Committee of Experts on the Transport of Dangerous Goods and on the Globally Harmonized System of Classification and Labelling of Chemicals

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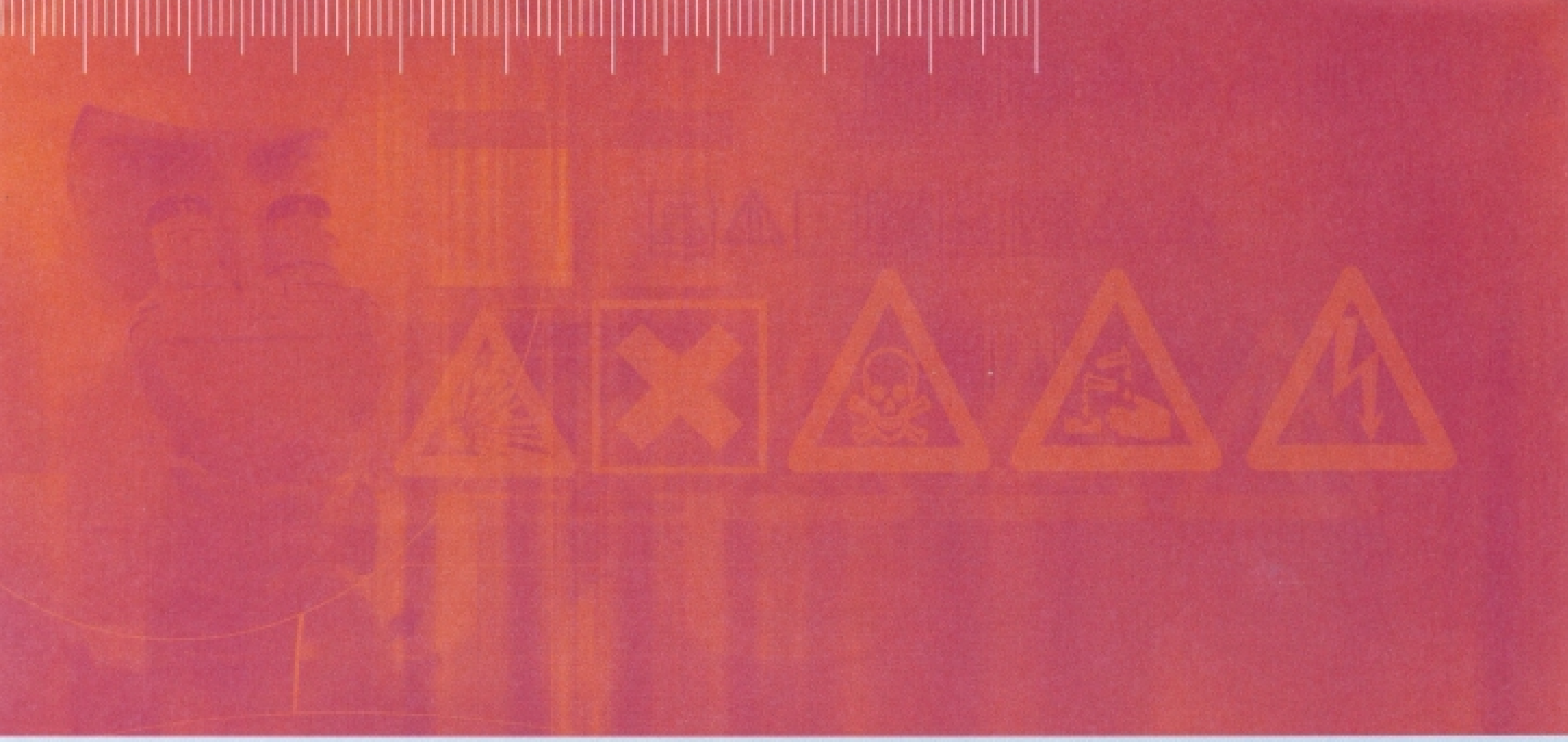
Possible categorization of lithium batteries for transport according to their hazard and effects when reacting

Transmitted by the expert from France[1]

(Revised version of the second study contained in INF.31)



STUDY REPORT 01/05/2016

N°DRA-16-148820-11057A

COMPARISON OF THERMAL AND TOXIC EFFECTS Of THE FIRE OF BATTERIES AND OTHER GOODS IN TRANSPORT BY A HEAVY GOODS VEHICLE

INERIS

maîtriser le risque
pour un développement durable

Comparison of thermal and toxic effects of the fire of batteries and other goods in transport by a heavy goods vehicle

Accidental Risks Division

People involved in the study: Guillaume LEROY, Philippe GONCALVES

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	Writing	Proofreading	Verification		Approval
NOM	P. GONCALVES	G. FAYET	T. DELBAERE	F. MERLIER	M-A. SOENEN
Qualité	Engineer of the Equipments and Systems Safety Assessment Unit Accidental Risk Division	Engineer of the Energetic Materials and Safety of the Chemical Reaction Unit Accidental Risk Division	Head of the Equipments and Systems Safety Assessment Unit Accidental Risk Division	Technical Support to the Administration Delegate Accidental Risk Division	Head of the Substances, Products and Processes Department Accidental Risk Division
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1 INTRODUCTION

1.1 CONTEXT

Within the frame of a technical support performed by INERIS to the French administration regarding the transport of batteries, the assessment of the relevance of categorizing batteries in order to propose evolutions in regulations for the transport of dangerous goods was studied.

In a previous report (Report No. DRA-14-141820-13186A), we studied, given the feedback of INERIS, external fire tests performed on batteries, the relevance to lead to a categorization of batteries for transport, and we described basic specifications to build the testing program for the categorization of batteries. It has been shown that, because of the wide variety of batteries currently on the market (particularly in terms of chemistry, geometry and design), thermal and toxic effects during a fire behavior test could vary (for the same amount of energy) by a factor of up to 20. However, only the case of the batteries was studied and, despite the great disparity in results (suggesting a relevance of the categorization), it is necessary, in order to conclude, to demonstrate that:

- The effects measured on batteries are not consistently larger than on goods classified as dangerous,
- The effects measured on batteries are not systematically lower than on goods classified as non-dangerous.

We have also identified battery suppliers, the cost of buying batteries, supply possibilities and the duration and cost of testing.

In 2015, we therefore modeled the thermal and toxic effects of a fire in a transport of several types of goods (classified as dangerous or not) during transport by heavy goods vehicles, to position two types of batteries, compared to a set of products.

1.2 STRUCTURE OF THE REPORT

This report is organized around the following four points:

1) Description of the implementation methodology for evaluating the distances of the thermal and toxic effects associated with the burning of a heavy goods vehicle carrying different loads,
2) Description of the characteristics of the heavy goods vehicle and the various loads studied. A wide spectrum of loads is designed to position the hazard potential of a heavy goods vehicle carrying batteries compared to that associated with other loads whose effects have already been characterized by INERIS.
3) Characterization of the source term. This chapter attempts to characterize the source terms of the fire loads described in 2). These source terms come in two aspects:
    - The thermal source term for the characterization of the flame,
    - The toxic source term associated with the nature and flow of fumes emitted by the combustion reaction.
4) Modeling of the distances of thermal and toxic effects from the source terms previously established and the methodology described in 1).

2 APPLIED METHODOLOGIES

This chapter presents the general methodologies used to determine the thermal and toxic effects associated with the fire of a heavy goods vehicle.

2.1 DETERMINATION OF THERMAL EFFECTS

The analysis of the basic parameters that influence the thermal flux received by a target has identified simple and conservative estimation methods. The obtained results represent a good approach to evaluate the magnitude of the phenomenon.

The proposed method to quantify the thermal flux received by a target subjected to thermal radiations, is based on the fact that the flux received depends on the position of the target compared to the volume occupied by the flames.

To evaluate the received flux, the flux emitted by the flame surface must first be established. The thermal source term is defined through:

1) The geometrical characteristics of the flame,
2) The power of fire (Section 4.1.1).

These two parameters allow defining the emitting power of the flame also called emittance (paragraph 4.1).

The combination of the geometry of the flame and its emittance is then used to estimate the flux received as represented by Figure 1.

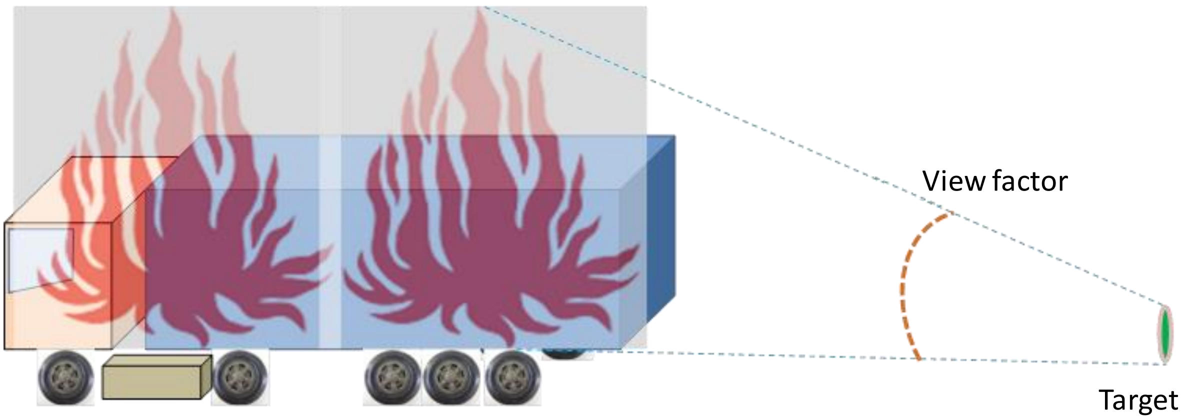


Figure 1: Illustration of the view factor

The flux received by the target will therefore increase with the view factor and the emittance. One objective of this study is therefore to compare the propensity of the various loads to generate major fires leading to high flame heights and significant emittance.

The hypothesis of considering only the effects associated with the flame radiation is justified as long as the target is away from the seat of the fire. Thermal radiation is indeed the privileged mode of transfer of heat from a certain distance from the fire. However, it should be noted that the results given for the radiative thermal effects are generally not relevant in the immediate environment of the flame, for which the effects related to convective transfer mode cannot be neglected. It is therefore appropriate to retain that in the vicinity of flames, it is not relevant to reason only in radiated flow. Therefore, the model used will no longer be valid for a distance less than a few meters.

2.2 DETERMINATION OF TOXIC EFFECTS

During a fire, large amounts of fumes are generated as a result of the combustion of the substances involved. These fumes are characterized by the formation of a plume above the flames whose dimensions depend in particular on the burning surface and the nature of the products involved.

In addition to their visual impact, these fumes can also have an impact on the environment and on people because of their toxicity.

The toxicity of the fumes can be estimated by determining the composition of smoke i.e., from a theoretical point of view from the elemental composition of the products involved, if known to be from an experimental side with tests carried out on a large scale. The latter determination is usually more accurate because it can integrate the presence of residues, while the theoretical approach generally assumes full conversion of the elements. It should be reminded that, as of today, in ranking the transport of dangerous goods, toxic effects of a fire of that transport are not considered. This parameter is therefore not considered for current classifications.

The interaction between the fire and the environment is shown in Figure 2; it is comprised of mainly three steps.

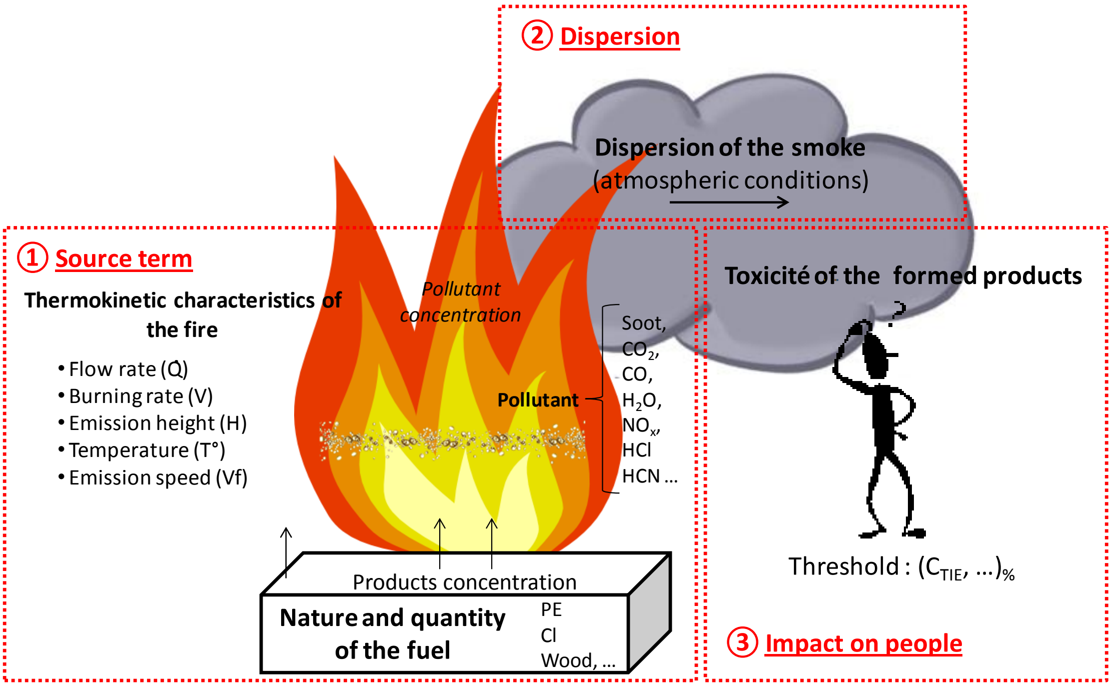


Figure 2: Schematic representation of the emission of pollutants generated by a fuel storage fire

The principle of calculating the dispersion of fire fumes is based on the following steps:

- Calculating the flow of the fumes inherent to the fire and the concentration of gases in these fumes (§ 5.1.2 and 1.1.1),
- Calculation of the atmospheric dispersion (§ 5.2.1)
- Comparison of the concentrations obtained in the previous step with the effect thresholds (§ 5.2 and 5.3).

3 DESCRIPTION OF COMBUSTIBLE ELEMENTS

This chapter introduces the combustible elements that may be involved in the fire of a heavy goods vehicle composed of a tractor and different loads.

3.1 DESCRIPTION OF THE HEAVY GOODS VEHICLE

The modeled carrier vehicle is a 38-tonne heavy goods vehicle consisting of a tractor and a trailer as shown in Figure 3. Its loading occupies the entire volume of the trailer.

Figure 3: Heavy goods vehicle studied

The heavy goods vehicle has the following general characteristics:

Maximum mass (tonnes)	38
Tractor mass (tonnes)	6
Empty trailer mass (tonnes)	7
Loading mass (tonnes)	25
Length (m)	16.5
Width (m)	2.5
Height (m)	4

Table 1 : Characteristics of the heavy goods vehicle studied

The maximum mass seen in Table 1 is the GVWR: Gross Vehicle Weight Rating.

The heavy goods vehicle studied is broken down into several components, namely:

- Wheels and mud guards,
- A tractor consisting of a cabin, a tank holding up to 0.82 m3 of diesel and a back deck for attachment of the trailer,
- A loaded trailer.

The unit mass of the elements composing the vehicle, excluding load, is presented in Table 2.

Part	Element	Unit mass (kg)	Number	Total mass (kg)
Road tractor	Wheel + mud guard	88	4	352
	Cabin	4 933(1)	1	4 933
	Diesel tank	680	1	1
Trailer	Trailer	Not useful(2)	1	Undefined
	Wheel + mud guard	88	12(3)	1056

Table 2 : Unit mass of the elements composing the vehicle

(1) Only the mass of the cabin is included in the total mass of the tractor as the rear platform of the tractor is comprised primarily of non-combustible metallic elements.

(2) The trailer being composed primarily of metallic materials and therefore non-combustible, its mass will not be useful in calculating the power generated by the burning of the heavy goods vehicle.

(3) The number of trailer wheels is usually doubled.

3.2 DESCRIPTION OF THE CONSIDERED LOADS

The objective is to compare the thermal and toxic effects related to the burning of heavy goods vehicles loaded with batteries, with fires of shipments of goods classified as hazardous as well as classified as non-hazardous. The list of the various loads selected is described in the following chapters. The different classes of dangerous goods are described in Appendix A.

3.2.1 Battery Packs of 2 different types

In the context of transport, this load is currently considered as dangerous goods and belongs to Class 9 "Miscellaneous Dangerous Goods." The technical characteristics of the two battery packs used in the study are described below:

- Battery 1: Capacity: 66.6 Ah; Energy: 23.7 kWh; SOC: 100%; Initial Tension: 398.4 V; Pouch Cells; Cathode: NMC; Anode: Graphite
- Battery 2: Capacity: 50 Ah; Energy: 16.5 kWh; SOC: 100%; Initial Tension: 355 V; Prismatic Cells; Cathode: NMC; Anode: Graphite.

A description of the different geometries and chemistries of the cells currently on the market is present in Appendix B, and the safety sheets of batteries tested at INERIS are presented in Appendix C.

3.2.2 Pallets of Aerosols

In the context of transport, this load is currently considered dangerous goods and belongs to Class 2.1 "Flammable gases". The technical characteristics of aerosols used for the study are described below:

- Packaged products: foam or shaving gel, body care product, household product or automobile maintenance product,
- Composition of Aerosols: liquid containing the active ingredient in a solvent and a gas propelling the product.

A safety sheet of a type for an aerosol tested at INERIS is presented in Appendix C.

3.2.3 Pallets of salads

In the context of transport, this load is not currently considered as dangerous goods.

3.2.4 Pallets of DVDs

In the context of transport, this load is not currently considered dangerous goods.

3.2.5 Pallets of various plastic drums

The different considered types of plastics are: rubber, textile, polyethylene and polyvinyl chloride. In the transport sense, this load is not currently considered dangerous goods.

3.2.6 Pallets of pesticides

In the context of transport, this load is currently considered as dangerous goods and belongs to Class 9 "*Miscellaneous Dangerous Goods"*. The technical characteristics of the tested items are described below:

- Different pesticides (e.g. 2-pyridine sulfonamide) and herbicides (e.g. chlorsulfuron).

A safety sheet for a type of product tested at INERIS is presented in Appendix C.

3.2.7 Polyurethane foam blocks

In the context of transport, this load is not currently considered as dangerous goods.

These loads are selected to compare a broad spectrum of fires and to use reliable data from the experiment. The different loads considered in the study are described in Table 3. They have all undergone fire tests at INERIS.

Nature of the load	Unit mass (kg)	Unit dimension (L x w x h) m^3	Number of items in the trailer	Total mass of the load (ton)	Reference
Battery pack N°1	280	1.2 x 0.75 x 0.8	89	24.9	INERIS Tests[1]
Battery pack N°2	232	1.3 x 0.68 x 0.4	107	24.8	INERIS Tests[1]
Pallets of aerosols	500	1.2 x 0.8 x 2	33	16.5	INERIS Tests[2]
Pallets of DVDs	266	1.2 x 0.8 x 1.8	33	8.8	INERIS Tests[3]
Pallets of salads	83	1.2 x 0.8 x 1.8	33	2.8	INERIS Tests[4]
Pallets of 4 drums containing various plastics	120	1.2 x 0.8 x 1	66	7.9	INERIS Tests[5]
Pallets of pesticides	233	1.2 x 0.8 x 2	33	7.7	INERIS Tests[6]
Polyurethane (PU) foam blocks	100	1.9 x 1 x 1.55	26	2.6	INERIS Tests[7]

Table 3: Loads considered in the study

The number of elements in the trailer is chosen so they occupy the entire volume of the trailer under the condition that the total mass of the load does not exceed 25 tonnes.

Given the dimensions of the components carried, a possible arrangement of the different loads in the heavy goods vehicle could be summarized in Figure 4. This is, in a major way, to occupy all available space in the trailer.

[1] Combustion tests on battery packs [Reference FIVE]

[2] INERIS – Omega 4 - Modeling a fire affecting a storage of aerosol generators - September 2002

[3] Combustion tests on a DVD pallet – [Reference Flumilog Tests]

[4] Combustion tests on a pallet of salads – [Reference Flumilog Tests]

[5] Combustion tests on a pallet of plastic drums – Confidential tests

[6] Combustion tests on a pallet containing pesticides – Confidential tests

[7] Combustion tests on polyurethane foam blocks – Confidential tests

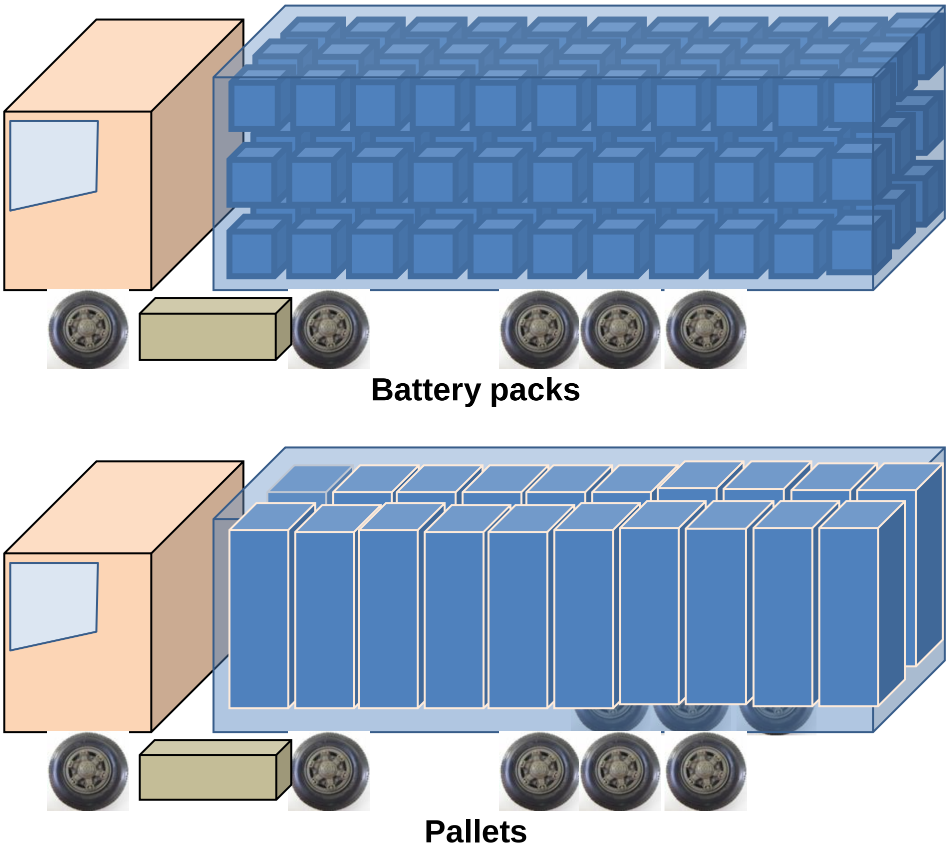


Figure 4: Loadings arrangement in the heavy goods vehicle

Concerning the pallets of plastic drums, they are small pallets of a height of 1 m that will therefore be disposed on the trailer on two levels.

4 <u>THERMAL EFFECTS</u>

4.1 SOURCE TERM

This part aims to characterize the thermal source term of the loads fire described in §3.2. This heat source term is associated to the geometric characteristics of the flame as well as its emittance.

The next step is to define the parameters that characterize the thermal source term of a fire, namely:

1) The total power of the fire,
2) The emittance of flame,
3) The flame height.

4.1.1 Power of the fire

4.1.1.1 APPLIED METHODOLOGY

First, the evaluation of the fire propagation kinetics in the loaded heavy goods vehicle is made using an INERIS tool developed to model the total power of the fire from a propagation model. The methodology consists of adding the power of the fire of the different components of the heavy goods vehicle:

1) The wheels,
2) The cabin,
3) The diesel slick,
4) The load.

To take into account the inertia of fire spread from one element to the other, it is considered that:

1) The propagation is performed only between two adjacent elements,
2) The fire of an element begins when the power of the fire of the adjacent element is at its maximum.

The methodology is applied by considering a fire starting at the loading level, a scenario which leads, according to the results, to the kinetics of the fastest fire.

The methodology is detailed in Figure 5.

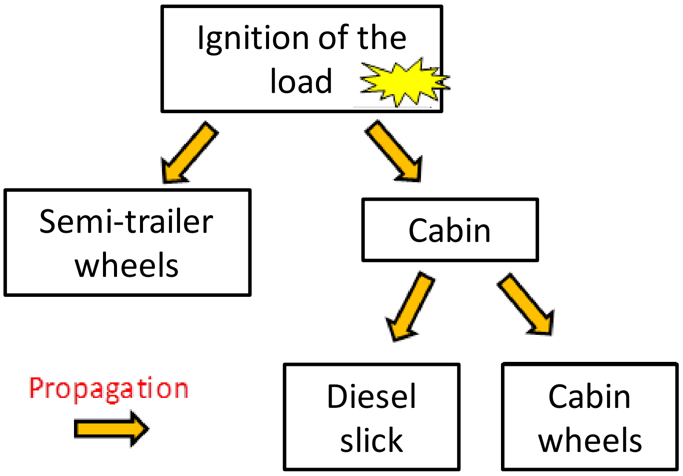
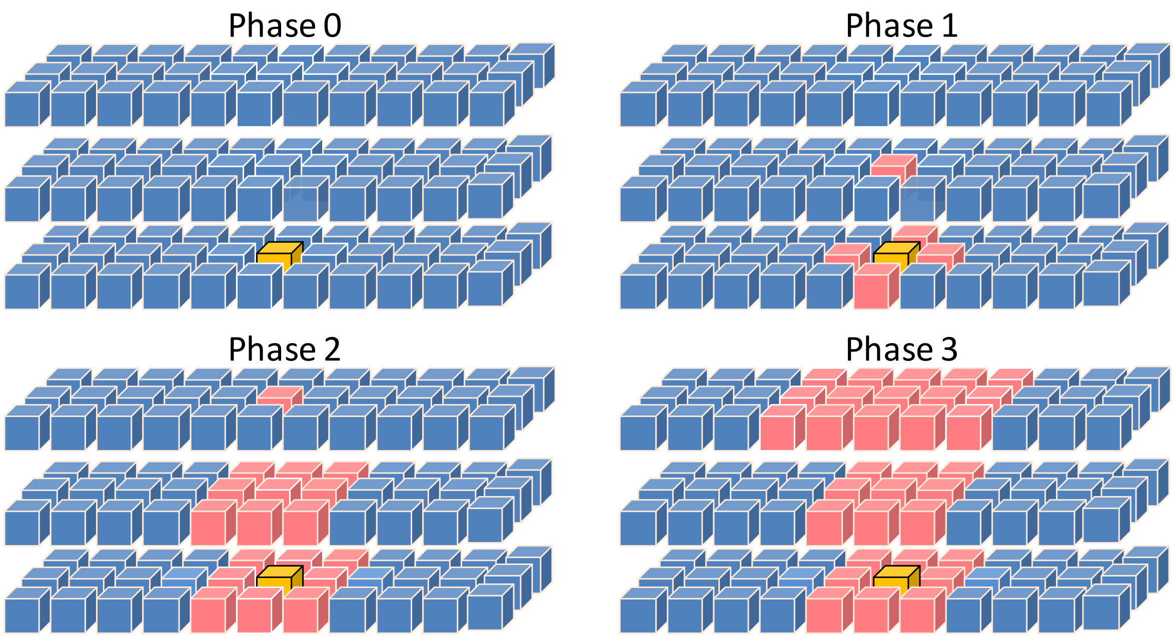


Figure 5: Applied methodology – fire starting at the load level

The spread in the load consisting of pallets follows the same law, meaning that the fire spreads gradually (from one element to its neighbors). However, the spread of fire in loads arranged over several levels (batteries or small pallets) follows a different law. A split view of the load of battery packs allows to better understand the fire spread process inside the load. Considering a fire starting in the center of the trailer, on the 1st level (majoring position in terms of kinetics) the evolution of the fire can be summarized in Figure 6.



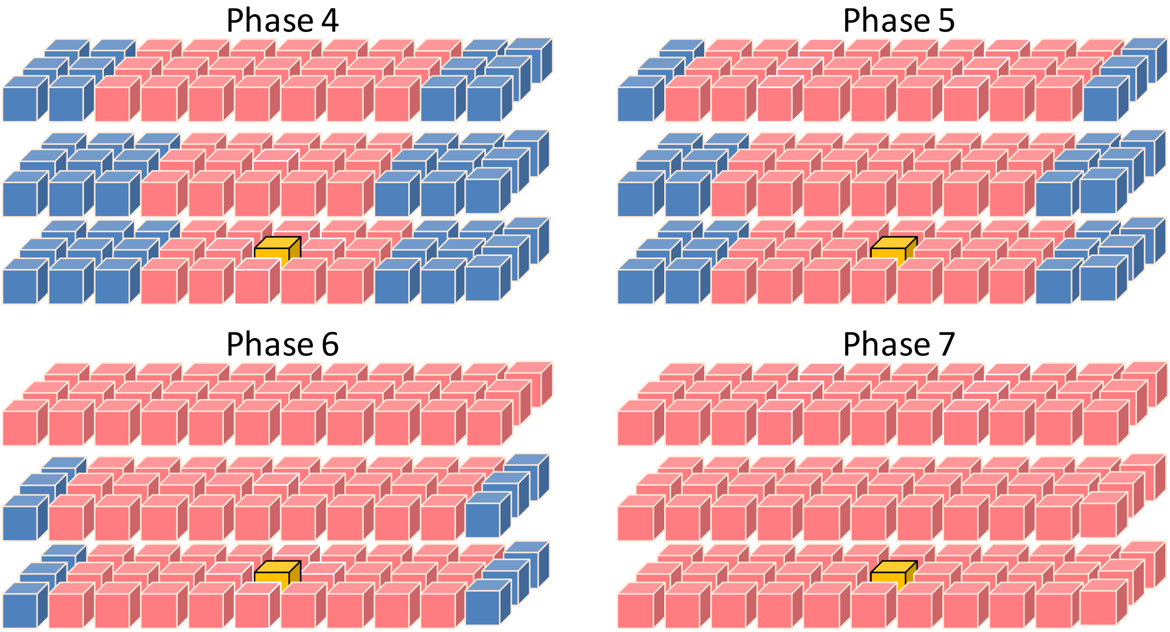


Figure 6: Mapping the spread of fire in a load of battery packs

Phase 0 is the inflammation of the first pack. The fire spreads from place to place by radiation and convection (phases 1 and 2), and takes the form of a V, which is characteristic of a load (phase 3). Then, when the fire reaches the upper batteries, the total power of the fire is stabilized because the flames then propagate in both directions (phases 4, 5 and 6). Eventually, the batteries at the ends of the load burn (phase 7), putting an end to the burning of the load.

The spread of the fire in a load of battery packs will therefore be likely to grow faster than a pallet storage because of the arrangement on several levels that promotes the spread of fire.

4.1.1.2 Power of single elements

The powers of single elements come from tests conducted at INERIS. They are represented in Figure 7.

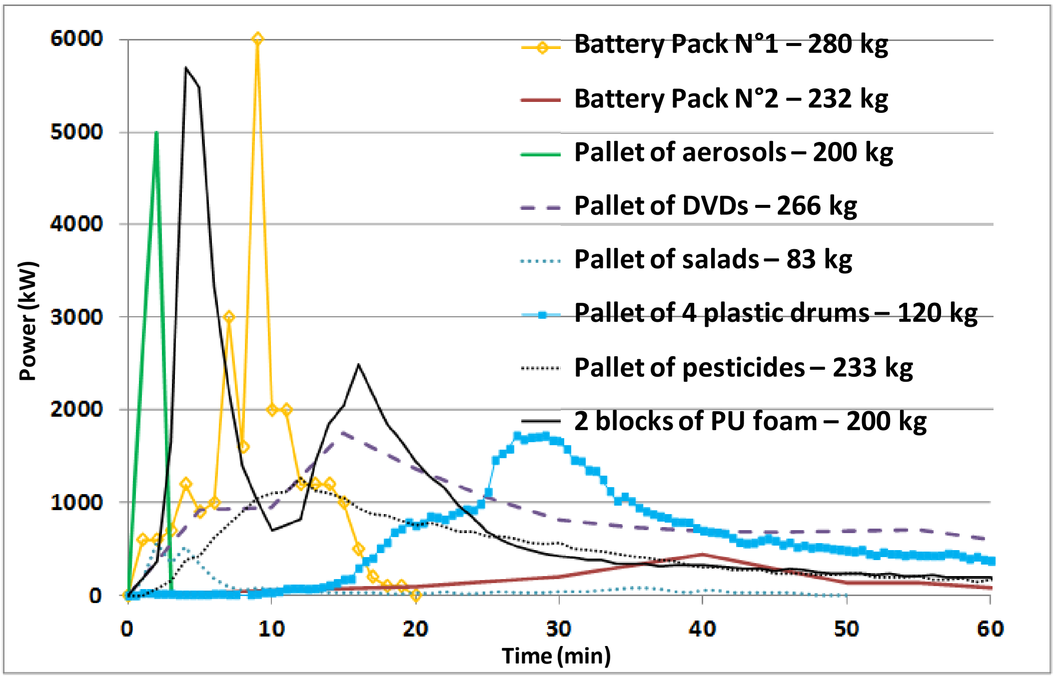


Figure 7: Power of the fire of single elements studied

The maximum power generated by the fire of battery pack N°1 (Figure 7) is similar to those developed by a pallet of aerosols and a 200 kg PU foam block. The observed order of magnitude is 5000 kW.

Similarly, pallets of DVDs, pallets of plastic drums, and pallets of pesticides with a maximum power of about 1750 kW are classified in the same power class.

Finally, the fire of battery pack N°2 develops a maximum power similar to that of light pallets of salads that is to say approximately 500 kW.

These powers can be classified into three very distinct levels, detailed in Table 4 below.

XXX: Battery

XXX: Merchandise classified as dangerous goods

XXX: Merchandise not classified as dangerous goods

Maximum thermal power level (kW)	Merchandise classified as dangerous goods	Merchandise not classified as dangerous goos
5000 - 6000	Battery pack N°1 Pallet of aerosols	2 PU foam blocks
1200 - 1750	Pallet of pesticides	Pallet of DVDs Pallet of plastic drums
400 - 600	Battery pack N°2	Pallet of salads

Table 4: Classification of the maximum powers of the fires of single elements

It is noted that for each power level, we find products classified as hazardous merchandise and others not classified. We especially note that, for the same type of product (in this case the batteries), the level of maximum power generated by a fire can vary by a factor of about ten. In order to refine the comparison, it is necessary to take into account the maximum power value generated per unit of energy (kW_{fire} / $kWh_{battery}$). The values obtained are therefore:

- 0,25 kW/kWh for battery pack N°1,
- 0,03 kW/kWh for battery pack N°2.

Thus, even reduced to a value per unit of energy, the maximum power developed by a fire of batteries may vary by a factor of about eight.

To help understand the parameters that are responsible for this difference of behavior, it is necessary to identify the characteristics of each pack that can influence the results of a fire behavior test. Table 5 below summarizes the similarities and differences between the two battery packs tested at INERIS (in bold, the characteristics which are different from one pack to another).

Characteristics	Battery pack N°1	Battery pack N°2
Pack exterior casing	**Aluminum + Steel**	**Steel + Thermoplastic**
Battery architecture	**Vertical**	**Horizontal**
Initial SOC	100%	100%
Capacity	**66 Ah**	**50 Ah**
Electrochemical energy	**23.7 kWh**	**16.5 kWh**
Cell chemistry	Cathode: NMC Anode: Graphite	Cathode: NMC Anode: Graphite
Cell geometry	**Pouch (plastic envelope)**	**Prismatic (steel envelope)**
Cell safety device	**None**	**Safety vent in case of overpressure**

Table 5: Characteristics of the two battery packs tested at INERIS

In the case of thermal effects, the characteristics that could impact the power generated by the fire are:

- The battery architecture: the spread of fire between two elements is much faster vertically than horizontally,
- The cell geometry: the plastic envelope pouch of the cells burns very easily and thus helps increase the overall power of fire,
- The amount of on-board electrochemical energy in the battery,
- The safety devices: a vent allows, in case of internal cell overpressure, to release the gases present, a part of which might not burn,
- The outer casing pack: the presence of a plastic casing burning easily, can significantly increase the power of the fire.

Because of the presence of plastic in the composition of the battery pack N°2 casing, we could have expected a maximum radiated power much more important (due to the combustion of the plastic). Actually, we have observed, at the end of the test, that a part of the plastic casing of this pack melted but no major combustion is observed. This demonstrates that it is not possible to make any conclusion as to the power that will be generated by a battery fire based solely on its composition.

On the one hand, the thermal effect of a battery is highly dependent on many parameters such as the amount of energy of the sample test, the sample structure, the chemical composition of samples, the architecture of the pack, etc. On the other hand, for two samples having the same chemistry and an electrochemical energy of the same order of magnitude, the power radiated per unit of energy can vary by a factor of eight.

4.1.1.3 Power of the full load

Although the power of the fire of the single element provides guidance on potential violence of the fire, it is necessary to compare the powers of loaded heavy goods vehicle fires considering:

- The energy contribution of the fire in the cabin, the tires of the heavy goods vehicle and the diesel fuel in the tank,
- The number of items that can be stored in the trailer based on their volume unit (battery pack, pallet or PU foam block)
- The kinetics of the burning load.

The power of the fire of the loaded heavy goods vehicle, estimated using the approach detailed in paragraph 4.1.1.1, is shown in Figure 8, for the various loadings described in the preceding paragraph. The number of items carried in the trailer is indicated in the figure.

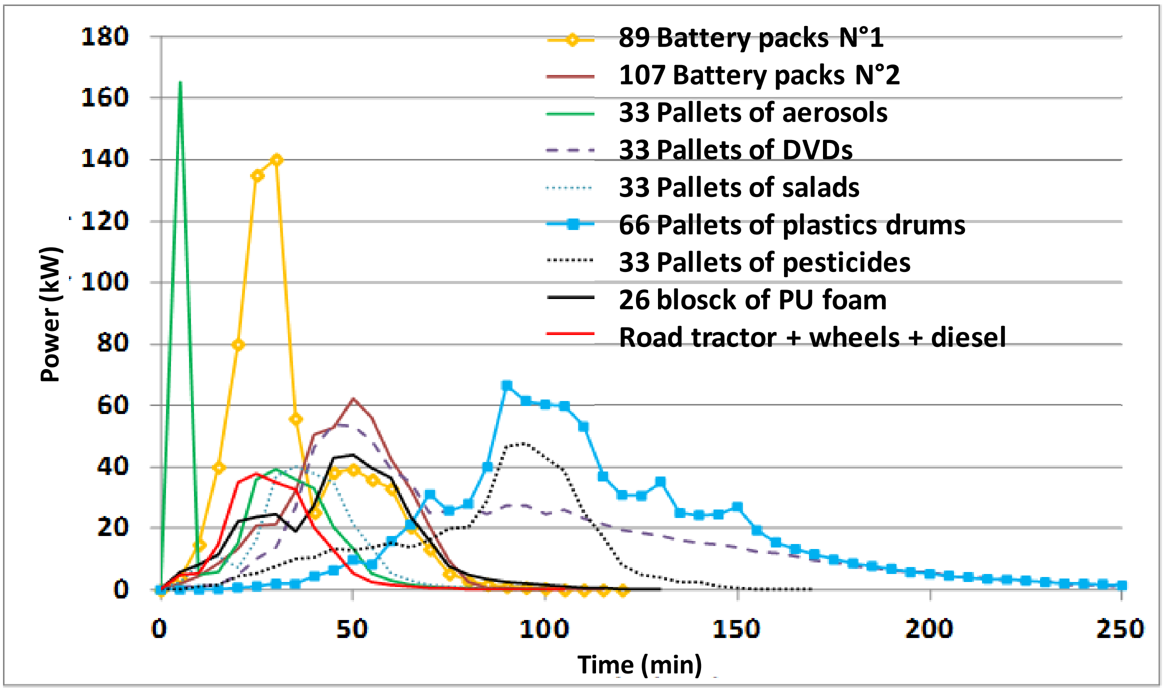


Figure 8: Total power of the fire of the Heavy Goods Vehicle depending on the type of loading. The data is summarized in Figure 9.

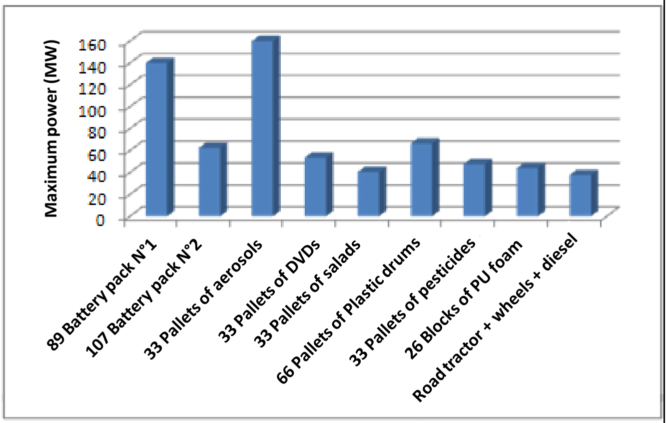
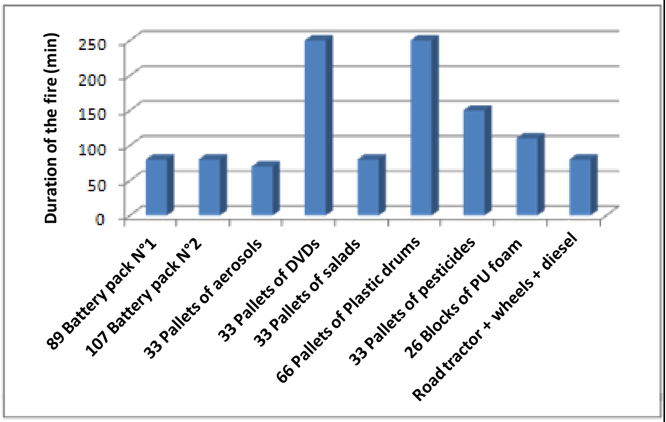
Maximum power of the fire (MW)	Duration of the fire (min)
	

Figure 9: Comparison of the maximum power of the fire and the duration of the fire depending on the type of loading

1) The power peaks of heavy goods vehicles fires loaded with battery packs N°1 and aerosol pallets are of the same order of magnitude, i.e. around 150 MW.
2) The power of heavy goods vehicle fire containing the other elements is between 38 and 66 MW, values 2-4 times lower than those associated with aerosols and battery packs N°1.
3) The duration of heavy goods vehicles fires loaded with pallets of DVDs and plastic drums are the most important (about 250 min) for powers not exceeding 60 MW. Although potentially at risk because of that duration, thermal effects will be limited regarding the effects associated with the burning of a heavy goods vehicle loaded with battery packs N°1.
4) The power peak related with the fire of plastic drums and pesticides occurs later (about 100 minutes after the ignition of the heavy goods vehicle) and does not exceed 60 MW. This slow kinetics of the fire would allow emergency services to circumscribe or even extinguish the fire before the occurrence of the peak power.
5) The power linked to the fire of salads pallets is of the same order of magnitude as that associated with the burning of the tractor. Indeed, the energy contribution of the salads pallets is low (less than 500 kW). This also applies to a wide range of water based foods.

Considering the scale effect between the single elements and the whole load is not likely to significantly change the previous conclusion except that only two distinct power classes could be proposed:

Maximum thermal power level (MW)	Merchandise classified as hazardous	Merchandise not classified as hazardous
140 - 160	**Battery pack N°1** **Pallet of aerosols**	
35 - 70	**Pallet of pesticides** **Battery pack N°2**	**Pallet of DVDs** **Pallet of plastic drums** **2 PU foam blocks** **Pallet of salads**

Table 6: Classification of the maximum powers of the fires of full loads

It is therefore observed that, for battery packs with energies and masses of the same order of magnitude, the maximum power developed during a fire of a full load can:

- Be higher or lower than values for fires of dangerous goods loads,
- Be higher or lower than the values for fires of non-dangerous goods loads.

In addition, given the characteristics of the two packs described in Table 5, it is not possible to conclude, based solely on the composition (external or internal) of the pack, on the amount of energy transported, etc. Many parameters are involved and influence the thermal behavior of a fire of a full load.

Based on this preliminary information, a categorization of batteries according to their thermal effect according to the results of an external fire test therefore seems feasible and justified.

4.1.2 Flame emittance and height

After determining the maximum power values emitted during fires of various loads, it is necessary, in order to be able to define the thermal source term of these fires, to determine the flame emittance and height.

The flame emittance is defined by the surface radiative power of the fire. It is an essential parameter to estimate the flux received by the target present in the flame environment and thus calculate the effect distances.

The flame emittance can be estimated using the following equation:

$$\phi_0 = \frac{\eta_r P_{tot}}{S_{fl}} \qquad \text{Equation 1}$$

P_{tot} = Maximum total power emitted by the loading fire (kW)

S_{fl} = Outer flame area (m²)

η_r = Radiative fraction (-)

To evaluate the flame area, the latter is considered, for simplification, as a parallelepiped having for floor area the loading area (13.5 x 2.5 m²). Its height is estimated using an empirical correlation called Thomas correlation[8].

For all loads except the load of aerosols pallets, the value of the radiative fraction is taken inclusively at 30%.

Table 7 shows the flame characteristics for each type of load at the power peak of the fire.

Nature of the load	**Max burning rate (g/m²/s)**	**Max flame height (m)**	**Maximum total power emitted by the load fire (kW)**	**Flamme surface (m²)**	**Max flame emittance (kW/m²)**
89 Battery packs N°1	167	11.9	140	421	100
107 Battery packs N°2	90	8.2	62.5	303	62
33 Pallets of aerosols	Undefined	10.0	165	361	100
33 Pallets of DVDs	78	7.5	53.7	280	57
33 Pallets of salads	60	6.4	40.4	246	49
66 Pallets of 4 drums containing various plastics	69	6.9	66.5	263	76
33 Pallets of pesticides	67	6.8	47.7	258	55
26 Polyurethane (PU) foam blocks	50	5.7	44	223	59

Table 7: Flame characteristics of various loads

[8] Thomas, The size of flames from natural fires, 9th international symposium on combustion, p 844-859, 1963

4.2 CALCULATION OF THE DISTANCES OF THERMAL EFFECTS

The characterization, made in the preceding paragraphs, for each load, of the source term defined with the maximum power emitted by the fire, the emittance of flame and the flame height, allows subsequently, through a modeling tool, to calculate the distances of thermal effects for various thresholds effects on people.

4.2.1 Selected effect thresholds

The results are expressed in the form of effects distances on human health related to radiative flux generated by a fire. Thus, the calculations include the thermal flux which may be received by an individual located at a certain distance from the flame front, on the perpendicular bisector of the front concerned, for an exposure time greater than 2 minutes.

The selected values are those recommended by the French Ministerial Decree of September 29, 2005 on the evaluation and consideration of the probability of occurrence, kinetics, intensity effects and severity of the consequences of potential accidents in the danger studies of classified facilities subject to authorization.

The main thermal effects thresholds are:

- **8 kW/m²: Significant Lethal Effects Threshold:** corresponds to the flux received over which one could observe 5% mortality in the exposed population[9],
- **5 kW/m²: Lethal First Effects Threshold:** corresponds to the flux received over which one could observe 1% mortality in the exposed population,
- **3 kW/m²: Threshold for Irreversible Effects:** corresponds to the received flux, above which irreversible effects might occur in the exposed population.

[9] The notion of "population at risk" does not include "hypersensitive" subjects

4.2.2 Thermal effects thresholds of the different types of loads studied

The thermal effects distances associated with fires of heavy goods vehicles carrying various loads are shown in Table 8 and in decreasing order.

Load	Effect distance in meters at the threshold of …		
	3kW/m²	5kW/m²	8kW/m²
Battery pack N°1	**38**	**30**	**23**
Aerosols	**36**	**28**	**22**
Pallets of DVDs	**24**	**18**	**13**
Pallets of plastic drums	**18**	**13**	**9**
Battery pack N°2	**17**	**12**	**9**
PU Blocks	**15**	**11**	**9**
Pallet of pesticides	**12**	**8**	**5**
Pallets of salads	**7**	**4**	**2**

Table 8: Thermal effects distances obtained for the various loads

Figure 10 illustrates the results obtained.

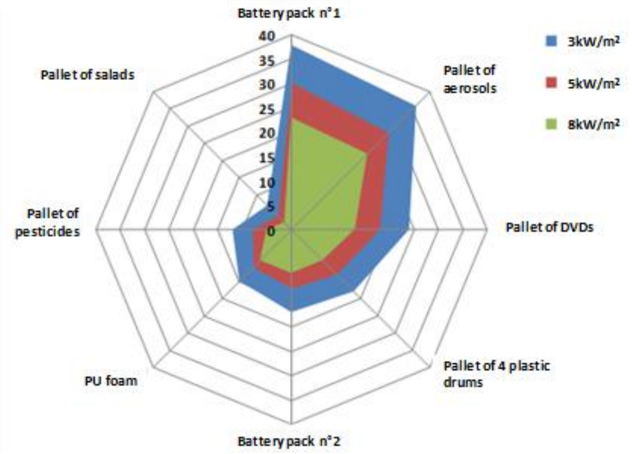


Figure 10: Thermal effects distances

Thermal effects distances related to the fire of a load of battery packs N°1 are of the same order of magnitude as those relating to the fire of a load of aerosol. They are 1.5 times higher than the effects distances related to the burning of a load of pallets of DVDs and between 2 and 3 times higher than those associated with loads of plastic drums, polyurethane foam blocks, pesticides and battery packs N°2. They are finally about 7 times higher than a fire of a load of salads.

4.3 CONCLUSION ON THE THERMAL EFFECTS

Regarding the data obtained from this study, we can conclude that:

- Modifying one or more parameters of the design of the battery (architecture, external and internal components, etc.) can induce strong variations in the maximum power generated by the fire,
- Depending on the battery tested, the measured thermal effects may be lower or higher than the measured effects on certain goods classified as dangerous by mean of transport (e.g. aerosols),
- Depending on the battery tested, the measured thermal effects may be lower or higher than the measured effects on certain goods classified as NOT dangerous by mean of transport (e.g. DVDs or plastic drums),
- Information on the constitution of a battery does not allow to conclude, without prior tests, on the violence of the measured thermal effects. For example, in our case, the presence of plastic on the battery pack N°2 casing causes one to suspect a much greater power of the fire.

This information allows us to conclude that a categorization of batteries for transport according to their thermal effect during a fire behavior test is relevant.

Future work will therefore be:

- To define a reliable and robust testing protocol to be able to test batteries and retrieve data needed for the evaluation of the thermal effect,
- To identify the relevant parameters for the categorization,
- To define one or more thresholds that will allow categorization of the batteries into one or more classes of thermal effect.

5 TOXIC EFFECTS

5.1 SOURCE TERM

This section aims to characterize the toxic source term of the fire of the loads described in §1. This toxic source term is associated with the nature and the flow of gaseous effluents emitted by the combustion reaction.

The source term, determining the toxic effects, consists of:

1) The speed of the fumes at the emission point,
2) The height of emission,
3) The flow of the fumes and the concentration of the various gases present in these fumes.

5.1.1 Emission speed and height

In the case of fires such as those considered in this study, the fumes are generated in the upper part of the volume formed by the flames. The first step in order to characterize the emission is to determine the height of the fumes emission. To do this, there are many empirical formulas published in the literature. We used the formula proposed by Heskestad[10] for this study. The height *h* obtained from the relationship proposed by Heskestad corresponds to the average height of the flames because, in reality, the latter are animated by an intermittent movement.

In the case of liquid hydrocarbon fires, Heskestad[10;11] showed that, at the height *h*, the average temperature difference between the fumes of the fire and the ambient air is close to 250 K. In addition, this same author provided an empirical correlation for determining the average speed of the fumes elevation to the height *h* depending on the amount of heat convected by the fumes. Experimental measurements show that at least 70% of the thermal power generated by a fire is convected.

5.1.2 Flow of fumes

After determining the speed and height of the emission of fumes, it is necessary, in order to determine the source term, to calculate the speed of the fumes emitted.

The fumes are composed of gases produced by burning the stricken heavy goods vehicle and the air driven by updrafts generated by the flames. The total flow of fumes is obtained by means of a formula proposed by Heskestad[10] and varies, depending on the power of the fire.

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[10] G. Heskestad - « Engineering Relations for Fire Plumes », Factory Mutual Research Corporation, Fire safety Journal, 7, 1984, pp 25-32

[11] G. Heskestad - « Fire Plume Air Entrainment according to two Competing Assumptions », Factory Mutual Research Corporation, 21th Symposium on Combustion/ the Combustion Institute, 1986/ pp 111-120

5.1.3 Determination of the concentrations of gaseous effluents present in fumes

Finally, to complete the determination of the source term, the mass concentration of each gaseous effluent in the combustion fumes must be determined. This concentration is characterized as the ratio of the emission rates of gaseous effluents by the total flow of fumes.

We must therefore first determine the emission rate of gaseous effluents based on the total mass of gaseous effluents emitted from the combustion of the loaded heavy goods vehicle.

The total mass of gaseous effluents emitted by the combustion of the heavy goods vehicle depending on the various loads is presented in Table 9.

	Combustible element	Total production of gaseous effluents (kg)							Reference
		CO	CO_2	HCl	HF	HCN	NO_2	SO_2	
Loading	**89 Battery N°1 pack**	174.17	12422.84	9.19	48.49	0.32	10.5	0	INERIS Tests[1]
	107 Battery N°2 pack	204.1	9772.51	14.34	49.26	0.32	7.59	0	INERIS Tests[1]
	33 Pallets of aerosols	140.44	2865.66	3.85	1.32	0.32	1.6	0	INERIS Tests[2]
	33 Pallets of DVDs	239.44	16280.16	6.69	1.32	0.32	6.02	0	INERIS Tests[3]
	33 Pallets of food type products (lettuces)	203.14	4083.36	3.85	1.32	0.32	1.6	0	INERIS Tests[4]
	66 Pallets of plastic	497.5	15154.86	578.05	608.52	0.32	9.39	14.78	INERIS Tests[5]
	33 Pallets of pesticides	259.24	10620.66	20.68	1.32	19.46	47.8	1023	INERIS Tests[6]
	26 Polyurethane (PU) foam blocks	195.77	5749.06	3.85	1.32	8.43	6.95	0	INERIS Tests[7]

Table 9: Total mass of gaseous effluents depending on the transported combustible elements

These data are from tests conducted by INERIS on each of the combustible elements. The test reference is entered in the last column of Table 9.

The mass of gaseous effluents from the burning of the cabin and tires is added to each load fire. These data are also derived from INERIS tests[12].

[12] Light vehicle combustion tests - [Reference FIVE]

The gaseous effluent emission rate is obtained from the power of the fire such as:

$$D_i(t) = \frac{P_i(t)}{P_{\max}} \alpha_i \qquad \text{Equation 2}$$

$$M_{tot_i} = \alpha_i \int_0^{Tfinal} \frac{P_i(t)}{P_{\max}} dt = \alpha_i * \frac{E_{tot}}{P_{\max}} \qquad \text{Equation 3}$$

With:

$D_i(t)$	=	Rate emission of the gaseous effluent *i* (kg/s)
$P_i(t)$	=	Fire power (W)
$P_{\max}$	=	Maximum total power (W)
α_i	=	Factor associated to the gaseous effluent i (kg/s)
E_{tot}	=	Fire's final total energy (J)
M_{tot_i}	=	Gaseous effluent total mass i (kg) from Table 9

The α_i coefficient used to calculate the emission rate of a gaseous effluent in Equation 2 is derived from Equation 3.

This coefficient is therefore a constant, which implies that each effluent's emission rate is proportional to the power of the fire. However, the concentration of each gaseous effluent in the fumes remains fixed throughout the duration of the fire. This can be explained by the fact that the total flow of fumes also varies in proportion to the power of the fire according to §5.1.2.

To illustrate this, the CO and HCl emission rates obtained in time for the burning of heavy goods vehicles containing battery packs are shown in Figure 11. Note that in a safe approach, the diesel tank is considered empty in order to limit the power of the fire and increase the toxic effects on the ground.

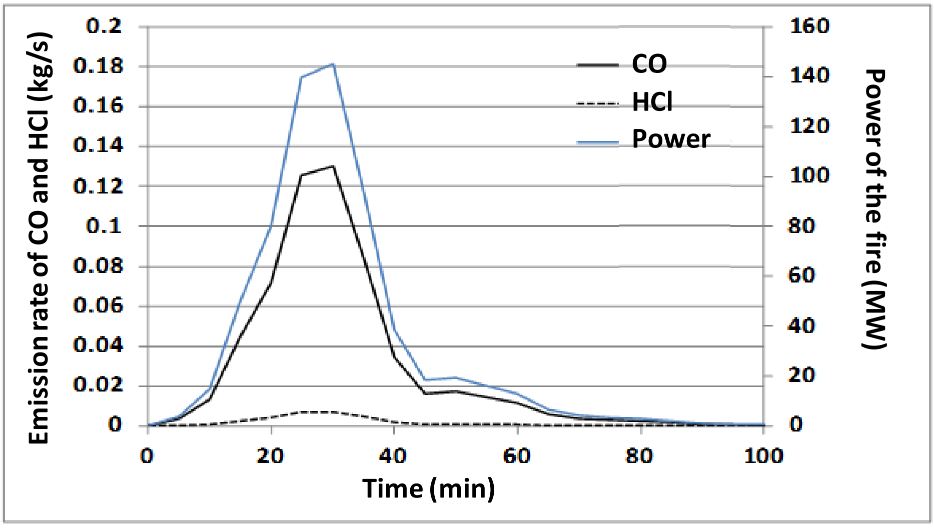

Figure 11: Emission rate of CO and HCl and power depending on time for the fire of a heavy goods vehicle carrying battery packs N°1

5.2 CALCULATION OF OPEN FIELD TOXIC EFFECT DISTANCES

5.2.1 Atmospheric dispersion

To understand free field toxic effects, elements of atmospheric dispersion are reviewed in this paragraph.

5.2.1.1 COMPUTING CODE

Atmospheric dispersion of gaseous effluents is modeled using the Phast computing code, version 6.53.

5.2.1.2 ATMOSPHERIC CONDITIONS

Meteorological conditions are described by numerous parameters, of which the main ones are tied, on the one hand, to atmospheric turbulence, and on the other, to wind speed. These two parameters, that characterize meteorological conditions, will not be dealt within this document. Similarly, for information regarding Pasquill classes, the reader is referred to the INERIS guide on dispersion, available on the INERIS website at: www.ineris.fr[13]

The most unfavorable results, regarding the effects likely to be felt, can be obtained when:

- the atmosphere is rather stable;
- wind speed is maximal.

However, each class of stability was indexed to the wind speed. Therefore, a wind speed of 10 m/s is not usually associated with stability class A. According to Pasquill[14], class B, for example, is associated with a maximum wind speed of 5 m/s.

[13] INERIS - OMEGA 12 - Atmospheric Dispersion (Computational mechanisms and tools) - DRA - December 2012

[14] “Atmospheric Diffusion”. 1974, Ellis Horwood.

In order to encompass the largest possible sample group of meteorological conditions, INERIS retained, as prescribed, 9 Pasquill[14] classes whose characteristics can be found in Table 10.

Atmospheric stability	Wind speeds considered (m/s)
A	3
B	3 and 5
C	5 and 10
D	5 and 10
E	3
F	3

Table 10: Retained meteorological conditions

The roughness parameter which allows taking into account the impact of ground roughness on fume dispersion was set at 0.1, which corresponds to a flat, sparsely inhabited environment.

5.2.2 Used toxic thresholds

The approaches used are:

- Additivity law of thresholds[15],
- Application of ISO 13 571[16] standard that allows to distinguish the effect of irritant gases from asphyxiating gases on people's capacity to evacuate a hazard zone.

5.2.2.1 ADDITIVITY LAW OF THRESHOLDS

In order to characterize fume toxicity, the threshold to retain is not specific to one gas, but to a mix of gases. In such a case, if the mix is made up of n pollutant gases denoted by P_1, P_2, P_3 …, the equivalent threshold is estimated using Equation 4.

$$\frac{1}{Threshold_{equivalent}} = \sum \frac{[Concentration \cdot of \cdot pollutant \cdot P_i]}{Threshold \cdot of \cdot pollutant \cdot P_i} \quad \text{Equation 4}$$

The previous expression allows taking into account the specific toxicity of each gas on the one hand, and to "add" their respective toxicities on the other, in a simplified fashion.

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[15] INERIS - Omega 16 - Toxicity and dispersion of fumes from a fire - Phenomenology and modeling of effects - ref: 57149 - 2005

[16] ISO 13571 – TC92 SC3 N335 International Standard – Life-threatening components of fire – guidelines for the estimation of time available for escape using fire data – 2007

It is clear that such an approach does not allow taking into account all potential synergistic or antagonistic effects caused by the simultaneous presence of various gases.

In France, a methodology[17] for determining acute toxicity thresholds was developed by INERIS, published in 2003 and revised in 2007: it allows fixing acute toxicity thresholds in the case of an accidental emission of a toxic substance into the atmosphere by an industrial facility. The main toxic effect thresholds developed for exposure periods of 1 to 60 minutes are the following:

- **Threshold for Significant Lethal Effects**: corresponds to the concentration in the air for a given exposure period above which one could observe 5% mortality at the edge of the exposed population[18],
- **Threshold for the First Lethal Effects**: corresponds to the concentration in the air for a given exposure period above which one could observe 1% mortality within the exposed population,
- **Threshold for Irreversible Effects**: corresponds to the concentration in the air for a given exposure period above which irreversible effects[19] could show up within the exposed population.

In our restricted environment study, the threshold considered is the Threshold for Irreversible Effects (TIE) at 60 min.

The Threshold for Irreversible Effects (TIE) retained for various products prone to being emitted by truck fires are given in Table 11 for an exposure time of 60 min.

Gaseous effluent	**TIE 60 min (ppm)**
CO	800
CO_2	50,000
HCl	40
HF	100
HCN	41
NO_2	40
SO_2	81

Table 11: Irreversible threshold values for each toxic gas

[17] French methodology for determining acute toxicity values in the case of an accidental emission of chemical substances into the atmosphere. INERIS 2007

[18] The idea of “exposed population” does not take into account “hyper-sensitive” subjects (for example, those with respiratory issues)

[19] Within the framework of this methodology, irreversible effects include: lesions with no functional repercussions (chemical burn), with functional repercussions (pulmonary fibrosis, loss of smell...) and irreversible functional injury (asthma).

5.2.2.2 APPLICATION OF ISO 13571 STANDARD

FED concept

The fractional effective dose is an asphyxiating gas model that allows the evaluation of asphyxiating effects of toxic fumes on the human body as a function of exposure time. It is expressed as follows:

$$X_{FED} = \sum_{t0}^{t1} \frac{CO}{35000} \Delta t + \sum_{t0}^{t1} \frac{HCN^{2,36}}{1.2x10^6} \Delta t \qquad \text{Equation 5}$$

With:

CO	=	CO concentration (ppm)
HCN	=	HCN concentration (ppm)
Δt	=	Time step (min)
$t1$	=	Exposure time of individual (min)

It is to be noted that the increased absorption rate of the asphyxiating gases due to hyperventilation is taken into account in Equation 5.

FEC concept

Fractional effective concentration allows evaluating the effects of irritant gases as a function of their concentrations in fumes[15].

$$X_{FEC} = \sum_{i=1}^{n} \frac{C_i}{Threshold_i} \qquad \text{Equation 6}$$

With:

C_i	=	Pollutant concentration i [ppm]
$Threshold_i$	=	Effect threshold for pollutant i [ppm]

Table 12 below provides threshold values for each irritant gas prone to being present in the combustion fumes. These values are taken from ISO 13571 standard[15].

Toxic gas	**$Threshold_i$ [ppm][15]**
HCl	1,000
HF	500
NO_2	250
SO_2	150

Table 12: Threshold values for each toxic gas

Retained criterion

Knowing that a threshold criterion of 1 for FED and FEC statistically serves to protect only half of the exposed population, and that the relationship between these indicators and the percentage of the population likely to suffer irritant or asphyxiating effects follows a log-normal distribution, INERIS retains a threshold criterion of 0.3 for the two indicators, which translates statistically to 11.4% of the population likely to suffer compromised tenability conditions. This value therefore allows, in a prudent fashion, to ensure the absence of the effect on 90% of the population. It is to be noted that an FED or FEC of 0.3 allows reverting back to concentrations greatly inferior to thresholdsof irreversible effects.

5.2.3 Open field toxic effect thresholds of various types of loads studied

The concentration of gaseous effluents is set such that the FEC or the FED does not exceed 0.3.

Table 13 shows:

- the equivalent threshold (§5.2.2.1) for an exposure of 60 min,
- the different concentrations of gaseous effluents obtained for an FEC or FED of 0.3 for various loads, ranked in increasing order (§5.2.2.2).

The lower the threshold value, the greater the toxic effects.

	Gaseous effluent threshold concentration (ppm) for the two approaches	
Loading	**Additivity law of TIE**	**ISO 13,571 approach**
33 pallets of pesticides	43,873	727
66 pallets of plastic barrels	35,039	879
26 blocks of PU foam	375,109	1,662
33 pallets of salads	305,800	1,671
33 pallets of DVD's	891,283	1,880
33 pallets of aerosol containers	787,507	2,174
107 Battery packs N°2	321,340	2,392
89 Battery packs N°1	422,201	5,346

Table 13: Open field gaseous effluent threshold concentrations

The additivity law leads to high thresholds which leads to low effect distances. This approach will not be applied in the report follow-up.

The threshold concentrations required to obtain a FEC or FED of 0.3 for a fire of pallets of pesticides are of the same order of magnitude as those for a fire of a load of plastic barrels. They are between 2 times weaker than for fires of blocks of PU foam, pallets of salads and pallets of DVDs, and approximately 3 times lower a fire of aerosols or of battery packs N°2. They are approximately 7 times lower for a fire of battery packs N°1.

We may note that, although the amounts of each gaseous effluent produced by the fire of a load of battery packs are greater than those of a fire of a load of aerosols, the toxic effects are less significant (greater concentration threshold). This is the due to the fume flow rate parameter (§5.1.2) which is much more significant in the case of a fire of battery packs.

The lowest threshold concentration of gaseous effluents is therefore the one associated with a fire of a load of pallets of pesticides, which therefore constitutes the envelope load in terms of toxic effects.

Figure 12 presents the various plumes obtained at the threshold isoconcentration for the load of pallets of pesticides for various atmospheric conditions. This means that inside the plume, the concentration of gaseous effluents exceeds the threshold concentration and may constitute a hazard for a person standing inside that zone.

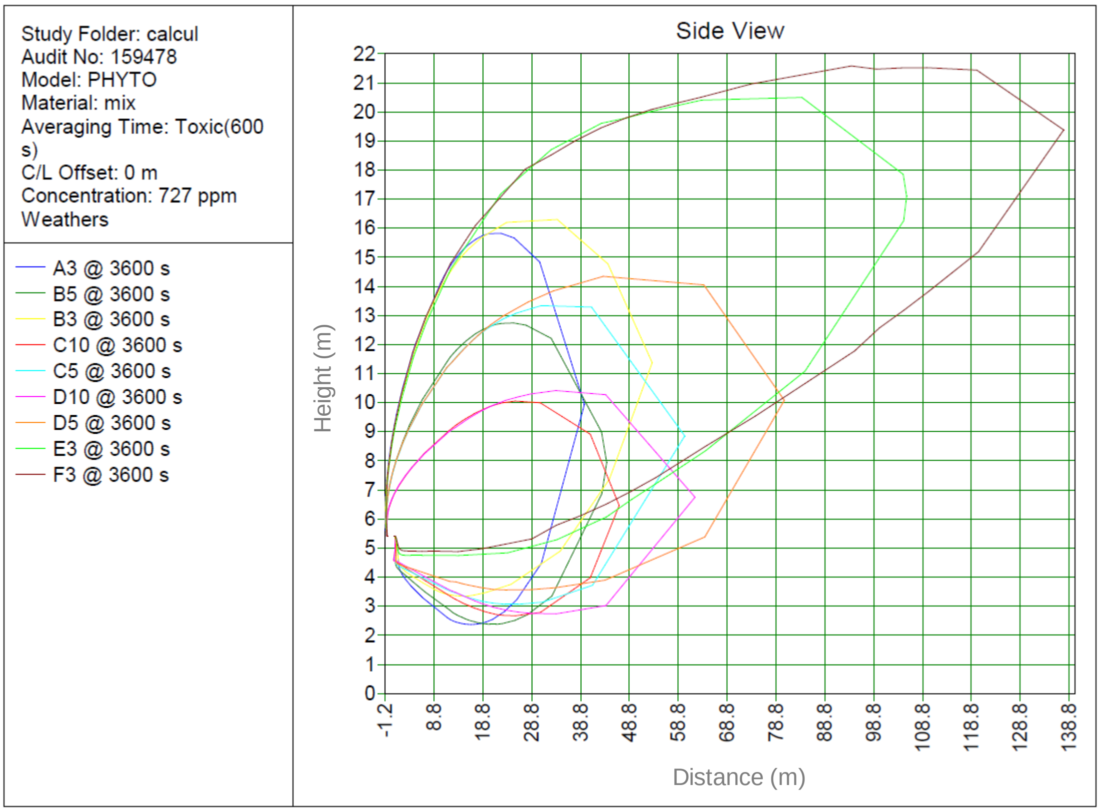

Figure 12: Smoke plumes at the threshold isoconcentration for various atmospheric conditions - pallets of pesticides

No matter the atmospheric conditions studied, no toxic effect at chest height was observed for a fire of pallets of pesticides. As the threshold concentrations of gaseous effluents calculated for the other loads were higher, a truck fire containing these various previously described loads will therefore not lead to toxic effects at chest height either.

5.3 CONFINED SPACE CALCULATION OF TOXIC EFFECT DISTANCES

5.3.1 Retained effect thresholds

It is to be noted that the study of toxic effects related to a vehicle fire in a confined space cannot be generalized since it is dependent on the geometric characteristics of the space (tunnel, parking lot...) and ventilation conditions. These specific studies are therefore performed on a case by case basis, using field study codes.

One qualitative approach that allows prioritizing toxic effects related to various loads in confined spaces would be to compare the amount of gaseous effluents emitted by the fires, for each load type, without taking into account the air entrainment which would depend on the ventilation of the confined space.

In our confined space study, we will use a data item which allows taking into account all the toxic elements present in the fumes. This data item is the TIE equivalent and is obtained using Equation 7.

$$\frac{1}{Threshold_{\text{equivalent}}} = \sum_{i=1}^{n} \frac{Csource_i}{Threshold_i} \qquad \text{Equation 7}$$

With:

$Csource_i$	=	Fraction of pollutant *i* at the source [ppm]
$Threshold_i$	=	Effect threshold for pollutant i [ppm]

This approach resembles the additivity law approach for thresholds described in paragraph 5.2.2.1 with the exception that the concentrations considered are those of source pollutants, having no information on the amount of air entrainment by the fire.

5.3.2 Confined space toxic effect thresholds of the various types of loads studied

Table 14 shows the volumetric concentrations of various gaseous effluents contained in the fumes for each load calculated on the basis of the test results presented in Table 9 as well as various TIE equivalents at the source of the various loads studied. The TIE equivalent at the source for a given load corresponds to the total concentration of the produced gaseous mix's gaseous effluents produced by the load fire and required to give rise to irreversible effects on people in 60 min. The various TIE equivalents at the source are ranked in increasing order, which means that the lower the value, the more significant the toxic effects.

	Combustible element	Volumetric concentration of gaseous effluents in fumes (-)							TIE equivalent at the source (ppm)
		CO	CO_2	HCl	HF	HCN	NO_2	SO_2	
Loading	66 pallets of plastic drums	4.35E-02	8.42E-01	3.87E-02	7.44E-02	2.90E-05	4.99E-04	5.64E-04	554
	33 pallets of pesticides	3.44E-02	8.97E-01	2.11E-03	2.46E-04	2.68E-03	3.86E-03	5.94E-02	989
	107 Battery packs N°2	3.14E-02	9.56E-01	1.69E-03	1.06E-02	5.11E-05	7.10E-04	0	4,434
	26 Blocks of polyurethane (PU) foam	5.06E-02	9.45E-01	7.63E-04	4.78E-04	2.26E-03	1.09E-03	0	5,309
	89 Battery packs N°1	2.13E-02	9.69E-01	8.64E-04	8.32E-03	4.07E-05	7.83E-04	0	5,834
	33 pallets of aerosols	7.13E-02	9.26E-01	1.50E-03	9.39E-04	1.69E-04	4.93E-04	0	5,850
	33 pallets of salads	7.23E-02	9.25E-01	1.05E-03	6.59E-04	1.18E-04	3.46E-04	0	6,520
	33 pallets of DVDs	2.26E-02	9.76E-01	4.84E-04	1.74E-04	3.13E-05	3.45E-04	0	14,091

Table 14: Volumetric concentrations and TIE equivalents for each load studied

Figure 13 compares equivalent TIEs at the source obtained for various loads. To help understand this, the data presented in this figure for each load result from the following formula:

$$\frac{Threshold_{equivalent\max}}{Threshold_{\text{equivalent}}} \qquad \text{Equation 8}$$

This formula implies that the greater the value, the greater the toxic effect.

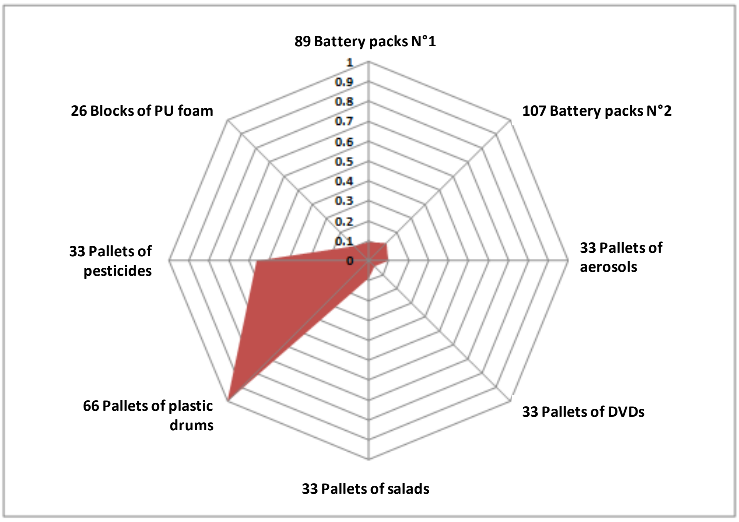

Figure 13: Qualitative analysis of toxic effects in confined spaces

The loads of pesticides products and plastics drums have the weakest TIE equivalents. Fire of these loads in a confined space will therefore lead to envelope toxic effects in comparison with other loads, and through experience, in comparison to all other load types not studied in the present study. Fire of loads of batteries, aerosols, salads and PU foam will lead to intermediate toxic effects, and fire of pallets of DVDs, to lower toxic effects. As a reminder, this qualitative approach only allows prioritizing toxic effects tied to the fires of the various loads studied.

These various threshold values can therefore be classified according to three distinct levels, detailed in Table 15.

TIE equivalent at the source (ppm)	Classified as hazardous goods	Not classified as hazardous goods
500 - 1,000	**Pallets of pesticides**	**Pallets of plastic drums**
4,400 - 6,500	**Battery packs N°2** **Pallets of aerosol containers** **Battery packs N°1**	**Pallets of salads** **Pallets of PU foam**
14,000 - 15,000		**Pallets of DVD's**

Table 15: Classification of TIE equivalents for fires of various loads studied

It is noted that for each potency level, with the exception of the 14,000 - 15,000 ppm level, we find products classified as dagerous goods and others that are not.

It is therefore observed that for battery stacks with energy and mass of the same order of magnitude, the TIE equivalents developed during a fire of a full load can:

- Be higher or lower than values for fires of dangerous goods loads,
- Be higher or lower than the values for fires of non-dangerous goods loads.

Moreover, in comparison to the characteristics of the two packs described in Table 5, it is impossible to conclude on the amount of energy transported, *etc.*, based solely on the composition (external or internal). A great number of parameters come into play and influence the toxic behavior of a full load fire.

According to this preliminary information, a classification of batteries as a function of their toxic effect according to the results of an external fire test therefore seems conceivable and justified.

5.4 CONCLUSION ON TOXIC EFFECTS

In view of the data obtained from this study we can conclude that:

- None of the studied loads show any toxic effect at chest level in an open field fire,
- Modifying one or more parameters in the design of the battery (architecture, external and internal components, etc.) may induce changes in the amount of gases produced,
- Toxic effects measured in a fire of a battery packs load can be lower or higher than measured effects on certain goods classified as dangerous in the transport sense (in our case, aerosols and pesticides),
- Depending on the battery tested, the toxic effects measured in confined spaces can be lower or higher than measured effects on certain goods classified as NOT dangerous in the transport sense (i.e. polyurethane foams),
- Information on the constitution of a battery does not permit a conclusion, without performing a test, about the importance of measured toxicity. For example, in our case, the presence of plastic on the battery pack N°2 casing causes one to suspect a much more important production of gaseous effluents (including CO and CO_2).

However, it is difficult to conclude on the relevance of the categorization of batteries for transport according to their toxic effects during an external fire test. Indeed, although this effect has been compared to other types of loading, none of these loads is classified as dangerous **for the toxic effects of these fumes**.

In addition, the likelihood of fire parameter has not been considered in this study. Now, although the toxic effects of batteries are, for example, equal to those of polyurethane foam, the likelihood of a fire starting, induced by the loading, is much higher in the case of batteries. It stresses that, for an equivalent toxicity, batteries, due to their higher fire probability, are more dangerous, in terms of toxicity, than a large number of loads.

Future work will therefore consist in:

- Identifying the relevant parameters to categorization,
- Setting, for these parameters, one or more thresholds that will allow to categorize batteries in one or more classes of toxicity,
- Defining a reliable and robust testing protocol in order to test batteries and retrieve data needed for the evaluation of the toxic effect.

6 GENERAL CONCLUSION

The study of thermal and toxic effects that may be generated by fires of several goods loads classified or not as dangerous to transport (including two types of battery packs) and based on tests previously conducted at INERIS has determined that:

- The effects can vary greatly from one battery type to another,
- The effects of battery loadings fires can be, depending on the battery type selected, lower or higher than fires of goods laodings classified as dangerous to transport as well as loads classified as NOT dangerous.

In order to carry out this classification, the future work will consist in:

- Defining of a reliable and resilient test protocol (used fuel, gas analysis method, …),
- Performing the tests on a representative current market sample,
- Defining the reference threshold values that will be used to classify the batteries.

An example of a final diagram illustrating a potential categorization procedure of a battery in a given class is presented in Appendix D.

TABLE OF APPENDICES

APPENDIX A:
VARIOUS CLASSES OF DANGEROUS GOODS

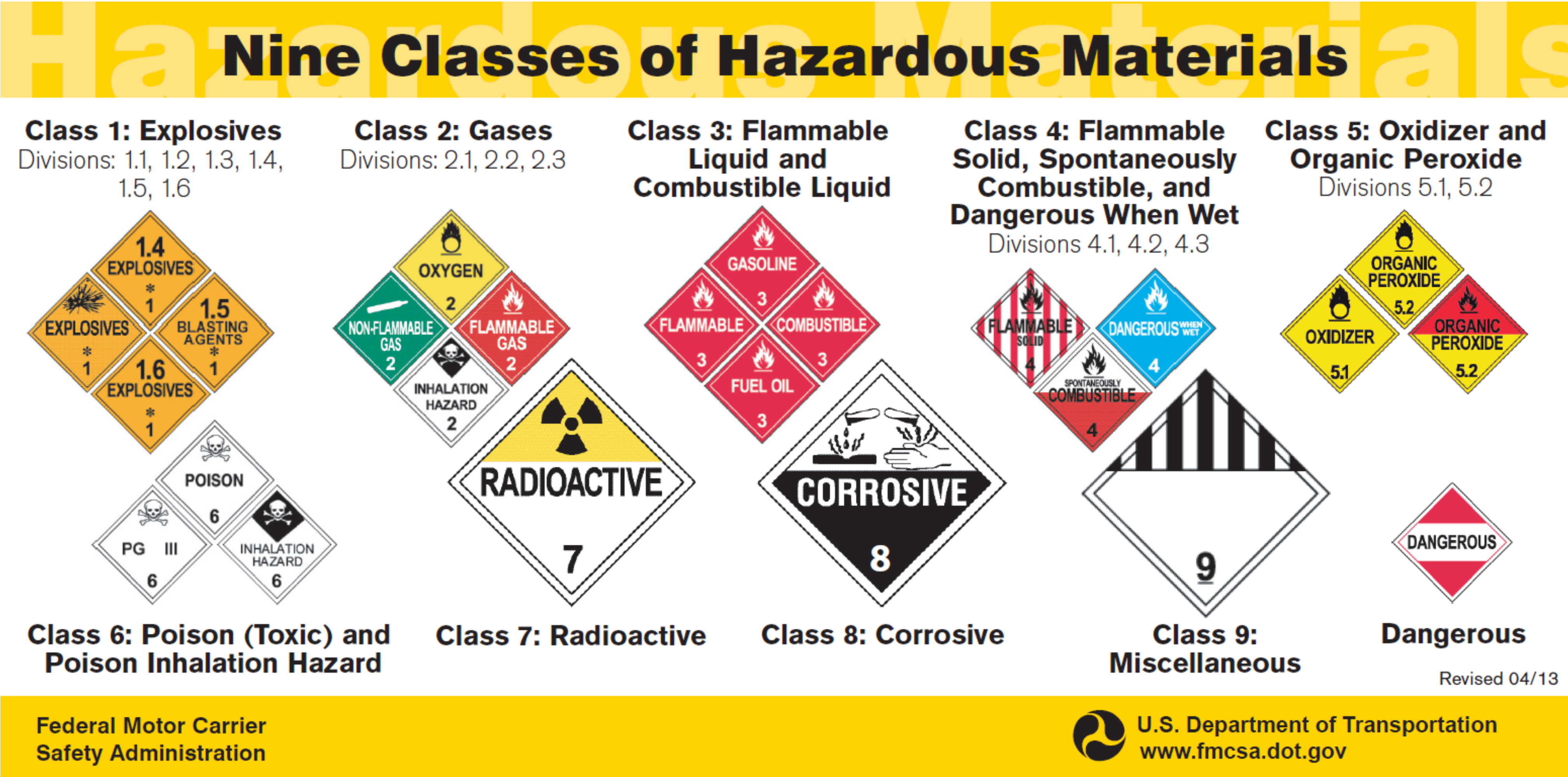

Figure 14: Nine classes of hazardous materials

APPENDIX B:
DESCRIPTION OF VARIOUS CELL GEOMETRIES AND CHEMISTRIES

A.i GEOMETRY

As far as cell geometry goes, four[20] types are currently used in the market (Figure 15):

- cylindrical cell: generally used for small cells. It is constructed by superimposing anode-separator-cathode-separator bands which are coiled around a central pivot
- prismatic cell: used for current greater than 10Ah. It's housing is rigid with protective elements (e.g.: safety valve)
- button cell: hardly used anymore for rechargeable lithium batteries
- pouch cell or: have a soft housing which is sealed close to the electrode-separator stack and allows for potential warping due to internal cell pressure.

Figure 15: Various lithium cell formats: cylindrical, prismatic and pouch

A.ii CHEMICAL COMPOSITION

Regarding chemical composition, we will distinguish between cathode and anode materials in the study below.

Currently, five[21] cathode materials are mostly present on the market:

- Cobalt Oxide, $LiCoO_2$ (LCO): material still widely used in current batteries due to its high energy density and its low auto-discharge, but has a higher cost (due to the Cobalt) and low thermal stability (runaway risk)
- Nickel-Manganese-Cobalt Oxide, $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (most widely used formula) (NMC): used more and more (particularly in electric vehicles), replacing cobalt oxide thanks to its greater thermal stability and lower cost.
- Nickel-Cobalt-Aluminum Oxide, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA): used more and more for stationary or mobile applications thanks to its high energy density and its long stability over time, but has a relatively high cost.

[20] http://batteryuniversity.com/learn/article/types_of_battery_cells

[21] N. Nitta, et al., Matter Today (2014)

- Manganese Oxide, $LiMn_2O_4$ (LMO): used more and more thanks to its lower cost relative to a cobalt oxide cathode, but has long-term cycleability which is inferior to other chemistries.
- Iron Phosphate, $LiFePO_4$ (LFP): used more and more thanks to its very strong thermal stability and its capacity to withstand high power levels, but has low energy density resulting from lower usage voltage than the preceding oxides

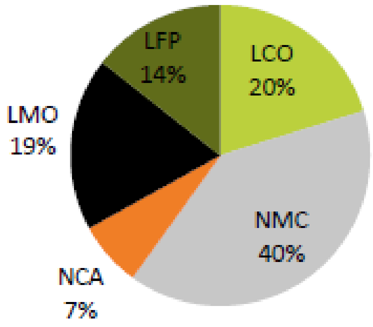

Figure 16: Lithium battery distribution forecast as relates to cathode material in 2020[22]

For anodes, two materials[21] are marketed on a large scale:

- Graphite: anode material present in the vast majority of current lithium batteries, thanks to its great abundance on earth, its low cost and strong thermal conductivity
- Lithium Titanate, $Li_4Ti_5O_{12}$ (LTO): used more and more thanks to its strong thermal stability, a capacity to withstand strong currents and long life, and despite a much higher cost than graphite as well as a lesser energy density.

Another type of lithium battery that is worth mentioning is the Lithium-Metal-Polymer battery developed solely by Batscap and used in the BlueCar electric vehicle. This battery is made up of a metallic lithium anode and a vanadium oxide, carbon and polymer-based cathode.

[22] The Worldwide battery market 2011-2015, Avicenne Energy Presentation, Batteries 2012

APPENDIX C:
EXAMPLES OF SAFETY DATA SHEETS FOR VARIOUS HAZARDOUS LOADS STUDIED

A.iii BATTERIES

MATERIAL SAFETY DATA SHEET March 7th, 2012

SECTION 11 – TOXICOLOGICAL INFORMATION

Routes of Entry:

Skin Contact: NO Skin Absorption: NO Eye contact: NO
Inhalation: NO Ingestion: NO

Acute Exposure	
Skin:	No effect noticed in routine handling of product.
Eyes:	The bulk solid has no effect on the eye.
Inhalation:	Not applicable.
Ingestion:	Ingestion is not likely, given the physical size and state of the cell.

Chronic Exposure	
Skin:	Not anticipated.
Eyes:	Not applicable.
Inhalation:	Not applicable.
Ingestion:	Ingestion is not a likely exposure route.

Exposure Limits:	Irritancy:	Sensitization:	Carcinogenicity:
None listed	None	Not anticipated	Not anticipated
Teratogenicity:	**Mutagenicity:**	**Reproductive toxicity:**	**Synergistic Products:**
Not anticipated	Not anticipated	Not anticipated	None expected

SECTION 12 – ECOLOGICAL INFORMATION

In case of the worn-out cell was disposed in land, the read tabs or the laminate film may be corroded, and leak electrolyte. But, we have no ecological information.

SECTION 13 – DISPOSAL CONSIDERATIONS

Do not disassemble or modify the cell. When the battery is throws away, be sure it is non-conducting by applying vinyl type to (+) and (-) terminals, and thrown away it in the method following the law of each countries. Always consult and obey all international, federal, provincial/state and local hazardous waste disposal laws. Some jurisdictions require recycling of this spent product.

SECTION 14 – TRANSPORT INFORMATION

UN No.:	UN Dangerous goods name:	UN Class:	
3480	LITHIUM ION BATTERIES	9	

There are some laws and regulations for transportation.
Please follow the law or regulation of each country.

Figur 17: Safety data sheet for battery pack N°1

A.iv Aerosols

Safety Data Sheet (SDS)

Date Prepared/Revised: 8/11/2015 Version no.: 01 Supersedes: (10/9/2014)

Mobility in soil: **No Data Available**
Results of PBT and vPvB assessment: **No Data Available**
Other adverse effects: **No Data Available**

13. Disposal Considerations

Waste Disposal: Dispose of material in accordance with EU, national and local requirements. For proper disposal of used material, an assessment must be completed to determine the proper and permissible waste management options permitted under applicable rules, regulations and/or laws governing your location.
Product / Packaging disposal: Dispose of packaging in accordance with federal, state and local requirements, regulations and/or laws governing your location.

14. Transportation Information

US DOT

UN Number	Proper Shipping Name	Hazard Class	Packing Group	Marine Pollutant	Special Provisions
UN1950	Aerosols	2.1	Not Applicable	Not Applicable	Reference 49 CFR 172.101

IMDG

UN Number	Proper Shipping Name	Hazard Class	Packing Group	Marine Pollutant	Special Provisions
UN1950	Aerosols	2.1	Not Applicable	Not Applicable	Reference IMDG code part 3

IATA:

UN Number	Proper Shipping Name	Hazard Class	Packing Group	Marine Pollutant	Special Provisions
UN1950	Aerosols, Flammable	2.1	Not Applicable	Not Applicable	Reference IATA Dangerous Goods Regulation

15. Regulatory Information

Workplace classification:
This product is considered hazardous under the OSHA Hazard Communication Standard (29 CFR 1910.1200). The Occupational Safety and Health Administration's interpretation of the product's hazard to workers.
SARA Title 3:
Section 311/312 Categorizations (40 CFR 372): This product is a hazardous chemical under 29 CFR 1910.1200, and is categorized as an immediate and delayed health, and flammability physical hazard.

Figure 18: Safety data sheet for aerosols

A.v Pesticides

Safety Data Sheet

DuPont™ Glean® XP Herbicide

Version 2.1

Revision Date 06/30/2015 Ref. 130000033378

Contaminated packaging : No applicable data available.

SECTION 14. TRANSPORT INFORMATION

IATA_C	UN number	:	3077
	Proper shipping name	:	Environmentally hazardous substance, solid, n.o.s. (Chlorsulfuron)
	Class	:	9
	Packing group	:	III
	Labelling No.	:	9MI
IMDG	UN number	:	3077
	Proper shipping name	:	ENVIRONMENTALLY HAZARDOUS SUBSTANCE, SOLID, N.O.S. (Chlorsulfuron)
	Class	:	9
	Packing group	:	III
	Labelling No.	:	9

Not regulated as a hazardous material by DOT.

SECTION 15. REGULATORY INFORMATION

Other regulations : This Safety Data Sheet is for a pesticide product registered by the US Environmental Protection Agency (USEPA) and is therefore also subject to certain labeling requirements under US pesticide law (FIFRA). These requirements differ from the classification criteria and hazard information required by OSHA for safety data sheets, and for workplace labels of non-pesticide chemicals. The following is the mandatory hazard information required by USEPA on the pesticide label:

CAUTION!

Harmful if swallowed. Wash hands thoroughly with soap and water after handling and before eating, drinking, chewing gum, using tobacco, or using the toilet.

SARA 313 Regulated : Chlorsulfuron

10 / 12

Figure 19: Safety data sheet for the herbicide chlorsulfuron

APPENDIX D:
EXAMPLE OF A POSSIBLE PROCEDURE FOR BATTERY TRANSPORT CLASSIFICATION

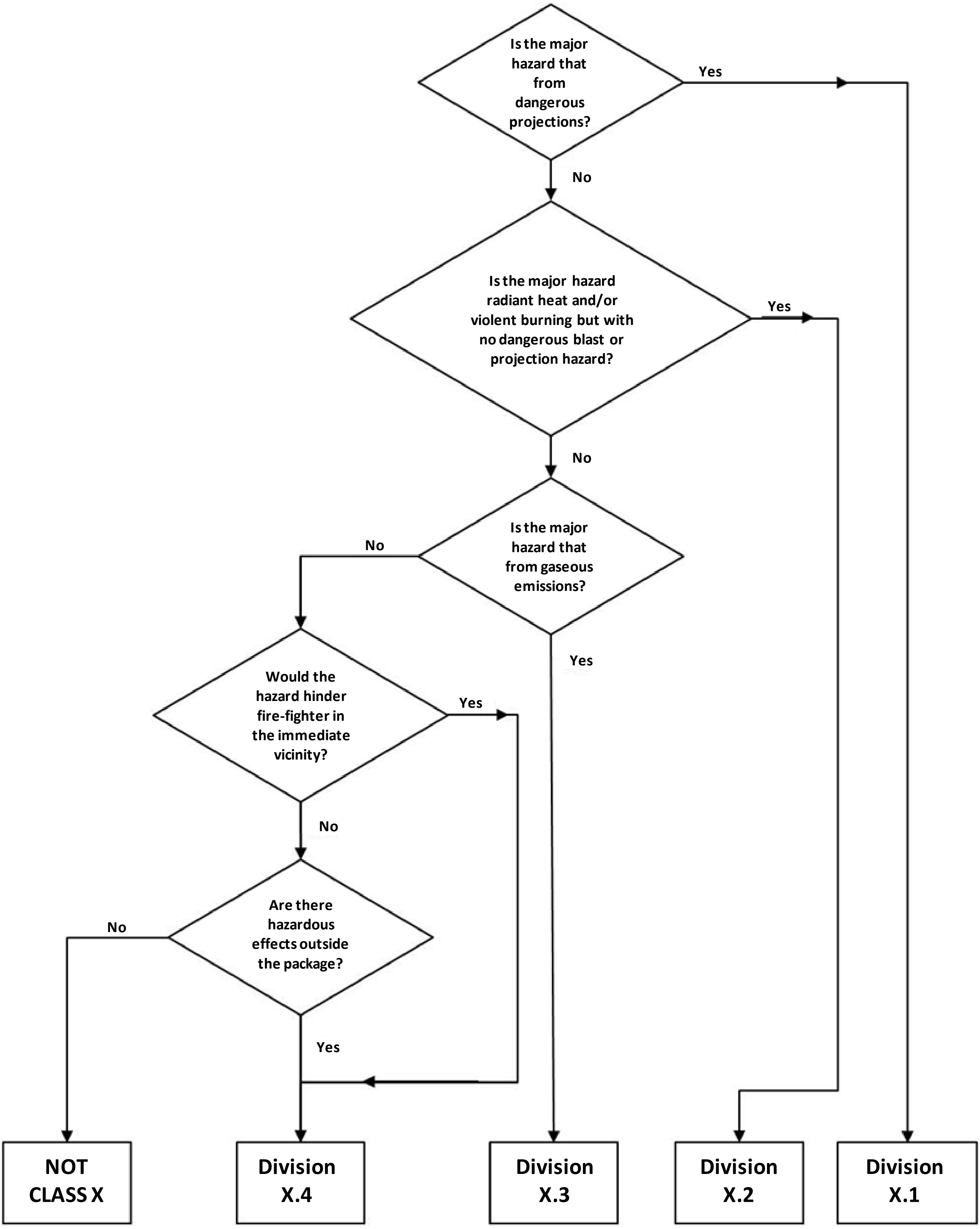

Figure 20: Example for a battery transport classification procedure

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Institut national de l'environnement industriel et des risques

Parc Technologique Alata
BP 2 - 60550 Verneuil-en-Halatte

Tél. : +33 (0)3 44 55 66 77 - Fax : +33 (0)3 44 55 66 99

E-mail : ineris@ineris.fr - **Internet :** http://www.ineris.fr