumice slabs and the silo walls (see Figure 18) were closed by mortar to avoid ignition transfer from cell to cell.

In the later erected part II steel relief flaps were attached to the upper end of the cells instead of pumice slabs to reduce the internal cell pressure (Figure 20).

6. Summary

A research program running over 12 years was financed by the Deutsche Forschungs Gemeinschaft (EN – German Research Foundation) to study silo problems in general. Among other projects, silo design protection against dust explosions was one of its subjects. Through experiments and the accompanying theoretical investigations recommendations for silo structures enduring dust explosions could be developed. These were applied for the design of a huge silo plant structure, built in two stages, where shortly after the first section was erected a dust explosion occurred

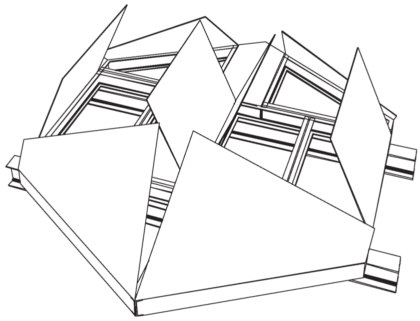

Figure 22. Mechanism of relief flaps

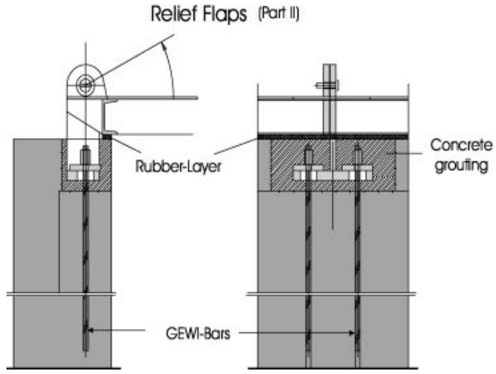

Figure 23. Fixing of relief flaps

which caused only negligible damage. The experience of this explosion led to minor amendments to the second stage, which meanwhile has been erected.

It may be mentioned that the proposed pressure scenario was discussed within bodies responsible for the German resp. Euro Codes. Finally since then this proposed design method has been integrated in the German and Euro Code.

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