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Reduction of the Vulnerability Zone of a Major Industrial Risk. Case of BLEVE in LPG Storage Sphere Hassi R'Mel, Algeria

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Abstract
A major risk is a rare natural occurrence bearing adverse consequences on human lives, equipment and environment as well; we must coordinate to address this issue. And with the increased number of habitations that are close to major industrial plants of high risk, a risk management is of utmost need and importance. This constitutes the rationale of our study. Throughout this work, we try to reduce the damages or at least control the targeted areas (Limit, Vulnerability) that have been affected by a major accident. Our work is very useful for handling an existing high-risk industrial installation that is close to urban areas. This research examines the volume parameter of a dangerous explosive substance as a parameter within the reach of an existing company that is near an urban area. We simulated the BLEVE phenomenon of an LPG storage sphere in Oil & Gas producing zone of Hassi R'Mel (Algeria) by using ALOHA® (V 5.4.7): a reputed tool for simulating dangerous phenomena. The article provides a methodology for the development of thermal effects (range of effect / volume) of the BLEVE phenomenon of an LGP sphere. This approach may help us during the decision-making that is relevant to determining the maximum fill level for a predefined impact area, which constitutes a second barrier of the risk reduction (limit) hierarchy. In addition, it can help us locate the risk within the scope of the company while at the same time avoiding the regulatory obligations related to industrial risks that affect populated areas.

Keywords
risk reduction, major risks, vulnerability, intensity, ALOHA simulation, BLEVE LPG and oil-&-gas industries

1. Introduction

The hydrocarbon industry is classified as one of the high-risk industries, where every industrial or commercial activity is subject to a wide variety of incidents or serious situations that can significantly disrupt its functioning, abort it or even ruin it [1]. Thus, the major risk would mean the possibility of the occurrence of a natural or an anthropogenic-origin accident whose impact may involve a large number of people, cause significant damage and exceed the response capacity of the locals [2]. With the catastrophic explosion of the liquefied natural gas (LNG) complex in Skikda -a city in north east of Algeria- that occurred in January 2004, resulting in 27 deaths and 73 injuries, weaknesses in major risk prevention procedure within the SONATRACH corporation. Facing such situations has become a major concern in our petroleum complexes ever since its occurrence. We can see nowadays that the oil and gas-related exploitation in Algeria gets 80% of the totality of major risks (fires, explosions, toxic risks) [3].

In addition, the concern of urbanization in the face of industrial risks has reached its peak in the site of Hassi-R'Mel. This city has known today a disproportionate and disordered expansion: the number of housing present in this Oil-&-Gas field has reached a seemingly critical level, and constitutes a permanent threat for the safety of both industrial heritage and that of the people who live there [4]. Consequently, in order to meet these industrial and societal expectations, an establishment of a prevention plan is deemed necessary for the preservation of the long-term viability of the companies and the continuance of these operational performances [3]. This extends to the national and international competitiveness.

Still, the prevention of major risks calls for the implementation of every possible measure in order to reduce the impact of an expected natural or man-made disaster, likely to touch people and property. It is part of a sustainable development strategy.

Likewise that, vulnerability reduction measures for already buildings and agglomerations in industrial high-risk areas (AKA mitigation measures) are mandatory and recommended measures to be included in the company's Industrial Risk Prevention Plan (IRPP), that is designed to limit human, equipment and environmental damage in the case of the emergence of such a phenomenon - the objective of our study - or even take precautionary actions to lighten the catastrophe's consequences and moderate them to be endurable for the society.

This is but a preventive approach aiming at reducing, on the one hand, the vulnerability of the stakes, and on the other hand, preventing the expansion of the accident. The vulnerability of a specific area or a given point is in the evaluation of the sensitivity of elements present in the area to a given effect [5].The present situation necessitates a thorough examination followed by a deep discussion. It must be done before the occurrence of future incidents, since the sustainability of our strategic businesses and the security of our facilities, our population and our national economy are at stake.

2. Presentation of the Study Area

In this work, we are interested in the hydrocarbon industrial complex which is located in the zone of Hassi R'Mel, and is declared as a high-risk zone by the executive decree № 05/476. This complex comprises several hydrocarbon processing modules with a Storage and Easy Transfer Center (CSTF). The latter (CSTF) is considered a critical source of danger, since it has a total storage capacity of 285000 m3 of condensate and 78000 m^3 of LPG.

The LPG storage and transfer site holds the following facilities:

- 12 spheres with a measured capacity of 6500 m^3 (7170 m^3 Max) each bearing a total storage capacity of 78000 m^3;
- six booster pumps P001 A / B / C / D / E / F: Flow rate 165 m^3/h at P = 15 to 18 bar each, of which three pumps have a second transfer function of LPG between the spheres;
- three pumps P002 A / B / C: Flow rate 350 m^3/h at P = 25 to 34 bar each, LPG shipping to the 24'' line with a flow rate of 350 m^3/h each;
- five turbocharger units with 12 LPG refrigerants.

This study uses one of 12 spheres as a study sample, Figure 1 and Table 1.

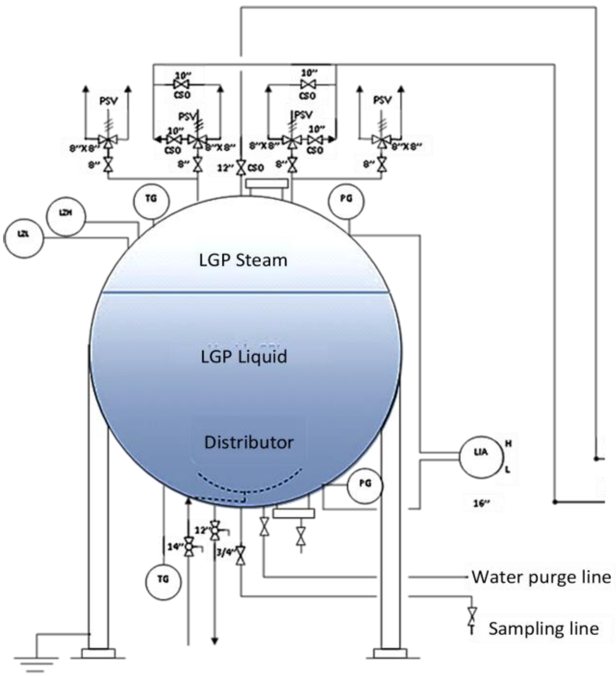

Fig. 1. LGP sphere design

Table 1. Characteristics of LGP spheres

Characteristics	Values
Substance	LPG
T Service (°C)	20
T Calculation (°C)	17 to93.3
P Service (bar)	5.34
P Test (bar)	9.6
Total volume (m^3)	7170
Real operating volume (m^3)	6508
Density (kg/m^3)	536
The largest connection diameter	14”
Volume of the retention basin (m^3)	2958
Surface of the retention basin (m^2)	4225

2. Method and Material

This paper stands on BLEVE simulation of an LPG sphere. It investigates the fields demonstrating the thermal effects of this phenomenon. The research team used ALOHA® v. 5.4.7software (AKA Aeral Locations of Hazardous Atmospheres), a mode ling software that estimates threat areas related to unsafe chemical releases, including toxic gas clouds, fires and explosions. It was jointly developed by the following two U.S entities: Environmental Protection Agency's Office of Emergency Preparedness and Response (EPA) and the National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA) [6, 7].

There were 100 BLEVE simulations of an LPG sphere - with a volume varying from (1 to 100) % (7170 m^3) - done with the recording of the results of the thermal effects only, because the zones with overpressure effects are always lower than those with thermal effects. Moreover and for the same reason, ALLOHA does not simulate the effects of overpressure [6]. Thermal effects are generated by the thermal radiations as an immediate consequence of a blast or a fire. It is described as continuous for all phenomena that last more than 2 minutes (pool fires, solid fires, inflamed jets), but transient for those whose duration did not extend to 2 minutes (fireballs, cloud fires). The continuous thermal effects generate a thermal flux expressed in kW/m^2.The transient thermal effects generate a thermal dose expressed in $(kW/m^2)^{4/3}\cdot s$ [8]. It also turns out that for short exposure times (<2 minutes) at high thermal flux values, the relationship between thermal effect (E) addressing the heat flux and the exposure time is constant and of the following form:

$$E = Q^n \times T \tag{1}$$

where:

E - the thermal dose, expressed in $(kW^{4/3}/m^2)\cdot s$;

Q – the heat flux received at time (t), evaluating in time, expressed in kW/m^2;

T- the total duration of exposure to the heat flux, expressed in seconds.

The specialized literature asserts that under such conditions, *n* always takes the value 4/3 [9, 10].

Since the BLEVE is a transient phenomenon, the line doses of the following thermal effects were adopted (Table 2) [11, 12, 13].

Table 2. Reference threshold of thermal effects

600 $(kW/m^2)^{4/3}\cdot s$	Zone of irreversible effects (Inner zone)
1000 $(kW/m^2)^{4/3}\cdot s$	Zone of the first lethal effects 1% (Middle zone)
1800 $(kW/m^2)^{4/3}\cdot s$	Zone of significant lethal effects (Outer zone)

And to adapt the dose lines of the thermal effects in $(kW/m^2)^{4/3}\cdot s$ with the thresholds used by ALOHA, we inverted the previous formula (Eq. 1) to determine the equivalent heat flux in kW/m^2. The result is as follows:

$$(1) \quad \leftrightarrow \quad Q = (E/T)^{1/n} \tag{2}$$

3. Results and Discussion

The analysis of the data of this research is quantitative; the units of measure are the capacity (% & m^3), the duration of exposure (s) and the range of the thermal effects. All parameters (location, weather, air exchange, matter ...) have been fixed. The capacity, however, has been variable.

As a first step, we determined the characteristics (diameter & duration) of the fireball, Table 3 and Figures 2 and 3. We have found that the BLEVE phenomenon is transient, because the maximum duration of the 7170 m^3 volume fireball was less than two minutes: it would not exceed 39 seconds.

The table presents the diversity in the characteristics of the fireball (Diameter & Duration), compared to the volume or filling rate. It should be noted that the duration of the fireball varies between 18 and 39 seconds which proves that the BLEVE is indeed a transient phenomenon. It has also been observed that the fireball diameter is very considerable and reaches respectively 316 meters in the least volume (1%) and 887 meters in the case of a total fill (100%) of the sphere.

Table 3. Fireball characteristics as per volume and fill rate

Fill Rate (%)	Volume (m^3)	Fireball Diameter (m)	Duration (s)
1	71.7	316	18
10	717	452	24
20	1434	542	27
30	2151	610	30
40	2868	665	32
50	3585	712	33
60	4302	754	35
70	5019	792	36
80	5736	826	37
90	6453	858	38
100	7170	887	39

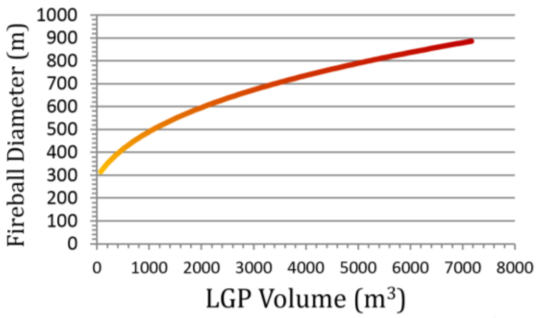

Fig. 2. Curve of (Fireball Diameter / Volume) of the LPG sphere

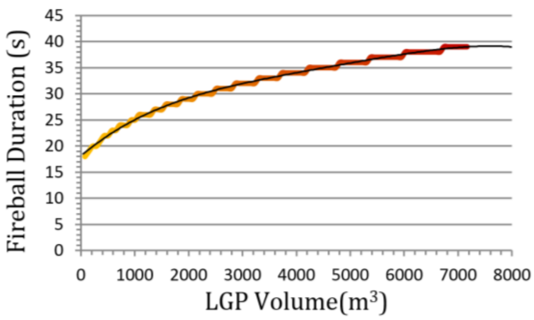

Fig. 3. Curve of (Fireball Duration / Volume) of the LPG sphere

The two previous curves reveal an increase in the duration and the diameter of the fireball with reference to the volume or fill capacity of the sphere: the fireball can reach a diameter of 900 meters, thus, the zone represents a threat of total mortality of 100% for humans. The shape of the diameter curve can be used as a reference in the design of installations and vulnerable structures such as control rooms. Also, it can be used in the realization of an action plan in case of fire or explosion.

Afterwards, using the formula (2) and fireball durations - previously measured -, heat doses $(kW/m^2)^{4/3}\cdot s$ were converted to heat fluxes using Microsoft Excel software. The results are summarized in the following Table 4 and Figure 4.

The curve in Figure 4 shows that humans can better withstand the intensity of the heat flow if the fireball was of a short duration, and if the zone of irreversible effects could reach 36 kW/m^2 for an exposure period of 5 seconds. After inserting thermal flows equivalent to the reference thermal doses of each capacity rate (from 1 to 100%), the simulation software ALOHA provided the results summarized herein after Table 5 and shown in the Figures 5 and 6.

Table 4. Thermal flows in relation to the exposure period
for each thermal dose thresholds

Fill rate (%)	Duration (s)	Thermal radiation flow in kW/m² equivalent of:		
		600 (kW/m²)⁴/³·s	*1000 (kW/m²)⁴/³·s*	*1800 (kW/m²)⁴/³·s*
1	18	13.873	20.349	31.623
10	24	11.180	16.400	25.486
20	27	10.235	15.013	23.331
30	30	9.457	13.873	21.558
40	32	9.011	13.217	20.540
50	33	8.805	12.916	20.071
60	35	8.425	12.358	19.205
70	36	8.249	12.100	18.803
80	37	8.081	11.854	18.421
90	39	7.768	11.395	17.707

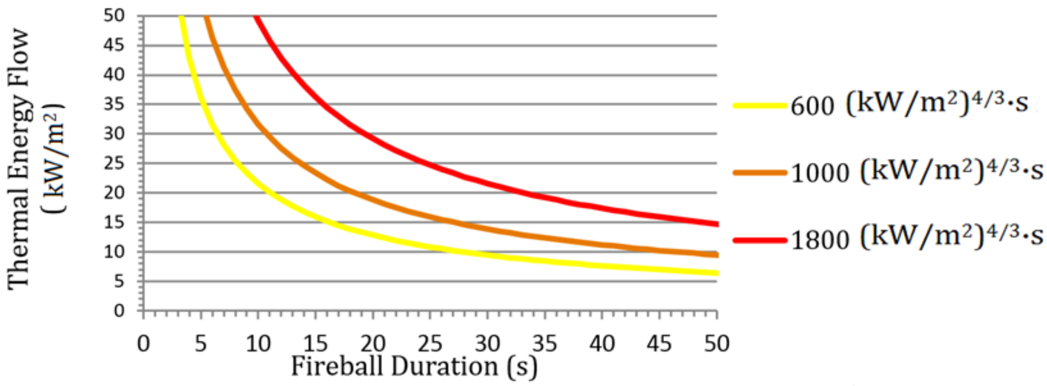

Fig. 4. Referential thermal dose curves (Flow / Duration)

Table 5. Range of thermal effects per to volume or fill rate

Fill rate (%)	Volume (m³)	Thermal effect distance (m)		
		600 (kW/m²)⁴/³.s	*1000 (kW/m²)⁴/³.s*	*1800 (kW/m²)⁴/³.s*
1	71.7	585	477	371
10	717	919	753	590
20	1434	1100	938	738
30	2151	1300	1100	862
39	2796.3	1500	1200	941
40	2868	1500	1200	961
50	3585	1600	1300	1000
60	4302	1700	1400	1100
70	5019	1800	1500	1200
80	5736	1900	1600	1300
90	6453	2000	1700	1300
100	7170	2100	1700	1400

The simulation reads that the range of the thermal effects is wide and can reach the radius of 2100 meters of irreversible harm to human beings. This means that several vulnerable areas would be at reach (roads, other factories, workers' residences, public gas stations ...). Also, it is notable that even with the minimum capacity of the sphere (1%), the range of these effects on humans is great (about 600 meters).

The curves set out in the Figures 5 and 6, show the appearance of thermal effects with respect to the volume of the LPG in a storage sphere with a maximum capacity of 7170 m³.

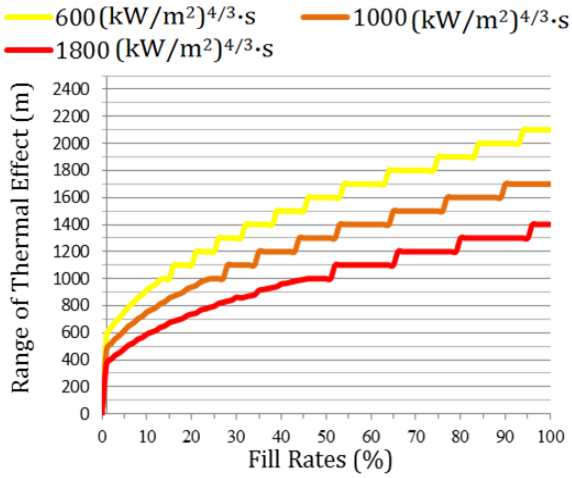

Fig. 5. Range of thermal effect versus fill rates

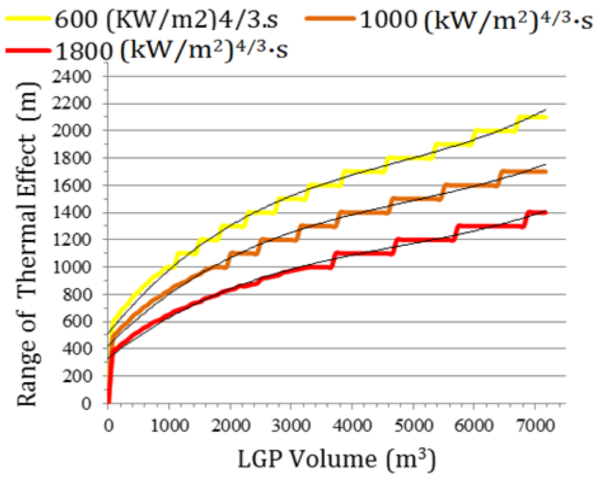

Fig. 6. Range of thermal effects versus LPG volume

These experimental curves (Volume / Effect range) can be used by the authorities as a reference for taking decisions. They can also be put to use to direct the Oil & Gas industry contractors in the procedure of authorization of exploitation of installations as classified according to the law Nº 04/20 and the Executive Decree Nº 06/198. Plus, the company can use them in the design of installations and in the realization of action plans [14], as well as the deployment of intervention if a fire or an explosion took place. These curves come to use when there are situations where the sphere is filled by an LPG volume of 1 to 100%, since the risk assessment studies that have been realized consider the 100% fill case solely.

In such a way and following the simulation of several tests, we managed to draw up a risk map (Risk Mapping) of the most remarkable cases (Intensity / Vulnerability) of the LPG sphere of the BLEVE, particularly:

In the first case when the filling reached 100%, Figure 7, the three areas of thermal effects exceeded the perimeter of the company and affected the vulnerable area (municipal public road, other factories, workers' residences, public gas station ...). In such an occurrence, the company has to obtain an operating license as its operations will be tied to risk prevention regulations as well as coordination requirements that are enforced by the local authorities (PPI-Special Emergency Plan and Rescue Organization Plan- ORSEC). The same applies to other companies (MAP Mutual Aid Plan) and the population involved (by informing, sensitizing and consulting).

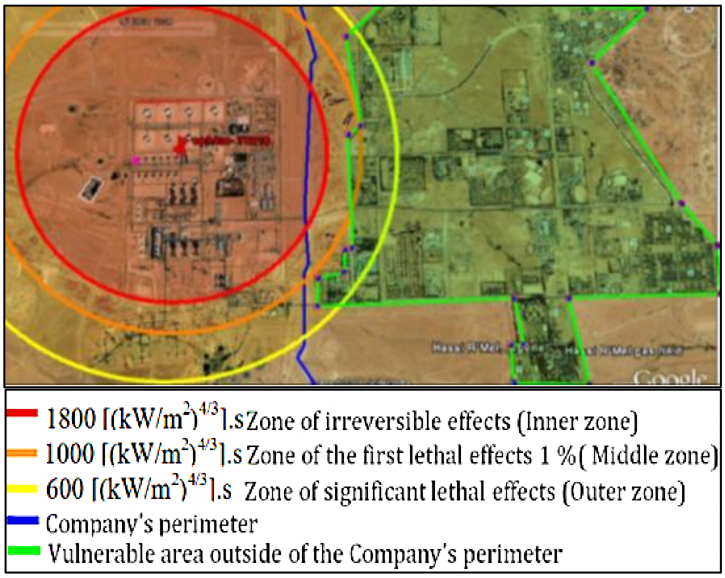

Fig. 7. Areas with thermal effects having an impact on humans with a volume of 100%

In the second case where the capacity is only about 39%, the effects exceeded the perimeter of the enterprise, but did not affect the vulnerable zone with the exception of the communal public road located in 1547 meters from the source, Figure 8. Therefore, the volume must not exceed 2800 m^3 in order to, first, avoid reaching the first vulnerable point which is located outside of the industrial complex, and second, to be able to limit the perimeter inside the same complex.

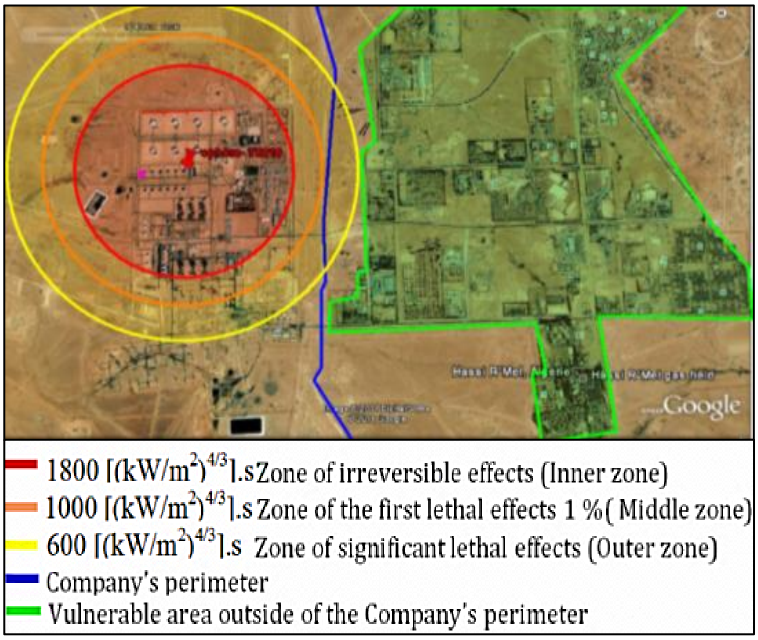

Fig. 8. Areas of thermal effects having an impact on humans with a volume of 39%

Hence, the maximum sphere volume must not exceed the fill rate of 21% with a volume of 1500 m^3, Figure 9, so that the risk can be limited in this perimeter, and a second safety barrier can be realised; it can protect all vulnerable points. During the meeting that has been held with the company's safety and operating service staff, the employees declared that they received an administrative notice ordering them not to exceed the fill rate of 20% for the LPG spheres. As a result, the company is only bound to make its own plans (Prevention Plan and Internal Intervention Plan -PII).

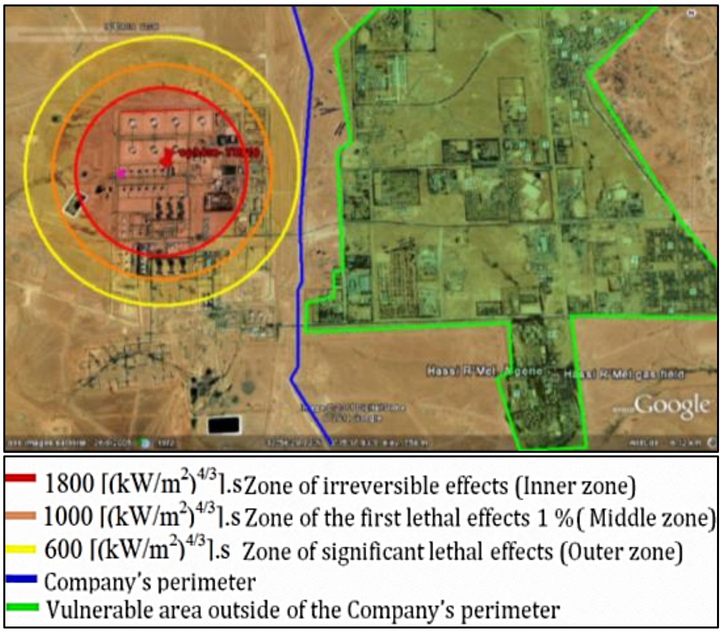

Fig. 9. Areas of thermal effects having an impact on humans with a volume of 21%

4. Conclusion

The results of this research make it evident that the application of the second step (limit the hazardous material) of the hierarchy of major industrial risk assessment is indeed very effective for the already-existing industrial complexes that are close to cluster zones. Also, as reported in this study, it is notable that the reduction of intensity, established by limiting of the dangerous substance, directly influences the endangered vulnerable area.

After simulating the BLEVE phenomenon of the LPG sphere, it became unmistakable that the volume parameter is the most important one in the evaluation of the intensity of the fireball. The risk mapping (Intensity / Vulnerability) shows that the use of the total capacity of the LPG spheres (7170 m^3) of the Hassi-R'Mel's Oil & Gas complex presents a risk that, in case of major accidents, would affect the vulnerable yet valuable stakes. For this purpose, it is recommended to limit the volume of the spheres to 39% (2800 m^3) to avoid endangering the vulnerable noxious zones and to put an end to the risk around the perimeter of the company. It is important to direct the attention towards the fact that the fill rate must not exceed 21% (1500 m^3), as indicates the internal administrative notice of the company that limits the volume of spheres to 20%. Adding to that, risk mapping (Intensity / Vulnerability) has proved to be an important tool in the implementation of prevention plans and the organization of rescue plans.

Finally, we conclude that the risk management, while plant designing and before project implementation, is useful to avoid non-compliance to regulations. The curves in this research can be utilized in the decision-making process from the design stage to the actual design phase pertinent to the realization of any project. Also, it is advisable for high risk industries to limit the risks inside their perimeters to avert the regulatory and social responsibilities that accompany major industrial risks. This constitutes a second barrier in the hierarchy of risk management (limit).

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Appendix

Table of simulation results of the BLEVE phenomenon of different LPG sphere volumes (7170 m³), SONATRACH Corporation, Hassi-R'Mel, Algeria

Fill rate (%)	Volume (m³)	Fireball diameter (m)	Fireball duration (s)	Thermal flux in (kW/m²) equivalent of the dose:			Range of thermal effect (m) to:		
				600 (kW/m²)^4/3·s	*1000 (kW/m²)^4/3·s*	*1800 (kW/m²)^4/3·s*	*600 (kW/m²)^4/3·s*	*1000 (kW/m²)^4/3·s*	*1800 (kW/m²)^4/3·s*
0	0	0	0	0	0	0	0	0	0
1	71.7	316	18	13.873	20.349	31.623	585	477	371
2	143.4	337	19	13.321	19.540	30.366	636	519	404
3	215.1	356	20	12.819	18.803	29.220	683	558	435
4	286.8	372	20	12.819	18.803	29.220	713	583	455
5	358.5	388	21	12.358	18.127	28.170	756	618	483
6	430.2	402	22	11.934	17.506	27.204	797	652	510
7	501.9	416	22	11.934	17.506	27.204	822	672	526
8	573.6	428	23	11.543	16.932	26.312	860	704	552
9	645.3	440	23	11.543	16.932	26.312	882	722	566
10	717	452	24	11.180	16.400	25.486	919	753	590
11	788.7	462	24	11.180	16.400	25.486	940	770	604
12	860.4	473	24	11.180	16.400	25.486	959	786	616
13	932.1	482	25	10.843	15.905	24.717	994	814	640
14	1003.8	492	25	10.843	15.905	24.717	1000	829	651
15	1075.5	501	26	10.529	15.444	24.001	1000	857	674
16	1147.2	510	26	10.529	15.444	24.001	1100	871	685
17	1218.9	518	26	10.529	15.444	24.001	1100	885	696
18	1290.6	526	26	10.529	15.444	24.001	1100	898	706
19	1362.3	534	27	10.235	15.013	23.331	1100	925	728
20	1434	542	27	10.235	15.013	23.331	1100	938	738
21	1505.7	550	27	10.235	15.013	23.331	1200	950	745
22	1577.4	557	28	9.960	14.609	22.703	1200	976	769
23	1649.1	564	28	9.960	14.609	22.703	1200	988	776
24	1720.8	571	28	9.960	14.609	22.703	1200	999	787
25	1792.5	578	28	9.960	14.609	22.703	1200	1000	796
26	1864.2	585	29	9.701	14.230	22.113	1300	1000	817
27	1935.9	591	29	9.701	14.230	22.113	1300	1000	825
28	2007.6	597	29	9.701	14.230	22.113	1300	1100	834
29	2079.3	604	29	9.701	14.230	22.113	1300	1100	842
30	2151	610	30	9.457	13.873	21.558	1300	1100	862
31	2222.7	616	30	9.457	13.873	21.558	1300	1100	858

32	2294.4	622	30	9.457	13.873	21.558	1400	1100	865
33	2366.1	627	30	9.457	13.873	21.558	1400	1100	873
34	2437.8	633	30	9.457	13.873	21.558	1400	1100	880
35	2509.5	639	31	9.228	13.536	21.035	1400	1200	913
36	2581.2	644	31	9.228	13.536	21.035	1400	1200	920
37	2652.9	649	31	9.228	13.536	21.035	1400	1200	927
38	2724.6	655	31	9.228	13.536	21.035	1400	1200	934
39	2796.3	660	31	9.228	13.536	21.035	1500	1200	941
40	2868	665	32	9.011	13.217	20.540	1500	1200	961
41	2939.7	670	32	9.011	13.217	20.540	1500	1200	965
42	3011.4	675	32	9.011	13.217	20.540	1500	1200	974
43	3083.1	680	32	9.011	13.217	20.540	1500	1200	981
44	3154.8	685	32	9.011	13.217	20.540	1500	1300	988
45	3226.5	689	32	9.011	13.217	20.540	1500	1300	994
46	3298.2	694	33	8.805	12.916	20.071	1600	1300	1000
47	3369.9	699	33	8.805	12.916	20.071	1600	1300	1000
48	3441.6	703	33	8.805	12.916	20.071	1600	1300	1000
49	3513.3	708	33	8.805	12.916	20.071	1600	1300	1000
50	3585	712	33	8.805	12.916	20.071	1600	1300	1000
51	3656.7	717	33	8.805	12.916	20.071	1600	1300	1000
52	3728.4	721	34	8.610	12.630	19.627	1600	1300	1100
53	3800.1	725	34	8.610	12.630	19.627	1600	1400	1100
54	3871.8	730	34	8.610	12.630	19.627	1700	1400	1100
55	3943.5	734	34	8.610	12.630	19.627	1700	1400	1100
56	4015.2	738	34	8.610	12.630	19.627	1700	1400	1100
57	4086.9	742	34	8.610	12.630	19.627	1700	1400	1100
58	4158.6	746	34	8.610	12.630	19.627	1700	1400	1100
59	4230.3	750	35	8.425	12.358	19.205	1700	1400	1100
60	4302	754	35	8.425	12.358	19.205	1700	1400	1100
61	4373.7	758	35	8.425	12.358	19.205	1700	1400	1100
62	4445.4	762	35	8.425	12.358	19.205	1700	1400	1100
63	4517.1	766	35	8.425	12.358	19.205	1700	1400	1100
64	4588.8	769	35	8.425	12.358	19.205	1800	1400	1100
65	4660.5	773	35	8.425	12.358	19.205	1800	1500	1100
66	4732.2	777	35	8.425	12.358	19.205	1800	1500	1200
67	4803.9	781	36	8.249	12.100	18.803	1800	1500	1200
68	4875.6	784	36	8.249	12.100	18.803	1800	1500	1200
69	4947.3	788	36	8.249	12.100	18.803	1800	1500	1200
70	5019	792	36	8.249	12.100	18.803	1800	1500	1200
71	5090.7	795	36	8.249	12.100	18.803	1800	1500	1200
72	5162.4	799	36	8.249	12.100	18.803	1800	1500	1200
73	5234.1	802	36	8.249	12.100	18.803	1800	1500	1200
74	5305.8	806	36	8.249	12.100	18.803	1800	1500	1200
75	5377.5	809	37	8.081	11.854	18.421	1900	1500	1200
76	5449.2	813	37	8.081	11.854	18.421	1900	1500	1200
77	5520.9	816	37	8.081	11.854	18.421	1900	1600	1200
78	5592.6	819	37	8.081	11.854	18.421	1900	1600	1200
79	5664.3	823	37	8.081	11.854	18.421	1900	1600	1200
80	5736	826	37	8.081	11.854	18.421	1900	1600	1300
81	5807.7	829	37	8.081	11.854	18.421	1900	1600	1300
82	5879.4	832	37	8.081	11.854	18.421	1900	1600	1300
83	5951.1	836	37	8.081	11.854	18.421	1900	1600	1300
84	6022.8	839	38	7.921	11.619	18.056	2000	1600	1300
85	6094.5	842	38	7.921	11.619	18.056	2000	1600	1300
86	6166.2	845	38	7.921	11.619	18.056	2000	1600	1300

87	6237.9	848	38	7.921	11.619	18.056	2000	1600	1300
88	6309.6	851	38	7.921	11.619	18.056	2000	1600	1300
89	6381.3	855	38	7.921	11.619	18.056	2000	1600	1300
90	6453	858	38	7.921	11.619	18.056	2000	1700	1300
91	6524.7	861	38	7.921	11.619	18.056	2000	1700	1300
92	6596.4	864	38	7.921	11.619	18.056	2000	1700	1300
93	6668.1	867	38	7.921	11.619	18.056	2000	1700	1300
94	6739.8	870	39	7.768	11.395	17.707	2100	1700	1300
95	6811.5	873	39	7.768	11.395	17.707	2100	1700	1300
96	6883.2	876	39	7.768	11.395	17.707	2100	1700	1400
97	6954.9	878	39	7.768	11.395	17.707	2100	1700	1400
98	7026.6	881	39	7.768	11.395	17.707	2100	1700	1400
99	7098.3	884	39	7.768	11.395	17.707	2100	1700	1400
100	7170	887	39	7.768	11.395	17.707	2100	1700	1400

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