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EXPLOSION HAZARD ASSESSMENT

IN ACCORDANCE WITH EUROPEAN DIRECTIVE 96/82/EC "SEVESO II": ISO-DAMAGE AREAS DUE TO ACCIDENTAL EXPLOSION

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Foreword

The obligations of the European Directive 96/82/EC on the control of major accident hazards, the so-called Seveso II Directive, became mandatory within the European Member States from 3 February 1999.
Explosive products have been included within the Seveso II Directive, in the categories of substances capable of generating a major accident. In addition to taking "all measures necessary to prevent major accidents", explosive manufacturers are also obliged "to limit their consequences for man and the environment". However, for explosives in particular, no procedures, nor specific reference values for damage calculation, are given either in the Directive or in the corresponding Italian Legislation, "Ministry of the Environment decree of 20 Oct. 1998".
This article presents a simplified but scientifically rigorous approach for the first approximation calculation of the effects on the surrounding area following an accidental explosion. As an example of the method of calculation, the damage areas in a hypothetical explosives manufacturing facility, as shown in Figure 1, will be analyzed.
The method proposed in this article can also be used for the analysis of explosions of gas in tanks or pipelines, of dust in silos, or of explosives or propellants in production, warehousing, transportation, and so forth.

Effects on the surrounding area following an accidental explosion

In an explosive reaction, detonation or deflagration, energy is released in fractions of seconds and consequently, the associated power is very high.
The explosion generates light, heat and gas. If prior to the explosion, the explosive was confined within a container, such as a process vessel, pipeline or building, the rapidly expanding gases almost instantaneously load the container walls at very high pressure, thus destroying it.
Continuing to expand, the gases shatter the container's fragments and generate a stress wave that propagates in the air, the air overpressure wave. In certain situations, this effect can also occur in the ground producing seismic waves.
Additionally, some constituents of the gases produced by the explosion may themselves present a problem for people, generically defined as "toxic" release. For example, nitrogen oxides (NO_x) are toxic, carbon monoxide (CO) is poisonous, and carbon dioxide (CO_2) is asphyxiating.
By ignoring "instantaneous thermal radiation" and "stationary thermal radiation", which are

generally not relevant in conventional explosions, the effects on the surrounding area following an accidental explosion can therefore be assessed by considering the following four categories of effect:

- Blast overpressure wave
- Projection of fragments
- Ground vibrations
- "Toxic" release

Threshold values for damage areas calculation

Having established the four categories required to assess the effects of an accidental explosion, the next step is to define threshold values for each of the damage categories at five indicative levels:

1. Highly Lethal
2. Lethal Boundary
3. Irreversible Injury
4. Reversible Injury
5. Damage to Structure, Domino Effect

As an aid to quantifying the threshold values, reference can be made to previous accidents in facilities, experiences from war and military experimentation.

Table 1 lists the relevant threshold values for the effects following an explosion in the example facility shown in Figure 1.

Table 1: Threshold values of the effects induced on the surroundings

	Area				
	1 Highly Lethal	**2** Lethal Boundary	**3** Irreversible Injury	**4** Reversible Injury	**5** Domino Effect
Blast overpressure wave, kPa (people in the structures)	55	24	16	8	350
Projection of fragments, density of "dangerous fragments" in open spaces, $1/m^2$		1/56			
Ground vibrations, mm/s	300	250	200	100	
"Toxic" release, (absorbed dose) ppm	LC50 (30min, hmn) NO_x = 315 CO = 5647 CO_2 =50000		IDLH NO_x=100 CO = 1200 CO_2 =40000		

It should be noted that all the actions from each of the effects overlap and combine during the explosion. Therefore, the damage threshold for an induced explosive effect has a lower value than would be applicable if that induced effect were to occur in isolation.

For example, calculations may indicate that for ground vibration alone damage should take place 110 m away and for air overpressure alone, 270 m away. However the combination of the two actions means that damage is actually found at a distance greater than 270 m.

Even within the same category of effect it may be necessary to consider the joint action of several acting elements, for example, "toxic release" where the explosion gases include NO_x, CO, and CO_2.

Quantity of explosive material involved in a major accident and its distribution in the facility

In the first approximation, a conservative, "worst case scenario", approach should be used. The mere presence of explosive material must be considered as leading to the possibility that an accident could occur in the specific "spot" where the explosive is present. A spot can be any area within a facility such as plant, production unit, tank or storage unit, pipeline, or generic transport system even if the explosive is present only for a short time, such as in discontinuous transportation, or the amount of explosive present is minimal.
The maximum quantity of explosive material that could contribute to the accident by mass-detonation has to be considered in the calculation of the extension of induced effects.
For any mixture of materials with different explosion energies, different types of explosives, gas, or dust-air mixtures, the material with the greatest explosion energy should be considered.
In essence, the calculation of the damage areas due to explosion should be made for each spot where the presence of explosive materials is foreseen, for the maximum amounts that may be present, and for the explosive material present that has the greatest explosion energy.
In any second phase of analysis, after the initial evaluation of the resulting damage areas and accident probability, it is then possible to focus attention on specific spots and to conduct further, secondary analysis of these particular spots. This "fine-tuning" may consist of:

- Reconsideration of the probability of the accident
- Refining model and resistance parameters of both of the confining donor and the acceptors, the impacted structures
- Adoption of more sophisticated calculation algorithms
- Performing tests to adapt the calculation algorithm to the specific site and context.

The explosion energies of the explosive materials in the example facility are listed in Table 2.

Table 2: Explosion energies for the example facility

Spot		Maximum explosion energy, GJ	Equivalent to TNT kg
1	Processing	120	26,549
2	Storage	460	101,770
3	Processing	7	1,549
4	Processing	3	664
5	Storage	280	61,947
n.n.	Discontinuous transport	80	17,688

Air overpressure wave

The rapid expansion of the explosion gases in the air produces an immediate pressure increase on the surroundings. The explosion pressure can reach values as high as 10 GPa. This overpressure falls off rapidly at a point near the explosion and continues to decay at a slower rate at increasing distance from the explosion until it returns to ambient values.
The explosion will also cause fragmentation to occur within structures, buildings that are damaged by the air overpressure wave. An allowance for the effects of this secondary fragmentation is included in the threshold values used in the calculations for air overpressure.
For the purposes of damage assessment, it is necessary to consider both the amplitude of the peak air overpressure and the rate at which the peak pressure decays, since both parameters affect the associated impulse, and related energy, of the explosion.
The calculation of the air overpressure peak, and of its associated impulse, is complex and

requires specific knowledge and experience. The value of the air overpressure peak, is dependent upon a number of factors such as:

- Explosion energy, shape, and power of the explosion
- Degree of confinement of the explosion
- Distance from the explosion
- Air pressure and atmospheric humidity
- Wind speed and direction;
- Distance from the center of explosion to the ground
- The morphology of the ground along which it propagates, for the resulting generation of Mach waves

However, in the first approximation, reference is made to normalized graphs in which peak pressure and impulse are given as a function of the distance scaled on the cube root of explosion energy, for explosions in free air at the surface or underground with different confinement. Also, a safety coefficient can be adopted to account for the neglected increment factors of the peak pressure, such as Mach wave, morphology and so on.
The values of the peak air overpressure given in Table 1 are indicative and constitute threshold values for the following damage scenarios:

Area 1 HIGHLY LETHAL - 55.2 kPa
High mortality and in general, very serious injuries due to impact against hard surface, projection of debris or collapse of walls and floors of building; eardrum rupture in 20% of the cases.
Nearly total destruction of unstrengthened buildings.

Area 2 LETHAL BOUNDARY - 24.1 kPa
Serious injuries and some cases of death due direct action such as impact against hard surfaces and indirect action from the projection of debris or the fall of walls and floors of buildings; perforation of the eardrum in 1% of the cases.
In buildings, 50% are damaged so badly as to require replacement.

Area 3 IRREVERSIBLE INJURY -15.9 kPa
High probability of ruptured eardrum and temporary loss of hearing from the direct action of the blast air overpressure wave, injuries from indirect action as above.
In unstrengthened buildings, 20% are damaged so badly as to require replacement.

Area 4 REVERSIBLE INJURY - 8.3 kPa
People outdoors are not injured by the explosion. Glass fragments from windows may injure people in buildings. The probability of glass breakage is low depending on old, crystallized panes or panes poorly mounted in their frames.
In unstrengthened buildings 5% are damaged so badly as to require replacement.

Area 5 DAMAGE TO STRUCTURE / DOMINO EFFECT - 350 kPa
This value has a wide range and is dependent on the type of “spot” impacted and the internal protections and hazardous material in the impacted spot

It should be noted that “barriers”, such as mounds, blast walls, can significantly reduce the damage corresponding to the given threshold values.
In order to graphically represent the results from the calculation, lines showing the boundary for each damage area can be drawn. These lines represent the points at which the damage is equal, equivalent to the relevant threshold value, and consequently the area within each shape that is formed is referred to as the “iso-damage area”.

The calculated values for the iso-damage areas due to air overpressure for each spot of the example facility are given in Table 3 and Figures 2 to 5.

Table 3: Radius, in metres, of the iso-damage areas due to air overpressure

Spot		A. 1	A. 2	A. 3	A. 4	A. 5
1	Processing	180	300	400	660	70
2	Storage	280	470	620	1040	110
3	Processing	70	120	150	260	30
4	Processing	50	90	120	190	20
5	Storage	240	400	530	880	90
n.n.	Discontinuous transport	160	260	350	580	60

Projection of fragments

The container, such as a process vessel, pipeline or building, will be shattered by the blast wave. The fragments from the container that are projected away from the explosion are a potential danger for people and structures in the surrounding area. This effect is known as primary fragmentation.

The damage effects from the secondary fragmentation caused by the air overpressure wave have already been made in the threshold values used in the calculations for air overpressure.

For primary fragmentation, throw distance and the mass of the fragments depend not only on the total explosion energy and decoupling of the explosive charge but also on initial velocity of the fragment, trajectory, dimensions, and density.

However, in the first approximation, reference is made to abaci in which the maximum projection distance of a “dangerous fragment” is given by the variation of the total explosion energy, type of container and relative direction of projection.

The value given earlier in Table 2 is indicative and constitutes a threshold for the following scenario:

Area 2 LETHAL BOUNDARY – 1 in 56 m^2

Density of fall equal to one “dangerous fragment” in an area of 56 m^2. These are fragments with impact energy greater than 78 N.m, whose action is considered as additional to that of the secondary fragments in the analysis of the air overpressure wave.

The iso-damage areas due to the projection of dangerous fragments in each spot of the example facility are given in Table 4 and Figures 2 to 5.

Table 4: Radius, in metres, of the iso-damage areas due to projection of fragments

Spot		A. 2
1	Processing	460
2	Storage	960
3	Processing	380
4	Processing	380
5	Storage	720
n.n.	Discontinuous transport	430

Ground vibrations

Seismic waves produced by the explosion propagate in the ground. These vibrations stress structures both directly, in the case of transient vibrations, and also indirectly, prolonged vibrations that trigger resonance.

For damage assessment, in addition to the amplitude of the vibration, predominant frequency of the vibration is also important. Among the factors that affect the values of the vibration peak and frequency are the total explosion energy, distance, geo-mechanical characteristics of the ground, explosion confinement. The damage effect from ground vibrations is normally negligible although it will become significant when an explosion occurs partly or fully underground.

Peak vibration is usually calculated by the statistical processing, power regression, of measurements for a specific explosion configuration and for the specific propagation media. Results are given in the form of an exponential decay law such as $\nu_i = K * R^{\alpha} * Q^{\beta}$, where ν_i is the amplitude of one of the 3 components of the vibration at a distance R from the explosion of a charge of energy Q, K, α and β are parameters depending on explosion configuration, geo-mechanical and morphological context in which the explosion takes place.

For the first approximation, reference is made to decay laws calculated from measurements in similar explosive events or extrapolation from similar explosive events.

The peak vibration threshold values given in Table 2 take into account high seismic transient frequencies and are indicative for the following scenarios:

Area 1 HIGHLY LETHAL – 300 mm/s
Weakening and collapse of constructions.

Area 2 LETHAL BOUNDARY – 250 mm/s
Collapse of construction with structural components of masonry and weakening of reinforced concrete, serious damage to structural components with steel framework.

Area 3 IRREVERSIBLE INJURY – 200 mm/s
Partial weakening of structural components.

Area 4 REVERSIBLE INJURY – 100 mm/s
Serious damage to architectural and structural components.

Specific construction solutions can reduce the damage corresponding to the given threshold values.

Iso-damage areas due to the ground vibration effect in each spot of the hypothetical facility are given in Table 5 and Figures 2 to 5.

Table 5: Radius, in metres, of the iso-damage areas due to ground vibrations

Spot		A. 1	A. 2	A. 3	A. 4
1	Processing	60	70	70	90
2	Storage	120	130	140	170
3	Processing	20	20	20	20
4	Processing	10	10	10	10
5	Storage	90	100	110	130
n.n.	Discontinuous transport	n.a.	n.a.	n.a.	n.a.

Toxic release

The types and amounts of gases and materials released by the explosion considered as "toxic" depend on the type and amount of explosive material that reacts, whether it be a substance, a compound, or a mixture. It should be noted that for damage assessment, the term "toxic" includes the normally accepted definitions of toxic, noxious, poisonous and asphyxiating.
The ground concentration of toxic materials will also depend on weather conditions, density of explosion gases, morphology of the ground and other factors effecting the dispersion of gas clouds.

In the first approximation, a dilution of the toxic substances released is calculated for a volume of air equal to that of a hemisphere with its centre at the point of explosion. The volume of the gases produced by the explosion will displace an equivalent volume of air and therefore the concentration of the toxic substances is calculated on a volume of air equal to that of the hemisphere reduced by the volume of the explosion gases. In order to allow consistency between damage assessments, the characteristic parameters of the air should be set equal to the "international air-type" parameters.
Certain meteorological and morphological conditions, such as down drafts, can cause a ground concentration of toxic materials that is greater than that obtained from a simple dilution calculation. In order to consider a worse case scenario, it may be necessary to compensate for this increase in concentration by means of a safety coefficient for the amount of explosion gas.
The values of toxic release concentration indicated in Table 2 for the three types of gases are indicative. Each one sets a threshold value for the respective scenario but they do not take into account the combination of actions.

The iso-damage areas due to the toxic release effect in each spot of the example facility considering the combination of the actions of the three gases are given in Table 6 and Figures 2 to 5.

Table 6: Radius, in metres, of the iso-damage areas due to toxic release

Spot		A. 1	A. 3
1	Processing	80	110
2	Storage	130	170
3	Processing	30	40
4	Processing	20	30
5	Storage	110	140
n.n.	Discontinuous transport	70	90

Iso-damage areas due to the actions of the explosion induced effects

Having calculated the iso-damage areas of each of the four damage categories for each spot, the "final" resulting iso-damage area of each spot will be equal to that obtained from the largest of each of the induced effects.
For example, at a particular spot, high-mortality conditions due to air overpressure waves may exist well outside the high-mortality area for toxic release. For this spot, the high mortality iso-damage area will be that due to overpressure.
For the example facility, the final iso-damage areas for each spot are given in Table 7 and are shown in Figure 6.

Table 7: Radius, in metres, of the iso-damage areas due to all of the induced effects

Spot		A. 1	A. 2	A. 3	A. 4	A. 5
1	Processing	180	460	460	660	70
2	Storage	280	960	960	1040	110
3	Processing	70	380	380	380	30
4	Processing	50	380	380	380	20
5	Storage	240	720	720	880	90
n.n.	Discontinuous transport	160	430	430	580	60

Similarly, the iso-damage areas for each of the five thresholds in the whole facility will result from the envelope of the corresponding threshold iso-damage areas of all the spots within the facility.
Figures 7 to 10 show the envelopes of the iso-damage areas in the example facility due to the combination of all the spots within the facility.

Italian legislative references

Ministry of Public Works decree of 9 May 2001; Legislative decree 334/99; Decree of the President of the Council of Ministers of 31 March 1989; Presidential decree 175/98; Ministry of the Environment decree of 20 Oct. 1998; Ministry of the Environment decree of 13 May 1996; Ministry of the Interior decree of 2 August 1984.

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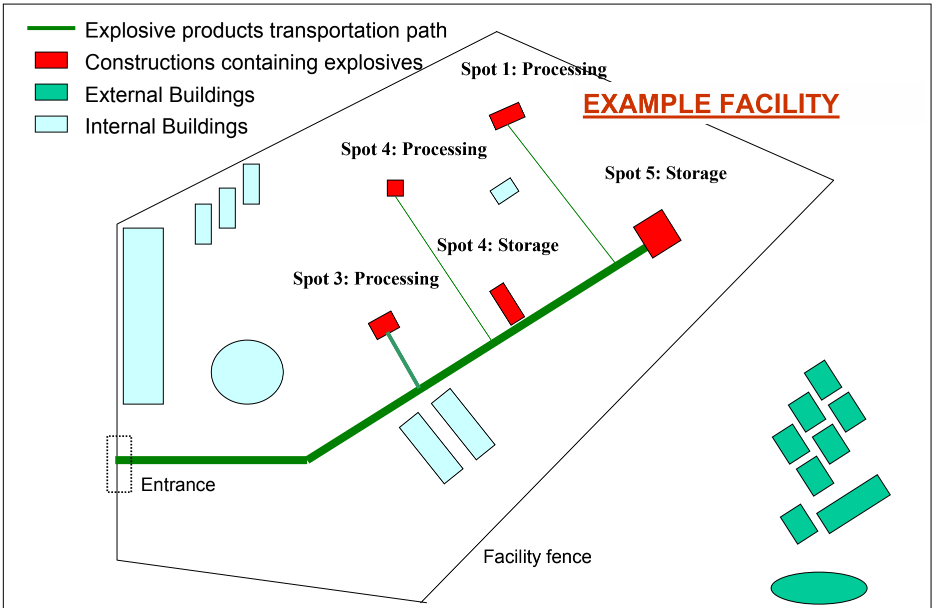

Figure 1

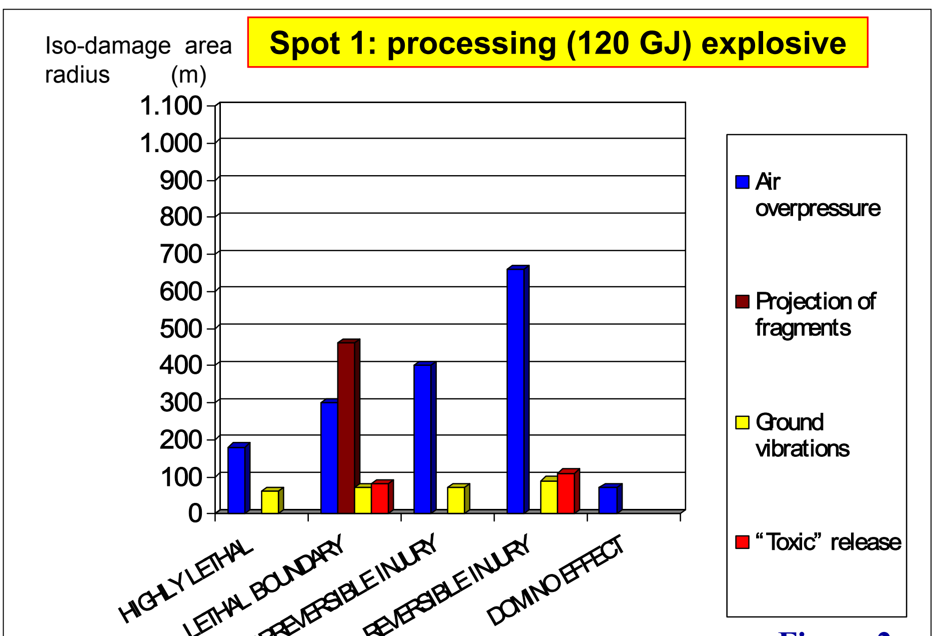

Figure 2

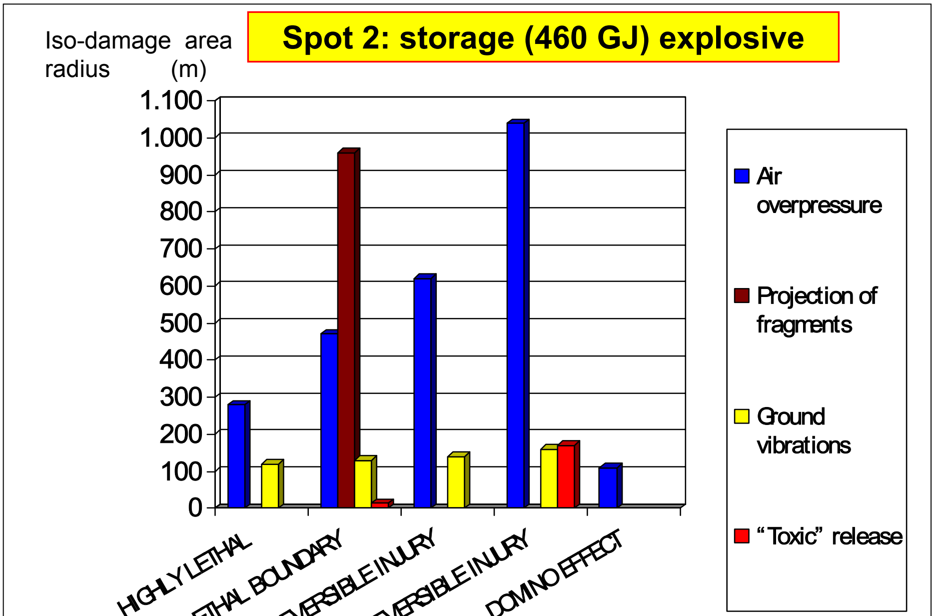

Figure 3

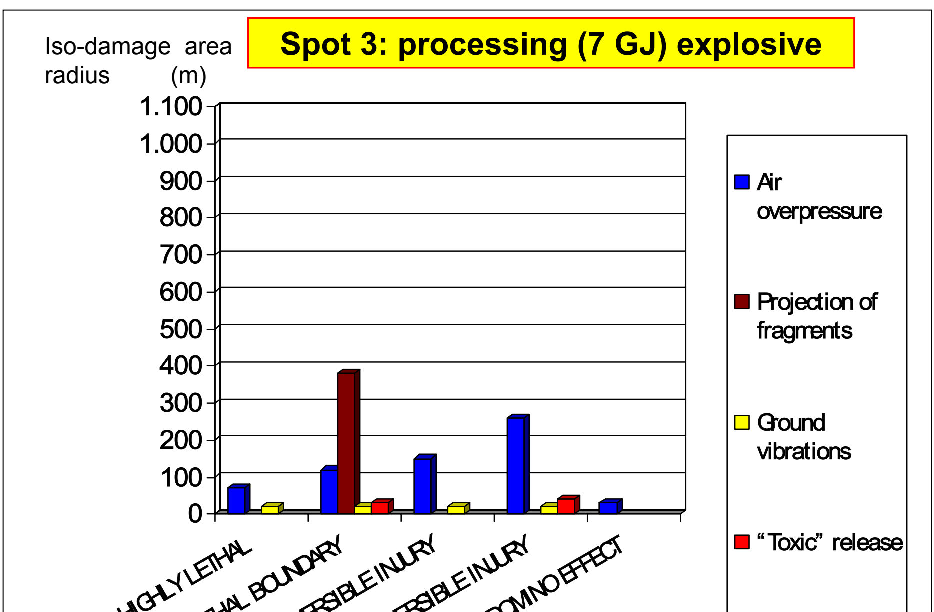

Figure 4

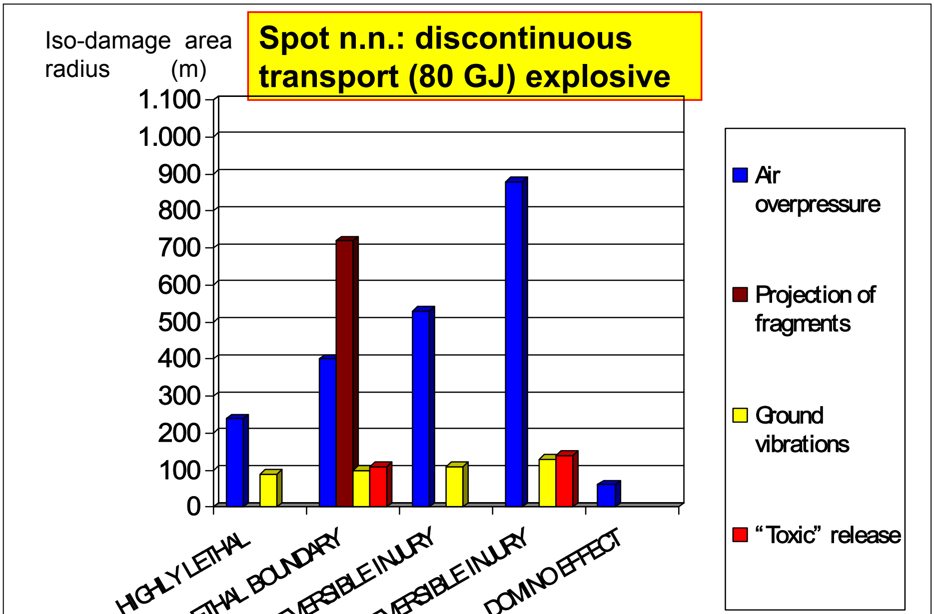

Figure 5

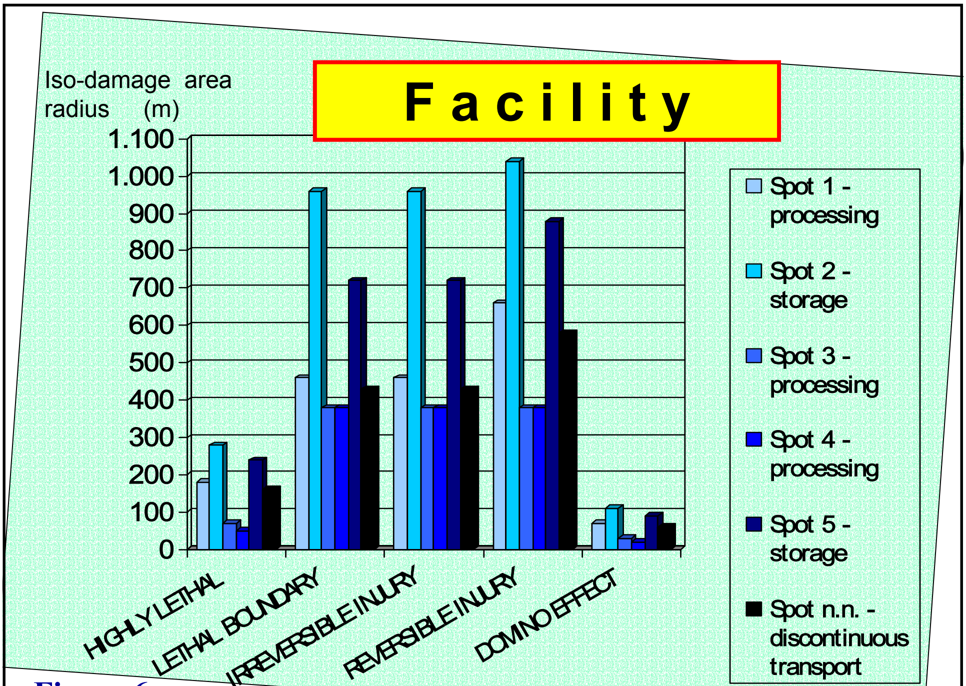

Figure 6

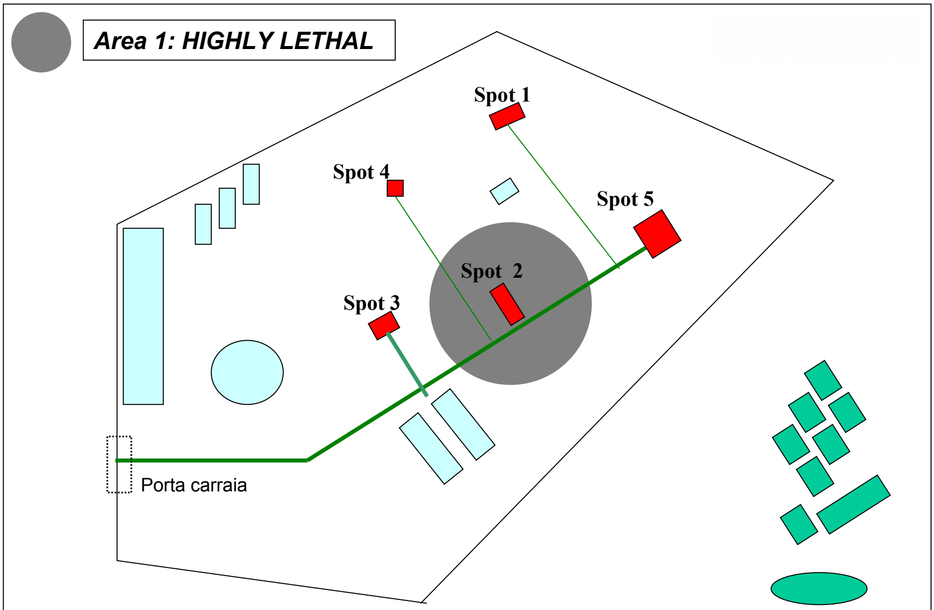

Figure 9a - Iso-damage area for accidental explosion in spot 2

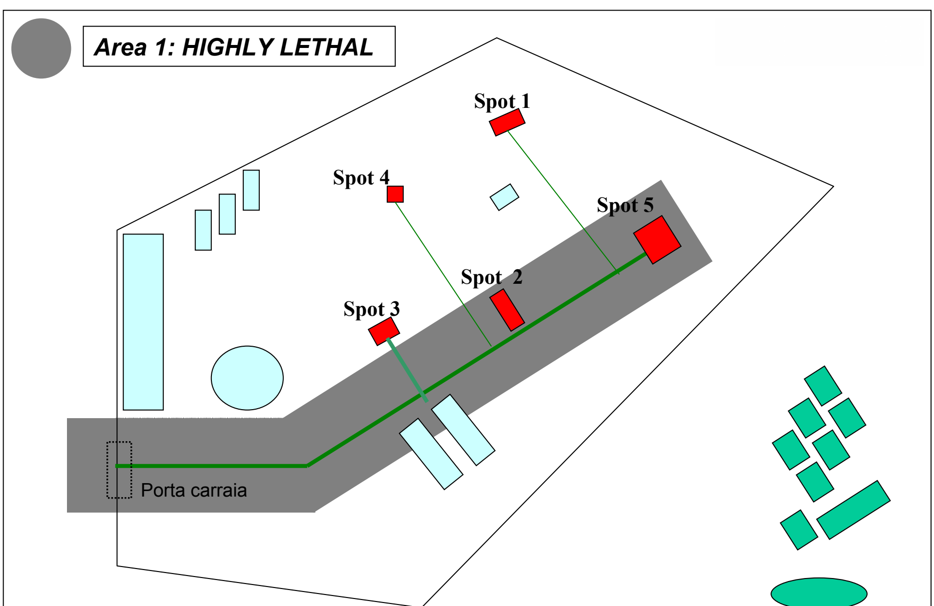

Figure 9b - Iso-damage area for accidental explosion in spot n.n.

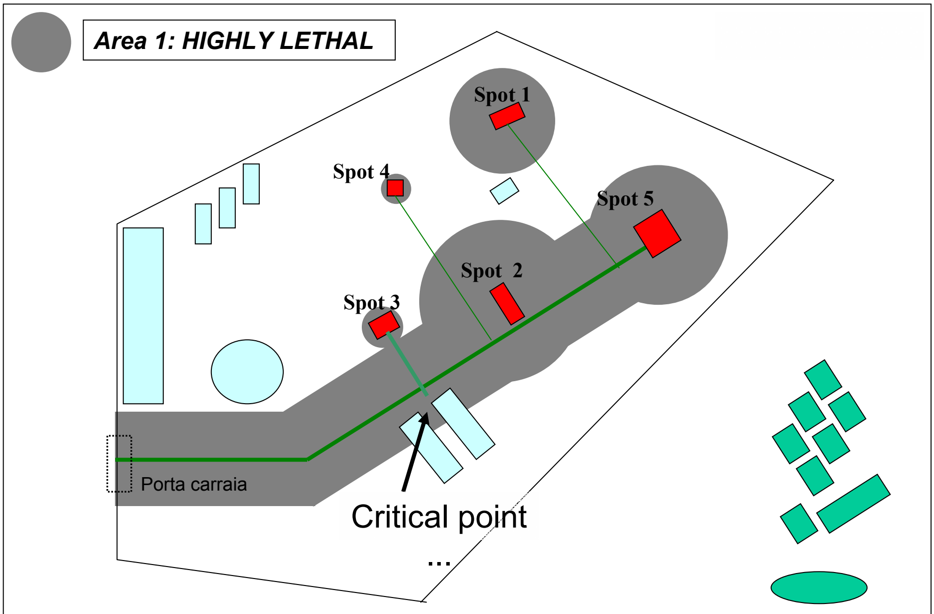

Figure 9c - Envelope of iso-damage areas of each spot of the hypothetical facility

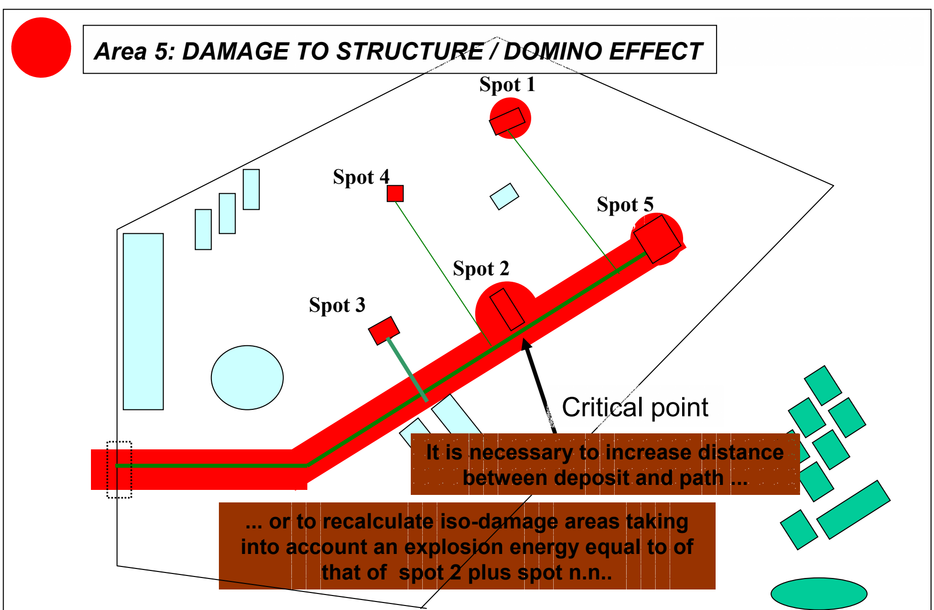

Figure 10 - Iso-damage areas

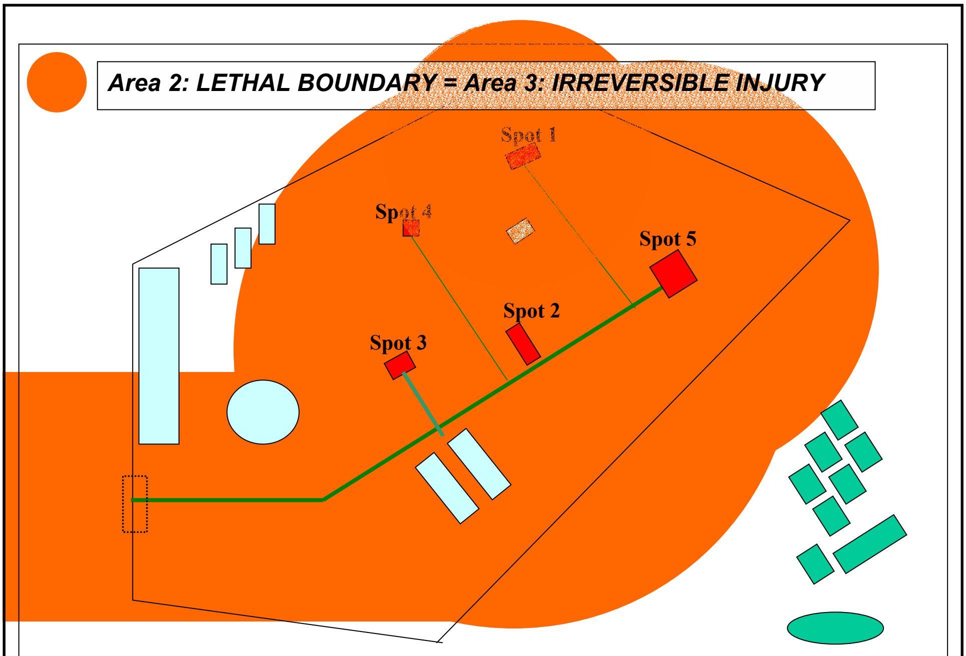

Figure 10 - Envelope of iso-damage areas of each spot of the hypothetical facility

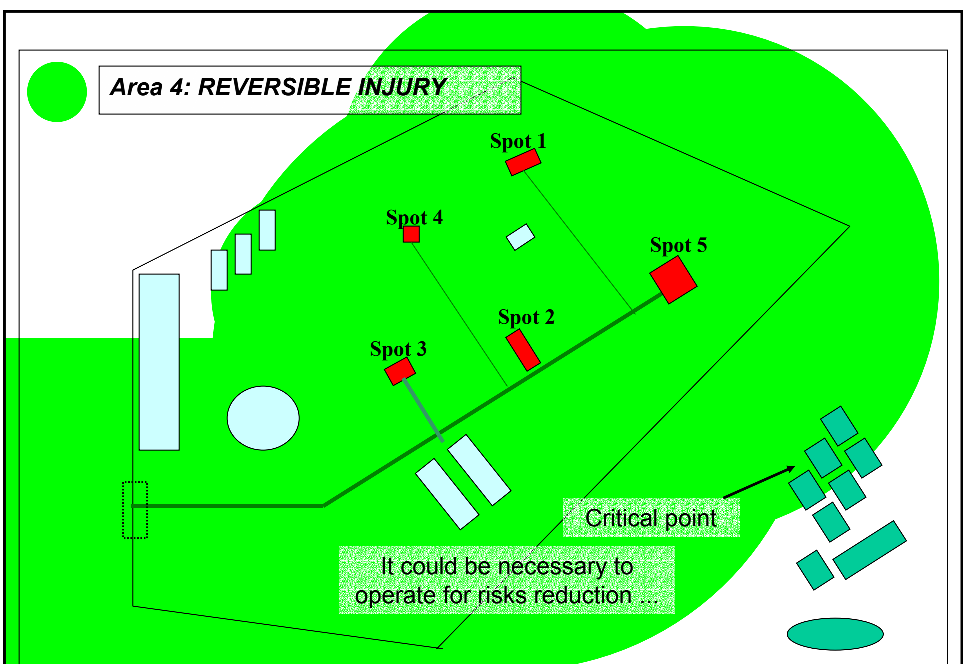

Figure 10 - Envelope of iso-damage areas of each spot of the hypothetical facility