EXPLOSION EFFECTS OF LPG-AIR MIXTURE IN CONGESTED AREAS

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Abstract. *In this work we used the Multi-Energy method to estimate the overpressure and the positive phase duration as a function of the distance from the explosion center, resulting from Vapour Cloud Explosions of LPG-air mixtures in highly congested areas near the LPG storage area. Simulations were made for square shaped zones planted with 10 m high trees and areas ranging from 50,000 m^2 to 250,000 m^2. The criterion used to evaluate the risk to a LPG storage sphere, was a maximum stretching of 0.2% of the diagonal arm braces. The explosion effects were studied for a 14.5 m of diameter LPG storage sphere, located at distances ranging from 10 m to 100 m away from the border of the congested area. The minimum safe distance from the congested area to the nearest structure seams to have a maximum value, but further conclusions would require a different approach as the loading would be Dynamic instead of Impulsive for grove areas bigger than 250,000 m^2. It is shown that congested areas of at least 100,000 m^2 can be a risk to the LPG spheres with the least amount of filling. From the storage units security point of view, its is possible to conclude based in the results, that it is better to keep a smaller number of full filled spheres than many spheres with less filling of LPG. It was estimated for congested areas with 25 % blockage ratio that the minimum safe distance, measured from the edge of the trees to the sphere, varies from 10 m, for 100,000 m^2 areas, to 87.6 m, for 250,000 m^2 areas. The tree spacing influence represented by the blockage ratio was also analyzed, showing how much its change can affect the sphere minimum safe distance. Finally, recommendations are made regarding the minimum safe distance between the spheres and the congested area, as well as other ways to lessen the risk represented by explosions resulting from the accidental formation of flammable mixtures inside them.*

Keywords. *explosion, effects, LPG, VCE , congested areas.*

1. Introduction

The study of accidents caused by the release of flammable liquids and gases, specially Vapour Cloud Explosions (VCE), has been increasingly done in the last decades. Identification of this kind of accident possible causes, as long as evaluating its consequences, are invaluable tools to minimize and possibly avoid its occurrence and indesirable results. There was a noticeable advance in its mechanisms and fenomena comprehension, as well as significant improvement of the effects evaluation methods in this period. Institutions like Christian Michelsen Research (CMR) and Prins Mauritz Laboratory (TNO)[1] have taken lead in developing computational codes and evaluation methods to be used directly by the most affected branches of flammable gas and liquid production, storage and processing industries, on and off-shore. This fruitful collaboration between private iniciative and research institutions devoted to the development of simulation tools, has proved itself of great value to lessen the involved risks and increase security of such industrial plants. In this work the proper management of groves and tree belts around petrochemical plants will be evaluated, showing that their use ignoring fire risk standards can help toxic and flammable products dispersion as well as increase their burning rate, leading to explosion. To do so, a hypothetical case analysis done over a tree grove will show that its presence can be a risk factor to the nearby plants and population. To evaluate partially obstructed Vapour Cloud Explosions the Multi-Energy method was used as the resulting overpressure predicting tool, and the structural analysis was made through a finite element simulation program to evaluate the interaction of the blast wave generated by the explosion with a sorage spherical tank of LPG.

1.1. Scenario Description and Assumed Hypothesis

The case scenario used in this VCE explosion evaluation is a LPG storage park, composed by steel spheres and close to a tree grove inside which it would be possible to have a LPG-air mixture explosion. The explosion calculation will be done as a stoichiometric propane-air reaction, because propane is the main gas in LPG composition.

In order to this scenario be representative of a reasonable number of similar situations, the sphere dimensions was chosen to be close to those found in refineries and most medium and big petrochemical plants.

The LPG storage parks are usually composed by a group of spheres connected to the refining, bottling or processing plant by a series of tube pipes. This conection site is usually unobstructed and easily accessible in case of fire combat. Being so, these areas are not usually seen as possible explosion scenarios, although flash fires could occur.

Usualy, tree belts around industrial plants help the process of gas dispersion in the atmosphere by increasing the surface roughness length. The present study differs from previous works by considering the tree grove as a possible risk to the LPG storage spheres. This possibility reflects the grove capacity to induce turbulence in the flow gas inside it. The greater the induced turbulence, higher overpressure will be generated in a fire inside the grove perimeter, resulting in an explosion instead of a flash fire[2,3]. This induced turbulence is a function of obstacle (trees in this case) dimensions and spacing, represented by the blockage ratio (β) of the site cross section[4,5].

Equally important in this evaluation are the total volume of the grove and its border distance to the spheres.

The main dimensions of the grove and its location relative to the sphere that could lead to a potential risk will be determined here, as well as the possible measures that could be taken in order to minimize this risk.

The scenario that will be analysed in this paper corresponds to a accidental release of LPG with formation of a flammable cloud of LPG-air inside a grove of Eucalyptus trees nearby, followed by an explosion with generation of a blast wave which would interact with a storage sphere. The aim of this paper is to establish the conditions that would lead to the collapse of the tank, with a considerable increase in the seriousness of the accident.

1.2. LPG Sphere

The LPG storage sphere and its supporting columns used in this study is made of welded steel plates, submitted to thermal stress release treatment before its use. The support columns are connected by diagonal bracing arms as structural reinforcement. Each column is fixed to the ground by only two bolts, allowing it to rotate around an axis perpendicular to the bolts, which can be considered as an articulated joint.

Basically the maximum expected wind force is used while dimensioning the horizontal forces on this kind of structure, which justifies its scarce column ground fixing and small bracing arm dimensions.

Figure 1 reproduces schematically the LPG storage sphere with its columns and bracing arms, pointing those arms that are subjected to the major traction stresses when a horizontal force is applied in the shown direction.

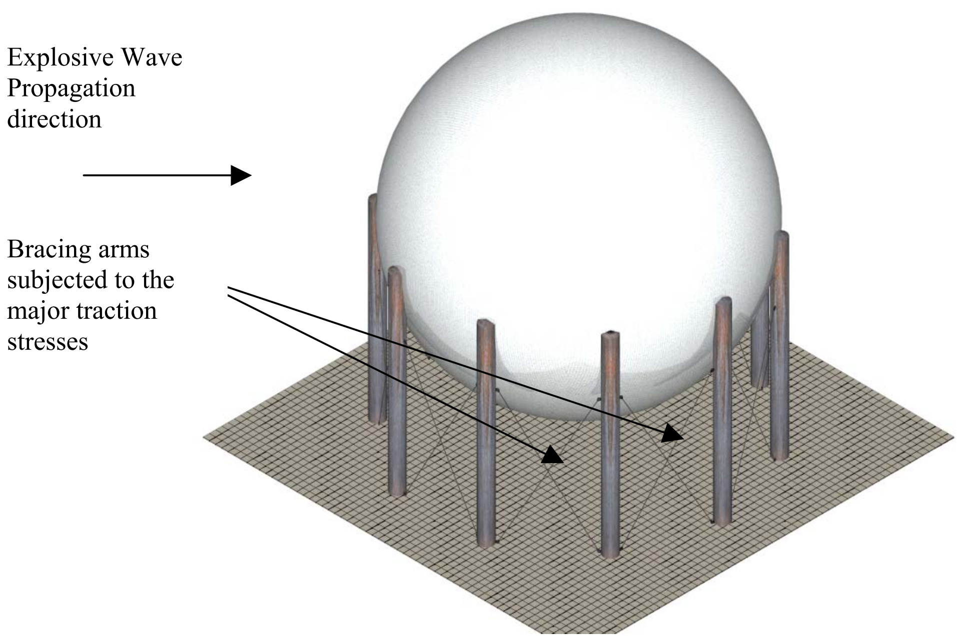

Figure 1: Simplified sketch of the LPG sphere with its columns and diagonal bracing arms.

The stress considered responsible by structural failure will be that capable of causing traction rupture in one of the critical bracing arms. These critical bracing arms are those connecting the middle supporting columns, considering the direction of the explosion wave propagation as shown in figure 1.

The traction stresses are more intense in those bracing arms due to the fact that their angle in relation to plane *XY* is the smaller among all bracing arms. Their failure would cause a rupture chain reaction among all other bracing arms as consequence of progressive lack of structure rigidity, what eventually would lead to total failure of the sphere supporting structure. For the reasons stated above only the critical bracing arms will be analised[6].

Other possible structural failure causes like column fixing bolt failure, welding rupture and other less probable ones will not be analised in this study.

The sphere natural oscillating period will be calculated for the explosion wave propagation direction only, despite other notorious forms of oscillation that could happen in this kind of structure.

Also the spherical shell elastic characteristics will not be considered, because its internal working pressure is many times greater than the overpressure it will be subjected to.

The simplifications above stated are based in the most probable failure cause found in the literature[6] and in structural models with compatible precision with the Multi-Energy method estimated results[7].

Some of the main dimensional characteristics of the LPG storage sphere are found in Table 1 together with the structure and stored masses calculated for two tipical filling situations.

Table 1: Main dimensional characteristics of the LPG storage sphere.

Characteristic:	**Value:**
Spherical Shell	
Inside diameter (m)	14,500
Outside diameter (m)	14,581
External perimeter (m)	45,810
External area (m2)	6,679,195
Volume (m3)	15,962,549
Shell thickness (m)	0.0405
Shell volume (m3)	269,007
Shell weight (kg)	211.708
Maximum gas weight - full (kg)	814.091
Total column weight - all 8 (kg)	969
Total weight - 25% full (kg)	415.554
Total weight - 75% full (kg)	822.599
Columns (hollow circular section)	
Number of columns	8
Height of column (m)	9.41
Outside diameter (m)	0.50
Thickness of wall (m)	0.01
Cross sectional area (m2)	0.01539
Transverse inertia moment (m4)	0.00046219
Elasticity constant for the structure (N/m)	2,190,000
Bracing arms (rigid circular section)	
Outside diameter (m)	0.025
Cross sectional area (m2)	0.00049
Arm length (m)	8,558
Distance between columns (m)	4.91
Height of top conection to the column (m)	7.01

1.3. Tree Grove Congested Area

In this work was used as VCE subjected congested area a tree grove, which has been modeled with the following characteristics to simplify calculations:

- <u>Rectangular area:</u> this hypothesis makes the congested area border to center distance to be more easily calculated and still maintain similarity in shape with groves found close to industrial plants;

- <u>Regular tree spacing</u>: this is also a simplificative hypothesis to make blockage ratio calculation easy, though it is also usual to have regular spacing in planted tree groves;

- <u>Tree modeling as cylinders</u>: this simplification supposes a constant medium tree diameter in the calculations, making total tree volume to be a sum of cylinders instead of conical sections;

Will be admitted some variation of the grove dimensions in order to verify their influence in the resulting explosion strength. These dimensions and their respective variation range, when applicable, can be seen in Table 2.

Table 2: Main dimensions of the tree planted congested area and their range bands.

Caracteristic:	**Range of variation:**
Tree height (m)	10 (maximum)
Tree spacing (m) / Blockage Ratio	1.2 to 2.4 / β=0.25 to 0.125
Congested area (m2)	50,000 to 250,000
Maximum tree diameter (m)	0.30 (constant)

2. Explosion Evaluation

2.1. Available Explosion Energy

In order to estimate the results of an explosion of gas using the Multi-Energy method, it is necessary to determine the volume of the region containing the flammable mixture, in the prtesent situation, the grove volume available to be filled by the LPG-air mixture. This value is the total grove volume less the tree occupied space, and can be calculated by this expression:

$$V_{mistura} = V_{horto} - V_{árvores} = (A_h \, . \, h_a) - [(\Pi \, d_a{}^2 / 4 \;) \, h_a \, . \, N_a] \tag{1}$$

where A_h is the grove area, h_a the tree height, d_a the medium tree diameter and N_a the total number of trees in the grove, calculated as follows:

$$N_a = \frac{A_h}{(e_a)^2} + \{[2.\frac{(A_h)^{0.5} - d_a}{e_a}] + 1\} \tag{2}$$

where e_a is the medium spacing between two adjacent tree center lines.

After the available mixture volume is known, it is easy to obtain through Eq. (3) the amount energy available for the explosion to be used by the Multi-Energy method:

$$E_Q = 3.5x10^6.\frac{(1+5.n_0).R.T_0}{m_{gás}.M.P_0} \tag{3}$$

where n_0 is the relation between the mole numbers of gas and air in a stoichiometric reaction, M is the gas molar mass, R the universal gas constant, T_0 and P_0 ambient temperature and pressure respectively.

The $3.5x10^6$ constant in Eq. (3) is the medium combustion energy released by hydrocarbons by unitary volume.

Based in this we define the scaling factor of the Multi-Energy method as:

$$\text{Scaling Factor} = (E_Q \, / \, P_0)^{1/3} \tag{4}$$

Congested areas like our grove shall use the Multi-Energy method curves number 8, seen in Fig. (2).

This choice is made based in the tree spacing observed in some groves like this, which corresponds to a blockage ratio β > 0.25 , that leads to maximum relative peak overpressure around 2, or a total pressure of 3 atmospheres after explosion.

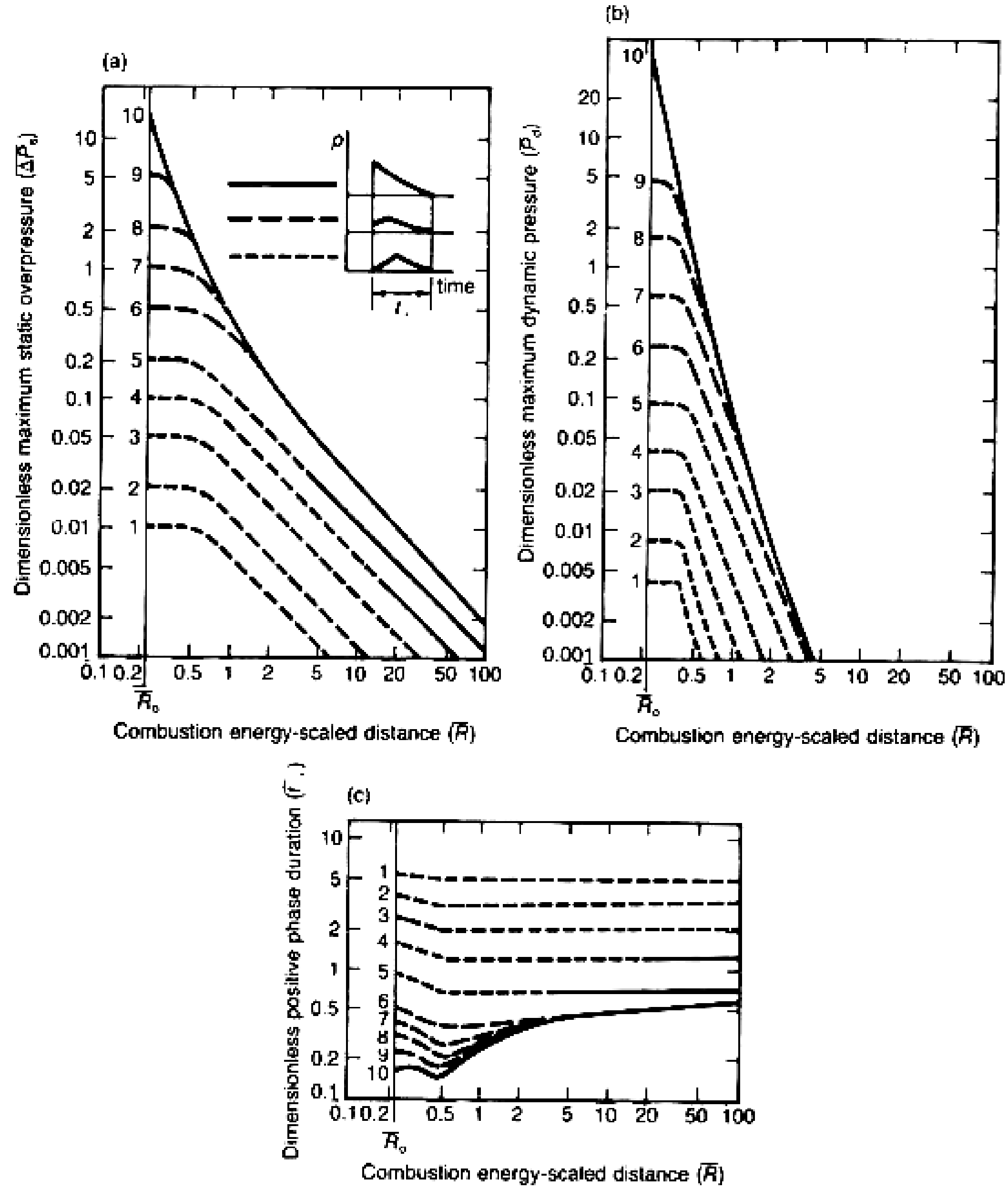

Figure 2: Scaled effects as function of scaled distance used by the Multi-Energy method [3, chap.17, pg.174, Fig.17.79]

2.2 Time-dependant Interaction Evaluation between Shock Wave and LPG Sphere

Having the peak side-on overpressure and positive pressure duration phase obtained from the Multi-Energy method for the desired distances from the grove center, the next step is to calculate the explosion wave interaction with the LPG sphere.

This interaction requires the knowledge of the effective pressure over the structure, which results from the explosion wave reflection while passing through it, plus the drag pressure generated by the associated wind.

For a spherical surface, there are no vertical or lateral forces F_Y and F_Z due to its simetry, only the horizontal pressure and drag force F_X .

Being the sphere a revolution surface with radius R_0, we can obtain the distances dx traveled by the explosion wave, the infinitesimal area dA_p , projected in X direction, and the incident angle θ between the the explosion wave front and the tangent to the sperical surface, through simple trigonometric relations.

In Fig. (3) the angles and characteristics used in these calculations can be seen over an R_0 radius sphere. They are the incident explosion wave velocity N_i (in double trace), the incident angle θ and the distance x traveled in the propagation direction until that moment.

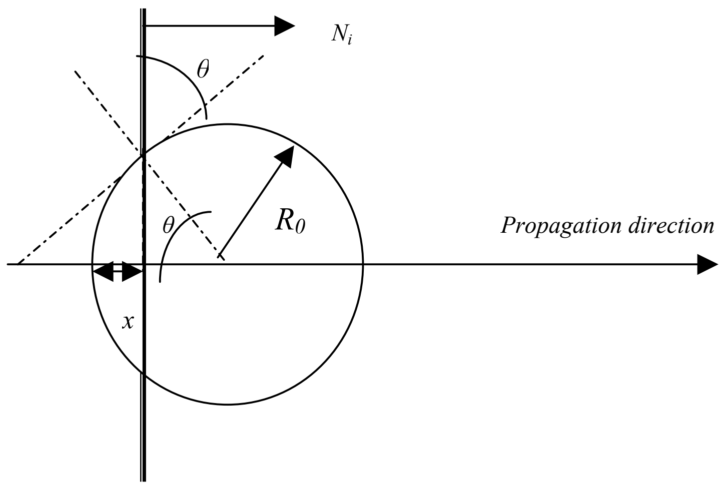

Figure 3: Blast wave interaction with a R_0 radius LPG Sphere, showing incident wave velocity (*Ni*), traveled distance after beginning of interaction (*x*) and incident angle (θ).

The incident angle θ is equal in the sphere to the angle formed between the line connecting the center to the tangent point of the sphere and the propagation direction. It is easy to deduce this angle as a function of the traveled distance *x*, as Eq. (5) shows:

$$\theta(x) = \arc\cos(1 - x / R_0) \qquad (5)$$

In a similar way it is easy to obtain the infinitesimal projected area dA_p , defined as a $R_0\, d\theta$ wide circular ring projected over a plane parallel to the incident wave, with a $2\pi R_0\, sen\theta$ perimeter, that could be expressed by the following function of the traveled distance *x*:

$$dA_p = 2\pi\, R_0 \cos\theta(x)\, dx \qquad (6)$$

Using these equations and Fig. (4) reflection coefficient curves, it is possible to determinate the reflected pressure P_S and dinamic pressure *Q* acting over each spherical surface fraction and their components in the wave propagation direction. Using the maximum side-on overpressure given by the Multi-Energy method for each distance x_{ie} from the grove center to the edge of the sphere, and adding the traveled distance *x* measured from the same edge to each surface point, gives the overpressure peaks over each fraction of the sphere surface.

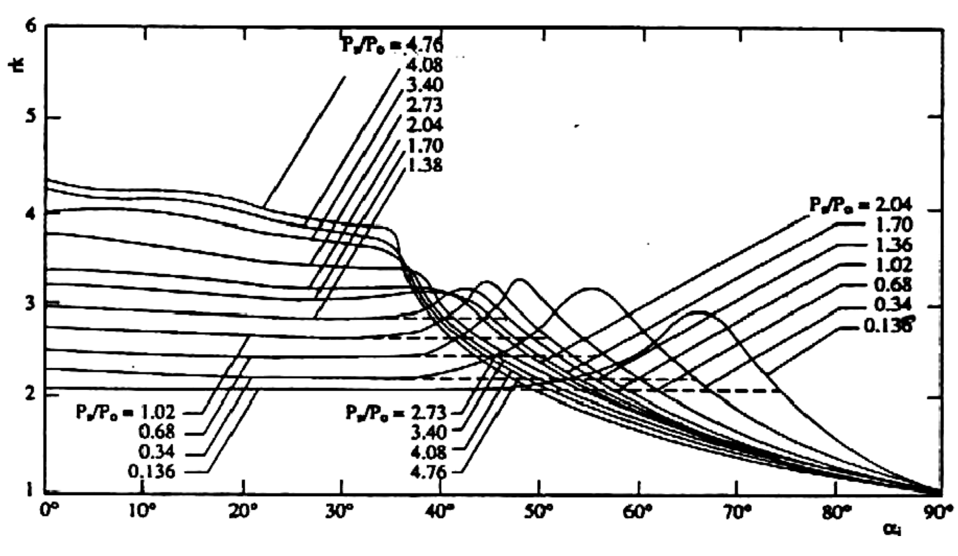

Figure 4: Shock Wave Reflection Coefficients for several P_S/P_0 relations [4, Fig. 2.5 pg. 80]

Next, using Eqs. (7) and (8) the time-dependent overpressure and dynamic pressure evolution is calculated over the infinitesimal area as follows:

$$P_S(x,t) = p_S\,(x)\,.\,(\,1 - t\,/\,t_d\,).\,e^{-b\,t\,/\,t_d} \tag{7}$$

$$Q(x,t) = q_S\,(x)\,.\,(\,1 - t\,/\,t_d\,).\,e^{-b\,t\,/\,t_d} \tag{8}$$

where factor *b* is found in the literature [1] for the desired peak overpressure.

Multiplying the dynamic pressure by the drag coefficient C_d, which is 0.47 for the sphere, results the drag pressure acting over the same infinitesimal area.

Until now, based on the Mutli-Energy method results, on geometric relations and pressure decaying formulas, it was possible to obtain the time-dependent pressure expressions acting over each fraction of the structure area.

The total resulting horizontal force on the sphere can be calculated integrating the pressures acting over its external surface, multiplied by the infinitesimal projected area over which it was acting, from the initial point X_0 until the final contact point X measured over the propagation direction, as can be seen in Eq. (9):

$$F_X(t) = \int_{X_0}^{X} \{[(P_S(x,t).\Lambda(x)] + [Q(x,t).C_d)]\}.dA_p(x) \tag{9}$$

where the first term refers to the reflected pressure and the second term to the dinamic pressure acting over the sphere.

The infinitesimal projected area obtained for Eq. (6) is positive until the middle of the sphere, and negative from that point on, so the integration of Eq. (9) automatically makes the balance between front and back acting forces on the sphere.

2.3. Choosing the Form of Analysis

The Multi-Energy method allows the estimation of the duration of time interval in which the blast wave has a positive pressure, or in other words, the time the blast wave will interact with the sphere. This time has to be compared to the natural period of the struture to see ihow the load has to be considered (static or dynamic).

Next step is to determinate the sphere natural period in order to choose the adequate structural form of analysis to be done. The natural period will be calculated only for oscilations in the explosion wave propagation direction as a matter of simplification.

The structure complexity makes the use of numerical simulation programs based on FEM (Finite Element Method) desirable, or even necessary, to obtain the bending elasticity constant.

Being so, modeling was made using 3D quadratic beam elements with 6 degrees of freedom per node based on the Timoshenko Beam for the columns and bracing arms, and the sphere was modeled using a 4-node shell element with 6 degrees of freedom per node based on the Love-Kirshoff thin shell theory, aplying an unitary force in the explosion wave propagation direction to obtain the structure displacement. This force, divided by the obtained displacement, gives the approximated elasticity constant *k* of the structure.

This procedure is based on a supposition that the structure behavior is completely linear and elastic, despite the fact that some plastic deformation will show up in the most critical points after some loading.

Then, the sphere natural oscilation period was determined for a filling range varying from 25% to 75% to identify the most indicated analysis form, with the use of Eq. (10):

$$k = 12\,.\,E\,.\,I_z\ /\ h^3 \tag{10}$$

where I_z is the column transversal cross section inertia moment and *h* its bigger dimension in the bending direction (total height).

It is possible to see in Tab. (3) the obtained natural periods for some filling situations as long as the positive phase duration for the extreme values of the variation range of grove area and grove border to sphere. Using those data it was possible to find the $t_d\,/\,t_\Pi$ relations which characterize this experiment.

Table 3: Values of t_d e t_Π and their relation with the A_h variation band used in this study.

Percentual LPG sphere filling	t_π *(s)*	**t_d / t_π relations for Tree planted congested areas with the following dimensions:**			
		A = 50,000 m^2		A = 250,000 m^2	
		t_d =0.167 s X_{borda}=10m	t_d =0.180 s X_{borda}=100m	t_d =0.253 s X_{borda}=10m	t_d =0.300 s X_{borda}=100m
25 %	2.90	0.058	0.062	0.087	0.103
75 %	4.44	0.038	0.041	0.057	0.068

As seen in Tab. (3), the t_d / t_Π relatios are at most 0.1, what leads to consider this as an Impulsive.

The tree grove area considered varied from 50,000 to 250,000 m^2 , and the grove border to sphere distances from 10 to 100 m.

From the results, we see that the time of duration of the blast wave is smaller or much smaller than the struture natural period, meaning that the load should be considred impulsive.

2.4. Finding the Maximum Tension for the Critical Bracing Arm

The minimum safe distance from the grove border to the sphere edge can be determined by finding the necessary impulse that would be necessary to stretch the critacal bracing arms beyond their limit. To do so, the applied force is increased until the resulting bracing arm length reaches its maximum stretching limit.

The inicial bracing arm length, according to Tab. (3) is 8.560 m, and the recommended stretching limit should be *ε=0.002* , or 0.2%, what gives a maximum tolerable length of 8.577 m before the bracing arm breaks.

After this procedure, the limiting loading impulse found was 540,000 N.s.

Now it is necessary to find the critical grove border to sphere distances, below which the resulting impulse over the sphere is equal or bigger than this limiting value.

The impulse is obtained integrating the acting force curve over the sphere surface, during all the explosion positive phase according to Eq. (11):

$$I = \int_0^{t_d} F_X(t).dt \tag{11}$$

Performing this calculation for grove areas of 100,000 m^2 or less, the resulting impulse is always less than the limiting value, even for distances as low as 10 m from the border to the sphere.

The obtained impulse values can be seen on Tab. (4) for grove border to sphere distances from 10 to 100 m in grove areas ranging from 50,000 to 250,000 m^2:

Table 4: Resulting Impulse for distances ranging from 10 to 100 m from the congested area border.

Distance from tree grove border (m)	**Resulting Impulse over the sphere (N.s x 10^5)**				
	A=50,000 m^2 Xcritical <0 m	A=100,000 m^2 Xcritical =9.9 m	A=150,000 m^2 Xcritical =17.7 m	A=200,000 m^2 Xcritical =56.8 m	A=250,000 m^2 Xcritical =87.6 m
10	5.052	5.394	5.504	5.937	6.270
20	4.383	4.841	5.370	5.824	6.143
50	3.701	4.460	5.010	5.462	5.793
100	3.233	3.944	4.493	4.953	5.273

These results were used to make the impulse as function of border distance curves seen in Fig. (5), ploted for grove areas A>100,000 m^2, which are those that could cause damage to the structure according to Tab. 4.

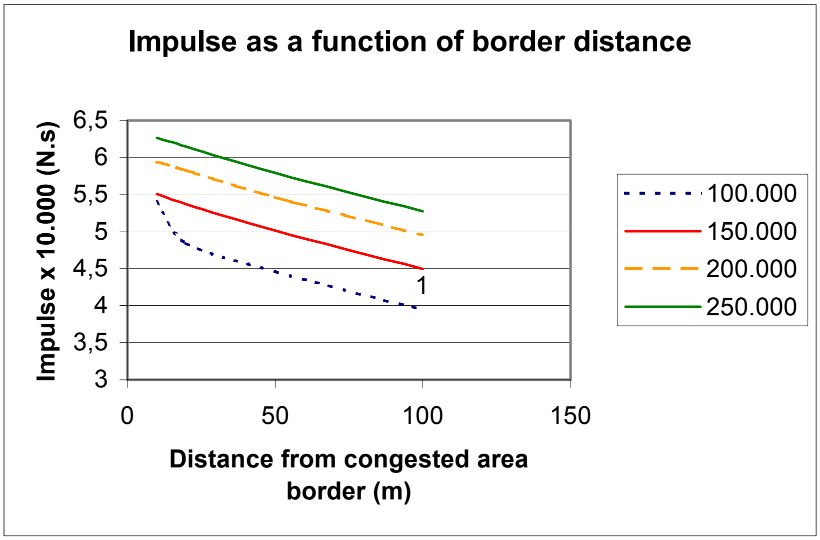

Figure 5: Impulse as a function of the distância from the border for congested areas between 100,000 and 250,000 m^2.

3. Discussion

The obtained critical grove border to sphere distances appear to show a tendency towards a limiting value, but above 250,000 m^2 areas the appropriated loading type would be the Dynamic type (not Impulsive) and other form of analysis would be needed before any conclusion could be taken. Nonetheless, grove areas of more than 250,000 m^2 are simply not realistic to be analysed.

It would be interesting to observe that a possible analysis mistake could result from hypothetically eliminating one in every pair of tree rows, an apparently reasonable suggestion to minimize the risk through lowering the blockage ratio of the grove. This apparent solution would not mean eliminating the entire grove and has an immediate effect on the maximum side-on overpressure generated during explosion. This action would result immediately in increasing tree spacing from 1.2 to 2.4 m, meaning a decrease of the blockage ratio from 0.25 to 0.125. The curves used by the Multi-Energy Method would be number 7 instead of 8, but the resulting impulse would be *increased* by 2.5% instead of being reduced. The reason for this unexpected behavior resides in the fact that bigger tree spacing resulted in a bigger available volume to be filled by the flammable LPG-air mixture, 3.69% more to be exact, increasing the final available explosion energy inside the cloud. The drop in generated side-on overpressure using curve 7 would happen pratically inside the cloud and would not affect the sphere, but the positive phase would increase and so the resulting impulse over the structure.

The considerations stated above indicate that the possible risk reduction options in case scenarios like the one studied here should either try to reduce the effective flammable mixture volume inside the grove area, structurally improve the LPG storage spheres, or increase their distance from the congested area border.

4.Conclusions

It was shown that congested areas with less than 100,000 m^2 by 10 m of height do not impose risk to LPG spheres like the ones used in this work, even with high blockage ratios. Congested areas bigger than this size can impose some degree of risk depending on their minimum distance from the closest LPG sphere of the storage park.

The most effective way to improve the sphere park safety, regarding a possible VCE in the grove area, would be to cut those trees that are closer to the sphere, diminishing the mixture volume and increasing the grove border-to-sphere distance, both factors that would lessen the risk.

Cutting the trees over some specified height would result in a smaller flammable mixture volume and a smaller risk, but it would be a short-lived solution because the trees would eventually grow and the same situation would present itself again.

Increasing tree spacing by cutting trees of alternate rows could be not only ineffective, but eventually worsen the explosion effects due to the resulting explosive mixture volume increase, as explained in section 3.

Based on the results, it is possible to conclude that it is better to maintain, as a safety measure, the smallest possible number of full filled spheres rather than dividing the available LPG volume among many of them. This reflects the fact that the sphere inertia will increase with its filling, making and its final displacement due to the loading to decrease and thus less prone to collapse.

Finally, it could be also suggested the reinforcement of the bracing arms to increase their resistance. This could be the only relatively simple structural modification depending on the way the sphere has been built, and a 15 to 20% increase in the bracing arms cross section would greatly improve the hole structure resistance to side loads.

5. References

[1]YELLOW BOOK, 1997. *"Methods for the Calculation of the Physical Effects of the Escape of Dangerous Materials (Liquids and Gases) – Part II",* 3. ed. TNO.

[2]KINNEY, Gilbert F. & GRAHAM, Kenneth J., 1985. "*Explosive Shocks in Air",* 2. ed. Springer-Verlag.

[3]LEES, Frank P., 1996. "*Loss Prevention in the Process Industries",* 2nd ed. Butterworth-Heinemann.

[4]MERCX, Paul, *"Curso Internacional sobre Avaliação dos Efeitos de Incêndios e Explosões para Análise de Riscos",* Rio de Janeiro, May 26th to 28th, 1997.

[5]BAKER, Quentin A. *et al*, 1994. "*Vapour Cloud Explosion Analysis",* Loss Prevention Simposium 28.

[6]WALL.J., 1978. "*Blast Loading on a Spherical Storage Vessel – An Investigation of Potential Hazards from Operations in the Canvey Island/Thurock Area*".

[7]Smith, P.D. and Hetherington, J.G., 1994 "*Blast and Ballistic Loading of Structures"*, Butterworth-Heinemann.