Waste Management 34 (2014) 1257–1263

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Occupational exposure in the fluorescent lamp recycling sector in France

François Zimmermann *, Marie-Thérèse Lecler, Frédéric Clerc, Alain Chollot, Eric Silvente, Jérome Grosjean

Department of Process Engineering, Institut National de Recherche et de Sécurité, 54500 Vandoeuvre-les-Nancy, France

A R T I C L E   I N F O

Article history:
Received 20 September 2013
Accepted 28 March 2014
Available online 24 April 2014

Keywords:
WEEE
Lamp recycling
Occupational exposure
Ambient concentration

A B S T R A C T

The fluorescent lamp recycling sector is growing considerably in Europe due to increasingly strict regulations aimed at inciting the consumption of low energy light bulbs and their end-of-life management. Chemical risks were assessed in fluorescent lamp recycling facilities by field measurement surveys in France, highlighting that occupational exposure and pollutant levels in the working environment were correlated with the main recycling steps and processes.

The mean levels of worker exposure are 4.4 mg/m^3, 15.4 µg/m^3, 14.0 µg/m^3, 247.6 µg/m^3, respectively, for total inhalable dust, mercury, lead and yttrium. The mean levels of airborne pollutants are 3.1 mg/m^3, 9.0 µg/m^3, 9.0 µg/m^3, 219.2 µg/m^3, respectively, for total inhalable dust, mercury, lead and yttrium. The ranges are very wide. Surface samples from employees' skin and granulometric analysis were also carried out. The overview shows that all the stages and processes involved in lamp recycling are concerned by the risk of hazardous substances penetrating into the bodies of employees, although exposure of the latter varies depending on the processes and tasks they perform. The conclusion of this study strongly recommends the development of a new generation of processes in parallel with more information sharing and regulatory measures.

1. Introduction

Whilst the availability of clear incandescent and conventional halogen lamps has fallen since the EU Ecodesign Directive (2009) prohibited the sale of certain traditional style energy intensive light bulbs, the growth in sales of discharge lamps is likely to continue in the years to come. Fluorescent lamps come under the category of discharge lamps in which the light is generated by an electric discharge in a gas or vapor. In this illumination process, a droplet of liquid mercury is introduced in the fluorescent lamp and a phosphor-coated glass tube is used to convert the ultraviolet light into visible light output (Aman et al., 2013). The phosphor coating is formed by special luminescent powder containing rare earth elements and metals.

In 2011, 30 million (4040 tons) spent lamps were collected in France, representing 35% of overall end-of-life recyclable lamps (Recylum, 2012). Compliance with the 2003 European WEEE directive (Directive 2002/96/EC) and the accreditation of Recylum in 2006, the French eco-organization devoted to the waste management of spent lamps, has led to the increased collection of spent lamps and better organization of the lamp recycling sector, reinforcing the activity of existing facilities and leading to the creation of facilities capable of handling this waste efficiently. The minimum targets of recycling efficiency of spent lamps fall within the scope of the new WEEE directive (Directive 2012/19/EU), i.e. 75% shall be recovered and 55% shall be prepared for re-use and recycled.

Although the RoHs directive (Directive 2002/95/EC) prohibited the use of certain hazardous substances in electrical and electronic equipment, the use of mercury is still permitted in fluorescent lamps because low-pressure mercury vapor is essential for them to work properly (European Commission, 2009). The amount of mercury in compact fluorescent lamp should be lower than 5 mg per lamp, while Santos et al. (2010) showed that 40% of the lamps analyzed contained more than this limit allowed by European Community. By crossing information on mercury distribution (Rey-Raap and Gallardo, 2012) and mercury speciation (Raposo et al., 2003) inside spent fluorescent lamps it is possible to highlight the fact that treating this e-waste cleanly is a difficult problem. Worldwide, various fluorescent lamp recycling scenarios (Rasapo and Roeser, 2001; Chang et al., 2007; Apisitpuvakul et al., 2008; Asari et al., 2008) have shown that a significant part of mercury is released into the environment by various media including emission into the air. Initiatives have emerged to remove mercury (Chang et al., 2009; Rey-Raap and Gallardo, 2013) and to

* Corresponding author. Tel.: +33 383509837.
E-mail address: francois.zimmermann@inrs.fr (F. Zimmermann).

http://dx.doi.org/10.1016/j.wasman.2014.03.023
0956-053X/

recover yttrium from spent fluorescent lamps (De Michelis et al., 2011). In fact, dust and powdery materials (e.g. yttrium-containing luminescent powder) can also be spread into the occupational atmosphere throughout the fluorescent lamp recycling process.

It is therefore assumed that handling and processing lamps can generate occupational health issues, depending on the processes, procedures and operations used, and on the degree they cause emissions. Despite growing awareness of health risks for workers in the e-waste recycling industry as a whole (Searl and Crawford, 2012; Lundgren, 2012) and the knowledge gained on the risks of mercury escaping from broken fluorescent lamps (Nance et al., 2012; Hu and Cheng, 2012; Salthammer et al., 2012), there is a lack of extensive exposure measurement data in the spent lamp recycling sector, especially in developed countries where management policies are being implemented.

The aim of this article is to review an exposure assessment in the five French spent fluorescent lamp recycling facilities that highlights occupational exposure and pollutant levels in the working environment and correlates them with the main recycling steps and processes. The locations of pollutant sources assumed in the discussion of this article were complemented using real-time measurements.

2. Material and methods

2.1. Description of treatment facilities

Two main types of treatment processes are involved in developed facilities for recycling fluorescent lamps:

- The "end cut" processes. A guide-chain leads the lamps into an enclosed, depressurised chamber. The metallic end-caps are removed by cutting and the luminescent powders deposited on the internal face of the glass are flushed out with jets of compressed air. The cleaned glass is milled. All the outputs are stored in separate containers. This type of process requires preliminary sorting of straight fluorescent lamps by length and diameter.
- The crushing processes. These processes are used either for fluorescent or compact fluorescent lamps. Batches of lamps are fed into a shredder or crusher where the degree of separation of the outputs varies as a function of the process. These types of processes generally function without any preliminary sorting.

Table 1 presents an overview of the facilities and processes reviewed in the lamp recycling sector.

2.2. Sampling, analysis and measurement methods

Assessing levels of exposure and pollution with dusts and metals was performed by taking personal and airborne samples, respectively. Particulate aerosols corresponding to the inhalable fraction (aerodynamic diameter <100 μm) were sampled at a flow-rate of 2 L/min in 37 mm closed cassettes on PVC capsules fused to a cellulose acetate filter (Accu-Cap™).

2.2.1. Metal-containing inhalable dust and mercury vapors

Inhalable dust concentrations were determined by gravimetry according to the INRS Metropol 002 method (INRS Metropol, 2009). Chemical analyses of metals were performed by plasma emission spectrometry using ICP Varian 720-ES. The latter required dissolving and mineralizing the capsules according to the INRS Metropol 003 method (INRS Metropol, 2008).

Mercury was sampled using Hydrar SKC Anasorb C300/500 mg at a flow-rate of 2 L min^{-1}. Plasma emission spectrometry analysis was performed by displacing the cold vapor after extraction according to the INRS Metropol 024 method (INRS Metropol, 2000).

The range of elements analyzed in the samples includes the following: Hg_{vapour}, Al, Ba, Be, Cd, Ce, Cr, Er, Eu, Fe, Gd, La, Mn, Ni, Pb, Pr, Sb, Sn, Si, Tb, Ti, Y, Yb, Zn.

In this study, the level of personal dust exposure and airborne dust corresponding to total inhalable dust and the level of personal exposure and airborne dust of key agents (e.g. Hg_{vapor}; and Pb, Y, Ba in the inhalable dust) were used to assess the atmospheric exposure of workers and evaluate process efficiency. Yttrium can be considered as a tracer of contamination caused by the release of fluorescent powders. Lead mainly stems from glass dust although it has been identified in fluorescent powders, too. The current French occupational exposure limit values (OEL) for yttrium, lead, barium and mercury are 1000 $\mu g/m^3$, 100 $\mu g/m^3$, 500 $\mu g/m^3$ and 20 $\mu g/m^3$, respectively.

2.2.2. Surface contamination

Surface samples from operators' skins and work surfaces were also taken using GhostWipes. Surface samples from workstations were taken over a 10 cm × 10 cm area. The skin of operators' hands and necks were mainly swabbed.

The amount of metal-containing dust deposited on operators' skin (hands and neck – in μg) was used as an indicator of surface contamination. There are currently no occupational regulatory limit values and no consensus values for surface pollution at national, european and international levels. In France, a reference value of 10 $\mu g/dm^2$ of lead is used as the limit set by the public health authorities in houses after construction (decree of May 12, 2009).

2.2.3. Granulometric analysis

A granulometric analysis was carried out to complement the quantitative atmospheric exposure data with particle size information. The particle size distribution was measured in liquid suspension using the Malvern Mastersizer X technique. This optical laser technique measures particle distribution by scattered light analysis. The distribution of particle volume is measured as a function of optical diameter. Imaging using a Jeol 7400-F field-emission gun scanning electron microscope was also performed.

2.2.4. Real-time measurement

In addition, real-time measurements were also taken by direct reading of atmospheric pollutant concentrations (dusts, mercury vapors) and dust granulometry using portable optical analyzers (MIE Personal DataRam photometer, LightHouse Handheld 3016-IAQ) and mercury detectors (Mercury Tracker 3000). Real-time measurements were performed during specific operations and periodically in the treatment facilities to support the hypothesis of emission sources.

3. Results

The granulometry of dust and powder emitted during the different steps of the treatment process showed that a significant proportion of the dust is in the alveolar fraction (Table 2), including a sizeable proportion of nanoparticles (Fig. 1).

Workers in lamp recycling facilities are commonly involved in versatile tasks covering all the processing stages: storage management, lamp sorting, process feeding, output management and other various activities (e.g. cleaning and maintenance operations). They are, however, devoted to only one type of treatment process. Their main work area is around this process, feeding it with spent lamps and managing the outputs when required. Table 3 gives the occupational atmospheric exposures of workers versus the two