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Pressures around vented silos

1. Introduction

NUON is preparing an extension of an existing power plant in Diemen. Part of the extension is the installation of several silos, to store wood pellets.
Since such pellets do pose a dust explosion hazard, the silos will be equipped with explosion venting. In case of a (vented) explosion, there will be a large fireball and a pressure wave into atmosphere, that may endanger existing or new installations and buildings.
Therefore NUON has requested ISMA to investigate these effects.

Remark: as is common for explosions and explosion protection: all pressures included are overpressures.

2. Available information

Since the installation is currently in the design stage, there are still several options. During a kick-off meeting on 8/10/2018 at Amsterdam, the available information was discussed.

Concerning the number and size of the silos: there will either be 4, 6 or 8 silos (with different volumes: the overall storage capacity will be similar). It was agreed that, for a first analysis, 2 situations will be investigated:

A. 8 silos (2 x 4) with a diameter of 8 m and a net volume of 564 m^3 each. Overall height: 18,85 m.
B. 4 silos (2 x 2) with a diameter of 9 m and a net volume of 1160 m^3 each. Overall height: 24,5 m.

For the explosion characteristics of the wood pellets following numbers will be used:

- P_{max} = 10 bar
- K_{st} = 200 bar.m/s

Also the reduced explosion pressure where the silo is designed for is not decided yet and might be effected by the results of the current investigation. It was agreed that, for the A silos, it will be assumed: P_{red} = 0,7 bar and, for the B silos: P_{red} = 0,5 bar.

With respect to the surroundings: several drawings were received from NUON. Based on these drawings the following installations and buildings will be considered:

- HAT. This is an existing large cylindrical vessel: diameter 27 m, height 50 m, located at 77 m from the centre of the closest silo.
- Workshop. This is an existing building. It consists of several parts, having different heights. The part closest to the silos has the maximum height: 15 m and will therefore be decisive for the explosion effects on this building. The distance to the centre of the nearest silo is 32 m.
- A new building (as part of the process). From this building several parts are important:
    - low rise part, located 7 m from the centre of the nearest silo. The height of this part is 8 m
    - High rise part, located 21 m from the centre of the nearest silo. The height is 31 m
    - Tower with elevator/staircase in front of the high rise part, located 15 m from the centre of the nearest silo. The height is 33 m.
- A neighbouring silo. The distance in between silos (centre to centre) is 12 m.

An impression of the lay-out is presented in figure 1.

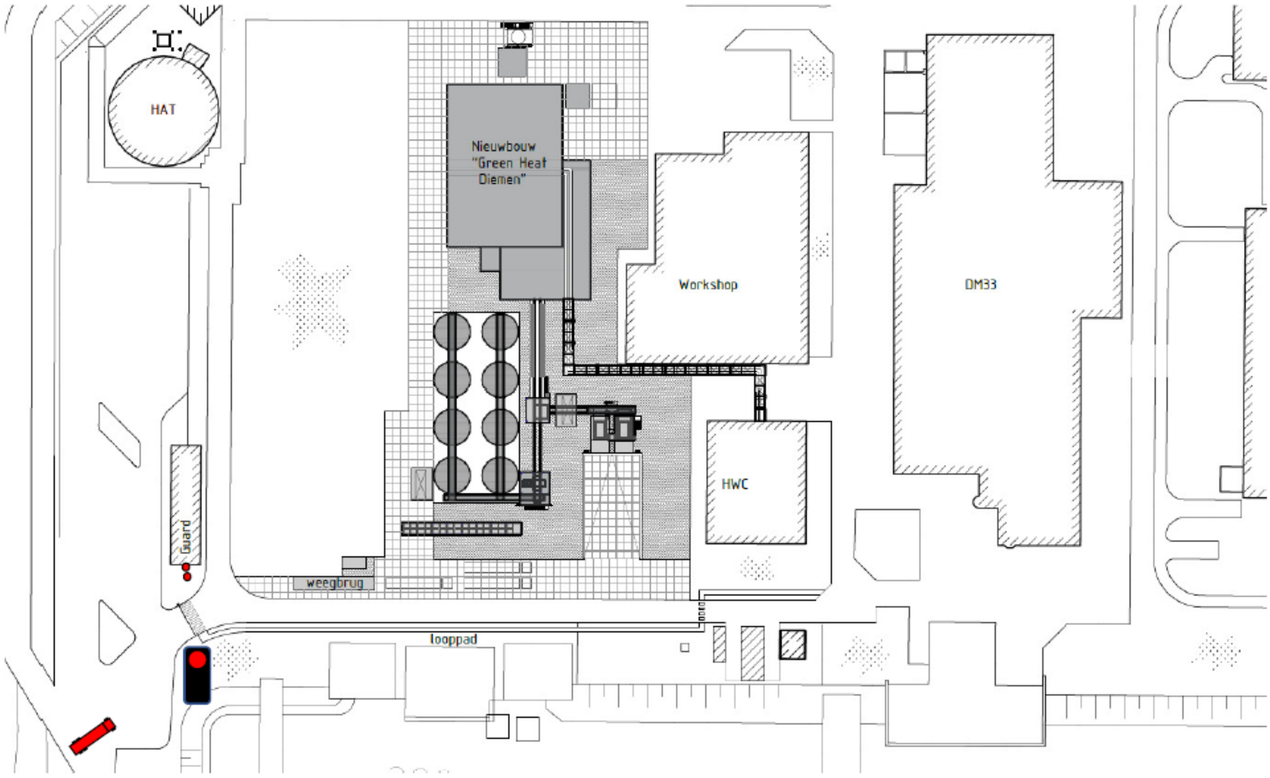

Figure 1: lay-out of the new installation (grey), with existing items

At first only the overpressures on these items will be calculated. Depending on the results it will be decided if also other items (further away) need to be included. If it is found that the calculated overpressures might be critical, the actual type of building/installation will be further evaluated.

3. Flame jet effects

In EN 14491:2012 a relation is given for the maximum flame jet length of a vented vessel. For vertical venting (as will be applied here) the relation is:

$$L_F = 8\ V^{1/3}$$

It is remarked in this standard that it is expected that the flame jet will not exceed 60 m. Therefore 60 m could be used as an upper limit for the length. However, the author of this report has been involved in a research program, where a model was developed to predict the length of the flame jet and the result was compared with *test data. The current formula is in agreement with the results of this program, but there is no reason to assume that the length of the flame will not exceed 60 m.*

The same standard also includes a relation for the maximum flame diameter:

$W_F \approx 2{,}8\ V^{1/3}$

Depending on the actual shape of the flame jet this diameter might arise close to the vented vessel, but also further away from the vent.

Based on these formula following is calculated for silos A and B:

Silo A, with V = 564 m^3 it is found: L_F = 66 m and W_F = 23 m
Silo B, with V = 1160 m^3 it is found: L_F = 84 m and W_F = 29 m

Experience, with respect to fire hazards, due to exposure to such a flame jet, is that, because of the rather short duration, there is mainly a risk to items/persons inside this flame jet. Outside the flame jet there is hardly a risk. Hence, safety distances due to the heat radiation are typically chosen as the dimensions of the flame jet (with probably a small safety margin. Of course, when items are present that are easily flammable, larger distances might be required.

Since all explosion vents will be installed on top of the silos, flame jets will be directed upwards. Hence there is only a fire hazard on the bridges that run over the silos. The common solution to prevent exposure of personnel to such flame jets is to prohibit all access to bridges during filling of silos.
Remarks:

- Currently it is proposed to have 2 rows of silos, with a bridge on top of each row. The distance in between the rows (centre-to centre) is about 12 m. Since the diameter of the flame is 23, resp. 29 m the flame jet from a vented silo will also endanger the bridge above the other row.
- If access to a bridge (during filling of a silo) would be required, it is recommended to protect the bridge with shielding (able to withstand also the pressure from the vented explosion). Deviating the flame jet (with deflectors) is not recommended.

4. Vent calculations

An important parameter for the pressure calculations is, apart from P_{red}, the vent area A of a silo. In order to determine A (with the given P_{red}) vent calculations were made with StuVent: an online software tool that is based on EN 14491:2012. The calculation sheets are included with this report.
With respect to the dimensions of the silo following was done:

- the diameter was chosen as specified (8 or 9 m)
- the height of the cone was chosen based on an assumed slope of 60°.
- the top was assumed to be flat (actually it will be slightly conical)
- the height of the cylinder was chosen such that the overall volume equals the specified value.

Following required vent area were obtained:

- Silo A: 11,86 m^2
- Silo B: 33,58 m^2

5. External overpressure calculations

EN 14491:2012 includes 2 relations to calculate the external pressure due to a vented explosion:

- The first relation is based on the possibility that, during the venting process, first a large amount of unburnt dust is released into atmosphere, which is ignited afterwards and causes an external dust

cloud explosion. Because of the rather low dust concentrations inside a silo during filling with wood pellets[1], such a scenario is considered most unlikely here. Therefore this relation was not used.
- The second method calculates the overpressures around the vent, caused by the vented explosion inside the silo. This method is relevant here. Since the pressure wave from the open vent has a very strong directional effect, the external pressures depend on the directions: the highest pressures will arise in front of the vent.

The overpressure P (bar) at a distance r (m) from the vent can be calculated with:

$$P = 1{,}24 \times P_{red} \times (D / r)^{1{,}35} / \{1 + (\alpha/56)^2\}$$

where:
- P_{red} = the reduced explosion pressure (0,7, resp. 0,5 bar)
- D = the equivalent diameter of the vent (3,89, resp. 6,54 m)
- α defines the direction: α = 0° means in front of the vent, α = 90° means sideways from the vent.

Remark: the diameter D was calculated assuming one single vent on each silo. Actually there will be several vents, distributed over the top of each silo. This will only effect the external pressures very close to the vent, but at the distances concerned here, this will have no significant influence anymore, on condition that the vents are more or less equally distributed over the top of the silo.

The calculated results (in mbar) are summarised in table 1 and 2.

Item	Hor. distance (m)	Vert. distance (m)	R (m)	α (°)	Pressure (mbar)
HAT	77	31	83	68	5,6
Workshop	32	-3	32	95	13,0
New: low rise	7	-11	13	147	21,6
New: high rise	21	12	24	60	34,6
New: tower	15	14	21	47	52,2
Next silo	12	0	12	90	52,9

Table 1: calculation results for silo A

Item	Hor. distance (m)	Vert. distance (m)	R (m)	α (°)	Pressure (mbar)
HAT	77	25	81	72	7,8
Workshop	32	-9	33	105	15,1
New: low rise	7	-16	17	156	19,4
New: high rise	21	7	22	72	45,8
New: tower	15	9	17	59	80,9
Next silo	12	0	12	90	76,3

Table 2: calculation results for silo B

[1] It is questionable if, during filling of a silo in free fall with wood pellets, an explosive mixture (dust concentrations above LEL) will always arise. But such explosive mixtures may at least arise occasionally. However, it is considered most unlikely that the concentrations will be far beyond the optimum concentration (about 10 x LEL) and would result into a large external dust cloud that is ignited outside.

Remark: A negative value for the vertical distance means this item is below the top of the silo.

Discussion
The overpressure is always calculated at the top of the item concerned. For items where this top level is below the silos (Workshop, low rise), this value is always decisive. For items where the top is higher than the silos, lower levels of this item might get higher overpressures, since for these lower levels the distance R is less, which is partly compensated by a larger value of α. For HAT, which is at a rather large distance, this will hardly have any effect. For the tower (and probably also for the high rise), however, lower levels might become decisive. Therefore, for the tower, the calculation (for silo A) was repeated assuming R = 15 m and α = 90° (hence: at the same level as the top of the silo). The overpressure at this level is calculated to be 39,2 mbar, below the value at the top (52,2 mbar): the somewhat smaller distance is more than compensated for by the much larger value of α.
Conclusion: the values in tables 1 and 2, calculated for the top of the various items, can be considered as being decisive for the item concerned.

6. Damage criteria

For the interpretation of the calculated pressures general damage criteria are required, to prevent that, for each item, the resistance needs to be calculated. Only for items that, according to these criteria, are endangered, further investigation would be necessary.

Buildings, (and other items in open air) are designed against wind loading. The actual design load is defined in local building codes and typically depends on details such as the location of the building (near the coast or inland) the height of the building and the environment: inside a built-up area or in open field. In practice (in the Netherlands) the typical design wind load is about 1 kPa (10 mbar).

For "normal" loads a safety margin (against the elastic limit) is applied: 1,5 for steel and 1,7 for reinforced concrete structures. The main reason is to prevent that local stress concentrations might exceed the yield stress and, with repeated loading, premature failure may arise due to fatigue. A (worst case) explosion, however, is to be considered as a "once in the lifetime" event. Therefore it is widely accepted that, for such accidental loadings, no safety margin is required, on condition that the structure has some ductility (= can deform somewhat plastically) which is the case for structural steel and reinforced concrete.

Therefore following limits can be used as lower limits for damage to buildings:
- Steel structures: 15 mbar.
- Reinforced concrete structures: 17 mbar.

If these pressures are exceeded this would not cause failure of the structure: permanent deformations will arise, causing a re-distribution of the stresses and, with very large deformation, a further increase of the resistance of the structural material. As a realistic estimate: failure is not to be expected at overpressures below 2 times the limits defined before for the onset of damage: 30, respectively 34, mbar.

Important
During World War II and during nuclear testing in the fifties much data were collected on overpressures where buildings would suffer serious damage. With the interpretation of these criteria it must be taken into account that the behaviour under a short duration shock wave will be different from the behaviour under a rather slow increasing, and long duration, pressure wave, as results from a vented silo. But even if this is taken into account the limits are much higher than the values indicated here:
- onset of window pane breakage: 10 mbar
- most window panes failed, hazard due to flying glass fragments: 30 mbar
- onset of structural damage: 170 mbar.

However, all buildings involved in those investigations were low-rise brick work houses. For such buildings usually other criteria (such as thermal and acoustic isolation) are decisive for the design of the walls, meaning the resistance against wind loading will be (much) higher.
This is also supported by practical experience: in case of very strong winds (in the Netherlands, hurricanes such as arise in US are different) it is not uncommon that a large window fails or that the cladding of an industrial building is blown off. But failure of low rise brickwork houses usually only arises when the building concerned was already in a very bad shape.

7. Interpretation of calculated overpressures.

From the formula presented in chapter 5 it is clear that there is a very strong directional effect: at similar distances, overpressures in front of the vent ($\alpha = 0°$) are 3,6 times higher than sideways ($\alpha = 90°$). In order to obtain similar overpressures, the safety distance in front of an explosion vent should be 2,5 times the safety distance sideways! If, during the detailed design of the silos, it would be considered to install some vents on the sides, this would have a very large impact on the external overpressures!

If incidental window pane failure within the plant limits is accepted, 15 mbar can be used as a safe lower limit for damage. Both for silo A and B, this limit is reached at a distance of about 30 m, for items where the height is not much more than the height of the silos.
Apart from the items (on short distance) that were considered in the calculations, there is only one item (at larger distance) that might become critical: a chimney with a height of 60 m on DM33. However, this chimney is located at about 100 m from the silos: much further than the HAT (77 m distance, height 50 m). Therefore pressures at this chimney will be well below the pressures calculated at HAT and not be critical.

Conclusion: none of the existing buildings/items will be submitted to pressures that would require a further evaluation.

The only building within the "hazard zone" is the new process building. This building, especially the wall of the high rise part facing the silos, and the tower need to be designed for overpressures that are beyond "standard" building design. However, the calculated pressures are not such that extreme building structures are required.

From the calculations it is also clear that the open front building that will be required for truck unloading, which is at a much larger distance than the low rise part of the new building and will have a similar height, does not require strengthening.

At an adjacent silo, the (maximum) overpressure (silo B) is 76,3 mbar. Therefore it is recommended to apply explosion vents that are designed to withstand at least a negative pressure of 0,1 bar.

If the adjacent silo would be empty, there is also a risk of buckling due to the external overpressure. An accurate buckling calculation of the silo (made of a large number of corrugated steel panels, bolted together) is very complicated and would require an advanced FEM. An example of such a silo is presented in figure 2.

Figure 2: example of a similar, bolted, silo

There are relations that enable to calculate the buckling pressure of a cylindrical vessel, with a homogeneous wall thickness[1]. Assuming a cylindrical height of 16 m (= silo B) a diameter of 9 m and a wall thickness of 6 mm, it is found that buckling will arise at 33 mbar! Of course: the pressure of 76,3 mbar will only arise at the top. Therefore additional calculations were made for the pressures at 5, resp. 10, m below the top: 49, resp. 30 mbar.

Conclusion: for a homogeneous steel silo, there is a risk of buckling of an empty silo, in case of an explosion in an adjacent silo. The structure of the proposed silo, however, will likely result into higher buckling pressures: a corrugated plate has much more stiffness than a flat plate.

8. Conclusions and recommendations.

From the analysis it can be concluded that, both for a design with 8 and 4 silos (having reduced explosion pressures of 0,7 and 0,5 bar) with vertical venting, none of the existing buildings and other items will be submitted to such overpressures that damage would be expected.

The wall of the new building facing the silos, especially the high rise part, needs to be designed for the calculated overpressures, which are considerably above standard building design pressures.

A reduction of this design pressure can be obtained by:

- increasing the distance from the silos towards this building
- modifying the layout: low rise part of the building in front of the high rise part
- reducing the reduced explosion pressure (increase vent area).

It was also found that, during an explosion, adjacent silos are at risk. It is recommended to apply explosion vents that are designed to withstand a negative pressure of 0,1 bar.
It is strongly recommended to verify (with the potential supplier of the silos) the vacuum resistance of these silos (which is similar to the resistance against an external overpressure).

[1] These are theoretical relations from the open literature, verified with small scale tests. However, the author of this report had the possibility to verify it for a 60 m^3 test vessel, that failed due to negative pressures and found a very good agreement.

Annex: Stuvent calculation sheets of silos A and B

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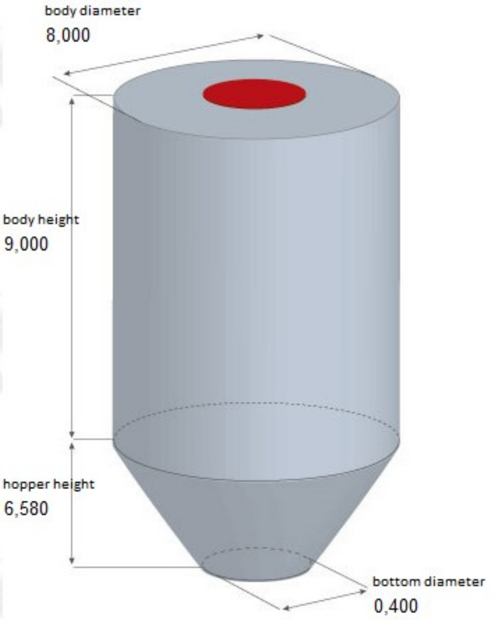
silo A

Dust explosion (EN14491:2012)

1. Cylindrical with hopper

vent on top



V_{Total} =	**568,426** m^3
L_{linear} =	**11,193** m
D_{EFF} =	**7,474** m
L/D =	**1,498**

V_{Total}	:	**568,426 m^3**
L/D	:	**1,498**
$P_{red,max}$	:	**0,70 bar**
Dust dispersion	:	**Standard**

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2. Product data

P_{max} : **10,00 bar**

K_{St} : **200 m.bar/s**

3. Rupture disk

P_{stat} : **0,10 bar**

P_{stat} tolerance : **10 %**

A : **11,861 m²**

4. No vent duct

5. Explosion effects

L_F (Flame length) : **60 m**

F_R (Recoil force) : **988 kN**

t_R (Duration) : **1,4 s**

I_R (Impulse) : **703,5 kN.s**

6. Disclaimer

This program is intended as a calculation aid for calculating vent areas according to the norms EN14491 and EN14994. It does not relieve the user of his/her duty to read and follow these norms and all relevant legal and juridical regulations and norms. In case of possible contradictions between the calculation results according to the norm and the calcularion results of this program, the calculation results according to the norm are binding. StuvEx does not accept any responsibility for the consequences, be it direct or indirect, of the use of this program or its results.

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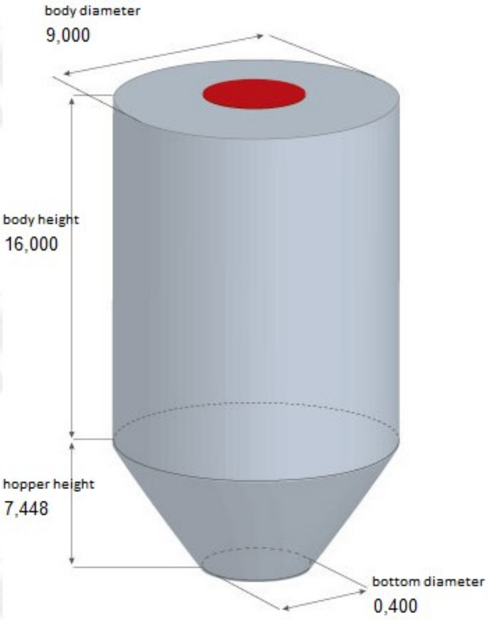
SIlo B

Dust explosion (EN14491:2012)

1. Cylindrical with hopper

vent on top



V_{Total} =	**1183,148** m^3
L_{linear} =	**18,483** m
D_{EFF} =	**8,597** m
L/D =	**2,150**

V_{Total}	:	**1183,148 m^3**
L/D	:	**2,150**
$P_{red,max}$	:	**0,50 bar**
Dust dispersion	:	**Standard**

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2. Product data

P_{max} : **10,00 bar**

K_{St} : **200 m.bar/s**

3. Rupture disk

P_{stat} : **0,10 bar**

P_{stat} tolerance : **10 %**

A : **33,581 m²**

4. No vent duct

5. Explosion effects

L_F (Flame length) : **60 m**

F_R (Recoil force) : **1998 kN**

t_R (Duration) : **1,4 s**

I_R (Impulse) : **1464,3 kN.s**

6. Disclaimer

This program is intended as a calculation aid for calculating vent areas according to the norms EN14491 and EN14994. It does not relieve the user of his/her duty to read and follow these norms and all relevant legal and juridical regulations and norms. In case of possible contradictions between the calculation results according to the norm and the calcularion results of this program, the calculation results according to the norm are binding. StuvEx does not accept any responsibility for the consequences, be it direct or indirect, of the use of this program or its results.