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Management of Lithium Batteries in the Treatment of WEEE: Dispersion Modelling and Containment Measures Applied to an Italian Case Study

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Fires originating from Waste from Electrical and Electronic Equipment (WEEE) containing lithium batteries pose a significant challenge for waste management facilities. This article aims to define fire containment measures for treatment plants and evaluate their effectiveness through a case study. After an overview of WEEE regulations and the risks associated with lithium batteries, both as standalone units and within electronic devices, the study analyzes a case study involving a WEEE treatment facility. It evaluates the consequences of an uncontrolled fire, specifically emissions from plastic items in WEEE storage. Using the ALOFT program, fire scenarios were modeled to assess the dispersion of volatile organic compounds (VOC) and Particulate matter (PM10). The study underscores the importance of addressing lithium battery fires in WEEE to support the EU’s recycling goals and ensure environmental and worker safety through a multi-partner approach.

* 1. Introduction

One of the most significant environmental challenges of the current historical period concerns waste management. In particular, waste electrical and electronic equipment (WEEE) represents an important part of the sector with a collection of approximately 6.11 kg per inhabitant, for a total of over 360,000 tonnes of equipment in Italy alone in 2022 (Centro di Coordinamento RAEE, 2022).

This article is dedicated to lithium batteries, which constitute a fundamental component of current electronic and electrical equipment, providing the necessary energy for their operation. It should be noted that lithium batteries surpass all other rechargeable battery options in terms of energy density and are therefore widely used in portable electronics. The increasing use of lithium batteries has opened up the delicate issue of their management during WEEE treatment: this is a multidimensional challenge that goes beyond the technical aspect and involves safety, environmental, economic and regulatory issues. In particular, companies that handle electrical and electronic equipment must face the risks of fire and environmental damage caused by batteries. For these reasons, the correct identification, handling, storage and disposal of lithium batteries is crucial for worker safety, environmental protection and the preservation of natural resources.

A case study relating to a leading company in the WEEE recycling sector is presented. Specifically, the production process, the problems arising from lithium batteries and the voluntary fire risk containment measures adopted are analysed. Emissions of particulate matter and volatile organic compounds resulting from an uncontrolled fire in the most at-risk phase of the treatment process have been quantified using the Aloft modelling software.

* 1. Waste management

Waste management represents one of the most significant environmental challenges of the current historical period. In particular, the production of waste electrical and electronic equipment has increased exponentially due to the increasingly massive spread of electronic devices in our daily lives. The proper management of WEEE waste has therefore become an important priority for many countries, in order to prevent environmental and health problems. The collection, transport and treatment of waste from electronic equipment are regulated by specific regulations, which require companies to responsibly manage end-of-life products.

Thanks to characteristics of high efficiency in energy storage, this type of battery is bringing important innovation in the field of renewable energy sources, in addition to having contributed to the spread of portable electronic products or electric vehicles (Zhang et al., 2023). For these reasons, there has been an exponential increase in the demand for lithium batteries, while the delicate issue of their disposal has not yet been adequately addressed. Lithium batteries are a type of battery that has different chemical compositions of its constituent parts. Primary batteries (non-rechargeable), called lithium metal batteries, consist of an anode made of lithium compounds and metallic lithium. Secondary batteries (rechargeable), called lithium-ion batteries, contain an anode made of a lithiated metal oxide, a cathode generally made of graphite, and lithium in ionic form as the electrolyte (Herreras-Martínez et al., 2021).

A battery is classified according to the amount of energy that can be stored inside it. This parameter also affects its capacity and the voltage across the battery itself.

Batteries inside devices can be removable or integrated; in the latter case, they are incorporated into the device itself and are not removable without the use of dedicated tools. Currently, most rechargeable batteries are integrated.

Although rechargeable, lithium-ion batteries must be replaced, as happens for all equipment after a more or less high number of charge and discharge phases.

The battery's performance during charging and discharging, in fact, undergoes a change over time, generating the phenomena of ageing and lifetime. The ageing of the secondary battery manifests itself through the reduction of its capacity, understood as maximum accumulable energy, and the increase of its internal resistance. When these parameters reach certain levels, the battery can no longer perform its functions. The end of life of a battery therefore does not coincide with the zero level of residual capacity but with 80% of the nominal capacity.

The ageing phenomenon is more pronounced when the battery is used in extreme or abusive conditions. Currently, there is no system to prevent the use of a secondary battery below its capacity, as, given the significant cost of replacement, the user tends to use the battery for as long as possible. However, when the battery capacity is reduced and the internal resistance is high, its stress is greater and this favours rapid loss of performance and susceptibility to equipment abuse, making it more dangerous. The secondary battery can also undergo degradation even if it is not used: this phenomenon is known as calendar ageing and can be influenced by external temperature and average state of charge (Corpo Nazionale dei Vigili del Fuoco, 2020).

The battery market has evolved towards products capable of providing high power while maintaining a reduced weight. For this reason, the battery components are designed to be lightweight, which translates into reduced partitions between the various cells and a thin outer coating. Due to these constructional characteristics, the partitions or coatings are fragile and easily punctured.

The main reasons why batteries can trigger a fire are short circuit and thermal runaway.

In the first case, contact between the two poles (positive and negative), generally separated through both internal and external connections, generates a short circuit. This phenomenon can be harmless or have sufficient thermal energy to generate the ignition of a fire. The risk of forming a short circuit is closely linked to the amount of residual charge still present in the battery when it is replaced.

The second phenomenon, called thermal runaway, occurs when the external environment is unable to completely dissipate the heat generated by exothermic reactions. The accumulation of heat, therefore, leads to an uncontrolled increase in the temperature and pressure of the internal components on the battery until it generates an explosion of energy sufficient to ignite the fire.

* 1. Methodology

In WEEE treatment facilities, fire incidents generated by lithium batteries are extremely numerous. In the plant under study, approximately 3 fire episodes occur per week. These events are recorded through the fire detection system consisting of thermal cameras installed both inside the covered areas and in the external areas of the line. The analysed plant has a total surface area of 55,450 m2, of which: 23,960 m2 is the covered surface of the building where the recovery activity takes place; an uncovered and waterproofed yard of 29,190 m2 for waste storage and vehicle transit; 2,300 m2 of green areas. In addition to WEEE, the plant also receives other similar waste in terms of recoverable metal components. The entire plant has a maximum storable waste quantity of 6000 tonnes, which includes both incoming waste for treatment and fractions obtained from recovery activities. The following presents a quantitative analysis of the effects of a fire with reference to the specific case of the plant's treatment line. The phase of the line that will be considered is the outdoor storage of reclaimed WEEE as it is the most at risk of fire. The impact that fires can have involves several complementary aspects, including: worker and citizen safety, environmental pollution, economic damages resulting from the loss of burnt materials, damage to structures and image damage. This analysis will only consider aspects of health and safety of workers and the population. Regarding WEEE fires, it was chosen to investigate the propagation of smoke produced by combustion. This choice stems from the fact that the combustible materials present in WEEE are almost exclusively plastic materials and that the treatment phase takes place outdoors.

Smoke from the combustion of plastic waste in open air spreads into the environment and is a main source of particulate matter (PM) pollution in the atmosphere; it is highly resistant to degradation and, therefore, represents a danger to human health (Borysov, et al., 2020). The quantities of reference waste for modelling were evaluated considering the most unfavourable real conditions. A maximum of two metal containers filled with waste can be deposited outside; each container has a volume of 25 m3 and a weight of 8 tonnes for a total of 16 tonnes of waste. To limit the storage time of reclaimed WEEE in the containers and thus limit the risk of fires, the company has arranged dedicated vehicles for transporting these containers to the section of the plant where the waste undergoes finer shredding, through grinders inerted with nitrogen to minimise ignition possibilities, which allows for the separation of components. These appliances, deprived of the most critical environmental components through previous reclamation operations such as batteries, cables, and electronic boards, are therefore deposited inside the metal containers.

It should be noted that the flammable materials present in the WEEE small appliances (R4) grouping are constituted by plastic materials which represent up to 35-40% by weight of small household appliances (Ballerini, 2021).

* + 1. Simulations

To evaluate the downstream distribution of smoke particulates produced by fires during the storage phase of WEEE the software ALOFT-FT® developed by National Institute of Standards and Technology (NIST) was utilized. This software models the downstream distribution of combustion products and the concentration of smoke from large outdoor fires. Smoke release from a fire can be modeled as a plume (McGrattan et al. 1997). The downstream length, shape, and extent of the smoke plume depend on wind speed and atmospheric stability, which are indicated by Pasquill-Gifford stability classes. There are six classes with further subdivisions based on different atmospheric conditions that vary in stability (Kahl & Chapman, 2018). The stability category corresponds to the standard deviation values of the prevailing wind direction in both horizontal and vertical directions. Typically, the smoke plume resides mainly in what is called the "planetary boundary layer" or "mixing layer" (Evans et al., 2001).

The behavior of the plume is also influenced by the phenomenon of thermal inversion, a specific meteorological condition characterized by the cooling of the air layer near the ground, resulting in an inversion of the vertical temperature gradient. In the presence of this phenomenon, characterized by particularly stable atmospheric conditions, the dispersion of pollutants is strongly inhibited for altitudes below 200 meters. Additionally, the movements of the plume are affected by ambient temperature and height. The phenomena associated are similar to the buoyancy effects expressed by Grashof (Lees, 2012).

Experiments revealed that simple smoke models do not capture the characteristics of the oblique plume and that the downstream distribution is not Gaussian (Walton et al.,2003). To address this issue, the NIST developed a smoke plume trajectory model that solves the fundamental Navier-Stokes equations, assuming that the component of the plume velocity in the wind direction is the same as the wind speed. The Reynolds number is fixed at 104, relating to flotation speed, vortical viscosity, and column height. This allows researchers and users to perceive the column as a two-dimensional element in the crosswind direction, while the downstream direction is monitored over time. The plume is analytically expressed with a grid, where a constant turbulent viscosity represents mixing and dissipation. The model does not show the fire's behavior over time but rather the smoke plume released during such a fire. The simulation starts several meters downstream of the fire, minimizing the small temperature variations characterizing the flow and radiant effect. As previously mentioned, the smoke tends to rise as it is warmer than the surrounding air. The wind speed is considered constant over the cross-section. In the nonlinear case, the plume penetrates the inversion layer, resulting in less particulate matter mixing towards the surface. For mathematical modeling, the principles of mass conservation, lateral and vertical momentum, and energy are applied.

In addition to the simplifications already introduced, the modeling includes four more:

* It does not consider heat exchange due to the radiant effect.
* The initial temperature and particle distribution are assumed Gaussian in the cross-section and non-Gaussian in the downstream section.
* The equations of motion are made dimensionless, and the three-dimensional system in a steady state can be considered a two-dimensional time-dependent system.
* The initial transverse velocity components (v, w) are assumed to be zero.

By considering the wind speed constant in the cross-section and replacing the spatial coordinate with the temporal one, the case can be described with a mixed system of partial differential equations. These are solvable using the finite difference technique. The solution relies on the Runge-Kutta method with variable steps and second order. The computational domain is divided into rectangular cells covering the entire plane in the downstream direction. The software inputs include wind speed and its variability, the atmospheric temperature profile, and fire parameters, while the output is the average smoke concentration in each computational cell from ground level to the top of the plume.

Using ALOFT-FT®, several simulations were conducted to evaluate eight possible fire scenarios for plastic materials contained in WEEE. For each scenario, the propagation of one of the combustion products considered in the study was analysed, namely PM10 particulate matter and volatile organic compounds (VOC). Particulate matter (PM10) emissions were investigated by creating specific simulations and modifying various parameters. The same was then repeated for volatile organic compounds. The environmental variables used in the simulations were ambient temperature of 25°C, geographical location, wind speed of 2 m/s or 5m/s and relative Pasquill class (D and F), and downwind distances chosen in a more limited area (1 km) and in surrounding areas (5 km). Regarding the fire area, the most unfavourable case was considered, namely a fire involving waste across the entire surface of both reclaimed WEEE waste containers. Each container has an upper surface of about 14 m2, for a total fire area of 28 m2, just above the minimum value of 25 m2 imposed by the ALOFT-FT® software for the simulation. In the simulations performed, the parameters for plastic materials were taken from the literature. Moreover, given the variability of the different types of plastics that make up the WEEE of the R4 grouping, the values of the parameters used for the simulations derive from an average of the data available for the different types of plastics (DiNenno, et al., 2002) (Janssens & Lyon, 2005) (Wu, et al., 2021) (National Air Quality Modelling & Assessment Unit, 2009). This approximation was also made in view of the fact that specific values for WEEE are not available in the literature. In this article, only two simulations are presented as illustrative examples.

* 1. Results

Airborne particulate matter represents the ensemble of solid and liquid atmospheric particles present in ambient air. The abbreviation PM10 identifies particles with an aerodynamic diameter not exceeding 10 µm.

The limit values for PM10 for the protection of human health have been defined in Annex XI of Legislative Decree No. 155/2010.



*Figure 1: Smoke Particulate PM10 concentration (micrograms/cubic meter – one hr avg) Vertical Plane. Downwind distance 5 km and wind speed of 2 m/s.*

Figure 1 analyses the distribution of PM10 in the case of moderately stable climatic conditions with a wind speed of 2 m/s, which corresponds to the average wind speed in the province where the plant is located; a downwind distance of 5 km was considered. From the simulation results, it is immediately noticeable that PM10 particles tend to rise from the ground and distribute at a variable height between 75 m and 100 m from the ground, even at a distance of a few tens of metres from the fire site. Under these conditions, however, it is noted that PM10 concentrations between 500 μg/m3 and 100 μg/m3 reach distances exceeding 5 km at a height of about 100-150 m.

The class of Volatile Organic Compounds (VOCs) includes numerous chemical compounds such as aliphatic, aromatic and chlorinated hydrocarbons, aldehydes, terpenes, alcohols, esters and ketones. The effects of VOCs on humans can be of various types, ranging from sensory inconvenience to severe alterations in health status (also carcinogenic).

The limit values for VOCs are expressed not only in Legislative Decree No. 161/2006 concerning the "Limitation of VOC emissions due to the use of organic solvents in certain paints and varnishes", but also in the Environmental Consolidated Act (Legislative Decree No. 152/2006) in Annex III of Part V, which states that in the case of gaseous effluents emitting VOCs classified as carcinogenic, mutagenic or toxic for reproduction in quantities greater than or equal to 10 g/h, a limit value of 2 mg/Nm3 applies, referring to the sum of individual VOCs. For emissions of VOCs classified as suspected of causing genetic alterations or suspected of causing cancer in emission quantities exceeding 100 g/h, a limit of 20 mg/Nm³ applies, referring to the sum of the masses of individual VOCs.



Figure 2: VOC Concentration *(micrograms/cubic meter – one hr avg*) *Vertical Plane. D*ownwind distance 1km and wind speed of 2 m/s.

In Figure 2, the simulation shows the distribution of VOCs on a day with moderately stable climatic conditions corresponding to a wind speed of 2 m/s; a downwind distance of 1 km was considered. As in the case of PM10, VOC emissions also tend to rise more rapidly from the ground compared to windier weather conditions. However, unlike what was observed with PM10, where reduced wind speeds resulted in a more extensive distribution of pollutants, for VOCs, the low wind corresponds to a concentration exceeding 50 μg/m3 that does not extend beyond 160 m from the fire site.

* 1. Conclusions

Lithium batteries have revolutionised the world of electrical and electronic products. Their high energy density and efficiency, as well as their long lifespan, have made this product desirable in various sectors, particularly contributing to the spread of consumer devices that have revolutionised daily life. However, the dangers of lithium batteries are now recognised following numerous fire incidents occurring worldwide. The high frequency of these incidents highlights the need to review the entire lithium battery management system, from design to disposal. There are already some contradictions in the regulations: lithium batteries are classified as dangerous goods by the European Agreement concerning the International Carriage of Dangerous Goods by Road, which provides specific packaging instructions to be applied during road transport, whilst in the European Waste Catalogue, lithium battery waste is identified as non-hazardous and therefore no hazard statements or safety management instructions are assigned. Given the magnitude of the fire problem and the absence of specific directives in lithium battery management, organisations representing the industry responsible for collecting and treating spent batteries and WEEE, together with manufacturers of household appliances and consumer electronic equipment, have developed a report containing a set of recommendations and best practices aimed at countering fires caused by lithium batteries contained in WEEE. Currently, the application of these guidelines remains a voluntary choice for companies.

In Italy, the Ministerial Decree of 26 July 2022 approved a new vertical technical rule of reference for the fire prevention design of waste storage and treatment facilities; regarding WEEE treatment facilities, the decree provides indications about the areas to be allocated for their storage.

Throughout this article, these topics have been extensively explored, including through consultation and collaboration with a company, a leading firm in WEEE treatment. The company has voluntarily adopted a series of technical, organisational and procedural measures that allow for containing the frequent phenomenon of fires occurring at its facilities, considerably limiting their extent. Moreover, the implemented fire detection and recording system has made it possible to identify that the most critical phase of treatment is the storage of reclaimed WEEE, theoretically free of hazardous components, including lithium batteries. This data, although apparently discordant with what has been expressed so far, highlights the objective difficulty of completely removing these batteries from devices. Indeed, the design and use of increasingly smaller batteries integrated into devices forces companies, obliged to separate them from WEEE by Legislative Decree 49/2014, to carry out macro-shredding of the WEEE itself to allow for the extraction of batteries which, during these operations, can be damaged and, if not extracted and managed, trigger a fire. For one facility, PM10 and VOC emissions that would be generated from an uncontrolled fire in the R4 grouping reclaimed WEEE storage area were also quantitatively assessed. The modelling of fire scenarios was conducted using the NIST ALOFT-FT® tool. The simulations showed that PM10 concentrations over extended areas exceed the limit values set by Legislative Decree no. 155/2010 in all fire scenarios considered.

Although a more stable atmospheric condition (class F), associated with lower wind speed, generates a greater distribution of particulate matter, greater atmospheric turbulence would be more dangerous for workers' health and safety as PM10 emissions would tend to remain suspended in the first few metres from the ground over a very extensive area compared to the fire location. However, this analysis has limitations deriving from the fuel characteristics considered for the calculation and the simplifications adopted by the modelling software. Further research could repeat the same simulations with other software and compare the results obtained; additional studies could explore the issues by performing simulations with ALOFT-FT® and comparing them with real data. Furthermore, it would be useful to investigate the emission of other combustion products, including gases emitted by lithium batteries, and their impact on humans and the environment.

Ultimately, this work brings forth a crucial reflection on the need to reconsider the general approach to WEEE management, taking into account the possibility of distinguishing between equipment containing lithium batteries and those that do not. A more targeted strategy could allow for the development of specific treatment protocols for lithium batteries, more effectively addressing the associated risks and limiting the volume of WEEE exposed to fires. Moreover, given the active role of citizens and ecological operators, it is important to promote awareness campaigns aimed at separating, where possible, batteries from WEEE before delivery to collection centres or at the centres themselves.

In summary, the recycling of electrical and electronic equipment represents an important element in achieving the EU's overall sustainability objectives. Currently, battery fires represent a real challenge for the recycling industry and the entire value chain: properly addressing the risk of fires caused by lithium batteries contained in WEEE through a multi-partner approach is essential to support recycling companies in protecting the environment and their workers.

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