Applied Radiation and Isotopes 113 (2016) 40–46

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

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

Radiological characterization of printed circuit boards for future elimination

Biagio Zaffora*, Matteo Magistris

CERN, 1211 Geneva 23, Switzerland

HIGHLIGHTS

- We proposed a general characterization process for activated Printed Circuit Boards (PCBs).
- Estimated a reference chemical composition for electronic boards.
- Calculated the radionuclide inventory and the importance of major radionuclides.
- Identified the chemical composition, the radiation field and the cooling time as sensible parameters for the activation of PCBs.
- Validated the characterization method with real-life cases of PCBs activated at CERN.

ARTICLE INFO

Article history:
Received 12 February 2016
Received in revised form
24 March 2016
Accepted 11 April 2016
Available online 13 April 2016

Keywords:
Radioactive waste
Radiological inventory
PCB
Electronic circuits

ABSTRACT

Electronic components like printed circuit boards (PCBs) are commonly used in CERN's accelerator complex. During their lifetime some of these PCBs are exposed to a radiation field of protons, neutrons and pions and are activated. In view of their disposal towards the appropriate final repository, a radiological characterization must be performed. The present work proposes a general characterization procedure based on the definition of a reference chemical composition, on the calculation of the corresponding radionuclide inventory and on the measurement of a tracer radionuclide. This method has been validated with real-life cases of electronic boards which were exposed to the typical radiation fields in CERN's accelerators. The activation studies demonstrate that silver is the key element with respect to the radiological characterization of electronic waste due to the production of Ag-110m and Ag-108m. A sensitivity analysis shows that the waiting time is the main parameter affecting the radionuclide inventory. Results also indicate that, as is the case of other families of radioactive waste, an accurate assessment of the radiological inventory of PCBs would require the precise knowledge of their chemical composition, as well as the radiation field to which they were exposed.

1. Introduction

At CERN (European Organization for Nuclear Research) electronic systems are widely installed in the tunnels of the accelerator's complex. Depending on their radiological history, at the end of their life time they can become radioactive electronic waste. Electronic waste represents 5% to 10% of the radioactive waste that will be produced at CERN before 2030. It is mainly composed of electrical and electronic elements such as amplifiers, cables, connectors, power systems, resistors and bare PCBs (Printed Circuit Boards). The present work aims at establishing a specific procedure for the radiological characterization of PCBs, which represent the most challenging part of electronic waste to be characterized, due to the presence of chemical impurities. Such characterization is a fundamental requisite for the final disposal of activated PCBs as radioactive waste.

There are very few written studies in scientific literature on the radiological characterization of electronic systems in view of their disposal as radioactive waste. The characterization process proposed here is primarily focused on particle accelerators, but the underlying principles can be applied to electronic waste which was activated via neutron irradiation in nuclear power plants.

A disposal pathway for radioactive electronic waste has not been identified at CERN yet. For the present study, it was assumed that the French national repository for very-low-level radioactive waste would be the most plausible option. Clearance from regulatory control is not presently considered at CERN because of the major characterization challenge represented by the activation of chemical impurities in PCBs. Despite uncertainties on the disposal pathway which will be adopted, this preliminary study on the

* Corresponding author.
E-mail address: biagio.zaffora@cern.ch (B. Zaffora).

http://dx.doi.org/10.1016/j.apradiso.2016.04.006

characterization of PCBs allows the identification of treatment and measurement constraints, the definition of traceability requirements regarding radiological history and the planning of future characterization campaigns.

A method to calculate a reference chemical composition for PCBs is presented in Section 2. The description of the characterization process and the results obtained by simulations are described in Section 3. A benchmark experiment with irradiation conditions, measurement results and their comparison with calculated values is presented in Section 4. The conclusion and perspectives are summarized in the last section of the article.

2. Materials and methods

2.1. Chemical reference composition

The chemical composition of the materials used in electronic systems is a crucial input parameter for the calculation of the radionuclide inventory. This section describes a conservative chemical composition that can be used as a reference when prior information on elements and trace content of PCBs is not available. The reference composition so obtained is used for calculations in the context of the general process of radiological characterization, presented in Section 3.

From a chemical point of view, PCBs are very complex entities; the number of elements they are made of can range from few to many dozens. A limited number of studies covering a detailed chemical analysis of PCBs can be found in written works such as Gooesy and Kellner (2003), Ogunniyi et al. (2009), Theo (1998). A conservative reference composition for PCBs was here defined by identifying the main materials used to fabricate electronic boards as described in Coombs (2007).

Each PCB is fabricated using a low number of basic units, such as metals (for the conductive layers and soldering), reinforcement structures (woven glass, mat glass and cotton paper) and resins (Jawitz, 1997). Materials for the reference composition are chosen on the frequency of their use at CERN.

For metals, the list of elements given by Gooesy and Kellner (2003) is used. In reference (Gooesy and Kellner, 2003), Goosey and Kellner propose the results of chemical analysis which were carried out in scraps of medium grade electronic boards collected in recycling facilities.

For resins and reinforcement structures dedicated calculations were carried out. In particular, for resins the repeat units of difunctional ($C_{18}H_{24}O_3$) and brominated difunctional epoxy ($C_{18}H_{24}O_3Br_4$) were selected. As described in reference (Coombs, 2007), a common version of epoxy used for printed circuit applications is manufactured from the reaction between epichlorohydrin and bisphenol-A. The bromination of the bisphenol-A provides flame retardancy. Difunctional and brominated difunctional epoxy are the results of the reactions described and will be considered as representative of the epoxy component for PCBs used at CERN. The percentage weight of each element of the polymeric molecules was calculated as follows:

$$wt\,(\%)_{i=C,H,O,Br} = \frac{n_i \times M_i}{\sum_{j=C,H,O,Br} (n_j \times M_j)} \tag{1}$$

where $wt\,(\%)$ is the percentage of weight of the generic element C, H, O or Br, n_i and n_j indicate the number of atoms of the elements i and j, M_i and M_j indicate the molar weight of the elements i and j.

Amongst all the reinforcement systems presently available on the market, fiberglass offers the best solution in terms of mechanical, electrical, physical and chemical constraints (Wallenberger et al., 2001) and is therefore the most frequently used.

Table 1
List of key elements in the reference chemical composition of PCBs as used at CERN.

Component	Weight contribution (%)
Silicon Dioxide	52–56
Calcium Oxide	16–25
Aluminum Oxide	12–16
Boron Oxide	5–10
Na-Oxide and K-Oxide	0–2
Magnesium Oxide	0–5
Iron Oxide	0.05–0.4
Titanium Oxide	0–0.8
Fluorides	0–1

For the construction of the reference composition the E-glass - or electrical grade glass - was chosen as representative of fibres of glass (Astm, 2011). References (Coombs, 2007; Wallenberger and Bingham, 2009) describe the reasons for the commercial success of E-glass in electronic applications including low cost, high production rate, non-flammability, resistance to heat and good electrical insulation. A detailed chemical composition of E-Glass can be found in references (Coombs, 2007; Wallenberger et al., 2001).

For the weight contribution of E-glass to the total weight of the reference composition, the same general Eq. (1) used for resins applies. This formula is adapted to the chemical elements present in the composition of the fiberglass. Table 1 shows the weight fraction of some key elements for the proposed reference composition of PCBs.

A set of 50 γ-ray spectrometry measurements were performed on electronic boards, which were activated either at CERN or at external irradiation facilities in 2012 and 2013.The chemical composition here presented is regarded as conservative in the sense that it predicted the production of every single γ-emitter that was detected during this validation experiment.

2.2. Calculation of hazard factors

The present work focuses on the possible disposal as radioactive waste of PCBs towards the French low-level repository (In French: *Très Faible Activité* or *TFA*) in the Aube district. The technical specifications for the radiological acceptance of such families are developed by the French National Radioactive Waste Management Agency (ANDRA) (ANDRA, 2013).

To define the radiological acceptability of a waste batch at the TFA repository, an hazard factor called IRAS[1] was defined as follows:

$$IRAS = \sum_i \frac{a_i}{10^j} \tag{2}$$

where a_i is the specific activity of the radionuclide i (in Bq/g) in the mass of the given waste and j is the TFA class number (0, 1, 2, 3) of the waste which gives an information about the radiological toxicity of a radionuclide.

When disposing of a batch of waste as TFA, the weight of each waste package and the total weight of the batch must be taken into account to determine the $IRAS_{batch}$:

$$IRAS_{batch} = \frac{\sum_k M_k \times IRAS_k}{\sum_k M_k} \tag{3}$$

where M_k is the weight of the k-package of the batch and $IRAS_k$ is the IRAS of the k-package of the batch calculated by the Eq. (2).

A necessary condition for a batch to meet the acceptance

[1] In French: *Indice Radiologique d'Acceptation en Stockage*.