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ANALYSIS OF THE EFFECTS OF EXPLOSION OF A HYDROGEN CYLINDER ON THE TRANSFER OF RADIOACTIVE LIQUID WASTES AT NUCLEAR POWER STATIONS

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ABSTRACT

This work presents a study of explosion effects of a stored hydrogen cylinder on the transfer of radioactive liquid wastes at nuclear power plants. The peak overpressure is calculated, as well as the strength of resulting fragments, thus confirming the main harmful effect of an explosion of flammable vapor cloud, based on the TNT Equivalent Method. The scenarios identified are calculated and compared with the overpressure ranges of 1%, 50% and 99% of structural damages, which were determined by the Eisenberg's Vulnerability Model. The results show that the overpressure and the resulting fragments from the explosion of a hydrogen gas cylinder are not able to cause the overturning of the tanker under study, and also show that a minimum distance of 30 meters between the hydrogen cylinder and the tanker can be considered a safe distance to the passage of this tanker during the transfer of radioactive liquid waste, in which the likelihood of occurrence of structural damages is less than 1%.

1. INTRODUCTION

Wastes are classified by their content of radioactivity. The waste classified as low-radioactive materials are used in plant operation, such as gloves, shoes, special clothes, equipment, tapes and even adhesive tape. Once collected and separated, these materials undergo a decontamination process to reduce their levels of radioactivity. Some materials are crushed and pressed, to occupy less space, and packaged in containers that block the passage of this radiation. The average radioactive waste, consisting of filters, liquid effluents and solidified resins are packed in a solid matrix of cement or bitumen and kept in suitable steel containers. Over time, these materials fall, but they have to be encapsulated and isolated and stored in monitored warehouses.

Nuclear plants deal with radioactive materials and hazardous chemicals commonly found in conventional chemical industry. An example of these latter is the storage of hydrogen gas cylinders in nuclear power plants, which is injected into the primary circuit in order to react with oxygen to produce water and thereby preventing corrosion of equipment and materials.

The processes employed and the materials handled and stored represent potential sources of various kinds of danger such as fire, explosion, fragments and release of toxic materials.

Garrison [1] analyzed one hundred biggest losses in the hydrocarbon processing industry, from 1957 to 1986. He found that 42% of those accidents were caused by vapor cloud explosions. His classification of vapor cloud explosions includes gas explosions in buildings as well as abroad (unconfined explosions). Events classified as explosions make up 22%. These explosions are probably uncontrolled reactions, explosions in solids, BLEVEs (boiling liquid expanding vapor explosions), the loss of containment, and gas explosions in the process internally.

The causes for a catastrophic event can be classified into one of the following categories:

- Mechanical failure or material;
- Corrosion;
- Pressurization;
- Increased fragility of storage tanks at low temperatures;
- Break due to the impact of shock waves and explosions of missiles;
- Human errors.

From accident records, it can be concluded that gas explosions have a tendency to repeat themselves under similar conditions. Therefore, it is important to investigate the accident, with a report of the results in the open literature and act appropriately.

Within this perspective, the objective of this paper is to analyze the effects of explosions in hydrogen cylinders during the transfer of liquid radioactive waste of low activity in nuclear power plants.

2. DESCRIPTION OF THE SCENARIO

2.1. Selected Characteristics of Substance

The substance selected for study is the hydrogen, which, at room temperature, is a highly flammable gas, colorless, odorless and tasteless. The gas density is the lowest known, is normally transported in steel cylinders at pressures between 150 and 200 bar.

2.2. Description of Development

Two different nuclear power plants, located in the same site were considered in this study. The first plant was called Nuclear Unit 1 (UN1) and the second, Nuclear Unit 2 (UN2).

The aim of the project is to implement a waste management program, with focus on reducing the volumes produced. To this end, all radioactive waste produced in Nuclear Units 1 and 2 are subject to technical and administrative measures, aimed at further reducing the volume within regulatory limits.

As part of the project, transfer operations of radioactive liquids of low activity are planned, via truck, from Nuclear Unit 1 (UN1) to Nuclear Unit 2 (UN2). These operations are intended to allow the UN1 liquid radioactive waste to be processed and packed in UN2.

The main purpose, and that justifies this engineering solution is to reduce the number of packaged radioactive generated during the life time of UN1, since the UN2 processing and packaging system of liquid radioactive waste is more efficient than that of the UN1 plant.

Another favorable point concerning the implementation of this project is the possibility of continuing the design changes necessary to improve the operating conditions of the UN1 liquid waste treatment.

An overview of the project is presented in Figure 1.

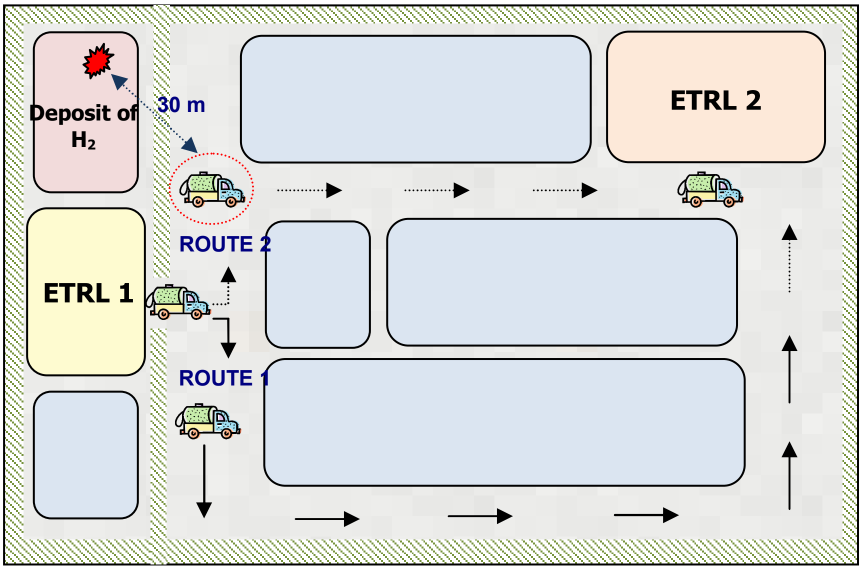


Figure 1 - Overview of the Enterprise

The transfer of radioactive liquid waste stored in UN1 will be conducted through a waste liquid transfer station (ETRL1) in UN1, use of transfer routes, as well as the use of waste liquid transfer station (ETRL2) in UN2. The vehicle displacement will be restricted to the two units of the protected area.

According to the explanation presented above, it is noted that the project transfer of radioactive liquid waste is composed of the following:

- Waste Liquids Transfer Station Unit 1 (ETRL 1);
- Tanker truck;
- Transfer Routes;
- Waste Liquids Transfer Station Unit 2 (ETRL 2).

Figure 1 shows the items mentioned above, emphasizing the critical point for the occurrence of accident scenarios. This critical point is the H_2 tank cylinder (located next to the Transfer Station Unit 1 - ETRL1).

2.3. Description of Accident Scenarios

From the standpoint of risk assessment, the evaluation of the consequences of fires and explosions requires a definition of the scenario in which the fire or explosion occurs.

The description of each accident scenario involves identifying the scene by their number and also the description of the cause, mechanisms of detection and its consequences, in addition to any relevant recommendations to reduce their chances of occurrence, or alternatively, its effects and thus reduce the radiological risk.

In the accident scenario under study, it is considered that after the tanker truck is loaded with liquid radioactive waste in ETRL1 it begins its displacement in order to go through Route 2 (Figure 1). It is assumed that when the tanker truck, fully loaded, is coming out of the transfer station there will be an explosion one of the hydrogen cylinders of the H_2 Deposit in UN1 at a distance of approximately 30 meters above the tank. Figure 1 shows the exact location where the truck is at the moment of explosion.

With the explosion of gas cylinder it is assumed that both the overpressure produced in the explosion, as well as some fragments of the cylinder will reach the tank.

2.3.1 Scenario 1

It is defined as a large spill of liquid waste arising from a fragment originated in the explosion of an existing pressurized cylinder next to the ETRL 1, causing the truck overturning and breaking of the hose (with the pump on) forming a pool, with subsequent evaporation of a fraction of the pool and forming a cloud with radioactive material.

The mechanisms of detection for this scenario are generally visual, noise and radiation detector, of which the latter is more likely to occur, because there is the occurrence of an explosion with the possibility of fragments hit the truck and causing its rollover. Eventually, there may be detected by visual means, for perceiving the occurrence of leakage.

As for the chances of occurrence of this accidental scenario, the leak is due to the overturning of the truck as a result of the blast fragments near the cylinder park which is near the ETRL 1. Therefore, it is necessary that pressure cylinders be there, the explosion occurs and at least one fragment hits the truck and be experiencing the transfer operation.

As the category of scenario severity considered is a guillotine leak in the hose, the liquid leakage is significant (> 10%), although it is not expected that the entire contents of the tanker leaks. The harmful effects may also be significant for the integrity of the tanker and the driver, although they are irrelevant to the environment, being a liquid of low activity.

2.3.2 Scenario 2

It is defined as a large spill of liquid waste arising from the shock wave originated in the explosion of existing pressurized cylinder next to the ETRL 1, causing the truck to rollover and disruption or disconnection of the hose, with the subsequent release of radioactive liquid from the hose and also from the overturned truck.

The mechanisms of detection for this scenario are generally visual, noise and radiation detector, of which the latter is more likely to occur, due to an explosion with the possibility of the resulting shock wave reach and lead to truck overturning. Eventually, it may be detected by visual means for detecting the occurrence of leakage.

As for the chances of accidental occurrence of this scenario, the leak is due to an explosion in the courtyard of a cylinder near the ETRL 1 and the subsequent shock wave of this explosion reaches the truck and causes its overturning, followed by the leak of radioactive liquid waste. Therefore, it is necessary the existence of pressure cylinders there, the explosion of at least one of them and the shock wave reaches the truck and causes it to roll over, and the transfer operation is underway.

As the category of scenario severity considered is a guillotine leak in the hose, the liquid leakage is significant (> 10%), although it is not expected that the entire contents of the tanker leaks. The harmful effects may also be significant for the integrity of the tanker and the driver, although they are irrelevant to the environment, being a liquid of low activity.

3. RESULTS AND DISCUSSION

As discussed, the explosion of an H_2 cylinder that can generate damage for the resulting shock wave and fragments was considered as the main event of accident scenarios.

3.1. Effects caused by overpressure

Damage caused by overpressure is measured, initially, by calculating the overpressure generated by the cylinder explosion and checking on a reference table (Table 1) what effects may result.

Table 1 - Losses and damages that may occur to the premises and persons by overpressure [2]

Overpressure (KPa)	Expected Damage
0.14	Loud bang (137 dB low frequency, 10 -15 Hz).
0.21	Occasional break large windows, which are already under stress.
0.28	Loud bang (143 dB) Breakglass.
0.69	Wrap small windows under strain.
1.03	Typical pressure in the cracks of the windows.
2.07	"Safe distance" (95% probability of serious injury does not occur beyond this area); Some damage to roofs of houses, 10% of break the window panes; Limit shrapnel.
2.76	Lower limit of structural damage.
3.4 – 6.9	Small and large windows are usually destroyed, and some of these have damaged the frame.
4.8	Minor damage in the structures of houses.
6.9	Partial demolition of homes, which will be uninhabitable.
6.9 – 13.8	Destruction of corrugated asbestos; Failed in the bonds of steel or aluminum panels, then strain; Destruction of mooring panels (boards) of timber houses common.
9.0	Slight distortion of the steel frame buildings closed
13.8	Partial collapse of walls and roofs of houses.
13.8 – 20.7	Destruction of the walls of concrete blocks or not reinforced.
15.8	Lower limit of serious damage to structures.
17.2	Destruction of 50% of brick houses.
20.7	Distortions of buildings with steel frame, which are moved from the foundations; Minor damage in heavy machinery (1360 kg), in industrial buildings.
27.6	Take breakdown of industrial coatings
34.5	Destruction of wooded areas; Light damage with large hydraulic presses (18200 kg) inside the buildings.
34.5 – 48.2	Almost total destruction of homes
48.2	Tipping wagon trains loaded
48.2 – 55.1	Kind of unreinforced brick 20 to 30 cm thick and shear stress.
62.0	Demolition of railroad boxcars
68.9	Probable total destruction of buildings, heavy machinery Parts (3200 kg) move and are very damaged; very heavy machine Parties resist
2068	Limit the edge of the crater.

The method chosen to calculate the overpressure generated was the TNT equivalent method [2] because it is a simple and rapid calculation method. The calculation steps are as follows:

1. Estimate the H_2 mass in the cylinder [kg];
2. Estimate the TNT equivalent mass in the H_2 cylinder [kg];
3. Estimate the scale distance, z [$m/kg^{1/3}$];
4. Estimate the overpressure, p_0 [kPa];
5. Evaluated (Table 1) what effect the estimated pressure causes.

According to Ref [3], a typical industrial H_2 cylinder has the characteristics which are described below.

Cylinder volume, $V_{cil} = 49 \times 10^{-3}$ m^3;

H_2 Mass, $M_{H2} = 0.65$ kg;

Storage pressure, p = 164 x 105 Pa.

These will be used in the calculations of the effects caused by an explosion.

For calculating the H_2 TNT equivalent mass, it is necessary to calculate the effect in terms of TNT. The calculation is done through Eq. (1), where we use an explosion efficiency equal to 4% [3], the H_2 combustion heat, $\Delta H_{c\,(H2)}$, equal to 141.6 x 103 kJ / kg [2] and the TNT heat of combustion, $\Delta H_{c\,(TNT)}$, equal to 4686 kJ / kg [4]. Thus we have:

$$M_{TNT} = \frac{M_{gás} \cdot \eta \cdot \Delta H_{c(gás)}}{\Delta H_{c(TNT)}} = 0.782kg \tag{1}$$

The scale distance, z, and the overpressure resulting from the explosion, p_0, were obtained from Eqs (2) and (3), respectively. Assuming the atmospheric pressure, p_a, equal to 101.3 kPa and the real distance, *d*, equal to 30 m, we have:

$$z_e = \frac{d}{\left(M_{TNT}\right)^{\frac{1}{3}}} = 32.563 m / kg^{\frac{1}{3}} \tag{2}$$

$$p_0 = \frac{1616\left[1 + \left(\frac{z_e}{4.5}\right)^2\right]}{\sqrt{1 + \left(\frac{z_e}{0.048}\right)^2} \cdot \sqrt{1 + \left(\frac{z_e}{0.32}\right)^2} \cdot \sqrt{1 + \left(\frac{z_e}{1.35}\right)^2}} \cdot p_a = 5.174 kPa \tag{3}$$

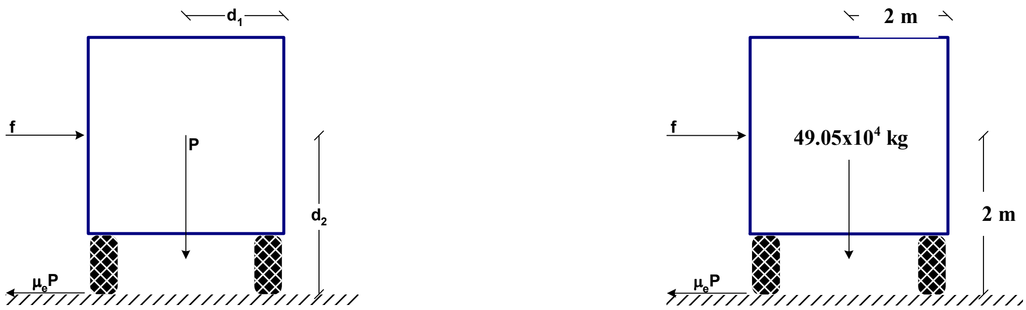
The damage expected for the overpressure calculated above, 5.174 kPa, is the destruction of windows, some of which may have damaged the frame (Table 1).

The same calculation, considering the TNT mass found in Eq. (1), was performed for the real distances of 5 m and 100 m. The results are presented in Table 2.

Table 2 – Distance versus structural damage of explosion

Distance (m)	Estimated Overpressure(kPa)	Structural Damage Expected
5	49.846	Shear stress
30	5.174	The windows are usually destroyed, and some of these have damaged the frame
100	1.527	Pressure typical for windows crack

Under Scenario 2, the overpressure can eventually lead the overturning of the truck. To examine this possibility, it is necessary to estimate the amount of overpressure that can cause this rollover. To this end, let us consider Figure 2(a). In this figure, f = force applied to the sidewall of the truck [N]; d_1 = half-width of the truck [m]; d_2 = half height truck [m]; P = truck weight [kg]; μ_e = static coefficient of friction.



(a) (b)

Figure 2 - (a) Schematic of forces for the analysis of the possibility of truck overturning due to pressure caused by explosion of a H_2 cylinder. (b) - Dimensions of the tanker

Conservatively, we will not consider the static coefficient of friction. Therefore, to overturning the truck is necessary that

$$f \times d_2 \geq P \times d_1 \tag{4}$$

Since $p = f/A$, where

p = applied overpressure [Pa]; A = side área of the trunk [m^2],

So,

$$p \geq \frac{P \times d_1}{A \times d_2} \tag{5}$$

Assuming that the truck has the dimensions shown in Figure 2(b) and 50 t mass , the excess overpressure found is 6.250 kPa.

Comparing this pressure, 6.250 kPa, with pressure resulting from Eq. (3), 5.174 kPa, it is concluded that interference will not overturning the tanker, located 30 m from the center of the explosion, due to the resulting overpressure

3.2. Effects caused by fragments

Under Scenario 1, the resulting fragments from the explosion of the H_2 cylinder may eventually lead to the truck overturning. Therefore, it is investigated if in fact a fragment resulting from the H_2 cylinder explosion has enough energy to break all energy barriers and lead to truck overturning.

Cylindrical vessels do not break evenly: they usually break on tops. Often their tops are designed along the axis of the vessel hull and distorted along the axis perpendicular to this axis [4].

In order to be conservative in the calculation of the effects caused by fragments the total mass of the cylinder is considered.

Now, one needs to estimate the mass of an empty H_2 cylinder. Assuming that a cylinder has a height H = 1.5 m, an external radius r_e = 15.0 cm and a thickness e = 8 mm (data of a typical industrial gas cylinder), its volume is given by:

$$V = \pi \cdot H \cdot \left(r_e^2 - r_i^2\right) = \pi \cdot H \cdot e \cdot \left(2r_e - e\right) \tag{6}$$

where V = volume of a cylinder [m^3], r_e = external radius [m], r_i = internal radius [m], H = cylinder height [m] and e = cylinder thickness [m].

Thus, V = 11 x 10^{-3} m^3. Assuming that the cylinder is made of steel, whose density (ρ) is equal to 7.8 x 10^3 kg/m^3, then the mass of the cylinder is given by

$$M_{cil} = (7.8.10^3) \cdot \left(11.10^{-3}\right) = 85.82kg \tag{7}$$

The fragment area can be calculated considering that we know its mass and also its thickness and density. Therefore,

$$A_{frag} = \frac{M_{cil}}{\rho \cdot e} \tag{8}$$

where: = A_{frag} = fragment area [m^2]; M_{cil} = total mass of the empty vessel [kg]; ρ = material density [kg/m^3] and e = thickness of cylinder [m].

Substituting values in Eq (8) we have A_{frag} = 1.38 m^2

The next step is to estimate the initial velocity of the fragment. To calculate the initial velocity, v_i, the TNO methodology will be used [5].

Step 1: Method of Kinetic Energy

Hydrogen gas is regarded as ideal gas, since the pressures involved in the scenario under study, are smaller than 300 MPa.

For this calculation will use the following parameters:

p_1 = 164 x 10^5 Pa; p_a = 101.3 x 10^3 Pa; V_g = 49 x 10^{-3} m^3; γ_1 = 1.405; M_v = 85.82 kg; A_{cin} = 0.6 (higher limit).

So:

$$E_{disp} = \frac{\left(p_1 - p_a\right) \cdot V_g}{\gamma_1 - 1} = 1.97.10^6 J \tag{9}$$

$$v_i = \sqrt{\frac{2 \cdot A_{cin} \cdot E_{disp}}{M_v}} = 165.97 m/s \tag{10}$$

Step 2: Method of Gel'fand

The following parameters will be used for this calculation

T_g = 298 K; R = 8.314 J/mol . K; $\mu_1 = 2.02 \times 10^{-3}$ kg/mol.

So:

$$a_1^2 = \frac{T_g \cdot \gamma_1 \cdot R}{\mu_1} = 1312.73 m/s \qquad (11)$$

$$\overline{P_1} = \frac{(p_1 - p_a) \cdot V_g}{(M_v \cdot a_1^2)} = \frac{(164.10^5 - 101.3.10^3) \cdot 49.10^{-3}}{85.82 \cdot 1.72.10^6} = 5.41.10^{-3} \qquad (12)$$

Figure 3 relates $\overline{P_1}$ with v_i/a_1, to obtai a fragment initial velocity resulting from the explosion of a H_2 cylinder equal to 32.82 m / s.

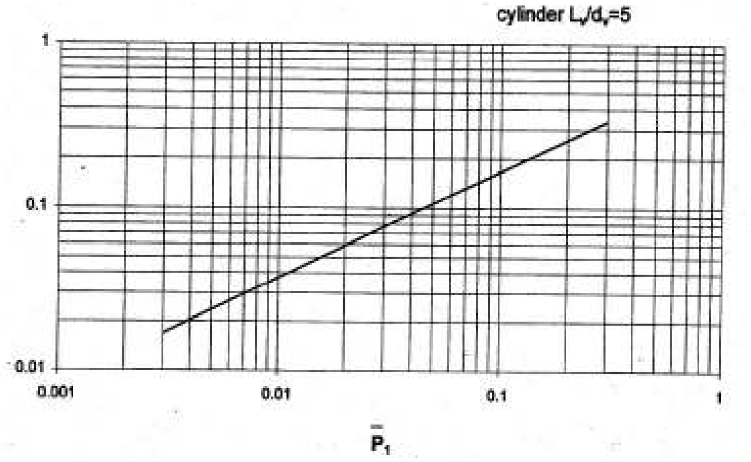


Figure 3 - Speed climbing fragment versus pressure for cylindrical vases containing ideal gas, where L_v and d_v are the height and diameter of the vessel, respectively [6]

Step 3: Method of Moore

The following parameters will be used for this calculation:

$E_{disp} = 1.97 \times 10^6$ J;

M_v = 85.82 kg;

M_c = 0.65 kg.

Thus, one obtains:

$$A_M = \frac{1}{1 + M_c / 2 \cdot M_v} = \frac{1}{1 + 0.65 / 2 \cdot 85.82} = 0.99 \qquad (13)$$

$$v_i = 1.092 \cdot \left(\frac{E_{disp} \cdot A_M}{M_v} \right)^{0.5} = 1{,}092 \cdot \left(\frac{1.97.10^6 \cdot 0.99}{85.82} \right)^{0.5} = 164.62 m/s \qquad (14)$$

The value found in Eq (14) for the initial velocity, v_i, is bigger than the value found by the method of Gel'fand. No correction is necessary, and therefore the fragment initial velocity, seen, according to the method of Gel'fand equals 32.82 m / s.

Once the fragment velocity is known, one can deduce the effect that the same would cause. For this, we calculate the force exerted on the truck:

$$F = \frac{m \cdot \Delta v}{\Delta t} \tag{15}$$

where, F = fragment force [N];

Δv = difference between initial and final fragments velocity [m/s];

Δt = impact time interval [s].

It is assumed that the approximate expression above is valid, that the difference between the speeds is equal to the initial velocity of the fragment and also that the impact time interval is 1 second. Thus we have

$$F = \frac{85.82 \cdot 32.82}{1} = 2816.6N \tag{16}$$

Finally, we calculate the pressure exerted by the fragment by dividing the force exerted by the affected area, which is the area of the fragment, as estimated by Eq (8).

$$P = \frac{2816.6}{1.38} = 2041Pa = 2.041kPa \tag{17}$$

Relating the overpressure found with the overpressure in Table 1, it follows that the expected damage to the overpressure of 2.041 kPa is 10% breaking of glass windows, some damage to roofs of homes and limit shrapnel.

Comparing the pressure calculated in Eq (17), 2.041 kPa, with the pressure that can lead to truck overturning found in Eq (5), 6.250 kPa, it is concluded that the fragment resulting from the explosion of a H_2 cylinder study cannot lead to truck overturning.

Since there is no impact of the fragment on the truck, the calculation of the maximum range of the fragment is not relevant.

3.3. Study of Explosions Effects

3.3.1. Eisenberg Vulnerability Model

Several effects resulting from a gas cloud explosion have been studied for many years and can be classified in two ways: damage to people and structures. The effects caused by the passage of a shock wave can be estimated by the Eisenberg Vulnerability Model, a method that makes use of the probit equations [2].

The estimated damage due to overpressure should consider the absolute value of pressure reached and its duration [7]. This is particularly important because the effects depend on the type of damage in the study.

Based on the Eisenberg Vulnerability Model [7], the probit equation related to structural damage is as follows,

$$\mathrm{Pr} = -23.8 + 2.92 \ln(p_0) \tag{18}$$

where:

Pr = probit variable; p_0 = peak pressure [Pa].

Thus, knowing the characteristics of the explosion, we can determine the peak overpressure of the shock wave, then probit value, and finally the damage likelihood. The relationship between probit and probability can be obtained from Table 3.

Table 3 - Relationship between the variable and the likelihood probit [2]

%	0	1	2	3	4	5	6	7	8	9
0	--	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
%	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

3.3.2. Probability of Structure Damage

In this section, we calculate the probability of structural damage, using the probit equation and the corresponding relative peak overpressure at distances of 5 m, 30 m and 100 m from the center of the explosion.

Replacing the overpressure values from Table 2 in Eq (18) we can find the probit values, Pr, through Table 3, relate these values with their probabilities. Table 4 presents the likelihood of structural damage to a given distance from the center of the explosion.

Table 4 - Relationship between distance from the center of the explosion and the likelihood of structural damage.

Distance (m)	**Estimated Operpressure (kPa)**	**Probit Variable**	**Probability of Occurrence of Structural Damage (%)**
5	49.864	7.78	99.7
30	5.174	1.17	< 1
100	1.527	-2.39	< 1

Another way to evaluate the effects of explosions is based on the Eisenberg Model, by determining the overpressure peak corresponding to the probability of each effect. The peak pressure, p_0, is determined from Eq (18) using probit value as the value taken from Table 3 corresponding to the probability of interest. The effects of the explosion relative to 1%, 50% and 99% will be assessed.

The probit equation, rearranged, is presented below:

$$p_0(\Pr) = e^{\frac{\Pr + 23.8}{2.92}} \tag{19}$$

Table 5 displays the overpressure peaks for the probabilities of 1%, 50% and 99% of occurrence of structural damage. Probit variables were taken from Table 3.

Table 5 - Peak overpressure needed to have that the probability of 1%, 50% and 99% occurrence of structural damage

Probability of Occurrence of Structural Damage (%)	**Probit Variable**	**Estimated Operpressure (kPa)**
1	2.67	8.648
50	5.00	19.207
99	7.33	42.658

From Table 5 it follows that an overpressure required to have a structural damage probability of 1% is 8.648 kPa, 50% is 19.207 kPa and 99% probability of damage is 42.658 kPa.

One can also determine the distance reached by an overpressure shock wave for the levels shown in Table 5. Eqs (2) and (3) of the TNT equivalent method will be used to determine the distances.

The results for the reached distances are displayed in Table 6.

Table 6 - Distance reached versus probability of structural damage

Probability of structural damage (%)	Estimated Overpressure (kPa)	Distance reached (m)
1	8.648	18.473
50	19.207	9.396
99	42.658	5.473

Com base nas Tabelas 10, 11 e 12, pode-se concluir que, uma distância de 30 metros ou mais pode se

Based on tables 4, 5 and 6 it can be concluded that a distance of 30 meters or more can be considered a safe distance for passing a truck, for which the likelihood of structural damage is less than 1%.

4. CONCLUSIONS

The main objective of this study was to evaluate the effects caused by overpressure and fragments resulting from a hydrogen cylinder explosion, to assess whether the transfer of liquid radioactive waste at the site of a nuclear power plant can cause radioactive leakage around the installation.

Two accident scenarios were considered. The first considers that the fragment resulting from the explosion of a pressurized cylinder causes the overturning of the tanker and subsequent leakage of liquid waste. The second one considers that the pressure resulting from the explosion of the pressurized cylinder causes the overturning of the tanker and subsequent leakage of liquid waste. Explosions were considered in both scenarios in the event of catastrophic failure of the cylinder.

The results of this work show that the pressure and the fragments generated by the explosion of a hydrogen gas cylinder are not able to cause the overturning of the tanker under study and a distance of 30 meters or more can be considered a safe distance to the passage of the tanker during the transfer of liquid radioactive waste, in which the likelihood of structural damage is less than 1%.

The safe distance for the probability of damage of 1% is 18.473 m for the 50% probability of damage is 9.396 m and for the 99% probability of structural damage is 5.473 m.

At a distance of 5 m from the center of the explosion, the probability of damage to structures is 99.7%. For distances equal to 30 m and 100 m, the probability of damage is less than 1%.

It is suggested to develop further work on:
- considering the actual number of H_2 cylinders in the plant;
- assessing the possibility of occurrence of domino effects in other parts of the scenario under study, taking into account an eventual risk analysis;
- considering the geometric characteristics and its real influence during the combustion of the vapor cloud, using, for example, computational fluid dynamics.
- collecting and using actual plant data.

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